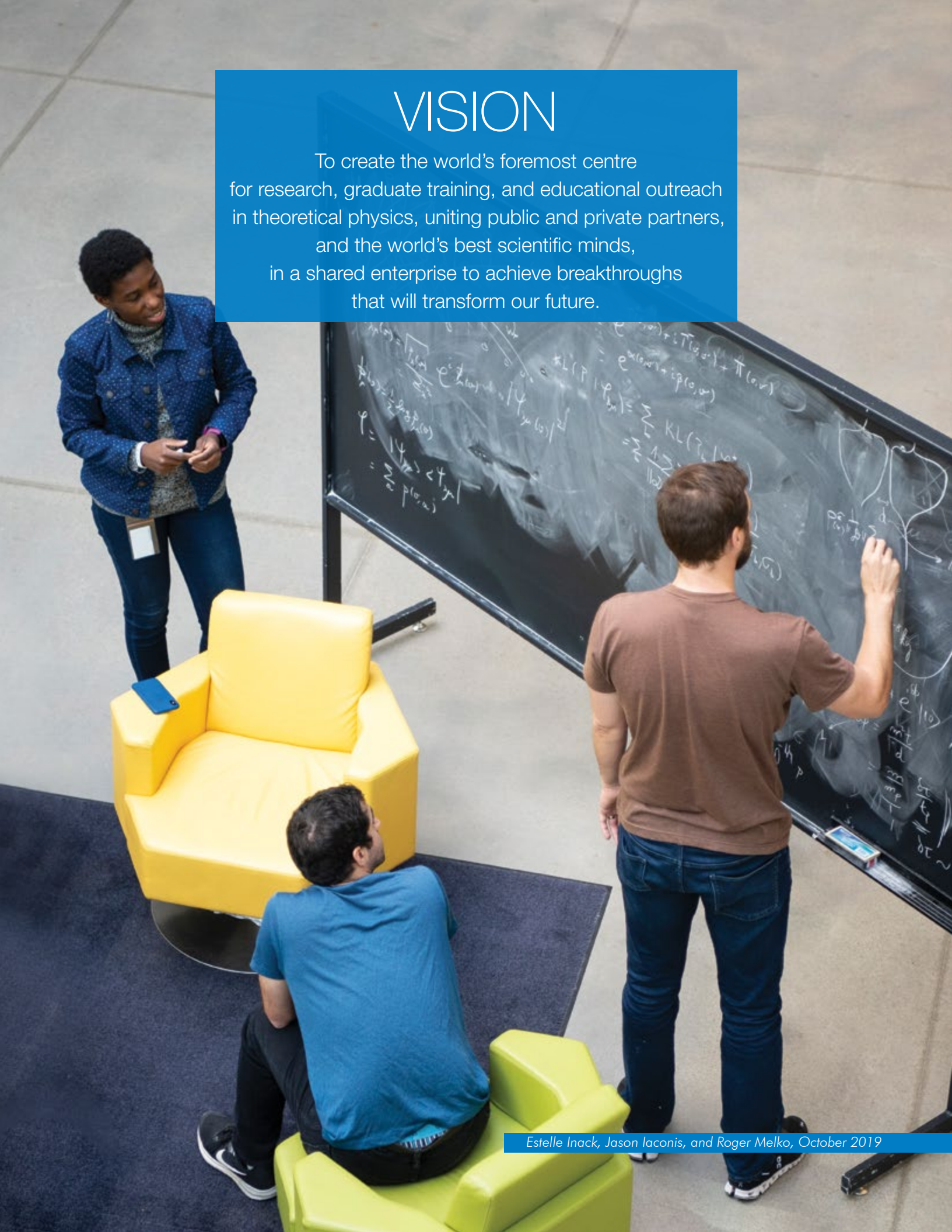
# 2020 ANNUAL REPORT

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

# VISION

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



*Estelle Inack, Jason Iaconis, and Roger Melko, October 2019*

# CONTENTS



This report covers the activities and finances
of Perimeter Institute for Theoretical Physics
from August 1, 2019, to July 31, 2020.

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

TODAY'S THEORETICAL PHYSICS
IS TOMORROW'S TECHNOLOGY

# MESSAGE FROM THE BOARD CHAIR

The coronavirus has made the past year very difficult. The loss of loved ones and the economic, social, and emotional impact of physical distancing measures have touched everyone.

I believe that Perimeter has been fortunate, and I want to acknowledge the efforts by Director Rob Myers and his team to ensure above all else the safety of Perimeter's employees, students, and visitors.

Also, as you know, a fundamental aspect of the Perimeter model is the extensive interaction among researchers and students. As you would expect, these types of interactions are hard to achieve safely in our current pandemic environment. That said, Perimeter used a number of tools and a lot of creativity to continue these interactions between researchers from Perimeter and around the world, both safely and effectively. The result is that a year that threatened to be very unproductive has produced or advanced a number of physics breakthroughs.

The Institute's model of attracting the world's best researchers and enabling them to pursue their most ambitious ideas is paying off. Under Rob's leadership, the Institute continues to move from strength to strength in quantum information science, as well as in the other major areas of theoretical physics. Our researchers set the global scientific agenda in many areas, as evidenced through their highly cited papers and groundbreaking international collaborations.

Perimeter faculty continue to make many game-changing physics breakthroughs. Also, this year marked the advancement of some Perimeter projects with very exciting commercialization opportunities. A few of the developments I want to acknowledge include the following:

> A team led by Roger Melko is collaborating with experimental physicists at Harvard University to improve the testing and reliability of quantum simulations. Being able to simulate quantum interactions opens the door to everything from creating new materials to developing new medicines.
>
> The visionary work by Will Percival came to fruition with the release of the largest three-dimensional map of the universe ever created. Through his work at the Extended Baryon Oscillation Spectroscopic Survey, Percival oversaw an ambitious initiative to measure more than 2 million galaxies and quasars for the project.
>
> I am excited about the Institute's work, led by Robert Spekkens, in "quantum causal inference." This new field capitalizes on remarkable new insights from foundational quantum theory to determine causal relationships within highly complex data sets. It has the potential to transform epidemiology, finance and insurance, risk modelling, and many other branches of fundamental science.

Successes like these informed a recent report from the Institute's Scientific Advisory Committee, an oversight body composed of eminent scientists from around the world.

> "Perimeter is unique in the scientific landscape, with a forward-looking, innovative, collaborative and inclusive climate," the Committee wrote. "It has greatly raised Canada's reputation in the field of high-level theoretical physics, and has shown a very high return on government investment, and at a fast pace."

I am proud of this glowing report from some of the top physics researchers around the world. I want to thank the Scientific Advisory Committee and their Chair Gabriela González for their comments and the work behind this very extensive report.

Perimeter is a fundamental partner in the "Quantum Valley." Quantum Valley is our quantum innovation ecosystem that supports and enables research and researchers as they drive scientific breakthroughs and develop transformative quantum technologies that are the basis for commercial products that change lives and build economies.

Perimeter's activities, including those with commercialization potential, along with the efforts at the Institute for Quantum Computing at the University of Waterloo, and at the Quantum Valley Ideas Lab, combine to make the Quantum Valley a global leader in both quantum research and in the commercialization of transformative quantum technologies. We already have a number of quantum start-up companies in the region, and we expect many more to be developed over the next few years and beyond.

I thank the Governments of Ontario and Canada, as well as the foundations and donors who so generously support the Institute and share our vision. The success of the large-scale public-private partnership at Perimeter not only enables our exciting activities but also raises our national and global brand, which has been an instrumental part of our ability to attract top researchers to Perimeter from around the world. In particular, I want to acknowledge the generous support of $10 million from the Riddell Family Foundation for Perimeter's Clay Riddell Centre for Quantum Matter. The research done by the Quantum Matter Centre will help develop exciting new quantum materials that will enable new approaches for everything from power grids to medical imaging.

In addition to our researchers, the Institute owes its success to the leadership of the members of our Board, Finance and Investment Committees, and Leadership Council. A special

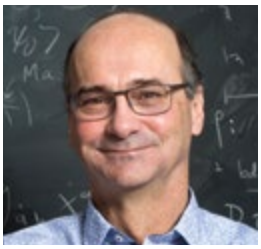
thanks this year to Amit Chakma, President Emeritus of Western University, who stepped down from the Board this year, and a warm welcome to Susan Baxter, Vice Chairman, Enterprise Strategic Client Group at Royal Bank of Canada, who recently joined us.

Canada, and the rest of the world, will of course make it through the current pandemic. The power of science, innovation, and human resilience, in my mind, assure this. Although we will come out of this experience with both mental and emotional scars, I believe that we will also come away from the experience with new wisdom and new resolve that will ensure future health, happiness, and success.

The Institute will continue to make new breakthroughs that will give this country an edge for decades to come – accelerating our post-COVID economic recovery and preparing us for what comes next.

I want to thank everyone who has shared my vision and contributed to the success of Perimeter to date. I also want to encourage you to continue your commitment to the future success of this exciting organization. The best is yet to come!

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



# MESSAGE FROM THE INSTITUTE DIRECTOR

Perimeter Institute is a place with its eye on the future. 2020, though, caught us by surprise.

In a way we were lucky: As theorists, we have no particle accelerators to tend to, no instruments to mind. When we became an online institution – which happened almost overnight in March – our simulations and calculations could go on. While our chalkboards had to stand empty, our ideas could follow us home.

Some of our researchers offered their expertise to biomedical collaborations as part of the worldwide effort to combat COVID-19. Research continued, including stunning new results in quantum matter, quantum simulation, field theory, and even foundational work on the nature of time itself. We learned new things about the universe, with major new work from the Event Horizon Telescope and the CHIME telescope. Our master's program, Perimeter Scholars International, went online. Our PhD students defended their theses on Zoom.

We underwent a major five-year review by Perimeter's Scientific Advisory Committee entirely online. And as you'll read in the pages ahead, we received a glowing report back on our trajectory, our research, and our standing in the international scientific community.

There were other silver linings: Our undergraduate summer program actually expanded. Since we didn't have to fly students in and house them, we were able to enroll 54 students instead of 20. Conferences expanded in the same way. Our classroom resources were more vital than ever, and we adapted them to work better for virtual learning. Physics talks also became more important than ever – they're the essential way that researchers exchange the results and ideas they're working on right *now*. So this summer, we launched an online, searchable, citable platform for physics lectures and seminars from Perimeter and other institutions around the world. It's called SciTalks.ca, and we hope it will be to physics talks what the free preprint server arXiv is to physics papers.

I am so proud of how the Perimeter community adapted to the pandemic – with resilience, creativity, and heart. We pulled together, and we are pulling through.

Perhaps the biggest lesson we can take from the pandemic is that in a universe as big and unpredictable as ours, we don't know what our challenges will be. It's clearer than ever that we should not let the horizon of our research be set by our current problems. We have to think further out, because the horizon of our imagination is bigger than the horizon of our problems.

For instance, we are beginning to imagine a new wave of technologies made possible by a much deeper understanding of the quantum realm. This research is poised to change the world. Perimeter prides itself on spotting these moments, and we are rising to meet the quantum moment with entrepreneurial agility. It is strategic and smart to pursue these opportunities.

And yet, if we only do the research we can imagine paying off, we will never move beyond the horizon set by our imaginations.

There is a third horizon: the vast horizon of what is possible. As theoretical physicists, it is our job to chart that third horizon. Somewhere ahead is a future we can't even imagine. As an institute, and as a human community, we should keep reaching for the stars.

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

# HOW PERIMETER MEASURES UP

## REPORT FROM THE SCIENTIFIC ADVISORY COMMITTEE

In May 2020, Perimeter's arm's-length Scientific Advisory Committee, an eminent panel of international scientists, completed a review of the past five years of Perimeter's scientific activity. Accompanied by a 290-page reference report, the Committee held 25 virtual sessions over four days, spanning eight time zones.

For a full list of Scientific Advisory Committee members, see page 45.

**From the Scientific Advisory Committee's Final Evaluation Report** (emphasis added):

"Perimeter is unique in the scientific landscape, with ***a forward-looking, innovative, collaborative and inclusive climate***. It has greatly raised Canada's reputation in the field of high-level theoretical physics, and has shown ***a very high return on government investment***, and at a fast pace.

"PI has stayed true to its inspiring and ambitious founding mission while adapting to new opportunities and changing times. Institute scientists have made ***a number of landmark discoveries*** in several different research areas, and ***an increasing number of very talented and diverse young scientists*** have emerged from its training programs. It is greatly valued in the scientific community for the ways in which it shares new knowledge and brings the community together to collaborate. ***Its remarkable outreach programs bring the adventure of discovery*** to students of many ages and may well incubate a new generation of Curies and Einsteins.

"Perimeter has major research strengths in several exciting areas of physics that are likely to see major advances, and others that will be realized in new technologies. The institute is well-positioned for growth in these areas, and potentially to make ***important, long-lasting contributions*** to science and technology."

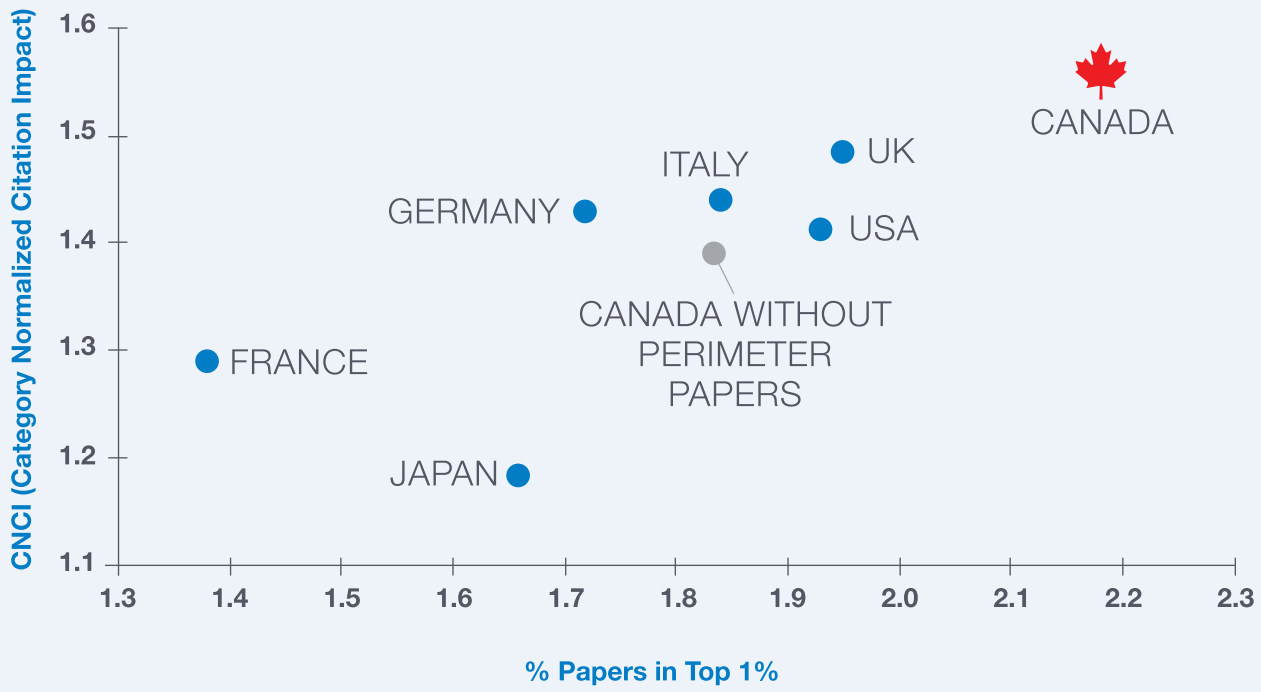
## MEASURING PERIMETER'S SCIENTIFIC IMPACT & QUALITY

A recent study shows that Canada ranks first among G7 countries in physics and space science when it comes to key measures of research quality and impact, and that Perimeter's contribution is vital to this ranking.

The bibliometric study, conducted by Clarivate Analytics, a global leader in research and data insights, assessed the impact and quality of Perimeter's research. The study measured Perimeter's research performance against that of Canada's overall physics and space science research community and against that of other countries.

The magnitude of Perimeter's contribution to these results is particularly striking given that its research faculty represents a small fraction (under 5 percent) of physics research faculty in Canada.

### PERIMETER'S CONTRIBUTION TO CANADA'S TOP RANKING IN PHYSICS QUALITY AND IMPACT AMONG G7 NATIONS (2019)




*In this graph, two measures of scientific quality and impact are plotted together and show clearly that Perimeter makes a key contribution to Canadian scientific excellence in physics. Canada ranks first among G7 nations in both measures, but without Perimeter's contribution, it would rank fourth overall.*

# RESEARCH

*"Perimeter was among the first to recognize that the merger of artificial intelligence and quantum physics is strategic to the futures of both fields. The Institute quickly helped establish a lab in a business incubator to ensure that the basic research performed at Perimeter would benefit Ontario and Canada first. The rapid execution – from recognizing opportunity to full lab operations – could not have been achieved in any other institute."*

*– Roger Melko, Perimeter Associate Faculty*

*Perimeter archives*

# 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 researchers.[1]

**6,282** papers published in more than 250 journals and on the arXiv since Perimeter's inception

**290,360** citations since inception

**743** papers published in 2019/20

**20** prizes and honours in 2019/20

## RESEARCH COMMUNITY

(as of July 31, 2020)

**24** Faculty, including 8 Perimeter Research Chairs

**22** Associate Faculty, including 1 Perimeter Research Chair

**42** Distinguished Visiting Research Chairs

**84** Postdoctoral researchers

**25** Simons Emmy Noether Fellows (8 new in 2019/20)

**55** Visiting Fellows

**7** Visiting Researchers

**108** Affiliate members

## CONFERENCES, WORKSHOPS, AND SEMINARS

**12** conferences and workshops attended by 995 scientists

**4** sponsored off-site conferences and workshops

**289** scientific talks, seminars, and colloquia

**13,082** talks (total) in the online Perimeter Institute Recorded Seminar Archive (PIRSA)

**712,271** views of Perimeter talks in 2019/20

## VISITORS

**353** scientific visitors

[1] *Unless otherwise indicated, figures are for August 1, 2019–July 31, 2020.*


*Davide Gaiotto, Liang Kong, and Lakshya Bhardwaj, Perimeter archives*

# PHASES SET TO STUN

Quantum materials research keeps revealing new states of matter.

In the past year, Perimeter researchers investigating quantum materials have made major advances that continue a 30-year trend of discovering and categorizing increasingly exotic states of matter whose quantum properties mystify, fascinate, and inspire materials scientists.

A “phase” or “state” is a form of matter with distinct properties. Most people are familiar with three common matter phases: solids, like ice and rocks, whose rigid molecular structure maintains a specific shape and volume; liquids, like water and whisky, which retain their volume but take on the shape of their container; and gases, like steam and helium, which vary in both volume and shape.

The most common naturally occurring phase of matter is plasma – the stuff stars are made from. Plasmas are similar to gases but can produce magnetic fields and conduct electricity.

Over the last century, scientists have created and discovered many phases of matter that exist under specialized conditions. These include Bose-Einstein condensates, a supercooled matter state that causes the material to behave as a single quantum particle; new superconductors, which conduct electricity with zero resistance; and superfluids, which flow with zero viscosity.

At Perimeter, through the Clay Riddell Centre for Quantum Matter and other research initiatives, advances in quantum physics and mathematics have continued to reveal new states of matter with new properties that continually push the boundaries of what is possible in materials science.

- Faculty members Yin-Chen He and Chong Wang improved how physicists understand “quantum spin liquids.” This phase of matter exhibits an unusual form of magnetism. In a normal magnet, spinning particles line up to create a magnetic field. In quantum spin liquids, the spins collectively fluctuate and shift, creating a fluid magnetic field. This magnetic fluidity persists even when the material is cooled to nearly absolute zero.

- Postdoctoral researcher Aaron Szasz studied a type of supercooled solid material that appears to become a “chiral spin liquid.” “Chiral” means the structure is asymmetrical – energy flows in one direction only around the edge of the material. Szasz’s recent paper on chiral spin liquids has already inspired many others, some of which speculate that this type of material might lead to new types of superconductors.
- Faculty member Davide Gaiotto and Senior Postdoctoral Researcher Theo Johnson-Freyd improved how scientists classify another group of matter states called “gapped phases.” Particles in these materials settle into very low energy states, which affect the materials’ physical properties. Gaiotto and Johnson-Freyd advanced the mathematics required to understand and categorize this group of unusual materials.

New states of matter do more than satisfy scientific curiosity. Their unusual properties could lead to the development of many powerful applications, from more efficient electricity distribution grids to quantum computers.

*Davide Gaiotto holds the Krembil Galileo Galilei Chair in Theoretical Physics.*

References:

X.-Y. Song (Harvard), C. Wang (Perimeter Institute), A. Vishwanath (Harvard), Y.-C. He (Perimeter Institute), “Unifying description of competing orders in two-dimensional quantum magnets,” *Nature Communications* 10, 4254, 2019, arXiv:1811.11186.

X.-Y. Song (Harvard), Y.-C. He (Perimeter Institute), A. Vishwanath (Harvard), C. Wang (Perimeter Institute), “From spinon band topology to the symmetry quantum numbers of monopoles in Dirac spin liquids,” *Phys. Rev. X* 10, 011033, 2020, arXiv:1811.11182.

A. Szasz (Perimeter Institute), J. Motruk (UC Berkeley), M.P. Zaletel (UC Berkeley), J.E. Moore (UC Berkeley), “Chiral spin liquid phase of the triangular lattice Hubbard model: A density matrix renormalization group study,” *Phys. Rev. X* 10, 021042, 2020, arXiv:1808.00463.

D. Gaiotto, T. Johnson-Freyd (Perimeter Institute), “Condensations in higher categories,” arXiv:1905.09566.

D. Gaiotto, T. Johnson-Freyd (Perimeter Institute), “Symmetry protected topological phases and generalized cohomology,” *JHEP*, 7, 2019, arXiv:1712.07950.

# THE CLAY RIDDELL CENTRE FOR QUANTUM MATTER

The promise of quantum matter is hard to overstate.

Exotic states of matter with quantum properties are clearly going to be key to a new wave of quantum technologies, including superconductors, quantum computers, quantum sensors, and quantum cryptography systems.

But to describe, create, and control these states requires deep understanding of how matter works at its most fundamental level. We need new theory, new tools, and new paradigms. It’s an interdisciplinary quest, pulling researchers and ideas in from condensed matter physics, quantum information, quantum field theory, mathematical physics, and even string theory. Fortunately, these are all areas where Perimeter has existing strengths.

To build on those strengths and to meet this moment, Perimeter is launching the new Clay Riddell Centre for Quantum Matter, made possible by a generous $10 million founding donation from the Riddell Family Charitable Foundation.

The new centre will allow Perimeter to recruit new researchers – from faculty to postdocs to students – and to develop new partnerships here in Canada’s emerging Quantum Valley.

“One of the remarkable things about condensed matter, or quantum matter in general, is the narrow gap between the theoretical ideas and commercial potential,” says Perimeter Director Rob Myers. “It’s an area that is primed to produce fascinating breakthroughs in the next decade.”

*Learn more about Clay Riddell and the Riddell Family Charitable Foundation on pages 40 and 41.*

*“One of the remarkable things about condensed matter, or quantum matter in general, is the narrow gap between the theoretical ideas and commercial potential.”*

*– Perimeter Director Robert Myers*

*Chong Wang, Perimeter archives*

*Laurent Freidel and Puttarak Jai-akson*

# TACKLING COMPLEX QUANTUM PROBLEMS

Quantum simulation: It's new, it's game-changing, and Perimeter researchers are on the front line.

When today's scientists and engineers have a complex system to study, a computer simulation is usually their first step. But when it comes to quantum systems, they hit a wall, because classical computers simply can't keep track of more than a handful of quantum variables.

For example, superconductors are a class of special materials in which electrons flow without resistance. Researchers around the world would love to understand this phenomenon better, but because the behaviour of these electrons is fundamentally quantum, simulating a system of just 30 electrons requires a top-of-the-line supercomputer. Simulating one with 300 electrons would require a computer with more bits of memory than there are atoms in the universe.

But there's an alternative: use quantum bits to track quantum variables.

Quantum simulation is the first practical implementation of this simple and powerful idea. Boiled down, it's the practice of learning about complex quantum systems by studying simpler, more controllable ones. As it becomes practical, it marks the beginning of an era in which simulators can tackle complex quantum problems – helping design materials for everything from batteries to pharmaceuticals, and opening the study of complex quantum systems from Bose-Einstein condensates to black hole interiors.

- The first step in any quantum simulation is setting up the quantum systems being studied. Systems are easiest to handle and understand in their ground state – just like it's easiest to understand a flock of birds if they're sitting on the ground. States in flight – states with a finite temperature, in the parlance – are more difficult but, naturally, more interesting and more widely applicable. This year, Faculty member Tim Hsieh developed a powerful, flexible protocol for setting up such finite-temperature states. Hsieh then worked with experimentalist Chris Monroe to implement the protocol in a world-leading ion trap facility, successfully creating what's known as a "thermofield double state" in the lab. It's a proof of concept for the protocol, and it's of immediate use to theorists: the entanglement structure of thermofield double states plays a key role in understanding the quantum aspects of black holes.
- Testing the validity of quantum simulation results is vital – and tricky. Associate Faculty member Roger Melko and his team collaborated with experimentalists at Harvard on a validation strategy involving machine learning. First, the experimentalists implemented a quantum state on their simulator. Then, using measurement data produced from the experiment, Melko's team attempted to reconstruct the state virtually in a neural network. The project was meant to challenge the neural network, but the script was flipped when Melko's team unexpectedly uncovered an error in the quantum simulator. The surprising result demonstrates the powerful role machine learning can play in understanding quantum simulation and quantum systems more generally.

As these Perimeter researchers lay the fundamental groundwork to push the field of quantum simulation forward, others are using quantum simulation to tackle problems that used to be out of reach. For instance, Faculty member Beni Yoshida used quantum simulation to study the inside of black

holes – particularly the way the information inside them gets scrambled. The landmark work not only provides the first verification of quantum information scrambling phenomena in the laboratory but also opens a new line of research: the laboratory simulation of quantum gravity phenomena.

Perimeter's varied work in quantum simulation is a beautiful example of how theory and experiment interact: new ideas and protocols make new experiments and technologies possible, and new experiments and technologies allow theorists to ask new questions. This exchange, where new paradigms meet new prototypes, has happened only a handful of times in the history of modern physics – and the result has always been revolutionary progress.

References:

J. Wu, T. Hsieh (Perimeter Institute), "Variational thermal quantum simulation via thermofield double states," *Phys. Rev. Lett.* 123, 220502, 2019, arXiv:1811.11756.

W.W. Ho (Harvard), T. Hsieh (Perimeter Institute), "Efficient variational simulation of non-trivial quantum states," *SciPost Phys.* 6 (29), 2019, arXiv:1803.00026.

D. Zhu (U. Maryland), S. Johri (Intel), N.M. Linke (U. Maryland), K.A. Landsman (U. Maryland), N.H. Nguyen (U. Maryland), C. Huerte Alderete (U. Maryland), A.Y. Matsuura (U. Maryland), T.H. Hsieh (Perimeter Institute), C. Monroe (U. Maryland), "Generation of thermofield double states and critical ground states with a quantum computer," *PNAS* 177(41), 2020, arXiv:1906.02699.

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, 2019, arXiv:1806.02807.

G. Torlai (Perimeter Institute), B. Timar (Caltech), E.P.L. van Nieuwenburg (Caltech), H. Levine (Harvard), A. Omran (Harvard), A. Keesling (Harvard), H. Bernien (U. Chicago), M. Greiner (Harvard), V. Vuletić (MIT), M.D. Lukin (Harvard), R.G. Melko (Perimeter Institute/ U. Waterloo), M. Endres (Caltech), "Integrating neural networks with a quantum simulator for state reconstruction," *Phys. Rev. Lett* 123, 230504, 2019, arXiv:1904.08441.

# DEMYSTIFYING THE EARLY UNIVERSE

*Christine Muschik*

Associate Faculty member Christine Muschik has expanded her team's "quantum simulation toolbox," which uses quantum and classical computing to simulate the behaviours of fundamental particles and forces. Muschik, who leads a new Perimeter-IQC joint initiative called Quantum Simulations of Fundamental Interactions, is working toward demystifying the high energy particle physics of the early universe, the internal workings of neutron stars, and many other open questions in theoretical physics.

Increasingly powerful quantum computers make it possible to create more accurate, complete, and complex models of quantum interactions. This past year, Muschik's team progressed on "lattice gauge theories," which treat space as a lattice of tiny particles rather than a smooth continuum. She is already in contact with experimental physicists about testing her team's simulations against real-world observations.

"Quantum technologies are developing rapidly. That represents an enormous scientific opportunity," Muschik says. "For future work, it would be fantastic to explore whether our hybrid quantum-classical algorithms could benefit from machine learning methods to push this technology even further."

# A QUANTUM LEAP

Quantum simulators can be thought of as single-purpose quantum computers. Like the analog computers of the 1940s, quantum simulators create a physical analog of the system under study. Like the computers of the 1940s, quantum simulators let researchers grasp problems that 10 years prior they could not even have reached for.

But for all their promise and all their immediate payoffs, quantum simulators are not the end of the line. A different kind of quantum computer – a general purpose, digital quantum computer – is on the horizon. Researchers at Perimeter are helping lay the groundwork for this second and more powerful wave of quantum computation.

For instance, one of the biggest challenges facing quantum computers is measurement error, and postdoctoral researcher Lena Funcke and collaborators have developed a method for reducing it. Powerfully general, the new method can be applied to any operator, any number of qubits, and any realistic bit-flip probability. The team verified their idea mathematically, then successfully tested it on IBM quantum hardware – ultimately reducing measurement error by an order of magnitude.

It's a tenfold leap toward our quantum future.

Reference:

L. Funcke (Perimeter Institute), T. Hartung, K. Jansen, S. Kühn, P. Stornati, X. Wang, "Measurement error mitigation in quantum computers through classical bit-flip correction," arXiv:2007.03663.

*Lena Funcke*

*Flaminia Giacomini*

# CLOCKS GO QUANTUM

"There is a problem with time."

That's how postdoctoral researcher Flaminia Giacomini boils down the big idea behind her research.

This new work starts where much of modern physics starts: with the rueful recognition that we have not one theory of the universe, but two. There's the generalization of quantum mechanics, known as quantum theory, and Einstein's theory of gravity, known as general relativity. They have proven notoriously difficult to combine, in part because they have different underlying ideas. Time is one of them.

Quantum time is actually the simpler of the two: at the quantum level, time ticks reliably along in the background, and measuring it simply entails looking at the appropriate clock.

Things are more complicated with relativity.

"In general relativity, time is dynamical," Giacomini says. That is, in general relativity, a clock is influenced by what's around it. Specifically, time bends and stretches near objects with mass. As clocks move past such an object, things can get messy, says Giacomini: "You can have different clocks which follow different trajectories, and they can tick differently."

Giacomini and her colleagues at the University of Vienna designed a thought experiment to combine Einsteinian and quantum views of time.

First, the researchers considered what would happen if physical clocks were placed in some gravitational field.

According to Einstein's general theory of relativity, a clock will run more slowly if placed next to a massive object, like a planet or a star. "Lower is slower," says Giacomini. "The closer to the mass, the slower the clock."

Next, the team layered on the quantum perspective. In quantum theory, a particle can have an uncertain position: until it is measured, it exists not in one position but in a range of possible positions. If a clock were placed next to a massive particle in such an uncertain position, then the ticking of the clock would become uncertain as well.

Add a second clock, and things become truly strange. The clocks will differ not only on what time an event happens but on whether an event happens at a precise time at all.

This groundbreaking work requires physicists to revise their concept of an "event" as something that happens at a precise point in time. In this work, a moment in time becomes as ambiguous and probabilistic as the location of a quantum particle.

The implications are profound. This uncertainty means that the tick of one clock can happen both before and after the tick of another. Events can no longer be definitively labelled first and second, before and after, cause and effect.

Moving forward, Giacomini plans to explore how factoring in the observer's frame of reference might help resolve or further illuminate the apparent uncertainty of time.

A reference frame tells you, say, whether you are on a fast-moving spaceship with a clock or watching the spaceship go by. In general relativity, it's always possible to ignore the bending of spacetime if you pick the right local reference frame. The Vienna team discovered that with the right reference frame, time can once again appear precise.

Giacomini has already developed the formalism for jumping into and out of such reference frames – made tricky because the relationships between different quantum reference frames can also create uncertainty. Now, she is pushing these difficult ideas even further. She wants to build these reference frames into "a superposition of spacetimes," she says. In other words, she envisions a reference frame that is both here and there, both before and after.

It's a challenging project, but one with big rewards.

"We quickly arrive at very deep questions about the nature of the world that we live in," Giacomini says.

And there's nothing like deep questions to fuel the search for deep answers.

*Flaminia Giacomini holds the Yvonne Choquet-Bruhat Postdoctoral Fellowship at Perimeter.*

Reference:

E. Castro-Ruiz (IQOQI Vienna), F. Giacomini (Perimeter Institute), A. Belenchia (Queen's University, Belfast), Č. Brukner (IQOQI Vienna), "Quantum clocks and the temporal localisability of events in the presence of gravitating quantum systems," *Nature Communications* 11, 2672, 2020, arXiv:1908.10165.

# LARGEST 3D MAP OF THE UNIVERSE

Some of the most significant gaps in our exploration of the history of the universe were filled in this year thanks to new analysis from the Sloan Digital Sky Survey (SDSS).

In July, SDSS released a comprehensive analysis of the largest three-dimensional map of the universe ever created. At the heart of the new results are detailed measurements of more than 2 million galaxies and quasars, covering 11 billion years of cosmic time, which have helped researchers make precise measurements of the expansion of the universe over time.

The results come from the Extended Baryon Oscillation Spectroscopic Survey (eBOSS), the latest of the SDSS's component surveys, for which Perimeter Associate Faculty member Will Percival is the survey scientist. It's a culmination of 15 years of work for Percival, who is also the director of the Waterloo Centre for Astrophysics at the University of Waterloo, where he holds the Mike and Ophelia Lazaridis Distinguished Chair in Astrophysics.

"We're incredibly proud of the results from eBOSS, but also of the tools and mechanisms we've developed to analyze the data," said Percival. "They will be an enormous asset as the next generation of galaxy surveys come online."

References:

23 papers were produced from this research, including:

eBOSS collaboration, "The completed SDSS-IV extended Baryon Oscillation Spectroscopic Survey: Large-scale structure catalogues for cosmological analysis," *MNRAS* 498 (2), 2020.

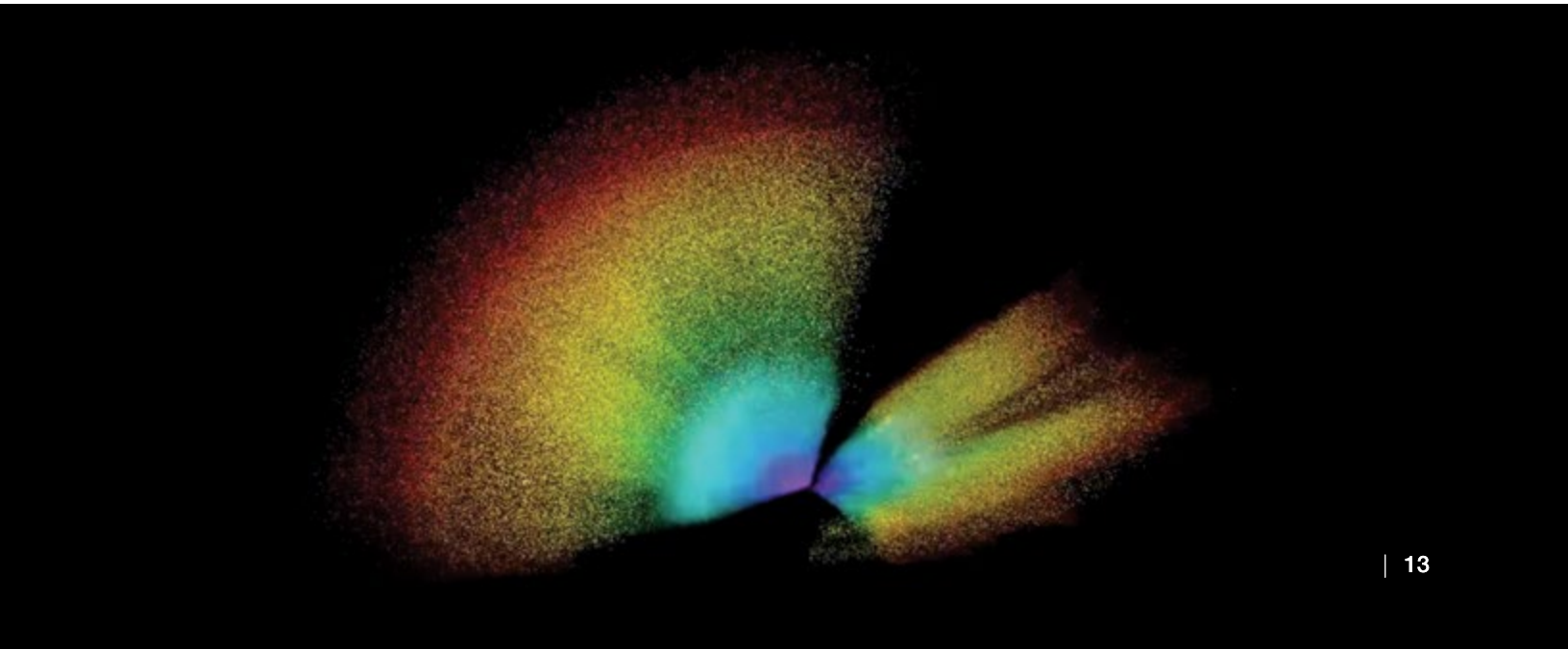
eBOSS collaboration, "The completed SDSS-IV extended Baryon Oscillation Spectroscopic Survey: Measurement of the BAO and growth rate of structure of the luminous red galaxy sample from the anisotropic power spectrum between redshifts 0.6 and 1.0," *MNRAS* 498 (2), 2020.

eBOSS collaboration, "The completed SDSS-IV extended Baryon Oscillation Spectroscopic Survey: BAO and RSD measurements from anisotropic clustering analysis of the quasar sample in configuration space between redshift 0.8 and 2.2," *MNRAS* 498 (2), 2020.

eBOSS collaboration, "The completed SDSS-IV extended Baryon Oscillation Spectroscopic Survey: BAO and RSD measurements from the anisotropic power spectrum of the quasar sample between redshift 0.8 and 2.2," *MNRAS* 498 (2), 2020.

eBOSS collaboration, "The completed SDSS-IV extended Baryon Oscillation Spectroscopic Survey: cosmological implications from two decades of spectroscopic surveys at the Apache Point observatory," arXiv:2007.08991.

*This map shows 11 billion years of the universe's history, with galaxies closest to Earth appearing in purple and blue, and distant galaxies in yellow and red. (Image © EPFL)*



*Davide Gaiotto and Kevin Costello, Perimeter archives*

PEOPLE

# MATH AND PHYSICS: BETTER TOGETHER

Kevin Costello is a mathematician. Davide Gaiotto is a mathematical physicist. Together, they are a powerful scientific force.

For centuries – at least as far back as Newton inventing calculus to make classical mechanics work – math and physics have worked alongside, against, and across each other. The boundaries between them have proven blurry and shifting, and are sometimes fiercely defended. Physicists and mathematicians do not normally work hand in hand.

But at Perimeter, it's different. Costello and Gaiotto work mostly together – in fact, they hold a pair of prestigious named chairs funded by the Krembil Foundation. Their collaboration has produced landmark work at a rapid pace. To the pair, that's proof of the power of true collaboration between mathematics and physics – something they believe is too rare.

"Other places have tried to bring math and physics together, but I'm not sure if they've been successful," says Costello.

"But at Perimeter our students are all here, together," Gaiotto says. "And not just the students. We are getting more mathematicians in the building, and we have a high concentration of physicists who are interested in math."

Adds Costello: "We've even convinced some of the very pure mathematicians to talk about quantum field theory." In the summer of 2019, the pair helped organize a workshop called "QFT for Mathematicians," which – to their delight – attracted some high-level participants.

"We are making a concrete effort to make things happen," says Gaiotto. "These collaborations are not just accidental. On the other hand, it's not that I think math needs to become more physical, or vice versa."

"Each field has its own biases," Costello says.

"Each has strengths and weaknesses," adds Gaiotto. "But one thing I'm sure of is – we do better together."

*Kevin Costello holds the Krembil William Rowan Hamilton Chair in Theoretical Physics, and Davide Gaiotto holds the Krembil Galileo Galilei Chair in Theoretical Physics.*

# CAN PHYSICS HELP IN THE FIGHT AGAINST COVID-19?

Cosmologists are not going to be the ones who defeat COVID-19. But as the novel coronavirus pandemic began to sweep the world in the spring of 2020, many researchers at Perimeter volunteered to use their skills in mathematics, modelling software, and problem solving to support health science researchers. Here are a few of the results:

## MUTATION TRACKING SOFTWARE

Faculty member Kendrick Smith is a cosmologist who's a world expert in developing mathematical techniques and software that extract fundamental physics from astronomical data. During the pandemic, Smith put his skills at the service of researchers from McMaster University and Sunnybrook Hospital, helping them develop a software pipeline for genetic sequencing of COVID-19 virus samples. The software, called SIGNAL, quickly became the main genetic sequencing software used in Ontario to better understand the virus's spread.

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

Reference: J.A. Nasir (McMaster), R.A. Kozak (Sunnybrook), P. Aftanas (Sunnybrook), A.R. Raphenya (McMaster), K.M. Smith (Perimeter Institute), F. Maguire (Dalhousie U.), H. Maan (University Health Network), M. Alruwaili (U. Liverpool), A. Banerjee (McMaster), H. Mbareche (Sunnybrook), B.P. Alcock (McMaster), N.C. Knox (National Microbiology Laboratory), K. Mossman (McMaster), B. Wang (University Health Network), J.A. Hiscox (U. Liverpool), A.G. McArthur (McMaster), S. Mubareka (Sunnybrook), "A comparison of whole genome sequencing of SARS-CoV-2 using amplicon-based sequencing, random Hexamers, and bait capture," *Viruses* 12(8), 2020, PMID: 32824272.

## BATCH TESTING SCHEMES

To make COVID-19 testing more widely available, Faculty member Neil Turok worked with colleagues at the African Institute for Mathematical Sciences, or AIMS, to develop new algorithms for "pooled testing" – the practice of combining samples from many people to test them together.

Pooled testing isn't a new idea, but Turok and colleagues found a new way to approach it. Their method, based on the geometry of cubes with more than three dimensions, can drastically reduce the number of tests needed and identify infected individuals within the pool. It is now being trialled in Rwanda and South Africa, where it has reduced the cost of mass COVID-19 testing by a factor of 15.

*Neil Turok holds the Mike and Ophelia Lazaridis Niels Bohr Chair in Theoretical Physics.*

Reference: L. Mutesa (U. Rwanda), P. Ndishimye (AIMS), Y. Butera (U. Rwanda), J. Souopgui (U. Rwanda), A. Uwineza (U. Rwanda), R. Rutayisire (U. Rwanda), E.L. Ndoricimpaye (Rwanda COVID Task Force), E. Musoni (Rwanda COVID Task Force), N. Rujeni (Rwanda COVID Task Force), T. Nyatanyi (Rwanda COVID Task Force), E. Ntagwabira (Rwanda COVID Task Force), M. Semakula (Rwanda COVID Task Force), C. Musanabaganwa (Rwanda COVID Task Force), D. Nyamwasa (Rwanda COVID Task Force), M. Ndashimye (AIMS), E. Ujeneza (AIMS), I.E. Mwikarago (Rwanda COVID Task Force), C. Mambo Muvunyi (Rwanda COVID Task Force), J.B. Mazarati (Rwanda COVID Task Force), S. Nsanzimana (Rwanda COVID Task Force), N. Turok (Perimeter Institute), W. Ndifon (AIMS), "A pooled testing strategy for identifying SARS-CoV-2 at low prevalence," *Nature*, 2020.

## LOCAL OUTBREAK MODELLING

Associate Faculty member Niayesh Afshordi is an astrophysicist who describes himself as obsessed with observational hints about the dark universe. Like astronomers finding out how dark matter and dark energy work by studying galaxy surveys, Afshordi and his collaborators from the University of Waterloo and computational science giant Wolfram Research analyzed the entire set of local US COVID-19 epidemics to pinpoint their drivers.

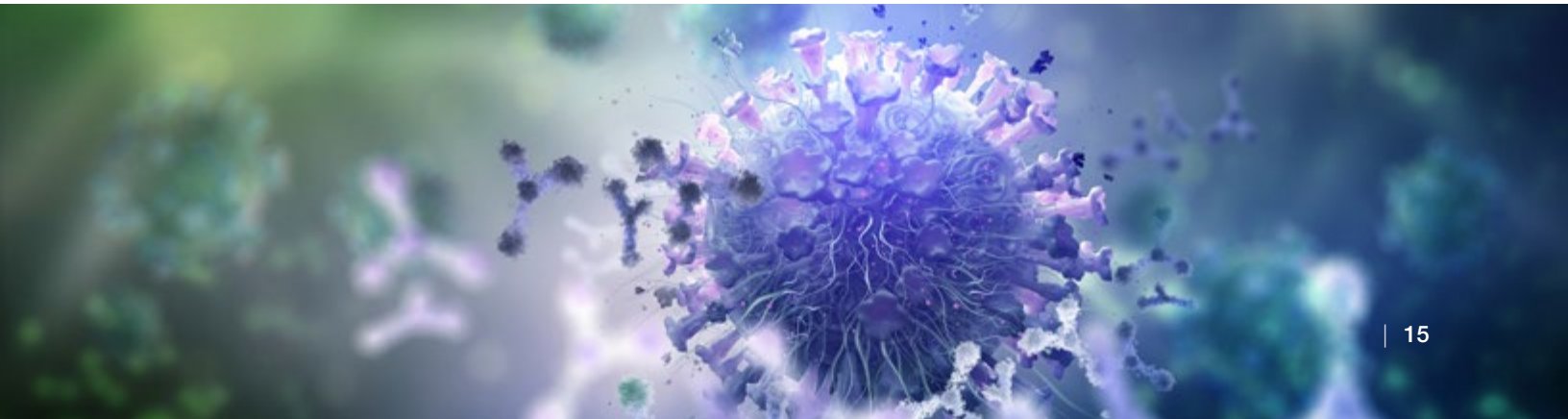
Then, the team used statistical techniques from cosmology to build a model of town-by-town, county-by-county coronavirus behaviours. The finished model is now available as a public dashboard that can help local authorities plan well and save lives.

Reference: N. Afshordi (Perimeter Institute/U. Waterloo), B. Holder (U. Waterloo), M. Bahrami (Wolfram), D. Lichtblau (Wolfram), "Diverse local epidemics reveal the distinct effects of population density, demographics, climate, depletion of susceptibles, and intervention in the first wave of COVID-19 in the United States," arXiv:2007.00159.

## NETWORK THEORY MODELLING

Postdoctoral researcher Mark Penney put his work on mathematical physics aside, joining forces with mathematical biologists from the University of Waterloo and the University of Guelph to build a computational model of how COVID-19 spreads. With an unusual approach to modelling based on network theory and on the physics of percolation, the team is developing powerful new understandings of how the coronavirus percolates through our social networks.

Their work could have several useful payoffs. For example, they believe that a strategy of vaccinating "highly connected" people – identified through a COVID alert exposure notification app – could achieve herd immunity with far fewer vaccinated individuals.



# EQUITY, DIVERSITY, AND INCLUSION

## CHANGING THE FACE OF RESEARCH

*"It was a rare privilege for me to be in an institute with so many colleagues with whom I could discuss research projects and potentially collaborate."*

*– Katie Mack, 2019/20 Simons Emmy Noether Fellow*

Many of the greatest contributions to science have come from members of previously excluded groups who brought new perspectives and insights – Albert Einstein and Emmy Noether being standouts of the 20th century. Perimeter Institute recognizes that imbalances persist, both in theoretical physics in general and at Perimeter. We are taking concrete actions to increase equity, diversity, and inclusion.

### PERIMETER INITIATIVES, 2019/20

This year, we initiated a partnership with ShiftHealth to work with the whole Perimeter community to develop an institutional roadmap and action plan for equity, diversity, inclusion, and accessibility.

Equity, diversity, and inclusion considerations have been integrated into all faculty searches.

Flaminia Giacomini was appointed to the Yvonne Choquet-Bruhat Fellowship, one of several postdoctoral fellowships named after famous female researchers that were created to help attract outstanding women researchers.

The work of the Inclusive PI Platform, made up of 50 members organized into 11 working groups, continues. Led by Perimeter researchers, staff, and students, the Platform empowers all members of the Perimeter community to engage in equity, diversity, and inclusion efforts; build community; and create a great working environment. Working groups address topics including mentoring, mental health, organization of seminars and meetings, diversity in physics, accessibility, and career and parental support.

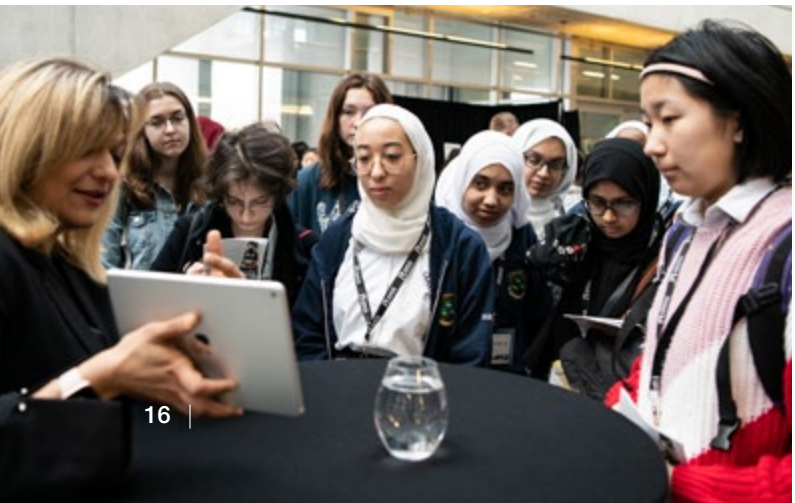
Achievements in 2019/20 include the following:

- The mental health working group organized regular lunches for Perimeter residents to discuss mental health issues and learn about the support offered by Perimeter.
- The harassment policy working group rewrote anti-harassment policies with straightforward, unambiguous language.
- The LGBTQ+ working group presented an informative and well-attended workshop on inclusivity in the workplace and organized a number of social events.
- The parental policies working group identified a need for more support for parents working at home during the pandemic. As a result, Perimeter provided temporary assistance with childcare to those who needed it.

The Outreach team consulted with Indigenous teachers in northern communities and in Nova Scotia to help shape educational resources and delivery methods (more info on page 34).

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

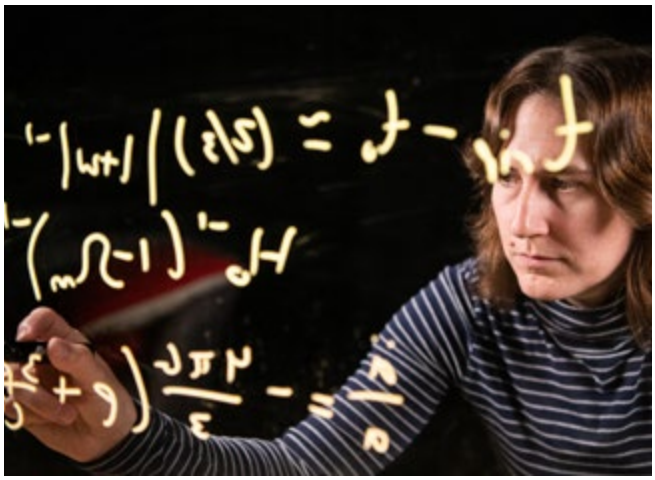
*"Inspiring Future Women in Science" conference, March 2020*



### EMMY NOETHER INITIATIVES

Perimeter's initiatives to bring and retain more women in science are collectively referred to as the Emmy Noether Initiatives, named after pioneering German mathematician Emmy Noether, whose work underpins much of modern physics. The Emmy Noether Initiatives aim to empower and support women to enter and succeed in physics. The initiatives range from outreach to high school students, to graduate training and career development opportunities for women scientists. They are supported, in part, through the generosity of the Emmy Noether Council and donors.

# SIMONS EMMY NOETHER FELLOWS PROGRAM



*Katie Mack*

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

Each fellow receives individually tailored supports that can include any (or all) of the following: teaching buyouts, travel expenses, housing, childcare, partial support to bring spouses or partners, support to bring graduate students and/or postdoctoral researchers from the fellow's home research group, and extensive administrative and logistical support. Many Simons Emmy Noether Fellows return in subsequent years, building ties to Perimeter and the wider scientific community. The program is having a remarkable impact:

In 2019/20:

- Eight fellows and visiting fellows spent a total of 368 days on collaboration and research at Perimeter Institute.
- More than 25 papers by current and past fellows resulting from their research visits were published, written, or updated.
- Seven fellows delivered 11 talks at Perimeter, including a public lecture by Katie Mack that has more than 18,000 views on YouTube.
- The international visibility and collaborative research opportunities inherent in the fellowships played a significant role in several successful fellowship and grant applications.
- Cosmologist Katie Mack finished her book *The End of Everything (Astrophysically Speaking)* while at Perimeter. The book was a *New York Times* editors' choice in August 2020.

## 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

**Sandra Wear**

## 2019/20 SIMONS EMMY NOETHER FELLOWS[2]

**Sayantani Bhattacharyya**, School of Physical Sciences, National Institute of Science Education and Research

**Cecilia Chirenti**, Universidade Federal do ABC

**Lavinia Heisenberg**, ETH Zurich

**Wei Li**, Institute of Theoretical Physics, Chinese Academy of Science

**Katie Mack**, North Carolina State University

**Catherine Meusburger**, Friedrich-Alexander University Erlangen-Nürnberg

**Monika Mościbrodzka**, Radboud University

**Sylvie Paycha**, University of Potsdam

*"There was a long-term problem that I was in the process of solving step by step, which I had already spent more than two years and was planning to spend another two years. But while at Perimeter, during discussion with another visitor (Masahito Yamazaki), we solved this problem using a different method. This collaboration was almost a serendipity because before our discussion, he wasn't working on this problem and I wasn't familiar with one crucial technique of which he is the expert."*

*– Wei Li, 2019/20 Simons Emmy Noether Fellow*

[2] *The visits of three of the newly appointed Simons Emmy Noether Fellows were deferred due to the pandemic.*

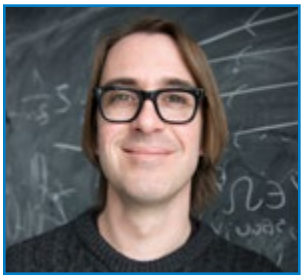
# HONOURS, AWARDS, AND MAJOR GRANTS

- **Avery Broderick**, Associate Faculty and Delaney Family John Archibald Wheeler Chair, earned several awards as part of the Event Horizon Telescope collaboration, including the 2020 Breakthrough Prize; the Einstein Medal, Albert Einstein Society; the Nelson P. Jackson Aerospace Award, National Space Club and Foundation; the 2020 Bruno Rossi Prize, American Astronomical Society; and the American Ingenuity Award in Physical Sciences, Smithsonian Institution.
- **Niayesh Afshordi**, Associate Faculty, earned the 2019 Buchalter Cosmology Prize — marking the sixth consecutive year the prize has recognized Perimeter research.
- **Kevin Costello**, Faculty and Krembil William Rowan Hamilton Chair, won the Eisenbud Prize for Mathematical Physics, American Mathematical Society, and was named an Honorary Member of the Royal Irish Academy.
- **Matthew Johnson**, Associate Faculty, was a member of the Quantum Simulators for Fundamental Physics Consortium that received a major grant from the UK Science and Technology Facilities Council.
- **Luis Lehner**, Faculty Chair, was named to the 2019 TD list of the 10 most influential Hispanic Canadians.
- **Christine Muschik**, Associate Faculty, earned a Sloan Research Fellowship for outstanding early-career researchers, Alfred P. Sloan Foundation, and was named an Azrieli Global Scholar for exceptional early-career researchers, Canadian Institute for Advanced Research.
- **Ue-Li Pen**, Associate Faculty, received a Humboldt Research Award, Humboldt Foundation, and a Simons Investigator Award. He also shared in the Governor General's Innovation Award as part of the CHIME collaboration and in the 2020 Breakthrough Prize as part of the Event Horizon Telescope collaboration.
- **Kendrick Smith**, Faculty and Daniel Family James Peebles Chair, along with Associate Faculty **Ue-Li Pen**, Computational Scientist Dustin Lang and other Perimeter researchers, received the Governor General's Innovation Award as part of the CHIME collaboration. Smith was also awarded the 2020 New Horizons in Physics Prize from the Breakthrough Foundation.
- **Sebastian Steinhaus**, postdoctoral researcher, won a prestigious €1 million research grant from the German Research Foundation's Emmy Noether Programme.
- **Pedro Vieira**, Faculty and Clay Riddell Paul Dirac Chair, received a renewal of the Simons Non-Perturbative Bootstrap Collaboration – Large International Group Grant as principal investigator, and the 2020 New Horizons in Physics Prize from the Breakthrough Foundation.
- **Huan Yang**, Associate Faculty, received the University of Guelph CEPS Assistant Professor Research Excellence Award.

In 2019/20, Perimeter scientists were awarded $1.45 million in new research grants from the Natural Sciences and Engineering Research Council of Canada, as well as grants and awards from other organizations.

# PERIMETER RESEARCHERS RECOGNIZED

## EISENBUD PRIZE AWARDED TO COSTELLO



Perimeter Faculty member Kevin Costello was awarded the 2020 Leonard Eisenbud Prize for Mathematics and Physics from the American Mathematical Society for his influential work to bring mathematics and physics closer together. Costello, who holds the Krembil William Rowan Hamilton Chair, is a leading mathematical physicist whose research uses tools from mathematics to explore string theory and quantum field theory.

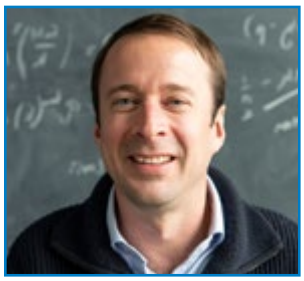
"He is respected by mathematicians and physicists alike and plays a unique role in breaking new and fertile ground on which the two communities can jointly develop directions of research, even while coming to a fuller understanding of important known phenomena," the Eisenbud citation states.

Costello said it was a great honour to receive the prize, which is awarded every third year, but was quick to say that the prize was just as much about his collaborators and Perimeter's research environment. "It's something that Perimeter does really well, this interdisciplinary research between math and physics," Costello said.

Originally from Cork, Ireland, Costello was also admitted as an Honorary Member of the Royal Irish Academy this year. The Royal Irish Academy is an independent forum founded in 1785, and election to membership of the Academy is considered the highest academic distinction in Ireland. Honorary membership is usually reserved for academics who have made a major contribution to their disciplines but who do not live in Ireland.

"It is said that the book of nature is written in the language of mathematics, and no one speaks that language more eloquently than Kevin Costello," said Perimeter Director Rob Myers. "His work is exactly the kind of research Perimeter strives for: bold, ambitious, and deep."

## CHIME RECEIVES GOVERNOR GENERAL'S INNOVATION AWARD



Perimeter Faculty member Kendrick Smith, Associate Faculty member Ue-Li Pen, Computational Scientist Dustin Lang, and PhD students Masoud Rafiei-Ravandi and Utkarsh Giri are all part of the Canadian Hydrogen Intensity Mapping Experiment (CHIME) collaboration. CHIME is an innovative radio telescope that has electrified the field of radio astronomy by detecting hundreds of fast radio bursts, powerful signals emanating from deep space. The entire CHIME team, which includes more than 50 scientists from Perimeter, McGill University, the University of British Columbia, the University of Toronto, and the National Research Council of Canada, was honoured for its work with the 2020 Governor General's Innovation Award.

"CHIME is a remarkable Canadian success story that is transforming our understanding of fast radio bursts, and has the potential to do much more," said Perimeter Director Rob Myers. "We're proud to be contributing to that success."

## MUSCHIK NAMED AZRIELI GLOBAL SCHOLAR

Associate Faculty member Christine Muschik has been named a Azrieli Global Scholar by the Canadian Institute for Advanced Research (CIFAR) for 2020-22. The prestigious program empowers early-career researchers to move beyond their own realms of expertise; to collaborate with researchers from other disciplines; and to find deeper, broader, and more complex answers to major scientific challenges.

Muschik is also an assistant professor at the University of Waterloo's Institute for Quantum Computing. As an Azrieli Scholar, she will expand her work in quantum simulation to explore fundamental mysteries about the origins and nature of physical reality itself.

"Consider a question like, 'Why does the universe have more matter than antimatter?' That's a question about why we even exist," she says. "Working with CIFAR – as well as with the Perimeter and the University of Waterloo – presents an amazing opportunity to explore these kinds of big questions from many different perspectives."

# RESEARCH COMMUNITY

## FACULTY AND ASSOCIATE FACULTY

In 2019/20, Perimeter Institute was home to 24 faculty members across nine research areas. Perimeter welcomed one new associate faculty member, Sergey Sibiryakov, who is cross-appointed with McMaster University, bringing the total to 22 associate faculty jointly appointed with nine partner universities across Canada.

For a full list of faculty and associate faculty, including biographies, see pages 51-58.

PEOPLE

Associate Faculty

### SERGEY SIBIRYAKOV

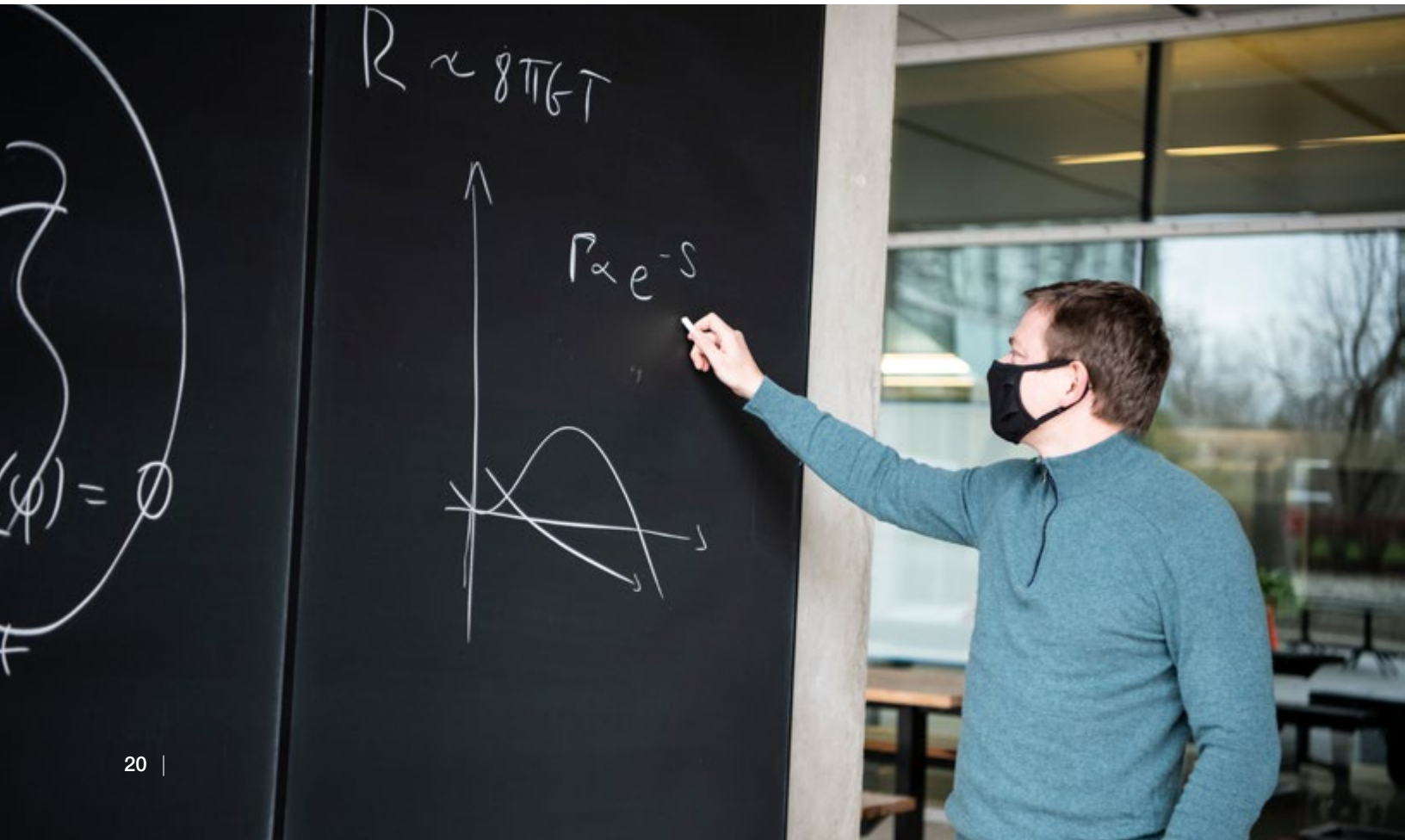
From the tiniest building blocks to the vast reaches of space, fundamental physics is done on a broad range of scales. Out of practicality, physicists tend to focus their research on some small part of that scale.

Sergey Sibiryakov, Perimeter Institute's newest associate faculty member, eschews that method. Sibiryakov's research interests span the breadth of scales: from high energy physics (including particle physics experiments) to cosmology, astrophysics, and the theory of gravity. "And, sometimes, more formal questions of quantum field theory," he adds. "My philosophy is to work on what is interesting to me – to learn something new."

"Sergey is an outstanding addition to Perimeter's faculty. He exemplifies the cross-disciplinary research that we aim to cultivate here at the Institute," says Perimeter Director Rob Myers.

Sibiryakov, who is cross-appointed with McMaster University, is looking forward to forging new connections at Perimeter, particularly with young researchers. "Students have fresh eyes on things," Sibiryakov says. "They start asking questions that would not come to your mind. That's very important."

*Sergey Sibiryakov*



*Mairi Sakellariadou, Sylvie Paycha, and Renate Loll at the "Emmy Noether Workshop: The Structure of Quantum Space Time," November 2019*

## VISITING FELLOWS, VISITING RESEARCHERS, AND AFFILIATE MEMBERS

Perimeter engages with the wider scientific community while diversifying its own by bringing accomplished researchers to the Institute for regular visits in several ways.

**Visiting Fellows** are appointed to renewable terms, retain their positions at home institutions, and enrich the Perimeter research community during their extended stays. In 2019/20, Visiting Fellows spent 536 days at the Institute. Five new Visiting Fellows were appointed, and seven others renewed, for a total of 55.

**Affiliate members** are scientists from Canadian universities who have an open invitation to visit Perimeter at any time to do research. This year, 18 Affiliate members were appointed or renewed, bringing the total to 108.

We also encourage applications from scientists to come as **Visiting Researchers** while on sabbatical leave from their faculty positions at home institutes. In 2019/20, seven Visiting Researchers made extended visits for a total of 953 research days.

## 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

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

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

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

**Kevin Costello**
Krembil William Rowan Hamilton Chair in Theoretical Physics

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

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

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

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

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

# WHAT PERIMETER DISTINGUISHED VISITING RESEARCH CHAIRS SAY

*"Being a Perimeter DVRC has been wonderful for me. It allows me to work uninterrupted for an extended period of time during my typically monthlong visits. This period of concentration is almost impossible to find elsewhere. Secondly, there are always amazing physicists at PI with whom I really value talking and finding out what they are thinking about."*

*– Katie Freese, University of Texas at Austin*

*"I have visited many research centers all over the globe, and only at PI I felt that I was submerged in the atmosphere where mathematicians can really learn new ideas from physicists, and vice versa."*

*– Yan Soibelman, Kansas State University*

*"It has been absolutely crucial to my development as a scientist. Perimeter has been an oasis in which research ideas have been germinated (often through discussions with others), developed, written, polished and published. I've found nowhere else that offers anything like the amazing environment at Perimeter for scientific discussion, seminars, and focused research."*

*– Adrian Kent, University of Cambridge*

*"Holding a Distinguished Visiting Research Chair is a great honour for me and a fantastic opportunity to take part in the magic world of PI. The free and open approach to research pioneered by PI is a lesson from which all of us can extract novel elements to be imported to our own institutions. The Distinguished Visiting Research Programme is an effective way of creating a strong network among leading research institutions across the globe, with exchanges and collaborations that are of mutual benefit."*

*– Maxim Pospelov, University of Minnesota*

## 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 a recent report on the impacts of the program, many DVRCs indicated that their collaborations resulted in new ideas and approaches, as well as published papers.

In 2019/20, DVRCs spent 294 days at the Institute. Two new DVRCs were appointed and 12 others were renewed, bringing the total to 42.

This year's new appointees are:

**Maxim Pospelov**, University of Minnesota – School of Physics & Astronomy

**Fernando Quevedo**, University of Cambridge – Department of Applied Mathematics and Theoretical Physics

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

PI PEOPLE

DVRC

### CARLO ROVELLI

Carlo Rovelli wants to turn black holes inside out. You may have heard of him: He's the author of one of the most famous popular science books of all time, *Seven Brief Lessons on Physics*. The book distills modern physics into 100 charming pages, has been published in 41 languages, and has sold more than a million copies. Or you may know him as one of the founders of loop quantum gravity, a leading candidate theory in the 80-year quest to unite general relativity with quantum mechanics.

As both writer and researcher, Rovelli keeps busy. He's published two more books and has another in the works. His continuing work on loop quantum gravity has been nothing short of field-defining.

He's also a DVRC who spent about six months at Perimeter in 2019/20, visiting from his home institution Université de la Méditerranée – Centre de physique théorique de Luminy. During that time, he completed five papers. Rovelli said that though the pandemic limited access to the Institute itself, he was able to carry on with online meetings and scientific collaboration that resulted in new projects.

"I think that the DVRC is one of the programs that makes the Perimeter a very special place. It motivates valuable people to converge; it brings a lot to the young PI researchers," he said.

*Lee Smolin and Carlo Rovelli, February 2020*

# CONFERENCES AND WORKSHOPS

In theoretical physics, advances happen fast on many fronts. Collaboration and communication are essential to this effort. Perimeter plays a key role in propelling 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 2019/20, 995 scientists from around the world attended 12 conferences and workshops hosted by Perimeter, in areas such as cosmology, quantum computing, quantum field theory, and indefinite causal structure.

See the full list of conferences on page 62.


The last three conferences planned for 2019/20 were reorganized as online events, including a conference on geometric representation theory, held jointly with the Max Planck Institute, that attracted more than 400 participants. The interactive format of the "Quantum Gravity 2020" online conference, with 172 participants, served as a blueprint for other organizations.

## WORKSHOP SEEKS TO UNIFY PHYSICS, AND TWO KEY THEORIES

Participants at the "Emmy Noether Workshop: The Structure of Quantum Space Time" gathered to tackle thorny issues, from the nature of spacetime to systemic barriers in academia. That's because most of the participants – all experts in various aspects of quantum gravity – were women.

"This is not a women's meeting – this is a meeting of quantum gravity, and it's mostly women," said Dorothea Bahns, a professor at the University of Göttingen. "For me, that's a great experience, because I think we've come a long way in 20 years. I think it's important to make this point and to convey this to others, to young students especially."

The workshop, which took place at Perimeter Institute for five days in November 2019, brought together more than 40 researchers. Several participants were current or former members of Perimeter's Simons Emmy Noether Fellows program, which provides visiting fellowships for talented women to help advance their research careers.

Bianca Dittrich, a Perimeter faculty member and one of the workshop organizers, said they kept the workshop's scientific theme deliberately broad to encourage discourse between the various approaches to quantum gravity that have sprung up in the past several decades.

"If you have very specialized workshops, people tend to also just communicate in very specialized language and don't see the advantages which you only see if you have a bit of an outside view," Dittrich said.

The mix of topics was clearly well received; by the end of the workshop, Dittrich had already received several requests to schedule a future one. "I do think it was very successful," she said.

*Participants at the "Emmy Noether Workshop: The Structure of Quantum Space Time," November 2019*


*Adam Riess (Space Telescope Science Institute) speaks at "Cosmological Frontiers in Fundamental Physics" conference, September 2019*

## SEMINARS AND COLLOQUIA

Constant learning, cross-disciplinary exploration, and open collaboration are the hallmarks of Perimeter's research community. Throughout the year, scientists, students, and visitors are invited to take part in seminars and colloquia that present the latest approaches and discoveries in theoretical physics.

Seminars and colloquia are recorded and made publicly available on the Perimeter Institute Recorded Seminar Archive (PIRSA).

In 2019/20, 289 seminars and colloquia were presented, including 56 virtual seminars, featuring speakers from outstanding institutions such as Harvard University, Max Planck Institute, Cornell University, MIT, the Institute for Advanced Study in Princeton, and York University.

*"This is an excellent idea, and this is exactly where one would expect the Perimeter Institute to take a world-wide lead – to be both at the frontier of research and at the frontier of communicating, sharing and stimulating research ideas using modern technology. We have got a long mileage out of printed words, peer reviewed publications and the like, but it is time to rethink how we do research, how we communicate in research communities."*

*– Artur Ekert, FRS Professor of Quantum Physics, Mathematical Institute, University of Oxford; Lee Kong Chian Centennial Professor, National University of Singapore Founding Director, Singapore Centre for Quantum Technologies*

## FROM PIRSA TO SCITALKS


At Perimeter, virtually all talks – whether from resident researchers, visiting scientists, course lecturers, or conference presenters – are professionally recorded and archived on PIRSA. With 13,082 talks (as of July 31, 2020), PIRSA is the largest video archive in theoretical physics worldwide. Videos have been seen by viewers in 179 countries around the world.

Created by and for researchers, PIRSA's design and organization reflect researchers' need for clear categorization by scientific subfield and for logical groupings, such as by conference, seminar series, or course title. The archive is free, searchable, and citable and is an invaluable way to share knowledge with both the Canadian and international science communities.

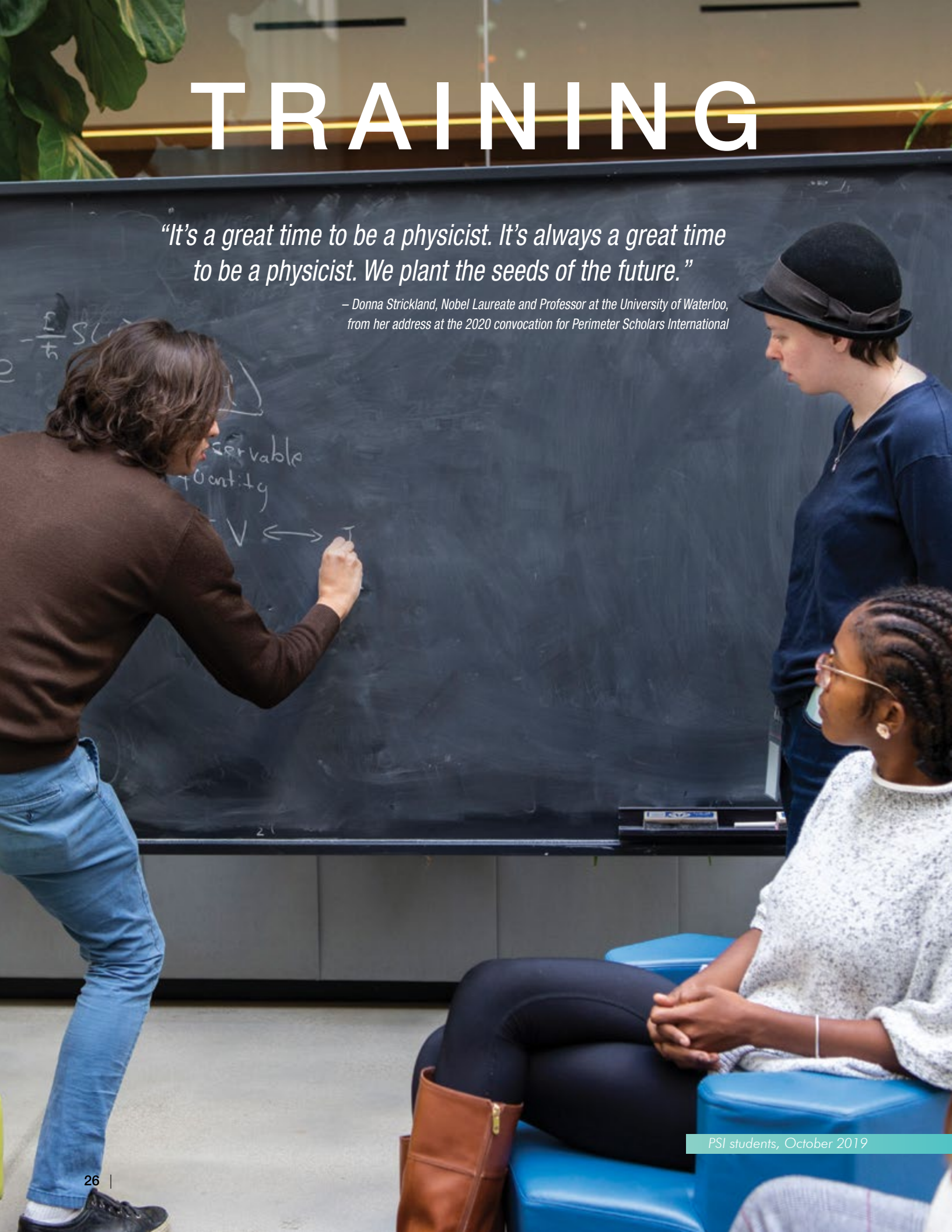
In 2020, Perimeter received a Simons Foundation grant to support the creation of a new, international hub that expands on the success of PIRSA and aims to revolutionize the world of scholarly communication in the way that the arXiv has done for print scientific papers. Directors and researchers at 40 institutions in 21 countries wrote letters of support for the grant, based on their positive experiences with PIRSA.

Perimeter accelerated the development of this project to support the global research community during the pandemic. It is now in the pilot phase and is called SciTalks (online at SciTalks.ca). This made-in-Canada video archive is home to more than 13,000 Perimeter talks and already lists talks from four prestigious international partners (with more on the way): CERN (European Organization for Nuclear Research); the Simons Institute for the Theory of Computing at the University of California, Berkeley; the International Centre for Theoretical Physics; and the South American Institute for Fundamental Research.

# TRAINING

*"It's a great time to be a physicist. It's always a great time to be a physicist. We plant the seeds of the future."*

*– Donna Strickland, Nobel Laureate and Professor at the University of Waterloo, from her address at the 2020 convocation for Perimeter Scholars International*



*PSI students, October 2019*

# **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 undergraduate enrichment program to our world-leading postdoctoral program – that aim to turn students into scientists.[3]

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

**84** Postdoctoral researchers

**77** PhD students from **33** countries

**26** Associate PhD students

**19** Visiting Graduate Fellows

**336** PSI graduates in 11 years, including **110** women (33 percent)

**26** PSI master's students, from 17 countries, including **13** women

**1** master's research student

**54** undergraduate summer school students from 21 countries, including **20** women

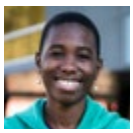
[3] *Unless otherwise indicated, figures are for August 1, 2019 – July 31, 2020.*

## POSTDOCTORAL RESEARCHERS

As full members of Perimeter's community for three to five years, these early-career scientists have complete research freedom and are encouraged to pursue ambitious research, with opportunities for cross-disciplinary collaboration and mentorship from senior scientists.

Perimeter's postdoctoral positions are highly sought after: from approximately 700 applications, 25 new postdocs joined Perimeter in 2019/20. The autonomy and experience pays off: In 2019/20, of the 22 who completed their term, several earned prestigious fellowships or grants, including Sebastian Steinhaus, who won a €1 million research grant from the German Research Foundation's Emmy Noether Programme and is now head of a junior research group at the Institute for Theoretical Physics at the University of Jena. Others have tenure track positions, including Béatrice Bonga, now an assistant professor at Radboud Universiteit Nijmegen. Two more have been hired in the private sector: a researcher and software engineer at Google and a senior data scientist at Loblaws. A total of 84 postdocs spent time at Perimeter in 2019/20; see the full list on page 59.

PEOPLE



Postdoctoral Researcher

### ESTELLE INACK

Estelle Inack works on harnessing the power of cutting-edge machine learning algorithms to study interesting problems in condensed matter and quantum computing. She was drawn to Perimeter because of its seminal work in quantum matter with artificial intelligence techniques, a burgeoning area of research that began just a few years ago.

Recently, Inack and colleagues from the Perimeter Institute Quantum Intelligence Lab (PIQuIL) and Vector Institute harnessed the power of neural networks to develop a new take on what's known as "annealing," applicable to both classical and quantum computers. Annealing is an optimization technique: it helps computers search for the best option among a range of possible solutions. Inack's neural net–powered version of annealing is already as good as the traditional methods – proof that neural nets can be useful in hard optimization problems.

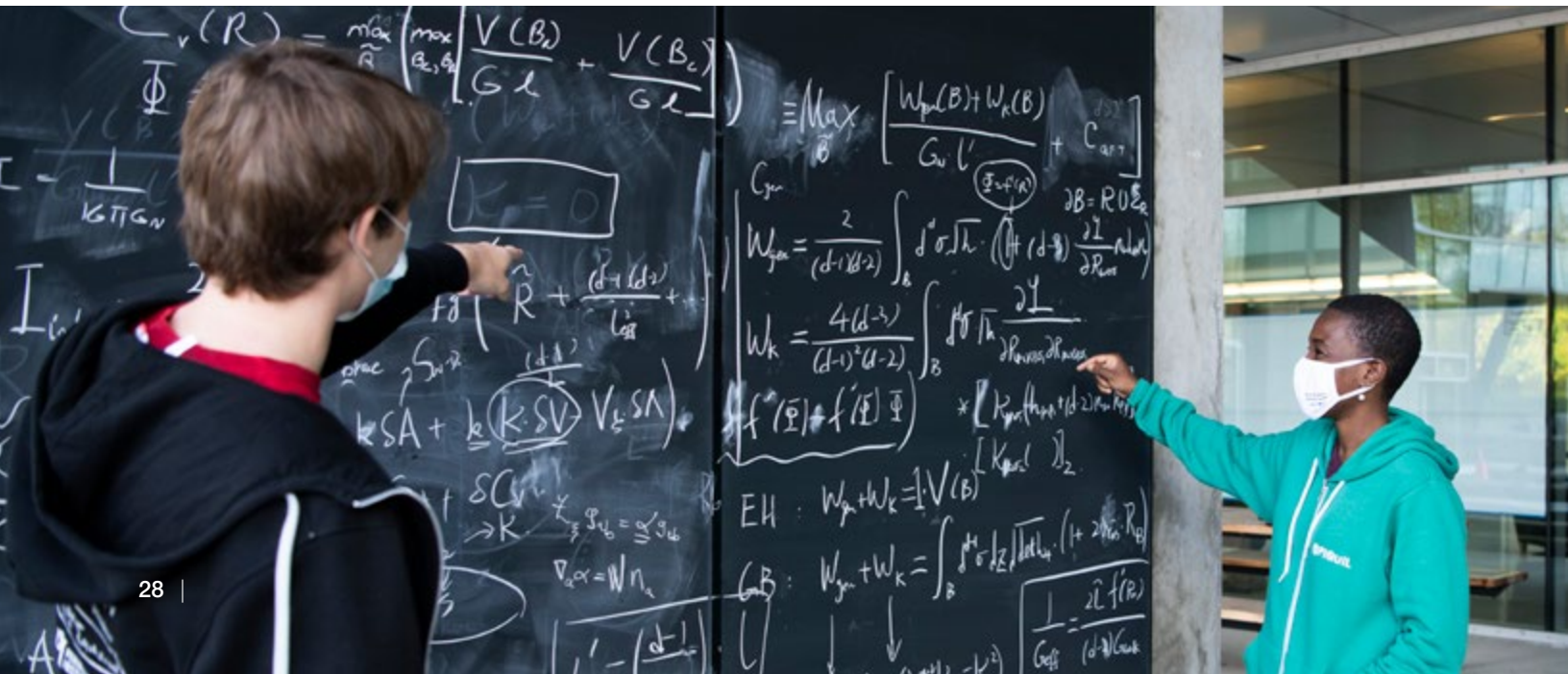
"Researchers from PIQuIL are among the pioneers in this field of study," Inack says. "The startup-like ecosystem of PIQuIL – where cross-pollination of ideas occurs between academia and industry – makes it an ideal place for me to foster my scientific career."

"The field has never been as ripe for breakthroughs as it is now, and it's exciting for me personally to watch the future of physics unfold through Estelle's work," says Roger Melko, Perimeter associate faculty member and leader of PIQuIL. "Estelle represents a new, young generation who sees the future of physics as a human-computer collaboration. Her research combining theoretical physics with the foundations of artificial intelligence will help seed the transformation of both disciplines."

Inack, who is from Cameroon, is in her second year of a four-year postdoctoral position at Perimeter.

*Estelle Inack is the Francis Kofi Allotey Postdoctoral Fellow at Perimeter Institute.*

*Estelle Inack and a visitor*



## PHD STUDENTS

Exceptional master's students who come to Waterloo from around the world for the Perimeter Scholars International (PSI) program are often recruited by Perimeter researchers and stay in Canada to continue their education and research. In 2019/20, 73 percent of Perimeter's PhD students were PSI graduates.

PhD students receive their degree from the partnering university where their supervisor has a full or adjunct appointment. This year, these included the University of Waterloo, McMaster University, and the University of Toronto.

Of the 11 students who graduated in 2019/20, many went on to prestigious postdoctoral fellowships, including at the Max Planck Institute, the University of California, Berkeley, and the Institute for Advanced Study, Princeton. Barak Shoshany, who completed his PhD in September 2019, already has a tenure track position as an assistant professor at Brock University. Some also began private sector careers with employers such as Canadian technology company Desire2Learn and RSJ Securities, a financial group based in Prague.

Perimeter had a total of 77 PhD students from 33 countries in 2019/20; see the full list on page 61.

PI PEOPLE

PhD Student

### T.C. FRASER

Thomas Coolican (T.C.) Fraser has the type of mind that can toss numerous ideas into the air, deftly grasp them, and connect them in a beautiful new pattern. It is perhaps not surprising, then, that Fraser, a graduate student in the second year of a PhD in quantum information and quantum foundations at Perimeter Institute, also loves juggling.

"I know it sounds silly, but certain aspects of juggling can be understood mathematically," he says. "Seeing which patterns are realistic, and which ones are not."

Seeing patterns and connections is also, it turns out, important to his research probing cause and effect in quantum correlations under the supervision of Perimeter Faculty member Robert Spekkens.

Fraser, who grew up in Renfrew, Ontario, wasn't entirely sure what specialty he wanted to pursue. Then he met postdoctoral researcher Elie Wolfe, who works in quantum foundations. "Everything he was saying was new to me." Fraser wanted to dive right in and ended up reinventing a mathematical framework for solving the so-called weighted hypergraph transversal problem.

"He is clearly on track to become one of the most innovative physicists of his generation," Wolfe says. "Perimeter's foundational research mission is providing T.C. the perfect environment to push his own limits."

*T.C. Fraser is supported by the Joanne Cuthbertson and Charlie Fischer Graduate Student Award.*

## ASSOCIATE POSTDOCTORAL RESEARCHERS AND PHD STUDENTS

Perimeter is an independent institution, but it doesn't stand in isolation. Our associate programs offer select postdoctoral researchers and PhD students visiting privileges, so they benefit from everything from courses to seminars and workshops, plus the opportunity to collaborate with Perimeter researchers. In 2019/20, there were 14 associate postdocs and 26 associate PhD students.

## VISITING GRADUATE FELLOWS

Perimeter offers senior PhD students from the broader science community a unique opportunity to expand their perspectives and participate fully in the Institute's research community. In 2019/20, 19 graduate fellows from 13 countries (including Switzerland, Italy, and China) visited for a total of 1,739 working days, from short visits of a few weeks to stays of up to 10 months, with the average visit lasting five months.

## VANIER CANADA GRADUATE SCHOLARS

Six PhD students at Perimeter Institute and the University of Waterloo have received prestigious Vanier Canada Graduate Scholarships from the Natural Sciences and Engineering Council of Canada. Each receives $50,000 per year for three years. Vanier Scholarships are designed to help Canadian institutions attract highly talented doctoral students and are based on academic excellence, research potential, and leadership qualities.

Anna Golubeva

Finnian Gray

Florian Hopfmueller

Fiona McCarthy

David Schmid

Lei Yang

# PERIMETER SCHOLARS INTERNATIONAL

PSI is a one-year master's-level course in theoretical physics that attracts exceptional students from around the world. On completion, students earn their Master of Science degree from the University of Waterloo, and a PSI certificate.

It's a highly competitive program: the 13 women and 13 men in the 2019/20 cohort were chosen from 688 applicants.

Students take courses in several research areas of theoretical physics and are encouraged to explore, solve problems, and research in disciplines outside their primary interests. "Homework is not just an assignment that you do to finish a course; it's a great opportunity for collaboration," says Beata Zjawin of Poland. "It's really rewarding to collaborate with people who do different kinds of research."

The small group of students came to Waterloo from across Canada and from 16 other countries, leading to a rich cultural experience as well. "The most interesting aspect of PSI for me was the amount of diversity that I experienced for the first time. It was the first time I was exposed to so many people from different nationalities and different languages," says Maryam Mudassar of Pakistan. "We put aside our differences and respected each other's opinions."

PSI equips students with the tools, research skills, and creative mindsets needed to succeed in physics, or any other field.

Of the 26 graduates, five are now resident PhD students at Perimeter; others are at prestigious institutions such as Stanford University, Cambridge University, and the University of California, Berkeley. Elizabeth Bennewitz is working with Canadian artificial intelligence start-up 1QBit, continuing research she began with them for her final master's project.

See the full list of PSI faculty and students on pages 60 and 62.


PSI faculty and students quickly adjusted to online learning in March, and all students successfully completed their degrees. Their online convocation ceremony in July had a silver lining: addresses from Nobel Laureates Donna Strickland, Steven Weinberg, and Art McDonald, as well as congratulatory messages from the Honourable Navdeep Bains, Canada's Minister of Innovation, Science and Industry, and the Honourable Ross Romano, Ontario Minister of Colleges and Universities.

*The PSI program was supported in 2019/20 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.*

# UNDERGRADUATE SUMMER ACCELERATOR

This fledgling program, launched in 2018 with a gift from Michael Serbinis and Laura Adams, gives talented undergraduate students an insider experience of research and a view of the many other possibilities that physics training opens up.

The summer school features a two-week academic program, designed to teach how theorists approach physics. Select students then go on to a summer-long internship, working on research projects with Perimeter postdocs or faculty mentors. This year's undergraduates were chosen from more than 700 applicants.

How exceptional are these students? Those who stayed for internships were unfazed to tackle research topics spanning the breadth of theoretical physics. One student studied entanglement in spin chains, a subset of condensed matter systems. Another looked at how galaxies and galactic clusters form and behave.

The projects are advanced: Madison Tindall, who is from Arthur, Ontario, studies chemical physics at Trent University in Peterborough. During her internship, she panned out for a wider view of the universe.

"I'm focused on uncovering the gravitational wave background through comparing gravitational wave data with existing backgrounds and maps," she says. "We're trying to replicate the results of a paper that did a similar thing, matching their plots so we can repeat their process with a different background or map."

Academic program administrators considered cancelling this program for the year. Instead, PSI Fellow Giuseppe Sellaroli came forward with a proposal to move the whole program online. Savings on travel and accommodations allowed for 54 students to participate, compared with 20 students in 2019.

*The Summer Undergraduate Accelerator program was supported in 2019/20 by Mike Serbinis and Laura Adams.*

# CAREER TRAJECTORIES

What can you accomplish with a degree in theoretical physics? Plenty, and Perimeter offers a suite of events, resources, and initiatives to help students and research trainees – from undergraduates up to senior postdocs – plan their path. Events in 2019/20 included workshops on creating a résumé and networking, as well as talks from industry leaders: Payam Pakarha, an astroparticle physicist working in the financial sector; Chris Luciuk, head of data science at Insight; and Ella Hilal, director of engineering at Shopify.

When Perimeter's annual Career Trajectories Day was cancelled, the People and Culture department stepped up with individual career counselling by phone or virtually, answering questions and helping students prepare for interviews and build their CVs.

# SEEDING INDUSTRY IN CANADA

Young theoretical physicists acquire skills that are portable and in high demand, including complex mathematics and numerical methods; independent, high-level problem solving; and the ability to communicate their research through written and oral presentations. Perimeter produces job-ready leaders with widely applicable skills for both research and industry.

Many alumni have gone on to found companies, lead new research programs, and innovate in sectors such as finance, cybersecurity, data science, artificial intelligence, biomedicine, and quantum technologies. The many Canada-based companies that have mined Perimeter talent include Loblaws, Scotiabank, Shopify, RBC, Desire2Learn, Xanadu, BMO, Element AI, Manulife Financial, Autodesk, and Siemens.

## HERE ARE A FEW INDUSTRY SUCCESS STORIES:

Ke Cai
**Scotiabank**
Senior Manager Enterprise Stress Testing, Toronto

Gunjan Lakhlani
**Royal Bank Canada**
Machine Learning Enterprise Mgt., Toronto

Solomon Owerre
**Loblaws**
Senior Chief Data Scientist, Brampton

Chenfeng Bao
**Desire2Learn**
Software Developer, Kitchener

Kyle Tate
**Shopify**
Director of Data Science, Ottawa

Pedro Ponte
**BMO Capital Markets**
Associate Trading Data Scientist, Toronto

Alexandre Yale
**Touchstone Intelligent Marketing**
Co-Founder & CDO, Montreal

Shreya Kumar
**Xanadu**
Data Scientist, Toronto

Jorge Escobado
**Drop**
VP Engineering Toronto

Kim-Tuyen Hoang
**Oz Optics**
Optical engineer, Ottawa

# OUTREACH

*"Perimeter's resources and training have been indispensable to keeping my students learning during the pandemic . . . As a teacher, I really appreciate the thought and care that goes into making these resources usable in our continuously changing teaching/learning settings."*

*– Iain Braithwaite, mathematics and science teacher*
*John F. Ross Collegiate Vocational Institute, Guelph, Ontario*

*ISSYP mentoring session, Perimeter archives*

# 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.[4]

## STUDENTS

**59,018,050** interactions in classrooms since 2006

**6,828,250** interactions in classrooms in 2019/20

**956** students attended presentations in 2019/20

**155** school students attended "Inspiring Future Women in Science" in 2020

**40** exceptional high school students – 18 Canadian, 22 international – attended the 2020 International Summer School for Young Physicists

## TEACHERS

**35,688** teachers reached globally by Perimeter's Teacher Network

**4,507** teachers trained at **200** workshops in 2019/20

**67** teachers attended EinsteinPlus teacher training camp in 2019/20

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

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

**25** resources translated into French

## SCIENCE FOR THE WORLD

**6** public lectures were viewed **745,752** times in 2019/20

**2,819,007** YouTube views in 2019/20

**10,578,792** YouTube views since 2009

[4] *Unless otherwise indicated, figures are since Perimeter's inception.*

# EINSTEINPLUS AND TEACHER WORKSHOPS


EinsteinPlus is Perimeter's flagship teacher training experience – a week-long professional development opportunity that brings modern physics to life, often delivered by the very researchers who are making discoveries in the field today.

The value of EinsteinPlus is exponential: Since its inception, more than 700 teachers from 43 countries have attended, taking inspiring ideas, new strategies, and educational resources home to share with students in their classrooms and with other teachers in their communities.

Though EinsteinPlus was not held in person in 2020, the enthusiasm for this popular program did not wane. "The Online Physics Teacher Camp has given me a lot of material and ideas for teaching. The topics are of high interest to students and I really enjoyed attending. I highly recommend it," said Denise Gurer from the United States. "The PI Online Physics Teacher Camp was an awesome experience that left me with tons of ways to improve my classroom! This is something every physics teacher should be signing up for," said Canadian teacher Christopher Sarkonak.

In addition, Perimeter offered 200 teacher workshops, including several in French, on everything from gravitational waves to black holes, from climate change to curved spacetime.


Because EinsteinPlus was offered online, Perimeter was able to expand the number of teachers who attended to 67, from 36 last year. Teachers who had not been able to leave their families for in-person sessions were able to attend this online version. Outreach teams also quickly created and delivered 24 subject-specific online workshops for teachers, with a focus on helping them create lesson plans and activities that work well in virtual classrooms.

*EinsteinPlus is supported by the Power Corporation of Canada.*

# COLLABORATING WITH INDIGENOUS COMMUNITIES

Perimeter Institute is honoured to be invited into Indigenous communities to participate in teacher professional development, sharing information and learning more about Indigenous ways of knowing. Since 2016, Perimeter has participated in over 25 teacher training workshops in Indigenous communities, collaborating with more than 450 teachers.

In February 2020, the educational outreach team visited Iqaluit for a three-day workshop with all area STEM teachers, and in March held workshops at the Matawa Teacher Conference in Thunder Bay. Working with First Nations, Métis, and Inuit educators is an extremely rewarding and reciprocal experience. The Outreach team continues to learn from teachers, students, and communities to authentically integrate Indigenous ways of knowing into educational resources and workshops.

# EDUCATIONAL RESOURCES

Perimeter's educational resources have been used across Canada and in 117 other 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, all directly connected to science curricula.

Resources developed in 2019/20 include *Tools for Teaching Science*, a guide for teachers striving to improve student learning; new black hole resources and breakout activities for use in classrooms; and three new French and, funded by the American Physical Society, six new Portuguese translations of resource kits.

The Outreach team quickly created "Adapting to Online Classrooms" – suggested strategies for adapting Perimeter resources and other classroom lesson plans for the virtual classroom. The strategies are available online in English, French, and Portuguese.

# INTERNATIONAL SUMMER SCHOOL FOR YOUNG PHYSICISTS

The screen showed an opaque tube, capped at both ends, with four pieces of rope hanging from its sides: It looked simple, but for nearly an hour, a group of 40 teenagers grew increasingly perplexed at its inner workings. Tug on any given string, and the other ones get pulled into the tube. How were they connected inside? They were determined to find out.

The black tube contains the essence of science – a set of physical phenomena that invite curiosity, hypothesis generation, and testing. It's a staple that's often used to kick off Perimeter's International Summer School for Young Physicists (ISSYP), an annual, gender-balanced program that invites students interested in physics to immerse themselves in Perimeter's environment.

ISSYP is a two-week intensive program, with physics lectures on topics including relativity and quantum mechanics interspersed with fun activities and socializing. And though this year the students never met in person, they all espoused the same curiosity and excitement for physics.

The impacts of the program can be felt widely and for many years. This year, participant Ólin Costa, a 17-year-old from Brasília, Brazil, plans to take his newfound problem-solving techniques and use them to help tutor other students at his school through a program called Project Feynman. "The knowledge which I got here in ISSYP will certainly help me to improve my classes, and help me to help people," he said.

Many ISSYP participants go on to excel in STEM education and careers. Gerardo de Jesus Saenz (2008) founded Territorium, a tech company focused on changing education. With offices in the United States, Mexico, and Colombia, Territorium has more than one million users.

Alumni Arunima Sen (2019) and Anna MacLennan (2020) have both been named in The Mars Generation's 24 under 24 Leaders and Innovators in STEAM and Space Awards, while Siena Castellon (2018) has been named a United Nations 2020 Young Leader for the Sustainable Development Goals.

This year, ISSYP looked a little different: It was held entirely online, with lessons presented via Zoom and augmented with virtual interactives. Half the students hailed from across Canada, with the other half logging in from international locales (selected from applicants in the same time zones as Canada to simplify coordination).

*The 2019/20 session of ISSYP was made possible by the support of the RBC Foundation, the Presenting Partner.*

*"Inspiring Future Women in Science" conference, March 2020*

# INSPIRING FUTURE WOMEN IN SCIENCE

The speakers were extraordinary: A theoretical astrophysicist and dynamic science communicator with an upcoming book about the end of the universe. A Canadian CEO whose STEM background helps guide an automobile parts manufacturing company with more than 29,000 employees in 17 countries. A biologist studying a difficult-to-treat type of breast cancer that is most prevalent in young Black women.

They also all happened to be women.

At Perimeter's annual "Inspiring Future Women in Science" conference, 155 high school students heard from an impressive range of speakers, panellists, and mentors, who shared their stories of science, technology, engineering, and math. The conference was also carried as a live webcast to five Ontario high schools.

The panellists wrapped up their appearance by answering the question, What's the one thing you wish you'd known in high school? Jessalyn Teed, a pilot and advocate for women in aviation, gave the following advice: "Network, network, network. Seek out community." Data scientist Sarah Sun said, "Be curious, be bold, and be courageous. It's okay to be scared, but stay curious."

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

*"I support the Perimeter Institute because I believe the work they are doing will drive ambitious scientific breakthroughs that will literally shape our future. Their commitment to supporting women in science and encouraging young women, in particular to pursue their interest in STEM, is vitally important as well to broadening the scope and reach of scientific research and development. Innovation and talent are at the heart of competitiveness for any industry, but in particular advanced manufacturing, making support of the Perimeter Institute profoundly important to the future of our sector, our economy and our world."*

*– Linda Hasenfratz, CEO, Linamar Corporation*

# SCIENCE COMMUNICATION AND MEDIA

More than ever, the public needs accurate and accessible science information from trusted organizations, and the critical-thinking skills to recognize it. Each year, Perimeter reaches hundreds of thousands of people in Canada and around the world with high-quality science communications designed to inform and enlighten. Through its websites, 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 2.8 million video views, an increase of 12 percent over last year, while the number of subscribers jumped by 28 percent. Our online home for accessible and shareable science content, insidetheperimeter.ca, features fascinating science content for all age groups and experiences – from fun quizzes suitable for elementary school kids, to longer features that delve into the current work of researchers. In 2019/20, Inside the Perimeter had more than 473,000 page views and almost 260,000 unique visitors, while the award-winning interactive website Quantum to Cosmos racked up more than 1.2 million page views.

We meet and engage with audiences where they are: on social media. This year, Perimeter's LinkedIn followers jumped by 26 percent, Twitter followers increased by 10 percent to more than 26,000, the Perimeter Facebook account grew to a following of more than 32,000, and the Instagram account reached nearly 5,000 followers.

By leveraging the full scope of Perimeter's online, on-location, and media engagement activities, we continue to build understanding and trust in science.

## AWARD-WINNING SCIENCE COMMUNICATION AND OUTREACH

Perimeter earned three gold and one bronze 2020 Prix d'Excellence awards from the Canadian Council for the Advancement of Education:

**GOLD:**

Best Media Relations Initiative: For leading the entire media relations strategy for an international consortium, related to releasing the first images of a black hole.

Best Advertisement or Poster: For educational posters explaining how the black hole image was obtained, and the significance of the breakthrough.

Best Use of Social Media: For contests that sent winners to two scientifically important locations: the Large Hadron Collider at CERN in Switzerland, and a mountaintop telescope in Hawaii.

**BRONZE:**

Best New Idea – Creativity on a Shoestring: For free physics wallpapers to be used on desktops, tablets, and phones featuring beautiful images.

## TOP 10 NEWS STORIES

- "Waterloo scientists help create 3D map of the universe," CBC's *The National*, July 19, 2020
- "Astronomers locate the source of mysterious cosmic radio bursts – with help from a Canadian instrument," *Globe and Mail*, January 6, 2020
- "We may have spotted a parallel universe going backwards in time," *New Scientist*, April 8, 2020
- "Global team of astrophysicists release largest ever 3D map of the universe," *National Post*, July 20, 2020
- "The mix of private and public funds that built a physics powerhouse," *Inside Philanthropy*, August 7, 2019
- "Spacetime 'echoes' from quantum black holes could soon change physics forever," *Vice*, February 10, 2020
- "Event Horizon Telescope reveals inner workings of quasar's jet," *Astronomy Now*, April 8, 2020
- "Machine learning could be Canada's edge in the global quantum computing arms race," *BetaKit*, March 10, 2020
- "Astrophysicist Katie Mack talks the end of the universe tonight! Here's how to watch live," Space.com, May 6, 2020
- "Black hole portrait wins Breakthrough Prize for Event Horizon Telescope's team," *GeekWire*, September 5, 2019

# PUBLIC LECTURES


From the beginning of the universe to the latest thinking on interstellar travel, Perimeter public lectures continue to inspire and inform local audiences in the Mike Lazaridis Theatre of Ideas, and audiences around the world through livestreams and YouTube.

This year's six public lectures were "Surviving the Century," delivered by Sir Martin Rees; Elizabeth Tasker on "The Hunt for Habitable Planets"; "Music of the Universe" by Gabriela González; Shohini Ghose on "The Quantum Revolution"; Bryan Gaensler's "Warp Drive and Aliens"; and Katie Mack's "The End of the Universe."

The lecture series was viewed 745,000 times in 2019/20, and many lectures continue to be immensely popular for months and even years afterward.

These lectures make a difference for general audiences who want to be challenged: 66 percent of attendees who responded to a survey told us they enjoy lectures that "make my brain hurt a bit," and 98 percent said the lectures inspire them to learn more. "We try to attend as many of the lectures as we can as a family. Thank you so much for providing them. They have helped spark an interest in science and big questions for my daughters and I greatly appreciate it," said one survey respondent.


A planned public lecture by Simons Emmy Noether Fellow Katie Mack, "The End of the Universe," was transformed into an online conversation that included a live question and answer segment with participants. The video has been viewed more than 18,000 times.

*BMO for Women was the Supporting Partner of the four public lectures delivered by women in 2019/20.*

*Shohini Ghose Public Lecture, March 2020*

# OUR FUTURE IS **BRIGHT**

These are exciting times: A revolution in quantum science and technology is in progress, spurred by the promise of quantum computing. Powerful technologies based on quantum physics are expected to transform many industries, and our understanding of the universe. Perimeter's diversified research portfolio is positioned for broad impact, driving major advances along many exciting frontiers.

In a world where scientific discovery, top talent, and technological innovation are critical to economic and societal success, Perimeter is a strategic asset that is indispensable to Canada's future.

Our new five-year plan advances our vision to become the world's foremost centre for theoretical physics, setting new standards in research, training, and outreach.

## RESEARCH

We will pursue breakthroughs that shape our collective future. We will accelerate ambitious research across the spectrum of foundational physics and sharpen focus on key cross-disciplinary initiatives that are ripe for major advances, including:

- Quantum matter, through the just-launched Clay Riddell Centre for Quantum Matter at Perimeter.
- The intersection of artificial intelligence and quantum science, through the Perimeter Institute Quantum Intelligence Lab.
- Quantum simulation, through growing partnerships with leading experimentalists.
- Quantum causal inference, through Perimeter's Quantum Causal Inference Lab.
- Data-driven cosmology, through partnerships with observational facilities like CHIME and the Event Horizon Telescope, and gravitational wave observatories. These partnerships open new windows into black holes, fast radio bursts, and other mysteries of the universe.

## TRAINING

We will train new generations of brilliant minds for leadership roles, not just in physics but anywhere that complex problems demand fresh solutions. We will bring the best and brightest graduate students and postdoctoral researchers to Perimeter and provide them with world-class scientific training. We will also:

- Work with our university partners to share resources and knowledge, creating a rising tide that lifts all of Canadian physics.
- Strengthen ties to our more than 1,000 alumni.
- Connect young scientists with career, networking, and mentoring opportunities, inside and outside academia.

## OUTREACH AND SCIENCE COMMUNICATION

Through training and support for teachers, classroom resources for students, flagship public lectures for the community, and digital science content for curious minds, we will share the wonders of science with the world. In the coming years, we will tailor our ambitious programs to be both more targeted and further reaching. We will:

- Deepen our reach across Canada to teachers and students from coast to coast to coast.
- Leverage new digital platforms to distribute high-quality, accessible science content worldwide.

## INCLUSION, DIVERSITY, EQUITY, AND ACCESSIBILITY

In all research, training, and outreach activities, we will actively welcome and empower groups who have been systemically marginalized from science – particularly women and girls, racialized people, and members of Canada's Indigenous communities. Building on the work of our volunteer-led, grassroots-driven Inclusive PI Platform, our Emmy Noether Initiatives, and our use of inclusiveness as a measure of success for all our events and programs, we will set new standards for inclusion, diversity, equity, and accessibility.

# ADVANCING PERIMETER'S MISSION

*"I think most of our family loves smart people, and we love what can happen when you bring smart people together. One of the things that's really attractive about Perimeter is just how purposeful they are at developing that pipeline of talent."*

*– Susan Riddell Rose, Director, Riddell Family Charitable Foundation*

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

Our government and private sector partners know that Perimeter is a major asset for Canada: an acknowledged leader in the lowest cost, highest impact area of science. Perimeter was founded on a key insight: today's theoretical physics is tomorrow's technology. Virtually every piece of modern technology has its roots in past physics breakthroughs: radio, television, semiconductors, computers, cell phones, lasers, fibre optics, the internet, GPS, diagnostic imaging, and more. Future technologies will flow from the next wave of physics breakthroughs. In supporting Perimeter, our partners help ensure near- and long-term competitiveness and prosperity in the country's future.

In 2019/20, Perimeter was in the third year of five-year funding agreements of $50 million each with the Government of Ontario and the Government of Canada. These investments continue to sustain a partnership that is essential to Perimeter's ongoing success, and they help position Ontario and Canada as a leading centre of theoretical physics on the global stage.

A generous $10 million commitment from the Riddell Family Foundation has enabled Perimeter to launch the Clay Riddell Centre for Quantum Matter. The 10-year commitment allows us to attract and retain exceptional talent, bringing together top faculty, postdoctoral researchers, and students in a collaborative environment. The Riddells were among our growing group of private donors, and Perimeter is now in an ideal position to become a national hub for foundational theoretical research in quantum matter.

"The Riddells' generous gift is an investment in the long game," says Rob Myers, Director of Perimeter. "It will enable us to bring brilliant young scientists from diverse areas, with diverse ideas, together in one place. That's how you get the breakthroughs that nobody can foresee. The kind that change everything."

## 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 our $100 million private sector campaign to grow to $53 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
Scott Griffin Foundation
The Krembil Foundation
Linamar Corporation
Maplesoft
The Marsland Family
Pattison Outdoor Advertising
Power Corporation of Canada
Ptarmigan Charitable Foundation
RBC Foundation
Riddell Family Charitable Foundation
Scotiabank
Michael Serbinis and Laura Adams
Shaw Communications
The Simons Foundation
Stavros Niarchos Foundation
Sun Life Financial Inc.
John Templeton Foundation
Neil Turok
Dr. Scott A. and Sherry Vanstone and family
Mac Van Wielingen, Viewpoint Foundation

## PERIMETER INSTITUTE LEADERSHIP COUNCIL

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

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

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

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

**Donald W. Campbell**
Senior Strategy Advisor, DLA Piper

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

**Catherine Delaney**
President, Delaney Capital Management Ltd.

**Edward Goldenberg**
Partner, Bennett Jones LLP

**Brad Marsland**
Vice President, Marsland Centre Ltd.

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

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

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

We thank **Carol Lee**, CEO and Co-Founder of Linacare Cosmetherapy, who completed eight years of service on the Leadership Council in October 2019.

## THANK YOU TO A GENEROUS SUPPORTER

### CLAY RIDDELL (1937-2018)

Clay Riddell was a geologist, a highly successful entrepreneur in Canada's energy sector, and a community builder, who received the Order of Canada in 2008 for his leadership and philanthropy. A long-time friend to the Institute, Riddell's first major gift supported the Clay Riddell Paul Dirac Chair, held by Pedro Vieira.

Prior to his passing in September 2018, he decided to make the vision for the Centre for Quantum Matter a reality.

He viewed the $10 million gift as a legacy for humanity. It will support scientists and scientists-in-training as they probe exotic new states of matter that hold the key to better understanding powerful quantum phenomena – laying the foundations for technologies of the future.

Rob Myers, Perimeter's Director, said, "Clay was a brilliant spirit, and through this gift he and his family have lit a bright path to our future."

## FAREWELL TO A FRIEND

### CHARLIE FISCHER, 1950-2020

Perimeter Institute pays tribute to generous friend and supporter Charlie Fischer. Charlie and his wife, Joanne Cuthbertson, are long-time Perimeter champions who have shown deep commitment and a shared vision for advancing humanity through science.

Charlie was awarded the 2020 Alberta Order of Excellence before his passing on June 17, 2020, and will be formally invested at a future ceremony. Charlie and Joanne were each invested as Members of the Order of Canada in November 2019.

Both Charlie and Joanne took a leadership role in highlighting Perimeter as "Canada's hidden gem," establishing a solid community of support in Calgary, throughout Alberta, and across the country. Joanne is a member of Perimeter's Board of Directors and sits on the Leadership Council. Six years ago, they created the Joanne Cuthbertson and Charlie Fischer Graduate Student Award, which currently supports PhD student T.C. Fraser.

"At Perimeter, our scientists are studying the forces of nature. Joanne and Charlie are undeniably two forces of nature. We can never thank them enough for their enthusiastic support of the Institute and their indefatigable commitment to raising Canadian society," said Rob Myers, Director of Perimeter. "Joanne and Charlie's efforts are a leading example of Perimeter's public-private partnership in action."

Charlie's passion will live on in all who have become a part of the Perimeter family.

# THANKS TO OUR SUPPORTERS

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

## ENDOWMENT FUND

**FOUNDER ($150M+)**

Mike Lazaridis

**$25M+**

Doug Fregin

**$10M+**

Jim Balsillie

## GOVERNMENT PARTNERS

Government of Canada
Government of Ontario

## ENDOWED INITIATIVES

BMO Financial Group Isaac Newton Chair in Theoretical Physics ($4 million)
Stavros Niarchos Foundation Aristarchus Chair in Theoretical Physics ($4 million)
The Peter and Shelagh Godsoe Family Foundation Award for Exceptional Emerging Talent ($1 million)

## PERIMETER RESEARCH MAJOR GIFTS

Clay Riddell Centre for Quantum Matter ($10 million)
Centre for the Universe at Perimeter Institute ($5 million)*
Mike and Ophelia Lazaridis Niels Bohr Chair in Theoretical Physics ($4 million)
Krembil Galileo Galilei Chair in Theoretical Physics ($4 million)
Krembil William Rowan Hamilton Chair in Theoretical Physics ($4 million)
Gluskin Sheff / Onex Freeman Dyson Chair in Theoretical Physics ($2 million)
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)
The Ptarmigan Foundation Stephen W. Hawking Fellowship ($400,000)
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, proud supporter of EinsteinPlus and Perimeter's Teacher Network
RBC Financial Group, Presenting Partner, International Summer School for Young Physicists
Mike Serbinis and Laura Adams, in support of the Undergraduate Theoretical Physics Summer Program

## ACCELERATORS CIRCLE ($50,000+)

The Cowan Foundation
Mac Van Wielingen, Viewpoint Foundation

## AWARDS ($35,000+)

The Savvas Chamberlain Family Foundation Anaximandros Fellowship
The Joanne Cuthbertson and Charlie Fischer Graduate Student Award
The Hellenic Heritage Foundation Anaximandros Fellowship
Brad and Kathy Marsland Honorary PSI Scholarship Award
Margaret and Larry Marsland Honorary PSI Scholarship Award

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

**$25,000+**

Airlie Foundation

Bosch Community Fund, on behalf of ESCRYPT in Canada

Brian Sullivan

Toyota Motor Manufacturing Canada (TMMC)

**$10,000+**

Denise and Terry Avchen, Environmental Research Advocates

The Boardwalk Partnership

Harbir and Monica Chhina

Kitchener Waterloo Community Foundation

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

Ottawa Community Foundation

Ildiko and Peter Paulson

Donald and Eleanor Seaman Family Foundation

Alex White

## FRIENDS (up to $9,999)

**$5,000+**

Mary and Ted Brough

Savvas Chamberlain Family Foundation

Jon and Lyne Dellandrea

Frederick Knittel

Renée Schingh and Robert Myers

Anonymous donor (1)

**$2,500+**

Don Campbell

J. DesBrisay and M. Cannell

Michael Duschenes

Goldman Sachs**

Robert Korthals and Janet Charlton

Jennifer Scully-Lerner**

**$1,000+**

Debbie and Ian Adare

Advancement International Foundation

John Attwell

The Breunsbach Family**

Douglas Brock

Rick Byers

Canada Gives: Schnurr Family Foundation

The Carson Family Foundation

David Cook

Ben and Mona Davies

Greg Dick

Peter Gillin

Edward Goldenberg

Michael Horgan

Ed Kernaghan

John Matlock

Leslie McCarley

Zoltan Petrany

W. Michael Roche

Beatrice Snyder Foundation**

Anonymous donor (1)

**$250 to $999**

Jeff Bakker

Jeremy Bell and Sunny Tsang

Mike Birch

Janice Blathwayt

Rene and Janet Couture

Matt Douglas

Liliane Dubois-Esnard

Michael Gagnier

Adam Gravitas

Warren Jackson

Nagaraja D Srinivas Jonnavittula

Jane E. Kay

Luis Lehner and Maria Beltramo

D'Arcy and Catherine Little

Jill Marshall**

Maneesh Mehta

Douglas Mortley-Wood

Dan Petru

Stefan and Shani Pregelj

Nem Radenovic

Neil Steven Rieck

Catalin Sandu

John and Bridget Tielemans

Jacqueline Watty

Anonymous donors (6)

An additional 138 donors have contributed gifts of up to $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

Dorian Hausman

Patrice E. Merrin

**$10,000+**

BMO for Women

Jane Kinney and Christian Bode

**$1,000+**

Jacqui Allard

Nancy Coldham

Andrea Grimm

Lisa Lyons Johnston

ODC Tooling & Molds in memory of Leejay Julius Levene

Laura Reinholz and Tony Fedun

Mary and Lee Sauer

**$250 to $999**

Tom and Cheryl Hintermayer

Beth Horowitz and Pat Munson

Sheri and David Keffer

Douglas Mortley-Wood

Leslie Rogers

Anonymous donors (2)

## 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, 2019, and July 31, 2020, and multi-year commitments of $50,000 and more.*
*Charitable Registration number: 88981 4323 RR0001*

# GOVERNANCE

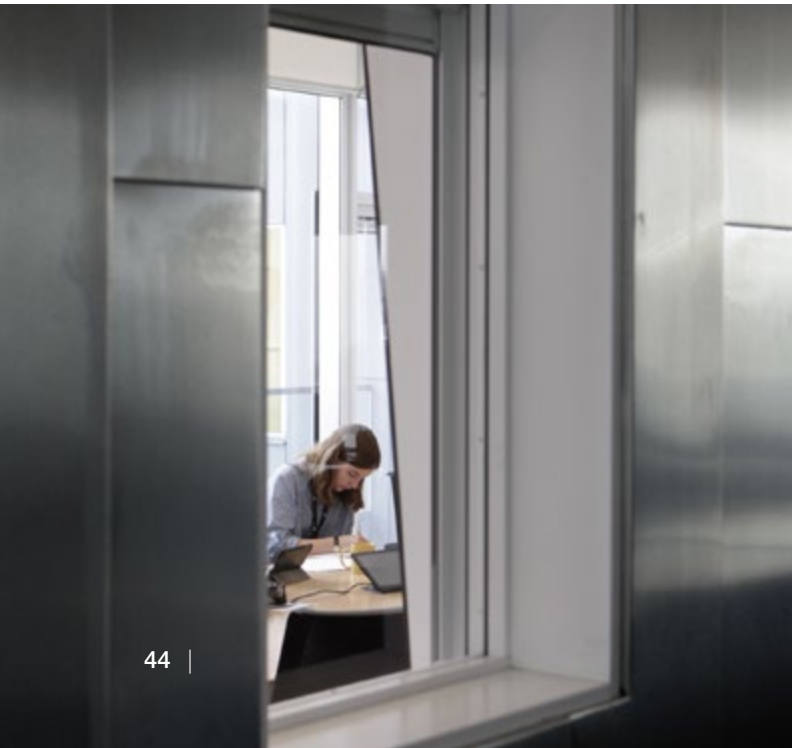
Perimeter Institute is an independent, not-for-profit, charitable corporation governed by a volunteer Board of Directors drawn from the private sector and academic community. The Board is the final authority on all matters related to the general structure and development of the Institute.

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.



# BOARD OF DIRECTORS

**Mike Lazaridis**, O.C., O.Ont., FRS, FRSC
Chair
Founder of Perimeter Institute
Managing Partner and Co-Founder,
Quantum Valley Investments

**Cosimo Fiorenza**
Vice Chair
Founding member of Perimeter Institute Board of Directors
Vice President and General Counsel,
Quantum Valley Investments

**Susan Baxter**
Vice Chairman, Enterprise Strategic Client Group at Royal Bank of Canada
Member of Perimeter Institute Leadership Council

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

**Michael Horgan**
Senior Advisor, Bennett Jones LLP

**Jane Kinney**
Retired Vice Chair, Deloitte

**Patrice Merrin**
Director: Glencore plc
and Samuel, Son & Co.
Co-Chair of Perimeter Institute Leadership Council

**Jeff Moody**
President and CEO, Gluskin Sheff + Associates Inc.

**Michael Serbinis**
Founder and CEO, League Inc.

We thank **Amit Chakma**, President Emeritus of Western University and current Vice-Chancellor of the University of Western Australia, who stepped down from the Board on July 1, 2020, after completing two years of service.

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

# SCIENTIFIC ADVISORY COMMITTEE

**Gabriela González**
Chair
Louisiana State University

**Fernando Brandao**
California Institute of Technology

**Marcela Carena**
University of Chicago

**Steven Carlip**
University of California, Davis

**Daniel Freed**
University of Texas at Austin

**Gilbert Holder**
University of Illinois

**David B. Kaplan**
University of Washington

**Juan Maldacena**
Institute for Advanced Study, Princeton

**Ramesh Narayan**
Harvard University

**Natalia Perkins**
University of Minnesota

**Sandu Popescu**
University of Bristol

We thank **Katherine Freese** of the University of Texas at Austin for her service on the Scientific Advisory Committee from 2017 to 2020.

# SENIOR LEADERSHIP

**Robert C. Myers**
Director

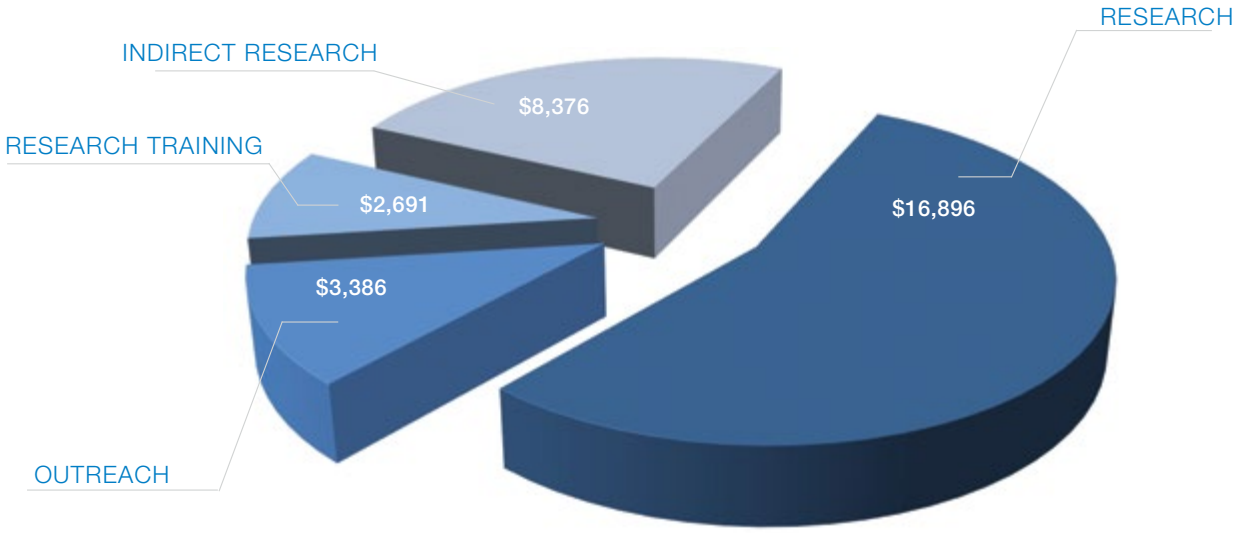
**Michael Duschenes**
Managing Director and Chief Operating Officer

**Luis Lehner**
Faculty Chair

# FINANCIALS

## SUMMARY OF OPERATING COSTS (refer to page 50)

For the year ended July 31, 2020
(in thousands of dollars)




The ongoing COVID-19 pandemic resulted in governments worldwide enacting measures to combat the spread of the virus. As a community, Perimeter has risen to this unprecedented challenge with resilience and flexibility, continuing to deliver on the Institute's mandate of research, training, and outreach.

Perimeter successfully transitioned to operate as a fully online institution almost overnight. Theoretical physics research does not require labs and lends itself well to solitary focus and group collaborations via an array of IT tools. Perimeter set up fully online courses for all students, and their training continued. Seminars, group meetings, and conferences all continued virtually and were shared worldwide. The Outreach team shared free resources and offered online professional development to support teachers and keep kids learning.

### Research

Advancing our understanding of the universe at the most fundamental level remains Perimeter's core focus. To that end, the Institute continued to invest in Perimeter's research mandate, with an emphasis on supporting a robust virtual environment. The overall 8 percent underspend from the prior year was due in large part to COVID-19 travel restrictions leading to fewer in-person collaborations, workshops, conferences, and seminars.

### Research Training

Perimeter continued to invest in innovative research training programs, such as the Perimeter Scholars International master's program, the PhD program, and the Visiting Graduate Fellows program, each of which attract and train top scientific talent – increasing expertise, advancing research, and producing job-ready leaders in many fields that drive economic growth. Expenses were 12 percent lower than the previous year owing to a strategic decision to decrease enrollment in some programs, and a reduction in travel and in-person participation due to pandemic restrictions. Throughout the pandemic, Perimeter allocated resources strategically, ensuring that all training program participants successfully completed their courses and were supported in the transition to the next phase of their careers.

### Outreach and Science Communications

Perimeter's world-class educational outreach program continued to offer educators classroom-ready digital and curriculum-compliant materials. The program reaches teachers and students worldwide, from the largest cities to remote and underserviced regions, helping prepare youth for high value STEM-based careers. The digital nature of much of Perimeter's existing content and expertise ensured the seamless transition to a virtual environment during the pandemic, allowing the

Institute to deliver programming for students, teachers, and the public at large with little interruption. The cancellation of in-house teacher and student programs and activities due to COVID-19 travel restrictions was a primary contributor to the 12 percent decline in expenditures.

**Indirect Research and Operations**

Indirect research and operating expenditures cover the costs of core support areas, including administration, advancement, information technology, and facilities. During COVID-19, strategic investments in new technologies were prioritized to facilitate and grow the Institute's online capabilities and web presence. Overall, indirect research and operations expenditures remained in line with prior years.

## INCOME

Federal and provincial governments continued to provide revenues in accordance with the terms of their grant agreements. In the prior year, the timing of receipt of federal contributions resulted 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.

To complement public investments, Perimeter has been able to secure significant and matching support from private companies, foundations, and donors. During this global crisis, Perimeter's private sector fundraising campaign remained very strong, generating close to $4 million to support the operations of the Institute, while research grant revenue from private foundations exceeded $700,000.

## FINANCIAL POSITION

The pandemic adversely impacted global commercial activity and contributed to significant volatility in certain equity and debt markets. Despite market volatility over the past year, marketable securities earned a return of more than 3 percent. The extent of disruptions to businesses globally and the subsequent impact on the economy going forward are difficult to assess; however, Perimeter's financial position remains strong and resilient. Under the guidance of the Investment Committee, funds remain invested in accordance with the Board-approved Investment Policies and Procedures, which reflect Perimeter's risk-return objectives.

## 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, 2020, Perimeter has completed the third 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, private funding plays a critical role in ensuring long-term viability. Perimeter Institute has established ambitious fundraising goals and 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.

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

Zeifmans

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

To the Directors of
Perimeter Institute

The accompanying summarized financial statements, which comprise the summarized statement of financial position as at July 31, 2020 and the summarized statement of operations and changes in fund balances for the year then ended, are derived from the audited financial statements of Perimeter Institute (the "Institute") for the year ended July 31, 2020.

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 summary and the audited financial statements do not reflect the effects of events that occurred subsequent to the date of our report on the audited financial statements.

**The Audited Financial Statements and Our Report Thereon**

We expressed an unmodified audit opinion on the audited financial statements in our report dated December 10, 2020. 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 10, 2020

Chartered Professional Accountants
Licensed Public Accountants

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

zeifmans.ca
T: 416.256.4000

## PERIMETER INSTITUTE

Summarized Statement of Financial Position
(in thousands of dollars)
as at July 31, 2020

| | 2020 | 2019 |
|---|---|---|
| **ASSETS** | | |
| Current Assets: | | |
| Cash and cash equivalents | $ 9,434 | $ 23,923 |
| Investments | 350,339 | 338,050 |
| Grants receivable | -- | 126 |
| Other current assets | 586 | 759 |
| | 360,359 | 362,858 |
| Property and equipment | 39,342 | 40,786 |
| TOTAL ASSETS | $ 399,701 | $ 403,644 |
| **LIABILITIES AND FUND BALANCE** | | |
| Current liabilities: | | |
| Accounts payable and other current liabilities | $ 1,690 | $ 1,850 |
| TOTAL LIABILITIES | 1,690 | 1,850 |
| Fund balances: | | |
| Invested in capital assets | 39,327 | 40,692 |
| Externally restricted | 11,740 | 17,396 |
| Internally restricted | 346,006 | 343,006 |
| Unrestricted | 938 | 700 |
| TOTAL FUND BALANCES | 398,011 | 401,794 |
| | $ 399,701 | $ 403,644 |

## PERIMETER INSTITUTE

Summarized Statement of Operations and Changes in Fund Balances
(in thousands of dollars)
For the Year Ended July 31, 2020

| | 2020 | 2019 |
|---|---|---|
| **Revenue** | | |
| Government grants | $ 15,000 | $ 22,192 |
| Donations | 3,842 | 3,293 |
| Research grants | 767 | 1,325 |
| | 19,609 | 26,810 |
| **Operating Expenses** | | |
| Research | 16,896 | 18,411 |
| Research training | 2,691 | 3,065 |
| Outreach and science communications | 3,386 | 3,850 |
| Indirect research and operations | 8,376 | 8,380 |
| | 31,349 | 33,706 |
| Excess of expenses over revenue from operations | (11,740) | (6,896) |
| Investment income | 10,261 | 6,571 |
| Amortization | (2,304) | (2,563) |
| Excess of expenses over revenue | (3,783) | (2,888) |
| Fund balances, beginning of year | 401,794 | 404,682 |
| Fund balances, end of year | $ 398,011 | $ 401,794 |

# 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 (2015-19), and the Max Planck Institute for Gravitational Physics (2018-present). He has also served on the editorial boards of *Annals of Physics* (2002-12) and the *Journal of High Energy Physics* (2007-present). Myers remains active in both teaching and supervising graduate students through his cross-appointment as an adjunct professor in the Department of Physics and Astronomy at the University of Waterloo. He has supervised and co-supervised over 150 postdoctoral fellows, PhD students, and master's students over his career, roughly 50 of whom now hold faculty positions around the world, including at Princeton, Cambridge, and Oxford.

**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. In 2019, he was named as one of TD's 10 Most Influential Hispanic Canadians.

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

**Latham Boyle** (PhD Princeton University, 2006) joined the Institute's faculty in 2010. From 2006 to 2009, he held a Canadian Institute for Theoretical Astrophysics Postdoctoral Fellowship and was a junior fellow of the Canadian Institute for Advanced Research. In recent years, Boyle's research interests have spanned a number of topics in cosmology, fundamental physics, and mathematical physics. In cosmology, he recently proposed (with Neil Turok and Kieran Finn) a new cosmological model, the "CPT-Symmetric Universe" (*Phys. Rev. Lett.* 121, 251301, 2018), in which the universe before the bang is the CPT mirror image of the universe after the bang. This model neatly explains certain observed features of our universe and makes a number of testable predictions for upcoming experiments. In fundamental physics, he recently pointed out (arXiv:2006.16265) an intriguing new connection between certain patterns in the Standard Model of particle physics and the structure of a remarkable mathematical object called the exceptional Jordan algebra. In mathematical physics, he introduced (with Kendrick Smith) the idea of "choreographic crystals" (*Phys. Rev. Lett.* 116, 015503, 2016), in which the basic elements perform a choreographed dance that can have much higher symmetry than any instantaneous snapshot reveals, and has investigated (with Paul Steinhardt, Madeline Dickens, and Felix Flicker) Penrose-like tilings and quasicrystals, including their relation to discrete conformal invariance and holography (*Phys. Rev. X* 10, 011009, 2020).

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

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

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

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

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

**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, two-dimensional conformal field theory, string theory, and quantum chromodynamics. Freidel has held positions at Pennsylvania State University and L'École Normale Supérieure and has been a member of France's Centre national de la recherche scientifique since 1995. He is also the recipient of several awards.

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

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

**Daniel Gottesman** (PhD California Institute of Technology, 1997) joined Perimeter's faculty in 2002. From 1997 to 2002, he held postdoctoral positions at the Los Alamos National Laboratory, Microsoft Research, and the University of California, Berkeley (as a long-term CMI Prize Fellow for the Clay Mathematics Institute). Gottesman has made seminal contributions that continue to shape the field of quantum information science through his work on quantum error correction and quantum cryptography. He has published over 75 papers, which have attracted well over 15,000 citations to date. He is also a fellow of the American Physical Society and a senior scientist with 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 had been a Moore Postdoctoral Fellow since 2015. Hsieh works in quantum matter, specializing in exotic states of matter whose physical behaviours are dictated by the mathematical structures of topology. His research interests also include quantum materials, entanglement, and applications of synthetic quantum systems for quantum simulation.

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

Fundamental Physics – as well as the Canadian Hydrogen Intensity Mapping Experiment (CHIME) and the Planck collaboration. He was awarded a 2020 New Horizons in Physics Prize, along with two colleagues. Smith has achieved several landmark results, including the first detection of gravitational lensing in the cosmic microwave background radiation. He holds a second PhD in mathematics from the University of Michigan.

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

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

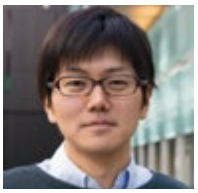
**Neil Turok** (PhD Imperial College London, 1983) is Director Emeritus and holds the Mike and Ophelia Lazaridis Niels Bohr Chair at Perimeter. He was the director of Perimeter's Centre for the Universe from 2017 to 2020. Previously, he was a professor of physics at Princeton University and Chair of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

**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 in the quantum information science program and a member of the Simons Collaboration on the Many Electron Problem. Vidal is currently on leave from Perimeter at X (formerly known as Google X).

**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 as N=4 SYM as a workhouse for developing such tools and on the S-matrix bootstrap program,

which constrains the possible space of all physical theory, in particular strongly coupled gauge and string theories. He is a principal investigator on the Simons Collaboration on the Non-perturbative Bootstrap. His many honours include a Sloan Research Fellowship, the Gribov Medal of the European Physical Society, the Raymond and Beverly Sackler International Prize in Physics from Tel Aviv University, and the 2020 New Horizons in Physics Prize.

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



**Beni Yoshida** (PhD Massachusetts Institute of Technology, 2012) joined Perimeter's faculty in July 2017, having initially arrived at the Institute as a senior postdoctoral researcher in 2015. Prior to that, he was a Burke Fellow at the Institute for Theoretical Physics at the California Institute of Technology (2012-15), where he worked in John Preskill's group. Yoshida's research focuses on applications of quantum information theory to problems of quantum many-body physics. 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 first prize in the 2019 Buchalter Cosmology Prize of the American Astronomical Society, and third prize in 2015.

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

**Avery Broderick** (PhD California Institute of Technology, 2004) began a joint appointment with Perimeter and the University of Waterloo in 2011 and was named the Delaney Family John Archibald Wheeler Chair in Theoretical Physics at Perimeter Institute in January 2017. He previously held postdoctoral positions at the Institute for Theory and Computation at the Harvard-Smithsonian Center for Astrophysics (2004-07) and the Canadian Institute for Theoretical Astrophysics (2007-11). Broderick is an astrophysicist with broad research interests, ranging from how stars form to the extreme physics in the vicinity of white dwarfs, neutron stars, and black holes. He is a key member of the Event Horizon Telescope (EHT) collaboration 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, along with several other awards.

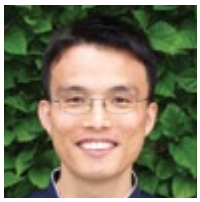
**Alex Buchel** (PhD Cornell University, 1999) is jointly appointed with Western University. Before joining Perimeter's faculty in 2003, he held research positions at the Institute for Theoretical Physics at the University of California, Santa Barbara (1999-2002) and the Michigan Center for Theoretical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

**Cliff Burgess** (PhD University of Texas at Austin, 1985) joined Perimeter's faculty as an associate member in 2004 and was jointly appointed to McMaster University's faculty in 2005. Prior to that, he was a member of the School of Natural Sciences at the Institute for Advanced Study and a faculty member at McGill University. Over two decades, Burgess has applied the techniques of effective field theory to high energy physics, nuclear physics, string theory, early-universe cosmology, and condensed matter physics. With collaborators, he developed leading string theoretic models of inflation that provide its most promising framework for experimental verification. Burgess' recent honours include a Killam Fellowship, fellowship of the Royal Society of Canada, and the CAP-CRM Prize in Theoretical and Mathematical Physics. He was awarded the Buchalter Cosmology Prize in both 2016 and 2017.

**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 is a fellow of both the American Physical Society and the Royal Society of Canada. He left Perimeter in September 2019.

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

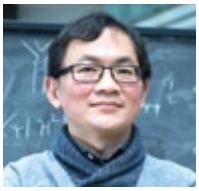
**Matilde Marcolli** (PhD University of Chicago, 1997) began a joint appointment with Perimeter and the University of Toronto in January 2018, after a decade as a professor of mathematics at the California Institute of Technology. She is a mathematical physicist whose research interests include computational 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. She left Perimeter Institute in July 2020 to return to her faculty position at Caltech.

**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 studies strongly correlated many-body systems, focusing on exotic emergent phenomena, quantum criticality, and entanglement. He emphasizes numerical methods as a theoretical technique, particularly the development of novel algorithms and machine learning methods for his research. Among his honours, he has received the Herzberg Medal from the Canadian Association of Physicists, the Young Scientist Prize in Computational Physics from the International Union of Pure and Applied Physics, an Early Researcher Award from the Ontario Ministry of Research and Innovation, and a Canada Research Chair in Computational Quantum Many-Body Physics.

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

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

**Ue-Li Pen** (PhD Princeton University, 1995) joined Perimeter in 2014. He is jointly appointed with the Canadian Institute for Theoretical Astrophysics at the University of Toronto, where he has been a professor since 1998. Pen is a theoretical astrophysicist who studies systems where basic physical effects can be isolated from astronomical complexities. His research projects include the non-linear dynamics of the cosmic neutrino background, 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. In 2019-20, he was part of the CHIME research team that received a Governor General's Innovation Award and was one of the 347 members of the Event Horizon Telescope collaboration to win the 2020 Breakthrough Prize in Fundamental Physics.



**Will Percival** (PhD University of Oxford, 1999) is jointly appointed at the University of Waterloo, where he holds the Mike and Ophelia Lazaridis Distinguished Research Chair in Astrophysics, and is the Director of the Waterloo Centre for Astrophysics. Percival is a cosmologist working primarily on galaxy surveys, using the positions of galaxies to measure the cosmological expansion rate and growth of cosmological structure. He 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. Since 2019, Pospelov has been a faculty member at the School of Physics and Astronomy of the University of Minnesota and a member of the William B. Fine Theoretical Physics Institute. Pospelov left Perimeter in August 2019.

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

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

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

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

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

## SENIOR MANAGEMENT

**Michael Duschenes**
Managing Director and Chief Operating Officer

**Stefan Pregelj**
Senior Director of Finance and Operations

**Greg Dick**
Executive Director of Advancement and Senior Director of Public Engagement

**Ben Davies**
Director of Information Technology

**James Forrest**
Director of Academic Programs

**Colin Hunter**
Director of Communications and Media

**Sheri Keffer**
Director of People and Culture

**John Matlock**
Director of External Relations and Public Affairs

**Sue Scanlan**
Director of Finance

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

## POSTDOCTORAL RESEARCHERS, 2019/20 (PhD granting institution)

Ben Albert (University of Pennsylvania)
Alvaro Martin Alhambra (University College London)
Masooma Ali (University of New Brunswick)
Anurag Anshu, joint with University of Waterloo/Institute for Quantum Computing (National University of Singapore)
Yoni BenTov (University of California, Santa Barbara)
Béatrice Bonga (Pennsylvania State University)
Jacob Bridgeman (University of Sydney)
Rodolfo Capdevilla, joint with University of Toronto (University of Notre Dame)
Sylvain Carrozza (Université Paris-Sud)
Taboka Chalebgwa (Stellenbosch University)
William Cunningham (Northeastern University)
Meiling Deng (University of British Columbia)
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)
Daniel Ignacio Egana-Ugrinovic (Rutgers University)
Job Feldbrugge, joint with Carnegie Mellon University (University of Waterloo)
Angelika Fertig (Max Planck Institute for Gravitational Physics)
Zachary Fisher (University of California, Berkeley)
Simon Foreman, joint with National Research Council (Stanford University)
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)
Flaminia Giacomini, Yvonne Choquet-Bruhat Fellow (University of Vienna)
Meng Guo (Harvard University)
Justin Hilburn, joint with the Institute for Quantum Computing (University of Oregon)
Matthijs Hogervorst (École Normale Supérieure)
Junwu Huang (Stanford University)
Nick Hunter-Jones (California Institute of Technology)
Estelle Inack, Francis Kofi Allotey Fellow (International Centre for Theoretical Physics)
Michael Jarret (University of Maryland)
Raghav Govind Jha (Syracuse University)
Theo Johnson-Freyd (University of California, Berkeley)
Benjamin Knorr (Friedrich Schiller University Jena)
Aleksander Kubica, joint with the Institute for Quantum Computing (California Institute of Technology)
Stefan Kuhn (Max Planck Institute of Quantum Optics)
Meenu Kumari (University of Waterloo)
Ravi Kunjwal (Institute of Mathematical Sciences, Chennai)
Ian Le (Northwestern University)
Felix Leditzky, joint with the Institute for Quantum Computing (University of Cambridge)
Adam Lewis (University of Toronto)
Xinyu Li, joint with the Canadian Institute for Theoretical Physics (Columbia University)
Jacob Lin (California Institute of Technology)
Zi-Wen Liu (Massachusetts Institute of Technology)
Han Ma, Philip W. Anderson Fellow (University of Colorado Boulder)
Mathew Madhavacheril, P.J.E. Peebles Fellow (Stony Brook University)
Ashley Milsted (Leibniz University of Hanover)
Moritz Munchmeyer (LPNHE Pierre and Marie Curie University)
Dominik Neuenfeld (University of British Columbia)
Tadashi Okazaki (Osaka University)
Naritaka Oshita (University of Tokyo)
Solomon Owerre (University of Montreal)
Zhen Pan, Yakov B. Zel'dovich Fellow (University of California, Davis)
Hakop Pashayan (University of Sydney)
Mark Penney (Oxford University)
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, joint with the Institute for Quantum Computing (Western University)
Jess Riedel (University of California, Santa Barbara)
Denis Rosset (University of Geneva, 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)
Alexandre Streicher (University of California, Santa Barbara)
Aaron Szasz (University of California, Berkeley)
Kostiantyn Tolmachov (Massachusetts Institute of Technology)
Dave Touchette (University of Montreal)
Michael Vasmer, joint with the Institute for Quantum Computing (University College London)
Alex Weekes (University of Toronto)
Sebastian Wetzel, joint with the National Research Council (Institute for Theoretical Physics, Heidelberg University)
Wolfgang Wieland (Centre de Physique Théorique)
Elie Wolfe (University of Connecticut)
Junya Yagi (Rutgers University)
Ziqi Yan (University of California, Berkeley)
Qiao Zhou (University of California, Berkeley)
Liujun Zou, John Bardeen Fellow (Harvard University)

## 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
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
Maxim Pospelov, University of Minnesota
Frans Pretorius, Princeton University
Fernando Quevedo, University of Cambridge
Carlo Rovelli, Université de la Méditerranée – Centre de physique théorique de Luminy
Subir Sachdev, Harvard University
Nathan Seiberg, Institute for Advanced Study, Princeton
Yan Soibelman, Kansas State University
Paul Steinhardt, Princeton University
Andrew Strominger, Harvard University
Raman Sundrum, University of Maryland
Gerard 't Hooft, Utrecht University
Barbara Terhal, Delft University of Technology – QuTech
Dam Thanh Son, University of Chicago
Senthil Todadri, Massachusetts Institute of Technology
Bill Unruh, University of British Columbia
Frank Verstraete, Universiteit Gent
Ashvin Vishwanath, Harvard University
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, 2019/20

### PSI FELLOWS

Tibra Ali
Agata Branczyk
Maité Dupuis
Ghazal Geshnizjani
Lauren Hayward
Emilie Huffman
David Kubiznak
Aldo Riello
Giuseppe Sellaroli
Daniel Wohns
Gang Xu

### PSI LECTURERS

Latham Boyle, Perimeter Institute
François David, Institut de Physique Théorique
William East, Perimeter Institute
Davide Gaiotto, Perimeter Institute
Jaume Gomis, Perimeter Institute
Daniel Gottesman, Perimeter Institute
Ruth Gregory, Durham University Science Laboratories
Alioscia Hamma, University of Massachusetts Boston
Eduardo Martin-Martinez, University of Waterloo
Kendrick Smith, Perimeter Institute
Pedro Vieira, Perimeter Institute
Chong Wang, Perimeter Institute

## PHD STUDENTS, 2019/20 (partner university, supervisor)

Jacob Abajian (University of Waterloo, Pedro Vieira)

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)

Yilber Bautista Chivata (York University, Matthew Johnson/Sean Tulin)

Matthew Beach (University of Waterloo, Roger Melko)

Sara Bogojevic (McMaster University, Cliff Burgess)

Pablo Bosch Gomez (University of Waterloo, Luis Lehner)

Kasia Budzik (University of Waterloo, Davide Gaiotto)

Dylan Butson (University of Toronto, Kevin Costello)

Juan Cayuso (University of Waterloo, Matthew Johnson)

Ramiro Cayuso (University of Waterloo, Luis Lehner)

Hong Zhe Chen (University of Waterloo, Robert Myers)

Wan Cong (University of Waterloo, David Kubiznak)

Maxence Corman (University of Waterloo, William East/Niayesh Afshordi)

Frank Coronado (University of Waterloo, Pedro Vieira)

Diego Delmastro (University of Waterloo, Jaume Gomis)

Christian Drago (University of Waterloo, Agata Branczyk)

Job Feldbrugge (University of Waterloo, Neil Turok)

Adrian Franco Rubio (University of Waterloo, Guifre Vidal)

Thomas (T.C.) 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)

Alexandre Homrich (University of Waterloo, Pedro Vieira)

Florian Hopfmueller (University of Waterloo, Lee Smolin/Robert Myers)

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)

Justin Kulp (University of Waterloo, Davide Gaiotto/Jaume Gomis)

Seth Kurankyi Asanti (University of Waterloo, Bianca Dittrich/ Lee Smolin)

Ji Hoon Le (University of Waterloo, Davide Gaiotto)

Raeez Lorgat (University of Toronto, Kevin Costello)

Ruochen Ma (University of Waterloo, Yin-Chen He)

Amalia Madden (University of Waterloo, Asimina Arvanitaki)

Hugo Marrochio (University of Waterloo, Robert Myers)

Fiona McCarthy (University of Waterloo, David Kubiznak/ Robert Mann)

Sebastian Mizera (University of Waterloo, Bianca Dittrich/ Freddy Cachazo)

Faroogh Moosavian (University of Waterloo, Davide Gaiotto)

Soham Mukherjee (University of Waterloo, Erik Schnetter)

Alexander Otto (University of Waterloo, Kevin Costello/Jaume Gomis)

Qiaoyin Pan (University of Waterloo, Maité Dupuis)

Masoud Rafiei-Ravandi (University of Waterloo, Kendrick Smith)

Surya Raghavendran (University of Toronto, Kevin Costello)

Miroslav Rapcak (University of Waterloo, Davide Gaiotto/ Jaume Gomis)

Matthew Robbins (University of Waterloo, Niayesh Afshordi/ Robert Mann)

Alexander Roman (University of Waterloo, Kendrick Smith/ Niayesh Afshordi)

Shan-ming Ruan (University of Waterloo, Robert Myers)

Nitica Sakharwade (University of Waterloo, Lucien Hardy)

Shenqi Sang (University of Waterloo, Tim Hsieh/Roger Melko)

Krishan Saraswat (University of Waterloo, Niayesh Afshordi)

Laura Sberna (University of Waterloo, Neil Turok)

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)

Nils Simeonsen (University of Waterloo, William East/Luis Lehner)

Barbara Soda (University of Waterloo, Lucien Hardy/Achim Kempf)

Aiden Suter (University of Waterloo, Ben Webster)

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)

Weicheng Ye (University of Waterloo, Tim Hsieh/Roger Melko)

Matthew Yu (University of Waterloo, Jaume Gomis)

Keyou Zeng (University of Toronto, Kevin Costello)

Yehao Zhou (University of Waterloo, Kevin Costello)

Yijian Zou (University of Waterloo, Guifre Vidal)

## MASTER'S STUDENTS, 2019/20 (country of origin)

### PERIMETER SCHOLARS INTERNATIONAL

Cristian Ardelean (Canada)
Elizabeth Bennewitz (United States)
Ivan Burbano Aldana (Colombia)
Yushao Chen (China)
Wan Zhen Chua (Malaysia)
Jeremy Cote (Canada)
Ghislaine Coulter-de Wit (United States)
Benjamin De Bruyne (Belgium)
Haoxing Du (China)
Remi Faure (France)
Navya Gupta (India)
Ian Holst (United States)
Nikhil Kalyanapuram (United States)
Alicia Lima (Cape Verde)
Shuwei Liu (China)
Maria Julia Maristany (Argentina)
Sheryl Mathew (India)
Maryam Mudassar (Pakistan)
Jonas Neuser (Germany)
Gloria Odak (Croatia)
Rick Perche (Brazil)
Dalila Pirvu (Romania)
Anniela Melissa Rodriquez Zarate (Mexico)
Joshua Sandor (Canada)
Bruno Torres (Brazil)
Beata Zjawin (Poland)

### MASTER'S RESEARCH STUDENTS

Yanyan Li (China)

## CONFERENCES AND WORKSHOPS, 2019/20

**Boundaries and Defects in Quantum Field Theory**
August 6-9, 2019

**Dynamics and Black Hole Imaging**
August 12-23, 2019

**Cosmological Frontiers in Fundamental Physics 2019**
September 3-6, 2019

**Simplicity III**
September 9-12, 2019

**Gravitational Waves Outside the Boxes**
October 23-25, 2019

**Everpresent Lambda: Theory Meets Observations**
November 11-15, 2019

**Emmy Noether Workshop: The Structure of Quantum Space Time**
November 18-22, 2019

**Symmetry, Phases of Matter, and Resources in Quantum Computing**
November 26-29, 2019

**Indefinite Causal Structure**
December 9-13, 2019

**Elliptic Cohomology and Physics**
May 25-28, 2020

**Geometric Representation Theory**
June 22-26, 2020

**Quantum Gravity 2020**
July 13-17, 2020

## ACADEMIC SPONSORSHIPS, 2019/20

Perimeter Institute was a proud sponsor of the following international conferences and workshops held elsewhere across Canada. A number of other sponsorships were awarded, but due to COVID-19, some events have been postponed. Perimeter will honour any affected sponsorships.

**Lepton Photon Interactions**
Toronto, Ontario
August 5-10, 2019

**Canadian Conference for Undergraduate Women in Physics 2020**
Toronto, Ontario
January 17-19, 2020

**Holography Workshop**
Goderich, Ontario
February 3-7, 2020

**Lake Louise Winter Institute 2020**
Lake Louise, Alberta
February 9-14, 2020

**Photo credits**

Adobe Stock: pp. 15, 18 | Tom Arban: pp. 38, 45 | EPFL: p. 13 | Scott Norsworthy: inside back cover | Gabriela Secara: pp. 6, 8–26, 28-32, 36-37, 47, front cover

# THANKS TO THE VISIONARIES

WE ARE DEEPLY GRATEFUL TO ALL OF OUR SUPPORTERS, INCLUDING:

**MIKE LAZARIDIS, FOUNDER**

**PUBLIC PARTNERS**

GOVERNMENT OF CANADA

GOVERNMENT OF ONTARIO

REGION OF WATERLOO

CITY OF WATERLOO

AND

**PERIMETER'S GROWING NETWORK OF PRIVATE PARTNERS AND SUPPORTERS WORLDWIDE**

For a list of Perimeter's private supporters, see **www.perimeterinstitute.ca/support-perimeter** or refer to page 42.


Canada PERIMETER INSTITUTE FOR THEORETICAL PHYSICS Ontario

31 Caroline St. N. | Waterloo | Ontario
Canada | N2L 2Y5 | 1 519 569 7600
perimeterinstitute.ca
Charitable registration number: 88981 4323 RR0001