2014/15 Annual Report to Canada's Department of Innovation, Science, and Economic Development

Covering the Objectives, Activities, and Finances
for the period August 1, 2014 to July 31, 2015 and
Statement of Objectives for Next Year and the Future

Submitted by: Neil Turok, Director
To: The Hon. Navdeep Bains, Minister of Innovation, Science, and Economic Development
Attn.: The Hon. Kirsty Duncan, Minister of Science
Attn.: The Hon. Bardish Chagger, Minister of Small Business and Tourism and MP for Waterloo

Vision: To create the world's foremost centre for foundational theoretical physics, uniting public and private partners, and the world's best scientific minds, in a shared enterprise to achieve breakthroughs that will transform our future.

Overview of Perimeter Institute

"Perimeter Institute is now one of the world's leading centres in theoretical physics, if not the *leading centre."*
– Stephen Hawking

In just 15 years, Perimeter Institute (PI) has delivered one of Canada's biggest research successes in decades: an innovative, world-leading centre of research, training, and outreach in the lowest-cost, highest-return area of science, fundamental physics.

Founded in 1999, in Waterloo, Ontario, Perimeter is an unprecedented effort to strategically accelerate discovery in this most basic area of science. Its visionary funding model unites public and private partners, and some of the world's best scientific minds, in a shared quest to achieve the next breakthroughs, which will transform our future.

Perimeter's rise – against steep odds – has been spectacular. The Institute has attracted top international talent to Canada, built a track record of discovery, earned a global reputation for research, and been ranked among the top centres worldwide in theoretical physics.

- Third-party audits of the Institute invariably give it top marks,[1] and it has earned a stellar reputation among scientific and political leaders, both nationally[2] and internationally.[3]
- "Mapping Scientific Excellence," a study led by the Max Planck Society in Germany, ranked scientific institutes worldwide based on objective data including publications and citations. Among theoretical physics research centres, Perimeter ranked second.[4]
- A 2011 study by Thomson Reuters ranking national citation impact in physics among G8 countries showed that Canada's scientific impact in physics has risen dramatically since Perimeter's inception. In 2010, Canada ranked first in physics citation impact; without Perimeter, Canada would have ranked fourth.[5]

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[1] See, for example, a KPMG audit from 2011: http://www.perimeterinstitute.ca/files/articles/attachements/pi_final_evaluation_report.pdf.

[2] "International and Canadian experts identified several infrastructure facilities associated with Physics and Astronomy that are an advantage for Canada, including the Canadian Light Source synchrotron, the Sudbury Neutrino Observatory/Laboratory, TRIUMF (Canada's national laboratory for particle and nuclear physics), and the Perimeter Institute for Theoretical Physics." p. 173, The State of Science and Technology in Canada, 2012, The Expert Panel on the State of Science and Technology in Canada, Council of Canadian Academies.

[3] See the 2006 NSERC Review of Perimeter Institute: http://www.perimeterinstitute.ca/files/page/attachments/info_drawn_from_2006_nserc_review_information.pdf

[4] L. Bornmanna, M. Stefanerb, F. de Moya Anegónc, and R. Mutzd, "What is the effect of country-specific characteristics on the research performance of scientific institutions? Using multi-level statistical models to rank and map universities and research-focused institutions worldwide," *Journal of Informetrics*, Volume 8, Issue 3 (2014), Pages 581-593.

[5] See: "Publication Output and Citation Impact of Perimeter Institute's Physics Research," Thomson Reuters, May 2012 (unpublished; available upon request), and "Bibliometric Evaluation and International Benchmarking of the UK's Physics Research."

- Through PI researchers, Canada has gained a place at the heart of the largest and most important experimental and observational efforts of our time, including the Large Hadron Collider at CERN (LHC), the Event Horizon Telescope (EHT), the Laser Interferometric Gravitational-Wave Observatory (LIGO), the Planck satellite, and the Square Kilometre Array (SKA). Perimeter scientists are first movers on the data, without Canada bearing millions of dollars for the experimental infrastructure. At the same time, the Institute's scientists work with leading Canadian experiments – such as SNOLAB and the Canadian Hydrogen Intensity Mapping Experiment (CHIME) – by helping to lead the planning, interpretation, and analysis of data.
- The Institute has built a reputation of being first in the world to hold gatherings on breaking ideas and experimental results, further positioning Canada at the cutting edge of research. For example, directly after the 2012 discovery of the Higgs boson, Perimeter held the first North American workshop examining its implications and future directions for particle physics. Similarly, in the wake of the 2014 BICEP2 claim of gravitational wave detection, Perimeter was the first to gather experts to analyze it, raising doubts (that were later validated).

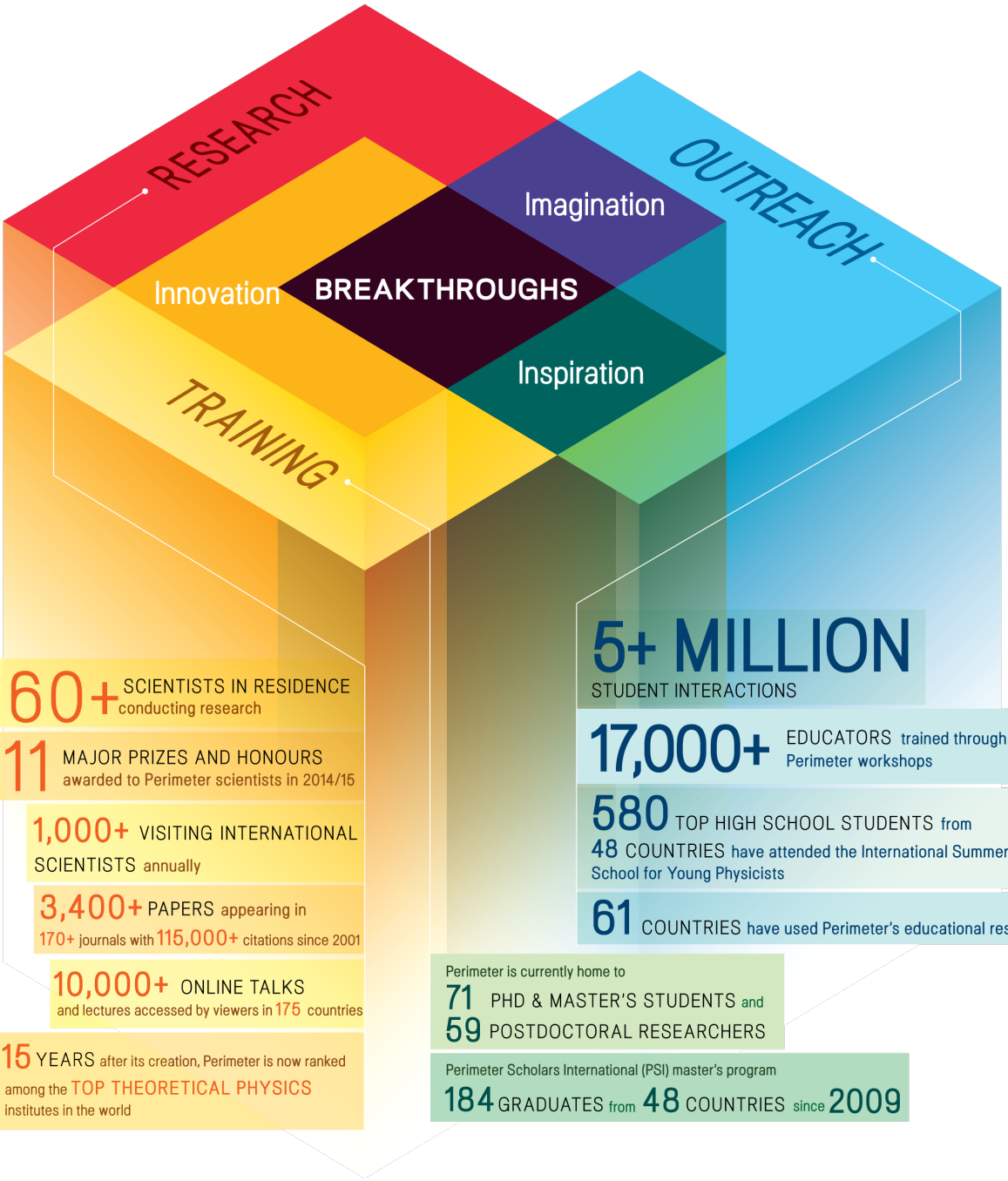
The Institute has attracted some of the most brilliant researchers in the world, from the best graduate students to renowned physics pioneers. Moreover, by collaborating with the national community, Perimeter has positioned Canada as a world leader in the field. The Institute has measurably raised the country's international standing in physics – through joint recruitment of top talent and collaborative training with numerous academic partners, and by providing unique resources to the entire national community.

Theoretical physics seeks to understand the universe at the most basic level: what it is made of, the forces that govern it, and the potential it holds. Because the field is so fundamental, each new advance literally changes our world.

Breakthroughs in physics are essential to our society and our future. Understanding the role of science in all of our lives is more important now than ever; thus, an integral part of Perimeter's mission is educational outreach to teachers, students, and the general public. The Institute's award-winning programs and resources seek to engage, educate, and inspire, communicating the importance of basic research, the joy of discovery, and the enduring power of ideas.

Perimeter is on track to become the world's leading centre in a field that is vital to our future. With the ongoing support of its public and private partners, Perimeter Institute will continue to be a catalyst for an innovation ecosystem, with all of the benefits and prosperity for the country that will follow for generations to come.

AN ACCELERATOR OF DISCOVERY



160+ SCIENTISTS IN RESIDENCE conducting research

11 MAJOR PRIZES AND HONOURS awarded to Perimeter scientists in 2014/15

1,000+ VISITING INTERNATIONAL SCIENTISTS annually

3,400+ PAPERS appearing in 170+ journals with 115,000+ citations since 2001

10,000+ ONLINE TALKS and lectures accessed by viewers in 175 countries

15 YEARS after its creation, Perimeter is now ranked among the TOP THEORETICAL PHYSICS institutes in the world

5+ MILLION STUDENT INTERACTIONS

17,000+ EDUCATORS trained through Perimeter workshops

580 TOP HIGH SCHOOL STUDENTS from **48** COUNTRIES have attended the International Summer School for Young Physicists

61 COUNTRIES have used Perimeter's educational resources

Perimeter is currently home to
71 PHD & MASTER'S STUDENTS and
59 POSTDOCTORAL RESEARCHERS

Perimeter Scholars International (PSI) master's program
184 GRADUATES from **48** COUNTRIES since **2009**

Contents

Director's Preface

We are entering the most exciting period in decades for fundamental physics. Observations and measurements drawn from the universe, on all scales, have greatly expanded the frontiers of our knowledge. We are living in a golden age of data of unprecedented power and range.

This data is surprising, in a very interesting way. It points to a universe of extreme simplicity on very large and very small scales, with all the complexity in between. Likewise, the universe's beginning and its far future seem puzzlingly simple, with all the complexity occurring at the intermediate epoch we live in. The most basic features, such as the dark energy, challenge the very framework upon which modern theories of physics have been built. They are guiding us towards radical new principles capable of reconciling quantum theory and relativity and explaining the simple yet currently paradoxical universe we find ourselves in.

Perimeter Institute is ideally positioned to become a world hub for the development of new theories and paradigms capable of meeting these challenges. Designed as the optimal environment within which to pursue foundational physics research, Perimeter is attracting world-leading young scientists who are opening up path-breaking new lines of research.

In the last year, Faculty members Natalia Toro and Philip Schuster shared the New Horizons in Physics Prize, the most prestigious prize in theoretical physics for early career scientists. Perimeter researchers have now won the prize three years in a row; no other institution has ever won it more than once. Another of our young faculty members, Pedro Vieira, won both a Sloan Foundation Fellowship and the Gribov Medal, the top European prize for young physicists. (Indeed, Perimeter is again unique for having three faculty members who have won the Gribov Medal, including Freddy Cachazo in 2009 and Davide Gaiotto in 2011.)

Not only are new paradigms required to understand the fundamental extremes of the cosmos, they are also needed to conceptualize the complex, quantum nature of matter on everyday scales. Xiao-Gang Wen, a world-renowned pioneer, joined Perimeter as the BMO Financial Group Isaac Newton Chair in Theoretical Physics, soon followed by Dmitry Abanin, a young leader in quantum condensed matter physics. We are now delighted to welcome Max Metlitski, a returning Canadian and one of the most brilliant young condensed matter theorists in the world. Max has just won the two top early-career prizes in condensed matter worldwide. His research centres on using quantum field theory, the basic tool which is foundational to all of physics, to describe complex many-body quantum materials which show enormous promise in new technological applications.

Mathematical physics has been another area of strong growth at Perimeter. Historically, exchanges between mathematics and physics have led to the field's greatest breakthroughs. Several of our faculty members are pioneers in mathematical physics, and last year we recruited Kevin Costello, an outstanding young mathematician, who is systematically placing quantum field theory on new mathematical foundations. Recently, we hired Alexander Braverman jointly with the University of

Toronto. Alexander is a leading light in the "geometric Langlands program," a related area of pure mathematics seeking to unify its main branches: analysis, algebra, and geometry.

Finally, as a part of our growing efforts in cosmology, Ue-Li Pen, one of the world's most original astrophysicists, has joined us as an associate faculty member, jointly appointed with the Canadian Institute for Theoretical Astrophysics in Toronto. Ue-Li realized that by mapping the hydrogen throughout the universe, a new kind of map could be constructed. This idea has evolved into the Canadian Hydrogen Intensity Mapping Experiment (CHIME), Canada's world-leading experimental effort to map the three-dimensional structure of the universe.

Perimeter is, I believe, unique among theory institutes for its combination of deep, mathematical theory and strong ties to experiment: the Large Hadron Collider, the Event Horizon Telescope, LIGO, SNOLAB, CHIME, and many more. Perimeter scientists are placing Canada not only at the forefront of developing new theories, but also of testing those theories to the limit in some of the most important experiments of our time.

In June, we held a new kind of scientific gathering, "Convergence," which brought together many of the world's most prominent physicists and most promising young minds, across all sub-fields. We challenged them to leave their comfort zones and take a "big picture" view of where physics stands now, and where the most exciting opportunities for basic discovery will be. Many attendees reached out afterward to say that it was perhaps the most exciting gathering they'd ever attended.

At Perimeter, we constantly challenge ourselves to be agile and entrepreneurial, always on the alert for important emerging directions, which are often interdisciplinary and fall outside of established fields. This year, we have established several new cutting-edge initiatives – on the emergence of spacetime, on tensor networks, on a new method for describing complex quantum systems, and on a project to observe the detailed structure of black holes – that bring together the right mix of expertise and young scientists around high-priority scientific research areas.

One of our own Board members, Art McDonald, provides a powerful illustration of what can be achieved through foresight, collaboration, and an insatiable curiosity about our universe. Art was recently co-awarded both the Nobel Prize in Physics and the Breakthrough Prize, for the discovery of neutrino oscillations at the pioneering SNO experiment in Sudbury. Art's trailblazing discoveries and contributions to building physics in Canada are an example to us all.

In the 20th century, discoveries in basic physics gave rise to trillions of dollars of new wealth, and millions of jobs, based on transistors, computers, MRI, GPS, wireless communications, smartphones, and much more. The 21st century economy will likely rest on innovations emerging from advances in quantum physics, such as quantum computers, sensors, communicators, and new superconductors. Indeed, Quantum Valley is emerging right here in Canada. Perimeter continues to be the wellspring of a flourishing quantum ecosystem that covers the spectrum from deep discovery and advanced training, to experimental labs, technology development, venture capital, and an entrepreneurial start-up culture. This combination is unparalleled anywhere on the planet.

The coming quantum revolution promises to be even more transformative than the digital revolution was. And this time, Canada can lead the way.

– Neil Turok

Executive Summary

Perimeter Institute's mission is to create and sustain the world's leading centre for foundational theoretical physics research, training, and outreach, fostering excellence and stimulating major scientific breakthroughs.

Each of the Objectives set out in last year's Corporate Plan plays a part in the Institute's comprehensive long-term strategy for achieving this ambitious goal. In 2014/15, the Institute made excellent progress, meeting or exceeding major targeted outcomes under all of its Objectives. This provides strong evidence that the Institute's strategic planning has been both sound and effective, and that it is on track to achieve its long-term vision.

Achievement Highlights, 2014/15

Advancing Fundamental Research

- ✓ Produced research discoveries of international impact and importance

- ✓ Sample research highlights include the following:
    - Quantum computing holds promise for tremendous advances in fields spanning communications, cryptography, medicine, and beyond. Unlocking that promise requires research bridging theory and experiment. Faculty member Robert Spekkens and colleagues at the Institute for Quantum Computing showed experimentally that certain kinds of correlations in a quantum circuit can imply causation, a discovery with both foundational significance and the potential for applications to quantum technology.
    - Quantum field theories (QFTs) are the basic language of particle physics, condensed matter, and much of cosmology, but calculating exact solutions for QFTs is often impossible. This year, Faculty member Pedro Vieira's ambitious, long-term research project to simplify such calculations attained a watershed result, bringing exact solutions for QFTs into reach for the first time.
    - Faculty member Dmitry Abanin and collaborators made major strides in defining the laws governing dynamics of quantum many-body systems, which are likely to be of great importance in next-generation technologies such as quantum computing.

- ✓ PI researchers received numerous national and international awards and honours, including the following:
    - Faculty members Philip Schuster and Natalia Toro were awarded the $100,000 New Horizons in Physics Prize by the Breakthrough Prize Foundation (formerly the Fundamental Physics Prize Foundation); this marked the third consecutive year a

Perimeter faculty member won, and no other institution in the world has even won two years in a row.
- Faculty member Pedro Vieira received a 2015 Sloan Research Fellowship.
- Faculty member Pedro Vieira was awarded the prestigious 2015 Gribov Medal by the European Physical Society, making him the third Perimeter faculty member to win since 2009.
- Distinguished Visiting Research Chair Matthew Fisher was awarded the 2015 Oliver E. Buckley Condensed Matter Physics Prize.
- Faculty member Lee Smolin was co-awarded the Buchalter Cosmology Prize by the American Astronomical Society.
- Director Neil Turok was elected a Fellow of the Royal Society of Canada.
- Former postdoctoral researcher Joseph Ben Geloun was awarded the 2015 Young Scientist Prize in Mathematical Physics by the International Union of Pure and Applied Physics, for work completed while at Perimeter.
- Associate Faculty member Avery Broderick is a co-investigator on a National Science Foundation grant that was awarded $6.5 million USD to support the Event Horizon Telescope experiment.
- Associate Faculty member Michele Mosca was awarded a three-year contract (worth over $600,000) with the Government of Canada to work on post-quantum cryptography.
- Three Perimeter researchers were awarded Early Researcher Awards worth $140,000 each by the Province of Ontario.
- Perimeter scientists were awarded $3.7 million in research grants.

Attracting the Brightest Minds

- ✓ Welcomed Kevin Costello, one of the world's top young mathematicians, as the Krembil Foundation William Rowan Hamilton Chair in Theoretical Physics

- ✓ Created three new Perimeter Research Chairs, bringing the total number to eight, and attracted the crucial private support that makes them possible:
  - Appointed cosmologist Paul Steinhardt of Princeton as the Richard P. Feynman Chair in Theoretical Physics (Visiting)
  - Appointed Pedro Vieira as the Clay Riddell Paul Dirac Chair in Theoretical Physics, supported by the Riddell Family Charitable Foundation
  - Appointed Freddy Cachazo as the Gluskin Sheff Freeman Dyson Chair in Theoretical Physics, supported by Gluskin Sheff + Associates
  - Funded Subir Sachdev's previously appointed chair, now known as the Cenovus Energy James Clerk Maxwell Chair in Theoretical Physics (Visiting)

- ✓ Recruited one new full-time faculty member and three part-time associate faculty members

- ✓ Appointed four eminent international scientists as Distinguished Visiting Research Chairs, bringing the total to 44, and eight accomplished researchers as Visiting Fellows, bringing the total to 22

- ✓ Appointed six outstanding women scientists as Emmy Noether Fellows

- ✓ Hired 18 postdoctoral researchers in 2014/15; recruited 17 more for 2015/16

Training the Scientists of the Future

- ✓ Trained 31 students from 16 countries through the Perimeter Scholars International (PSI) master's program

- ✓ Provided advanced training to 42 PhD students in conjunction with surrounding universities

- ✓ Three departing postdoctoral researchers obtained tenure-track faculty positions

A Global Hub for Scientific Interaction

- ✓ Expanded ties to major experimental efforts throughout the world

- ✓ Held 15 conferences and workshops, attended by 873 scientists from around the world

- ✓ Partnered on eight joint workshops and conferences held at Perimeter and co-sponsored an additional 11 off-site workshops and conferences

- ✓ Presented 325 scientific talks

- ✓ Hosted 450 visiting scientists to do collaborative and individual research

- ✓ Shared the Institute's scientific events virtually with over 82,000 visitors from 170 countries

- ✓ Provided expertise and assistance to the African Institute for Mathematical Sciences – Next Einstein Initiative (AIMS-NEI)

Inspiring Through Outreach

- ✓ Reached over 1 million students through Perimeter programs and in-class resources, bringing the total to more than 5 million students to date

- ✓ Created three new educational modules: *Black Holes*, *The Physics of Innovation*, and *Contemporary Physics*

- ✓ Partnered with Chalk.com to make the Institute's educational resources available to more than 100,000 educators worldwide

- ✓ Launched planning and strategy for Canada 150, a massive nationwide celebration for which Perimeter was chosen as leader of the Innovation Pillar

- ✓ Hosted the 13th International Summer School for Young Physicists (ISSYP) and gave 18 Physica Phantastica presentations – reaching 2,400 students across Canada

- ✓ Held EinsteinPlus summer teaching intensive for 45 educators from around the world

- ✓ Delivered 130 workshops to over 3,000 educators across Canada and abroad, ultimately reaching more than 225,000 students

- ✓ Substantially increased digital and social media communications and impact

- ✓ Received major coverage in national and international media, including *Nature*, *The Globe and Mail*, *Wired*, and more

- ✓ Delivered eight public lectures to capacity audiences on-site and to expanding online audiences through the Perimeter Public Lecture Series, presented by Sun Life Financial

Creating an Optimal Research Environment

- ✓ Continued to foster a climate of collaboration, exchange, and gender equity

- ✓ Achieved LEED Silver Certification for the Stephen Hawking Center at Perimeter Institute

- ✓ Enhanced Perimeter's IT systems

Growing the Public-Private Partnership

- ✓ Attracted over $5.3 million in new commitments from individuals, corporations, and foundations

- ✓ Raised awareness and donations to the Emmy Noether Circle, providing focused support to women in physics

- ✓ Worked with partners at all levels of government to provide insight and guidance on science-related public policy initiatives

- ✓ Continued to act as a catalyst for the emerging Quantum Valley ecosystem

Statement of Objectives for 2014/15

Objective 1: Deliver world-class research discoveries

Objective 2: Become the research home of a critical mass of the world's leading theoretical physicists

Objective 3: Generate a flow-through of the most promising talent

Objective 4: Become the second research home for many of the world's outstanding theorists

Objective 5: Act as a hub for a network of theoretical physics and math centres around the world

Objective 6: Increase Perimeter's role as Canada's focal point for foundational physics research

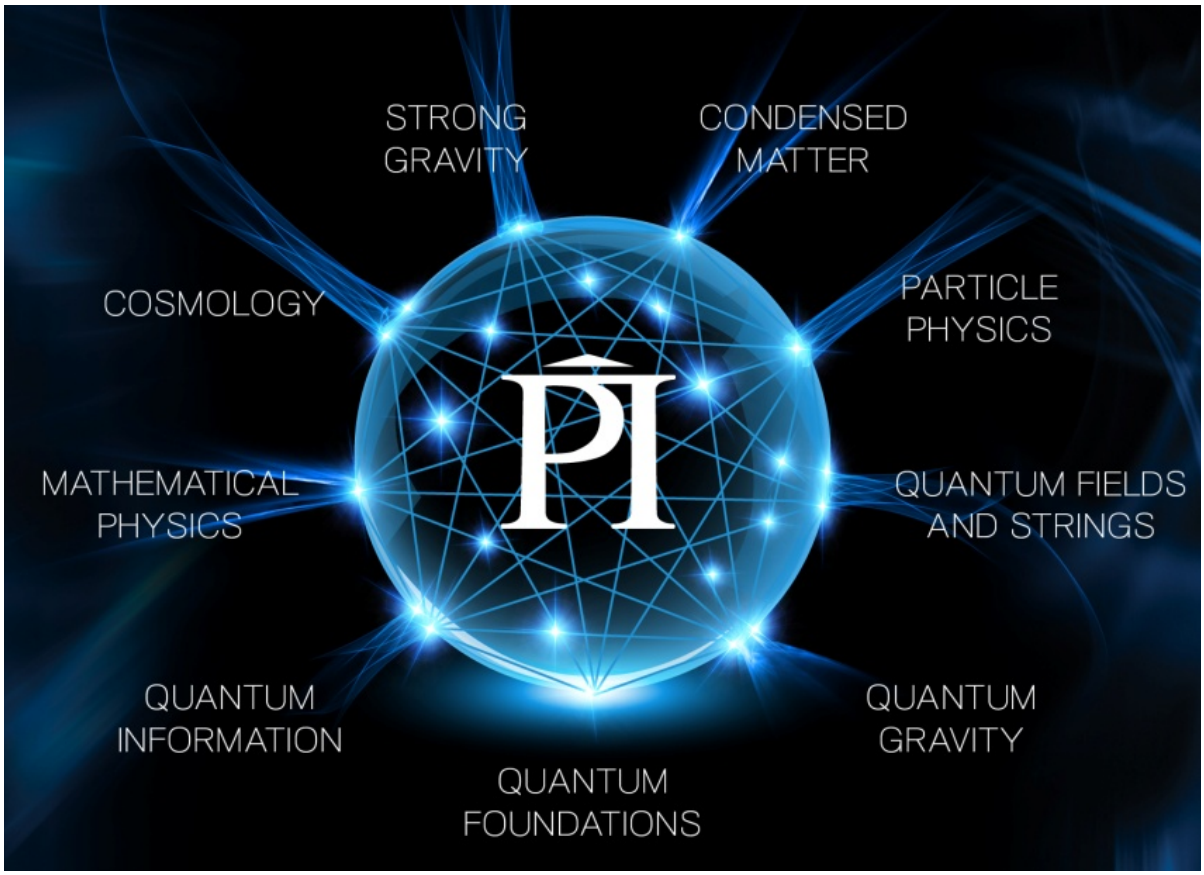
Objective 7: Host timely, focused conferences, workshops, seminars, and courses

Objective 8: Engage in high-impact outreach

Objective 9: Create the world's best environment and infrastructure for theoretical physics research, training, and outreach

Objective 10: Continue to build on Perimeter's highly successful public-private partnership funding model

Objective 1: Deliver world-class research discoveries



Summary of Achievements

- Advanced fundamental research through 365 high-calibre papers[6]
- Since inception, Perimeter researchers have produced more than 3,400 papers appearing in over 170 journals, which have attracted more than 115,000 citations to date, attesting to the importance and long-term impact of PI research[7]

Highlights

[6] This reflects the one-year period from August 1, 2014 to July 31, 2015. Each publication has been counted only once, regardless of how many Perimeter researchers collaborated on it.
[7] This data comes from the Google Scholar and Spires databases.

Condensed Matter

The challenge of condensed matter physics can be summed up in a single observation: the behaviour of a system with many particles can be very different from that of the particles that make it up. Condensed matter physicists study these many-body systems, especially those that are in a condensed state. At Perimeter, researchers tackle such fundamental issues as the nature of magnets or the difference between conductors and insulators, as well as cutting-edge questions such as whether we can describe gravity as a property of a material, or tailor an exotic form of quantum matter for use inside quantum computers.

The Theory of (Quantum) Evolution

For decades, physicists have thought of quantum-ness as something that we see only on microscopic scales or in very cold systems. After all, quantum phenomena such as superposition and entanglement typically cancel out when large systems reach thermal equilibrium – a process called thermalization.

In practice, thermalization happens so rapidly that there hasn't been much need to understand how quantum systems evolve. In the past, researchers even might have said that quantum systems don't evolve: they just vanish.

But all this has changed, because researchers have discovered a class of systems that do not thermalize. In these so-called localized many-body systems, quantum effects are seen in systems with a large number of particles, evolving dynamically over a long time. As a result, the problem of understanding how quantum systems evolve has come to the fore. The strange behaviour of such systems may be important, even useful, in the design of various quantum technologies.

Perimeter researchers have recently taken some of the first major strides in exploring the laws governing the dynamics of quantum many-body systems.

Perimeter Faculty member **Dmitry Abanin**, postdoctoral researcher **Zlatko Papić**, and **Maksym Serbyn** (a graduate student at MIT and a Perimeter visitor) are developing new laws of quantum dynamics in many-body localized systems, which can be used in place of the traditional laws of statistical mechanics. It is a general result that can be applied to any strongly disordered experimental quantum many-body system – a kind of new rulebook for examining a broad class of systems.

This ambitious research program has been ongoing for several years, has been remarkably influential, and has stimulated several research groups to join the study of many-body localization.

Within the past year, Abanin and Papić have worked with a number of other researchers to take these ideas even further. A number of their recent papers have provided insights into largely unexplored questions about many-body localization, such as whether it can occur in systems with no disorder.

It's one important step toward the quantum leap we need.

References:

D.A. Abanin (Perimeter Institute), W. De Roeck (University of Leuven), and F. Huveneers (Paris Dauphine University), “A theory of many-body localization in periodically driven systems,” arXiv:1412.4752.

Z. Papić (Perimeter Institute and Institute for Quantum Computing/University of Waterloo), E.M. Stoudenmire (Perimeter Institute), and D.A. Abanin (Perimeter Institute and Institute for Quantum Computing/University of Waterloo), “Is Many-Body Localization Possible in the Absence of Disorder?” arXiv:1501.00477.

The Coldest Sea

Cold is quantum.

At very low temperatures, in many systems such as superconductors and superfluids, particles seem to lose their individual identities and become governed by a single quantum wave function. It’s like separate ponds merging into one sea. The ultra-cold system then becomes a tool for exploring the fundamental laws of nature.

Perimeter postdoctoral researcher **Juan Carrasquilla** has worked with a team of experimentalists based at Pennsylvania State University on a new technique for pushing the lower boundary of cold. It’s called quantum distillation: the selective evaporation of atoms in specific states from an ultra-cold cloud of atoms.

Their two-fold goal was to learn to observe the never-before-seen phenomenon of quantum distillation, and to use it to create a new ultra-cold state they dubbed a “doublon sea.”

Their procedure begins with dropping a lattice of lasers across the cold gas, trapping atoms in a crystal of light. Each space in the crystal was occupied by one, two, or very occasionally three atoms – or, in the parlance of condensed matter, singlons, doublons, and triplons. The process of quantum distillation involves boiling away the singlons, leaving only doublons behind.

The team succeeded in observing quantum distillation, though the pure doublon sea they had hoped to create still contained a few singlons. It’s not a failure, though, because the real significance of this work is as a proof of principle: the researchers have demonstrated that this new process of quantum distillation works, and has the potential to create extremely special, low-entropy states.

This work is a good demonstration of the way theorists and experimentalists work in tandem in fields like quantum materials. The idea of quantum distillation was initially proposed theoretically. The researchers built an experiment to test the possibility, but they needed a theorist – Carrasquilla – to build a numerical simulation of the system.

As with the work of Abanin and Papić (above), the ultimate purpose of this research is to address general questions in non-equilibrium quantum dynamics – one of the most exciting frontiers in understanding the behaviour of quantum matter.

Reference:

L. Xia (Pennsylvania State University), L.A. Zundel (Pennsylvania State University), J. Carrasquilla (Perimeter Institute and Pennsylvania State University), A. Reinhard (Pennsylvania State University), J.M. Wilson (Pennsylvania State University), M. Rigol (Pennsylvania State University), and D.S. Weiss (Pennsylvania State University), "Quantum distillation and confinement of vacancies in a doublon sea," *Nature Phys.* 11, 316-320 (2015), arXiv:1409.2882.

Cosmology

Cosmologists at Perimeter Institute seek to understand the makeup and structure of the universe, and the rules governing its origins and evolution. Many of the most interesting clues about physics beyond the Standard Model come from cosmological observations that can probe length scales, time scales, and energy scales that are beyond the reach of terrestrial laboratories. Cosmology is intrinsically connected to other branches of research at Perimeter, including particle physics, quantum fields and strings, and strong gravity.

A New Era Dawns

Cosmology poses the ultimate questions: How did the universe begin? How did it evolve? Where is it going? These questions, among the oldest and deepest asked by humankind, are the central concerns of cosmology.

To these are added newer questions: How do we model the "big bang"? What is dark matter, which is needed to explain why clusters of galaxies don't fly apart? What is dark energy, the mysterious something that is causing the accelerated expansion of our universe?

Until recently, answers to these questions were out of reach. But as a result of the new tools that are now available to probe these mysteries, cosmology has entered a golden age.

The tools have included the Wilkinson Microwave Anisotropy Probe (WMAP), which mapped the cosmic microwave background radiation (CMB), relic background radiation from the big bang. Building upon this, in early 2015, the European Space Agency (ESA) Planck satellite provided the highest quality full-sky maps of the universe ever produced. Cosmologists at Perimeter are part of the large collaborations that have been analyzing that data, aiming to provide a better understanding of our cosmos.

One of those researchers is **Kendrick Smith**, who has been leading an effort to study the primordial density perturbations. Along with Leonardo Senatore and current Perimeter Distinguished Visiting Research Chair **Matias Zaldarriaga**, Smith authored two landmark 2009 papers which used the five-year WMAP data to check whether the CMB measurements are "Gaussian" – that is, whether the temperature data forms a smooth curve.

Over the past decade, one of the central goals in cosmology has been to measure the non-Gaussianity of the primordial density perturbation, because if there is non-Gaussianity, cosmologists would have to re-think inflation, or perhaps inflation is much more complicated than they thought.

Recently, Smith has played a key role in analyzing the 2013 and 2015 Planck data to show, with unprecedented precision, that – as far as we can tell – our cosmological initial conditions seem to have been perfectly Gaussian, with no hint of primordial non-Gaussianity so far.

These results represent a significant step forward in our knowledge of the early universe, and a fundamental new constraint in theoretical cosmology.

Reference:

K. Smith (Perimeter Institute) et al., "Planck 2015 Results. XVII. Constraints on primordial non-Gaussianity," arXiv: 1502.01592.

New Cosmological Solutions

Cosmologists usually focus on understanding the physics and evolution of the universe from shortly after the big bang singularity until the present.

Although the big bang model can explain the expansion of the universe and how it cooled and produced the galaxies and stars we see today, the problem is that the equations break down in the very far past at the singularity, where density, temperature, and curvature of the universe become infinite.

That obscures the ability to understand the nature of the big bang. This means that the most basic questions in cosmology are still wide open: Did the universe really begin at the big bang? If so, how and why? If not, what is the correct picture?

In recent years, Richard P. Feynman Chair **Paul Steinhardt** and Perimeter Institute Director **Neil Turok** have been attacking these questions from a variety of angles. By proposing a modification of gravity with increased symmetries, they manage to tame the big bang singularity.

In a recent series of papers, they have uncovered a range of novel cosmological ideas and phenomena in their model, including new cosmological solutions in which a contracting universe passes through an exotic anti-gravity phase before beginning its re-expansion.

In more recent work, they have also tracked the quantum evolution of the universe through contraction and then re-expansion, smoothly passing through the singularity.

This work suggests that it is very possible for physicists to one day understand the big bang and answer the most basic questions about the beginning of the universe.

References:

I. Bars (University of Southern California), P. Steinhardt (Princeton University), and N. Turok (Perimeter Institute), "Local Conformal Symmetry in Physics and Cosmology," *Phys. Rev. D* 89 043515 (2014), arXiv:1307.1848.

S. Gielen (Imperial College London) and N. Turok (Perimeter Institute), "A Perfect Bounce," arXiv:1510.00699.

Mathematical Physics

In mathematical physics, new problems in physics give rise to new mathematics to solve them and new mathematics open doors to new understanding of the physical universe. Newton invented modern calculus because he needed it to understand mechanics – and calculus went on to redefine all of physics. The development of quantum theory in the 20th century both spurred and was spurred by advances in mathematical fields such as linear algebra and functional analysis. Perimeter's mathematical physics researchers continue this grand tradition.

Physicists Weave a Web to Mathematics

A major contribution in the field of mathematical physics in 2015 was the publication of a massive 400-page paper by Perimeter's Krembil Foundation Galileo Galilei Chair in Theoretical Physics, **Davide Gaiotto**, along with Gregory Moore and Edward Witten, which brings together a number of tools from advanced mathematics and string theory to analyze the structure of massive two-dimensional field theories.

Along with supersymmetry, which has been proposed as a solution to both cosmic and subatomic mysteries in physics, these theories are important in mirror symmetry, which is central to current research in geometry.

Mirror symmetry is also fundamental to understanding aspects of quantum field theory, the language that describes all the many-body interactions in nature, such as the interactions of particles in a collider.

In the paper, Gaiotto, Moore, and Witten sketch applications of the theory they develop (the theory of webs) to objects of interest in current mathematical research. The work exemplifies the significant impact that researchers at Perimeter have had on mathematics.

Reference:

D. Gaiotto (Perimeter Institute), G. Moore (Rutgers University), and E. Witten (Institute for Advanced Study), "Algebra of the Infrared: String Field Theoretic Structures in Massive N=(2,2) Field Theory In Two Dimensions," arXiv:1506.04087.

Improving on Connes

In the late 1970s, pioneering French mathematician Alain Connes developed a branch of mathematics called noncommutative geometry, a framework in which the standard model of particle physics, coupled to Einstein gravity, could be elegantly reformulated.

In 2014, Perimeter Faculty member **Latham Boyle** discovered a way of simplifying and generalizing Connes' principle, making it into a tool to construct new unified models of particle physics.

Boyle's innovation removes a number of open questions in the original formulation of Connes' proposal, giving it greater potential predictive power.

It is an unusual case of a physicist improving a mathematical framework – the kind of fruitful interaction of fields that Perimeter aims to encourage with its recently strengthened emphasis on mathematical physics.

Reference:

S. Farnsworth (Perimeter Institute) and L. Boyle (Perimeter Institute), "Rethinking Connes' approach to the standard model of particle physics via non-commutative geometry," *New J. Phys.* 17 023021 (2015), arXiv:1408.5367.

Particle Physics

Particle physics explores nature's constituents and interactions at the most fundamental level. As such, it has strong overlaps with string theory, quantum gravity, and cosmology. At Perimeter, particle physics researchers often compare theoretical ideas with both astrophysical observations and Earth-bound experiments like the ones carried out at the Large Hadron Collider, and study how such results can help us map the physics beyond the Standard Model.

Tick Tock Goes the Dark Matter

Physicists and astronomers are now fairly confident dark matter exists. Based on the way they can predict its clustering and detect its gravitational effects on large scales, they infer dark matter makes up about a quarter of the "stuff" of the universe.

The true identity of dark matter, however, remains one of the most vexing questions in physics, since it doesn't interact with us in the ways we can typically measure. Much research in particle physics at Perimeter Institute is devoted to understanding what this abundant-but-elusive stuff actually is.

Is dark matter made of particles? If so, how big or small or heavy are those particles? What if it doesn't resemble our traditional ideas of matter at all?

In a paper published in *Nature Physics*, Perimeter Associate Faculty member **Maxim Pospelov** and collaborator Andrei Derevianko of the University of Nevada investigate that possibility. What if, they ask, dark matter isn't composed of particles, but stable structures within a field that pervades spacetime?

Picture a field with cracks in it, like broken safety glass. The field itself might be undetectable, the way perfectly clear glass is invisible. But the cracks are a different matter. Just as the cracks in glass can be seen, the cracks in the field can – perhaps – be detected.

The researchers contend that we might be able to detect them with instruments we already have: atomic clocks, laser interferometers, and gravitational wave detectors.

This take on dark matter is known as topological dark matter, and the cracks themselves are generically called topological defects (TDs). You can think of these TDs as a stationary backdrop to the universe, and the Earth crashing through it at speeds of about 300 kilometres per second.

When an atomic clock crosses a TD, Pospelov and Derevianko contend, it would either slow down or speed up, depending on the nature of the interaction. If one had a network of atomic clocks, an encounter with a TD would look like a wave of such out-of-synch events, which should be detectable.

The researchers calculated that a dark matter topological defect passing through the satellites surrounding Earth would cause clocks of the GPS system to go out of sync in a characteristic pattern, over a span of about three minutes.

Reference:

A. Derevianko (University of Nevada) and M. Pospelov (Perimeter Institute and University of Victoria), "Hunting for topological dark matter with atomic clocks," *Nature Phys.* 10, 933-936 (2014), doi:10.1038/nphys3137, arXiv:1311.1244.

A Gravitational Atom in the Sky

If dark matter is presumed to be a particle, the question becomes what kind of particle – and that's no small question.

Faculty member **Asimina Arvanitaki**, a theoretical particle physicist, recently explored a scenario in which black holes could actually provide clues to the identity of dark matter.

Suppose, she argued, that a particle's size – or, more technically, its Compton wavelength – is comparable to that of a black hole. Such a particle can become bound by the intense gravity of the black hole, dragged by its rotating spacetime into a kind of lockstep – a process theorized by, and eventually named after, astrophysicist Roger Penrose.

Bound together by the Penrose process, the particle and the black hole become what Arvanitaki calls a "gravitational atom in the sky." The notion poses intriguing possibilities in the hunt for nature's underlying building blocks, including dark matter.

As the incredible forces of the black hole wreak havoc on the surrounding spacetime, a process called superradiance causes the number of particles to grow very quickly – exponentially – in the orbit around the black hole, extracting energy and angular momentum from the black hole.

Particles can transition between energy states, producing gravitons (similar to how transitions of electrons in atoms can produce photons – the process by which a laser works). Pairs of particles can also annihilate, transforming into a pair of gravitons – one of which is absorbed by the black hole, the other escaping it. Both phenomena create a signal that can be detected on Earth: gravitational waves.

Arvanitaki believes this process may allow researchers to diagnose the presence of a particle called the QCD axion, a hypothetical elementary particle that is considered by many to be a potential candidate for dark matter.

Reference:

A. Arvanitaki (Perimeter Institute), M. Baryakhtar (Stanford University), and X. Huang (Stanford University), "Discovering the QCD Axion with Black Holes and Gravitational Waves," *Phys. Rev. D* 91 084011 (2015), arXiv:1411.2263.

Quantum Fields and Strings

Quantum field theory is the modern paradigm with which we understand particle physics, condensed matter systems, and many aspects of early universe cosmology. It is used to describe the interactions of elementary particles, the dynamics of many-body systems, and critical phenomena, all with exquisite accuracy. Perimeter researchers are producing world-leading advances in quantum field theories.

String theory is a theoretical framework which was proposed as a unified description of all particles and forces in nature, including gravity. It is based on the idea that at very short distances, all particles should in fact be seen to be extended one-dimensional objects – that is, "strings." Modern string theory has grown to be a broad and varied field of research with connections to and implications for quantum gravity, particle physics, and cosmology, as well as mathematics.

Simplifying Ultra-hot Chaos

In ordinary matter, quarks never go it alone. They are always bound tightly by gluons within larger particles, such as protons and neutrons. But in extreme conditions, these particles can "melt," forming an ultra-hot plasma in which quarks and gluons escape their particles.

It's called a quark-gluon plasma, or QGP. It's thought to have existed in the first instants following the big bang. And it's reproduced in the little bangs produced at our highest intensity particle colliders.

The tiny droplets of QGP produced by colliders exist only for an instant. Like super-hot fireballs, they quickly expand and cool into ordinary matter. But the details of that expansion are not well understood. The system is initially far out of equilibrium, and modelling it requires extremely complex computations.

Perimeter postdoctoral researcher **Michal P. Heller** is trying to simplify those calculations. His work brings together two different fields – hydrodynamics and string theory.

The standard modelling for plasma experiments uses relativistic hydrodynamics, a theory similar to that describing the motion of water, but incorporating special relativity. (QGP and its microscopic constituents move with large velocities, at which relativistic effects become important.)

Some researchers, including Heller, have simplified the problem with a trick from string theory: they have equated relaxation of the QGP "fireball" to a black hole reaching equilibrium in a hypothetical five-dimensional space.

But five-dimensional calculations involving Einstein's equations are still very complicated. Heller has pushed the idea further, and made things simpler, by developing a method that incorporates part of those calculations into a four-dimensional description that is coupled to conventional hydrodynamics equations.

Current experimental and theoretical approaches aren't sensitive enough to capture and analyze in detail the evolution of QGP fireballs, but Heller's work is a step in this direction. The payoff may

someday be a better understanding of what happens after the little bangs in hadron colliders – and what happened after the big bang at the birth of universe.

Reference:

M.P. Heller (Perimeter Institute, University of Amsterdam, and National Centre for Nuclear Research, Poland), R.A. Janik (Jagiellonian University), M. Spaliński (University of Białystok and National Centre for Nuclear Research, Poland), and P. Witaszczyk (Jagiellonian University), "Coupling Hydrodynamics to Nonequilibrium Degrees of Freedom in Strongly Interacting Quark-Gluon Plasma," *Phys. Rev. Lett.* 113, 261601 (2014), arXiv:1409.5087.

Finishing the Quilt

One of the most basic questions in string theory is what happens when strings interact. One fruitful way of tackling that question has been to turn it into one of topology. For example, picture a single closed string – that is, a tiny vibrating loop of energy. In the same way a point moving through space traces a straight or curvy line, that string moving through space draws a cylinder – a kind of wobbly drinking straw. In the parlance of string theory, this surface is known as the string's world sheet.

As the string begins to interact with other strings and with its environment, it creates more complex topologies – more complex world sheets – which of course require more complex calculations.

Perimeter Faculty member **Pedro Vieira** is engaged in an ambitious, long-term research project to simplify these calculations, and bring the string interactions into analytic reach for the first time. He's had many collaborators, most recently including Perimeter PhD students **Lucia Cordova** and **Joao Caetano** and postdoctoral researchers **Benjamin Basso**, **Shota Komatsu**, and **Amit Sever**.

The basic thrust of the research has been to learn first to cut the complex topologies into pieces, and then to patch those pieces back together – string theory as quilting. The researchers learned to cut the topologies describing closed strings (or loops) into hexagons and the open strings as pentagons. They then developed mathematics that allow them to stitch these pieces back together, thus creating arbitrarily large and complex world sheets.

There has always been a risk that this program could fail at the last minute – that the behaviour of the world sheets at the points where they are mathematically cut and stitched could be just too complex to manage. But this year, the research program passed that major milestone, and the various pieces were at last put together.

This is a major result, which may well have long-term impact on both string theory and particle physics.

References:

B. Basso (École Normale Supérieure), J. Caetano (Perimeter Institute, University of Waterloo, King's College London, and University of Porto), L. Cordova (Perimeter Institute and University of Waterloo), A.

Sever (Tel Aviv University), and P. Vieira (Perimeter Institute), “OPE for all Helicity Amplitudes,” *JHEP* 10.1007 08 (2015) 018, arXiv:1412.1132.

B. Basso (École Normale Supérieure and ICTP South American Institute for Fundamental Research), S. Komatsu (Perimeter Institute and ICTP South American Institute for Fundamental Research), and P. Vieira (Perimeter Institute and ICTP South American Institute for Fundamental Research), “Structure Constants and Integrable Bootstrap in Planar N=4 SYM Theory,” arXiv:1505.06745.

B. Basso (École Normale Supérieure and ICTP South American Institute for Fundamental Research), J. Caetano (Perimeter Institute, University of Waterloo, King’s College London, University of Porto, and ICTP South American Institute for Fundamental Research), L. Cordova (Perimeter Institute, University of Waterloo, and ICTP South American Institute for Fundamental Research), A. Sever (Tel Aviv University), and P. Vieira (Perimeter Institute and ICTP South American Institute for Fundamental Research), “OPE for all Helicity Amplitudes II. Form Factors and Data analysis,” arXiv:1508.02987.

Quantum Foundations

The study of quantum foundations concerns the conceptual and mathematical underpinnings of quantum theory. Research in quantum foundations at Perimeter Institute aims to refine and reformulate quantum theory in ways that express its true nature and structure. Research in this field is closely tied with work in quantum gravity and quantum information.

Quantum Cause and Effect

Correlation does not imply causation. That's a caution drilled into scientists and statisticians alike. If you have only two variables, A and B, and they seem to rise and fall together, it does not necessarily mean that A effects B, or B effects A. They could merely share a common cause. Unless you can actively experiment on the system, it is impossible to tell a cause-effect relation from a common-cause relation. Hence the caution.

But the caution now needs to be updated. Recent research from Perimeter and the Institute for Quantum Computing says that in a quantum world, certain kinds of correlations can imply causation.

The research is both theoretical and experimental. Perimeter Faculty member **Robert Spekkens** and PhD student **Katja Ried** worked with Max Planck Institute scientist Dominik Janzing from the theoretical end. They considered the situation of an observer who takes two measurements of a quantum variable – say, the polarization of a photon – at two different points in time. The observer does not know if she is measuring the same photon twice (that is, if she is measuring a cause-effect relationship), or if she is measuring each of a pair of entangled photons (that is, if she is measuring a common-cause relationship). The theorists' crucial insight was that the correlations observed in the cause-effect case have a different pattern than those arising from a common cause according to quantum theory, allowing them to tell the two scenarios apart.

The theory became reality at the Institute for Quantum Computing, where Kevin Resch's group built a circuit wherein the experimenter herself does not know the causal relation. Just as the theorists predicted, the patterns of correlations revealed which causal structure was realized.

The take-away message is that correlation does not imply causation unless it's quantum. This discovery has both foundational significance and the potential for applications to quantum technology.

Reference:

K. Ried (Perimeter Institute and Institute for Quantum Computing/University of Waterloo), M. Agnew (Institute for Quantum Computing/University of Waterloo), L. Vermeyden (Institute for Quantum Computing/University of Waterloo), D. Janzing (Max Planck Institute for Intelligent Systems), R.W. Spekkens (Perimeter Institute), and K.J. Resch (Institute for Quantum Computing/University of Waterloo), "A quantum advantage for inferring causal structure," *Nature Phys.* 11, 414-420 (2015) doi:10.1038/nphys3266.

Questioning Weak Values

New work by Perimeter postdoctoral researcher **Joshua Combes** and Chris Ferrie of the University of New Mexico asserts that a key technique used to probe quantum systems may not be so quantum after all.

The technique in question is called "weak measurement," and it works something like this. Say you want to measure the spin of some particles. You would prepare particles in some particular state, say spin up, throwing away the data from particles that are spin down. This is called "pre-selection." Later, you would detect the particles in a final state, again throwing away spin-down particles. This is called "post-selection."

You also make a measurement in between. In order to minimize disturbances to the system, you measure that spin as gently – as weakly – as possible, and average over a large number of trials.

Combining pre-selection, post-selection, and weak measurement gives an unexpected result, which can be glimpsed in the title of the landmark 1988 paper by **Yakir Aharonov** (now a Perimeter Distinguished Visiting Research Chair) et al., "How the measurement of a component of the spin of a spin-½ particle can turn out to be 100." This odd outcome – a measurement that should be +½ or -½ turning out to be 100 – is called a "weak value," and it is thought to be an important new window into the quantum world.

But could weak values have a purely classical analogue? That's the question Combes and Ferrie set out to answer.

Where Aharonov et al. considered spinning particles, Combes and Ferrie considered flipping coins. By combining the same rules of pre-selection, post-selection, and weak measurement, they replicated weak values – even though coins are clearly not quantum. The "weak value" in this case is an artifact of classical statistics and classical disturbances. The title of their paper: "How the result of a single coin toss can turn out to be 100 heads."

The provocative work generated six formal comments in rebuttal and a related paper by Perimeter postdoctoral researcher **Matthew Pusey**.

Reference:

C. Ferrie (University of New Mexico) and J. Combes (Perimeter Institute and University of New Mexico), "How the Result of a Single Coin Toss Can Turn Out to be 100 Heads," *Phys. Rev. Lett.* 113, 120404 (2014).

Quantum Gravity

Quantum gravity is concerned with unifying Einstein's general theory of relativity and quantum theory into a single theoretical framework. Perimeter researchers are actively pursuing a number of approaches to this problem, including loop quantum gravity, spin foam models, asymptotic safety, emergent gravity, string theory, and causal set theory. The search for quantum gravity overlaps with other areas such as cosmology, particle physics, and the foundations of quantum theory.

Time Comes First

It is present everywhere, yet untouchable. It defines everything, yet resists definition: Time.

Time vexes many kinds of thinkers, but perhaps no one is more vexed than physicists. Perimeter Faculty member **Lee Smolin** and collaborator Marina Cortês are trying to get a grip on time, proposing a new class of models of quantum spacetime based on adding energy and momenta to causal sets. (This work builds upon earlier work on other causal set models done by Perimeter researchers **Rafael Sorkin** and **Cohl Furey**.)

Smolin and Cortês began from the hypothesis that time is both fundamental and irreversible – a bold assertion, given that most physicists see time as a property that "emerges" as a consequence of more fundamental physical laws. Causality results directly from this irreversibility; the future is created continuously out of the present through the activity of time. Energy and momentum are likewise fundamental properties; spacetime emerges through the activity of time – again, in diametric contrast to prevailing views. Every event has a unique "fingerprint" – the signature sum of the events that preceded it and no others.

These fundamentals result in a universe that is as asymmetric as possible. The authors developed their theory analytically, illustrating it through numerical simulations of a simplified model of a universe in which space has only a single dimension.

In two subsequent papers, the authors developed a quantum version of the energetic causal sets framework, and link it to a pre-existing approach to merging quantum mechanics and spacetime, called loop quantum gravity. The new framework holds key implications for fundamental physics – indeed, the authors argue that the primacy of time, and its irreversibility, must be incorporated into contemporary physics. It could point the way to a unification of quantum mechanics with relativity – the "Holy Grail" of contemporary theoretical physics.

The work received the inaugural Buchalter Prize, which was created "to stimulate ground-breaking theoretical, observational, or experimental work in cosmology that challenges, extends, or illuminates current models and/or helps explain the cosmic expansion from first principles."

References:

M. Cortês (Perimeter Institute, University of Edinburgh, and University of Lisbon) and L. Smolin (Perimeter Institute), "The Universe as a Process of Unique Events," *Phys. Rev. D* 90, 084007 (2014), arXiv:1307.6167.

M. Cortês (Perimeter Institute, University of Edinburgh, and University of Lisbon) and L. Smolin (Perimeter Institute), "Quantum energetic causal sets," *Phys. Rev. D* 90, 044035 (2014).

M. Cortês (Perimeter Institute, University of Edinburgh, and University of Lisbon) and L. Smolin (Perimeter Institute), "Spin foam models as energetic causal sets," arXiv:1407.0032.

A Fresh (and Stringy) Look at Spacetime

Perimeter Faculty member **Laurent Freidel** has pushed string theory back to its basics, rebuilt it, and revealed startling implications about the nature of space and time.

This is an ongoing project, largely done with collaborators Robert Leigh (University of Illinois at Urbana-Champaign) and Djordje Minic (Virginia Tech). The collaboration's most recent paper, "Metastring Theory and Modular Spacetime," builds upon two earlier ones by the same authors. The general thrust of the work is to apply a newly discovered principle, relative locality, to string theory.

This principle of relative locality was previously developed by Freidel and PI Faculty member **Lee Smolin**, among others.

In the new research program, Freidel, Leigh, and Minic apply the relative locality principle to string theory and find that the string does not move in classical spacetime, but moves in a novel quantum geometry they call modular spacetime. This gives a deeper understanding of some of the symmetries and dualities of string theory in terms of a basic symmetry of quantum theory called Born duality, according to which the dynamics can be equally well expressed in terms of spacetime coordinates or momenta.

This work exemplifies the interdisciplinarity Perimeter seeks to foster. Leigh and Minic are string theorists who visit PI regularly and have served as examiners for the PSI program, while Freidel is a specialist in quantum gravity.

Reference:

L. Freidel (Perimeter Institute), R.G. Leigh (University of Illinois at Urbana-Champaign), and D. Minic (Virginia Tech), "Metastring Theory and Modular Space-time," arXiv:1502.08005.

Quantum Information

Quantum computers, which capitalize on quantum effects such as "superposition" and "entanglement" to achieve processing power far surpassing present-day computers, are expected to revolutionize how we work, communicate, and live. Much theoretical research is required, however, before these technologies can emerge. Perimeter researchers explore quantum error correction – the techniques needed to safeguard and verify information amid the errors inherent to quantum computation. Researchers also pursue the foundations of quantum cryptography, which capitalizes on uniquely quantum laws – such as the uncertainty principle – to safeguard private information. Many of Perimeter's quantum information researchers collaborate with scientists at our nearby experimental partner, the Institute for Quantum Computing (IQC) at the University of Waterloo, and some hold joint appointments at both institutes. Together, Perimeter and IQC are transforming the region into the world's "Quantum Valley."

Scattershot Boson Sampling

If you are flipping coins and hope to turn up five heads at the same time, you have two options: take five coins and keep flipping them until the odds finally work in your favour, or flip a lot of coins at once and only count the ones that turn up heads.

That second method, it turns out, is highly effective if applied to a device called a boson sampler, considered to be a potential precursor to quantum computing.

In a boson sampler, photons are sent into an interferometer, pass through beam splitters, and emerge on the other side.

To generate the photons, experimentalists use parametric down-conversion (PDC) to create paired photons that split off in opposite directions; one goes into the interferometer, the other heralds their twinned existence.

But there is no simple and reliable way to generate paired photons on demand. In order to create 30 photons at once (enough to run an experiment that is too hard for a classical computer to simulate), researchers could wait so long – weeks, months, or longer – that it renders the experiment impractical.

In 2013, a new "scattershot" approach was suggested. Just like flipping many coins increases the chances of having five turn up heads, triggering a lot of PDCs at once is more likely to generate enough photons to run a worthwhile experiment.

This year, Perimeter Institute postdoctoral researcher **Daniel Brod** was part of an international theory-and-experiment collaboration that did just that.

The scattershot boson sampling experiment, performed in the quantum optics lab of Fabio Sciarrino at the Sapienza University of Rome and published in the new web-based journal *Science Advances*, collected data 4.5 times faster than earlier samplers.

"This approach promises exponentially larger improvements as the experiments scale up," Brod says.

The improvement also addresses one of the big problems facing boson sampling: the reliance on PDC photon sources. The team showed that, even without photons-on-demand, it is possible to generate enough photons to run a worthwhile experiment.

Reference:

D.J. Brod (Perimeter Institute) et al., "Experimental scattershot boson sampling," *Sci. Advances* Vol. 1, no. 3 (2015), e1400255, DOI: 10.1126/sciadv.1400255.

Harnessing Quantum Decoherence

Imagine a tennis ball is being bombarded by transparent paper clips coming from all around it. The paper clips are hard to see, but every time one hits the tennis ball, the sphere moves a little bit. Over time, you can deduce the presence of the paper clips even though you cannot see them directly because you see the tennis ball move back and forth apparently at random.

Now, suppose the paper clips are instead bombarding a bowling ball. The bowling ball will move much less than the tennis ball, so you won't be able to see its movement. However, the paper clips change direction radically when they hit the bowling ball, and which direction they bounce depends on where the bowling ball is.

If you could put the bowling ball in a quantum superposition – that is, in two places at once – the paper clips will find out where the ball is located, destroying the quantumness of the bowling ball's superposition and collapsing it to be only in one place.

PI postdoctoral fellow **Jess Riedel** has investigated this scenario and shown that quantum decoherence can indeed be a powerful tool for detecting particles (in the example's case, transparent paperclips) which would be invisible to purely classical measurements. Such a process might be useful, for instance, for detecting dark matter particles.

This research is timely because the sensitivity of this technique grows quickly with the size of the superposed object, and experiments creating large superpositions have recently seen rapid progress. So-called matter interferometers have produced superpositions of giant molecules with a hundred atoms, and superpositions of tens of thousands of atoms will be possible in the near future.

Reference:

C.J. Riedel (Perimeter Institute and IBM Watson Research Center), "Decoherence from classically undetectable sources: A standard quantum limit for diffusion," arXiv:1504.03250.

Strong Gravity

From the big bang to neutron stars and black holes, Perimeter research into strong gravity explores cosmic cataclysms powerful enough to warp the fabric of spacetime. These areas of space where gravity is extremely strong serve as a natural experiment where researchers can theoretically "test" the validity of our current theory of gravity (Einstein's general relativity) and investigate alternative theories. Perimeter researchers also seek to understand and characterize the ways that curved or dynamical spacetimes are connected to other fundamental questions of physics.

One of the major themes within strong gravity research this year has been the correspondence between conformal field theories (CFT) and anti-de Sitter spacetime (AdS). This correspondence naturally arises in theories of quantum gravity, such as string theory or M-theory.

This has been a hot area of theoretical physics research for the past two decades, ever since physicist Juan Maldacena proposed the correspondence between the two.

It has led to the conjectured holographic principle in which gravitational phenomenon in (d+1)-spatial dimensions can be mapped on a theory that has just d-spatial dimensions. (Imagine taking a globe and doing the transformations to make it into a flat map.)

Most recently, Perimeter Faculty member **Luis Lehner**, Associate Faculty member **Alex Buchel**, and postdoctoral researcher **Stephen Green** have been studying how instabilities in anti-de Sitter spacetime would impact black hole formation.

As well as providing further insights into the collapsing and dispersing processes that govern waves in anti-de Sitter space and eventual gravitational collapse, their studies have uncovered a remarkable connection between the stability or instability properties of AdS spacetime and the famous Fermi-Pasta-Ulam problem, an apparent paradox in chaos theory arising from the fact that many complicated enough physical systems exhibit almost exactly periodic behaviour.

Meanwhile, PSI Fellow **David Kubiznak** and PI Affiliate **Robert Mann** have been working in an area that provides a new perspective on black hole thermodynamics, by looking at black holes from the viewpoint of chemistry.

They find that both charged and rotating black holes exhibit novel chemical-type phase behaviour. This has opened up a new approach to understanding black hole thermodynamics, generating a groundswell of activity with over 120 papers written in the past three years. Kubiznak, Mann, and several PI graduate students have been involved in studying the various aspects of this approach. Their most recent finding is a brand new class of black holes that are "super-entropic," having an entropy greater than that expected from standard thermodynamic considerations.

References:

V. Balasubramanian (Western University), A. Buchel (Perimeter Institute and Western University), S. Green (University of Guelph), L. Lehner (Perimeter Institute), and S. Liebling (Long Island University),

"Holographic Thermalization, stability of AdS, and the Fermi-Pasta-Ulam-Tsingou paradox," *Phys. Rev. Lett.* 113 071601 (2014), arXiv:1403.6471.

A. Buchel (Perimeter Institute and Western University), S. Green (Perimeter Institute), L. Lehner (Perimeter Institute), and S. Liebling (Long Island University), "Conserved quantities and dual turbulent cascades in Anti-de Sitter spacetime," *Phys. Rev. D* 91 064026 (2015), arXiv:1412.4761.

B. Dolan (National University of Ireland and Dublin Institute for Advanced Studies), D. Kastor (University of Massachusetts), D. Kubiznak (Perimeter Institute), R.B. Mann (University of Waterloo and Perimeter Institute), and J. Traschen (University of Massachusetts), "Thermodynamic Volumes and Isoperimetric Inequalities for de Sitter Black Holes," *Phys. Rev. D* 87 104017, arXiv:1301.5926.

N. Altamirano (Perimeter Institute and National University of Córdoba), D. Kubiznak (Perimeter Institute and University of Waterloo), R.B. Mann (University of Waterloo), and Z. Sherkatghanad (Isfahan University of Technology), "Thermodynamics of rotating black holes and black rings: phase transitions and thermodynamic volume," *Galaxies* 2 89 (2014), arXiv:1401.2586.

R. Hennigar (University of Waterloo), D. Kubiznak (Perimeter Institute and University of Waterloo), and R.B. Mann (University of Waterloo), "Entropy Inequality Violations from Ultraspinning Black Holes," *Phys. Rev. Lett.* 115 031101 (2015), arXiv:1411.4309.

Honours, Awards, and Major Grants

Many Perimeter researchers have received national and international recognition for their work in 2014/15. Notable among these are the following:

- Faculty members Philip Schuster and Natalia Toro were awarded a $100,000 USD New Horizons in Physics Prize by the Breakthrough Prize Foundation (formerly the Fundamental Physics Prize Foundation); this marked the third consecutive year a Perimeter faculty member won, and no other institution in the world has ever won twice.

- Faculty member Pedro Vieira received a 2015 Sloan Research Fellowship, valued at $55,000 USD, from the Alfred P. Sloan Foundation.

- Faculty member Pedro Vieira was awarded the prestigious 2015 Gribov Medal by the European Physical Society, making him the third Perimeter faculty member to win since 2009.

- Director Neil Turok was elected a Fellow of the Royal Society of Canada.

- Distinguished Visiting Research Chair Matthew Fisher was awarded the 2015 Oliver E. Buckley Condensed Matter Physics Prize of the American Physical Society.

- Associate Faculty member Cliff Burgess was awarded a CERN Scientific Associate position.

- Director Neil Turok was awarded an honorary doctorate degree by the University of Stellenbosch in South Africa.

- Faculty member Luis Lehner was named to the Scientific Council of the International Centre for Theoretical Physics – South American Institute for Fundamental Research in Brazil.

- Faculty member Lee Smolin was ranked 22nd on *Prospect* magazine's "World Thinkers 2015" list.

- Faculty member Lee Smolin and his collaborator, Marina Cortês, were awarded the inaugural Buchalter Cosmology Prize by the American Astronomical Society for their paper, "The Universe as a Process of Unique Events;" Faculty member Luis Lehner and Associate Faculty member Matthew Johnson were among the prize's third place winners.

- Postdoctoral fellow David Marsh was awarded a Royal Astronomical Society Research Fellowship.

- Former postdoctoral researcher Joseph Ben Geloun was awarded the 2015 Young Scientist Prize in Mathematical Physics by the International Union of Pure and Applied Physics, for work completed while at Perimeter.

- Visiting Fellow Eduardo Martinez-Martin was awarded a prestigious 2015 John Charles Polyani Prize from the Council of Ontario Universities, valued at $20,000.

- Faculty member Lee Smolin was a third prize winner in the 2015 Foundational Questions Institute (FQXi) essay contest on the connection between physics and mathematics. Associate Postdoctoral Researcher Matthew Leifer was a second prize winner.

- Associate Faculty member Avery Broderick is a co-investigator on a National Science Foundation Mid-Scale Innovations Program Grant that was awarded $6,500,000 USD (2015-2020), supporting infrastructure and operations tied to the Event Horizon Telescope experiment.

- Associate Faculty member Michele Mosca was awarded a three-year contract (worth over $600,000) with the Government of Canada to work on post-quantum cryptography.

- Faculty member Lee Smolin was awarded a $690,000 USD grant from the John Templeton Foundation for work on fundamental time asymmetry.

- Distinguished Visiting Research Chairs Patrick Hayden and Ashvin Vishwanath were each awarded Simons Investigators grants.

- Faculty members Davide Gaiotto and Jaume Gomis received a John Templeton Foundation Grant of $190,000 USD for their proposal, “Charting out the space of quantum field theories.”

- Faculty member Lucien Hardy was the co-recipient of a $148,000 USD grant from the Foundational Questions Institute (FQXi) for his project, “Categorical Compositional Physics.”

- Faculty member Robert Spekkens was the co-recipient, along with Perimeter Affiliate Kevin Resch, of a $99,000 USD grant from the Foundational Questions Institute (FQXi) for their project, “Experimental test of intrinsically quantum causal relations.”

- Distinguished Visiting Research Chair Adrian Kent received a $105,000 USD grant from the Foundational Questions Institute (FQXi) for his project, “Quasiclassical events in Relativistic Quantum Field Theory.”

- Associate Postdoctoral Researcher Matthew Leifer received a $52,000 USD grant from the Foundational Questions Institute (FQXi) for his project, “Quantum Theory in the Block Universe.”

- Three Perimeter researchers were awarded Early Researcher Awards worth $140,000 each by the Province of Ontario:
    - Faculty member Philip Schuster
    - Faculty member Kendrick Smith
    - Associate Faculty member Itay Yavin

- Perimeter scientists were awarded NSERC Discovery Grants totalling $2,364,000 (over terms of up to five years), as follows:
    - Faculty member Asimina Arvanitaki: $90,000 ($30,000/year over three years)
    - Faculty member Philip Schuster: $350,000 ($70,000/year over five years)
    - Faculty member Lee Smolin: $19,000 over one year
    - Faculty member Pedro Vieira: $365,000 ($73,000/year over five years)
    - Associate Faculty member Niayesh Afshordi: $210,000 ($42,000/year over five years)
    - Associate Faculty member Alex Buchel: $350,000 ($70,000/year over five years)
    - Associate Faculty member Cliff Burgess: $400,000 ($80,000/year over five years)
    - Associate Faculty member Itay Yavin: $340,000 ($68,000/year over five years), plus a Discovery Accelerator Supplement of $40,000/year over three years
    - PSI Fellow David Kubiznak: $120,000 ($24,000/year over five years)

Objective 2: Become the research home of a critical mass of the world's leading theoretical physicists

Summary of Achievements

- Appointed Kevin Costello, Freddy Cachazo, Pedro Vieira, and Paul Steinhardt as Perimeter Research Chairs, bringing the total to eight
- Obtained investments from Gluskin Sheff + Associates, the Riddell Family Charitable Foundation, and Cenovus Energy to fund three Perimeter Research Chairs
- Recruited Max Metlitski as a full-time faculty member
- Jointly appointed three new associate faculty members (Alexander Braverman, Markus Mueller, and Ue-Li Pen) and renewed five more, bringing the total to 17

Highlights

Perimeter Research Chairs

The Perimeter Research Chairs program is designed to assemble world-leading scientists in strategically chosen fields, offering them a unique opportunity to maximize both their productivity and potential for major breakthroughs. Perimeter provides chairholders with the necessary resources to make rapid progress on key problems, enabling them to organize conferences, host collaborators, and attract the best graduate students and postdoctoral researchers in the world. Perimeter further enables chairholders to devote themselves fully to their research by freeing them from teaching requirements and providing excellent administrative support.

Named for the legendary scientists whose insights helped define modern physics, the Perimeter Research Chairs are envisioned as the most prestigious chairs in theoretical physics worldwide. They are funded through major gifts of up to $4 million, supporting exceptional emerging talent, young faculty reaching their peak years of research productivity, and renowned physics pioneers. Through its Emmy Noether initiatives, Perimeter is committed to bridging the gender gap in physics, and the Institute is actively seeking private partners to fund Perimeter Research Chairs for top female scientists.

Perimeter faculty members are known internationally as some of the leading researchers in their respective fields and they routinely receive offers to go elsewhere. The Perimeter Research Chairs program is thus crucial in not only attracting top scientists to Perimeter, but also in ensuring those that are already here remain in the world's best environment for accelerating discovery. Each new appointment sends the message that Perimeter, and Canada, is the place to do ground-breaking research in theoretical physics.

The past year has been a very successful one for the Perimeter Research Chairs program, exceeding targeted objectives. In August of 2014, Perimeter welcomed the fifth chairholder,[8] **Kevin Costello**, one of the world's top young mathematicians, who is the **Krembil Foundation William Rowan Hamilton Chair in Theoretical Physics**.

Since then, the Institute has appointed three new chairs:

- **Paul Steinhardt as the Richard P. Feynman Chair in Theoretical Physics (Visiting)**, who will spend three months a year at Perimeter in conjunction with his position at Princeton University
- **Pedro Vieira as the Clay Riddell Paul Dirac Chair in Theoretical Physics**, supported by a $1 million investment from the Riddell Family Charitable Foundation
- **Freddy Cachazo as the Gluskin Sheff Freeman Dyson Chair in Theoretical Physics**, supported by a $2 million investment from Gluskin Sheff + Associates

In addition, in summer 2015, Perimeter obtained a $300,000 commitment from Cenovus Energy in support of support Subir Sachdev as the Cenovus Energy James Clerk Maxwell Chair in Theoretical Physics (Visiting).

New Perimeter Research Chair Appointments in 2014/15:

Freddy Cachazo (PhD Harvard University, 2002) is the Gluskin Sheff Freeman Dyson Chair in Theoretical Physics at Perimeter Institute, where he has been a faculty member since 2005. From 2002 to 2005, he was a Member of the School of Natural Sciences at the Institute for Advanced Study in Princeton. Cachazo is one of the world's leading experts in the study and computation of scattering amplitudes in quantum chromodynamics (QCD) and N=4 super Yang-Mills (MSYM) theories. His many honours include the Gribov Medal of the European Physical Society (2009), the Rutherford Memorial Medal in Physics from the Royal Society of Canada (2011), the Herzberg Medal from the Canadian Association of Physicists (2012), and a New Horizons in Physics Prize from the Fundamental Physics Prize Foundation (2014).

Kevin Costello (PhD University of Cambridge, 2003) joined Perimeter in August 2014 from Northwestern University, where he had been a faculty member since 2006. He is the inaugural Krembil Foundation William Rowan Hamilton Chair in Theoretical Physics at Perimeter Institute. Previously, he was a Chapman Fellow at Imperial College London (2003-05) and the Dixon Instructor at the University of Chicago (2005-06). Costello works on the mathematical aspects of quantum field theory and string theory. He is the author of *Renormalization and Effective Field Theory*, a path-breaking monograph introducing powerful new mathematical tools into the theory of quantum fields. Costello's previous

[8] The other chairholders are (in order of appointment date): (1) Xiao-Gang Wen, the BMO Financial Group Isaac Newton Chair in Theoretical Physics; (2) Neil Turok, the Mike and Ophelia Lazaridis Niels Bohr Chair in Theoretical Physics; (3) Davide Gaiotto, the Krembil Foundation Galileo Galilei Chair in Theoretical Physic; and (4) Subir Sachdev, the Cenovus Energy James Clerk Maxwell Chair in Theoretical Physics (Visiting).

honours include an Alfred P. Sloan Research Fellowship and several prestigious grants from the National Science Foundation in the United States.

Paul Steinhardt (PhD Harvard University, 1978) is the Richard P. Feynman Chair in Theoretical Physics at Perimeter Institute (Visiting) and the Albert Einstein Professor in Science at Princeton University, where he is also the Director of the Princeton Center for Theoretical Science. His research interests span particle physics, astrophysics, cosmology, and condensed matter physics. With Neil Turok, he developed a cyclic model for cosmology, according to which the big bang is explained as a collision between two "brane-worlds" in M-theory. In addition to his continued research on inflationary and cyclic cosmology, Steinhardt has been one of the developers of a new class of disordered "hyperuniform" photonic materials with complete bandgaps, and he conducted a systematic search for natural quasicrystals that has culminated in discovering the first known example. In 2011, Steinhardt led a successful geological expedition to Far Eastern Russia to find new information about its origin and retrieve more samples, and in 2014, the International Mineralogical Association officially accepted another new mineral into its official catalogue, naming it "steinhardtite." He is a Fellow in the American Physical Society (APS) and a member of the National Academy of Sciences. Among his many honours, he shared the P.A.M. Dirac Medal from the International Centre for Theoretical Physics (2002) for his role as one of the architects of the inflationary model of the universe; the Oliver E. Buckley Prize of the APS (2010) for his contributions to the theory of quasicrystals; and the John Scott Award (2012), also for his work on quasicrystals.

Pedro Vieira (PhD École Normale Supérieure and the Theoretical Physics Center at the University of Porto, 2008) is the Clay Riddell Paul Dirac Chair in Theoretical Physics at Perimeter Institute, where he has been a faculty member since 2009. Prior to that, he was a Junior Scientist at the Max Planck Institute for Gravitational Physics (Albert Einstein Institute) from 2008 to 2009. Vieira's research concerns the development of new mathematical techniques for gauge and string theories, ultimately aiming at the solution of a realistic four-dimensional gauge theory. His research interests also include the related areas of the AdS/CFT correspondence and theoretical calculations of scattering amplitudes. "Y-system for scattering amplitudes," a paper by Vieira and his collaborators, won the 2012 Best Paper Prize from the Institute of Physics (IOP) and the Editorial Board of *Journal of Physics A*. In 2015, he was awarded both a Sloan Research Fellowship and the Gribov Medal of the European Physical Society.

Faculty

In addition to the Perimeter Research Chairs, the Institute has continued to expand its full-time faculty, which is comprised of eminent senior scientists and leading young researchers from across the spectrum of theoretical physics. In 2014/15, Perimeter recruited Max Metlitski, an outstanding young researcher who will add to the Institute's growing strength in condensed matter. Metlitski will arrive in the fall of 2015, bringing the Institute's faculty to 25, in line with targeted objectives.

New Faculty Recruited in 2014/15:

Max Metlitski (PhD Harvard University, 2011) will join Perimeter's faculty in the fall of 2015. He comes to Waterloo from the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara, where he's been a Postdoctoral Research Associate since 2011. Metlitski is a condensed matter physicist whose work has contributed to the theory of quantum criticality in metals and to the understanding of topological phases in the presence of interactions. In 2014, he won the William L. McMillan Award, which recognizes outstanding contributions by a young condensed matter physicist.

Associate Faculty

Perimeter's Associate Faculty program is designed to attract and retain top scientific talent through joint appointments with Canadian university partners. Associate faculty spend up to 50 percent of their time at Perimeter, in addition to teaching and conducting research at a partner institution.

The program has succeeded in bringing highly respected international scientists to Canada by highlighting the unique opportunities afforded by both Perimeter and its partner institutes.[9] Each such recruitment success adds to the country's growing strength in fundamental physics, while also making both Perimeter and its partners more attractive to outstanding junior faculty, postdoctoral researchers, and graduate students.

In 2014/15, in line with targeted objectives, Perimeter appointed three new associate faculty members: **Alexander Braverman** (with the University of Toronto), **Markus Mueller** (with Western University), and **Ue-Li Pen** (with the Canadian Institute for Theoretical Astrophysics at the University of Toronto). Braverman and Mueller, who will both contribute to Perimeter's growing strength in mathematical physics, provide further evidence of the program's success in bringing international scientists to Canada (from the United States and Germany, respectively). Braverman and Pen also mark the Institute's first joint hires with Toronto, one of the country's most prestigious universities.

Over the past year, Perimeter also renewed the terms of five existing associate faculty.[10] The Institute now has 17 associate faculty.

[9] In recent years, Perimeter has attracted a number of top researchers from prestigious positions in the US, including David Cory (Massachusetts Institute of Technology), Itay Yavin (New York University), and, most recently, Raffi Budakian (University of Illinois at Urbana-Champaign).

[10] Associate faculty are appointed for fixed terms ranging from three to seven years. All five whose terms were due to end in 2014/15 were successfully renewed. They are: Alex Buchel (Western University), David Cory (Institute for Quantum Computing/University of Waterloo), Raymond Laflamme (Institute for Quantum Computing/University of Waterloo), Roger Melko (University of Waterloo), and Michele Mosca (Institute for Quantum Computing/University of Waterloo).

New Associate Faculty Appointments in 2014/15:

Alexander Braverman (PhD Tel Aviv University, 1998) joined Perimeter in July 2015, jointly appointed with the University of Toronto. He was previously a member of Brown University's faculty (2004-15) and held lecturer positions at Harvard University (2000-04) and the Massachusetts Institute of Technology (1997-99). Braverman specializes in a number of areas with applications to mathematical physics, including algebraic geometry, representation theory, number theory, and the geometric Langlands program. He has been a Clay Mathematics Institute Prize Fellow and a Simons Fellow in Mathematics.

Markus Mueller (PhD Technical University of Berlin, 2007) joined Perimeter in July 2015, jointly appointed with Western University, where he holds the Canada Research Chair in the Foundations of Physics. Prior to that, he was a Junior Research Group Leader at the Institute for Theoretical Physics at the University of Heidelberg, and held postdoctoral positions at Perimeter Institute, the University of Potsdam, and the Max Planck Institute for Mathematics in the Sciences. Mueller is a mathematical physicist working in quantum information and quantum foundations, with particular interest in statistical physics, generalized probabilistic theories, and algorithmic information theory.

Ue-Li Pen (PhD Princeton University, 1995) joined Perimeter in December 2014. He is jointly appointed with the Canadian Institute for Theoretical Astrophysics (CITA) at the University of Toronto, where he has been a professor since 1998 and Associate Director since 2009. Prior to that, he held fellowships at Princeton University (1994-95) and Harvard University (1995-98). Pen is a theoretical astrophysicist who studies systems where basic physical effects can be isolated from astronomical complexities. His research interests include 21cm cosmology, HPC simulations, gravitational waves, pulsars, and radio interferometry. Among his many honours, Pen is a Senior Fellow of the Canadian Institute for Advanced Research in the Cosmology and Gravity program and an Adjunct Professor at the Tata Institute for Fundamental Research in India.

Objective 3: Generate a flow-through of the most promising talent

Summary of Achievements

- Appointed 18 postdoctoral researchers in 2014/15 and recruited 17 more for 2015/16
- Three departing postdoctoral researchers obtained tenure-track faculty positions
- Successfully ran the sixth year of the Perimeter Scholars International (PSI) master's program for 31 students and provided ongoing training for 42 PhD students
- Brought 21 Visiting Graduate Fellows to the Institute
- Provided research training to four exceptional undergraduate students

Highlights

Postdoctoral Researchers

From master's students to leading postdoctoral scientists, Perimeter develops the skills required to drive scientific discovery and seed the innovation ecosystem.

Perimeter Institute hosts the world's largest group of independent postdoctoral researchers in theoretical physics, and is known for its stimulating and supportive environment. In 2014/15, Perimeter appointed 18 postdoctoral researchers and recruited an additional 17 for 2015/16, exceeding targeted outcomes. Perimeter received 629 applications for its 2015/16 postdoctoral positions and achieved the highest acceptance rate in the Institute's history, attesting to its growing international reputation.

Postdocs at Perimeter have full research independence and are encouraged to pursue novel, ambitious lines of research. The Institute offers them collaboration opportunities which are second to none through numerous strategic partnerships with experimental and observational facilities, including TRIUMF, SNOLAB, and the Institute for Quantum Computing at the University of Waterloo (see Objective 6). Perimeter also leverages its partnerships to offer joint postdoctoral positions to top candidates.[11]

Training at Perimeter pays off. In 2014/15, despite an extremely competitive worldwide academic market, three departing postdoctoral researchers have obtained tenure-track faculty positions:

- Lilia Anguelova (Institute of Nuclear Research and Nuclear Energy, Bulgaria)
- Nikolay Bobev (Institute for Theoretical Physics at the University of Leuven)
- Zlatko Papić (University of Leeds)

[11] For example, Perimeter leveraged one such joint offer with the Canadian Institute for Theoretical Astrophysics (CITA) at the University of Toronto to recruit I-Sheng Yang for 2015/16.

Several other departing postdocs obtained prestigious positions at top international institutions, including Durham University, Imperial College London, and the California Institute of Technology.

Perimeter Scholars International (PSI) Master's Program

"If I had extremely talented undergrads asking me what to do next, I would tell them to do the PSI program…. There's nothing better – nothing even close – in my opinion."
– Nima Arkani-Hamed, Perimeter Distinguished Visiting Research Chair

Perimeter Scholars International (PSI) is a master's level program that attracts highly talented university graduates from around the world, bringing them to the cutting edge of theoretical physics in one academic year. PSI's innovative curriculum features modular three-week courses taught by top international lecturers, including many of the Institute's own researchers.[12] Students receive tutorial support from six postdoctoral-level PSI Fellows and several graduate teaching assistants. Upon completion of the program, they receive a master's degree from the University of Waterloo.

PSI is designed to foster the critical-thinking and problem-solving skills needed for research excellence, rather than the rote memorization encouraged by test-based models in more traditional university settings. PSI brings graduates with high scientific potential to Canada. From each PSI class, Perimeter selects the best among them for continued doctoral training. Eleven students – just over one-third of the 2014/15 class – are remaining in Canada for their PhD studies, eight of them at Perimeter. Others will be pursuing their doctoral degrees at top international institutions, including the University of Oxford, Stanford University, and the University of California, Berkeley. If past experience holds, still others will go on to found start-ups or work in government service, medicine, or tech-based industries.[13]

The PSI program also strengthens Perimeter's ties with its regional partners, with faculty from nearby universities participating in teaching and research project supervision. All PSI classes are made available to non-Perimeter graduate students who obtain special permission, thereby enriching graduate course offerings throughout the region.

- In 2014/15, the PSI program trained 31 students, six of them women, from 16 countries, in line with targeted objectives.
- PSI continues to grow in prestige and competitiveness. For the upcoming 2015/16 class, Perimeter received 472 applications from 76 countries, up 29 percent over last year.[14]

[12] In 2014/15, the PSI faculty comprised 21 lecturers, including 11 Perimeter researchers, one Visiting Fellow, and nine other international scientists.
[13] Examples of past successes outside academia include Saurabh Madaan (Data Scientist, Google, San Francisco), Henry Reich (Creator, *MinutePhysics*, Montana), Anabelle Spinoulas (Analyst and Transport Modeller, TransPosition, Brisbane, Australia), and Imogen Wright (Co-Founder and Algorithm Developer, Hyrax Biosciences, Cape Town, South Africa).
[14] For the 2015/16 class, 30 students from 18 countries have been accepted, including nine women. The program also had an extremely high 74 percent acceptance rate, up from 61 percent last year.

PhD Program

Training in theoretical physics instills a unique combination of advanced quantitative skills, analysis, and creativity that is highly sought after in both academia and industry. People trained in theoretical physics at Perimeter are making key contributions to many fields of science, as well as industry, finance, and government.[15]

Since Perimeter is not itself a degree-granting institution, the PhD program brings top calibre students to both Perimeter and to the partner universities from which they receive their degrees, constituting a significant talent gain for Canada. As planned, two-thirds of the Institute's PhD students are graduates of the PSI program, as Perimeter faculty continue to recruit top PSI graduates for doctoral studies.

At year's end, Perimeter had 42 PhD students in residence and three more being supervised by Perimeter associate faculty while in residence at partner universities.

- Seven PhD students supervised by Perimeter faculty graduated from partner universities in 2014/15.
- Siavash Aslanbeigi was hired by Scotiabank in Toronto as a Manager of Risk Analytics, Anton van Niekerk joined Athena Software in Waterloo as a Report Writer and Data Query Specialist, and the others obtained competitive postdoctoral fellowships at the Institute for Advanced Study, University of Calgary, University of Iceland, University of Cambridge, and Radboud University, Nijmegen.

Visiting Graduate Fellows

The Visiting Graduate Fellows program brings advanced PhD students from around the world to spend several months at the Institute, enabling them to both benefit from and add to Perimeter's vibrant research community at a pivotal time in their training. For Fellows, it is an opportunity to interact with leading researchers and attend scientific talks they would not have access to at their home institutions.

- In 2014/15, Perimeter hosted 21 Visiting Graduate Fellows for a total of 22 visits, meeting targeted outcomes.

Undergraduate Students

The Undergraduate Student program brings top Canadian and international undergraduates to Perimeter to complete two- to four-month research projects with the Institute's postdoctoral researchers, who gain valuable mentorship experience. The program also functions as a first point of

[15] Examples of past successes outside academia include Jorge Escobedo (Chief Technology Officer, Canopy Labs, Toronto), Jonathan Hackett (Consultant, The Boston Consulting Group, Toronto), Cozmin Ududec (Co-Founder and Risk Management Lead, Invenia Technical Computing, Winnipeg), and Alexandre Yale (Senior Data Analyst, Alchemy Worx, Montreal).

contact with promising students, giving Perimeter a recruiting advantage as they progress through their career. Alumni of this program who had returned to Perimeter in 2014/15 included PSI student Shreya Prasanna Kumar, PhD student Dalimil Mazac, and postdoctoral researcher Matteo Smerlak.

- This year, Perimeter provided research training to four exceptional undergraduate students from top institutions, including the Massachusetts Institute of Technology, University of Alberta, and University of Cambridge.

Objective 4: Become the second research home for many of the world's outstanding theorists

Summary of Achievements

- Appointed four leading scientists as Distinguished Visiting Research Chairs and renewed nine more, bringing the total to 44
- Appointed eight accomplished researchers as Visiting Fellows and renewed one more, bringing the total to 22
- Welcomed six early-career researchers as Emmy Noether Fellows and recruited seven more
- Hosted 450 visiting scientists for a total of 530 visits

Highlights

Distinguished Visiting Research Chairs

Perimeter's unique Distinguished Visiting Research Chairs (DVRC) program is one of the Institute's most successful – a strategic and cost-effective means of bringing world-leading scientists to Perimeter for extended periods. DVRCs are appointed to renewable three-year terms, while retaining permanent positions at their home institutions.

Perimeter's DVRCs – including such luminaries as Yakir Aharonov, Gabriela Gonzalez, Gerard 't Hooft, and Leonard Susskind – collectively span an enormous range of expertise (see Appendix B: Distinguished Visiting Research Chairs). They come to Perimeter to do research, collaborate, and participate in all facets of life at the Institute. In November 2014, for example, Nima Arkani-Hamed gave a very popular Public Lecture on "Quantum Mechanics and Spacetime in the 21st Century."

For DVRCs, time spent at Perimeter is highly productive, since they are free from their usual teaching and administrative duties. Meanwhile, their presence as conference participants, seminar speakers, and collaborators greatly enhances Perimeter's research environment and inspires its resident community. In June 2015, the Institute was especially pleased to welcome 17 DVRCs as part of "Convergence."

In 2014/15, Perimeter appointed four new DVRCs and renewed nine more,[16] exceeding targeted objectives and bringing the total to 44 DVRCs at year's end. The community is as active as ever, with 32 DVRCs making a total of 53 visits over the past year.

[16] Yakir Aharonov, Nima Arkani-Hamed, Ignacio Cirac, Patrick Hayden, Leo Kadanoff, Adrian Kent, and Ramesh Narayan renewed their terms through 2018, while Leonard Susskind and Bill Unruh renewed theirs through 2019.

New Distinguished Visiting Research Chair Appointments in 2014/15:

Joseph Incandela (PhD University of Chicago, 1986) is the Pat and Joe Yzurdiaga Chair in Experimental Science and Professor of Physics at the University of California, Santa Barbara. He specializes in high energy experimental physics and has worked on several experiments in his career, including the UA2 experiment at CERN, where he studied W and Z bosons and searched for charged Higgs bosons, and the CDF experiment at the Fermi National Accelerator Laboratory (Fermilab), where he led the construction and design of silicon detectors and co-led the successful search for the top quark using lifetime tagging of b quark jets. More recently, he has served in a number of leadership roles tied to the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider at CERN; he was CMS Spokesperson and, in July 2012, he announced the historic discovery of the Higgs boson. For his leadership roles in CMS, he was awarded a Special Breakthrough Prize in Fundamental Physics from the Breakthrough Prize Foundation in 2013. He was elected a member of the US National Academy of Sciences in 2015.

Iakov (Yan) Soibelman (PhD Rostov University, 1985) is a Professor of Mathematics at Kansas State University. His research interests include quantum groups, deformation theory, algebraic geometry, topology, symplectic geometry, representation theory, non-commutative geometry, differential equations, mathematical physics, and string theory. In collaboration with Maxim Kontsevich, Soibelman developed new algebraic and geometric methods for studying various aspects of homological mirror symmetry. More recently, they introduced a notion of motivic Donaldson-Thomas invariants and proposed a new type of wall-crossing formulas for such invariants. Soibelman is a member of the American Mathematical Society and the Kiev Mathematical Society, and the founder of the Manhattan Mathematical Olympiad. He is also a past Fellow of the Sloan Foundation and the Clay Mathematics Institute, and has held visiting professorships at numerous prestigious institutions, including Harvard University, the Massachusetts Institute of Technology, and the University of Cambridge.

Frank Verstraete (PhD University of Leuven, 2002) is a Professor of Physics at the University of Vienna, where he leads the quantum theory group focused on the study of entanglement in many-body quantum systems. His other research interests include quantum information theory, strongly correlated quantum systems and their numerical simulation, and linear and multilinear algebra. Verstraete also holds a professorship at the University of Ghent and has worked previously with Ignacio Cirac at the Max Planck Institute for Quantum Optics and with John Preskill at the California Institute of Technology. In 2009, he won the Lieben Prize, given annually by the Austrian Academy of Sciences.

Matias Zaldarriaga (PhD Massachusetts Institute of Technology, 1998) is a Professor of Astrophysics at the Institute for Advanced Study who has made many influential and creative contributions to our understanding of the early universe, particle astrophysics, and cosmology as a probe of fundamental physics. Much of his work centres on understanding the clues about the earliest moments of our universe encoded in the cosmic microwave background, the faint glow of radiation generated by the big bang. Early in his career, Zaldarriaga co-wrote computer software known as CMBFAST that has become a standard tool for astronomers interpreting observations of the cosmic microwave background. Among his many honours, he has been awarded Sloan and McArthur Fellowships, the Helen B. Warner Prize of the American Astronomical Society, and the Gribov Medal of the European Physical Society.

Visiting Fellows

The Visiting Fellows program is an important means of bringing accomplished researchers to Perimeter for regular visits. Much like DVRCs, Visiting Fellows span a wide range of expertise, are appointed to renewable terms, and retain their positions at their home institutions while coming to Perimeter for extended research visits of up to six months each year. The program also allows Perimeter to maintain productive ties with promising young researchers and the elite institutions at which they are based.

The program continued to grow in 2014/15, attracting eight new Visiting Fellows and renewing one more.[17] At year's end, Perimeter had 22 Visiting Fellows, exceeding targeted objectives. These talented researchers continue to enrich the Institute's research environment, with 12 Visiting Fellows making a total of 15 visits over the course of the year.

New Visiting Fellow Appointments in 2014/15:

Philippe Corboz (PhD ETH Zurich, 2008) is an Assistant Professor in Theoretical Condensed Matter Physics at the Institute for Theoretical Physics at the University of Amsterdam, having completed postdoctoral work at ETH Zurich, the Swiss Federal Institute of Technology, and the University of Queensland. His research interests include condensed matter, computational physics, quantum many-body physics, strongly correlated systems, and computer programming.

Fay Dowker (PhD University of Cambridge, 1991) is a Professor of Theoretical Physics at Imperial College London and an Affiliate of the Institute for Quantum Computing at the University of Waterloo. Her research interests include quantum gravity, the foundations of quantum mechanics, and causal set theory. Dowker completed her PhD under the supervision of Stephen Hawking and held previous positions at Queen Mary University of London, Fermilab, the California Institute of Technology, and the University of California, Santa Barbara.

Jerome Gauntlett (PhD University of Cambridge, 1991) is the Head of Theoretical Physics at Imperial College London, having previously held research positions at Queen Mary University of London, the California Institute of Technology, and the University of Chicago. His principal research interests include string theory, supersymmetry, quantum field theory, and black holes. Recently, Gauntlett has been investigating whether string theory techniques can be used to study exotic states of matter that arise in condensed matter physics. He is a Fellow of the Institute of Physics and served as a scientific consultant for the 2014 film *The Theory of Everything*.

Jutho Haegeman (PhD Ghent University, 2011) is a postdoctoral researcher at Ghent University, working with Distinguished Visiting Research Chair Frank Verstraete. His research interests concern the description of condensed matter systems and quantum field theories using tensor network states or related methods. In particular, Haegeman is investigating new ideas and algorithms for extracting the low-energy description of microscopic quantum Hamiltonians using the tensor network philosophy.

[17] Ruth Gregory renewed her term through the fall of 2020.

John Laiho (PhD Princeton University, 2004) is an Assistant Professor at Syracuse University, having previously held research positions at the Fermi National Accelerator Laboratory (Fermilab), Washington University in St. Louis, and University of Glasgow. Laiho is a theoretical particle physicists, whose research interests include lattice QCD, flavor physics and CP violation, chiral perturbation theory, and lattice gravity.

Si Li (PhD Harvard University, 2011) is a Professor at the Yau Mathematical Sciences Center at Tsinghua University and an Affiliate Member at the Kavli Institute for the Physics and Mathematics of the Universe. He was previously an Assistant Professor at Boston University. Li's research interests centre on the interplay between geometry and physics – specifically algebraic and complex geometry, quantum field theory, and string theory. He was awarded a New World Mathematics Award in 2012 for his doctoral thesis.

Eduardo Martin-Martinez (PhD Universidad Complutense de Madrid, 2011) is a Research Assistant Professor at the Institute for Quantum Computing at the University of Waterloo. Martin-Martinez's research combines the fields of quantum information science, quantum field theory, and general relativity; in particular, he studies quantum effects induced by gravity from the perspective of quantum information. He is the recipient of numerous awards, including a prestigious Banting Postdoctoral Fellowship (2012) and the John Charles Polanyi Prize for Physics (2014).

Brian Swingle (PhD Massachusetts Institute of Technology, 2011) is a Postdoctoral Research Fellow at Stanford University, having previously held a Simons Fellowship in condensed matter at Harvard University. Swingle works at the interface of quantum matter, quantum information, and quantum gravity; his particular interests include quantum entanglement, strongly correlated systems, spin liquids and the physics of fractionalization, experimental signatures of strongly correlated phases, quantum information and computation, and holographic duality and string theory.

Emmy Noether Fellows

Amalie Emmy Noether was a German mathematician known for her ground-breaking contributions to abstract algebra and theoretical physics. Albert Einstein described her as the most important woman in the history of mathematics, yet she faced many obstacles as a woman in a male-dominated field. In her honour, Perimeter created the Emmy Noether Fellows program, with the aim of providing a vital boost to promising women in physics. It is part of Perimeter's Emmy Noether Initiative, an array of programs designed to meaningfully increase the number of women entering and flourishing in the field of fundamental physics.

Emmy Noether Fellows span a wide range of expertise and spend up to one year pursuing their research in Perimeter's dynamic scientific environment while on leave from their home institutions. They are encouraged to collaborate, participate in conferences and workshops, and generally enjoy the freedom to focus fully on their research at a crucially important early stage of their careers.

Perimeter offers tremendous staff support for both the Fellows and their families, and the program is designed to be flexible and responsive to their needs.[18]

In 2014/15, Perimeter welcomed six Emmy Noether Fellows and recruited seven more for 2015/16.[19] Applicant numbers have tripled since last year, demonstrating the program's growing prestige.

New Emmy Noether Fellows in 2014/15:

Alejandra Castro is an assistant professor at the University of Amsterdam, specializing in new approaches toward classical and quantum gravity. Her work seeks to explain the microscopic origin of black hole thermodynamics and the emergence of spacetime in quantum gravity.

Orit Davidovich is a Boas assistant professor at Northwestern University, specializing in topological field theory, fusion categories, and modular categories.

Astrid Eichhorn is a postdoctoral fellow at Imperial College London, whose research focuses on quantum gravity (mostly asymptotic safety). In her research, Eichhorn is seeking to establish a bridge between quantum gravity and particle physics.

Belén Paredes is a junior professor at Madrid's Institute for Theoretical Physics (IFT), UAM-CSIC, whose research interests include novel phases of matter, quantum entanglement, and engineering quantum matter for quantum information processing.

Catherine Pépin is a permanent researcher at France's Institut de Physique Théorique, CEA-Saclay, with a focus on emergent quantum phenomena. In particular, her recent work has examined zero-temperature phase transitions (called quantum critical points) in heavy fermion systems and high-temperature superconductors.

Silke Weinfurtner is a Royal Society Research Fellow and Nottingham Research Fellow at the University of Nottingham, specializing in questions of quantum gravity, strong gravity, and condensed matter physics. Much of her research focuses on the quest to design and carry out table-top experiments to explore quantum gravity.

[18] This includes arrangements for childcare to allow families to travel with Fellows, housing provisions, and deferments where needed. For example, when one of the 2014/15 Emmy Noether Fellows, Kathryn Zurek, landed a faculty position at the Lawrence Berkeley National Laboratory, Perimeter allowed her to defer the fellowship while she made the move and got settled.

[19] The Emmy Noether Fellows who were recruited for 2015/16 are Fiona Burnell (University of Minnesota), Barbara Drossel (Darmstadt University of Technology), Shirley Ho (Carnegie Mellon University), Natalia Perkins (University of Minnesota), Katarzyna Rejzner (University of York), Rachel Rosen (Columbia University), and Sarah Shandera (Pennsylvania State University).

Visitor Program

Perimeter Institute's visitor program brings scientists from around the world to Waterloo. Visitors benefit from having the time and space to conduct the intense, sustained work required to tackle tough problems, which is often done in collaboration with the Institute's resident scientists. In addition, the program enables Perimeter researchers to stay abreast of recent developments, exchange ideas, and spark new collaborations.

The visitor program is also a recruitment aid, showcasing the Institute's vibrant research environment and the excellent administrative support that enables scientists to maximize their productivity. In the past year, visits by potential recruits have led to new appointments at all levels – including, notably, Faculty member Max Metlitski and Associate Faculty members Markus Mueller and Ue-Li Pen.

- In 2014/15, Perimeter hosted 450 visiting scientists for a total of 530 visits, exceeding targeted objectives.[20]

[20] This included a strategic mix of affiliates, collaborators, potential recruits, and seminar and colloquia speakers, as well as 32 Distinguished Visiting Research Chairs and 12 Visiting Fellows.

Objective 5: Act as a hub for a network of theoretical physics and math centres around the world

Summary of Achievements

- Hosted the Tri-Institute Summer School on Elementary Particles (TRISEP) in July 2015
- Renewed partnerships with the International School for Advanced Studies (SISSA), the International Centre for Theoretical Physics – South American Institute for Fundamental Research (ICTP-SAIFR), and the University of Porto
- Recruited Prince Osei as the third Fields-Perimeter Institute Africa Postdoctoral Fellow
- Began work on the next WGSI Summit, to be held in the spring of 2016
- Provided continued expertise in support of the successful African Institute for Mathematical Sciences – Next Einstein Initiative (AIMS-NEI)
- Partnered on eight workshops and conferences with national and international partners and sponsored an additional 11 off-site scientific gatherings (see Objective 7)

Highlights

Collaborations and Partnerships

Perimeter partners with many leading centres in Canada and abroad, strengthening its position as a global research hub and opening up collaboration opportunities for its scientists. In addition to formal institutional partnerships, Perimeter enjoys many productive informal partnerships through its faculty, including at international institutions like the Thomas Jefferson National Accelerator Facility (Jefferson Lab), Canadian Hydrogen Intensity Mapping Experiment (CHIME), Event Horizon Telescope (EHT), Square Kilometre Array (SKA), TRIUMF, and the Large Hadron Collider at CERN.

In 2014/15, Perimeter strengthened ties in the international physics community through a number of ongoing partnerships, both formal and informal.

- The Institute renewed productive partnerships with the International School for Advanced Studies (SISSA), the International Centre for Theoretical Physics – South American Institute for Fundamental Research (ICTP-SAIFR), and the University of Porto through 2016, 2019, and 2020, respectively.
- The Institute hosted several important international conferences, including “EHT 2014” in November 2014. The Event Horizon Telescope is the first astronomical instrument capable of imaging the horizon of a known black hole, and this conference brought together more than 100

members of the EHT community to look at how to fully exploit the unique opportunities it provides.[21]

Fields-Perimeter Institute Africa Postdoctoral Fellowship

Perimeter and The Fields Institute for Research in Mathematical Sciences at the University of Toronto have partnered to fund four one-year joint postdoctoral fellowships for African nationals who have recently completed their PhDs. Prince Osei of Ghana was recently selected as the third fellow; he will arrive in the fall of 2015, to be based at Perimeter. Osei's research concerns quantum gravity and mathematical physics, and he has previously collaborated with Perimeter Faculty member Bianca Dittrich.

Tri-Institute Summer School on Elementary Particles (TRISEP)

The Tri-Institute Summer School on Elementary Particles (TRISEP) is a two-week, international summer school for graduate students and postdoctoral researchers on hot topics in particle physics. In partnership with fellow Canadian institutes TRIUMF and SNOLAB, Perimeter hosted the third annual summer school in July 2015, with topics including cosmology, the Standard Model, astroparticle physics, and modern amplitude techniques. The school's lecturers also included Perimeter researchers Natalia Toro and Song He, as well as Distinguished Visiting Research Chair Matias Zaldarriaga.

The Waterloo Global Science Initiative (WGSI)

The Waterloo Global Science Initiative (WGSI) is an independently funded, non-profit partnership between Perimeter Institute and the University of Waterloo. WGSI's mandate is to promote dialogue on complex global issues and to catalyze the long-range thinking necessary to advance ideas, opportunities, and strategies for a secure and sustainable future. It seeks to fulfill this mandate through its Summit Series, Blueprints, and related "impact activities."

In 2014/15, the WGSI team continued to distribute the *Learning 2030 Blueprint* and wrapped up related impact activities. Building on the successes of the 2011 and 2013 Summits, and in line with targeted objectives, planning is underway for the next Summit in 2016, which will explore scientific and technological approaches aimed at decreasing reliance on non-renewable energy sources and improving the well-being of the energy isolated.

Global Outreach

AIMS-NEI

To date, Perimeter's Global Outreach efforts have largely focused on the African Institute for Mathematical Sciences – Next Einstein Initiative (AIMS-NEI), a project founded by Perimeter Director

[21] Distinguished Visiting Research Chairs James Bardeen and Gabriela Gonzalez were among those in attendance.

Neil Turok in 2003 to establish a pan-African network of centres providing advanced mathematical and scientific education to exceptional African graduates. The AIMS network has grown from a single centre in South Africa to a network of five across the continent, with the most recent centre opening in Tanzania in the fall of 2014.

From the beginning, Perimeter's goal has been to provide expertise and guidance, acting as a resource to AIMS as they wrote their own success story. In 2014/15, Perimeter continued to leverage the expertise of both its research and administrative staff to assist the AIMS-NEI network.

- Perimeter staff provided expertise to assist with a successful $25 million proposal to the MasterCard Foundation.
- Perimeter staff have shared administrative expertise in preparations for the launch of AIMS-Tanzania and the inaugural Next Einstein Forum, which will be held in Senegal in March 2016.
- Perimeter Director Neil Turok participated in an October 2014 event in Ottawa to provide an update on AIMS-NEI to existing and potential supporters.
- Perimeter researchers continue to be involved in teaching at AIMS centres.

Objective 6: Increase Perimeter's role as Canada's focal point for foundational physics research

Summary of Achievements

- Appointed three associate faculty members with partners at the University of Toronto and Western University (see Objective 2)
- Partnered with the University of Waterloo to hold the PSI master's program and involved faculty from Canadian universities as research project supervisors and lecturers[22] (see Objective 3)
- Hosted eight joint workshops and conferences with regional and national academic partners, and sponsored an additional 11 (see Objective 7)
- Deepened ties with experimental and observational centres in Canada and abroad
- Continued to work closely with all relevant partners to foster the Quantum Valley ecosystem
- Appointed nine new Affiliates from across the country and renewed an additional 89, giving the Institute 113 Affiliates in total

Highlights

Engagement with Experimental Centres

Experiment is the ultimate test of all theory. Recognizing the importance of theory-experiment interactions, Perimeter has established ties with experimental and observational centres around the world, and continued to strengthen these relationships in 2014/15.

Perimeter's key experimental partner continues to be the Institute for Quantum Computing (IQC) at the University of Waterloo. IQC is led by Executive Director Raymond Laflamme and Deputy Directors Michele Mosca, David Cory, and Kevin Resch. Laflamme, Mosca, and Cory are all associate faculty at Perimeter, while Resch is a PI Affiliate. Many more PI researchers are cross-appointed at IQC.[23]

Examples abound of the progress that can happen when theorists and experimentalists work together. Perimeter Faculty member Robert Spekkens and PhD student Katja Ried recently worked with Resch and others at IQC to open new lines of inquiry for quantum systems. Perimeter postdoctoral researcher Juan Carrasquilla is part of a team that took an ultra-cold gas called a Bose-Einstein condensate and further "cooled" it by distilling it into a more orderly state.

[22] These included Anton Burkov, University of Waterloo; Joseph Emerson, Institute for Quantum Computing at the University of Waterloo; Marcel Franz, University of British Columbia; and David Morrissey, TRIUMF.

[23] Associate Faculty member Raffi Budakian is also jointly appointed at IQC, as is Visiting Fellow Eduardo Martin-Martinez, and postdoctoral researchers Gus Gutoski, Zhengfeng Ji, Huan Yang, and Joshua Combes. Faculty member Dmitry Abanin and Senior Research Affiliate Steve MacLean are associates at IQC, and the institutes share a number of affiliates as well.

Such exciting collaborations are only expected to grow, as Perimeter scientists deepen connections with many major experimental efforts throughout the world.

In particle physics and particle astrophysics, for example, Perimeter has built substantial ties to experimental and observational centres, both nationally and internationally. Faculty members Philip Schuster and Natalia Toro have extensive experimental connections, including at the Thomas Jefferson National Accelerator Facility (JLab), Large Hadron Collider (LHC) at CERN, and SLAC National Accelerator Laboratory. They are the co-spokespeople for A Prime Experiment (APEX) at JLab – an exceptional position for theorists – and are also involved in the Heavy Photon Search and the Beam Dump Experiment.

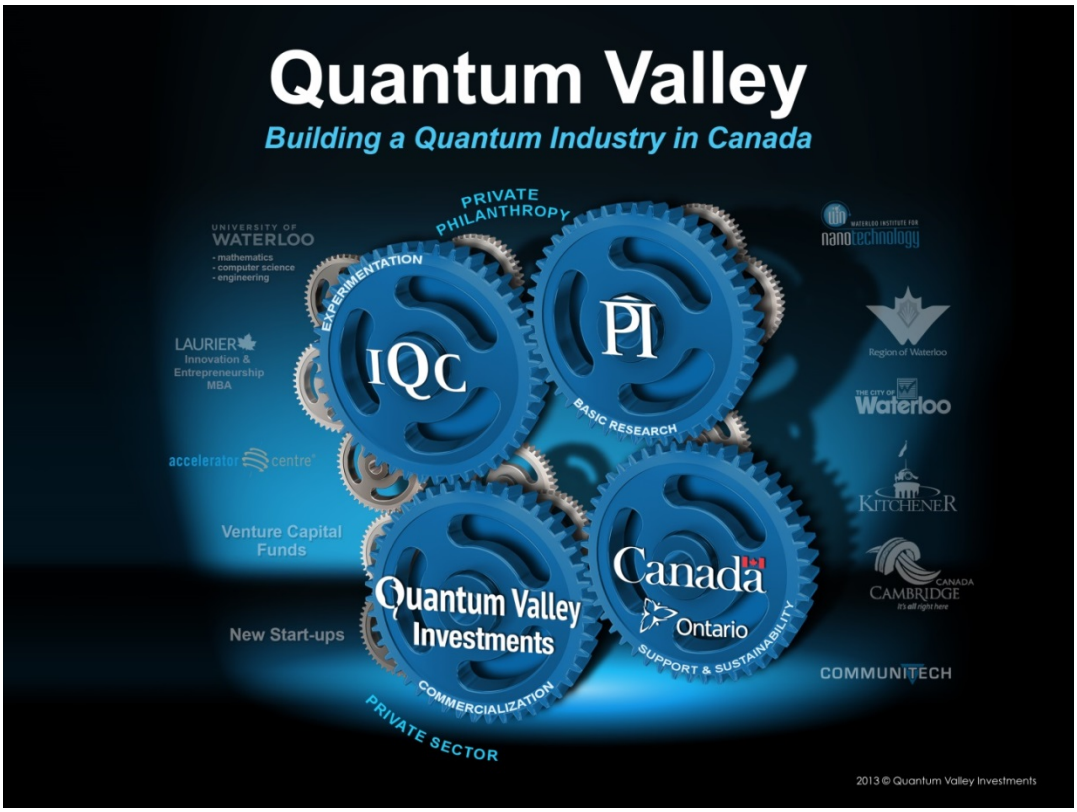
Within Canada, Perimeter is increasing its efforts to build ties to the Sudbury Neutrino Observatory (SNOLAB) and other centres for experiments in particle astrophysics. Art McDonald, who was recognized with the 2015 Nobel Prize in Physics for his work with the SNO experiment, has been a Perimeter Board member since 2011, and he is advising the Institute with regards to a joint search with Queen's University for a new faculty hire. Such strategic joint hires aim to foster a flow of personnel between Perimeter and top experimental centres, stimulating new ideas both for the analysis and exploitation of existing experiments and for the design of new ones. In addition to those with SNOLAB, discussions are underway with the new director of TRIUMF, Dr. Jonathan Bagger, about deepening collaborations between the two institutions to build particle physics in Canada.

In the fields of cosmology and astrophysics, Perimeter is similarly connected to observation and experiment. Associate Faculty member Avery Broderick is a member of the Event Horizon Telescope (EHT), which is working to directly observe the immediate environment of a black hole for the first time. This year, the EHT Initiative at Perimeter was launched, aiming to build a team of faculty members, postdoctoral researchers, and graduate students to conduct leading-edge analysis of astrophysical data collected by the EHT. Faculty member Kendrick Smith, meanwhile, works on a number of experimental collaborations aimed at measuring the cosmic microwave background (CMB), including the Planck satellite, Hyper-Suprime Cam (HSC) project at the Subaru telescope, and Canadian Hydrogen Intensity Mapping Experiment (CHIME). Discussions have been initiated with the Dunlap Institute for Astronomy and Astrophysics at the University of Toronto to build collaborative ties.

Lastly, Perimeter connects with experiment through its conference program, and several conferences in 2014/15 revolved directly around experimental findings and challenges.[24] In partnership with experimental particle physics labs TRIUMF and SNOLAB, Perimeter hosted the third edition of the Tri-Institute Summer School on Elementary Particles (TRISEP) in July 2015. (For a comprehensive list of Perimeter's Research Ties to Experiment, see Appendix G.)

[24] These included "EHT 2014" (November 10-14, 2014), "Preparing for the High-Luminosity Run of the LHC" (June 8-9, 2015), "Convergence" (June 20-24, 2015), and "TRISEP 2015" (July 6-17, 2015). For further details, refer to Appendix G: Perimeter's Research Ties to Experiment.

Catalyst for Quantum Valley



"We are currently in the midst of a second quantum revolution. The first quantum revolution gave us new rules that govern physical reality. The second quantum revolution will take these rules and use them to develop new technologies."

– Gerard Milburn, Director of the Centre for Engineered Quantum Systems at the University of Queensland

In the 20th century, trillions of dollars of new wealth, and millions of jobs, were created from breakthroughs in fundamental physics – transistors, computers, MRI, GPS, wireless communications, smartphones, and much more. Now, in the 21st century, the quantum revolution has begun, with even greater potential.

Quantum information is one of the fastest moving fields in science, seeing rapid progress across a broad spectrum from fundamental theory to early prototype components and devices. It is now widely believed that quantum technologies could well transform society much as the first wave of classical computers did. In the next two decades, experts believe quantum devices could find applications in areas as disparate as cryptography, oil exploration, and non-invasive medical diagnostics.

A "Quantum Valley" – analogous to Silicon Valley – is emerging in Waterloo Region. Perimeter is the wellspring of a flourishing quantum ecosystem that covers the spectrum from theory and foundational discovery and training (at Perimeter), to experimental research at the Institute for Quantum Computing

at the University of Waterloo. The third piece of the ecosystem is Quantum Valley Investments, a private company that provides laboratory infrastructure (at the nearby Research Advancement Centre II and related "Quiet Labs"), commercialization expertise, and venture capital investment. All of this is surrounded by Waterloo Region's vibrant entrepreneurial start-up culture, which is strongly oriented toward technology development.

In 2014/15, the Institute continued to work closely with experimentalists at IQC and other key players in Waterloo Region[25] to ensure Canada remains at the forefront of international efforts to create new quantum industries, which will in turn spark major job and value creation.

Perimeter also recruited a number of quantum and condensed matter specialists, including Associate Faculty member Markus Mueller; Distinguished Visiting Research Chair Frank Verstraete; Visiting Fellows Fay Dowker, Eduardo Martin-Martinez, and Brian Swingle; Emmy Noether Fellows Belén Paredes and Catherine Pépin (see Objective 4); and numerous postdoctoral researchers.

Affiliate Members

Since shortly after Perimeter's creation, the Institute's Affiliate program has been a crucial means of connecting the foundational physics research community across Canada. Affiliates are select researchers, from universities and research institutions across the country, who are invited to Perimeter for regular informal visits.

Affiliates gain access to an active community of researchers spanning the entire spectrum of physics, allowing them to explore ideas they might not otherwise be exposed to at their home institutions. Meanwhile, Perimeter strengthens its connections with more than 25 of Canada's top research centres and provides its resident scientists with new collaboration opportunities. The result is a net gain for the entire physics community.

In 2014/15, Perimeter appointed nine new Affiliates and renewed an additional 89 through 2018, ensuring this vibrant community of scientists will continue to enrich the Institute's research environment.

- Perimeter now has 113 Affiliates, meeting targeted outcomes (see Appendix D, Affiliate Members).

[25] This includes the surrounding academic community (including the Quantum-Nano Centre, the Waterloo Institute of Nanotechnology, and the University of Waterloo), the region's vibrant start-up community (including Communitech and Universal Quantum Devices), and venture capitalists (such as Quantum Valley Investments, Mike Lazaridis' latest venture).

Objective 7: Host timely, focused conferences, workshops, seminars, and courses

Summary of Achievements

- Held 15 conferences and workshops, attended by 873 scientists from around the world
- Presented 325 scientific talks (283 seminars and 42 colloquia)
- Partnered on eight joint workshops and conferences held at Perimeter and sponsored an additional 11 off-site workshops and conferences
- Delivered four courses to researchers and students from surrounding universities

Highlights

Conferences and Workshops

- Held 15 focused conferences and workshops, exceeding targeted objectives[26]
- Hosted more than 250 scientists for "Convergence," a new kind of physics conference providing a "big picture" overview of fundamental physics and its future

Perimeter has built an internationally renowned conference program by selecting topics with high potential for stimulating significant outcomes. In 2014/15, 873 scientists attended Institute conferences and workshops, demonstrating its role as a major node of exchange for theoretical physics. The conference program also strengthens Perimeter's ties to institutional partners; this year, the Institute partnered on eight workshops and conferences with national and international partners[27] and sponsored an additional 11 off-site scientific gatherings.[28]

[26] These included: (1) "EHT 2014"; (2) "Mathematical Physics Workshop"; (3) "PI Day" [October 2014]; (4) "Superluminality in Effective Field Theories for Cosmology"; (5) "(Mock) Modularity, Moonshine, and String Theory"; (6) "Superstring Perturbation Theory"; (7) "PI Day" [April 2015]; (8) "4 Corners Southwest Ontario Condensed Matter Physics Symposium 2015"; (9) "PI-CITA Day 2015"; (10) "Information Theoretic Foundations for Physics"; (11) "Flux Tubes"; (12) "GAP 2015: Geometry & Physics"; (13) "Preparing for the High-Luminosity Run of the LHC"; (14) "Convergence"; and (15) "TRISEP 2015."

[27] These included: (1) "EHT 2014," (2) "Mathematical Physics Workshop," (3) "Superluminality in Effective Field Theories for Cosmology," (4) "Superstring Perturbation Theory," (5) "Information Theoretic Foundations for Physics," and (6) "Convergence," all with the Templeton Foundation; (7) "GAP 2015: Geometry & Physics," with the Fields Institute and the University of Waterloo; and (8) "TRISEP 2015," with TRIUMF and SNOLAB.

[28] These included: (1) "5th IUPAP International Conference on Women in Physics," Wilfrid Laurier University; (2) "New Phenomena at the Upgraded LHC," TRIUMF; (3) "Isham at 70: Modern Issues in Foundations of Physics," Imperial College, London, UK; (4) "PQCrypto 2014," University of Waterloo; (5) "Testing Gravity 2015," Simon Fraser University; (6) "Lake Louise Winter Institute 2015," University of Alberta; (7) "Progress in Ab Initio Techniques in Nuclear Physics," TRIUMF; (8) "Theory Canada 10," University of Calgary; (9) "Contextuality and Non-Locality as Resources for Quantum Information," University of British Columbia; (10) "5th Nanoscale Magnetic Resonance Imaging (NanoMRI) Conference," Institute for Quantum Computing at the University of Waterloo; and (11) "Women in Physics Canada 2015," University of Toronto.

Selected conference highlights:

- **"PI Days"** (October 22-23, 2014 and April 28, 2015): Now in their second year, PI Days are internal workshops devoted to fostering interdisciplinary discussions and new collaborations among Perimeter researchers. Faculty and postdoctoral researchers from across Perimeter's nine research areas share their latest work, issue challenges to one another, and engage in lively discussion aimed at building research connections within the Perimeter community. The October 2014 workshop involved more than 75 students and researchers, and focused on new directions, particularly non-equilibrium physics. The April 2015 workshop brought together 19 Perimeter researchers to explore ideas in topics of broad interest across disciplines, which resulted in lively, at times heated debate. The question of whether experiments could be done to confirm the quantum origin of the inhomogeneities in the early universe resonated particularly strongly with participants.

- **"EHT 2014"** (November 10-14, 2014): The Event Horizon Telescope is the first astronomical instrument capable of imaging the horizon of a known black hole. By assembling a global network of existing millimetre and sub-millimetre wavelength observatories, the EHT can access the extraordinary resolutions required via Very Long Baseline Interferometry. Already, it has detected horizon-scale structure around the supermassive black holes at the centre of the Milky Way and the giant elliptical galaxy M87. This was the second in a conference series designed to bring together the full EHT community, from instrument builders to theoretical modellers, for the purpose of fully exploiting the unique opportunities that the EHT provides. The meeting also led to an official EHT collaboration, a long-awaited step in the project.

- **"Convergence"** (June 20-24, 2015): With more than 250 registered participants, "Convergence" brought together many of the world's best physics minds to probe the field's most exciting ideas and chart a course for 21st century physics. Envisioned as a new kind of conference providing a "big picture" overview of fundamental physics and its future, it attracted 17 Perimeter Distinguished Visiting Research Chairs and a significant contingent of the Institute's alumni. The event also celebrated, through commemorative lectures, the centenaries of two defining discoveries of the 20th century: Noether's theorem and Einstein's theory of general relativity.

- **"TRISEP 2015"** (July 6-17, 2015): This international summer school is organized jointly by the Perimeter Institute for Theoretical Physics, SNOLAB, and TRIUMF, Canada's laboratory for particle and nuclear physics. "TRISEP 2015" featured lectures by leading experts in the field of particle physics and was designed to be very interactive, with ample time for questions, discussions, and interaction with the speakers. The school was intended for graduate students of all levels who were already exposed to quantum field theory. One attendee praised the summer school's utility, saying, "These two weeks have been more useful than any two months of classes I've ever taken."

Seminars and Colloquia

Seminars and colloquia foster collaboration and share knowledge from leading international researchers, allowing Perimeter scientists to remain at the cutting edge of research across the spectrum of theoretical physics. Seminars and colloquia are an important part of the intellectual life of the institute, and are given by both resident and visiting scientists. In 2014/15 alone, the community benefitted from talks by Distinguished Visiting Research Chairs Nima Arkani-Hamed, Abhay Ashtekar, James Bardeen, Savas Dimopoulos, S. James Gates Jr., Matilde Marcolli, Barbara Terhal, Senthil Todadri, Bill Unruh, Ashvin Vishwanath, Steven White, and Mark Wise.

- In 2014/15, Perimeter held a total of 325 scientific talks (283 seminars and 42 colloquia), exceeding targeted outcomes.

Courses

Perimeter seeks to share the expertise of its resident and visiting scientists by having them present topical courses on cutting-edge areas. These courses are open to students of surrounding universities, thereby enhancing their course offerings.

In 2014/15, Perimeter offered one advanced for-credit course – "Fundamentals of Astrophysics," taught by Perimeter Associate Faculty member Niayesh Afshordi (September-December 2014) – and three non-credit mini-courses: "Entanglement Entropy and the Area Law," taught by Perimeter Senior Researcher Rafael Sorkin (October 2014); "Higher-Spin Gravity: One Learner's Perspective," taught by Perimeter postdoctoral researcher Yasha Neiman (May 2015); and "Unruh-DeWitt Detectors in RQI: From the Basics to Frontiers," taught by Shih-Yuin Lin, a visiting professor from the National Changhua University of Education (May 2015). The Institute also opened up all PSI courses to students at surrounding universities (with special permission) as three-week, non-credit mini-courses.

Online Video Archive

Nearly all talks held at Perimeter are recorded and can be viewed in the Video Library section of Perimeter's website or through the Perimeter Institute Recorded Seminar Archive (PIRSA) at www.pirsa.org. This free, searchable, and citable video archive of seminars, conferences, workshops, and courses was developed by the Institute to share knowledge with the international scientific community, and has become an important and widely used resource for the field.

- 82,845 unique visitors from more than 170 countries accessed Perimeter's video archive in 2014/15, accounting for 628,796 page views.

Objective 8: Engage in high-impact outreach

Summary of Achievements

- Reached more than 1 million students through Perimeter programs and educational resources, bringing the total to more than 5 million students to date
- Hosted the 13th International Summer School for Young Physicists (ISSYP) and gave 18 Physica Phantastica presentations – reaching over 2,400 students across Canada
- Delivered 130 workshops to over 3,000 educators across Canada and abroad, ultimately reaching more than 225,000 students
- Created three new educational modules: *Black Holes*, *The Physics of Innovation*, and *Contemporary Physics*
- Developed a digital distribution partnership with Chalk.com to share Perimeter educational resources, which are currently used in 61 countries
- Presented eight engaging public lectures to capacity audiences on-site and reached a larger global audience than ever before with webcasts in conjunction with prominent media partners
- Launched planning and strategy for Canada 150, a massive nationwide celebration for which Perimeter was chosen as leader of the Innovation Pillar
- Significantly increased Perimeter's digital media communications and social media impact

Highlights

Student Programs and Products

International Summer School for Young Physicists (ISSYP)

The International Summer School for Young Physicists (ISSYP) is a pillar of Perimeter's outreach efforts. The program brings Canadian and international students with demonstrated scientific potential to Perimeter for two weeks of intensive instruction, including mentoring sessions and lab tours of the Institute's experimental partners. Students receive first-hand experience with cutting-edge research at an age when they are actively weighing career directions. Follow-up surveys with ISSYP alumni indicate that more than 70 percent credit the program with inspiring them to pursue a career in math or physics.

- In July 2015, Perimeter hosted the 13th edition of ISSYP for 40 top students – including 20 Canadians from seven provinces and 20 international students from 12 countries, with equal representation of males and females.
- The RBC Foundation also renewed its support of the program for three years beginning in 2014/15, becoming the presenting sponsor.

Physica Phantastica Presentations

Physica Phantastica presentations provide entertaining and accessible introductions to modern physics. These large-scale presentations are generally delivered to audiences of 50-200, and are designed to share the wonder, mystery, and joy of science with students, teachers, and the general public.

- In 2014/15, 18 presentations were delivered to over 1,700 students and teachers, and more than 900 members of the general public.

Aboriginal Engagement

In 2014/15, Perimeter continued its partnership with Actua, one of Canada's leading STEM (science, technology, engineering, and mathematics) outreach organizations for youth, particularly among Aboriginal Canadians. Perimeter Outreach staff trained Actua associates from across the country on Perimeter resources; the Actua associates then delivered the content to Aboriginal students during the summer months. Perimeter and Actua also began strategizing to expand their collaborative reach to Aboriginal communities across Canada tied to the Canada 150 celebrations.

- Perimeter partners reached more than 1,000 Aboriginal youth with the Institute's resources.

Ministry of Education Partnership

Perimeter Institute has entered into a four-year partnership with the Ontario Ministry of Education. The partnership will empower educators across the province with modern resources and training, and inspire and engage youth in class and through extra-curricular enrichment. It will allow Perimeter to create new resources that are curriculum-linked and available online, as well as reach out to teachers and students where they live with new travelling and digital science exhibits, in partnership with other science outreach organizations.

The primary objective of this partnership is to equip all Ontario students in publicly funded schools – including at-risk students and those living in underserviced areas of the province – with the scientific skills and knowledge required to meet future challenges.

Programs and Resources for Teachers

EinsteinPlus

The EinsteinPlus Teachers' Camp is a one-week summer workshop for high school educators that shares effective strategies for teaching key concepts in modern physics, facilitates peer exchange, and introduces teachers to Perimeter's educational resources. Surveys of past participants indicate that they view the experience as a top-calibre professional development opportunity.

- In July 2015, Perimeter hosted 45 teachers from around the world for the latest edition of EinsteinPlus.[29]

The Perimeter Teacher Network

EinsteinPlus alumni continue to form the core of Perimeter's Teacher Network, a peer-to-peer network of skilled, highly motivated educators who are trained to share the Institute's proven modern physics educational resources and pedagogical strategies with their with fellow teachers in their home districts. The Teacher Network includes more than 55 teachers from around Ontario and across Canada, making it an integral part of the Institute's strategy for building the capacity of educators to share modern science with their students.

- Over the past year, educators in Perimeter's Teacher Network delivered 104 workshops to over 2,000 educators, ultimately reaching 150,000 students.
- In line with targeted objectives, Perimeter held four Teacher Network training camps in Waterloo (two), Calgary, and Vancouver, reaching 445 teachers in total.

On-location Teacher Workshops and Conference Presentations

Presentations at major educational conferences and gatherings are a cost-effective means of significantly increasing the reach of Perimeter's outreach products and programs. The Institute continues to select targeted gatherings of teachers for grades 7 through 12 in both the Canadian and international educational communities.

- In 2014/15, Outreach staff delivered 27 on-location workshops at teacher conferences in Canada and abroad, reaching more than 1,000 educators and 75,000 students, exceeding targeted outcomes.[30]

Educational Resources

Product Creation

Produced with the input of working physics educators and scientists, Perimeter's educational modules are the Institute's primary means of introducing students to modern physics. Though Canadian students

[29] This included 23 Canadian teachers (spanning eight provinces) and 22 international teachers (spanning 11 countries).

[30] These included, among others, the annual conferences of the Science Teachers' Association of Ontario (Toronto, Canada), American Association of Physics Teachers Summer Meeting (Maryland, USA), Association for Science Education (in both Reading, UK, and Aberdeen, Scotland), National Science Teachers Association (Chicago, USA), Ontario Association of Physics Teachers (Guelph, Canada), Physics Teachers Resource Agents (College Park, USA), and High School Teachers Program at CERN (Geneva, Switzerland).

remain Perimeter's primary focus, these resources have been deployed in over 60 countries worldwide. Feedback indicates that they are used and re-used in classrooms, multiplying their impact over time.

The Institute employs a balanced approach to educational product creation. *Inspirations* content aims to intrigue younger students and motivate them to continue with math and science in senior grades, while *Explorations* modules deliver more challenging ideas and technical content to senior high school students, preparing them for post-secondary education in math, science, and engineering.

- In fall 2014, Perimeter released a new *Inspirations* resource, *The Expanding Universe*, which shares cutting-edge cosmology research (such as recent developments with the Planck satellite) with students in grades 7 to 12.
- Over the past year, in line with targeted objectives, the Institute converted its existing resources for digital distribution and created three new e-modules: *Black Holes*, *The Physics of Innovation*, and *Contemporary Physics*.
- Two e-courses on modern physics have been completed to support top math and physics students with advanced lessons to prepare them for university-level physics.

Online Resources

Publishing high-quality resources online allows Perimeter to scale its reach and impact worldwide. Perimeter has now divided its large, full-kit classroom resources into more accessible e-modules for distribution online, with a broadened scope to reach students in Grades 7 to 12.

All Perimeter resources, both physical copies and online, will continue to be offered free to Canadian educators, but are also available to international teachers through Perimeter's online store. Perimeter has also increased its efforts to provide crucial training on the use of these resources.

In February 2015, Perimeter announced a new distribution partnership with Chalk.com, an online collaboration space for teachers, which makes the Institute's educational resources available to more than 100,000 educators worldwide. The Chalk.com platform gives teachers access to Perimeter's suite of educational resources and also facilitates collaboration on lesson planning, delivery, and evaluation between the schools and districts using them. Perimeter's resources are the first premium content on Chalk.com, a reflection of their excellent reputation among teachers.

Lastly, Perimeter and Canada's Department of Foreign Affairs, Trade and Development (DFATD) are continuing to collaborate on strategy and content distribution in Canada and abroad. Discussions are in progress regarding how Perimeter can contribute to the strengthening of secondary education in Burma.

Digital and Social Media Outreach

Perimeter Institute aims to be the leading source of fascinating, accurate, and shareable physics content online. Digital and social media are crucial to this strategy, as they reach all segments of Perimeter's audience: students, teachers, journalists, influencers, policymakers, and the science research community.

During 2014/15, Perimeter substantially increased its digital and social media outreach efforts, through enhanced use of its Facebook and Twitter channels, a major increase in video creation/sharing through its YouTube channel, and innovative digital media outreach initiatives, including the successful Slice of PI series (fun and sharable monthly science content).

Slice of PI:

"Slices of PI" are distributed monthly, presenting accessible content to a growing list of e-subscribers, through targeted outreach to physics/science influencers (Physics Today, Physics is Awesome, etc.), and through organic social media sharing (Facebook, Twitter, Google+, etc.).

- In 2014/15, successful examples included:
  - **Pioneering Women of Physics**, was shared widely (including by io9.com and *Scientific American*) and drove over 16,000 visitors to Perimeter's website.
  - **Science Fiction That Became Science Fact**, was shared by influential Twitter accounts including Physics Central, Fermilab, Discovery News, and Communitech, driving 7,500 visitors to Perimeter's website.
  - **General Relativity from A to Z,** celebrating the 100th anniversary of Einstein's theory, was widely shared, including by Albert Einstein's estate, resulting in over 52,000 visits to Perimeter's website.

Video:

In 2014/15, Perimeter significantly increased its YouTube channel content, resulting in large viewership growth. The channel gained more than 5,400 subscribers, taking the total subscriber base to just under 10,000.

- Viewership of PI's YouTube channel was up **119 percent** in 2014/15, to 537,322 video views.[31]

Social Media:

Perimeter's Twitter following increased by roughly 3,400 followers for a total of 10,808, while the Institute's Facebook page gained approximately 8,200 new fans for a total of 13,782. This is the result of daily content sharing, increased quality of content, live-tweeting during Public Lectures and other events, and targeted influencer outreach.

- Both Perimeter's Twitter and Facebook accounts experienced their fastest periods of growth since their creation in 2014/15.

[31] Successful examples include: Nima Arkani-Hamed's Public Lecture: 37,500 views; The Black Hole at the Birth of the Universe: 19,100 views; Subir Sachdev's Public Lecture: 37,000 views; Amanda Peet's Public Lecture: 16,448 views

Programs for the General Public

Public Lecture Series

Perimeter's flagship Public Lecture Series continues to be one of the Institute's most popular programs. In 2014/15, in line with targeted objectives, Perimeter presented eight accessible, engaging lectures to sold-out audiences in the Institute's Mike Lazaridis Theatre of Ideas. In addition, all lectures are now webcast to online audiences around the world through PI's website and presenting media partners including *Maclean's*, CBC, *National Post*, *Scientific American*, and *COSMOS*.

Online webcast viewership has exceeded expectations, averaging more than 2,000 per lecture. All lectures are professionally recorded and available for on-demand playback through Perimeter's website, YouTube, and media partners, with over 235,000 views in 2014/15. The Institute has also considerably extended the reach of the talks with advance trailers and marketing, as well as supplementary online chats with Perimeter researchers.

The 2014/15 season presented engaging talks on scientific topics ranging from interstellar voyaging to the unusual properties of water. Highlights included Subir Sachdev on quantum entanglement and superconductivity, Jon Butterworth on working at the Large Hadron Collider at CERN, and Kendrick Smith's "State of the Universe" address on cosmology in the 21st century.

- PI's Public Lectures were viewed over 235,000 times in 2014/15.

Canada 150

In 2014/15, Perimeter Institute was selected by Canadian Heritage to lead the Innovation Pillar of the nationwide Canada 150 celebrations to be held in 2017. Perimeter launched the planning and coordination stages of this additional outreach effort, which will include a cross-country educational outreach tour, a crowdsourced digital hub showcasing Canadian innovation, and a national public awareness campaign. As leader of the Canada 150 Innovation Pillar, Perimeter will steer these projects in close collaboration with partner organizations including Actua, the Institute for Quantum Computing, the Canadian Association of Science Centres, and the Canadian Science and Technology Museums Corporation.

Stratford Festival

Over the past year, in line with targeted outcomes, Perimeter began work on a collaboration with the Stratford Festival tied to their 2015 theme of Discovery. In September 2015, Perimeter and the Stratford Festival will co-host an event aimed at celebrating the connection between art and science, as well as introducing Perimeter to new audiences. The evening will include a reading of excerpts from Michael Frayn's *Copenhagen*, a play based around a meeting between Niels Bohr and Werner Heisenberg. It will

be followed by a discussion of the work's science and drama between Perimeter Faculty member Lucien Hardy and Stratford's Artistic Director, Antoni Cimolino.

Media Coverage

Perimeter has continued to actively share the wonder and discovery of theoretical physics with major media. In 2014/15, the Institute received major coverage in both national and international media, including *Nature*, CBC, *WIRED*, and many more. Highlights included:

- "Are 'weak values' quantum after all?" by Tushna Commissariat, in *Physics World*[32]
  - This article examined new research findings on the subject of weak values. One of the researchers on this project is Perimeter postdoctoral researcher Joshua Combes, who was interviewed for the article and is quoted throughout.
- "Scientists Search for Evidence of the Multiverse in the Big Bang's Afterglow," by Olena Shmahalo, in *WIRED*[33]
  - This article about the development of a test for the multiverse theory featured Perimeter Associate Faculty member Matthew Johnson, who is quoted throughout. The online version also includes a video produced by PI on the subject.
- "Looking for the keys to the next big thing in physics," by Ashley Csanady, in *Canada.com*[34]
  - This is one example of the coverage of Perimeter Faculty members Natalia Toro and Philip Schuster winning the New Horizons in Physics Prize at the Breakthrough Prize award ceremony. Their research is featured, they are each quoted throughout, and there is a focus on PI being the right environment for creating breakthroughs.
- "Perimeter Institute's formula for a calculated reboot," by Ivan Semeniuk, in *The Globe and Mail*[35]
  - This feature on Perimeter's unique positioning to reboot physics and drive breakthroughs in the field compares the Institute's researcher talent to that of Einstein and Noether. There is also a brief mention of the $4 million funding announcement made at "Convergence."
- "Physicists launch fight to make data more important than theory," by Michael Brooks, in *New Scientist*[36]
  - This feature article about the need for testable theories in physics draws heavily from Perimeter's "Convergence" conference and includes numerous quotes from Director Neil Turok.

[32] October 9, 2014 edition: http://physicsworld.com/cws/article/news/2014/oct/09/are-weak-values-quantum-after-all
[33] November 18, 2014 edition: http://www.wired.com/2014/11/multiverse-big-bang
[34] December 3, 2014 edition: http://o.canada.com/news/looking-for-the-keys-to-the-next-big-thing-in-physics
[35] June 23, 2015 edition: http://www.theglobeandmail.com/news/national/formula-for-a-calculated-physics-reboot/article25080342
[36] July 1, 2015 edition: https://www.newscientist.com/article/mg22730283-900-physicists-launch-fight-to-make-data-more-important-than-theory

Objective 9: Create the world's best environment and infrastructure for theoretical physics research, training, and outreach

Summary of Achievements

- Sought to increase the Institute's diversity of ideas and emphasis on collaboration, and met with leaders with experience in fostering a climate of exchange in academic settings
- Achieved LEED Silver Certification for the Stephen Hawking Center at Perimeter Institute
- Launched first phase of a new intranet portal and began work on the project's second phase

Highlights

Building a Climate of Collaboration and Exchange

Perimeter strives to create and maintain a highly collaborative, inclusive culture that attracts the very best from around the world. The Institute recognizes that diversity at all levels, from students to senior researchers to administrative staff, is crucial to promoting creative and innovative thinking.

Theoretical physics as a whole has relatively low rates of participation by women; redressing this imbalance is an institutional priority. Perimeter has created several initiatives to attract and retain outstanding women at all career levels – including the "Inspiring Future Women in Science" conference aimed at high school students, the Emmy Noether Fellows (see Objective 4), and the Emmy Noether Council, which seeks to champion and support Perimeter's Emmy Noether initiatives (see Objective 10).

Historically, many of the great breakthroughs in science have come from collaborations across the boundaries of disciplines. Perimeter was designed to foster such collaborations, and as the Institute has grown, it has created programs to nurture such cross-disciplinary collaborations and exchanges.

In February 2015, Perimeter hosted Abigail Stewart, the Sandra Schwartz Tangri Distinguished University Professor and Director of the University of Michigan ADVANCE Program, which seeks to improve the campus environment for all faculty – particularly women and underrepresented minorities – in terms of recruitment, retention, climate, and leadership. Dr. Stewart delivered a colloquium outlining the process of institutional change, drawing on her experience at Michigan, and met with members of Perimeter's faculty and administrative staff for a wide-ranging discussion on areas for improvement at the Institute. Efforts to become a leader in the field in terms of diversity are ongoing.

- The Institute began to seek support for Perimeter Research Chairs to support female physicists at the highest levels of achievement (see Objective 2).
- Perimeter launched weekly interdisciplinary lunch meetings to foster informal scientific interactions between students, postdocs, faculty, and visitors across all research areas.

- Six early-career researchers came to Perimeter under the Emmy Noether Visiting Fellowship program, which allowed them to spend one to three months immersed in the Institute's collaborative research environment while on leave from their home institute (see Objective 4).

Environmental Leadership

Perimeter's iconic, award-winning facility, including the Stephen Hawking Centre expansion, was designed to inspire deep thinking, encourage collaboration, and maximize research productivity – but it was also designed with the environment in mind.

In March 2015, the Stephen Hawking Centre at Perimeter Institute received LEED Silver Certification after an independent review by the Canadian Green Building Council. The Leadership in Energy and Environmental Design (LEED) rating system takes into account everything from design and construction to waste management, energy use, and plant selection for gardens. The Stephen Hawking Centre was designed by Toronto-based Teeple Architects, and was supported by the Canada Foundation for Innovation, Ontario's Ministry of Research and Innovation, and private donors.

E-Journal Access and Library Collections

An in-house library is essential to building Perimeter's research and learning communities. In 2014/15, Perimeter continued to expand its library collections, in line with a multi-year strategy to provide resident and visiting researchers with comprehensive research resources. The library added 89 new texts, bringing the total to 5,313 in the print collection (5,811 in all formats), with additional electronic subscriptions to 123 journals that researchers and students can access on-site and remotely.

IT Systems Upgrades and Initiatives

In 2014/15, Perimeter continued efforts to upgrade its website functionality and IT infrastructure to optimize workflow and realize efficiencies, in line with targeted outcomes.

Most notably, in November 2014, the Institute launched the first phase of a new intranet portal project, providing a primary access point for organizational information, applications, and forms, as well as event management tools and a master calendar. Work has begun on the project's next phase, which will fully integrate the broader Perimeter community – including alumni, spouses, and visitors – and improve the mechanisms for tracking and reporting scientific activities.

Other IT updates were executed as planned, including the following:

- Upgraded, event ticketing, conference registration, accounting, payroll, and employee management systems
- Deployed IT systems and equipment to enhance long-distance scientific collaborations

- Migrated Perimeter's communications to the ORION network, increased the capacity of the Scientific Computing Environment (a shared research server farm), and commenced upgrade to the Perimeter Institute Recorded Seminar Archive (PIRSA)

Objective 10: Continue to build on Perimeter's highly successful public-private partnership funding model

Summary of Achievements

- Finalized a $2 million commitment from Gluskin Sheff + Associates to fund a new Perimeter Research Chair
- Obtained pledges for three additional Perimeter Research Chairs from the Stavros Niarchos Foundation ($4 million), the Riddell Family Charitable Foundation ($1 million), and Cenovus Energy ($300,000)
- Secured substantial private investments for training and outreach initiatives, including $500,000 from the Peter and Shelagh Godsoe Family Foundation, $300,000 from the RBC Foundation, and $100,000 from Sun Life Financial
- Worked with Foreign Affairs, Trade, and Development Canada to extend the reach of the Institute's training and outreach programs

Highlights

Public Partners

Perimeter Institute is funded through an innovative public-private partnership, which shares the opportunities and benefits of long-term investment in fundamental research. Perimeter's public partners understand that ongoing, strategic investment in foundational theoretical physics positions Canada and Ontario for success in an extremely cost-effective field with an unmatched record of advancing human knowledge, and seeding innovation. As many independent reviews and audits demonstrate, Perimeter is already providing excellent return on investment.[37] [38] [39]

The Government of Canada and Province of Ontario may justly claim credit for many of the Institute's considerable achievements. Investment from all levels of government helped establish Perimeter and sustained support from the public sector has been critical to the Institute's success to date. These

[37] See, for example, a KPMG audit from 2011 (http://www.perimeterinstitute.ca/files/articles/attachements/pi_final_evaluation_report.pdf), which concluded: "Research conducted within PI's core fields is of great importance and of consequence. Some of the research is reaching ground-breaking, revolutionary, and transformative levels and international experts have strong positive opinions of both the research and PI researchers."

[38] See 2006 NSERC Review of Perimeter Institute: http://www.perimeterinstitute.ca/files/page/attachments/info_drawn_from_2006_nserc_review_information.pdf

[39] "International and Canadian experts identified several infrastructure facilities associated with Physics and Astronomy that are an advantage for Canada, including the Canadian Light Source synchrotron, the Sudbury Neutrino Observatory/Laboratory, TRIUMF (Canada's national laboratory for particle and nuclear physics), and the Perimeter Institute for Theoretical Physics," p. 173, The State of Science and Technology in Canada, 2012, The Expert Panel on the State of Science and Technology in Canada, Council of Canadian Academies.

partnerships are also pivotal in establishing Canada as the world's Quantum Valley, ready to reap the benefits of the next great technological revolution (see Objective 6).

2014/15 marked the third year of five-year, $50 million funding agreements with both the Government of Canada and the Province of Ontario. Perimeter continues to responsibly steward all public investments using best practices in financial management and to fulfill all reporting requirements.

In 2014/15, in line with targeted objectives, Perimeter continued to work with public partners to position Canada at the forefront of foundational physics during one of the most exciting times in the field's long history. Highlights of these activities included the following:

- Provided updates and briefings to key leaders across ministries, agencies, and levels of government, including His Excellency the Right Honourable David Johnston, Governor General of Canada; new NSERC President Dr. Mario Pinto; and senior leaders at Industry Canada, the Privy Council Office, and several Ontario Ministries (Education; Economic Development, Employment, and Infrastructure; Research and Innovation; Finance; etc.)
- Worked with Foreign Affairs, Trade, and Development Canada (DFATD) to share talent mobility opportunities, such as those tied to the PSI master's program, contributing to an increase in high quality applications[40]
- Agreed in principle to a memorandum of understanding with DFATD to assist with international educational outreach
- Explored Canada 150 programming opportunities with Canadian Heritage, applied to the innovation-themed Signature Event pillar, and established a formal working relationship with the Canada Science and Technology Museum in advance of other 2017 celebrations
- Explored new programming opportunities with the Ontario Ministry of Education, aiming to accelerate STEM engagement in classrooms and communities across the province
- Worked with partners at all levels of government on other agendas, from providing insight and guidance on science- and technology-related public policy initiatives, to hosting international colleagues in support of provincial and national initiatives

Private Partners

Private partners who share and invest in Perimeter's vision are crucial to the Institute's ability to attain and sustain global leadership in theoretical physics research, training, and outreach over the long term.

Broadly, Perimeter Institute's Advancement efforts seek to raise awareness of the importance of having a "crown jewel" of fundamental research in Canada. Through their support, private donors demonstrate their commitment to research as a driver of next-generation science and technology, and ultimately societal well-being. Donors – from private individuals to corporations and foundations – are increasingly

[40] In 2014/15, PSI received a 29 percent increase in applications, including from 10 jurisdictions for the first time: Azerbaijan, Bahrain, Cambodia, Hungary, Iraq, Kosovo, Mauritius, Palestine, Tanzania, and Uganda.

receptive to this message, as evidenced by the increasing private support Perimeter attracted in 2014/15.

Perimeter's long-term Advancement strategy encompasses individual philanthropists, corporations, and foundations whose missions align with Perimeter's, as well as members of the general public who want to share in the joy and excitement of discovery.

In 2014/15, the Institute continued to refine its strategy, with three major areas of focus: Perimeter Research Chairs, Emmy Noether Initiatives, and major gifts, as outlined below.

Since Perimeter is a young institution without a long history or alumni base, significant efforts are devoted to raising awareness of the Institute and its activities. In 2014/15, the Institute expanded the membership of its volunteer Leadership Council and Emmy Noether Councils. These volunteer fundraising committees, which are comprised of prominent, highly motivated champions of Perimeter, reach out through their networks to widen the circle of support across Canada and the US.

The Institute also held several very successful special events in the last year, including high-profile speaking engagements and gatherings at Perimeter, across Canada, and internationally.[41] These events helped Perimeter substantially widen its pool of supporters. Networks of interested potential donors now exist in a number of key centres, including Vancouver, Montreal, Toronto, Calgary, New York City, and Silicon Valley.

Funding the Perimeter Research Chairs

In 2014/15, the Institute had major success in attracting private support for Perimeter Research Chairs, as follows:

- The Stavros Niarchos Foundation pledged $4 million donation to support the Stavros Niarchos Foundation Aristarchus Chair, to be held by Perimeter Faculty member Asimina Arvanitaki.
- Gluskin Sheff + Associates finalized a $2 million commitment to fund the Gluskin Sheff Freeman Dyson Chair in Theoretical Physics, held by Perimeter Faculty member Freddy Cachazo.
- The Riddell Family Charitable Foundation pledged $1 million to support the Clay Riddell Paul Dirac Chair in Theoretical Physics, held by Perimeter Faculty member Pedro Vieira.
- Cenovus Energy pledged $300,000 to support the Cenovus Energy James Clerk Maxwell Chair in Theoretical Physics (Visiting), held by Subir Sachdev.

[41] Events included: Private dinners hosted by Perimeter Board members, Leadership Council members, and supporters of the Institute, in Calgary, Silicon Valley, and Toronto; a Ticker Club luncheon in Toronto, featuring Mike Lazaridis as guest speaker, in November 2014; An Emmy Noether event for 25 guests, hosted by Jennifer Scully at Goldman Sachs in Toronto in February 2015; Perimeter's "Inspiring Future Women in Science" Day in March 2015, which included 11 Advancement guests, plus their daughters and friends; Release of TD's Canadian Women and Philanthropy report, and a discussion of its impacts, with 30 attendees at Perimeter in May 2015; VIP invitations to almost 70 current partners and prospective donors to attend public events at "Convergence," a major conference at Perimeter in June 2015.

The Perimeter Research Chairs program is a key component of the Institute's strategy for achieving major research breakthroughs (see Objective 2). Envisioned as the most prestigious chairs in theoretical physics worldwide and designed to assemble top scientists in strategically chosen fields, the Perimeter Research Chairs are supported through major gifts of up to $4 million.

An investment in a Perimeter Research Chair is an investment in the lifeblood of science: brilliant, curiosity-driven scientists. This program gives Perimeter a crucial competitive edge in attracting and retaining top theoretical physicists, each of whom serves as a magnet for other leading scientists. Chairholders include exceptional emerging talent, young faculty reaching their peak years of research productivity, and renowned physics pioneers.

Emmy Noether Initiatives

Women have historically been underrepresented in physics, particularly at the highest levels of the field. Perimeter's Emmy Noether initiatives aim to help combat the gender imbalance in the field, attracting more outstanding female scientists to Perimeter's research community and inspiring more young women to pursue physics in high school and university. The Institute's Emmy Noether initiatives have continued to gain momentum in 2014/15, raising awareness, attracting new partners, and building connections for the future.

- In March 2015, in commemoration of International Women's Day, Perimeter hosted its "Inspiring Future Women in Science" conference, giving more than 200 high school girls a glimpse into the lives of women in science, technology, engineering, and math.
- Perimeter began to seek support for Perimeter Research Chairs to be held by top female scientists, demonstrating the Institute's support for female physicists at the highest levels of achievement (see Objective 2).
- The Institute hosted Dr. Abigail Stewart, an expert in improving institutional cultures for women and other underrepresented groups (see Objective 9).
- Perimeter welcomed six Emmy Noether Fellows and recruited seven more (see Objective 4).

Major Gifts

Beyond the Perimeter Research Chairs and Emmy Noether Initiatives, the Institute seeks funding for its outstanding scientific training at the graduate and postdoctoral levels; for its educational outreach programs for students, teachers, and the general public; and for special events such as "Convergence," according to the interests of donors. Several of the most significant gifts in this category over the last year include the following:

- The Peter and Shelagh Godsoe Family Foundation finalized a commitment for $500,000 to fund the Peter and Shelagh Godsoe Family Foundation Award for Exceptional Emerging Talent, an annual $25,000 award to support one of the Institute's deserving students.

- The RBC Foundation renewed their support for the International Summer School for Young Physicists (ISSYP), investing $300,000 over three years beginning in 2014/15 to become ISSYP's presenting sponsor (see Objective 8).
- Sun Life Financial renewed sponsorship of the Perimeter Public Lecture Series for one year, investing $100,000.
- The Bank of Montreal (BMO) donated $50,000 to sponsor "Convergence," Perimeter's biggest conference of 2014/15 and its first alumni reunion.
- Private donors Joanne Cuthbertson and Charlie Fisher donated $65,000 to support an extraordinary graduate student.

Overview of Financial Statements, Expenditures, Criteria, and Investment Strategy

Summarized Financial Statements of

PERIMETER INSTITUTE

Year Ended July 31, 2015

Zeifmans

Zeifmans

REPORT OF THE INDEPENDENT AUDITORS ON THE SUMMARY FINANCIAL STATEMENTS

To the Directors of
Perimeter Institute

The accompanying summary financial statements, which comprise the summary statement of financial position as at July 31, 2015 and the summary statement of operations and changes in fund balances for the year then ended, are derived from the audited financial statements of Perimeter Institute (the "Institute") for the year ended July 31, 2015. We expressed an unmodified audit opinion on those financial statements in our report dated December 11, 2015. Those financial statements, and the summary financial statements, do not reflect the effects of events that occurred subsequent to the date of our report on those financial statements.

The summary financial statements do not contain all the disclosures required by Canadian accounting standards for not-for-profit organizations. Reading the summary financial statements, therefore, is not a substitute for reading the audited financial statements of the Institute.

Management's Responsibility for the Summary Financial Statements

Management is responsible for the preparation of a summary of the financial statements in accordance with Canadian accounting standards for not-for-profit organizations.

Auditor's Responsibility

Our responsibility is to express an opinion on the summary financial statements based on our procedures, which were conducted in accordance with Canadian Auditing Standard (CAS) 810, "Engagements to Report on Summary Financial Statements."

Opinion

In our opinion, the summary financial statements derived from the audited financial statements of the Institute for the year ended July 31, 2015 are a fair summary of those financial statements, in accordance with Canadian accounting standards for not-for-profit organizations.

Zeifmans LLP

Toronto, Ontario
December 11, 2015

Chartered Accountants
Licensed Public Accountants

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NEXIA INTERNATIONAL

PERIMETER INSTITUTE
Summarized Statement of Financial Position
as at July 31, 2015

	2015	2014
ASSETS		
Current assets:		
Cash and cash equivalents	$ 9,230	$ 15,958
Investments	302,796	264,333
Government grants receivable	4,671	5,680
Other current assets	706	809
	317,403	286,780
Property and equipment	46,412	49,457
TOTAL ASSETS	$ 363,815	$ 336,237
LIABILITIES AND FUND BALANCE		
Current liabilities:		
Accounts payable and other current liabilities	$ 1,095	$ 1,692
TOTAL LIABILITIES	1,095	1,692
Fund balances:		
Invested in capital assets	46,399	49,974
Externally restricted	117,866	121,873
Internally restricted	188,840	78,840
Unrestricted	9,615	83,858
TOTAL FUND BALANCES	362,720	334,545
	$ 363,815	$ 336,237

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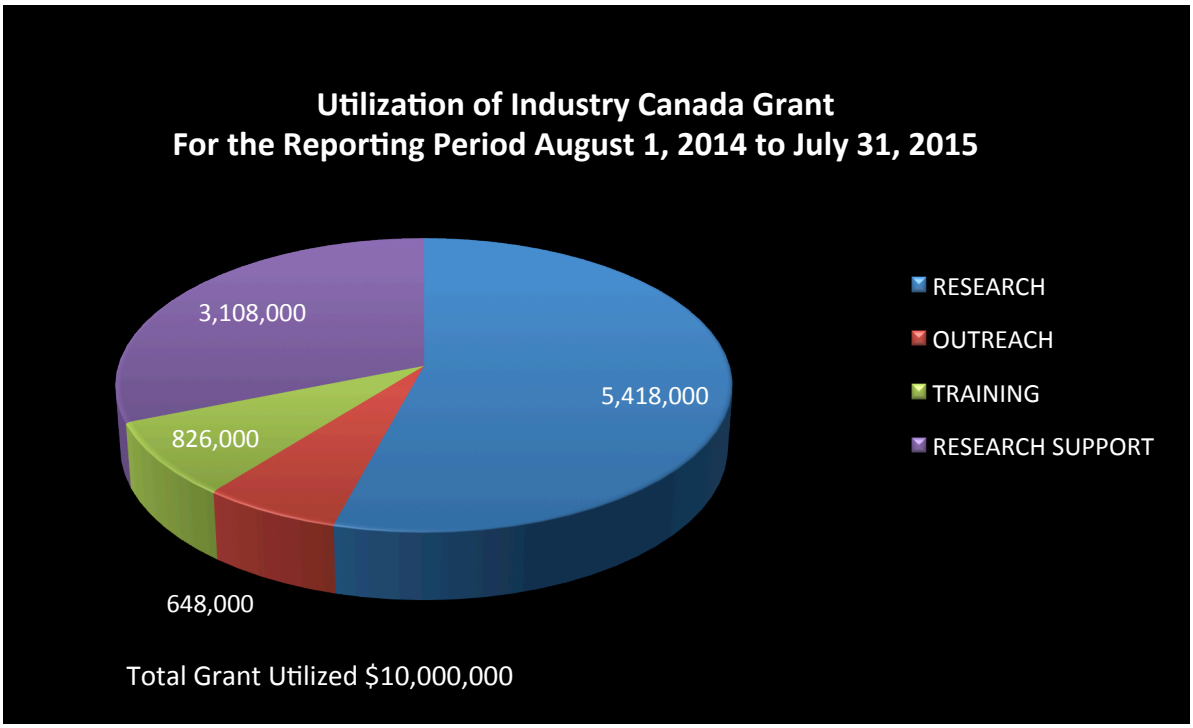
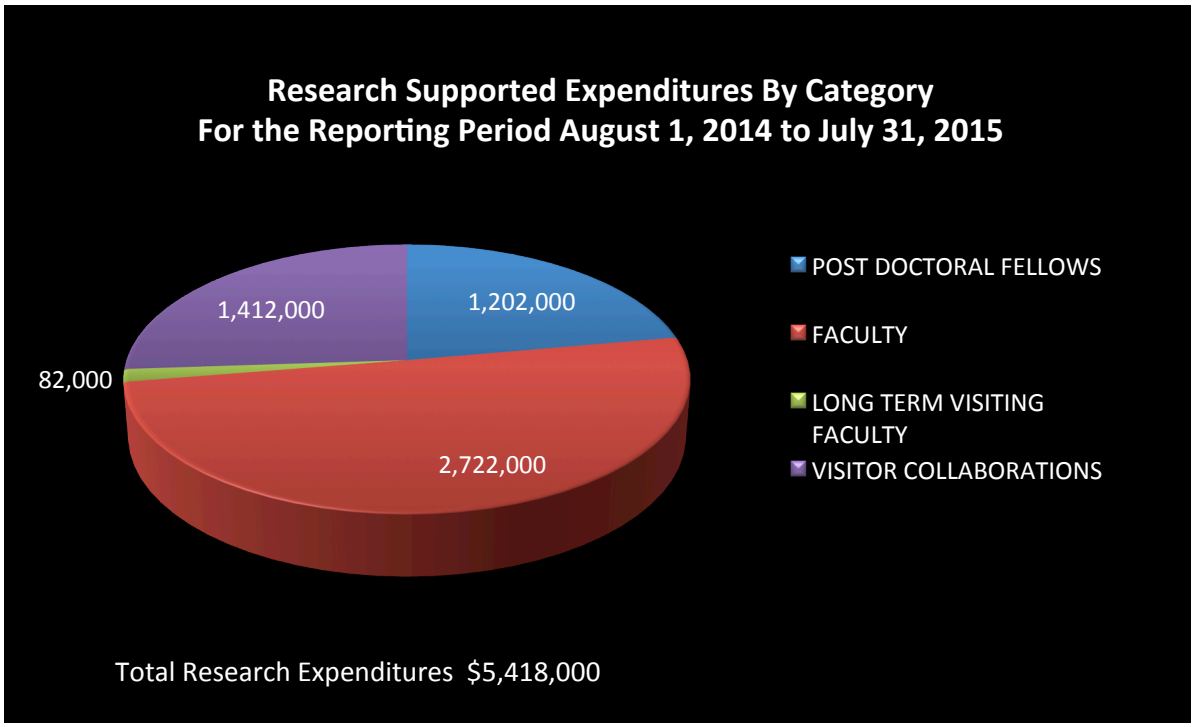
PERIMETER INSTITUTE

Summarized Statement of Operations and Changes in Fund Balances
For the Year Ended July 31, 2015

	2015	2014
Revenue		
Government grants	$ 21,548	$ 19,526
Research grants	3,073	1,850
Donations	2,691	761
	27,312	22,137
Expenses		
Research	14,635	13,002
Research training	1,799	2,034
Outreach and science communications	2,694	3,112
Indirect research and operations	6,313	5,770
	25,441	23,918
Excess of revenue over expenses (expenses over revenue) before amortization, gain on disposal of property and equipment and investment income	1,871	(1,781)
Amortization	(2,941)	(3,838)
Gain on disposal of property and equipment	111	
Investment gain	29,134	41,635
Excess of revenue over expenses	28,175	36,016
Fund balances, beginning of year	334,545	298,529
Fund balances, end of year	$ 362,720	$ 334,545

Expenditure of Industry Canada Grant





Performance Evaluation Strategy

Scientific

Perimeter Institute has a wide array of performance monitoring and evaluation policies, systems, and processes (both internal and external) that have been developed over the years and are re-evaluated and updated on a regular basis. These initiatives to measure outcomes, results, and impact include:

Performance Monitoring – Internal

- Annual reports on research activity submitted to the Institute's Director by all faculty and associate faculty members for evaluation
- Annual performance reviews of all research staff
- Ongoing monitoring of publication and citation records
- Post-conference reports and evaluation
- Visitor research activity reports and ongoing tracking of all output
- Regular updates and monitoring of progress of all scientific programs
- Mid-term researcher performance reviews
- Postdoctoral fellow mentorship program
- Monitoring of postdoctoral fellows' post-Perimeter placement success
- Monitoring of researchers' international presence and impact through collaborations and invitations to lecture
- Internal review and evaluation process of all outreach programs and products

Performance Monitoring – External

- Regular reporting to international Scientific Advisory Committee (SAC) with subsequent performance assessment and recommendations (see Appendix F for a list of SAC members)
- Review of faculty hires and promotions by Scientific Advisory Committee
- Peer review of publications
- Performance audits and reviews in accordance with grant agreements
- External review and evaluation process of all outreach programs and products

Investment Strategy

Public-Private Partnership

Perimeter Institute exists through a cooperative and highly successful public-private approach to investment that provides for ongoing operations while, at the same time, safeguarding future opportunities.

Public partners contribute to research, training, and outreach activities and, in keeping with individual grant requirements, receive ongoing updates, reports, and yearly audited financial statements as required to ensure value for money while remaining aware of the Institute's research productivity and outreach impact.

Private funds from a continuously growing donor base are used, in part, to fund operations, while a portion is protected in an endowment that is primarily designed to receive and increase donated monies by maximizing growth and minimizing risk in order to contribute to the strongest possible long-term financial health of the Institute.

Perimeter Institute continues to be an innovative example of a public-private partnership, uniting government and philanthropists in a common quest to secure the transformative potential of scientific research in Canada.

Governance

Perimeter Institute is an independent, not-for-profit corporation governed by a volunteer Board of Directors drawn from the private sector and academic community. The Board is the final authority on all matters related to the general structure and development of the Institute (see Appendix E: Board of Directors).

The Board of Directors is supported in fulfilling its fiduciary responsibilities with respect to financial management of the Institute through two Board committees. The Investment Committee is responsible for overseeing the investment and management of funds received according to a Board-approved investment policy that outlines guidelines, standards, and procedures for the prudent investment and management of funds. The Finance and Audit Committee is responsible for overseeing Perimeter Institute's policies, processes, and activities in the areas of accounting, internal controls, risk management, auditing, and financial reporting. The Board also forms other committees as required to assist it in discharging its duties.

Reporting to the Board of Directors, the Institute's Director is a pre-eminent scientist responsible for developing and implementing the overall strategic direction of the Institute. The Managing Director and Chief Operating Officer reports to the Director and is in charge of day-to-day operations, supported by a team of administrative staff. The Institute's resident scientists play an active role in scientific operational

issues via participation on various committees in charge of scientific programs. Committee chairs report to the Faculty Chair and Deputy Faculty Chair, who assist the Institute's Director with matters such as recruitment, the granting of tenure, and program reviews.

The Scientific Advisory Committee (SAC), comprised of eminent international scientists (see Appendix F: Scientific Advisory Committee), offers independent scrutiny and advice, helping to ensure Perimeter's activities meet high standards of scientific excellence. Members participate in thorough reviews of PI's scientific, training, and educational outreach programs, after which the Chair writes a report to the Board of Directors and the Institute's Director.

Objectives for 2015/16

Statement of Objectives, 2015/16

The successes outlined in the preceding pages provide strong evidence that the Institute's strategic planning has been both sound and effective, and that it is well on track to achieve its paramount long-term goal: to create and sustain the world's foremost centre for foundational theoretical physics research, training, and outreach, fostering scientific excellence and stimulating research breakthroughs that will transform our future.

The strategic objectives that follow, which have guided institutional strategy for more than five years, are currently in review. In the coming year, the Institute will revise these objectives as necessary to reflect Perimeter's growing international stature and new opportunities to be a leader in fundamental science. The advancement of Perimeter's core mission will continue to inform every facet of the Institute's research, training, and outreach efforts.

Objective 1: Deliver world-class research discoveries

Objective 2: Become the research home of a critical mass of the world's leading theoretical physicists

Objective 3: Generate a flow-through of the most promising talent

Objective 4: Become the second research home for many of the world's outstanding theorists

Objective 5: Act as a hub for a network of theoretical physics and math centres around the world

Objective 6: Increase Perimeter's role as Canada's focal point for foundational physics research

Objective 7: Host timely, focused conferences, workshops, seminars, and courses

Objective 8: Engage in high-impact outreach

Objective 9: Create the world's best environment and infrastructure for theoretical physics research, training, and outreach

Objective 10: Continue to build on Perimeter's highly successful public-private partnership funding model

Appendices

Note: Where applicable, appendices reflect the Perimeter community as of July 31, 2015.

Appendix A: Faculty and Associate Faculty Members

Faculty

Neil Turok (PhD Imperial College London, 1983) was Professor of Physics at Princeton University and Chair of Mathematical Physics at the University of Cambridge before assuming his current position as Director of Perimeter Institute. Turok's research focuses on developing fundamental theories of cosmology and new observational tests. His predictions for the correlations of the polarization and temperature of the cosmic background radiation (CBR) and of the galaxy-CBR correlations induced by dark energy were recently confirmed. With Stephen Hawking, he discovered instanton solutions describing the birth of inflationary universes. His work on open inflation forms the basis of the widely discussed multiverse paradigm. With Paul Steinhardt, he developed an alternative, cyclic model for cosmology, whose predictions are so far in agreement with all observational tests. Among his many honours, Turok was awarded Sloan and Packard Fellowships and the James Clerk Maxwell medal of the Institute of Physics (UK). He is a Canadian Institute for Advanced Research (CIFAR) Fellow in Cosmology and Gravity, a Fellow of the Royal Society of Canada, and a Senior Fellow of Massey College at the University of Toronto. In 2012, Turok delivered the CBC Massey Lectures. The lectures were published as *The Universe Within*, a bestseller which won the 2013 Lane Anderson Award, Canada's top prize for popular science writing. Born in South Africa, Turok founded the African Institute for Mathematical Sciences (AIMS) in Cape Town in 2003. AIMS has since expanded to a network of five centres – in South Africa, Senegal, Ghana, Cameroon, and Tanzania – and has become Africa's most renowned institution for postgraduate training in mathematical science. For his scientific discoveries and his work founding and developing AIMS, Turok was awarded a TED Prize in 2008. He has also been recognized with awards from the World Summit on Innovation and Entrepreneurship (WSIE) and the World Innovation Summit on Education (WISE).

Dmitry Abanin (PhD Massachusetts Institute of Technology, 2008) joined Perimeter in 2012 after postdoctoral positions at Harvard University and the Princeton Center for Theoretical Science. Abanin is a leading young condensed matter theorist whose research has focused on developing a theoretical understanding of Dirac materials, focusing on quantum transport of charge and spin and finding new ways of controlling their electronic properties. Some of his theoretical work has been experimentally confirmed by groups at Harvard University, the University of Manchester, Columbia University, the University of California, Riverside, the Max Planck Institute, and elsewhere. In 2014, he received a Sloan Research Fellowship.

Asimina Arvanitaki (PhD Stanford University, 2008) joined Perimeter's faculty in 2014. She previously held research positions at the Lawrence Berkeley National Laboratory at the University of California,

Berkeley (2008-11), and the Stanford Institute for Theoretical Physics at Stanford University (2011-14). Arvanitaki is a particle physicist who specializes in designing new experiments to test fundamental theories beyond the Standard Model. She pioneered the use of optically levitated dielectric objects to detect gravitational waves. Arvanitaki also works on theoretical challenges raised by experimental results, such as a model of particle physics influenced by string theory called "split SUSY."

Latham Boyle (PhD Princeton University, 2006) joined the Institute's faculty in 2010. From 2006 to 2009, he held a Canadian Institute for Theoretical Astrophysics (CITA) Postdoctoral Fellowship; he is also a Junior Fellow of the Canadian Institute for Advanced Research (CIFAR). Boyle has studied what gravitational wave measurements can reveal about the universe's beginning. With Paul Steinhardt, he derived "inflationary bootstrap relations" that − if confirmed observationally − would provide compelling support for the theory of primordial inflation. He co-developed a simple algebraic technique for understanding black hole mergers and constructed the theory of "porcupines": networks of low-frequency gravitational wave detectors that function together as gravitational wave telescopes.

Freddy Cachazo (PhD Harvard University, 2002) is the Gluskin Sheff Freeman Dyson Chair in Theoretical Physics at Perimeter Institute, where he has been a faculty member since 2005. From 2002 to 2005, he was a Member of the School of Natural Sciences at the Institute for Advanced Study in Princeton. Cachazo is one of the world's leading experts in the study and computation of scattering amplitudes in quantum chromodynamics (QCD) and N=4 super Yang-Mills (MSYM) theories. His many honours include the Gribov Medal of the European Physical Society (2009), the Rutherford Memorial Medal in Physics from the Royal Society of Canada (2011), the Herzberg Medal from the Canadian Association of Physicists (2012), and a New Horizons in Physics Prize from the Fundamental Physics Prize Foundation (2014).

Kevin Costello (PhD University of Cambridge, 2003) joined Perimeter in August 2014 from Northwestern University, where he had been a faculty member since 2006. He is the inaugural Krembil Foundation William Rowan Hamilton Chair in Theoretical Physics at Perimeter Institute. Previously, he was a Chapman Fellow at Imperial College London (2003-05) and the Dixon Instructor at the University of Chicago (2005-06). Costello works on the mathematical aspects of quantum field theory and string theory. He is the author of *Renormalization and Effective Field Theory*, a path-breaking monograph introducing powerful new mathematical tools into the theory of quantum fields. Costello's previous honours include an Alfred P. Sloan Research Fellowship and several prestigious grants from the National Science Foundation in the United States.

Bianca Dittrich (PhD Max Planck Institute for Gravitational Physics, 2005) joined Perimeter's faculty in 2012 from the Albert Einstein Institute in Potsdam, Germany, where she led the Max Planck Research Group "Canonical and Covariant Dynamics of Quantum Gravity." Dittrich's research focuses on the construction and examination of quantum gravity models. Among other important findings, she has provided a computational framework for gauge invariant observables in canonical general relativity. Dittrich has received the Otto Hahn Medal of the Max Planck Society, which recognizes outstanding young scientists, and an Early Researcher Award from the Province of Ontario.

Laurent Freidel (PhD L'École Normale Supérieure de Lyon, 1994) joined Perimeter Institute in 2006. Freidel is a mathematical physicist who has made many notable contributions in the field of quantum gravity; he possesses outstanding knowledge of a wide range of areas including integrable systems, topological field theories, 2D conformal field theory, and quantum chromodynamics. Freidel has held positions at Pennsylvania State University and L'École Normale Supérieure and has been a member of France's Centre National de la Recherche Scientifique (CNRS) since 1995. He is also the recipient of several awards, including two ACI-Blanche grants in France.

Davide Gaiotto (PhD Princeton University, 2004) joined Perimeter in 2012 and holds the Krembil Foundation Galileo Galilei Chair in Theoretical Physics. Previously, he was a postdoctoral fellow at Harvard University from 2004 to 2007 and a long-term Member at the Institute for Advanced Study in Princeton from 2007 to 2012. Gaiotto works in the area of strongly coupled quantum fields and has already made several major conceptual advances that have potentially revolutionary implications. His honours include the Gribov Medal of the European Physical Society (2011) and a New Horizons in Physics Prize from the Fundamental Physics Prize Foundation (2013).

Jaume Gomis (PhD Rutgers University, 1999) joined Perimeter Institute in 2004, declining a European Young Investigator Award by the European Science Foundation to do so. Prior to that, he worked at the California Institute of Technology as a Postdoctoral Scholar and as the Sherman Fairchild Senior Research Fellow. His main areas of expertise are string theory and quantum field theory. In 2009, Gomis was awarded an Early Researcher Award for a project aimed at developing new techniques for describing quantum phenomena in nuclear and particle physics.

Daniel Gottesman (PhD California Institute of Technology, 1997) joined Perimeter's faculty in 2002. From 1997 to 2002, he held postdoctoral positions at the Los Alamos National Laboratory, Microsoft Research, and the University of California, Berkeley (as a long-term CMI Prize Fellow for the Clay Mathematics Institute). Gottesman has made seminal contributions which continue to shape the field of quantum information science through his work on quantum error correction and quantum cryptography. He has published over 50 papers, which have attracted well over 4,000 citations to date. He is also a Senior Fellow in the Quantum Information Processing program of the Canadian Institute for Advanced Research (CIFAR) and a Fellow of the American Physical Society (APS).

Lucien Hardy (PhD University of Durham, 1992) joined Perimeter's faculty in 2002, having previously held research and lecturing positions at various European universities including the University of Oxford, Sapienza University of Rome, the University of Durham, the University of Innsbruck, and the National University of Ireland. In 1992, he found a very simple proof of non-locality in quantum theory which has become known as Hardy's theorem. He currently works on characterizing quantum theory in terms of operational postulates and applying the insights obtained to the problem of quantum gravity.

Luis Lehner (PhD University of Pittsburgh, 1998) began a joint appointment with Perimeter and the University of Guelph in 2009 and became a full-time faculty member at Perimeter in 2012. He previously held postdoctoral fellowships at the University of Texas at Austin and the University of British Columbia, and he was a member of Louisiana State University's faculty from 2002 to 2009. Lehner's many honours

include the Honor Prize from the National University of Cordoba, Argentina, a Mellon pre-doctoral fellowship, the CGS/UMI outstanding dissertation award, and the Nicholas Metropolis award. He has been a PIMS fellow, a CITA National Fellow, and a Sloan Research Fellow, and he is currently a Fellow of the Institute of Physics, the American Physical Society, the International Society for General Relativity and Gravitation, and the Canadian Institute for Advanced Research (CIFAR) in the Cosmology and Gravity program.

Robert Myers (PhD Princeton University, 1986) is one of the leading theoretical physicists working in string theory in Canada. After attaining his PhD, he was a postdoctoral researcher at the Institute for Theoretical Physics at the University of California, Santa Barbara, and a Professor of Physics at McGill University, before moving to Perimeter in 2001. He has made seminal contributions to our understanding of black hole microphysics and D-branes. Among Myers' many honours, he has received the Herzberg Medal (1999), the CAP-CRM Prize (2005), and the Vogt Medal (2012). He is also a Fellow of both the Royal Society of Canada and the Cosmology and Gravity program of the Canadian Institute for Advanced Research (CIFAR).

Subir Sachdev (PhD Harvard University, 1985) became the James Clerk Maxwell Chair in Theoretical Physics at Perimeter Institute (Visiting) in 2014. He has been a Professor of Physics at Harvard University since 2005. Sachdev has made prolific contributions to quantum condensed matter physics, including research on quantum phase transitions and their application to correlated electron materials like high-temperature superconductors, and he authored the seminal book, *Quantum Phase Transitions*. In recent years, he has exploited a remarkable connection between the electronic properties of materials near a quantum phase transition and the quantum theory of black holes. Sachdev's previous honours include an Alfred P. Sloan Foundation Fellowship and a John Simon Guggenheim Memorial Foundation Fellowship. He is a Fellow of the American Physical Society and a member of the U.S. National Academy of Sciences, and he was a Perimeter Distinguished Visiting Research Chair from 2009 to 2014.

Philip Schuster (PhD Harvard University, 2007) joined Perimeter's faculty in 2010. He was a Research Associate at SLAC National Accelerator Laboratory from 2007 to 2010. Schuster's area of specialty is particle theory, with an emphasis on physics beyond the Standard Model. He has close ties to experiment and has investigated various theories that may be discovered at experiments at the Large Hadron Collider (LHC) at CERN. With members of the Compact Muon Solenoid (CMS) experiment at the LHC, he developed methods to characterize potential new physics signals and null results in terms of simplified models, facilitating more robust theoretical interpretations of data. He is also a co-spokesperson for the APEX collaboration at the Thomas Jefferson National Accelerator Facility in Virginia. With Natalia Toro, he was awarded the 2015 New Horizons in Physics Prize by the Breakthrough Prize Foundation.

Kendrick Smith (PhD University of Chicago, 2007) joined Perimeter in 2012 from Princeton University, where he was the Lyman P. Spitzer Postdoctoral Fellow since 2009. Prior to that, he held the PPARC Postdoctoral Fellowship at the University of Cambridge from 2007 to 2009. Smith is a cosmologist with a foot in the worlds of both theory and observation. He is a member of several experimental teams, including the WMAP collaboration, which won the 2012 Gruber Cosmology Prize, as well as QUIET,

CHIME, and the Planck collaboration. He was also involved in the start-up phase of the major Hyper-Suprime Cam project at the Hawaii-based Subaru telescope. Smith has achieved several landmark results, including the first detection of gravitational lensing in the cosmic microwave background (CMB) radiation. He holds a second PhD in mathematics from the University of Michigan.

Lee Smolin (PhD Harvard University, 1979) is one of Perimeter Institute's founding faculty members. Prior to joining Perimeter, Smolin held research positions at the Institute for Advanced Study, the Institute for Theoretical Physics at the University of California, Santa Barbara, the Enrico Fermi Institute at the University of Chicago, Yale University, Syracuse University, and Pennsylvania State University. Smolin's research is centred on the problem of quantum gravity, with particular focus on loop quantum gravity and deformed special relativity, though his contributions span many areas. His papers have generated over 6,500 citations to date and he has written or co-written five non-technical books. Smolin's many honours include the Majorana Prize (2007), the Klopsteg Memorial Award (2009), the Buchalter Cosmology Prize (2014), and election as a Fellow of both the American Physical Society and the Royal Society of Canada.

Robert Spekkens (PhD University of Toronto, 2001) joined Perimeter's faculty in 2008, after holding a postdoctoral fellowship at Perimeter and an International Royal Society Fellowship at the University of Cambridge. His research is focused upon identifying the conceptual innovations that distinguish quantum theories from classical theories and investigating their significance for axiomatization, interpretation, and the implementation of various information-theoretic tasks. Spekkens is a previous winner of the Birkhoff-von Neumann Prize of the International Quantum Structures Association.

Paul Steinhardt (PhD Harvard University, 1978) is the Richard P. Feynman Chair in Theoretical Physics at Perimeter Institute (Visiting) and the Albert Einstein Professor in Science at Princeton University, where he is also the Director of the Princeton Center for Theoretical Science. His research interests span particle physics, astrophysics, cosmology, and condensed matter physics. With Neil Turok, he developed a cyclic model for cosmology, according to which the big bang is explained as a collision between two "brane-worlds" in M-theory. In addition to his continued research on inflationary and cyclic cosmology, Steinhardt has been one of the developers of a new class of disordered "hyperuniform" photonic materials with complete bandgaps, and he conducted a systematic search for natural quasicrystals that has culminated in discovering the first known example. In 2011, Steinhardt led a successful geological expedition to Far Eastern Russia to find new information about its origin and retrieve more samples, and in 2014, the International Mineralogical Association officially accepted another new mineral into its official catalogue, naming it "steinhardtite." He is a Fellow in the American Physical Society (APS) and a member of the National Academy of Sciences. Among his many honours, he shared the P.A.M. Dirac Medal from the International Centre for Theoretical Physics (2002) for his role as one of the architects of the inflationary model of the universe; the Oliver E. Buckley Prize of the APS (2010) for his contributions to the theory of quasicrystals; and the John Scott Award (2012), also for his work on quasicrystals.

Natalia Toro (PhD Harvard University, 2007) joined Perimeter in 2010 after completing a postdoctoral fellowship at the Stanford Institute for Theoretical Physics. Toro has developed a framework for few-parameter models of possible new physics signals and has played a major role in integrating new

techniques, called “on-shell effective theories,” into the program of searches at the Compact Muon Solenoid experiment at the Large Hadron Collider (LHC) at CERN. She is an expert in the study of dark forces that couple very weakly to ordinary matter and is co-spokesperson for APEX, an experiment searching for such forces at the Thomas Jefferson National Accelerator Facility. With Philip Schuster, she was awarded the 2015 New Horizons in Physics Prize by the Breakthrough Prize Foundation.

Guifre Vidal (PhD University of Barcelona, 1999) joined Perimeter’s faculty in 2011 from the University of Queensland in Brisbane, where he was an Australian Research Council Federation Fellow and Professor in the School of Mathematics and Physics. He did postdoctoral fellowships at the University of Innsbruck in Austria and the Institute for Quantum Information at the California Institute of Technology before joining the University of Queensland. Vidal works at the interface of quantum information and condensed matter physics, using tensor networks to compute the ground state of quantum many-body systems on a lattice and to issue a classification of the possible phases of quantum matter or fixed points of the renormalization group flow. His past honours include a Marie Curie Fellowship, awarded by the European Union, and a Sherman Fairchild Foundation Fellowship.

Pedro Vieira (PhD École Normale Supérieure and the Theoretical Physics Center at the University of Porto, 2008) is the Clay Riddell Paul Dirac Chair in Theoretical Physics at Perimeter Institute, where he has been a faculty member since 2009. Prior to that, he was a Junior Scientist at the Max Planck Institute for Gravitational Physics (Albert Einstein Institute) from 2008 to 2009. Vieira’s research concerns the development of new mathematical techniques for gauge and string theories, ultimately aiming at the solution of a realistic four-dimensional gauge theory. His research interests also include the related areas of the AdS/CFT correspondence and theoretical calculations of scattering amplitudes. “Y-system for scattering amplitudes,” a paper by Vieira and his collaborators, won the 2012 Best Paper Prize from the Institute of Physics (IOP) and the Editorial Board of *Journal of Physics A*. In 2015, he was awarded both a Sloan Research Fellowship and the Gribov Medal of the European Physical Society.

Xiao-Gang Wen (PhD Princeton University, 1987) joined Perimeter’s faculty in 2012 as the BMO Financial Group Isaac Newton Chair in Theoretical Physics. Widely recognized as one of the world’s leaders in condensed matter theory, he pioneered the new paradigm of quantum topological order, used to describe phenomena from superconductivity to fractionally charged particles, and he has invented many new mathematical formalisms. Wen authored the textbook *Quantum Field Theory of Many-body Systems: From the Origin of Sound to an Origin of Light and Electrons*. He was previously a Distinguished Moore Scholar at the California Institute of Technology and the Cecil and Ida Green Professor of Physics at the Massachusetts Institute of Technology, as well as one of Perimeter’s own Distinguished Visiting Research Chairs. He is also a Fellow of the American Physical Society.

Associate Faculty

Niayesh Afshordi (PhD Princeton University, 2004) is jointly appointed with the University of Waterloo. He was the Institute for Theory and Computation Fellow at the Harvard-Smithsonian Center for Astrophysics from 2004 to 2007 and a Distinguished Research Fellow at Perimeter Institute from 2008 to 2009. Afshordi began his appointment as an associate faculty member in 2010. He specializes in interdisciplinary problems in fundamental physics, astrophysics, and cosmology. In 2010, he was awarded a Discovery Accelerator Supplement from the Natural Sciences and Engineering Research Council of Canada (NSERC).

Alexander Braverman (PhD Tel Aviv University, 1998) joined Perimeter in July 2015, jointly appointed with the University of Toronto. He was previously a member of Brown University's faculty (2004-15) and held lecturer positions at Harvard University (2000-04) and the Massachusetts Institute of Technology (1997-99). Braverman specializes in a number of areas with applications to mathematical physics, including algebraic geometry, representation theory, number theory, and the geometric Langlands program. He has been a Clay Mathematics Institute Prize Fellow and a Simons Fellow in Mathematics.

Avery Broderick (PhD California Institute of Technology, 2004) began a joint appointment with Perimeter and the University of Waterloo in 2011. He previously held postdoctoral positions at the Institute for Theory and Computation at the Harvard-Smithsonian Center for Astrophysics (2004-07) and the Canadian Institute for Theoretical Astrophysics (2007-11). Broderick is an astrophysicist with broad research interests, ranging from how stars form to the extreme physics in the vicinity of white dwarfs, neutron stars, and black holes. He has recently been part of an international effort to produce and interpret horizon-resolving images of supermassive black holes, studying how black holes accrete matter, launch the ultra-relativistic outflows observed, and probe the nature of gravity in their vicinity.

Alex Buchel (PhD Cornell University, 1999) is jointly appointed with Western University. Before joining Perimeter's faculty in 2003, he held research positions at the Institute for Theoretical Physics at the University of California, Santa Barbara (1999-2002), and the Michigan Center for Theoretical Physics at the University of Michigan (2002-03). Buchel's research efforts focus on understanding the quantum properties of black holes and the origin of our universe, as described by string theory, as well as developing analytical tools that could shed new light on strong interactions of subatomic particles. In 2007, he was awarded an Early Researcher Award from Ontario's Ministry of Research and Innovation.

Raffi Budakian (PhD University of California, Los Angeles, 2000) joined Perimeter in 2014, jointly appointed with the Institute for Quantum Computing (IQC) at the University of Waterloo. He also holds the Nanotechnology Endowed Chair in Superconductivity at IQC and the Waterloo Institute for Nanotechnology (WIN). Budakian previously held a faculty position at the University of Illinois at Urbana-Champaign and research positions at the University of California, Los Angeles, and the IBM Almaden Research Center in San Jose. He is an experimental condensed matter physicist whose research focuses on developing ultra-sensitive spin detection techniques for single spin imaging and quantum readout. In 2005, Budakian won a World Technology Award for his work in the detection and manipulation of quantum spins.

Cliff Burgess (PhD University of Texas at Austin, 1985) joined Perimeter's faculty as an associate member in 2004 and was jointly appointed to McMaster University's faculty in 2005. Prior to that, he was a Member in the School of Natural Sciences at the Institute for Advanced Study in Princeton and a faculty member at McGill University. Over two decades, Burgess has applied the techniques of effective field theory to high energy physics, nuclear physics, string theory, early-universe cosmology, and condensed matter physics. With collaborators, he developed leading string theoretic models of inflation that provide its most promising framework for experimental verification. Burgess' recent honours include a Killam Fellowship, Fellowship of the Royal Society of Canada, and the CAP-CRM Prize in Theoretical and Mathematical Physics.

David Cory (PhD Case Western Reserve University, 1987) is jointly appointed with the Institute for Quantum Computing and the University of Waterloo. He previously held research positions at the University of Nijmegen in The Netherlands, the National Research Council at the Naval Research Laboratory in Washington, D.C., and the Massachusetts Institute of Technology. He also led research and development activities in nuclear magnetic resonance at Bruker Instruments. Since 1996, Cory has been exploring the experimental challenges of building small quantum processors based on nuclear spins, electron spins, neutrons, persistent current superconducting devices, and optics. In 2010, he was named the Canada Excellence Research Chair in Quantum Information Processing. Cory chairs the advisory committee for the Quantum Information Processing program at the Canadian Institute for Advanced Research (CIFAR).

James Forrest (PhD University of Guelph, 1994) joined Perimeter in 2014 as the Institute's Academic Programs Director and an associate faculty member. He is jointly appointed at the University of Waterloo, where he's been a professor since 2000. His research focuses on the physics of soft matter on the nanoscale, with particular emphasis on polymers and proteins, glass transition in confined geometry, and surface and interfacial properties of polymers. Among his many honours, Forrest is a Fellow of the American Physical Society and co-recipient of the 2013 Brockhouse Medal of the Canadian Association of Physicists.

Matthew Johnson (PhD University of California, Santa Cruz, 2007) began a joint appointment with Perimeter and York University in 2012. Prior to that, he was a Moore Postdoctoral Scholar at the California Institute of Technology and a postdoctoral researcher at Perimeter. Johnson is a cosmologist, whose interdisciplinary research seeks to understand how the universe began, how it evolved, and where it is headed. To this end, he designs data analysis algorithms to confront fundamental theory with observations of the cosmic microwave background radiation. In 2012, Johnson was awarded a New Frontiers in Astronomy and Cosmology grant from the University of Chicago and the John Templeton Foundation.

Raymond Laflamme (PhD University of Cambridge, 1988) is a founding faculty member of Perimeter Institute and founding Director of the Institute for Quantum Computing, where he is jointly appointed. He held research positions at the University of British Columbia and Peterhouse College, University of Cambridge, before moving to the Los Alamos Research Laboratory in 1992, where his interests shifted from cosmology to quantum computing. Since the mid-1990s, Laflamme has elucidated theoretical

approaches to quantum error correction and in turn implemented some in experiments. Laflamme has been Director of the Quantum Information Processing program at the Canadian Institute for Advanced Research (CIFAR) since 2003. He is a Fellow of CIFAR, the American Physical Society, and the American Association for the Advancement of Science, and holds the Canada Research Chair in Quantum Information. With colleagues, he founded Universal Quantum Devices, a start-up commercializing spin-offs of quantum research.

Sung-Sik Lee (PhD Pohang University of Science and Technology, 2000) joined Perimeter in 2011 in a joint appointment with McMaster University, where he is an Associate Professor. He previously worked as a postdoctoral researcher at the Pohang University of Science and Technology, the Massachusetts Institute of Technology, and the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara. Lee's research focuses on strongly interacting quantum many-body systems using quantum field theory, as well as the intersections between condensed matter and high energy physics. His recent work has included using gauge theory as a lens through which to examine the phenomenon of fractionalization, efforts to apply the AdS/CFT correspondence from string theory to quantum chromodynamics and condensed matter, and building a non-perturbative approach to understanding unconventional metallic states of matter.

Roger Melko (PhD University of California, Santa Barbara, 2005) joined Perimeter in 2012, while retaining his appointment with the University of Waterloo, where he has been since 2007. Prior to that, he was a Wigner Fellow at Oak Ridge National Laboratory (2005-07). Melko is a condensed matter theorist who develops new computational methods and algorithms to study strongly correlated many-body systems, focusing on emergent phenomena, ground state phases, phase transitions, quantum criticality, and entanglement. Among his honours, he has received an Early Researcher Award, the International Union of Pure and Applied Physics Young Scientist Prize in Computational Physics from the Council on Computational Physics, and the Canada Research Chair in Computational Quantum Many-Body Physics (Tier 2).

Michele Mosca (DPhil University of Oxford, 1999) is jointly appointed with the Institute for Quantum Computing at the University of Waterloo. He is a founding member of Perimeter Institute, as well as co-founder and Deputy Director of the Institute for Quantum Computing. Mosca has made major contributions to the theory and practice of quantum information processing, including several of the first implementations of quantum algorithms and fundamental methods for performing reliable computations with untrusted quantum apparatus. His current research interests include quantum algorithms and complexity, and the development of cryptographic tools that will be safe against quantum technologies. Mosca's numerous academic honours include Canada's Top 40 Under 40 award (2010), the Premier's Research Excellence Award (2000-05), Fellow of the Canadian Institute for Advanced Research (CIFAR) since 2010, Canada Research Chair in Quantum Computation (2002-12), and University Research Chair at the University of Waterloo (2012-present).

Markus Mueller (PhD Technical University of Berlin, 2007) joined Perimeter in July 2015, jointly appointed with Western University, where he holds the Canada Research Chair in the Foundations of Physics. Prior to that, he was a Junior Research Group Leader at the Institute for Theoretical Physics at

the University of Heidelberg, and held postdoctoral positions at Perimeter Institute, the University of Potsdam, and the Max Planck Institute for Mathematics in the Sciences. Mueller is a mathematical physicist working in quantum information and quantum foundations, with particular interest in statistical physics, generalized probabilistic theories, and algorithmic information theory.

Ue-Li Pen (PhD Princeton University, 1995) joined Perimeter in December 2014. He is jointly appointed with the Canadian Institute for Theoretical Astrophysics (CITA) at the University of Toronto, where he has been a professor since 1998 and Associate Director since 2009. Prior to that, he held fellowships at Princeton University (1994-95) and Harvard University (1995-98). Pen is a theoretical astrophysicist who studies systems where basic physical effects can be isolated from astronomical complexities. His research interests include 21cm cosmology, HPC simulations, gravitational waves, pulsars, and radio interferometry. Among his many honours, Pen is a Senior Fellow of the Canadian Institute for Advanced Research in the Cosmology and Gravity program and an Adjunct Professor at the Tata Institute for Fundamental Research in India.

Maxim Pospelov (PhD Budker Institute of Nuclear Physics, 1994) is jointly appointed with the University of Victoria and became an associate faculty member at Perimeter in 2004. He previously held research positions at the University of Quebec at Montreal, the University of Minnesota, McGill University, and the University of Sussex. Pospelov works in the areas of particle physics and cosmology.

Itay Yavin (PhD Harvard University, 2006) began a joint appointment with Perimeter and McMaster University in 2011. Previously, he was a Research Associate at Princeton University and a James Arthur Postdoctoral Fellow at New York University. Yavin's research focuses on particle physics and the search for physics beyond the Standard Model. In particular, he is interested in the origin of electroweak symmetry breaking and the nature of dark matter. Most recently, he has worked on interpreting puzzling data coming from experiments looking for dark matter in the lab.

Appendix B: Distinguished Visiting Research Chairs

Yakir Aharonov is a professor of theoretical condensed matter physics at Chapman University and Professor Emeritus at Tel Aviv University. He has made seminal contributions in quantum mechanics, relativistic quantum field theories, and interpretations of quantum mechanics. In 1998, he received the prestigious Wolf Prize for his 1959 co-discovery of the Aharonov-Bohm effect. In 2010, US President Barack Obama awarded him the National Medal of Science, the highest scientific honour bestowed by the United States government.

Nima Arkani-Hamed of the Institute for Advanced Study is one of the world's leading particle physicists and a previous long-term visitor at Perimeter. He has developed theories on emergent extra dimensions, "little Higgs theories," and proposed new models that can be tested using the Large Hadron Collider (LHC) at CERN in Switzerland. In 2012, Arkani-Hamed was one of the inaugural winners of the Fundamental Physics Prize.

Abhay Ashtekar is the Eberly Professor of Physics and Director of the Institute for Gravitation and the Cosmos at Pennsylvania State University. As the creator of Ashtekar variables, he is one of the founders of loop quantum gravity. His many research interests include black hole entropy, quantum cosmology and the very early universe, generalizations of quantum mechanics, mathematical aspects of quantum field theory, and many areas of both quantum gravity and general relativity. Among his many honours, Ashtekar has been an Alfred P. Sloan Research Fellow, Honorary Fellow of the Indian Academy of Sciences, President of the International Society for General Relativity and Gravitation, and a Fellow of both the American Physical Society and the American Association for the Advancement of Science. In 2007, he was awarded the Distinguished Scholar Prize of the American Chapter of the Indian Association of Physics.

Leon Balents is a Professor of Physics and a Permanent Member of the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara. He researches nearly all areas of condensed matter theory, contributing to the theory of new topological phases of electrons. Balents works on frustrated magnetism (mostly quantum), correlation phenomena in oxide heterostructures, coupled electron dynamics with hyperfine interactions in quantum dots, the quantum Hall effect in graphene, ultra-cold trapped atoms, one-dimensional electron gases, and topological aspects of insulators with strong spin orbit interactions. Balents' past honours include a Career Award of the National Science Foundation, Alfred P. Sloan Foundation Fellowship, and Packard Foundation Fellowship. He was elected a Fellow of the American Physical Society in 2013.

James Bardeen is an Emeritus Professor of Physics at the University of Washington in Seattle. He has made major contributions in general relativity and cosmology, including the formulation, with Stephen Hawking and Brandon Carter, of the laws of black hole mechanics, and the development of a gauge-invariant approach to cosmological perturbations and the origin of large-scale structure in the present universe from quantum fluctuations during an early epoch of inflation. His recent research focuses on improving calculations of the generation of gravitational radiation from merging black hole and neutron star binaries by formulating the Einstein equations on asymptotically null constant mean curvature

hypersurfaces. This makes possible numerical calculations with an outer boundary at future null infinity, where waveforms can be read off directly, without any need for extrapolation. Bardeen received his PhD from Caltech under the direction of Richard Feynman.

Ganapathy Baskaran is an Emeritus Professor at the Institute of Mathematical Sciences, Chennai in India, where he recently founded the Quantum Science Centre. He has made important contributions to the field of strongly correlated quantum matter. His primary research focus is novel emergent quantum phenomena in matter, including biological ones. He is well known for his contributions to the theory of high temperature superconductivity and for discovering emergent gauge fields in strongly correlated electron systems. He predicted p-wave superconductivity in Sr_2RuO_4, a system believed to support Majorana fermion mode, which is a popular qubit for topological quantum computation. In recent work, he predicted room temperature superconductivity in optimally doped graphene. From 1976 to 2006, Baskaran contributed substantially to the Abdus Salam International Centre for Theoretical Physics in Trieste, Italy. He is a past recipient of the S.S. Bhatnagar Award from the Indian Council of Scientific and Industrial Research (1990); the Alfred Kasler ICTP Prize (1983); Fellowships of the Indian Academy of Sciences (1988), the Indian National Science Academy (1991), and the Third World Academy of Sciences (2008); and the Distinguished Alumni Award of the Indian Institute of Science, Bangalore (2008).

Patrick Brady is a Professor of Physics and the Director of the Leonard E. Parker Center for Gravitation, Cosmology, and Astrophysics at the University of Wisconsin-Milwaukee. His research interests include the dynamics of gravitational collapse, black holes, the detection of gravitational waves using interferometric gravitational wave detectors, and numerical relativity, including simulation of binary coalescence. Brady received a Research Corporation Cottrell Scholar Award and a Sloan Research Fellowship in 2002, and was made a Fellow of the American Physical Society (APS) in 2010. He has served as Secretary/Treasurer and Vice-Chair of the APS Topical Group in Gravitation and on the Executive Committee of the LIGO Scientific Collaboration. He also has six awards from the National Science Foundation.

Alessandra Buonanno is the Director of the Astrophysical and Cosmological Relativity division of the Max Planck Institute for Gravitational Physics (Albert Einstein Institute) in Potsdam, Germany, and a College Park Professor at the University of Maryland, College Park. Buonanno's research centres around gravitational wave physics and cosmology of the early universe, specifically focused on the analytical modeling of the dynamics and gravitational-wave emission from coalescing black holes, the interface between analytical and numerical relativity, and the search for gravitational waves with ground-based detectors, such as LIGO, GEO600, and Virgo. Buonanno has been a Fellow of the Alfred P. Sloan Foundation and a Radcliffe Fellow at the Radcliffe Institute for Advanced Study at Harvard University. She is currently a Fellow of the International Society on General Relativity and Gravitation and the American Physical Society.

Juan Ignacio Cirac, Director of the Theory Division of the Max Planck Institute of Quantum Optics in Germany, is a leading quantum information theorist whose group received the 2009 Carl Zeiss Research Award. His research aims to characterize quantum phenomena and to develop a new theory of

information based on quantum mechanics, work which may ultimately lead to the development of quantum computers.

Savas Dimopoulos has been on the faculty of Stanford University since 1979. In that span, he has also taught at Boston University, Harvard University, and the University of California, Santa Barbara, and he was a staff member at CERN from 1994 to 1997. Dimopoulos is a leading particle physicist, well known for his work on constructing theories beyond the Standard Model. With collaborators, he has done foundational work on the Minimal Supersymmetric Standard Model (MSSM) and proposed the "ADD" model of large extra dimensions. Among his many honours, Dimopoulos has received the Tommassoni Prize in Physics, the J.J. Sakurai Prize in Theoretical Physics from the American Physical Society, and a Distinguished Alumnus Award from the University of Houston. He was an Alfred P. Sloan Foundation Fellow and is currently a fellow of both the Japanese Society for the Promotion of Science and the American Academy of Arts and Sciences.

Lance Dixon is a theoretical particle physicist and a Professor at Stanford University. He has made ground-breaking contributions to the calculation of perturbative scattering amplitudes and his work has provided a deeper understanding of quantum field theory and led to powerful new tools for computing processes in quantum chromodynamics. Dixon's current research in phenomenology focuses on precision calculation in quantum chromodynamics, as applied to the Large Hadron Collider at CERN, where he spent a sabbatical in 2010 as the LHC began full operations. He also studies the quantum structure of supersymmetric gauge theories and theories of gravity. Dixon is a Fellow of the American Physical Society and a co-recipient of its 2014 J.J. Sakurai Prize.

Matthew Fisher is a condensed matter physicist at the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara. His research has focused on strongly correlated systems, especially low-dimensional systems, Mott insulators, quantum magnetism, and the quantum Hall effect. Fisher received the Alan T. Waterman Award from the National Science Foundation in 1995 and the National Academy of Sciences Award for Initiatives in Research in 1997. He was elected as a Member of the American Academy of Arts and Sciences in 2003 and to the National Academy in 2012. In 2015, he was a co-recipient of the Oliver E. Buckley Condensed Matter Physics Prize of the American Physical Society. He has over 170 publications.

S. James Gates Jr. is the John S. Toll Professor and Director for the Center for String and Particle Theory at the University of Maryland, College Park. Gates' research has made numerous contributions to supersymmetry, supergravity, and superstring theory, including the introduction of complex geometries with torsion (a new contribution in the mathematical literature), and the suggestion of models of superstring theories that exist purely as four-dimensional constructs similar to the Standard Model of particle physics. He has won the Public Understanding & Technology Award from the American Association for the Advancement of Science (AAAS), the Klopsteg Award from the American Association of Physics Teachers (AAPT), and the US National Medal of Science. Gates is a Fellow of both AAAS and the American Physical Society, and a past President of the National Society of Black Physicists. In 2011, he was elected to the American Academy of Arts and Sciences. He serves on the US President's Council

of Advisors on Science and Technology, the Maryland State Board of Education, the Board of Directors of the Fermi National Laboratory, and the Board of Trustees for the Society for Science and the Public.

Alexander Goncharov is a Professor in the Department of Mathematics at Yale University. Prior to joining Yale's faculty, he was a professor at Brown University, the Max Planck Institute for Mathematics, and the Massachusetts Institute of Technology. Goncharov's research primarily concerns mathematical physics, including arithmetic algebraic geometry and representation theory. He is known for the Goncharov conjecture, which suggests that the cohomology of certain motivic complexes coincides with pieces of K-groups. In 1992, Goncharov won the European Mathematical Society Prize.

Gabriela González is a Professor of Physics and Astronomy at Louisiana State University and the spokesperson for the LIGO Scientific Collaboration, a worldwide endeavour probing gravitational wave astronomy. Her work focuses on the detection of gravitational waves. She worked as a staff scientist with the MIT-LIGO group and was a faculty member at Penn State University before joining LSU in 2001. In 2007, she was awarded the Edward A. Bouchet Award by the American Physical Society.

F. Duncan M. Haldane is the Eugene Higgins Professor of Physics at Princeton University. His research explores strongly interacting quantum many-body condensed matter systems using non-perturbative methods. In particular, his concerns include the entanglement spectrum of quantum states, topological insulators and Chern insulators, and both the geometry and model wave functions of the fractional quantum Hall effect. Haldane is a former Alfred P. Sloan Research Fellow and is currently a Fellow of the Royal Society of London, Institute of Physics (UK), American Physical Society, American Association for the Advancement of Science, and American Academy of Arts and Sciences. Haldane has been awarded the Oliver E. Buckley Condensed Matter Physics Prize of the American Physical Society (1993) and the Dirac Medal of the International Centre for Theoretical Physics (2012).

Patrick Hayden is a Professor of Physics at Stanford University. He is a leader in quantum information science who has contributed greatly to our understanding of the absolute limits that quantum mechanics places on information processing, and how to exploit quantum effects for computing and communication. He has also made some key insights on the relationship between black holes and information theory. Among his honours, Hayden is a past Sloan Research Fellow and Rhodes Scholar. He also held the Canada Research Chair in the Physics of Information at McGill University prior to joining Stanford.

Joseph Incandela is the Pat and Joe Yzurdiaga Chair in Experimental Science and Professor of Physics at the University of California, Santa Barbara. He specializes in high energy experimental physics and has worked on several experiments in his career, including the UA2 experiment at CERN, where he studied W and Z bosons and searched for charged Higgs bosons, and the CDF experiment at the Fermi National Accelerator Laboratory (Fermilab), where he led the construction and design of silicon detectors and co-led the successful search for the top quark using lifetime tagging of b quark jets. More recently, he has served in a number of leadership roles tied to the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider at CERN; he was CMS Spokesperson and, in July 2012, he announced the historic discovery of the Higgs boson. For his leadership roles in CMS, he was awarded a Special Breakthrough

Prize in Fundamental Physics from the Breakthrough Prize Foundation in 2013. He was elected a member of the US National Academy of Sciences in 2015.

Theodore A. (Ted) Jacobson is a Professor of Physics at the University of Maryland, College Park. He is a leading researcher in the field of gravitational physics and a devoted and accomplished educator. Jacobson's research has focused on quantum gravity, testing the foundations of relativity theory, and the nature of Hawking radiation and black hole entropy. He has authored more than 100 scientific papers, which have received over 6,800 citations. He is a Fellow of both the American Physical Society and the American Association for the Advancement of Science. In addition, Jacobson has served on the editorial board of *Physical Review D* and as a Divisional Editor for *Physical Review Letters*.

Shamit Kachru has been a Professor of Physics at Stanford University since 1999. He is an expert in string theory and quantum field theory, and their applications in cosmology, condensed matter, and elementary particle theory. He has made central contributions to the study of compactifications of string theory from ten to four dimensions, especially in the exploration of mechanisms which could yield string models of dark energy or cosmic inflation. Kachru has also made notable contributions to the discovery and exploration of string dualities, to the study of models of supersymmetry breaking in string theory, and to the construction of calculable dual descriptions of strongly-coupled particle physics and condensed matter systems using the AdS/CFT correspondence. Kachru's many honours include a Department of Energy Outstanding Junior Investigator Award, Alfred P. Sloan Foundation Fellowship, Bergmann Memorial Award, Packard Foundation Fellowship, and ACIPA Outstanding Young Physicist Prize.

Leo Kadanoff is a theoretical physicist and applied mathematician based at the James Franck Institute at the University of Chicago. He is a pioneer of complexity theory and has made important contributions to research in the properties of matter, the development of urban areas, statistical models of physical systems, and the development of chaos in simple mechanical and fluid systems. He is best known for the development of the concepts of 'scale invariance' and 'universality' as they are applied to phase transitions. More recently, he has been involved in the understanding of singularities in fluid flow. Among his many honours, Kadanoff is a past recipient of the US National Medal of Science, the Grande Medaille d'Or of the Académie des Sciences de l'Institut de France, the Wolf Foundation Prize, the Boltzmann Medal of the International Union of Pure and Applied Physics, and the Centennial Medal of Harvard University. He is also a past President of the American Physical Society.

Adrian Kent is a Reader in Quantum Physics with the University of Cambridge. He has previously held positions as an Enrico Fermi Postdoctoral Fellow at the University of Chicago, a member of the Institute for Advanced Study, and a Royal Society University Research Fellow at the University of Cambridge. Prior to becoming a DVRC, Kent was an associate faculty member at Perimeter Institute. His research focuses on the foundations of physics, quantum cryptography, and quantum information theory, including the physics of decoherence, novel tests of quantum theory and alternative theories, and new applications of quantum information.

Renate Loll is a Professor of Theoretical Physics at the Institute for Mathematics, Astrophysics and Particle Physics of the Radboud University in Nijmegen, Netherlands. Her research centres on quantum gravity, the search for a consistent theory that describes the microscopic constituents of spacetime geometry and the quantum-dynamical laws governing their interaction. She has made major contributions to loop quantum gravity and, with her collaborators, has proposed a novel theory of quantum gravity via "Causal Dynamical Triangulations." Loll heads one of the largest research groups on non-perturbative quantum gravity worldwide and is the recipient of a prestigious personal VICI-grant of the Netherlands Organization for Scientific Research.

Matilde Marcolli is a Professor of Mathematics at the California Institute of Technology, who also holds a Courtesy Appointment at Florida State University and an Honorary Professorship at Bonn University. She is a mathematical physicist whose research interests include gauge theory and low-dimensional topology, algebraic-geometric structures in quantum field theory, and noncommutative geometry with applications to number theory and models of particle physics, quantum gravity, and cosmology. Among her many honours, Marcolli has won the Heinz Maier Leibnitz Prize and the Sofja Kovalevskaya Award, both in 2001, and held many visiting research positions. She has also written four books, most recently *Feynman Motives* in 2009, and edited several others.

Joel Moore is a Professor of Physics at the University of California, Berkeley, studying condensed matter. His research concerns the collective quantum physics of electrons and atoms, including topological insulators and other new states of matter. In particular, Moore studies strongly correlated materials and devices and uses concepts from quantum information theory to analyze problems in condensed matter. His work has been recognized by a Simons investigatorship, Hellman and JSPS fellowships, and an NSF CAREER award. He serves on the advisory boards of *Physical Review B* and *JSTAT,* and is a Member-at-Large of the APS Division of Condensed Matter Physics.

Ramesh Narayan is the Thomas Dudley Cabot Professor of the Natural Sciences at Harvard University. He is an astrophysicist who has won international renown for his research on black holes. Narayan has also carried out research in a number of other areas of theoretical astrophysics, including accretion disks, gravitational lensing, gamma-ray bursts, and neutron stars. He is a Fellow of the Royal Society of London and the American Association for the Advancement of Science, and a member of the International Astronomical Union and the American Astronomical Society.

Sandu Popescu is a Professor of Physics at the H.H. Wills Physics Laboratory at the University of Bristol and a member of the Bristol Quantum Information and Computation Group. He has made numerous contributions to quantum theory, ranging from the very fundamental to the design of practical experiments (such as the first teleportation experiment), to patentable commercial applications. His investigations into the nature of quantum behaviour, with particular focus on quantum non-locality, led him to discover some of the central concepts in the emerging area of quantum information and computation. Popescu is a past recipient of the Adams Prize (Cambridge) and the Clifford Patterson Prize of the Royal Society (UK).

Frans Pretorius is a Professor of Physics at Princeton University. His primary field of research is general relativity, specializing in numerical solution of the field equations. His work has included studies of gravitational collapse, black hole mergers, cosmic singularities, higher dimensional gravity, models of black hole evaporation, and using gravitational wave observations to test the dynamical, strong-field regime of general relativity. He also designs algorithms to efficiently solve the equations in parallel on large computer clusters, and software to manipulate and visualize the simulation results. Among his honours, Pretorius was awarded a Sloan Research Fellowship (2007) and the Aneesur Rahman Prize for Computational Physics of the American Physical Society (2010). He is also a Scholar in the Canadian Institute for Advanced Research (CIFAR) Cosmology and Gravity program.

Peter Shor is the Morss Professor of Applied Mathematics at MIT. In 1994, he formulated a quantum algorithm for factoring, now known as Shor's algorithm, which is exponentially faster than the best currently-known algorithm for a classical computer. He also showed that quantum error correction was possible and that one can perform fault-tolerant quantum computation on a quantum computer. Shor continues to focus his research on theoretical computer science, specifically on algorithms and quantum computing. Among his many honours, Shor has received the Nevanlinna Prize (1998), the International Quantum Communication Award (1998), the Gödel Prize of the Association of Computing Machinery (1999), and a MacArthur Foundation Fellowship (1999). He is also a member of the National Academy of Science (2002) and a fellow of the American Academy of Arts and Sciences (2011).

Iakov (Yan) Soibelman is a Professor of Mathematics at Kansas State University. His research interests include quantum groups, deformation theory, algebraic geometry, topology, symplectic geometry, representation theory, non-commutative geometry, differential equations, mathematical physics, and string theory. In collaboration with Maxim Kontsevich, Soibelman developed new algebraic and geometric methods for studying various aspects of homological mirror symmetry. More recently, they introduced a notion of motivic Donaldson-Thomas invariants and proposed a new type of wall-crossing formulas for such invariants. Soibelman is a member of the American Mathematical Society and the Kiev Mathematical Society, and the founder of the Manhattan Mathematical Olympiad. He is also a past Fellow of the Sloan Foundation and the Clay Mathematics Institute, and has held visiting professorships at numerous prestigious institutions, including Harvard University, the Massachusetts Institute of Technology, and the University of Cambridge.

Dam Thanh Son is a University Professor of Physics at the University of Chicago, a prestigious post that includes appointments at the University's interdisciplinary research institutes, the Enrico Fermi Institute and the James Franck Institute. Son is renowned for his broad research interests; he gained international prominence for his application of ideas from string theory to the physics of the quark gluon plasma. His work encompasses several areas of theoretical physics, including string theory, nuclear physics, condensed matter physics, particle physics, and atomic physics. Among his honours, Son was named an Alfred P. Sloan Foundation Fellow in 2001 and a Fellow of the American Physical Society in 2006.

Andrew Strominger is the Gwill E. York Professor of Physics at Harvard University and Director of the Center for Fundamental Laws of Nature. His research has encompassed the unification of forces and particles, the origin of the universe, and the quantum structure of black holes and event horizons, using

a variety of approaches. Among Strominger's major contributions, he is the co-discoverer of Calabi-Yau compactifications and the brane solutions of string theory. With collaborators, he gave a microscopic demonstration of how black holes are able to holographically store information. Strominger's recent research has focused on universal aspects of black holes and horizons, which do not depend on detailed microphysical assumptions.

Raman Sundrum is a Distinguished University Professor at the University of Maryland, College Park, and the Director of the Maryland Center for Fundamental Physics. His research is in theoretical particle physics and focuses on theoretical mechanisms and observable implications of extra spacetime dimensions, supersymmetry, and strongly coupled dynamics. In 1999, with Lisa Randall, Sundrum proposed a class of models that imagines the real world as a higher-dimensional universe described by warped geometry, which are now known as the Randall-Sundrum models. Sundrum won a Department of Energy Outstanding Junior Investigator Award for 2001/02 and is a Fellow of both the American Physical Society (2003) and the American Association for the Advancement of Science (2011).

Leonard Susskind is the Felix Bloch Professor of Theoretical Physics at Stanford University. Regarded as one of the fathers of string theory, he has also made seminal contributions to particle physics, black hole theory, and cosmology. Susskind's current research centres upon questions in theoretical particle physics, gravitational physics, and quantum cosmology.

Gerard 't Hooft is a Professor at the Institute for Theoretical Physics at Utrecht University. He shared the 1999 Nobel Prize in Physics with Martinus J.G. Veltman "for elucidating the quantum structure of electroweak interactions." His research interests include gauge theories in elementary particle physics, quantum gravity and black holes, and fundamental aspects of quantum physics. In addition to being a Nobel laureate, 't Hooft is a past winner of the Wolf Prize, the Lorentz Medal, the Franklin Medal, and the High Energy Physics Prize from the European Physical Society, among other honours. He is a member of the Royal Netherlands Academy of Arts and Sciences (KNAW) and is a foreign member of many other science academies, including the French Académie des Sciences, the National Academy of Sciences (US), and the Institute of Physics (UK). 't Hooft's present research concentrates on the question of nature's dynamical degrees of freedom at the tiniest possible scales. In his latest model, local conformal invariance is a spontaneously broken symmetry, which may have very special implications for the interactions between elementary particles.

Barbara Terhal has been a Professor of Theoretical Physics at RWTH Aachen University in Germany since 2010. Prior to that, she spent eight years as a research staff member at the IBM Watson Research Center in New York. Terhal's research interests lie in quantum information theory – ranging from quantum entanglement to quantum cryptography and quantum algorithms – and she is currently working on quantum error correction and its realization in solid-state qubits, as well as quantum complexity theory. She is a Fellow of the American Physical Society and an Associate Member of the Quantum Information Processing program of the Canadian Institute for Advanced Research (CIFAR).

Senthil Todadri is an Associate Professor of Physics at the Massachusetts Institute of Technology (MIT). Todadri's research interests are in condensed matter theory. Specifically, he is working to develop a

theoretical framework to describe the behaviour of electronic quantum matter in circumstances in which individual electrons have no integrity. A prime example is the quest for a replacement for the Landau theory of Fermi liquids that describes many metals extremely successfully, but fails in a number of situations studied in modern experiments in condensed matter physics. He is a past Sloan Research Fellow and winner of a Research Innovation Award from the Research Corporation for Science Advancement.

William Unruh is a Professor of Physics at the University of British Columbia who has made seminal contributions to our understanding of gravity, black holes, cosmology, quantum fields in curved spaces, and the foundations of quantum mechanics, including the discovery of the Unruh effect. His investigations into the effects of quantum mechanics of the earliest stages of the universe have yielded many insights, including the effects of quantum mechanics on computation. Unruh was the first Director of the Cosmology and Gravity program at the Canadian Institute for Advanced Research (1985-1996). His many awards include the Rutherford Medal of the Royal Society of Canada (1982), the Herzberg Medal of the Canadian Association of Physicists (1983), the Steacie Prize from the National Research Council (1984), the Canadian Association of Physicists Medal of Achievement (1995), and the Canada Council Killam Prize (1996). He is an elected Fellow of the Royal Society of Canada, a Fellow of the American Physical Society, a Fellow of the Royal Society of London, and a Foreign Honorary Member of the American Academy of Arts and Science.

Frank Verstraete is a Professor of Physics at the University of Vienna, where he leads the quantum theory group focused on the study of entanglement in many-body quantum systems. His other research interests include quantum information theory, strongly correlated quantum systems and their numerical simulation, and linear and multilinear algebra. Verstraete also holds a professorship at the University of Ghent and has worked previously with Ignacio Cirac at the Max Planck Institute for Quantum Optics and with John Preskill at the California Institute of Technology. In 2009, he won the Lieben Prize, given annually by the Austrian Academy of Sciences.

Ashvin Vishwanath is an Associate Professor in the Department of Physics at the University of California, Berkeley. His primary field is condensed matter theory, with a focus on magnetism, superconductivity, and other correlated quantum phenomena in solids and cold atomic gases. Vishwanath is particularly interested in novel phenomena, such as topological phases of matter, non-fermi liquids, and quantum spin liquids. He has recently been interested in realizing Majorana and Weyl fermions in solids and in using concepts from quantum information, such as entanglement entropy, to characterize novel phases of matter. His past honours include a Sloan Research Fellowship (2004), the CAREER Award of the National Science Foundation (2007), the Outstanding Young Scientist Award of the American Chapter of Indian Physicists (2010), and the Simons Foundation Sabbatical Fellowship (2012).

Zhenghan Wang is a Principal Researcher at Microsoft Research Station Q on the campus of the University of California, Santa Barbara (UCSB), and a Professor of Mathematics at UCSB. His main interests are quantum topology, mathematical models of topological phases of matter, and their application to quantum computing. Wang and his colleagues at Microsoft have been responsible for many developments, including showing that an anyonic quantum computer can perform any

computation that the more traditional qubit quantum computer can. He is currently working on the theoretical foundations of the field of anyonics, broadly defined as the science and technology that cover the development, behaviour, and application of anyonic devices.

Steven White is a Professor in the Department of Physics at the University of California, Irvine. His primary research concerns condensed matter theory with an emphasis on numerical approaches for strongly correlated magnetic and superconducting systems. In 1992, White invented the density matrix renormalization group (DMRG), a numerical variation technique for high accuracy calculations of the low energy physics of quantum many body systems. For his efforts, White has been recognized as a Fellow of the American Physical Society (1998) and the American Association for the Advancement of Science (2008). In 2003, he won the Aneesur Rahman Prize, the highest honour in the field of computational physics given by the American Physical Society.

Mark Wise is the John A. McCone Professor of High Energy Physics at the California Institute of Technology. He has conducted research in elementary particle physics and cosmology, and shared the 2001 Sakurai Prize for Theoretical Particle Physics for the development of the "Heavy Quark Effective Theory" (HQET), a mathematical formalism that enables physicists to make predictions about otherwise intractable problems in the theory of the strong interactions of quarks. He has also published work on mathematical models for finance and risk assessment. Wise is a past Sloan Research Fellow, a Fellow of the American Physical Society, and a member of the American Academy of Arts and Sciences and of the National Academy of Sciences.

Matias Zaldarriaga is a Professor of Astrophysics at the Institute for Advanced Study who has made many influential and creative contributions to our understanding of the early universe, particle astrophysics, and cosmology as a probe of fundamental physics. Much of his work centres on understanding the clues about the earliest moments of our universe encoded in the cosmic microwave background, the faint glow of radiation generated by the big bang. Early in his career, Zaldarriaga co-wrote computer software known as CMBFAST that has become a standard tool for astronomers interpreting observations of the cosmic microwave background. Among his many honours, he has been awarded Sloan and McArthur Fellowships, the Helen B. Warner Prize of the American Astronomical Society, and the Gribov Medal of the European Physical Society.

Appendix C: Visiting Fellows

Jonathan Barrett (PhD Trinity College, Cambridge, 2002) is an Associate Professor at the University of Oxford. He works in the areas of quantum foundations, quantum information, and quantum computation, with a particular focus on cryptography and aspects of quantum non-locality. Recently, he has been investigating information processing in formalisms more general than quantum theory.

Eugenio Bianchi (PhD Scuola Normale Superiore di Pisa, 2010) is an Assistant Professor of Physics at Pennsylvania State University. He previously held a Marie Curie Postdoctoral Fellowship at the Centre de Physique Théorique de Luminy in France and a Banting Postdoctoral Fellowship at Perimeter Institute. Bianchi's research seeks to understand the quantum nature of spacetime and his work lies at the interface between general relativity, quantum field theory, and thermodynamics. In 2013, he received the inaugural Bronstein Prize for his work in loop quantum gravity.

Fernando Brandão (PhD Imperial College London, 2008) is a Reader at University College London and a Researcher in the Quantum Architectures and Computation Group at Microsoft Research. In 2016, he will join the faculty of the California Institute of Technology. His research concerns quantum information, quantum computing, and quantum optics, particularly their interplay with mathematics and computer science in understanding the possibilities and limitations of quantum mechanical systems. Among his honours, Brandão won the Quantum Electronics and Optics Division Prize of the European Physical Society (2009), a QIPC European Quantum Information Young Investigator Award (2013), and the Aspen Center for Physics Block Award (2014).

Vitor Cardoso (PhD Instituto Superior Técnico, 2003) is a Professor at the Instituto Superior Técnico (IST) in Lisbon, Portugal, a Distinguished Visiting Researcher at the Sapienza University of Rome, and an Adjunct Professor of Physics at the University of Mississippi. His research concerns general relativity and black hole physics. Cardoso leads the gravity team at IST's Multidisciplinary Center for Astrophysics (CENTRA), where they are seeking to understand black hole dynamics in generic spacetimes and to discriminate between different gravity theories using gravitational wave observations. Cardoso's many honours include Fulbright (2008) and Gulbenkian (2010) scholarships, and the Ordem de Sant'Iago da Espada (2015).

Giulio Chiribella (PhD University of Pavia, 2006) is an Associate Professor at the University of Hong Kong. His research interests lie in quantum information theory, quantum foundations, and mathematical physics – particularly at the intersection of these fields. In 2010, Chiribella won the Hermann Weyl Prize for his work on the application of group theoretical models to the problem of quantum estimation of states and processes.

Philippe Corboz (PhD ETH Zurich, 2008) is an Assistant Professor in Theoretical Condensed Matter Physics at the Institute for Theoretical Physics at the University of Amsterdam, having completed postdoctoral work at ETH Zurich, the Swiss Federal Institute of Technology, and the University of Queensland. His research interests include condensed matter, computational physics, quantum many-body physics, strongly correlated systems, and computer programming.

Fay Dowker (PhD University of Cambridge, 1991) is a Professor of Theoretical Physics at Imperial College London and an Affiliate of the Institute for Quantum Computing at the University of Waterloo. Her research interests include quantum gravity, the foundations of quantum mechanics, and causal set theory. Dowker completed her PhD under the supervision of Stephen Hawking and held previous positions at Queen Mary University of London, Fermilab, the California Institute of Technology, and the University of California, Santa Barbara.

Jerome Gauntlett (PhD University of Cambridge, 1991) is the Head of Theoretical Physics at Imperial College London, having previously held research positions at Queen Mary University of London, the California Institute of Technology, and the University of Chicago. His principal research interests include string theory, supersymmetry, quantum field theory, and black holes. Recently, Gauntlett has been investigating whether string theory techniques can be used to study exotic states of matter that arise in condensed matter physics. He is a Fellow of the Institute of Physics and served as a scientific consultant for the 2014 film *The Theory of Everything*.

Ruth Gregory (PhD University of Cambridge, 1988) is a Professor in the Departments of Physics and Mathematical Sciences at Durham University. Her research centres on the interface between fundamental high energy physics and cosmology, including exploring simple braneworld models to determine what physical features they can have. In 2006, she was awarded the Maxwell Medal of the Institute of Physics (UK). Gregory has lectured as part of the PSI master's program since its creation.

Razvan Gurau (PhD University of Paris, 2007) is a Researcher at the Centre National de la Recherche Scientifique (CNRS) at École Polytechnique in France. His research interests lie in mathematical physics, particularly in both perturbative and non-perturbative aspects of the renormalization of quantum field theories. His work is relevant for physics problems ranging from quantum gravity to condensed matter. For his work in quantum gravity, Gurau won the Hermann Weyl Prize in 2012.

Jutho Haegeman (PhD Ghent University, 2011) is a postdoctoral researcher at Ghent University, working with Distinguished Visiting Research Chair Frank Verstraete. His research interests concern the description of condensed matter systems and quantum field theories using tensor network states or related methods. In particular, Haegeman is investigating new ideas and algorithms for extracting the low-energy description of microscopic quantum Hamiltonians using the tensor network philosophy.

Zohar Komargodski (PhD Weizmann Institute of Science, 2008) is a Senior Scientist in the Department of Particle Physics and Astrophysics at the Weizmann Institute of Science. His work spans quantum field theory, conformal symmetry, supersymmetry, quantum gravity, and particle physics phenomenology. Komargodski is most known for his proof, with Adam Schwimmer, of the "a-theorem," a long-open conjecture of quantum field theory. For this and other work on the dynamics of four-dimensional field theories, Komargodski won the prestigious New Horizons in Physics Prize from the Fundamental Physics Prize Foundation. In addition, he is a recipient of the Gribov Medal of the European Physical Society and an Adjunct Professor of Theoretical Physics at the Niels Bohr International Academy in Denmark.

John Laiho (PhD Princeton University, 2004) is an Assistant Professor at Syracuse University, having previously held research positions at the Fermi National Accelerator Laboratory (Fermilab), Washington

University in St. Louis, and University of Glasgow. Laiho is a theoretical particle physicists, whose research interests include lattice QCD, flavor physics and CP violation, chiral perturbation theory, and lattice gravity.

Christopher Laumann (PhD Princeton University, 2010) is an Assistant Professor in the Department of Physics at the University of Washington. He previously held postdoctoral positions at Perimeter Institute and Harvard University. Laumann's research primarily concerns condensed matter, quantum information, and quantum computing, with particular interests in disordered systems, topological phases of quantum matter, and spin glasses.

Si Li (PhD Harvard University, 2011) is a Professor at the Yau Mathematical Sciences Center at Tsinghua University and an Affiliate Member at the Kavli Institute for the Physics and Mathematics of the Universe. He was previously an Assistant Professor at Boston University. Li's research interests centre on the interplay between geometry and physics – specifically algebraic and complex geometry, quantum field theory, and string theory. He was awarded a New World Mathematics Award in 2012 for his doctoral thesis.

Etera Livine (PhD Centre de Physique Théorique, Marseille, 2003) is a Researcher for the Centre National de la Recherche Scientifique (CNRS) at the Laboratoire de Physique of the École Normale Supérieure de Lyon, in France. He works in the area of quantum gravity, with a focus on spinfoam models, and he is interested in deriving effective dynamics for quantum cosmology from these models.

Eduardo Martin-Martinez (PhD Universidad Complutense de Madrid, 2011) is a Research Assistant Professor at the Institute for Quantum Computing at the University of Waterloo. Martin-Martinez's research combines the fields of quantum information science, quantum field theory, and general relativity; in particular, he studies quantum effects induced by gravity from the perspective of quantum information. He is the recipient of numerous awards, including a prestigious Banting Postdoctoral Fellowship (2012) and the John Charles Polanyi Prize for Physics (2014).

David Skinner (PhD University of Oxford, 2003) is a tenure-track Lecturer at the University of Cambridge. Skinner is interested in mathematical aspects of quantum field theories, particularly their overlap with twistor theory and string theory. His recent work explores the rich geometric structures present in the scattering amplitudes of four-dimensional gauge theory.

Kris Sigurdson (PhD California Institute of Technology, 2005) is an Associate Professor in Physics and Astronomy at the University of British Columbia. He works in the areas of particle astrophysics and cosmology, with a focus on dark matter and dark energy. His recent work includes a unified theory for the origin of dark matter and atoms in the early universe and developing, with a Canadian team, a novel new radio interferometer that can make a three-dimensional map of the universe to measure properties of dark energy.

Brian Swingle (PhD Massachusetts Institute of Technology, 2011) is a Postdoctoral Research Fellow at Stanford University, having previously held a Simons Fellowship in condensed matter at Harvard University. Swingle works at the interface of quantum matter, quantum information, and quantum

gravity; his particular interests include quantum entanglement, strongly correlated systems, spin liquids and the physics of fractionalization, experimental signatures of strongly correlated phases, quantum information and computation, and holographic duality and string theory.

Thomas Vidick (PhD University of California, Berkeley, 2011) is an Assistant Professor in the Department of Computing and Mathematical Sciences at the California Institute of Technology. Vidick's research is centered on problems at the interface of quantum computing, complexity theory, and cryptography. He studies complexity-theoretic aspects of quantum phenomena such as entanglement, and likes to explore the application of ideas from quantum computing to fields as diverse as pseudo randomness, discrete optimization, or functional analysis. In 2011, Vidick won the Bernard Friedman Memorial Prize in Applied Mathematics.

Neal Weiner (PhD University of California, Berkeley, 2000) is a Professor in the Department of Physics and Director of the Center for Cosmology and Particle Physics (CCPP) at New York University. He has broad interests in particle physics and cosmology, with a general focus on physics beyond the Standard Model. In this broad field, his work has included studies of extra dimensional theories (large, small, warped, and flat), supersymmetry, grand unification, flavor, neutrino mass, dark matter, inflation, and dark energy, as well as relationships between the different subjects.

Appendix D: Affiliate Members

Name	Institution	Research Area(s)
Arif Babul	University of Victoria	Cosmology
Leslie Ballentine	Simon Fraser University	Quantum Foundations
Richard Bond	University of Toronto/Canadian Institute for Theoretical Astrophysics (CITA)	Cosmology
Ivan Booth	Memorial University	Strong Gravity
Vincent Bouchard	University of Alberta	Quantum Fields and Strings
Robert Brandenberger	McGill University	Cosmology
Gilles Brassard	University of Montreal	Quantum Information
Anne Broadbent	University of Ottawa	Quantum Information
Jim Bryan	University of British Columbia	Mathematical Physics
Anton Burkov	University of Waterloo	Condensed Matter
Benoit Charbonneau	University of Waterloo	Mathematical Physics
Gang Chen	University of Toronto	Condensed Matter
Jeffrey Chen	University of Waterloo	Condensed Matter
Andrew Childs	University of Waterloo/Institute for Quantum Computing	Quantum Information
Kyung Soo Choi	University of Waterloo/IQC	Quantum Information
Matthew Choptuik	University of British Columbia	Strong Gravity
Dan Christensen	Western University	Quantum Gravity
James Cline	McGill University	Cosmology, Particle Physics
Alan Coley	Dalhousie University	Strong Gravity
Andrzej Czarnecki	University of Alberta	Particle Physics

Name	Institution	Research Area(s)
Saurya Das	University of Lethbridge	Quantum Gravity
Arundhati Dasgupta	University of Lethbridge	Quantum Gravity
Keshav Dasgupta	McGill University	Quantum Fields and Strings
Rainer Dick	University of Saskatchewan	Particle Physics
Joseph Emerson	University of Waterloo/IQC	Quantum Foundations
Valerio Faraoni	Bishop's University	Cosmology
Marcel Franz	University of British Columbia	Condensed Matter
Doreen Fraser	University of Waterloo	Philosophy
Andrew Frey	University of Winnipeg	Cosmology
Valeri Frolov	University of Alberta	Cosmology, Quantum Gravity
Jack Gegenberg	University of New Brunswick	Quantum Gravity
Ghazal Geshnizjani	University of Waterloo	Cosmology
Amir Masoud Ghezelbash	University of Saskatchewan	Quantum Gravity
Shohini Ghose	Wilfrid Laurier University	Quantum Information, Quantum Computation
Florian Girelli	University of Waterloo	Quantum Gravity, Applied Math
Daniel Green	University of Toronto/CITA	Cosmology
Thomas Gregoire	Carleton University	Particle Physics
Marco Gualtieri	University of Toronto	Mathematical Physics
John Harnad	Concordia University	Mathematical Physics
Jeremy Heyl	University of British Columbia	Astrophysics
Gilbert Patrick Holder	McGill University	Astrophysics
Carl Hoefer	Western University	Philosophy

Name	Institution	Research Area(s)
Bob Holdom	University of Toronto	Particle Physics
Michael Hudson	University of Waterloo	Cosmology
Viqar Husain	University of New Brunswick	Cosmology, Quantum Gravity
Lisa Jeffrey	University of Toronto	Quantum Fields and Strings, Mathematical Physics
Thomas Jennewein	University of Waterloo/IQC	Quantum Information
Catherine Kallin	McMaster University	Condensed Matter
Joel Kamnitzer	University of Toronto	Mathematical Physics
Joanna Karczmarek	University of British Columbia	Quantum Fields and Strings
Spiro Karigiannis	University of Waterloo	Mathematical Physics, Differential Geometry
Mikko Karttunen	University of Waterloo	Condensed Matter, Biology
Achim Kempf	University of Waterloo	Quantum Information
Yong-Baek Kim	University of Toronto	Condensed Matter
David Kribs	University of Guelph	Quantum Information
Hari Kunduri	Memorial University	Strong Gravity
Gabor Kunstatter	University of Winnipeg	Quantum Gravity, Quantum Mechanics
Kayll Lake	Queen's University	Strong Gravity
Debbie Leung	University of Waterloo	Quantum Information
Randy Lewis	York University	Particle Physics
Hoi-Kwong Lo	University of Toronto	Quantum Information
Michael Luke	University of Toronto	Particle Physics
Adrian Lupascu	University of Waterloo/IQC	Quantum Information
Norbert Lütkenhaus	University of Waterloo/IQC	Quantum Information

Name	Institution	Research Area(s)
A. Hamed Majedi	University of Waterloo/IQC	Nanotechnology
Alexander Maloney	McGill University	Quantum Fields and Strings
Robert Mann	University of Waterloo	Quantum Fields and Strings, Quantum Gravity
Gerry McKeon	Western University	Particle Physics
Brian McNamara	University of Waterloo	Cosmology
Volodya Miransky	Western University	Quantum Information
Guy Moore	McGill University	Particle Physics
Ruxandra Moraru	University of Waterloo	Mathematical Physics, Pure Math
David Morrissey	TRIUMF	Particle Physics
Norman Murray	University of Toronto/CITA	Astrophysics
Wayne Myrvold	Western University	Philosophy
Julio Navarro	University of Victoria	Cosmology
Ashwin Nayak	University of Waterloo	Quantum Information
Elisabeth Nicol	University of Guelph	Condensed Matter
Don Page	University of Alberta	Cosmology
Prakash Panangaden	McGill University	Quantum Foundations
Manu Paranjape	University of Montreal	Particle Physics
Amanda Peet	University of Toronto	Quantum Foundations, Quantum Fields and Strings
Alexander Penin	University of Alberta	Condensed Matter, Particle Physics
Harald Pfeiffer	University of Toronto/CITA	Strong Gravity
Marco Piani	University of Waterloo/IQC	Quantum Information

Name	Institution	Research Area(s)
Levon Pogosian	Simon Fraser University	Cosmology
Dmitri Pogosyan	University of Alberta	Cosmology
Eric Poisson	University of Guelph	Strong Gravity
Erich Poppitz	University of Toronto	Particle Physics
David Poulin	University of Sherbrooke	Quantum Foundations
Robert Raussendorf	University of British Columbia	Quantum Information
Ben Reichardt	University of Southern California	Quantum Information
Kevin Resch	University of Waterloo/IQC	Quantum Information
Adam Ritz	University of Victoria	Particle Physics
Moshe Rozali	University of British Columbia	Quantum Fields and Strings
Barry Sanders	University of Calgary	Quantum Information
Kristin Schleich	University of British Columbia	Strong Gravity
Douglas Scott	University of British Columbia	Cosmology
Sanjeev Seahra	University of New Brunswick	Cosmology, Quantum Gravity
Peter Selinger	Dalhousie University	Mathematical Physics
Gordon Semenoff	University of British Columbia	Quantum Fields and Strings
John Sipe	University of Toronto	Condensed Matter, Quantum Foundations
Aephraim Steinberg	University of Toronto	Quantum Information
James Taylor	University of Waterloo	Cosmology
Andre-Marie Tremblay	University of Sherbrooke	Condensed Matter
Sean Tulin	York University	Particle Physics
Johannes Walcher	McGill University	Quantum Fields and Strings

Name	Institution	Research Area(s)
Mark Walton	University of Lethbridge	Quantum Fields and Strings
John Watrous	University of Waterloo	Quantum Information
Steve Weinstein	University of Waterloo	Quantum Foundations
Lawrence Widrow	Queen's University	Astrophysics
Don Witt	University of British Columbia	Particle Physics, Quantum Fields and Strings
Bei Zeng	University of Guelph	Quantum Information

Appendix E: Board of Directors

Mike Lazaridis, O.C., O.Ont., Chair, is Managing Partner and Co-Founder of Quantum Valley Investments (QVI), which he and Doug Fregin established in Waterloo. In 2013, they launched QVI with $100 million to provide financial and intellectual capital for the development and commercialization of quantum physics and quantum computing breakthroughs. QVI aims to help transform ideas and early-stage breakthroughs into commercially viable products, technologies, and services. It is Mr. Lazaridis' latest venture in more than a decade's work aimed at creating a "Quantum Valley" in Waterloo by bringing the world's best minds in physics, engineering, mathematics, computer science, and materials science together to collaborate on cutting-edge quantum research.

In 1984, Mr. Lazaridis co-founded BlackBerry (formerly Research In Motion) with Mr. Fregin. They invented the BlackBerry device, created the smartphone industry, and built Canada's largest global tech business. Mr. Lazaridis served in various positions including Co-Chairman and Co-CEO (1984-2012) and Board Vice Chair and Chair of the Innovation Committee (2012-13).

Mr. Lazaridis is the Founder and Board Chair of Perimeter Institute, where he helps generate important private and public sector funding for the Institute. He also founded the Institute for Quantum Computing and the Quantum-Nano Centre, both at the University of Waterloo. He has donated more than $170 million to Perimeter and more than $100 million to IQC.

Among his many honours, Mr. Lazaridis is a Fellow of the Royal Society of Canada and has been named to both the Order of Ontario and the Order of Canada. He was listed on the *Maclean's* Honour Roll as a distinguished Canadian in 2000, named as one of *Time*'s 100 Most Influential People, honoured as a *Globe and Mail* Nation Builder of the Year in 2010, selected as the 2013 Visionary of the Year by the Intelligent Community Forum, and awarded the Ernest C. Manning Principal Award, Canada's most prestigious innovation prize.

Mr. Lazaridis holds an honorary doctoral degree in engineering from the University of Waterloo (where he formerly served as Chancellor), as well as Doctors of Laws from McMaster University, the University of Windsor, and Laval University. In addition to his many professional and personal accomplishments, Mr. Lazaridis won an Academy Award and an Emmy Award for technical achievements in the movie and TV industries for developing a high-speed barcode reader that greatly increased the speed of editing film.

Mr. Lazaridis was born in Istanbul, Turkey. He moved to Canada in 1966 with his family, settling in Windsor, Ontario.

Cosimo Fiorenza, Vice Chair, is the Vice-President and General Counsel of the Infinite Potential Group. Previously, he spent approximately 20 years with major Toronto law firms, where he specialized in corporate tax. During his tenure on Bay Street, he advised some of Canada's largest corporations and biggest entrepreneurs on income tax and commercial matters with a focus on technology and international structure. Mr. Fiorenza helped establish and is a Founding Director of Perimeter Institute. In addition to his current role as Vice Chair, he is Co-Chair of the Perimeter Leadership Council and a

member of the Perimeter Finance Committee. In these capacities, he regularly assists and supports Perimeter's management team in a variety of contexts including financial, legal, and advancement matters. Mr. Fiorenza is also a member of the Board of Directors of the Institute for Quantum Computing at the University of Waterloo. He holds a degree in Business Administration from Lakehead University and a law degree from the University of Ottawa. He was called to the Bar in Ontario in 1991.

Joanne Cuthbertson, LL.D., was the first elected Chair of EducationMatters (Calgary's unique public education trust), founder of SPEAK (Support Public Education – Act for Kids), and a recipient of the Calgary Award (Education). She is Chancellor Emeritus of the University of Calgary, Co-chair of the Scholars' Academy she established upon retirement, and Dean's Circle Chair in the Faculty of Environmental Design. Ms. Cuthbertson serves as a Fellow of Glenbow Museum and as Director of the Alberta Bone & Joint Health Institute, and she is a Queen Elizabeth II Diamond Jubilee Medal recipient.

Peter Godsoe, O.C., O.Ont., is the former Chairman and Chief Executive Officer of Scotiabank, from which he retired in March 2004. He holds a BSc in Mathematics and Physics from the University of Toronto, an MBA from the Harvard Business School, and is a CA and a Fellow of the Institute of Chartered Accountants of Ontario. Mr. Godsoe remains active through a wide range of corporate boards and non-profit directorships.

Michael Horgan joined Bennett Jones LLP, one of Canada's premier business law firms, as a Senior Advisor in October 2014. Prior to his work in the private sector, Mr. Horgan had a distinguished 36-year career as a federal public servant, including five years as Canada's Deputy Minister of Finance (2009-2014). Other past positions have included Deputy Minister of both Environment Canada and Indian and Northern Affairs, Executive Director (Canada, Ireland, Caribbean) of the International Monetary Fund, and senior roles in the Privy Council Office. Mr. Horgan has been awarded the Prime Minister's Outstanding Achievement Award for Public Service (2007) and the Queen's Diamond Jubilee Medal (2013). He holds a BA in economics from Concordia University and master's degrees in economics from Queen's University and Princeton University.

Art McDonald, O.C., O.Ont., was the Director of the Sudbury Neutrino Observatory (SNO) in Ontario, Canada, for more than 20 years, where he led a team of international collaborators in discovering that elementary subatomic particles, called neutrinos, change from one type to another while traveling from the sun to the Earth. The SNO experiment also confirmed that neutrinos have a tiny, but nonzero mass. McDonald is the former Gordon and Patricia Gray Chair in Particle Astrophysics at Queen's University in Kingston. As Professor Emeritus, he is still active in research on dark matter and neutrinos at the SNOLAB underground laboratory. Professor McDonald has received numerous awards for his research, including the Benjamin Franklin Medal in Physics, alongside researcher Yoji Totsuka (2007), the Henry Marshall Tory Medal from the Royal Society of Canada (2011), and the Nobel Prize in Physics (2015). He was named an Officer of the Order of Canada in 2007, and he is a member of the Order of Ontario, as well as the Royal Societies of both Canada and the UK.

John Reid is the Audit Leader for KPMG in the Greater Toronto area. During his 35-year career, he has assisted both private and public sector organizations through various stages of strategic planning,

business acquisitions, development, and growth management. His experience spans all business sectors and industries with a focus on mergers and acquisitions, technology, and health care. Mr. Reid has served on many hospital boards throughout Canada and has also been a director on many university and college boards.

Michael Serbinis is the founder and CEO of LEAGUE, a new digital health start-up. He is a leader known as a visionary entrepreneur who has built several transformative technology platforms across industries. Mr. Serbinis was the founder and CEO of Kobo, a digital reading company that burst onto the publishing scene in 2009, driving $110 million in sales in its very first year and becoming the only global competitor to Amazon's Kindle with 20 million customers in 190 countries. He is currently the founder of Three Angels Capital, a member of the Board of Trustees at the Ontario Science Centre, and a member of YPO. He holds a BSc in engineering physics from Queen's University and an MSc in industrial engineering from the University of Toronto.

Appendix F: Scientific Advisory Committee

Perimeter Institute's Scientific Advisory Committee (SAC) provides key support in achieving the Institute's strategic objectives, particularly in the area of recruitment.

Renate Loll, Radboud University (2010-Present), Chair
Professor Loll is a Professor of Theoretical Physics at the Institute for Mathematics, Astrophysics and Particle Physics of the Radboud University in Nijmegen, Netherlands. Her research centres on quantum gravity, the search for a consistent theory that describes the microscopic constituents of spacetime geometry and the quantum-dynamical laws governing their interaction. She has made major contributions to loop quantum gravity and, with her collaborators, has proposed a novel theory of quantum gravity via "Causal Dynamical Triangulations." Loll heads one of the largest research groups on non-perturbative quantum gravity worldwide and is the recipient of a prestigious personal VICI-grant of the Netherlands Organisation for Scientific Research.

Ganapathy Baskaran, Institute of Mathematical Sciences, Chennai (2013-Present)
Professor Baskaran is an Emeritus Professor at the Institute of Mathematical Sciences, Chennai in India, where he recently founded the Quantum Science Centre. He has made important contributions to the field of strongly correlated quantum matter. His primary research focus is novel emergent quantum phenomena in matter, including biological ones. He is well known for his contributions to the theory of high temperature superconductivity and for discovering emergent gauge fields in strongly correlated electron systems. He predicted p-wave superconductivity in Sr_2RuO_4, a system believed to support Majorana fermion mode, which is a popular qubit for topological quantum computation. In recent work, he predicted room temperature superconductivity in optimally doped graphene. From 1976 to 2006, Baskaran contributed substantially to the Abdus Salam International Centre for Theoretical Physics in Trieste, Italy. He is a past recipient of the S.S. Bhatnagar Award from the Indian Council of Scientific and Industrial Research (1990); the Alfred Kasler ICTP Prize (1983); Fellowships of the Indian Academy of Sciences (1988), the Indian National Science Academy (1991), and the Third World Academy of Sciences (2008); and the Distinguished Alumni Award of the Indian Institute of Science, Bangalore (2008).

Mark Wise, California Institute of Technology (2013-Present)
Professor Wise is the John A. McCone Professor of High Energy Physics at the California Institute of Technology. He has conducted research in elementary particle physics and cosmology, and shared the 2001 Sakurai Prize for Theoretical Particle Physics for the development of the "Heavy Quark Effective Theory" (HQET), a mathematical formalism that enables physicists to make predictions about otherwise intractable problems in the theory of the strong interactions of quarks. He has also published work on mathematical models for finance and risk assessment. Wise is a past Sloan Research Fellow, a Fellow of the American Physical Society, and a member of the American Academy of Arts and Sciences and of the National Academy of Sciences.

Appendix G: Perimeter's Research Ties to Experiment

Perimeter scientists are connected to many of the world's most important experimental efforts. The list that follows provides a representative sample of such involvement from Perimeter researchers.

- **Dmitry Abanin** works directly with several leading groups of graphene experimentalists, including those headed by Philip Kim and Amir Yacoby (the Harvard graphene groups)[42] and by Alberto Morpurgo (the Geneva graphene group).[43] He also works with an experimental group in Munich on questions related to cold atoms and many-body dynamics.
- **Asimina Arvanitaki** is part of the ARIADNE collaboration (Axion Resonant InterAction DetectioN Experiment),[44] which is looking for axion mediated interactions in matter. She has also proposed a number of experimental tests of fundamental physics using optically-levitated sensors, atomic clocks, and nuclear magnetic resonance.
- **Avery Broderick and Tim Johannsen** are members of the Event Horizon Telescope project,[45] which is working to directly observe the immediate environment of a black hole for the first time.
- **Raffi Budakian** works with the Institute for Quantum Computing on developing a new class of experimental tools for ultrasensitive detection of electron and nuclear spins.
- **David Cory** works with the Institute for Quantum Computing on the development of quantum sensors and actuators, which probe and control the subatomic world with incredible precision, and will likely form the building blocks of future quantum computers.
- **Eder Izaguirre** is part of the Fermi Large Area Telescope (LAT) experiment,[46] which looks for gamma rays. He is also involved in the Beam Dump eXperiment (BDX) at Jefferson Lab.[47]
- **Matthew Johnson** is a Perimeter cosmologist who analyzes data from experiments measuring the cosmic microwave background, or CMB.
- **Raymond Laflamme** is the director of the Institute for Quantum Computing, where, among several other efforts at the intersection of theory and experiment, he is developing blueprints for quantum information processors such as linear optics quantum computing. Laflamme is also a founder of Universal Quantum Devices (http://uqdevices.com), a start-up commercializing spinoffs of quantum information research.
- **Maxim Pospelov** is an associate member of the BaBar collaboration,[48] which studies the physics of b-quarks and other intermediate mass particles. He also directly collaborates with

[42] Refer to http://kim.physics.harvard.edu and http://yacoby.physics.harvard.edu.
[43] Refer to http://dpmc.unige.ch/gr_morpurgo.
[44] Refer to http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.113.161801.
[45] Refer to https://perimeterinstitute.ca/research/research-initiatives/event-horizon-telescope-eht-initiative and http://www.eventhorizontelescope.org.
[46] Refer to https://www-glast.stanford.edu.
[47] Refer to http://arxiv.org/abs/1406.3028.
[48] Refer to http://www.slac.stanford.edu/BFROOT.

experimental physicists at TRIUMF and Fermilab, and is part of the Global Network of Magnetometers for Exotic (GNOME) experiment.[49]

- **Philip Schuster and Natalia Toro** work jointly, and have extensive connections to experiment. They were the lead developers of the "Simplified Models" approach, which is now the standard way to handle data at the Large Hadron Collider at CERN, in Geneva, Switzerland. They also pioneered new experiments at smaller colliders, including three at the Jefferson Laboratories collider: the Beam Dump eXperiment (BDX), which searches for dark matter, and the A-Prime EXperiment (APEX) and Heavy Photon Search (HPS) experiments, which search for unknown forces.[50] They are spokespeople for APEX.
- **Kendrick Smith** is a member of several major experimental collaborations aimed at measuring the cosmic microwave background, or CMB. These include the landmark WMAP and Planck satellite experiments[51] and the ground-based CAPMAP and QUIET CMB experiments.[52] He is also involved in the HSC survey[53] (a new experiment to observe distant galaxies using the Subaru telescope), and is part of the Canadian Hydrogen Intensity Mapping Experiment (CHIME),[54] aiming to measure the radio sky using the first large Canadian research telescope in more than 50 years.
- **Robert Spekkens** works with experimentalists at the Institute for Quantum Computing to demonstrate the quantum advantage for inferring causal relations from correlations and to implement robust tests of the quantum phenomenon of contextuality.
- **Itay Yavin** is leading an effort for a new experiment at the Large Hadron Collider to look for new particles with a charge a thousand times smaller than that of the electron. Yavin is also a lead developer of RECAST, a framework which recasts data from the Large Hadron Collider in such a way as to allow for testing of alternative hypotheses and searches for new physics. RECAST is housed at Perimeter.[55]

Several Perimeter researchers are part of the Search for Hidden Particles (SHiP) project, an 85-member proposal aiming to launch a new fixed-target experiment at CERN. These include **Wolfgang Altmannshofer**, **Stefania Gori**, **Eder Izaguirre**, **Gordan Krnjaic**, **Maxim Pospelov**, and **Brian Shuve**.

Individual researchers are also involved in smaller experimental projects, such as **Juan Carrasquilla**,[56] co-author of a paper published in *Nature Physics* about distillation of a Bose-Einstein condensate, and **Daniel Brod**, who worked with an Italian quantum optics group to make and analyze a boson sampler, a potential precursor to quantum computing.

[49] Refer to http://arxiv.org/abs/1303.5524.
[50] For more information on these experiments, refer to http://arxiv.org/abs/1406.3028, http://arxiv.org/abs/1301.2581, and http://arxiv.org/abs/1310.2060.
[51] Refer to http://map.gsfc.nasa.gov and http://www.cosmos.esa.int/web/planck.
[52] Refer to http://cfcp.uchicago.edu/research/projects/capmap.html and http://quiet.uchicago.edu.
[53] Refer to http://subarutelescope.org/Projects/HSC/HSCProject.html.
[54] Refer to http://chime.phas.ubc.ca.
[55] For more on RECAST, refer to http://arxiv.org/abs/1010.2506 and http://recast.it.
[56] Refer to http://perimeterinstitute.ca/news/quantum-distillery.

Perimeter also connects to experiment through its conference program, with several conferences in 2014/15 revolving directly around experimental findings and challenges. These included:

- **"EHT 2014"**: The Event Horizon Telescope is the first astronomical instrument capable of imaging the horizon of a known black hole. Held in November 2014, this was the second in a conference series designed to bring together the full EHT community, from instrument builders to theoretical modellers, for the purpose of fully exploiting the unique opportunities that the EHT provides.[57]
- **"Convergence"**: Held in June 2015, Convergence brought together theorists and experimentalists to provide a "big picture" overview of fundamental physics and its future. Lectures and discussions included the latest research in condensed matter, exoplanets, gravitational wave detection, and more.[58]
- **"Preparing for the High-Luminosity Run of the LHC"**: This workshop, held in June 2015, brought together high energy particle experimentalists and theorists to brainstorm about the challenges and possibilities they would face with the planned high-luminosity run of the LHC. Among the topics covered were new detector technologies, new trigger strategies, contingency plans for each inverse attobarn, and confronting increased pile-up.[59]

[57] Refer to http://perimeterinstitute.ca/conferences/eht-2014.
[58] Refer to http://perimeterinstitute.ca/research/conferences/convergence.
[59] Refer to http://perimeterinstitute.ca/conferences/preparing-high-luminosity-run-lhc-0.

Appendix H: Media Highlights

In 2014/15, Perimeter Institute received coverage in both national and international media, including *The Globe and Mail*, *The New York Times*, *WIRED, Maclean's*, TVO, CBC, BBC News, *Nature*, and *Scientific American*, among others. Highlights are included below.

Outlet	Headline	Date	Summary
Scientific American	The Black Hole at the Beginning of Time	August 2014	The cover story for the August 2014 edition, this article discusses the work of Niayesh Afshordi, Robert Mann, and Razieh Pourhasan, which posits the Big Bang was preceded by a four-dimensional black hole, creating a three-dimensional event horizon that forms our current universe
CBC.ca **Syndicated by Yahoo! Canada & *Scientific American* Blog**	Schrödinger's cat explained on physicist's 127th birthday	August 12, 2014	Showcasing and explaining the Schrödinger's Cat video from *The Quantum Tamers*, timed for the August "Slice of PI" in conjunction with Schrödinger's birthday
National Geographic	Cosmic Dust Clouds Gravitational Wave Finding	September 22, 2014	News article about the Planck data that refuted BICEP2 gravitational waves findings; Neil Turok was interviewed and is quoted throughout
Science	Breakthrough lost in coin toss?	October 3, 2014	Feature-length news article about new research findings on the subject of weak values; one of the researchers on this project is PI's Josh Combes, who was interviewed for the article and is quoted throughout
WIRED	How Gravity Explains Why Time Never Runs Backward	November 5, 2014	Article about new research findings on the "arrow of time"; one of the researchers involved is PI's Flavio Mercati, who was interviewed for the article and is quoted throughout
WIRED	Scientists Search for Evidence of the Multiverse in the Big Bang's Afterglow	November 18, 2014	Article about the development of a test for the multiverse theory concept, featuring and quoting PI's Matthew Johnson; the online article also includes a video produced by PI on the subject of testing the multiverse theory
Maclean's	Foreign powers: Canada's most powerful non-Canadians	November 23, 2014	A list of the top five influential non-Canadians living and working in Canada; Neil Turok is on the list at number two
Canada.com **Also appeared in *The Windsor Star* and *The Province***	Looking for the keys to the next big thing in physics	December 3, 2014	Article about PI's Natalia Toro and Philip Schuster winning the New Horizons in Physics Prize at the Breakthrough Prize ceremony; their research is featured, each is quoted throughout, and there is a focus on PI being the proper environment for creating

			breakthroughs
Canada.com **Also appeared in *Edmonton Journal*, *The Province*, *Leader Post*, *Star Phoenix*, and *Windsor Star***	Let 2015 be the year of the light	January 18, 2015	Article announcing the UNESCO International Year of Light; the article is heavily built around Perimeter's January "Slice of PI" images
Motherboard	Cosmologists Discovered a New Kind of Crystal by Looking at Satellite Orbits	February 18, 2015	Article about new research conducted by PI's Kendrick Smith and Latham Boyle
The Globe and Mail	After two years lying dormant, the Large Hadron Collider again revs up	March 12, 2015	PI's Asimina Arvanitaki figures prominently in this feature article by Ivan Semeniuk about the restart of the LHC
CBC Online	How Canada's geek capital is marking Super Pi Day	March 13, 2015	PI's popular "Slice of PI" series featured a video celebrating pi (3.1415) to coincide with "Pi Day" on March 14, 2015 (3/14/15)
CBC National Radio *Quirks and Quarks* Broadcast	Quirks Question Road Show	June 6, 2015	Recorded on location at PI, the annual Q&A show covered a range of science topics, but included several PI references in promotion, broadcasts, and podcasts; PI Associate Faculty member Avery Broderick is interviewed
The New York Times	Black Hole Hunters	June 8, 2015	PI Associate Faculty member Avery Broderick is quoted in this article regarding the Event Horizon Telescope; the article is the outcome of media relations dating back to Perimeter's "EHT 2014" conference
The Globe and Mail	Perimeter Institute's formula for a calculated physics reboot	June 23, 2015	A feature on PI's unique positioning to reboot physics and drive breakthroughs in the field; the talent accumulated at PI is compared to the unique talents of Einstein and Noether, and the article also mentions the $4 million funding announcement made at "Convergence"
The Globe and Mail	Theoretical physics is a low-cost, high-yield investment	June 30, 2015	An op-ed by BMO CEO Bill Downe, created in conjunction with Perimeter, discussing why investing in theoretical physics is a good idea
New Scientist	Physicists launch fight to make data more important than theory	July 1, 2015	Feature article about the need for testable theories in physics – drawn heavily from "Convergence" and including numerous quotes from Neil Turok
Nature News	'Half-pipe' telescope will probe dark energy in teen Universe	July 29, 2015	Feature on the CHIME radio telescope, quoting PI's Kendrick Smith; the journalist learned about CHIME while covering "Convergence" at Perimeter

COSMOS	The universe that begins again	July 30, 2015	Feature on the search for gravitational waves, with a significant focus on the work of Neil Turok and PI-affiliated researcher Paul Steinhardt, including a number of quotes