2017
ANNUAL REPORT

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

VISION

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

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This report covers the activities and finances of Perimeter Institute for Theoretical Physics from August 1, 2016, to July 31, 2017

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WELCOME

Just one breakthrough in theoretical physics can change the world.

Perimeter Institute is an independent research centre located in Waterloo, Ontario, Canada, founded in 1999 to accelerate breakthroughs in our understanding of the universe.

Here, scientists seek to discover how the universe works at all scales – from the smallest particle to the entire cosmos.

Their ideas are unveiling our remote past, explaining the world we see around us, and enabling the technologies that will shape our future, just as past discoveries in physics have led to electricity, computers, lasers, and a nearly infinite array of modern electronics.

Perimeter is training the next generation of physics pioneers, and sharing the power and importance of scientific discovery with the world.

The science is complex, but the basic Perimeter equation is simple: Bright minds. Illuminating ideas. Brilliant future.

Step inside the Perimeter.

AN ACCELERATOR OF DISCOVERY

RESEARCH

160+ SCIENTISTS IN RESIDENCE conducting research

12 MAJOR PRIZES AND HONOURS awarded to Perimeter scientists in 2016/17

1,000+ VISITING INTERNATIONAL SCIENTISTS annually

4,600+ PAPERS appearing in 170+ journals with 210,000+ citations since 2001

11,000+ ONLINE TALKS and lectures accessed by viewers in 175 COUNTRIES

18 YEARS after its creation, Perimeter is now ranked among the TOP THEORETICAL PHYSICS institutes in the world

OUTREACH

30 MILLION STUDENT INTERACTIONS since 2001

20,000+ EDUCATORS trained through Perimeter workshops since 2005

725 TOP HIGH SCHOOL STUDENTS from 58 COUNTRIES have attended the International Summer School for Young Physicists since 2003

65+ COUNTRIES have used Perimeter's educational resources

TRAINING

In 2016/17, Perimeter was home to

59 POSTDOCTORAL RESEARCHERS

49 PHD STUDENTS and

27 PSI MASTER'S STUDENTS from 20 COUNTRIES

MESSAGE FROM THE BOARD CHAIR

Answers to the most basic questions hold the seeds of breakthroughs.

Fundamental physics has entered an era of rapid advances on many fronts. The past year alone saw great advances across the spectrum of physics. We watched neutron stars collide, saw leaps in the application of machine learning to physics problems, and made major strides towards practical quantum computation. Fuelling it all was one simple thing: the quest for a greater understanding of the world around us. It's a quest that is gathering momentum.

Perimeter researchers are working at the most productive and challenging interfaces in the field: where gravitational wave astronomy is transforming cosmology, where machine learning is helping discover powerful quantum materials, where information theory meets quantum information, where pure mathematics meets quantum field theory, and much more.

Perimeter is recognized as one of the largest theoretical physics institutes in the world and continues to attract top researchers from around the globe to make their important contributions here. Increasingly, we hear about international researchers or students who ask their mentors, teachers, or advisors for recommendations on where to pursue their physics careers and, increasingly, Perimeter is at or near the top of the list of recommended destinations. This is another sign of Perimeter's success and something that I am personally very proud of.

For some time, it's been clear that a new quantum revolution is coming, based on a deeper understanding of quantum mechanics. It will transform how we view and manipulate matter and energy, manufacture new materials, compute and communicate, store and secure data, and more. Whether you read *The Economist*, *The Globe and Mail*, *The Wall Street Journal*, or the latest science reports from U.S. Congress, it is quite clear that the second quantum revolution is here.

Perimeter Institute and its partners in the Quantum Valley continue to take the necessary steps to ensure that Canada establishes itself as a global leader in quantum research and in the development and commercialization of new transformative quantum technologies.

Perimeter plays a critical role in the Quantum Valley. As we know, it all starts with basic research. Perimeter's international profile brands the region and Canada, attracting top researchers from across Canada and around the world. Perimeter researchers and students make advances that increase our fundamental knowledge of quantum information science, while helping us understand and interpret new discoveries from other centres around the world. This fundamental knowledge is the starting point for the development of new quantum technologies and industrial infusion and development in the Quantum Valley and Canada.

Also, the track record that Perimeter has built over the past 18 years gives us international recognition and credibility that helps us attract investment and other top talent from around the world to the Waterloo Region and Canada. The result is a large-scale comprehensive quantum ecosystem that includes all of the major elements that we believe will be necessary to establish the Quantum Valley as a leader in the second quantum revolution.

But scientists cannot do this alone. Perimeter is the result of a very successful and long-standing public-private partnership with the Government of Canada and the Province of Ontario, which have been vital and visionary partners since its inception.

I am thrilled that more and more individuals, foundations, and corporations have come to appreciate Perimeter's importance to our collective future. In 2014, the Institute undertook its first major advancement campaign with a very ambitious target of raising $25 million in new private funds. I am pleased to report that this past July, we surpassed it. I want to thank all of the Institute's donors. Your investment and support is enabling the science that will drive our future and your leadership will help emphasize the importance of supporting basic research to others.

Building these successes is a team effort. I would like to thank the entire Perimeter team, as well as its many volunteers and champions. This includes our Leadership Council, our Emmy Noether Council, our Finance and Investment Committees, and my fellow Board members. I would like to acknowledge, in particular, Director Neil Turok, whose vision has guided the Institute for nine years, and whose unbridled enthusiasm for science has proven highly contagious.

The great challenge – and great beauty – of physics is its unpredictability. Even the most basic questions can overturn our expectations and unleash unforeseen benefits.

We don't know exactly what breakthroughs will happen next, where this new knowledge will lead us, or what new technologies will follow. All we know for certain, from historical precedent, is that fundamental physics research is the surest catalyst of discovery, innovation, and value creation.

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

MESSAGE FROM THE INSTITUTE DIRECTOR

Humans have always wondered about their origins and their destiny, but ours is the first generation to probe the entire universe. We have been given a unique opportunity to discover how it all works and what it may allow us to do.

Space-based probes, global networks of radio telescopes, giant particle accelerators, and gravitational wave detectors are allowing us to view phenomena from the quantum to the cosmos, allowing us to test theories to their limits, as never before. What we have found is amazing: the universe is both extremely simple, with the same laws discovered on Earth holding everywhere, and yet deeply paradoxical. How and why did it all emerge from a big bang? What is the dark energy now taking over, and why is this happening?

That is why, at Perimeter, we've created the Centre for the Universe. It will be a focused research hub that will leverage the expertise we have built in fundamental physics to seek answers to some of science's biggest questions. Launched with a $5 million anonymous donation, the Centre's prime goal is to design and analyze new observations and experiments to shed light on key mysteries. In tandem, the Centre will support the development and testing of new theoretical ideas and techniques. Centre scientists will interact with, and inform, the entire Perimeter community about developments in cosmology and the clues they provide to profound new theoretical advances. We are delighted to report that Neal Dalal, a pioneer in using clever astronomical observations to reveal the fundamental character of dark matter and the primordial density variations, has just joined our faculty.

Closer to home, a second quantum revolution is clearly underway. This time, it is driven by some of the strangest and most counterintuitive properties of quantum physics. The first quantum revolution allowed us to understand and control how electricity flows in devices, giving rise to computers, lasers, modern electronics, and communications. The second revolution promises to be even more profound, allowing us to design materials and systems which exploit large-scale collective quantum behaviour to achieve extraordinary sensitivity and, in some cases, effects which would be impossible in any classical system.

This is another area where Perimeter can play to its strengths. So, this year, we have started to lay the groundwork for a second major initiative, the Centre for Quantum Matter. We are thrilled to be joined by three of the top young theorists working in quantum condensed matter and quantum information: Yin-Chen He, Tim Hsieh, and Beni Yoshida. Each brings a highly creative research program. They are joining Perimeter because they sense a big opportunity, to collectively build a world-leading effort.

Outside of these two focused initiatives, we have recently hired several extraordinary scientists working across the spectrum of physics. Savas Dimopoulos, a renowned particle theorist, has accepted the Archimedes Chair in Theoretical Physics (Visiting). Ben Webster, a leading mathematician with strong interests in physics, has been jointly appointed with the University of Waterloo. In 2018, eminent mathematical physicist Matilde Marcolli will move to Perimeter and the University of Toronto, from the California Institute of Technology.

Perimeter is becoming a special centre for the world: a unique community of minds pursuing basic questions about the universe, challenging each other, and drawing on one another's strengths and enthusiasm, to make breakthroughs in the service of humanity.

Canada provides a supportive environment – increasingly distinguished by its international, collaborative outlook, its intellectual freedom, its openness to critical thinking and evidence-based reasoning, and its encouragement of youth. Indeed, by helping Canada shine as a beacon of enlightenment in a troubled world, Perimeter is providing an opportunity to demonstrate that these principles pay off.

This year, as Canada celebrated its 150th anniversary, I was honoured to travel across the country as part of Innovation150, a Perimeter-led celebration of Canada's innovative past, present, and future. Innovation150 was a collaborative effort among five scientific outreach organizations, including a museum-scale exhibition on the quantum world, and science exhibits and festivals that visited communities across Canada, setting up in gyms and community centres, to the delight of kids and families and curious minds from coast to coast to coast. I was fortunate to participate by giving a talk, "We Are Innovators," whose aim was to explain innovation as a fundamental, human quality and to inspire young people to embrace curiosity, creativity, courage, and collaboration as the means to building a better future.

Though we are humbled by how much there is yet to do, we are also excited by our rare opportunity.

– Neil Turok, Director and Mike and Ophelia Lazaridis Niels Bohr Chair

RESEARCH

How did the universe begin? What is it made of? What are the forces that shape it? What is dark matter? How can we understand and harness the quantum world?

This year, Perimeter scientists produced **502 papers.**[1] Since its inception, the Institute's scientists have produced over **4,600 papers**, which have appeared in over **170 journals**, attracting well over **210,000 citations.**[2]

[1] This reflects the one-year period from August 1, 2016 to July 31, 2017. Each publication has been counted only once, regardless of how many Perimeter researchers collaborated on it.

[2] This data comes from the Google Scholar and Spires databases.

From the outer reaches of the cosmos to the tiny realm of subatomic physics, Perimeter scientists are pursuing some of the deepest challenges in science. Floods of new data are revealing the universe as never before, shedding new light on old questions, and increasing the probability of breakthroughs.

Take, for example, the budding field of gravitational wave physics. Gravitational waves were predicted as part of Einstein's theory of general relativity, which posits that space and time are woven together into the fabric of spacetime. The theory describes how moving masses could emit ripples of distortion that would travel throughout that fabric.

It was nearly a century before those ripples were observed for the first time, when LIGO (the Laser Interferometer Gravitational-Wave Observatory) detected gravitational waves from a pair of colliding black holes in 2015. Since then, progress has been swift and considerable: when the Virgo detector in Italy came online, researchers could triangulate the sources of waves with increasing accuracy, and the recent detection of a neutron star merger in both gravitational waves and across the electromagnetic spectrum marked the dawn of "multimessenger astronomy."

In fundamental physics, it is difficult to know when – or even whether – an idea will lead to a tangible payout. Gravitational waves began as a sidenote in a theory a hundred years ago, but are now poised to become a crucial tool to advance our understanding of nature: scientists will use them to test theories of gravity, to determine how chemical elements are created, and, perhaps, to peer back to the instants just after the big bang.

At Perimeter, researchers are encouraged to pursue their most ambitious ideas, and to push beyond traditional research specializations into new areas, where breakthroughs are most likely to occur.

From ubiquitous chalkboards and conversation spaces, to boundary-pushing conferences and a vibrant visiting scientist program, Perimeter has cultivated an environment designed to facilitate collaboration and interdisciplinary interactions. The culture of collaboration also reaches beyond the walls of the building: Perimeter researchers have connections with world-class institutions across the globe and cutting-edge experiments such as LIGO, the Event Horizon Telescope, and the Large Hadron Collider at CERN.

The pages ahead outline just a few of the ways Perimeter researchers are making progress on some of the most difficult topics in physics, such as how the universe began, understanding the nature of space and time, and pushing the limits of quantum computation.

"I've worked at fantastic places like Berkeley, Stanford, and CERN, but Perimeter is unique. Here it feels like my possibilities are endless."

– Asimina Arvanitaki, Stavros Niarchos Foundation Aristarchus Chair, winner of the 2017 New Horizons Prize in Physics

THE BROAD REACH OF QUANTUM INFORMATION

The world of quantum physics, which describes our universe on the smallest of scales, is full of puzzling effects and counterintuitive ideas. Particles can be in a state of superposition – a bit like being in two places at the same time – or entangled with one another, such that a measurement on one particle instantly affects another, no matter how far apart the particles are.

The next quantum revolution is likely to be built on harnessing and exploiting these strange properties to create full-scale quantum computers that could be used to model phenomena too complex for conventional computers, create unbreakable encryption codes, and solve problems previously thought to be unsolvable.

Quantum information theorists at Perimeter are laying down the theoretical underpinnings that will make quantum computation, communication, cryptography, and security possible – and exploring the limits of what will be possible once these technologies arrive on the scene.

Many of Perimeter's quantum information researchers collaborate with scientists and experimentalists at the nearby Institute for Quantum Computing at the University of Waterloo. Many researchers are also working at the interface of quantum information and other seemingly disparate fields in physics, where they are making unanticipated and important advances on problems in condensed matter, quantum gravity, string theory, and more.

A LIMIT ON QUANTUM COMPRESSION

Transmitting information is the bread and butter of computing, both for our everyday "classical" computers and for their future quantum counterparts. One of the keys to swift and efficient information communication is compression: encoding information in as few bits, or qubits (quantum bits), as possible.

The interactive nature of communication and information theory is a key focus for Perimeter postdoctoral researcher **Dave Touchette**, whose research ties together theories of computation and quantum information.

In a recent paper, Touchette and co-authors investigated what kind of compression was possible for two parties working to compute a mathematical function by exchanging quantum information.

The result was surprising: the group discovered that some functions require an exponentially large exchange of information in order to compute them, even though the information contained within the function was very low. Their result clarifies what kind of compression is possible for tasks involving quantum communication, and builds on a similar finding by computer scientists who looked only at classical communication.

It also closes the door on a long-standing open question in quantum communication complexity called the "strong direct sum problem," which asks whether the amount of resources required to solve a problem scales linearly with the number of copies of the problem.

The work has already made ripples in the international quantum information community: it was presented at the 2017 Symposium on the Theory of Computing, one of the top conferences in theoretical computer science, and was selected as a plenary talk for the 20th Annual Conference on Quantum Information Processing.

THE QUANTUM CHAOS OF BLACK HOLES

New Perimeter Faculty member **Beni Yoshida** is not your standard quantum information theorist. His research lies at a unique intersection of three fields – quantum information, condensed matter, and string theory – with a current focus on the connection between quantum chaos and black holes.

In a recent paper, Yoshida and graduate students at Stanford University and the California Institute of Technology investigated the behaviour of quantum chaos in black holes – objects that are thought to be among the most chaotic things in nature.

Chaos applies to systems where a slight change in an initial condition has a drastic effect on the system in the future. A commonly touted example is the "butterfly effect," wherein the delicate flutter of a butterfly's wings has the potential to influence the formation of extreme weather systems like a tornado on the other side of the world.

Mathematicians and physicists have long used a technique called "random matrix theory," which describes chaotic behaviour in many systems, from condensed matter and biological networks to finance and economics. However, in the last several years, researchers studying the dynamics of black holes – like Yoshida – developed a new method for characterizing the chaotic behaviour of many-body quantum systems called "out-of-time-ordered correlation functions" (OTOCs).

In their new research, Yoshida and his collaborators showed that at times up to the "scrambling time" – the time required for an initial quantum perturbation to propagate through the entire black hole – OTOC functions were able to explain the physics of the system in places where random matrix theory fails. After the scrambling time, random matrix theory performed better than the OTOC functions.

The researchers also proposed a new kind of quantum information theoretic concept, called k-invariance, to describe the transition from early- to late-time chaos. Their work provides a theoretical framework for understanding the power and applicability of random matrix theory – a result that promises to be useful for fields beyond black hole physics, including quantum information, quantum statistical physics, and condensed matter.

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PERIMETER FACULTY

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Pedro Vieira, Clay Riddell Paul Dirac Chair in Theoretical Physics

Beni Yoshida

A CONFLUENCE OF IDEAS

At its heart, physics is a search for simplicity. Despite the dense equations that cover Perimeter's blackboards, researchers are seeking a simple set of universal organizing principles that describe a host of complex phenomena.

Often, progress is made by drawing seemingly disparate ideas and approaches together – these confluences illuminate new paths.

One such pathway that is becoming increasingly robust is an idea called "holography" (see below). In the past two decades, holography, which started as a single insight in an esoteric area, has blossomed into a near-ubiquitous tool applied from condensed matter to pure mathematics.

At Perimeter – where cross-disciplinary collaboration is the norm – researchers are combining ideas from quantum information and holography to see new connections between quantum entanglement and spacetime geometry. Others are drawing together old approaches in particle physics to discover a wealth of new quantum field theories beyond those previously known.

The quantum fields and strings research area is one of the largest at Perimeter, and also one of the most diverse, with research programs spanning from condensed matter to quantum gravity, and from cosmology to pure math.

THE S-MATRIX BOOTSTRAP

How do we understand the universe? Is it like a mosaic, assembled piece by piece until a coherent picture comes into view? Or is it more like a symphony, in which the music emerges from the application of consistent rules like pitch and key signature?

That second idea – in which the particles that make up matter are determined by what is permitted by underlying rules and principles – is known as the "bootstrap." Given a certain set of consistent parameters, the theory goes, the universe essentially pulls itself up by its bootstraps.

For quantum theorists, the bootstrap has been picking up steam – and Perimeter is a key node of action.

Leading the charge is **Pedro Vieira**, who holds the Clay Riddell Paul Dirac Chair at Perimeter. In the past year, Vieira has strengthened this path of inquiry and identified promising new avenues of discovery.

Most bootstrap research is on theories of massless particles, the so-called "conformal bootstrap" program. Another approach from the 1960s is the "S-matrix" program, which seeks to define self-consistent rules of interactions for both massless and massive particles. Vieira, however, is working to combine ideas from both to develop new insights into general theories describing all quantum particles.

Vieira and his collaborators – an international team consisting of Miguel Paulos, João Penedones, Jonathan Toledo, and Balt van Rees – aim to narrow down the window of what is possible under principles of consistency, and ultimately to understand where this consistency comes from. In the paper "The S-matrix Bootstrap II," they proved it was indeed possible to define the space of all quantum field theories, albeit in a simplified two-dimensional universe. A year later, in "The S-matrix Bootstrap III," they managed to extend these findings to a four-dimensional spacetime – like our own.

COMPLEXITY IN HOLOGRAPHY

What is holography? In its simplest terms, holography posits that a 3D object inside a cylinder can be understood by looking at the 2D outline it creates on the cylinder's surface. For physicists, this means complex problems in gravity (the inside) can be translated into simpler (and solvable) questions about particles and fields (the surface) – or vice versa. It is, in essence, a translation device. The key is to know enough about both disciplines that you can identify the points at which such translation is possible.

Holography is now home to a new confluence of ideas. The last eight years have seen a growing understanding that quantum information and quantum gravity can exchange tools and perspectives, leading to important insights on both sides. Holography provides the arena in which combinations of ideas are being tested.

Quantum entanglement appears to play a particularly important role. Much of the work in this area has focused on "entanglement entropy." (By "cutting out" part of the system to study, you inevitably lose information about hidden quantum links; this missing information corresponds to entropy.) But in 2015, Perimeter Distinguished Visiting Research Chair **Leonard Susskind**, Visiting Fellow **Brian Swingle**, and collaborators proposed that, by looking beyond entropy, one could use an idea from computer science called "computational complexity" as a tool in understanding the growth of spacetime inside a black hole.

In the context of holography, they conjectured that the complexity of a state in the boundary theory (that is, written on the edge of the cylinder) can equate with the "gravitational action" of a particular region in the bulk (the space inside the cylinder). In short, complexity equals action. But there was a hitch: there was no proper definition of the gravitational action for these regions.

Perimeter Faculty Chair **Robert Myers**, Deputy Faculty Chair **Luis Lehner**, Senior Researcher **Rafael Sorkin**, and Perimeter Affiliate **Eric Poisson** went in search of a solution. It took time, but in a paper published in 2016, they provided the needed definition, which in turn provided a proper foundation for the new complexity=action proposal and stimulated a wide number of studies by researchers around the world.

Myers then launched a systematic program of studying holographic complexity with a number of junior researchers, including PSI student **Pratik Rath**, PhD student **Hugo Marrochio**, and postdoctoral researcher **Shira Chapman**. Last year, with Visiting Graduate Fellow **Ro Jefferson**, he decided to test Susskind et al.'s conjecture directly, by providing the first calculations of computational complexity in a quantum field theory. This allowed for a comparison with the holographic calculations. Their simple model showed remarkable similarities with certain aspects of holographic complexity that Myers and co-authors had found earlier. It pointed to the correctness of the conjecture, and has opened up a new path to understanding computational complexity in quantum field theory.

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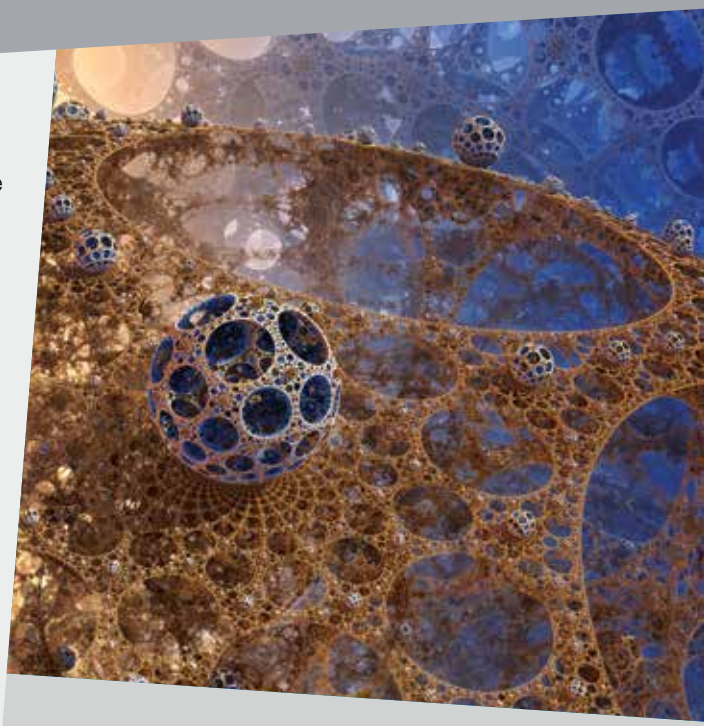

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(cross-appointed with other institutions)

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Avery Broderick, Delaney Family John Archibald Wheeler Chair in Theoretical Physics (University of Waterloo)

Alex Buchel (Western University)

Raffi Budakian (Institute for Quantum Computing (IQC)/University of Waterloo)

Cliff Burgess (McMaster University)

David Cory (IQC/University of Waterloo)

Matthew Johnson (York University)

Raymond Laflamme (IQC/University of Waterloo)

Sung-Sik Lee (McMaster University)

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Ben Webster (University of Waterloo)

Jon Yard (University of Waterloo)

NEW LIGHT ON OLD PROBLEMS

When physics talks to mathematics, great things happen.

Newton invented calculus as a mathematical language to express his theories of motion – and calculus went on to remake mathematics. Riemann's mathematical theory of curvature turned up in Einstein's theory of relativity almost a century later. The development of quantum theory in the 20th century both spurred and was spurred by advances in mathematical fields such as linear algebra and functional analysis. In the early 1960s, American physicist Murray Gell-Mann used the math principles of group theory to organize what was then called "the particle zoo," and to predict the existence of quarks.

Perimeter's work in mathematical physics is part of that grand tradition. Researchers sometimes work to produce mathematical tools to build new physical understandings. They sometimes use physics as a lens through which to view mathematics and spur mathematical progress.

If, as Galileo wrote, the book of nature is written in the language of mathematics, then Perimeter researchers are hard at work on the translation.

A TALE OF TWO BRIDGES

There was once a Canadian who revolutionized mathematics. In 1967, Robert Langlands discovered mathematical bridges that link number theory with harmonic analysis with geometry. Mathematicians were astonished: these fields are so far apart it was as if Langlands had discovered bridges linking different planets. Physicists took interest too: some believe that Langlands' bridges could be used to connect the two great planets of physics – quantum field theory and general relativity – into a unified whole.

There is a problem with Langlands' bridges, though: while they have worked in every case tested, mathematicians cannot prove that they will always work. The vast effort to prove Langlands' conjectures goes by the name of the "Langlands program."

For 10 years, **Davide Gaiotto**, the Krembil Galileo Galilei Chair in Theoretical Physics at Perimeter Institute, has been at work on a piece of the Langlands program. He is attempting to prove that one of Langlands' bridges, known technically as the geometric Langlands duality, will always stand. He's been doing that by comparing it to another bridge, the S-duality from supersymmetric gauge theory.

The idea that the S-duality bridge and the geometric Langlands bridge might be related was not Gaiotto's: Anton Kapustin and Edward Witten proposed it in 2006. Gaiotto's work has been to make the relation between the two bridges explicit, and to use gauge theory ideas to clarify and ultimately prove the geometric Langlands duality. This year, with help from PhD student **Miroslav Rapcak**, he finally succeeded.

This is work at the cutting edge of mathematical physics, so naturally it is difficult to summarize, but the advantage of Gaiotto's approach boils down to this: the S-duality bridge is a theory in physics. Physical intuition can be used to guide and organize the calculations. If a certain direction of mathematical argument makes no physical sense, it can be ruled out.

"This is a case where quantum theory is giving something new and interesting to the mathematicians," says Gaiotto. "Just using gauge theory, I ended up producing the same path to a proof that mathematicians working on the geometric Langlands program had already been following, but with some extra insights that I think will allow them to complete the proof at last."

Who knows where that bridge will take us?

USEFULNESS AND BEAUTY

It's odd but it seems to be true – when it comes to mathematics, the more beautiful a thing is, the more useful it is likely to be.

By that standard, Penrose tilings ought to be useful. Like familiar tilings of bricks in a basketweave or hexagons in a honeycomb, Penrose tilings use a couple of simple shapes to completely fill a

plane. But unlike these tilings, Penrose's simple shapes never form a repeating pattern. To the pattern-seeking human eye, Penrose tilings are mesmerizing.

And they did indeed lead to deeper mathematics, including the discovery of Ammann grids, in which Penrose tilings are described in terms of sets of irregularly spaced parallel lines. They even drove some progress in physics. For instance, if you place one atom at every vertex of a Penrose tiling, you get an exotic state of matter known as a quasicrystal: a discovery so significant that it was the basis for the 2011 Nobel Prize for Chemistry.

The useful beauty of these structures has long fascinated Perimeter Faculty member **Latham Boyle**. This year, working with **Paul Steinhardt**, the Daniel Family Richard P. Feynman Chair in Theoretical Physics (Visiting), Boyle completed a years-long quest to find every possible Ammann grid.

They started from the bottom, finding the 10 one-dimensional Ammann grids, and proving mathematically that only 10 exist. These 10 lattices are the building blocks from which all higher dimensional Ammann grids are made.

Now able to construct Ammann grids at will, the pair began exploring them. "We discovered a beautiful higher-dimensional geometrical picture that explains where the remarkable properties of the Ammann grid come from," says Boyle. It's as if a trigonometry student who'd been studying parabolas and ellipses and other figures created by slicing a cone with a plane suddenly discovered the cone.

From there, Steinhardt and Boyle were able to show that only a small number of Ammann grids exist: a handful in two dimensions, a handful in three, one in four, and none at all in higher dimensions. They also built new Penrose-like tilings for the new 2D Ammann grids. Some were previously known; most were not.

These mathematical results have physical implications. For instance, Boyle has a forthcoming paper about using these new mathematical tools to describe scale-invariant systems, like the conformal field theories that are central to modern physics. But he doubts the applications will stop there. "I think they are the beautiful and natural mathematical structures that are bound to still have many other, unanticipated applications," he says.

In short, the newly discovered patterns are beautiful. So they may well turn out to be useful, too.

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A NEW GOLDEN AGE: READING SIGNALS FROM THE COSMOS

The 2015 detection of gravitational waves was described by many scientists – even those not typically prone to hyperbole – as the "discovery of the century."

The phrase was apt not only because the detection confirmed a prediction made by Albert Einstein a century earlier, but because it marked a turning point that is expected to drive much of 21st-century astrophysics.

It could also be said that the discovery was 1.3 billion years in the making. That's how long gravitational waves, created by two colliding black holes, rippled the fabric of spacetime before passing through the ultra-sensitive detectors of LIGO, the Laser Interferometer Gravitational-Wave Observatory.

The ability to detect and measure gravitational waves is an advance comparable to how the original telescope enabled us to see further than was possible with the naked eye.

The detection opened a new era of astrophysics. As more gravitational wave detectors come online in the next few years, scientists will be able to glean increasingly rich information about the universe around us. Gravitational waves may even lead researchers to the next great scientific theory.

For some researchers, the most exciting prospect is that gravitational wave astronomy may help us put Einstein's theory of general relativity to the ultimate test; for others, gravitational waves may allow us to peer beyond the light-trapping plasma soup of the early universe and see the moment it all began, the big bang.

THE ORIGIN OF EVERYTHING

For Perimeter Institute Director **Neil Turok**, that latter possibility is especially tantalizing.

The conventional picture of the big bang holds that the universe began with a singularity – a single point, taking up no space at all, from which the entire universe and everything in it burst into existence. That picture is problematic, because it posits an "impossibility," namely an event where the laws of physics don't apply.

Turok and collaborators have been developing an alternate scenario in which the big bang is a natural intermediate state in a smoothly evolving universe. What makes this scenario feasible is quantum physics, according to which things that are classically impossible become possible.

In a paper published in *Physical Review Letters*, Turok and Perimeter postdoctoral researcher **Steffen Gielen** point out that the stuff present in the early universe – high-energy radiation and matter – was to a first approximation conformal, meaning that it does not depend on scale. How, they asked, would such a universe behave through the lens of quantum mechanics? Remarkably well, it turns out.

By exploiting the fact that quantum behaviour involves complex numbers – numbers including the imaginary number *i* – Turok and Gielen demonstrated that a universe described in such terms could pass smoothly across a big bang singularity, emerging safely on the other side. They term this a "perfect bounce" and are now developing it as a new and more complete theory of the big bang.

While the idea of a big bounce is not new (Turok has been a leading proponent of cyclical cosmology for more than a decade), the recent work with Gielen has simplified the picture and brought it closer to completeness.

While the development of these ideas is largely theoretical and mathematics-based, at present, there are exciting future prospects of using gravitational wave astronomy to look back to the earliest moments of the big bang and so check (and hopefully verify) the theory.

DISCERNING THE GENTLE STRAINS OF BLACK HOLE COLLISIONS

For Deputy Faculty Chair **Luis Lehner**, the detection of gravitational waves opens other intriguing possibilities, including the ability to put Einstein's theory of general relativity to the ultimate test.

With several gravitational wave detectors now available (and more coming online in quick succession), it is possible to detect, with increasingly precise sensitivity and localization, both gravitational

waves and their electromagnetic counterparts. Lehner's research aims to produce reliable predictions for detectors to use in search of such signals, and to maximize the amount of information that can be gleaned from those signals to test general relativity – a theory that is incredibly robust but also known to be incomplete.

Lehner and colleagues realized that within the so-called "ringdown" of black hole mergers (a cascade of signals from the event), they could search the less-dominant signals to put general relativity to a very strong test.

Waves are created before, during, and after a pair of black holes careen into one another. If the resulting black hole has no "hair" (that is, no distinguishing traits other than its mass, spin, and charge), the ringdown signals should provide a trove of data.

Lehner, with Perimeter Distinguished Visiting Research Chair **Frans Pretorius** and **Huan Yang** of Princeton (an incoming Perimeter associate faculty member with the University of Guelph), proposed a method to seek specific signals within the ringdown to glean detailed information about the behaviour of the black hole and, by extension, about general relativity.

Currently, the only ringdown data available from black hole mergers is the "loudest" mode, which have too low a signal-to-noise ratio to provide sufficient information for testing general relativity.

But the researchers believe gravitational wave detectors such as Advanced LIGO and other finely tuned experiments will, with enough precision, measure secondary modes in the ringdowns over the course of a year, providing sufficient data to test (and, perhaps one day, even replace) general relativity.

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S. Gielen (Imperial College London) and N. Turok (PI), "Quantum Propagation across Cosmological Singularities," *Phys. Rev. D* 95, 103510 (2017).

H. Yang (Princeton University), K. Yagi (Princeton University), J. Blackman (California Institute of Technology), L. Lehner (PI), V. Paschalidis (Princeton University), F. Pretorius (Princeton University), and N. Yunes (Montana State University), "Black Hole Spectroscopy with Coherent Mode Stacking," *Phys. Rev. Lett.* 118, 161101 (2017).

THE CENTRE FOR THE UNIVERSE

Our cosmos is revealing itself as never before through cutting-edge instruments like gravitational wave detectors, linked telescope arrays, and space-based probes. It's a golden scientific opportunity and, to take advantage of it, Perimeter recently created the **Centre for the Universe at Perimeter Institute**.

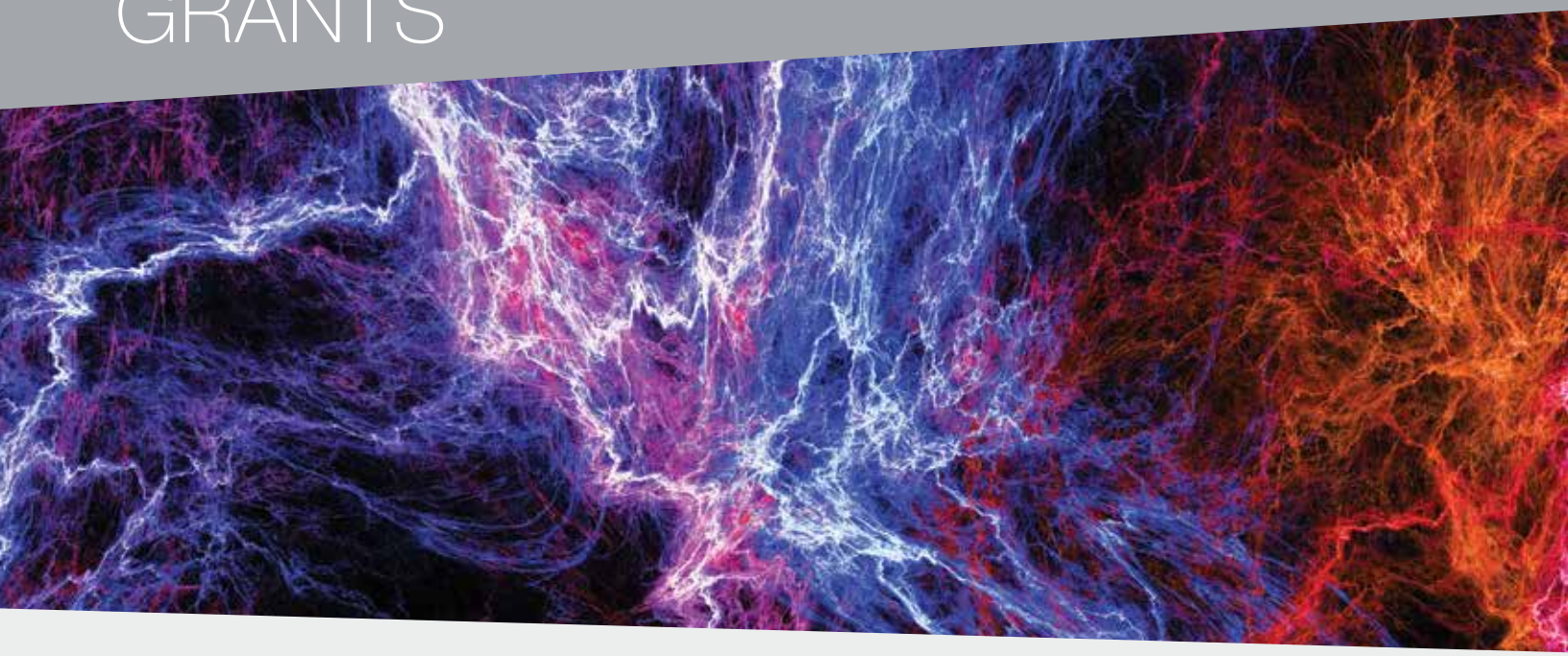
Supported by an anonymous $5 million founding donation, to be matched by a similar contribution from Perimeter's endowment, the Centre will assemble a mix of eminent international scientists and rising stars to tackle questions about black holes, the big bang, dark matter, dark energy, and other big challenges in cosmology. The Centre will be led by Perimeter's Director, Neil Turok.

Through partnerships with the Canadian Institute for Theoretical Astrophysics (CITA) and the Dunlap Institute at the University of Toronto, the University of Waterloo, Queen's University, SNOLAB, the University of Guelph, and York University, the Centre for the Universe will support leading-edge data analysis and concept development of experiments, as well as new theoretical paradigms and methods.

"Cosmology is one of the most exciting fields in science today. We are on the verge of major discoveries about the universe and its origins. I hope and expect many of those discoveries will be made at Perimeter."

– Stephen Hawking, Perimeter Distinguished Visiting Research Chair

HONOURS, AWARDS, AND MAJOR GRANTS



- **Asimina Arvanitaki**, the Stavros Niarchos Foundation Aristarchus Chair in Theoretical Physics, and Distinguished Visiting Research Chair **Frans Pretorius** were each among the winners of the 2017 New Horizons in Physics Prize.
- Distinguished Visiting Research Chair **Andrew Strominger** won the 2017 Breakthrough Prize in Fundamental Physics.
- Associate Faculty member **Raymond Laflamme** was awarded the 2017 CAP-CRM Prize in Theoretical and Mathematical Physics by the Canadian Association of Physicists and the Centre de recherches mathématiques.
- **Kevin Costello**, the Krembil William Rowan Hamilton Chair in Theoretical Physics, won the Berwick Prize of the London Mathematical Society.
- **Neil Turok**, Perimeter Director and Mike and Ophelia Lazaridis Niels Bohr Chair, was named an Honorary Fellow of the Institute of Physics.
- Distinguished Visiting Research Chair **Xiao-Gang Wen** was awarded the 2017 Oliver E. Buckley Condensed Matter Physics Prize of the American Physical Society.
- **Neil Turok** was awarded the 2017 John Wheatley Award of the American Physical Society for his work developing centres of excellence in science and math through the African Institute for Mathematical Sciences – Next Einstein Initiative.
- Visiting Fellow **Simon Caron-Huot** won the 2017 Gribov Medal of the European Physical Society.
- Distinguished Visiting Research Chair **Nathan Seiberg** was awarded the 2016 Dirac Medal of the Abdus Salam International Centre for Theoretical Physics.
- Distinguished Visiting Research Chair **Sandu Popescu** was elected as a Fellow of the Royal Society (UK).
- For the third year in a row, Faculty Chair **Robert Myers** was recognized on the "Highly Cited Researchers" list compiled by Thomson Reuters' Intellectual Property and Science division (now Clairvate Analytics), a measure of some of the world's most influential scientific minds. Distinguished Visiting Research Chair **Juan Ignacio Cirac** was also on the 2016 list, his second straight appearance.

- Postdoctoral researcher **Elliot Nelson** was awarded second prize in the 2016 Buchalter Cosmology Prize competition of the American Astronomical Society, while Associate Faculty member **Cliff Burgess** and his colleagues won third prize.
- Nine Perimeter-authored papers were named "Highlights of 2016": three papers in the *Journal of Physics A: Mathematical and Theoretical*, three in the *New Journal of Physics*, two in *Classical and Quantum Gravity*, and one in *Journal of Physics: Condensed Matter*.
- Perimeter scientists were awarded more than **$3.5 million** in research grants from agencies including the Natural Sciences and Engineering Research Council of Canada, the John Templeton Foundation, and the Simons Foundation.

A TOP DESTINATION FOR EMERGING STARS

The New Horizons in Physics Prize, awarded by the Milner Foundation, recognizes young scientists who have done ground-breaking work early in their careers. Established in 2012, it has become one of the most prestigious and widely watched markers of rising stars in science.

In 2017, **Asimina Arvanitaki**, the Stavros Niarchos Foundation Aristarchus Chair, became Perimeter's fifth winner in the prize's five-year history. Stanford has four. Princeton has three. No other institution in the world has won in multiple years.

Arvanitaki seeks to identify the ultimate constituents of matter, which has traditionally been done by smashing particles together at high energies at particle accelerators. Arvanitaki has pioneered a complementary approach, using new technologies to devise small-scale experiments.

"We are seeking to probe fundamental physics in ways that would not have been possible even 10 years ago," she explains. "This award indicates that we are on the right track, with the potential to obtain important results with low-cost experiments on even-shorter time scales."

Arvanitaki is emblematic of the young researchers that Perimeter has become known for attracting: creative yet rigorous, and able to seize opportunities that others may have missed.

RECRUITMENT

PI BY THE NUMBERS

Perimeter is the world's largest theoretical physics community:

21 faculty, including eight Perimeter Research Chairs

16 associate faculty cross-appointed with partner universities, including one Perimeter Research Chair

54 Distinguished Visiting Research Chairs

34 Visiting Fellows

59 postdoctoral researchers

77 graduate students[1]

[1] This includes 49 PhD students, 27 Perimeter Scholars International (PSI) master's students, and one additional master's student. All numbers reflect the Perimeter community as of July 31, 2017.

At Perimeter, great questions and new ideas are prized over hierarchy. On any given day, a postdoctoral researcher can walk into the Black Hole Bistro, sit down with one of the luminaries in their field and a PhD student, and spark up an exciting new collaboration. Perimeter's vibrant, collaborative community comprises the world's largest independent centre for theoretical physics, and it continues to grow.

PERIMETER RESEARCH CHAIRS

Named for legendary scientists whose insights helped define physics, Perimeter Research Chairs are scientific trailblazers. This year, the Institute appointed two new Perimeter Research Chairs: astrophysicist **Avery Broderick** as the Delaney Family John Archibald Wheeler Chair in Theoretical Physics, supported by the Delaney Family, and particle physicist **Savas Dimopoulos** as the Archimedes Chair in Theoretical Physics (Visiting).

Broderick is a world leader in the analysis of astrophysical data and a key member of the international Event Horizon Telescope collaboration, engaged in a historic effort to produce the first-ever image of a black hole. He joined Perimeter as an associate faculty member in 2011 and continues to split his time between the University of Waterloo and Perimeter, where he will play a crucial role in developing the new Centre for the Universe (see page 17).

Dimopoulos, a giant in the field of particle physics, seeks to understand the fundamental constituents of matter. In his four decades of research, he has

originated many of the theoretical ideas that guide the field. His appointment as Archimedes Chair (Visiting) brings him to Perimeter for four months per year, while allowing him to retain his faculty position at Stanford University.

The Institute now has nine Perimeter Research Chairs, with more expected in the coming years.

FACULTY

In addition to the Perimeter Research Chairs, Perimeter recruited four rising stars to join its faculty.

Neal Dalal will join Perimeter's faculty in October 2017, from the University of Illinois at Urbana-Champaign, where he has been an Assistant Professor since 2011. 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

DISTINGUISHED VISITING RESEARCH CHAIRS

Scott Aaronson, University of Texas at Austin
Yakir Aharonov, Chapman University and Tel Aviv University
Nima Arkani-Hamed, Institute for Advanced Study
Abhay Ashtekar, Pennsylvania State University
Leon Balents, University of California, Santa Barbara
James Bardeen, University of Washington
Itzhak Bars, University of Southern California
Ganapathy Baskaran, Institute of Mathematical Sciences, Chennai
Charles Bennett, IBM Thomas J. Watson Research Center
Patrick Brady, University of Wisconsin-Milwaukee
Alessandra Buonanno, Max Planck Institute for Gravitational Physics (Albert Einstein Institute) and University of Maryland, College Park
John Cardy, University of California, Berkeley, and University of Oxford
Juan Ignacio Cirac, Max Planck Institute of Quantum Optics
Lance Dixon, Stanford University
Matthew Fisher, University of California, Santa Barbara
Dan Freed, University of Texas at Austin
Katherine Freese, University of Michigan
S. James Gates Jr., Brown University
Gabriela González, Louisiana State University
Duncan Haldane, Princeton University
Stephen Hawking, University of Cambridge
Patrick Hayden, Stanford University
Joseph Incandela, University of California, Santa Barbara
Ted Jacobson, University of Maryland, College Park
Shamit Kachru, Stanford University
Anton Kapustin, California Institute of Technology
Adrian Kent, University of Cambridge
Renate Loll, Radboud University, Nijmegen
John March-Russell, University of Oxford
Matilde Marcolli, California Institute of Technology
Joel Moore, University of California, Berkeley
Ramesh Narayan, Harvard University
Sandu Popescu, University of Bristol
Frans Pretorius, Princeton University
Nathan Seiberg, Institute for Advanced Study
Peter Shor, Massachusetts Institute of Technology
Iakov (Yan) Soibelman, Kansas State University
Dam Thanh Son, University of Chicago
Paul Steinhardt, Princeton University
Andrew Strominger, Harvard University
Raman Sundrum, University of Maryland, College Park
Leonard Susskind, Stanford University
Gerard 't Hooft, Utrecht University
Barbara Terhal, RWTH Aachen University
Senthil Todadri, Massachusetts Institute of Technology
William Unruh, University of British Columbia
Frank Verstraete, University of Vienna and University of Ghent
Ashvin Vishwanath, Harvard University
Zhenghan Wang, Microsoft Research Station Q
Xiao-Gang Wen, Massachusetts Institute of Technology
Steven White, University of California, Irvine
Mark Wise, California Institute of Technology
Matias Zaldarriaga, Institute for Advanced Study
Alexander Zamolodchikov, Stony Brook University

matter using cosmological data. Dalal is the first faculty member hired as part of the new Centre for the Universe.

Beni Yoshida joined Perimeter's faculty in July 2017, having previously spent three years as a Burke Fellow at the Institute for Theoretical Physics at the California Institute of Technology. His interdisciplinary work focuses on topological order and quantum chaos, with implications for quantum information theory, condensed matter, string theory, and black holes. (Refer to page 11 for a highlight of Yoshida's recent work.)

In the spring of 2018, Yoshida will be joined by **Yin-Chen He** and **Timothy Hsieh**. Currently a Gordon and Betty Moore Fellow at Harvard University, He is a condensed matter researcher interested in spin liquids, topological phases, and numerical simulations. Hsieh will join Perimeter from the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara; his research explores quantum materials, entanglement, and dynamics.

Together, these three exceptional young researchers will lead Perimeter's Quantum Matter Initiative, seeking to advance research at the intersection of condensed matter physics, quantum information, quantum gravity, and string theory.

ASSOCIATE FACULTY

Since day one, Perimeter has partnered with the surrounding academic community to attract leading scientists to Canada. Through these joint appointments, both partners get the benefits of great research and rapid pollination of ideas. This year, several new appointments brought exceptional scientists north from established careers in the United States.

Jon Yard arrived from Microsoft Research in September 2016, jointly appointed with the Institute for Quantum Computing and the Department of Combinatorics and Optimization at the University of Waterloo. Yard brings expertise in several areas of growing strength at Perimeter, including quantum information, mathematical fields, quantum fields, and condensed matter.

In July 2017, **Ben Webster** began a joint appointment with the University of Waterloo after holding faculty positions at the University of Virginia, Northeastern University, and the University of Oregon. He strengthens Perimeter's expertise in mathematical physics, algebraic geometry, and representation theory.

Matilde Marcolli accepted a joint appointment with the University of Toronto and will arrive in January 2018, after a decade as a Professor of Mathematics at the California Institute of Technology. She is a mathematical physicist whose work has applications to several areas of research focus at Perimeter, including particle physics, quantum gravity, and cosmology.

DISTINGUISHED VISITING RESEARCH CHAIRS

Perimeter is the second research home of more than 50 of the top physicists in the world. Distinguished Visiting Research Chairs (DVRCs) are appointed to renewable three-year terms and make extended research visits to Perimeter, while retaining permanent positions at their home institutions.

This unique program widens Perimeter's scientific community to include a considerable fraction of the field's leading lights. DVRCs participate in all facets of life at the Institute – from giving seminars and organizing conferences to collaborating with colleagues and participating in outreach activities. DVRCs report that time spent at Perimeter is highly productive; they are exposed to a diverse array of new ideas while free from their usual teaching and administrative duties.

This year, Perimeter appointed six new DVRCs and renewed seven more, bringing the total to 54 DVRCs spanning every branch of theoretical physics – including luminaries such as **Alessandra Buonanno**, **Duncan Haldane**, **Stephen Hawking**, and **Frans Pretorius**.

The Distinguished Visiting Research Chairs program is supported by Cenovus Energy.

VISITING FELLOWS

The Visiting Fellows program is another way that Perimeter engages with the wider scientific community while diversifying its own, bringing highly promising researchers to the Institute for regular visits. Like DVRCs, Visiting Fellows are appointed to renewable terms, retain their positions at home institutions, and enrich Perimeter's research environment during extended research stays.

This year, Perimeter appointed seven new Visiting Fellows and renewed three more, bringing the total to 34 Visiting Fellows spanning a wide range of expertise.

POSTDOCTORAL RESEARCHERS

Tackling some of the most challenging problems in physics requires creativity and fresh perspectives, which makes early-career scientists uniquely equipped to help push the field forward. That's why Perimeter hosts the world's largest community of independent postdoctoral researchers in theoretical physics, and provides them with complete research freedom.

Perimeter is known internationally as a place where ambitious scientists can do career-defining work. This year, 24 new postdocs joined Perimeter, with 19 more recruited for next year. As full members of the research community, postdocs can invite collaborators, organize conferences, and present work internationally. This experience pays off: in an extremely competitive international academic market, 13 departing postdoctoral researchers obtained tenure-track faculty positions in 2016/17.

BENI YOSHIDA: AT HOME IN THE INTERSECTIONS

As a youngster, **Beni Yoshida** was predisposed to hands-on experiments rather than theory. Unfortunately, he wasn't very good at them.

"I was very bad at building instruments. I did experiments when I was an undergrad and I broke lots of instruments," Yoshida recalls. "It was a disaster."

He did, however, have a knack for mathematical problem solving. The compromise between Yoshida's proclivities and his passions was theoretical physics. He did his PhD at MIT under the supervision of quantum information pioneers Edward Farhi and Peter Shor. What would typically be the start of a specialty became a stepping-stone: during his grad studies and first postdoc, at Caltech, Yoshida took an unconventional turn, using quantum information theory to study condensed matter physics. Later, he added a new interest: quantum gravity.

Now a faculty member at Perimeter, Yoshida finds it natural to work at the intersection of seemingly disparate fields.

In physics, he says, many difficult open questions remain. "There are reasons why they are being left as open questions: because the existing methods didn't work," he says. "By borrowing ideas or inventing new concepts inspired by other fields, we can often make very important progress."

TRAINING THE NEXT GENERATION

PSI FACULTY, 2016/17

James Forrest (Director), Perimeter Institute and University of Waterloo

Tibra Ali, Perimeter Institute

Stephen Bartlett, University of Sydney

Richard Cleve, Institute for Quantum Computing (IQC)/University of Waterloo

David Cory, Perimeter Institute and IQC/University of Waterloo

Kevin Costello, Perimeter Institute

François David, Institute of Theoretical Physics/CEA-Saclay

Maité Dupuis, Perimeter Institute

Davide Gaiotto, Perimeter Institute

Jaume Gomis, Perimeter Institute

Ruth Gregory, Durham University

David Kubiznak, Perimeter Institute

Matthew Leifer, Chapman University

Debbie Leung, IQC/University of Waterloo

Frank Marsiglio, University of Alberta

Eduardo Martin-Martinez, IQC/University of Waterloo

Michele Mosca, Perimeter Institute and IQC/University of Waterloo

Kevin Resch, IQC/University of Waterloo

Kendrick Smith, Perimeter Institute

Sean Tulin, York University

Neil Turok, Perimeter Institute

Guifre Vidal, Perimeter Institute

Pedro Vieira, Perimeter Institute

Dan Wohns, Perimeter Institute

Gang Xu, Perimeter Institute

PERIMETER SCHOLARS INTERNATIONAL

Brilliant young minds are the lifeblood of science. Since the Institute created Perimeter Scholars International (PSI) in 2009, it has become one of the most sought-after master's programs in theoretical physics worldwide. This year, 561 applicants vied for fewer than 30 spots in the intense one-year program and, among students Perimeter made an offer to, the acceptance rate was higher than Harvard or Stanford.

At PSI, students are exposed to the full spectrum of the field, while learning skills that will serve them well in academia and beyond – such as independent thinking and computer-based model development. The innovative curriculum emphasizes problem solving over rote learning and collaboration over competition. Run in partnership with the University of Waterloo, graduating students receive a master's degree from Waterloo and a PSI certificate from Perimeter.

In 2016/17, PSI trained 27 students, including seven women, from 20 countries. Sixteen graduates have remained in Canada for their doctoral studies, 14 of them at Perimeter. Many others went on to top international institutions, including Harvard University, Princeton University, and the Massachusetts Institute of Technology. Applications for 2017/18 rose nine percent, and an outstanding incoming class has been selected, comprising 31 students from 22 countries, including 14 women.

The PSI program was generously supported in 2016/17 by: Burgundy Asset Management; The Hellenic Heritage Foundation; The Ira Gluskin and Maxine Granovsky Gluskin Charitable Foundation; Maplesoft; Brad and Kathy Marsland; Margaret and Larry Marsland; The Savvas Chamberlain Family Foundation; and members of the Emmy Noether Circle.

"My experience has been very enlightening. I have gotten to meet people that I normally just read about in books, like Lee Smolin. It's a very surreal experience…. It is my hope that in the future, more African students can experience this great institute just as I have had the good fortune to experience."

– Eugene Adjei, 2016/17 PSI student

PHD STUDENTS

Many PSI students continue on to doctoral studies with Perimeter faculty. Perimeter's PhD program continues to bring top students not only to Perimeter, but also to the Canadian partner universities where they ultimately receive their degrees. Students are trained in a world-class research environment, with unparalleled opportunities to interact with scientific leaders. They are encouraged to do original research, jump-starting their careers within a supportive, collaborative environment. Students develop a unique and valuable skill set that includes advanced analytical, problem-solving, and quantitative skills, and graduates have gone on to successful careers in academia, government, technology, and finance.

Nine PhD students supervised by Perimeter faculty graduated from partner universities in 2016/17. At year's end, Perimeter had 49 PhD students in residence, with an additional 11 PhD students supervised by Perimeter associate faculty while in residence at partner universities.

In 2016/17, three PhD students were the recipients of the following awards: the Joanne Cuthbertson and Charlie Fischer Graduate Student Award, the Ira Gluskin and Maxine Granovsky Gluskin Charitable Foundation Honorary Scholarship Award, and the Peter and Shelagh Godsoe Family Foundation Exceptional Emerging Talent Award.

VISITING GRADUATE FELLOWS

Since 2011, Perimeter's Visiting Graduate Fellows program has provided an avenue for PhD students from around the world to make extended visits to the Institute, interacting with leading researchers at a pivotal time in their training. These young researchers both benefit from – and contribute to – the Institute's dynamic research environment. In 2016/17, Perimeter hosted 32 Visiting Graduate Fellows for a total of 39 visits, with continued growth expected in the coming year.

"One always needs to think very deeply when they are trying to create something new. You always base your creations on something, on your ideas from before, and you need to identify these ideas very precisely and understand where they come from. That's my goal, and that's probably a lifelong challenge – to really understand where all my ideas come from and how reliable they are. That's part of being a physicist.'"

– Barbara Šoda, 2016/17 PSI student

CATALYZING RAPID PROGRESS

Participants at "PI day" conference

BY THE NUMBERS

In 2016/17, Perimeter ...

Held 20 conferences and workshops, attended by 867 scientists from around the world

Presented 308 scientific talks (267 seminars and 41 colloquia)

Partnered on five joint workshops and conferences held at Perimeter, and sponsored an additional 14 off-site workshops and conferences (nine in Canada)

CONFERENCES AND WORKSHOPS

The current era of physics is defined by collaboration. The most exciting advances from particle physics to cosmology are coming out of large-scale efforts like the Large Hadron Collider and the Laser Interferometer Gravitational-Wave Observatory.

Collaboration on cutting-edge science also lies at the heart of Perimeter's renowned conference program. Each year, the Institute brings together hundreds of researchers to tackle some of the toughest problems facing the field. Conferences focus on leading-edge topics with the potential for significant outcomes, and the program's reputation allows the Institute to attract the top thinkers in the chosen subjects. Because the program is highly flexible, Perimeter often hosts workshops on topics that have yet to be addressed anywhere else.

In 2016/17, 867 scientists from around the world attended 20 conferences and workshops here, with all proceedings recorded and available online.

SEMINARS AND COLLOQUIA

Large conferences are not the only means of encouraging a vibrant exchange of ideas at Perimeter. Seminars and colloquia given by resident and visiting scientists are an essential element of the Institute's intellectual life, sharing pioneering research as it happens, challenging established modes of thought, and fostering collaboration across fields.

In the past year, Perimeter hosted 308 scientific talks (267 seminars and 41 colloquia). Talks were given by a number of luminaries from across the Institute's areas of research focus, including Distinguished Visiting Research Chairs **Abhay Ashtekar**, **John Cardy**, **Katherine Freese**, and **Andrew Strominger**.

PHYSICS TALKS ONLINE

Almost all scientific talks at Perimeter are recorded and can be viewed for free in the Video Library section of Perimeter's website or through the Perimeter Institute Recorded Seminar Archive (PIRSA) at pirsa.org. This searchable and citeable archive of over 11,000 seminars, conferences, workshops, and courses was developed by the Institute to share knowledge with the international scientific community, and has become the leading online institutional video archive in theoretical physics.

In 2016/17, Perimeter's video archive was accessed by 108,966 unique visitors from more than 190 countries, accounting for 894,217 page views.

A GLOBAL LEADER

"This is probably one of the most convivial places I have ever been. You don't have to rush around; people don't bother you if you don't want to be, but if you want to be bothered, you find people to talk to. It's just a remarkable place."

– Rainer Weiss, 2017 Nobel Laureate

Perimeter researchers are working on some of the most difficult problems in physics, so it's crucial that they not only collaborate with one another, but also with the broader international community. Leaving large segments of the world population out of the conversation does everyone a disservice.

Perimeter aims to encourage, and benefit from, this much-needed diversity of thought – both in-house, through the Institute's lively visitor and affiliate programs, and on national and international scales through productive institutional partnerships and global outreach. By strengthening bonds within the scientific community, Perimeter is precipitating the breakthroughs of the future.

VISITOR PROGRAM

It's hard to run out of people to talk to at Perimeter, thanks in large part to the Institute's active visitor program. With over 400 scientific visitors annually, resident scientists are constantly exposed to fresh perspectives, through seminar talks, chance encounters in the Black Hole Bistro, or planned collaboration visits.

Leading scientists from around the world come to Perimeter because they know they will have the time and space necessary to focus on research and initiate new collaborations. The program also aids recruitment by showcasing the Institute's unique and vibrant research environment.

In 2016/17, Perimeter hosted 406 visiting scientists for a total of 459 visits, including 17 Distinguished Visiting Research Chairs, 10 Visiting Fellows, and 10 Emmy Noether Visiting Fellows. The rest were short-term visitors, including affiliates, collaborators, seminar and colloquia speakers, and potential recruits. In the past year, visits to Perimeter ultimately led to new appointments at all levels – including Faculty members **Yin-Chen He** and **Timothy Hsieh**, and Associate Faculty member **Ben Webster**.

AFFILIATES

Perimeter's Affiliate program brings select researchers from universities and research institutes across Canada to Perimeter for regular informal visits. The program enriches both Perimeter and the national physics community; affiliates gain access to the Institute's research community, while Perimeter deepens its connections to more than 25 of Canada's top research centres. In 2016/17, Perimeter appointed eight new affiliates and renewed 15 more through 2019, bringing the total community of affiliates to 120. (Refer to page 66 for a complete list.)

COLLABORATIONS AND PARTNERSHIPS

By partnering with leading centres in Canada and abroad, Perimeter provides collaboration opportunities to its scientists while strengthening its position as a global research hub.

In 2016/17, Perimeter signed a new partnership to promote scientific exchanges with the Vienna-based Institute for Quantum Optics and Quantum Information (IQOQI) of the Austrian Academy of Sciences, and strengthened several existing partnerships, including those with TRIUMF and SNOLAB.

Having completed its initial five-year term, the Fields-Perimeter Institute Africa Postdoctoral Fellowship with the Fields Institute for Research in Mathematical Sciences was renewed through 2022, with the African Institute for Mathematical Sciences – Next Einstein Initiative (AIMS-NEI) formally joining the partnership. The one-year postdoctoral fellowships will continue to be available to African nationals who have recently completed their PhDs, jointly funded by Fields and Perimeter, with AIMS-NEI assisting in identifying candidates.

With the founding of the Centre for the Universe, Perimeter will also bolster ties with a number of experimental and observational facilities to which the Institute has previously been linked through its faculty – such as the Event Horizon Telescope (EHT), Square Kilometre Array (SKA), and Canadian Hydrogen Intensity Mapping Experiment (CHIME).

GLOBAL OUTREACH

Perimeter Institute aims to catalyze the growth of emerging scientific centres of excellence around the world by providing expertise and guidance, acting as a resource as they cultivate their own successes.

In 2016/17, Perimeter continued to provide support to its two primary global outreach partners: AIMS-NEI, a pan-African network of centres providing mathematical and scientific education to exceptional African graduates, and the South American Institute for Fundamental Research (SAIFR), an emerging centre of excellence in theoretical physics located at São Paulo State University (UNESP) in Brazil.

By encouraging joint scientific conferences and exchanges, Perimeter supports, and gains insights from, new voices in physics and mathematics. In the past year, Perimeter postdoctoral researcher **Prince Osei** moved to Rwanda to become the Project Developer of Quantum Leap Africa, a brand new information science and quantum technology hub created by AIMS, while more than a dozen Perimeter researchers, students, and educational outreach staff spent time at SAIFR.

In addition, Perimeter has ramped up efforts to share its expertise in educational outreach. Institute staff have worked with not only SAIFR, but a number of other partners to build programs akin to Perimeter's successful student and teacher camps – including the European Organization for Nuclear Research (CERN), Laser Interferometer Gravitational-Wave Observatory (LIGO), and the Brainport technology region in the Netherlands.

KENDRICK SMITH: THE EVENTUAL COSMOLOGIST

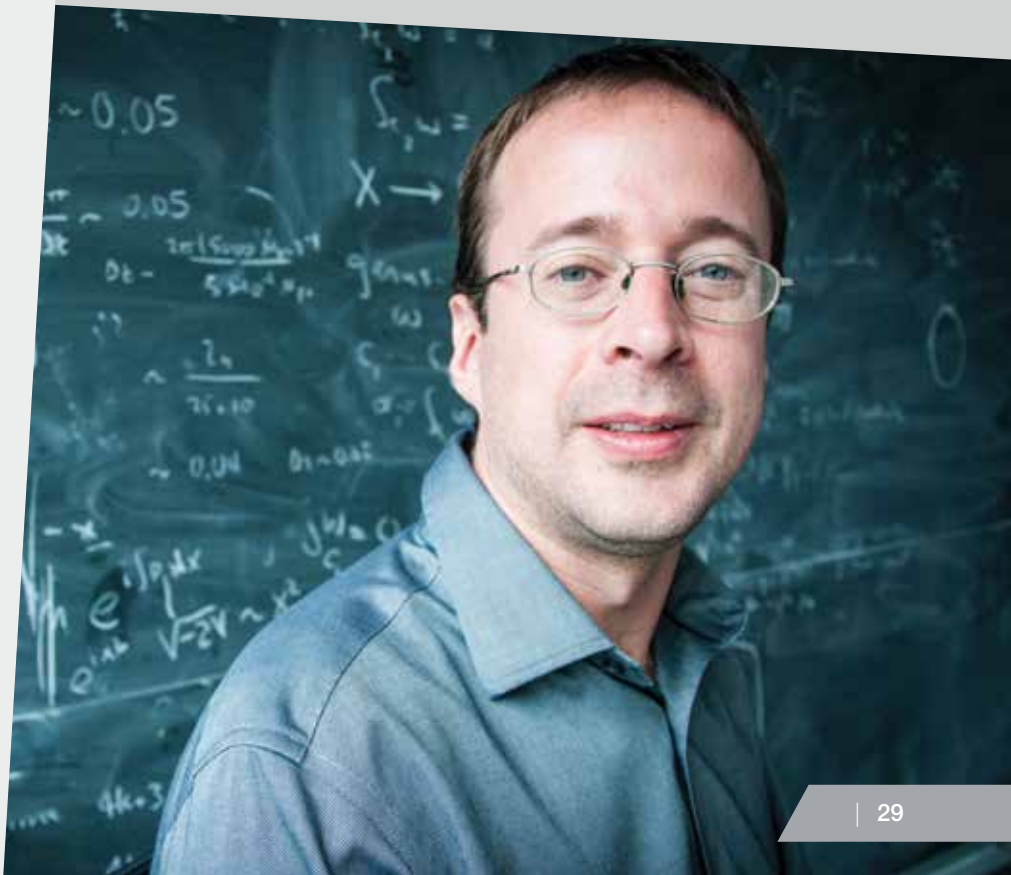
Perimeter Faculty member **Kendrick Smith** is in the vanguard of a new trend: data-driven cosmology. What was once a data-starved science is now grappling with data overflow as new experiments scrutinize the cosmos with unprecedented depth and breadth.

With PhDs in both mathematics and physics, plus time as a software developer, Smith can call upon a unique skill set to probe the fertile ground between theory and analysis.

Smith is Perimeter's link to one the most exciting new experiments in cosmology: the Canadian Hydrogen Intensity Mapping Experiment (CHIME) in British Columbia.

When CHIME comes online in late 2017, it is expected to generate torrents of data – and to detect hundreds of mysterious cosmic flickers known as "fast radio bursts." (In comparison, only 26 FRBs have been detected so far.) In fact, it's going to create too much data to store, so Smith has developed algorithms that will perform real-time analysis, essentially combing the sand as it slips through his fingers.

He's excited about what will emerge. "CHIME is really a big computer science problem disguised as a physics problem," he says. "It's going to be game-changing."



EDUCATIONAL OUTREACH AND PUBLIC ENGAGEMENT

"It was really interesting just to be in a place where ideas seem unlimited. This encouraged me to continue to pursue theoretical physics. It just opens my mind to what sort of research is possible at some point in my future."

– Isabel Sands, Moreland Hills, OH, ISSYP 2017 participant

BY THE NUMBERS

Facilitated nearly **10 million** student interactions through in-class resources and programs

Delivered **123** workshops to over **3,700** educators across Canada and abroad

Gave **11** Physica Phantastica presentations to over **825** Canadian students

Attracted over **875,000** YouTube video views

THE INTERNATIONAL SUMMER SCHOOL FOR YOUNG PHYSICISTS (ISSYP)

It's a summer experience that has catalyzed the careers of many budding scientists.

Perimeter's long-running International Summer School for Young Physicists immerses exceptional high schoolers from around the world in Perimeter's vibrant scientific community, challenging them to learn more than they thought possible in just two weeks.

Days are packed with talks from leading scientists, mentoring sessions, and field trips to cutting-edge experimental facilities like SNOLAB (a neutrino laboratory located deep in a Sudbury mine) and the Institute for Quantum Computing at the University of Waterloo – as well as plenty of time to argue about theories and ideas. Participants say that the real highlight is the friendships forged with other kids from around the world who share their passion for physics.

This year, Perimeter hosted the 15th edition of ISSYP, with 20 Canadians and 20 international students from 13 other countries, evenly split between young women and men.

The 2016/17 edition of ISSYP was made possible by the continued generous support of the RBC Foundation, ISSYP's Presenting Partner. Additional support was received from Maplesoft, Perimeter's Educational Outreach Champion.

EINSTEINPLUS

At EinsteinPlus, teachers from across Canada and around the globe connect with Perimeter's educational outreach team to find creative ways of igniting a passion for physics among their students. For teachers, the one-week summer workshop is an outstanding professional development opportunity, as they are introduced to Perimeter's educational resources and presented with effective, engaging methods for teaching key concepts in modern physics.

In 2017, Perimeter hosted 45 teachers: 23 Canadians and 22 international teachers spanning eight countries.

Support for EinsteinPlus was provided by Maplesoft, Perimeter's Educational Outreach Champion.

INSPIRING FUTURE WOMEN IN SCIENCE

Women are still underrepresented in STEM careers, but the tides are turning. That was one of the hopeful messages delivered at this year's edition of the "Inspiring Future Women in Science" conference, which brought nearly 200 young women in high school to Perimeter to connect with successful women at various stages of STEM careers. As part of Perimeter's Emmy Noether Initiatives, which seek to attract and retain more women in physics, the day-long conference featured keynote talks, a Q&A panel, and mentoring sessions.

Linamar Corporation was the Presenting Sponsor of the 2017 "Inspiring Future Women in Science" conference.

"Every day, I learned new things. Every day, every hour, I was thinking about, 'This is amazing. How can I bring this experience to my students?'"

– Rebecca Messer, Northfield High School, Northfield, MN, EinsteinPlus 2017 participant

PUBLIC LECTURE SERIES

With compelling talks on everything from black holes and mathematics to regenerative medicine and the physics of Wall Street, Perimeter's Public Lecture Series continues to be one of the Institute's most popular public outreach programs.

This year, Perimeter presented eight engaging talks to full-house crowds in the Mike Lazaridis Theatre of Ideas and to online audiences around the world. Highlights of the 2016/17 season included Amber Straughn discussing a new era in astronomy; Perimeter's own Michele Mosca on cutting-edge quantum technologies; and "The Truth is in the Stars: A Panel on Science and Creativity," which featured a screening of William Shatner's recent documentary and a panel discussion of the influence of *Star Trek*.

All lectures are professionally recorded, webcast live, and available for on-demand playback via Perimeter's website, YouTube, and media partners – including *Maclean's*, *Forbes*, *Scientific American*, and *The Guardian*. Online audiences can participate in real-time by asking questions and receiving answers from Perimeter outreach staff and researchers via Twitter. The 2016/17 season has amassed over 230,000 online views.

BMO Financial Group was the Presenting Sponsor of the 2016/17 Perimeter Public Lecture Series.

CULTURAL EVENTS

Creativity, inquiry, experiment, and contemplation – science and art are perhaps more alike than not. Cultural events at Perimeter, such as the Classical World Artists Series, are a welcome artistic complement to the Institute's research activities, and serve to broaden its connections to the community. This year, top-calibre artists delivered captivating performances in the Mike Lazaridis Theatre of Ideas, including the Chamber Music Society of Lincoln Center, Christian Tetzlaff and Lars Vogt, David Fray, and Angèle Dubeau and La Pietà.

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

DIGITAL AND SOCIAL MEDIA OUTREACH

Through its website, social media channels, and many partnerships, Perimeter shares news and big ideas from the forefront of science, aiming to be the leading source of accurate, fascinating, and shareable physics content online.

Last year, the Institute added another publishing platform dedicated to sharing the joy and power of science with the world. With the goal of contributing to a more scientifically engaged society, insidetheperimeter.ca is home to timely, in-depth physics articles; the *Inside the Perimeter* magazine archive; a library of more than 300 science videos (including Public Lectures and other webcasts); and the award-winning "Slice of PI" series, a monthly serving of fun science facts designed for social media sharing. Despite launching midway through the year, the site's accessible, engaging content was accessed by nearly 90,000 unique visitors, accounting for more than 175,000 page views.

Social media engagement continued its steady growth this year: Perimeter's Facebook fans increased 15 percent, while Twitter followers jumped by 20 percent. YouTube subscribers increased by nearly 40 percent, and Perimeter's videos were viewed 878,960 times, bringing the channel's total views to date to more than 3.5 million.

MEDIA COVERAGE

Major media look to Perimeter as a reliable source of high-quality theoretical physics news, content, commentary, and insight. This year, Perimeter research, people, and activities received major coverage in national and international media, including in-depth articles in outlets including *Scientific American*, *The Globe and Mail*, *The Guardian*, *The Economist*, *Gizmodo*, *Maclean's*, and many more.

THE GLOBE AND MAIL

SCIENTIFIC AMERICAN

MACLEAN'S

The Economist

theguardian

GIZMODO

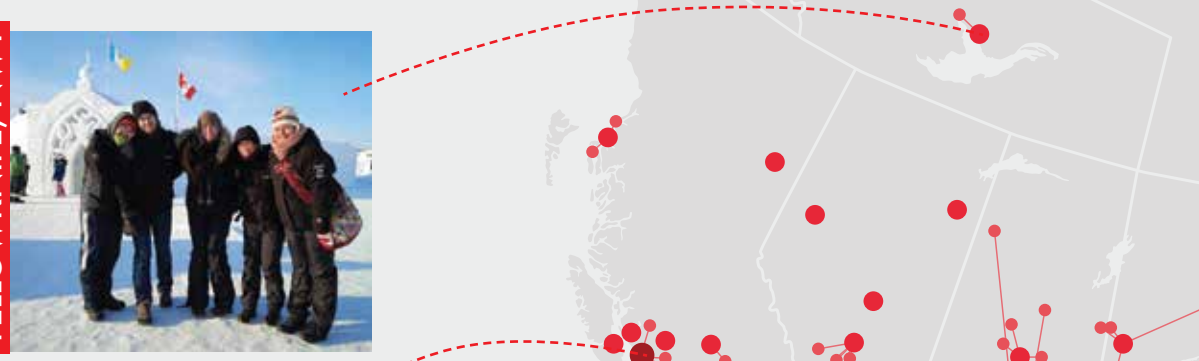
INNOVATION150

With its track record of producing successful large-scale science festivals, Perimeter was selected by the Department of Canadian Heritage to lead Innovation150, a signature initiative of Canada's sesquicentennial celebrations. Working with four other leading Canadian outreach partners – Actua, the Institute for Quantum Computing (IQC) at the University of Waterloo, Ingenium, and the Canadian Association of Science Centres – Perimeter developed content to celebrate Canadian ingenuity and led a cross-Canada tour designed to inspire the next generation of pioneering thinkers.

The Innovation150 program included major festivals, inspiring talks by Perimeter Director Neil Turok, online contests, and more. The Power of Ideas national tour has rolled in and out of communities from coast to coast to coast, bringing with it an immersive, hands-on exhibit and an engaging live presentation. Students young and old have had the chance to explore demonstrations modelled on the Event Horizon Telescope and the Large Hadron Collider, formulate string theories with Perimeter's "mystery tube," make their own weather stations in the Actua Maker Mobile, and much more.

In the process, the seeds just may have been planted for Canada's next great innovations.

In addition to major funding from the Government of Canada, Innovation150 received private support from Shaw Communications, the Cowan Foundation, the Toyota Canada Foundation, Pattison Outdoor, and Superior Lodging.



YELLOWKNIFE, NWT

VANCOUVER, BC

"Innovation, in my view, is a process, not an outcome. It can be learned and cultivated in our society. Anyone can be a part of it and everyone should. It actually defines who we are, and where we are going."

– Neil Turok, launching the "We Are Innovators" tour in Vancouver in January

SASKATCHEWAN

"There was so much energy in the building! Students got hands-on with technologies they would otherwise not have access to, and teachers got that spark to keep going and take risks in classroom learning. The impact is huge."

– Jenna Crossman, teacher at Carlton Comprehensive Public High School, Prince Albert, Saskatchewan

The three-month "Innovation Festival: Saskatchewan" featured the Power of Ideas tour, the Canada Wide Science Fair, the Vancouver Aquarium's AquaVan 150 "wet lab," "QUANTUM: The Exhibition," and events across the province.

Supported by the federal government through Canadian Heritage, Innovation150 was delivered through a partnership between Perimeter Institute, Actua, the Institute for Quantum Computing at the University of Waterloo, the Canadian Association of Science Centres and its members, Ingenium, and collaborations in every province and territory.

"It's pretty cool to have this come here, because usually we have to go places to see stuff. To have this cool tour come to Yellowknife is pretty sweet. It's a good opportunity for everyone here."

– Sebastian Toner, École St. Patrick High School, Yellowknife, NT

BY THE NUMBERS:

5 *major innovation festivals*

190+ *communities*

1,200+ *classroom resources delivered to teachers*

100,000+ *Power of Ideas attendees*

2.8 million+ *online clicks, shares, and likes*

ST. JOHN'S, NL

The Power of Ideas hit its most easterly point – St. John's, Newfoundland – in time for Science Literacy Week in September.

SYDNEY, NS

"Science is fun and it should be fun. You can set yourself up for a career in science that is only limited by your imagination and energy."

– Nobel Prize laureate and Perimeter Board member Arthur B. McDonald speaking at his former high school, the Sydney Academy

HAMILTON, ON

As grand prize winners of the "In Every Class" contest, Cathedral High School was transformed into a science wonderland for a day.

"You never know who wants to be a scientist. And things like this, they might create future scientists."

– Sophia Lim, Grade 12 student, Cathedral High School

Find stories of innovation, tour highlights, and more at innovation150.ca.

A WORLD-CLASS RESEARCH ENVIRONMENT

Perimeter is the largest purpose-built theoretical physics research centre in the world, accommodating up to 250 researchers and students.

Perimeter strives to create an environment in which everyone – students, scientists, and visitors – can do their best work. It encompasses everything from the structure of its iconic building to sustaining a culture that's challenging yet respectful, dynamic yet deeply contemplative.

It starts with Perimeter's iconic building, custom-designed to inspire big ideas (and recognized with a Governor General's Medal in Architecture in 2006). From its striking design to its meditative reflecting pool, inviting collaboration spaces, and cozy nooks for quiet contemplation, the Institute is a playground for the mind (and there are actual swings, too).

Researchers are never far from a blackboard, and every table in the Black Hole Bistro is stocked with pencils and paper to record ideas and calculations that crop up over lunch. When chalk or paper won't do, the Institute's seminar rooms have video-conferencing capabilities, and high-quality recordings of most talks are available in Perimeter's vast online archive.

Looking to run a complex simulation? Perimeter offers a state-of-the-art computational environment that includes access to high-performance computing and an in-house scientific computation expert. Need help landing funding for your next star grad student? Organizing a workshop? Arranging a visiting scientist's visa? Perimeter's administrative staff can help.

It's all designed to provide an environment that offers full spectrum support for learning, thinking, and discovery.

EMPLOYEE RECOMMENDED WORKPLACE

How do you know if an organization is a good place to work? Ask the people that work there. That's the simple yet effective idea behind the inaugural Employee Recommended Workplace Awards, jointly created by *The Globe and Mail* and Morneau Shepell.

Employees from companies across Canada were asked to complete a confidential survey on the four pillars of work, life, mental health, and physical health. The aggregate of a company's employee responses determined the organization's score – and Perimeter employees had plenty of positive things to say.

In June 2017, Perimeter was named the grand prize winner for the mid-sized category in the not-for-profit/government sector, lauded for its inspiring and family-focused environment. Employees cited the excellent exercise facilities, on-site yoga classes, peer mental health support, kid's room, and frequent family activities among the reasons they considered Perimeter a great place to work.

"We're trying to create a fantastic environment for the world's top scientists and their families," explained Michael Duschenes, Chief Operating Officer and Managing Director at Perimeter. "We have an extremely family-friendly facility here. It's not uncommon to see blackboards full of math on the top section and doodles of cats or fish at the bottom because we encourage staff and scientists to bring their families into the building."

ADVANCING PERIMETER'S MISSION

PUBLIC-PRIVATE PARTNERSHIP

Partnership is in Perimeter's DNA, from its ties to experimental and observational centres, to the administration of its graduate programs with local universities, to its visionary public-private partnership funding model.

This year saw milestones passed on both the public and private sides of the partnership. On the public side, Perimeter finalized new five-year, $50 million funding agreements with both the Province of Ontario and Government of Canada. These renewed investments continue a fruitful partnership that has been at the heart of the Institute's success dating back to its early days.

On the private side, Perimeter achieved its target, set in 2014, of raising $25 million from private individuals, corporations, and foundations. In the past year, Perimeter received an anonymous $5 million founding donation for the Centre for the Universe. Gifts from Cenovus Energy – in support of the Distinguished Visiting Research Chairs program – and the Delaney Family – to create the Delaney Family John Archibald Wheeler Chair in Theoretical Physics, held by Avery Broderick – also helped push Perimeter past its $25 million target. With ambitious plans on the horizon, Perimeter is excited to bring more private partners into the fold in the coming years.

Over the past year, Perimeter increased awareness of its mission in the Greater Toronto Area, with events in the MaRS Discovery District and at the TIFF Bell Lightbox, and across the country via the Innovation150 tour. Friends of Perimeter Institute, a US-based charity, was also launched.

Together with new and long-cherished partners who believe in the transformative power of physics, Perimeter will strengthen its position as a leader in the global scientific community at a time when opportunities for major discovery abound.

"We chose to support Avery's efforts because his work is both fascinating and ground-breaking. We are thrilled to support Avery and the Perimeter Institute."

– Catherine (Kiki) and Ian Delaney

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MEMBERS OF PERIMETER LEADERSHIP CIRCLES

Emmy Noether Circle	Directors Circle	Accelerators Circle

PERIMETER INSTITUTE LEADERSHIP COUNCIL

The Leadership Council is comprised of prominent individuals who act as ambassadors for Perimeter in the business and philanthropic communities, helping the Institute grow strategically.

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Member, Board of Directors, Perimeter Institute

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Harry Zarek
President and CEO, Compugen Inc.

** Term ended in 2017*

AVERY BRODERICK

A supermassive black hole churns at the heart of the Milky Way galaxy. To see it clearly, we'd need a telescope the size of a city – which is infeasible – so scientists have flipped the problem and turned the Earth into a telescope.

The Event Horizon Telescope (EHT) is a global array of interconnected telescopes all pointing at the black hole called Sagittarius A*. The highest resolution instrument in the history of astronomy, the EHT is expected to soon provide humanity's first glimpse of a black hole.

Avery Broderick, who holds the Delaney Family John Archibald Wheeler Chair in Theoretical Physics at Perimeter, leads the Institute's Event Horizon Telescope Initiative, which will analyze and interpret the vast amounts of data that pour in from the EHT.

"We are looking at multiple sources – which is a point of pride for us," Broderick says.

"Sagittarius A* will become a laboratory for us to understand how these behemoths grew. We can compare and contrast Sagittarius A* with the M87 black hole [in the Virgo constellation] and a slew of other active galactic nuclei for which we cannot resolve the horizons."

"For the first time, we're going to be able to check, validate, or maybe even invalidate ideas about how black holes operate in practice."

The prospect of actually seeing the shadow of a black hole is intoxicating, and Broderick hopes to share the wonder of it with the world.

"Those of us who are fortunate enough to be professional scientists lucked out and didn't have to stop questioning," he says. "Nurturing that inner child – in ourselves and in others – is part of the duty of being a scientist."

Avery Broderick holds the Delaney Family John Archibald Wheeler Chair in Theoretical Physics at Perimeter Institute, which was created in 2017 with support from the Delaney Family.

THE EMMY NOETHER COUNCIL

Council volunteers provide expertise and other support, helping the Emmy Noether Circle bring more women into physics.

Patrice Merrin, Co-Chair*
Director, Glencore plc, Arconic Inc., and Kew Media Group
Co-Chair, Leadership Council, Perimeter Institute

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District Vice President, Scotiabank (West New Brunswick)

** Term ended in 2017*

THE NEXT NOETHERS

Curiosity doesn't have a gender – and yet the image of a physicist historically has.

As a woman, Emmy Noether didn't fit that image. Fortunately, she refused to accept that women should not join the pursuit of knowledge, even though she did so unpaid or underpaid through most of her career. Her foundational work in abstract algebra created a breakthrough theorem that connects conservation laws with symmetries in nature, and which continues to be used in every branch of physics today.

This remarkable woman is a fitting namesake to Perimeter's Emmy Noether Initiatives, which aim to effect real change in the underrepresentation of women in physics. Backed by a committed group of funders and champions of women in science called the Emmy Noether Circle, these efforts support women at all stages of their career, from high school students through to Perimeter faculty.

Emmy Noether Visiting Fellowships are a cornerstone of the Emmy Noether Initiatives, supporting women at critical stages of their careers by enabling them to spend up to a year in Perimeter's thriving, multidisciplinary community. The Institute welcomed 10 Emmy Noether Visiting Fellows in the last year, for a total of 12 visits.

Conferences were another highlight of the 2016/17 Emmy Noether Initiatives. Perimeter hosted "Women in Physics Canada 2017" jointly with the University of Waterloo, as well as the Institute's annual "Inspiring Future Women in Science" conference for high school students. The Institute also sponsored the "International Conference for Women in Physics" at the University of Birmingham in the UK.

Emmy Noether Initiatives are supported by donors from the Emmy Noether Circle. For a full list, refer to page 43.

KASIA REJZNER

When **Kasia Rejzner** was a girl in Poland, her parents thought she would probably become an artist. Instead, her natural curiosity drew her to math and physics, where her creativity found a different kind of outlet.

Today, Rejzner is something of a rarity: a woman probing the mathematical foundations of quantum field theory and quantum gravity.

It is abstract work that often leaves her juggling two research programs. But during three working visits to Perimeter as an Emmy Noether Visiting Fellow in 2016/17, she was able to stitch her work together, and have a whole lot of fun in the process.

"What's great about PI is that I can work with people from all my subjects," she said. "There has been a lot of very constructive exchange of ideas. Every day, I bump into somebody and we start talking. Things are just moving at such a speed, it's really unique."

The life of a scientist is not easy. There is little stability at the start, and job opportunities often require uprooting your life for a new location. This can be a particular challenge for women wanting to have a family, or who already have children. But with special supports like Perimeter's Emmy Noether Initiatives, Rejzner hopes women will see that there is a place for them in science.

Science is hugely rewarding, creative, and collaborative, she says. If more young women see her and decide to join her at the vanguard of mathematics and physics, all the better.

THANKS TO OUR SUPPORTERS

ENDOWMENT FUND

FOUNDER ($150M+)
Mike Lazaridis

$25M+
Doug Fregin

$10M+
Jim Balsillie

GOVERNMENT PARTNERS

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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

Mike and Ophelia Lazaridis Niels Bohr Chair in Theoretical Physics ($4 million)
Gluskin Sheff Freeman Dyson Chair in Theoretical Physics ($2 million)
John Templeton Foundation – Templeton Frontiers Program at Perimeter Institute ($2 million)
Krembil Galileo Galilei Chair in Theoretical Physics ($2 million)
Krembil William Rowan Hamilton Chair in Theoretical Physics ($2 million)
Clay Riddell Paul Dirac Chair in Theoretical Physics ($1 million)
Delaney Family John Archibald Wheeler Chair in Theoretical Physics ($500,000)
Daniel Family Richard P. Feynman Chair (Visiting) in Theoretical Physics ($300,000)

CORPORATE AND SPONSORSHIP PARTNERS ($100,000+)

BMO Financial Group, Presenting Sponsor, Perimeter Public Lecture Series
Maplesoft, Perimeter Educational Outreach Champion
RBC Financial Group, Presenting Partner, International Summer School for Young Physicists

AWARDS ($50,000+)

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

ACCELERATORS CIRCLE ($50,000+)

The Cowan Foundation
Jon and Lyne Dellandrea
Corinne Squire and Neil Turok

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

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$25,000+

Donald and Eleanor Seaman Family Foundation

$10,000+

The Boardwalk

Harbir and Monica Chhina

The Kitchener and Waterloo Community Foundation
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$2,500+

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$1,000+

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

Simon Haysom, in memory of Elsie Haysom

IN-KIND SUPPORT

Shaw Communications

Steinway Piano Gallery Toronto

EMMY NOETHER CIRCLE

Emmy Noether was a brilliant scientist whose work underpins much of modern physics. Perimeter's Emmy Noether Initiatives – funded by Emmy Noether Circle donors – support and encourage women in science.

FOUNDING DONOR ($105,000)

The Bluma Appel Community Trust

$25,000+

Anne-Marie Canning

Linamar Corporation

Dr. Scott and Sherry Vanstone

$10,000+

Burgundy Asset Management Ltd.

Patrice E. Merrin

$5,000+

Andrew and Lillian Bass

Jennifer Scully-Lerner

$2,500+

Maria Antonakos and Harald Stover

Heather and John Clark

$1,000+

Andrea Grimm

Beth S. Horowitz

Lisa Lyons Johnston

Vicki Saunders

Steven and Suzan Wilson - Rebel Homes Inc.

$250 to $999

Chelsea and Keegan Arnott

Alexandra Brown

KPMG Management Services LP

This list reflects gifts received between August 1, 2016 and July 31, 2017, and multi-year commitments of $50,000 and more.

GOVERNANCE

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

Financial planning, accountability, and investment strategy are carried out by the Board's Investment and Finance and Audit Committees. 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 is in charge of day-to-day operations, supported by a team of administrative staff.

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

The Scientific Advisory Committee (SAC), comprised of eminent international scientists, offers independent scrutiny and advice, providing key support in achieving the Institute's strategic objectives, particularly in the area of recruitment.

BOARD OF DIRECTORS

Mike Lazaridis, O.C., O.Ont., Chair, is Managing Partner and Co-Founder of Quantum Valley Investments (QVI), which he and Doug Fregin established in Waterloo. In 2013, they launched QVI with $100 million to provide financial and intellectual capital for the development and commercialization of quantum physics and quantum computing breakthroughs. QVI aims to help transform ideas and early-stage breakthroughs into commercially viable products, technologies, and services. It is Mr. Lazaridis' latest venture in nearly two decades of work aimed at creating a Quantum Valley in Waterloo by bringing the world's best minds in physics, engineering, mathematics, computer science, and materials science together to collaborate on cutting-edge quantum research.

In 1984, Mr. Lazaridis co-founded BlackBerry (formerly Research In Motion) with Mr. Fregin. They invented the BlackBerry device, created the smartphone industry, and built Canada's largest global tech business. Mr. Lazaridis served in various positions including Co-Chairman and Co-CEO (1984-2012) and Board Vice-Chair and Chair of the Innovation Committee (2012-13).

Mr. Lazaridis is the Founder and Board Chair of Perimeter Institute, where he helps generate important private and public sector funding for the Institute. He also founded the Institute for Quantum Computing (IQC) and the Quantum-Nano Centre, both at the University of Waterloo. He has donated more than $170 million to Perimeter and more than $100 million to IQC.

Among his many honours, Mr. Lazaridis is a Fellow of the Royal Society of London and the Royal Society of Canada, and he has been named to both the Order of Ontario and the Order of Canada. He was listed on the *Maclean's* Honour Roll as a distinguished Canadian in 2000, named as one of *Time*'s 100 Most Influential People, honoured as a *Globe and Mail* Nation Builder of the Year in 2010, and awarded the Ernest C. Manning Principal Award, Canada's most prestigious innovation prize.

Mr. Lazaridis holds an honorary doctoral degree in engineering from the University of Waterloo (where he formerly served as Chancellor), as well as Doctors of Laws from Laval University, McMaster University, Western University, and the University of Windsor. In addition to his many professional and personal accomplishments, Mr. Lazaridis won an Academy Award and an Emmy Award for technical achievements in the movie and TV industries for developing a high-speed barcode reader that greatly increased the speed of editing film.

Mr. Lazaridis was born in Istanbul, Turkey. He moved to Canada in 1966 with his family, settling in Windsor, Ontario.

Cosimo Fiorenza, Vice-Chair, is the Vice-President and General Counsel of Quantum Valley Investments and the Quantum Valley Investment Fund. Previously, he spent approximately 20 years with major Toronto law firms, where he specialized in corporate tax. During his tenure on Bay Street, he advised some of Canada's largest corporations and biggest entrepreneurs on income tax and commercial matters with a focus on technology and international structure. Mr. Fiorenza helped establish and is a Founding Director of Perimeter Institute. In addition to his current role as Vice-Chair, he is Founding Co-Chair of the Perimeter Leadership Council and a member of the Perimeter Finance Committee. In these capacities, he regularly assists and supports Perimeter's management team in a variety of contexts including financial, legal, and advancement matters. Mr. Fiorenza is also a member of the Board of Directors of the Institute for Quantum Computing at the University of Waterloo. He holds a degree in business administration from Lakehead University and a law degree from the University of Ottawa. He was called to the Bar in Ontario in 1991.

Joanne Cuthbertson, LL.D., was the first elected Chair of EducationMatters (Calgary's unique public education trust), founder of SPEAK (Support Public Education – Act for Kids), and a recipient of the Calgary Award (Education). She is Chancellor Emeritus of the University of Calgary, Co-Chair of the Scholars' Academy she established upon retirement, and Dean's Circle Chair in the Faculty of Environmental Design. Ms. Cuthbertson serves as a Fellow of Glenbow Museum and as Director of the Alberta Bone and Joint Health Institute, and she is a Queen Elizabeth II Diamond Jubilee Medal recipient. She is also a Co-Chair of Perimeter's Leadership Council.

Peter Godsoe, O.C., O.Ont., is the former Chairman and Chief Executive Officer of Scotiabank, from which he retired in 2004. He holds a BSc in mathematics and physics from the University of Toronto, an MBA from the Harvard Business School, and is a CA and a Fellow of the Institute of Chartered Accountants of Ontario. Mr. Godsoe remains active through a wide range of corporate boards and non-profit directorships.

Michael Horgan is a Senior Advisor at Bennett Jones LLP, one of Canada's premier business law firms. Prior to his work in the private sector, he led a distinguished 36-year career as a federal public servant, including five years as Canada's Deputy Minister of Finance. Mr. Horgan has been awarded the Prime Minister's Outstanding Achievement Award for Public Service and a Queen Elizabeth II Diamond Jubilee Medal.

Art McDonald, C.C., was the Director of the Sudbury Neutrino Observatory (SNO) experiment for over 20 years, and is Emeritus Professor at Queen's University. He shared the 2015 Nobel Prize in Physics and the 2016 Breakthrough Prize in Fundamental Physics for the SNO experiment that showed neutrinos have mass. Professor McDonald has received numerous other awards for his research, including the 2011 Henry Marshall Tory Medal from the Royal Society of Canada and the 2007 Benjamin Franklin Medal in Physics, alongside researcher Yoji Totsuka. He was named an Officer of the Order of Canada in 2007 and promoted to a Companion of the Order of Canada in 2015.

Jeff Moody is President and CEO at Gluskin Sheff + Associates, a Canadian independent wealth management firm. Prior to joining Gluskin Sheff in 2001, Mr. Moody held a number of senior investment industry positions in both Canada and England, including Co-Head of Global Fixed Income at BMO Nesbitt Burns and Managing Partner with Gryphon Investment Counsel. In addition to his service on Perimeter's Board, where he is also the Chair of the Investment Committee, Mr. Moody is a trustee for the Jeremy and Judith Freedman Family Foundation. He received a BA in economics from Western University.

John Reid recently retired after serving as the Audit Leader for KPMG in the Greater Toronto area. During his 35-year career, he assisted both private- and public-sector organizations through various stages of strategic planning, business acquisitions, development, and growth management. His experience spans all business sectors and industries with a focus on mergers and acquisitions, technology, and health care. Mr. Reid has served on many hospital boards throughout Canada and has also been a director on many university and college boards.

Michael Serbinis is the Founder and CEO of LEAGUE, a digital health start-up that launched in 2015. He is a leader known as a visionary entrepreneur who has built several transformative technology platforms across industries. Mr. Serbinis was the Founder and CEO of Kobo, a digital reading company that burst onto the publishing scene in 2009, driving $110 million in sales in its very first year and becoming the only global competitor to Amazon's Kindle with 20 million customers in 190 countries. He is the Founder of Three Angels Capital, a member of the Board of Trustees at the Ontario Science Centre, and a member of YPO. He holds a BSc in engineering physics from Queen's University and an MSc in industrial engineering from the University of Toronto.

SCIENTIFIC ADVISORY COMMITTEE

Gabriela González, Louisiana State University (2017-Present), Chair

Professor González is a Professor of Physics and Astronomy at Louisiana State University, whose work focuses on the detection of gravitational waves. From 2011 to 2017, she was the spokesperson for the LIGO Scientific Collaboration, a worldwide endeavour probing gravitational wave astronomy. She worked as a staff scientist with the MIT-LIGO group and was a faculty member at Pennsylvania State University before joining LSU in 2001. In 2007, she was awarded the Edward A. Bouchet Award by the American Physical Society.

Steve Carlip, University of California, Davis (2017-Present)

Professor Carlip has been a member of the faculty at the University of California, Davis since 1990. He is a high energy theorist who works on one of the fundamental unsolved problems in modern theoretical physics, the effort to combine general relativity and quantum mechanics into a consistent quantum theory of gravity. His current interests include (2+1)-dimensional quantum gravity, the quantum gravitational basis of black hole thermodynamics, and causal dynamical triangulations. Carlip is a Fellow of the American Physical Society and the Institute of Physics (UK).

Katherine Freese, University of Michigan (2017-Present)

Professor Freese is the George E. Uhlenbeck Professor of Physics at the University of Michigan, as well as a Guest Professor at Stockholm University. Her research covers a wide range of topics in theoretical cosmology and astroparticle physics; she has been working to identify the dark matter and dark energy that permeate the universe, as well as to build a successful model for the early universe immediately after the big bang. Freese has been a Sloan Foundation Fellow and a Simons Foundation Fellow in Theoretical Physics, and she has been a Fellow of the American Physical Society since 2009. In 2014, she published her first popular science book, *The Cosmic Cocktail: Three Parts Dark Matter*.

Shamit Kachru, Stanford University (2015-Present)

Professor Kachru has been a Professor of Physics at Stanford University since 1999. He is an expert in string theory and quantum field theory, and their applications in cosmology, condensed matter, and elementary particle theory. He has made central contributions to the study of compactifications of string theory from ten to four dimensions, especially in the exploration of mechanisms which could yield string models of dark energy or cosmic inflation. Kachru has also made notable contributions to the discovery and exploration of string dualities, to the study of models of supersymmetry

breaking in string theory, and to the construction of calculable dual descriptions of strongly coupled particle physics and condensed matter systems using the AdS/CFT correspondence. Kachru's many honours include a Department of Energy Outstanding Junior Investigator Award, Alfred P. Sloan Foundation Fellowship, Bergmann Memorial Award, Packard Foundation Fellowship, and ACIPA Outstanding Young Physicist Prize.

David B. Kaplan, University of Washington (2017-Present)

Professor Kaplan is a Senior Fellow at the Institute for Nuclear Theory at the University of Washington, where he has also been a Professor of Physics since 1998. He previously served as Director of the Institute for Nuclear Theory from 2006 to 2016. Kaplan's research interests include the application of quantum field theory to the strong interactions, lattice field theory, quantum computing, cosmology, and physics beyond the Standard Model. He has been elected to the American Physical Society, Washington State Academy of Sciences, National Academy of Sciences, and American Academy of Arts and Sciences. He has also received the National Science Foundation Presidential Young Investigator Award and an Alfred P. Sloan Foundation Fellowship.

Ramesh Narayan, Harvard University (2017-Present)

Professor Narayan is the Thomas Dudley Cabot Professor of the Natural Sciences at Harvard University. He is an astrophysicist who has won international renown for his research on black holes. Narayan has also carried out research in a number of other areas of theoretical astrophysics, including accretion disks, gravitational lensing, gamma-ray bursts, and neutron stars. He is a Fellow of the Royal Society of London and the American Association for the Advancement of Science, and a member of the International Astronomical Union and the American Astronomical Society.

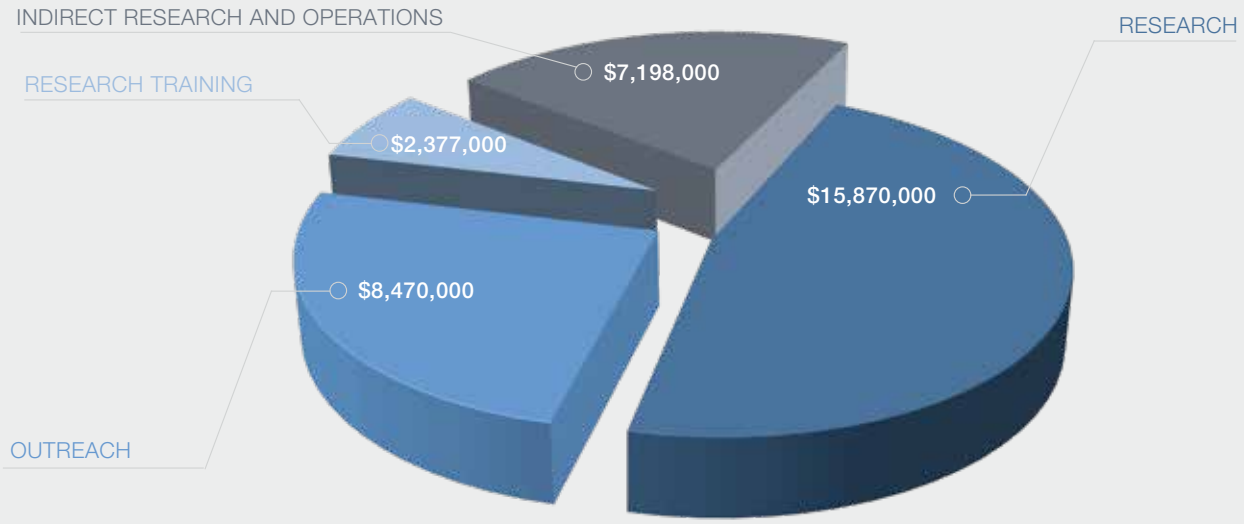
Barbara Terhal, RWTH Aachen University (2015-Present)

Professor Terhal has been a Professor of Theoretical Physics at RWTH Aachen University in Germany since 2010. Prior to that, she spent eight years as a research staff member at the IBM Watson Research Center in New York. Terhal's research interests lie in quantum information theory – ranging from quantum entanglement to quantum cryptography and quantum algorithms – and she is currently working on quantum error correction and its realization in solid-state qubits, as well as quantum complexity theory. She is a Fellow of the American Physical Society and an Associate Member of the Quantum Information Processing program of the Canadian Institute for Advanced Research.

FINANCIALS

SUMMARY OF OPERATING COSTS (REFER TO PAGE 52)

For the year ended July 31, 2017



Research

Perimeter's mission is to advance our understanding of the universe at the most fundamental level. To that end, the Institute continued to invest in creating a research environment that fosters breakthroughs, growing Perimeter's resident researcher base and providing an influx of visiting researchers through various programs. In 2016/17, Perimeter increased its investment in research by three percent over the prior year, in line with planned growth.

Research Training

Brilliant young people are the lifeblood of science. Over the last year, Perimeter continued to offer innovative research training programs that help emerging scientists refine their ideas and interests through lively academic and research interactions. A modest one percent increase over the prior year's spending allowed for increased participation in the successful Visiting Graduate Fellows program, while Perimeter Scholars International and the PhD program, delivered in collaboration with university partners, continued to attract exceptional graduate students from around the world.

Outreach and Science Communications

Perimeter's world-class educational outreach programs convey the wonder and mystery of the universe and the importance of scientific breakthroughs to audiences across Canada and beyond. Investment in the Institute's inspirational programs and products for students, teachers, and the general public doubled in 2016/17 owing to Innovation150, the Perimeter-led signature initiative of the Government of Canada's sesquicentennial celebrations. This increased investment allowed Perimeter to offer opportunities for youth, families, and communities across the country to experience travelling science exhibitions, major city-wide festivals, and other innovation-themed activities.

Indirect Research and Operations

Indirect research and operating expenditures cover the costs of core support areas, including administration, advancement, information technology, and facilities. Perimeter continues to maximize efficiencies, as demonstrated by a two percent reduction in these expenditures (21 percent of total expenditures this year, compared to 23 percent last year). This further shows Perimeter's ability to scale effectively as new projects and initiatives are executed.

INCOME

Perimeter's private sector fundraising campaign remained very strong, generating approximately $6 million to support the operations of the Institute. Meanwhile, federal and provincial governments continued to provide revenues in accordance with the terms of their grant agreements, and private foundational research grant revenue increased by $1.13 million (60 percent over the prior year), demonstrating wide support for Perimeter's mandate among the private and public sectors.

FINANCIAL POSITION (REFER TO PAGE 51)

Perimeter has put itself in a strong financial position through years of prudent investing, building a $325 million endowment fund to secure the future of the Institute.

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

THE LONG-TERM PLAN

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

In 2016/17, Perimeter renewed five-year commitments of $50 million from both the federal and provincial governments, providing combined funding of $100 million over the next five years, ending in 2022. The continuous, multi-year government commitments reinforce Perimeter's strong collaboration with public partners and clearly demonstrate that the Institute is viewed as an excellent and strategic government investment.

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

Zeifmans

REPORT OF THE INDEPENDENT AUDITORS ON THE SUMMARIZED FINANCIAL STATEMENTS

To the Directors of Perimeter Institute

The accompanying summarized financial statements, which comprise the summarized statement of financial position as at July 31, 2017 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, 2017. We expressed an unmodified audit opinion on those financial statements in our report dated December 20, 2017. Those financial statements, and the summarized financial statements, do not reflect the effects of events that occurred subsequent to the date of our report on those financial statements.

The summarized financial statements do not contain all the disclosures required by Canadian accounting standards for not-for-profit organizations. Reading the summarized financial statements, therefore, is not a substitute for reading the audited financial statements of the Institute.

Management's Responsibility for the Summarized Financial Statements

Management is responsible for the preparation of a summary of the audited 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 summarized financial statements.

Auditor's Responsibility

Our responsibility is to express an opinion on the summarized financial statements based on our procedures, which were conducted in accordance with Canadian Auditing Standard (CAS) 810, "Engagements to Report on Summary Financial Statements."

Opinion

In our opinion, the summarized financial statements derived from the audited financial statements of the Institute for the year ended July 31, 2017 are a fair summary of those financial statements, in accordance with the basis developed by management, which includes removing the statement of cash flows, retaining major subtotals, totals and comparative information, and retaining the information from the audited financial statements dealing with matters having a pervasive or otherwise significant effect on the summarized financial statements.

Other Matter

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

Zeifmans LLP

Toronto, Ontario
December 20, 2017

Chartered Accountants
Licensed Public Accountants

PERIMETER INSTITUTE

Summarized Statement of Financial Position
as at July 31, 2017

	2017	2016
ASSETS		
Current Assets:		
Cash and cash equivalents	$ 6,771,000	$ 7,127,000
Investments	324,504,000	306,393,000
Grants receivable	38,000	4,170,000
Other current assets	1,282,000	1,807,000
	332,595,000	319,497,000
Property and equipment	42,786,000	44,607,000
TOTAL ASSETS	$ 375,381,000	$ 364,104,000
LIABILITIES AND FUND BALANCE		
Current liabilities:		
Accounts payable and other current liabilities	$ 1,043,000	$ 1,315,000
TOTAL LIABILITIES	1,043,000	1,315,000
Fund balances:		
Invested in capital assets	42,772,000	44,576,000
Externally restricted	122,077,000	123,050,000
Internally restricted	203,440,000	188,840,000
Unrestricted	6,049,000	6,323,000
TOTAL FUND BALANCES	374,338,000	362,789,000
	$ 375,381,000	$ 364,104,000

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PERIMETER INSTITUTE

Summarized Statement of Operations and Changes in Fund Balances
For the Year Ended July 31, 2017

	2017	2016
Revenue		
Government grants	$ 19,078,000	$ 22,794,000
Donations	5,652,000	6,479,000
Research grants	2,987,000	1,855,000
	27,717,000	31,128,000
Expenditures		
Research	15,870,000	15,403,000
Research training	2,377,000	2,145,000
Outreach and science communications	8,470,000	4,203,000
Indirect research and operations	7,197,000	6,617,000
	33,914,000	28,368,000
Excess of revenue over expenses (expenses over revenue) before amortization and investment income (loss)	(6,197,000)	2,760,000
Amortization	(2,437,000)	(2,581,000)
Investment income (loss)	20,183,000	(110,000)
Excess of revenue over expenses	11,549,000	69,000
Fund balances, beginning of year	362,789,000	362,720,000
Fund balances, end of year	$ 374,338,000	$ 362,789,000

Zeifmans

LOOKING AHEAD: PRIORITIES AND OBJECTIVES FOR THE FUTURE

Perimeter Institute is on track to achieve its overriding goal: to create and sustain the world's leading centre for foundational theoretical physics research, training, and outreach. To build on the Institute's momentum, Perimeter has established a set of strategic objectives to guide its continued development. The advancement of the Institute's core mission will continue to inform every facet of its research, training, and outreach efforts.

Achieve breakthroughs in our understanding of the universe, drawing insights from and contributing to the whole spectrum of theoretical physics, focusing strategically on research areas that offer the greatest opportunity for major discoveries.

Create the world's strongest community of theoretical physics researchers by continuing to attract and retain top international talent and providing them with unparalleled infrastructure and support to help maximize productivity.

Attract and develop the next generation of brilliant researchers by providing exceptional graduate training opportunities that prepare students for cutting-edge research and by giving postdoctoral researchers the unmatched freedom and support necessary to pursue ambitious research and advance their careers.

Attract outstanding visiting scientists by holding timely, focused conferences, workshops, and seminars on cutting-edge topics and facilitating a constant flow of eminent and emerging physicists for both short-term and extended collaboration visits.

Act as Canada's hub for foundational physics research, strengthening connections with institutions across the country and enabling frontier research, high-quality training, and public engagement.

Catalyze and support the creation of centres of excellence for math and physics research, training, and outreach in developing countries, sharing knowledge and expertise globally and promoting the emergence of vast new pools of scientific talent.

Share the transformative power of theoretical physics across Canada and around the world, inspiring a new generation of scientific explorers through high-impact educational outreach, while engaging the general public with the wonder and excitement of basic physics research.

Continue to strengthen Perimeter's visionary public-private partnership by demonstrating excellent return on investment, securing sustained funding from government partners, and expanding the Institute's private sector support base.

APPENDICES

FACULTY

Neil Turok (PhD Imperial College London, 1983) is the Director of Perimeter Institute. He was Professor of Physics at Princeton University and Chair of Mathematical Physics at the University of Cambridge before assuming his current position in 2008. In 2013, he was also appointed to the Mike and Ophelia Lazaridis Niels Bohr Chair at Perimeter. Turok's research focuses on developing fundamental theories of cosmology and new observational tests. His predictions for the correlations of the polarization and temperature of the cosmic background radiation (CBR) and of the galaxy-CBR correlations induced by dark energy have been confirmed. He developed the single bubble open inflationary universe model with Stephen Hawking, among others. He also developed the cyclic universe model with Paul Steinhardt. Currently, he is working on a new approach to quantum cosmology which resolves the big bang singularity and explains the emergence of time. With Ue-Li Pen, he has recently shown how gravitational waves may be used to constrain and observe physical phenomena in the primordial universe. Among his many honours, Turok was awarded Sloan and Packard Fellowships and the James Clerk Maxwell medal of the Institute of Physics (UK). He is a Canadian Institute for Advanced Research Fellow in Cosmology and Gravity and a Senior Fellow of Massey College at the University of Toronto. In 2012, Turok was selected to deliver the CBC Massey Lectures, broadcast across Canada. The lectures were published as *The Universe Within*, a bestseller which won the 2013 Lane Anderson Award, Canada's top prize for popular science writing. Born in South Africa, Turok founded the African Institute for Mathematical Sciences (AIMS) in Cape Town in 2003. AIMS has since expanded to a network of six centres – in South Africa, Senegal, Ghana, Cameroon, Tanzania, and Rwanda – and has become Africa's leading institution for postgraduate training in mathematical science. For his scientific discoveries and his work building AIMS, Turok was awarded a TED Prize in 2008, as well as awards from the World Summit on Innovation and Entrepreneurship and the World Innovation Summit on Education. In 2016, he was awarded the John Torrence Tate Medal for International Leadership in Physics by the American Institute of Physics. He was made an Honorary Fellow of the Institute of Physics in the UK and named as winner of the John Wheatley Award of the American Physical Society. He was also chosen as the Gerald Whitrow Lecturer of the Royal Astronomical Society.

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 also works on theoretical challenges raised by experimental results, such as a model of particle physics influenced by string theory called "split SUSY." 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; he was also a Junior Fellow of the Canadian Institute for Advanced Research. Boyle has studied what gravitational wave measurements can reveal about the universe's beginning. With Paul Steinhardt, he derived "inflationary bootstrap relations" that – if confirmed observationally – would provide compelling support for the theory of primordial inflation. He co-developed a simple algebraic technique for understanding black hole mergers and constructed the theory of "porcupines": networks of low-frequency gravitational wave detectors that function together as gravitational wave telescopes. With Shane Farnsworth, Boyle discovered a reformulation of Connes' non-commutative geometry that greatly simplifies and unifies its axioms, and elucidates its connection to the standard model of particle physics. With Kendrick Smith, he developed the idea of "choreographic crystals" in which the basic elements perform a choreographed dance that can have a much higher symmetry than any instantaneous snapshot reveals. Most recently, with Steinhardt, he has been developing a new approach to Penrose-like tilings and exploring new applications of these structures to physics.

Freddy Cachazo (PhD Harvard University, 2002) is the Gluskin Sheff Freeman Dyson Chair in Theoretical Physics at Perimeter Institute, where he has been a faculty member since 2005. From 2002 to 2005, he was a Member of the School of Natural Sciences at the Institute for Advanced Study in Princeton. Cachazo is one of the world's leading experts in the study and computation of scattering amplitudes in gauge theories, such as quantum chromodynamics and N=4 super Yang-Mills (MSYM), 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).

Kevin Costello (PhD University of Cambridge, 2003) joined Perimeter in 2014 from Northwestern University, where he had been a faculty member since 2006. He is the Krembil William Rowan Hamilton Chair in Theoretical Physics. Previously, he was a Chapman Fellow at Imperial College London (2003-05) and the Dixon Instructor at the University of Chicago (2005-06). 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.

Savas Dimopoulos (PhD University of Chicago, 1978) joined Perimeter as the Archimedes Chair in Theoretical Physics (Visiting) in September 2016, while retaining his position as the Hamamoto Family Professor in the School of Humanities and Sciences at Stanford University, where he has been on the faculty since 1979. In that span, he has also taught at Boston University, Harvard University, and the University of California, Santa Barbara, and he was a staff member at CERN from 1994 to 1997. Dimopoulos is a leading particle physicist, well known for his work on constructing theories beyond the Standard Model. With collaborators, he has done foundational work on the Minimal Supersymmetric Standard Model (MSSM) and proposed the "ADD" model of large extra dimensions. Among his many honours, Dimopoulos has received the Tommassoni Prize in Physics, the J.J. Sakurai Prize in Theoretical Physics from the American Physical Society, and a Distinguished Alumnus Award from the University of Houston. He was an Alfred P. Sloan Foundation Fellow and is currently a Fellow of both the Japanese Society for the Promotion of Science and the American Academy of Arts and Sciences.

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

Laurent Freidel (PhD L'École Normale Supérieure de Lyon, 1994) joined Perimeter Institute first as a visitor in 2002 and then as faculty in 2006. Freidel is a mathematical physicist who has made many notable contributions in the field of quantum gravity, developing spin foam models, among other things. He has also introduced several new concepts in this field, such as group field theory, relative locality, and metastring theory and modular spacetime. He possesses outstanding knowledge of a wide range of areas including gravitational physics, integrable systems, topological field theories, 2D conformal field theory, string theory, and quantum chromodynamics. Freidel has held positions at Pennsylvania State University and L'École Normale Supérieure and has been a member of France's Centre National de la Recherche Scientifique since 1995. He is also the recipient of several awards.

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

Jaume Gomis (PhD Rutgers University, 1999) joined Perimeter Institute in 2004, declining a European Young Investigator Award by the European Science Foundation to do so. Prior to that, he worked at the California Institute of Technology as a Postdoctoral Scholar and as the Sherman Fairchild Senior Research Fellow. His main areas of expertise are string theory and quantum field theory. 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.

Daniel Gottesman (PhD California Institute of Technology, 1997) joined Perimeter's faculty in 2002. From 1997 to 2002, he held postdoctoral positions at the Los Alamos National Laboratory, Microsoft Research, and the University of California, Berkeley (as a long-term CMI Prize Fellow for the Clay Mathematics Institute). Gottesman has made seminal contributions which continue to shape the field of quantum information science through his work on quantum error correction and quantum cryptography. He has published over 50 papers, which have attracted well over 4,000 citations to date. He is also a Senior Fellow in the Quantum Information Processing program of the Canadian Institute for Advanced Research and a Fellow of the American Physical Society.

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, University of Durham, University of Innsbruck, and National University of Ireland. In 1992, he found a very simple proof of non-locality in quantum theory which has become known as Hardy's theorem. He has worked on characterizing quantum theory in terms of operational postulates and providing an operational reformulation of quantum theory. He has recently shown how to reformulate general relativity in operational terms. This is seen as a stepping stone en route to finding a theory of quantum gravity.

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, and became Deputy Faculty Chair in 2014. He previously held postdoctoral fellowships at the University of Texas at Austin and the University of British Columbia, and he was a member of Louisiana State University's faculty from 2002 to 2009. Lehner's many honours include the Honor Prize from the National University of Cordoba, Argentina, a Mellon pre-doctoral fellowship, the CGS/UMI outstanding dissertation award, and the Nicholas Metropolis award. He has been a PIMS fellow, a CITA National Fellow, and a Sloan Research Fellow, and he is currently a Fellow of the Institute of Physics, the American Physical Society, the International Society for General Relativity and Gravitation, and the Canadian Institute for Advanced Research in the Cosmology and Gravity program. Lehner also serves on the Scientific Council of the International Centre for Theoretical Physics – South American Institute for Fundamental Research and the Advisory Board of the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara.

Robert Myers (PhD Princeton University, 1986) is one of the leading theoretical physicists working on string theory and quantum gravity in Canada. After attaining his PhD, he was a postdoctoral researcher at the Institute for Theoretical Physics at the University of California, Santa Barbara, and a Professor of Physics at McGill University, before joining Perimeter as one of the founding faculty members in 2001. He was named Faculty Chair in 2010. Myers has made seminal contributions to our understanding of black hole microphysics, D-branes, and the application of entanglement entropy to holography and renormalization group flows. Among his many honours, he has received the Canadian Association of Physicists' Herzberg Medal (1999), the CAP-CRM Prize (2005), and the Vogt Medal (2012). He is also a Fellow of both the Royal Society of Canada and the Cosmology and Gravity program of the Canadian Institute for Advanced Research. Myers was named on Thomson Reuters' list of the "World's Most Influential Scientific Minds" in 2014, 2015, and 2016.

Subir Sachdev (PhD Harvard University, 1985) joined Perimeter in 2014 and holds the Cenovus Energy James Clerk Maxwell Chair in Theoretical Physics (Visiting). He has been a Professor of Physics at Harvard University since 2005. Sachdev has made prolific contributions to quantum condensed matter physics, including research on quantum phase transitions and their application to correlated electron materials like high-temperature superconductors, and he authored the seminal book, *Quantum Phase Transitions*. In recent years, he has exploited a remarkable connection between the electronic properties of materials near a quantum phase transition and the quantum theory of black holes. Sachdev's previous honours include an Alfred P. Sloan Foundation Fellowship and a John Simon Guggenheim Memorial Foundation Fellowship. He is a Fellow of the American Physical Society and a member of the U.S. National Academy of Sciences.

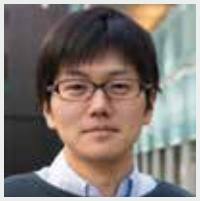
Kendrick Smith (PhD University of Chicago, 2007) joined Perimeter in 2012 from Princeton University, where he was the Lyman P. Spitzer Postdoctoral Fellow. Prior to that, he held the PPARC Postdoctoral Fellowship at the University of Cambridge from 2007 to 2009. Smith is a cosmologist with a foot in the worlds of both theory and observation. He is a member of several experimental teams, including the WMAP collaboration, which won the 2012 Gruber Cosmology Prize, as well as CHIME and the Planck collaboration. Smith has achieved several landmark results, including the first detection of gravitational lensing in the cosmic microwave background (CMB) radiation. He holds a second PhD in mathematics from the University of Michigan.

Lee Smolin (PhD Harvard University, 1979) is one of Perimeter Institute's founding faculty members. Prior to joining Perimeter, Smolin held faculty positions at Yale University, Syracuse University, and Pennsylvania State University. Smolin's research is centred on the problem of quantum gravity, where he helped to found loop quantum gravity, though his contributions span many areas, including quantum foundations, cosmology, particle physics, the philosophy of physics, and economics. His more than 195 papers have generated over 19,400 citations to date. He has written four 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 a postdoctoral fellowship at Perimeter and an International Royal Society Fellowship at the University of Cambridge. His field of research is the foundations of quantum theory, where he is known for his work on the interpretation of the quantum state, the principle of noncontextuality, the nature of causality in a quantum world, and the characterization of the symmetry-breaking and thermodynamic properties of quantum states as resources. Spekkens co-edited the book *Quantum Theory: Informational Foundations and Foils*, and he is a Project Leader of the "Quantum Causal Structures" collaboration. 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 (FQXi) essay contest, "Questioning the Foundations: Which of Our Assumptions are Wrong?"

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

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, ultimately aiming at the solution of a realistic four-dimensional gauge theory. His research interests also include the AdS/CFT correspondence, theoretical calculations of scattering amplitudes, and correlation functions in interacting quantum field theories. He is a Principal Investigator on the Simons Collaboration on the Nonperturbative Bootstrap. In 2015, Vieira was awarded both a Sloan Research Fellowship and the Gribov Medal of the European Physical Society.



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 Fellow in 2015. Prior to that, he was a Burke Fellow at the Institute for Theoretical Physics at the California Institute of Technology (2012-15), where he worked in John Preskill's group. Yoshida's research focuses on applications of quantum information theory to problems of quantum many-body physics. In particular, he has used the techniques of quantum coding theory to find novel topological phases of matter and developed a framework of classifying fault-tolerant logical gates by using topological gauge theories. He has also recently developed an interest in black hole physics.

ASSOCIATE FACULTY

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

Alexander Braverman (PhD Tel Aviv University, 1998) joined Perimeter in 2015, jointly appointed with the University of Toronto. He was previously a faculty member at Brown University (2004-15) and held lecturer positions at Harvard University (2000-04) and the Massachusetts Institute of Technology (1997-99). Braverman specializes in a number of 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 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 collaboration, an international effort to produce and interpret horizon-resolving images of supermassive black holes, studying how black holes accrete matter, launch the ultra-relativistic outflows observed, and probe the nature of gravity in their vicinity.

Alex Buchel (PhD Cornell University, 1999) is jointly appointed with Western University. 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.

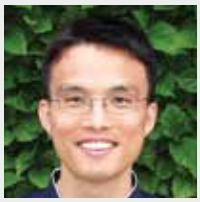
Raffi Budakian (PhD University of California, Los Angeles, 2000) joined Perimeter in 2014, jointly appointed with the Institute for Quantum Computing (IQC) at the University of Waterloo. He also holds the Nanotechnology Endowed Chair in Superconductivity at IQC and the Waterloo Institute for Nanotechnology. Budakian previously held a faculty position at the University of Illinois at Urbana-Champaign and research positions at the University of California, Los Angeles, and the IBM Almaden Research Center in San Jose. He is an experimental condensed matter physicist whose research focuses on developing ultra-sensitive spin detection techniques for single spin imaging and quantum readout. In 2005, Budakian won a World Technology Award for his work in the detection and manipulation of quantum spins.

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

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

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

Raymond Laflamme (PhD University of Cambridge, 1988) is a founding faculty member of Perimeter Institute. He is jointly appointed with the Institute for Quantum Computing, where he served as founding Executive Director and where he remains a faculty member. 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 has been Director of the Quantum Information Processing program at the Canadian Institute for Advanced Research (CIFAR) since 2003. He is a Fellow of CIFAR, the American Physical Society, the Royal Society of Canada, and the American Association for the Advancement of Science, and holds the Canada Research Chair in Quantum Information. In 2017, he was awarded the 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.



Sung-Sik Lee (PhD Pohang University of Science and Technology, 2000) joined Perimeter in 2011 in a joint appointment with McMaster University, where he is an Associate Professor. He previously worked as a postdoctoral researcher at the Pohang University of Science and Technology, the Massachusetts Institute of Technology, and the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara. Lee's research focuses on strongly interacting quantum many-body systems, 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 quantum renormalization group.

Roger Melko (PhD University of California, Santa Barbara, 2005) joined Perimeter in 2012, while retaining his appointment with the University of Waterloo, where he has been since 2007. Prior to that, he was a Wigner Fellow at Oak Ridge National Laboratory (2005-07). Melko is a condensed matter theorist who develops new computational methods and algorithms to study strongly correlated many-body systems, focusing on emergent phenomena, ground state phases, phase transitions, quantum criticality, and entanglement. Among his honours, he has received the Herzberg Medal from the Canadian Association of Physicists, the Young Scientist Prize in Computational Physics from the International Union of Pure and Applied Physics, an Early Researcher Award from the Ontario Ministry of Research and Innovation, and a Canada Research Chair in Computational Quantum Many-Body Physics (Tier 2).

Michele Mosca (DPhil University of Oxford, 1999) is jointly appointed with the Institute for Quantum Computing (IQC) at the University of Waterloo. He is a founding member of Perimeter Institute, as well as co-founder of IQC. He is also a Professor in the Department of Combinatorics and Optimization of the University of Waterloo's Faculty of Mathematics, and the co-founder and Director of CryptoWorks21, an NSERC-funded training program in quantum-safe cryptography. Mosca co-founded the ETSI-IQC workshop series in quantum-safe cryptography, which brings together a broad range of stakeholders working toward globally standardized quantum-safe cryptography, and co-founded evolutionQ Inc. in order to support organizations as they evolve their quantum-vulnerable systems and practices to quantum-safe ones. 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 academic honours, including the Premier's Research Excellence Award (2000-05), Fellowship of the Canadian Institute for Advanced Research since 2010, Canada Research Chair in Quantum Computation (2002-12), and University Research Chair at the University of Waterloo (2012-present).

Ue-Li Pen (PhD Princeton University, 1995) joined Perimeter in 2014. He is jointly appointed with the Canadian Institute for Theoretical Astrophysics at the University of Toronto, where he has been a professor since 1998 and is currently Interim Director. Prior to that, he held fellowships at Princeton University (1994-95) and Harvard University (1995-98). Pen is a theoretical astrophysicist who studies systems where basic physical effects can be isolated from astronomical complexities. His research interests include 21cm cosmology, HPC simulations, gravitational waves, pulsars, and radio interferometry. Among his many honours, Pen is a Senior Fellow of the Canadian Institute for Advanced Research in the Cosmology and Gravity program.

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

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 around 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.

Jon Yard (PhD Stanford University, 2005) joined Perimeter in September 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 fields, quantum fields, and condensed matter. With Graeme Smith, he received the 2009 Pat Goldberg Memorial Best Paper Award from IBM Research for proving that quantum capacity does not completely characterize the utility of a channel for transmitting quantum information.

SENIOR MANAGEMENT

Managing Director and Chief Operating Officer
Michael Duschenes

Senior Director of Finance and Operations
Stefan Pregelj

Director of Academic Programs
James Forrest

Director of Advancement
Heather Clark

Director of Communications and Media
Colin Hunter

Director of Educational Outreach
Greg Dick

Director of External Relations and Public Affairs
John Matlock

Director of Finance
Sue Scanlan

Director of Information Technology
Ben Davies

Director of People and Culture
Sheri Keffer

Director of Publications
Natasha Waxman

RESIDENT RESEARCHERS

Resident Research Affiliate
John Moffat

Senior Research Affiliate
Steve MacLean

Senior Researcher
Rafael Sorkin

POSTDOCTORAL RESEARCHERS, 2016/17

** Indicates PSI Fellow ** Indicates Director's Fellow*

Tibra Ali*
Masha Baryakhtar
Alice Bernamonti
Joseph Bramante
Agata Branczyk*
Courtney Brell
Sylvain Carrozza
Shira Chapman
Lorenzo Di Pietro
William East**
Angelika Fertig
Federico Galli
Martin Ganahl
Marc Geiller
Steffen Gielen
Roman Gold
Henrique Gomes
Stephen Green
Daniel Guariento
Lauren Hayward Sierens*
Ben Heidenreich
Richard Hill
Junwu Huang
Michael Jarret
Theo Johnson-Freyd
Heeyeon Kim
Shota Komatsu
David Kubiznak*
Ravi Kunjwal
Robert Lasenby
Ian Le
Ashley Milsted
Moritz Munchmeyer
Elliot Nelson
Nestor Ortiz
Prince Osei
Solomon Owerre
Roji Pius
Jorge Alejandro Preciado
Hung-Yi Pu
Djordje Radicevic
C. Jess Riedel
Aldo Riello
Julian Rincon
Ana Belen Sainz
Jamie Sikora
Matteo Smerlak
Dave Touchette
Matt von Hippel
Yuan Wan
Chenjie Wang
Alex Weekes
Wolfgang Wieland
Daniel Wohns*
Elie Wolfe
Gang Xu*
I-Sheng Yang
Shuo Yang
Jie Zhou

James Forrest (Director), Perimeter Institute and University of Waterloo

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

PHD STUDENTS, 2016/17 (partner university, supervisor)

Natacha Altamirano (University of Waterloo, Niayesh Afshordi)
Jasdeep Bains (University of Waterloo, Robert Myers)
Andrzej Banburski (University of Waterloo, Laurent Freidel/Lee Smolin)
Chenfeng Bao (University of Waterloo, Neil Turok)
Jacob Barnett (University of Waterloo, Lee Smolin)
Lakshya Bhardwaj (University of Waterloo, Davide Gaiotto)
Pablo Bosch Gomez (University of Waterloo, Luis Lehner)
Dylan Butson (University of Toronto, Kevin Costello)
Lin-Qing Chen (University of Waterloo, Laurent Freidel/Lee Smolin)
Frank Coronado (University of Waterloo, Pedro Vieira)
Clement Delcamp (University of Waterloo, Bianca Dittrich/Lee Smolin)
Job Feldbrugge (University of Waterloo, Neil Turok)
Adrian Franco Rubio (University of Waterloo, Guifre Vidal)
Utkarsh Giri (University of Waterloo, Kendrick Smith)
Lucia Gomez Cordova (University of Waterloo, Pedro Vieira)
Elizabeth Gould (University of Waterloo, Niayesh Afshordi)
Markus Hauru (University of Waterloo, Guifre Vidal)
Florian Hopfmueller (University of Waterloo, Laurent Freidel)
Qi Hu (University of Waterloo, Guifre Vidal)
Nafiz Ishtiaque (University of Waterloo, Jaume Gomis)
Mansour Karami (University of Waterloo, Niayesh Afshordi/Avery Broderick)
Seth Kurankyi Asante (University of Waterloo, Bianca Dittrich/Lee Smolin)
Tian Lan (University of Waterloo, Xiao-Gang Wen)
Peter Lunts (McMaster University, Sung-Sik Lee)
Gabriel Magill (McMaster University, Cliff Burgess)
Hugo Marrochio (University of Waterloo, Robert Myers)
Dalimil Mazac (University of Waterloo, Davide Gaiotto)
Jonah Miller (University of Guelph, Erik Schnetter)
Sebastian Mizera (University of Waterloo, Freddy Cachazo/Bianca Dittrich)
Seyed Faroogh Moosavian (University of Waterloo, Davide Gaiotto)
Heidar Moradi (University of Waterloo, Xiao-Gang Wen)
Chiamaka Okoli (University of Waterloo, Niayesh Afshordi)
Pedro Ponte (University of Waterloo, Roger Melko)
Masoud Rafiei Ravandi (University of Waterloo, Kendrick Smith)
Miroslav Rapcak (University of Waterloo, Davide Gaiotto/Jaume Gomis)
Nitica Sakharwade (University of Waterloo, Lucien Hardy)
Laura Sberna (University of Waterloo, Neil Turok)
Andres Schlief (McMaster University, Sung-Sik Lee)
David Schmid (University of Waterloo, Robert Spekkens)
Mohamad Shalaby (University of Waterloo, Avery Broderick)
Barak Shoshany (University of Waterloo, Laurent Freidel)
Vasudev Shyam (University of Waterloo, Lee Smolin)
Todd Sierens (University of Waterloo, Robert Myers)
Cedric Sinamuli Musema (University of Waterloo, Robert Mann)
David Svoboda (University of Waterloo, Laurent Freidel/Ruxandra Moraru)
Qingwen Wang (University of Waterloo, Niayesh Afshordi)
Ryan Westernacher-Schneider (University of Guelph, Luis Lehner)
Yasaman Yazdi (University of Waterloo, Niayesh Afshordi)
Guojun Zhang (University of Waterloo, Freddy Cachazo)

MASTER'S STUDENTS, 2016/17 (country of origin)

** Not a part of Perimeter Scholars International*

Eugene Adjei (Ghana)
Javier Arguello Luengo (Spain)
Alvaro Ballon Bordo (Peru)
Yilber Fabian Bautista Chivata (Colombia)
Juan Cayuso (Argentina)
Barak Gabai (Israel)
Anna Golubeva (Russia)
Tomas Gonda (Slovakia)
Alfredo Guevara (Chile)
Jeremy Kelly-Massicotte (Canada)*
Emily Kendall (New Zealand)
Richard Lopp (Germany)
Shengqiao Luo (China)
Fiona McCarthy (Ireland)
Alan Morningstar (Canada)
Surya Raghavendran (USA)
Tomas Reis (Portugal)
Andrei Shieber (Israel)
Olivier Simon (Canada)
Barbara Soda (Croatia)
Suraj Srinivasan (Canada)
Nathanan Tantivasadakarn (Thailand)
Nick Van den Broeck (Belgium)
Annie Wei (USA)
Jingxiang Wu (China)
Yigit Yargic (Turkey)
Yehao Zhou (China)
Yijian Zou (China)

SCIENTIFIC VISITORS, 2016/17

** Indicates Distinguished Visiting Research Chair*
*** Indicates Visiting Fellow*
**** Indicates Emmy Noether Visiting Fellow*

Ben Albert, University of Pennsylvania

Alvaro Martin Alhambra, University College London

Jan Ambjorn, University of Copenhagen/Niels Bohr Institute

Haipeng An, California Institute of Technology

Matthew Anderson, Louisiana State University

Catherine Antwi, University of Ghana

Fabio Anza, University of Oxford

Andrea Appel, University of Southern California

Michael Appels, Durham University

Igal Arav, Tel Aviv University

Abhay Ashtekar*, Pennsylvania State University

Benjamin Assel, European Organization for Nuclear Research (CERN)

Alexander Atanasov, Yale University

Thomas Bachlechner, Columbia University

Newshaw Bahreyni, Gettysburg College

Pinaki Banerjee, Institute of Mathematical Sciences, Chennai

Hans Bantilan, Queen Mary University of London

Till Bargheer, German Electron Synchotron (DESY)

John Barrett, Imperial College London

Itzhak Bars*, University of Southern California

Stephen Bartlett, University of Sydney

Ganapathy Baskaran*, Institute of Mathematical Sciences, Chennai

Brian Batell, University of Pittsburgh

Chris Beasley, Northeastern University

Edwin Beggs, Swansea University

Shalev Ben-David, Massachusetts Institute of Technology (MIT)

Paolo Benincasa, Autonomous University of Madrid/Institute of Theoretical Physics (UAM-CSIC)

Charles Bennett, IBM Thomas J. Watson Research Center

David Ben-Zvi, University of Texas at Austin

Juan Bermejo-Vega, Free University of Berlin

Argelia Bernal, University of Guanajuato

Daniel Berwick-Evans, University of Illinois at Urbana-Champaign

Zhen Bi, University of California, Santa Barbara

Eugenio Bianchi**, Pennsylvania State University

Ginestra Bianconi, Queen Mary University of London

Agnese Bissi, Harvard University

Celine Boehm***, Durham University

Pranjal Bordia, Ludwig Maximilian University of Munich

Radja Boughezal***, Argonne National Laboratory

Suddhasattwa Brahma, Fudan University

Eric Brown, Institute of Photonic Sciences (ICFO)

Dan Browne, University College London

Joren Brunekreef, Radboud University, Nijmegen

João Caetano, École Normale Supérieure

Andrei Caldararu, University of Wisconsin-Madison

Hugo Camargo, National Autonomous University of Mexico (UNAM)

Miguel Campiglia, University of Montevideo

Vitor Cardoso**, University of Lisbon/Higher Technical Institute (IST)

John Cardy*, University of California, Berkeley, and University of Oxford

Steve Carlip, University of California, Davis

Simon Caron-Huot, McGill University

Laura Castelló-Gomar, Institute of the Structure of Matter (IEM)

Sarah Caudill, University of Wisconsin-Milwaukee

Eric Cavalcanti, Griffith University

Hitesh Changlani, Johns Hopkins University

Wissam Chemissany, University of Hannover

Chien-Yi Chen, University of Victoria

Gang Chen, Fudan University

Hsin-Yu Chen, University of Chicago

Jeffrey Chen, University of Waterloo

Weiqiang Chen, Southern University of Science and Technology of China

Meng Cheng, Yale University

Sergey Cherkis, University of Arizona

Gil Young Cho, Korea Advanced Institute of Science and Technology

Aaron Chou, Fermi National Accelerator Laboratory (Fermilab)

Andrey Chubukov, University of Minnesota

Cyril Closset, European Organization for Nuclear Research (CERN)

Katy Clough, King's College London

Joshua Combes, University of Queensland

Dagoberto Contreras, University of British Columbia

Antonin Coutant, University of Nottingham

Pedro Cunha, University of Aveiro

Erik Curiel, Ludwig Maximilian University of Munich

Joseph Curtin, Independent

Leo Cuspinera, Durham University

Mariusz Dabrowski, University of Szczecin

Raffaele D'Agnolo, École Polytechnique Fédérale de Lausanne

Neal Dalal**, University of Illinois at Urbana-Champaign

Saurya Das, University of Lethbridge

Anne Davis, University of Cambridge

Richard Davison, Harvard University

Marco de Cesare, King's College London

Gemma De las Cuevas***, University of Innsbruck

Mykola Dedushenko, California Institute of Technology

Francesco D'Eramo, University of California, Santa Cruz

Andrei Derevianko, University of Nevada, Reno

Pablo Diaz Benito, University of Lethbridge

Emanuela Dimastrogiovanni, Case Western Reserve University

Tudor Dimofte, University of California, Davis

Lance Dixon*, Stanford University

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CONFERENCES AND WORKSHOPS, 2016/17

Formulating and Finding Higher-Order Interference
August 3-5, 2016

Quantum Machine Learning
August 8-12, 2016

Low Energy Challenges for High Energy Physicists II
August 22-26, 2016

Experimental Quantum Foundations
September 23, 2016

2016 Midwest Relativity Meeting
October 13-15, 2016

Infrared Problems in QED and Quantum Gravity
December 7-8, 2016

Exact Operator Algebras in Superconformal Field Theories
December 14-16, 2016

Hitchin Systems in Mathematics and Physics
February 13-17, 2017

Tensor Networks for Quantum Field Theories II
April 18-21, 2017

Quantum Field Theory on Manifolds with Boundary and the BV Formalism
May 8-12, 2017

Shape Dynamics Workshop
May 15-17, 2017

4 Corners Southwestern Ontario Condensed Matter Symposium 2017
May 25, 2017

PI Day
June 1, 2017

International Workshop on Quantum Spin Ice
June 7-9, 2017

Radiative Corrections at the Intensity Frontier of Particle Physics
June 12-14, 2017

Making Quantum Gravity Computable
June 19-23, 2017

Bounce Scenarios in Cosmology
June 26-28, 2017

New Directions in Dark Matter and Neutrino Physics
July 20-22, 2017

Contextuality, Conceptual Issues, Operational Signatures, and Applications
July 24-28, 2017

Women in Physics Canada 2017
July 26-28, 2017

ACADEMIC SPONSORSHIPS, 2016/17

Perimeter sponsored the following off-site conferences and workshops:

"11th International Workshop on Neutrino-Nucleus Scattering in the Few GeV Region (NuINT 2017)," Fields Institute for Research in Mathematical Sciences/University of Toronto

"16th Canadian Summer School on Quantum Information (CSSQI 2017)," University of Sherbrooke

"2016 Fields Medal Symposium," Fields Institute for Research in Mathematical Sciences/University of Toronto

"CIMPA Research School on Combinatorial and Computational Algebraic Geometry," University of Ibadan, Nigeria

"Gauge Theories, Supergravity, and Superstrings," Benasque Science Center, Spain

"International Conference for Women in Physics," University of Birmingham, UK

"Lake Louise Winter Institute 2017," University of Alberta

"Means, Methods, and Results in the Statistical Mechanics of Polymeric Systems II," Fields Institute for Research in Mathematical Sciences/University of Toronto

"New Directions in Theoretical Physics 2," Higgs Centre for Theoretical Physics/University of Edinburgh, Scotland

"Operator Systems in Quantum Information," University of Guelph

"Quantum Information," Benasque Science Center, Spain

"Testing Gravity 2017," Simon Fraser University

"Theory Canada 12," York University

"Workshop on Representation Theory in Quantum Information," University of Guelph

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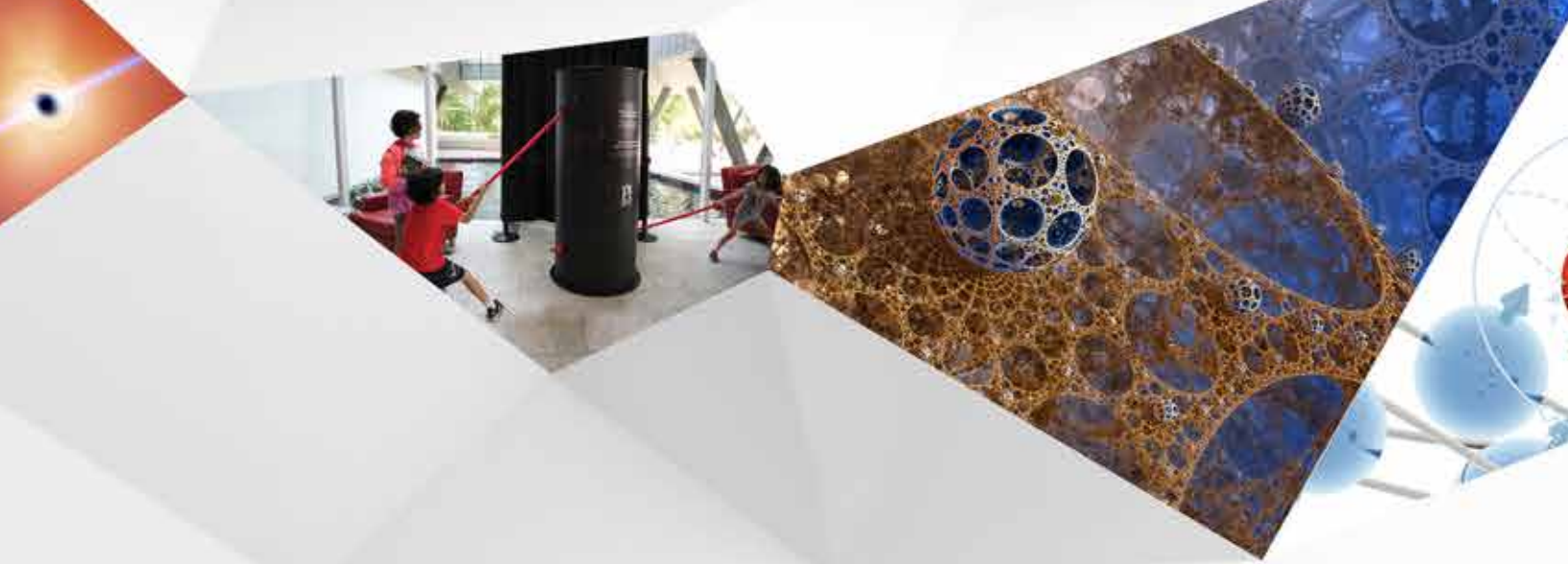

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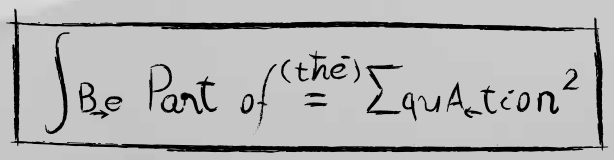

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