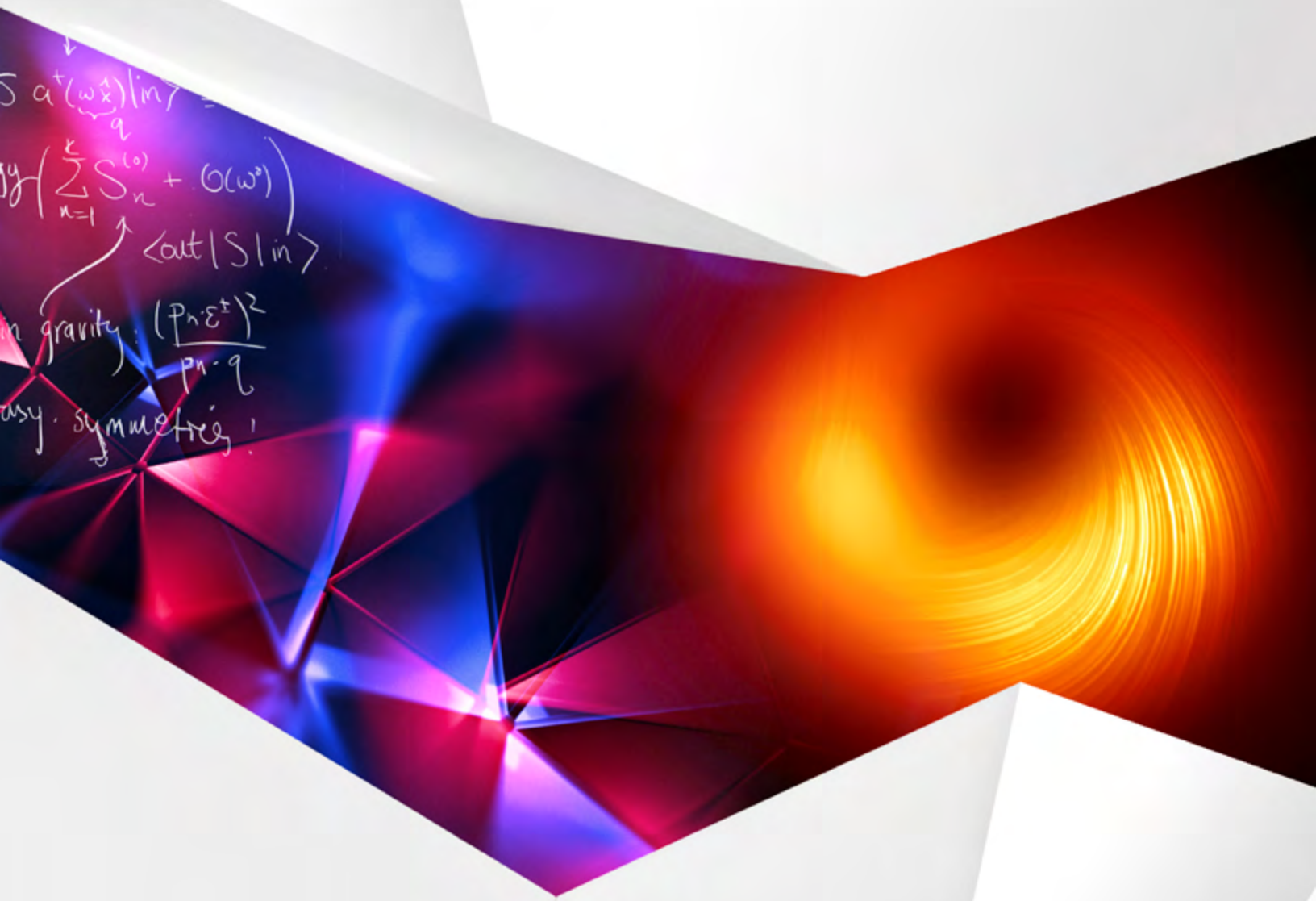
2021 ANNUAL REPORT

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS



VISION

To create the world's foremost centre
for research, graduate training, and educational outreach
in 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.

Susanne Schander and Ana-Maria Raclariu

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This report covers the activities and finances
of Perimeter Institute for Theoretical Physics
from August 1, 2020, to July 31, 2021.

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

TODAY'S THEORETICAL PHYSICS
IS TOMORROW'S TECHNOLOGY

MESSAGE FROM THE BOARD CHAIR

It's not very Canadian to be boastful, but some things need to be said.

Perimeter Institute is an incredible place. In just two decades since its inception, it's become one of the largest and best theoretical physics institutes on the planet.

Fundamental scientific research and the search for breakthroughs is in many ways a competitive endeavour, and Perimeter has put Canada on the podium. For instance, a recent study showed that Perimeter raised Canada from fourth place to first among G7 nations in physics and space science in key measures of research quality and impact.

In what other scientific field can Canada boast about building, from scratch, one of the largest and most prestigious centres in the world?

There is more at stake here than status. There is, first and foremost, scholarship: Perimeter discoveries advance our understanding of the universe and our place in it. Perimeter researchers have published thousands of peer-reviewed scientific papers, spanning areas of study from quantum fields and strings to particle physics to cosmology. They're pioneering whole new fields and being recognized with some of the most prestigious honours in science.

There is also economic impact. History has shown that theoretical physics can transform economies, especially over the long term. An example of this is the long journey that started with the discovery of Maxwell's equations of electromagnetism, followed by quantum mechanics. These breakthroughs led to early quantum electromechanical devices like the transistor, to microelectronics, and to our current moment in the information age – when we each carry billions of transistors and a portal to global knowledge in our pockets.

Finally, there is talent. It's the rocket fuel of the information age. Perimeter not only draws the best and brightest minds to Canada from around the world, it also helps build the next generation of talent. Our graduate and postdoctoral programs have trained more than a thousand new scientists. Our educational resources are used millions of times each year in classrooms around the globe – they're lighting up the young minds that are our future.

I've been involved with Perimeter for nearly 10 years as a member of the Board of Directors. I've seen its achievements up close, and I've watched it grow. When I was asked to take over from the legendary Mike Lazaridis as Board Chair, I said yes without hesitation. I know our other new Board members – new Vice Chair Jane Kinney, Nobel Prize winner Donna Strickland, and gravitational waves pioneer Gabriela Gonzáles – feel the same about Perimeter and its potential.

It's a true honour to be a part of building and sustaining such a fountain of discovery. This is a place that was crucial to that jaw-dropping first image of a black hole. These are people who devised software that turned a low-cost Canadian telescope into the best detector of fast radio bursts on the planet, who are investigating new states of matter and new geometries of spacetime, who helped map 2 billion galaxies, who are teaching AIs to be more quantum.

It's incredible stuff.

You don't often get the chance to have global impact, and impact that will last for generations is the rarest of accomplishments. There is no doubt in my mind that Perimeter scientists are working on something that will prove to be the starting point of a new journey – one that, just like the one from Maxwell's equations to the information age, will ultimately transform our world. When you look at the current state of, say, quantum computing, it's as hard for us to predict the long-term outcomes as it would have been for the Wright Brothers to predict the space shuttle, but it's easy to feel the potential to take flight.

What Mike Lazaridis started in Perimeter was a gift to all Canadians, to the world, and to the future. We've achieved a lot, and definitely earned some bragging rights. But this is only the start. The arc of scientific progress is long: we're in Year 21 of a hundred-year-plus journey. Perimeter is our stake in the future, powering breakthroughs that, over the long term, will help all of Canada, our economy and humanity as a whole.

– **Michael Serbinis**
Chair of the Board of Directors

MESSAGE FROM THE INSTITUTE DIRECTOR

For Perimeter, and for the world, 2021 has been a year of change. The pandemic is now well into its second year, a reminder that nature, and science, set their own time scales. An annual report like this is, by definition, annual. But sometimes it's worth taking a longer view.

Perimeter is now 20 years old. In that time, Perimeter has gone from an idea – some said a crazy one – to one of the top institutions of theoretical physics in the world.

The original "crazy" idea came from Mike Lazaridis. Mike invented the BlackBerry, which launched the worldwide smartphone industry. But even in the midst of starting this revolution, Mike thought bigger. He realized that the BlackBerry and virtually every other modern technology was based on past breakthroughs in theoretical physics. He asked a simple, inspiring question: *Where will the next breakthroughs come from – the ones that will transform the lives of our grandchildren's grandchildren?*

Perimeter was created as an answer: an independent institute devoted solely to theoretical physics. One that would gather brilliant minds, remove the typical constraints of academia, and seek nothing less than breakthroughs. Mike donated a third of his personal wealth to help found Perimeter. Federal, provincial, and local governments joined in, and Perimeter was born.

In the two decades since, Mike has devoted thousands of hours of his energy and wisdom as Chair of Perimeter's Board. This year, he stepped back – a little – to become Founding Board Chair Emeritus and Perimeter's greatest champion and friend. It has been an honour and a pleasure to work with Mike, and all of us – at Perimeter and across the community of science – express our deepest gratitude for his incredible contributions.

We now welcome a new Board Chair, Mike Serbinis. Like Mike Lazaridis, Mike Serbinis is a tech entrepreneur, a leader in Canada's young tech vanguard. He has been a member of the Perimeter Board since 2014. His passion for science runs deep: He invented a propulsion system for space vehicles while in high school, before going on to co-found many successful companies, including Kobo, Critical Path, DocSpace, and most recently, League. He brings energy, daring, and vision to everything he does. I've no doubt that Perimeter will reach new heights with his help and guidance (see page 46).

Our new Board Chair often points out that Perimeter is a hundred-year project. Sometimes we need to take in more than a year's progress to get a sense of the scale of the transformation that science makes possible.

For instance, Perimeter's Centre for the Universe is now in its fifth year of operation (see pages 16-21). Five years ago, black holes were still seen as theoretical objects. Now, thanks to the Event Horizon Telescope, they will forever be a part of our picture of the universe. Five years ago, the CHIME telescope was under construction. Now, it's vaulted Canada to the forefront of radio astronomy. Perimeter didn't build the EHT or CHIME hardware, but we made the crucial early investments in smart people and big ideas that made these projects possible.

A track record like the one from the Centre for the Universe shows that the science we do at Perimeter is bigger than any one paper, any one researcher, or any one year. That's why we were excited to launch the Clay Riddell Centre for Quantum Matter, supported by a generous $10 million gift from the Riddell Family Charitable Foundation, in October 2020. The new centre will explore new materials with quantum properties – things like superconductors and topological insulators – helping to accelerate the creation of powerful new quantum technologies, which are clearly coming.

Perimeter is emerging as a leader in this strategically important field (see pages 8-11). In fact, one of our new faculty recruits, Dominic Else, just won one of the top prizes for young physicists – the New Horizons prize – for his work in this area. I can't wait to see what five years of concentrated work at the Centre for Quantum Matter will bring.

In the two decades since Perimeter was launched, our researchers have made an impressive string of breakthroughs. Our Outreach team has reached tens of millions of students. Our training programs have helped launch the careers of over a thousand scientists. We've become a magnet for top talent from across Canada and around the world. Just this year, in addition to Dominic Else, we recruited Sabrina Gonzalez Pasterski, a stellar young researcher in the emerging field of celestial holography, to our faculty and Anton Burkov and Theo Johnson-Freyd as associate faculty members (see pages 24-25).

The one year focused on in this report is striking; the five years you'll glimpse here and there are impressive; the twenty-year sweep is truly amazing. We have much to look back on, but still more to look forward to. We are emerging from this pandemic stronger, with an even deeper conviction that science is our future, and the best is yet to come.

– **Robert Myers**, Director and BMO Financial Group Isaac Newton Chair in Theoretical Physics at Perimeter Institute

PERIMETER HELPS POSITION CANADA AT THE FOREFRONT OF RESEARCH

To ensure transparency and accountability, Perimeter Institute is regularly assessed through independent third-party evaluations that measure performance, scientific impact, and value for its public and private partners.

In 2020/21, the Audit and Evaluation Branch of Canada's Ministry of Innovation, Science and Economic Development undertook an extensive assessment of Perimeter's operations and financial model from 2016 to 2020. Here are a few conclusions about Perimeter's relevance, performance, and efficiency:

"PI has contributed to ***major scientific breakthroughs*** in theoretical physics and continues to advance the field. Further, its research in quantum theory is leading to ***applications in artificial intelligence and*** supporting start-up companies in ***quantum computing***, with an increasing number of PI researchers applying their knowledge in the private sector."

"***PI is unique in Canada***, and internationally, in its size and independent nature as a not-for-profit institute unaffiliated with a university, as well as in its breadth of research, ***particularly in quantum areas***."

"The public-private approach also provides PI with the ***flexibility to pursue unique research*** opportunities quickly and efficiently ***to position Canada at the forefront*** of research advancements and breakthroughs."

STEP INSIDE THE PERIMETER

At Perimeter Institute, 2020/21 was a year of new breakthroughs, new connections, and new ways of learning. Here are just a few of the achievements highlighted in the pages ahead.

Research

Four years since its launch, find out more about the scientific breakthroughs of the Centre for the Universe – including a leading role in the first-ever image of a black hole, unprecedented discoveries by CHIME, and new ideas about axions – all of which have brought it significant global recognition (pages 16-21). Learn about hybrid quantum computing and other research at the frontiers of theoretical physics on pages 12-15. And read about the incredible developments coming out of the Clay Riddell Centre for Quantum Matter in just its first year of operation on pages 8-11.

Training

For the first time ever, the Perimeter Scholars International master's program was held entirely online, due to the pandemic. Learn how these exceptional students and instructors created a remarkable, supportive community on page 34.

Outreach

As teachers around the world continued to work in digital classrooms, Perimeter stepped up with an online intensive camp, more teacher training workshops, and new resources to help teachers adapt. Learn more on pages 36-41.

Inclusion, diversity, equity, and accessibility

New questions, new solutions: at Perimeter we believe that theoretical physics thrives when it includes the broadest possible scope of humanity. Find out how we're working to make that possible on pages 22-23.

Community

Excellent research can't happen without an excellent community of support. Throughout this report, we've highlighted just a few of the people from Perimeter's administrative staff who are Making It Work.

RESEARCH

"Working at Perimeter gives me the freedom to pursue my own research, while also broadening my interests and learning from world leading experts."

– Cristina Mondino, postdoctoral researcher

Cristina Mondino

RESEARCH by the numbers

At Perimeter Institute, we strive to achieve breakthroughs in our understanding of the universe, connect to outstanding scientists from across Canada and around the world, and create the world's strongest community of theoretical researchers.[1]

502 papers published in 2020/21

351,264 citations since inception

6,784 papers published in more than 250 journals and on the arXiv since Perimeter's inception

8 prizes and honours in 2020/21

RESEARCH COMMUNITY

25 Faculty, including 7 Perimeter Research Chairs

21 Associate Faculty, including 1 Perimeter Research Chair

44 Distinguished Visiting Research Chairs

79 Postdoctoral researchers

4 Simons Emmy Noether Fellows appointed

52 Visiting Fellows

114 Affiliate members

CONFERENCES, WORKSHOPS, AND SEMINARS

7 conferences and workshops attended by more than 1,000 scientists

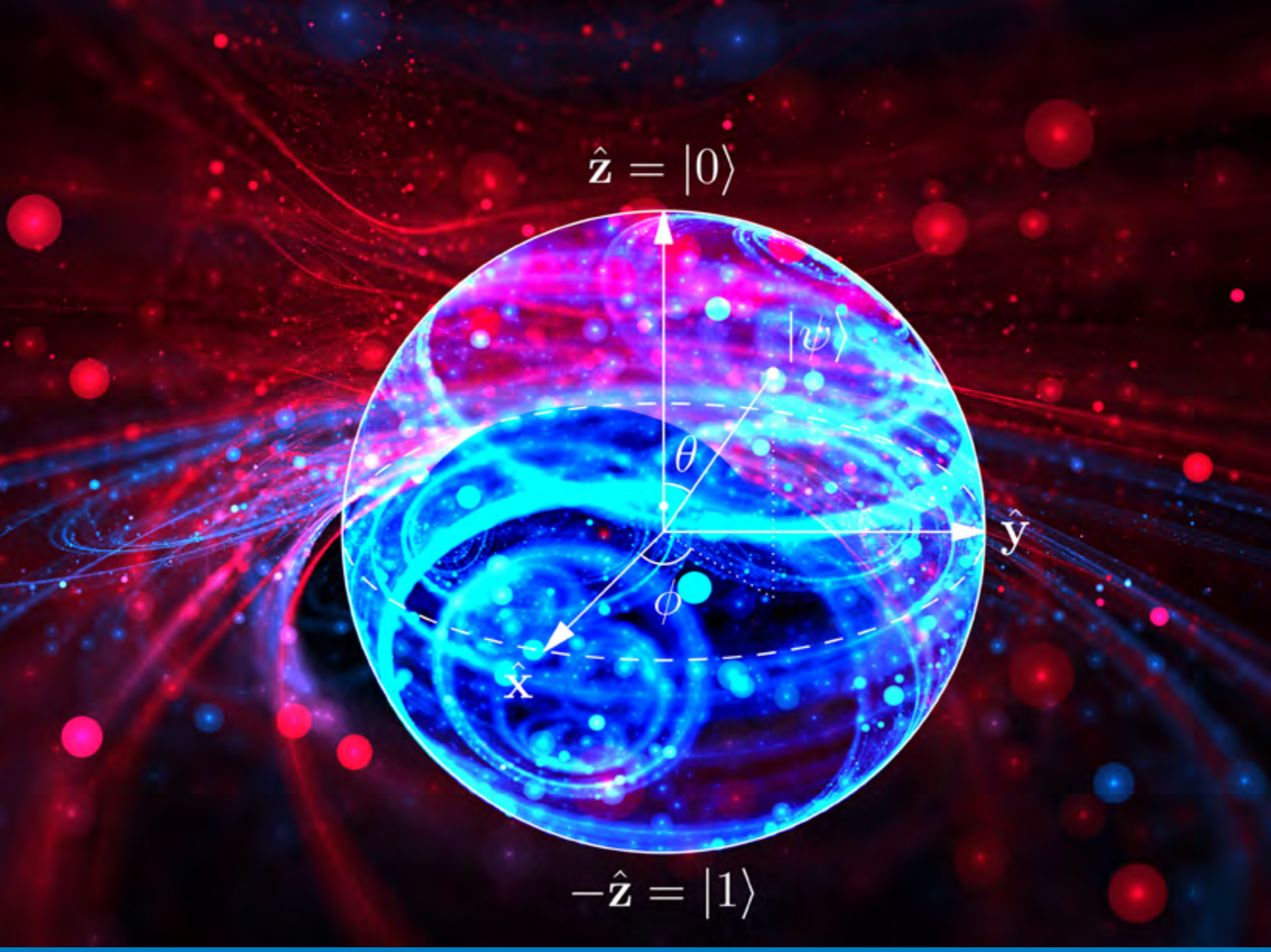
7 sponsored off-site academic conferences and workshops

296 scientific talks, seminars, and colloquia attended by more than 10,000 people

13,547 talks in the online Perimeter Institute Recorded Seminar Archive (PIRSA) since inception

464,534 PIRSA views in 2020/21

[1] *Unless otherwise indicated, figures are for August 1, 2020–July 31, 2021.*



FROM THE QUANTUM . . .

Our society stands poised for a technological revolution. We are already seeing the first wave of technologies based on harnessing subtle and powerful features of quantum mechanics, and more are clearly coming. One of the many ways that Perimeter researchers are accelerating this revolution is through the study of quantum matter – that is, exotic states of matter that are defined by their quantum properties.

In 2020, a visionary $10 million investment by the Riddell Family Charitable Foundation helped supercharge this research at Perimeter with the launch of the **Clay Riddell Centre for Quantum Matter**. Researchers at this centre, and at the Perimeter Institute Quantum Intelligence Lab, bring together ideas from quantum matter physics, quantum information, and cutting-edge computer science to deepen our understanding and improve our control of quantum materials.

The breakthrough work done in the Clay Riddell Centre's first year is blazing the path toward a quantum future.

PHASE TRANSITION: A NEW WAY TO INVESTIGATE QUANTUM MATTER

Deep in a simulation of an unbuilt quantum computer, Perimeter researchers at the Clay Riddell Centre for Quantum Matter have glimpsed new physics.

Roger Melko is an associate faculty member, cross-appointed at Perimeter and the University of Waterloo, and the founder of the Perimeter Institute Quantum Intelligence Lab. Recently, in simulations of how a quantum circuit should work, Melko and collaborators glimpsed something unusual: a new type of phase transition.

Melko's team are world leaders in the difficult work of simulating quantum states of matter. Here, their simulations are state-of-the-art digital replicas of a quantum computer's circuit board. The circuit can have two different kinds of behaviour: one in which a quantum property called entanglement grows rapidly, and one in which entanglement grows significantly more slowly.

The transition between the two kinds of behaviour isn't gradual, it's sudden: a phase transition, like ice melting into water, or graphite shifting into diamond.

"It looks almost identical to a phase transition in matter," says Melko. "That's the first part that's amazing. You have this really non-trivial quantum circuit that's built in the lab – it has nothing to do with matter or materials or so on – yet it has a phase transition that looks like a phase transition in matter.

"The second part that's amazing is that even though it looks like something we would see in matter, there are some things we don't understand about it. It's clearly a new kind of phase transition that doesn't seem to occur in the natural world."

"It's called a measurement-induced phase transition," Melko says. "I think it can only really occur in a quantum computer."

This new class of phase transition caught the interest of physicists around the world. One of them was Perimeter Faculty member Tim Hsieh.

Hsieh, who this year received a prestigious Early Researcher Award from the Ontario Ministry of Colleges and Universities, is interested in quantum materials broadly – and particularly in artificially created quantum materials, which give researchers more control and power over quantum effects and better ways of encoding quantum information.

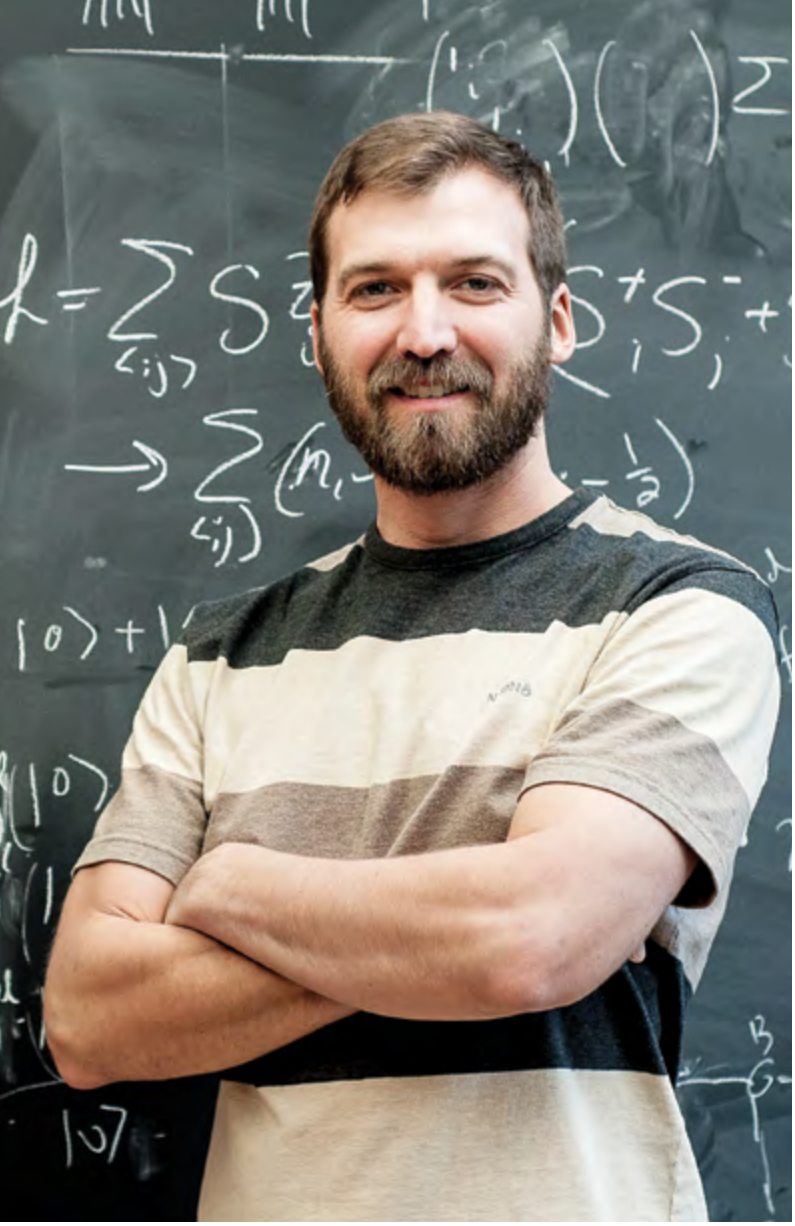
In the new kind of phase transition, he spotted a new way to investigate phases of quantum matter. "I decided to look at the phase in which the measurements dominate and give rise to a low-entanglement final state," he says.

Usually, measurement erases effects like entanglement and superposition: open the box, and Schrödinger's Cat is no longer in alive/dead superposition: kitty is now either fully alive or fully dead.

But that's not what's happening in this quantum circuit, where even the post-measurement phase contains long-range quantum correlations. In fact, says Hsieh, it's even more interesting than that. The structure of the measurements you make during the phase transition helps preserve and control these long-range correlations.

Continued on page 10

▼ *Tim Hsieh*



Roger Melko

Continued from page 9

He calls the low-entanglement phases of the quantum circuit "measurement-protected quantum phases." They belong to a class of phases known as dynamical phases or non-equilibrium phases. Most states describe structure; dynamical states describe behaviour. Think of describing a clock, for example: the most salient thing isn't the length of the hands or the layout of the numbers (the *structure*) but the fact that the hands move at a particular speed (the *behaviour*).

Dynamical phases are important, but they're challenging for physicists. "Over the last decade we've come to understand equilibrium phases pretty well," Hsieh says. "But dynamical phases, phases that are out of equilibrium – that's the Wild West. We don't have the law out there yet."

Structuring the measurements in the phase transition gives Hsieh a new tool to explore the wild land of non-equilibrium phases. The newly opened line of study is attracting interest from quantum matter researchers around the world.

This moment has a historical parallel. One of the first things Galileo did on perfecting the telescope was demonstrate it to the leaders of Venice, who used it as a spyglass to give tactical advantage to their sea-going state. Galileo himself, though, turned the telescope upward, and this new way of looking at the heavens shifted our entire view of what the heavens were.

Quantum computers could be the same. The tactical advantages they might give in faster or more powerful computing are huge and just over the horizon. But the new view they give us on the quantum world is opening right now.

References:

S. Sang, T. Hsieh (Perimeter Institute), "Measurement protected quantum phases," *Phys. Rev. Research* 3, 023300, 2021, arXiv:2004.09509.

S. Czischek (U. Waterloo), G. Torlai (AWS Center), S. Ray (1QBit), R. Islam (IQC), R. Melko (Perimeter Institute/U. Waterloo), "Simulating a measurement-induced phase transition for trapped-ion circuits," *Phys. Rev. A* 104, 062405, 2021, arXiv:2106.03769.

PEOPLE

Faculty

CHONG WANG

How strange could quantum matter be? Perimeter Faculty member Chong Wang is finding out. Wang studies "ultra-quantum" matter, a special case of condensed matter where the particles that make up a substance are correlated with one another through quantum entanglement.

Wang, who did his PhD at MIT followed by a postdoc at Harvard, is currently developing theoretical tools to study a phenomenon known as quantum criticality. This occurs when quantum fluctuations cause different phases of matter to compete with one another. "Very roughly speaking, the system does not know which phase to go into and shows fluctuating behaviours of all the competing phases," Wang says.

Understanding the conditions that allow different phases to be connected through a quantum criticality could be key in unlocking other cutting-edge quantum materials, including high-temperature superconductors, which are expected to play crucial roles for next-generation technologies such as lossless energy transfer.

"Condensed matter physics, very often, is about the study of the emergence of beauty," says Wang. "For a theorist, your daily life has two goals: one is to get the most beautiful structure for your theory; the other is try to explain the most puzzling experiment. Often, the two goals run in parallel, but occasionally, they meet. Then something awesome happens."

▲ *Estelle Inack*

NEURAL NETWORKS REACH NEW PEAKS OF OPTIMIZATION

"Imagine you're driving in the Himalayas, and someone asks you to find the deepest valley," says Estelle Inack. "How would you do it?"

The quest for the deepest valley among many valleys – the best solution among many solutions – is an optimization problem. Optimization problems are ubiquitous, popping up from pharmaceuticals to finance.

Inack is the Francis Kofi Allotey Postdoctoral Fellow at Perimeter. Her recent work involves one approach to optimization problems called annealing, which maps the problem of navigating the Himalayas into the language of physics. Physicists have established frameworks for expressing and solving this problem. "If you can write the problem as a Hamiltonian," notes Inack, "then optimization is equivalent to finding the ground state. Physicists are very good at that."

Inack takes us back to the Himalayas. "You're trying to find the lowest valley by driving your car." Sometimes, she says, there's a snag. "You can be in a valley and the next mountain is so steep that you can't go up," says Inack. Then you might find a low valley but miss the even lower valley next door. A good solution, but not an optimal one.

"In a second search, we give you superpowers. Now you can go through mountains." Deep in the simulation, these superpowers take the form of quantum tunnelling. This approach is called quantum annealing.

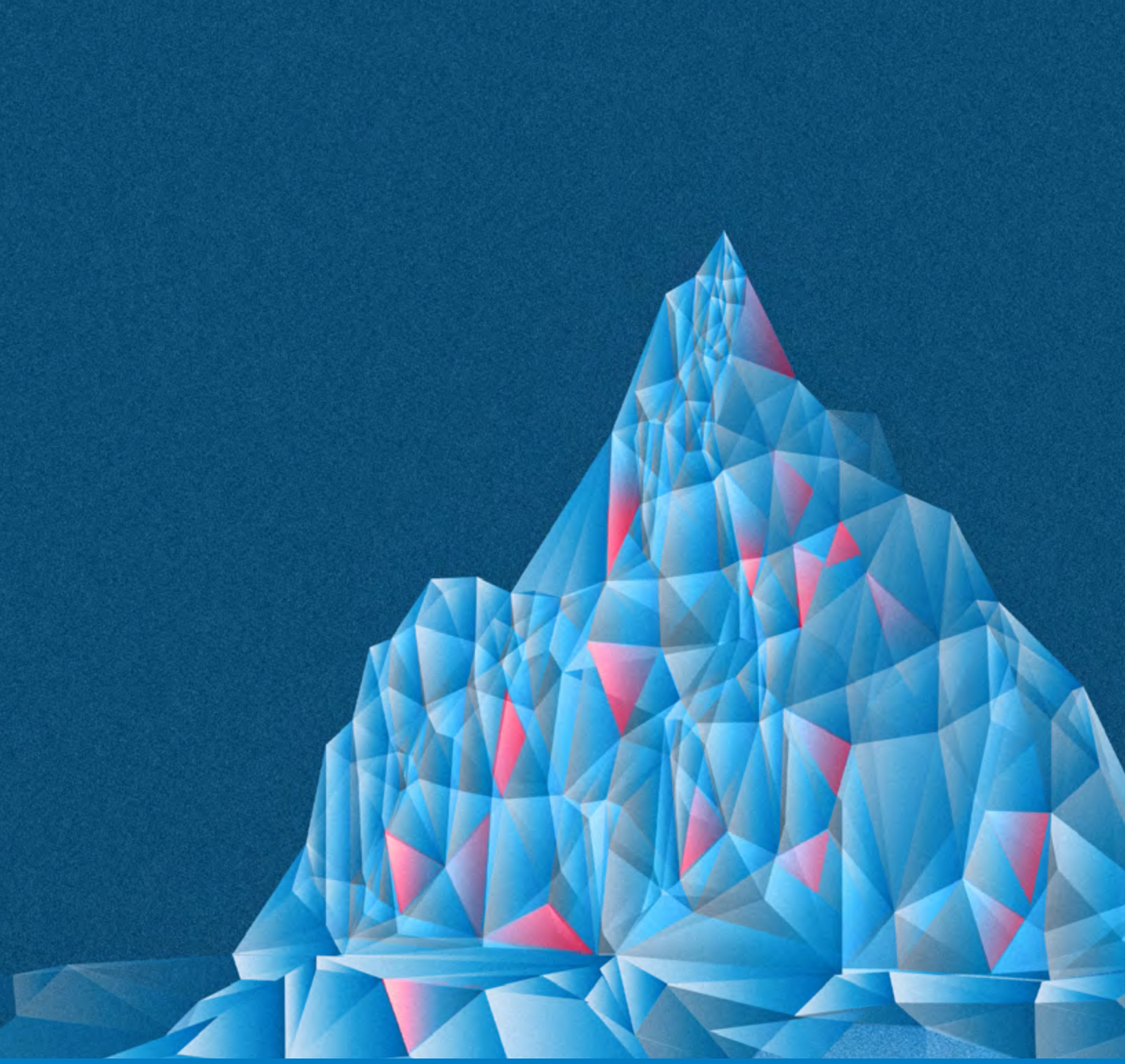
Simulated annealing is a well-established technique, but Inack and other researchers at the Perimeter Institute Quantum Intelligence Lab have put a new spin on it. They've found a way to implement it using an artificial neural network, making it faster and more powerful.

It's so powerful and so promising that Inack has set about commercializing it: she's co-founded a company called yiyaniQ. "It comes from my local language, Basa'a," explains Inack, who is originally from Cameroon. "Yi means intelligence, and Yaani means tomorrow. The Q is for quantum, of course."

The initial plan for yiyaniQ is to use that quantum intelligence to speed up derivative pricing – one of the hardest problems in finance – but the applications could easily be as endless as the Himalayas.

Reference:

M. Hibat-Allah (U. Waterloo/Vector), E.M. Inack (Perimeter Institute), R. Wiersema (U. Waterloo/Vector), R.G. Melko (Perimeter Institute/U. Waterloo), J. Carrasquilla (U. Waterloo/Vector), "Variational neural annealing," *Nat. Mach. Intell.* 3, 952-61, 2021, arXiv:2101.10154.



. . . TO THE CUTTING EDGE . . .

From the promise of quantum computers to the mystery of dark energy to the huge challenge of quantum gravity, Perimeter researchers tackle tough problems with innovative approaches.

MEASURABLY ADVANCING QUANTUM-CLASSICAL COMPUTER HYBRIDS

As a theorist interested in moving from the whiteboard to real-world experiments, Perimeter Associate Faculty member Christine Muschik takes every opportunity to advance both science and technology. This year, she was part of a team that outlined a new approach to hybridizing classical and quantum computers.

Pairing a regular computer's processor and a quantum processor in a feedback loop makes it possible to solve hard optimization problems with tremendous real-world potential.

"This takes us closer to the things researchers dream about: creating new medicines, discovering lighter, stronger materials for airplanes, improving atmospheric carbon capture," she says.

Muschik and her collaborators propose using a uniquely quantum property known as "entanglement" in a new way to improve information processing.

Entanglement is essential to all quantum computing, but the team found a new method of sequentially measuring entangled states that makes hybrid quantum-classical computing more powerful and robust and provides major advantages over existing approaches.

Since receiving her PhD in 2010, Muschik has witnessed – and contributed to – an accelerated transformation of quantum technologies. Quantum tech is still in an early, somewhat experimental stage, but recently it has become much more accessible, offering fewer constraints on the curiosity and intellect of physicists like Muschik.

The hybrid systems she is developing can drive new approaches and advances in fields from cosmology to particle physics. In Muschik's own field, hybrid computing could help advance a central challenge that has confounded theoretical physicists for decades: how classical physics emerges in a quantum world.

Quantum computing has also made the leap from academic campus to industry, with established tech giants and new start-ups pouring tremendous resources into achieving "quantum supremacy," an industry term for the milestone of a quantum computer solving a useful or interesting problem that is impossible for classical computers.

Muschik works on both sides of that divide, advancing fundamental knowledge and propelling those new ideas to change the world.

"We play a dual role, not only simulating the physics now, but also focusing on method development for future quantum computers," she says. "This is how you pave the way to scale it up for future generations."

Reference:

R.R. Ferguson (U. Waterloo), L. Dellantonio (U. Waterloo), A. Al Balushi (U. Waterloo), K. Jansen (NIC, DESY), W. Dür (ITP), C.A. Muschik (Perimeter Institute/IQC), "Measurement-based variational quantum eigensolver," *Phys. Rev. Lett.* 126, 220501, 2021, arXiv:2010.13940.

▼ *Christine Muschik*

THE SNOWY ROUTE TO A SPIN FOAM BREAKTHROUGH

Deep down, the universe is granular, pixelated: made up of small chunks that cannot be broken down further. That's the central message of quantum theory. Gravity, meanwhile, says that spacetime is smooth: often it's described as a rubber sheet. There's no pixelation in that picture, and the two theories – quantum theory and gravity – don't play well together.

Unifying quantum theory and gravity is one of the great challenges of modern science: physicists have been searching for a unifying framework for almost a century. Loop quantum gravity (LQG) is one of several proposed frameworks. LQG builds a quantum spacetime from the quantum up, by attempting to define what the smallest possible chunk of spacetime might look like.

Many LQG researchers are interested in a structure called a spin foam. In a spin foam, chunks of spacetime, described in part by a quantum number called "spin," stick together like soap bubbles.

Researchers hope that if they can construct a big enough spin foam, they will arrive at a quantum description of spacetime – that is, something that looks foamy and quantum close up, but smooth as a rubber sheet if you zoom far enough out. To check to see if they're on the right track, researchers would like to simulate a large chunk of spin foam.

Spin foams, it turns out, are hard to simulate.

Each chunk of spacetime inside a spin foam is described mathematically by something called a wave function. But before even a single chunk can be simulated, its wave function must be solved. Researchers refer to this as "computing the amplitudes." Computing the amplitude for a single chunk of spacetime is hard, but doable. Start using multiple chunks to build a spacetime, and the amplitude problem quickly amplifies, becoming too much for even high-performance computers.

The amplitude problem was where LQG remained stuck, until Perimeter Faculty member Bianca Dittrich had a breakthrough.

Specifically, Dittrich broke through some shore ice and got stuck in a crevasse. She was on the shores of Lake Huron at what she calls "a winter camp for quantum gravity researchers."

▼ *Bianca Dittrich*

Fortunately, Dittrich wasn't alone, and she didn't stay stuck in the ice for long. Equally fortunate, she was about to have a second, less literal breakthrough.

Also at the camp was Perimeter PhD student Seth Asante, who has since completed his degree and is now the Fields-AIMS-Perimeter Postdoctoral Fellow. Together, Dittrich and Asante realized it might be possible to use a mathematical language called higher gauge theory to reformulate the description of the spacetime chunks, such that the physics remained the same, but the mathematics through which the ideas were expressed was easier. It's akin to (though much more complicated than) changing Newton's famous "force = mass × acceleration" to read "force = change in momentum" instead.

Pulling off this repackaging took a year, but the result was a new model of spin foams that had two big advantages. First, the amplitudes didn't need to be calculated – they emerged naturally from the description. Second, the way in which the dynamics were encoded in the model was much more transparent. Think again of reformulating Newton in terms of momentum: it means momentum doesn't have to be calculated, and it makes momentum transfer much easier to study.

In terms of ease of simulation, their model was a runaway success. "Previous attempts to simulate spin foams require high-performance computers and take months," says Dittrich. "We could do simulations for slightly bigger chunks of spacetime on our laptops in minutes."

Not only were simulations possible, they were promising. They show, for example, that spin foams can produce gravitational waves. It's the first time that LQG has been shown to reproduce the same dynamics predicted by general relativity.

What was once the spin foam stumbling block has become the spin foam milestone. With this new framework, quantum gravity models may well come into computational reach for the first time.

References:

S.K. Asante, B. Dittrich, J. Padua Argüelles (Perimeter Institute), "Effective spin foam models for Lorentzian quantum gravity," *Class. Quantum Grav.* 38, 195002, 2021, arXiv:2104.00485.

S.K. Asante (Perimeter Institute), B. Dittrich (Perimeter Institute), H.M. Haggard (Bard College), "Effective spin foam models for four-dimensional quantum gravity," *Phys. Rev. Lett.* 125, 231301, 2020, arXiv:2004.07013.

PEOPLE

Postdoctoral Researcher

CRISTINA MONDINO

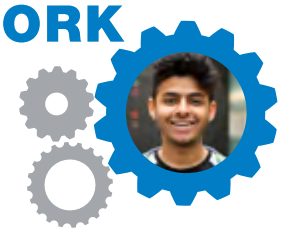
Originally from Italy, and with a PhD from the New York University Center for Cosmology and Particle Physics, Cristina Mondino arrived at Perimeter in 2020 and holds the Chien-Shiung Wu Postdoctoral Fellowship.

Along with collaborators, her research on dark matter substructure has been published in *Physical Review Letters*, tackling an open question about dark matter: How does it behave on length scales smaller than the size of the smallest galaxies, where its effects have not yet been directly measured?

"Our analysis did not find evidence for dark matter structures in the current data but opened the way to a new type of dark matter searches with promising detection prospects in the near future," Mondino says.

"My goal now is to further develop the tools that we used to extract more information from current and future data. Working at Perimeter gives me the freedom to pursue my own research, while also broadening my interests and learning from world leading experts."

MAKING IT WORK



"I really like to work here, because growing up I never thought I would have a role in helping scientists with their research. I see all these scientists here – prestigious scientists – and I'm proud to support them."

Freshly graduated from Conestoga College, Ishan Jani joined Perimeter two years ago. He works as a technology specialist in the IT department, supporting researchers, administrative staff, and students. Throughout the pandemic, Jani and the rest of the IT staff were instrumental in ensuring that all research, training, outreach, and advancement activities could continue easily and securely.

. . . TO THE COSMOS

Imaging black holes, deciphering fast radio bursts (FRBs), harnessing gravitational waves, uncovering the big bang, mapping dark matter and dark energy – there's never been a more exciting time to do research in astrophysics and cosmology. Perimeter researchers are formulating new theories and interfacing with data from leading-edge experiments to glean insights into the inner workings of our universe.

Launched four years ago, Perimeter's **Centre for the Universe** was made possible thanks to a generous donation from an anonymous philanthropist. It brings together a mix of eminent international leaders and rising young stars who collaborate to develop theoretical techniques, design experiments, and analyze new observations.

A LAUNCHPAD FOR SUCCESS

Since Einstein predicted the existence of black holes in 1916, generations of astronomers have been driven to find and understand them. They pursued glimmers of indirect evidence but ultimately dreamed of building telescopes powerful enough to see black holes directly. After a century of steady progress, the Event Horizon Telescope (EHT) finally realized this dream in 2019.

The result was one of the most extraordinary events in the history of science: it is estimated that over 4 billion people have seen the image of the black hole that lies at the heart of the M87 galaxy. Scientists at the Centre for the Universe, including Associate Faculty member Avery Broderick, who holds the Delaney Family John Archibald Wheeler Chair, provided solutions to deep data analysis problems that were crucial to this achievement; in other words, they helped make history.

With the reality of black holes firmly established, and powerful new instruments like the EHT and the Laser Interferometer Gravitational-Wave Observatory (LIGO) to probe them, Centre for the Universe researchers are proposing ingenious ways to capitalize on their extreme environments.

Faculty member Asimina Arvanitaki, who holds the Stavros Niarchos Foundation Aristarchus Chair, has theorized that black holes could be used as particle detectors to find "axions." These ultra-light particles are the last prediction of the Standard Model of particle physics to remain undetected. Physicists have sought them for more than five decades, but – if they exist – axions may interact with us very weakly or only through the force of gravity. As a result, Earth-based detectors come up short. Taking advantage of the gravitational extremes of black holes, Arvanitaki proposed combining gravitational wave observatories with a property of black holes known as "superradiance" to detect the axion.

Centre for the Universe researchers have also shown that black holes can act as natural laboratories for studying the very nature of gravity. By developing a robust understanding of the gravitational wave signals that black holes emit when colliding, faculty members – including William East and Luis Lehner – are developing novel ways to put general relativity and other theories of gravity to the test.

Meanwhile, a Canadian telescope, CHIME (the Canadian Hydrogen Intensity Mapping Experiment), has also made revolutionary discoveries. At the Centre for the Universe, researchers including Faculty member and current Centre Director Kendrick Smith, who holds the Daniel Family James Peebles Chair, created new algorithms to search CHIME data for Fast Radio Bursts (FRBs), a recently identified type of explosive cosmic event whose origin is a mystery. These algorithms have been so successful that CHIME has found 20 times more radio bursts than all other telescopes in the world combined – a result that has propelled Canada to global leadership in radio astronomy. The wealth of new data is leading to a flurry of new insights on the origins of FRBs.

In a short time, the Centre for the Universe has developed into a vibrant community of physicists at every career stage, from graduate students to veteran researchers. It has become a focal point for collaboration, connecting partner universities around Ontario and beyond. Researchers work together through partnerships with Canadian institutions, including the Canadian Institute for Theoretical Astrophysics, the Dunlap Institute at the University of Toronto, the University of Waterloo, Queen's University, York University, and SNOLAB.

What's more, the training and mentorship programs for early researchers at the Centre have been a launchpad for success: students trained at the Centre have been hired as researchers by elite universities around the world, including Harvard, Cambridge, and Princeton.

But these groundbreaking achievements are just the beginning of what the Centre hopes to accomplish. Every grand project in cosmology begins with a new idea and a small investment of resources. Where will the next breakthroughs come from, and which ideas hold the most promise for discovery? Centre for the Universe researchers are exploring some of these possibilities now, including simulating the big bang with quantum computers, finding new connections between black holes and particle physics, and creating new experiments that build on the success of the EHT and CHIME.

Scientists at the Centre have been at the nexus of a recent explosion of discoveries in astrophysics and cosmology.

▼ *Kendrick Smith*

BURSTS OF INSIGHT FROM CHIME

CHIME continues to accelerate progress in the quest to understand the origin of a mysterious phenomenon known as fast radio bursts.

FRBs are immensely energetic blasts of radio waves that last for only microseconds, faster than the blink of a human eye. First detected in 2007, only a few dozen more were spotted throughout the next decade – that is, until CHIME was powered on in 2018. Located near Penticton, British Columbia, the telescope found 13 FRBs in its first month of debugging, running at just a fraction of its full capacity. It was enough to make the cover of *Nature*, one of the most prestigious research journals.

"FRBs have become a central unsolved problem for the twenty-first century," says Kendrick Smith, a CHIME researcher and Perimeter faculty member who holds the Daniel Family James Peebles Chair. "They are at least a thousand times brighter than the brightest radio pulses we've ever seen in our galaxy, and the physics that produces them is not understood."

In the past several years, CHIME has established itself as a powerhouse in FRB detection, with discoveries pouring in at a breakneck pace that shows no signs of abating. In June 2020, the collaboration announced the detection of an FRB that repeats its bursts in a predictable way every 16.3 days. And in November 2020, the first FRB within our own Milky Way galaxy was reported, with an intensity 3,000 times greater than that of any previously measured burst. It appeared to originate from a type of neutron star known as a magnetar.

In June 2021, the CHIME collaboration released the telescope's first publicly available FRB catalogue, containing data on 535 bursts. In addition to significantly expanding the library of known FRBs, the catalogue also yields clues as to their properties.

"One of the really powerful aspects of the CHIME/FRB survey is that we're observing 24/7, so we are surveying the sky in a uniform way," says Perimeter computational scientist and CHIME researcher Dustin Lang. "As we build up a large collection of FRBs observed in this uniform way, we can start to understand what the whole population of FRBs is, based on the known fraction of them that we observe – which is the key to unravelling their origins."

The bursts are evenly distributed in space, seeming to arise from any and all parts of the sky, and fall into two classes: those that repeat, and those that do not. The observations suggest that the repeaters and one-offs may arise from separate mechanisms and astrophysical sources.

"CHIME is by far the most powerful telescope in the world for finding FRBs. It's made Canada a global leader in this field."

– Kendrick Smith

Even without a conclusive determination of their origin, FRBs are turning out to be more than just a curiosity. CHIME researchers have also developed a plan to use the bursts to map out the distribution of gas throughout space and deepen their understanding of the large-scale structure of the universe.

"In the case of the fast radio bursts, we did everything that we said we could do, and more," Smith says. "CHIME is by far the most powerful telescope in the world for finding FRBs. It's made Canada a global leader in this field."

The collaboration is now working on an ambitious follow-up project known as CHORD, the Canadian Hydrogen Observatory and Radio-transient Detector. The pan-Canadian initiative involves collaborations between Perimeter, the Dominion Radio Astrophysical Observatory, the University of Toronto, McGill University, the University of Calgary, NRC Herzberg, and other institutions. CHORD also involves collaborations with Canadian private sector companies focused on engineering, wireless communications, digital signal processing, and high-performance computing.

Building directly on the success of CHIME, CHORD will offer unprecedented observation capabilities. The facility will consist of a central array of 512 high-precision six-metre dishes located next to the CHIME array in British Columbia, with two outrigger stations, including one at the Algonquin Radio Observatory in Ontario. It's anticipated to be about 10 times more powerful than CHIME.

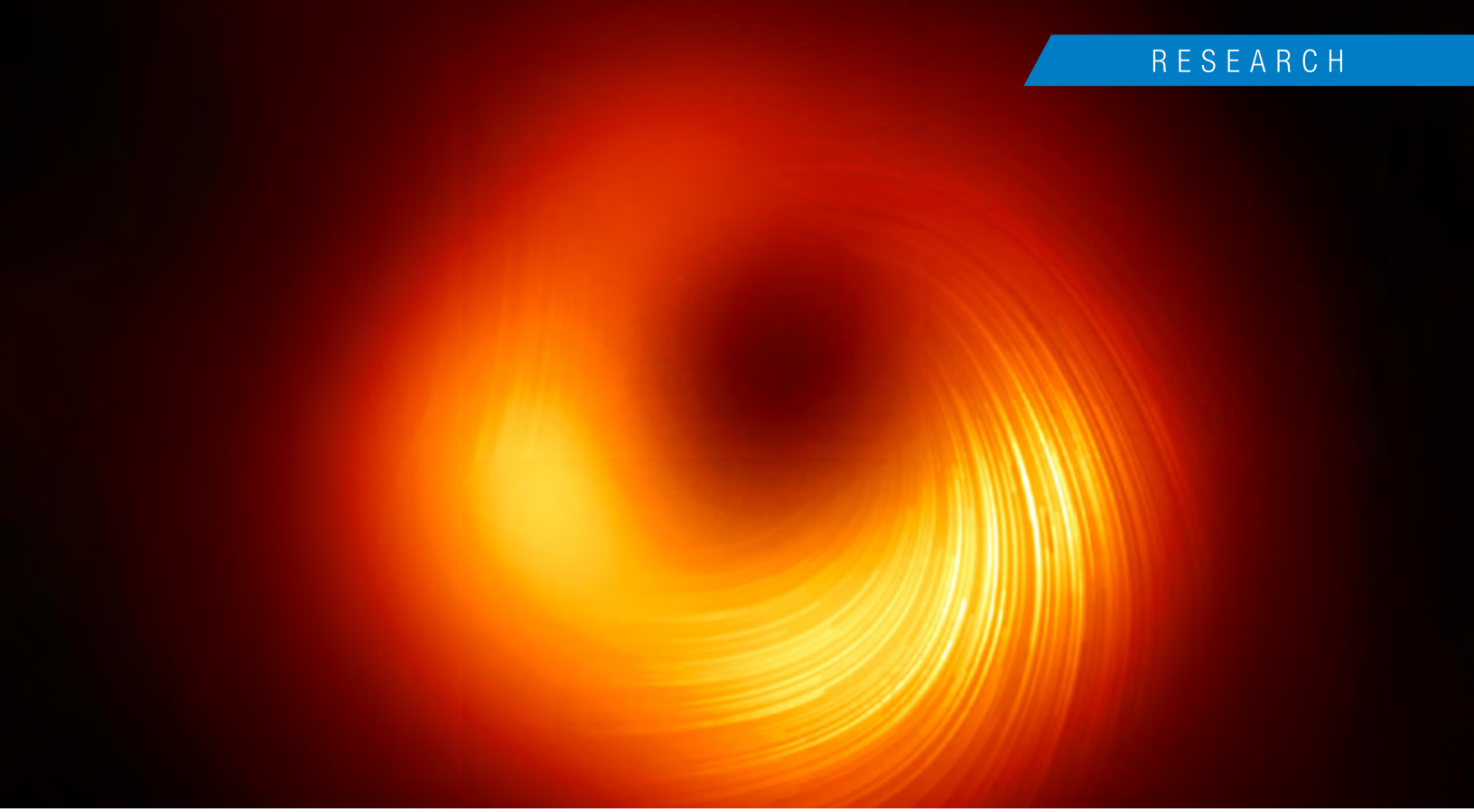
"Who knows what we'll find?" Smith says. "When you open up this huge discovery space, there's lots of room for surprises. It feels more like exploring a new world than following some roadmap that you can predict in advance."

References:

CHIME/FRB collaboration, "Periodic activity from a fast radio burst source," *Nature* 582, 351-55, 2020, arXiv:2001.10275.

CHIME/FRB collaboration, "A bright millisecond-duration radio burst from a Galactic magnetar," *Nature* 587, 54-58, 2020, arXiv:2005.10324.

◀ *Kendrick Smith and team at the CHIME telescope*



NEW IMAGES AND TOOLS FROM THE EVENT HORIZON TELESCOPE

The EHT collaboration made history in 2019 when it revealed humanity's first look at a black hole. But rather than marking an ending, the landmark image was just the beginning of the EHT's emerging legacy.

While troubleshooting the development of the EHT, researcher Avery Broderick, an associate faculty member who holds the Delaney Family John Archibald Wheeler Chair at Perimeter, developed a powerful new tool for radio astronomy. Broderick and his collaborator Dominic Pesce – a postdoctoral fellow at the Center for Astrophysics of the Harvard College Observatory and the Smithsonian Astrophysical Observatory – wanted to ensure that they could get the most out of the enormous amount of data flowing through the EHT pipeline.

"The EHT is a cutting-edge instrument," says Broderick. "It produces an extraordinary dataset unlike any previous dataset – much higher resolution, access to the kinds of physics that were never accessible before. But we have all kinds of problems that no other dataset has."

One major difficulty stems from the fact that each individual telescope collects light in a unique way. The uncertainty in the total measurement is affected by the errors and uncertainties at each facility. The problems are particularly pronounced for a property of light known as polarization, which indicates how electromagnetic waves are oriented as they travel through space.

To solve this problem, Broderick and Pesce capitalized on the fact that station-based errors generate correlations that can easily be described throughout a given data set. With a stroke of ingenious and elegant mathematical insight, they discovered a method of combining observations to circumvent the errors completely.

The new observational quantity, dubbed a "closure trace," doesn't require any increase in observational equipment, but the gains in observational power are enormous. The result is a powerful new technique – the first of its kind in more than 60 years.

Equipped with new tools, the EHT researchers set out on their next ambitious project: to image the M87 black hole in polarized light, which is strongly affected by the presence of magnetic fields. Imaging it in this way allows researchers to access previously hidden information.

On March 24, 2021, the collaboration unveiled the new M87 black hole portrait. The result is a spectacular image that shows a crisp swirl of polarized light around the event horizon.

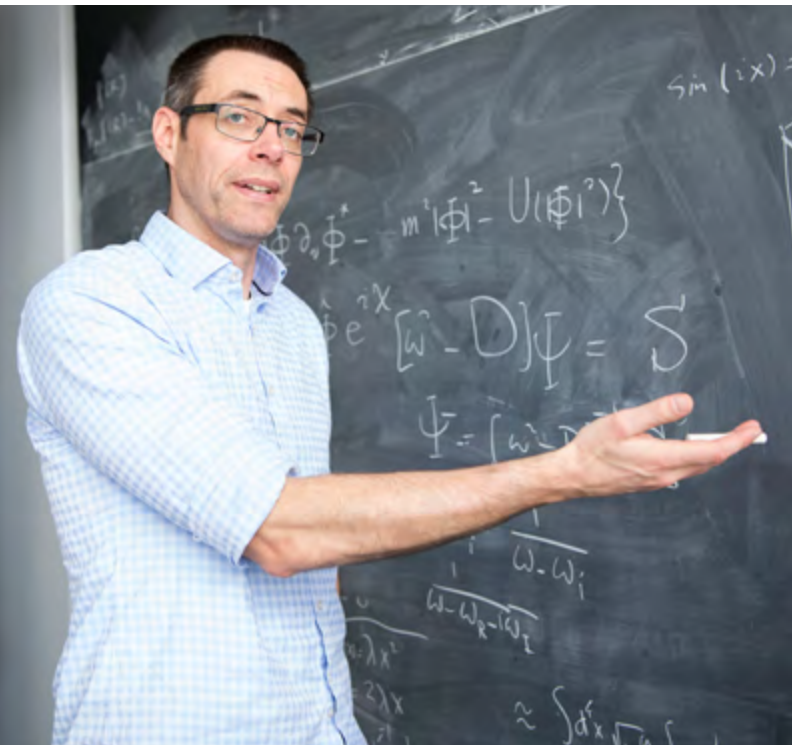
Understanding magnetic fields via polarized light has enormous potential for unlocking the mysteries of black holes. Researchers believe, for example, that they are crucial in explaining the energetic jets that emerge from the core of the M87 galaxy, which emit more energy per second than 2 billion suns and extend for thousands of light years.

References:

EHT collaboration, "First M87 Event Horizon Telescope results. VII. Polarization of the ring," *Astrophys. J. Lett.* 910, L12, 2021, arXiv:2105.01169.

A.E. Broderick (Perimeter Institute/U. Waterloo), D.W. Pesce (Center for Astrophysics), "Closure traces: Novel calibration-insensitive quantities for radio astronomy," *Astrophys. J. Lett.* 904, 126, 2020, arXiv:2010.00612.

A FIVE-YEAR QUEST TO MAP THE UNIVERSE



▲ *Will Percival*

There is a pattern printed on the fabric of spacetime.

Patches of dense and less-dense mass were frozen into place in the early universe, in the moment when electrons and protons joined together to create neutral hydrogen and light began to move freely. In the billions of years since, what was a ripple in primordial gas has become a subtle statistical difference in the distribution of galaxies.

In 2020, a new instrument called the Dark Energy Spectroscopic Instrument, or DESI, began a survey of millions of galaxies designed to spot this pattern.

"All the elements of DESI's design are pushed toward doing a lot of measurements, fast," says Perimeter computational scientist Dustin Lang, who did much of the intense software work and data collection required to get DESI up and running. "We mass-produce galaxy distance measurements."

"We aim to observe on the order of 30 million galaxies," says Will Percival, a Perimeter associate faculty member and one of the founders of the DESI project.

DESI will spend five years building a new 3D map of the universe, examining how the pattern printed on spacetime stretched as the universe expanded. Its ultimate aim is to learn about the mysterious accelerator of that expansion: dark energy.

A NEW CONNECTION

A new connection to three gravitational wave observatories – and an international collaboration involving thousands of researchers worldwide – could pave the way for Faculty member Luis Lehner and other Perimeter researchers to uncover new information about our universe.

Lehner, along with Faculty member Will East, postdoctoral researchers Reed Essik and Suvodip Mukherjee, and eight students, are entering the LIGO-VIRGO-Kagra Scientific Collaboration, with Associate Faculty members Daniel Siegel and Huan Yang joining soon. The collaboration connects three gravitational wave observatories – LIGO, with two observatories in the US; the VIRGO detector, located near Pisa, Italy; and the Kagra detector, located in Kamioka, Japan – as well as over 1,500 scientists worldwide. It's the latest example in a history of strong partnerships between Perimeter's theorists and researchers at observational and experimental centres in Canada and around the world.

"By participating in the LIGO-VIGRO-Kagra collaboration, Perimeter researchers will be able to access and analyze data as it is obtained and develop new ideas to explore fundamental questions about our universe," Lehner says. "These include the nature of gravity at black hole and cosmological scales, particle physics, and some of the most energetic astrophysical phenomena."

The Perimeter team and their collaborators are embarking on the first stage of a program to study non-classical black holes and their potential consequences in gravitational wave observations. The gravitational wave data will also provide a new lens on the testing of dark matter and cosmological models.

MAKING IT WORK

"Physics is one of our best tools for understanding our wild and wonderful universe. It's a pleasure to be able to share that feeling of awe and help make science accessible to all."

Stephanie Keating has a PhD in astronomy and astrophysics from the University of Toronto. She has been at Perimeter for six years, where she started off as an outreach scientist. In her role as Senior Scientific Writer/Editor, Grants and Awards Lead, Keating communicates fascinating and complex research through feature stories and sharable social media content, while supporting researchers and Perimeter through proposals, reports, grants, and award nominations.

GLOBAL RECOGNITION OF THE CENTRE FOR THE UNIVERSE

In the first four years of operation, researchers connected to the Centre for the Universe, and the collaborations they are involved in, have received many major awards and recognitions.

2020/21

- CHIME collaboration awarded the Lancelot Berkeley Prize from the American Astronomical Society.
- CHIME collaboration named a runner up for the 2020 Breakthrough of the Year by *Science* magazine.
- EHT collaboration received the 2021 Group Achievement Award in astrophysics from the Royal Astronomical Society.

2019/20

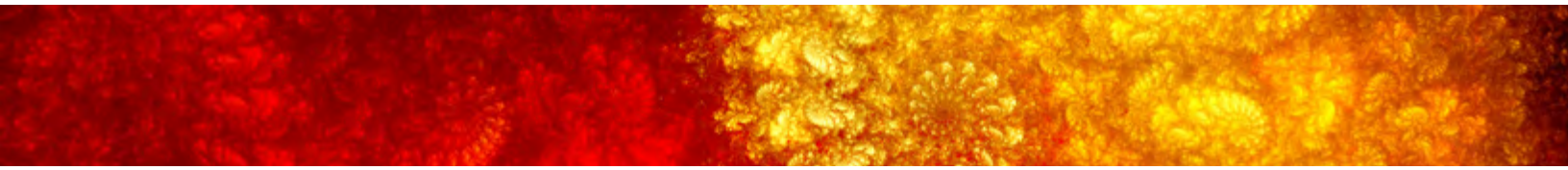
- EHT collaboration earned several awards including the 2020 Breakthrough Prize; the Einstein Medal, Albert Einstein Society; the Nelson P. Jackson Aerospace Award, National Space Club and Foundation; the 2020 Bruno Rossi Prize, American Astronomical Society; and the American Ingenuity Award in Physical Sciences, Smithsonian Institution.
- CHIME collaboration received the Governor General's Innovation Award.
- Kendrick Smith, Faculty and Daniel Family James Peebles Chair, awarded the 2020 New Horizons in Physics Prize from the Breakthrough Foundation.
- Huan Yang, Associate Faculty, received the University of Guelph CEPS Assistant Professor Research Excellence Award.

2018/19

- Neil Turok, Director Emeritus of Perimeter and Mike and Ophelia Lazaridis Niels Bohr Chair, named an Officer of the Order of Canada (Honorary), and Docteur honoris causa from the Catholic University of Louvain.
- EHT collaboration awarded the Diamond Achievement Award from the National Science Foundation.
- Kendrick Smith co-awarded the Giuseppe and Vanna Cocconi Prize of the European Physical Society's High Energy and Particle Physics Division and named a Canadian Institute for Advanced Research Fellow.

2017/18

- Asimina Arvanitaki, Faculty and Stavros Niarchos Foundation Aristarchus Chair, won the 2017 Giuseppe Sciacca International Science Prize.
- Kendrick Smith co-awarded the 2018 Breakthrough Prize in Fundamental Physics as part of the Wilkinson Microwave Anisotropy Probe (WMAP) experiment.
- Neil Turok and postdoctoral researcher Steffen Gielen awarded second prize in the 2017 Buchalter Cosmology Prize competition of the American Astronomical Society.



HONOURS, AWARDS, AND MAJOR GRANTS

- **Avery Broderick**, Associate Faculty and Delaney Family John Archibald Wheeler Chair, was an inaugural recipient of the Excellence in Science Research Award, from the Faculty of Science at the University of Waterloo.
- **Laurent Freidel**, Faculty, earned second prize from the Gravity Research Foundation Award for Essays 2021.
- **Tim Hsieh**, Faculty, received an Early Researcher Award of $140,000 over five years from the Ontario Ministry of Colleges and Universities.
- Associate Faculty member **Raymond Laflamme** and postdoctoral researcher **Michael Vasmer**, in partnership with University College London, are recipients of an $850,000 Quantum Technologies Canada-UK grant from the Natural Sciences and Engineering Research Council of Canada (NSERC) and Innovate UK. Laflamme and Vasmer both hold joint positions with the Institute for Quantum Computing.
- **Luis Lehner**, Faculty, was appointed to the Scientific Advisory Board of the Oskar Klein Centre in Stockholm.

In 2020/21, some Perimeter scientists received research grant extensions from NSERC, as well as grants and awards from other organizations.

INCLUSION, DIVERSITY, EQUITY, AND ACCESSIBILITY

We recognize that imbalances persist in theoretical physics in general, and at Perimeter. We are taking concrete actions to increase inclusion, diversity, equity, and accessibility (IDEA) within our community and to ensure that our outreach and training programs for the public are barrier-free and welcoming for people from historically excluded groups. The following is not a comprehensive list: Perimeter endeavours to deliver all its research, training, and outreach programs through an IDEA lens, and further examples can be found throughout this report.

PERIMETER INITIATIVES, 2020/21

This year, Perimeter continued a partnership with Shift Health and began the next steps to a more inclusive, diverse, equitable, and accessible community. Shift Health undertook internal and external assessments, which included a survey open to all Perimeter residents, in-depth interviews, and benchmarking with other organizations. The results were shared with all residents, and an IDEA strategy and implementation roadmap is being created based on the findings. The work has strong support: 93 percent of survey respondents support the development of an IDEA strategy at Perimeter.

Changing the culture starts with honest discussions and with harnessing the wisdom of multiple views and experiences. The Inclusive PI Platform, founded in 2018, is a grassroots, volunteer-led effort. Forming collaborative working groups and ensuring all voices are heard are core operating principles. About 25 percent of all Perimeter community members are actively involved, with 55 members in eight working groups.

Inclusive PI Platform working groups worked more than 40 initiatives and events in 2020/21. Here are a few highlights:

Accessibility group: Updated Perimeter's multi-year accessibility plan; supported training for a staff member on accessible spaces; and began developing an "accessibility toolbox" for presentations, conferences, social media posts, and visitors.

Anti-racism group: Launched an ambitious self-education effort and organized a colloquium about the history of Indigenous peoples.

Community and communication group: Communicated Platform activities through a weekly email and Perimeter's intranet, and created an IDEA resource library.

LGBTQ2A+ group: Organized social meet-ups; hosted weekly Pride Month events in June; and promoted connections between Perimeter and local LGBTQ2A+ organizations.

Mental health group: Advocated for the creation of an in-house therapist program that provided 176 consultations in the last six months of the year; created a mental wellness podcast series; and launched an Allies program.

Parental policies group: Designed new parental support policies and developed resources for parents.

Respectful environment group: Updated and created new policies; organized several well-attended training workshops led by the Sexual Assault Support Centre of Waterloo Region.

Women in physics group: Published stories on women scientists on the Inside the Perimeter website; organized events, including a screening of *Picture a Scientist* about women in science; and completed a survey of women researchers at Perimeter.

In partnership with private and public supporters, Perimeter continued to offer its programs to high school students, graduate students, teachers, and the general public at no or little cost, ensuring economic background is not a barrier to access.

EMMY NOETHER INITIATIVES

Perimeter's programs to attract and retain more women in science are collectively referred to as the Emmy Noether Initiatives, named after pioneering German mathematician Emmy Noether, whose work underpins much of modern physics. The Emmy Noether Initiatives aim to empower and support women and girls to enter, and succeed in, physics. The initiatives range from outreach to high school students, through events such as "Inspiring Future Women in Science," to graduate training and career development opportunities for women researchers. The initiatives are supported, in part, through the generosity of the Emmy Noether Council and donors in the Emmy Noether Circle (see page 45).

EMMY NOETHER COUNCIL

Council volunteers provide expertise, donations, and other support to all Emmy Noether initiatives, helping to bring more women into physics.

Sherry Shannon-Vanstone, Chair
President & CEO, Profound Impact

Anne-Marie Canning
Culturalpreneur and gender empowerment philanthropist

Nancy Coldham
Founding Partner, CG Group

Lisa Lyons Johnston
President and Publisher,
Kids Can Press, Corus Entertainment Inc.

Michelle Osry
Partner, Deloitte Canada (Vancouver)

Laura Reinholz
Head of Workplace Experience, GTA, BMO Financial Group

Yasemin Sezer
Head, Technology and Operations,
LTI Canada

Sandra Wear
Entrepeneur, CMO, Advisor on Growth, Product Strategy, and Exits

Perimeter Institute would like to thank **Jennifer Scully-Lerner** and **Julie Barker-Merz**, who completed their terms in 2020/21, for their service on the Emmy Noether Council.

SIMONS EMMY NOETHER FELLOWS PROGRAM

Supported by the Simons Foundation, this program targets early- and mid-career women researchers of exceptional promise from around the world. Fellows spend up to one year focused on their research within Perimeter's vibrant, family-friendly environment and are provided with space, unconstrained research time, and freedom from teaching and administrative responsibilities.

Each fellow receives individually tailored supports, which can include travel expenses, housing, childcare, partial support to bring spouses or partners, support to bring graduate students and/or postdoctoral researchers, and administrative and logistical support. Many Simons Emmy Noether Fellows return in subsequent years, continuing to build ties to Perimeter and the wider scientific community.

The program has lasting impact as these women continue their careers. Highlights of former Simons Emmy Noether Fellows during 2020/21 include:

- **Sarah Shandera** (2015/16) was recently appointed as Director of the Penn State Institute for Gravitation and the Cosmos, a multidisciplinary institute. She also held a Perimeter postdoctoral fellowship from 2009 to 2011.
- **Ling-Yan Hung** (2018/19) has been appointed a full professor at the Yau Mathematical Sciences Center, Tsinghua University (starting in 2022). She also held a Perimeter postdoctoral fellowship from 2009 to 2012.
- **Christine Muschik** (2018/19) has emerged as a research leader. She is now a Perimeter associate faculty member and the leader of Perimeter's QFun initiative. Read more about her research on page 13.
- **Sylvia Paycha** (2019/20) helped make a film documenting the experiences of 86 women from 37 countries throughout the pandemic, called *Words of Women in Mathematics in the Time of Corona*.

[2] All deferred visits will be honoured as public health guidelines and travel restrictions allow.

2020/21 SIMONS EMMY NOETHER FELLOWS

Four researchers were appointed in 2020/21 but have deferred their visits due to the pandemic. [2]

Laura Bernard, French National Centre for Scientific Research at the Laboratory for the Universe and Theory, France

Isabel Cordero-Carrión, Department of Mathematics at the University of Valencia, Spain

Sarah Croke, School of Physics and Astronomy at the University of Glasgow, United Kingdom

Maria Elena Tejeda-Yeomans, Universidad de Colima, Mexico

Sarah Shandera (Simons Emmy Noether Fellow 2015/16)

RESEARCH COMMUNITY

FACULTY AND ASSOCIATE FACULTY

In 2020/21, Perimeter Institute was home to 25 faculty members across nine research areas. This year, the Institute recruited outstanding young researchers Sabrina Gonzalez Pasterski from Princeton University and Dominic Else from the Massachusetts Institute of Technology. Perimeter also welcomed two new associate faculty members: Anton Burkov, who is cross-appointed with the University of Waterloo, and Theo Johnson-Freyd, cross-appointed with Dalhousie. There are now 21 associate faculty jointly appointed with eight partner universities across Canada.

For a full list of faculty and associate faculty, including biographies, see pages 53-60.

BRIGHT STARS HEADED TO PERIMETER

Perimeter has recruited two exceptional young scientists to its faculty, who will join their colleagues at the Institute in 2022 after wrapping up research terms at Princeton and Harvard.

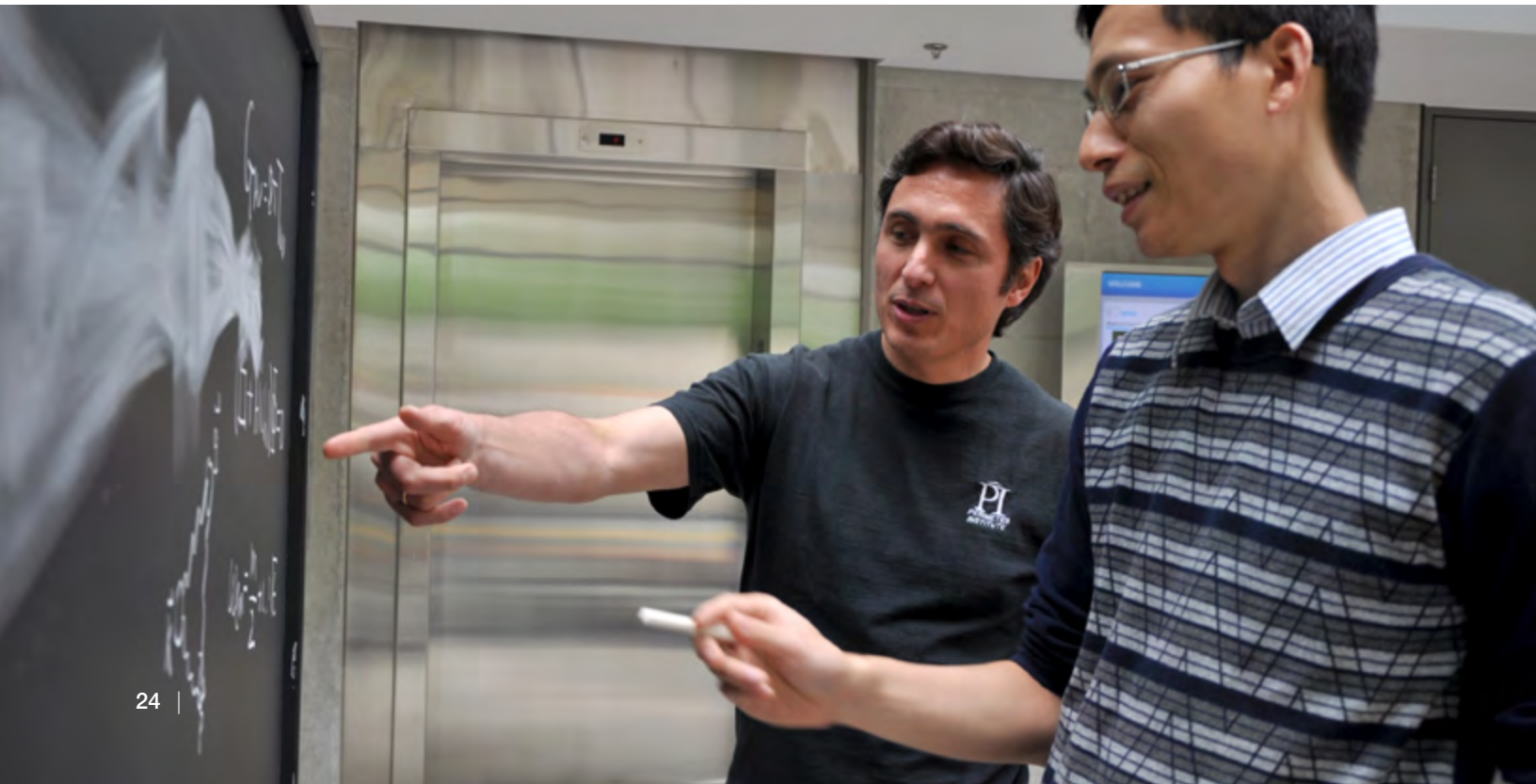
Sabrina Gonzalez Pasterski is a high energy theorist who joined Perimeter's Faculty in 2021. She received her PhD from Harvard under Andrew Strominger and is currently on leave, completing her term as a PCTS Associate Research Scholar at Princeton University. Her graduate work on the infrared triangle, spin memory effect, and celestial holographic dictionary helped usher an interdisciplinary program she is excited to bring to Perimeter. Her Celestial Holography Initiative has brought together leading researchers from the relativity, amplitudes, and bootstrap communities to tackle fundamental questions about quantum gravity in asymptotically flat spacetimes.

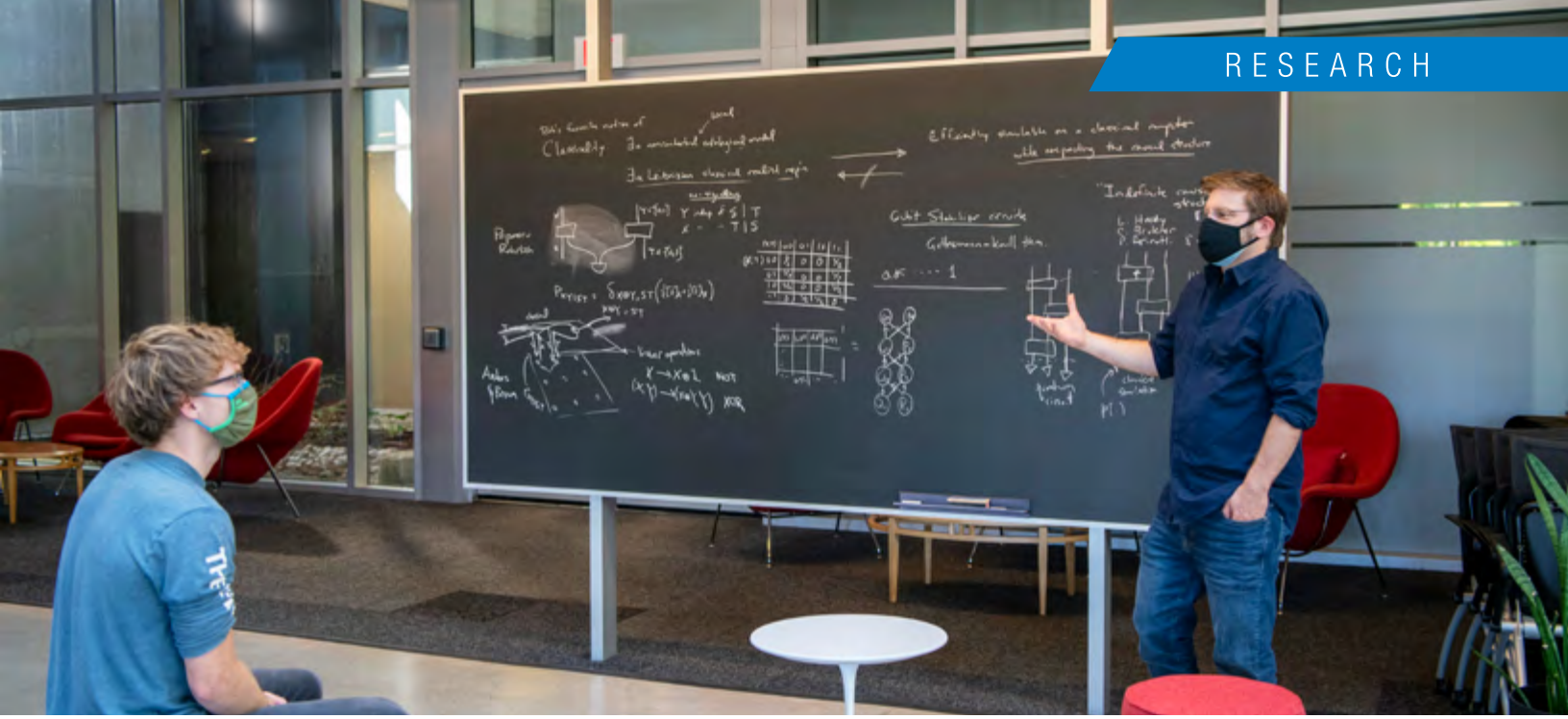
Dominic Else also joined Perimeter's faculty in 2021 and will soon be collaborating with scientists at the Institute's Clay Riddell Centre for Quantum Matter, following his completion of a research term at Harvard University. Else recently won the New Horizons in Physics Prize for his "pioneering theoretical work" on new phases of non-equilibrium quantum matter, including time crystals (crystals that break time-translational symmetry rather than spatial symmetry, as typical crystals do).

Both new recruits exemplify Perimeter's strategy of finding and recruiting exceptional emerging talent as they are entering their peak years of research productivity, says Perimeter Director Robert Myers.

"Sabrina and Dominic are extraordinary young minds pushing the boundaries of fundamental physics," he says. "They will take research in bold, creative new directions, and we're delighted to welcome both to the Perimeter community."

▼ *Luis Lehner and Huan Yang*





▲ *Robert Spekkens and PSI student Matthew Fox*

FRESH PERSPECTIVES AND NEW TIES

Two new associate faculty members have joined Perimeter, enhancing the Institute's research in quantum matter and mathematical physics, while strengthening ties to the University of Waterloo and creating a new connection to Dalhousie University.

Anton Burkov is a quantum matter theorist. A faculty member at the University of Waterloo, Burkov's research focuses on strongly correlated many-particle physics and the interplay of strong correlations and non-trivial electronic structure topology. His recent work includes pioneering studies of topological semi-metals. His research has connections to other fields of physics, including particle physics and quantum computing.

Theo Johnson-Freyd is a mathematical physicist cross-appointed with Dalhousie University. Johnson-Freyd, who recently finished a postdoctoral fellowship at Perimeter, studies applications of higher category theory and homotopy theory to quantum field theory and to quantum matter. This year, he was named as an inaugural member of the newly established Simons Collaboration on Global Categorical Symmetries.

"Anton and Theo both work in fields with connections to many other areas. They are terrific researchers who have already brought exciting research ideas and new collaborations to Perimeter," says Perimeter Director Robert Myers.

PERIMETER RESEARCH CHAIRS

Named for legendary scientists whose insights helped define physics, and supported by donors, Perimeter Research Chairs are doing groundbreaking research in their fields.

Robert Myers
Director, Perimeter Institute
BMO Financial Group Isaac Newton Chair in Theoretical Physics

Asimina Arvanitaki
Stavros Niarchos Foundation Aristarchus Chair in Theoretical Physics

Avery Broderick (Associate Faculty)
Delaney Family John Archibald Wheeler Chair in Theoretical Physics

Freddy Cachazo
Gluskin Sheff / Onex Freeman Dyson Chair in Theoretical Physics

Kevin Costello
Krembil William Rowan Hamilton Chair in Theoretical Physics

Savas Dimopoulos
Stanford University
Coril Holdings Archimedes Chair in Theoretical Physics (Visiting)

Davide Gaiotto
Krembil Galileo Galilei Chair in Theoretical Physics

Subir Sachdev
Harvard University
Cenovus Energy James Clerk Maxwell Chair in Theoretical Physics (Visiting)

Kendrick Smith
Daniel Family James Peebles Chair in Theoretical Physics

Neil Turok
Director Emeritus
Mike and Ophelia Lazaridis Niels Bohr Chair in Theoretical Physics

VISITING SCIENTISTS

In 2020/21, there were no in-person scientific visits to Perimeter due to the ongoing pandemic, but the national and international theoretical physics community continued to maintain strong ties to the Institute though virtual collaborations, conferences, and partnerships. We look forward to a transition to in-person visitors in the coming year as public health guidelines and travel restrictions allow.

DISTINGUISHED VISITING RESEARCH CHAIRS

Perimeter is a second research home to many of the world's top physicists. Distinguished Visiting Research Chairs (DVRCs) are appointed to renewable three-year terms and normally make extended research visits to Perimeter, while retaining permanent positions at their home institutions.

While here, they use the time away from their home institutions to focus intensively on their research and, at the same time, energize our research community by entering into new collaborations with resident scientists, co-organizing conferences, and presenting talks on the ideas they're most excited about. In a 2019/20 report on the impacts of the program, many DVRCs indicated that their collaborations resulted in new ideas and approaches, as well as published papers.

"For nearly 10 years, as a DVRC, I have been making a couple of visits every year and spending a few months in each visit," says Ganapathy Baskaran, from the Institute of Mathematical Sciences in Chennai, India. "My last visit to Perimeter ended in early September 2019. It seems much longer than two years. I miss interaction with colleagues, postdocs, visitors, and students, and weekly colloquia and the regular seminars."

Sandu Popescu is a professor at the University of Bristol and a member of Perimeter's Scientific Advisory Committee. He has been a DVRC for 12 years. "Perimeter is an oasis of calm, where I can be alone and think with no disturbance, yet, when I feel the need, I can just simply go downstairs and have fascinating scientific discussions with some of the best people in the world," he says.

"It's a place where I feel at home, where I have so many friends, both among my scientist colleagues and among the wonderful staff. A place where I feel inspired, and that I miss a lot. A place I hope to visit again soon."

In 2020/21, two new DVRCs were appointed, bringing the total to 44. This year's new appointees are:

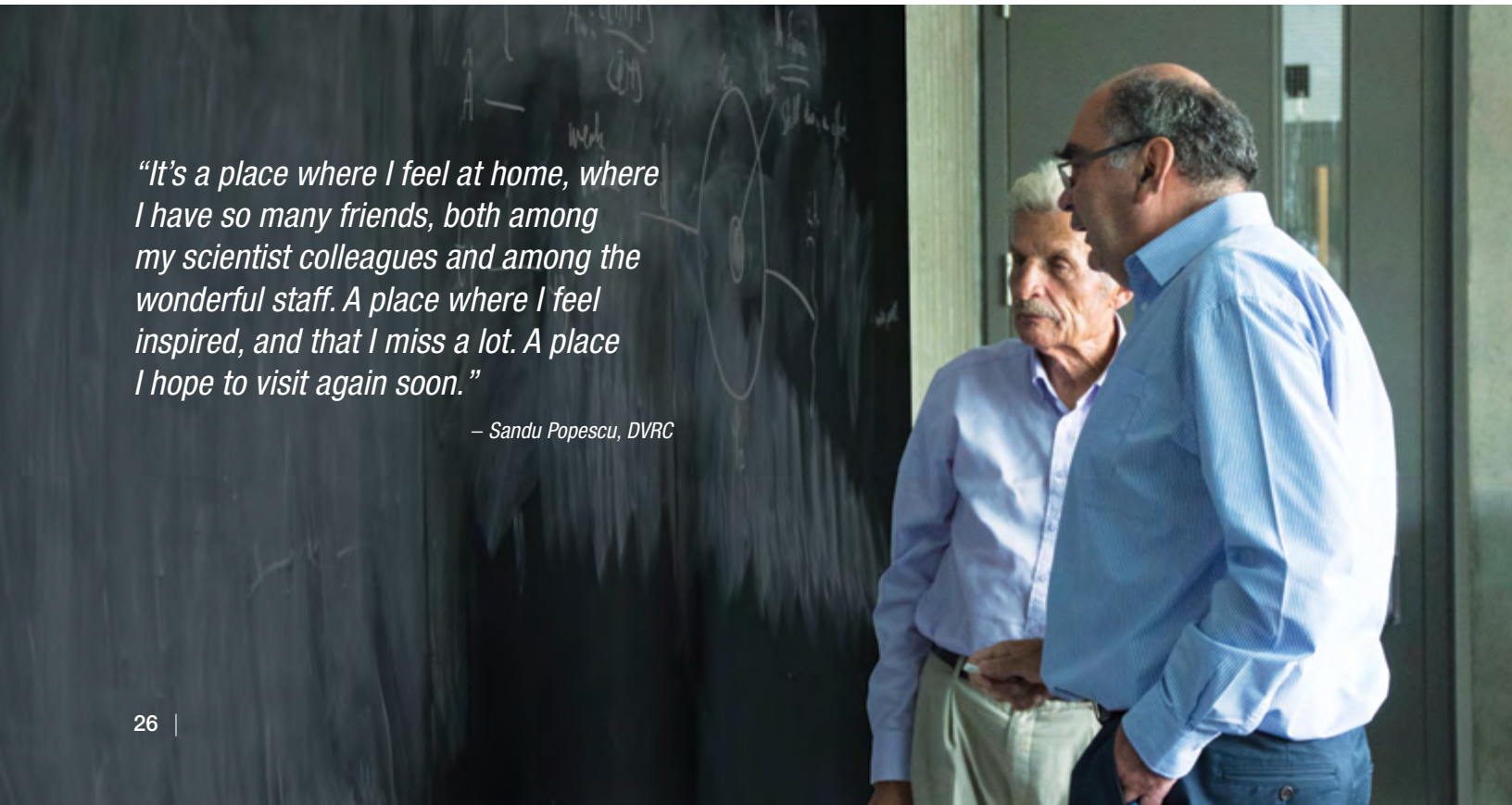
Juna Kollmeier
Canadian Institute for Theoretical Astrophysics

Guifre Vidal
X – The Moonshot Factory

For a full list of DVRCs, see page 62.

The Distinguished Visiting Research Chair program was supported in part by Cenovus Energy for 2020/21.

▼ *Yakir Aharonov and Sandu Popescu (2016)*



VISITING FELLOWS, VISITING RESEARCHERS, AND AFFILIATE MEMBERS

Perimeter engages with the wider scientific community while diversifying its own by bringing accomplished researchers to the Institute for regular visits in several ways in addition to the DVRC program and the Simons Emmy Noether Fellowships.

Visiting Fellows are appointed to renewable terms, retain their positions at home institutions, and enrich the Perimeter research community during their extended stays. In 2020/21, seven new Visiting Fellows were appointed, for a total of 52.

Affiliate members are scientists from Canadian universities who have an open invitation to visit Perimeter at any time to do research. This year, nine new Affiliate members were appointed, bringing the total to 114, from 31 universities.

We also encourage applications from scientists to come as **Visiting Researchers** while on sabbatical leave from their faculty positions at home institutes and look forward to continuing this program in the future.

"Perimeter is exceptional minds, mostly young, set loose on the hardest problems in physics. They're too ambitious to know the meaning of impossible, so they routinely defy it."

– Robert Myers, Director, Perimeter Institute

CONFERENCES AND WORKSHOPS

Advances in physics are happening fast on many fronts, and Perimeter's renowned conference program has been bringing theorists together, often with experimentalists, in crucial conversation for almost 20 years. Conferences focus on leading-edge topics with the potential for significant outcomes, and Perimeter often hosts conferences on emerging topics that haven't yet been addressed anywhere else.

In 2020/21, there were no in-person conferences, but online registration and attendance were far higher than expected. More than 1,000 scientists from around the world attended seven conferences and workshops hosted by Perimeter, in areas such as quantum matter, particle physics, mathematical physics, quantum gravity, and general relativity. Associate Faculty member Roger Melko says the online conferences helped him build more connections with researchers around the world than ever before, and the aim is to strengthen these new interactions as public health guidelines allow.

Conferences and seminars are recorded and made freely available online to the scientific community through the Perimeter Institute Recorded Seminar Archive (PIRSA) and SciTalks (see more below).

See the full list of conferences on page 64.

MAKING IT WORK

"My job is very engaging and dynamic, and I have the opportunity to meet scientists and students, from around the world, in all stages of their career."

Stephanie Mohl has been the Conference Program Lead at Perimeter for 11 years. She manages and provides support for 10 to 20 conferences annually, with anywhere from 10 to 300 attendees each. To pull it all off, she works closely with scientific organizers and coordinates everything from Bistro service to AV recordings.

WOMEN IN MATH AND PHYSICS CONFERENCE

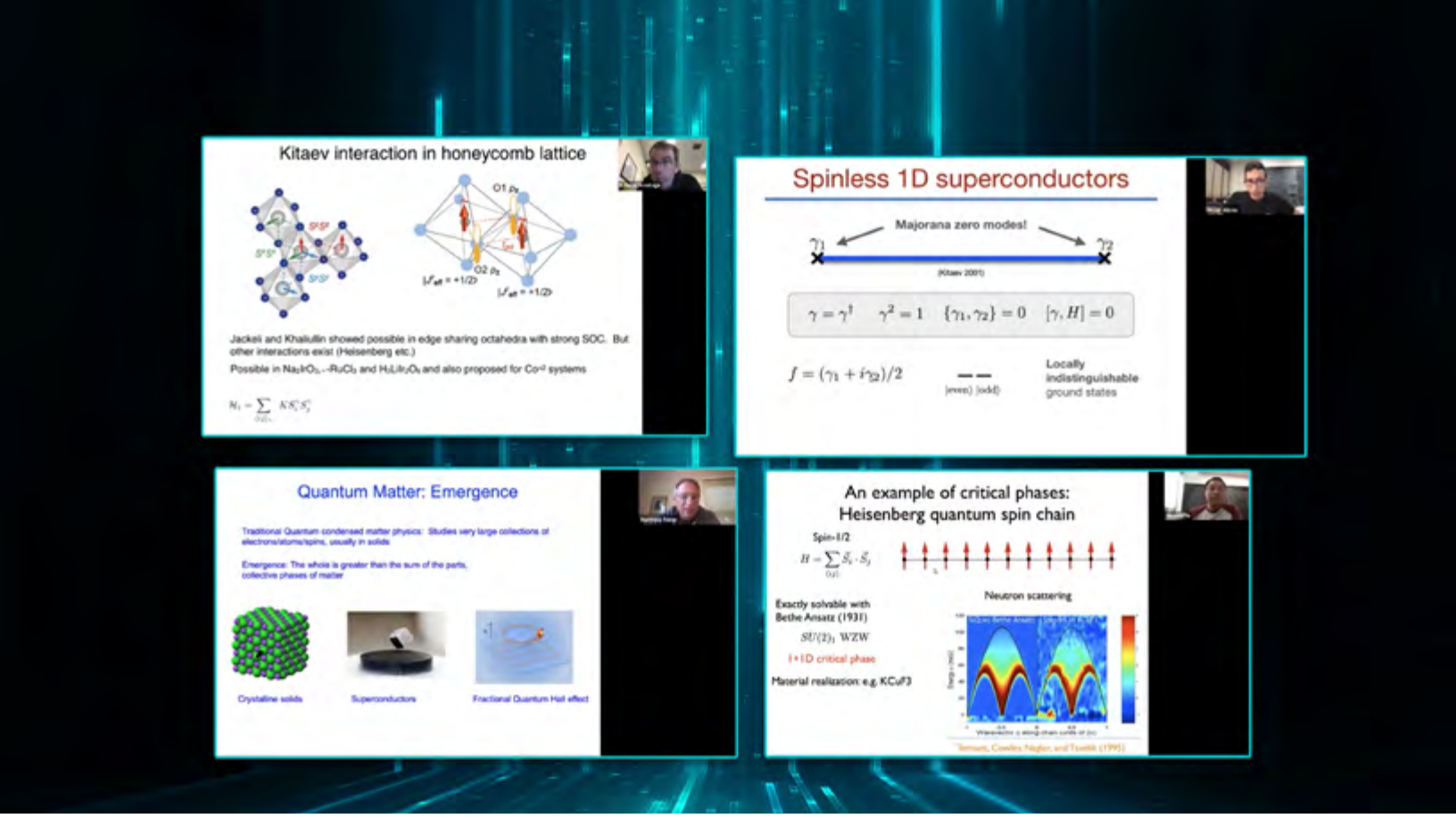
Connecting women mathematicians and physicists, identifying new trends in research, and encouraging a mentoring scheme between senior and junior participants – it all happened when over 100 participants gathered for the "Women at the Intersection of Mathematics and Theoretical Physics", hosted by Perimeter and held virtually in February 2021.

Primarily, but not exclusively, for women, the conference was co-organized by Perimeter Faculty member Bianca Dittrich, Associate Faculty member Theo Johnson-Freyd, former Simons Emmy Noether Fellows Katarzyna Rejzner and Sylvie Paycha, and others. To encourage parent-scientist participation, Perimeter offered financial support to cover additional costs that might be incurred for childcare.

Dittrich thinks these types of conferences can play an important role in supporting the work of women researchers. "I think the prime focus on women comes from women being, typically, quite in the minority. Personally, I found the few occasions where there were mostly women quite a bit more relaxed and open, with less competitive behaviour," she says.

She hopes that the conference will help women build networks and build confidence in a field where that can be difficult. "This might be a particularly important aspect for younger women, who may want to have advice from other women, about issues that tend to fall more in the experience of women," Dittrich says.

▼ *Screen captures from "Women at the Intersection of Mathematics and Theoretical Physics"*



▲ *Screen captures from the Quantum Matter Frontier Seminars*

SEMINARS AND COLLOQUIA

Throughout the year, resident scientists and those from other institutions give seminars and colloquia on their latest research, promoting scientific exchange and often sparking collaboration across disciplines.

In 2020/21, Perimeter hosted 266 seminars and 30 colloquia, which attracted just over 10,000 participants. Twenty-six percent of these talks were delivered by women, an increase of 11 percent over the previous year. Increasing the number of talks given by women has been a focus of IDEA strategies at the Institute.

With few exceptions, every seminar and colloquium is recorded and posted to the Perimeter Institute Recorded Seminar Archive (PIRSA) – a searchable online database that now catalogues more than 13,500 videos, which were viewed over 464,000 times in 2020/21 alone. These recorded talks have become a valued resource worldwide, particularly to those who are not at major research centres.

With support from the Simons Foundation, Perimeter has also created a new international hub that expands on the success of PIRSA. SciTalks.ca is now in the testing phase and carries the full PIRSA catalogue, as well as additional talks from partners at CERN, the Simons Institute, the International Centre for Theoretical Physics, and the South American Institute for Fundamental Research, making more than 14,200 videos available to brilliant minds, no matter where they are.

THE FRONTIER OF QUANTUM MATTER

Several Perimeter faculty and associate faculty members have created a seminar series that offers a deeper look into multiple facets of one topic over a longer period of time.

The Quantum Matter Frontier Seminars began in September 2020, co-organized by Perimeter Faculty members Tim Hsieh and Chong Wang, Associate Faculty members Anton Burkov (jointly appointed with the University of Waterloo) and Sung-Sik Lee (jointly appointed with McMaster University), and Yong-Baek Kim from the University of Toronto.

“We wanted to provide a useful service to the quantum matter community, and to help mitigate the impact of COVID-related disruptions in the field – in particular the lack of regular, in-person seminars,” says Burkov. He says there is also a benefit to Perimeter and the Ontario universities involved, in helping to disseminate their current research to the broader community.

“The goal is to feature particularly new research topics and get high-quality speakers,” Hsieh says. “The format was somewhat unique – with substantial flexibility in length, speakers could elaborate as much as they wanted. I think it is a success, based on feedback we’ve received from participants.”

The Quantum Matter Frontier Seminars have featured speakers from prestigious institutes such as Johns Hopkins University, Harvard, Yale, Stanford, NYU – and of course, Perimeter. Held weekly, there were 21 seminars in the series in 2020/21, and the series continues in fall of 2021 with a slate of eight more speakers.

TRAINING

"Perimeter Institute has been a wonderful place for me to extend my knowledge on frontier quantum matter research with a network of ever-curious physicists."

– Lei Gioia Yang, PhD student

Niayesh Afshordi and student

TRAINING by the numbers

Perimeter aims to attract and develop the next generation of brilliant minds. We know that young people are the lifeblood of science, and we have programs – from our master's program for exceptional international students to our world-leading PhD program – that aim to turn students into scientists. [3]

More than **1,000** young scientists trained since 2006

79 Postdoctoral researchers from 23 countries including 18 women

70 PhD students from 29 countries including 14 women

21 Perimeter Scholars International students from 13 countries, including 9 women

357 PSI graduates in 12 years, including 119 women (33%)

50 Associate postdoctoral researchers and associate PhD students

1 Visiting Graduate Fellow[4]

[3] *Unless otherwise indicated, figures are for August 1, 2020–July 31, 2021.*
[4] *Due to the ongoing pandemic, Perimeter's in-person Visiting Graduate Fellows program did not run in 2020/21; however, one student participated in an online-only program.*

POSTDOCTORAL RESEARCHERS

Perimeter is home to one of the world's largest cohorts of postdoctoral researchers in theoretical physics. These early-career scientists are fully immersed in Perimeter's multidisciplinary environment, where they are given complete research freedom, encouragement to tackle ambitious problems, and mentorship from senior scientists. In addition to three-year terms, Perimeter has prestigious named four-year fellowships, senior five-year fellowships, and jointly appointed fellowships with partner universities.

Perimeter's postdoctoral positions are highly sought after: from 772 applicants, 12 new postdocs joined Perimeter in 2020/21. Of those who completed their term this year, several chose to stay at Perimeter for further opportunities, including Elie Wolfe as a research associate and Theo Johnson-Freyd as a new associate faculty member. Others went on to tenure track positions, including Felix Leditzky as assistant professor at the University of Illinois and Moritz Munchmeyer as faculty at the University of Wisconsin. Many have shifted to careers in industry, including Martin Ganahl and Adam Lewis at Google's X (The Moonshot Factory) and Qiao Zhou as a manager of market risk measurement at Bank of Nova Scotia.

Perimeter had a total of 79 postdocs from 23 countries in 2020/21; see the full list on page 61.

PI PEOPLE

Postdoctoral Researcher

HAN MA

Han Ma is the Philip W. Anderson Fellow at Perimeter. Originally from China, she completed her PhD at the University of Colorado Boulder.

In early 2019, she attended a conference in Aspen and had an inspired discussion with Associate Faculty member Sung-Sik Lee. This led to further collaboration, and Ma arrived at Perimeter as a postdoctoral researcher in 2019.

As a member of the highly interdisciplinary team at the Clay Riddell Centre for Quantum Matter, Ma plans to work on the quantum renormalization group method in order to understand the universal behaviour of various quantum phases and phase transitions. She is an active contributor to the research community and has delivered many seminars, including at Cornell and Harvard.

"At Perimeter, it's easy for people from different fields to interact. Interdisciplinary progress is usually made out from these collaborations. It is very helpful to my personal research trying to understand condensed matter systems by an approach building upon concepts from high energy physics," Ma says.

"The environment in PI of thinking and working freely encourages me to always have the passion and persistency to challenge hard problems."

PI PEOPLE

Postdoctoral Researcher

FERESHTEH RAJABI

With a PhD from Western University and close ties to quantum optics experimentalists at the Institute for Quantum Computing and astrophysicists at Perimeter, postdoctoral researcher Fereshteh Rajabi turned her focus to fast radio bursts (FRBs).

FRBs are bright, ultra-brief radio signals that often originate from outside our galaxy and whose origins are unknown. Recently, Rajabi and her colleagues considered a simple dynamical relativistic model to explain the spectro-temporal structure often displayed by repeating FRBs – those that flash more than once. Along with a follow-up paper, this research has motivated new searches by astrophysicists around the world that could shed light on the underlying mechanism of repeating FRBs.

"I find Perimeter Institute an excellent environment for interdisciplinary exploration. Researchers are given maximum freedom to explore different avenues, or combine them," Rajabi says. "PI harvests and supports creativity and opens doors for collaborations with top-notch researchers around the world. This is incredibly important for early-career researchers such as me."

ASSOCIATE POSTDOCTORAL RESEARCHERS AND PHD STUDENTS

Perimeter is an independent institution that maintains strong ties with Ontario universities such as the University of Waterloo, McMaster University, the University of Toronto, York University, Western University, and Queen's University. The Institute's associate programs offer selected postdoctoral researchers and PhD students from those universities specific privileges, so they benefit from much of what Perimeter offers: from courses and seminars to opportunities to collaborate with researchers. During 2020/21, all collaborations with associates took place online. This year, there were a total of 11 associate postdocs and 39 associate PhD students.

PHD STUDENTS

Perimeter is an extraordinary place for students to complete a PhD, with opportunities to engage with prestigious scientists in all disciplines. Students receive their degree from the partnering university where their supervisor has a full or adjunct appointment. This year, these included the University of Waterloo, McMaster University, the University of Toronto, the University of Guelph, and York University.

Many of the exceptional students from around the world who graduate from the Perimeter Scholars International (PSI) program stay in Canada to continue their education and research. In 2020/21, 66 percent of Perimeter's PhD students were PSI graduates.

Of the students who completed their PhD in 2020/21, many went on to prestigious postdoctoral fellowships, including Laura Sberna at the Max Planck Institute for Gravitational Physics and Vasudev Shyam at Stanford University. Others began private sector careers, including Florian Hopfmueller at Canadian advanced computing company 1QBit, Qingwen Wang at Deloitte, and Yijian Zou at Google's X (The Moonshot Factory).

Perimeter had a total of 70 PhD students from 29 countries in 2020/21; see the full list on page 63.

PI PEOPLE

PhD Student

LEI GIOIA YANG

Lei Yang arrived at Perimeter in 2017 from New Zealand to attend the PSI master's program and is staying on to complete her PhD under the supervision of Anton Burkov and Chong Wang, and in collaboration with researchers at the Clay Riddell Centre for Quantum Matter.

Her research revolves around the "sociology" of particles in topological materials, with an emphasis on semi-metals and metals. "More specifically, my study focuses on a new type of anomaly that we dub 'unquantized anomalies,' which occur in metallic materials," she says. In the long run, she aspires to come up with theorems that strongly govern a wide range of behaviours, such as entanglement structure and symmetry breaking phases, in quantum materials.

"Perimeter Institute has been a wonderful place for me to extend my knowledge on frontier quantum matter research with a network of ever-curious physicists," Yang says.

STUDENT AWARDS

Many students at Perimeter are supported by awards, grants, and scholarships. Here are just a few of those awards:

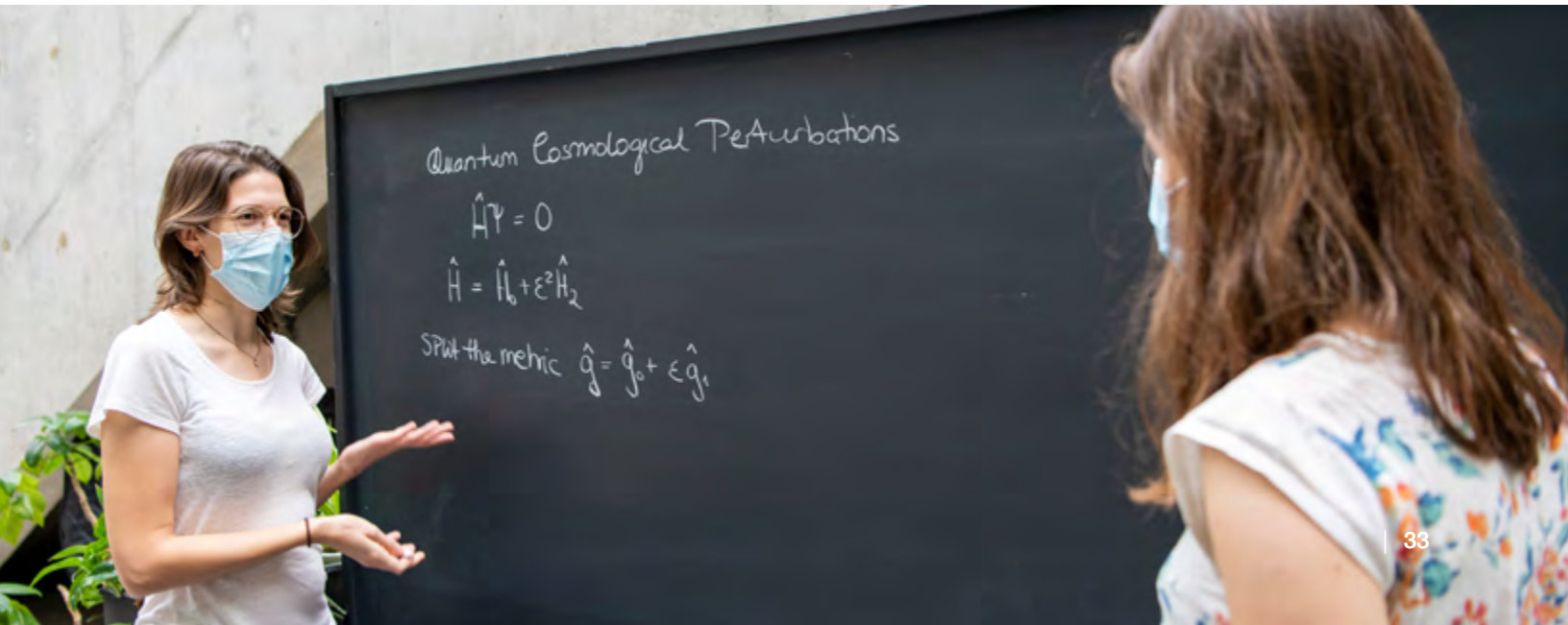
PhD students Finnian Gray and Lei Yang are recipients of the highly competitive Vanier Canada Graduate Scholarships from the Natural Sciences and Engineering Research Council of Canada, awarded for academic excellence, research potential, and leadership qualities.

PhD student Xiu-Zhe (Roger) Luo won the inaugural Wittek Quantum Prize for Open Source Software, administered by the Quantum Open Source Foundation. Luo works with Perimeter Associate Faculty member Roger Melko at the Perimeter Institute Quantum Intelligence Lab.

Lena Funcke received the Leona Woods Distinguished Postdoctoral Lectureship Award from the US Department of Energy's Brookhaven National Laboratory for her work at the intersection of fundamental particles, the cosmos, and quantum computing.

Daniel Egana-Ugrinovic, Olga Papadoulaki, and Suvodip Mukherjee received special bridge fellowships from the Simons Foundation, designed to provide support to postdoctoral researchers during the pandemic.

▼ *Susanne Schander and Ana-Maria Raclariu*



PERIMETER SCHOLARS INTERNATIONAL

While many people spent the past year learning to interact with others at a two-metre distance, the 21 students enrolled in Perimeter's master's program were figuring out how to collaborate from their homes in Canada and 12 other countries around the world.

Through sheer determination and adaptability, the members of the 2021 PSI graduating class developed into an extraordinary community of emerging scientists. It was the first time that PSI students completed the entire program online.

"We were first isolated from the outside world by quarantine, and further isolated by having to spend so much time on our schoolwork, which no one around us in our daily lives could probably even understand," said Kelly Wurtz in her valedictorian speech at the online PSI graduation ceremony. "And so, to a large extent, our community was each other. My twenty fellow students became a large part of my support network."

PSI is a one-year master's-level course in theoretical physics that attracts exceptional students from around the world. On completion, students earn their master of science degree from the University of Waterloo, and a PSI certificate. It's a highly competitive program: the nine women and 12 men in the 2020/21 cohort were chosen from more than 900 applicants. Eight "PSIons" are continuing on at Perimeter to pursue PhDs.

Perimeter faculty and staff who have worked with the master's program for many years were impressed with how effectively it transitioned to virtual, distanced interactions. They gave much credit to the graduating students and to the PSI lecturers and fellows for making the year a success.

"They completed an extremely challenging program in a time of global crisis, all without ever coming to Perimeter," says Robert Myers, the Institute's Director. "Our graduates follow many paths. Some carry on with theoretical physics. Others found companies, study cancer treatments, become innovators, and more. All of them carry the Perimeter spirit. Nobody captures that spirit better than this year's PSI graduates."

In addition to the degree-granting master's program, PSI offers free online learning modules that allow motivated students and physics enthusiasts to study graduate-level theoretical physics independently and at their own pace. In 2021, 992 unique users enrolled in an average of 1.5 courses each, for a total of 1,515 enrollments in courses such as quantum field theory, quantum matter, and statistical physics.

See the full list of PSI faculty and students on pages 62-63.

The PSI program was supported in 2020/21 by The Hellenic Heritage Foundation, Brad and Kathy Marsland, Margaret and Larry Marsland, The Savvas Chamberlain Family Foundation, and members of the Emmy Noether Circle.

2021/22 PSI students

CAREER TRAJECTORIES

A degree in physics doesn't only lead to a life in academia, and Perimeter's Trajectories initiatives are designed to help students and early-career researchers, from undergraduates to postdocs, find careers that are exciting and fulfilling to them. Trajectories offers workshops and networking opportunities, a suite of resources on job hunting and career development, and individual support for résumé development and honing interview skills.

In 2020/21, there were three online Trajectories events for students. Former Perimeter postdoctoral researcher Will Cunningham discussed his role at Toronto-based software start-up Agnostiq during the "Making a Change" lunch-and-learn session. Students had one-on-one time with over a dozen quantum technologies insiders, from Google, Spotify, 1QBit, the National Research Council of Canada, ISARA Corporation, Xanadu, and others, at Virtual Speed Networking Day. And at the "Career Paths in Academia" event, five former Perimeter residents shared their experiences – from early-career assistant professors at smaller universities, to a full faculty member at Cambridge University.

A PERFECT ENTANGLEMENT: PHYSICISTS AND QUANTUM START-UPS

Many scientists enjoy taking on real-world challenges alongside their curiosity-driven research. And many commercial tech companies are sympathetic to the idea of advancing scientific research as they bring new products to market.

The result: an increasing number of Perimeter physicists are working with quantum start-ups like Xanadu or Agnostiq. The trend is most pronounced among postdoctoral researchers planning careers in a world where fundamental research and entrepreneurial ventures have never been closer.

Recent postdoctoral researcher William Cunningham studied quantum gravity at Perimeter. During that time, he began working with Agnostiq, which serves sectors like finance, where quantum computing plays a growing role in security, analysis, and other areas. Cunningham found it natural to adapt his expertise from one to the other.

"The methodology is similar," he says. "In both places, I use machine learning and quantum algorithms. Since these are relatively new techniques, there is great interest in understanding how they may be leveraged in both theoretical and applied research."

Venture capital firms have been pouring money into quantum start-ups, even as theoretical physicists work to understand the fundamental science. That opens up opportunities for people like postdoctoral researcher Michael Vasmer to establish a footing in both worlds.

Vasmer works with a Toronto-based company called Xanadu, which is developing new computing technologies based on "photonic qubits," a promising, adaptable means of storing and processing quantum information.

"In my field of quantum error correction – as in quantum information more broadly – there is quite a large overlap between the interests of theoretical physicists and of industry," he says. "From my perspective, this is because the central problem is the same: we want to try to build a fault-tolerant quantum computer."

Quantum computing is at an exciting stage, and those with the right skills can traverse the worlds of academia and industry, getting exciting glimpses into our quantum future.

MAKING IT WORK

"It's incredibly satisfying to support students as they begin their training in physics – particularly our younger students from around the world in our PSI program – and then watch them go on to remarkable careers."

Debbie Guenther has been at Perimeter for 18 years, 13 of them as Academic Program Manager. She provides support for the teaching staff and 60 to 70 PSI and PhD students, assisting with everything from accommodation to mental wellness supports, academic records, and support for teaching staff.

OUTREACH

"They are so brilliant, and their lesson plans and resources are honestly fail-proof."

– Hayley McKay, science teacher, Sundre High School, Alberta

Perimeter Online Teachers' Camp, 2020

OUTREACH by the numbers

Great science deserves to be shared with the people whose lives it touches – and that's everyone. Perimeter is recognized as an international leader in science outreach, striving to increase scientific literacy by sharing the transformative power of physics with students, teachers, and curious people everywhere.[5]

STUDENTS

152,000 student interactions[6]

640 student interactions in 2020/21

67 million student interactions through resources[7]

8 million student interactions through resources in 2020/21

285 students participated in "Inspiring Future Women in Science" in 2021

39 exceptional high school students – 20 Canadian, 19 international – participated in the 2021 International Summer School for Young Physicists

TEACHERS

41,000 educators trained through Perimeter workshops

4,700 teachers trained at 152 workshops in 2020/21

46 teachers from 19 countries participated in EinsteinPlus online camp in 2020/21

125 countries in which Perimeter educational resources have been used

114 in-class resources available to teachers across Canada and around the world

SCIENCE FOR THE WORLD

7 public lectures viewed 130,000 times in 2020/21

6 million YouTube views in 2020/21, a 211% increase

110,000 YouTube subscribers, a 36% increase

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[5] *Unless otherwise indicated, figures are since Perimeter's inception.*
[6] *Perimeter interactions with students at events and workshops.*
[7] *Estimated number of times students have interacted with Perimeter's educational resources.*

FEARLESS PHYSICS: TEACHING THE TEACHER

A researcher mysteriously disappears, along with the secret launch codes for a new networking satellite. A group of teachers stumble across the missing scientist's private journal, which is filled with cryptic notes and possible hints as to her whereabouts. They work together at top speed to solve clues whose secrets appear to be connected to the world of particle physics.

This escape room–style mystery, "Igniting the Orbitron," was one of the most popular exercises at this year's Online Teachers' Camp. The camp helps teachers from across Canada and around the world hone their abilities to engage students with the latest ideas in theoretical physics.

The online camp evolved from EinsteinPlus, an annual in-person camp that typically draws 40 to 50 teachers to Waterloo each year to collaborate and learn in person. The camp moved online during the pandemic, a transition that came with some side benefits, including making it easier for people to participate from abroad. The camp attracted 46 educators from Canada and 18 other countries.

"You had so many intellectual minds connecting from around the world. It was amazing, and also intimidating at first," said Hayley McKay, a science teacher from Sundre High School in Alberta. "But by the time we got to the last session, I didn't want it to end."

Sessions focused on challenging subjects, ranging from black holes to wave-particle duality. Experts gave talks to bring teachers up to speed on the current state of science, while physics teaching experts encouraged exploration of hands-on physics activities, teaching tools, gadgets, and pedagogical strategies designed to make these ideas relatable and accessible for students.

In addition to the one-week intensive EinsteinPlus camp, in 2020/21 Perimeter hosted 152 teacher workshops with 4,700 participants, most of them online. Perimeter also partnered with the International Centre for Theoretical Physics – South American Institute for Fundamental Research in Brazil to host 79 workshops, with a total of 2,719 participants. Subjects included the mystery of dark matter, wave-particle duality, GPS and relativity, quantum physics, black holes, and the expanding universe.

McKay says the teacher trainers and workshops will continue to help her grow as a teacher. "They are so brilliant, and their lesson plans and resources are honestly fail-proof."

Perimeter's teacher training programs are supported by the Power Corporation of Canada and the Bosch Community Fund on behalf of ESCRYPT in Canada.

EDUCATIONAL RESOURCES

In classrooms across Canada and 124 other countries around the world, Perimeter's free digital resources are used to give teachers the confidence to teach physics, and students an exciting, interactive way to explore and learn. Each compilation explains an important topic in physics, or science more broadly, and includes lesson plans, hands-on activities and demos, modifiable worksheets, background information for teachers, and original Perimeter videos.

All educational resources are available in French and English, and further translations are ongoing, with 17 resources available in Portuguese and 15 available in Spanish. New resources developed in 2020/21 include the units "Exploring Light with Optics," "Investigating Planck's Constant with LEDs," "Beyond the Atom," and "Igniting the Orbitron."

Perimeter's educational resources are developed with educators and address curriculum guidelines in every province. In 2021, members of the Outreach team attended three virtual events to gain additional knowledge of the Indigenous educational space: the Indspire National Gathering for Indigenous Education, the Canadian Indigenous Science and Engineering Society STEM panel, and the American Indian Science and Engineering Society Leadership Summit.

▲ *International Summer School for Young Physicists*

YOUNG PHYSICISTS FIND COMMUNITY AT SUMMER SCHOOL

The International Summer School for Young Physicists (ISSYP) is the ultimate summer camp for high schoolers with a passion for science. Though forced to go online-only by the pandemic, the 39 high school students who participated built connections that they say could last a lifetime.

The two-week intensive camp included 20 students from Canada and 19 from a total of 10 other countries. For many years, ISSYP has been gender balanced, and this year was no exception.

"I can go on YouTube and learn stuff on my own," says student Gina Bilic of Winnipeg. "But collaborating with these international students and the teachers was something extraordinary. I met kids from Spain and Dubai. We're interested in the same stuff, but we all have different experiences."

In addition to differences in geography, culture, and background, students arrived at the summer school with varied skills in different aspects of physics. Some were stronger in math, while others had particular interests in cosmology or quantum physics. Students and teachers concurred, though, that passion and enthusiasm were the most reliable predictors of success. Career mentorship is a major component of the summer school, with students making connections and learning about options for pursuing jobs in physics.

Launched in 2004, ISSYP has been attended by more than 900 students from 62 countries. Many have gone on to further education and careers in STEM fields.

"The program allowed a whole bunch of us who think similarly about this very specific subject matter to connect," says Hassan Elshabasy of Calgary, who started an honours physics degree at the University of Waterloo in the fall. "A lot of students from the program are going to UW next year as well. So we'll stay in touch with each other, and also with people at the Perimeter Institute."

The 2020/21 session of ISSYP was made possible by the support of presenting partner RBC Foundation, in support of RBC Future Launch.

MAKING IT WORK

"I have the opportunity every day to get people not only interested in, but inspired by, the natural world. I see my role as transmitting my passion for physics to teachers, and helping kids identify and nurture the budding scientist inside them."

Damian Pope is the Senior Manager of Scientific Research in Perimeter's Outreach department, where he has worked for 16 years. He spearheaded the creation of Perimeter's educational resources, trains educators, and teaches programs to students and the general public. With a PhD in quantum information and quantum foundations from the University of Queensland, his development of educational products and programs involves extensive collaboration with Perimeter researchers.

INSPIRING FUTURE WOMEN IN SCIENCE

Four women scientists, speaking from their labs, offices, and homes, shared their experiences with high school and university students around the world for Perimeter's annual "Inspiring Future Women in Science" event.

In celebration of the International Day of Women and Girls in Science, Perimeter hosted a question-and-answer session with four women whose research spans the depths of the oceans to the farthest reaches of the universe.

On the panel were Jessica Schaub, a first-generation university student completing a master's degree in oceanography; Tiera Fletcher, an aerospace engineer, writer, and motivational speaker; Roopali Chaudhary, a cell biologist and entrepreneur with a passion for increasing diversity in STEMM fields; and Asimina Arvanitaki, an award-winning particle physicist from Perimeter's own faculty.

The women shared their experiences and answered questions about the challenges and rewards of completing a PhD, the value of skills such as creativity and communication, and gender balance in their fields. The discussion inspired one participant to consider not only her own career but how she could become a role model for others.

"Like Dr. Chaudhary, I am also an immigrant, and I've been shy and introverted for most of my life," said Adithi Iyer, a participant from Whitby, Ontario. "I found it extremely inspiring when Dr. Chaudhary said you shouldn't let your background or gender stop you from entering a field of your interest. Why should I let the fact that I don't have many role models who look like me deter me from following my passions in STEM, when I can get out there and become that role model for someone else?"

For the first time, the event was held entirely online, enabling a global reach. Teachers from 25 countries and from 39 school boards across Canada registered their classes for the event.

The event was sponsored by Linamar, a Canadian advanced manufacturing company. In her remarks, Linamar CEO Linda Hasenfratz highlighted the variety of STEM careers available, and the high demand for people in those careers, which often come with great earning potential.

"Science and technology are great choices for anyone who is naturally curious about the world around them," she said. She also urged young women to research these fields and keep their options open. "You don't have to complete your life plan at 16 or 17 years old."

The 2020/21 "Inspiring Future Women in Science" event was made possible by the support of presenting sponsor Linamar Corporation.

SCIENCE COMMUNICATION AND MEDIA

The COVID-19 pandemic has laid bare the need for scientific literacy in all corners of society. Providing the public with accurate, accessible scientific information has been baked into Perimeter's mission since day one, and the Institute continued to reach hundreds of thousands of people around the world over the past year. Through its websites, social media channels, and media partnerships, Perimeter continues to be a leading source of engaging and informative physics content.

A RENEWED WEB PRESENCE

As organizations around the globe scrambled to improve their online presence at the onset of the pandemic, a major overhaul of Perimeter's website was already well under way. Unveiled in February 2021, the shiny new perimeterinstitute.ca provides the Institute's audiences with a responsive, accessible, mobile-friendly site that seamlessly integrates Perimeter's other digital platforms. Mobile traffic has doubled since the new site's launch, and the site had 1 million page views from over 320,000 visitors in 2020/21.

Complementing the institutional site, insidetheperimeter.ca, Perimeter's home for accessible and shareable science content, continued to provide everything from in-depth features exploring the scientists' latest work to fun quizzes for science lovers of all ages. Over the last year, insidetheperimeter.ca has attracted more than 225,000 unique visitors and nearly 350,000 page views.

To understand the public's hunger for high-quality science content, one need look no further than Perimeter's rapidly

growing social media channels. Perimeter's YouTube channel had more than 6 million video views in 2020/21, a 211 percent increase over last year, while subscribers jumped by 36 percent over last year, totalling more than 110,000.

Audience growth was a constant across all the Institute's social platforms: Perimeter's combined Twitter and Facebook following reached 60,000, while its LinkedIn and Instagram accounts both saw double-digit gains (10 and 11 percent, respectively).

PROMINENT MEDIA COVERAGE OF PERIMETER

- "New quantum centre in Ontario to probe nature's deepest and weirdest secrets," Canadian Press, October 16, 2020
- "Astronomers glimpse black hole's magnetic personality," *The Globe and Mail*, March 24, 2021
- "Celebrating Emmy Noether, Sameera Moussa, Caroline Bleeker, Toshiko Yuasa and other inspiring women in science," *Physics World*, October 16, 2020
- "'Hot-spotting': Give COVID-19 vaccine to potential super-spreaders first to make limited supplies more effective: researchers," *National Post*, December 23, 2020
- "Clay Riddell Centre for Quantum Matter launching after $10-million donation for Perimeter Institute hub," *Calgary Herald*, October 15, 2020
- "The mystery at the heart of physics that only math can solve," *Quanta Magazine*, June 10, 2021
- "Hamilton-raised Kobo founder is new Perimeter chair," *Hamilton Spectator*, May 31, 2021
- "Scientists release first image of magnetic fields around black hole," Canadian Press, March 24, 2021
- "Pilot project pairing tech mentors with Indigenous youth," CTV News, November 9, 2020
- "The importance of funding quantum physics, even in a pandemic," *Inside Philanthropy*, October 21, 2020

PUBLIC LECTURES

2020/21 was a unique year for Perimeter's long-running public lecture series. Though the Institute was unable to welcome the public into the building, the series continued through webcasts, both live and on-demand, to audiences around the globe.

This year's slate included seven engaging talks, spanning "The Fascinating, Weird World of Quantum Matter" by Karen Hallberg and "The Invisible Universe" by Priyamvada Natarajan, to "A Solution to the Stable Marriage Problem" by Emily Riehl, and Catherine Beauchemin's timely talk, "A Physicist's Adventures in Virology." In all, these talks garnered more than 130,000 views – a number that will continue to climb in the coming months. Over the last five years, the Institute's lectures have been viewed more than 2 million times.

ADVANCING PERIMETER'S MISSION

"Now, more than ever, we must harness all the brightest minds in science. Perimeter's Emmy Noether Initiatives are changing the under-representation of women in theoretical physics. I am proud to have helped establish the Emmy Noether Emerging Talent Fund to advance women in science at Perimeter and build a brighter future for Canada and, indeed, the world."

– Anne-Marie Canning, Culturalpreneur and Perimeter Emmy Noether Champion

Perimeter is supported by the Government of Canada and the Government of Ontario, as well as by significant philanthropic support from private sector corporations, foundations, and individuals. Together, we aim to build the world's best theoretical physics institute.

Our government and philanthropic partners understand that an investment in theoretical physics is an investment in the lowest-cost, highest-impact area of science. Perimeter is an independent, ambitious leader in the field, and was founded on the recognition that today's theoretical physics is tomorrow's technology. Future technologies, including breakthroughs in quantum computing and machine learning, will flow from the next wave of physics breakthroughs. The Institute's government and philanthropic partners are supporting a major asset for Canada and helping ensure near- and long-term competitiveness and prosperity in Ontario.

In 2020/21, Perimeter was in the fourth year of five-year funding agreements of $50 million each with the Government of Ontario and the Government of Canada. These investments continue to sustain a partnership that is essential to Perimeter's ongoing success and help position Ontario and Canada as a leading centre of theoretical physics on the global stage.

Over one-third of Perimeter's annual operating budget is supported by a community of visionary philanthropic supporters, which continues to grow. One group of supporters, the Emmy Noether Circle, has helped launch the Emmy Noether Emerging Talent Fund, a fund devoted to advancing women at critical stages of their education and careers at Perimeter and beyond.

This inspiring collective of donors and volunteers understands that when everyone can contribute, breakthroughs are inevitable. In 2021, their philanthropic commitments to the fund reached nearly $1 million, ambitiously surpassing the initial $250,000 goal and pushing us closer to the $2.5 million target.

Perimeter is committed to building a physics community where all can thrive and find a sense of belonging. The Emmy Noether Council and Emmy Noether Circle donors are adding powerful energy and resources to our collective vision.

SUPPORTING THE VISION

Perimeter Institute recognizes and thanks the visionary supporters who have made cumulative gifts totalling $100,000 or more since 2014, following the lead of Perimeter's Founding Donor, Mike Lazaridis. These generous gifts and grants have helped our private sector campaign grow to $54 million in commitments.

Anonymous (2)
Airlie Foundation
BMO Financial Group
Gary Brown
Anne-Marie Canning
Cenovus Energy
Coril Holdings
The Cowan Foundation
Joanne Cuthbertson and Charlie Fischer
The Daniel Family Foundation
The Delaney Family
The Ira Gluskin & Maxine Granovsky Gluskin Charitable Foundation
Gluskin Sheff + Associates Inc.
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The Simons Foundation
Corinne Squire and Neil Turok
Stavros Niarchos Foundation
Brian Sullivan
Sun Life Financial
John Templeton Foundation
Dr. Scott A. and Sherry Vanstone and family
Mac Van Wielingen, Viewpoint Foundation

TAMING INFINITY

Stephen Hawking and others puzzled over a remarkable feature of gravity, which is still hard to digest today – that gravity works like a hologram. A four-dimensional universe like our own (three space dimensions, one time) should be described by a two-dimensional membrane, a hologram of sorts, living at infinity, at "the end of the universe."

Ana-Maria Raclariu, Perimeter's new Ptarmigan Foundation Stephen W. Hawking Fellow, is pushing that research in bold new directions. She is taming infinity and its symmetries with the vision of extracting a novel holographic description of gravity that can revolutionize our picture of the universe.

Raclariu is an extraordinary scientist venturing down paths no researcher has explored before. She will continue to make her mark in the world of physics with her research and work within the new Celestial Holography Initiative being launched at Perimeter.

Thanks to a generous gift from the Ptarmigan Foundation, Raclariu's four-year fellowship is fully supported. The Ptarmigan Foundation is perfectly aligned with Perimeter's work to foster greater equality and inclusion in science. Perimeter is grateful for this visionary support, which allows the Institute to attract and retain gifted experts like Raclariu, who are expanding our understanding of the cosmos.

▲ *Ana-Maria Raclariu*

"Our family is delighted that the Perimeter Institute has been able to attract Ana-Maria as our first Stephen W. Hawking Fellow. She is an amazingly talented young woman with a research focus that Dr. Hawking would enjoy," says Richard Bird, president of the Ptarmigan Foundation.

"Ana-Maria is just the kind of young scientist who will gain from as well as contribute to the stature of Perimeter Institute, and Canada, as a centre of excellence for research in theoretical physics."

PERIMETER INSTITUTE LEADERSHIP COUNCIL

The 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.

Joanne Cuthbertson, Co-Chair
Member, Board of Directors, Perimeter Institute
Chancellor Emerita, University of Calgary

Patrice Merrin, Co-Chair
Former member, Board of Directors, Perimeter Institute
Director: Glencore plc, and Samuel, Son & Co.

Susan Baxter
Member, Board of Directors, Perimeter Institute
Vice Chair, RBC Wealth Management, RBC Financial Group

Donald W. Campbell
Senior Strategy Advisor, DLA Piper

Harbir Chhina
Executive Vice President and Chief Technology Officer, Cenovus Energy

Catherine Delaney
President, C.A. Delaney Capital Management Ltd.

Edward Goldenberg
Partner, Bennett Jones LLP

Brad Marsland
Vice President, Marsland Centre Ltd.

Jennifer Scully-Lerner
Vice President, Goldman Sachs
Co-Chair, Emmy Noether Council, Perimeter Institute

Trevin Stratton
Chief Economist, Canadian Chamber of Commerce

Alfredo Tan
Senior Vice President, Rogers Sports and Media

THANKS TO OUR SUPPORTERS

An ever-growing group of 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.

ENDOWMENT FUND

FOUNDER ($150M+)

Mike Lazaridis

$25M+

Doug Fregin

$10M+

Jim Balsillie

GOVERNMENT PARTNERS

Government of Canada

Government of Ontario

ENDOWED INITIATIVES

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

Stavros Niarchos Foundation Aristarchus Chair in Theoretical Physics ($4 million)

The Peter and Shelagh Godsoe Family Foundation Award for Exceptional Emerging Talent ($1 million)

PERIMETER RESEARCH MAJOR GIFTS

Clay Riddell Centre for Quantum Matter ($10 million)

Centre for the Universe at Perimeter Institute ($5 million)*

Mike and Ophelia Lazaridis Niels Bohr Chair in Theoretical Physics ($4 million)

Krembil Galileo Galilei Chair in Theoretical Physics ($4 million)

Krembil William Rowan Hamilton Chair in Theoretical Physics ($4 million)

Gluskin Sheff / Onex Freeman Dyson Chair in Theoretical Physics ($2 million)

Coril Holdings Archimedes Chair in Theoretical Physics (Visiting) ($1 million)

Clay Riddell Paul Dirac Chair in Theoretical Physics ($1 million)

Daniel Family James Peebles Chair in Theoretical Physics ($1 million)

Delaney Family John Archibald Wheeler Chair in Theoretical Physics ($500,000)

The Ptarmigan Foundation Stephen W. Hawking Fellowship ($400,000)

Cenovus Energy James Clerk Maxwell Chair in Theoretical Physics (Visiting)

Anonymous (1)

* Anonymous donor

CORPORATE AND SPONSORSHIP PARTNERS ($100,000+)

Cenovus Energy, in support of the Distinguished Visiting Research Chair program

Maplesoft, Perimeter Educational Outreach Champion

Power Corporation of Canada, proud supporter of EinsteinPlus and Perimeter's Teacher Network

RBC Foundation, Presenting Partner, International Summer School for Young Physicists and GoPhysics, in support of RBC Future Launch

Mike Serbinis and Laura Adams, in support of the Undergraduate Theoretical Physics Summer Program

ACCELERATORS CIRCLE ($50,000+)

The Cowan Foundation

Brian Sullivan

Mac Van Wielingen, Viewpoint Foundation

AWARDS ($35,000+)

The Savvas Chamberlain Family Foundation Anaximandros Fellowship

The Joanne Cuthbertson and Charlie Fischer Graduate Student Award

The Hellenic Heritage Foundation Anaximandros Fellowship

Brad and Kathy Marsland Honorary PSI Scholarship Award

Margaret and Larry Marsland Honorary PSI Scholarship Award

DIRECTORS CIRCLE ($10,000 to $49,999)

$25,000+

Airlie Foundation

Bosch Community Fund, on behalf of ESCRYPT in Canada

Connor, Clark & Lunn Financial Group

The Scott Griffin Foundation

Toyota Motor Manufacturing Canada (TMMC)

$10,000+

The Boardwalk Partnership

Cenovus Energy

Harbir and Monica Chhina

Ed Kernaghan

The Kitchener Waterloo Community Foundation:

- McMurtry Family Fund
- The Musagetes Fund
- The John A. Pollock Family Fund

Oriole Foundation

Donald and Eleanor Seaman Family Foundation

John and Karen Sechrist

Alex White

FRIENDS (up to $9,999)

$5,000+

Denise and Terry Avchen, Environmental Research Advocates**

Mary and Ted Brough

Jon and Lyne Dellandrea

Michael Duschenes

Renée Schingh and Robert Myers

$2,500+

Don Campbell

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Robert Korthals and Janet Charlton

Jennifer Scully-Lerner**

Kelly Sinclair

$1,000+

Jeremy Anderson

John Attwell

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The Breunsbach Family**

The Carson Family Foundation

Ben and Mona Davies

Greg Dick

Michael Gagnier

Michael Horgan

John Matlock

Gordon McKay

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$250 TO $999

Debbie and Ian Adare

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John Brennen

David Cook

Matt Douglas

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Adam Gravitis

Denis Havey

Mike Horsley

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Luis Lehner and Maria Beltramo

Maneesh Mehta

George Meierhofer

Suzanne Morris

Bill and Jan Mustard

Nem Radenovic

Adele Robertson

Catalin Sandu

LeAnne Thorfinnson

Stephanie Tse

Jacqueline Watty

Nancy Wong

Anonymous (5)

An additional 92 donors have contributed gifts of up to $250.

GIFTS OF CELEBRATION, HONOUR, AND MEMORY

Carolyn Crowe Ibele, in memory of Dr. Richard A. Crowe

Mrs. Margaret Tovell, in memory/honour of Mr. David Tovell

EMMY NOETHER CIRCLE

Emmy Noether was a brilliant scientist whose work underpins much of modern physics. Perimeter's Emmy Noether Initiatives – funded by Emmy Noether Circle donors – support and encourage women in science. For more information, see pages 22 and 23.

FOUNDING DONOR

The Bluma Appel Community Trust

MAJOR GIFTS

The Simons Emmy Noether Fellows Program at Perimeter Institute ($600,000)

$100,000+

Anne-Marie Canning

Linamar Corporation

Brian Sullivan

Dr. Scott and Sherry Vanstone and family

$25,000+

Andrew and Lillian Bass

Dorian Hausman

Patrice E. Merrin

$10,000+

Jane Kinney and Christian Bode

Rigel Kent Security

$5,000+

Jerome Bolce

John and Karen Sechrist

Kim Tremblay

$1,000+

Andrea Grimm

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Bryon Bellows

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Beth Horowitz and Pat Munson

Sheri and David Keffer

Sebastian Mizera**

Douglas Mortley-Wood

Neil Steven Rieck

Leslie Rogers

Anonymous (1)

An additional 24 donors have contributed gifts up to $250 (1**)

*** Supporter of Friends of Perimeter Institute Inc., a 501(c)(3) public charity in the United States dedicated to promoting and supporting education, research, and programs that expand the public knowledge and understanding of theoretical physics.*

Supporter lists reflect gifts received between August 1, 2020, and July 31, 2021, and multi-year commitments of $50,000 and more.

Charitable Registration number: 88981 4323 RR0001

GOVERNANCE AND FINANCE

GOVERNANCE

Perimeter Institute is an independent, not-for-profit, charitable 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 Committee and the Finance and Audit Committee. The Board also forms other committees as required to assist it in performing its duties.

Reporting to the Board of Directors, the Institute's Director is a pre-eminent scientist responsible for developing and implementing the overall strategic direction of the Institute. The Managing Director and Chief Operating Officer reports to the Director and oversees day-to-day operations, supported by a team of administrative staff.

Perimeter's resident scientists play an active role in scientific operational issues via participation on various committees in charge of scientific programs. Committee chairs report to the Faculty Chair, who assists the Institute's Director with matters such as program reviews, recruitment, and the granting of tenure.

The Scientific Advisory Committee, composed of eminent international scientists, offers independent scrutiny and advice, and provides key support in achieving the Institute's strategic objectives.

BOARD OF DIRECTORS

Michael Serbinis
Chair, Board of Directors
Finance and Audit Committee Member
Founder and CEO, League Inc.

Jane Kinney
Vice Chair, Board of Directors
Finance and Audit Committee Chair
Investment Committee Member
Retired Vice Chair, Deloitte

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Joanne Cuthbertson, C.M.
Co-Chair of Perimeter Institute Leadership Council
Chancellor Emerita, University of Calgary

Gabriela González
Distinguished Visiting Research Chair
Professor, Louisiana State University
Department of Physics and Astronomy

Michael Horgan
Finance and Audit Committee Member
Senior Advisor, Bennett Jones LLP

Donna Strickland
Professor, University of Waterloo
Department of Physics and Astronomy
2018 Nobel Prize in Physics

For full biographies of the Board, go to www.perimeterinstitute.ca/people

A NEW SHIFT IN MISSION CONTROL

In 1999, a visionary young engineer named Mike Lazaridis launched the BlackBerry – the catalyst from which the entire smartphone revolution grew.

It was an amazing innovation, but Lazaridis was keenly aware that it depended on scientific discoveries from decades or even a century before. He founded Perimeter to seek the next big breakthrough, the one that will transform the lives of our grandchildren's grandchildren. Lazaridis has served as Perimeter's Board Chair ever since, helping Perimeter grow from an upstart to a world-leading centre for theoretical physics.

This year, he passed the torch to a new Board Chair, Mike Serbinis. Like his predecessor, Serbinis is a technological entrepreneur, co-founder of a series of companies, including Kobo, Critical Path, DocSpace, and League.

"Mike Serbinis is the best of Canada's young tech vanguard," says Perimeter Director Robert Myers. "He's a builder steeped in science, and he brings the energy and daring Perimeter needs to build a brighter future."

"It's amazing how far Perimeter has come in just 20 years," says Serbinis. "But in a larger sense, we're just getting started."

The Institute – conceived of as a moonshot – is dropping its first stage rockets and firing its boosters. With the change

comes a new shift in mission control: a renewal of the volunteer Board of Directors.

Retiring members include Founding Vice Chair Cosimo Fiorenza, the Vice President and General Counsel of Quantum Valley Investments, who has served on the Perimeter Board for 22 years. Also stepping down are Patrice Merrin, who served on the Board for three years and will continue as Co-Chair of the Perimeter Institute Leadership Council, and Jeff Moody, who has spent six years with the Board and continues to sit on the Investment Committee. We thank all of them for their outstanding service and continued ties to Perimeter.

The renewed seven-person Board – five women and two men – includes a mix of leaders from science, technology, industry, and academia.

The new Vice Chair is Jane Kinney. With over 30 years of experience in the financial services sector, Kinney recently retired as Vice Chair of Deloitte Canada and member of the firm's leadership team.

"I see my role as helping steer Perimeter through the pandemic and whatever other challenges arise – there will always be something," says Kinney. "I'm passionate about good governance, about financial planning, about risk management, about all the other nuts and bolts that keep a complex organization thriving."

New Board member Gabriela González is a professor of physics and astronomy at Louisiana State University. Her scientific leadership credentials include serving as LIGO spokesperson from 2011 to 2017, the period in which LIGO discovered the first direct evidence of gravitational waves.

"Mike [Serbinis] has a vision that there should be scientific knowledge in the board, and more contact between the board and the scientists," says González. She's ideally placed for the mission, as a frequent visitor who served as Chair of Perimeter's Scientific Advisory Committee from 2017 to 2021.

New Board member Donna Strickland is a professor in the Department of Physics and Astronomy at the University of Waterloo and is one of the recipients of the 2018 Nobel Prize in Physics.

"The kind of science I do is a little bit different from the kind of science Perimeter does," Strickland says. "But there's a level at which all science speaks the same language. We push back the boundaries of what's possible."

The new Board is eager to see Perimeter grow and thrive. "Perimeter is a long-term investment that will pay off exponentially," says Serbinis. "The work we do here will yield profound results – not only for the future of technology, but for the future of Canada and all of humanity."

SCIENTIFIC ADVISORY COMMITTEE

Marcela Carena
Chair
Fermi National Accelarator Laboratory

Marica Branchesi
Gran Sasso Science Institute

Fernando Brandao
California Institute of Technology

Fay Dowker
Imperial College London

Daniel Freed
University of Texas at Austin

Charles Gammie
University of Illinois at Urbana-Champaign

Gian Francesco Giudice
European Organization for Nuclear Research (CERN)

Gilbert Holder
University of Illinois

Juan Maldacena
Institute for Advanced Study, Princeton

Natalia Perkins
University of Minnesota

Sandu Popescu
University of Bristol

Perimeter Institute would like to thank the following people for their service on the Scientific Advisory Committee from 2017 to 2021: **Steven Carlip**, University of California, Davis; **Gabriela González**, Louisiana State University; **David B. Kaplan**, University of Washington; and **Ramesh Narayan**, Harvard University.

SENIOR LEADERSHIP

Robert C. Myers
Director

Paul Smith
Managing Director and Chief Operating Officer

Laurent Freidel
Faculty Chair

FAREWELL TO MICHAEL DUSCHENES

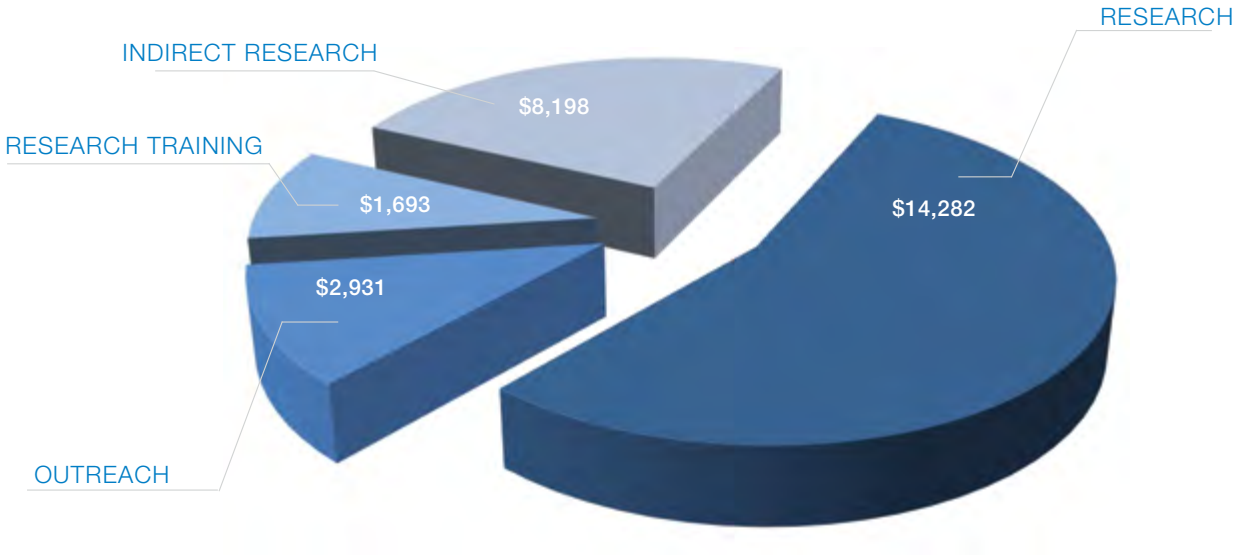
This year, Perimeter bid a fond farewell to former Managing Director and Chief Operating Officer Michael Duschenes, who ushered the Institute through transformative growth during his 17-year tenure, building the senior management team and shepherding many successful initiatives, including the construction of the Stephen Hawking Centre and the launch of the Perimeter Scholars International (PSI) program.

Joining Perimeter in 2021 as Managing Director and Chief Operating Officer is Paul Smith, a trained scientist with deep experience in research, industry, and management, most recently as Vice President at Xerox, and Centre Director of the Xerox Global Materials Research Centre, located in Ontario. A named inventor on 78 patents, Smith holds both a PhD in chemistry from the University of Bath and an MBA from the University of Toronto's Rotman School of Management.

FINANCIALS

SUMMARY OF OPERATING COSTS (refer to page 52)

For the year ended July 31, 2021
(in thousands of dollars)



With the ongoing COVID-19 pandemic, and governments worldwide enacting measures to combat the spread of the virus, Perimeter's entire fiscal year was impacted by transitions in and out of lockdown. As a community, everyone at the Institute has risen to this unprecedented challenge with resilience and flexibility, and Perimeter remained a global hub of theoretical physics research, training, and outreach.

Research activities continued through virtual collaborations, conferences, workshops, and seminars. The 2021 PSI class completed their entire program online. The Outreach team delivered outstanding programs to teachers, students, and the general public virtually – while also creating new educational resources for digital classrooms.

Whenever possible, and as protocols allowed, the Institute took opportunities to reintroduce in-person interactions, bringing core staff, researchers, and students back to continue research and training in small groups.

The Institute is looking forward to a full return to normal operations, including face-to-face collaborations, support for emerging researchers, and in-person training and outreach.

Research

Advancing our understanding of the universe at the most fundamental level remains Perimeter's core focus. The Institute continued to invest in the research mandate, with an emphasis on supporting a robust virtual environment, led by a world-renowned faculty across nine research fields, and one of the largest cohorts of theoretical physics postdoctoral researchers in the world. The overall 15 percent underspend for the year was due in large part to COVID-19 travel restrictions leading to no in-person workshops, conferences, and seminars, and few in-person collaborations or interactions overall. There were also no international or Canadian visitors for the year, and Simons Emmy Noether Fellows deferred their visits.

Research Training

Perimeter continued to invest in innovative research training programs, such as the PSI master's program and the PhD program. Each program attracts and trains top scientific talent – increasing expertise, advancing research, and producing job-ready leaders in many fields that drive economic growth in Canada. Expenses were more than 35 percent lower than the previous year, in part because PSI and PhD students completed their entire year virtually, leading to no costs for accommodation, meals, or travel. Throughout the pandemic, Perimeter allocated resources strategically, making a concerted effort to understand the needs of each student in each country, taking into account time differences and individual living situations.

Outreach and Science Communications

Perimeter's world-class educational outreach program built on the success of its rapid pivot to digital resources during

the previous year. The team continued to offer educators classroom-ready digital and curriculum-compliant materials and created new ways of engaging – including offering the Online Teachers' Camp, a digital version of Perimeter's EinsteinPlus in-person summer program for educators. Outreach programs continued to reach teachers and students across Canada and around the globe, from the largest cities to remote and underserviced communities, preparing youth for STEM-based careers. The digital nature of much of Perimeter's existing content and expertise ensured the continued transition to a virtual environment with little interruption and spurred reassessments of some outreach programs and delivery models. The cancellation of in-house teacher and student programs and activities during 2020/21 resulted in no travel costs and was the primary contributor to the 13 percent decline in expenditures.

Indirect Research and Operations

Indirect research and operating expenditures cover the costs of core support areas, including administration, advancement, information technology, and facilities. There was a small increase in technology spending to ensure everyone had the tools to remain productive and stay connected. While maintaining the building to be ready to welcome everyone back, some funds were redirected to maximize support for everyone in the organization, including additional health and wellness supports and in-house counselling programs. Perimeter invested in a healthy community to maintain productivity levels and retain staff and researchers during this challenging time. Overall, indirect research and operations expenditures remained in line with prior years.

INCOME

Perimeter continues to receive significant support from the public sector, the private sector, and research grants.

Federal and provincial governments continued to provide revenues in accordance with the terms of their grant agreements. Ongoing major investments from the Governments of Canada and Ontario demonstrate recognition of Perimeter's value for money and strong return on investment among its public funders.

To complement public investments, Perimeter has been able to secure generous support from the private sector, including corporations, foundations, and donors. Even during the ongoing pandemic, Perimeter's private sector fundraising campaign, as well as grant revenue from private foundations, generated close to $4.8 million to support the operations of the Institute.

FINANCIAL POSITION

Perimeter's financial position remains strong and resilient. Under the guidance of the Investment Committee, funds remain invested in accordance with Board-approved Investment Policies and Procedures.

Although the global economic recovery was uneven during this period, Perimeter's return on investments was just over 13 percent for the year. This strong performance allows the Institute to protect itself from major market events or dips in the future. This return also offers Perimeter the flexibility and speed to take advantage of scientific opportunities as they arise, creating major assets for Canada and Ontario as a global centre of theoretical research and technology development.

THE LONG-TERM PLAN

Perimeter Institute exists through cooperative and highly successful public and private partnerships that provide for ongoing operations while safeguarding future opportunities.

As of July 31, 2021, Perimeter has completed the fourth year of five-year commitments of $50 million from both the federal and provincial governments, providing combined funding of $100 million over the five-year period. The multi-year government commitments Perimeter has received since inception demonstrate the Institute's strong collaboration with public partners and that Perimeter is viewed as an excellent and strategic government investment.

In addition, both the Governments of Ontario and Canada have signalled their ongoing confidence in Perimeter Institute with grants that will continue from 2022 to 2024.

In addition to government support, private funding plays a significant role in ensuring Perimeter's long-term success. The Institute has established ambitious fundraising goals and innovative ways to expand its sources of funds from the private sector. In accordance with donor requests, private sector donations may be used as contributions toward operational expenditures or protected in an endowment fund designed to minimize risk and maximize growth.

Finally, the endowment continues to be managed to enhance long-term financial stability through capital preservation, while providing a stable income stream that supports the execution and acceleration of the Institute's mandate.

Zeifmans

REPORT OF THE INDEPENDENT AUDITORS ON THE SUMMARIZED FINANCIAL STATEMENTS

To the Directors of
Perimeter Institute

The accompanying summarized financial statements, which comprise the summarized statement of financial position as at July 31, 2021 and the summarized statement of operations and changes in fund balances for the year then ended, are derived from the audited financial statements of Perimeter Institute (the "Institute") for the year ended July 31, 2021.

In our opinion, the accompanying summary financial statements are a fair summary of the audited financial statements in accordance with the basis developed by management, which includes removing the statement of cash flows and retaining major subtotals, totals and comparative information.

Summary Financial Statements

The summary financial statements do not contain all the disclosures required by Canadian accounting standards for not-for-profit organizations. Reading the summary financial statements, therefore, is not a substitute for reading the audited financial statements of the Institute. The summary and the audited financial statements do not reflect the effects of events that occurred subsequent to the date of our report on the audited financial statements.

The Audited Financial Statements and Our Report Thereon

We expressed an unmodified audit opinion on the audited financial statements in our report dated December 16, 2021. 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.

Management's Responsibility for the Summary Financial Statements

Management is responsible for the preparation of the summary financial statements on a basis developed by management, which includes removing the statement of cash flows, retaining major subtotals, totals and comparative information, and retaining the information from the audited financial statements dealing with matters having a pervasive or otherwise significant effect on the summary financial statements.

Auditor's Responsibility

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

Other matter

The audited financial statements of the Institute are available upon request by contacting the Institute.

Zeifmans LLP

Toronto, Ontario
December 16, 2021

Chartered Professional Accountants
Licensed Public Accountants

201 Bridgeland Avenue | Toronto
Ontario | M6A 1Y7 | Canada

zeifmans.ca
T: 416.256.4000

PERIMETER INSTITUTE

Summarized Statement of Financial Position
(in thousands of dollars)
as at July 31, 2021

	2021	2020
ASSETS		
Current Assets:		
Cash and cash equivalents	$ 7,470	$ 12,878
Investments	391,593	346,895
Grants receivable	17	—
Other current assets	962	586
	400,042	360,359
Property and equipment	37,825	39,342
TOTAL ASSETS	$ 437,867	$ 399,701
LIABILITIES AND FUND BALANCE		
Current liabilities:		
Accounts payable and other current liabilities	$ 2,290	$ 1,690
TOTAL LIABILITIES	2,290	1,690
Fund balances:		
Invested in capital assets	37,639	39,327
Externally restricted	8,810	11,740
Internally restricted	388,506	346,006
Unrestricted	622	938
TOTAL FUND BALANCES	435,577	398,011
	$ 437,867	$ 399,701

PERIMETER INSTITUTE

Summarized Statement of Operations and Changes in Fund Balances
(in thousands of dollars)
For the Year Ended July 31, 2021

	2021	2020
Revenue		
Government grants	$ 15,085	$ 15,000
Donations	3,923	3,842
Research grants	848	767
	19,856	19,609
Expenses		
Research	14,282	16,896
Research training	1,693	2,691
Outreach and science communications	2,931	3,386
Indirect research and operations	8,198	8,376
	27,104	31,349
Excess of expenses over revenue from operations	(7,248)	(11,740)
Investment income	47,130	10,261
Amortization	(2,316)	(2,304)
Excess of revenue over expenses (expenses over revenue)	37,566	(3,783)
Fund balances, beginning of year	398,011	401,794
Fund balances, end of year	$ 435,577	$ 398,011

APPENDICES

FACULTY

Robert Myers (PhD Princeton University, 1986) is the Director and BMO Financial Group Isaac Newton Chair at Perimeter Institute. A native of Deep River, Ontario, he joined Perimeter as a founding faculty member in 2001, was its Scientific Director from 2007 to 2008, served as Faculty Chair from 2011 to 2018, and became Director in 2019. Prior to coming to Perimeter, he was a professor of physics at McGill University. Myers' research focuses on foundational questions in quantum theory and gravity. His contributions span a broad range, from quantum field theory to gravitational physics, black holes, and cosmology. Several of his discoveries, such as the "Myers effect" and "linear dilaton cosmology" have been influential in seeding new lines of research. His current research focuses on the interplay of quantum entanglement and spacetime geometry and on applying new tools from quantum information science to the study of quantum gravity. Among his honours, Myers has been awarded the Herzberg Medal by the Canadian Association of Physicists (1999), the CAP-CRM Prize in Theoretical and Mathematical Physics by the Canadian Association of Physicists and the Centre de recherches mathématiques (2005), the Vogt Medal by the Canadian Association of Physicists and TRIUMF (2012), the Queen Elizabeth II Diamond Jubilee Medal (2013), and the Distinguished Alumni Award from the University of Waterloo (2018). In 2006, he was elected a fellow of the Royal Society of Canada. Myers has been recognized as one of the world's most influential scientists, appearing on the Thomson Reuters/Clarivate Analytics list of "Highly Cited Researchers," multiple times. He has been a member of the Canadian Institute for Advanced Research in the Cosmology and Gravity program (1998-2017) and an associate member in the Gravity and the Extreme Universe program (2017-present). He has served on numerous advisory boards, including the Banff International Research Station (2001-05), the Kavli Institute for Theoretical Physics (2012-16), the William I. Fine Theoretical Physics Institute (2015-19), and the Max Planck Institute for Gravitational Physics (2018-present). He has also served on the editorial boards of *Annals of Physics* (2002-12) and the *Journal of High Energy Physics* (2007-present). Myers remains active in both teaching and supervising graduate students through his cross-appointment as an adjunct professor in the Department of Physics and Astronomy at the University of Waterloo. He has supervised and co-supervised over 150 postdoctoral fellows, PhD students, and master's students over his career, roughly 50 of whom now hold faculty positions around the world, including at Princeton, Cambridge, and Oxford.

Laurent Freidel (PhD L'École Normale Supérieure de Lyon, 1994) joined Perimeter Institute first as a visitor in 2002 and then as faculty in 2006. He was appointed as Faculty Chair in 2021. Freidel is a mathematical physicist who has made many notable contributions in the field of quantum gravity, developing spin foam models, among other things. He has also introduced several new concepts in this field, such as group field theory, relative locality, and metastring theory and modular spacetime. He possesses outstanding knowledge of a wide range of areas, including gravitational physics, integrable systems, topological field theories, two-dimensional conformal field theory, string 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 since 1995. He is also the recipient of several awards.

Asimina Arvanitaki (PhD Stanford University, 2008) is the Stavros Niarchos Foundation Aristarchus Chair in Theoretical Physics at Perimeter Institute, where she has been a faculty member since 2014. She previously held research positions at the Lawrence Berkeley National Laboratory at the University of California, Berkeley (2008-11) and the Stanford Institute for Theoretical Physics at Stanford University (2011-14). Arvanitaki is a particle physicist who specializes in designing new experiments to test fundamental theories beyond the Standard Model. These experiments rely on the latest developments in metrology, such as atomic clocks and the optical trapping and cooling of macroscopic objects. She recently pioneered a new experiment that can look for new spin-dependent forces in nature at an unprecedented level of precision. Arvanitaki has also shown how astrophysical black holes can diagnose the presence of new particles through the process of black hole superradiance, giving signatures that can appear in LIGO or any future gravitational wave telescope. She was co-awarded the 2017 New Horizons in Physics Prize by the Breakthrough Prize Foundation.

Latham Boyle (PhD Princeton University, 2006) joined the Institute's faculty in 2010. From 2006 to 2009, he held a Canadian Institute for Theoretical Astrophysics Postdoctoral Fellowship and was a junior fellow of the Canadian Institute for Advanced Research. In recent years, Boyle's research interests have spanned a number of topics in cosmology, fundamental physics, and mathematical physics. In cosmology, he recently proposed (with Neil Turok and Kieran Finn) a new cosmological model, the "CPT-Symmetric Universe" in which the universe before the bang is the CPT mirror image of the universe after the bang. This model neatly explains certain observed

features of our universe and makes a number of testable predictions for upcoming experiments. In fundamental physics, he recently pointed out an intriguing new connection between certain patterns in the Standard Model of particle physics and the structure of a remarkable mathematical object called the exceptional Jordan algebra. In mathematical physics, he introduced (with Kendrick Smith) the idea of "choreographic crystals," in which the basic elements perform a choreographed dance that can have much higher symmetry than any instantaneous snapshot reveals, and has investigated (with Paul Steinhardt, Madeline Dickens, and Felix Flicker) Penrose-like tilings and quasicrystals, including their relation to discrete conformal invariance and holography.

Freddy Cachazo (PhD Harvard University, 2002) is the Gluskin Sheff / Onex Freeman Dyson Chair in Theoretical Physics at Perimeter Institute, where he has been a faculty member since 2005. Cachazo is one of the world's leading experts in the study and computation of scattering amplitudes in gauge theories, such as quantum chromodynamics and N=4 super Yang-Mills, and in Einstein's gravity theory. His many honours include the Gribov Medal of the European Physical Society (2009), the Rutherford Memorial Medal in Physics from the Royal Society of Canada (2011), the Herzberg Medal from the Canadian Association of Physicists (2012), a New Horizons in Physics Prize from the Fundamental Physics Prize Foundation (2014), and the CAP-CRM Prize in Theoretical and Mathematical Physics from the Canadian Association of Physicists and the Centre de recherches mathématiques (2016). In 2018, he was selected to inaugurate Harvard's Center of Mathematical Sciences and Applications lecture series on mathematical physics in honour of Raoul Bott.

Kevin Costello (PhD University of Cambridge, 2003) is the Krembil William Rowan Hamilton Chair in Theoretical Physics. He joined Perimeter in 2014 from Northwestern University, where he had been a faculty member since 2006. Costello works on the mathematical aspects of quantum field theory and string theory. He is the author of *Renormalization and Effective Field Theory*, a path-breaking monograph introducing powerful new mathematical tools into the theory of quantum fields, and co-author of *Factorization Algebras in Quantum Field Theory*. Costello's previous honours include an Alfred P. Sloan Research Fellowship, the Berwick Prize of the London Mathematical Society, and several prestigious grants from the National Science Foundation in the United States. In 2018, he was elected as a fellow of the Royal Society (UK). In 2020, he was awarded the Leonard Eisenbud Prize of the American Mathematical Society and was elected an Honorary Member of the Royal Irish Academy.

Neal Dalal (PhD University of California, San Diego, 2002) joined Perimeter in October 2017 from the University of Illinois at Urbana-Champaign, where he had been an assistant professor since 2011. Prior to that, he was a postdoctoral researcher at the Institute for Advanced Study and a senior research associate at the Canadian Institute for Theoretical Astrophysics. His research probes the fundamental physics of cosmology, the structure of the universe, and the formation of galaxies, and he has pioneered several tests of the nature of dark matter using cosmological data.

Bianca Dittrich (PhD Max Planck Institute for Gravitational Physics, 2005) joined Perimeter's faculty in 2012 from the Albert Einstein Institute in Potsdam, Germany, where she led the Max Planck Research Group "Canonical and Covariant Dynamics of Quantum Gravity." Dittrich's research focuses on the construction and examination of quantum gravity models and related topics in mathematical physics. Among other important findings, she has provided a computational framework for gauge invariant observables in general relativity, constructed new realizations of quantum geometry, identified holographic properties of background independent quantum gravity, and made crucial contributions to establish the continuum limit in spin foams. Dittrich has received the Otto Hahn Medal of the Max Planck Society, which recognizes outstanding young scientists; an Early Researcher Award from the Ontario Ministry of Research and Innovation; and an NSERC Discovery Accelerator Award.

William East (PhD Princeton University, 2013) joined Perimeter as a Director's fellow in 2016 and became a member of the faculty in January 2018. Prior to that, he was a postdoctoral fellow at the Kavli Institute for Particle Astrophysics and Cosmology at Stanford University (2013-16). East uses numerical methods and high-performance computing to study violent astrophysical phenomena – such as black hole mergers and the collision of dense stars – as a probe of extreme gravity and new fundamental physics. For his thesis, he was awarded the Nicholas Metropolis Award of the American Physical Society (2015) and the Jürgen Ehlers Prize of the International Society on General Relativity and Gravitation (2016).

Davide Gaiotto (PhD Princeton University, 2004) holds the Krembil Galileo Galilei Chair in Theoretical Physics. He joined Perimeter in 2012. Previously, he was a postdoctoral fellow at Harvard University (2004-07) and a long-term member at the Institute for Advanced Study in Princeton (2007-12). Gaiotto works in the area of strongly coupled quantum fields and has already made major conceptual advances. His honours include the Gribov Medal of the European Physical Society (2011) and the New Horizons in Physics Prize from the Fundamental Physics Prize Foundation (2013).

Jaume Gomis (PhD Rutgers University, 1999) joined Perimeter Institute in 2004, declining a European Young Investigator Award by the European Science Foundation to do so. Prior to that, he worked at the California Institute of Technology as a postdoctoral scholar and as the Sherman Fairchild Senior Research Fellow. His main areas of expertise are string theory, quantum field theory, and mathematical physics. Gomis was awarded an Early Researcher Award from the Ontario Ministry of Research and Innovation for a project aimed at developing new techniques for describing quantum phenomena in nuclear and particle physics. In 2019, Gomis was awarded the CAP-CRM Prize in Theoretical and Mathematical Physics from the Canadian Association of Physicists and the Centre de recherches mathématiques for his contributions to string theory and strongly coupled gauge theories.

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 that continue to shape the field of quantum information science through his work on quantum error correction and quantum cryptography. He has published over 75 papers, which have attracted well over 15,000 citations to date. He is also a fellow of the American Physical Society and a senior scientist with Keysight Technologies. In July 2021, Gottesman took a leave of absence to join the University of Maryland.

Lucien Hardy (PhD University of Durham, 1992) joined Perimeter's faculty in 2002, having previously held research and lecturing positions at various European universities, including the University of Oxford, Sapienza University of Rome, the University of Durham, the University of Innsbruck, and the National University of Ireland. In 1992, he found a very simple proof of non-locality in quantum theory, which has become known as Hardy's paradox. He has worked on characterizing quantum theory in terms of operational postulates and providing operational reformulations of both quantum theory and general relativity. This is seen as a stepping stone en route to finding a theory of quantum gravity. He proposed the quantum equivalence principle, seen as a possible bridge between quantum field theory and quantum gravity. Most recently, he has worked on a time symmetric operational formulation of quantum theory.

Yin-Chen He (PhD Fudan University, 2014) joined Perimeter in July 2018 from Harvard University, where he had been a Moore Postdoctoral Fellow since 2016. Prior to that, he spent two years as a postdoctoral researcher at the Max Planck Institute for the Physics of Complex Systems. He is a condensed matter researcher interested in strongly correlated systems, particularly quantum spin liquids, quantum criticality, conformal field theory, topological phases of matter, quantum field theory, and numerical simulations.

Timothy Hsieh (PhD Massachusetts Institute of Technology, 2015) joined Perimeter in March 2018 from the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara, where he had been a Moore Postdoctoral Fellow since 2015. Hsieh works in quantum matter, specializing in exotic states of matter whose physical behaviours are dictated by the mathematical structures of topology. His research interests also include quantum materials, entanglement, and applications of synthetic quantum systems for quantum simulation.

Luis Lehner (PhD University of Pittsburgh, 1998) began a joint appointment with Perimeter and the University of Guelph in 2009, joined Perimeter as a full-time faculty member in 2012, served as Deputy Faculty Chair from 2014 to 2017, and as Faculty Chair from March 2018 to 2021. He was previously a member of Louisiana State University's faculty (2002-09). 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 APS Nicholas Metropolis award. He has been a Pacific Institute for the Mathematical Sciences Fellow, a Canadian Institute for Theoretical Astrophysics National Fellow, and a Sloan Research Fellow, and he is currently a fellow of the Institute of Physics, the American Physical Society, the International Society for General Relativity and Gravitation, and the Canadian Institute for Advanced Research in the Gravity and the Extreme Universe program. Lehner also serves on the Scientific Council of the International Centre for Theoretical Physics – South American Institute for Fundamental Research and the Oskar Klein Centre of the University of Stockholm. He is also the theorist in residence for the Gravitational Wave International Committee. In 2019, he was named as one of TD's 10 Most Influential Hispanic Canadians.

Kendrick Smith (PhD University of Chicago, 2007) is the Daniel Family James Peebles Chair in Theoretical Physics at Perimeter Institute, where he has been a faculty member since 2012. He is also the Director of Perimeter's Centre for the Universe. He previously held postdoctoral positions at Princeton University (2009-12) and the University of Cambridge (2007-09). Smith is a cosmologist with a foot in the worlds of both theory and observation. He is a member of several experimental teams, including the Wilkinson Microwave Anisotropy Probe (WMAP) collaboration – which won the 2012 Gruber Cosmology Prize and the 2018 Breakthrough Prize in Fundamental Physics – as well as the Canadian Hydrogen Intensity Mapping Experiment (CHIME) and the Planck

collaboration. He was awarded a 2020 New Horizons in Physics Prize, along with two colleagues. Smith has achieved several landmark results, including the first detection of gravitational lensing in the cosmic microwave background radiation. He holds a second PhD in mathematics from the University of Michigan.

Lee Smolin (PhD Harvard University, 1979) is one of Perimeter Institute's founding faculty members. Prior to joining Perimeter, Smolin held faculty positions at Yale University, Syracuse University, and Pennsylvania State University. Smolin's research is centred on the problem of quantum gravity – where he helped to found loop quantum gravity – though his contributions span many areas, including quantum foundations, cosmology, particle physics, the philosophy of physics, and economics. His 210 papers have generated more than 11,000 citations to date. He has written five non-technical books and co-written a book on the philosophy of time. Smolin's honours include the Majorana Prize (2007), the Klopsteg Memorial Award (2009), the Buchalter Cosmology Prize (2014), and election as a fellow of both the American Physical Society and the Royal Society of Canada.

Robert Spekkens (PhD University of Toronto, 2001) joined Perimeter's faculty in 2008, after holding an International Royal Society Fellowship at the University of Cambridge. His field of research is the foundations of quantum theory, where he is known for his work on the epistemic view of quantum states, the principle of non-contextuality, the nature of causality in a quantum world, and the quantification of various properties of quantum states as resources. Spekkens co-edited the book *Quantum Theory: Informational Foundations and Foils*, and he leads the Causal Inference and Quantum Foundations Initiative at Perimeter. He was awarded the Birkhoff-von Neumann Prize of the International Quantum Structures Association in 2008 and won first prize in the 2012 Foundational Questions Institute essay contest, "Questioning the Foundations: Which of Our Assumptions Are Wrong?"

Neil Turok (PhD Imperial College London, 1983) is Director Emeritus and holds the Mike and Ophelia Lazaridis Niels Bohr Chair at Perimeter. He was the Director of Perimeter's Centre for the Universe from 2017 to 2020. Previously, he was a professor of physics at Princeton University and Chair of Mathematical Physics at the University of Cambridge. Turok is a leader in developing and testing theories of the universe. His team's predictions for polarization-temperature correlations in the cosmic background radiation (CBR) and for galaxy CBR correlations induced by dark energy were confirmed at high precision. He pioneered investigations of many theoretical proposals, including cosmic strings, "single-bubble" inflationary universes – the basis of the multiverse paradigm – and cyclic universe models. Recently, he and his collaborators have developed a new, foundational approach to quantum path integrals, with applications ranging from cosmology to particle physics and radio astronomy. They also proposed a new picture of the cosmos – the CPT-invariant universe – giving the simplest yet explanation for cosmic dark matter. Turok founded the African Institute for Mathematical Sciences, a network of centres of excellence for maths and science training, research, and public outreach spanning the African continent. In 2016, he was awarded an Honorary Fellowship of the UK Institute of Physics and the John Torrence Tate Medal of the American Institute of Physics for International Leadership in Physics. In 2019, he was named an Officer of the Order of Canada. He is the author of *The Universe Within*, a popular science bestseller. In 2020, he was appointed to the Higgs Chair in Theoretical Physics at the University of Edinburgh and has been on leave from Perimeter since July 2020.

Pedro Vieira (PhD École Normale Supérieure and the Theoretical Physics Center at the University of Porto, 2008) has been a faculty member since 2009. Prior to that, he was a junior scientist at the Max Planck Institute for Gravitational Physics (Albert Einstein Institute) from 2008 to 2009. Vieira's research concerns the development of new mathematical techniques for gauge and string theories in their non-perturbative regimes. He focuses both on a very special theory known as N=4 SYM as a workhouse for developing such tools and on the S-matrix bootstrap program, which constrains the possible space of all physical theory, in particular strongly coupled gauge and string theories. He is a principal investigator on the Simons Collaboration on the Non-perturbative Bootstrap. His many honours include a Sloan Research Fellowship, the Gribov Medal of the European Physical Society, the Raymond and Beverly Sackler International Prize in Physics from Tel Aviv University, and the 2020 New Horizons in Physics Prize.

Chong Wang (PhD Massachusetts Institute of Technology, 2015) joined Perimeter as a faculty member in 2018 from Harvard University, where he had been a junior fellow at the Harvard Society of Fellows since 2015. Wang works on the theory of quantum condensed matter physics, including topological phases of matter, quantum criticality, quantum Hall effects and spin liquids, and their relationship to modern aspects of quantum field theory.

Beni Yoshida (PhD Massachusetts Institute of Technology, 2012) joined Perimeter's faculty in July 2017, having initially arrived at the Institute as a senior postdoctoral researcher in 2015. Prior to that, he was a Burke Fellow at the Institute for Theoretical Physics at the California Institute of Technology (2012-15), where he worked in John Preskill's group. Yoshida's research focuses on applications of quantum information theory to problems of quantum many-body physics and quantum gravity. In particular, he has used the techniques of quantum coding theory to construct toy models of the AdS/CFT correspondence and discovered information retrieval processes from black holes by using the quantum information scrambling phenomena.

Dominic Else and **Sabrina Pasterski** were recruited to the Perimeter faculty in 2021 and are scheduled to arrive in 2022. See more information on page 24.

ASSOCIATE FACULTY

Niayesh Afshordi (PhD Princeton University, 2004) is jointly appointed with the University of Waterloo. Previously, he was the Institute for Theory and Computation Fellow at the Harvard-Smithsonian Center for Astrophysics (2004-07) and a Distinguished Research Fellow at Perimeter Institute (2008-09). Afshordi began his appointment as an associate faculty member in 2009. He specializes in interdisciplinary problems in fundamental physics, astrophysics, and cosmology. In the past two years, he has adapted these skills into modelling the COVID-19 epidemic dynamics, which could help inform public policy. Among his honours, Afshordi has received a Discovery Accelerator Supplement from the Natural Sciences and Engineering Research Council of Canada, an Early Researcher Award from the Ontario Ministry of Research and Innovation, and the Vainu Bappu Gold Medal from the Astronomical Society of India. He also won first prize in the Buchalter Cosmology Prize of the American Astronomical Society in 2019, and third prize in 2015.

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

Avery Broderick (PhD California Institute of Technology, 2004) began a joint appointment with Perimeter and the University of Waterloo in 2011 and was named the Delaney Family John Archibald Wheeler Chair in Theoretical Physics at Perimeter Institute in January 2017. 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 is a key member of the Event Horizon Telescope (EHT) collaboration, which revealed the first image of a black hole event horizon to the world in April 2019. He studies how black holes accrete matter and launch the ultra-relativistic outflows observed, probing the nature of gravity in their vicinity. Broderick is a co-winner (with the EHT collaboration) of the Diamond Achievement Award and the 2020 Breakthrough Prize in Fundamental Physics, along with several other awards.

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

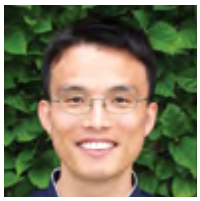
Cliff Burgess (PhD University of Texas at Austin, 1985) joined Perimeter's faculty as an associate member in 2004 and was jointly appointed to McMaster University's faculty in 2005. Prior to that, he was a member of the School of Natural Sciences at the Institute for Advanced Study and a faculty member 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. He was awarded the Buchalter Cosmology Prize in both 2016 and 2017.

Anton Burkov (PhD Indiana University, 2002) joined Perimeter in 2020. His cross-appointment is as a professor in the Department of Physics and Astronomy, University of Waterloo, where he has been since 2007. Burkov is a theoretical quantum condensed matter physicist, with a particular interest in topological and strong correlation phenomena in quantum matter. He is well known for pioneering work on gapless topological phases of matter, such as Weyl and Dirac semi-metals, with several of his publications on this subject in the "ISI Web of Knowledge Highly Cited Papers" list. He is one of the principal investigators (and the only one from Canada) in the US Department of Energy's Energy Frontier Research Center on Topological Semimetals.

Matthew Johnson (PhD University of California, Santa Cruz, 2007) began a joint appointment with Perimeter and York University in 2012. Prior to that, he was a Moore Postdoctoral Scholar at the California Institute of Technology and a postdoctoral researcher at Perimeter. Johnson is a theoretical cosmologist whose interdisciplinary research seeks to understand how the universe began, how it evolved, and where it is headed. Johnson has made contributions to fields ranging from inflationary cosmology and string theory to numerical relativity and cosmic microwave background radiation data analysis. His research has attracted competitive funding from the Natural Sciences and Engineering Research Council of Canada, the Foundational Questions Institute, and the New Frontiers in Astronomy and Cosmology grant program administered by the University of Chicago.

Theo Johnson-Freyd (PhD University of California, Berkeley, 2013) is jointly appointed at Dalhousie University, where he is an assistant professor in the Department of Mathematics and Statistics. Johnson-Freyd is a mathematical physicist whose research focuses on higher algebraic aspects of quantum fields and condensed matter. Prior to appointment to his current position in 2021, he was a senior postdoctoral researcher at Perimeter, and from 2013 to 2016 was a National Science Foundation postdoctoral fellow and Ralph Boas Assistant Professor at Northwestern University. He is the co-author of *Berkeley Lectures on Lie Groups and Quantum Groups* (forthcoming from World Scientific). Johnson-Freyd is a principal investigator for the Simons Collaboration on Global Categorical Symmetries and a recipient of the NSERC Discovery Accelerator Supplement.

Raymond Laflamme (PhD University of Cambridge, 1988) is jointly appointed at the Institute for Quantum Computing at the University of Waterloo, where he served as founding Executive Director from 2002 to 2017. He is also the Mike and Ophelia Lazaridis John von Neumann Chair in Quantum Information at the University of Waterloo and the Canada Research Chair in Quantum Information. He held research positions at the University of British Columbia and Peterhouse College, University of Cambridge, before moving to the Los Alamos National 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 was Director of the Quantum Information Processing program at the Canadian Institute for Advanced Research (CIFAR) from 2003 to 2016. He is an advisor to the Quantum Information Science program at CIFAR and a fellow of the American Physical Society, the Royal Society of Canada, and the American Association for the Advancement of Science, and he was named an Officer of the Order of Canada in 2017. He was awarded the 2017 CAP-CRM Prize in Theoretical and Mathematical Physics by the Canadian Association of Physicists and the Centre de recherches mathématiques. With colleagues, Laflamme founded Universal Quantum Devices, a start-up commercializing spin-offs of quantum research, and leads QuantumLaf Inc., a consulting start-up.



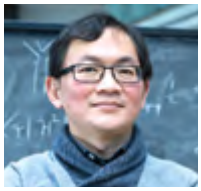
Sung-Sik Lee (PhD Pohang University of Science and Technology, 2000) joined Perimeter in 2011 in a joint appointment with McMaster University, where he is a professor. He previously worked as a postdoctoral researcher at the Pohang University of Science and Technology, the Massachusetts Institute of 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, quantum field theory, and the AdS/CFT correspondence. His recent work has included low energy effective field theories for non-Fermi liquids and construction of holographic duals for general quantum field theories based on the quantum renormalization group.

Debbie Leung (PhD Stanford University, 2000) joined Perimeter in 2019. She started as a faculty member of the Institute for Quantum Computing and the Department of Combinatorics and Optimization at the University of Waterloo in 2005. She is currently a University Research Chair, and she was previously a Tier 2 Canada Research Chair (2005-15). Before that, she was a Tolman Postdoctoral Fellow at the Institute for Quantum Information, California Institute of Technology (Caltech), after spending four months at the Workshop on Quantum Computation (September-December 2002) at the Mathematical Sciences Research Institute, Berkeley, following a two-year postdoctoral fellowship at the Physics of Information group at the IBM TJ Watson Research Center (2000-02). After a BSc in physics and mathematics from Caltech in 1995, she did a PhD in physics at Stanford under the supervision of Professor Yoshihisa Yamamoto and Professor Isaac Chuang.

Roger Melko (PhD University of California, Santa Barbara, 2005) joined Perimeter in 2012, while retaining his appointment with the University of Waterloo, where he has been since 2007. Prior to that, he was a Wigner Fellow at Oak Ridge National Laboratory (2005-07). Melko is a scientific lead at the Perimeter Institute Quantum Intelligence Lab and at Creative Destruction Lab, and a faculty affiliate at Vector Institute for Artificial Intelligence. He is a condensed matter theorist who studies strongly correlated many-body systems, focusing on exotic emergent phenomena, quantum criticality, and entanglement. He emphasizes numerical methods as a theoretical technique, particularly the development of novel algorithms and machine learning methods for his research. Among his honours, he has received the Herzberg Medal from the Canadian Association of Physicists, the Young Scientist Prize in Computational Physics from the International Union of Pure and Applied Physics, an Early Researcher Award from the Ontario Ministry of Research and Innovation, and a Canada Research Chair in Computational Quantum Many-Body Physics.

Michele Mosca (DPhil University of Oxford, 1999) is jointly appointed with the Institute for Quantum Computing (IQC) at the University of Waterloo. He is a founding member of Perimeter Institute, as well as a co-founder of IQC. He is a professor in the Department of Combinatorics and Optimization of the University of Waterloo's Faculty of Mathematics. He co-founded the quantum-safe cryptography training program CryptoWorks21, the not-for-profit Quantum-Safe Canada, and the ETSI-IQC workshop series in quantum-safe cryptography, which brings together a broad range of stakeholders working toward globally standardized quantum-safe cryptography. He co-founded evolutionQ Inc. to support organizations as they evolve their quantum-vulnerable systems and practices to quantum-safe ones, and softwareQ Inc. to provide quantum software services and tools. His research interests include quantum computation and cryptographic tools that will be safe against quantum technologies, and he is globally recognized for his drive to help academia, industry, and government prepare our cyber systems to be safe in an era with quantum computers. Mosca co-authored the respected textbook *An Introduction to Quantum Computing.* He has received numerous honours, including the Premier's Research Excellence Award (2000-05), the Canada Research Chair in Quantum Computation (2002-12), the University Research Chair at the University of Waterloo (2012-19), the Queen Elizabeth II Diamond Jubilee Medal (2013), the St. Jerome's University Fr. Norm Choate Lifetime Achievement Award (2017), and a Knighthood (Cavaliere) in the Order of Merit of the Italian Republic (2018).

Christine Muschik (PhD Max Planck Institute for Quantum Optics, 2011) joined Perimeter in 2019, in a joint position with the Institute for Quantum Computing in Waterloo, where she has been since 2017. Muschik works on developing novel methods for quantum information processing and on quantum simulations of problems from high energy physics. She has devised pioneering protocols for harnessing dissipation (setting a new record for entanglement lifetime in 2011), for the first deterministic teleportation between matter systems over a macroscopic distance (*Nature Physics* 2013), and for new types of quantum simulations (*Nature* 2016, 2019). Her work on quantum simulations of problems from high energy physics was selected by *Physics World* as one of the top 10 breakthroughs in physics 2016. Muschik has received a Simons Emmy Noether Fellowship at Perimeter (2018), a Sloan Research Fellowship for outstanding early-career researchers (2019), and a New Frontiers grant for high risk, high-reward innovations (2019). In 2020, she was named a Canadian Institute for Advanced Research Azrieli Global Scholar.



Ue-Li Pen (PhD Princeton University, 1995) joined Perimeter in 2014. He is the Director of the Academia Sinica Institute of Astronomy and Astrophysics in Taiwan and is jointly appointed with the Canadian Institute for Theoretical Astrophysics at the University of Toronto, where he has been a professor since 1998. Pen is a theoretical astrophysicist who studies systems where basic physical effects can be isolated from astronomical complexities. His research projects include the non-linear dynamics of the cosmic neutrino background, 21 cm intensity mapping, pulsar VLBI scintillometry, and the Canadian Hydrogen Intensity Mapping Experiment (CHIME). Pen is known for developing innovative tools to create new fields of research. His pioneering work on 21 cm intensity mapping opens a new window for the precision study of dark energy and neutrinos. His use of natural plasma in our galaxy as a giant telescope spawned the field of scintillometry, enabling new glimpses into enigmatic pulsars and the unsolved fast radio bursts. Among his many honours, Pen is a senior fellow of the Canadian Institute for Advanced Research in the Gravity and the Extreme Universe program. In 2018, he became just the second researcher at a Canadian institution to receive a Simons Investigator Award from the Simons Foundation since the program's introduction in 2012. He was part of the CHIME research team that received a Governor General's Innovation Award in 2020 and the Lancelot Berkeley Prize from the American Astronomical Society in 2021. He was also one of the 347 members of the Event Horizon Telescope collaboration to win the 2020 Breakthrough Prize in Fundamental Physics.

Will Percival (PhD University of Oxford, 1999) is jointly appointed at the University of Waterloo, where he holds the Mike and Ophelia Lazaridis Distinguished Research Chair in Astrophysics, and is the Director of the Waterloo Centre for Astrophysics. Percival is a cosmologist working primarily on galaxy surveys, using the positions of galaxies to measure the cosmological expansion rate and growth of cosmological structure. He currently holds senior scientific management positions within the Euclid experiment and has served in a number of management positions for other surveys, including the Dark Energy Spectroscopic Instrument (DESI) and the extended Baryon Oscillation Spectroscopic Survey (eBOSS). Over the next decade, the resulting galaxy surveys will transform our knowledge of dark energy, the physical mechanism accelerating the present-day cosmological expansion rate. Among his many honours, Percival has received the 2008 Fowler Prize of the Royal Astronomical Society and a Distinguished Scientist fellowship from the Chinese Academy of Sciences in 2016.

Sergey Sibiryakov (PhD Institute for Nuclear Research of the Russian Academy of Sciences, 2004) joined Perimeter in 2020 from École Polytechnique Fédérale de Lausanne and CERN, where he had been a faculty member since 2013. He is jointly appointed with the Department of Physics and Astronomy at McMaster University. His research interests range from particle physics phenomenology to cosmology and the theory of gravitation. He is co-author of a series of groundbreaking works establishing consistency of the approach to quantum gravity known as “gravity with anisotropic scaling.” Sibiryakov’s previous honours include the Medal of the Russian Academy of Sciences Prize for Young Scientists and several grants and fellowships from Russian and Swiss foundations.

Daniel Siegel (PhD Max Planck Institute for Gravitational Physics & University of Potsdam, 2015) joined Perimeter in 2019, jointly appointed with the University of Guelph. Previously, he was at Columbia University, where he had been a postdoctoral fellow and a NASA Einstein Fellow since November 2015. His research connects fundamental physics with the cosmos. It spans various disciplines – gravitational physics, nuclear and high energy astrophysics, transient astronomy – to unravel the fundamental physics of compact binary mergers and other relativistic astrophysical systems as well as their implications for nuclear physics and cosmology.

Ben Webster (PhD University of California, Berkeley, 2007) joined Perimeter in July 2017, jointly appointed with the Department of Pure Mathematics at the University of Waterloo. He previously held faculty positions at the University of Virginia, Northeastern University, and the University of Oregon. Webster’s research centres on connections between representation theory, mathematical physics, geometry, and topology, including knot homology, the geometry of symplectic singularities, and categorification. Among his honours, he has received a Sloan Research Fellowship and a CAREER award from the National Science Foundation in the United States. In 2019, he was awarded the Golden Jubilee Research Excellence award from the University of Waterloo’s Faculty of Mathematics.

Huan Yang (PhD California Institute of Technology, 2013) joined Perimeter in September 2017 from Princeton University, where he stayed for one year as a postdoctoral fellow. He is jointly appointed with the University of Guelph. Yang is a theoretical astrophysicist whose areas of expertise are black holes, neutron stars, and gravitational waves, with strong connections to recent observations. In particular, he explores strong-field gravitational astrophysics and fundamental physics with strongly gravitating systems. Yang’s recent work aims to understand physics buried within existing data and provide new insights to guide future observational efforts.

Jon Yard (PhD Stanford University, 2005) joined Perimeter in 2016, jointly appointed with the Institute for Quantum Computing and the Department of Combinatorics and Optimization at the University of Waterloo. He previously held research positions at McGill University (2005), the California Institute of Technology (2005-07), Los Alamos National Laboratory (2007-12), and Microsoft Research (2012-16). Yard’s research interests include quantum information, mathematical physics, quantum fields, and condensed matter. With Graeme Smith, he received the 2009 Pat Goldberg Memorial Best Paper Award from IBM Research for proving that quantum capacity does not completely characterize the utility of a channel for transmitting quantum information.

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CONFERENCES AND WORKSHOPS, 2020/21

Online School on Ultra Quantum Matter
August 10-14, 2020

Postdoctoral Researcher Welcome
October 14 & 16, 2020

Tensor Networks: From Simulation to Holography III
November 16-20, 2020

Octonions and the Standard Model (weekly series)
February 8-May 17, 2021

Women at the Intersection of Mathematics and Theoretical Physics
February 22-25, 2021

The 24th Capra Meeting on Radiation Reaction in General Relativity
June 7-11, 2021

Quantizing Time
June 14-18, 2021

ACADEMIC SPONSORSHIPS, 2020/21

Perimeter Institute was a proud sponsor of the following conferences and workshops hosted elsewhere in Canada. All were held virtually. Perimeter will honour any sponsorship commitments to conferences and workshops that have been postponed due to public health guidelines and travel restrictions.

Canadian Undergraduate Physics Conference
November 5-8, 2020

58th Winter Nuclear and Particle Physics Conference
February 11-14, 2021

Cosmological Frontiers in Fundamental Physics
May 24-27, 2021

Atlantic General Relativity Meeting
May 25-29, 2021

The 49th Annual Canadian Operator Symposium
May 31-June 4, 2021

Tri-Institute Summer School on Elementary Particles (TRISEP)
June 14-25, 2021

2021 Canadian Association of Physicists Congress
July 6-9, 2021

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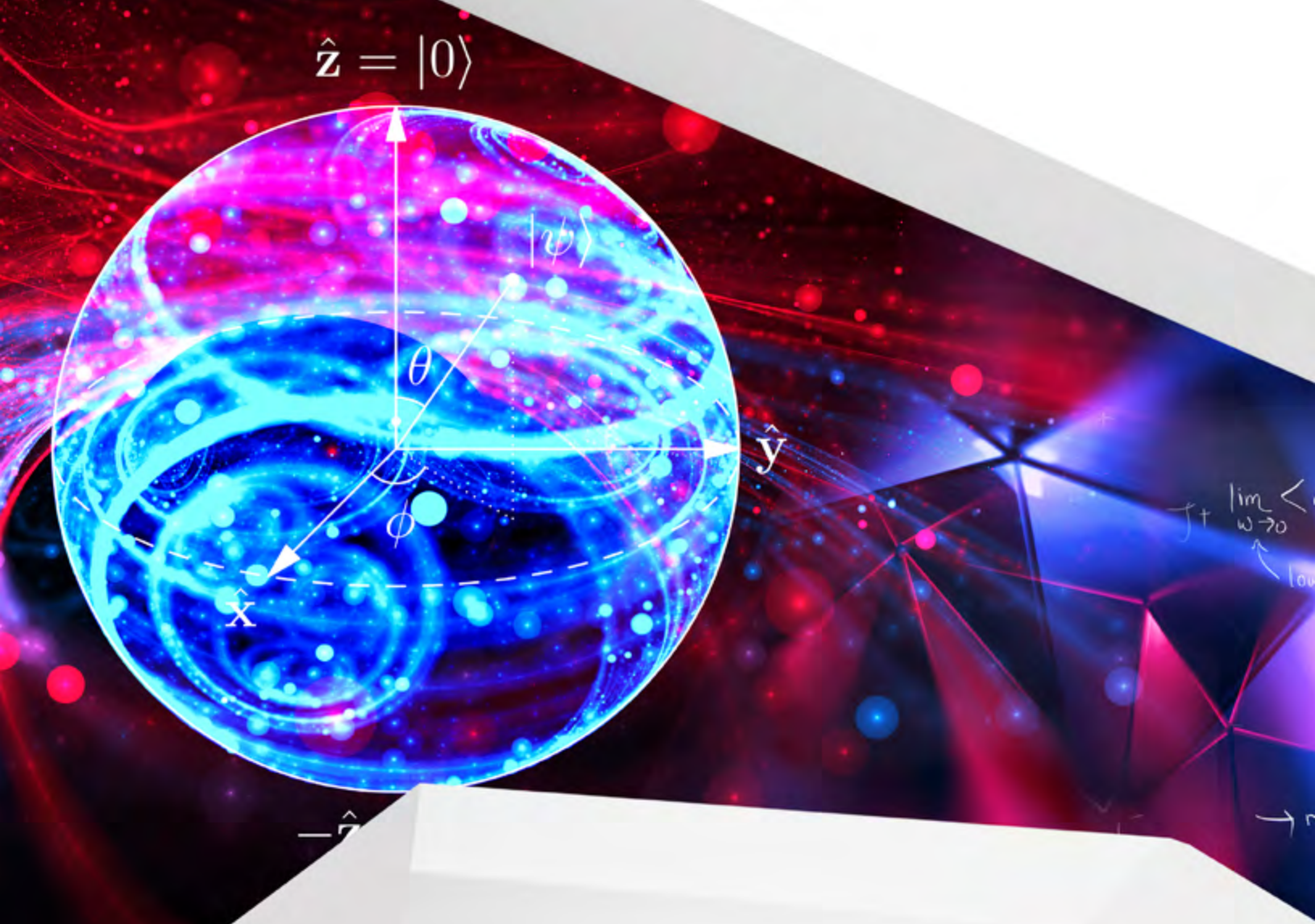

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