PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

2012 ANNUAL REPORT

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.

CONTENTS

This report covers the activities and finances of Perimeter Institute for Theoretical Physics from August 1, 2011 to July 31, 2012.

BACKGROUND AND PURPOSE

Perimeter Institute for Theoretical Physics was founded in 1999, in Waterloo, Ontario, Canada. Its goal is to foster breakthroughs in our understanding of the universe at the most fundamental level. To this end, the Institute supports foundational theoretical physics research, training, and educational outreach.

Perimeter has grown into one of the world's leading centres of theoretical physics, home to over 150 researchers, ranging from master's students to eminent senior scientists. Perimeter houses the world's largest group of independent postdoctoral researchers in theoretical physics and receives well over 600 applications per year for approximately 10 postdoctoral fellowships. Over 1,000 researchers from around the world visit Perimeter annually, making the Institute a global hub for the interchange of ideas.

Why theoretical physics? Because time and again, its insights into the most basic properties of the universe have led to new technologies. From Newton to Maxwell to Einstein, basic physics has spawned the technologies upon which modern society is built – from plumbing to electricity, smartphones to satellites. Its ideas have repeatedly sparked innovation and led to the creation of entirely new industries. Today, theoretical physics continues to open new doors to the future – from quantum computers to new energy technologies. One breakthrough in theoretical physics can literally change the world.

Perimeter is not just about research. Brilliant young people are the lifeblood of science, which is why the Institute has developed innovative and highly sought-after graduate training programs, including Perimeter Scholars International. Sharing the excitement and wonder of science with the wider public is also vital to the emergence of new talent, and so Perimeter conducts award-winning outreach to students, teachers, and the general public.

MESSAGE FROM THE BOARD CHAIR

"Here, today's premier theoretical physicists are able to set their minds free, to learn, and to envision what is and what can be. To understand the nature of the universe and everything in between is no small undertaking. But those here at this institute are confronting these questions head-on."

– The Right Honourable David Johnston, Governor General of Canada

I founded Perimeter based on a simple insight: all of the scientific and technological progress that our civilization has made was founded on advances in basic physics. It makes sense when you think about it – deep understanding opens new doors. Just a handful of insightful theorists can have a huge impact. So bringing them together, and giving them the support to pursue their most ambitious ideas, seemed like an excellent investment in the future of Canada. Put simply, today's theoretical physics is tomorrow's technology.

The returns have been greater, and have come sooner, than I ever dreamed.

I didn't dare imagine that barely a decade after Perimeter's founding, Stephen Hawking would be stating publicly that he feels it may now be the best institute of its kind in the world. And yet that is just what's happened.

Year after year, we have seen the quality of Perimeter's research rise. This was vividly brought home to me when I saw the recent Thomson Reuters study showing that in 2010, Canada ranked first in citation impact in physics among G8 countries; without Perimeter, it would have ranked fourth. That's incredible.

Over the last year, we have seen several spectacular new hires. Perimeter now competes with leading institutions around the world for top talent – and wins. Hiring the brightest talent is the surest route to producing exceptional research.

The biggest story in science this year was the first glimpse of the Higgs boson, right about where theorists predicted it would be almost half a century ago. It was a great example of how theory drives discovery: without a conceptual framework for organizing the fundamental particles and the ability to make precise mathematical predictions, the Higgs discovery would have been impossible.

The Higgs discovery was big news about nature on the tiniest scales. Early in 2013, we will learn about the universe on the very largest scales, from the Planck satellite's first data release. Perimeter will be a leader in the theoretical interpretation of these data.

And on everyday scales, it is both gratifying and exciting to see how Perimeter has seeded an important community in quantum science – right here in Waterloo – that is now being called "Quantum Valley."

Many, myself included, believe that quantum computing, quantum detectors, and quantum information science hold game-changing technological potential. Waterloo has become a hub for this burgeoning field, covering the full spectrum from basic theory here at Perimeter to experiment and fabrication and computer science at the Institute for Quantum Computing at the University of Waterloo.

Perimeter's theorists are positioned to seed innovation on many fronts. For example, in order to realize quantum technologies, we need new materials. Here again, theory is a crucial driver. In recent years, Perimeter has made outstanding hires of theorists whose work may be the key to unlocking novel quantum materials and phases of matter.

I'm not the only one who's excited about Perimeter. From day one, the governments of Canada and Ontario have shown visionary and steadfast support for the Institute, knowing that it is creating new resources – of talent and knowledge – that will serve us all into the future.

I would like to thank Perimeter's Board of Directors for their dedication and leadership, and to welcome Art MacDonald, one of Canada's most eminent physicists and a founder of the SNOLAB facility. We are already benefitting from his expertise and wisdom.

Over the past year, I've been delighted with the enthusiasm for and commitment to Perimeter expressed by many leading figures in Canadian society. In particular, I would like to thank the Executive Committee of our Leadership Council: Kiki Delaney, Jon Dellandrea, Arlene Dickinson, Cosimo Fiorenza, Carol Lee, and Maureen Sabia. We are deeply grateful for your efforts to explain the importance of Perimeter and to widen our support base. It has been wonderfully gratifying to learn of generous gifts from several visionary Canadians. We welcome you all as you join with us in ensuring Perimeter's success.

Lastly, I would like to congratulate Neil Turok and Perimeter's wonderful team. The progress of the past year has been thrilling. Every day, Perimeter reminds me that if you're going to dream, you should dream as big as the universe.

– Mike Lazaridis

MESSAGE FROM THE INSTITUTE DIRECTOR

This year, physics took a rare turn on centre stage, as the news that the Higgs boson had been detected by experiments at the Large Hadron Collider at CERN in Switzerland made headlines around the world. I was at CERN just after the great event, and it was wonderful to see how many young physicists were involved and to experience the buzz of their success.

Finding the Higgs was the culmination of decades of work to verify a theory developed all the way back in 1964. Think about that for a moment: nearly five decades ago, a few individuals – using basic physics principles like relativity and quantum theory – were able to 'see' deeply into the structure of matter, at the mind-bogglingly remote scale of a billionth the size of an atom! The greatest experiment of all time, and the work of thousands of physicists from nearly 100 countries, was driven by those initial theoretical glimpses of reality.

Perimeter is a strategic attempt to advance the same kind of fundamental insights that Higgs and his colleagues had, in the belief that there will be similar implications for the experiments and technologies of the future. We too are looking deeply into the very nature of the universe.

It's amazing, really, how far science can sometimes see. I recently had the pleasure of giving this year's CBC Massey Lectures, a series of five talks presented to live audiences across Canada, broadcast on national radio, and published as a book. In researching and writing the lectures, I came across example after example of our amazing human capability to anticipate and understand how the universe works – from Democritus in ancient Greece hypothesizing that atoms existed 2,000 years before the proof came in, to Galileo realizing that mathematics governed the solar system, to Maxwell's discoveries about the nature of electromagnetism and light, which led to radio, television, and the whole of today's wireless world.

This is not to say that Democritus discovered nuclear power, or that Galileo foresaw the space probe that bears his name, or that Maxwell carried a BlackBerry. The practical applications of discoveries in theoretical physics are rarely obvious at first. But when they inevitably come, they are far-reaching.

Perimeter was founded on that principle – that one deep insight, one breakthrough in physics can change the world. Our mission is to make those breakthroughs. We cannot predict what they will be or how long they will take. But we can optimize our chances by attracting exceptional talents, providing an inspirational environment and a culture that strongly encourages its scientists to aim high and pursue their most ambitious and creative approaches to fundamental scientific questions.

Our success is crucially dependent on the quality of our researchers, of course, and we have several notable new recruits this year. Xiao-Gang Wen, who became the BMO Financial Group Isaac Newton Chair in Theoretical Physics, is a world-renowned scientist whose landmark discovery of topological order holds great promise for discovering novel states of matter and quantum materials, which may become the basis of future quantum devices. He has given great impetus to our research efforts in condensed matter, which has emerged as a major focus of research here at Perimeter and one that is synergistic with ongoing work at our nearby experimental partner institute, the Institute for Quantum Computing at the University of Waterloo.

Davide Gaiotto, who has already made major discoveries in quantum field theory, became the inaugural Galileo Chair. In addition, we were joined by Bianca Dittrich, a young leader in quantum gravity, and Avery Broderick, who has done pioneering work to produce the world's first images of black holes. Next year, several more outstanding recruits will arrive, including Dmitry Abanin and Roger Melko in condensed matter and Matthew Johnson and Kendrick Smith in cosmology.

We are seeding the ground for the future in other ways too. This year, our award-winning outreach programs have captivated more and more students, teachers, and members of the general public than ever – indeed, this year our outreach program reached its *millionth* student! The *MinutePhysics* YouTube channel, produced at Perimeter by PSI alum Henry Reich, reached over one million subscribers. Our PSI master's program has also started to bear fruit: of our 96 graduates to date, a full third have remained in Ontario for their PhDs.

In the last four years, Perimeter has nearly doubled in size to become one of the largest theoretical physics institutes in the world. Yet through all of its growth, Perimeter has retained its remarkable spirit – of intensity, ambition, and fun. As a community, we believe that physics is a means not only to understand the world, but to see deeply into the heart of nature, and in so doing, to open new doors to the future.

– Neil Turok

RESEARCH

DRIVING EXCELLENCE

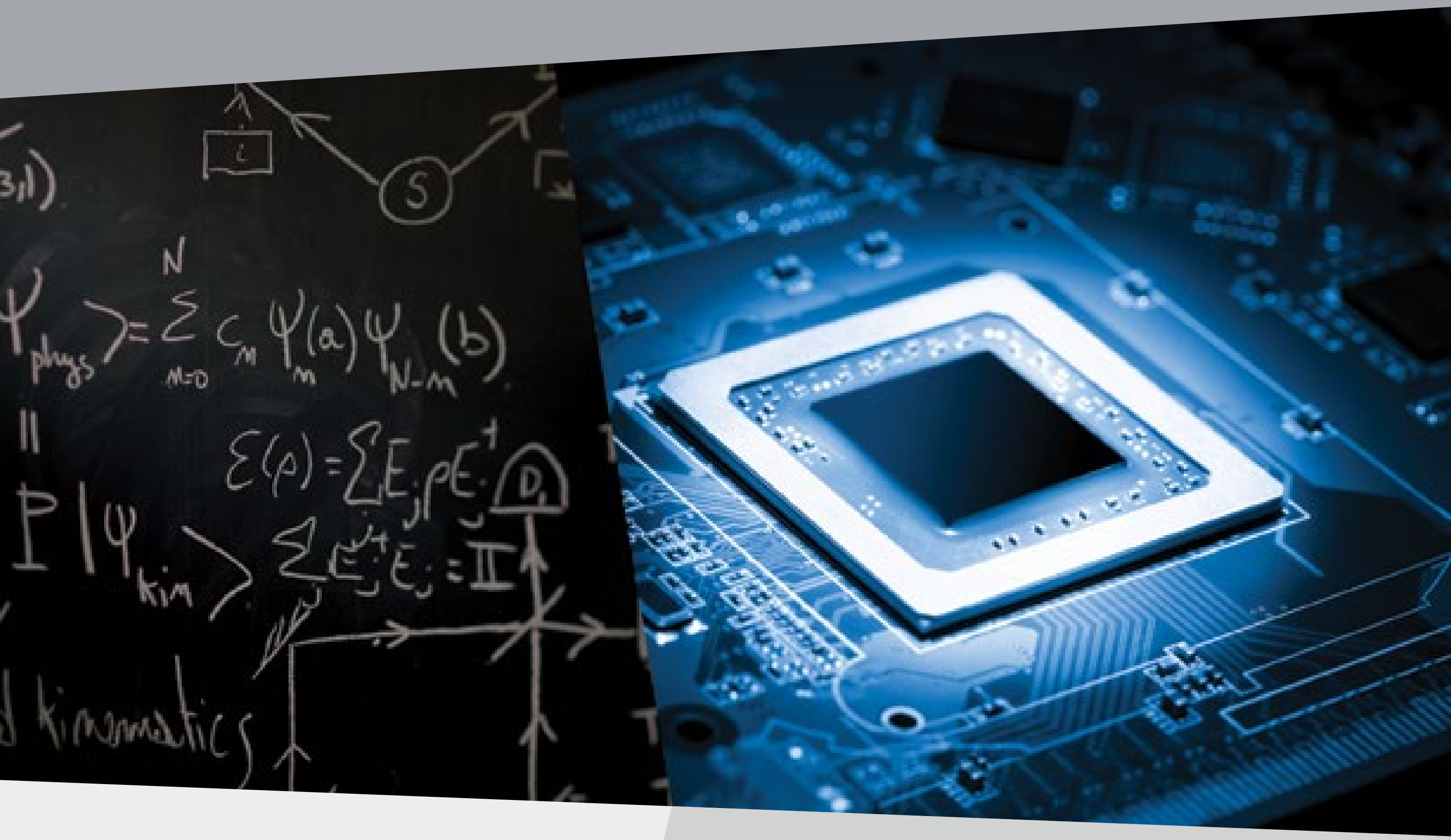
A recent study by Thomson Reuters showed that in 2010 Canada ranked first in physics citation impact among G8 countries; without Perimeter, Canada would have ranked fourth.

Perimeter's mission is to make the research breakthroughs that will transform our future.

Our strategy is to bring the world's most brilliant scientific minds together under one roof, to collaborate outside the strictures of traditional academic departments. We encourage our researchers to tackle the most difficult, pressing problems they can find, using all available insights and tools.

Our nine research fields have been chosen strategically. We investigate everything from the subatomic (and smaller) scales of particle physics and string theory, to the table-top scales of condensed matter systems, to the cosmological scales that seek to describe the whole of space and time. We are interested in intersections: the way condensed matter informs cosmology; the way particle theory informs mathematics and vice versa; the way abstruse questions about the nature of quantum mechanics lead to practical advances in quantum computation. We value work at the intersection of theory and experiment. We believe, in short, that our whole is greater than the sum of our parts.

Perimeter's choice of complementary disciplines is unique, and our emphasis on ambitious, unconstrained scientific inquiry has created a vibrant and growing research community. The following pages outline some of that community's high points from 2011/12.



PI BY THE NUMBERS

As of July 31, 2012, Perimeter's research community included …

18 full-time Faculty

12 Associate Faculty

24 Distinguished Visiting Research Chairs

38 Postdoctoral Researchers

72 Graduate students

THEORY BECOMES INNOVATION

Each scientific breakthrough is like a lens that makes our vision sharper, allowing us to see further, to envision new solutions to old problems.

Take the transistor. In the early 20th century, the Bell telephone company struggled for decades with vacuum tubes. They depended on them for controlling current in their telephone and telegraph systems, but they were hot, noisy, costly to manufacture, and fragile.

After World War II, Bell Labs assembled a team of researchers to tackle the problem from first principles. With the new lens of quantum theory as their guide, scientists realized why certain materials conduct electricity efficiently and some don't. The Bell Labs team came to realize that puzzling materials called semiconductors could be used to exquisitely control electrical current, the key to building the transistor. The inventors – William Brattain, John Bardeen, and William Shockley – won a Nobel Prize for their work.

Quantum theory had helped spawn the fundamental unit – the nerve cell – of all electronics. The transistor in turn gave us Silicon Valley and the Information Age. If you have a phone in your pocket or a computer nearby, there are billions of transistors currently within your reach. And the transistor is just one part of the story of how the quantum revolution has transformed the world. Lasers, MRIs, digital cameras, solar cells, and smoke detectors are among the many spin-offs of the first quantum revolution.

Today, the field of quantum information may transform the world again with novel technologies based on quantum properties like superposition and entanglement.

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 are those who study these many-body systems, especially those that are in a condensed state. At Perimeter, these 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.

PROVING THE HOLOGRAM

At Perimeter and places like it, the phrase 'AdS/CFT' – short for anti de Sitter space/conformal field theory – comes up a lot. The AdS/CFT correspondence is a conjecture which states that two apparently distinct theories are actually equivalent. Specifically, it relates a D-dimensional (say, four-dimensional) quantum field theory to a D+1-dimensional (say, five-dimensional) theory of quantum gravity. That makes AdS/CFT a kind of holographic theory – that is, a theory that adds or subtracts a single dimension, so called because of the way holograms encode three-dimensional images on a flat (two-dimensional) surface.

The AdS/CFT correspondence sounds technical, and it is. But in the last 10 years, it has become an important tool in many fields of physics. It is central to modern superstring theory and it has opened new lines of research into quantum gravity and quantum field theories, especially the strongly coupled field theories that tell us how quarks and gluons interact. In that context, it is widely used in heavy ion physics, condensed matter physics, and beyond.

But is it true?

The many successes of AdS/CFT as a tool are only circumstantial evidence. Ideally, one would want to derive the correspondence from first principles. Moreover, because the idea originally came from string theory, the mathematical tools haven't proved general enough to help with quantum field theories that are, for one reason or another, difficult to embed in string theories.

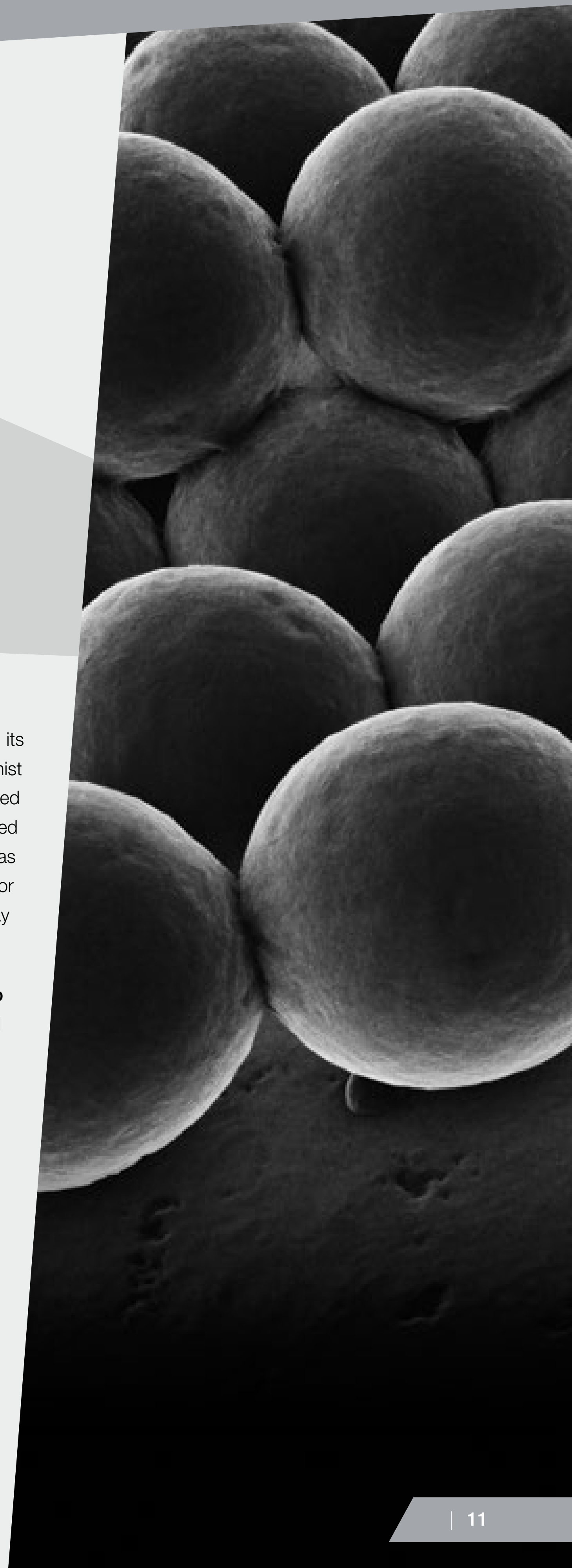
This year, **Perimeter Associate Faculty member Sung-Sik Lee** took the first step in both proving AdS/CFT and extending its reach. Specifically, he came up with a prescription that allows us to construct a holographic duality for a general quantum field theory from first principles. Lee's work may open the way to study a wider class of quantum field theories using holographic techniques.

REDUCTIONISM VS. EMERGENCE

In physics, you can build your understanding from the top down or the bottom up. The bottom-up approach is known as reductionism: the idea that if you know enough about the properties of the smallest pieces of a system and the rules that govern them, you can predict the behaviour of the system as a whole. The top-down view is known as emergence. It stresses that the collective behaviour of a system can be very different from the behaviour of the individual components.

Emergence and reductionism are clearly different paths, but they are not usually directly in conflict. The exception is the notion of 'strong emergence,' which says that in certain cases it might not be possible to predict the behaviour of a system from knowledge of its parts – that is, there might be no path from bottom to top and the reductionist approach would inevitably fail. This would explain why physicists have struggled for decades to build effective theories of condensed matter phenomena based on first principles. In particular, the exotic form of quantum matter known as topologically ordered matter has been resistant to description via natural or realistic Hamiltonians. (A Hamiltonian is a mathematical description of the way a physical system changes.) Might topological order be strongly emergent?

Well, no. This year, **Perimeter Postdoctoral Researcher Lukasz Cincio** and **Perimeter Faculty member Guifre Vidal** were able to solve a model of a system with emergent topological order, starting – at the bottom, as it were – with only the microscopic description of the parts. Specifically, they were able to start with a realistic Hamiltonian and show not only that the system it describes is topologically ordered, but also numerically extract a thorough characterization of that order. The researchers' approach is valid for other Hamiltonians as well – meaning that what they have developed is a general method to compute the properties of emergent topological order starting from microscopic descriptions only. They have, in short, mapped a path from the bottom to the top.



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COSMOLOGY

Cosmologists at Perimeter Institute are working to pin down the constituents and history of our universe and the rules governing its origin and evolution. They look for solutions to some of physics' most enduring problems at length scales and energies that could never be matched in an earth-bound lab. Cosmology also connects deeply with other areas of research at Perimeter Institute, including particle physics, quantum gravity, quantum fields and strings, and strong gravity.

BETWEEN THE LAST CRUNCH AND THE FIRST BANG

What happened before the big bang? It depends on whom you ask.

The common idea is that the big bang singularity was the beginning of space and time – nothing happened *before* the big bang because time itself did not exist until the big bang. However, to explain the structure of the universe we actually observe, this model relies on inflation – that is, a brief period of hyper-expansion in the universe's first trillionth of a trillionth of a trillionth of a second, during which the large-scale structure of the universe was set. Inflation comes with a set of problems – enough problems to prompt the development of alternative ideas.

One alternative idea, developed by **Perimeter Distinguished Visiting Research Chair Paul J. Steinhardt** and **Perimeter Director Neil Turok**, is called cyclical cosmology. In the cyclic model, the big bang is actually a bounce: a transition from an earlier contracting universe to the present expanding one. There have been bang-crunch-bang-crunch models before, but in this model, the cycles are interlinked. In fact, in this model, the large-scale structure of our universe was set during a phase of slow contraction before the big bang – in the previous version of the universe, as it were.

The biggest open questions in the cyclic model are about the bounce itself – the transition from crunch to bang. This year, Turok and collaborators developed a new possibility for how this bounce might have happened. Before this, research had considered two possibilities: that the contracting universe (or, technically, its cosmic scale factor) might shrink to zero during the big crunch and then expand into the big bang, or that it might shrink to some small but non-zero size. The new model involves an antigravity phase between the big crunch and the big bang. This antigravity phase would help explain the origin of the expansion in the big bang.

The result may be useful for the construction of complete bouncing cosmologies like the cyclic model.

LOOKING FOR LITHIUM

The oldest stars don't contain as much lithium as they should.

It's called the lithium shortfall and it's a major hole in an otherwise highly successful model of big bang nucleosynthesis, which predicts what kinds of atoms should have been forged in the universe's first 17 minutes. The ratios of hydrogen to helium and hydrogen to deuterium match the theory perfectly, but lithium is a different story. When astronomers measure the fraction of lithium held in the oldest observable stars, they find only one-third as much of the lithium-7 isotope as our best understanding of big bang nucleosynthesis theory would lead us to expect. This has led to a large volume of work studying how lithium might be suppressed during nucleosynthesis or destroyed in stars.

Taking a different approach, **Perimeter Associate Faculty members Maxim Pospelov** and **Niayesh Afshordi** suggest that perhaps the lithium was never in the stars in the first place. More particularly, they have investigated a mechanism that can deplete lithium in spatial locations where stars are being formed.

Charge, say the Perimeter researchers, might be the key. Consider hydrogen recombination, the moment where the expanding plasma of the early universe cooled to the point that the formation of neutral hydrogen was energetically favoured. Lithium ions would have already existed at that moment, but because lithium recombines at a lower temperature than hydrogen, the universe still had some cooling to do before those Li+ ions could go looking for electrons to make them neutral. At that point, there were far fewer free electrons around, so a large fraction of the lithium would have stayed electrically charged.

In their new work, Pospelov and Afshordi show that the charged lithium would stay coupled to the fraction of hydrogen that was charged – and note that this H+ is known to have diffused against the flow of gravity. The Li+, therefore, would have tended to flow 'up' out of the gravity wells in which stars were forming. The effect is small on average, but could be large in some key areas. It's possible that when we measure the elements captured in early stars, we are indirectly measuring this effect.

In other words, when we look for primordial lithium in stars, we might be looking in the wrong place.

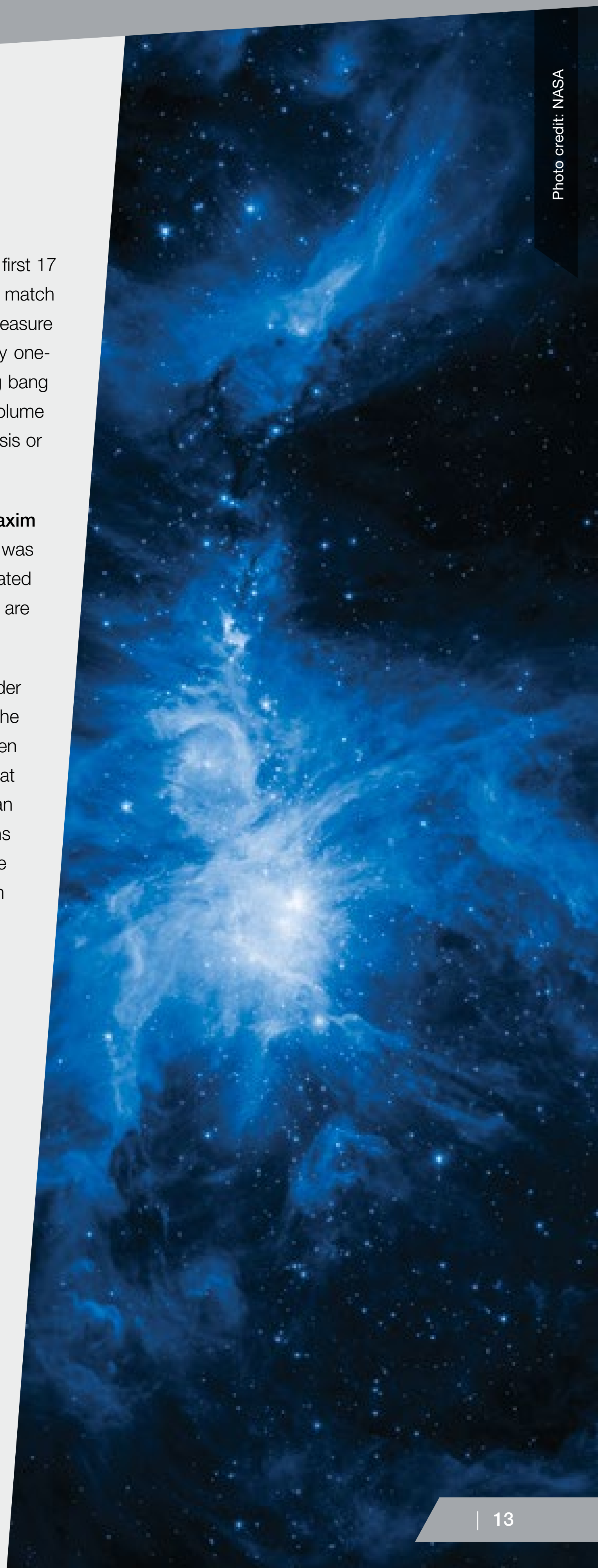
Photo credit: NASA

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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.

UNTWISTING GRAVITONS

Twistor space: it was introduced by physics giant Roger Penrose in the 1960s. He hoped it would be a new arena for the description of physical theories. Specifically, he hoped to reformulate the theory of gravity as described in Einstein's general relativity, using twistor space to replace our familiar spacetime. He knew that spacetime *needed* to be replaced, after all: in areas where it is curved too steeply, such as at the core of a black hole or at the big bang, it fails miserably.

But twistor space did not quite succeed, at least when it came to gravity. It turned out to be a very useful space in which to study theories that are conformally invariant – loosely speaking, that means physics that don't depend on scale – and twistor space is now widely used in particle physics and mathematics. But it made no significant dent in the problems of Einstein's gravity. One clear disadvantage is that gravity, as it happens, is not conformally invariant.

This year, **Perimeter Faculty member Freddy Cachazo** and **Senior Postdoctoral Researcher David Skinner** found a way to use the problem with Einstein's gravity in twistor space to their advantage.

Consider gravitons. A graviton is a hypothetical particle that carries the force of gravity, in the same way photons carry the electromagnetic force. In Einstein's gravity, every graviton carries a great deal of information and has both conformal and non-conformal parts. This dense tangle of information means that the (analytic) calculation of scattering amplitudes for a seemingly simple process – two gravitons scattering off each other producing many more – has always been intractable. Cachazo and Skinner's idea was to do that calculation in twistor space. The space's preference for conformal elements shows explicitly where gravity breaks conformal symmetry.

In other words, formulating gravity in twistor space mathematically unbraids the calculation, separating it into conformal and non-conformal parts. This new way of organizing the mathematics made it possible for Cachazo and Skinner to write down a compact analytic formula for graviton-graviton scattering for the first time.

This formulation for graviton-graviton scattering is analogous to the Witten formulation for gluon-gluon scattering. Like gravitons and photons, gluons are force carriers – specifically, they mediate the strong force, which holds protons and similar particles together. When it was discovered in 2003, the gluon-scattering formulation revealed many previously hidden properties of gluons and hence taught us more about the strong force. The Cachazo-Skinner graviton-scattering formulation, similarly, may reveal properties of gravity that have been hidden since Einstein first published the theory of general relativity a hundred years ago.

UNFLATTENING QUANTUM GRAVITY

It's one of the most basic and pressing questions in modern physics: what is the fundamental nature of spacetime? Quantum mechanics suggests that at some level space could be granular – that is, made of discrete pieces that cannot be broken apart. Field theory, meanwhile, teaches us that at some level space should fluctuate randomly. Can one put these two ideas together into a coherent framework describing randomly fluctuating discrete spaces? To do so would be a major step toward the Holy Grail of today's physics: unifying quantum field theory and general relativity into a theory of quantum gravity.

About 40 years ago, researchers began to make progress on a simplified version of quantum gravity which imagines space to be just two-dimensional. In the intervening decades, a highly successful theory of random two-dimensional surfaces has been extensively developed. Since the 1990s, many attempts have been made to build on the success of the theory of two-dimensional random spaces by constructing an analogous theory of random three-dimensional spaces. All proved fruitless – until **Perimeter Senior Postdoctoral Fellow Razvan Gurau** made a breakthrough.

Beginning in 2010, Gurau published a series of papers which showed how the two-dimensional models could be generalized to produce models with three dimensions or more. Specifically, Gurau used coloured tensor models – a formalism that's been extensively developed here at Perimeter – to create a so called '1/N expansion' of the 2D models. In other words, he showed how the two-dimensional models could be generalized to produce models with three dimensions or more.

This work quickly attracted the attention of other researchers in quantum gravity, both at Perimeter and at other leading centres around the world. The last year and a half has seen remarkable and rapid developments in quantum gravity, much of it seeded by Gurau's work.

For instance, **Perimeter Postdoctoral Researcher Joseph Ben Geloun** has introduced a new class of tensor field models, which are renormalizable at all orders of perturbation theory. (Roughly, that means the models don't return infinite results when calculating physical quantities, no matter what level of accuracy the calculations are done to.) The new models have great relevance to both quantum gravity and more general quantum field theory, and may even be the right setting to produce a three- or four-dimensional theory of quantum gravity – unflattening gravity at last.

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PARTICLE PHYSICS

Particle physics is the science which identifies 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.

THE MANY INTERSECTIONS OF THEORY AND EXPERIMENT

Particle physics made global headlines this year when the Higgs boson was discovered at last. It seemed like an overnight triumph, but in fact it was nearly 50 years in the making: theoretical physicists first proposed the Higgs mechanism in 1964. Nor does the discovery of the particle mean the work is over. Finding the Higgs does not simply mean an old theory was proven right. It means new theories can be tested more sharply than ever. In fact, an early stop on the road to such new physics came in August, when physicists from around the world gathered at Perimeter to discuss questions raised by the newly discovered Higgs.

The discovery of the Higgs boson in many ways illustrates the way researchers at Perimeter often work at the intersection of theory and experiment. New ideas from theorists can motivate new experiments – or guide existing ones. For example, **Perimeter Faculty member Freddy Cachazo** pioneered new techniques for calculating scattering amplitudes, which are the basic calculations required to analyze what happens when two particles collide. The Cachazo-Svrcek-Witten expansion, the Britto-Cachazo-Feng recursion relations, and the Britto-Cachazo-Feng-Witten construction have already been incorporated into powerful software, such as BlackHat, to generate scattering amplitudes for the analysis of experimental data at the Large Hadron Collider, helping to drive the search for the Higgs.

Theorists can also extend the reach of experiments. For instance, this year, **Perimeter PhD student Andrzej Banburski** and **Faculty member Philip Schuster** discovered that a new generation of particle physics experiments designed to search for new forces will also be able to look for an exotic kind of atom: true muonium.

True muonium is a bound state of a muon and an anti-muon. (A muon is a subatomic particle rather like a heavy electron.) It's considered an atom: the muon stands in for the electron and the anti-muon stands in for the proton in the atomic nucleus. True muonium has long been theorized to exist and its cousin muonium – the bound state of an electron and an anti-muon – was discovered in 1960. True muonium, though, has never been detected. If it could be found, and its properties measured, it could provide new insights into the so-called g-2 anomaly, a long-standing and puzzling difference between the properties the Standard Model predicts the muon should have and the properties of the muon as measured by experiments. True muonium would also be a window into bound-state physics more generally.

Theorists often re-examine existing results. After all, particle physics experiments tend to be big, long-running, and expensive. Often, they're designed to find one kind of particle or test one particular theory, but are capable of finding and testing many. A new effort called RECAST aims to define exactly which alternative models existing experiments can test and what the alternate signal might look like in the existing data. The effort is spearheaded by **Perimeter Associate Faculty member Itay**

Yavin and implemented and hosted by Perimeter's scientific computing team.

RECAST is not itself an experiment, or even a re-analysis of existing data from an experiment, but rather a framework to collect and standardize analysis requests to experimental collaborations from the broader research community. It does not have or require access to the data itself. Rather, it recasts the results of existing analysis into the context of a new theory, by comparing the existing analysis to the expected signal generated by the new particles or particle spectra.

Like Perimeter itself, RECAST strives to serve as a meeting place and a common language connecting theorists interested in alternative signals with the experimental collaborations responsible for relevant searches.

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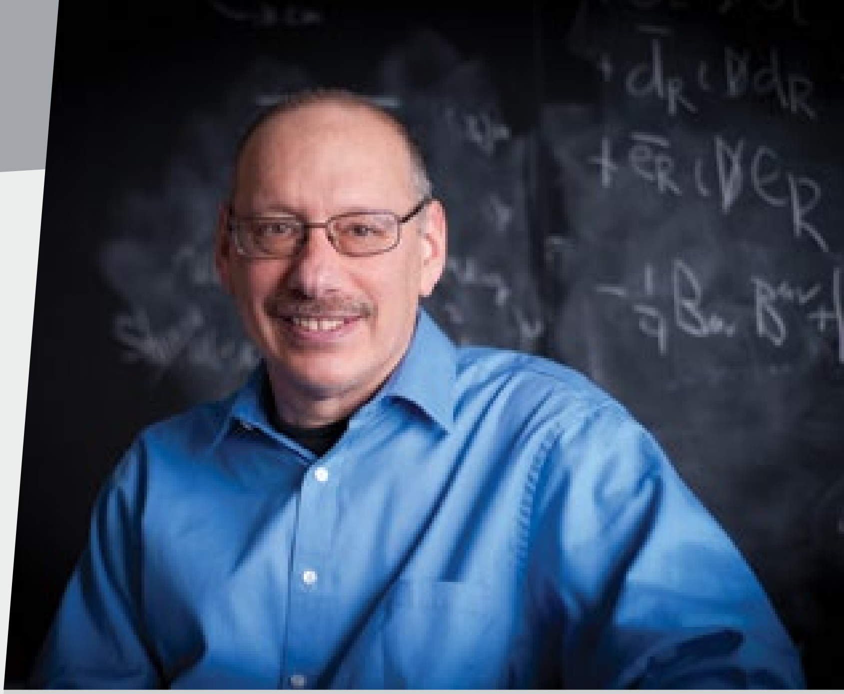

PROFILE: MARK WISE

I'm a pretty unlikely physicist. You could say I grew up on the mean streets of Toronto, except in those days Toronto had no mean streets. And I was an abysmal student. I failed grade 9 math. But at a certain point, I decided I had to be good at something, and as it clearly wasn't going to be sports or fixing things or anything that required me to charm other humans, I thought I'd try science.

Lo and behold, I was good at it. I picked physics because it was just interesting enough – something I was good at, but that still challenged me. And it's kept me busy all these years. Right now, I'm working on some cosmology related to the early universe. I'm interested in things that happen at quite high temperatures, when matter is not made of atoms, but the constituents of the atoms – protons and electrons, and even smaller, quarks and gluons. Understanding what happens at that temperature might explain why we have a universe made up of matter and not antimatter, which is quite puzzling when you stop to think about it.

My work is driven by the idea that there are missing parts to the laws of nature and I'd like to understand those missing links. That isn't the sort of thing you can easily work on all the time because it's a big question. So smaller questions drive my day-to-day research, but it would be nice, before I ride off into the sunset, to know what those missing pieces are.

I've been involved with Perimeter since its early days. It's very strange to walk in and see what it's become – what an unlikely success story! The whole trick, I think, is the quality of the researchers PI hires. These are the kind of people who are going to answer my missing parts questions, if anybody can.

Perimeter continues to amaze me.

– Mark Wise

Mark Wise, a professor of theoretical physics at Caltech and a pioneer in the development of heavy quark effective theory, joined Perimeter as a Distinguished Visiting Research Chair (DVRC) in 2009. He recently renewed his DVRC appointment and continues to visit Perimeter several times a year.

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 to produce 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 strong connections to quantum gravity, particle physics, and cosmology, as well as mathematics.

CHANGING THE FIELD (THEORY)

Quantum field theory is one of the most successful and flexible tools that physicists have ever developed. Particle physicists use a quantum field theory called the Standard Model to precisely describe the behaviour of all known particles. Electronic engineers use a different quantum field theory to describe and design today's electronic devices. Condensed matter physicists use quantum field theories to describe superconductors and other exotic materials. These various and very successful quantum field theories have one thing in common: they are weakly coupled.

In quantum field theory, the coupling constant is a number that determines the strength of a given force. If this constant is quite a bit less than one, the theory is said to be weakly coupled. This is the case for the electromagnetic, weak, and gravitational forces. If the constant is on the order of one or larger, the theory is strongly coupled, which is the case for the strong force – the force that binds quarks together. We understand weakly coupled quantum field theories fairly well – but strongly coupled quantum field theories have never been well understood.

Perimeter Faculty member Davide Gaiotto is working to change that. Some years ago, he developed a framework to define an enormous class of four-dimensional quantum field theories with eight supercharges, now known as the class S. Systematizing existing knowledge of field theories in this way generated a flood of new insights – but the impact of Gaiotto's framework doesn't stop there. The class S not only includes all of the standard N=2 field theories, but many more previously unknown theories, many of which are strongly coupled. This opened new avenues to study strongly coupled field theories.

Gaiotto is currently pursuing a framework analogous to the class S framework for three-dimensional field theories. There are surprising connections to deep mathematics, including knot theory, three-manifold invariants, and cluster algebra. The physics payoff is the possibility of mapping out a large class for three-dimensional conformal field theories and computing the systemically protected properties.

This progress in our theoretical understanding of strongly coupled field theories has broad potential. It could lead to deep mathematical advances, help us tailor exotic quantum systems to practical applications, and even advance our understanding of the fundamental laws of the universe.

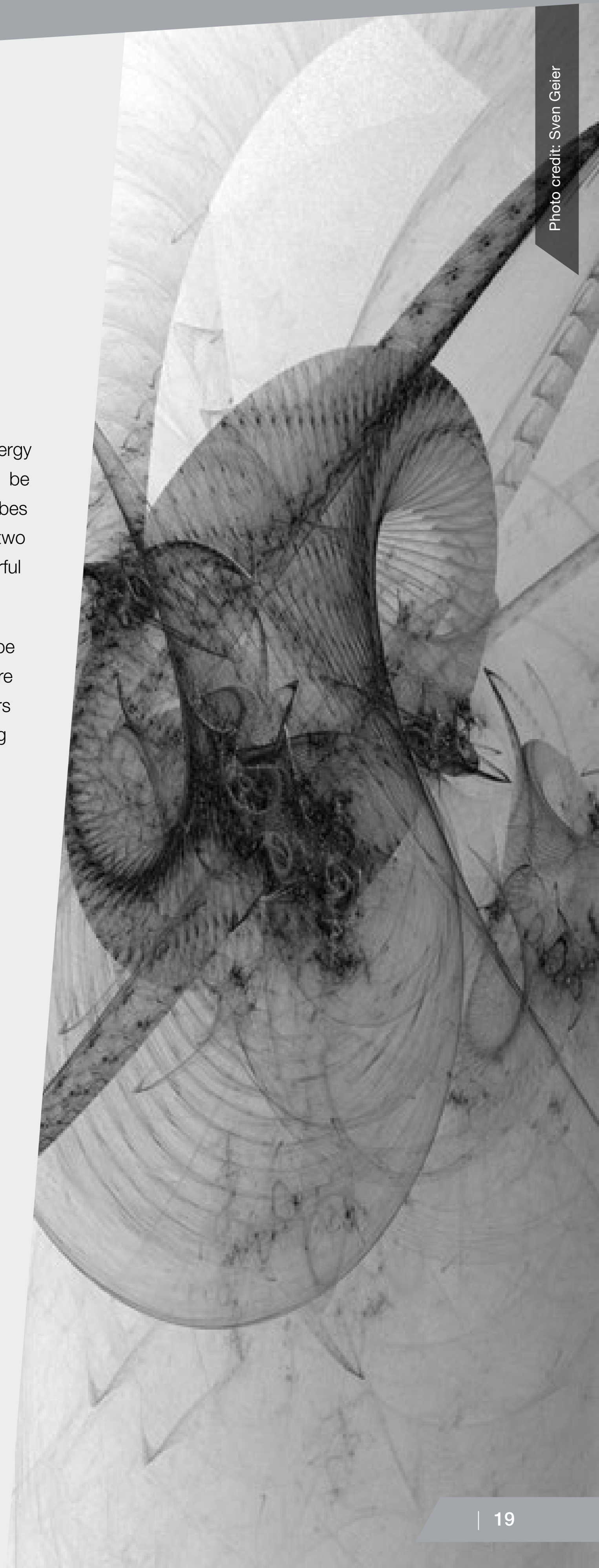
Photo credit: Sven Geier

TAILORING THE STRINGS

In string theory, the fundamental particles are small vibrating loops of energy known, appropriately, as strings. The behaviour of such strings can be described by two main processes. The first is propagation, which describes how the strings move in space and time. It's by far the simpler of the two processes and it can already be efficiently computed using powerful techniques such as integrability.

In addition to describing how strings propagate, we need to describe how they interact. This second process, interaction, is much more difficult to describe than propagation. This year, Perimeter researchers and collaborators took important first steps toward understanding string interactions.

The advance was made by **Perimeter Faculty member Pedro Vieira, Senior Postdoctoral Researcher Amit Sever, PhD student Jorge Escobedo**, and their collaborators. Using techniques of holography and integrability, the researchers described string interactions in terms of a process they call 'tailoring,' because it brings to mind cutting strings apart lengthwise and sewing the long edges back together.

In a series of follow-up papers, these authors and others have continued to develop this line of research, streamlining techniques and expanding the scope of the research to account for more quantum effects. Discoveries like this may well bring a full description of string dynamics into reach for the first time.

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QUANTUM FOUNDATIONS

The study of quantum foundations concerns the conceptual and mathematical underpinnings of quantum theory. Research into quantum foundations at Perimeter Institute is particularly concerned with reconstructing quantum theory from more natural postulates and reformulating the theory in ways that elucidate its conceptual structure. This work naturally interfaces with research in quantum information and quantum gravity.

DOES SPACE HAVE TO BE THREE-DIMENSIONAL?

In a quantum world, systems don't get simpler than this: a qubit – or quantum bit – is a quantum system with just two states. While a classical bit is like an arrow that will always point either straight up or straight down, the quantum superposition of a qubit's up and down states allows for a full 360 degrees of sideways – the point of the 'arrow' of a qubit traces the surface of a sphere.

So a qubit can be viewed as three-dimensional, like space itself. That's long been known. In fact, the idea that the quantum bit state space and physical space might somehow be logically intertwined has become a widespread paradigm. But what is the exact relationship? Which one of the two determines the other? Could a similar relationship also exist if space were four-dimensional or two-dimensional?

Actually, says **Perimeter Postdoctoral Researcher Markus Mueller**, there is something special about d=3.

Mueller and his collaborator imagined a pair of people trying to use a probabilistic physical system of some kind (such as the spin of a particle) to send a signal about spatial direction (up, for example). They didn't specify how many dimensions the space that the signalers were living in should have or which rules should govern the outcome probabilities of the physical system the signalers were using. But when they checked various sets of probability rules and various numbers of dimensions against a set of postulates describing what is possible and what is impossible, they found that only the combination of quantum theory and three-dimensional space results in our usual notion of what's possible. In other words, a certain natural interplay between geometry and probability is only possible if space has three dimensions and if outcome probabilities of measurements are exactly as predicted by quantum theory.

This result suggests that researchers should explore the idea that neither quantum theory nor spacetime are separately fundamental, but that both might have a common origin in information.

FINE-TUNING BELL'S THEOREM

Figuring out causal structure – what causes what – can be difficult when things get quantum. For instance, there's quantum entanglement: according to certain interpretations of quantum theory, when two particles are entangled, measurements performed on one of them can instantaneously affect the other. But how can this be?

This year, **Perimeter Faculty member Robert Spekkens** and former **PSI student Christopher Wood** (now a PhD student at Perimeter and the Institute for Quantum Computing) investigated algorithms for deducing causal structure that were developed by machine learning researchers. Their goal was to see what the algorithms might tell us about the possibility of a causal explanation of quantum correlations.

Take the correlated outcomes of measurements on entangled particles mentioned above. Such correlations have been extensively probed via Bell's theorem. Traditionally, Bell's result is summarized as a dilemma between giving up realism and giving up locality. (Broadly, realism is the notion that the fundamental concepts of a physical theory ought to refer to microscopic systems and their states, rather than anthropocentric concepts such as observers and measurements. Locality, meanwhile, is the idea that an object is influenced directly only by its immediate surroundings.) Informed by causal discovery algorithms, the Perimeter researchers set locality not against realism – a fuzzy notion, after all – but Reichenbach's principle, which is the assumption that every correlation must be explained either by direct causation or by a common cause.

Previous work along these lines had preferred to resolve the dilemma by giving up Reichenbach's principle. The Perimeter researchers kept it, arguing that it is central to the scientific worldview. They also argued that the assumption of locality can be replaced with a 'no fine-tuning' principle: an assumption that nature does not carefully fiddle with the controls to enforce an artificial statistical independence between two variables when, in fact, they are causally related.

Reframing Bell's theorem in this way is valuable because it gives a new perspective on its implications. For instance, it shows that neither models with superluminal causation nor models with retrocausation (causes acting backward in time) can resolve this version of the dilemma – they still require fine-tuning.

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ASSOCIATE FACULTY

(cross-appointed with other institutions)

Niayesh Afshordi
(University of Waterloo)

Avery Broderick
(University of Waterloo)

Alex Buchel
(Western University)

Cliff Burgess
(McMaster University)

David Cory
(Institute for Quantum Computing/
University of Waterloo)

Adrian Kent
(University of Cambridge)

Raymond Laflamme
(Institute for Quantum Computing/
University of Waterloo)

Sung-Sik Lee
(McMaster University)

Luis Lehner
(University of Guelph)

Michele Mosca
(Institute for Quantum Computing/
University of Waterloo)

Maxim Pospelov
(University of Victoria)

Itay Yavin
(McMaster University)

QUANTUM GRAVITY

Quantum gravity is concerned with unifying Einstein's general theory of relativity and quantum theory into a single theoretical framework. At Perimeter Institute, 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.

SPINNING UP SPACETIME

Quantum theory and the modern theory of gravity, Einstein's general relativity, don't fit easily together. There are many reasons why, but here's one: relativity radically changed classical notions about space and time, while quantum theory largely preserves those notions. It's fitting, therefore, that one of the approaches to combining quantum theory with gravity, loop quantum gravity or LQG, would fundamentally change our picture of space and time.

Initially developed in the early 1980s, LQG has progressed to the point where it can provide a detailed – albeit still untested – physical and mathematical picture of quantum spacetime. Specifically, LQG proposes that, at the smallest scale, space looks like a fine fabric woven of closed loops. These networks of loops are called spin networks.

Spin networks provide a language to describe the quantum geometry of space. To describe the evolution of such a network – to describe not space but spacetime – requires a formalism called spin foams. The development of spin foams allowed loop quantum gravity to address such matters as causality, light cones, and the like – to begin to give sensible answers about the nature of space and time on the shortest possible scales.

Spin foams were pioneered by several people, including **Perimeter Faculty member Laurent Freidel**. It was Freidel (collaborating with Perimeter visitor Kirill Krasnov) who first wrote down a spin foam model that corresponds to four-dimensional quantum gravity. The seminal work answered many questions and was the first to describe the relationship between the quantum and the classical in a satisfying way.

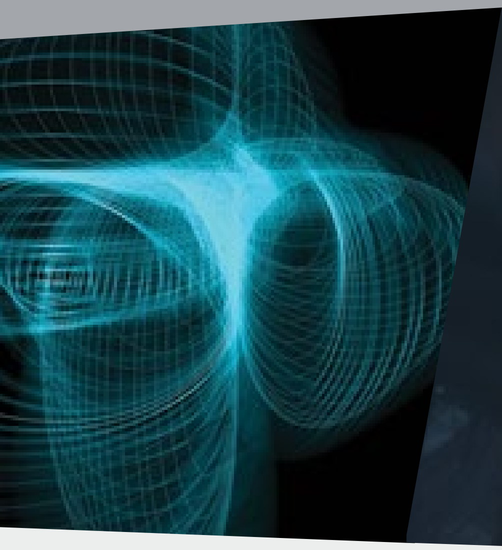
Freidel's discovery was too technical to receive much attention at the time, but it turned out to be very useful. The model he created continues to be the most widely used spin foam model, the basis of most of the studies being done today.

Work in spin foams and LQG continues on many fronts, including some here at Perimeter: it was spin foams, for instance, that allowed Eugenio Bianchi to calculate the entropy of a black hole, as outlined below. For his part, Freidel is working on a new continuum interpretation of loop quantum gravity.

BUILDING BLACK HOLES

How do you build a black hole? Ask **Perimeter Postdoctoral Researcher Eugenio Bianchi**. Taking a loop quantum gravity approach, Bianchi recently re-derived a famous equation for the entropy of black holes from first principles.

A formula for the entropy of a black hole may seem like an obscure result, but it's actually an important signpost on the road to quantum gravity. The formula – which is called the Bekenstein-Hawking equation – is one of the very few in physics that contains constants from both quantum mechanics and Einstein's gravitation. This tantalizing intersection between the two great physics theories of the 20th century has long fascinated researchers who are struggling to unify them into a 21st century theory of quantum gravity.



Loop quantum gravity is one of several competing theories proposed by these quantum gravity researchers. Among other things, LQG predicts that at a very small scale, spacetime is made of discrete chunks which cannot be further divided – in much the same way that Lego blocks only come in multiples of the same length.

LQG researchers have always calculated the entropy of black holes by counting the number of different ways a black hole's horizon can be 'built' out of such spacetime blocks. This build-and-count approach gave only a partial match for the Bekenstein-Hawking formula – but even this partial match was considered a triumph.

Bianchi was able to take this work one step further. Using a new formalism called spin foams (see above), he was able to study the energy and temperature of each of the spacetime blocks and assign them each an entropy. His resulting calculation for the total entropy of a black hole was a perfect match for the Bekenstein-Hawking formula.

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PROFILE: BIANCA DITTRICH

In school, I was interested in things like geo-ecology and chaos theory. But it turned out that what I liked about those subjects was always the physics.

My main field of research is quantum gravity, whose aim is to unify Einstein's beautiful theory of spacetime, general relativity, with quantum theory. Thus, we are pursuing the ancient questions on the nature of space and time, which we now know must be quantum.

An old idea about the nature of spacetime is that it is made up of many basic building blocks, similar to how ordinary matter is made up of atoms. The big challenge is to construct consistent models for such atomic spacetimes and to show that on large scales one recovers a smooth spacetime, as we know it.

The analogy of spacetime and matter made up from atoms is very tempting. There is an important difference, however: whereas matter atoms can be described as moving in space and time, spacetime atoms form space and time. The formulation of a theory which does not require a spacetime background is one part of my research.

Another part is to show that one recovers smooth spacetime out of atomic spacetime models. Here, as in condensed matter, we are using statistical physics, to investigate the large-scale limit of quantum gravity models.

Perimeter is the ideal place to conduct such research. It is very challenging, investigating the basics of physics. And it involves different research areas, like gravity, quantum field theory, quantum foundations, and condensed matter, all of which are represented here. Indeed, the collaborative atmosphere at Perimeter has been very helpful to push my research ahead.

– Bianca Dittrich

Faculty member Bianca Dittrich joined Perimeter in 2012 from the Albert Einstein Institute in Potsdam, Germany.

QUANTUM INFORMATION

Quantum mechanics has redefined information and its fundamental properties. Researchers in this field work to understand the properties of quantum information and explore the possibilities (and impossibilities) of quantum computing. At Perimeter, this includes research into quantum cryptography, which studies the trade-off between information extraction and disturbance, and research into quantum error correction, which studies methods for protecting information against decoherence. Researchers also bring quantum information techniques and insights to other areas of physics, including quantum foundations and condensed matter.

Many of Perimeter's quantum information researchers work closely with researchers at our nearby experimental partner, the Institute for Quantum Computing (IQC). Others hold joint appointments at both Perimeter and IQC. Together, the two institutes have made the region a world leader in the new field of quantum information processing.

TESTING QUANTUM THEORY IN SPACE

Quantum mechanics is the most thoroughly tested theory physics has and it's never yet been wrong. Its stunning precision predicts many properties of fundamental particles to an accuracy of one part in a trillion.

And yet, quantum mechanics has never been tested at scales longer than a hundred-odd kilometres. It's also never been tested in a varying gravitational field. **Perimeter Associate Faculty member Raymond Laflamme, Perimeter Affiliate researcher Thomas Jennewein**, and collaborators from IQC propose a way to change both those things. They want to use satellites.

The collaboration recently published a paper outlining various optical experiments that satellites could perform which would directly test quantum theory. After all, we know that quantum mechanics is incomplete, in the sense that it is not yet unified with the theory of gravitation, general relativity. At larger length scales – ideally approaching the radius of the local curvature of spacetime – and in varying gravitational fields, one might possibly see interactions between gravity and quantum mechanics. If so, a satellite-based platform should be ideal for measuring the effects of such interactions, or at least putting an upper bound on how strong its effects might be. The experiments might even be able to distinguish between competing theories of how gravity and quantum mechanics interact.

The satellite experiments have implications for quantum computing as well. Quantum mechanics is often thought of as governing the world of the small; at everyday scales, quantum effects smooth out and become invisible, and it is as if we live in a classical world. What quantum information has taught us is that "quantum = small" is not quite right. We've learned instead that quantum effects show up in systems that are isolated from their surroundings. When things are small, it is easy to isolate them, but it should in principle be possible to build an isolated system that's large. Building a large system that exhibits quantum effects is one of the challenges we need to overcome to build a quantum computer. Building a large quantum system in the form of an earth-to-satellite network would, therefore, not only be a step toward proving that quantum mechanics are valid at large scales, but also serve as an important demonstration that practical-sized quantum computers are possible.

The Canadian Space Agency is actively considering building and launching the proposed satellite, though any launch would still be years away.

PRISONERS OF THEIR OWN DEVICE

On paper, quantum cryptography offers the ultimate in security. The rules of quantum mechanics state that any disturbance of the system, even a single observation, changes the system. This lends itself beautifully to cryptography, since any attempt at eavesdropping would change the system and be detected.

The idea of device independence in quantum cryptography is an extension of this promise: a mathematical proof that allows users to trust messages sent by quantum devices without trusting anything at all about the quantum devices used. One could even, in principal, generate a secure key using a device that was built by an eavesdropper and later use this key for secure communication.

This year, **Perimeter Postdoctoral Researcher Roger Colbeck, Perimeter Associate Faculty member Adrian Kent**, and collaborators put a dent in the promise of device-independent quantum cryptography. The researchers showed that if the apparatus used for generating secure keys is used more than once, the eavesdropper could design it to smuggle out critical information about old keys by disguising that information as legitimate outputs.

Previous studies of device-independent quantum cryptography – a technology which still exists only on paper – have considered only cases where a cryptographic device was used once. Because the cost of one-off devices would add up quickly, this is unlikely to be practical. The authors concluded by putting forth new ideas regarding how to fix the re-use problem. There is still hope for useful device-independent quantum cryptography, but almost certainly not with the full scope as previously envisioned.

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PROFILE: RAYMOND LAFLAMME

I proved Stephen Hawking wrong.

Whenever I say those five words during a speech, the audience suddenly perks up, as if a little jolt of electricity has been delivered to their seats. I always get a kick out of that.

When I say, "I proved Stephen Hawking wrong," I'm not boasting (although it's certainly a lovely credential to have on my résumé). I say it because I know it will spark curiosity.

Curiosity is the force that drives everything I do – from getting my hands greasy under my 1979 VW van to manipulating the subatomic particles of the quantum world – and I love to inspire curiosity in others. When I say the Hawking line, I can almost see a wave of curiosity rippling through the audience. "How on earth," they seem to be wondering, "could anyone prove the world's most famous physicist wrong?"

The simple answer: curiosity.

There's a complicated answer too, of course. It involves explaining how, while I was a student of Hawking's at Cambridge University, I mathematically demonstrated that time does not reverse direction in a contracting universe, as Hawking had asserted. But I got into theoretical physics – after a false start in actuarial science – merely because of curiosity. I took a great course on Einstein's special theory of relativity, and I thought, "Wow, this is amazing. This is what I want to do."

Today, I work in the field of quantum information and quantum computing. We are harnessing the weirdness of the quantum world to build devices of unprecedented power that process information using the rules of quantum mechanics. Although I have some ideas what such a computer might be able to do, I am sure that they only scratch the surface – it is like asking people who just discovered fire to say how far their rocket can go. But I certainly am curious.

– Raymond Laflamme

Raymond Laflamme was attracted to Perimeter from Los Alamos National Laboratory in Perimeter's earliest days. His curiosity pushed him to the experimental realm and he founded the Institute for Quantum Computing, of which he has been director since 2002 – while continuing to hold a joint appointment at Perimeter. In 2010, he created, with colleagues, Universal Quantum Devices, a start-up to commercialize some spinoffs of quantum technologies.

STRONG GRAVITY

Strong gravity research builds our understanding of systems where gravity is very strong and spacetime is steeply curved, from black holes and neutron stars to the big bang singularity itself. At Perimeter, our researchers use the extreme conditions of strong gravity systems as a kind of natural experiment to test the validity of our current theory of gravity, Einstein's general relativity, and investigate alternative theories. They also investigate the ways in which curved or dynamical spacetimes are linked with a range of other problems in fundamental physics.

THE BIRTH CRY OF A BLACK HOLE?

Might we someday predict – and then carefully observe – the birth of a black hole? **Perimeter Associate Faculty member Luis Lehner** thinks it's possible.

Lehner has been studying the mergers in compact binaries – that is, binary 'star' systems where both stars are extraordinarily dense: either neutron stars or black holes. There are two kinds of compact binary mergers: one in which a neutron star orbiting a black hole gets destroyed and sucked in, and another in which two neutron stars spiral together and collide, then collapse, creating a new black hole. Either type of violent event releases gravitational waves. Indeed, binary neutron star mergers are widely thought to be the ideal source for the signals that the new gravitational wave detectors are working to capture for the first time.

What Lehner and his collaborators, including **Senior Postdoctoral Researcher Chad Hanna**, have developed is a new model that, for the first time, examines the magnetic fields both inside and outside the colliding stars; previous models had to make simplifications that made them unable to cope with either the inside or the outside. These results show that there should be a strong electromagnetic counterpart to the gravitational wave signal the neutron star merger puts out.

Having two signals – one gravitational and one electromagnetic – gives us two ways to observe the same event. That's a new and hot idea in the field, and it goes by the name 'multimessenger astronomy.' Lehner's result will be key as scientists work to understand to what extent multimessenger astronomy is possible.

The promise of multimessenger astronomy is more than just two sets of data. It allows one model to check the other. It also allows us to look at different parts of the system – at gravitational waves from deep within the stars and electromagnetic signals from their surface, for instance. And – because gravitational waves ramp up gradually in advance of neutron star mergers – the gravitational signal could give us warning that a neutron star merger is about to happen, allowing us to turn our telescopes and catch the electromagnetic burst that is the birth cry of a black hole.

DO BLACK HOLES HEAT THE UNIVERSE?

Perimeter Associate Faculty member Avery Broderick has been studying a class of black holes known as teraelectronvolt or TeV blazars: that is, the accreting supermassive black holes at the hubs of some galaxies that emit jets of very high energy gamma rays – photons in the TeV range. What he's discovered may require us to rewrite the thermal history of the recent universe.

The key is the realization that the universe is not transparent to TeV radiation. The X-rays and UV light emitted by stars and black holes vastly outshine the TeV light from blazars, but most X-ray or

UV photons can pass across the width of the universe without interacting with anything. In contrast, most of the TeV photons emitted by the blazars eventually collide with infrared photons in the intergalactic medium, creating an electron/positron pair. Broderick's new approach is to treat these pairs as a beam of plasma. Powerful plasma instabilities in the beam quickly dissipate its energy. The beams may be small, on cosmic scales, but the universe is large, and every point is inside one of these beams. The net result is that the intergalactic medium (IGM), the thin gas that fills the voids between galaxies, is heated by several orders of magnitude.

This heating of the IGM by blazars would solve several puzzles in cosmology – the simplest being that the temperature of the IGM is much higher than the existing models would predict it to be. Broderick is developing more detailed models, but already it seems that blazars, while fairly rare, may have a huge influence on the temperature and structure of the universe as a whole.

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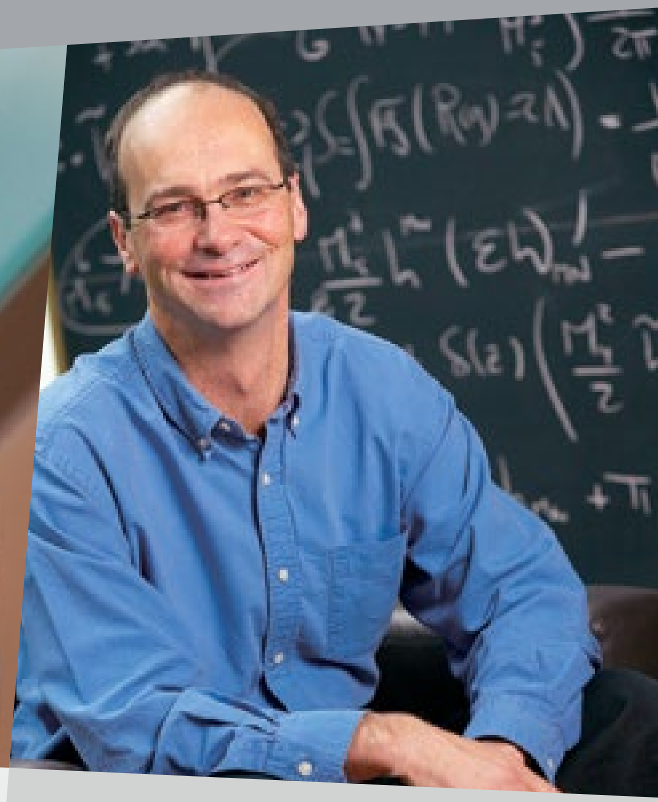
Photo credit: ESO

HONOURS, AWARDS, AND GRANTS

"Atomic Orbitals" by artist Reinhard Reitzenstein

Many Perimeter researchers received national and international recognition in 2011/12. Notable among these are the following:

- **Director Neil Turok** was selected to deliver the 2012 Massey Lectures, which will be presented in five cities across Canada, aired nationally on CBC Radio, and published as a book.
- **Faculty member Robert Myers** won the Canadian Association of Physicists-TRIUMF 2012 Vogt Medal for his important contributions to subatomic physics.
- **Faculty member Freddy Cachazo** won the Canadian Association of Physicists 2012 Herzberg Medal, for outstanding early career achievements by a physicist.
- **Distinguished Visiting Research Chair Nima Arkani-Hamed** won the $3 million Fundamental Physics Prize for his "original approaches to outstanding problems in particle physics, including the proposal of large extra dimensions, new theories for the Higgs boson, novel realizations of supersymmetry, theories for dark matter, and the exploration of mathematical structures in gauge theory scattering amplitudes."
- The 2012 Best Paper Prize, given by the Institute of Physics (IOP) and the Editorial Board of *Journal of Physics A*, was awarded to "Y-system for scattering amplitudes" by **Faculty member Pedro Vieira**, **Senior Postdoctoral Fellow Amit Sever**, et al.
- **Director Neil Turok** and **Faculty member Lee Smolin** were awarded $2 million by the John Templeton Foundation to create the Templeton Frontiers Program at Perimeter Institute to catalyze path-breaking research in quantum foundations and information, foundational cosmology, and the emergence of spacetime.
- **Faculty member Pedro Vieira** was awarded an Early Researcher Award from Ontario's Ministry of Economic Development and Innovation.
- **Associate Faculty member Adrian Kent** was awarded a grant from the John Templeton Foundation of £178,000, 2011-13.
- **Associate Faculty member Raymond Laflamme** was named a Fellow of the American Physical Society for his visionary leadership in the field of quantum information science.
- **Associate Faculty member Raymond Laflamme** was named a Fellow of the American Association for the Advancement of Science.
- **Senior Postdoctoral Fellow Razvan Gurau** was awarded the 2012 Hermann Weyl Prize for the discovery and development of the theory of coloured random tensors.
- **Postdoctoral Researcher Eugenio Bianchi** was awarded a Banting Postdoctoral Fellowship to be held at Perimeter.



- **Director Neil Turok** was named to the International Advisory Committee of the Higgs Centre for Theoretical Physics at the University of Edinburgh.
- **Associate Faculty member Michele Mosca** and co-applicants were awarded a Natural Sciences and Engineering Research Council (NSERC) CREATE grant of $1.65 million, 2012-18.
- **Associate Faculty member David Cory** and co-applicants were awarded an NSERC CREATE grant of $1.65 million, 2012-18.
- **Senior Research Affiliate John Moffat** was awarded a John Templeton Foundation grant of $222,000 over three years to support his research into promising alternative models in physics.
- **Postdoctoral Researcher Matthew Johnson** (now an Associate Faculty member) and co-applicants were awarded a New Frontiers in Astronomy and Cosmology grant of $270,000 over two years.
- Ten Perimeter researchers were awarded NSERC Discovery Grants totalling over $1.6 million (over three- to five-year terms). **Latham Boyle**, **Avery Broderick**, and **Philip Schuster** were awarded Early Career Supplements.
- **Faculty member Philip Schuster** was awarded a $120,000 Discovery Accelerator Supplement from NSERC.

ROBERT MYERS WINS CAP-TRIUMF VOGT MEDAL

This year, **Faculty member Robert Myers** was honoured with the 2012 Vogt Medal of the Canadian Association of Physicists (CAP) and TRIUMF, Canada's national laboratory for nuclear and particle physics research. Named for nuclear physicist Erich Vogt, the founder of TRIUMF, the award recognizes outstanding contributions to subatomic physics. Myers' work has spanned several areas, including foundational string theory, gravitational physics, and string cosmology. A founding member of Perimeter's faculty, Myers served as Interim Scientific Director from 2007 to 2008 and is now Chair of the Faculty.

RECRUITMENT

Galileo Chair Davide Gaiotto

Great science is, first and foremost, about people, and Perimeter has been exceptionally fortunate in attracting many of the brightest talents in the field to its faculty.

THE PERIMETER RESEARCH CHAIRS

The Perimeter Research Chairs program is designed to attract stellar, senior researchers to Perimeter and to Canada. Five chairs are planned in all, each named for scientists whose insights helped define modern physics: Neils Bohr, Albert Einstein, Leonhard Euler, James Clerk Maxwell, and Isaac Newton.

In May 2012, we welcomed **Xiao-Gang Wen** as the inaugural BMO Financial Group Isaac Newton Chair in Theoretical Physics. Wen comes to Perimeter from MIT and is a global leader in the quest to discover new forms of matter. In 1989, he introduced the notion of topological order, enabling physicists to describe a new class of matter – topological matter – which exhibits quantum entanglement properties at macroscopic scales. It was a breakthrough that opened up major new research directions and topological matter is now one of the most active research areas in condensed matter physics. His subsequent discoveries include topological insulators, which show strong promise for use in quantum computers. Wen's research has implications well beyond his own field, advancing quantum information science, high energy physics, mathematics, and even the development of new models of the universe.

Searches are now in progress to identify the next Perimeter Research Chairs.

GALILEO CHAIR

In addition to the five Perimeter Research Chairs for senior scientists, a new position, the Galileo Chair, was created this year to attract an exceptional early career scientist. In May 2012, **Davide Gaiotto**, widely regarded as the leading young quantum field theorist worldwide, arrived from the Institute for Advanced Study in Princeton as the inaugural Galileo Chair. Gaiotto works in the area of strongly coupled quantum fields and has already made several major conceptual advances that have potentially revolutionary implications. In 2011, Gaiotto won the Gribov Medal of the European Physical Society.

FACULTY

Perimeter welcomed several outstanding new faculty members in 2011/12:

Bianca Dittrich joined Perimeter from the Albert Einstein Institute in Potsdam where she headed the Max Planck Research Group “Canonical and Covariant Dynamics of Quantum Gravity.” A young leader in the field of quantum gravity, Dittrich’s research focuses on the construction and examination of quantum gravity models and she recently developed a computational framework for gauge invariant observables in canonical general relativity. In 2007, she received the Otto Hahn Medal of the Max Planck Society, which recognizes outstanding young scientists.

Cosmologist **Kendrick Smith**, who will join Perimeter from Princeton University next year, has 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 and the Planck collaboration. He has achieved several landmark results, including the first detection of gravitational lensing in the cosmic microwave background (CMB) radiation.

Dmitry Abanin will join Perimeter from Harvard, where he has been a postdoctoral fellow since 2011. As a condensed matter theorist, Abanin’s 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, Manchester, Columbia, UC Riverside, the Max Planck Institute, and elsewhere.

Perimeter Postdoctoral Researcher Eugenio Bianchi recently took a loop quantum gravity approach to duplicating the famous Bekenstein-Hawking formula for black hole entropy (see p. 22-23). In this picture, he presents his work to Stephen Hawking, one of the formula’s creators and a Perimeter Distinguished Visiting Research Chair.

ASSOCIATE FACULTY

In addition to full-time faculty, Perimeter often works with nearby universities to make joint hires through its Associate Faculty program, enabling the Institute to recruit top scientific talent to Canada and to spread the benefit among multiple institutions. This year, Perimeter made three such joint appointments, increasing research strength in key areas.

Astrophysicist **Avery Broderick**'s broad research interests range from star formation to the extreme physics in the vicinity of white dwarfs, neutron stars, and black holes. Recently, he has been part of an international effort to produce and interpret horizon-resolving images of supermassive black holes, studying their dynamics and the nature of gravity in their vicinity. He completed his PhD at Caltech in 2004 and held postdoctoral positions at the Harvard-Smithsonian Center for Astrophysics (2004-07) and the Canadian Institute for Theoretical Astrophysics (2007-11). He is jointly appointed with the University of Waterloo.

Cosmologist **Matthew Johnson**'s 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. Johnson completed his PhD at the University of California, Santa Cruz, in 2007 and was a Moore Postdoctoral Scholar at Caltech from 2007 to 2010, when he joined Perimeter as a postdoctoral fellow. He will be jointly appointed with York University in Toronto, starting in August 2012.

Condensed matter theorist **Roger Melko** 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. After completing his PhD at the University of California, Santa Barbara (2005), he was a Wigner Fellow at Oak Ridge National Laboratory (2005-07) before joining the University of Waterloo in 2007. He received an Early Researcher Award in 2010. Melko joins Perimeter in fall 2012, while retaining his appointment with the University of Waterloo.

DISTINGUISHED VISITING RESEARCH CHAIRS

The Perimeter Distinguished Visiting Research Chairs (DVRC) program is unique worldwide. The program enables leading scientists to visit the Institute for extended periods each year while retaining permanent positions at their home institutions. During their three-year terms, they become part of Perimeter's community in all respects: conducting research, collaborating with colleagues, organizing conferences, teaching in the PSI program, and contributing to the Institute's outreach efforts.

Perimeter's DVRCs include luminaries such as **Stephen Hawking**, **Nima Arkani-Hamed**, **Leonard Susskind**, **Mark Wise**, and Nobel laureate **Gerard 't Hooft**, with expertise spanning the entire spectrum of theoretical physics. Their presence sparks new ideas and collaborations, and greatly enhances Perimeter's resident research community. This year, **Ashvin Vishwanath** became a DVRC, giving the Institute 24 at the end of 2011/12. In addition, **Adrian Kent** and **Ramesh Narayan** accepted appointments to begin in 2012/13.

POSTDOCTORAL RESEARCHERS

Many of the great discoveries in physics were made by surprisingly young scientists. With this in mind, Perimeter provides its postdoctoral researchers with exceptional opportunities to maximize their research potential at a pivotal stage in their careers.

Perimeter is a top destination for many of the world's brightest early career scientists and home to the largest group of independent theoretical physics postdoctoral researchers in the world. This year, 15 new postdocs were selected from over 650 applicants. As full partners in Perimeter's research community, they are encouraged to pursue novel, ambitious lines of research, invite scientific collaborators, travel, and organize conferences.

Today's cutting-edge experiments are yielding data that was previously out of reach, so contact between theorists and experimentalists is more important than ever. This year, Perimeter instituted the GO Program, which gives early career particle physicists new opportunities to work with experimentalists at centres such as CERN, FermiLab, Jefferson Lab, TRIUMF, SNOLAB, and SLAC.

DISTINGUISHED VISITING RESEARCH CHAIRS

Dorit Aharonov, Hebrew University

Yakir Aharonov, Chapman University and Tel Aviv University

Nima Arkani-Hamed, Institute for Advanced Study

James Bardeen, University of Washington

Ganapathy Baskaran, Institute of Mathematical Sciences, Chennai

Juan Ignacio Cirac, Max Planck Institute of Quantum Optics

S. James Gates, University of Maryland

Stephen Hawking, University of Cambridge

Patrick Hayden, McGill University

Christopher Isham, Imperial College London

Leo Kadanoff, James Franck Institute/University of Chicago

Renate Loll, Radboud University, Nijmegen

Malcolm Perry, University of Cambridge

Sandu Popescu, University of Bristol

Frans Pretorius, Princeton University

Subir Sachdev, Harvard University

Eva Silverstein, Stanford University

Paul Steinhardt, Princeton University

Leonard Susskind, Stanford University

Gerard 't Hooft, Utrecht University

Senthil Todadri, Massachusetts Institute of Technology

William Unruh, University of British Columbia

Ashvin Vishwanath*, University of California, Berkeley

Mark Wise, California Institute of Technology

* Indicates DVRC appointed in 2011/12

RESEARCH TRAINING

"What inspired me the most was looking at all my classmates working so hard, and the researchers – they never stop. They reminded me that I had a dream. I always wanted to discover something that no one else had yet, to study something new. To understand a little bit more about the universe."

– Paulina Corona Ugalde, PSI Class '11

PERIMETER SCHOLARS INTERNATIONAL

Perimeter recognizes that brilliant young people are the lifeblood of theoretical physics. Perimeter Scholars International (PSI), the Institute's master's program, brings exceptional university graduates from around the world to the cutting edge of theoretical physics in one academic year.

The program is structurally innovative, with courses taught in three-week modules by Perimeter faculty and other top lecturers from around the world, providing a broad range of expertise and perspectives. Students not only experience the full spectrum of theoretical physics, but also learn key skills such as computer-based model development, independent thinking, and collaborative problem solving. In the latter part of the program, students defend original research theses, many of which are later accepted for publication. The program is run in partnership with the University of Waterloo, which confers a master's degree upon its completion.

In 2011/12, 37 students from 20 countries completed PSI. Notably, 11 of this year's graduates are women, reflecting the Institute's strong commitment to gender equity in the field. Fourteen of this year's graduates are now pursuing their PhDs in Canada, seven of them with Perimeter Faculty and Associate Faculty members. Others have gone on to excellent programs at Oxford, Princeton, Caltech, and elsewhere.

The PSI program was generously supported in 2011/12 by: The Bluma Appel Community Trust, Burgundy Asset Management, The Ira Gluskin and Maxine Granozsky Gluskin Charitable Foundation, The Kitchener and Waterloo Community Foundation – The John A. Pollock Family Fund, and Scotiabank.

PHD STUDENTS

Faculty supervised 35 PhD students over the past year. As Perimeter is not a degree-granting institution, doctoral students ultimately receive their degrees from a partnering university where their faculty supervisor has an affiliation. Perimeter's rich environment offers students unparalleled opportunities to interact with research leaders from around the world and to develop further career opportunities.

VISITING GRADUATE FELLOWS

The newly-launched Visiting Graduate Fellows program brought 10 promising doctoral candidates from around the world to the Institute for extended research visits in 2011/12. With stays ranging from two months to nearly a year, Fellows are able to join Perimeter's research community and interact with leading researchers at a pivotal time in their scientific training.

UNDERGRADUATE RESEARCH

Postdoctoral researchers develop mentoring skills by supervising two- to four-month summer research projects with undergraduates. Last summer, eight talented students from around the world developed their research skills while absorbing the rich variety of talks, conferences, and happenings at Perimeter.

PSI 2011/12 FACULTY

John Berlinsky (Director), Perimeter Institute

Dmitry Abanin, Perimeter Institute

Carl Bender, Washington University

Latham Boyle, Perimeter Institute

Freddy Cachazo, Perimeter Institute

David Cory, Perimeter Institute and Institute for Quantum Computing/University of Waterloo

François David, Institute of Theoretical Physics/ CEA-Saclay

Jaume Gomis, Perimeter Institute

Daniel Gottesman, Perimeter Institute

Ruth Gregory, Durham University

Alioscia Hamma, Perimeter Institute

Matthew Johnson, Perimeter Institute

Leo Kadanoff, James Franck Institute/University of Chicago

Adrian Kent, University of Cambridge

Louis Leblond, Perimeter Institute

Luis Lehner, Perimeter Institute

Renate Loll, Radboud University, Nijmegen

David Morrissey, TRIUMF

Frans Pretorius, Princeton University

Carlo Rovelli, Centre of Theoretical Physics/ Aix-Marseille University

Veronica Sanz, York University

Philip Schuster, Perimeter Institute

Robert Spekkens, Perimeter Institute

Natalia Toro, Perimeter Institute

Nandini Trivedi, Ohio State University

Neil Turok, Perimeter Institute

Pedro Vieira, Perimeter Institute

Konstantin Zarembo, NORDITA (Nordic Institute for Theoretical Physics)

RESEARCH EVENTS

BY THE NUMBERS

In 2011/12 …

- Held 17 timely, focused conferences and workshops, attended by 1,013 scientists from around the world
- Partnered on 7 joint workshops and conferences with other institutions, and sponsored an additional 11
- Presented 299 scientific talks, all made available online at www.pirsa.org

CONFERENCES, WORKSHOPS, AND SUMMER SCHOOLS

There is no substitute for the intense focus and unexpected human interactions at scientific gatherings. Time and again, discussion, debate, and unexpected ideas catalyze new insights and discovery.

Perimeter's flexibility enables it to rapidly identify and capitalize on promising new areas, and the Institute is often the first in the world to host a conference on an emerging area or new discovery.

In 2011/12, the Institute held 17 conferences and workshops, attended by over 1,000 scientists from around the world. By strategically choosing timely, focused topics, Perimeter aims to accelerate progress and act as a major node of exchange for ground-breaking research.

COLLOQUIA AND SEMINARS

Perimeter provides a rich environment for knowledge exchange, with 271 seminars and 28 colloquia held over the last year. The Institute hosts 11 active weekly seminar series, fostering collaboration with researchers around the globe.

Particularly notable from the past year were talks by **DVRCs Yakir Aharonov**, **James Bardeen**, **Ganapathy Baskaran**, **Ramesh Narayan**, **Frans Pretorius**, **Subir Sachdev**, **Senthil Todadri**, **William Unruh**, **Ashvin Vishwanath**, and **Mark Wise**.

CONFERENCE HIGHLIGHT: "HIGGS: NOW AND IN THE FUTURE"

Theorists and experimentalists have traditionally viewed themselves as members of different tribes. Yet in the last several years, particle physicists in both camps have realized that they need to cooperate to have the best shot at discovering new physics beyond the Standard Model.

In advance of July's announcement confirming the discovery of the Higgs boson, this two-day workshop (April 23-24, 2012) brought together leading theorists and experimentalists from the ATLAS collaboration at the Large Hadron Collider to discuss recent Higgs-related developments and chart the way forward. The conference was a major success that built consensus on how to proceed strategically to plan and interpret upcoming experiments.

It exemplified the cross-fertilization of ideas between theory and experiment Perimeter seeks to foster and a second conference with a related focus, but centred on the CMS experiment, was held in August.

"Discussions at PI have contributed to an ongoing strategic shift in the management and intellectual direction taken by the collaboration. Within my group, the PI workshop is seen as a turning point in our strategic development, and the discussions we enjoyed there should seed changes which will have a large impact on our future work."

– Steve Worm, CMS Group, Experimental Division B, speaking about the CMS theory/experiment conference held at Perimeter in August 2012

PERIMETER INSTITUTE RECORDED SEMINAR ARCHIVE

Scientists and students all over the world can access over 6,000 talks, lectures, and colloquia online via the Perimeter Institute Recorded Seminar Archive (PIRSA) at www.pirsa.org. This permanent, free, searchable, and citable archive of video-recorded seminars, conferences, workshops, and courses was developed by the Institute to share knowledge with the international scientific community. It is an important scientific resource for the field, as evidenced by the continued rise in site traffic year over year. Last year, more than 75,000 unique visitors from 166 countries accessed nearly 675,000 pages on PIRSA.

Scientists and students all over the world can access over 6,000 talks, lectures, and colloquia online via the Perimeter Institute Recorded Seminar Archive (PIRSA) at **www.pirsa.org.**

LINKAGES

BY THE NUMBERS

In 2011/12 …

- Over 1,000 scientists visited Perimeter to do research and attend conferences

VISITOR PROGRAM

Fresh voices invigorate discussion. Over the last year, Perimeter's lively scientific visitor program brought 401 scientists for research visits (in addition to over 600 conference participants). Whether for a few days or a full sabbatical, coming to Perimeter provides visiting scientists with time, space, and ample opportunities to attend conferences and talks, exchange ideas, and spark new collaborations with colleagues.

AFFILIATES

Through the Institute's Affiliate member program, select faculty from Canadian universities are invited to make regular visits, work with Perimeter's resident scientists, and attend research events. Affiliates enrich Perimeter's community, helping to build regional and national research links between Perimeter and Canadian universities. In 2011/12, 17 new Affiliate members joined, bringing the total membership to 119. The program continues to strengthen research linkages between Perimeter and the Canadian scientific community, while in turn enriching the Institute's research environment.

NATIONAL LINKAGES

Modern physics is inherently collaborative. The big questions are so complex that they can rarely be answered by a single researcher, or even by a single institution. Collaboration is vital and sharing intellectual wealth enriches all.

Perimeter aims to serve as a hub for theoretical physics in Canada. In addition to longstanding and productive ties with the Institute for Quantum Computing at the University of Waterloo, Perimeter partners with regional universities, including McMaster, Guelph, and Western, via cross-appointments, adjunct appointments, joint postdoctoral fellowships, and graduate training. The Institute also provides unique resources and leadership to the national scientific community through conferences, workshops, and courses.

Perimeter has strong ties with research organizations across the country, including the Canadian Institute for Theoretical Astrophysics (CITA), Canadian Institute for Advanced Research (CIFAR), Fields Institute, SNOLAB, TRIUMF, Centre de Recherches Mathématiques, Pacific Institute for Mathematical Sciences (PIMS), and in the Mathematics of Information Technology and Complex Systems (MITACS) research networks.

INTERNATIONAL LINKAGES

Perimeter maintains links with many research institutions around the world. In particular, it has strengthened links to observational and experimental centres in particle physics. **Faculty members Philip Schuster** and **Natalia Toro** have established highly productive collaborative ties to experimentalists at the Large Hadron Collider and, in 2011/12, the Institute formally launched its "Get Out" (GO) Program for postdoctoral researchers in particle physics, enabling them to work with experimental peers at centres like CERN, TRIUMF, and SNOLAB.

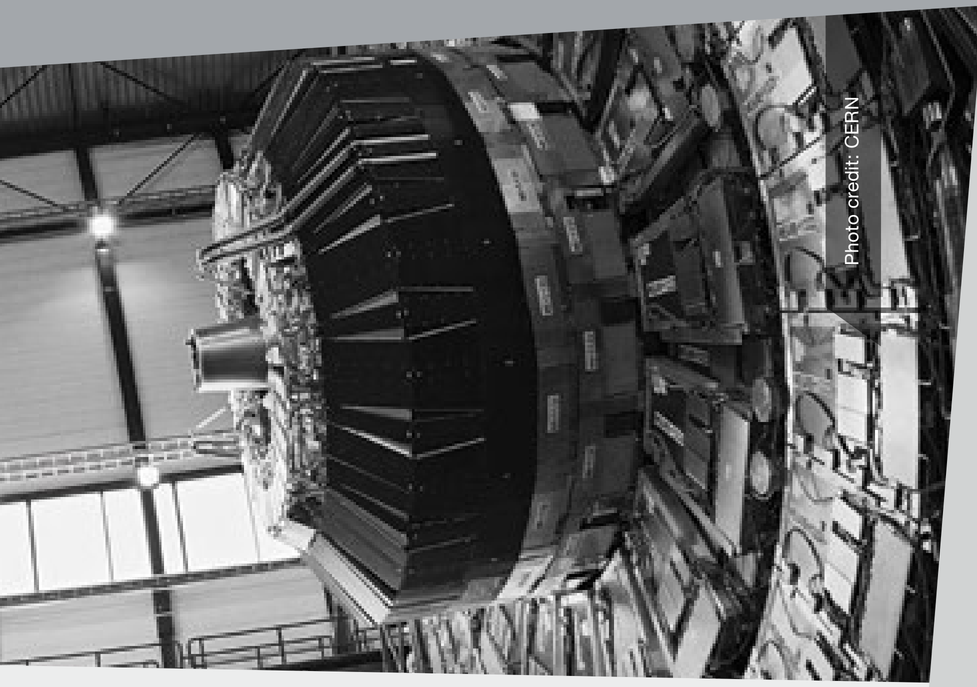


Photo credit: CERN

Last year, Perimeter also concluded two new partnership agreements to facilitate scientific collaboration with the International Centre for Theoretical Physics-South American Institute for Fundamental Research (ICTP-SAIFR) in Brazil and the Institute of Mathematical Sciences (IMSc) in India.

GLOBAL OUTREACH: BUILDING A BRIDGE TO AFRICA

Science not only generates knowledge and technologies, it is also a powerful unifying force for humanity. The language and methods of science cut across cultures, languages, and religious differences in ways which few other human activities can.

Perimeter Institute's Global Outreach initiative shares expertise in order to help catalyze the growth of centres of excellence in theoretical physics and math around the world. Its focus is the African Institute for Mathematical Sciences-Next Einstein Initiative (AIMS-NEI), a pan-African initiative founded by **Perimeter Director Neil Turok** to establish a network of centres providing advanced mathematical and scientific education to the continent's most exceptional graduates.

It has built a bridge between Perimeter and Africa: researchers and graduate students have gone to AIMS centres as tutors and lecturers, Perimeter staff members have provided professional assistance in their areas of expertise, and several AIMS graduates have come to Perimeter to pursue graduate studies.

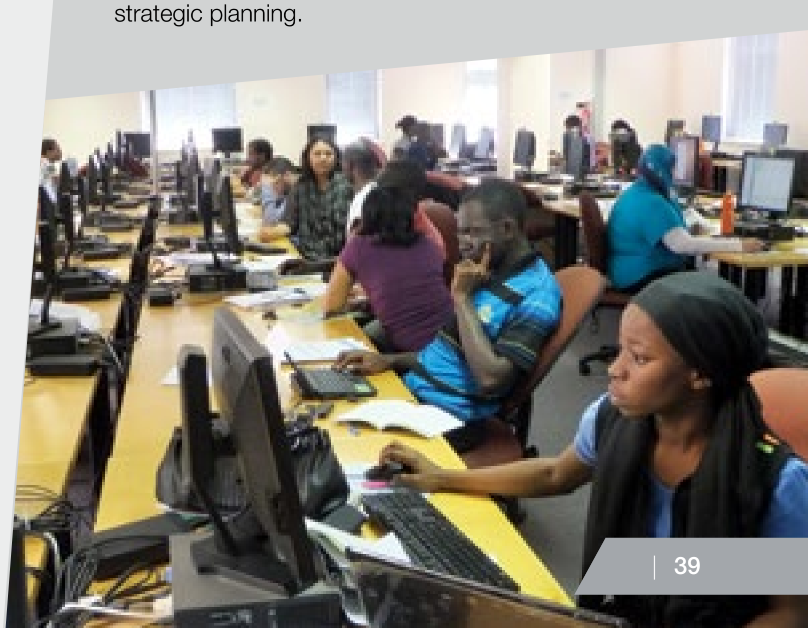
EXPORTING EXPERIENCE

When he first arrived in Senegal, **Perimeter Chief Operating Officer Michael Duschenes** wondered what he could really do to help. He had successfully guided several organizations, including Perimeter, from start-up through rapid growth to flourishing stability. Would his experience be applicable in an African setting?

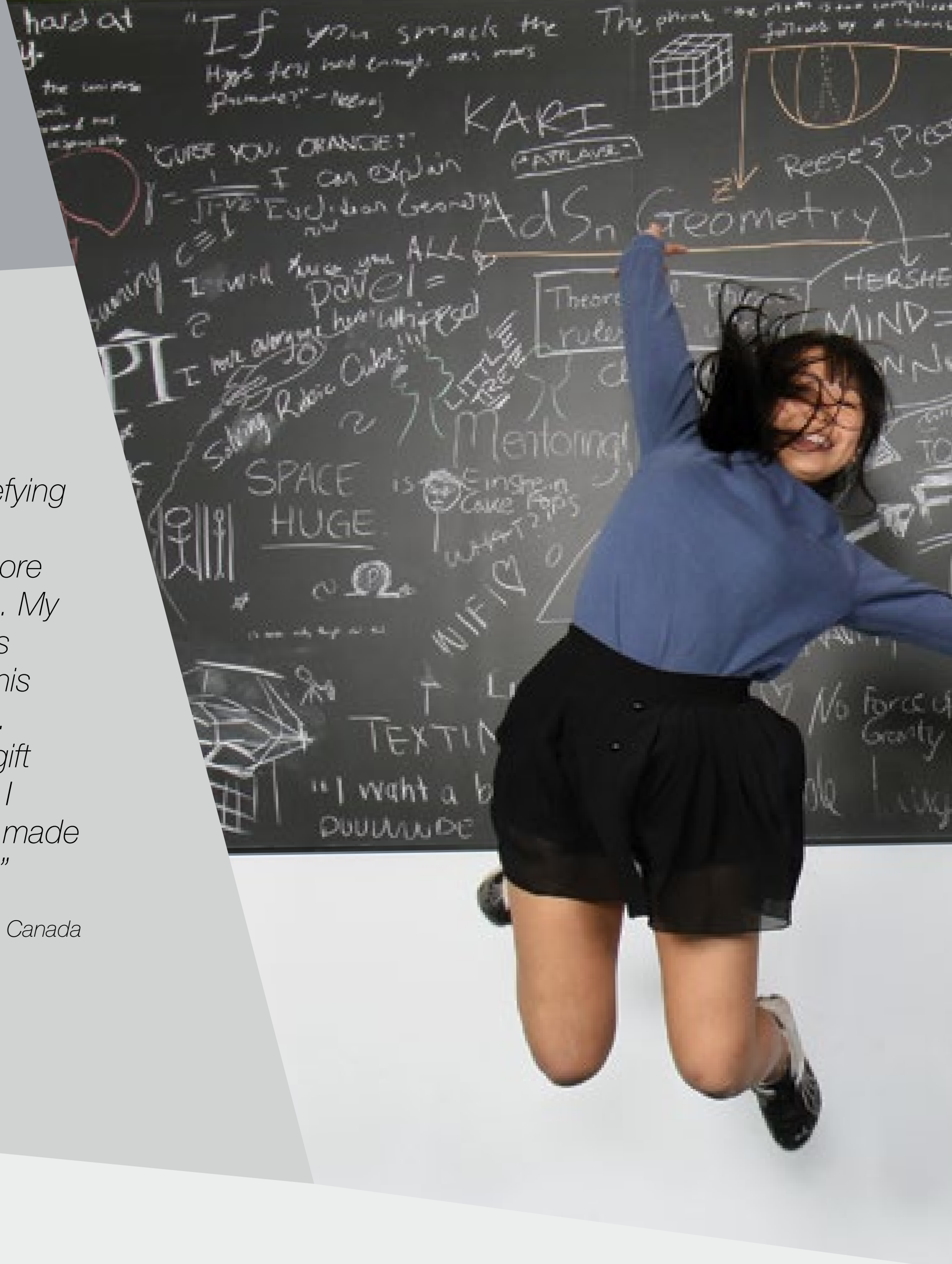
As he met with staff over the course of the next week, he found that they indeed confront many of the same organizational, logistical, and planning issues that he does, though often with enormous additional challenges. He took his meals with the AIMS students and recalls being moved by the contrast between the beautiful setting, with sandy beaches and tropical foliage surrounding the centre, and the students' often difficult stories of where they had come from – to say nothing of their intense commitment to succeed.

"My visit to AIMS really reinforced why global outreach is such a valuable part of Perimeter's mandate," says Duschenes. "We're part of a global enterprise, trying to solve some of the toughest problems in science. Success will require contributions of people from all over the world. Exporting some of the experience we have gained to help accelerate the creation of these centres is one part of the international role Perimeter can play. And we end up learning as much from them as they do from us."

A fruitful dialogue ensued and Duschenes has since returned to Africa twice to help with AIMS' business and strategic planning.



OUTREACH



"Physics claws at the unknown, defying boundaries and smiling into murky depths. In my eyes, there isn't a more pure or passionate search for truth. My experience at ISSYP, above all, has proven my thirst in the search for this beautiful truth to be unquenchable. … This experience is the greatest gift imaginable. I've learned more than I could have ever imagined and I've made lifelong friends that I'll never forget."

– 2012 ISSYP participant Alycia Leonard, Canada

Sharing the excitement and wonder of physics feeds the soil in which science grows.

At Perimeter, educational outreach is a core part of our mission. We have developed a comprehensive suite of materials and programs, each tailored for specific audiences: students, teachers, and the general public.

INSPIRING YOUNG PEOPLE

Over one million students have been reached through Perimeter's award-winning outreach programs and resources to date.

Inspiring young people about science fosters key skills like curiosity, critical thinking, and the rigorous, open testing of ideas. Best of all, it unlocks the joy of solving challenging problems.

The International Summer School for Young Physicists

2012 marked the 10th year of the International Summer School for Young Physicists (ISSYP), which brings exceptional high school students to Perimeter every summer to live and breathe physics for two intense weeks in a spirit of internationalism and camaraderie. This year, the Institute hosted 39 students from 12 countries, who learned about modern physics, met scientists, toured research labs, and forged lasting friendships. Nearly 500 students have participated in ISSYP since its launch in 2003 and over 70 percent of alumni surveyed credit ISSYP with inspiring them to pursue careers in math and science.

ISSYP was generously supported in 2011/12 by RBC Foundation.

Photo credit: Dave Dick

Taking the Show on the Road: GoPhysics! and Physica Phantastica

This year, six one-day GoPhysics! camps were held across the country, giving a snapshot of the ISSYP experience to approximately 25 students at a time.

In addition, over 2,100 students throughout Ontario and the rest of Canada got excited about physics through entertaining and accessible Physica Phantastica presentations. Physica Phantastica seeds scientific literacy and creativity among grades 7 to 12, illuminating connections between the scientific enquiry into the forces governing the universe and the discovery of new knowledge and technologies.

> *"I spent the best 16 days of my life studying concepts of physics that completely redefined the way I look at the world around me, with the most brilliant group of people I have ever met."*
>
> *– 2012 ISSYP participant Radhika Singhal, India*

PARTNERING WITH TEACHERS

EinsteinPlus

"It completely changed the way I teach physics."

– 2012 EinsteinPlus participant Olga Michalopouloso, Georgetown District High School, Georgetown, Ontario

Modern physics concepts can be tough to understand, let alone teach to students, but Perimeter is here to help. This year, 52 teachers from Canada and abroad dedicated part of their summer vacations to the EinsteinPlus National Teachers' Workshop (E+), a one-week intensive workshop that gives participants effective teaching strategies and introduces them to Perimeter's in-class resources.

E+ alumni form the core of Perimeter's Teacher Network, a peer-to-peer training program comprising over 60 teachers throughout Ontario and across the country who are trained in sharing Perimeter's resources with fellow educators in their home districts. The Network greatly extends the reach of our Outreach program: in 2011/12, Network teachers delivered 65 workshops to 1,500 educators, who in turn reached over 112,500 Canadian high school students.

Perimeter staff also presented 18 on-location workshops at teacher conferences this year to over 1,800 educators.

In-class Resources

By showing the connections between everyday life and physics, Perimeter's *Inspirations* in-class modules aim to intrigue and motivate junior high school students to continue with math and science in senior grades. This year's release, *The Process of Science*, showcased the habits of mind that scientists practice in their search for answers.

The Perimeter Teacher Network greatly extends the reach of our Outreach program: in 2011/12, Network teachers delivered 65 workshops to 1,500 educators, who in turn reached over 112,500 Canadian high school students.

Beyond the Atom – Remodelling Particle Physics

Explorations modules, aimed at senior high school students, delve deeper into more challenging ideas and technical content, providing excellent preparation for post-secondary education in math, science, and engineering. This year saw the timely release of *Beyond the Atom – Remodelling Particle Physics*, which deals with the Higgs boson, one of the hottest topics in all of science.

All of Perimeter's educational resources are developed with extensive input from both scientists and teachers, ensuring they are cutting edge and engaging in the classroom.

Development of The Process of Science *module was generously supported by The Cowan Foundation.*

In the Books

Sections of several Perimeter modules have been incorporated into the Physics 12 *textbook and are expected to reach Ontario high school physics students for years to come.*

THE Brain*STEM* UNCONFERENCE

A revolution in global science education is afoot – and it's being broadcast on YouTube.

Inspired by the work of digital media educators and entrepreneurs like *MinutePhysics*, *Smarter Every Day, Radiolab*, and Khan Academy, this three-day idea incubator kicked off Perimeter's Brain*STEM* initiative and brought together creators from around the world with overlapping interests in three spheres: science, education, and entrepreneurship.

A Who's Who of online science creators – with well over 300 million views and 2.5 million subscribers collectively – converged on Perimeter in June 2012. Instead of passively listening to 'sage on the stage' presentations, participants at the Brain*STEM* unconference collaborated to set the agenda, discuss, ideate, and begin to map the way forward for education in a global, digital world. Teams of students also competed to create the next cool game, video, or app in a 48-hour build-a-thon competition.

*The Brain*STEM *unconference was held in collaboration with Waterloo-based Communitech and funded by the Federal Economic Development Agency for Southern Ontario. Perimeter's Brain*STEM *initiative will also include the creation of an in-class resource, training for teachers and guidance counsellors, and a public launch event – all aimed at illustrating the link between scientific thinking and entrepreneurship and inspiring youth to pursue careers in science, technology, engineering, and mathematics (STEM).*

Julian Barbour giving a Public Lecture

SCIENCE FOR ALL: BECAUSE THE FUTURE STARTS NOW

To shape our future wisely, we all need to understand and value science. For the general public, Perimeter hosts free lectures featuring an all-star lineup of scientists and thinkers. We bring science into pubs and living rooms with public festivals and materials designed to engage and fascinate.

Speaking Science: Perimeter Public Lectures

Presented by Sun Life Financial, the Perimeter Public Lecture Series brings the excitement of cutting-edge science to the public. The lectures are extremely popular, with all 600 tickets consistently snapped up within minutes. In 2011/12, 11 accessible, engaging talks were presented on topics ranging from research and collaboration in space to black holes and the existence of time.

Through Perimeter's ongoing partnership with TVO, the lectures are professionally recorded, broadcast, and shared online on TVO, Perimeter's website, and iTunes University. This partnership also produced *Stephen Hawking: The Power of Ideas*, which has been viewed online nearly 70,000 times to date.

Waterloo Global Science Initiative

The Waterloo Global Science Initiative (WGSI) is an independently funded, non-profit partnership between Perimeter Institute and the University of Waterloo whose mandate is to catalyze the long-range thinking that can advance ideas, opportunities, and strategies for the future. Its inaugural conference, Equinox Summit: Energy 2030, in June 2011, brought together scientists, policy experts, entrepreneurs, and young leaders from around the world to explore new technologies for the production, storage, and distribution of electric power.

In February 2012, the *Equinox Blueprint: Energy 2030* was released at the annual meeting of the American Association for the Advancement of Science (AAAS). It summarized the recommendations of Equinox Summit participants on potentially transformative technologies and strategies for their implementation. Through briefings and other activities, the report has been shared with more than 1,200 stakeholders worldwide, including science and technology leaders in industry and government.

American Association for the Advancement of Science

This year, Perimeter was there as the American Association for the Advancement of Science (AAAS) held its annual meeting in Vancouver. Attended by over 6,000 researchers, policymakers, educators, and media, it is the world's largest general science gathering. **Director Neil Turok** served as meeting co-chair and **Perimeter Board Chair Mike Lazaridis** gave a plenary talk, while Perimeter scientists and partners gave several presentations.

Media Engagement

In 2011/12, Perimeter Institute received major coverage in both national and international media, including *The Globe and Mail*, *National Post*, *Toronto Star*, *Maclean's*, CTV, CBC, NBC, *Wall Street Journal*, *Australian Herald*, *Nature*, *Science*, *National Geographic News*, *Der Spiegel*, and *The Economist*, among others.

Jordi Savall in concert

Cultural Events

"Artists and scientists differ in outcome, but our process is parallel. We share the energy of research and inspiration and interconnectivities. We share creativity as our source."

– Artist Reinhard Reitzenstein, whose sculptures based on atomic orbitals graced the Perimeter Atrium in 2012

Cultural events complement the Institute's research and outreach activities and provide a way to connect with the community at large. Made possible through paid ticketing and private support, presentations are designed to stimulate and enthrall. This year's popular presentations ranged from concerts by musical innovators like Laurie Anderson to an art exhibit inspired by concepts in atomic physics and concerts by classical masters.

The Classical World Artists series at Perimeter is generously supported by The Kitchener and Waterloo Community Foundation – Musagetes Fund.

MINUTEPHYSICS

Henry Reich had a tough time choosing between the arts and science, so in the end he chose both.

After graduating with a master's degree from Perimeter Scholars International (PSI), he headed west, intending to go to film school at UCLA in Los Angeles. While waiting for classes to begin, he uploaded an 85-second video on YouTube called "What is Gravity?" that explained one of physics' central concepts accessibly, using simple hand-drawn sketches and wry humour.

Subsequent videos followed weekly and, very soon, Henry had a viral sensation on his hands.

He has now created dozens of videos on subjects ranging from the Hairy Ball Theorem to the Higgs boson to why it's dark at night. His videos had been viewed over 60 million times by late 2012.

"PSI was fundamental in facilitating *MinutePhysics*," Reich says, citing the program's spirit of creativity and risk-taking, as well as the breadth of its teaching. "How much you learn over the course of a year in the PSI program is pretty astounding."

In 2011, Henry returned to Perimeter as its first Film & Media Digital Artist-in-Residence. In addition to creating *MinutePhysics* videos, he works with the Outreach team on new educational resources and co-organized the Brain*STEM* unconference for online science creators in June 2012.

ADVANCING PERIMETER'S MISSION

"Boundless curiosity is one of the most valuable resources we have. It is inexhaustible, and when we harness it, it has the power to change the world. A place like Perimeter recognizes the power of curiosity: it encourages scientists to collaborate and pursue their most ambitious work. I'm proud to support an institute that is bringing Canada to the forefront of research in theoretical physics."

– Catherine Delaney, Perimeter Institute Leadership Council Member

Perimeter began with a single bold insight: our entire technological society rests on physics' past discoveries – and its next discoveries will unlock the future.

As a fully independent research centre, Perimeter pursues a simple strategy: bring the world's best minds together in an inspiring environment, offer them unequalled research freedom, and enable them to focus on solving the deepest problems in theoretical physics.

Perimeter's ambitious mission, unique research community, and enterprising spirit have already attracted some of the world's top scientists. On any given day, over 150 researchers are at work in our state-of-the-art facility. Over a thousand scientists visit every year. Our faculty includes both renowned thinkers and rising young stars. Eminent scientists like Stephen Hawking have made Perimeter their second research home.

Today, Perimeter is funded by an ever-growing group of public and private supporters. They know that the best investment we can make is in our own capacity to question, to explain, and to understand.

PERIMETER INSTITUTE LEADERSHIP COUNCIL

The Perimeter Institute Leadership Council is a group of prominent individuals who volunteer their time, offer their guidance, and act as ambassadors for Perimeter to the business and philanthropic communities.

We are honoured to have this exceptional group of volunteers on board, and we would like to thank the Leadership Council for their support and hard work in 2011/12.

Mike Lazaridis, O.C., O.Ont.
Council Co-Chair
Founder and Chair, Board of Directors, Perimeter Institute
Founder, Board Vice-Chair, and Chair of the Innovation Committee, BlackBerry

Cosimo Fiorenza
Council Co-Chair
Vice-Chair, Board of Directors, Perimeter Institute
Vice-President and General Counsel, Infinite Potential Group

Jon S. Dellandrea, C.M.
Council Co-Chair
President and CEO, Sunnybrook Foundation

Alexandra (Alex) Brown
President, Aprilage Inc.

David Caputo
Co-Founder, President, and CEO, Sandvine

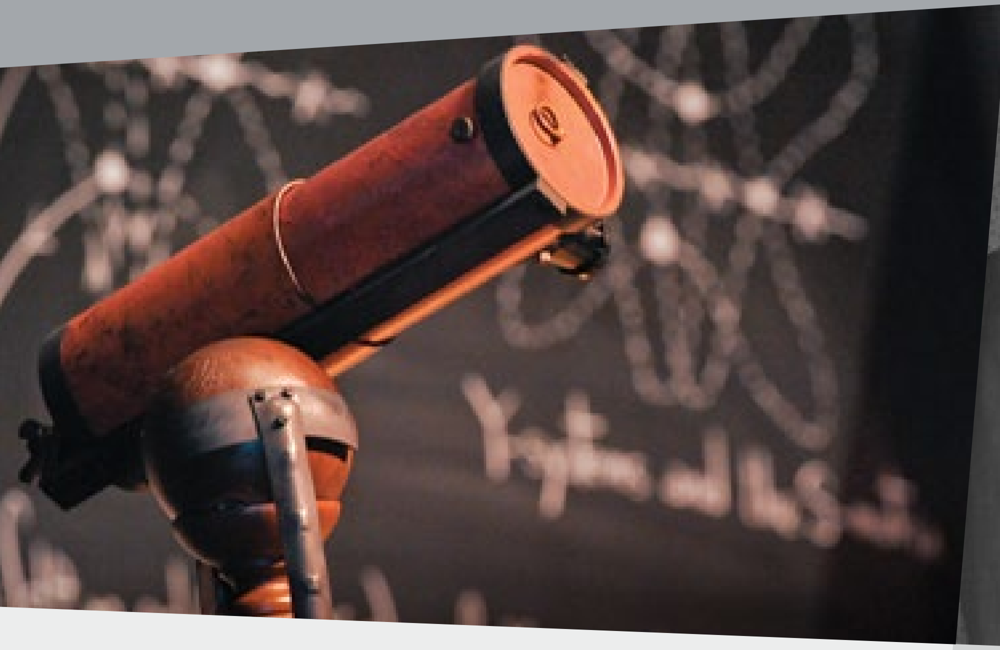
Savvas Chamberlain, C.M.
CEO and Chairman, Exel Research Inc.

Jim Cooper
President and CEO, Maplesoft

Catherine A. (Kiki) Delaney, C.M.
President, C.A. Delaney Capital Management Ltd.

Arlene Dickinson
CEO, Venture Communications Ltd.

Ginny Dybenko
Executive Director – Stratford Campus, University of Waterloo



H. Garfield Emerson, Q.C.
Principal, Emerson Advisory

Edward S. Goldenberg
Partner, Bennett Jones LLP

Tim Jackson
Vice-President, University Relations, University of Waterloo

Tom Jenkins
Executive Chairman and Chief Strategy Officer, Open Text Corporation

Farsad Kiani
President and CEO, The Ensil Group of Companies

Carol A. Lee
Co-Founder and CEO, Linacare Cosmetherapy Inc.

Michael Lee-Chin, O.J.
Executive Chairman and CEO, Portland Investment Counsel Inc.

Don Morrison
Philanthropist

Gerry Remers
President and COO, Christie Digital Systems Canada Inc.

Bruce M. Rothney, C.A.
President and Country Head, Canada, Barclays Capital Canada Inc.

Maureen J. Sabia, O.C.
Chairman of the Board, Canadian Tire Corporation Ltd.

Kevin Shea
Chair, Ontario Media Development Corporation

DONOR PROFILE: PETER AND SHELAGH GODSOE

This year, the Peter and Shelagh Godsoe Family Foundation made a generous gift to help fund Perimeter's research, training, and outreach activities.

"It was Mike Lazaridis and his passion and vision for PI," says Peter Godsoe, explaining why he and his wife, Shelagh, support Perimeter. "It's a vision and today a reality, with Neil Turok's leadership, to be a leading centre for theoretical physics – a centre where brilliant young minds gather together and make a difference not just for Canada, but for the world. With such a strategy, how could we say no?"

Peter, who is the retired Chairman and CEO of Scotiabank and a member of Perimeter's Board of Directors since 2008, received his BSc degree from the University of Toronto in mathematics and physics and his MBA from Harvard. His wife, Shelagh, has liberal arts and library degrees, also from U of T, and shares Peter's passion for Perimeter Institute and the opportunities it presents.

"Theoretical physics has changed the world positively in so many ways, ranging from cell phones and MRIs to understanding the cosmos. It's exciting to think about what a difference these ideas will make in the world to come," say Peter and Shelagh. "We're proud to be a small part of this wonderful success."

THANKS TO OUR SUPPORTERS

An ever-growing group of both public and private donors has helped make Perimeter what it is today: a world-leading centre for fundamental research, scientific training, and educational outreach. We are deeply grateful to all our supporters.

FOUNDER

Mike Lazaridis ($170 million)

ENDOWED GIFTS

Doug Fregin ($30 million)

Jim Balsillie ($10 million)

PERIMETER SPECIAL INITIATIVES

BMO Financial Group Isaac Newton Chair in Theoretical Physics ($4 million)

John Templeton Foundation – Templeton Frontiers Program at Perimeter Institute ($2 million)

CORPORATE DONORS

SPONSORS ($100,000+)

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The Peter & Shelagh Godsoe Family Foundation

DIRECTORS CIRCLE

$50,000+

Jon and Lyne Dellandrea

Brad and Kathy Marsland

Larry and Margaret Marsland

$30,000+

Maria Antonakos and Harald Stover

Don Campbell

Michael and Kathy Duschenes

Cosimo and Christina Fiorenza

Carol A. Lee

Barbara Palk and John Warwick

Dr. Neil Turok

$20,000+

Savvas and Christine Chamberlain

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Dave Caputo

Ginny Dybenko

H. Garfield Emerson

Richard and Donna Ivey

Reid Family

Bruce and Lisa Rothney

Maureen J. Sabia

$5,000+

Catherine A. Delaney

Dorian Hausman

Frederick Knittel

$2,500+

Ian and Debbie Adare

Greg Dick

Edward S. Goldenberg

Kevin Lynch

$1,000+

Alexandra Brown

Tim Jackson

Dave and Sue Scanlan

Alex White

… plus 1 anonymous

FRIENDS

Jeremy Bell and Sunny Tsang

John Biggs

Paulette Bourgeois

Richard Byers

Jason C.

Duncan Campbell

Piyush Chugh

J. DesBrisay and M. Cannell

James Facey

Vaishali, Vithushan, and L. Ganesh

Lorne Glazer

Timothy Hensman

Jane Hill

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Judi Jewinski

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Dietmar Sommerfeld
Dave Soock
Peter Suma
Nancy Theberge
Sree Ram Valluri
Peeranut Visetsuth
Dustin Windibank
Sam Znaimer
… plus 13 anonymous

EMMY NOETHER CIRCLE

$250,000+

The Ira Gluskin and Maxine Granovsky Gluskin Charitable Foundation

$100,000+

The Bluma Appel Community Trust

GIFTS IN CELEBRATION, HONOUR, AND MEMORY

Carolyn Crowe Ibele, in memory of Dr. Richard A. Crowe
Leslie Donovan, in memory of Sheila Donovan
Leslie Donovan, in honour of Martyn Poliakoff
Michael Normand, in memory of Clarence John Normand

FOUNDATION DONORS

The Cowan Foundation
The Henry White Kinnear Foundation
The Kitchener and Waterloo Community Foundation
- Musagetes Fund
- The John A. Pollock Family Fund

IN-KIND GIFTS

Christie Digital Systems Canada Inc.
nienkämper
The Record Community Partnership Program
Steinway Piano Gallery
TVO
Westbury National Show Systems Inc.

PERIMETER INSTITUTE PUBLIC PARTNERS

Government of Canada
Government of Ontario
Region of Waterloo
City of Waterloo

The above reflects gifts pledged or received from August 1, 2011 to December 31, 2012.

CATALYZING CHANGE: THE BLUMA APPEL COMMUNITY TRUST

Diversity breeds excellence. When great minds with diverse ideas come together, major advances become possible. This principle has been a key to Perimeter's success: contrasting approaches to fundamental questions are encouraged here and have enabled important scientific discoveries.

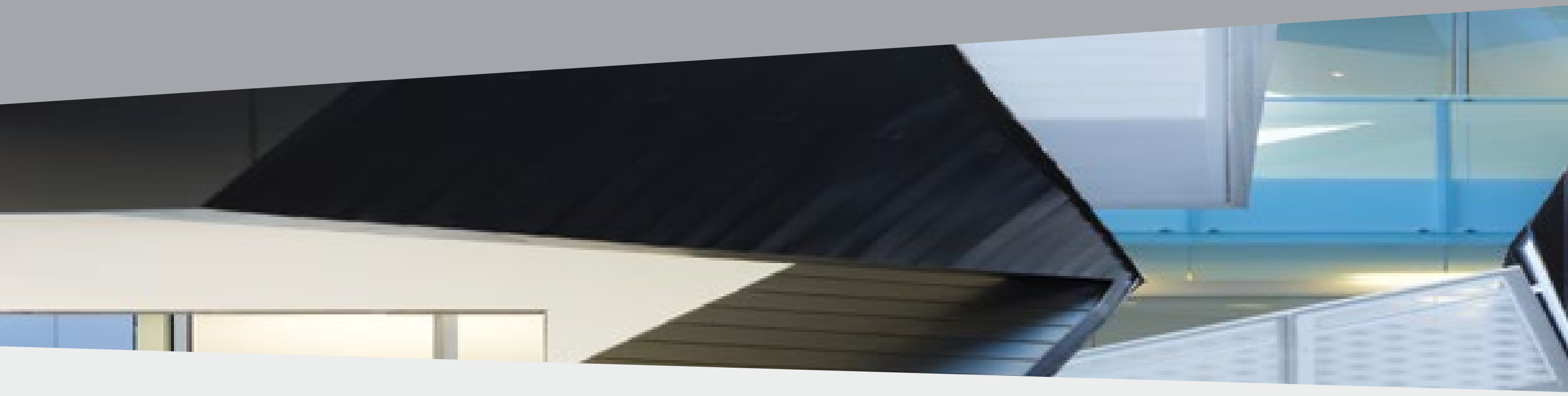
In the 20th century, places from hospitals to boardrooms to universities were transformed as significantly more women entered the workforce. That transformation has been slow to occur in physics, but Perimeter is trying to accelerate it by providing outstanding opportunities to female physicists and developing programs that will encourage young women to choose scientific careers.

This year, we received our first gift to support women in physics from The Bluma Appel Community Trust: $35,000 per year over three years for the PSI master's program. This gift will give three talented young women exceptional scientific training that will serve them well, wherever their careers take them.

It is a fitting gift. A tireless Canadian philanthropist, Bluma Appel was a champion for women in historically male-dominated environments, such as politics and corporate boardrooms. Her vision and generosity launched initiatives which transformed society, and individual lives.

We are grateful to The Bluma Appel Community Trust for this generous gift.

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.

Financial planning, accountability, and investment strategy are carried out by the Board's Investment and Finance & Audit Committees. 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 Chief Operating Officer (COO) reports to the Director and is in charge of day-to-day operations. Support for the COO is provided 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 Director.

The Scientific Advisory Committee (SAC), composed of eminent scientists drawn from the international community, is an integral oversight body, created to assist the Board of Directors and the Director to ensure objectivity and a high standard of scientific excellence.

BOARD OF DIRECTORS

Mike Lazaridis, O.C., O.Ont., Chair, is Founder, Board Vice-Chair, and Chair of the Innovation Committee of BlackBerry (formerly Research In Motion Limited). A visionary, innovator, and engineer of extraordinary talent, he transformed the communications industry with the development of the BlackBerry®. He is the recipient of many technology and business awards, a Fellow of the Royal Society of Canada, and a recipient of both the Order of Ontario and the Order of Canada.

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 the 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.

Peter Godsoe, O.C., O.Ont., is the former Chairman & 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.

Kevin Lynch, P.C., O.C., is a distinguished former public servant with 33 years of service with the Government of Canada. Most recently, Dr. Lynch served as Clerk of the Privy Council, Secretary to the Cabinet, and Head of the Public Service of Canada. Prior roles included Deputy Minister of Finance, Deputy Minister of Industry, and Executive Director (Canada, Ireland, Caribbean) of the International Monetary Fund. He is presently the Vice-Chair of BMO Financial Group.

Steve MacLean is President of the Canadian Space Agency (CSA). A physicist by training, in 1983 he was selected as one of the first six Canadian astronauts and he has participated in missions on the Space Shuttles Columbia (1992) and Atlantis (2006) to the International Space Station. In addition to senior roles within the CSA and extensive experience with NASA and the International Space Station, he is a strong supporter of science literacy and child education.

Art McDonald has been the Director of the Sudbury Neutrino Observatory (SNO) experiment for over 20 years. He holds the Gordon and Patricia Gray Chair in Particle Astrophysics at Queen's University and works on the new SNO+ and DEAP experiments at the international SNOLAB, researching an accurate measurement of neutrino mass and seeking to observe directly dark matter particles making up a large fraction of the universe. Professor McDonald has received numerous awards for his research, including the 2011 Henry Marshall Tory Medal from the Royal Society of Canada and the 2007 Benjamin Franklin Medal in Physics, alongside researcher Yoji Totsuka. He was named an Officer of the Order of Canada in 2007.

Barbara Palk recently retired as President of TD Asset Management Inc., one of Canada's leading money management firms, and as Senior Vice-President of TD Bank Financial Group. She is a Fellow of the Canadian Securities Institute, a CFA Charterholder, and a member of both the Toronto Society of Financial Analysts and the Institute of Corporate Directors. Ms. Palk is Chair of the Board of Queen's University and a member of the Boards of the Ontario Teachers' Pension Plan, TD Asset Management, USA Funds Inc., and Greenwood College School. She is a recipient of the Ontario Volunteer Award and was honoured by the Women's Executive Network in 2004 as one of Canada's Most Powerful Women: Top 100 in the Trailblazer category.

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.

SCIENTIFIC ADVISORY COMMITTEE

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.' Professor 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. Professor Loll is a Perimeter Institute Distinguished Visiting Research Chair and is also a lecturer in the Perimeter Scholars International program.

Matthew Fisher, Kavli Institute for Theoretical Physics/University of California at Santa Barbara (2009-Present). Professor Fisher is a condensed matter theorist whose research has focused on strongly correlated systems, especially low-dimensional systems, Mott insulators, quantum magnetism, and the quantum Hall effect. He 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. Professor Fisher has over 160 publications.

Brian Greene, Columbia University (2010-Present). Professor Greene is a Professor of Mathematics and Physics at Columbia University, where he is co-Director of the Institute for Strings, Cosmology, and Astroparticle Physics (ISCAP). Professor Greene has made ground-breaking discoveries in superstring theory, exploring the physical implications and mathematical properties of the extra dimensions the theory posits. His current research centres on string cosmology, seeking to understand the physics of the universe's first moments. Professor Greene is well known for his work on communicating theoretical physics for general audiences, and his books include *The Elegant Universe*, which has sold more than a million copies worldwide; *The Fabric of the Cosmos*, which spent six months on The New York Times Best Seller list; and *Icarus at the Edge of Time, A Children's Tale*. A three-part NOVA special based on *The Elegant Universe* won both the Emmy and Peabody Awards.

Erik Peter Verlinde, Institute of Theoretical Physics/University of Amsterdam (2010-Present). Professor Verlinde is a Professor of Theoretical Physics at the Institute for Theoretical Physics at the University of Amsterdam. He is world renowned for his many contributions, including Verlinde algebra and the Verlinde formula, which are important in conformal field theory and topological field theory. His research centres on string theory, gravity, black holes, and cosmology. Professor Verlinde recently proposed a holographic theory of gravity which appears to lead naturally to the observed values of dark energy in the universe.

Birgitta Whaley, Berkeley Quantum Information and Computation Center/University of California, Berkeley (2010-Present). Professor Whaley is a Professor in the Department of Chemistry at the University of California, Berkeley, where she is Director of the Berkeley Quantum Information and Computation Center. Professor Whaley's research centres on understanding and manipulating quantum dynamics of atoms, molecules, and nanomaterials in complex environments to explore fundamental issues in quantum behaviour. She has made major contributions to the analysis and control of decoherence and universality in quantum information processing, as well as to the analysis of physical implementations of quantum computation. Professor Whaley is also known for her theory of molecular solvation in nanoscale superfluid helium systems. Her current research includes theoretical analysis of quantum information and computation, coherent control and simulation of complex quantum systems, macroscopic quantum coherence, and quantum effects in biological systems.

FACILITY

"It is a tremendous honour to have this expansion of Perimeter Institute named for me. … The centre's clear focus, inspiring design, and productive research interactions will no doubt attract many leading scientists here. Perimeter is on a great path, and I am delighted to be associated with it."

– Stephen Hawking

Perimeter Institute is located in Waterloo, Ontario, Canada, approximately an hour from Toronto. Waterloo Region is home to two major universities – the University of Waterloo and Wilfrid Laurier University – and over 800 high-tech companies.

Perimeter's iconic building is a state-of-the-art facility designed to inspire big ideas and maximize research productivity. Its thoughtful design incorporates ubiquitous chalkboards, lively open collaboration and teaching areas, serene areas for solitary concentration, cutting-edge IT infrastructure, and the warm and inviting Black Hole Bistro.

THE STEPHEN HAWKING CENTRE

The spectacular Stephen Hawking Centre (SHC) expansion, which opened this year, has nearly doubled the Institute's size to 120,000 square feet. It accommodates up to 250 researchers and students, making Perimeter the largest centre for theoretical physics research in the world.

The Government of Canada (via the Canada Foundation for Innovation) and Ontario's Ministry of Research and Innovation provided a total of $20.8 million toward the expansion, which was completed on schedule and under budget. The balance came from private funds raised by the Institute. Perimeter thanks its visionary supporters, public and private.

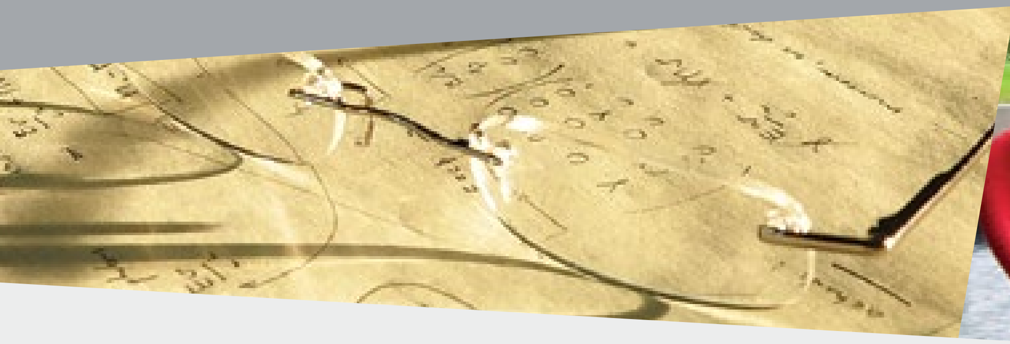
Designed by Teeple Architects, the SHC was honoured with a 2012 Design Excellence award from the Ontario Association of Architects and was selected for the William G. Dailey Award of Excellence as "the best overall project in the city" at the City of Waterloo's 2012 Urban Design Awards.

More than 11,000 people attended the SHC Grand Opening celebrations in September 2011, which spanned three days of tours, exhibits, public lectures, and special events. Many more tuned in to two days of science-based programming on-air and online via TVO, our presenting media partner.

BEYOND THE BLACKBOARD

This year, Perimeter launched the High Performance Computing Cluster (HPCC), a supercomputer capable of executing complex analyses and simulations required by much of modern physics. Combined with the expertise in numerical and computational algorithms provided by Perimeter's Research Technology Group, the HPCC takes computational physics at Perimeter to a new level.

FINANCIALS



RESULTS OF OPERATIONS

In 2011/12, Perimeter Institute continued to make good progress on all initiatives in its five-year strategic plan.

A major facility expansion representing a substantial capital expenditure, the Stephen Hawking Centre at Perimeter Institute, was successfully completed. The Institute continued to spend strategically on its core mission areas of research, training, and outreach, increasing expenditures in these areas by over $2 million, or 15 percent, over the previous year. $1.2 million, or 60 percent, of this increase was in research, Perimeter's major focus area, and was largely due to new faculty recruitment. Strategic recruitment will remain a priority as the Institute continues to build a critical mass of researchers over the coming years.

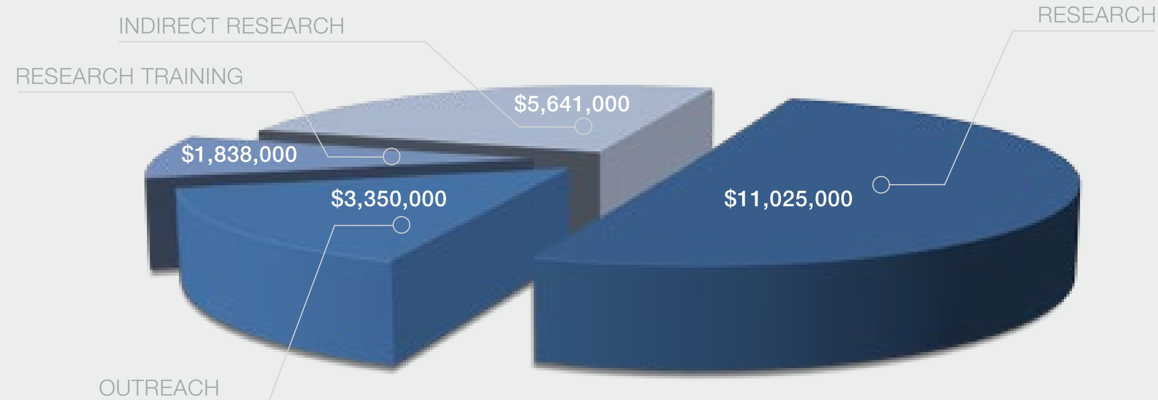
The Institute increased investment by nine percent in its research training programs, Perimeter Scholars International and the PhD program, both of which, in collaboration with university partners, attract highly talented graduates from around the world. Outreach and science communications expenditures increased by 29 percent, extending Perimeter's reach to students, teachers, and the general public through existing and new programs and pedagogical materials.

Indirect research and operating expenditures cover the costs of core support areas, including administration, information technology, and facilities. As anticipated, facility and information technology expenditures comprised 70 percent of the overall $1.1 million increase in 2011/12, as researchers and staff moved into the new Stephen Hawking Centre. The costs of the Institute's advancement activities are also included under indirect research and operations. Advancement activities generated over $1 million in donations (and a total of $7.8 million in commitments) as the Institute continued to expand and enhance its public-private funding model.

Perimeter Institute's investment strategy, strong oversight, and portfolio management allowed its endowment fund to generate $7.6 million. This success occurred despite a challenging macro environment.

OPERATING EXPENDITURE SUMMARY

For the year ended July 31, 2012



FINANCIAL POSITION

Even with the completion of the Stephen Hawking Centre, a significant capital project, Perimeter Institute continues to experience a strong working capital position. This position allows the Institute to act quickly on targets of opportunity, giving it a considerable competitive advantage in accelerating its research and outreach objectives. Although bank indebtedness is incurred during the year, it is strategically leveraged and used only as a temporary measure.

The endowment fund primarily allows for the accumulation of private funds to address the Institute's future needs. The $213 million fund consists of a portfolio mix of domestic equities, international equities, fixed income, and alternative investments specifically designed in accordance with PI's risk-return objectives.

RISKS AND UNCERTAINTIES

Perimeter Institute exists through a cooperative and highly successful public-private partnership that provides for ongoing operations while safeguarding future opportunities.

New funding commitments of $50 million from the federal government (ending March 31, 2017) and $50 million from the provincial government (ending July 31, 2021) reinforce PI's strong collaboration with public partners and the value they see in investing in the Institute.

The multi-year government commitments totalling $100 million clearly demonstrate that the Institute is perceived by government as an excellent investment; however, no guarantee of future funding beyond the above commitment exists.

Perimeter Institute is also seeking to raise yearly operating funds for the Institute, as well as increase endowment assets over the coming years, through an ambitious private sector fundraising initiative.

Private sector donations, in accordance with donor requests, are either utilized as contributions towards operational expenditures or are protected in an endowment fund. The endowment fund is designed to maximize growth and minimize risk in order to contribute to the strongest possible long-term financial health of the Institute. Although the endowment is invested in a diversified portfolio and managed by an active investment committee of experts, market values do vary over time.

ZEIFMANS
LLP
CHARTERED ACCOUNTANTS

201 Bridgeland Avenue
Toronto, Ontario M6A 1Y7
Tel: (416) 256-4000
Fax: (416) 256-4001
Email: info@zeifmans.ca
www.zeifmans.ca

To the Directors of
Perimeter Institute

The accompanying summary financial statements, which comprise the summary statement of financial position as at July 31, 2012, the summary statement of operations and changes in fund balances for the year then ended, are derived from the financial statements of Perimeter Institute (the "Institute") as at, and for the year ended, July 31, 2012. We expressed an unmodified audit opinion on those financial statements in our report dated December 7, 2012. 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 generally accepted accounting principles. 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 audited financial statements in accordance with Canadian generally accepted accounting principles.

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 of Summary Financial Statements."

Opinion

In our opinion, the summary financial statements derived from the audited financial statements of the Institute as at, and for the year ended July 31, 2012 are a fair summary of those financial statements, in accordance with Canadian generally accepted accounting principles.

Zeifmans LLP

Toronto, Ontario	Chartered Accountants
December 7, 2012	Licensed Public Accountants

Zeifmans LLP is a member of Nexia International, a worldwide network of independent accounting and consulting firms.

NEXIA INTERNATIONAL

CA

PERIMETER INSTITUTE

SUMMARIZED STATEMENT OF FINANCIAL POSITION

AS AT JULY 31, 2012

	2012	2011
ASSETS		
Current assets:		
Cash and cash equivalents	$ 1,697,000	$ 1,082,000
Investments	211,417,000	218,970,000
Government grants receivable	4,294,000	2,145,000
Other current assets	1,151,000	2,168,000
Assets held for sale	1,235,000	---
	219,794,000	224,365,000
Property and equipment	55,281,000	55,489,000
TOTAL ASSETS	$ 275,075,000	$ 279,854,000
LIABILITIES AND FUND BALANCE		
Current liabilities:		
Bank overdraft	$ 732,000	$ 577,000
Bank indebtedness	2,245,000	1,330,000
Accounts payable and other current liabilities	2,331,000	6,168,000
TOTAL LIABILITIES	$ 5,308,000	$ 8,075,000
Fund balance		
Invested in capital assets	56,495,000	53,536,000
Externally restricted	105,589,000	100,128,000
Internally restricted	78,840,000	78,840,000
Unrestricted	28,843,000	39,275,000
TOTAL FUND BALANCES	269,767,000	271,779,000
	$ 275,075,000	$ 279,854,000

ZEIFMANS LLP CHARTERED ACCOUNTANTS

PERIMETER INSTITUTE

SUMMARIZED STATEMENT OF OPERATIONS AND CHANGES IN FUND BALANCES

FOR THE YEAR ENDED JULY 31, 2012

	2012	2011
Revenue:		
Government grants	$ 14,412,000	$ 18,190,000
Other income	741,000	425,000
Donations	1,142,000	212,000
	16,295,000	18,827,000
Expenses:		
Research	11,025,000	9,748,000
Research training	1,838,000	1,688,000
Outreach and science communications	3,350,000	2,601,000
Indirect research and operations	5,641,000	4,535,000
TOTAL OPERATING EXPENDITURES	21,854,000	18,572,000
Excess of revenue over expenses (expenses over revenue) before investment income and amortization	(5,559,000)	255,000
Amortization	(4,098,000)	(1,573,000)
Investment income	7,645,000	20,940,000
Excess of revenue over expenses (expenses over revenue)	2,012,000	19,622,000
Fund balances, beginning of year	271,779,000	252,157,000
FUND BALANCES, END OF YEAR	$ 269,767,000	$ 271,779,000

ZEIFMANS LLP
CHARTERED ACCOUNTANTS

LOOKING AHEAD: PRIORITIES AND OBJECTIVES FOR THE FUTURE

In the coming year, the Institute will continue to advance its core mission and goals, based upon the following strategic objectives:

Deliver world-class research discoveries by continually seeking to advance fundamental research across Perimeter's areas of focus, encouraging complementary approaches and a collaborative atmosphere which maximizes cross-fertilization and the probability of breakthroughs.

Become the research home of a critical mass of the world's leading theoretical physicists by continuing to recruit top talent, offering research opportunities second to none, and fostering cooperative links throughout the Canadian and international research community.

Generate a flow-through of the most promising talent by recruiting the world's top postdoctoral researchers, facilitating researcher engagement with experimental and observational centres, attracting and training brilliant young graduate students through the PSI program and recruiting the best for further PhD training, and providing research training opportunities to promising undergraduate students.

Become the second research home for many of the world's outstanding theorists by continuing to recruit top scientists to the Distinguished Visiting Research Chairs program, attracting Visiting Researchers and Visiting Fellows of exceptional calibre, and developing agreements that encourage joint activities between researchers at Perimeter and leading centres throughout the world.

Act as a hub for a network of theoretical physics and math centres around the world, seeking partnership and collaboration opportunities that can help accelerate the creation of centres of excellence in math and physics.

Increase Perimeter's role as Canada's focal point for foundational physics research by continuing to develop national and international relationships, maximizing technologies allowing remote participation, and fostering research interaction opportunities between faculty members and affiliates across the country.

Host timely, focused conferences, workshops, seminars, and courses on cutting-edge topics.

Engage in high impact outreach by communicating the importance of basic research and the power of theoretical physics to general audiences, while also providing unique opportunities and high quality resources to educators and students.

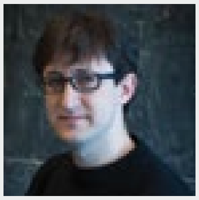
Create the world's best environment and infrastructure for theoretical physics research, training, and outreach.

Continue to build on Perimeter's highly successful public-private partnership funding model.

APPENDICES

FACULTY

Neil Turok (PhD Imperial College London, 1983) joined the Institute as its Director in 2008, having previously held positions as a Professor of Physics at Princeton University and Chair of Mathematical Physics at the University of Cambridge. Turok's work 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 and of the galaxy-cosmic background correlations induced by dark energy have been confirmed. With Stephen Hawking, he discovered instanton solutions describing the birth of inflationary universes. His work on open inflation forms the basis of the now-popular multiverse paradigm. With Paul Steinhardt, 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. Among his many honours, Turok was awarded Sloan and Packard Fellowships and the 1992 James Clerk Maxwell medal of the Institute of Physics (UK). He is a Canadian Institute for Advanced Research (CIFAR) Fellow in Cosmology and Gravity and was selected to deliver the 2012 CBC Massey Lectures. Born in South Africa, Turok founded the African Institute for Mathematical Sciences (AIMS) in Cape Town, South Africa. He has been recognized with a TED Prize and awards from the World Summit on Innovation and Entrepreneurship (WSIE) and the World Innovation Summit on Education (WISE).



Latham Boyle (PhD Princeton University, 2006) joined the Institute as a junior Faculty member 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 recently 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) has been a Faculty member at Perimeter 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 an Early Researcher Award (2007), the Gribov Medal of the European Physical Society (2009), the Rutherford Memorial Medal in Physics from the Royal Society of Canada (2011), and the Herzberg Medal (2012).

Bianca Dittrich (PhD Max Planck Institute for Gravitational Physics, 2005) joined Perimeter's faculty in January 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. In 2007, Dittrich received the Otto Hahn Medal of the Max Planck Society, which recognizes outstanding young scientists.

Laurent Freidel (PhD L'École Normale Supérieure de Lyon, 1994) joined Perimeter Institute in September 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. Freidel is also the recipient of several awards, including two ACI-Blanche grants in France.

Davide Gaiotto (PhD Princeton University, 2004) joined Perimeter in May 2012. 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. In 2011, he was awarded the Gribov Medal of the European Physical Society.

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 40 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 as a Faculty member 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.

Fotini Markopoulou (PhD Imperial College London, 1998) joined the Institute as one of its first Faculty members in 2001, prior to which she held postdoctoral positions at the Albert Einstein Institute (2000-01), Imperial College London (1999-2000), and Pennsylvania State University (1997-99). Markopoulou is a past recipient of First Prize in the Science and Ultimate Reality Young Researchers Competition in honour of J.A. Wheeler (2001). She was also awarded an Alexander von Humboldt Fellowship for Experienced Researchers at the Albert Einstein Institute in Germany.

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).

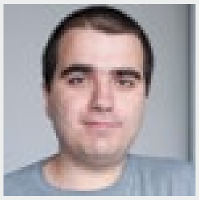
Philip Schuster (PhD Harvard University, 2007) joined Perimeter's faculty in 2010. He was a Research Associate at SLAC National Accelerator Laboratory from 2007 to 2010. Schuster's area of specialty is particle theory, with an emphasis on physics beyond the Standard Model. He has close ties to experiment 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.

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 6,400 citations to date and he has written four non-technical books. Smolin's many honours include the Majorana Prize (2007), the Klopsteg Memorial Award (2009), 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.

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 upcoming 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.

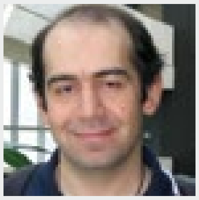
Guifre Vidal (PhD University of Barcelona, 1999) joined Perimeter's faculty in 2011 from the University of Queensland in Brisbane, where he was an Australian Research Council Federation Fellow and Professor in the School of Mathematics and Physics. He did postdoctoral fellowships at the University of 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 Paris and the Theoretical Physics Center at University of Porto, 2008) joined Perimeter in 2009 from the Max Planck Institute for Gravitational Physics (Albert Einstein Institute), where he was a Junior Scientist 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*. He also won an Early Researcher Award in 2012.

Xiao-Gang Wen (PhD Princeton University, 1987) joined Perimeter's faculty in May 2012. 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).

Avery Broderick (PhD California Institute of Technology, 2004) began a joint appointment with Perimeter and the University of Waterloo in September 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. 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), before joining Perimeter's faculty in 2003. 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.

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 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).

Adrian Kent (PhD University of Cambridge, 1986) is jointly appointed with the University of Cambridge. Prior to joining Perimeter's faculty, he was 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. Kent's 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.

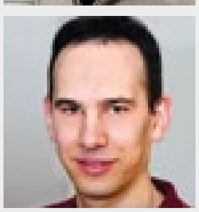
Raymond Laflamme (PhD University of Cambridge, 1988) is a founding Faculty member of Perimeter Institute and founding Director of the Institute for Quantum Computing, where he is jointly appointed. He held research positions at the University of British Columbia and Peterhouse College, University of 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 recently 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.

Luis Lehner (PhD University of Pittsburgh, 1998) began a joint appointment with Perimeter and the University of Guelph in 2009. 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 Canadian Institute for Advanced Research (CIFAR) in the Cosmology and Gravity program, the Institute of Physics, and the American Physical Society.

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).

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.

RESIDENT RESEARCHERS

Senior Researcher
Christopher Fuchs

Senior Researcher
Rafael Sorkin

Resident Research Affiliate
John Moffat

POSTDOCTORAL RESEARCHERS, 2011/12

Haipeng An
Lilia Anguelova
Ido Ben-Dayan
Joseph Ben Geloun
Eugenio Bianchi
Hector Bombin
Valentin Bonzom
Oliver Buerschaper
Eric Chitambar
Lukasz Cincio
William Edwards
Astrid Eichhorn
Adrienne Erickcek
Cecilia Flori
Steffen Gielen
Simone Giombi
Razvan Gurau
Alioscia Hamma
Chad Hanna
Janet Hung
Matthew Johnson
Tim Koslowski
Louis Leblond
Mercedes Martin-Benito
Paul McFadden
Leonardo Modesto
Alberto Montina
Markus Mueller
Satoshi Nawata
Robert Pfeifer
Josef Pradler
Luiz Santos
Natalia Saulina
Amit Sever
Yanwen Shang
David Skinner
Misha Smolkin
Carlos Tamarit

SCIENTIFIC VISITORS, 2011/12

** Indicates Distinguished Visiting Research Chair*
*** Indicates Visiting Fellow*
**** Indicates long-term Visiting Researcher*
Please note that researchers who made multiple visits are listed only once.

Dmitry Abanin, Harvard University
Samson Abramsky, University of Oxford
Prateek Agrawal, University of Maryland, College Park
Yakir Aharonov*, Chapman University and Tel Aviv University
Emil Akhmedov***, Institute for Theoretical and Experimental Physics
Stephon Alexander, Haverford College
Jan Ambjorn, Utrecht University
Giovanni Amelino-Camelia, Sapienza University of Rome
Luigi Amico***, University of Catania
Edward Anderson, University of Cambridge
Damiano Anselmi***, University of Pisa
Francesco Aprile, University of Barcelona
Sujay Ashok, Institute of Mathematical Sciences, Chennai
Benjamin Assel, École Normale Supérieure
Benjamin Bahr, Max Planck Institute for Gravitational Physics (Albert Einstein Institute)
Cosimo Bambi, Arnold Sommerfeld Center for Theoretical Physics/Ludwig Maximilian University of Munich
Jean-Daniel Bancal, University of Geneva
Aristide Baratin, Centre de Physique Theorique, Ecole Polytechnique France
Enrico Barausse, University of Maryland
James Bardeen*, University of Washington
Neil Barnaby, University of Minnesota
Howard Barnum, University of New Mexico
Jonathan Barrett**, Royal Holloway/ University of London
Itzhak Bars, University of Southern California
Stephen Bartlett, University of Sydney
Ganapathy Baskaran*, Institute of Mathematical Sciences, Chennai
Benjamin Basso, Princeton University
Hugo Beauchemin, Tufts University
John Bell, Western University
Carl Bender, Washington University
Dionigi Benincasa, Imperial College London
Cedric Beny, University of Hannover
Lasha Berezhiani, New York University
Joshua Berger, Cornell University
Tirthabir Biswas, Loyola University New Orleans
Monika Blanke, Cornell University
Norbert Bodendorfer, Institute for Theoretical Physics III/University of Erlangen-Nürnberg
Rutger Boels, University of Hamburg
Ivan Booth, Memorial University
Nassim Bozorgnia, University of California at Los Angeles
Kamil Bradler, McGill University
Fernando Brandao, Federal University of Minas Gerais
Robert Brandenberger, McGill University
Courtney Brell, University of Sydney
Aharon Brodutch, Macquarie University
Benjamin Brown, Imperial College London
Dan Browne, University College London
Michel Buck, King's College London
Timothy Budd, Institute for Theoretical Physics/Utrecht University
Matthew Buican, European Organization for Nuclear Research (CERN)
Fiona Burnell, University of Oxford
Francesco Buscemi, University of Nagoya
Philip Candelas***, University of Oxford
Sylvain Carrozza, Max Planck Institute for Gravitational Physics (Albert Einstein Institute)
Hilary Carteret, University of Calgary
Horacio Casini, Bariloche Atomic Centre
Simon Caterall, Syracuse University
Sarah Chadburn, University of Durham
John Chalker, University of Oxford
Claudio Chamon, Boston University
Mikhail Chapochnikov, École Polytechnique Fédérale de Lausanne

Xie Chen, Massachusetts Institute of Technology

Eric Chitambar, University of Toronto

Hyung S. Choi, John Templeton Foundation

Bryan Clark, Princeton University

Kate Clements, Imperial College London

James Cline, McGill University

Emilio Cobanera, Indiana University Bloomington

Bob Coecke, University of Oxford

Samuel Colin, Griffith University

Philippe Corboz, Swiss Federal Institute of Technology Zurich

Miguel Costa, University of Porto

David Craig***, Le Moyne College, Syracuse

Francis-Yan Cyr-Racine, University of British Columbia

Bartek Czech, University of British Columbia

Oscar Dahlsten, University of Oxford

Mauro D'Ariano, University of Pavia

Saurya Das, University of Lethbridge

Arundhati Dasgupta, University of Lethbridge

Rhys Davies, University of Oxford

Henrique de Andrade Gomes, University of California, Davis

Xenia de la Ossa***, University of Oxford

Albert De Roeck, European Organization for Nuclear Research (CERN)

Adrian Del Maestro, University of Vermont

Lidia del Rio, Swiss Federal Institute of Technology Zurich

Tommaso Demarie, Macquarie University

Francesco D'Eramo, Massachusetts Institute of Technology

Andrei Derevianko, University of Nevada

Massimiliano Di Ventra, University of California at San Diego

Jacobo Diaz-Polo, Louisiana State University

Babette Doebrich, German Electron Synchrotron (DESY)

Fay Dowker, Imperial College London

Nadav Drukker, Imperial College London

Luming Duan, University of Michigan

Maïté Dupuis, Institute for Theoretical Physics III/University of Erlangen-Nürnberg

Jacek Piotr Dziarmaga, Institute of Physics/Jagiellonian University

Jeff Egger, University of Edinburgh

Joseph Emerson***, Institute for Quantum Computing/University of Waterloo

Rouven Essig, C.N. Yang Institute of Theoretical Physics/Stony Brook University

John Estes, University of California at Los Angeles

Jason Evans, University of Tokyo

Jacques Farine, SNOLAB

Brian Feldstein, Institute for the Physics and Mathematics of the Universe (IPMU)

Bo Feng, Zhejiang University

Pedro Ferreira, University of Oxford

Andy Ferris, University of Sherbrooke

Steve Flammia, University of Washington

Raphael Flauger, Institute for Advanced Study and New York University

Felix Flicker, University of Bristol

Omar Foda, University of Melbourne

Ricky Fok, York University

Jean-Francois Fortin, University of California, San Diego

Melissa Frei, Rochester Institute of Technology

Herbert Fried, Brown University

Tobias Fritz, Institute of Photonic Sciences

Gregory Gabadadze***, New York University

Ilmar Gahramanov, University of Hamburg

S. James Gates Jr.*, University of Maryland

Yufei Ge, Massachusetts Institute of Technology

Jack Gegenberg, University of New Brunswick

Marc Geiller, APC France

Dina Genkina, University of Maryland

Damien George, National Institute for Subatomic Physics (Nikhef)

Ghazal Geshnizjani, State University of New York at Buffalo

Vasco Goncalves, University of Porto

Alexey Gorshkov, California Institute of Technology

David Gosset, Institute for Quantum Computing/University of Waterloo

Darren Grant, University of Alberta

Barry Green, African Institute for Mathematical Sciences (AIMS)-South Africa

Daniel Green, Institute for Advanced Study

Stephen Green, University of Chicago

Lauren Greenspan, University of Porto

Eric Greenwood, Case Western Reserve University

Ruth Gregory**, University of Durham

Nikolay Gromov, King's College London

Tarun Grover, University of California, Berkeley

Zheng-Cheng Gu, Kavli Institute for Theoretical Physics/University of California, Santa Barbara

Yelena Guryanova, University of Bristol

Yuri Gusev, Lebedev Physical Institute, Moscow

Jeongwan Haah, California Institute of Technology

Jutho Haegeman, Ghent University

Hal Haggard, University of California, Berkeley

Gabor Halasz, University of Cambridge

Sebastian Halter, Max Planck Institute for Physics, Munich

Muxin Han, Centre of Theoretical Physics / Aix-Marseille University

Tao Han, University of Pittsburgh

Daniel Lord Harlow, Stanford University

John Harnad, Concordia University

Steve Harris***, Saint Louis University

Patrick Hayden*, McGill University

Song He, Max Planck Institute for Gravitational Physics (Albert Einstein Institute)

Jonathan Heckman, Institute for Advanced Study

Thomas Hertog, Astroparticle and Cosmology (APC)/Paris Diderot University

Philipp Hoehn, Institute for Theoretical Physics/Utrecht University

Kazuo Hosomichi, Yukawa Institute for Theoretical Physics/Kyoto University

Pavan Hosur, University of California, Berkeley

Jinrui Huang, University of California, Irvine

Michael Hudson, University of Waterloo

Taylor Hughes, University of Illinois at Urbana-Champaign

Scott Hughes***, Massachusetts Institute of Technology

Viqar Husain, University of New Brunswick

Dragan Huterer, University of Michigan

Adrian Hutter, Swiss Federal Institute of Technology Zurich

Kenneth Intriligator, University of California at San Diego

Eder Izaguirre, Stanford University

Sarah Jackson, African Institute for Mathematical Sciences (AIMS)-South Africa

Prerit Jaiswal, Stony Brook University

Dominik Janzing, Max Planck Institute for Biological Cybernetics

Romuald Janik***, Neils Bohr Institute/University of Copenhagen

Kristan Jensen, University of Victoria

Liang Jiang, California Institute of Technology

Leo Kadanoff*, James Franck Institute/University of Chicago

Manoj Kaplinghat, University of California, Irvine

Marc Kamionkowski, John Hopkins University

Yong-Baek Kim, University of Toronto

Jukka Kiukas, University of Hannover

John Klauder***, University of Florida

Takeshi Kobayashi, Canadian Institute for Theoretical Astrophysics/University of Toronto

Robert Koenig, IBM Thomas J. Watson Research Center

Amy Kolan, St. Olaf College

Zohar Komargodski, Institute for Advanced Study

Eiichiro Komatsu, University of Texas at Austin

Gregory Korchemsky, Institut de Physique Theorique, CEA Saclay

Ryszard Kostecki, University of Warsaw

Pavel Kovtun***, University of Victoria

Jerzy Kowalski-Glikman, University of Wroclaw

Gordan Krnjaic, John Hopkins University

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CONFERENCES AND WORKSHOPS, 2011/12

Mathematica Summer School 2011
July 31-August 6, 2011

Exact Results in Gauge/Gravity Dualities
August 8-12, 2011

Integrability in Gauge/String Theories
August 15-19, 2011

Unravelling Dark Matter
September 22-24, 2011

Tensor Networks for Quantum Field Theories
October 24-25, 2011

Emergence and Effective Field Theories
October 26-28, 2011

Effective Field Theory and Gravitational Physics
November 28-30, 2011

Recent Progress in Quantum Algorithms
April 11-13, 2012

Higgs: Now and in the Future
April 23-24, 2012

4-Corner Southwest Condensed Matter Symposium 2012
May 3, 2012

GAP 2012 (Geometry and Physics)
May 5-7, 2012

Conformal Nature of the Universe
May 9-12, 2012

The Canadian Society for the History and Philosophy of Science (CHSPS) Annual Meeting
May 28, 2012

Background and Methods of Highly Frustrated Magnetism
June 3, 2012

Exploring AdS/CFT Dualities in Dynamical Settings
June 4-8, 2012

Back to the Bootstrap II
June 11-15, 2012

Relativistic Quantum Information
June 25-28, 2012

COURSES, 2011/12

Introduction to Pure Spinor Formalism of the Superstring
Instructor: Nathan Berkovits, Institute for Theoretical Physics/Sao Paulo State University
August 23-26, 2011
Viewable at: http://www.pirsa.org/C11030

AdS/CFT Correspondence
Instructors: Lilia Anguelova and Robert Myers, Perimeter Institute
October 24-December 15, 2011 and January 2-30, 2012

Topos Quantum Physics
Instructor: Cecilia Flori, Perimeter Institute
January 9-February 17, 2012
Viewable at: http://www.pirsa.org/C12016

Advanced Quantum Field Theory
Instructor: Cliff Burgess, McMaster University and Perimeter Institute
January 10-April 3, 2012
Viewable at: http://www.pirsa.org/C12018

Advanced General Relativity
Instructor: Eric Poisson, University of Guelph
January 11-April 18, 2012
Viewable at: http://www.pirsa.org/C12017

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Perimeter sponsored the following Canadian and international scientific events and activities in 2011/12:

"2nd AQuA Student Congress on Quantum Information and Computation and the 9th Canadian Student Conference on Quantum Information," Institute for Quantum Computing/University of Waterloo

"3rd Conference of the Canadian Prairie Theoretical Physics Network," First Nations University

"12th Canadian Summer School on Quantum Information," Institute for Quantum Computing/University of Waterloo

"14th Canadian Conference on General Relativity and Relativistic Astrophysics," Memorial University

"21st International Laser Physics Workshop," University of Calgary

"60th Birthday Conference in Honor of John Preskill," California Institute of Technology

"Cape Town International Cosmology School 2012," Stellenbosch Institute for Advanced Studies

"Lake Louise Winter Institute 2012," University of Alberta

"QIP 2012," University of Montreal

"Theory Canada 7," University of Lethbridge

"Women in Physics Canada," University of British Columbia

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