# 2019 ANNUAL REPORT

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

# VISION

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

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This report covers the activities and finances of Perimeter Institute for Theoretical Physics from August 1, 2018, to July 31, 2019.

PERIMETER PI INSTITUTE FOR THEORETICAL PHYSICS

*TODAY'S THEORETICAL PHYSICS*
*IS TOMORROW'S TECHNOLOGY*

# MESSAGE FROM THE BOARD CHAIR

I can hardly believe nearly two decades have passed since I proposed a big idea – an audacious idea, according to many who heard it – to launch a world-leading independent theoretical physics research centre in Waterloo, Ontario, Canada. To me, the rationale behind the idea was crystal clear.

Breakthroughs in theoretical physics sparked the information revolution and underpin every technology we rely on today, from smartphones to lifesaving medical devices. Just imagine what could happen if we purpose-built a place for the world's most brilliant minds to freely tackle the biggest unsolved mysteries in fundamental physics.

Perimeter has transformed from an idea into a reality that continues to exceed even my own vision for it.

The Institute's success is built upon the convergence of bold ideas and the very best researchers from around the world who have chosen Perimeter as the place to contribute to the advancement of science.

This past February, we celebrated the appointment of Robert Myers as Perimeter's Director. Our goal was to find a world-class and internationally respected scientist with the vision to advance Perimeter's foundational goals of conducting exemplary research, training the next generation of talent, and sharing science through educational outreach.

That a search committee made up of leading scientists from around the world and across a number of fields of physics strongly and unanimously recommended and endorsed Rob for the role is further evidence of the calibre of the researchers who have chosen to become part of PI.

I want to thank Neil Turok for his outstanding leadership as Perimeter's Director over the past decade, and I want to wish Rob all the best as he takes the reins. I couldn't be more confident about the future of the Institute under Rob's leadership.

Rob's appointment happened at the start of an especially exciting year of discovery and breakthroughs for Perimeter. Members of Canada's CHIME telescope collaboration – including a team at Perimeter led by Faculty member Kendrick Smith – announced the detection of an unprecedented quantity of mysterious distant explosions called fast radio bursts. The game-changing research, made possible by innovative computer code devised by Kendrick and colleagues, is a milestone for radio astronomy that earned Kendrick the New Horizons in Physics Prize from the Breakthrough Prize Foundation. Perimeter researchers have now won seven New Horizons Prizes in the award's short history – more than any other institution in the world.

This past spring, humanity got its first collective look at a real black hole thanks to an image released by the Event Horizon Telescope (EHT) collaboration. Perimeter is one of 13 international partner organizations in the EHT – the only Canadian partner – and Associate Faculty member Avery Broderick and colleagues in Perimeter's EHT Initiative were pivotal to the breakthrough. The EHT team allowed people worldwide to "see the unseeable," which earned the collaborators the prestigious $3 million Breakthrough Prize in Fundamental Physics.

The past two decades have seen Perimeter and its partner organizations in the Quantum Valley ecosystem establish global leadership for Ontario and Canada in the new quantum industry. Organizations around the globe are now looking to Waterloo, Ontario, for insights on how to connect theory and experiment at the quantum frontier, and on the development of new technologies, products, and businesses that will increasingly define and drive this new global industry.

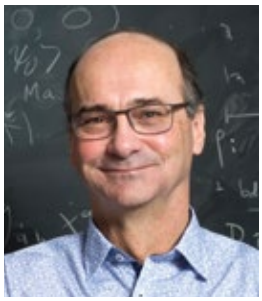
As we reach this 20-year milestone, we celebrate the progress that has been made by Perimeter and across the Quantum Valley. We celebrate the vision, courage, and hard work of many people who have made my "audacious" idea a reality, for which I am personally grateful.

My thanks in particular to our investors in this grand partnership – the Governments of Ontario and Canada for their ongoing support, and the growing number of generous foundations and donors who are vital parts of the equation.

I also want to thank the entire Perimeter team – including our Board members, our Finance & Investment Committees, our Leadership Council, and our Scientific Advisory Committee members – all of whom volunteer their time and guidance to the Institute. Particular thanks to Joanne Cuthbertson and Patrice Merrin, Co-Chairs of the Leadership Council, and Cosimo Fiorenza, Vice Chair of the Board.

We also celebrate our progress to date as a measure of what is possible moving forward. As we embark on the next stage in the development of Perimeter Institute and the Quantum Valley, our progress to date shows us what is possible. The foundations that we have built over the past 20 years enable us to drive forward at an accelerated pace. I believe that the future promises more scientific breakthroughs, new quantum technologies, and new quantum start-ups in Ontario and Canada. I am very excited about the future for Perimeter Institute and the Quantum Valley.

– **Mike Lazaridis**, O.C., O.Ont., FRS, FRSC
Chair, Board of Directors



# MESSAGE FROM THE INSTITUTE DIRECTOR

It is my honour and pleasure to introduce Perimeter's annual report for 2018/19.

I became Perimeter's third director this past February, 2019, but I first heard about Perimeter back in 2000, when I met the Institute's founder, Mike Lazaridis. Mike had just created the world's first full-fledged smartphone.

That device was about to reshape the world, but Mike didn't want to talk about that. He wanted to talk about theoretical physics. He saw the smartphone as a triumph of theoretical physics, since every one of its marvellous capabilities was the result of past breakthroughs in our field – electromagnetism, Einstein's relativity, and lots of quantum mechanics. And now, he wanted to talk about where the next breakthroughs would come from: ones that would shape the lives of our children and grandchildren and great-grandchildren.

Mike proposed that we create a new institute dedicated to making those breakthroughs, tackling the deepest and most difficult problems in physics, bringing together many of the world's best minds, right here in Canada.

I was struck by the simplicity, the clarity, the audacity of his vision. Those are the hallmarks of a powerful idea. As a scientist, I know how precious ideas like that really are. Soon after, I left my position at McGill and joined Perimeter as one of its founding faculty members.

Nineteen years later, the power of Perimeter's founding vision continues to inform every aspect of what we do. And we've done a great deal.

We've trained over 1,000 young scientists here. We do it in new ways, aiming to create fearless researchers and leaders. We give our postdoctoral fellows full research autonomy and opportunities they wouldn't get anywhere else. This year, our master's program, Perimeter Scholars International, graduated its 10th class. Our PhD program is growing, and we just launched a summer research accelerator for undergraduates. These young people go on to do extraordinary things – whether in research, industry, teaching, or government. All carry the Perimeter spirit: that breakthroughs are possible and that it is up to us to strive for them.

Our Educational Outreach team has created dozens of high-quality classroom resources for elementary and high school students that have been used over 50 million times across Canada and around the world. We've trained 30,000 teachers to better engage students with physics and the scientific mindset that comes with it. Our outstanding science communications – like our Quantum to Cosmos interactive website and our renowned public lectures – have been viewed millions of times, inspiring bright minds everywhere.

Above all, we seek research breakthroughs – from the foundations of the quantum world to the full scope of the cosmos. The array of achievements is dazzling. Among many honours and awards, this year our researchers won *three* of the prestigious Breakthrough Prize Foundation prizes. Avery Broderick (who holds the Delaney Family John Archibald Wheeler Chair) shared in the Breakthrough Prize as a leader in the Event Horizon Telescope collaboration. Avery and his team did much of the critical theoretical work behind humanity's first image of a black hole, an event that captured the world's imagination. Over 4 billion people – half of the global population – are estimated to have seen that image. Kendrick Smith (who holds the Daniel Family James Peebles Chair) won the New Horizons Prize for the crucial role he played in the detection of unprecedented numbers of fast radio bursts by Canada's CHIME telescope. Pedro Vieira (who holds the Clay Riddell Paul Dirac Chair) won the New Horizons Prize for blazing new paths in quantum field theory.

*"Above all, we seek research breakthroughs – from the foundations of the quantum world to the full scope of the cosmos. The array of achievements is dazzling. Among many honours and awards, this year our researchers won three of the prestigious Breakthrough Prize Foundation prizes."*

Our horizons are bright: longstanding challenges are coming within reach, with new data, new approaches, new experiments. There are clearly breakthroughs coming in quantum technology – ultra-precise sensors, new materials, new computers, and much more. Our researchers are helping to lay the theoretical foundation on which those future quantum technologies will be built.

At Perimeter, what was once an audacious idea has become a reality. This gives me confidence that the ideas, theorems, and breakthroughs being born here today will result in a new generation of wonders that our grandkids will hold in their hands.

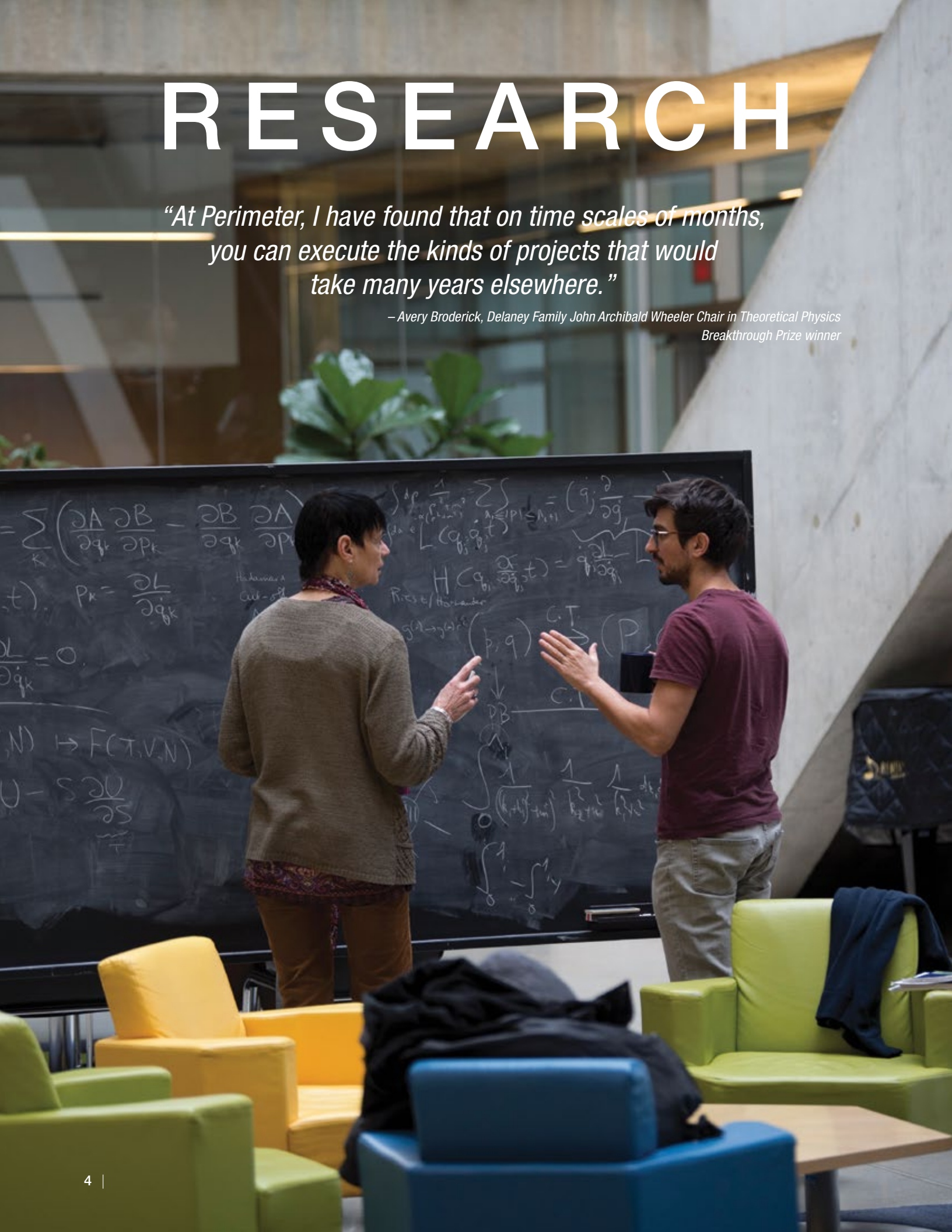
It is my great privilege to carry Mike's founding vision forward – with simplicity, clarity, and audacity.

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

# RESEARCH

*"At Perimeter, I have found that on time scales of months, you can execute the kinds of projects that would take many years elsewhere."*

*– Avery Broderick, Delaney Family John Archibald Wheeler Chair in Theoretical Physics*
*Breakthrough Prize winner*



# RESEARCH by the numbers

At Perimeter Institute, we strive to achieve breakthroughs in our understanding of the universe, attract outstanding visiting scientists, and create the world's strongest community of theoretical physics researchers.

**5,792** papers published in 218 journals since Perimeter's inception

**289,613** citations since inception

**459** papers published in 2018/19

**17** prizes and honours in 2018/19

## RESEARCH COMMUNITY

(as of July 31, 2019)

**24** Faculty

**21** Associate Faculty

**11** Perimeter Research Chairs

**44** Distinguished Visiting Research Chairs

**63** Postdoctoral researchers

**23** Simons Emmy Noether Fellows (6 new in 2018/19)

**51** Visiting Fellows

**15** Visiting Researchers

**113** Affiliate members

## CONFERENCES, WORKSHOPS, AND SEMINARS, 2018/19

**11** conferences and workshops attended by 620 scientists

**12** sponsored off-site workshops

**315** scientific talks, seminars, and colloquia

**12,438** talks (total) in the online Perimeter Institute Recorded Seminar Archive (PIRSA)

**737,024** views of Perimeter talks in 2018/19, from viewers in 183 countries

## VISITORS

**512** scientific visitors

# SEEING THE UNSEEABLE

BREAKTHROUGH PRIZE

Two decades ago, Avery Broderick reflects, “I was among a ragtag group of dreamers who yearned to do something not just scientifically interesting, but brand new. We staked our careers and reputations on an endeavour we believed would someday bear fruit.”

On April 10, 2019, that risk paid off – big time.

After years of theoretical research and technical ingenuity spanning continents, Broderick, who holds the Delaney Family John Archibald Wheeler Chair at Perimeter and leads the Institute’s Event Horizon Telescope (EHT) Initiative, stood among the leaders of the EHT collaboration at a press conference in Washington, DC, as they unveiled the world’s first image of a black hole.

“We have gone right to the edge of the event horizon and seen the point of no return,” he said during the press conference. “It is an extraordinary moment in science.”

The image reveals the black hole – an incredibly massive and compact object with gravity so intense that nothing, not even light, can escape – at the heart of the Messier 87 galaxy in the Virgo galactic cluster, 55 million light years from Earth.

The EHT’s observations and resulting image match theoretical predictions with incredible precision. Those predictions date back to Albert Einstein, whose theory of general relativity predicted the bending of light and spacetime by black holes.

The landmark image is the result of a worldwide collaboration of more than 200 researchers from 13 partner organizations – with Perimeter as the sole Canadian partner – and dozens of affiliate organizations. That collaboration was necessary to create a precision-linked network of eight telescopes around

the world to form the "Earth-sized" virtual telescope of the EHT, which achieved unprecedented resolution.

Broderick, who is jointly appointed at the University of Waterloo, and members of Perimeter's EHT Initiative devised predictive models and simulations that guided the development of the EHT and analyzed vast amounts of data obtained through the EHT's observations. A 2014 conference at Perimeter was also one of the key early meetings at which the EHT collaboration formally took shape.

The image shows a bright circular ring of superheated gas circling the dark patch where the event horizon – the black hole's point of no return – absorbs anything that crosses it, creating a black shadow or silhouette.

Creating the EHT was a formidable challenge that required upgrading and connecting a worldwide network of eight existing telescopes on mountaintops in Antarctica, Chile, Hawaii, Mexico, and other remote locations.

The EHT enables a technique called very-long-baseline interferometry, which synchronizes telescope facilities and uses the rotation of the Earth to scan the sky. The resolution this achieves is great enough to read the fine print on a dime in South Africa from a vantage point in New York City.

While capturing the image of a black hole is a remarkable achievement, this is merely a stepping stone. A new era in astrophysics is dawning. With the EHT in their arsenal, researchers have an incredibly powerful tool for making advances in our understanding of space, time, and gravity.

Just as Galileo's early telescope revolutionized humanity's understanding of its place in the universe, the EHT's discoveries about black holes – the universe's most mysterious and powerful phenomena – will shape our collective future. "This first image doesn't represent the end of an endeavour, but the beginning of an era," says Broderick. "We are now entering an era of research with benefits we have only begun to imagine."

*Avery Broderick holds the Delaney Family John Archibald Wheeler Chair in Theoretical Physics. Find out more about the Delaney family on page 39.*

Reference:

The Event Horizon Telescope collaboration, "First M87 Event Horizon Telescope results. I." *Astrophys. J. Lett.* 875(1), 2019, arXiv: 1906.11238.

*"Perimeter is proud to be a partner in this remarkable international collaboration. It inspires us all as to what an extraordinary place the universe really is, and how much there is to discover in it."*

*– Perimeter Director Robert Myers*

*Avery Broderick*

*Tobias Fritz, Robert Spekkens, and Elie Wolfe*

# A BREAKTHROUGH IN THE SCIENCE OF CAUSE AND EFFECT

Perimeter Faculty member Robert Spekkens and postdoctoral researchers Elie Wolfe and Tobias Fritz have used approaches inspired by fundamental quantum physics to create an important new tool for obtaining causal accounts of correlations that's making waves well beyond physics.

Figuring out what causes what can be challenging. For instance, if one observes a positive correlation, it may be due to a cause-effect relationship, but it might also be due to a common cause: ice cream sales tend to correlate with cases of sunburn, but only because they both increase on sunny days.

This is what makes scientific questions about causation challenging. Is a given gene complex really the cause of a given syndrome? Can an upturn in the economy truly be attributed to some particular policy? Is a drug treatment really effective? Understanding causal mechanisms is clearly of critical importance to many disciplines, including epidemiology, economics, and health science. It is also critical to machine learning – indeed, an entire field, called causal inference, has arisen to study it. As artificial intelligence (AI) pioneer Judea Pearl has emphasized, for an AI to be truly intelligent, it will have to encompass understandings of cause and effect.

For a given assumption about causal structure (i.e., what causes what in some collection of variables), it is possible to derive limits on the strength of the correlations between them. Suppose you have a given hypothesis about the causal structure, then you can determine those limits, and if data are subsequently found to violate those limits, you have to conclude that your hypothesis is wrong. The question is: How does one derive these limits (or constraints) for any given causal structure? This is a central problem that the field of causal inference tries to solve.

Curious about the implications of recent work in causal inference, several years ago, Spekkens had an important insight: he realized that a crucial tool in the foundations of quantum theory called "Bell inequalities" could be reframed as a solution to a causal inference problem for a particular causal structure. The work was very influential and led many quantum foundations researchers to start reconsidering certain quantum puzzles through a causal inference lens.

Spekkens and his collaborators also started thinking about the potential for a flow of ideas in the opposite direction (i.e., from the field of quantum foundations to causal inference). They wondered: Could techniques for deriving Bell-like inequalities be generalized to other causal structures?

They found that they could. By 2016, Spekkens, Wolfe, and Fritz had created a full-fledged algorithm called "the inflation technique" that could work out the limits on correlations for any causal structure. It enables researchers to evaluate hypotheses about underlying causal structure from a given pattern of correlations in data. The inflation technique thus enables researchers to rule some hypotheses about causation in and others out.

The researchers knew that it would be useful beyond physics. Data scientists, for example, also want to find inequalities that indicate which correlations are consistent with a given causal structure. So Spekkens and his collaborators submitted their work to a computer science publication, the *Journal of Causal Inference*, where it was warmly received.

In follow-up work to the original article, Wolfe and Miguel Navascués, from the Institute for Quantum Optics and Quantum Information at the Austrian Academy of Sciences, then showed that the technique could be used to discover every possible constraint implied by a causal structure – no matter how complex.

Today, the inflation technique is generating excitement both among quantum researchers and in the field of causal inference, where it is likely to find its most significant applications in machine learning. Physicist Nicolas Gisin of the University of Geneva, whose work spans quantum theory and experiment, believes that the inflation technique is likely to become a standard tool in his field. Computer scientist Ilya Shpitser, of Johns Hopkins University, a leading researcher in causal inference, described the work as a new way of thinking about a crucial problem: "It appears as if the inflation technique is going to shed much light on this question, or perhaps even solve it entirely!"

References:

E. Wolfe, R. Spekkens, T. Fritz (Perimeter Institute), "The inflation technique for causal inference with latent variables," *J. Causal Inference* 7(2), 2019, arXiv:1609.00672.

M. Navascués (IQOQI Vienna), E. Wolfe (Perimeter Institute), "The inflation technique completely solves the causal compatibility problem," arXiv:1707.06476v2.

# FROM QUANTUM FOUNDATIONS TO AI-POWERED DIAGNOSTICS

The career of Ciaran Lee, a 2013 Perimeter Scholars International (PSI) master's graduate, shows how basic research can translate into startling real-world applications. In Lee's case, pondering the foundations of quantum theory ultimately led to innovations in medical diagnosis.

As part of his training at Perimeter, Lee and Faculty member Robert Spekkens explored Bell's theorem – a seminal result in quantum theory – from the perspective of a branch of machine learning known as causal inference. Lee's PSI research project eventually led to a new tool for distinguishing between different causal hypotheses based on observed correlations, published in the *Journal of Causal Inference*.

After PSI, Lee did his PhD at University College London on other topics in quantum theory but maintained a keen interest in causal inference. Based on this expertise, he was hired after graduation by UK-based start-up Babylon Health, which develops AI for medical diagnosis.

By introducing causal inference techniques that he'd learned about at Perimeter into Babylon Health's AI software, Lee and his team helped bring its diagnostic accuracy to equal that of expert clinicians – and it continues to improve. In 2018, Babylon Health's Series C funding round, based partly on the new diagnostic AI, raised an astonishing $550 million (USD). The company is now valued at more than $2 billion (USD) and is greatly expanding the reach of affordable diagnostic tools to improve health across the globe.

*Kendrick Smith*

# OUR MYSTERIOUS SURPRISE

**NEW HORIZONS PRIZE**

"Once a decade or so, astronomers discover a new type of mysterious event in the universe," says Perimeter Faculty member Kendrick Smith. "In the 1960s, pulsars were an unexpected mystery; in the 70s, gamma ray bursts were a surprise, and so on. In the 21st century, our mysterious surprise is the fast radio burst."

Fast radio bursts, or FRBs, are brief pulses of radio-frequency light originating in deep space. By the time they reach Earth, they are faint – as faint as a cellphone signal sent from the moon – but they don't start out that way. It's not known what produces them, but whatever it is releases as much energy in a few milliseconds as our sun does over 80 years.

The first FRB was spotted in 2007. In the decade-long intensive search that followed, only 25 more turned up. Puzzlingly, one and only one seemed to repeat. With such scarce data, research into FRBs could only creep forward.

That all changed with the commissioning of a new telescope, the Canadian Hydrogen Intensity Mapping Experiment, or CHIME. "In a world full of huge international collaborations, CHIME is a small, Canada-only project," Smith says. "Turning it into an FRB hunter was a chance to make Canada a leader in one of the hottest problems in astrophysics."

The CHIME telescope is unusual, in a few ways. It looks like a set of skateboarder half-pipes. But the really interesting part is that it's a "software telescope" – it collects signals from many different directions at the same time and uses advanced algorithms to line up all the signals. CHIME captures a huge amount of data – equivalent to all the cellphone traffic in North America – every second. This raw sensitivity is CHIME's strength, but also its challenge. In such an avalanche of data, an FRB – faint and brief – could easily be missed. Making things even harder is the need to spot FRBs in real time. "It's too much data to save to disk, so you only get to look at it during a little window of time when it's in memory," explains Smith.

This is exactly the kind of challenge at which Smith excels. With a first PhD in math, a second in cosmology, and a stint as a software engineer in between, his revolutionary approach mixes physics, data analysis, statistics, and pure mathematics to find the signals in the incredible rush of data generated by new experiments like CHIME.

Leading a small team at Perimeter, Smith developed several breakthrough algorithms for sorting and analyzing the CHIME data. He and his team then implemented this new mathematics as software. The result was an FRB search that ran a hundred times faster than anyone expected. It opened

up the possibility of new kinds of searches, new kinds of experiments – and it turned the CHIME telescope into the world's best FRB hunter.

The CHIME team started spotting FRBs right away. In January 2019, they captured global headlines – including a cover of *Nature* – with a first batch of detections. In August, they announced an even larger collection – of hundreds. In all, they've also spotted nine "repeater" FRBs.

The CHIME results injected rocket fuel into the study of FRBs. For instance, the CHIME team is beginning to pick apart the differences between repeating FRBs and those that have not yet been observed to repeat. A breakthrough in our understanding seems imminent.

For his work in developing novel techniques to extract fundamental physics from astronomical data, Smith was recognized as one of this year's winners of the 2020 New Horizons in Physics Prize.

Meanwhile, Smith's data-mining approach to astronomy has implications well beyond FRBs and CHIME.

Cosmology was once a data-starved science, sometimes stumbling in near darkness. Now, with new experiments generating more data than we can possibly store, it is squinting into a blinding light. Smith and scientists like him are leading the way in bringing our big-data world into focus.

*Kendrick Smith holds the Daniel Family James Peebles Chair in Theoretical Physics.*

References:

CHIME/FRB collaboration, "A second source of repeating fast radio bursts," *Nature* 566, pp. 235-238, 2019, arXiv:1901.04525.

CHIME/FRB collaboration, "Observations of fast radio bursts at frequencies down to 400 megahertz," *Nature* 566, pp. 230-234, 2019, arXiv:1901.04524.


# DINING AT THE MULTIMESSENGER BANQUET

*Asimina Arvanitaki, Luis Lehner, and William East*

In 2015, gravitational waves – ripples in the very fabric of space and time – were detected for the first time by a new type of instrument. That detection created a new field: multimessenger astronomy, which combines gravitational signals with signals from other sources, like conventional telescopes. This new field allows us to probe astrophysical objects and events as never before.

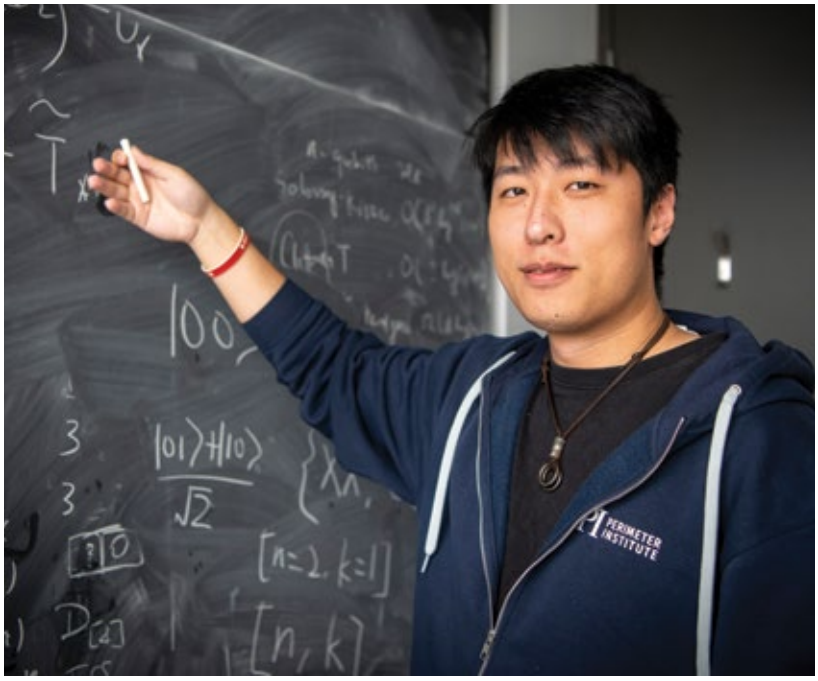
Multimessenger astronomy has already dished up a banquet of new observational data – black hole mergers, neutron star mergers, gamma ray bursts, and more. That's created new opportunities for theorists, who are needed both to interpret incoming data and to make predictions to guide future experiments.

Perimeter researchers Luis Lehner, Asimina Arvanitaki, Huan Yang, Will East, and others, are all involved in using multimessenger approaches to push our understanding of the universe – how it evolves, and its constituents.

"Coming together in a multidisciplinary way is crucial, not only to address some of the challenges but also to bring in the next generation of people who can talk more than one language on this front," says Lehner, Perimeter Faculty Chair. "I'm anxious today for an answer I know will be needed twenty years from now."

*Asimina Arvanitaki holds the Stavros Niarchos Foundation Aristarchus Chair in Theoretical Physics.*

# AN ALL-POWERFUL QUANTUM JUICER




*Zi-Wen Liu*

Suppose you own a health food shop and you want to offer customers a variety of juices. Apple, orange, grapefruit, carrot, beet, wheatgrass – something for any appetite you might encounter.

Now imagine that each type of fruit or vegetable requires its own specific juicing equipment. To make apple juice, you need an apple juicer. For carrot juice, a carrot juicer. And so on. The investment required would gobble up your profits, and you'd be ill-prepared to capitalize on the latest trendy superfruits.

Now, if you want to make anything – from a manufactured product to a new kind of computer – you have to consider the required resources systematically. That's called resource theory. For quantum computing and quantum experiments, you use quantum resource theory. Until recently, the study of quantum resource theory mostly targeted single fruits. Each type of quantum "resource" – entanglement, for example – was like a different type of fruit, for which a corresponding juicer (or resource theory) must be developed.

That's about to change, thanks to recent work by Perimeter postdoctoral researcher Zi-Wen Liu and collaborators Kaifeng Bu (Zhejiang University and Harvard University) and Ryuji Takagi (Massachusetts Institute of Technology). The trio developed a framework – the rough quantum equivalent of a multipurpose juicer – that can characterize the practical usefulness of any quantum resource, regardless of type.

The paper, published in *Physical Review Letters*, was highlighted as an Editor's Suggestion. Liu's work is expected to have broad applicability to fields that use quantum resources, like quantum computing and quantum information.

"My way of looking at resource theory is that I just wanted to develop the most powerful juicer with the most functions," said Liu.

# YOU CALL THAT A PIQUIL?

We've all heard that machine learning is transforming industry. What's less known is that it holds powerful potential for fundamental physics. Increasingly, machine learning is being used in cutting-edge research in quantum matter, materials, and devices.

To take advantage of this emerging revolution, Perimeter Associate Faculty member Roger Melko recently founded the Perimeter Institute Quantum Intelligence Lab (PIQuIL) – and yes, it's pronounced "pickle."

Melko's pioneering work helped kick off a firestorm of new research at the nexus of artificial intelligence (AI) and quantum matter. PIQuIL is the first AI lab formed directly out of a physics institute, with research spanning quantum physics and machine learning. A partnership between Perimeter, 1QBit, and the National Research Council, its mission is to accelerate research in fields at the "complexity frontier."

Major goals along this frontier include building quantum computers and synthetic quantum matter. Researchers at PIQuIL routinely collaborate with experimental quantum computing laboratories, as well as top machine learning theorists and practitioners. Collaborations with top academic and industry players, such as the Institute for Quantum Computing, Harvard, Google, and IBM, give the lab unique access to the best existing quantum hardware.

With an eye on developing innovators for future quantum industries, PIQuIL also offers undergraduate and graduate training, tapping into the large pool of talent that universities are producing in Canada and abroad.

PIQuIL is actively developing next-generation AI software for scientific research and industry. Members of the lab have already published important results and developed an open-source platform and algorithms for AI-enabled discovery.

Headquartered at the Communitech Data Hub, a start-up incubator, PIQuIL has over a dozen researchers so far, a strategic mix of research, academia, and industry – a number projected to rise to 24 in 2020. Quantum computing start-up 1QBit has located five research staff at PIQuIL to take advantage of research synergies.

It's a heady brine – keep an eye on the PIQuIL.

*Bianca Dittrich, Etera Livine, Christophe Goeller, and Aldo Riello*

# OPEN DATA TO ADVANCE RESEARCH

Computer simulations have become a vital part of physics research. But it can be difficult to reproduce results and check their viability if the source code or the data generated in simulations is unavailable. On top of that, not every researcher has access to high-performance computers.

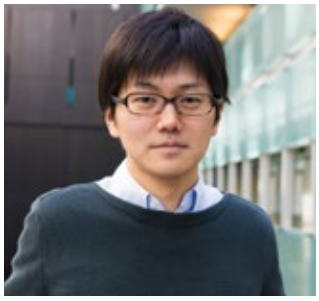
Recently, Perimeter researchers worked with Perimeter information technologists and colleagues from Erlangen University, Hamburg University, and the University of Vienna to create an open-access database to share simulations and data.

“Our motivation was to accelerate the development of numerical tools for exploring quantum spacetime,” said Faculty member Bianca Dittrich. “These tools will be essential to deriving predictions that can guide experiments.”

The “Encyclopedia of quantum geometries” is housed within the open-science Zenodo platform funded through CERN, OpenAIRE, and the European Union. Researchers can upload their data to the encyclopedia with a link to source code, making the data accessible while giving credit to the authors via a DOI. A DOI is a digital object identifier, and it’s a stable way of associating authors to their work. A Letter about the new platform was published in *Nature*.

“We hope that this database can help change the mindset of the community to share their data and allow more people to explore numerical techniques,” said co-author Sebastian Steinhaus, a Perimeter postdoctoral researcher.

# PUTTING THE QUBITS TOGETHER AGAIN



In the quantum world, things are notoriously tricky to keep track of.

For example, a single quantum bit – or qubit, the building block of quantum computing – can be fairly well understood in isolation. It becomes increasingly difficult to keep tabs on it – and the information it holds – when it interacts with more qubits. Imagine adding a drop of cream to your coffee and trying to follow its motion as you stir. The system is too chaotic to follow the movement at that level.

The study of this increasing complexity at the quantum level is called quantum information scrambling. It is important because manipulating large numbers of qubits in quantum computers – a rapidly developing technology – could allow us to perform some computations that would otherwise be impossible.

Perimeter Faculty member Beni Yoshida became fascinated with the phenomenon thanks to an unlikely inspiration – a 2007 paper by Patrick Hayden and John Preskill about the

"black hole information paradox" made famous by Stephen Hawking. The paradox is as follows: relativity says that black holes swallow everything that falls into them – like matter and light – trapping it permanently inside. However, quantum mechanics tells us that black holes emit energetic photons, called Hawking radiation, which are thought to ultimately "evaporate" entirely through this process. When they do, however, all the information about everything that fell in would be forever lost. That loss would violate a law of physics.

That 2007 paper proposed a thought experiment whereby information "lost" in a black hole could be reconstructed from the Hawking radiation. It got Yoshida thinking: Could a similar idea be applied to tackling the problem of quantum information scrambling?

Yoshida proposed a thought experiment in which a measurement of a quantum system is made in the present, then in the future, and then in the present again, and then returning to the future for one more measurement. It would be akin to determining where the droplet of cream landed in your cup after the coffee has been stirred. You would have to measure all the molecules again and then retrace their paths back to the droplet as it hit the surface of your coffee.

Of course, since scientists can't time travel, these measurements are a theoretical, mathematical tool. But such tools are often the starting points to experimental and practical applications – your GPS, for example, wouldn't work had Albert Einstein not made theoretical predictions about spacetime on his blackboard.

Once Yoshida had developed his idea into a mathematical tool, he worked with Alexei Kitaev at the California Institute of Technology to put it to the test experimentally, with real qubits. They developed a simple protocol for reconstructing quantum states by measuring Hawking radiation. This protocol was then implemented on a prototype quantum computer at the University of Maryland's Joint Center for Quantum Information and Computer Science – arguably the best ion trap system in the world – by a team led by Christopher Monroe.

The result: the first experimental verification of quantum information scrambling, a result that was published in the prestigious journal *Nature*.

It's an exciting result, with potential implications not only for black hole research but also for quantum computing and quantum matter, a field that studies how new states of matter with powerful properties can be created by controlling quantum states.

For Yoshida, it's an energizing demonstration of the interplay between deep theoretical research and experimental science.

"I have nice motivation to think about experimental observations which actually tie into very, very fundamental questions in quantum gravity," he says. "It's really nice that these kinds of deep, deep questions are actually connected to physical, experimental realizations. Both fields can motivate each other."

Reference:

K. A. Landsman (U. Maryland), C. Figgatt (U. Maryland), T. Schuster (UC Berkeley), N. M. Linke (U. Maryland), B. Yoshida (Perimeter Institute), N. Y. Yao (UC Berkeley), C. Monroe (U. Maryland), "Verified quantum information scrambling," *Nature* 567, pp. 61-65, 2019, arXiv:1806.02807.

# BLUEPRINTS FOR POWERFUL PHENOMENA

Physics is often a process of breaking things into smaller and smaller pieces to understand what makes it all tick. Timothy Hsieh works the other way.

By coming up with new combinations of nature's tiniest pieces, he seeks to create blueprints for novel materials and uncover phenomena that could be more powerful than the sum of their parts, thanks to the power of the quantum realm.

Hsieh works in condensed matter, specializing in phases of "quantum matter" whose physical behaviour is dictated by topology, which is the mathematical study of properties robust to twists and deformations. Hsieh's goal is to come up with arrangements and interactions of building blocks that produce new phenomena.

"It's like a quantum form of Legos, except you cannot really see the pieces," Hsieh explains. "You can be creative – that's key for me."

# EQUITY, DIVERSITY, AND INCLUSION

## CHANGING THE FACE OF RESEARCH

*"If we can set examples here about building an inclusive community, that could have real impact more generally and be that shining example that hopefully others would follow."*

*– Shohini Ghose, Perimeter Affiliate researcher and Equity, Diversity, and Inclusion Specialist*

Brilliance comes in many forms and from many perspectives. To solve the toughest problems in physics, we need all of the brightest minds. We're committed to breaking down systemic barriers to physics education and research and to providing a genuinely inclusive environment for all.

### PERIMETER INITIATIVES, 2018/19

- Participated in consultations on the Natural Sciences and Engineering Research Council (NSERC) Dimensions program and endorsed the new Dimensions Charter, a set of principles to promote equity, diversity, and inclusion across Canada's academic landscape.
- Appointed quantum physicist and Perimeter Affiliate researcher Shohini Ghose as Perimeter's first Equity, Diversity, and Inclusion Specialist.
- Formed the PI Inclusion Platform, an array of working groups comprising 60 students, scientists, and administrative staff. Each of the working groups focuses on areas of collective interest, such as mental health, LGBTQ+, and career advancement.
- In partnership with our private and public supporters, enabled talented high school students, undergraduates, graduate students, and teachers to participate in training programs at no cost, ensuring economic background is not a barrier to access.
- Consulted with Indigenous teachers in northern communities to better understand their needs and to help shape educational resources and delivery methods for the future.

### EMMY NOETHER INITIATIVES

Perimeter Institute aims to effect real change in the under-representation of women in theoretical physics through a series of special initiatives named after pioneering German mathematician Emmy Noether. The initiatives provide a continuous arc – outreach to high school girls, training for undergraduates and graduates, and career development for researchers up to the most senior levels – aiming to inspire and provide leadership.

### EMMY NOETHER COUNCIL

Council volunteers provide expertise, donations, and other support, helping bring more women into physics.

**Jennifer Scully-Lerner**, Co-Chair
Vice President, Goldman Sachs
Leadership Council Member, Perimeter Institute

**Sherry Shannon-Vanstone**, Co-Chair
President & CEO, S.V. Initiatives

**Julie Barker-Merz**
Regional President, Greater Toronto Area,
BMO Financial Group

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

**Michelle Osry**
Partner, Deloitte Canada (Vancouver)

**Laura Reinholz**
Director, BMO for Women, BMO Financial Group

**Vicki Saunders***
Founder, SheEO

**Sandra Wear**
Vice President, Marketing, ActiveState

*Term ended July 2019.

# SIMONS EMMY NOETHER FELLOWS PROGRAM

Timed to support women at a critical stage of their careers, these annual fellowships enable visiting scientists to spend up to a year in Perimeter's thriving, multidisciplinary community. The scientists gain a unique opportunity to pursue their work intensively, free of teaching and administrative duties, and develop new international peer networks.

Flexibility is a key feature of the program. Perimeter works with fellows to tailor their stays, arranging teaching buyouts with their home institutions and providing nearby accommodation and childcare if required. Simons Emmy Noether Fellows are invited to return as visitors in the three years after their fellowship term. The program is having a remarkable impact.

In 2018/19:

- Eleven fellows and visiting fellows spent a total of 818 days on research and collaboration at Perimeter Institute.
- As a result of their visits, fellows produced approximately 40 papers.
- Seven fellows delivered lectures at Perimeter, including a public lecture by Phiala Shanahan that has more than 55,000 views on YouTube.
- Fellows co-organized several conferences and workshops.
- During her time as a fellow, Christine Muschik prepared a successful $250,000 grant application to the Government of Canada's New Frontiers in Research Fund. Muschik became a Perimeter Associate Faculty member in June 2019.

*The Simons Emmy Noether Fellows program is supported by the Simons Foundation.*


*Phiala Shanahan*

*"I have begun several research projects in completely new directions, and established collaborations with people working in quite different fields."*

*– Phiala Shanahan,*
*Massachusetts Institute of Technology*
*2018/19 Simons Emmy Noether Fellow*

## 2018/19 SIMONS EMMY NOETHER FELLOWS

**Valentina Forini**, City University of London
**Ling-Yan (Janet) Hung**, Center for Quantum Control, Fudan University
**Karen Livesey**, University of Colorado – Colorado Springs
**Christine Muschik**, University of Waterloo
**Phiala Shanahan**, Massachusetts Institute of Technology
**Sherry Suyu**, Max Planck Institute for Astrophysics

# HONOURS, AWARDS, AND MAJOR GRANTS

- **Robert Myers**, Director of Perimeter Institute and BMO Financial Group Isaac Newton Chair, was honoured with the 2018 Distinguished Alumni Award from the University of Waterloo, presented by the Faculty of Science.
- **Neil Turok**, Director Emeritus of Perimeter and Mike and Ophelia Lazaridis Niels Bohr Chair, was named an Officer of the Order of Canada (Honorary), presented by the Governor General of Canada.
- **Neil Turok** also received the Docteur honoris causa from the Catholic University of Louvain.
- Faculty member **Jaume Gomis** was awarded this year's CAP-CRM Prize in Theoretical and Mathematical Physics for his contributions to string theory and strongly coupled gauge theories.
- Faculty member **Kendrick Smith**, the Daniel Family James Peebles Chair, was awarded the 2020 New Horizons in Physics Prize from the Breakthrough Prize Foundation.
- **Kendrick Smith** was co-awarded the Giuseppe and Vanna Cocconi Prize of the European Physical Society's High Energy and Particle Physics Division for his work on the Wilkinson Microwave Anisotropy Probe (WMAP) and Planck experiments.
- **Kendrick Smith** was also named a Canadian Institute for Advanced Research (CIFAR) Fellow in the Gravity and the Extreme Universe program.
- Faculty member **Pedro Vieira**, the Clay Riddell Paul Dirac Chair, was awarded the 2020 New Horizons in Physics Prize from the Breakthrough Prize Foundation.
- Associate Faculty member **Avery Broderick**, the Delaney Family John Archibald Wheeler Chair, was co-awarded the 2020 Breakthrough Prize as part of the Event Horizon Telescope (EHT) collaboration.
- **Avery Broderick** also received a Diamond Achievement Award from the National Science Foundation (shared with the EHT collaboration).
- Faculty member **Kevin Costello**, the Krembil William Rowan Hamilton Chair, was awarded the 2020 Leonard Eisenbud Prize for Mathematics and Physics from the American Mathematical Society.
- **Subir Sachdev**, the Cenovus Energy James Clerk Maxwell Chair (Visiting), and Distinguished Visiting Research Chairs **Dam Thanh Son** and **Xiao-Gang Wen**, were awarded the 2018 Dirac Medal and Prize from the International Centre for Theoretical Physics.
- Associate Faculty member **Matthew Johnson** was awarded a 2018 Buchalter Cosmology Prize.
- Postdoctoral researcher **Davide Racco** was awarded a 2018 Buchalter Cosmology Prize.
- Faculty member **Guifre Vidal** was named a CIFAR Fellow in the Quantum Information Science program.
- Associate Faculty member **Ben Webster** received a Golden Jubilee Research Excellence Award from the University of Waterloo Faculty of Mathematics.
- Postdoctoral researcher **Lena Funcke** was the recipient of the 2019 Dieter Rampacher Prize, awarded by the Max Planck Society.

In 2018/19 Perimeter scientists were awarded $2.4 million in new research grants from agencies including the Natural Sciences and Engineering Research Council, the Foundational Questions Institute, and CIFAR.

# PERIMETER RESEARCHERS WIN BREAKTHROUGH AND NEW HORIZONS PRIZES

The first-ever image of a black hole's event horizon made headlines around the world and earned the EHT collaboration many accolades, including the $3 million (USD) Breakthrough Prize in Fundamental Physics, one of the field's most prestigious prizes.

Avery Broderick, who holds the Delaney Family John Archibald Wheeler Chair and leads Perimeter's EHT Initiative, led theoretical work behind the now-iconic image and shared in the prize.

"We now stand at the beginning of an empirical era of black hole science that a decade ago would be considered science fiction. We look forward with enormous excitement to being part of the steady stream of transformative results over the next many years," Broderick said.

Other Perimeter researchers sharing in the prize are Associate Faculty member Ue-Li Pen; postdoctoral researcher Hung-Yi Pu; PhD student Paul Tiede; and associate PhD students Boris Georgiev, Britton Jeter, and Chunchong (Rufus) Ni.

Perimeter is one of 13 partner organizations in the EHT collaboration – and the only Canadian one.

This marks the second time that Perimeter researchers have been honoured with the $3 million (USD) Breakthrough Prize. Kendrick Smith, who holds the Daniel Family James Peebles Chair, shared in the 2018 prize.

Perimeter scientists also earned two of the three New Horizons in Physics Prizes, $100,000 (USD) awards that recognize early-career scientists making important progress on fundamental problems.

Smith and two colleagues were honoured "for the development of novel techniques to extract fundamental physics from astronomical data." Smith was a leading researcher in this year's landmark detections of an unprecedented number of fast radio bursts by Canada's CHIME telescope.

Pedro Vieira, who holds the Clay Riddell Paul Dirac Chair, and Visiting Fellow Simon Caron-Huot were recognized "for profound contributions to the understanding of quantum field theory." Vieira is blazing rich new conceptual paths to understanding the language that describes nature at its most fundamental level.

Perimeter researchers have now won seven New Horizons Prizes in the award's short history – more than any other institution in the world.


*EHT Initiative at Perimeter*


*Kendrick Smith*


*Pedro Vieira*

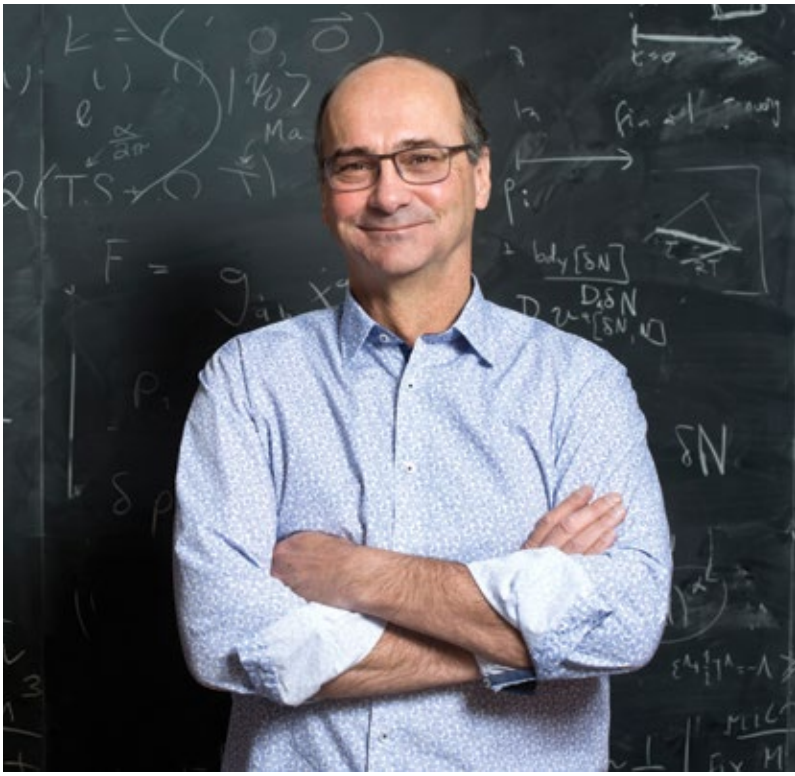
# RESEARCH COMMUNITY

## FACULTY

In 2018/19, Perimeter Institute appointed Robert Myers as its new Director and welcomed new Faculty member Chong Wang for a total of 24 faculty. We also welcomed three new associate faculty, who are jointly appointed with partner Canadian universities, bringing the total to 21 associate faculty cross-appointed with nine universities across Canada.

For a full list of faculty and associate faculty, including biographies, see pages 49-56.

## MYERS NAMED NEW DIRECTOR



Robert Myers, a theoretical physicist ranked among the world's most influential scientists, has been appointed the new Director of Perimeter Institute. Myers now also holds the BMO Financial Group Isaac Newton Chair.

Born in Deep River, Ontario, Myers was one of Perimeter's founding faculty members. He has long been recognized as one of the world's most influential scientists: in 2014, 2015, 2016, and 2017, he appeared on the Thomson Reuters/ Clarivate Analytics list of "Highly Cited Researchers," highlighting researchers whose citations rank in the top one percent of their fields.

His research focuses on foundational questions in quantum theory and gravity. 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.

Myers' appointment as Director follows Neil Turok's 10-year directorship. Turok remains at Perimeter as Director Emeritus and a full-time researcher leading the Institute's cosmology research hub, the Centre for the Universe at Perimeter Institute, and holds the Mike and Ophelia Lazaridis Niels Bohr Chair.

PEOPLE

Faculty

### CHONG WANG

Condensed matter and many-body quantum physics encompass some of the strangest phenomena in some of nature's most complex systems.

Traditionally, scientists figure out how a complex system works by calculating one small part and extrapolating across the whole. That doesn't work for the systems Chong Wang studies.

Wang probes some of the stranger regimes in many-body quantum physics – such as quantum spin liquids, topological insulators, quantum Hall effects, and quantum phase transitions – and their connections to modern aspects of quantum field theory.

Unlocking those puzzles is a challenge, but it's also a huge opportunity. "It's a complicated, messy problem, but very often at the end, a very beautiful picture emerges," Wang says. "It's a miracle that simplicity can ever emerge from something so complex."

## NEW ASSOCIATE FACULTY

PEOPLE

Associate Faculty

### DEBBIE LEUNG

Debbie Leung studies the fundamental properties of quantum information, including properties of entanglement; non-local games; methods for communicating quantum, classical, or private classical data; properties and applications of quantum error correcting codes; and how privacy arises in quantum mechanics. She also has a keen interest in understanding quantum theory in the context of black hole dynamics, or other potential non-linearities, such as closed time-like curves. Leung is cross-appointed with the Department of Combinatorics and Optimization and the Institute for Quantum Computing (IQC) at the University of Waterloo.

PEOPLE

Associate Faculty

### CHRISTINE MUSCHIK

Christine Muschik works on developing novel methods for quantum information processing and on quantum simulations of problems from high energy physics, seeking to understand the fundamental building blocks of nature. At Perimeter, she will draw together experts from many fields to develop new quantum simulation methods that can address many open questions in physics: Why is there more matter than antimatter? What happens inside neutron stars? What exactly happened during the big bang? Muschik is cross-appointed with the IQC at the University of Waterloo, where she leads the quantum optics theory group.

PEOPLE

Associate Faculty

### DANIEL SIEGEL

Daniel Siegel looks at the tiny inside the huge: he uses supercomputers to simulate violent cosmic events, like the collision of two neutron stars, paying particular attention to subatomic processes. Modelling the particle physics inside astrophysics gives Siegel new insight into how the universe is assembled. For instance, this year Siegel and collaborators proposed that most of the gold in the universe comes not from neutron star mergers, as previously thought, but from whirling, dying stars called collapsars. The research was published in the journal *Nature*. Siegel is cross-appointed with the University of Guelph.

## PERIMETER RESEARCH CHAIRS

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

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

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

**Asimina Arvanitaki**
Stavros Niarchos Foundation Aristarchus Chair in Theoretical Physics

**Avery Broderick**
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**
Coril Holdings Archimedes Chair in Theoretical Physics (Visiting)

**Davide Gaiotto**
Krembil Galileo Galilei Chair in Theoretical Physics

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

**Kendrick Smith**
Daniel Family James Peebles Chair in Theoretical Physics

**Pedro Vieira**
Clay Riddell Paul Dirac Chair in Theoretical Physics

## 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 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 2018/19, DVRCs spent 201 days at the Institute. In addition, five new DVRCs were appointed and six more were renewed, bringing the total to 44.

This year's new appointees are:

**Mina Aganagic**, University of California, Berkeley

**Gian Francesco Giudice**, European Organization for Nuclear Research (CERN)

**David B. Kaplan**, University of Washington

**Carlo Rovelli**, Université de la Méditerranée – Centre de physique théorique de Luminy

**Subir Sachdev**, Harvard University

*The Distinguished Visiting Research Chair program is supported by Cenovus Energy.*

*"I've known the Institute from the very beginning, and I saw it grow up very quickly, with a fantastic reputation. Many of my colleagues don't consider themselves really up-to-date if they haven't visited this Institute many times."*

*– Gerard 't Hooft, Perimeter Distinguished Visiting Research Chair and 1999 Nobel Laureate*

## 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 many ways.

**Visiting Fellows** are appointed to renewable terms, retain their positions at home institutions, and enrich the Perimeter research community during their extended stays. This year, eight new Visiting Fellows were appointed and four others were renewed, for a total of 51.

**Affiliate members** are scientists from Canadian universities who have an open invitation to visit Perimeter at any time to do research. This year, 34 Affiliate members were appointed or renewed, bringing the total to 113.

We also encourage applications from scientists to come as **Visiting Researchers** while on sabbatical leave from their faculty positions at home institutes. In 2018/19, 15 Visiting Researchers visited for a total of 2,475 research days.

PI PEOPLE

Visiting Researcher

### OLIVER SCHLOTTERER

Oliver Schlotterer, a postdoctoral fellow at the Max Planck Institute for Gravitational Physics in Germany, came to Perimeter for a very, very full year.

During his time at the Institute, he undertook a wide-ranging collaboration with Freddy Cachazo, who holds the Gluskin Sheff / Onex Freeman Dyson Chair at Perimeter. They brought diverse points of view to bear on an important subject in high energy physics called scattering amplitudes. Scattering amplitudes are the calculated predictions of how particles will behave in high energy interactions, and they are crucial to understanding what matter is composed of, and how it behaves.

Alongside his research, Schlotterer supervised two master's students, organized a workshop, and taught courses. Now with a prestigious European Research Council grant in hand to start a research group at Uppsala University, he plans to return the favour, building a research bridge to Perimeter – and of course, inviting Cachazo for research visits.

*"Perimeter is a dream that came true, a place of genius and inspiration. It is hard to imagine a better place to study, to do research, and to be inspired and transformed for a young scientist interested in fundamental questions."*

*– Valerio Faraoni, Professor at Bishop's University and Perimeter Affiliate member*

# CONFERENCES AND WORKSHOPS

In theoretical physics, advances are happening fast on many fronts. Collaboration and communication are essential to this effort. The Institute plays a key role in catalyzing rapid research progress with can't-miss workshops and conferences attended by scientists from around the world. Conferences and seminars are recorded and made freely available online to the scientific community.

In 2018/19, 620 scientists from around the world attended 11 conferences and workshops at Perimeter, in areas such as cosmology, machine learning, mathematical physics, and quantum field theory.

## CREATING A RESEARCH COMMUNITY BY THE BOOTSTRAP

Tables are set up, chalkboards scribbled on, ideas exchanged. New collaborations form on the spot. Perimeter's usually quiet atrium is transformed into the hub of an entire research field during the Bootstrap 2019 conference, attended by over 200 researchers from around the world.

"We like to see ideas unvarnished," says Perimeter Faculty member and conference co-organizer Pedro Vieira, encouraging blackboard talks over slides.

It's hard to believe that 10 years ago, this entire research community didn't exist.

Vieira and João Penedones (then a Perimeter postdoctoral researcher) organized the first bootstrap conference at Perimeter in 2011. It was small: three days long, with about 20 participants.

Things took off from there: there are now hundreds of researchers around the world pursuing "bootstraps" in areas ranging from condensed matter to particle physics and quantum gravity. Dozens of important papers a year are produced.

"I think it's fair to say this community was created here in that first meeting," says Vieira. "Many important projects started here."

*Pedro Vieira is the Clay Riddell Paul Dirac Chair in Theoretical Physics.*

# SEMINARS AND COLLOQUIA

Constant learning, cross-disciplinary exploration, and open collaboration are the hallmarks of our research community. Throughout the year, scientists, students, and visitors are invited to take part in seminars and colloquia that feed the mind and spark new ways to approach problems. Seminars and colloquia are recorded and made publicly available on the Perimeter Institute Recorded Seminar Archive (PIRSA).

In 2018/19, 315 seminars and colloquia were presented, featuring speakers from outstanding institutions such as Harvard, Kyoto University, Max Planck Institute, MIT, NASA Jet Propulsion Lab, Oxford, Princeton, and Yale.

## FROM PIRSA TO PERIMETER

Ten years ago, Vasudev Shyam was a bored and underperforming student in a Bangalore school. Then 13, he found the course material unchallenging, but he didn't have access to India's upper echelon of schools.

Curious about physics, he happened upon PIRSA, an online repository of more than 10,000 Perimeter lectures and lessons. He started with public lectures, then worked his way to more complex seminars and colloquia. Before long he was working out problems on his own, and even conducting independent research.

He contacted Perimeter, shared his work, and was admitted to the Perimeter Scholars International master's program at age 18.

Now 23, Shyam is completing his PhD at Perimeter. He has published nine papers to date (five of them single authored) and is well on his way to a bright research career.

With 12,438 talks (as of July 31, 2019), PIRSA is the largest video archive in theoretical physics worldwide. It is an indispensable resource for physicists around the world, from students to senior scientists – and who knows how many untapped talents like Shyam, driven by curiosity and a thirst for knowledge. Perimeter strives to give all brilliant minds – regardless of their geographic, economic, or cultural backgrounds – access to excellence. As a free, global resource, PIRSA is a powerful tool in that mission.

*Vasudev Shyam and William Donnelly*

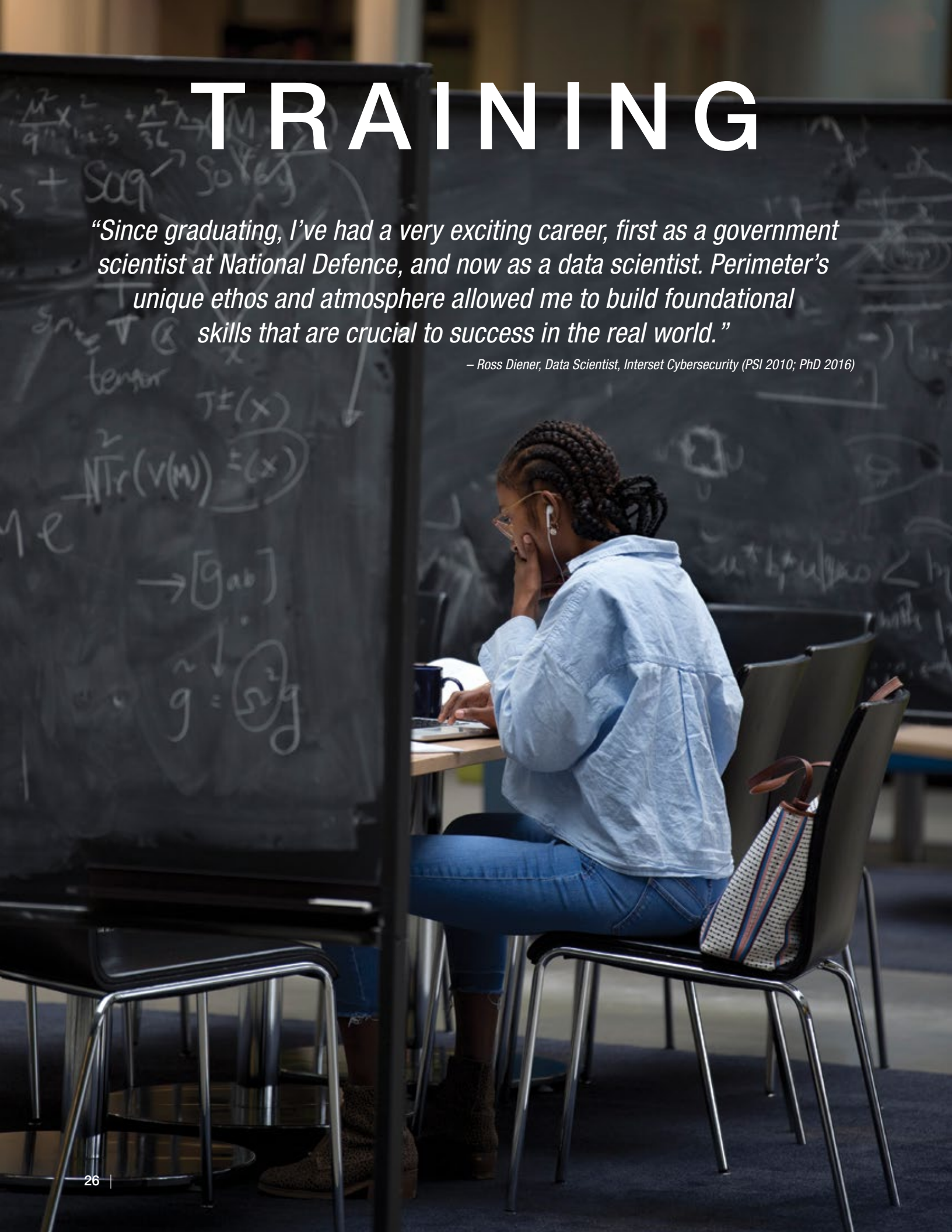
*"Sitting at my computer in Bangalore, I opened a portal to Perimeter that changed my life."*

*– Vasudev Shyam, PhD student*

# TRAINING

*"Since graduating, I've had a very exciting career, first as a government scientist at National Defence, and now as a data scientist. Perimeter's unique ethos and atmosphere allowed me to build foundational skills that are crucial to success in the real world."*

*– Ross Diener, Data Scientist, Interset Cybersecurity (PSI 2010; PhD 2016)*



# **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 brand-new undergraduate enrichment program to our world-leading postdoctoral program – that aim to turn students into scientists.

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

**63** Postdoctoral researchers (as of July 31, 2019)

**58** PhD students from **28** countries (in 2018/19)

**25** Associate PhD students (in 2018/19)

**46** Visiting Graduate Fellows (in 2018/19)

**310** PSI graduates in 10 years, including **97** women (31 percent)

**33** PSI master's students, including **10** women (in 2018/19)

**23** undergraduate summer school students (in 2018/19)

**4** Vanier Canada Graduate Scholarships (in 2018/19)

**1** NSERC Gilles Brassard Doctoral Prize for Interdisciplinary Research (in 2018/19)

**120** attended Career Trajectories conference

## POSTDOCTORAL RESEARCHERS

As full members of Perimeter's community for three to five years, these early-career scientists have unique opportunities: complete research freedom, encouragement to do ambitious work, and mentorship from senior scientists. This autonomy and experience pays off: in 2018/19, two have been hired as data scientists – one with Xanadu, a quantum computing start-up in Toronto, and one with a large, fast-growing international company – and others took up academic careers, research positions, and prestigious fellowships. The postdoctoral positions are highly sought after: from 673 applications, 19 new postdocs joined us at Perimeter in 2018/19.

## VISITING GRADUATE FELLOWS

Perimeter offers senior PhD students a unique opportunity to expand their perspectives and participate fully in the Institute's research community. In 2018/19, 46 graduate fellows from 20 countries visited, from short visits to stays up to almost one year, with the average visit lasting five months.

PI PEOPLE

Postdoctoral Researcher

### BÉATRICE BONGA

Postdoctoral researcher Béatrice Bonga describes herself as passionate about general relativity. Among other things, Bonga models the kinds of astrophysical systems that might produce gravitational waves, with an eye toward helping the next generation of gravitational wave detectors sharpen their observations. With collaborators, she recently discovered surprising tidal resonances that can arise in systems where two small black holes orbit one supermassive black hole.

Perimeter has been the perfect place to pursue this challenging work, she says. "Here, I'm surrounded by top researchers in numerical physics, in general relativity. There are lots of visitors. There is new information coming in from the astronomy and cosmology researchers. People are excited, people are optimistic."

Bonga completes her postdoctoral fellowship at Perimeter in 2019 and will take up a new faculty position in 2020.

## PHD STUDENTS

The Perimeter Scholars International (PSI) master's program attracts exceptional international students, and Perimeter keeps them. Sixty-five percent of Perimeter's PhD students this year were graduates of the PSI program. That means they're recruited by Perimeter supervisors and are continuing their education and research in Canada.

PhD students receive their degree from the partnering university where their supervisor has a full or adjunct appointment. These include the University of Waterloo, the University of Guelph, the University of Toronto, York University, McMaster University, and Western University.

At year's end, Perimeter had 58 PhD students from 28 countries, with an additional 25 associate PhD students supervised by Perimeter faculty and associate faculty at partner universities.

*In 2018/19, two PhD students were the recipients of the Peter and Shelagh Godsoe Family Foundation Exceptional Emerging Talent Awards. In addition, one student was the recipient of the Joanne Cuthbertson and Charlie Fischer Graduate Student Award.*

PI PEOPLE

PhD Student

### ANNA GOLUBEVA

PhD student Anna Golubeva's research combines physics and machine learning. Working with her supervisor Roger Melko's group at the University of Waterloo and the Perimeter Institute Quantum Intelligence Lab, she says, "We're using physics to develop machine learning, and we use machine learning to solve problems in physics."

It's a powerful combination, and Golubeva's research has attracted accolades. This year, Golubeva received the prestigious NSERC Gilles Brassard Doctoral Prize for Interdisciplinary Research, awarded annually to an outstanding Vanier Canada Graduate Scholar whose work crosses traditional boundaries.

Golubeva is confident that interdisciplinary work is the key to unlocking some of the universe's best kept secrets. "Nature is not split into subfields of biology, physics, mathematics – it's all one. Our understanding of nature can be advanced when we step over the boundaries."

## VANIER CANADA GRADUATE SCHOLARS


Anna Golubeva


Florian Hopfmueller


Fiona McCarthy


David Schmid

Four PhD students at Perimeter Institute and the University of Waterloo have received prestigious Vanier Canada Graduate Scholarships. Anna Golubeva, Florian Hopfmueller, Fiona McCarthy, and David Schmid will each receive $50,000 per year for three years during their doctoral studies. Vanier Scholarships, funded by the Government of Canada, are designed to help Canadian institutions attract highly talented doctoral students. Scholars are chosen on the basis of academic excellence, research potential, and leadership qualities.

# PERIMETER SCHOLARS INTERNATIONAL

Ten years ago, PSI was born out of a desire to rethink graduate education in physics. The master's level program aimed to turn students into scientists, equipping them to confront very hard problems independently and creatively.

The formula is simple, yet powerful: recruit outstanding students from around the world; be deliberate in selecting for diversity; offer short courses taught by world-class physicists; and place a focus on cooperation over competition. Courses provide grounding in a broad swath of modern theoretical physics.

The 10-month program introduces students to research across theoretical physics, equipping them with the tools, skills, and mindsets needed to succeed in physics – or indeed in many fields. On completion, students earn their Master of Science degree in Physics from the University of Waterloo, and a Perimeter Scholars International certificate.

Ten years on, more than 300 PSIons, as they're called, have been trained at Perimeter. Some have gone on to pursue doctorates, postdocs, and research careers. Some have founded companies. Others are working on treatments for cancer, or in finance and tech. All of them carry the PSI spirit with them.

In 2018/19, 33 brilliant young people from across Canada and 22 other countries, including 10 women, were selected from 512 applicants. Twenty-five are now doing doctoral studies at prestigious institutions, including 11 at the University of Waterloo, as well as at the Max Planck Institute, MIT, Princeton, and Stanford, while others have gone on to careers in the private sector.

See the full list of PSI faculty and students on pages 58-59.

*The PSI program was supported in 2018/19 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.*

# PSI TURNS 10

"It's still really up there on the list of the most extraordinary things I've ever done," says Imogen Wright of her experience at PSI.

That's saying a lot for someone with two PhDs who went on to work in software development for Amazon and then co-founded a bioinformatics company. Wright was valedictorian of the first PSI graduating class, back in 2010.

Wright's company, Hyrax Biosciences, based in Cape Town, South Africa, is making major advances in one of the most pressing health issues in sub-Saharan Africa: using genetics and statistical analysis to predict drug resistance for people with HIV.

She credits PSI with enhancing key skills that she still uses today.

"I draw massively on the method of abstract thinking that doing a lot of theoretical physics teaches you," she says. "If the average computer scientist can go to three or four levels of abstraction from whatever the underlying data is that they're looking at, by the end of PSI, I could go to seven or eight."

# UNDERGRADUATE SUMMER ACCELERATOR

In May 2019, 23 science undergrads from across Canada and around the world stepped up to the chalkboards at Perimeter as part of the inaugural Undergraduate Theoretical Physics Summer Program.

Over two intense weeks, students learned from leading scientists and worked together to grapple with real research problems. Fourteen stayed through the summer to do research projects with Perimeter scientists, and one is staying for the master's program.

"This is a really good program to learn about what you're interested in and to get hands-on experience," said Anya Forestell, a 22-year-old from Fredericton, New Brunswick, who is currently studying physics and astronomy at the University of Waterloo. "There's such a diversity of physics going on here."

Gebremedhin Dagnew, 23, is a student at Middlebury College in Vermont. He said his time at Perimeter broadened his knowledge within the field and made his path clear.

"It's a validation for myself that I do want to pursue research and that I want to continue my graduate studies in physics."

*The Undergraduate Theoretical Physics Summer Program was made possible by the support of Michael Serbinis and Laura Adams.*

# SITTING ON A GOLD MINE

What can you do with an advanced degree in theoretical physics? As it turns out, almost anything.

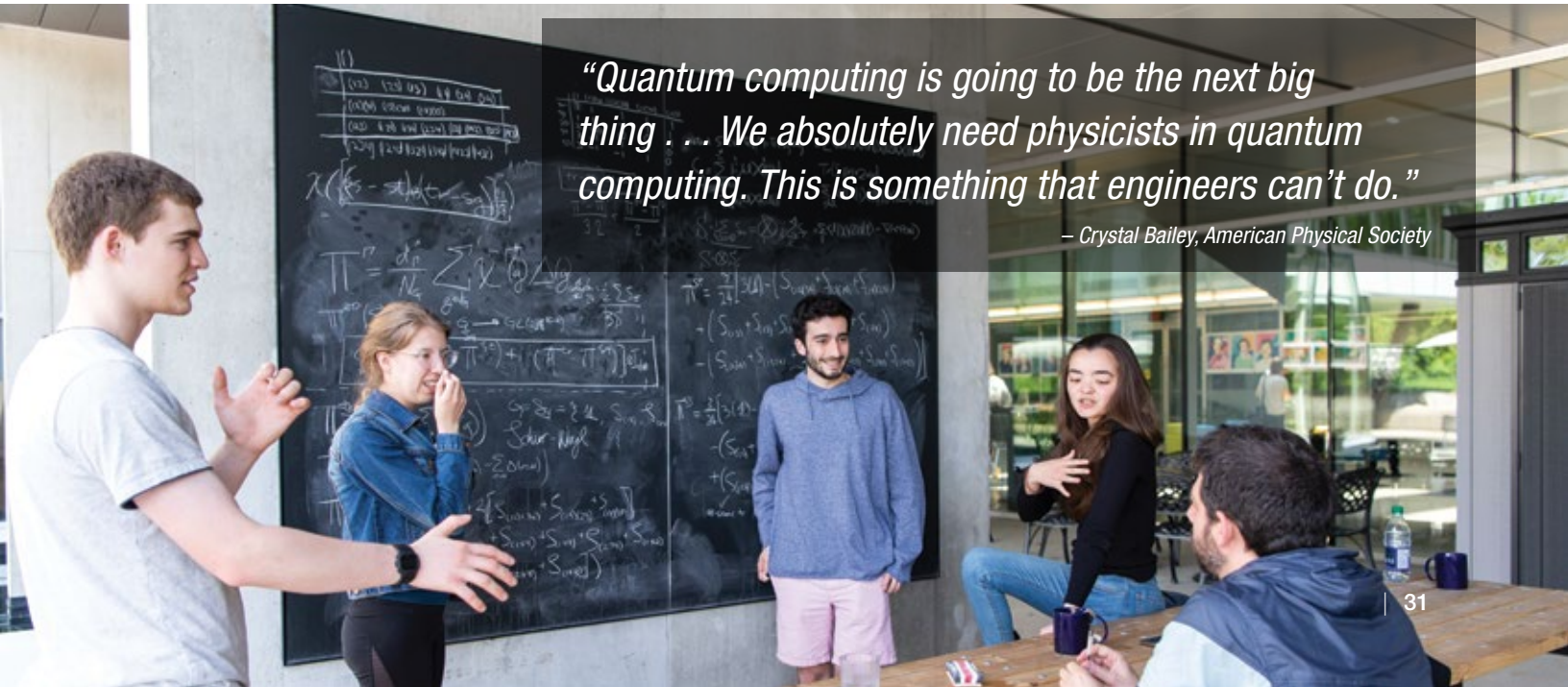
That's the point of Perimeter's annual Career Trajectories conference, which encourages graduate students and postdoctoral researchers to consider all possible career paths – whether in academia or beyond – and to think deeply about how best to make contributions to the world. Physics training can seed society with critical thinkers and problem solvers who bring these skills to a variety of fields.

"Physics students are sitting on a gold mine, and some of them don't know it. We have the skills to solve big problems," said Natacha Altamirano, a Perimeter alum who earned a PhD in cosmology and is now a data scientist working in venture capital.

This year's conference attracted 120 attendees from Perimeter Institute and eight other Ontario universities and institutions, as well as representatives from Canadian businesses such as Sun Life, Shopify, D-Wave Systems, and OpenText.

## A DEGREE IN THEORETICAL PHYSICS CAN LEAD TO CAREERS IN:

- quantum computing
- machine learning
- finance and insurance
- data science
- advanced manufacturing
- precision medicine
- pharmaceutical research
- government and public policy
- science communications



*"Quantum computing is going to be the next big thing . . . We absolutely need physicists in quantum computing. This is something that engineers can't do."*

*– Crystal Bailey, American Physical Society*

# OUTREACH

*"What I've learned about physics will improve my classroom content. What I've learned about learning will revolutionize it."*

*– Teacher Jeremy Wegner*

# 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.

## STUDENTS

**52,189,800** interactions in classrooms since 2006

**10,972,000** interactions in classrooms in 2018/19

**13,396** students attended presentations in 2018/19

**174** high school students attended Inspiring Future Women in Science 2019

**40** exceptional high school students – 16 from Canada, 24 international – attended the 2019 International Summer School for Young Physicists

## TEACHERS

**31,181** teachers reached globally by Perimeter's Teacher Network

**5,132** teachers trained at **153** workshops in 2018/19

**36** teachers attended EinsteinPlus teacher training camp in 2018/19

**106** countries in which Perimeter educational resources have been used

**107** in-class science resources available to teachers across Canada and around the world

**22** resources translated into French

## SCIENCE FOR THE WORLD

**9** public lectures were viewed **546,825** times in 2018/19

**2.5** million YouTube views in 2018/19 – a 77 percent increase this year

**7.1** million YouTube views since 2009

# EINSTEINPLUS AND TEACHER NETWORK

How do you become a spectacular physics educator? For Katemari Rosa, it started with the one-week intensive camp that brings science to life for teachers.

"I had an amazing experience at PI and still talk about it to my students and to teachers. I always encourage people to check out (and use!) PI resources, as well as to attend the workshops," she says.

EinsteinPlus is all about exponential growth. Every teacher goes home ready to bring modern physics to classrooms that might have 25 kids apiece. Every teacher trained as a peer educator can train dozens of other teachers. Every package of education resources sent to a school can reach multiple classrooms full of students, year over year.

It's a powerful equation. Perimeter has been teaching and training teachers for a decade and, in that time, has seen the number of students reached grow from thousands, to tens of thousands, to millions.

Rosa went on to earn a PhD in Science Education at Columbia University, then returned to Brazil where she works at the

Federal University of Bahia, coordinating a program that builds partnerships at public schools.

*EinsteinPlus was supported by Maplesoft.*

# EDUCATIONAL RESOURCES

From Prince Edward Island to Nunavut to British Columbia, Perimeter's educational resources have been used across Canada and in more than 100 countries around the world. Digital resources designed to help teachers explain a range of important physics topics – and science more broadly – are available for Grades 5-12. Each resource includes lesson plans, hands-on activities and demonstrations, background information for teachers, and original Perimeter videos. Best of all for teachers, the resources are directly connected to science curricula.

New resources developed in 2018/19 include Grade 12 Contemporary Physics and Grade 12 Fields, both available in French and English. Perimeter also developed a lesson plan to provide context around the exciting news of the world's first black hole image: Understanding the Image of M87. Over 100,000 students have worked with the resource in their classrooms, discovering the rich science behind black holes and the iconic image. Eight resources have been translated into Portuguese and are currently being used in workshops and classrooms in Brazil.

# AT HOME AND AWAY

Hands-on demonstrations make physics fun and accessible. That's why Perimeter hit the road, visiting communities across Ontario with the Power of Ideas exhibit, a multimedia experience that showcases the six most powerful ideas in physics history and their transformative effect on our world.

The Outreach team, along with special guests, also delivers interactive, engaging Physica Phantastica and other specialty presentations to school groups in Perimeter's 200-seat Mike Lazaridis Theatre of Ideas.

In 2018/19, almost 27,000 students, teachers, and members of the public attended these educational events.

*The Power of Ideas was supported by the Ontario Ministry of Education.*

*"Now more than ever, the work of institutes such as Perimeter is vitally important to the things that make us responsible, engaged citizens of the world, and of Canada."*

***– Alison Peden, Perimeter supporter***


# INTERNATIONAL SUMMER SCHOOL FOR YOUNG PHYSICISTS

Each summer, the International Summer School for Young Physicists (ISSYP) plunges 40 exceptional high school students from across Canada and around the world into the deep end of theoretical physics. They also find themselves surrounded by peers who share their passion for science, often for the first time in their lives.

"It's like you're seeing copies of yourself," says Vennisa Owusu-Barfi, from Accra, Ghana. "Because you hadn't ever met any person like you, you'd think, 'Oh, you're one in a billion.' But then you come here and you see that other people, too, are very similar to you."

This year's cohort, which was gender balanced, included 16 from Canada, representing eight provinces, and 24 students from countries including Brazil, Ethiopia, Romania, Switzerland, Turkey, the UK, and the US.

These exceptional students attended lectures on topics including quantum mechanics, relativity, and cosmology, then broke off into group sessions to tackle research topics with a mentor. They had the opportunity to connect with world-class researchers and even visited the Sudbury Neutrino Observatory, located deep underground in a working nickel mine.

Taylor Walters, from Milly Bay, British Columbia, recalls discussions with Perimeter researchers that opened her eyes to the possibilities of interdisciplinary exploration that could encompass her interests in physics, cognitive science, and computer science.

"Finding my own intersection of my passions is really what's going to drive me forward," she said.

*The 2018/19 session of ISSYP was made possible by the support of the RBC Foundation, the Presenting Partner. Additional support was provided by Maplesoft.*

# INSPIRING FUTURE WOMEN IN SCIENCE

Science suffers from an image problem: students who love the subject often have no idea just how many career paths it opens up.

The 2019 Inspiring Future Women in Science conference helped lay down breadcrumbs on that path for 174 young women in high school. The annual conference is an opportunity to break down stereotypes about who, exactly, can be a STEM professional, and this year featured presentations from a photonics researcher, a doctor, the CEO of an environmental science company, a forensic pathologist, and more.

*The 2019 Inspiring Future Women in Science conference was made possible by the support of Linamar Corporation, the Presenting Sponsor.*

# SCIENCE COMMUNICATION AND MEDIA

Science is about more than technological progress and the prosperity it creates. It teaches critical thinking, rewards intellectual bravery, and celebrates pure curiosity.

Perimeter is a trusted source of scientific content for curious minds across Canada and around the world. Through its websites, *Inside the Perimeter* magazine, social media channels, and partnerships, the Institute continues to be a leading source of accurate and engaging physics content.

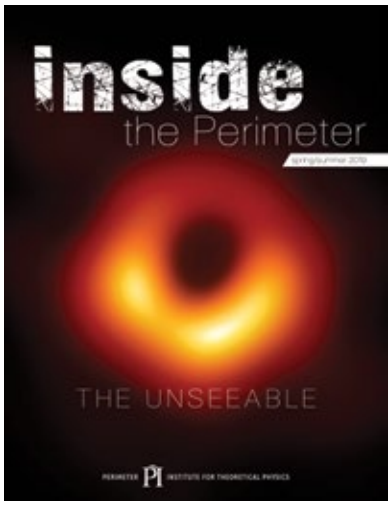
Across all channels, we see a growing appetite for high-quality science content. Last year, our YouTube channel had over 2.5 million video views, and subscribers jumped 50 percent. Our online home for accessible and shareable science content, insidetheperimeter.ca, had nearly half a million views and over 200,000 unique visitors.

We try to meet people where they are: on social media. This year, Perimeter's LinkedIn followers jumped by 24 percent, while Twitter followers increased by 14 percent and the Perimeter Facebook account grew to a following of more than 30,000.

The first-ever image of a black hole was front-page news in hundreds of media outlets all over the world. As the only Canadian partner organization in the Event Horizon Telescope collaboration, Perimeter received widespread front-page media coverage in outlets including the *New York Times* and the *Washington Post*. Our original video content, including explanatory videos and a panel discussion, quickly garnered 500,000+ views on YouTube.

## AWARD-WINNING SCIENCE COMMUNICATION AND OUTREACH

- *Inside the Perimeter*, our semi-annual print magazine, took home a silver Prix d'Excellence from the Canadian Council for the Advancement of Education (CCAE) in the Best Print Magazine category.
- QuantumToCosmos.ca earned a bronze Prix d'Excellence from the CCAE. Launched in 2018, this interactive website takes viewers on a journey through all scales of the universe and has over 1 million page views so far.





## TOP 10 NEWS STORIES

- "Darkness visible, finally: Astronomers capture first ever image of a black hole"
  *The New York Times*
  April 10, 2019
- "This is what a black hole looks like: Researchers photograph an abyss larger than our solar system"
  *The Globe and Mail*
  April 10, 2019
- "A second mysterious repeating fast radio burst has been detected in space"
  CNN
  January 10, 2019
- "Perimeter Institute for Theoretical Physics appoints new director"
  *The Globe and Mail*
  March 1, 2019
- "The physics of Kawhi Leonard's game-winning shot"
  CBC's *The National*
  May 13, 2019
- "In Einstein's Unfinished Revolution, author Lee Smolin argues it's time for realism to reassert itself at the core of physics"
  *The Globe and Mail*
  June 14, 2019
- "How Canadian astronomy made the black hole photo possible"
  CBC's *Quirks & Quarks*
  April 12, 2019
- "Robert Myers named as new director of the Perimeter Institute for Theoretical Physics"
  *Physics World*
  February 28, 2019
- "The secret of dark matter could be a particle the size of a planet"
  *New Scientist*
  May 29, 2019
- "Perimeter Public Lecture: A pioneering female physicist on discovering a new kind of star"
  *Maclean's*
  October 24, 2018


*Jocelyn Bell Burnell*

# PUBLIC LECTURES

*"The Public Lecture Series provides an opportunity for me, a general member of the public, to be engaged in the science of today, expanding my knowledge and awareness of the world around us."*

*– Public Lecture attendee*

With riveting talks spanning the scientific gamut, from the discovery of pulsars to taking pictures of black holes, Perimeter's flagship Public Lecture Series continued to inspire and inform.

This year's nine talks were presented to full-house crowds and growing online audiences around the world. More than 78,000 people tuned in to watch livestreams, and the 2018/19 talks have been viewed more than 546,000 times.

These lectures make a difference: 97 percent of survey respondents say the lectures inspire them to learn more. "I want to thank Perimeter for what I have learned from your public lectures and outreach, and for inspiring my kids," said one survey respondent, whose children went on to post-secondary education in computer science and nanotechnology engineering.

*BMO for Women was the Supporting Partner of the four public lectures delivered by women in 2018/19.*

# CULTURAL EVENTS

Cultural events at Perimeter refresh the mind and spark the imagination – for our resident scientists and for the surrounding community.

The 2018/19 Classical World Artists series included captivating performances by violinist Leila Josefowicz and pianist John Novacek, cellist Jonathan Roozeman, pianist David Fray, and vocal ensemble Schola Antiqua of Chicago. Perimeter also hosted installations and performances by artists such as Canadian musician Ron Sexsmith and Italian puppeteer Massimo Shuster.

*The Classical World Artists series is supported by the Kitchener Waterloo Community Foundation – Musagetes Fund.*

*Leila Josefowicz*

# ADVANCING PERIMETER'S MISSION

*"It was Perimeter's world-acclaimed position in the pantheon of physics that first got my attention. I learned about their approach as an incubator of innovation and their mission to unlock the secrets of the universe in benefit of humankind. That captured my imagination. But it was the creation of the Emmy Noether Emerging Talent Fund – a program ensuring the advancement of women and youth in physics – that won my heart and unwavering support."*

*– Anne-Marie Canning, Toronto philanthropist and supporter of the Emmy Noether Emerging Talent Fund*

Perimeter is supported by the Government of Canada and the Government of Ontario, as well as a growing group of international private sector donors. Together, we aim to build the world's best theoretical physics institute.

Our government and private sector partners understand that theoretical physics is a low-cost, high-impact investment in science, technology, and the future. Breakthroughs in theoretical physics can revolutionize society – from quantum computing and machine learning to precision medicine and pharmaceutical research.

In 2018/19, Perimeter was in the second year of a five-year, $50 million funding agreement with the Government of Ontario and the Government of Canada. These investments continue 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.

In 2018/19, individual, corporate, and foundation donors committed $21 million, including multi-year commitments from the Riddell Family Charitable Foundation, the Krembil Foundation, and Gluskin Sheff + Associates. Friends of Perimeter Institute, the Institute's US-based 501(c)(3), is developing an upward trend in its second year since receiving public charitable status, and has potential for steady growth in the coming years. This brings our $100 million private sector campaign to a total of $52 million.

Perimeter Institute's visionary funding model is a major reason for its success to date, uniting public and private sector partners to share the opportunities, benefits, and responsibilities for long-term investment in fundamental research. Perimeter is now ranked among the top theoretical physics institutes in the world during one of the most exciting periods in the field's history.

## SUPPORTING THE VISION

Perimeter Institute recognizes and thanks the following donors 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 have helped put our $100 million private sector campaign over the halfway mark, with $52 million in commitments so far.

Anonymous (1)
BMO Financial Group
Gary Brown
Anne-Marie Canning
Cenovus Energy
Coril Holdings Ltd.
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.
The Peter and Shelagh Godsoe Family Foundation
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Mac Van Wielingen, Viewpoint Foundation

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Chancellor Emerita of the University of Calgary

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**Trevin Stratton**
Chief Economist, Canadian Chamber of Commerce

**Alfredo Tan**
Chief Digital & Innovation Officer, WestJet

## A MOMENT TO REMEMBER

In the middle of a busy work day, Ian Delaney put a business call on hold – not a common occurrence. But the Event Horizon Telescope (EHT) collaboration was about to make a big announcement, and he didn't want to miss it.

Delaney is chairman of both Westaim Corporation and the Ontario Air Ambulance Services Co., and for the last two years, the Delaney Family Foundation has supported Avery Broderick's research through the Delaney Family John Archibald Wheeler Chair in Theoretical Physics. Catherine (Kiki) Delaney, Ian's wife, has also been a member of Perimeter's Leadership Council since 2010.

As the EHT revealed the first-ever image of a black hole to the world that day, Broderick was one of the EHT's leaders on the podium, describing his team's role in the landmark achievement to the world's assembled media.

It was an inspiring moment. "It's yet another confirmatory piece of why and how Perimeter works. It's a terrific model for Canada," Delaney said. He's optimistic that the image – an incredible scientific achievement in its own right – will also be a launchpad for future breakthroughs.

"My family are great believers in the concept of Perimeter Institute. It's leading edge. Canada's contribution here is dramatic."

*Avery Broderick, Catherine Delaney, and Ian Delaney*

# 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

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)

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

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

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

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

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

*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, supporter of EinsteinPlus and Perimeter's Teacher Network

RBC Financial Group, Presenting Partner, International Summer School for Young Physicists

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

## ACCELERATORS CIRCLE ($50,000+)

The Cowan Foundation

Robert and Pearl Radnitz**

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+**

Bosch Community Fund, on behalf of ESCRYPT in Canada

Robin and Robert Ogilvie

Toyota Motor Manufacturing Canada (TMMC)

**$10,000+**

Denise and Terry Avchen, Environmental Research Advocates

The Boardwalk

Mary and Ted Brough

Kitchener Waterloo Community Foundation
- McMurtry Family Fund
- The Musagetes Fund
- Pollock Family Fund

Ottawa Community Foundation

Donald and Eleanor Seaman Family Foundation

Brian Sullivan

The TRH Foundation

Alex White

## FRIENDS (UP TO $9,999)

**$5,000+**

Jerome Bolce

Savvas Chamberlain Family Foundation

Harbir and Monica Chhina

Michael Duschenes

Renée Schingh and Robert Myers

…plus one anonymous donor

**$2,500+**

Don Campbell

Goldman Sachs**

Michael Horgan

Robert Korthals and Janet Charlton

John Matlock

Jennifer Scully-Lerner**

**$1,000+**

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Nancy Wong

John Yee

… plus 15 anonymous donors

149 donors have contributed gifts less than $250.

## GIFTS OF CELEBRATION, HONOUR, AND MEMORY

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

## 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.*

**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

Dr. Scott and Sherry Vanstone and family

**$25,000+**

Andrew and Lillian Bass

BMO for Women

Patrice E. Merrin

**$10,000+**

Burgundy Asset Management Ltd.

Jane Kinney and Christian Bode

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Heather and John Clark

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Laura Reinholz and Tony Fedun

**$250 to $999**

Sylvia Anstey

Mary Ann Burrows and Luke Hohenadel

Lisa Lyons Johnston

Douglas Mortley-Wood

Kim Tremblay

…plus two anonymous donors

## GIFTS OF CELEBRATION, HONOUR, AND MEMORY

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

*** 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.*

*This list reflects gifts received between August 1, 2018, and July 31, 2019, and multi-year commitments of $50,000 and more.*

*Charitable Registration number: 88981 4323 RR0001*

# 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 and Finance Committee, 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, providing key support in achieving the Institute's strategic objectives, particularly around recruitment.

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**Michael Serbinis**
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We thank **John Reid**, a founding member of Perimeter's Board of Directors, who completed 19 years of service to the Board on December 31, 2018.

*For full biographies of the Board, go to* www.perimeterinstitute.ca/people/board-directors.

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We thank **Barbara Terhal** (Delft University of Technology) and **Shamit Kachru** (Stanford University), who each completed their service to the Scientific Advisory Committee in April 2019.

# SENIOR LEADERSHIP

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**Michael Duschenes**
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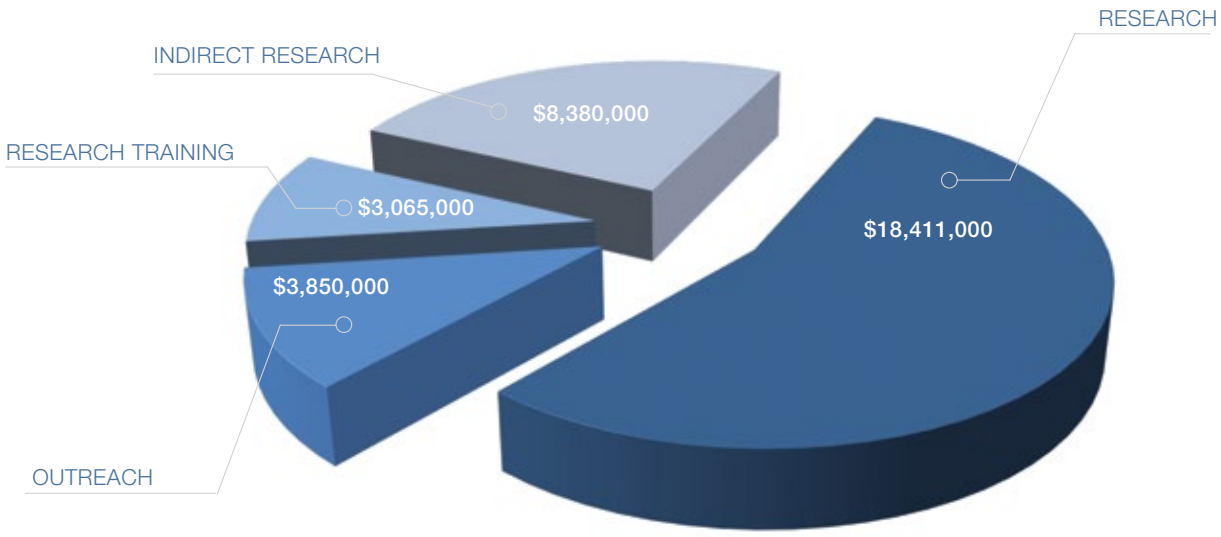
**Luis Lehner**
Faculty Chair

# FINANCIALS

## SUMMARY OF OPERATING COSTS (refer to page 48)

For the year ended July 31, 2019




### Research

Advancing our understanding of the universe at the most fundamental level remains Perimeter's focus. To that end, the Institute continued to invest in creating a research environment that fosters breakthroughs by growing Perimeter's resident researcher base. Although compared to a university, the researcher base is not large, the researchers' impact is outsized. In 2018/19, Perimeter increased its investment in research by more than 10 percent over the prior year, in line with growth objectives.

### Research Training

Over the last year, Perimeter continued to offer innovative research training programs, such as the Perimeter Scholars International (PSI) master's program, the PhD program, and the Institute's Visiting Graduate Fellows program, each of which attracted emerging scientists. These high-calibre programs will not only train the next generation of leading physicists but also provide them with a widely applicable skill set for problem solving, critical thinking, and collaboration. Support for these programs remained strong and comparable to the prior year, increasing by two percent.

### Outreach and Science Communications

Perimeter's world-class educational outreach program is built on the principle of leverage: Perimeter reaches teachers to reach students. These teachers convey the wonder and mystery of the universe and the importance of scientific breakthroughs. Perimeter's spend in this area was reduced compared with the prior year as certain specifically funded programs concluded. Nonetheless, through its cost-effective leverage model, the Institute continued to deliver major impact for students, teachers, and the public at large through its core suite of inspirational programs, products, and communications.

### Indirect Research and Operations

Indirect research and operating expenditures cover the costs of core support areas, including administration, advancement, information technology, and facilities. Perimeter continues to maximize efficiencies where possible, maintaining a world-class research institute by investing the majority of its funds into its core mandate of research, training, and educational outreach. In 2018/19, indirect research and operations composed slightly less than 25 percent of the Institute's overall expenditure, in line with historical averages.

## INCOME

Perimeter's private sector fundraising campaign remained strong, generating over $3 million to support the operations of the Institute, while research grant revenue from private foundations exceeded $1 million. Meanwhile, federal and provincial governments continued to provide revenues in accordance with the terms of their grant agreements. In the prior year, certain federal contributions were received in advance, resulting in additional income recognition. 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.

## FINANCIAL POSITION

**(refer to page 47)**

Perimeter's financial position continues to remain very robust. Its endowment is 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.

Perimeter's investments consist of a portfolio mix of domestic equities, international equities, fixed income, and alternative investments specifically designed in accordance with Perimeter's risk-return objectives. This allows for the accumulation of private funds to address the Institute's future needs and provides the near-term flexibility to react to targeted research opportunities that may present themselves. The investment of marketable securities earned a return of almost two and a half percent over the past year.

## 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, 2019, Perimeter has completed the second 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 to government support, Perimeter Institute consistently seeks innovative ways to expand its sources of funds from the private sector. Private sector donations, in accordance with donor requests, are either used as contributions toward operational expenditures or protected in an endowment fund designed to maximize growth and minimize risk. However, investment returns can be volatile and susceptible to economic conditions. Under the direction of the Investment Committee, funds are invested in accordance with the Board-approved Investment Policies and Procedures.

Zeifmans

## REPORT OF THE INDEPENDENT AUDITORS ON THE SUMMARIZED FINANCIAL STATEMENTS

To the Directors of
Perimeter Institute

### Opinion

The summary financial statements, which comprise the summary statement of financial position as at July 31, 2019, 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") as at and for the year ended July 31, 2019.

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, 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.

### 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 Audited Financial Statements and Our Report Thereon

We expressed an unmodified audit opinion on the audited financial statements in our report dated December 5, 2019. 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 5, 2019

Chartered Professional Accountants
Licensed Public Accountants

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Ontario | M6A 1Y7 | Canada

zeifmans.ca
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## PERIMETER INSTITUTE

Summarized Statement of Financial Position
as at July 31, 2019

| | 2019 | 2018 |
|---|---|---|
| **ASSETS** | | |
| Current Assets: | | |
| Cash and cash equivalents | $ 23,923,000 | $ 16,881,000 |
| Investments | 338,050,000 | 342,928,000 |
| Grants receivable | 126,000 | 3,442,000 |
| Other current assets | 759,000 | 679,000 |
| | 362,858,000 | 363,930,000 |
| Property and equipment | 40,786,000 | 42,046,000 |
| TOTAL ASSETS | $ 403,644,000 | $ 405,976,000 |
| **LIABILITIES AND FUND BALANCE** | | |
| Current liabilities: | | |
| Accounts payable and other current liabilities | $ 1,850,000 | $ 1,294,000 |
| TOTAL LIABILITIES | 1,850,000 | 1,294,000 |
| Fund balances: | | |
| Invested in capital assets | 40,692,000 | 41,948,000 |
| Externally restricted | 17,396,000 | 56,567,000 |
| Internally restricted | 343,006,000 | 305,441,000 |
| Unrestricted | 700,000 | 726,000 |
| TOTAL FUND BALANCES | 401,794,000 | 404,682,000 |
| | $ 403,644,000 | $ 405,976,000 |

# PERIMETER INSTITUTE

Summarized Statement of Operations and Changes in Fund Balances

For the Year Ended July 31, 2019

| | 2019 | 2018 |
|---|---|---|
| **Revenue** | | |
| Government grants | $ 22,192,000 | $ 29,383,000 |
| Donations | 3,293,000 | 6,424,000 |
| Research grants | 1,325,000 | 1,086,000 |
| | 26,810,000 | 36,893,000 |
| **Expenses** | | |
| Research | 18,411,000 | 16,466,000 |
| Research training | 3,065,000 | 2,996,000 |
| Outreach and science communications | 3,850,000 | 4,880,000 |
| Indirect research and operations | 8,380,000 | 8,068,000 |
| | 33,706,000 | 32,410,000 |
| Excess of revenue over expenses (expenses over revenue) before investment and amortization impacts | (6,896,000) | 4,483,000 |
| Amortization | (2,563,000) | (2,747,000) |
| Investment income | 6,571,000 | 28,608,000 |
| Excess of revenue over expenses (expenses over revenue) | (2,888,000) | 30,344,000 |
| Fund balances, beginning of year | 404,682,000 | 374,338,000 |
| Fund balances, end of year | $ 401,794,000 | $ 404,682,000 |

# 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 many 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-present), 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, 48 of whom now hold faculty positions around the world, including at Princeton, Cambridge, and Oxford.

**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. Boyle's research interests include cosmology, fundamental physics, and mathematical physics. In cosmology, he recently proposed (with Kieran Finn and Neil Turok) 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 has developed (with Shane Farnsworth) the area of "non-associative geometry" and shown how it may be used to reinterpret the Standard Model of particle physics and predict certain extensions of this model. In mathematical physics, he has developed (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; he has found (with Paul Steinhardt) all the natural analogues (in two dimensions and higher) of the famous Penrose tiling; and he has shown (with Felix Flicker and Madeline Dickens) how close cousins of these tilings (which they call "conformal quasicrystals") naturally live at the boundary of hyperbolic space and are connected to the notion of holography, which plays a central role in high energy physics.

**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) joined Perimeter in 2014 from Northwestern University, where he had been a faculty member since 2006. He is the Krembil William Rowan Hamilton Chair in Theoretical Physics. 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).

**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. Among other important findings, she has provided a computational framework for gauge invariant observables in canonical general relativity, constructed new realizations of quantum geometry, and identified holographic properties of background independent gravity. Dittrich has received the Otto Hahn Medal of the Max Planck Society, which recognizes outstanding young scientists, and an Early Researcher Award from the Ontario Ministry of Research and Innovation.

**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).

**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. 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, 2D 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.

**Davide Gaiotto** (PhD Princeton University, 2004) joined Perimeter in 2012 and holds the Krembil Galileo Galilei Chair in Theoretical Physics. 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 a New Horizons in Physics Prize from the Fundamental Physics Prize Foundation (2013).

**Jaume Gomis** (PhD Rutgers University, 1999) joined Perimeter Institute in 2004, declining a European Young Investigator Award by the European Science Foundation to do so. Prior to that, he worked at the California Institute of Technology as a postdoctoral scholar and as the Sherman Fairchild Senior Research Fellow. His main areas of expertise are string theory, 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 50 papers, which have attracted well over 13,000 citations to date. He is also a fellow of the American Physical Society and a Senior Scientist with Quantum Benchmark.

**Lucien Hardy** (PhD University of Durham, 1992) joined Perimeter's faculty in 2002, having previously held research and lecturing positions at various European universities, including the University of Oxford, Sapienza University of Rome, the University of Durham, the University of Innsbruck, and the National University of Ireland. In 1992, he found a very simple proof of non-locality in quantum theory, which has become known as "Hardy's theorem." He 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. Most recently, he has proposed the quantum equivalence principle, seen as a possible bridge between quantum field theory and quantum gravity.

**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'd been a Moore Postdoctoral Fellow since 2015. Hsieh works in condensed matter, specializing in exotic states of matter whose physical behaviours are dictated by the mathematical structures found in 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 has been Faculty Chair since March 2018. 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 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 Cosmology and Gravity program. Lehner also serves on the Scientific Council of the International Centre for Theoretical Physics – South American Institute for Fundamental Research and the Advisory Board of the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara. He is also the theorist in residence for the Gravitational Wave International Committee.

**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 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 207 papers have generated 11,741 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.

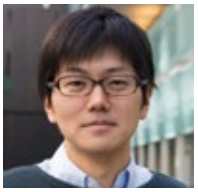
**Robert Spekkens** (PhD University of Toronto, 2001) joined Perimeter's faculty in 2008, after holding an International Royal Society Fellowship at the University of Cambridge. His field of research is the foundations of quantum theory, where he is known for his work on the interpretation of the quantum state, the principle of non-contextuality, the nature of causality in a quantum world, and the characterization of the symmetry-breaking and thermodynamic 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 is also director of the Centre for the Universe here. 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 pictures. Recently, he and his collaborators have developed a new, foundational approach to path integrals, with applications ranging from quantum 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 math and science training, research, and public outreach spanning the African continent. In 2019, he was named an Officer of the Order of Canada (honorary), and 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. He is the author of *The Universe Within*, a popular science bestseller in Canada.

**Guifre Vidal** (PhD University of Barcelona, 1999) joined Perimeter's faculty in 2011 from the University of Queensland in Brisbane, where he was a professor in the School of Mathematics and Physics. Vidal works at the interface of quantum information, condensed matter physics, and quantum field theory. He develops tensor network algorithms to compute ground states of quantum many-body systems and has proposed a modern formulation of the renormalization group, based on quantum circuits and entanglement. He is currently developing non-perturbative tools for strongly interacting quantum fields and exploring the use of tensor networks in holography. His past honours include a European Union Marie Curie Fellowship, a Sherman Fairchild Foundation Fellowship, and an Australian Research Council Federation Fellowship. Vidal is a fellow of the Canadian Institute for Advanced Research and a member of the Simons Collaboration on the Many Electron Problem.

**Pedro Vieira** (PhD École Normale Supérieure and the Theoretical Physics Center at the University of Porto, 2008) is the Clay Riddell Paul Dirac Chair in Theoretical Physics at Perimeter Institute, where he has been a faculty member since 2009. Prior to that, he was a junior scientist at the Max Planck Institute for Gravitational Physics (Albert Einstein Institute) from 2008 to 2009. Vieira's research concerns the development of new mathematical techniques for gauge and string theories in their non-perturbative regimes. He focuses both on a very special theory known at N=4 SYM as a workhouse for developing such tools and also 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 Nonperturbative 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 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. In particular, he has used the techniques of quantum coding theory to find novel topological phases of matter and developed a framework of classifying fault-tolerant logical gates by using topological gauge theories. He has also recently developed an interest in black hole physics.

## 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. 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 third prize in the 2015 Buchalter Cosmology Prize of the American Astronomical Society.

**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 that 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.

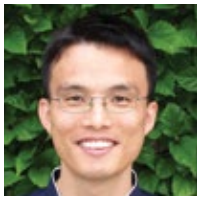
**Alex Buchel** (PhD Cornell University, 1999) is jointly appointed with Western University. Before joining Perimeter's faculty in 2003, he held research positions at the Institute for Theoretical Physics at the University of California, Santa Barbara (1999-2002) and the Michigan Center for Theoretical 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 in 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.

**David Cory** (PhD Case Western Reserve University, 1987) joined Perimeter in 2010 and is jointly appointed as a professor of chemistry at the University of Waterloo and Deputy Director of Research at the Institute for Quantum Computing. He was previously a professor of nuclear science and engineering at the Massachusetts Institute of Technology. Since 1996, Cory has been exploring the experimental challenges of building small quantum processors based on nuclear spins, electron spins, neutrons, persistent current superconducting devices, and optics. In 2010, he was named the Canada Excellence Research Chair in Quantum Information Processing. Cory is the principal investigator of the $144 million Transformative Quantum Technologies program, with $76 million in funding from the Canada First Research Excellence Fund. He chairs the advisory committee for the Quantum Information Processing program at the Canadian Institute for Advanced Research, and he is a fellow of both the American Physical Society and the Royal Society of Canada.

**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.

**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 held 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 phys/math from Caltech in 1995, she did a PhD in physics at Stanford under the supervision of Professor Yoshihisa Yamamoto and Professor Isaac Chuang.

**Matilde Marcolli** (PhD University of Chicago, 1997) began a joint appointment with Perimeter and the University of Toronto in January 2018, after a decade as a professor of mathematics at the California Institute of Technology. She is a mathematical physicist whose research interests include computational linguistics, differential and algebraic geometry and topology, and mathematical models for cosmology and neuroscience. Among her many honours, Marcolli has won the Heinz Maier Leibniz Prize and the Sofja Kovalevskaja Award, both in 2001, and held many visiting research positions. She has also written five books, most recently *Noncommutative Cosmology* in 2018, and edited several others.

**Roger Melko** (PhD University of California, Santa Barbara, 2005) joined Perimeter in 2012, while retaining his appointment with the University of Waterloo, where he has been since 2007. Prior to that, he was a Wigner Fellow at Oak Ridge National Laboratory (2005-07). Melko is a condensed matter theorist who develops new computational methods and algorithms to study strongly correlated many-body systems, focusing on emergent phenomena, ground state phases, phase transitions, quantum criticality, and entanglement. Among his honours, he has received 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 (Tier 2).

**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. She has held a faculty position at the Institute for Quantum Computing in Waterloo since 2017. Muschik works on developing novel methods for quantum information processing and on quantum simulations of problems from high energy physics. She 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 and *Nature* 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 for faculty-level scientists (2018), a Sloan Research Fellowship for outstanding early-career researchers (2019), and a New Frontiers grant for high-risk, high-reward innovations (2019).

**Ue-Li Pen** (PhD Princeton University, 1995) joined Perimeter in 2014. He is jointly appointed with the Canadian Institute for Theoretical Astrophysics at the University of Toronto, where he has been a professor since 1998 and is currently Interim Director. 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, 21cm intensity mapping, pulsar VLBI scintillometry, and the Canadian Hydrogen Intensity Mapping Experiment (CHIME). Among his many honours, Pen is a senior fellow of the Canadian Institute for Advanced Research in the Cosmology and Gravity 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.

**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. 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 holds senior scientific management positions within the Dark Energy Spectroscopic Instrument (DESI), extended Baryon Oscillation Spectroscopic Survey (eBOSS), and Euclid experiments. 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.

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

**Daniel Siegel** (PhD Max Planck Institute for Gravitational Physics & University of Potsdam, 2015) joined Perimeter in 2019 from 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 held a one-year postdoctoral fellowship. 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.

## SENIOR MANAGEMENT

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Senior Director of Finance and Operations

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Director of Academic Programs

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Director of Finance

**Ben Davies**
Director of Information Technology

**Sheri Keffer**
Director of People and Culture

**Natasha Waxman**
Director of Publications, Grants and Awards

## POSTDOCTORAL RESEARCHERS, 2018/19 (PhD granting institution)

Ben Albert (University of Pennsylvania)
Alvaro Martin Alhambra (University College London)
Anurag Anshu (National University of Singapore)
Yoni BenTov (University of California, Santa Barbara)
Béatrice Bonga (Pennsylvania State University)
Jacob Bridgeman (The University of Sydney)
Sylvain Carrozza (Université Paris-Sud)
William Cunningham (Northeastern University)
Richard Derryberry (University of Texas at Austin)
Lorenzo Di Pietro (Weizmann Institute of Science)
Galyna Dobrovolska (University of Chicago)
William Donnelly (University of Maryland, College Park)
Angelika Fertig (Max Planck Institute for Gravitational Physics)
Zachary Fisher (University of California, Berkeley)
Tobias Fritz (Max Planck Institute for Mathematics)
Lena Funcke (Ludwig Maximilian University of Munich)
Thomas Galley (University College London)
Federico Galli (Vrije Universiteit Brussel)
Martin Ganahl (Graz University of Technology)
Meng Guo (Harvard University)
Matthijs Hogervorst (École Normale Supérieure)
Junwu Huang (Stanford University)
Emilie Huffman (Duke University)
Nick Hunter-Jones (California Institute of Technology)
Estelle Inack (International Centre for Theoretical Physics)
Michael Jarret (University of Maryland)
Theo Johnson-Freyd (University of California, Berkeley)
Aleksander Kubica (California Institute of Technology)
Stefan Kuhn (Max Planck Institute of Quantum Optics)
Ravi Kunjwal (Institute of Mathematical Sciences, Chennai)
Ian Le (Northwestern University)
Adam Lewis (University of Toronto)
Zi-Wen Liu (Massachusetts Institute of Technology)
Han Ma (University of Colorado, Boulder)
Mathew Madhavacheril (Stony Brook University)
Ashley Milsted (Leibniz University of Hanover)
Moritz Munchmeyer (LPNHE Pierre and Marie Curie University)
Tadashi Okazaki (Osaka University)
Naritaka Oshita (University of Tokyo)
Solomon Owerre (University of Montreal)
Zhen Pan (University of California, Davis)
Daniele Pranzetti (Centre de Physique Théorique)
Hung-Yi Pu (National Tsing-Hua University)
Petr Pushkar (Columbia University)
Davide Racco (University of Geneva)
Djordje Radicevic (Stanford University)
Fereshteh Rajabi (University of Western Ontario)
Jess Riedel (University of California, Santa Barbara)
Aldo Riello (Centre de Physique Théorique)
Denis Rosset (Université de Genève, GAP-Optique)
Ana Belen Sainz (Polytechnic University of Catalonia)
John Selby (Imperial College London)
Jamie Sikora (Institute for Quantum Computing, University of Waterloo)
Antony Speranza (University of Maryland)
Sebastian Steinhaus (University of Potsdam)
Kostiantyn Tolmachov (Massachusetts Institute of Technology)
Dave Touchette (University of Montreal)
Alex Weekes (University of Toronto)
Wolfgang Wieland (Centre de Physique Théorique)
Elie Wolfe (University of Connecticut)
Ziqi Ya (University of California, Berkeley)
Junya Yagi (Rutgers University)
Qiao Zhou (University of California, Berkeley)

## DISTINGUISHED VISITING RESEARCH CHAIRS

Scott Aaronson, University of Texas at Austin
Mina Aganagic, University of California, Berkeley
Yakir Aharonov, Chapman University
Abhay Ashtekar, Pennsylvania State University
Leon Balents, Kavli Institute for Theoretical Physics
James Bardeen, University of Washington
Ganapathy Baskaran, Institute of Mathematical Sciences, Chennai
Charles Bennett, IBM
Edo Berger, Harvard University
Patrick Brady, University of Wisconsin – Milwaukee
Alessandra Buonanno, Max Planck Institute for Gravitational Physics – Albert Einstein Institute
John Cardy, University of California, Berkeley
Lance Dixon, SLAC National Accelerator Laboratory
Matthew Fisher, Kavli Institute for Theoretical Physics
Katherine Freese, University of Texas at Austin
Gian Francesco Giudice, European Organization for Nuclear Research (CERN)
Gabriela González, Louisiana State University
Ted Jacobson, University of Maryland
Shamit Kachru, Stanford University
David B. Kaplan, University of Washington
Adrian Kent, University of Cambridge
Renate Loll, Radboud Universiteit Nijmegen
John March-Russell, University of Oxford
Sandu Popescu, University of Bristol
Frans Pretorius, Princeton University
Carlo Rovelli, Université de la Méditerranée – Centre de physique théorique de Luminy
Subir Sachdev, Harvard University
Nathan Seiberg, Institute for Advanced Study
Yan Soibelman, Kansas State University
Paul Steinhardt, Princeton University
Andrew Strominger, Harvard University
Raman Sundrum, University of Maryland
Leonard Susskind, Stanford University
Barbara Terhal, Delft University of Technology – QuTech
Dam Thanh Son, University of Chicago
Gerard 't Hooft, Utrecht University
Senthil Todadri, Massachusetts Institute of Technology
Bill Unruh, University of British Columbia
Frank Verstraete, Universiteit Gent
Ashvin Vishwanath, Harvard University
Zhenghan Wang, Microsoft Station Q
Xiao-Gang Wen, Massachusetts Institute of Technology
Mark Wise, California Institute of Technology
Alexander Zamolodchikov, Stony Brook University

## ACADEMIC PROGRAMS

James Forrest, Director

Perimeter Institute and University of Waterloo

Professor Forrest joined the University of Waterloo's faculty in 2000 and became Perimeter's Academic Programs Director in 2014. He was the Director of the Guelph-Waterloo Physics Institute from 2005 to 2010 and has served in several administrative roles at Waterloo. His research focuses on the physics of soft matter on the nanoscale, particularly polymers and proteins, glass transition in confined geometry, and surface and interfacial properties of polymers. Among his many honours, Forrest is a fellow of the American Physical Society and co-recipient of the 2013 Brockhouse Medal of the Canadian Association of Physicists.

## PERIMETER SCHOLARS INTERNATIONAL TEACHING FACULTY, 2018/19

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Agata Branczyk, Perimeter Institute
Maïté Dupuis, Perimeter Institute
Lauren Hayward Sierens, Perimeter Institute
David Kubiznak, Perimeter Institute
Dan Wohns, Perimeter Institute
Gang Xu, Perimeter Institute

**PSI LECTURERS**

Latham Boyle, Perimeter Institute
François David, Institut de physique théorique – Commissariat à l'énergie atomique (CEA) – Saclay
William East, Perimeter Institute
Davide Gaiotto, Perimeter Institute
Jaume Gomis, Perimeter Institute
Daniel Gottesman, Perimeter Institute
Ruth Gregory, Durham University Science Laboratories
Aliosica Hamma, University of Massachusetts, Boston
Matthew Leifer, Chapman University
Eduardo Martin-Martinez, University of Waterloo – Institute for Quantum Computing
Kendrick Smith, Perimeter Institute
Rakesh Tiwari, McGill University
Sean Tulin, York University
Pedro Vieira, Perimeter Institute

## PHD STUDENTS, 2018/19 (partner university, supervisor)

Eugene Adjei (University of Waterloo, Agata Branczyk)
Alvaro Ballon Bordo (University of Waterloo, David Kubiznak/Robert Myers)
Chenfeng Bao (University of Waterloo, Neil Turok)
Jacob Barnett (University of Waterloo, Lee Smolin)
Matthew Beach (University of Waterloo, Roger Melko)
Pablo Bosch Gomez (University of Waterloo, Luis Lehner)
Dylan Butson (University of Toronto, Kevin Costello)
Juan Cayuso (University of Waterloo, Matthew Johnson)
Wan Cong (University of Waterloo, David Kubiznak)
Frank Coronado (University of Waterloo, Pedro Vieira)
Diego Delmastro (University of Waterloo, Jaume Gomis)
Job Feldbrugge (University of Waterloo, Neil Turok)
Adrian Franco Rubio (University of Waterloo, Guifre Vidal)
Thomas (TC) Fraser (University of Waterloo, Robert Spekkens)
Utkarsh Giri (University of Waterloo, Kendrick Smith)
Anna Golubeva (University of Waterloo, Roger Melko)
Lucia Gomez Cordova (University of Waterloo, Pedro Vieira)
Tomas Gonda (University of Waterloo, Robert Spekkens)
Finnian Gray (University of Waterloo, David Kubiznak/Robert Mann)
Alfredo Guevara (University of Waterloo, Freddy Cachazo)
Juan Hernandez (University of Waterloo, Robert Myers)
Florian Hopfmueller (University of Waterloo, Laurent Freidel)
Qi Hu (University of Waterloo, Guifre Vidal)
Nafiz Ishtiaque (University of Waterloo, Jaume Gomis)
Puttarak Jai-akson (University of Waterloo, Laurent Freidel)
Ding Jia (University of Waterloo, Lucien Hardy)
Seth Kurankyi Asante (University of Waterloo, Bianca Dittrich/Lee Smolin)
Ji Hoon Lee (University of Waterloo, Davide Gaiotto)
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Andrei Schieber (University of Waterloo, Lucien Hardy)
Andres Schlief Carvajal (McMaster University, Sung-Sik Lee)
David Schmid (University of Waterloo, Robert Spekkens)
Barak Shoshany (University of Waterloo, Laurent Freidel)
Vasudev Shyam (University of Waterloo, Lee Smolin)
Barbara Soda (University of Waterloo, Lucien Hardy/Achim Kempf)
David Svoboda (University of Waterloo, Laurent Freidel/Ruxandra Moraru)
Paul Tiede (University of Waterloo, Avery Broderick)
Qingwen Wang (University of Waterloo, Niayesh Afshordi)
Jingxiang Wu (University of Waterloo, Davide Gaiotto)
Lei Yang (University of Waterloo, Anton Burkov)
Yigit Yargic (University of Waterloo, Lee Smolin)
Yehao Zhou (University of Waterloo, Kevin Costello)
Yijian Zou (University of Waterloo, Guifre Vidal)

## MASTER'S STUDENTS, 2018/19 (country of origin)

Jacob Abajian (United States)
Wasif Ahmed (Bangladesh)
Artur Avkhadiev (Russia)
Ivana Babic (Croatia)
Sara Bogojevic (Serbia)
Francisco Borges (Venezuela)
Katarzyna Budzik (Poland)
Blanca Alicia Castro Bermudez (Mexico)
Ramiro Cayuso (Argentina)
Vincent Chen (Canada)
Samuel Cree (Australia)
Fatih Dinc (Turkey)
Diego Garcia Sepulveda (Chile)
Elliott Gesteau (France)
Diego Gutierrez Coronel (Colombia)
Mohamed Hibat Allah (Morocco)
Justin Kulp (Canada)
Katherine Latimer (United States)
Elise LePage (United States)
Yanyan Li (China)
Ruochen Ma (China)
Amalia Madden (United Kingdom)
Nastasia Makki (Russia/Lebanon)
Aoibheann Margalit (Ireland)
Matija Medvidovic (Croatia)
Andre Nascimento Alcantara Pereira (Brazil)
Ho Nam Nguyen (Vietnam)
Jairo Martin Rojas Huamani (Peru)
Renato Gomes Souza (Brazil)
Aiden Suter (Australia)
Leander Thiele (Germany)
Matthew Yu (United States)
Keyou Zeng (China)

## CONFERENCES AND WORKSHOPS, 2018/19

**Foundations of Quantum Mechanics**
July 30-August 3, 2018

**Higher Algebra and Mathematical Physics**
August 13-17, 2018

**Wide Field Astronomy in Canada**
October 10-12, 2018

**CHIME-FRB Collaboration Meeting**
November 26-27, 2018

**Cohomological Hall Algebras in Mathematics and Physics**
February 25-March 1, 2019

**PI CITA Day 2019**
April 2, 2019

**Quantum Matter: Emergence & Entanglement 3**
April 22-26, 2019

**Many-Body States and Dynamics Workshop II**
June 13, 2019

**QFT for Mathematicians**
June 17-28, 2019

**Machine Learning for Quantum Design**
July 8-12, 2019

**Bootstrap 2019**
July 15-August 2, 2019

## ACADEMIC SPONSORSHIPS, 2018/19

Perimeter Institute was a proud sponsor of the following off-site conferences and workshops:

**2018 International Congress of Mathematical Physics**, Montreal

**2019 Canadian Conference for Undergraduate Women in Physics**, University of Ottawa

**Testing Gravity 2019**, Simon Fraser University

**Lake Louise Winter Institute 2019**, Lake Louise

**Quantum Gravity Workshop**, Camp Kintail, Ontario

**Many Facets of Complexity: From Quantum Information to Holography**, University of Windsor

**Flavour Physics and CP Violation**, University of Victoria

**Atlantic General Relativity Workshop and Conference 2019**, University of New Brunswick

**Theory Canada 14**, University of British Columbia

**CAP 2019**, Simon Fraser University

**Women in Physics Canada**, McGill University

**Quantum Theory and Symmetry XI**, University of Montreal

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