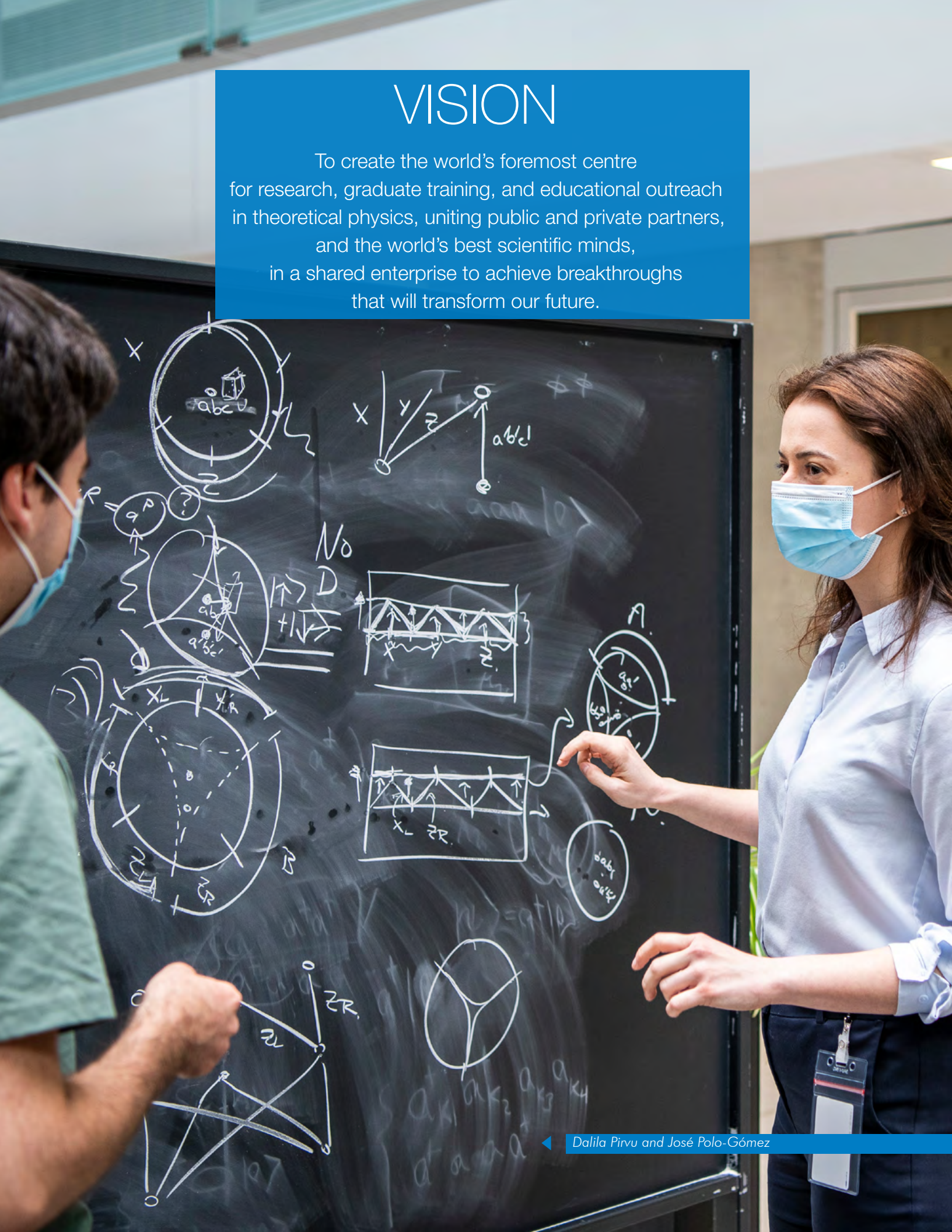
2022 ANNUAL REPORT

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.



Dalila Pirvu and José Polo-Gómez

CONTENTS

This report covers the activities and finances of
Perimeter Institute for Theoretical Physics
from August 1, 2021, to July 31, 2022.

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

TODAY'S THEORETICAL PHYSICS
IS TOMORROW'S TECHNOLOGY

MESSAGE FROM THE BOARD CHAIR

Scientific revolutions happen gradually, then suddenly – nowhere more so than in quantum physics. Discoveries and theories about the quantum realm, which have been building quietly for decades, are "suddenly" disrupting research and technology organizations, creating a tsunami of new knowledge and attracting new business investments. It's no coincidence that this year's Nobel Prize honoured foundational work on quantum entanglement.

I'm lucky to have a front seat to this revolution, as so much of it happens right here. It's happening across Perimeter Institute.

It's happening at the Perimeter Institute Quantum Intelligence Lab, a research and training hub where residents from academia, government, and industry collaborate at the intersection of artificial intelligence and quantum systems.

It's happening at Perimeter's Clay Riddell Centre for Quantum Matter, which focuses on new quantum states of matter. Quantum matter is poised to revolutionize transportation, energy storage, power distribution, and medical diagnostics, while also revealing new insights about the fundamental nature of matter and energy.

It's happening through Perimeter's Quantum Causal Inference Initiative, which is building a Canadian powerhouse for research at the nexus of statistics and quantum theory.

It's happening in Perimeter's research related to quantum gravity, quantum computing and simulation, cosmology, particle physics, and more, across the Institute's nine interconnected research fields, involving over 120 resident researchers and hundreds of visiting scientists.

This building and these people are about much more than the quantum revolution. But right now, quantum physics is having a *moment*. And through our alliances with the Institute for Quantum Computing, the provincial and federal governments, and many partners in the tech, banking, insurance, and energy sectors, Perimeter has become a leader in the quantum revolution.

In the 10 years I've been part of the Institute, quantum research has gone from being barely on the radar of major institutions to being a strategic priority for every G20 nation. As climate change, global conflict, and challenges to national security all seem to be having their own gradually-then-suddenly moments, investing in these rapidly changing technologies just keeps increasing in importance. It restores my optimism to see how Perimeter scientists and the Institute's talented staff consistently go above and beyond to make the most of these advances.

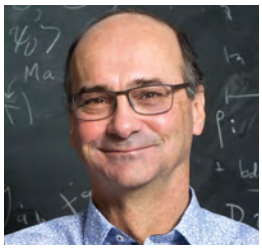
The governments, businesses, and communities who profit most from these advances will be those that can attract, foster, and empower experts in quantum science. Many places around the world are currently scrambling to develop such ecosystems, while ours here in Canada is already well established. Among the G7, Perimeter lifts Canada to the rank of number one in physics and space science research by measures of quality and impact. This is not only a source of great pride but also an important strategic advantage for Canada.

Now is the time to press that advantage, by doubling down on investments in Canadian fundamental research and applied technology. If we empower these brilliant people to keep pushing the boundaries of what's possible, Perimeter researchers will forge a more sustainable, prosperous, and fascinating future – for Canada and for the world, for next year, and for a century from now.

I am grateful to others who support this vision. This year, we were delighted that the Government of Ontario increased its annual investment to $12 million per year and that the Government of Canada renewed Perimeter's funding through 2024. It has also been a great year on the private support front, with several major gifts, including $10 million in renewed support for faculty research chairs from the Daniel Family Foundation and the Riddell Family Charitable Foundation, and $1.5 million in new support from Intact Financial Corporation.

Finally, a thank you to my fellow Board members for their generosity, vision, and leadership. Thanks especially to Joanne Cuthbertson, who is stepping down from the Board after nearly a decade. I would also like to welcome BMO's Chief Talent Officer, Karen Collins, and CIBC's Chief Financial Officer, Hratch Panossian, to Perimeter's Board of Directors. The Institute will benefit greatly from your experience and ideas. We're excited to have you join us on the incredible journey that lies ahead.

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



MESSAGE FROM THE INSTITUTE DIRECTOR

This year, life returned – cautiously and gradually – to our beautiful building. Students returned: After two disrupted years, the 2021/22 class of Perimeter Scholars International was held in person. Visitors returned: We held the first in-person conferences in two years. Early-career women scientists with Simons Emmy Noether fellowships who had deferred their visits began to schedule them. Teachers from across Canada and around the world returned to our summer teacher training workshop, EinsteinPlus, and from there will take modern physics teaching out to thousands of students. Six young scientists whose work or training was cut off by the war in Ukraine accepted special positions here. And, of course, our resident researchers and staff are back.

We learned a lot during the pandemic, and some of the adaptations we made have had unexpected benefits: Hybrid conferences, for example, allow more attendance from scientists with parenting and caregiving responsibilities and are more accessible for researchers with disabilities and people from remote and disadvantaged places. We're committed to continuing them, and to other changes that proved useful.

But Perimeter is and always has been about people. It's about chance collisions and deep interactions. It's about the fizz and spark of science. It's about imagining the unimaginable. All of this is easier to do in person.

That's particularly true as what was once unimaginable comes to pass: The quantum moment, which our founder Mike Lazaridis so presciently foresaw, has arrived. This year, both the Nobel and the Breakthrough Prizes were awarded for pioneering work in quantum science. Huge investments from governments and big companies continue to fuel enormous growth and rapid advances in quantum research around the world. New quantum enterprises are emerging – some of them started by Perimeter scientists. We are seeing quantum computational techniques applied in the finance and manufacturing sectors. Quantum materials are on the edge of creating better superconductors and ultra-powerful sensors.

Investing in quantum research seems like a safe bet now, but 20 years ago – when many people were still uncertain about it – Mike founded Perimeter. The Institute seeded Canada's quantum efforts and has played a vital role in making Canada a key player in the quantum revolution ever since.

This year, we recruited two outstanding new research faculty members in quantum information, who will join us in fall 2023. Sisi Zhu, arriving from Caltech, is a theorist with a background in atomic and optical physics who works closely with experimentalists. She is doing pioneering work in quantum noise, and our colleagues at the Institute for Quantum Computing are eager to have her in town. Alex May, joining us from Stanford, is an information theorist who is interested in holography or quantum gravity and its surprising connections to quantum information processing and quantum error correction.

These new hires join many other researchers here who demonstrate that there is more to this quantum moment than just quantum computers. It includes people doing things that sound exotic, such as trying to understand spacetime through the lens of quantum information or using nascent experimental quantum computers to understand gravity.

Maintaining a broad, ambitious research portfolio that confronts foundational questions from many angles is a key part of the Perimeter philosophy. We do not limit ourselves to work that has obvious, immediate payoffs. The sparks coming off our blackboards again are arcing across the full frontier of theoretical physics, embracing collaboration, cross-disciplinary work, and contrasting approaches. This quantum moment – and many past physics breakthroughs – has shown that ideas that begin by seeming exotic can go on to change the world.

We are grateful for the supporters who also see it this way, from the Government of Canada and the Province of Ontario, which both awarded funding through 2024, to the private donors who stepped forward with gift commitments of over $12.5 million.

At Perimeter, we believe that we have a role in creating an amazing future. This extends to the enterprise of physics itself. We're here to make breakthroughs in our understanding of our universe. We can't afford to leave any great thinkers behind. This year, we completed our Strategic Plan for Equity, Diversity, and Inclusion (EDI). While Perimeter is already engaged in EDI efforts on many fronts – from our outreach programs to our Emmy Noether Initiatives to our volunteer-led Inclusive PI Platform – we can still do better. This plan provides a framework for doing so.

There are challenges all around us, and science must face them bravely and directly. But we cannot let the horizon of our problems be the horizon of our imagination. Our imagination is bigger than our problems – and our universe is bigger than our imagination.

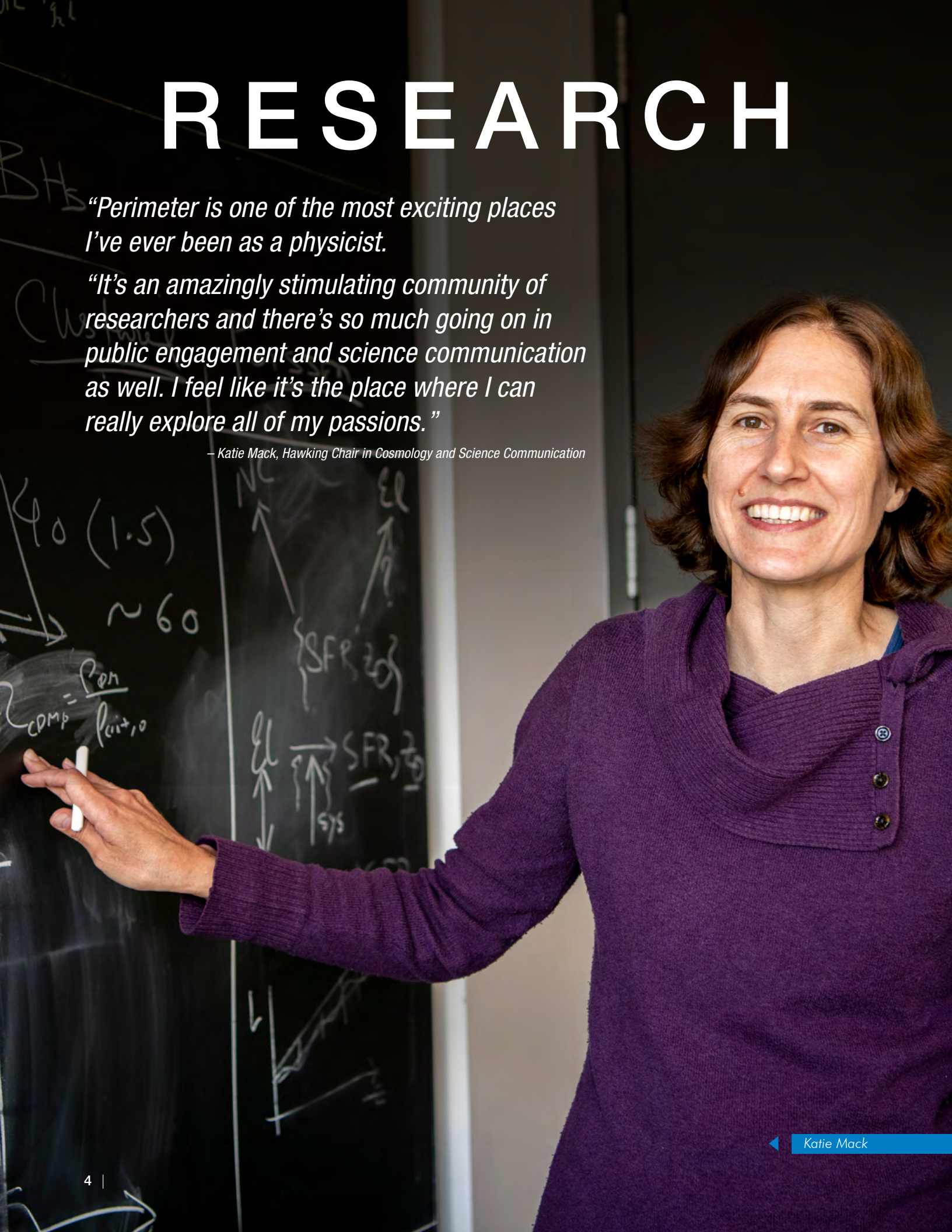
– **Robert Myers**, Director and BMO Financial Group Isaac Newton Chair in Theoretical Physics at Perimeter Institute

RESEARCH

"Perimeter is one of the most exciting places I've ever been as a physicist.

"It's an amazingly stimulating community of researchers and there's so much going on in public engagement and science communication as well. I feel like it's the place where I can really explore all of my passions."

– Katie Mack, Hawking Chair in Cosmology and Science Communication



Katie Mack

RESEARCH by the numbers

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

568 papers published in 2021/22

7,199 papers published in more than 250 journals and on the arXiv since Perimeter's inception

403,916 citations since inception

11 prizes and honours in 2021/22

RESEARCH COMMUNITY

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

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

1 Outreach Faculty

3 Teaching Faculty and

3 Research Scientists

2 Visiting Perimeter Research Chairs

41 Distinguished Visiting Research Chairs

72 postdoctoral researchers

4 newly appointed Simons Emmy Noether Fellows

61 Visiting Fellows

100 Affiliate members

CONFERENCES, WORKSHOPS, AND SEMINARS

6 conferences and workshops attended by **852** scientists

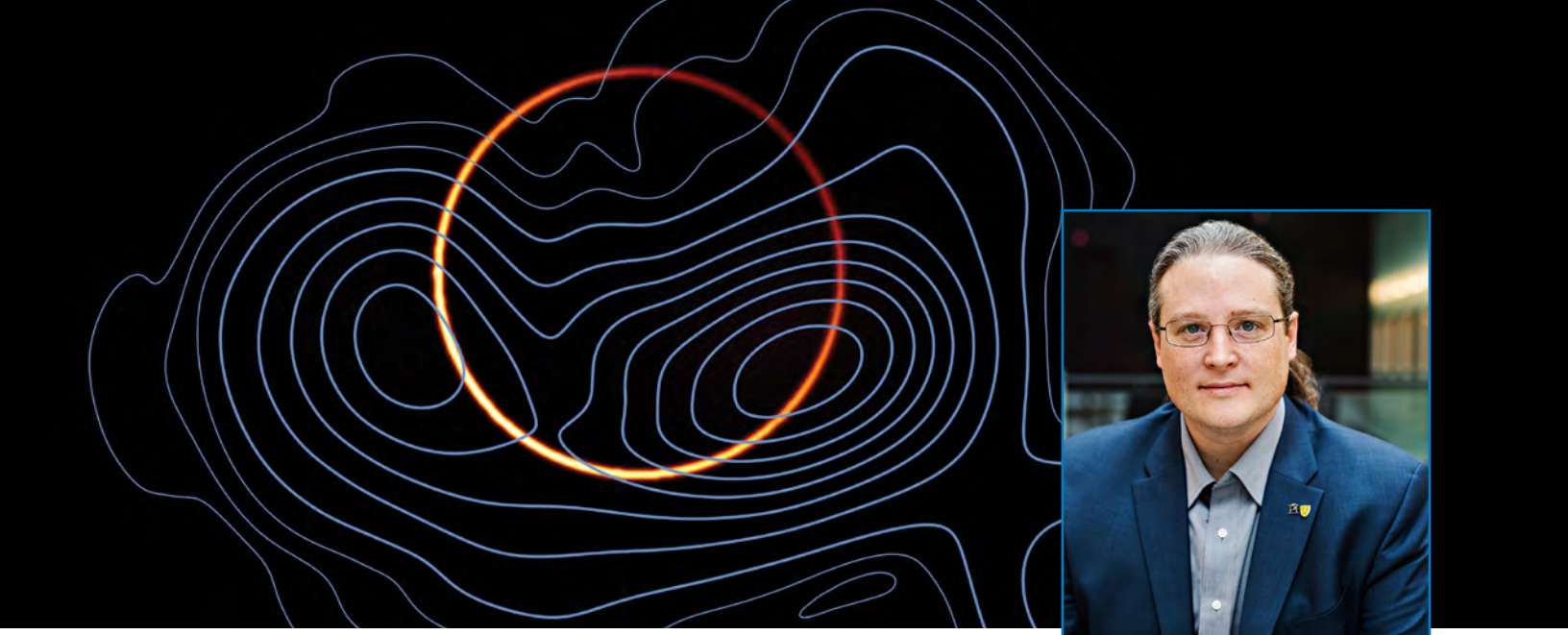
7 sponsored off-site academic conferences and workshops

305 scientific talks, seminars, and colloquia with a total attendance of more than **8,000**

14,215 talks in the online Perimeter Institute Recorded Seminar Archive (PIRSA) since inception

194,000 PIRSA views in 2021/22 by viewers in **177** countries

[1] *Unless otherwise indicated, figures are for August 1, 2021–July 31, 2022.*



Avery Broderick

THE PHOTON RING: A BLACK HOLE READY FOR ITS CLOSE-UP

When scientists unveiled humanity's historic first image of a black hole in 2019, they knew it was just the beginning and that even richer imagery and insights were waiting to be teased out of the data. This year, that promise paid off, as a team of researchers led by Research Associate Faculty member Avery Broderick used sophisticated imaging algorithms to "remaster" the image and peer deeper into the shadows than ever before.

Black holes were considered unseeable until scientists coaxed them out of hiding with the Event Horizon Telescope (EHT), a globe-spanning network of telescopes. Using eight observatories on four continents, all pointed at the same spot in the sky and linked together with nanosecond timing, the EHT researchers observed two black holes in 2017. Two years of hard work later, they revealed the world's first image of a black hole.

The landmark image of the black hole at the centre of the M87 galaxy, which graced the front page of newspapers around the world in 2019, was a brilliant but fuzzy ring of light. Researchers describe the image as having two halves. The first half is driven by astrophysical processes: matter falling into the black hole at high speeds, radiating bright light as it falls. The second is driven by gravitational processes: light being bent by the warped space near the black hole's event horizon. The first part is brighter. The second is of much more interest to scientists.

The "remastering" research team used their robust theoretical understanding of the astrophysical processes around black holes to model the first half of the image – the fuzz of light produced by the infalling matter – and then subtract it from the data set. "It's very much like using polarized sunglasses to remove glare," says Broderick, who holds the Delaney Family John Archibald Wheeler Chair at Perimeter.

This after-the-fact filtering was possible because the EHT is a "computational instrument at its heart," says Broderick. "It is as dependent on algorithms as it is upon steel. Cutting-edge algorithmic developments have allowed us to probe key features of the image."

With the fuzzy light of infalling matter filtered away, what's left is a special class of light: the photons that are whipped around the black hole by its intense gravity, completing part of an orbit before escaping. "In a sense, they tell us what's behind the black hole, and not merely what's around it," says Broderick. When added together, those formerly orbiting photons produce what's known as a photon ring. It is composed of a series of increasingly sharp sub-rings, which the team then stacked to get the full image.

The photon ring is a rich source of information. Some of the photons in the ring have come very close to the event horizon and contain information about the structures and processes there. A study of the photon ring has already allowed the team to measure the mass of the M87 black hole with unprecedented accuracy and helped them glimpse the innermost part of the black hole's jets – that is, the bright, tight beams of ionized matter emerging from the black hole's rotational poles.

"We turned off the searchlight to see the fireflies," explains Broderick. "We have been able to do something profound – to resolve a fundamental signature of gravity around a black hole."

Reference:

A.E. Broderick (Perimeter Institute/U. Waterloo), D.W. Pesce (Harvard-Smithsonian Center for Astrophysics), R. Gold (U. Southern Denmark), P. Tiede (Perimeter Institute/U. Waterloo), et al., "The photon ring in M87*," *Astrophys. J.* 935, 61 (2022), arXiv:2208.09004.

Avery Broderick holds the Delaney Family John Archibald Wheeler Chair in Theoretical Physics.

CONSTRAINING DARK MATTER WITH THE LSST

A team of researchers led by Perimeter postdoctoral researcher Daniel Egaña-Ugrinovic have shown that the upcoming Vera Rubin Observatory's Legacy Survey of Space and Time (LSST) may provide clues to the nature of dark matter.

One of the great mysteries of modern physics, dark matter is a hypothetical form of matter thought to account for approximately 85 percent of the matter in the universe. Because the gravity from dark matter shapes the large-scale structure of the universe, scientists generally agree dark matter exists but know very little about it. The consensus view is that it is some kind of yet-to-be-discovered particle or class of particles.

In the new study, Egaña-Ugrinovic looks for dark matter particles in surprising and distant flashes of light.

The researchers begin with the understanding that most galaxies are centred on supermassive black holes and that when stars pass near these holes, they are disrupted by the extreme gravity. The resulting stellar flares produce bright flashes that can be observed in sky surveys such as the LSST.

The frequency of these events, known as stellar tidal disruption events, depends on the black hole's mass and spin. In turn, the spin of a black hole could be affected by potential dark matter particles known as ultra-light bosons. Ultra-light bosons, if they exist, would interact very weakly with ordinary matter, making them extremely challenging to detect directly.

The team, which included researchers from Perimeter Institute, Stony Brook University, and Northwestern University, showed that by using the LSST to observe the frequency of stellar tidal disruption events, they could place constraints on the properties of these particles. The results were published in *Nature Communications*.

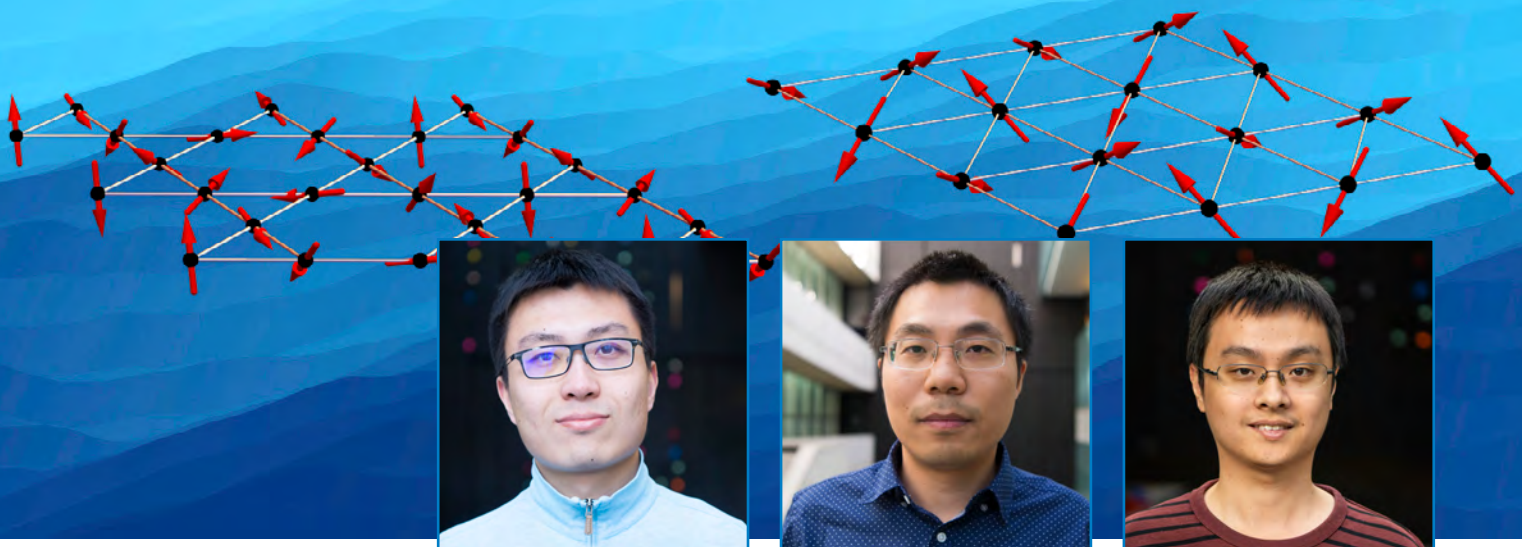
"We have strong evidence from cosmological observations and fascinating theoretical arguments that point towards the existence of yet-undiscovered particles, with experiments from high-energy colliders to astrophysical observatories trying to find them," says Egaña-Ugrinovic.

"As thousands and thousands of stars fall into black holes at ginormous distances from Earth, they produce flashes of light that the Vera Rubin Observatory will allow us to see. Perhaps unexpectedly, we could end up locating these new particles by looking at beautiful flares in the sky!"

Reference:

P. Du (Stony Brook), D. Egaña-Ugrinovic (Perimeter Institute), R. Essig (Stony Brook), G. Fragione (Northwestern), R. Perna (Stony Brook), "Searching for ultra-light bosons and constraining black hole spin distributions with stellar tidal disruption events," *Nat. Commun.* 13, 4626 (2022), arXiv:2202.01215.

Daniel Egaña-Ugrinovic



Chong Wang, Yin-Chen He, and Liujun Zou

DIVING INTO QUANTUM SPIN LIQUIDS

For Research Faculty member Chong Wang and his colleagues Research Faculty member Yin-Chen He and postdoctoral researcher Liujun Zou, exploring quantum spin liquids is like deep diving into unexplored oceanic environments.

Like dazzling underwater reefs, hypothesized materials called quantum spin liquids are exotic environments. In them, particles swim, shimmer, and interact with one another in complex, highly entangled ways on intricate crystal lattices.

Like divers, the researchers who study these theoretical environments often say that it is like exploring a different world. Where divers use scuba gear, these researchers use mathematics.

"We theoretically picture the forms in another universe," says Zou. "Even if there is no pre-existing quantum material that is known to exhibit a phenomenon, we can point out that this phenomenon is theoretically possible."

"Each dimension is a different challenge and has its own rich stories."

– Chong Wang, Research Faculty

Wang, He, and Zou are among the theoretical physicists connected to the Clay Riddell Centre for Quantum Matter at Perimeter, a research hub where scientists seek to explore the intrinsic properties of quantum mechanics to understand and uncover new states of matter.

They use mathematics to predict the possible configurations and movements of electrons in these materials. They also model their properties in different dimensions, such as one or two spatial dimensions instead of the three that we are used to. One dimension would be a chain of interacting atoms. Two would be a sheet, or a material where the interesting effects happen only at the surface. "Each dimension is a different challenge and has its own rich stories," Wang says.

And just as in oceanic environments, fantastic new discoveries may lie in wait in these theoretical worlds.

One such recent deep theoretical dive by Wang, He, and Zou revealed a possible new class of quantum spin liquids they are calling Stiefel liquids, named after mathematician Eduard Stiefel, who made important contributions to the study of topological phases of matter.

Quantum spin liquids and the Stiefel liquids subclass are not liquids in the conventional sense. Rather, the spins of the electrons in a quantum spin liquid are related to one another the way atoms in an ordinary liquid are related to one another: packed closely enough that neighbours interact, but sliding around with no regular arrangement.

Electron spins are responsible for a material's magnetic properties. In magnets, electrons will line up their spin, or orient themselves in an orderly way, with their north poles pointing in the same direction. At ultra-cold temperatures, many materials see their spins "freeze" into regular arrangements and become magnetic.

But in quantum spin liquids, the configuration of the electrons on the lattices makes it difficult for the electrons to line up in an orderly way. If the electrons are interacting on a lattice with adjoining triangular patterns, a tug-of-war can ensue and the material becomes a "frustrated magnet," with electrons in a constantly fluctuating, liquid-like state, even at the lowest temperatures. Hence the name "quantum spin liquid."

The strongly interacting fluctuating particles would constantly be exhibiting what is known as quantum criticality, an in-between stage where matter is transitioning from one phase to another. The unique properties of quantum spin liquids

might make them enormously useful in applications such as quantum computing or higher-temperature superconductivity, where materials can transmit electricity with no resistance, even at room temperatures.

In their recent work, Wang, He, and Zou described how, at least in theory, Stiefel liquids could emerge and have these properties, which could be useful in future technologies. But Zou adds that Stiefel liquids could also force an expansion of the "theoretical toolbox" for understanding quantum matter in general. That's because standard techniques for understanding quantum matter won't work for Stiefel liquids.

"That means that we will need to have new theoretical tools to even study these strongly interacting systems properly," Wang says. The Stiefel liquids proposal opens that investigation.

"It forces us to expand the horizons of our understanding. It forces us to develop new tools, which can then be applied to other problems, and that may lead to a technological application," Zou says. In other words, it might help build not better scuba gear but cutting-edge submersibles, capable of diving deeper into quantum worlds.

Reference:
L. Zou, Y.-C. He, C. Wang (Perimeter Institute), "Stiefel liquids: Possible non-Lagrangian quantum criticality from intertwined orders." *Phys. Rev. X* 11, 031043 (2021), arXiv:2101.07805.

NEW COLLABORATION AIMS TO STRENGTHEN OUR GRASP OF THE STRONG FORCE

Davide Gaiotto, who holds the Krembil Galileo Galilei Chair at Perimeter, is part of an ambitious new Simons Collaboration that aims to advance our understanding of quantum chromodynamics (QCD).

Since it was first theorized over 50 years ago, QCD has been a wildly successful description of the strong nuclear force. It provides an explanation for how protons and neutrons are bound within atomic nuclei, as well as how quarks and gluons are confined inside protons and neutrons.

However, there are still many unanswered questions about exactly how confinement works. The project has its sights set on answering them, describing QCD's confinement theory as "an unsolved problem of fundamental importance in physics."

The confinement process leads to some weird mathematical oddities, including something called the "mass gap," in which quantum particles that have no mass and can travel at the speed of light clump together irreversibly into massive particles. This process cannot be analyzed with current theoretical tools, yet it seems to have been demonstrated in experiments and in computer simulations of QCD, posing an ongoing mystery in quantum physics. The new Simons Collaboration will renew efforts to solve the mass gap puzzle.

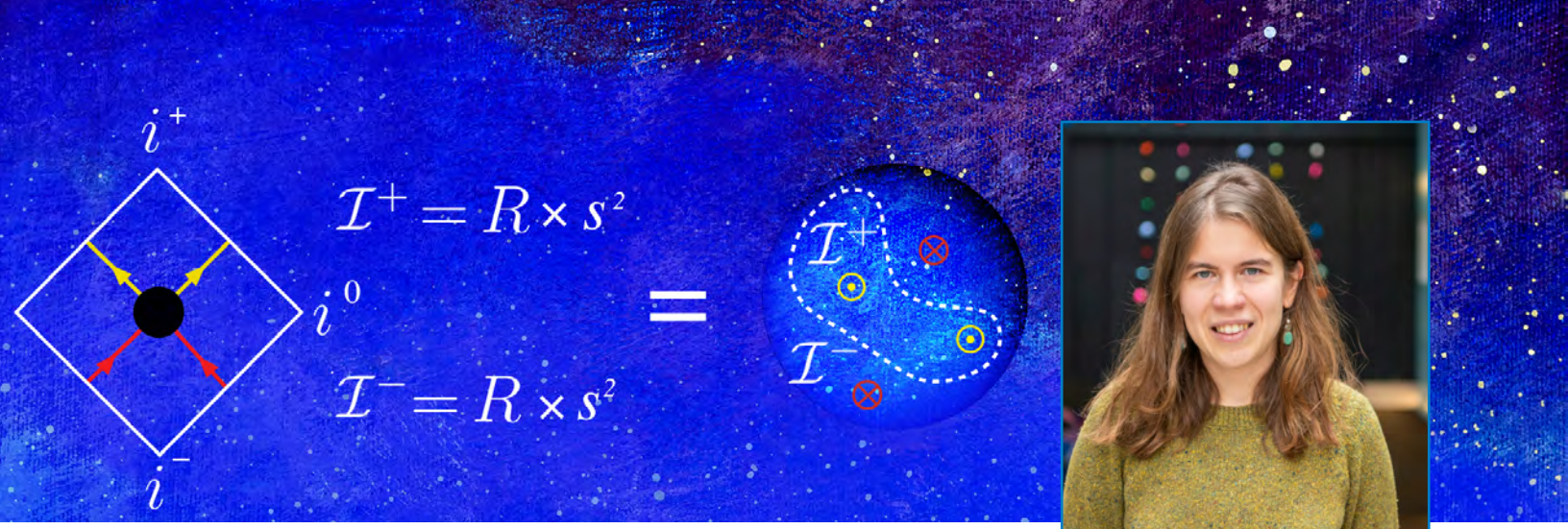
The researchers will also explore the dynamics of QCD strings. Sometimes called chromoelectric flux tubes, these strings connect quarks with anti-quarks. The collaboration plans to take advantage of recent advances in computer modelling to better understand these strings.

The new collaboration is led by Igor Klebanov of Princeton University and involves researchers from 13 institutions in six countries. It is funded over four years by the Simons Foundation.

"The collaboration offers a venue to compare different perspectives on the problem and to formulate novel questions," says Gaiotto.

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

Davide Gaiotto ▶



Ana-Maria Raclariu

A NEW TAKE ON HOLOGRAPHY

In theoretical physics, holography is essentially the idea that you can tell what's in a gift by examining the wrapping paper – that you can describe the universe by describing the surface that encloses it.

More technically, the holographic principle states that physicists should be able to describe any kind of spacetime in terms of a field theory (that is, a theory about particles and their interactions) that lives on "wrapping paper" enclosing this spacetime. Holography has provided two generations of theorists with a powerful suite of tools for cracking tough problems and exploring big ideas.

But while the holographic principle says this technique should work for any spacetime, in practice theorists have only one good example of a gift-and-wrapping pair. Now, researchers like Perimeter's Ana-Maria Raclariu, are hoping to pull off this spacetime-to-field-theory trick a second time.

Raclariu, Perimeter's Ptarmigan Foundation Stephen W. Hawking Postdoctoral Fellow, is a researcher in what's known as celestial holography. This fast-growing subfield is the focus of one of Perimeter's newest research initiatives, which aims to accelerate progress in the field.

The existing gift-and-wrapping pair – the first and most well-explored realization of the holographic principle – is known as the AdS/CFT duality. The spacetime involved is anti-de Sitter space. It's a kind of negatively curved spacetime that's important in string theory.

An important caveat: we don't live in anti-de Sitter space. "We know that the real universe is not a negatively curved spacetime," says Raclariu.

Celestial holography researchers want to work with a spacetime that's asymptotically flat – that is, flat if looked at from far away. "It's a much better match for our universe," says Raclariu.

The holographic principle suggests that there should be a way to describe our universe by describing the field theory that lives on some infinitely distant horizon. Raclariu invokes the old image of the Earth surrounded by a dome of fixed stars to help people picture this: "In astronomy, there is this notion of a celestial sphere, which is essentially what you see if you look at the night sky," she says. "In this case, the proposal is that the dual theory is going to live on this celestial sphere, on this two-dimensional surface. So that's why it's called celestial holography."

Recently, Raclariu collaborated with Harvard postdoc Monica Pate, Nima Arkani-Hamed of the Institute for Advanced Studies (Princeton), and Harvard's Andrew Strominger on pioneering new work in celestial holography. Their research was published in the *Journal of High Energy Physics*. Though the paper describes one of the simplest possible particle interactions that would occur on the celestial sphere, it's an early landmark for the subfield and important evidence that celestial holography is workable.

Ultimately, researchers in celestial holography would like to be able to do what researchers in AdS/CFT can already do: turn these insights about field theory into insights about gravity. It would be a powerful step forward, because the gravity in question would be much closer to the gravity of our own universe.

There are so many gravitational mysteries that could be tackled. Physicists could perhaps describe black holes or the big bang. They could resolve the black hole information paradox, where information theory, quantum theory, and gravitational theory collide. They could even crack the puzzle of quantum gravity entirely.

"Of course, we are very far away from this currently," says Raclariu. "It's the big thing that drives us. In the meantime, we make these small steps toward it."

Reference:

N. Arkani-Hamed (Princeton), M. Pate (Harvard), A.-M. Raclariu (Perimeter Institute), A. Strominger (Harvard), "Celestial amplitudes from UV to IR," *J. High Energ. Phys.* 2021, 62 (2021), arXiv:2012.04208.

Ana-Maria Raclariu holds the Ptarmigan Foundation Stephen W. Hawking Postdoctoral Fellowship at Perimeter.

CHIME REVEALS POSSIBLE CONNECTION BETWEEN FAST RADIO BURSTS AND NEUTRON STARS

A new result from the CHIME/FRB Collaboration adds to a growing body of evidence that strongly suggests that many fast radio bursts (FRBs) originate from neutron stars. In a paper published in *Nature*, the team reported the detection of an FRB that emits pulses in periodic succession, the first of its kind to be seen.

FRBs are immensely energetic blasts of radio waves that last for only microseconds, faster than the blink of a human eye. The first FRB was detected in 2007, and only a few dozen more were spotted throughout the next decade. Since 2017, the Canadian Hydrogen Intensity Mapping Experiment (CHIME) has detected thousands of FRBs, which are helping astronomers crack the mystery of their origins.

The new signal, FRB 20191221A, persisted for up to three seconds: 1,000 times longer than the average FRB. Within this window were clear periodic bursts of radio waves that repeated every 0.2 seconds. This type of subpulse periodicity is an entirely new phenomenon.

The team suspects the signal could emanate from certain types of neutron stars – extremely dense, rapidly spinning collapsed cores of giant stars. The most likely culprits are radio pulsars or magnetars. The powerful magnetic fields on these stars can produce bursts of X-rays and gamma rays – and, likely, FRBs as well.

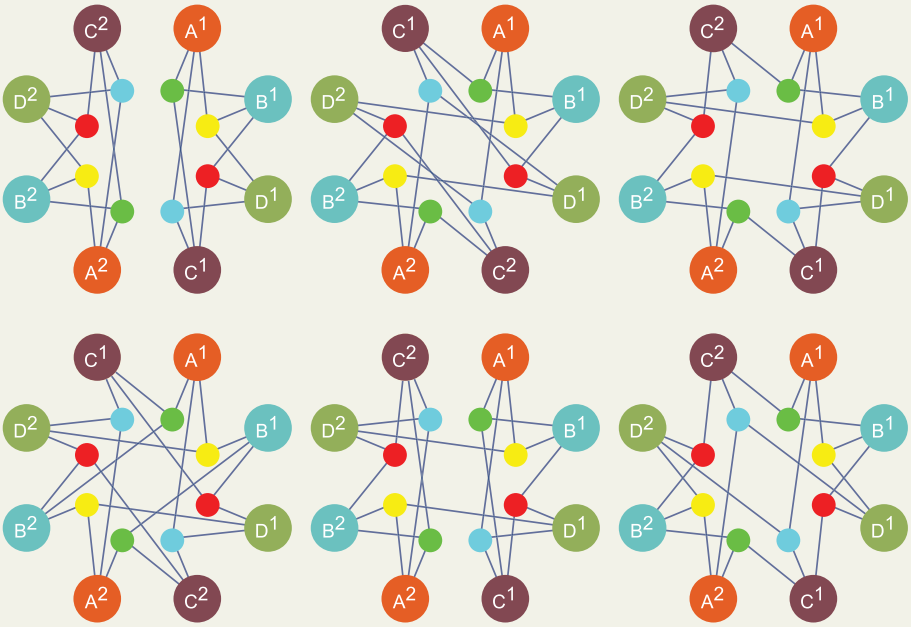
"It's the first time that a non-repeating FRB has been tied to a neutron star," says Kendrick Smith, a member of the CHIME/FRB Collaboration and a Perimeter research faculty member who holds the Daniel Family James Peebles Chair.

"That's an open question in the field, whether repeating and non-repeating FRBs are the same type of object, or whether they're unrelated phenomena that both produce radio pulses," Smith says. "We don't yet know whether all FRBs are magnetars. We definitely know that *some* of them are magnetars."

Reference:
CHIME/FRB Collaboration, "Sub-second periodicity in a fast radio burst," *Nature* 607, 256-59 (2022), arXiv:2107.08463.

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

Kendrick Smith ▶



Elie Wolfe

ON THE SHOULDERS OF BELL

In our everyday experience, if someone rolls a bowling ball down the aisle at the bowling alley, the pins come down only after the ball hits them. Also, the pins cannot be affected by a strike happening in another lane far away. Cause precedes effect (causality), and an object like a bowling ball can only be influenced directly by its immediate surroundings (locality). These are the notions that define our common sense reality.

Unfortunately for common sense, quantum theory says that the universe cannot be both local and causal. For instance, we know that if two particles are entangled at the quantum level, then no matter how far apart they are, they will still be correlated. It's as if watching the bowling pin fall in lane one gives you information about what's happening in lane two – even if lane two is on the other side of the universe.

Early on, physicists including Einstein believed there might be some hidden connection between the pins in lane one and lane two – "a hidden variable" – linking them like a piece of string.

In the 1960s, theorist John Bell proved that no hidden variable model could ever be reconciled with certain predictions of quantum theory. Later, experimentalists designed ever stronger empirical tests of Bell's theorem.

Just recently, the Nobel Prize in Physics was awarded to three scientists — Alain Aspect, John F. Clauser, and Anton Zeilinger — who closed all the possible loopholes in Bell's tests. In announcing the Nobel Prize, Eva Olsson, a member of the Nobel Committee for Physics, said Aspect, Clauser, and Zeilinger's work "opened doors to another world, and it has also shaken the very foundations of how we interpret measurements."

"Bell's theorem was shocking," says Perimeter Research Scientist Elie Wolfe. It pulled the plug on simple hidden variable models. What happens in lane one really is connected to what happens in lane two, and there is no string.

Wolfe is part of a team of scientists who recently took Bell's theorem a step further, proving that in fact you cannot understand the universe two pins at a time.

More technically, they've shown that non-locality is inherently "multipartite" – that is, involving multiple parties, not just pairs of systems. One loose analogy is to imagine being in a rainforest where three tribes speak different languages but each tribe has some words in common with each of the other two. You cannot get a complete story of the language origins simply by studying them in pairs. You would have to study all three together. In other words, no matter how well you understand the physics of every possible pair of entangled particles, it's not enough. It is not possible to describe composite systems in terms of their parts.

This multipartiteness is not a quirk of the particular way we've formulated our understanding of quantum mechanics. It will be fundamental to any future theory that is compatible with quantum theory, Wolfe says.

Wolfe and colleagues' new work rejects a class of theories broader than all hidden variable theories, leading to the conclusion that "nature's nonlocality must be boundlessly multipartite," as Wolfe wrote in a recent paper. (A companion paper focuses specifically on the failure of solely bipartite connections.)

Wolfe and his team have been exploring a broad class of theories known as generalized probabilistic theories. This broad class of theories "tries to situate quantum theory as one of an infinite spectrum of possible theories," he says.

Another interesting aspect of this work is that it involves intersecting interests between two separate groups of scientists – those working on machine learning and those working on quantum physics.

"Entanglement is a resource that's available in nature, like

water and oil and electricity, and we can do all kinds of things with it," says Wolfe. "And it turns out that three-way entanglement is its own unique resource."

For now, it's fair to say this remarkable result is – as a bowler might put it – striking.

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X. Coiteux-Roy (USI), E. Wolfe (Perimeter Institute), and M.-O. Renou (ICFO BIST), "Any physical theory of nature must be boundlessly multipartite nonlocal," *Phys. Rev. A* 104, 052207 (2021), arXiv:2105.09380.

X. Coiteux-Roy (USI), E. Wolfe (Perimeter Institute), and M.-O. Renou (ICFO BIST), "No bipartite-nonlocal causal theory can explain nature's correlations," *Phys. Rev. Lett.* 127, 200401 (2021), arXiv:2105.09381.

RESEARCHERS ACHIEVE FIRST QUANTUM SIMULATION OF BARYONS

Richard Feynman once memorably summed up the challenge of simulating quantum events with computers: "Nature isn't classical, dammit," he said. "If you want to make a simulation of nature, you'd better make it quantum mechanical."

A team of researchers led by Christine Muschik, research associate faculty member at Perimeter and associate professor at the Institute for Quantum Computing (IQC) at the University of Waterloo, have taken that advice to heart and simulated quantum objects with a quantum computer. Specifically, they performed the first-ever simulation of baryons (a class of particles that includes protons and neutrons) on a quantum computer.

"Instead of smashing particles in an accelerator, a quantum computer may one day allow us to simulate these interactions that we use to study the origins of the universe and so much more."

– Christine Muschik, Research Associate Faculty

Muschik leads the Quantum Interactions Group at IQC, as well as Quantum Simulations of Fundamental Interactions, a joint research initiative between IQC and Perimeter.

Working with Randy Lewis from York University, Muschik's team developed a resource-efficient quantum algorithm that allowed them to do calculations of non-Abelian baryon and meson masses on IBM's cloud quantum computer paired with a classical computer.

In their hybrid set-up, a classical and a quantum computer were tied together to create a closed feedback loop. The classical computer was tasked with parts of a problem that it could do easily, and then the quantum computer took over the parts that were too – well – *quantum* for the classical computer. The problem was passed back and forth.

With this landmark step of simulating baryons on a quantum computer, the researchers are blazing a trail toward quantum simulations that can be far beyond the capabilities and resources of even the most powerful supercomputers in the world.

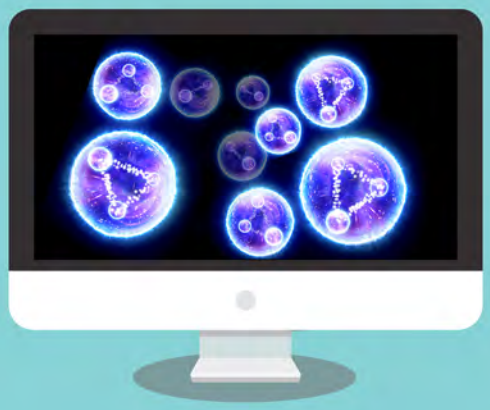
This breakthrough demonstration is an important step toward a new era where the revolutionary potential of quantum computers is realized and can be used to create quantum simulations that might help scientists study neutron stars, for example, or learn more about the earliest moments of the universe.

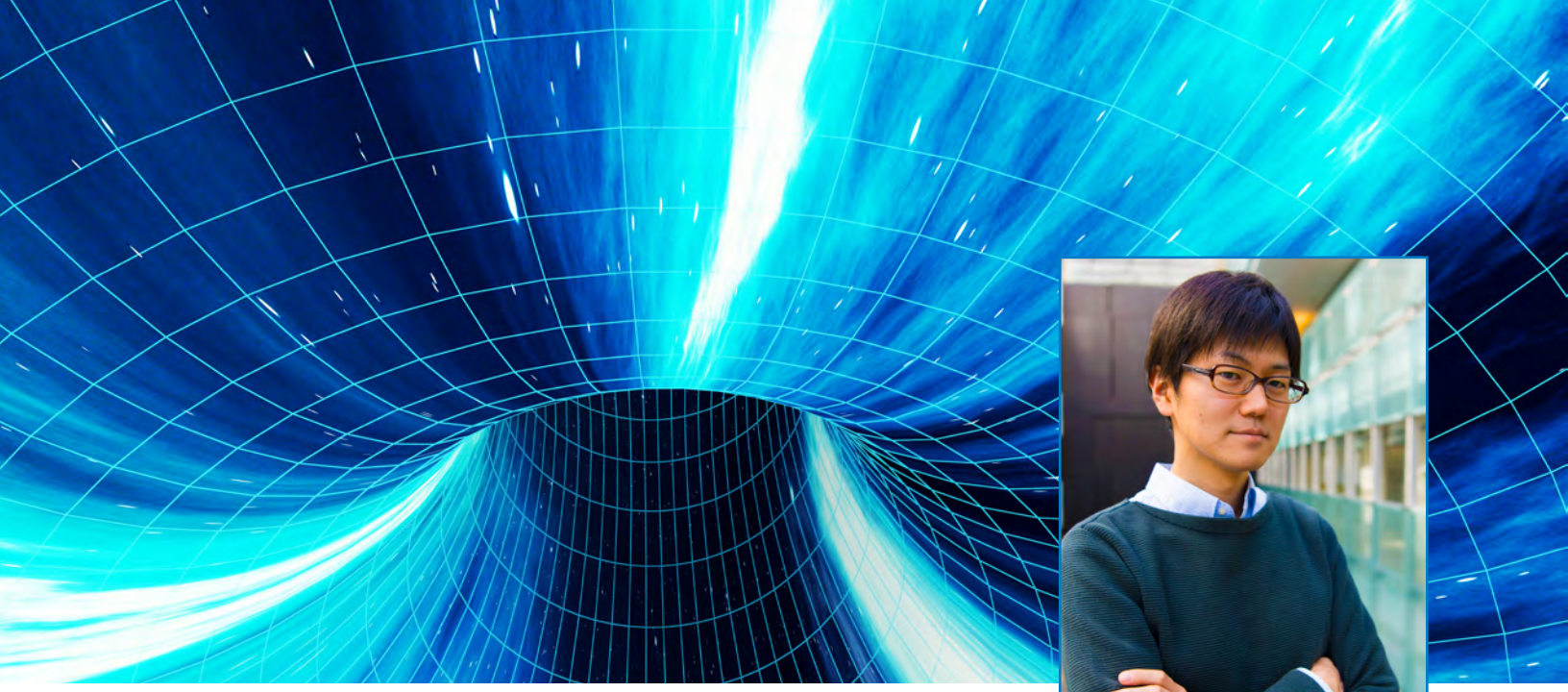
"Instead of smashing particles in an accelerator, a quantum computer may one day allow us to simulate these interactions that we use to study the origins of the universe and so much more," Muschik says.

Reference:

Y.Y. Atas (IQC/U. Waterloo), J. Zhang (IQC/U. Waterloo), R. Lewis (York U.), A. Jahanpour (IQC/U. Waterloo), J.F. Haase (IQC/U. Waterloo), C.A. Muschik (Perimeter Institute/IQC/U. Waterloo), "SU(2) hadrons on a quantum computer via a variational approach," *Nat. Commun.* 12, 6499 (2021), arXiv:2102.08920.

Christine Muschik ▶





Beni Yoshida

DROP A QUBIT INTO A BLACK HOLE AND GET IT BACK – WITH A TRAVERSABLE WORMHOLE

Suppose you had a diary full of quantum information – something so secret that you wanted to destroy it utterly. You throw it into a black hole. Can it ever be recovered?

Perimeter Research Faculty member Beni Yoshida says it can – and the protocol he developed to do it has become a powerful experimental tool to investigate the quantum dynamics of many-body systems and perhaps a key advance toward building practical quantum technologies.

The question of whether information, like your quantum diary, is really lost forever when it falls into a black hole is called the black hole information paradox. Gravitationally, we know that once an object, like the quantum diary, crosses the black hole's event horizon, it can't come back. But quantum information theory says that no quantum information can ever be lost. On the face of it, both can't be true. This puzzle has occupied physicists for the best part of half a century now. Like many broken places in physics, it's a place where breakthroughs happen: the black hole information puzzle has driven progress in every subfield it touches.

Yoshida, who recently won the Nishinomiya Yukawa Memorial Prize, has been on the track of his own answer to the quantum diary question for years. The work has taken him – and the field – on a long and surprising journey. The first milestone came in 2015, when Yoshida and his collaborators developed a proof, based on information theory, that quantum information does indeed escape from a black hole in the form of Hawking radiation: the faint glow produced by particles formed at the event horizon.

But, of course, there's a huge step between proving that quantum information escapes and knowing how to take that shredded information and put the quantum diary back together. Researchers across the field were generally pessimistic about the chances of reassembly – but in 2017, Yoshida and Alexei Kitaev of the California Institute of Technology developed a protocol, again based in quantum information theory, for recovering information from a black hole.

Both the 2015 proof and the 2017 protocol involve a phenomenon known as quantum information scrambling, which is thought to take place inside black holes.

An intuitive picture of a "scrambling" might look something like the tumbling cage full of numbered balls used in bingo halls. But quantum scrambling is different: each "ball" is a qubit, and it doesn't just bounce around, it interacts with other qubits, and the information it carries becomes less localized – that is, it can no longer be described by drawing out and looking at one particular ball. As more and more qubits interact in broader systems, the information becomes less and less localized.

If black holes act as quantum scramblers, then the information in your tossed quantum diary may seem lost, but in fact it's encoded in the correlations between the particles inside the black hole – as well as in the Hawking radiation that escapes from that black hole. Yoshida's protocol is a set of mathematical instructions showing how to decode it.

It's not just secret diarists and black hole scientists who are interested in how quantum information is spread through a system of qubits. It's a vital question for anyone studying quantum many-body systems, including researchers looking to characterize or control quantum materials and those looking to build quantum computers.

Knowing this, Yoshida and other collaborators started speculating about testing his information retrieval protocols in other quantum systems – ones a little more amenable to study than black holes. Yoshida and other collaborators worked with Chris Monroe of the Joint Quantum Institute at the University of Maryland and ran a test using a handful of very cold ions, carefully controlled using laser pulses. The results were published in a landmark 2019 *Nature* paper. It was, Yoshida says, "the first paper to simulate physics of quantum black holes and observe quantum information scrambling in a convincing manner."

But even that was not the end of the story. The protocol keeps getting refined – it now includes a particular kind of quantum scrambling called coherent scrambling – then experimentalists expand their tests, and the field moves forward. Yoshida describes his latest work as a collaboration between Berkeley, Harvard, Perimeter, and the University of Maryland, including cutting-edge experimentalists.

As we approach the era of practical quantum technologies, understanding quantum scrambling will be crucial. And a question that started with a thought experiment about books in black holes may hold the answers that will shape our quantum future.

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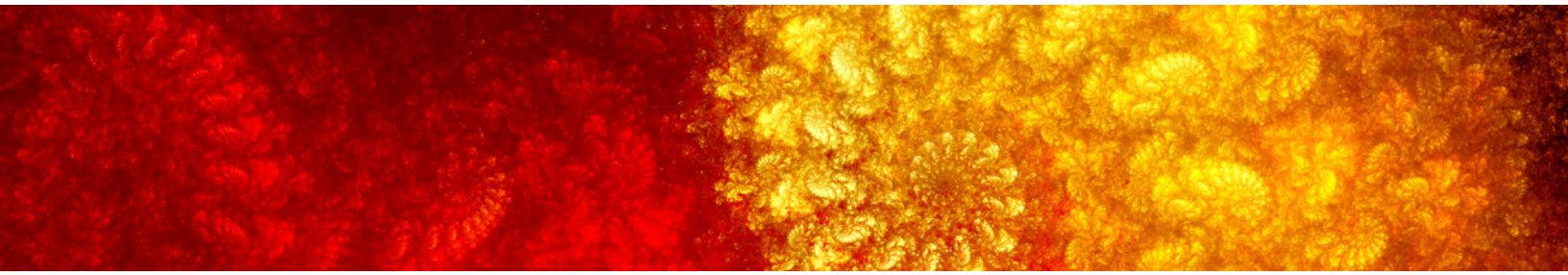
T. Schuster (UC Berkeley), B. Kobrin (UC Berkeley), P. Gao (MIT), I. Cong (Harvard), E.T. Khabiboulline (Harvard), N.M. Linke (U. Maryland), M.D. Lukin (Harvard), C. Monroe (U. Maryland), B. Yoshida (Perimeter Institute), N.Y. Yao (UC Berkeley), "Many-body quantum teleportation via operator spreading in the traversable wormhole protocol," *Phys. Rev.* X 12, 031013 (2022), arXiv:2102.00010.



HONOURS, AWARDS, AND MAJOR GRANTS

- **Cliff Burgess**, research associate faculty member, was awarded Best Book in Physics and Chemistry by the Association of American Publishers for his book *Introduction to Effective Field Theory*.
- **Kevin Costello**, research faculty member and Krembil William Rowan Hamilton Chair, won the John L. Synge Award from the Royal Society of Canada for work that "brings modern mathematical techniques to bear" in a "widely used theoretical paradigm in physics."
- **Katherine (Katie) Mack**, outreach faculty member and Hawking Chair in Cosmology and Science Communication, was named a 2022-2024 CIFAR Azrieli Global Scholar.
- **Roger Melko**, research associate faculty member, was awarded the Brockhouse Medal by the Canadian Association of Physicists and the Division of Condensed Matter and Materials Physics.
- **Christine Muschik**, research associate faculty member, received a President's Research Excellence Award of the University of Waterloo and was named a University Research Chair at the University of Waterloo.
- **Robert Myers**, Perimeter Director and BMO Financial Group Isaac Newton Chair, and **Will Percival**, research associate faculty member, were each named to the Clarivate Analytics 2021 Highly Cited Researchers list for the fifth time.
- **Kendrick Smith**, research faculty member and Daniel Family James Peebles Chair, along with a team of CHIME researchers, was co-awarded the Lancelot Berkeley Prize from the American Astronomical Society, awarded annually for "highly meritorious work in advancing the science of astronomy."
- **Lee Smolin**, research faculty member, was ranked the third most influential physicist by Academic Influence.
- **Beni Yoshida**, research faculty member, received the Nishinomiya Yukawa Memorial Prize in Theoretical Physics, awarded annually to an outstanding theoretical physicist under 40.
- In 2021/22, Perimeter scientists were awarded $2.24 million in new research grants from agencies including the Natural Sciences and Engineering Research Council of Canada, Compute Canada, the Canadian Institute for Advanced Research (CIFAR), the National Science Foundation, the Simons Foundation, and the Templeton Foundation.

PERIMETER RESEARCHERS NAMED AMONG WORLD'S MOST INFLUENTIAL SCIENTISTS

The 2021 Highly Cited Researchers list from Clarivate Analytics includes Perimeter's Director Robert Myers and Research Associate Faculty member Will Percival, who is also a faculty member and Director of the Waterloo Centre for Astrophysics at the University of Waterloo.

The list recognizes pioneers who have published multiple papers that rank among the top 1 percent of most-cited papers in their fields over the last decade according to Web of Science, a large database of reputable journals.

In scientific papers, citations give credit to the results and ideas of other scientists. Citations are thus an important measure of scientific impact, showing how a researcher's work influences the ideas and research of other scientists.

According to Clarivate, "Of the world's scientists and social scientists, Highly Cited Researchers truly are one in 1,000."

This is the fifth time since 2014 that Myers has been on the list. Percival has also been named to the list in four previous years.

Myers, one of Perimeter's founding faculty members and its Director since 2019, has made major contributions in a broad range of areas, from gravitational physics and black holes to foundational quantum field theory and string theory. He has written more than 230 papers, which have been cited more than 30,000 times, according to the INSPIRE database.

Percival, an astrophysicist, is a lead scientist for the Sloan Digital Sky Survey, an international collaboration that released a comprehensive analysis of the largest three-dimensional map of the universe ever created. His 262 papers have been cited more than 40,000 times, according to the INSPIRE database.

MELKO WINS BROCKHOUSE MEDAL

Perimeter Research Associate Faculty member Roger Melko, who is also a faculty member at the University of Waterloo, has been awarded this year's CAP/DCMMP Brockhouse Medal.

Awarded by the Canadian Association of Physicists (CAP) and the Division of Condensed Matter and Materials Physics (DCMMP), the Brockhouse Medal recognizes significant experimental or theoretical contributions to condensed matter and materials physics.

"Roger is a bold innovator and a creative thinker," says Perimeter Director Robert Myers. "His work has broad and profound implications, and his impact will only continue to grow. The Brockhouse Medal is a wonderful and well-deserved honour."

Melko's career has been characterized by a fascination with both computers and the exotic phases of matter where quantum effects dominate, known as quantum matter. He leads the Perimeter Institute Quantum Intelligence Lab, a research centre and training hub for future leaders at the intersection of artificial intelligence and quantum science. As a dedicated mentor for the next generation of scientists, his impact extends well beyond his field. Trainees from Melko's lab are emerging as young leaders in their fields and are highly sought after in both academia and industry.

◀ *Roger Melko*

EQUITY, DIVERSITY, AND INCLUSION

Black, Indigenous, and other racialized people, women, and people with disabilities are underrepresented in theoretical physics, both at Perimeter and in the scientific community more broadly. Over the past decade, there have been many efforts related to equity, diversity, and inclusion (EDI) at Perimeter, and they have unquestionably enhanced the Institute's culture, leading to successes in gender parity in many outreach and training programs. Some of these efforts have illuminated areas where we can do more, particularly at senior levels.

The following EDI initiatives are not a comprehensive list; Perimeter intentionally integrates best practices and policies related to EDI into all research, training, and outreach programs, and further examples can be found throughout this report. In addition to efforts aimed at people from historically underrepresented groups, Perimeter continues to offer most of its programs and resources at little or no cost, ensuring economic background is not a barrier to access.

INCLUSIVE PI PLATFORM

Founded in 2018, the Inclusive PI Platform is a volunteer-driven effort whose core operating principles are collaboration and ensuring all voices are heard. About 25 percent of all Perimeter community members – including faculty, postdocs, students, and administrative staff – are actively involved. Members form working groups in areas of mutual interest, forming new groups or retiring existing ones as circumstances warrant.

This year, 62 members in eight working groups drove change in the following areas: 2SLGBTQA+, accessibility, anti-racism, climate change, mental health, parental policies, seminars, and women in physics. The Platform also includes an allyship training program and a respectful environment program that reviews and updates Perimeter policies each year.

The Inclusive PI Platform is embedded in Perimeter's culture. Working groups developed and supported approximately 40 initiatives and events in 2021/22, many of them rooted in the lived experience of Platform members and achieved in collaboration with Perimeter leadership.

For example:

- Members of the parental policies group worked with Perimeter's People and Culture team to enhance benefits available for people on parental leave.
- The 2SLGBTQA+ group hosted social events designed to foster a welcoming and inclusive environment and was instrumental to improvements made to Perimeter's all-gender washrooms.
- The women in physics group worked with the Outreach and Communications departments to host panel discussions and share stories of women physicists on Perimeter's website and through social media.
- The seminars group has worked to make scientific discussions more inclusive, both by inviting speakers and by developing clear guidelines so that all attendees are respected and feel comfortable contributing.

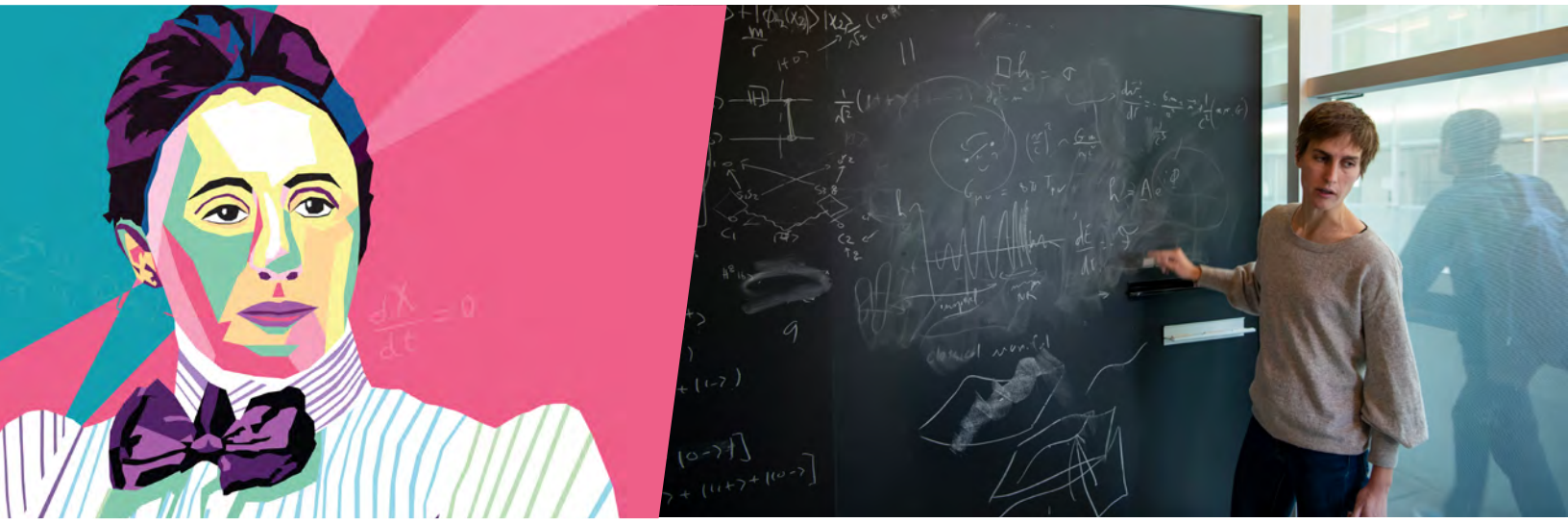
STRATEGIC PLAN FOR EDI

In 2021/22, Perimeter developed and approved its comprehensive Strategic Plan for EDI and hired an experienced leader to facilitate its implementation. The plan lays out Perimeter's objectives, key activities, and methods for measuring progress in the coming years. The overarching goals of the plan are to:

- Build a culture where everyone can contribute fully to Perimeter's mission
- Promote shared responsibility for EDI across the whole Perimeter community
- Support the development of a diverse pipeline of future physicists
- Set an example that inspires change within the broader physics community

Critical elements of the plan include mentoring, attracting, and retaining people from equity-deserving groups at senior research, staff, and governance levels. It is also crucial that everyone at Perimeter becomes invested in the process, and it is expected that 95 percent of all researchers, staff, and students will participate in at least one training or EDI initiative each year. And, just as we do with science, we'll back up our efforts with data – by setting benchmarks and assessing progress through regular surveys and data collection.

EMMY NOETHER INITIATIVES



Laura Bernard

Perimeter's programs to attract and retain more women in science are collectively referred to as the Emmy Noether Initiatives, named after pioneering German mathematician Emmy Noether, whose work underpins much of modern physics. The Emmy Noether Initiatives aim to empower and support women and girls to enter, and succeed in, physics.

The initiatives include outreach to high school students through the "Inspiring Future Women in Science" event (see page 36), support of graduate students through the Emerging Talent Fund (see the profile of Kasia Budzik on page 29), and career development opportunities for women researchers. The initiatives are supported, in part, through the generosity of the Emmy Noether Council and donors in the Emmy Noether Circle (see page 41).

EMMY NOETHER COUNCIL

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

Anne-Marie Canning
Culturalpreneur and gender empowerment philanthropist

Nancy Coldham
Founding Partner, CG Group

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

Michelle Osry
Partner, Deloitte Canada (Vancouver)

Laura Reinholz
Head of B2C Customer Experience, BMO Financial Group

Yasemin Sezer
Executive Director, Capco

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

Perimeter Institute would like to thank **Sherry Shannon-Vanstone** for her generous service on the Emmy Noether Council from 2015 to 2022, including five years as Chair.

SIMONS EMMY NOETHER FELLOWS PROGRAM

For exceptional early- and mid-career women physicists, Simons Emmy Noether Fellowships offer an opportunity to make their mark on their field at a strategic moment in their careers. While on leave from their home institutions, fellows spend up to a year at Perimeter solely focused on their research, free to take full advantage of the Institute's abundant opportunities to network and develop new collaborations.

Each fellow receives individually tailored supports designed to reduce the barriers that many women face, which can include travel expenses, housing, childcare, and partial support to bring spouses or partners. They also receive support to bring graduate students and/or postdoctoral researchers, and administrative and logistical support. The program has made a measurable difference in the careers of many recipients. Past fellows have achieved tenure or high-profile positions, published in top-tier journals, and advanced exciting research programs. Two former Simons Emmy Noether Fellows are now a part of Perimeter faculty: Christine Muschik, research associate faculty member, and Katie Mack, Hawking Chair in Cosmology and Science Communication.

In 2021/22, seven Simons Emmy Noether Fellows spent 221 days at Perimeter Institute, including fellows who were appointed in earlier years but deferred their visits due to the pandemic.

PI PEOPLE

Simons Emmy Noether Fellow

URBASI SINHA

For Urbasi Sinha, the power of physics can be found in the cross-current of theory and experiment.

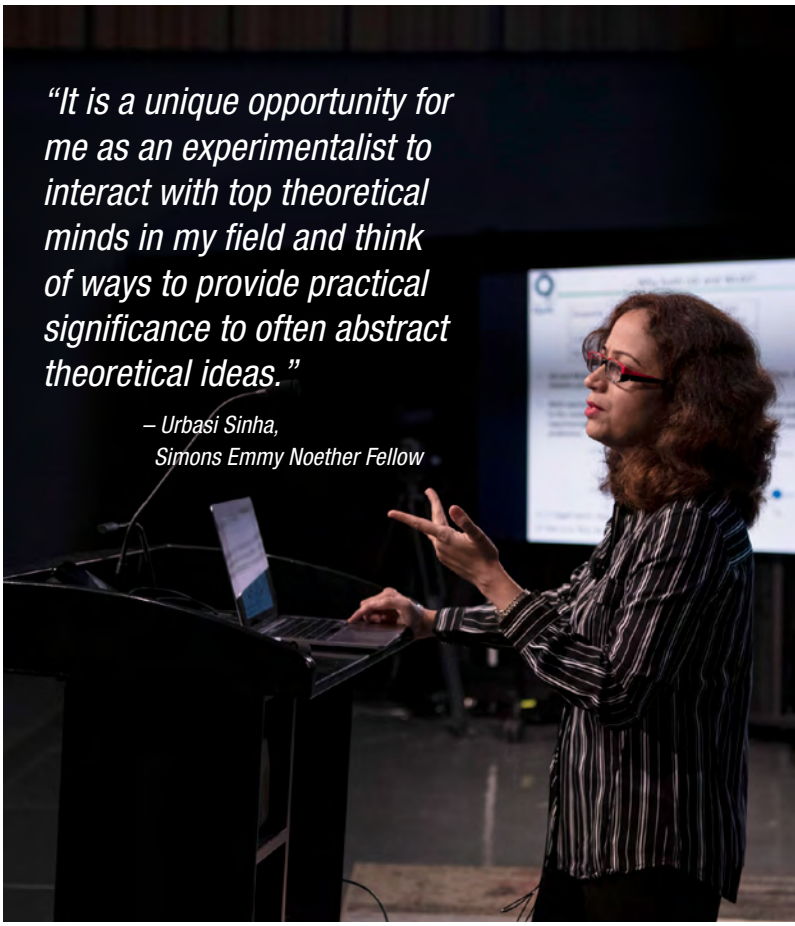
She began in the practical world of experiment, studying superconducting devices as a graduate student at the University of Cambridge.

Sinha credits Raymond Laflamme, a research associate faculty member at Perimeter and the founding Director at IQC at the University of Waterloo, for drawing her toward the cutting-edge possibilities in quantum computing, quantum communications, and quantum optics while she was a postdoctoral researcher at IQC.

As a postdoctoral researcher at IQC, she led a "triple slit" variation on the famous "double slit" experiment to test the Born rule, one of the fundamental axioms of quantum mechanics. The celebrated results provided the most rigorous empirical validation of this rule to date.

Sinha returned to Bangalore, India, where she became a professor at the Raman Research Institute and now leads the Quantum Information Computing Laboratory. Originally appointed as a Simons Emmy Noether Fellow in 2020, her research visit was delayed due to the pandemic. She was finally able to arrive for a research visit in 2022, where she spoke about her work in photonic quantum science and technologies and building a global quantum internet at a colloquium.

"For me, this is a great program. It is a unique opportunity for me as an experimentalist to interact with top theoretical minds in my field and think of ways to provide practical significance to often abstract theoretical ideas," Sinha says.



Urbasi Sinha

Each collaboration at the intersection of experimental and theoretical physics is a virtuous circle, with each element reinforcing and strengthening the other, she says. "This fellowship is a means of providing further impetus towards more such revolutionary practical realizations."

Karen Yeats

2021/22 SIMONS EMMY NOETHER FELLOWS

Four researchers were newly appointed in 2021/22:

Alice Bernamonti,
Università degli Studi di Firenze

Anna Ijjas,
New York University

Marilena Loverde,
Stony Brook University

Karen Yeats,
Simon Fraser University

Alessia Platania and Benjamin Knorr ▲

RESEARCH COMMUNITY

FACULTY AND ASSOCIATE FACULTY

In 2021/22, Perimeter Institute was home to 26 research faculty members – including one newly recruited – across nine research areas, as well as three teaching faculty members and one newly recruited outreach faculty member. There are now 22 research associate faculty jointly appointed with seven partner universities across Canada, including one new recruit.

For a full list of faculty and associate faculty, including biographies, see pages 49-57.

NEWLY RECRUITED RESEARCHERS

The following exceptional scientists joined Perimeter in 2021/22. The new recruits exemplify Perimeter's strategy of finding and recruiting outstanding emerging talent as they are entering their peak years of research productivity.

Junwu Huang first came to Perimeter as a postdoctoral researcher in 2017 and joined the research faculty in 2022. He designs novel small-scale experiments to look for light weakly coupled particles as dark matter in the universe, and new searches based on astrophysical and cosmological observations for new physics motivated by string theory, including axions, cosmic strings, and new vacua in the landscape.

Katherine (Katie) Mack joined Perimeter in 2022 as its first outreach faculty member and the inaugural Hawking Chair in Cosmology and Science Communication. Read more about her career and role at Perimeter on page 21.

David Gosset joined Perimeter's research associate faculty in 2021 and collaborates with scientists at the Clay Riddell Centre for Quantum Matter. He is jointly appointed with IQC, has been an associate professor at the University of Waterloo since 2018, and is a CIFAR Fellow in the Quantum Information Science program.

Gosset works on theoretical questions relevant to small quantum computers, including understanding the computational power of constant-depth quantum circuits and the limits of classical simulation algorithms. He has also investigated the computational power and complexity of quantum many-body systems and the application of physics-inspired tools from these areas to quantum computer science.

Additionally, in 2021/22, Perimeter recruited two exceptional young scientists who will arrive at the Institute as research faculty in 2023.

Sisi Zhou works on quantum information and condensed matter, focusing on quantum error correction and optimizing quantum sensing. She will join Perimeter after completing a postdoctoral fellowship at the Institute for Quantum Information and Matter at the California Institute of Technology.

Alex May is a quantum information and quantum gravity theorist who is interested in how these fields can be used to glean insights from one another. He will join Perimeter from Stanford University, where he holds a joint It from Qubit and Q-Farm Fellowship.

PEOPLE

Outreach Faculty

KATIE MACK

In 2022, theoretical cosmologist Katherine (Katie) Mack joined Perimeter Institute as the inaugural Hawking Chair in Cosmology and Science Communication. Her research concerns the physics of the universe from beginning to end, including topics such as dark matter, black holes, early-universe physics, and the formation of the first galaxies.

Mack earned her PhD from Princeton University before completing postdoctoral fellowships at the University of Cambridge and the University of Melbourne. She became an assistant professor of physics at North Carolina State University in 2018, where she was a member of the university's Leadership in Public Science Cluster. She was also a Simons Emmy Noether Fellow at Perimeter in 2020 and a Visiting Fellow in 2021 and was named a CIFAR Azrieli Global Scholar in 2022.

"Perimeter is one of the most exciting places I've ever been as a physicist," Mack says. "It's an amazingly stimulating community of researchers and there's so much going on in public engagement and science communication as well. I feel like it's the place where I can really explore all of my passions."

Throughout her career, Mack has placed an emphasis on sharing science with the broader public. She has amassed a following of more than 400,000 on Twitter, and her popular writing has appeared in major publications including *Scientific American*, *Slate*, *Sky & Telescope*, and *BBC Science Focus*.

In 2020, she released her first book, *The End of Everything (Astrophysically Speaking)*, which examines five ways the universe could end and the mind-blowing lessons each scenario reveals about the most important concepts in cosmology. It was named a *New York Times* Notable Book, among many other accolades.

In her role at Perimeter, she will build on her cosmology research program while also working to share physics beyond the research community through public events, outreach, and training programs. She will be a valuable resource for her fellow researchers, sharing her broad scientific interests as well as her experiences and expertise in science communication.

"Katie's unique talents will allow her to make important contributions in all facets of Perimeter – not only as a terrific researcher but also as a gifted science communicator who builds bridges between scientists and the wider world," says Perimeter Director Robert Myers.

PERIMETER RESEARCH CHAIRS

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

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

Asimina Arvanitaki
Stavros Niarchos Foundation Aristarchus Chair
in Theoretical Physics

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

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

Kevin Costello
Krembil William Rowan Hamilton Chair in Theoretical Physics

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

Davide Gaiotto
Krembil Galileo Galilei Chair in Theoretical Physics

Subir Sachdev (Visiting)
Harvard University
Cenovus Energy James Clerk Maxwell 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

Freddy Cachazo and Andrew Strominger ▲

VISITING SCIENTISTS

The visiting scientist programs are a means by which Perimeter engages with the wider scientific community from across Canada and around the world, while diversifying its own community. In the second half of 2021/22, scientific visitors began returning to Perimeter to continue long-standing research ties or establish new ones. Over the year, 163 visitors – including Distinguished Visiting Research Chairs (DVRCs), Visiting Fellows, Affiliates, seminar speakers, and other collaborators and guests – spent a total of 2,818 days at Perimeter.

DISTINGUISHED VISITING RESEARCH CHAIRS

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

DVRCs use their time at Perimeter to focus intensively on their research, often in collaboration with Perimeter researchers, as well as to co-organize conferences and present seminars.

In 2021/22, four new DVRCs were appointed, bringing the total to 41. This year's new appointees are:

Caslav Brukner
Vienna Center for Quantum Science and Technology

Glennys Farrar
New York University

Dan Freed
University of Texas at Austin

Hiranya Peiris
University College London

For a full list of DVRCs, see page 60.

VISITING FELLOWS, AFFILIATE MEMBERS, AND VISITING RESEARCHERS

Visiting Fellows are appointed to renewable terms, retain their positions at home institutions, and enrich the Perimeter research community during their extended stays. In 2021/22, nine new Visiting Fellows were appointed, for a total of 61.

Affiliate members are faculty members from Canadian universities who have an open invitation to visit Perimeter at any time to do research. This year, five new Affiliate members were appointed, bringing the total to 100, from 31 universities.

We also encourage applications from scientists to come as **Visiting Researchers** while on sabbatical leave from their faculty positions at home institutes. In 2021/22, one Visiting Researcher spent 30 days at Perimeter, and we look forward to resuming this program at pre-pandemic levels over the coming year.

BEST OF BOTH WORLDS: HARMONIZING THEORY AND EXPERIMENT

Researchers Rob Spekkens and Kevin Resch are interrogating the nature of causality in quantum mechanics – and the fusion of theory and experiment is helping to solve some long-standing puzzles at the edge of known physics.

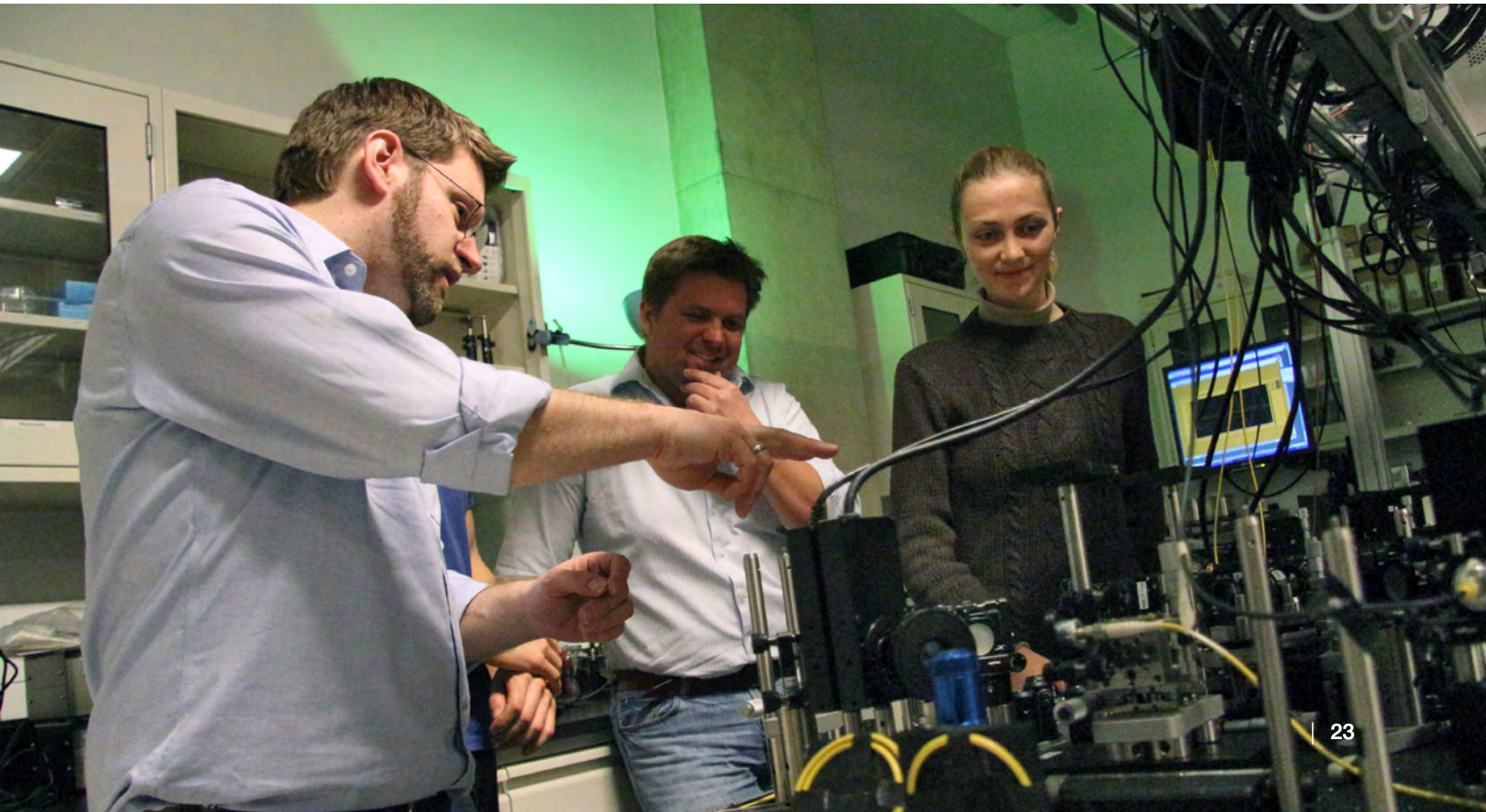
They've known each other since their days in graduate school, 25 years ago, where Spekkens trained in theoretical physics and Resch became an experimentalist. But their distinct areas of expertise haven't kept them from collaborating. In fact, their combined talents make them a uniquely productive team. Spekkens, a Perimeter research faculty member, is a quantum foundations researcher, and Resch, a faculty member at IQC and in the Department of Physics at the University of Waterloo, and a Perimeter Affiliate, is an expert in experiments in quantum optics.

Together with a group of talented graduate students and postdocs, they are asking new questions of nature to identify conceptual innovations in quantum theory and examine the ways in which it differs from the classical theories that preceded it.

Realizing their research goals were complementary, the pair quickly established a working relationship and have, since 2015, co-authored seven papers and two conference proceedings. "One thing that's distinctive about our collaboration is that we tend to put the theory and experiment together in one paper," Spekkens says.

"In some cases, that's been essential, because there's a lot of back and forth," Resch says. "The theory might start with assumptions that can't be realized in an experiment.... So it's important to be able to think about a practical implementation and make sure the theory can deal with it."

Robert Spekkens, Kevin Resch, and Katja Ried



CONFERENCES AND WORKSHOPS

Perimeter brings together hundreds of top scientists each year – from theorists to researchers working in experimental and observational centres – to keep pace with new advances and to tackle ambitious questions. These crucial conversations help shape the future of physics research in Canada and around the world. Perimeter often hosts conferences on emerging topics that haven't yet been addressed anywhere else, focusing on those with high potential for significant outcomes.

In April 2022, Perimeter welcomed in-person conference participants for the first time in two years. Over the year, the Institute held six conferences (five hybrid and one online only), attended by a total of 852 scientists. Topics included gravitational waves, quantum criticality, global categorical symmetries, and quantum field theory for mathematicians. The Institute also sponsors physics conferences held elsewhere, supporting Canadian research partners and helping to build research capacity across the country.

Despite a return to in-person conferences and workshops, Perimeter intends to continue hybrid access for most events, both to provide increased accessibility and to reduce the carbon footprint associated with travel. Conferences and seminars are recorded and made freely available online to the scientific community through the Perimeter Institute Recorded Seminar Archive (PIRSA) and SciTalks.

See the full list of Perimeter conferences and sponsored conferences on page 62.

GRAVITATIONAL WAVES BEYOND THE BOXES

With gravitational wave discussions swirling around her, Maya Fishbach felt an energy that has been hard to detect during two years of a global pandemic.

"We've been pretending for two years that we can do things completely remotely, as if science isn't social, but that's not the case," says Fishbach, a researcher from Northwestern University in Illinois and visiting postdoc at Perimeter, who gave a talk at the Institute's first in-person scientific workshop since the COVID-19 pandemic hit.

For gravitational wave researchers, who are in a new and rapidly evolving scientific field, getting together to talk about methods and results has become increasingly important.

The five-day workshop, "Gravitational Waves Beyond the Boxes II," was a hybrid event, offered both in person and online. But the 40 researchers and students who participated in person once again filled a physical space that was designed for collaboration.

Perimeter's blackboard-lined think spaces, informal interaction areas, intimate theatre, and welcoming bistro were filled with conversations that researchers and their students have missed deeply since the pandemic lockdowns began in Canada in March 2020.

"Most of the great ideas today are not born in isolation," says Patricia Schmidt, a researcher from the University of Birmingham who spoke at the conference. "They come from interactions, talking to people, bouncing ideas off each other, attending talks that may be related to your research, but not necessarily something you are working on right now. That is what inspires and sparks new ideas."

Fishbach says much of the discussion at the conference was about the challenges of transitioning from an era of a handful of gravitational wave detections to an era with a large number of them. These large data sets are exciting treasure troves of discovery that will provide plenty of work in the coming years for young researchers.

"A big part of it is figuring out what are the interesting questions that we actually want to answer now that we have this huge data set," Fishbach says. It's also about making sure there are good tools available for analyzing all these data and clearing up any uncertainties about what the data are saying, she adds.

"The timing for this workshop is great because many of the topics being discussed are about the opportunities and challenges. It's about how we make this transition and how we should prepare for future detections," says Huan Yang, a Perimeter research associate faculty member and co-organizer of the conference.

◀ Gravitational Waves Beyond the Boxes II

Lucy Liuxuan Zhang and Daniel Gottesman giving special colloquium, “Fault tolerance as topology,” a duet for chalk and violin

SEMINARS AND COLLOQUIA

Throughout the year, resident scientists and those from other institutions give seminars and colloquia to share new research, promote scientific exchange, and spark collaboration across disciplines.

In 2021/22, Perimeter hosted 280 seminars and 25 colloquia, which attracted 8,128 participants. Increasing the number of talks given by women has been a focus of EDI strategies at the Institute; this year, 23 percent of the talks were delivered by women.

With few exceptions, each seminar and colloquium is recorded and posted to PIRSA – a free, searchable online database that now catalogues more than 14,200 videos, which were viewed over 194,000 times by viewers in 177 countries in 2021/22. These recorded talks are a valuable resource for the science community across Canada and worldwide, particularly for students, early-career researchers, and those who are not at major research centres.

With support from the Simons Foundation, Perimeter has also created an international hub that expands on the success of PIRSA. SciTalks.ca is now in the testing phase and carries the full PIRSA catalogue, as well as additional talks from partners at CERN, the Simons Institute, the International Centre for Theoretical Physics, and the South American Institute for Fundamental Research.

Global Categorical Symmetries

TRAINING

"The learning curve for pursuing research in theoretical physics is very steep. PSI provides the perfect opportunity for us to strengthen our foundations and, at the same time, get exposed to cutting-edge research."

– Manu Srivastava, Perimeter Scholars International (PSI) student

Robert Spekkens with PSI students

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 training – from undergraduate summer school and a master's program for exceptional international students, to our world-leading PhD and postdoctoral programs featuring close collaboration with top researchers – that turns students into scientists.[2]

More than **1,100** students and postdoctoral researchers trained since 2006

72 Postdoctoral researchers from 21 countries including 18 women

74 PhD students from 29 countries including 17 women

21 Perimeter Scholars International (PSI) students from 12 countries, including 10 women or non-binary students

378 PSI graduates in 13 years, including 125 women and 1 non-binary student

62 PSI Start students and 11 PSI Start interns from 8 countries

13 Associate postdoctoral researchers

38 Associate PhD students

[2] *Unless otherwise indicated, figures are for August 1, 2021–July 31, 2022.*

POSTDOCTORAL RESEARCHERS: TACKLING AMBITIOUS RESEARCH PROBLEMS

Perimeter is home to one of the world's largest communities of postdoctoral researchers in theoretical physics. Fully immersed in Perimeter's multidisciplinary environment, these early-career scientists pursue independent research programs, tackling ambitious problems with mentorship from senior scientists.

That autonomy and experience pays off. Postdoc Estelle Inack, founder of financial tech start-up yiyaniQ, was recruited to stay at Perimeter as a research scientist. Others have shifted to careers in industry, including Modjtaba Shokrian Zini, a quantum algorithm researcher at Xanadu; William Donnelly, a senior rendering researcher at Electronic Arts; Mark Penney, who works in market risk measurement at Scotiabank; and Richard Derryberry, now a quantitative researcher at Jump Trading. Those who went on to tenure-track positions include Mathew Madhavacheril as assistant professor at the University of Pennsylvania, Meng Guo as assistant professor at the University of Illinois, and Suvodip Mukherjee as reader (equivalent to assistant professor) at the Tata Institute of Fundamental Research in Mumbai, India.

In addition to three-year terms, Perimeter has prestigious four-year named fellowships, five-year senior fellowships, and jointly appointed fellowships with partner universities. The positions are highly sought after: from 960 applicants, 20 new postdocs joined Perimeter in 2021/22.

Perimeter had a total of 72 postdocs from 21 countries this year; see the full list on pages 58-59.

PI PEOPLE

Postdoctoral Researcher

ALI ASSEM MAHMOUD

When Ali Assem Mahmoud arrived in Waterloo from Cairo, Egypt, he became one of the tiny handful of African graduate students studying mathematics and physics in Canada. After earning a PhD at the University of Waterloo in the field of combinatorics and optimization, and a postdoc position at the University of Ottawa, he became the Fields-AIMS-Perimeter Postdoctoral Fellow at Perimeter.

The Fields-AIMS-Perimeter Postdoctoral Fellowship is the result of a unique trilateral partnership between Perimeter, the African Institute for Mathematical Sciences (AIMS), and the Fields Institute for Research in Mathematical Sciences in Toronto.

The fellowship supports African nationals during their postgraduate training, giving them a chance to work closely with mathematics and physics researchers in Canada. Ultimately, the program aims to advance science in Africa and the world.

It's been a challenging period academically and in terms of culture, says Mahmoud. But it was worth it because it helped him diversify his world view. In turn, that will help as he teaches increasingly diverse student populations. "I learned a lot about other cultures, and that will be reflected in everything I do."

PI PEOPLE

Postdoctoral Researcher

AIDA AHMADZADEGAN

In 2021, Perimeter postdoctoral researcher Aida Ahmadzadegan launched ForeQast, a quantum technology company that helps clients optimize their logistics planning using the power of quantum hybrid algorithms and machine learning.

Combining excellence in research with economic potential, Ahmadzadegan's quantum start-up was one of nine companies that graduated from the Creative Destruction Lab quantum stream mentorship program. The program is designed to kickstart promising young companies in the field of quantum technologies.

ForeQast leverages artificial intelligence and quantum computing to enable the optimization of last-mile delivery. This includes identifying inefficient delivery routes and ensuring environmentally sustainable operations by taking quantum technology research and applying it to real-world problems.

"I hope to build ForeQast to be the platform of the future," Ahmadzadegan says, "where the power of quantum computing can be made mainstream to address logistics and supply chain problems."

"I hope to build ForeQast to be the platform of the future, where the power of quantum computing can be made mainstream to address logistics and supply chain problems."

– Aida Ahmadzadegan,
Postdoctoral researcher and ForeQast founder

PHD STUDENTS: EXTRAORDINARY OPPORTUNITIES

With opportunities to work with some of the world's most accomplished theorists, and to connect with visitors and collaborators from around the world, Perimeter is an extraordinary place to earn a PhD. Students receive their degree from the partner university where their supervisor has a full or adjunct appointment, including the University of Waterloo, McMaster University, the University of Toronto, the University of Guelph, and York University.

Many of the exceptional students who graduate from the Perimeter Scholars International (PSI) program stay in Canada to continue their education and research. In 2021/22, 57 percent of Perimeter's PhD students were PSI graduates.

Of the students who completed their PhD in 2021/22, many went on to prestigious postdoctoral fellowships, including Anna Golubeva at the National Science Foundation's Institute for Artificial Intelligence and Fundamental Interactions, Masoud Rafiei-Ravandi at McGill University, and Paul Tiede at the Harvard-Smithsonian Center for Astrophysics. Graduate Alvaro Ballon Bordo now works in the private sector as a quantum computing educator at Xanadu Quantum Technologies.

Perimeter had a total of 74 PhD students from 29 countries in 2021/22; see the full list on page 61.

PEOPLE

PhD Student

KASIA BUDZIK

Kasia Budzik first came to Perimeter as a high school student from Poland back in 2014 to attend the International Summer School for Young Physicists (ISSYP) and returned to earn a master's degree in the PSI program. Now she's in her third year as a PhD student whose research focuses on twisted holography, under the supervision of mathematical physicist Davide Gaiotto.

Holography is a powerful tool or a bridge linking pairs of theories in areas that appear to be completely unrelated (for more about holography, see page 10). This bridge, known as a duality, can be used to translate complex or intractable problems in one area of physics into manageable problems in another. In the context of twisted holography, "twisting" means restricting to a subsector of the duality – akin to taking a magnifying glass to a specified spot on a page. With this approach, physicists can define things more mathematically, subsector by subsector, and ultimately attempt to prove the duality more rigorously.

"I really like being at Perimeter, ever since my time as an ISSYP student," Budzik says. "I like what I'm working on, and I'm making the most of being here in the building daily. I am very happy to be back and immersed in all that Perimeter has to offer – attending seminars and collaborating with fellow students in person – it's the best way to do physics."

Kasia Budzik is supported in part by the Emmy Noether Emerging Talent Fund.

PEOPLE

PhD Student

XIU-ZHE (ROGER) LUO

Though he is still working on his PhD thesis, Xiu-Zhe (Roger) Luo has already been recognized for his work in understanding the physics behind quantum computing algorithms. Last year, he won the inaugural Wittek Quantum Prize for Open Source Software from a competitive pool of more than 50 candidates.

Luo is part of the Perimeter Institute Quantum Intelligence Lab, a research centre and training hub led by Research Associate Faculty member Roger Melko. Luo's connection to Melko and Perimeter was invaluable in helping Luo on his quest to learn more about quantum computing and led to an internship with QuEra Computing. There, he was part of a collaboration of scientists from QuEra, Harvard, MIT, the University of Innsbruck, and other institutions that achieved a quantum computing speed-up.

"My personal goal was to learn more about QuEra and how their hardware works. I've learned a lot. My next step is to work on more theories," Luo says.

ASSOCIATE POSTDOCTORAL RESEARCHERS AND PHD STUDENTS

As an independent institution, Perimeter maintains strong partnerships with universities across Ontario and Canada. The associate postdoctoral researcher and associate PhD student programs are helping to build those ties. These programs offer young researchers from partner universities the opportunity to participate in the full range of activities at Perimeter, from attending courses, seminars, and colloquia to collaborating with Perimeter's world-class faculty. During 2021/22, Perimeter hosted 13 associate postdocs and 38 associate PhD students, coming from the University of Waterloo, McMaster University, the University of Toronto, York University, Western University, and Queen's University.

PERIMETER SCHOLARS INTERNATIONAL: BIG PICTURE THINKING

If you ask the 2022 PSI graduating class, they will tell you they've forged bonds that they will carry with them for years to come. What's more, they've done so while scaling the challenging landscape of theoretical physics.

The PSI master's program is intense. It attracts top students from around the world and introduces them to the full breath of modern theoretical physics through core classes, followed by electives and two months working directly with Perimeter faculty. The culmination of the program is the research essay, which students defend in front of peers and mentors.

It's a challenging but energizing environment. One of this year's PSI students, Sofia Gonzalez Garcia, described how the chance to work directly with faculty, postdocs, and PhD students at Perimeter made the program uniquely valuable. "They're the ones revolutionizing science," she said. "And at least for me personally, it's really changed the way I see and interact with academia."

Manu Srivastava valued the bonds the students forged with one another. "I knew that academically research-wise PSI was going to be a great experience. I knew I was going to learn a lot, and maybe mature a little as a researcher. And all that has definitely been true. But what I had not expected was to find a family here," he said.

He praised Perimeter for enabling big picture thinking without pressuring researchers to find immediate applicability in business or technology, trusting that new insights will be valuable on longer time scales. "This kind of blue-sky research, this thing Perimeter is doing, is extremely important I think, in the long term."

"I knew that academically research-wise PSI was going to be a great experience. I knew I was going to learn a lot, and maybe mature a little as a researcher. And all that has definitely been true. But what I had not expected was to find a family here."

– Manu Srivastava, PSI 2022 alum

On completion of PSI, students earn a master's degree from the University of Waterloo and a PSI certificate. It's a highly competitive program: the 21 students in the 2021/22 cohort were chosen from more than 400 applicants. Six "PSIons" are continuing their education at Perimeter to pursue PhDs.

In 2021/22, Perimeter introduced a new program that will support some students to integrate internships with industry partners into their master's – earning the degree over two years, rather than the usual one. Two students took part in the inaugural two-year program, interning with QuEra and Google, and will graduate in 2023.

In addition to the degree-granting program, PSI offers free online learning modules that allow motivated students and physics enthusiasts around the world to study graduate-level theoretical physics independently and at their own pace. In 2021/22, almost 1,350 unique users enrolled in an average of 1.5 courses each, for a total of 2,012 enrollments in courses such as quantum field theory, quantum matter, and statistical physics.

See the full list of PSI academic staff and students on pages 60-61.

The PSI program was supported in 2021/22 by the Savvas Chamberlain Family Foundation, the Hellenic Heritage Foundation, the Marsland Family, and members of the Emmy Noether Circle.

2022 PSI graduation

PSI START: OPENING PATHWAYS FOR FUTURE PHYSICISTS

In high school in India, Rahul Balaji's curiosity often led him to seek out resources beyond what his school could offer. One day he discovered a set of Perimeter's online lectures, which introduced him to concepts in theoretical physics, captivated his attention, and eventually brought him to Waterloo.

During the summer of 2022, Balaji and a group of like-minded students participated in PSI Start, Perimeter's revamped undergraduate program. It offers students in their third year of undergraduate studies an extra boost, preparing them for graduate training. It brings them into contact with Perimeter researchers, who walk them through some of the more challenging – and promising – aspects of fundamental physics research.

PSI Start interns 2022

PSI Start has two parts: an online school and an internship program. The online school runs for 10 weeks and combines synchronous lessons with independent study on various topics. One of Balaji's peers in the program, Hyo Jung (Catherine) Park, found the online school to be a valuable opportunity to expand her understanding. "I really appreciate that we can learn some theoretical physics that we cannot learn in our undergraduate institutions," she said.

For the last two weeks of the online school, students work on projects in small groups under the supervision of Perimeter researchers. For students like Balaji and Park who want to put their newfound knowledge into practice, the 16-week PSI Start internship offers the opportunity of working with researchers on site at Perimeter.

Sixty-two students from Canada and around the world participated in the PSI Start online school this year. Eleven interns came from eight countries: Canada, India, Georgia, China, Ecuador, Brazil, the Republic of Korea, and the US.

"I would definitely recommend the program," Balaji said. "If you already know you want to work in theoretical physics, or you're passionate about it and have been for a long time, this is the place to come to, because this is where you can realize it to the fullest potential."

The PSI Start program is supported by Michael Serbinis and Laura Adams.

"If you already know you want to work in theoretical physics, or you're passionate about it and have been for a long time, this is the place to come to, because this is where you can realize it to the fullest potential."

– Rahul Balaji, PSI Start participant

CAREER TRAJECTORIES

A career in academia isn't the only avenue for physics graduates. Perimeter alumni have gone on to successful careers in a multitude of fields: quantum technology, health care, finance, data science, and more. Some have gone on to found their own companies. Perimeter's Trajectories initiatives are designed to help early-career researchers, from undergraduates to postdocs, find careers that suit their unique skills and knowledge. Trajectories offers workshops and networking opportunities, a suite of resources on job hunting and career development, and individual support for resume development and interview skills.

In 2021/22, Perimeter hosted seven Trajectories events – with a total of around 200 participants – including academic and industry networking events, a lunch and learn session on transitioning from research to industry, and a workshop on creating a strong postdoc application. Students also had the opportunity to learn how to convert an academic CV into an industry-relevant resume.

SUPPORT FOR STUDENTS IN UKRAINE

In spring 2022, Perimeter began offering positions in theoretical physics for postdoctoral researchers and graduate students whose study or research has been interrupted by the war in Ukraine. Two graduate students and four postdoctoral researchers accepted positions, and in the coming year the Institute expects to offer at least seven more. High school students and teachers from Ukraine have also made use of Perimeter's wide catalogue of educational resources.

OUTREACH

"Physics is like a vessel for teaching those skills that are useful whether you become a physicist, a lawyer, or anything else. The skills are transferable. That is the beauty of physics."

– Saara Naudts, physics teacher, Mayfield Secondary School, Caledon, Ontario

OUTREACH by the numbers

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

STUDENTS

942 International Summer School for Young Physicists participants since inception

38 International Summer School for Young Physicists participants in 2022

489 students participated in "Inspiring Future Women in Science" in 2022

TEACHERS

45,000 educators trained through Perimeter workshops since inception

3,337 teachers trained at **146** workshops in 2021/22

36 teachers from **10** countries participated in EinsteinPlus teacher training camp in 2021/22

132 countries in which Perimeter educational resources have been used

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

SCIENCE FOR THE WORLD

20 million YouTube views since inception

4 million YouTube views in 2021/22

16,000 podcast downloads in 2021/22

1.3 million website page views[3] in 2021/22

[3] *Includes Perimeter Institute website and Inside the Perimeter website.*

EinsteinPlus 2022 ▲

EINSTEINPLUS: A SHOT OF ADRENALIN FOR HIGH SCHOOL PHYSICS

An "O-wing flyer" made of paper zips across the classroom. A cellphone on the end of a string spins rapidly in the air. Laser pointer light – bisected by a strand of hair – makes diffraction patterns on a wall.

These are scenes from a workshop designed to teach fundamental concepts in physics using only materials found in a dollar store. The creators of these DIY science demos are high school teachers from across Canada and around the world. This is EinsteinPlus, Perimeter's flagship professional development program for teachers, held in person for the first time in three years in summer 2022.

The week-long intensive workshop injects a shot of adrenalin into high school physics teaching. This year, 22 Canadian teachers and 14 teachers from nine other countries came to learn innovative strategies for teaching complex physics topics and test drove interactive resources they'll use to inspire their students back home. Perimeter cosmologist Katie Mack and particle physicist Asimina Arvanitaki also shared the latest on research in their fields with attendees.

"The opportunities to build relationships, during and after EinsteinPlus, with colleagues from around the world is priceless. If I could, I would come back every year," says Kieran Faw, a teacher at Brookfield High School in Ottawa. "Perimeter Institute establishes a safe learning environment where we can get messy and try new teaching pedagogies that at first may be uncomfortable."

And that's the whole idea. Getting educators out of their comfort zone opens up opportunities to grapple with difficult topics in new and fun ways.

Dave Fish, Perimeter's teacher-in-residence and a facilitator for EinsteinPlus, says the program gives teachers the opportunity to deepen their understanding of physics concepts and broaden their instructional approaches.

"This year, we had a fantastic group of teachers who will be returning to their classrooms inspired by spending quality time with other like-minded teachers," Fish says. "But inspired is not sufficient. These teachers also go back equipped with classroom-ready resources, materials, and a network of other teachers to lean on."

In addition to EinsteinPlus, more than 3,300 educators participated in 146 Perimeter teacher training workshops in 2021/22 on topics from telescopes to atoms to what it takes to win a Nobel Prize.

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

"The opportunities to build relationships, during and after EinsteinPlus, with colleagues from around the world is priceless. If I could, I would come back every year."

– Kieran Faw, physics teacher, Brookfield High School, Ottawa, Ontario

EDUCATIONAL RESOURCES

Today, scientific discoveries are happening at lightning speed. Perimeter's Educational Outreach team works year-round to refresh educational material and incorporate the latest science, adding content inspired by recent research breakthroughs such as the discovery of the Higgs boson or the historic picture of the M87 black hole. As Canadian curriculums continue to change, Perimeter keeps up – and stays ahead of the curve. When Perimeter released its first educational resource in 2008, limited modern physics was taught in most Canadian classrooms. Now, students can do a lab to calculate the value of an unknown mass while drawing connections to how astronomers measure the speeds of stars in galaxies as compelling evidence for dark matter. Members of Perimeter's Teacher Network are present on most curriculum-writing teams across the country, ensuring students stay empowered to explore current science.

Teachers themselves will sometimes suggest a topic for a new activity or resource, but educator involvement doesn't end there. Feedback from teachers who test the material in their classrooms continually guides the development of new resources.

The resources are used in classrooms across Canada and 131 other countries around the world. Each compilation explains an important topic in physics, or science more broadly, and includes lesson plans, hands-on activities and demos, modifiable worksheets, background information for teachers, and original Perimeter videos. All educational resources are available in French and English, and further translations are ongoing, with 19 resources available in Portuguese and 18 available in Spanish, helping to expand Perimeter's reach in Europe and North and South America.

SUMMER SCHOOL IMMERSES STUDENTS IN A UNIVERSE OF IDEAS

Can you power a boat with no moving parts? The answer is yes, thanks to the physics of electromagnetic fields. On a busy afternoon in July, a gender-balanced class of 38 high school students – half from across Canada and half from 14 other countries around the world – put the laws of physics to the test, building their own propulsion systems with a battery that uses the sodium and chlorine ions in ordinary tap water to produce thrust. It was just one of many hands-on lessons over the course of two weeks, all designed to introduce physics concepts to passionate young learners.

The International Summer School for Young Physicists (ISSYP) aims to simulate the collaborative environment of real-world science. Participants learn from hands-on experience and by working through problems with peers, in addition to more traditional lectures. They also have a rare opportunity to work through research problems under the mentorship of Perimeter researchers, with lots of time for questions.

"ISSYP created a really interesting outlet for taking myself from my standard classes into a much more advanced, rigorous program," said Alberta student Stryder Hamilton. "I've never had an opportunity to apply math in such a deep way. It doesn't matter what your strength is, or where you feel like you're lacking…there are some fantastic scientists here just to discuss and provoke you even further."

Launched in 2004, ISSYP has been attended by 942 students, half from Canada and half from 64 other countries.

Those alumni include Tim Hsieh, originally from the US and now a Perimeter research faculty member and the Director of the Clay Riddell Centre for Quantum Matter. This year, things came full circle as Hsieh guided the 2021/22 ISSYP participants into the world of quantum theory.

"I was a participant in ISSYP years ago. It was actually the first time I learned anything about quantum mechanics, and it just blew my mind. And it's been in the back of my mind ever since then, until now," he said. "So, I hope I'll be able to convey some of the weird features of quantum mechanics and its consequences.... Ideally, one of you will be back here, giving a much better version of this keynote, in another decade or so."

The 2021/22 session of ISSYP was made possible by the support of presenting partner RBC Foundation, in support of RBC Future Launch.

INSPIRING FUTURE WOMEN IN SCIENCE

From her native Brazil, Julia Fernanda de Lucas Rocha tuned in to a live event hosted by Perimeter Institute. There she saw something she doesn't normally get a chance to see: four successful women from underrepresented communities talking passionately about their work in traditionally male-dominated professions in STEM and how they overcame challenges to get where they are today.

"We still see more men than women studying in these areas around the world," Rocha said. "But we are in the 21st century, and so why should there not be more women in engineering, math, physics, chemical fields?" she added. "I felt inspired to continue my study in physics."

The live question-and-answer webinar took place on February 10, tied to the United Nations International Day of Women and Girls in Science. Launched in 2015, the annual event is just one part of Perimeter's equity, diversity, and inclusion efforts aimed at encouraging young women interested in science and technology. This year, 489 students attended. The event is also recorded and available on Perimeter's YouTube channel, where it has been viewed more than 1,400 times.

This year's event featured Emily Ackerman, a systems biology postdoctoral researcher and disability community activist; Ella Chan, a medical student and digital media outreach specialist; Yumna Nasir, a construction and facilities management director; and Laurie Rousseau-Nepton, an astronomer based in Hawaii who is an Innu woman and a member of the Mashteuiatsh community (Pekuakamiulnuatsh First Nation) in Québec.

Rousseau-Nepton, who is based at the Canada-France-Hawaii Telescope in Hawaii, said it's important not to be limited by what others think you are good at or should pursue. "If you love what you do, then you will get good at it over the years. You have so many years ahead and so many things to learn."

The 2021/22 "Inspiring Future Women in Science" event was made possible by the support of presenting sponsor Linamar Corporation.

SCIENCE COMMUNICATION AND MEDIA

Perimeter is a trusted voice in science, and that role is more important than ever. The Institute is a powerful advocate for the value of scientific education and literacy and for the scientific process as one of humanity's best tools for overcoming global challenges. It is essential to promote an understanding of scientific research, how conclusions are reached, and how to interpret and assess the veracity of information.

Perimeter reaches audiences where they are through a variety of channels: social media, videos, podcasts, traditional media, and more. Perimeter's quality science content is regularly shared with growing audiences on Facebook, Twitter, Instagram, LinkedIn, and YouTube; the Institute's accounts collectively have 222,000 followers and subscribers. In 2021/22, Perimeter's LinkedIn followers grew by 33 percent, and its Twitter followers grew by 15 percent.

Perimeter's YouTube channel – home to fascinating conversations, in-depth lectures on the latest research, and engaging demonstrations of physics concepts – continues to be enormously popular, with over 140,000 subscribers, including 27,000 new subscribers this year alone. Perimeter's videos have been viewed over 20 million times in total, including more than 4 million views in 2021/22.

In addition, about 190,000 unique visitors contributed to more than 300,000 page views of Inside the Perimeter, the Institute's flagship website for engaging, informative, and entertaining science content for audiences of all ages, while the Perimeter Institute website was viewed more than a million times by 277,000 unique visitors.

CONVERSATIONS AT THE PERIMETER

During the pandemic, the Institute suspended in-person lectures, but the hiatus provided an opportunity to reimagine the lecture series to better reach audiences in a shifting digital landscape. In 2021/22, *Conversations at the Perimeter,* a new series of long-format discussions with scientists, was developed and recorded. Season 1 launched in the spring of 2022 and includes 11 episodes, released on YouTube and all major podcast platforms, introducing Perimeter to entirely new audiences.

The first season featured Perimeter researchers Avery Broderick on black hole breakthroughs, Katie Mack on how the universe might end, Raymond Laflamme on the life-changing power of curiosity, Timothy Hsieh on the magic of quantum, and Meenu Kumari on the realm where quantum meets classical, among others. Perimeter Distinguished Visiting Research Chair and popular science author Carlo Rovelli talked about physics and philosophy. The first season has proved very successful, with more than 16,000 downloads and over 105,000 views on YouTube.

PROMINENT MEDIA COVERAGE OF PERIMETER

- Astronomers peer into Milky Way's core for first-ever image of 'supermassive black hole next door,' *The Globe and Mail*, May 22, 2022
- Physics seeks the future, *The Economist*, August 25, 2021
- A new place for consciousness in our understanding of the universe, *New Scientist*, March 30, 2022
- First James Webb images show us "creation as it happens," says Hawking Chair in Cosmology, *BBC Science Focus*, July 14, 2022
- Opinion: It's time to double down on Canadian science and tech investment, *Calgary Herald*, October 28, 2021
- Physics equations compete for your approval; exoplanets that never were, *Physics World*, March 18, 2022
- Image of black hole unveiled, CTV National News, May 12, 2022
- Astronomers are gearing up for never-before-seen merger between two black holes, *Inverse*, February 3, 2022
- It's impossible to tell if this story exists, according to quantum physics, *Popular Mechanics*, August 23, 2021
- How the new science of biocosmology redefines our understanding of life, *Discover*, April 29, 2022

ADVANCING PERIMETER'S MISSION

"Our father, Clay Riddell, a geologist by profession and a true explorer and entrepreneur at heart, was passionate about the possibilities the Perimeter Institute represents. He believed strongly, and our family agrees, that investing in exceptional people, who are passionate about their bold ideas and have the humility to learn and persevere, will lead to extraordinary outcomes. This epitomizes why we are confident investments we make in the Perimeter Institute will contribute to breakthroughs in theoretical physics that will profoundly influence the social order."

– Sue Riddell-Rose, Director, Riddell Family Charitable Foundation

In a world of short-term, application-oriented research, Perimeter Institute stands out. Our scientists go after some of the deepest, hardest questions in science.

Why? Because it's the path to breakthroughs.

Breakthroughs in our understanding of the universe's fundamental forces and particles bring possibilities for harnessing them in new ways. Past physics breakthroughs have had huge impacts on science and led to world-changing technologies like computers, electronics, wireless communications, atomic energy, medical imaging, and GPS – and to exciting emerging technologies like quantum computing.

Today's theoretical physics truly is tomorrow's technology.

Perimeter is supported by the Government of Canada and the Government of Ontario and by philanthropic support from private sector corporations, foundations, and individuals.

Our partners understand that an investment in theoretical physics is an investment in the lowest-cost, highest-impact area of science, and that Perimeter is a strategic scientific asset for Canada's future. Together, we aim to build the world's best theoretical physics institute.

The Governments of Canada and Ontario have provided major operating funding to Perimeter since its beginnings. This year, the Governments of Canada and Ontario concluded agreements to support Perimeter through 2024, with avenues for further renewal. These investments continue to sustain Perimeter's ongoing success and help position Ontario and Canada as a leading centre of theoretical physics on the global stage.

Perimeter's community of visionary philanthropic supporters continues to grow, providing over one-third of the Institute's annual operating budget. In the past year, Perimeter attracted $12.5 million in new commitments, including transformational gifts from the Daniel Family Foundation, the Riddell Family Charitable Foundation, and Intact Financial Corporation.

SUPPORTING THE VISION

Perimeter Institute recognizes and thanks the visionary supporters who have made cumulative gifts totalling $100,000 or more since 2014, following the lead of Perimeter's Founding Donor, Mike Lazaridis. These generous gifts have helped our private sector campaign to grow to $66 million in commitments.

Airlie Foundation
BMO Financial Group
Anne-Marie Canning
Cenovus Energy
Coril Holdings
The Cowan Foundation
Joanne Cuthbertson and Charlie Fischer
The Daniel Family Foundation
The Delaney Family
The Ira Gluskin & Maxine Granovsky Gluskin Charitable Foundation
Gluskin Sheff + Associates Inc.
The Peter and Shelagh Godsoe Family Foundation
Scott Griffin Foundation
Intact Financial Corporation
The Krembil Foundation
Linamar Corporation
Maplesoft
The Marsland Family
James Mossman
Stavros Niarchos Foundation
Pattison Outdoor Advertising
Power Corporation of Canada
Ptarmigan Charitable Foundation
RBC Foundation
Riddell Family Charitable Foundation
Scotiabank
Michael Serbinis & Laura Adams
Shaw Communications
Dr. Scott A. and Sherry Shannon-Vanstone and family
The Simons Foundation
Corinne Squire & Neil Turok
Brian Sullivan
Sun Life Financial
John Templeton Foundation
Mac Van Wielingen, Viewpoint Foundation

Thank you to our two donors who generously gave anonymously.

WOMEN WHO HAVE BROADENED OUR HORIZONS

For over a decade, Sherry Shannon-Vanstone and Joanne Cuthbertson have been Perimeter champions, generous donors, and vital parts of the Institute's volunteer leadership teams. They each believe deeply in the importance of excellence and in widening horizons, particularly for young people in STEM.

Joanne Cuthbertson is the former Chancellor of the University of Alberta, with a string of professional and philanthropic projects aimed at ensuring that students from every walk of life have access to quality education. She is one of Canada's most influential philanthropic leaders in education, creating new pathways for thousands of young people.

Sherry Shannon-Vanstone knows the importance of encouraging young women in science firsthand: It wasn't until the president of her university convinced her that she'd be wasted on studying anything but pure mathematics that she set her sights on making it a career. She earned a master's in mathematics and went on to a hugely successful career in cryptography that has included founding three tech businesses.

Combine these two women, and you get the nucleus of something amazing.

As the Chairs of Perimeter's two leadership councils, they have championed Perimeter through their wide networks, engaging many new friends and attracting supporters for the Institute, many of whom have individually and collectively made transformative gifts.

After an incredible 10 years of service, we applaud both, and celebrate their high notes:

In addition to Cuthbertson's service on our Board of Directors from 2013 to 2022, she established the Joanne Cuthbertson and Charlie Fischer Graduate Student Award for students pursuing doctoral studies at Perimeter. As Chair of the Leadership Council, she shared her passion and voice widely, inspiring thought leaders and change agents across Canada to be part of advancing humanity through physics, and helping Perimeter achieve dramatic growth in its private sector contributions. This includes strategic leadership contributions supporting the Clay Riddell Centre for Quantum Matter, and the Daniel Family James Peebles Chair held by Kendrick Smith, Director of the Centre for the Universe.

Shannon-Vanstone led the Emmy Noether Council, which seeks support to bring more women and diversity into science and to address exciting opportunities in physics. She recently spearheaded the Emmy Noether Emerging Talent Fund, which aims to establish 10 perpetual PhD awards to attract more outstanding women to pursue their scientific training at Perimeter. The Emmy Noether Emerging Talent Fund quickly surpassed its initial $250,000 fundraising goal, and in 2021/22 reached $1 million and named three young scholars as the fund's first awardees.

Director Robert Myers says, "Joanne and Sherry are forces of nature. Their energy and dedication have inspired a dynamic group of volunteers and private sector supporters to be a part of a grand adventure in philanthropy. Their generosity and advocacy have helped the Institute become a national gem and a global leader. We are so grateful to have them as part of our Perimeter family."

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, Chair
Member, Board of Directors, Perimeter Institute
Chancellor Emerita of the University of Calgary

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

Donald W. Campbell
Senior Counsel, Norton Rose Fulbright

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

Catherine (Kiki) Delaney
President, Delaney Capital Management Inc.

Edward Goldenberg
Partner, Bennett Jones LLP

Linda Hasenfratz
Chief Executive Officer, Linamar Corporation

Brad Marsland
Vice President, Marsland Centre Ltd.

Jennifer Scully-Lerner
Vice President, Goldman Sachs

Trevin Stratton
Economic Advisory Leader and Partner, Deloitte

Alfredo Tan
Senior Vice President & Managing Director, Loblaw Media

Perimeter thanks Patrice Merrin, former Co-Chair, for her six years of service with the Leadership Council.

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)
Daniel Family James Peebles Chair in Theoretical Physics ($6 million)
Clay Riddell Paul Dirac Chair in Theoretical Physics ($6 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)
Intact Financial Corporation ($1.5 million)
Cenovus Energy James Clerk Maxwell Chair in Theoretical Physics (Visiting) ($1 million)
Coril Holdings Archimedes Chair in Theoretical Physics (Visiting) ($1 million)
Delaney Family John Archibald Wheeler Chair in Theoretical Physics ($500,000)
Michael Serbinis & Laura Adams, in support of the PSI Start and PSI Bridge programs ($500,000)
The Ptarmigan Foundation Stephen W. Hawking Fellowship ($400,000)
* Anonymous donor

CORPORATE AND SPONSORSHIP PARTNERS ($100,000+)

BMO Financial Group, in support of the BMO Inclusion, Diversity, Equity, and Accessibility Postdoctoral Fellowship Award
Power Corporation of Canada, proud supporter of EinsteinPlus and Perimeter's Teacher Network
RBC Foundation, proud supporter of International Summer School for Young Physicists and GoPhysics

ACCELERATORS CIRCLE ($50,000+)

The Cowan Foundation
John and Deborah Harris Family Foundation
Brian Sullivan
Mac Van Wielingen, Viewpoint Foundation

FELLOWSHIPS & AWARDS ($35,000+)

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

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

$25,000+

Airlie Foundation

Denise and Terry Avchen, Environmental Research Advocates**

Bosch Community Fund, on behalf of ESCRYPT in Canada

Cenovus Energy

Harbir & Monica Chhina

Connor, Clark & Lunn Financial Group

The Scott Griffin Foundation

Ed Kernaghan

Toyota Motor Manufacturing Canada (TMMC)

Woodbridge Foam Corporation

$10,000+

The Boardwalk Partnership

The Kitchener and Waterloo Community Foundation

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

Donald and Eleanor Seaman Family Foundation

Alex White

FRIENDS (up to $9,999)

$5,000+

Mary and Ted Brough

Jon and Lyne Dellandrea

Oriole Foundation

Renée Schingh and Robert Myers

John and Karen Sechrist

LeAnne Thorfinnson and Tony Lee

$2,500+

Don Campbell

J. DesBrisay and M. Cannell

Michael Duschenes

Robert Korthals and Janet Charlton

Jennifer Scully-Lerner**

Kelly Sinclair

$1,000+

Jeremy Anderson

John Attwell

Jeff Bakker

The Breunsbach Family**

The Carson Family Foundation

Ben and Mona Davies

Greg Dick

Michael Gagnier

Michael Horgan

Daniel Lauzon

Yicen Lu

Allison Maher

John Matlock

Gordon McKay

Schnurr Family Foundation

Carl Wurtz

$250 TO $999

Mike Birch

Kostadinka Bizheva

John Brennen

Sai L Chan

David Chapman**

David Cook

Fred Cornish

Rene and Janet Couture

Matt Douglas

Rosalie Foyle

Giresh Ghooray

Adam Gravitis

Denis Havey

Mike Horsley

Nagaraja D Srinivas Jonnavittula

Blair Kent

Vladimir Kremerman**

Gilbert Kuipers

Luis Lehner and Maria Beltramo

D'Arcy and Catherine Little

Ian MacRobbie

Richard Marker

Maneesh Mehta

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Marc Milgrom and Gayle Wagman

Suzanne Morris

Bill and Jan Mustard

Gordon Nicholls

Nem Radenovic

Adele Robertson

Catalin Sandu

Stephanie Tse

Jacqueline Watty

Nancy Wong

Thank you to our four donors who generously gave anonymously.

An additional 87 donors have contributed gifts of up to $250 (11**).

GIFTS OF CELEBRATION, HONOUR, AND MEMORY

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

*** 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, 2021, and July 31, 2022, and multi-year commitments of $50,000 and more.
Charitable Registration number: 88981 4323 RR0001

EMMY NOETHER CIRCLE

Emmy Noether was a brilliant scientist whose work underpins much of modern physics. Perimeter's Emmy Noether Initiatives – funded by Emmy Noether Circle donors – support and encourage women in science. For more information, see pages 18-19.

FOUNDING DONOR

The Bluma Appel Community Trust

TRANSFORMATIONAL GIFTS

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

$100,000+

Anne-Marie Canning

Linamar Corporation

Brian Sullivan

Dr. Scott A. and Sherry Shannon-Vanstone and family**

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

$25,000+

Andrew and Lillian Bass

Dorian Hausman

Patrice E. Merrin

$10,000+

Jane Kinney and Christian Bode

Wendy Reed

TENUMBRA

FRIENDS (UP TO $9,999)

$5,000+

Jerome Bolce

John and Karen Sechrist

Kim Tremblay

$1,000+

Shelley Fisher

Andrea Grimm

Lisa Lyons Johnston

Susan Monteith

Mary and Lee Sauer

Michelle Savoy

Patricia M. Woroch

$250 TO $999

Byron Bellows

Tania Framst

Tom and Cheryl Hintermayer

Beth Horowitz and Pat Munson

Sheri and David Keffer

Jessica Knox

Sebastian Mizera**

Douglas Mortley-Wood

Neil Steven Rieck

Leslie Rogers

Yasemin Sezer

Thank you to our one donor who generously gave anonymously.

An additional 15 donors have contributed gifts of up to $250.

GIFTS OF CELEBRATION, HONOUR, AND MEMORY

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

GOVERNANCE AND FINANCE

GOVERNANCE

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

Financial planning, accountability, and investment strategy are carried out by the Board's Investment Committee and the Finance and Audit Committee. The Board also forms other committees as required to assist it in performing its duties.

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

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

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

BOARD OF DIRECTORS

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

Jane Kinney
Vice Chair
Investment Committee member
Finance and Audit Committee Chair
Retired Vice Chair, Deloitte

Susan Baxter
Investment Committee Chair
Finance and Audit Committee member
Perimeter Institute Leadership Council
Vice Chairman, RBC Wealth Management

Karen Collins
Chief Talent Officer, BMO Financial Group

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

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

Donna Strickland
Professor, University of Waterloo,
Department of Physics and Astronomy

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

Perimeter Institute would like to thank Joanne Cuthbertson for her generous service on the Board of Directors from 2013 to 2022.

SCIENTIFIC ADVISORY COMMITTEE

Marcela Carena
Chair
Fermilab National Accelerator Laboratory

Marica Branchesi
Gran Sasso Science Institute

Fernando Brandao
Institute for Quantum Information and Matter

Fay Dowker
Imperial College London

Daniel Freed
University of Texas at Austin

Charles Gammie
University of Illinois at Urbana-Champaign

Gian Francesco Giudice
European Organization for Nuclear Research (CERN)

Gilbert Holder
University of Illinois at Urbana-Champaign

Juan Maldacena
Institute for Advanced Study, Princeton

Natalia Perkins
University of Minnesota

Sandu Popescu
University of Bristol

SENIOR LEADERSHIP

Robert C. Myers
Director

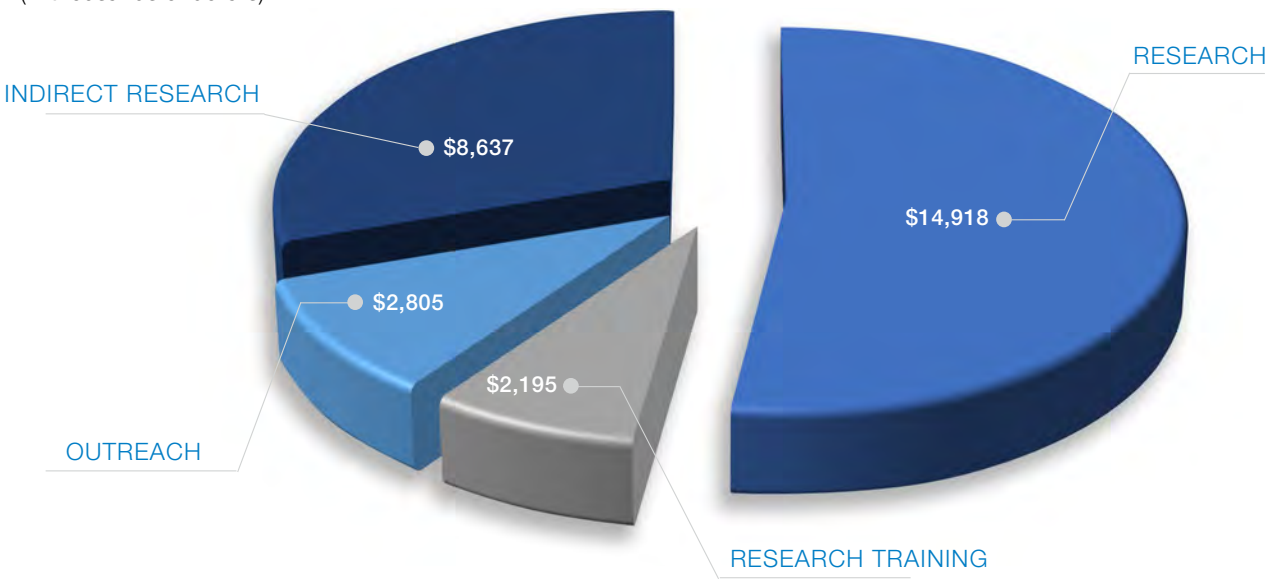
Paul Smith
Managing Director and Chief Operating Officer

Laurent Freidel
Faculty Chair

FINANCIALS

SUMMARY OF OPERATING COSTS (refer to page 48)

For the year ended July 31, 2022
(in thousands of dollars)



As a community, everyone at Perimeter rose to the unprecedented challenge of the pandemic, adapting to continue delivering world-class experiences and outcomes in theoretical physics research, training, and outreach. As restrictions and public health guidelines related to COVID-19 eased over the 2021/22 fiscal year, Perimeter began to resume all activities and programs at or near pre-pandemic levels.

Research activities in the first and second quarter continued through virtual and in-person collaborations, workshops, and seminars, with in-person conferences and research visits resuming in the third quarter. Perimeter Scholars International (PSI) students returned to Waterloo for the full 10 months of in-person training. The Outreach team delivered high-quality programs to teachers, students, and the general public online but also in person through conferences and workshops. The EinsteinPlus teacher training camp was held in person at Perimeter for the first time since 2019.

Whenever possible, the Perimeter community has adapted based on lessons learned during this period, continuing to invest in a world-class virtual and hybrid environment. This has allowed the Institute to reduce travel costs, carbon emissions, and barriers to access, while returning to valuable in-person research collaborations, hands-on training, and inspiring public events as health protocols allowed.

RESEARCH

Advancing our understanding of the universe at the most fundamental level remains Perimeter's core focus. The Institute continued to invest in the research mandate, with an emphasis on supporting a robust hybrid and in-person environment, led by a world-renowned faculty across nine research fields, and one of the largest cohorts of theoretical physics postdoctoral researchers in the world. Faculty and postdoctoral researcher recruitment continued at the expected pace – COVID-19 did not prevent highly talented researchers from choosing Perimeter. Research expenditures increased by 4 percent over 2020/21 but were still slightly lower than pre-pandemic levels. This was due, in part, to limitations on in-person research visits and in-person conferences in the first half of the year; there were fewer Canadian and international visitors overall than in a typical year.

RESEARCH TRAINING

The Institute continued to invest in innovative research training programs, such as the PSI master's program, the PhD program, and the newly redesigned undergraduate program, PSI Start. Each program attracts and trains top scientific talent – increasing expertise, advancing research, and producing job-ready leaders in many fields that drive economic growth in Canada. Though Perimeter's online training programs were successful throughout the pandemic, nothing replaces the in-person experience. Expenditures were approximately 30 percent higher than the previous year as students were invited back to campus with comprehensive health protocols in place, and with the associated costs for accommodation, meals, and travel. Perimeter continues to allocate training resources strategically, making a concerted effort to work with each student to ensure a successful arrival, including assistance with visas and COVID-19 protocols for international students.

OUTREACH AND SCIENCE COMMUNICATIONS

Perimeter's world-class educational outreach program has continued to build on the success of its pivot to digital resources during the previous two years, leveraging what was learned in the digital environment. The Outreach team continued to offer educators classroom-ready digital and curriculum-compliant materials, and online and in-person professional development workshops. EinsteinPlus, Perimeter's flagship professional development program for educators, was offered in person to Canadian and international teachers. Other outreach programs continued to reach teachers, students, and the general public, from the largest cities to remote and underserviced communities, helping to prepare youth for STEM-based careers and to inform the public about the value of scientific research. A new podcast, *Conversations at the Perimeter,* reached new audiences. Total outreach expenditures in 2021/22 were consistent with the previous year, but the balance of spending has shifted among programs.

INDIRECT RESEARCH AND OPERATIONS

Indirect research and operating expenditures cover the costs of core support areas, including administration, advancement, information technology, and facilities. Perimeter continues to invest in technology, understanding that hybrid and online environments are a part of the future and allow for greater breadth of audiences and improved access for more people. While maintaining the building and creating a safe and healthy environment, there were some additional costs related to health protocols, such as rapid testing. Perimeter continued to invest in a healthy community to maintain productivity levels and retain staff and researchers during this challenging time. Overall, indirect research and operations expenditures remained in line with prior years.

INCOME

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

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

To complement public investments, Perimeter has been able to secure generous support from the private sector, including corporations, foundations, and donors. The Institute achieved an increase over the previous year in both its private sector fundraising campaign and its grant revenue from private foundations, which generated approximately $5.4 million to support the Institute's operations.

FINANCIAL POSITION

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

Despite realizing strong returns for the first six months of the fiscal year, a market downturn in the latter half of the year resulted in negative returns of approximately 3.5 percent. The Investment Committee and the overall governance that it deploys aims for risk objectives that produce steady, predictable returns. However, variabilities are inevitable over time, and Perimeter is in a strong financial position to withstand them, while retaining the flexibility and speed to take advantage of scientific opportunities as they arise, creating major assets for Canada and Ontario as a global centre of theoretical research and technology development.

THE LONG-TERM PLAN

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

As of July 31, 2022, Perimeter has completed the final year of five-year commitments of $50 million from both the federal and provincial governments, which provided combined funding of $100 million. 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. The Government of Ontario has committed to grants totalling $24 million from 2022 to 2024; the Government of Canada has committed to grants totalling $20 million in the same period while inviting Perimeter to apply for 2024-2029 funding through the Strategic Science Fund.

In addition to government support, private funding plays a crucial role in ensuring Perimeter's long-term success, and the Institute has established ambitious fundraising goals. Government funding is critical to Perimeter's ability to attract philanthropic support. Donors depend on the continued confidence and oversight of public sector funders as evidence of the value of their investments. In accordance with donor requests, private sector donations may be used as contributions toward operational expenditures or protected in an endowment fund designed to minimize risk and maximize growth.

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

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, 2022 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, 2022.

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

Summary Financial Statements

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

The Audited Financial Statements and Our Report Thereon

We expressed an unmodified audit opinion on the audited financial statements in our report dated December 15, 2022. 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 15, 2022

Chartered Professional Accountants
Licensed Public Accountants

PERIMETER INSTITUTE

Summarized Statement of Financial Position
(in thousands of dollars)
as at July 31, 2022

	2022	2021
ASSETS		
Current Assets:		
Cash and cash equivalents	$ 41,943	$ 7,470
Investments	343,011	391,593
Grants receivable	14	17
Other current assets	1,184	962
	386,152	400,042
Property and equipment	36,521	37,825
TOTAL ASSETS	$ 422,673	$ 437,867
LIABILITIES AND FUND BALANCE		
Current liabilities:		
Accounts payable and other current liabilities	$ 2,354	$ 2,290
TOTAL LIABILITIES	2,354	2,290
Fund balances:		
Invested in capital assets	36,497	37,639
Externally restricted	12,638	8,810
Internally restricted	370,204	388,506
Unrestricted	980	622
TOTAL FUND BALANCES	420,319	435,577
	$ 422,673	$ 437,867

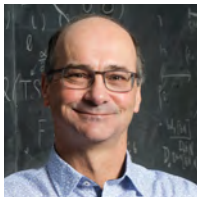
PERIMETER INSTITUTE

Summarized Statement of Operations and Changes in Fund Balances
(in thousands of dollars)
For the Year Ended July 31, 2022

	2022	2021
Revenue		
Government grants	$ 24,000	$ 15,085
Research grants	1,232	848
Donations	4,225	3,923
	29,457	19,856
Expenses		
Research	14,918	14,282
Research training	2,195	1,693
Outreach and science communications	2,805	2,931
Indirect research and operations	8,637	8,198
	28,555	27,104
Excess of revenue over expenses (expenses over revenue) before investment and amortization impacts	902	(7,248)
Amortization	(2,287)	(2,316)
Investment (loss) income	(13,873)	47,130
Excess of (expenses over revenue) revenue over expenses	(15,258)	37,566
Fund balances, beginning of year	435,577	398,011
Fund balances, end of year	$ 420,319	$ 435,577

APPENDICES

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

Laurent Freidel (PhD L'École Normale Supérieure de Lyon, 1994) joined Perimeter Institute first as a visitor in 2002 and then as faculty in 2006. He was appointed as Faculty Chair in 2021. Freidel is a mathematical physicist who has made many notable contributions in the field of quantum gravity, introducing the concept of corner symmetry to resolve entanglement, and developing spin foam models, among other things. He has also introduced several new concepts in this field, such as local holography, group field theory, relative locality, and metastring theory and modular spacetime. He possesses outstanding knowledge of a wide range of areas, including gravitational physics, integrable systems, topological field theories, two-dimensional conformal field theory, string theory, and quantum chromodynamics. Freidel has held positions at Pennsylvania State University and L'École Normale Supérieure and has been a member of France's Centre national de la recherche scientifique since 1995. He is also the recipient of several awards.

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

Latham Boyle (PhD Princeton University, 2006) joined the Institute's faculty in 2010. From 2006 to 2009, he held a Canadian Institute for Theoretical Astrophysics Postdoctoral Fellowship and was a junior fellow of the Canadian Institute for Advanced Research. In recent years, Boyle's research interests have spanned a number of topics in cosmology, fundamental physics, and mathematical physics. In cosmology, he recently proposed and has been developing (with Neil Turok) a new cosmological model in which the big bang is a kind of mirror and the universe

before the bang is the CPT mirror image of the universe after the bang. This line of thought leads to rigid new explanations for a number of observed features of our universe (including its homogeneity, isotropy, and flatness; the arrow of time; dark matter; and several properties of the primordial perturbations, along with a clue to why the cosmological constant is so mysteriously small). In fundamental physics, he recently pointed out an intriguing new connection between certain patterns in the Standard Model of particle physics and the structure of a remarkable mathematical object called the exceptional Jordan algebra. With Kendrick Smith, he introduced "choreographic crystals," which are new types of "crystals" in which the basic elements perform a choreographed dance that can have much higher symmetry than any instantaneous snapshot reveals. With Paul Steinhardt, he found all "Penrose-like tilings" (cousins of the famous Penrose tiling) in all dimensions. With Madeline Dickens and Felix Flicker, he discovered that the regular tessellations of hyperbolic space (which play a central role in the burgeoning field of "discrete holography") induce self-similar quasiperiodic tilings (like the Penrose tiling) at the boundary of hyperbolic space and pointed out their importance for discrete holography.

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

Kevin Costello (PhD University of Cambridge, 2003) is the Krembil William Rowan Hamilton Chair in Theoretical Physics. He joined Perimeter in 2014 from Northwestern University, where he had been a faculty member since 2006. Costello works on the mathematical aspects of quantum field theory and string theory. He is the author of Renormalization and Effective Field Theory, a path-breaking monograph introducing powerful new mathematical tools into the theory of quantum fields, and co-author of *Factorization Algebras in Quantum Field Theory*. Costello's previous honours include an Alfred P. Sloan Research Fellowship, the Berwick Prize of the London Mathematical Society, and several prestigious grants from the National Science Foundation in the United States. In 2018, he was elected as a fellow of the Royal Society (UK). In 2020, he was awarded the Leonard Eisenbud Prize of the American Mathematical Society and was elected an Honorary Member of the Royal Irish Academy. In 2022, he received the John L. Synge Award from the Royal Society of Canada for outstanding research in mathematical sciences.

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

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

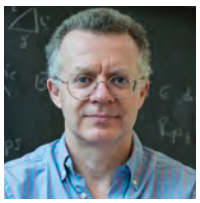
William East (PhD Princeton University, 2013) joined Perimeter as a Director's fellow in 2016 and became a member of the faculty in January 2018. Prior to that, he was a postdoctoral fellow at the Kavli Institute for Particle Astrophysics and Cosmology at Stanford University (2013-16). East uses numerical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

Dominic Else (PhD University of California, Santa Barbara, 2018) joined Perimeter in 2022 and is collaborating with scientists at the Institute's Clay Riddell Centre for Quantum Matter. He has recently completed a research term at Harvard University. In 2021, Else won the New Horizons in Physics Prize from the Breakthrough Prize Foundation for his "pioneering theoretical work formulating novel phases of non-equilibrium quantum matter, including time crystals."

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). He is also one of the principal investigators in the Simons Collaboration on Confinement and QCD Strings.

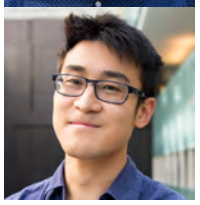
Jaume Gomis (PhD Rutgers University, 1999) joined Perimeter Institute in 2004, declining a European Young Investigator Award by the European Science Foundation to do so. Prior to that, he worked at the California Institute of Technology as a postdoctoral scholar and as the Sherman Fairchild Senior Research 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.

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



Yin-Chen He (PhD Fudan University, 2014) joined Perimeter in July 2018 from Harvard University, where he was a Moore Postdoctoral Fellow from 2016 to 2018. 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 was a Moore Postdoctoral Fellow from 2015 to 2018. Hsieh is the Director of Perimeter's Clay Riddell Centre for Quantum Matter. His research focuses on 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. He is also the recipient of an Early Researcher Award from the Ontario Ministry of Colleges and Universities.



Junwu Huang (PhD Stanford University, 2017) joined Perimeter as a postdoctoral researcher in 2017 and became a member of the faculty in June 2022. He designs novel small-scale experiments to look for light weakly coupled particles as dark matter in the universe, and new searches based on astrophysical and cosmological observations for new physics motivated by string theory, including axions, cosmic strings, and new vacua in the landscape.

Luis Lehner (PhD University of Pittsburgh, 1998) began a joint appointment with Perimeter and the University of Guelph in 2009, joined Perimeter as a full-time faculty member in 2012, served as Deputy Faculty Chair from 2014 to 2017, and as Faculty Chair from March 2018 to 2021. He was previously a member of Louisiana State University's faculty (2002-09). Lehner's many honours include the Honor Prize from the National University of Cordoba, Argentina; a Mellon pre-doctoral fellowship; the CGS/UMI outstanding dissertation award; and the APS Nicholas Metropolis award. He has been a Pacific Institute for the Mathematical Sciences Fellow, a Canadian Institute for Theoretical Astrophysics National Fellow, and a Sloan Research Fellow, and he is currently a fellow of the Institute of Physics, the American Physical Society, the International Society for General Relativity and Gravitation, and the Canadian Institute for Advanced Research in the Gravity and the Extreme Universe program.

Lehner also serves on the Scientific Council of the International Centre for Theoretical Physics – South American Institute for Fundamental Research and the Oskar Klein Centre of the University of Stockholm. He is also the theorist in residence for the Gravitational Wave International Committee. In 2019, he was named as one of TD's 10 Most Influential Hispanic Canadians.

Sabrina Gonzalez Pasterski (PhD Harvard University, 2019) is a high energy theorist who joined the Perimeter faculty in 2021 after completing a postdoctoral fellowship at the Princeton Center for Theoretical Science. Her research prior to joining Perimeter includes discovering infinite dimensional symmetry enhancements of the S-matrix, a new observable memory effect in gravity, and a framework for generalizing these features of infrared physics to other theories. As the founder and principal investigator of Perimeter's new Celestial Holography Initiative, she is leading a team of amplitude, mathematical physics, and quantum gravity researchers in a concerted effort to tackle the problem of uniting our understanding of spacetime with quantum theory by encoding our universe as a hologram.

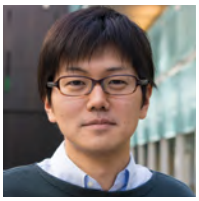
Kendrick Smith (PhD University of Chicago, 2007) is the Daniel Family James Peebles Chair in Theoretical Physics at Perimeter Institute, where he has been a faculty member since 2012. He is also the Director of Perimeter's Centre for the Universe. He previously held postdoctoral positions at Princeton 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. Smith is a co-winner, as part of the CHIME research team, of a Governor General's Innovation Award in 2020, the Lancelot Berkeley Prize from the American Astronomical Society in 2021, and the Brockhouse Canada Prize from the Natural Sciences and Engineering Research Council of Canada in 2022. 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 Quantum Causal Inference 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?"

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 was a junior fellow at the Harvard Society of Fellows from 2015 to 2018. Wang works on the theory of quantum condensed matter physics, including topological phases of matter, quantum criticality, quantum Hall effects and spin liquids, and their relationship to modern aspects of quantum field theory.



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

Neil Turok, Director Emeritus and Mike and Ophelia Lazaridis Niels Bohr Chair, and Daniel Gottesman are on leave.

Alex May and **Sisi Zhou** were recruited to the Perimeter research faculty in 2022 and are scheduled to arrive in 2023. See more information on page 20.

RESEARCH ASSOCIATE FACULTY

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

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

Avery Broderick (PhD California Institute of Technology, 2004) began a joint appointment with Perimeter and the University of Waterloo in 2011 and was named the Delaney Family John Archibald Wheeler Chair in Theoretical Physics at Perimeter Institute in January 2017. He previously held postdoctoral positions at the Institute for Theory and Computation at the Harvard-Smithsonian Center for Astrophysics (2004-07) and the Canadian Institute for Theoretical Astrophysics (2007-11). Broderick is an astrophysicist with broad research interests, ranging from how stars form to the extreme physics in the vicinity of white dwarfs, neutron stars, and black holes. He is a key member of the Event Horizon Telescope (EHT) collaboration, which revealed the first image of a black hole event horizon to the world in April 2019. He studies how black holes accrete matter and launch the ultra-relativistic outflows observed, probing the nature of gravity in their vicinity. Broderick is a co-winner (with the EHT collaboration) of the Diamond Achievement Award and the 2020 Breakthrough Prize in Fundamental Physics, along with several other awards.

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

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

recent honours include a Killam Fellowship, fellowship of the Royal Society of Canada, and the CAP-CRM Prize in Theoretical and Mathematical Physics. He was awarded the Buchalter Cosmology Prize in both 2016 and 2017. His book *Introduction to Effective Field Theories* was named the Best Book in Physics and Chemistry in 2022 by the Association of American Publishers.

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

David Gosset (PhD Massachusetts Institute of Technology, 2011) is jointly appointed with the Institute for Quantum Computing (IQC) and has been an associate professor at the University of Waterloo since 2018. Prior to that, he held positions as a postdoctoral fellow at IQC and at the California Institute of Technology and as research staff at the IBM T.J. Watson Research Center. Gosset's research focuses on quantum algorithms and complexity theory. Among other awards and honours, he earned the Outstanding Paper Prize at the 2019 Conference on the Theory of Quantum Computation, the Pat Goldberg Memorial Best Paper Award in 2016 and 2018, and the Sherman Fairchild Prize Postdoctoral Fellowship at Caltech for 2015-16.

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

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

Raymond Laflamme (PhD University of Cambridge, 1988) is jointly appointed at the Institute for Quantum Computing at the University of Waterloo, where he served as founding Executive Director from 2002 to 2017. He is also the Mike and Ophelia Lazaridis John von Neumann Chair in Quantum Information at the University of Waterloo and the Canada Research Chair in Quantum Information. He held research positions at the University of British Columbia and Peterhouse College, University of Cambridge, before moving to the Los Alamos National Laboratory in 1992, where his interests shifted from cosmology to quantum computing. Since the mid-1990s, Laflamme has elucidated theoretical approaches to quantum error correction and in turn implemented some in experiments. Laflamme was Director of the Quantum Information Processing program at the Canadian Institute for Advanced Research (CIFAR) from 2003 to 2016. He is an advisor to the Quantum Information Science program at CIFAR and a fellow of the American Physical Society, the Royal Society of Canada, and the American Association for the Advancement of Science, and he was named an Officer of the Order of Canada in 2017. He was awarded the 2017 CAP-CRM Prize in Theoretical and Mathematical Physics by the Canadian Association of Physicists and the Centre de recherches mathématiques. With colleagues, Laflamme founded Universal Quantum Devices, a start-up commercializing spin-offs of quantum research, and leads QuantumLaf Inc., a consulting start-up.

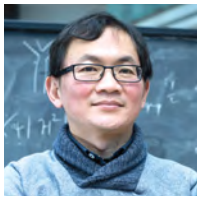
Sung-Sik Lee (PhD Pohang University of Science and Technology, 2000) joined Perimeter in 2011 in a joint appointment with McMaster University, where he is a professor. He previously worked as a postdoctoral researcher at the Pohang University of Science and Technology, the Massachusetts Institute of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

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

Roger Melko (PhD University of California, Santa Barbara, 2005) joined Perimeter in 2012, while retaining his appointment with the University of Waterloo, where he has been since 2007. Prior to that, he was a Wigner Fellow at Oak Ridge National Laboratory (2005-07). Melko leads the Perimeter Institute Quantum Intelligence Lab, heads the Quantum Stream at Creative Destruction Lab, and is a faculty affiliate at Vector Institute for Artificial Intelligence. He is a condensed matter theorist who studies strongly correlated many-body systems, focusing on exotic emergent phenomena, quantum criticality, and entanglement. He emphasizes numerical methods as a theoretical technique, particularly the development of novel algorithms and machine learning methods for his research. Among his honours, he has received the Herzberg Medal from the Canadian Association of Physicists, the Young Scientist Prize in Computational Physics from the International Union of Pure and Applied Physics, an Early Researcher Award from the Ontario Ministry of Research and Innovation, and a Canada Research Chair in Computational Quantum Many-Body Physics. In 2021, he was awarded the Brockhouse Medal from the Canadian Association of Physicists and the Division of Condensed Matter and Materials 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. In 2022, she received a University Research Chair at the University of Waterloo.



Ue-Li Pen (PhD Princeton University, 1995) joined Perimeter in 2014. He is the Director of the Academia Sinica Institute of Astronomy and Astrophysics in Taiwan and is jointly appointed with the Canadian Institute for Theoretical Astrophysics at the University of Toronto, where he has been a professor since 1998. Pen is a theoretical astrophysicist who studies systems where basic physical effects can be isolated from astronomical complexities. His research projects include the non-linear dynamics of the cosmic neutrino background, 21 cm intensity mapping, pulsar VLBI scintillometry, and the Canadian Hydrogen Intensity Mapping Experiment (CHIME). Pen is known for developing innovative tools to create new fields of research. His pioneering work on

21 cm intensity mapping opens a new window for the precision study of dark energy and neutrinos. His use of natural plasma in our galaxy as a giant telescope spawned the field of scintillometry, enabling new glimpses into enigmatic pulsars and the unsolved fast radio bursts. Among his many honours, Pen is a senior fellow of the Canadian Institute for Advanced Research in the Gravity and the Extreme Universe program. In 2018, he became just the second researcher at a Canadian institution to receive a Simons Investigator Award from the Simons Foundation since the program's introduction in 2012. He was part of the CHIME research team that received a Governor General's Innovation Award in 2020 and the Lancelot Berkeley Prize from the American Astronomical Society in 2021. He was also one of the 347 members of the Event Horizon Telescope collaboration to win the 2020 Breakthrough Prize in Fundamental Physics.

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

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

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

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

OUTREACH FACULTY

Katherine (Katie) Mack (PhD Princeton University, 2009) joined Perimeter in June 2022 to become the inaugural Hawking Chair in Cosmology and Science Communication. She previously held the position of assistant professor at North Carolina State University after carrying out postdoctoral fellowships at the Kavli Institute for Cosmology in Cambridge and at the University of Melbourne. Her primary research interests are in theoretical cosmology, astroparticle physics, early-universe theory, and galaxy formation. She is particularly interested in the physics and astrophysics of dark matter, and how we might find clues about dark matter's fundamental nature by examining its impact on the formation and evolution of the earliest cosmic structures. She was selected as a CIFAR Azrieli Global Scholar in 2022 and a TED Fellow in 2020.

TEACHING FACULTY

Maïté Dupuis (PhD École Normale Supérieure de Lyon, 2010) is the Director of Academic and Research Programs at Perimeter and an adjunct associate professor in the Applied Mathematics department and in the Physics and Astronomy department of the University of Waterloo. Dupuis was a postdoctoral fellow at the Institute for Quantum Gravity of the Fredrich Alexander University Erlangen-Nuremberg in Germany. In 2013, she became a Banting Postdoctoral Fellow in the Applied Mathematics department of the University of Waterloo. In 2017, she joined the Perimeter Institute Academic Programs department as a teacher, supervisor, and mentor. She was named Assistant Director of Academic Programs in 2020. She is a co-founder of the Inclusive PI Platform and has served as Co-Chair since its inception in 2018.

Lauren Hayward (PhD University of Waterloo, 2017) is a teaching faculty member at Perimeter and an adjunct assistant professor in the Department of Physics and Astronomy at the University of Waterloo. She works within the field of computational quantum matter physics, and her research interests involve using numerical methods to study phenomena such as phase transitions and quantum entanglement. She also develops academic programs and teaches courses in statistical mechanics, condensed matter theory, and machine learning. She is the co-host of the podcast series *Conversations at the Perimeter*, where she interviews world-leading theoretical physicists about how to unravel the mysteries of the universe.

David Kubiznak (PhD University of Alberta, 2008) joined Perimeter in August 2011 from the Department of Applied Mathematics and Theoretical Physics at the University of Cambridge, where he had been a Herchel Smith Postdoctoral Fellow since 2008. As a teaching faculty member, Kubiznak has contributed toward teaching and developing the Perimeter Scholars International master's program and has supervised many students over the years. His research focuses on black holes and their mathematical properties. He is one of the co-founders of a new subdiscipline of black hole thermodynamics called the black hole chemistry. Kubiznak is also a recipient of the Governor General's Gold Medal at the University of Alberta and Milan Odehnal's Award from the Czech Physical Society.

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James Forrest, Director of Academic Partnerships

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Lauren Hayward, Teaching Faculty

David Kubiznak, Teaching Faculty

Gang Xu

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Jaime Redondo Yuste (Spain)

Shawn Skelton (Canada)

Manu Srivastava (India)

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CONFERENCES AND WORKSHOPS, 2021/22

Postdoctoral Researcher Welcome
October 28-29, 2021

Gravitational Waves Beyond the Boxes II
April 4-8, 2022

Quantum Criticality: Gauge Fields and Matter
May 16-20, 2022

Global Categorical Symmetries
June 6-17, 2022

QFT for Mathematicians 2022
(one week in person, one week online)
June 20-30, 2022

Cold Atom Molecule Interactions (CATMIN)
July 14-15, 2022

ACADEMIC SPONSORSHIPS, 2021/22

Perimeter Institute was a proud sponsor of the following conferences and workshops hosted elsewhere and held in person or online.

Lake Louise Winter Institute 2022
Hosted by the University of Alberta
February 20-25, 2022, in Lake Louise, Alberta

Cosmological Frontiers 2022
Hosted by the Solvay Institute
April 26-28, 2022, in Brussels, Belgium

Atlantic General Relativity (AGR) 2022
Hosted by Memorial University
May 16-19, 2022, online

Canadian Astronomical Society (CASCA) Annual General Meeting
Hosted by University of Waterloo
May 16-20, 2022, online

Canadian Association of Physicists (CAP) Congress
Hosted by CAP
June 5-10, 2022, in Hamilton, Ontario

Quantum Information Structure of Spacetime
Hosted by Western University
June 6-10, 2022, in London, Ontario

Tri-Institute Summer School on Elementary Particles (TRISEP) 2022
Hosted by TRIUMF
July 4-15, 2022, in Vancouver, British Columbia

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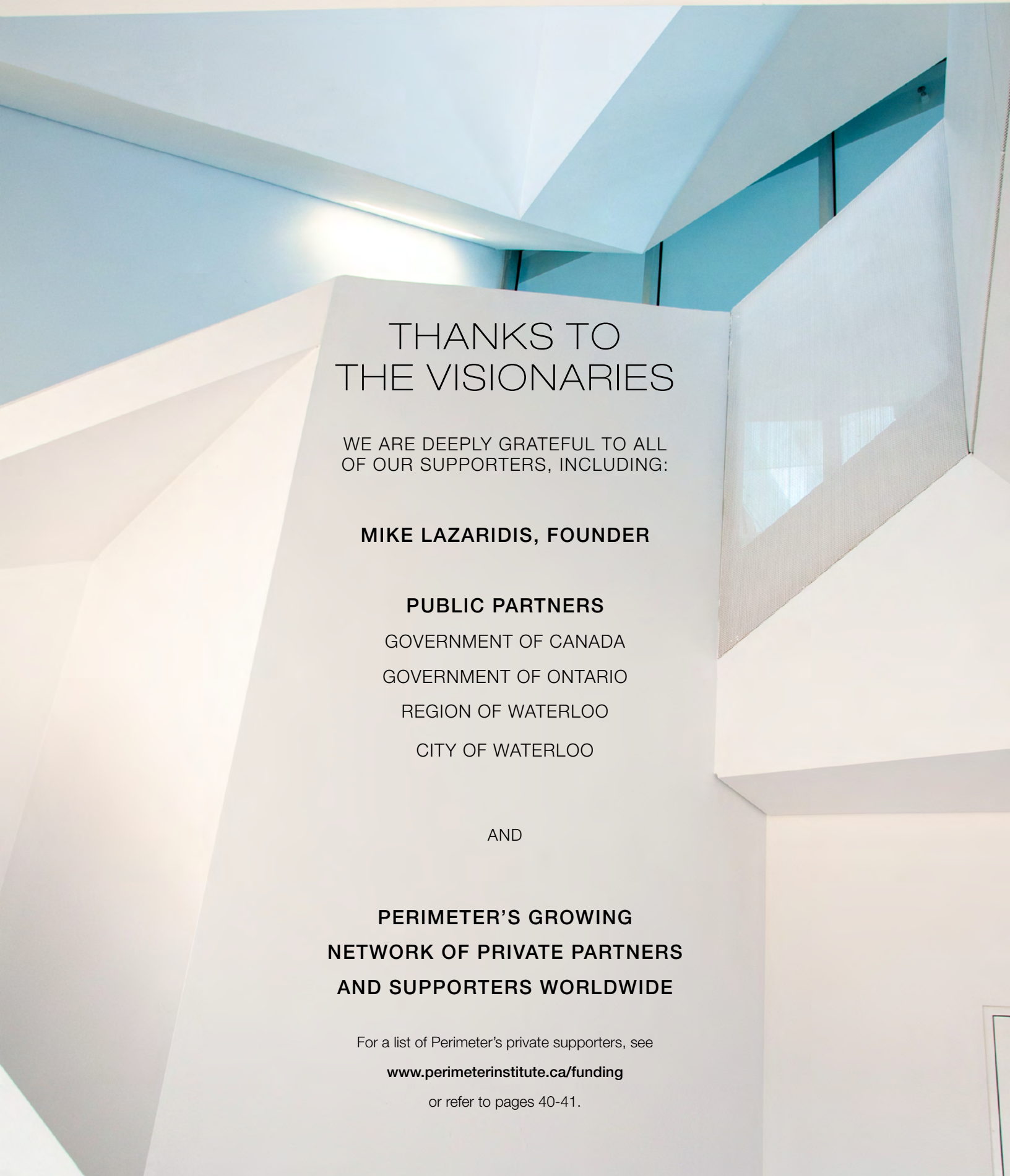

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