2015
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

CONTENTS

This report covers the activities and finances of Perimeter Institute for Theoretical Physics from August 1, 2014, to July 31, 2015.

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WELCOME

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

Here, brilliant physicists explore the nature of reality – from the infinitesimal to the infinite.
Their ideas are unveiling our remote past and enabling the technologies that will shape our future.

Perimeter is training the next generation of physics pioneers and sharing the power 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

11 MAJOR PRIZES AND HONOURS awarded to Perimeter scientists in 2014/15

1,000+ VISITING INTERNATIONAL SCIENTISTS annually

3,400+ PAPERS appearing in 170+ journals with 115,000+ citations since 2001

10,000+ ONLINE TALKS and lectures accessed by viewers in 175 COUNTRIES

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

OUTREACH

5+ MILLION STUDENT INTERACTIONS

17,000+ EDUCATORS trained through Perimeter workshops since 2005

580 TOP HIGH SCHOOL STUDENTS from 48 COUNTRIES have attended the International Summer School for Young Physicists since 2003

61 COUNTRIES have used Perimeter's educational resources

TRAINING

In 2014/15, Perimeter was home to

59 POSTDOCTORAL RESEARCHERS

42 PHD STUDENTS and

29 PSI MASTER'S STUDENTS from 18 COUNTRIES

MESSAGE FROM THE BOARD CHAIR

I am routinely asked, "Is theoretical physics – and specifically quantum mechanics – useful for anything practical?" My answer is, "Yes – Everything!"

Quantum mechanics is essential to every natural science. Quantum mechanics led directly to the transistor, the integrated circuit, Silicon Valley, lasers, superconductors, fibre optics, LED lighting, digital cameras, personal computers, the Internet, wireless digital communications, smartphones, flat panel TVs, video games, modern chemistry, molecular biology (including DNA and proteins), MRI, CAT scans, X-rays, and most of the things that we now take for granted. An author recently noted that more than one-third of the US economy involves technologies and products based on quantum mechanics, and this is only from our first discoveries more than a century ago. Physics has not stood still.

The important work done by researchers at Perimeter Institute and the researchers conducting experiments at the Institute for Quantum Computing at the University of Waterloo has created a solid foundation for the establishment of Quantum Valley in the Waterloo Region of Ontario, Canada.

I believe that we can draw a comparison to researchers at Bell Labs in New Jersey, as well as researchers and graduates from California institutions including Stanford, Berkeley, Santa Cruz, San José State, and others, who helped lay the foundations for Silicon Valley in Northern California. Their work created technologies whose commercialization led to early Silicon Valley companies such as Fairchild, Intel, Hewlett Packard, and Rockwell.

The Quantum Valley of Canada already has a number of new companies that are working toward the development and commercialization of transformative new quantum technologies for global markets. We are optimistic that they, like the early Silicon Valley companies, will lay the foundation for a global large-scale quantum technology commercialization ecosystem in Canada.

The Government of Canada and the Province of Ontario have been fundamental partners and investors in Perimeter since inception as part of one of Canada's most successful public-private partnerships. Perimeter is also very appreciative of the investment from a growing

number of private donors who have provided funding and lent their personal brands in support of the exciting opportunity for Canada that I believe the Institute represents. This year, Gluskin Sheff + Associates, Cenovus Energy, and Clayton Riddell put their weight directly behind Perimeter's research by funding Perimeter Research Chairs for Freddy Cachazo, Subir Sachdev, and Pedro Vieira, respectively. The Stavros Niarchos Foundation has pledged to support an additional chair. The Peter and Shelagh Godsoe Family Foundation and the RBC Foundation have each stepped forward to support Perimeter's vital work in training the next generation of scientists.

As Chair of Perimeter's Board of Directors, it is my happy job to thank some of those volunteers who make Perimeter possible. This includes our Leadership Council, our Emmy Noether Council, and our Board of Directors. In particular, I'd like to welcome new Board member Indira Samarasekera, former President and Vice-Chancellor of the University of Alberta and a leader in Canadian education, research, and technology. Perimeter is honoured to have the support and guidance of such visionary leaders. I want to personally congratulate Art McDonald, a member of our Board of Directors, for his 2015 Nobel Prize in Physics and Breakthrough Prize in Fundamental Physics. Art shared these prizes for the work he led at Canada's SNOLAB, the world's leading facility for the study of neutrinos and dark matter physics.

Today, we find ourselves awash in new experimental data, from the earlier Planck satellite to CERN's breathtaking discovery of the Higgs boson, and now the detection of gravity waves by LIGO confirming the predictions of Einstein's theory of general relativity. Theoretical physics is on the verge of new discovery. The last time this occurred, a century ago, theoretical physics gave us quantum mechanics and relativity – and their application has since led to the greatest industrial revolution and value creation the world has ever known. I believe that we are poised for the next big breakthrough in our understanding of spacetime, energy, matter, extra dimensions, and gravity that will empower the next great quantum industrial revolution. And I believe Perimeter Institute will continue to play a key and fundamental role for Canada, its citizens, its universities, its industry, and its prosperity.

– Mike Lazaridis

MESSAGE FROM THE INSTITUTE DIRECTOR

We are entering the most exciting period in decades for fundamental physics. Observations and measurements drawn from the universe, on all scales, are expanding the frontiers of our knowledge. We are living in a golden age of data of unprecedented power and range.

This data is astonishing, in a wonderful and challenging way. It has revealed extreme simplicity in the universe on the largest and smallest accessible scales. In contrast, the universe is extremely complex on the everyday, intermediate scales with which we are most familiar. Likewise, the universe's beginning and its far future seem puzzlingly simple, with all the complexity occurring around the intermediate epoch we live in. Basic features of our cosmological model, such as the dark energy, challenge the very framework upon which modern theories of physics have been built (i.e., the theory of quantum fields). They are guiding us toward radical new principles capable of reconciling quantum theory and relativity, and explaining the simple – yet currently paradoxical – universe we find ourselves in.

Perimeter Institute is ideally positioned to develop new theories and paradigms capable of addressing these puzzles. Designed as the optimal environment for foundational physics research, Perimeter is attracting world-leading young scientists who are opening up path-breaking new lines of research. In the last year, Faculty members Natalia Toro and Philip Schuster shared the New Horizons in Physics Prize, the most prestigious prize in theoretical physics for early-career scientists. Researchers at Perimeter have won the prize three years in a row; no other institution's researchers have done so more than once. Another of our young faculty members, Clay Riddell Paul Dirac Chair Pedro Vieira, won the Gribov Medal, the top European prize for young physicists. Again, Perimeter is unique for having three faculty members who have won this accolade, including Gluskin Sheff Freeman Dyson Chair Freddy Cachazo in 2009 and Krembil Galileo Galilei Chair Davide Gaiotto in 2011.

Not only are new paradigms required to understand the extremes of the cosmos, they are also needed to conceptualize the complex, quantum properties of matter on everyday scales. Xiao-Gang Wen, a pioneer in this field, joined Perimeter as the BMO Financial Group Isaac Newton Chair, soon followed by Dmitry Abanin, a young leader in quantum condensed matter physics. We are delighted to welcome Max Metlitski, a returning Canadian and pioneer in his own right. Max has just won the two top early-career prizes in condensed matter physics. His research centres on using quantum field theory to describe complex many-body quantum materials, many with novel and surprising properties suggesting powerful new technological applications.

One of Perimeter's most distinctive research areas is the field of quantum foundations. We are delighted to welcome Markus Mueller, a young leader in this field, as an associate with Western University. Markus explores connections with causality and relativity, as well as the mathematical structures in quantum theory.

Historically, exchanges between mathematics and physics have often been the key to new breakthroughs. Several of our faculty members are pioneers in mathematical physics. Last year, we were very pleased to be joined by Krembil William Rowan Hamilton Chair Kevin Costello, a pure mathematician who is exploring radically new mathematical foundations for quantum field theory. Recently, Alexander Braverman joined us as an associate with the Department of Mathematics at the University of Toronto. He is a leading light in the "geometric Langlands program," an area of pure mathematics related to quantum field theory which seeks to unify math's main branches: analysis, algebra, and geometry.

As a part of our growing efforts in cosmology, Ue-Li Pen, one of the most original and creative astrophysicists worldwide, has joined us as an associate with the Canadian Institute for Theoretical Astrophysics in Toronto. One of his most significant contributions was to point out that the neutral hydrogen throughout the universe could provide us with a 3D map of the cosmos, with vast information about its structure. With the help of key experimentalists, this idea evolved into the Canadian Hydrogen Intensity Mapping Experiment (CHIME), Canada's world-leading effort to map the structure of the universe.

Perimeter is, I believe, unique among theory institutes for its combination of mathematical theory and strong ties to experiment: the Large Hadron Collider, the Event Horizon Telescope, LIGO, SNOLAB, CHIME, and many more. Perimeter scientists are placing Ontario and Canada not only at the forefront of developing new theories, but also of testing those theories to the limit in some of the most important experiments of our time.

In June, we held an unusual scientific gathering, "Convergence," which brought together many of the world's most prominent experimental and theoretical physicists, across all subfields, along with very promising young scientists. We challenged them all to leave their comfort zones and take a "big picture" view of where physics stands now, and where the most exciting opportunities for the future will lie. Many attendees reported that they'd never before been exposed to such a wide range of physics, and many felt it was one of the most exciting gatherings they'd ever attended.

At Perimeter, we challenge ourselves to be agile, entrepreneurial, and on the alert for promising new directions. These often fall in between rather than within more established fields. This year, we have established several new cutting-edge initiatives – on the emergence of spacetime, on tensor networks, on a new method for describing complex quantum systems, and on a project to observe the detailed structure of black holes – that bring together the right mix of expertise and youthful talent to promote rapid progress.

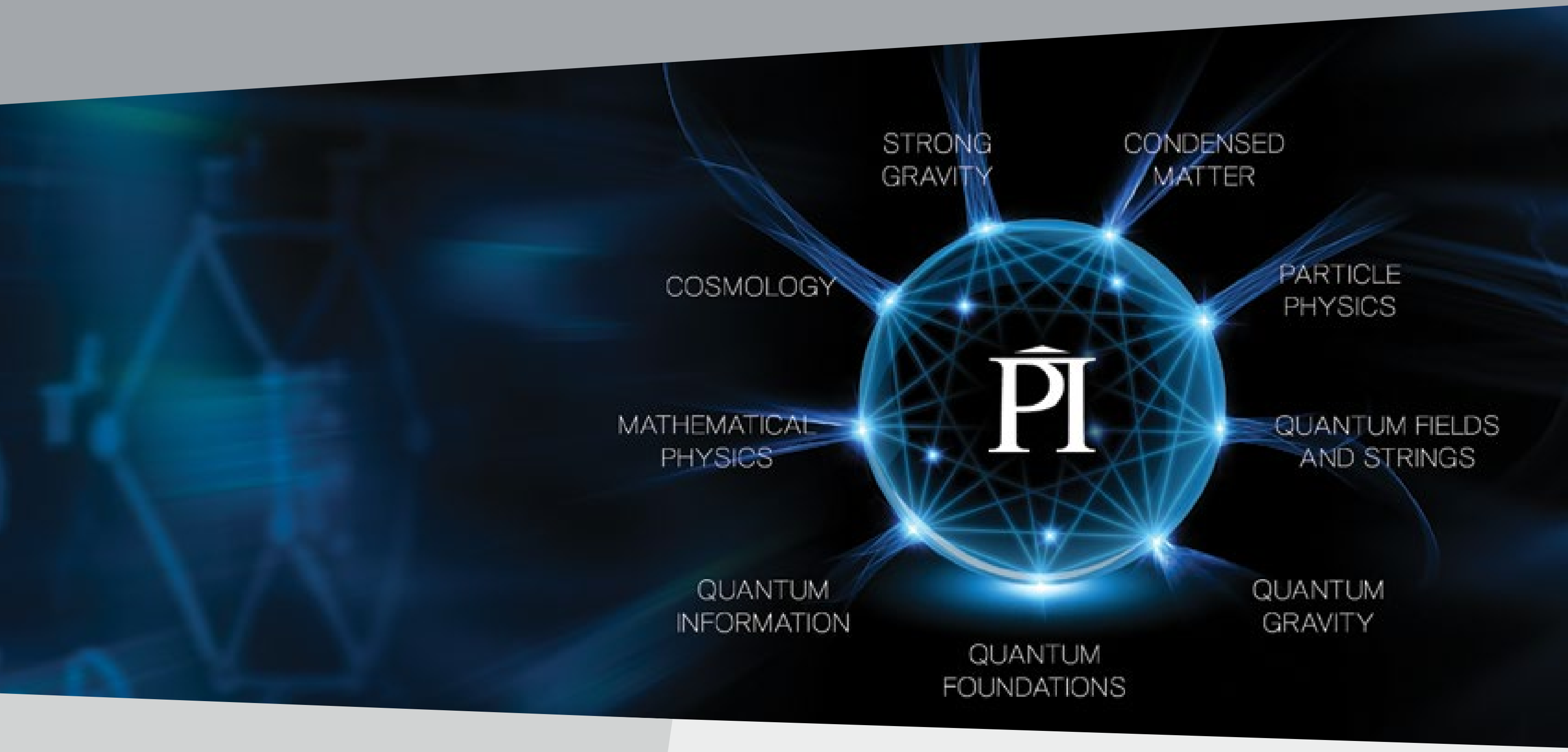
One of our own Board members, Art McDonald, has shown us what can be achieved with foresight, collaboration, and an adventurous spirit, by winning both the Nobel Prize in Physics and the Breakthrough Prize, for his discovery of neutrino oscillations at the SNO experiment in Sudbury. His trailblazing research and his contributions to building physics in Canada are a fantastic example to us all.

In the 20th century, discoveries in basic physics gave rise to millions of jobs and trillions of dollars of new wealth, based on transistors, computers, MRI, GPS, wireless communications, smartphones, and more. The 21st century economy will most likely rest on innovations from quantum physics, including quantum computers, sensors, communicators, and other devices. Perimeter Institute is proud to be a part of the Quantum Valley emerging right here in Ontario. We aim to be the wellspring of a flourishing quantum ecosystem that covers the spectrum from basic physics discoveries and advanced training, to experimental labs, technology development, venture capital, and an entrepreneurial, start-up culture. The combination could, we believe, be unparalleled anywhere on the planet.

The coming quantum revolution is likely to be even more transformative than the digital revolution. And this time, we believe, Canada can lead the way.

– Neil Turok

RESEARCH



"Are we on the verge of the next scientific and technological revolution? Those of us who invest in Perimeter Institute are betting that we are."

– Bill Downe,
CEO of BMO Financial Group,
the Presenting Sponsor of the "Convergence" conference and supporter of the BMO Financial Group Isaac Newton Chair in Theoretical Physics at Perimeter Institute

How did the universe begin? What is it made of? What is the nature of dark energy and dark matter? How do we understand and harness the quantum world?

Perimeter researchers tackle big ideas – forging new theories about the nature of the universe – from space and time to matter and information.

From the outer reaches of the cosmos to the infinitesimal realm described by particle physics and string theory, our universe is unveiling itself at an unprecedented rate, thanks to explorers at the forefront of theoretical physics.

Perimeter research spans nine strategically chosen fields. The Institute's researchers are leaders in their respective areas, but the true strength of Perimeter's approach lies at the intersections of the fields – the unexpected discoveries that happen when a cosmologist and a mathematical physicist chat at the coffee machine, or a string theorist bumps into a quantum gravity expert at one of the Institute's ubiquitous blackboards.

Perimeter brings brilliant minds together under one roof, encouraging them to tackle nature's toughest questions. Collaboration fuels discovery. With interdisciplinary research networks spanning the globe, Perimeter's scientists connect with top institutions and experiments worldwide.

IMAGINING THE FUTURE AND MAKING IT POSSIBLE

In 1959, when computers still filled entire rooms, theoretical physicist Richard Feynman imagined the future, and it was smaller.

“Why cannot we write the entire 24 volumes of the *Encyclopædia Britannica* on the head of a pin?” he asked in a famous lecture at Caltech. He went further, asserting that not only could you encode every letter in a handful of “bits” on the face of the head of a pin, but you could use the interior of the pin as well!

“There is plenty of room at the bottom!” Feynman told his audience. He even ruminated about fiddling with atoms, in the deepest realm of nature where classical physics is supplanted by the laws of quantum mechanics. “We can manufacture in different ways. We can use, not just circuits, but some system involving quantized energy levels or the interactions of quantized spins,” he predicted.

Now, Feynman’s vision is being realized. Quantum computing may well be the revolution that shapes the 21st century.

QUANTUM INFORMATION

Quantum computers, which capitalize on quantum effects such as "superposition" and "entanglement" to achieve processing power far surpassing present-day computers, are expected to revolutionize how we work, communicate, and live. Much theoretical research is required, however, before these technologies can emerge. Perimeter researchers explore quantum error correction – the techniques needed to safeguard and verify information amid the errors inherent to quantum computation. Researchers also pursue the foundations of quantum cryptography, which capitalizes on uniquely quantum laws – such as the uncertainty principle – to safeguard private information. Many of Perimeter's quantum information researchers collaborate with scientists at our nearby experimental partner, the Institute for Quantum Computing (IQC) at the University of Waterloo, and some hold joint appointments at both institutes. Together, Perimeter and IQC are transforming the region into the world's "Quantum Valley."

SCATTERSHOT BOSON SAMPLING

If you are flipping coins and hope to turn up five heads at the same time, you have two options: take five coins and keep flipping them until the odds finally work in your favour, or flip a lot of coins at once and only count the ones that turn up heads.

That second method, it turns out, is highly effective if applied to a device called a boson sampler, considered to be a potential precursor to quantum computing.

In a boson sampler, photons are sent into an interferometer, pass through beam splitters, and emerge on the other side.

To generate the photons, experimentalists use parametric down-conversion (PDC) to create paired photons that split off in opposite directions; one goes into the interferometer, the other heralds their twinned existence.

But there is no simple and reliable way to generate paired photons on demand. In order to create 30 photons at once (enough to run an experiment that is too hard for a classical computer to simulate), researchers could wait so long – weeks, months, or longer – that it renders the experiment impractical.

In 2013, a new "scattershot" approach was suggested. Just like flipping many coins increases the chances of having five turn up heads, triggering a lot of PDCs at once is more likely to generate enough photons to run a worthwhile experiment.

This year, Perimeter Institute postdoctoral researcher **Daniel Brod** was part of an international theory-and-experiment collaboration that did just that.

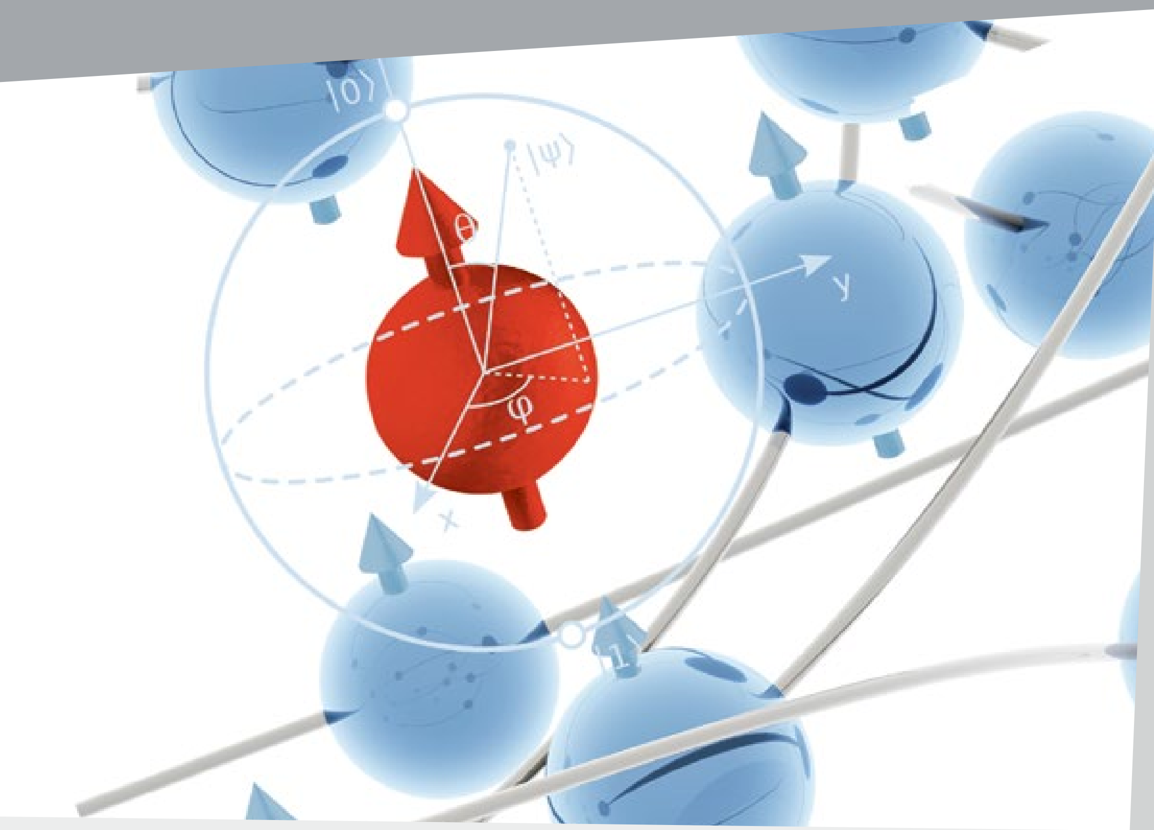
The scattershot boson sampling experiment, performed in the quantum optics lab of Fabio Sciarrino at the Sapienza University of Rome and published in the new web-based journal *Science Advances*, collected data 4.5 times faster than earlier samplers.

"This approach promises exponentially larger improvements as the experiments scale up," Brod says.

The improvement also addresses one of the big problems facing boson sampling: the reliance on PDC photon sources. The team showed that, even without photons-on-demand, it is possible to generate enough photons to run a worthwhile experiment.

Reference:

D.J. Brod (Perimeter Institute) et al., "Experimental scattershot boson sampling," *Sci. Advances* Vol. 1, no. 3 (2015), e1400255, DOI: 10.1126/sciadv.1400255.



HARNESSING QUANTUM DECOHERENCE

Imagine a tennis ball is being bombarded by transparent paper clips coming from all around it. The paper clips are hard to see, but every time one hits the tennis ball, the sphere moves a little bit. Over time, you can deduce the presence of the paper clips even though you cannot see them directly because you see the tennis ball move back and forth apparently at random.

Now, suppose the paper clips are instead bombarding a bowling ball. The bowling ball will move much less than the tennis ball, so you won't be able to see its movement. However, the paper clips change direction radically when they hit the bowling ball, and which direction they bounce depends on where the bowling ball is.

If you could put the bowling ball in a quantum superposition – that is, in two places at once – the paper clips will find out where the ball is located, destroying the quantumness of the bowling ball's superposition and collapsing it to be only in one place.

PI postdoctoral fellow **Jess Riedel** has investigated this scenario and shown that quantum decoherence can indeed be a powerful tool for detecting particles (in the example's case, transparent paperclips) which would be invisible to purely classical measurements. Such a process might be useful, for instance, for detecting dark matter particles.

This research is timely because the sensitivity of this technique grows quickly with the size of the superposed object, and experiments creating large superpositions have recently seen rapid progress. So-called matter interferometers have produced superpositions of giant molecules with a hundred atoms, and superpositions of tens of thousands of atoms will be possible in the near future.

Reference:

C.J. Riedel (Perimeter Institute and IBM Watson Research Center), "Decoherence from classically undetectable sources: A standard quantum limit for diffusion," arXiv:1504.03250.

IT FROM QUBIT

Jacob Bekenstein and Stephen Hawking rocked theoretical physics in the 1970s by showing that black holes have entropy and radiate thermal radiation.

Interestingly, entropy plays a key role in quantum information theory as well. Bekenstein and Hawking's discoveries are now recognized as the first clues of profound connections between quantum information theory and Einstein's theory of gravity, general relativity.

They are qualitatively very different theories. Einstein's theory of gravity gives a geometric picture of spacetime, while quantum mechanics is a theory of particles with indeterminacy at its heart. Figuring out how to knit them together (since they both describe the same universe) has bedevilled physicists for over half a century.

Recently, remarkable progress has been made using a set of mathematical approaches called holography, and Faculty member **Robert Myers** is one of the world leaders in this exciting area. In August 2015, Perimeter hosted the "Quantum Information in Quantum Gravity II" workshop, one in a series of meetings that are helping this remarkable new research area to coalesce. The connections are so promising that the Simons Foundation provided a major five-year grant, "It from Qubit," to develop this area, led in part by Myers, with Perimeter as one of its hubs.

MATHEMATICAL PHYSICS

In mathematical physics, problems originally encountered in physics give rise to new mathematics needed to solve them, and, likewise, new mathematical tools may open doors to new ways of understanding the physical universe. Newton invented the calculus of infinitesimals because he needed it to understand mechanics – and calculus went on to redefine all of physics. 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. Perimeter's mathematical physics researchers continue this grand tradition.

PHYSICISTS WEAVE A WEB TO MATHEMATICS

A significant contribution to mathematical physics in 2015 was the publication of a 400-page paper by Perimeter's Krembil Galileo Galilei Chair in Theoretical Physics, **Davide Gaiotto**, along with Gregory Moore (Rutgers University) and Edward Witten (Institute for Advanced Study), which brings together a number of powerful tools from advanced mathematics and string theory to analyze the structure of massive two-dimensional field theories.

The theories concerned involve supersymmetry, proposed as a solution to both cosmic and subatomic mysteries in physics, and they are also important in mirror symmetry, a topic central to current research in geometry.

Gaiotto, Moore, and Witten sketch applications of the approach (the theory of webs) to objects of interest in current mathematical research. The work exemplifies the significant impact that theoretical physics researchers at Perimeter are having on pure mathematics and the importance of powerful mathematical tools for understanding the behaviour of quantum fields, our most basic description of nature.

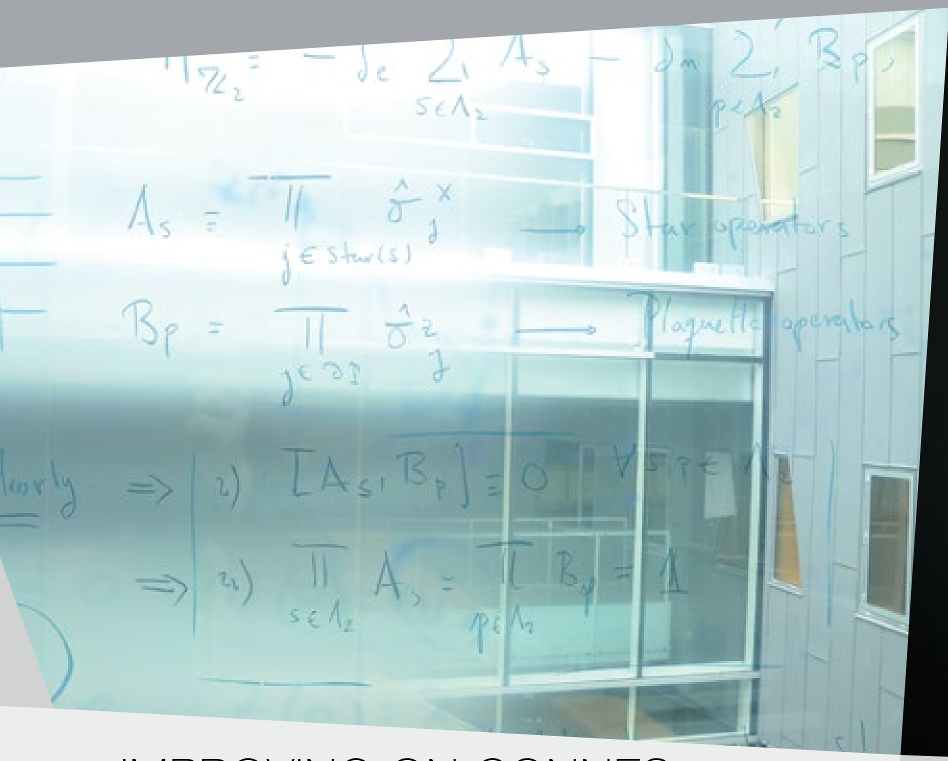
PROOFREADING AN INFINITE DICTIONARY

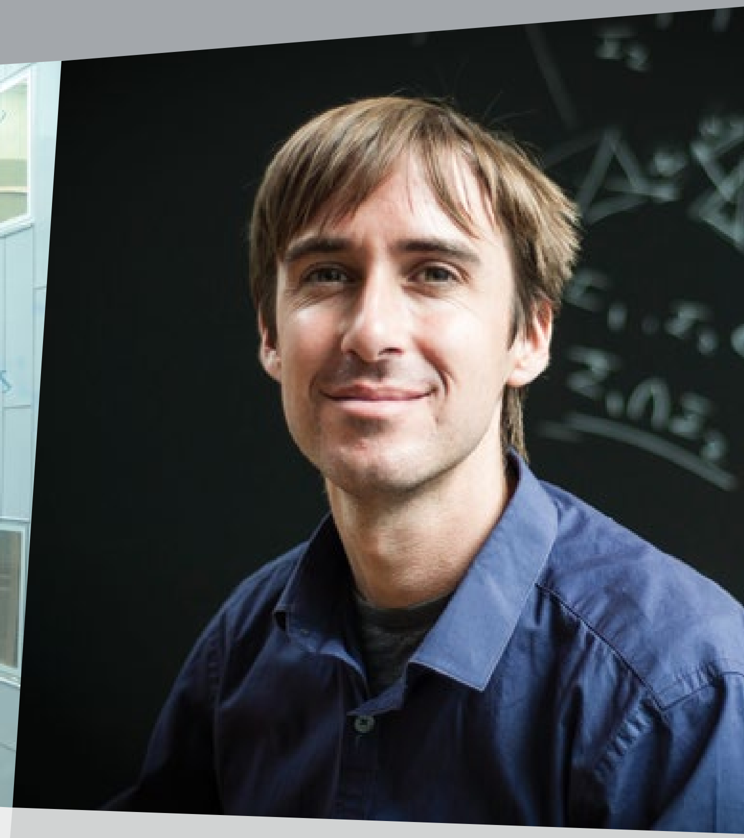
In 1998, Juan Maldacena proposed the impossible: a translation dictionary between certain theories of gravity and certain field theories. It's called the AdS/CFT correspondence, or sometimes the gravity/gauge duality, and it gives physicists a way to tackle, for example, a hard problem in condensed matter by rewriting it into the language of black holes. The language of the two theories is so starkly different that it's often hard to believe that the reality being described is the same. And yet, Maldacena asserted, it is.

Although initially met with skepticism, Maldacena's proposal has now been tested and used in over 10,000 papers. It is absolutely central to string theory and widely used all over physics – yet a mathematical proof is still lacking.

The main difficulties with developing a mathematical proof of this "dictionary" are that it would have to include an infinite number of words and a single failure could destroy it.

Kevin Costello, Perimeter's Krembil William Rowan Hamilton Chair in Theoretical Physics, has started an ambitious and novel program for a proof of Maldacena's proposal. Costello's program, conducted with Perimeter Visiting Fellow **Si Li**, is rigorously constructing part of the gravity theory, and formulating the correspondence in mathematical terms.





IMPROVING ON CONNES

In the late 1970s, pioneering French mathematician Alain Connes developed a branch of mathematics called noncommutative geometry, a framework in which the standard model of particle physics, coupled to Einstein's gravity, could be elegantly reformulated.

In 2014, Perimeter Faculty member **Latham Boyle** and co-author **Shane Farnsworth** (a Perimeter graduate student) discovered a way of simplifying and generalizing Connes' principle, making it into a tool to construct new unified models of particle physics.

Their innovation removes a number of open questions in the original formulation of Connes' proposal, giving it greater potential predictive power.

It is an unusual case of a physicist improving a mathematical framework – the kind of fruitful interaction of fields that Perimeter aims to encourage with its recently strengthened emphasis on mathematical physics.

References:

D. Gaiotto, G. Moore, and E. Witten, "Algebra of the Infrared: String Field Theoretic Structures in Massive N=(2,2) Field Theory In Two Dimensions," arXiv:1506.04087.

K. Costello and S. Li, "Quantization of Open-Closed BCOV Theory-I," arXiv:1505.06703.

S. Farnsworth and L. Boyle, "Rethinking Connes' approach to the standard model of particle physics via non-commutative geometry," *New J. Phys.* 17 023021 (2015), arXiv:1408.5367.

MATH + PHYSICS = BEAUTIFUL IDEAS

When I was a child in Cork, Ireland, my father subscribed to *Scientific American*. It featured these wonderful mathematical columns which told you, for instance, how to program the Mandlebrot set. I would try to do this on my home computer. I couldn't quite do it – I was 10 – but the beauty of it got me excited and led to a career in mathematical physics.

In 2013, while at Northwestern University, I was invited to join Perimeter as the Krembil William Rowan Hamilton Chair.

It's a unique environment, where there is strong collaboration between mathematicians and string theorists, cosmologists, particle physicists, and others. Most recently, I have been working on ideas related to supergravity – a combination of Einstein's theory of gravity and supersymmetry. It's a beautiful idea that is very fun to try to understand.

In a place where pure mathematics and theoretical physics intersect, exciting things can happen. When a mathematician and a physicist approach the same problem, they'll always take different points of view. It is useful to get different perspectives and this collaboration sparks my curiosity in a way reminiscent of those *Scientific American* puzzles.

– Kevin Costello,
Krembil William Rowan Hamilton Chair in Theoretical Physics

COSMOLOGY

Almost all the clues we have about physics beyond the Standard Model come from cosmology, where observations probe length scales, time scales, and energy scales way beyond the reach of terrestrial laboratories. Cosmology therefore provides a natural focal point for much of the fundamental physics research conducted at Perimeter, including particle physics, quantum fields and strings, and strong gravity. Cosmologists at Perimeter Institute are seeking to bring all of these fields together, in order to understand the biggest questions about the universe, including its contents, structure, origins, and evolution.

A NEW ERA DAWNS

For most of human history, the big questions in cosmology have seemed more like philosophy than science: How did the universe begin? How did it evolve? Where is it going? More recent questions include: What is dark matter, needed to explain the clustering of galaxies? What is dark energy, the mysterious something that is causing the expansion of our universe to accelerate?

Until recently, answers to these questions seemed beyond reach. But spectacular new observations combined with new theoretical insights have brought cosmology into a golden era, in which the greatest mysteries are finally becoming accessible to science.

One of the most significant advances has been the advent of precision mapping of the relic radiation left over from the big bang. The cosmic microwave background radiation (CMB) has been mapped in exquisite detail by NASA's WMAP satellite and by the European Space Agency's Planck satellite. Dozens of smaller scale experiments are also underway, mapping the CMB's fine structure, including its polarization, and searching for signals of an early inflationary phase of the universe. Cosmologists at Perimeter have played leading roles in predicting the observational consequences of cosmological theories and in analyzing the gigantic data sets.

One of those researchers is **Kendrick Smith**, who has led the effort to study the statistical pattern of the primordial density variations, responsible for seeding structures in the universe. He developed the most efficient and complete methods to search for primordial deviations from Gaussianity. Along with Leonardo Senatore and current Perimeter Institute Distinguished Visiting Research Chair **Matias Zaldarriaga**, Smith published two landmark papers in 2009 analyzing the five-year WMAP data. In 2013 and 2015, he led the data analysis effort which resulted in a far stronger limit on non-Gaussianity from the Planck data. This impressive result is one of the key outcomes of the Planck satellite project. It rules out many theoretical models and points to a remarkable simplicity in whatever mechanism generated the structures in the universe.

NEW COSMOLOGICAL SOLUTIONS

Most theoretical studies and models of cosmology focus on the physics and the evolution of the universe from shortly after the big bang singularity until the present.

Although Einstein's equations for gravity, combined with standard model physics, can explain the expansion of the universe and how it cooled and produced the galaxies and stars we see today, the equations break down at the initial singularity 14 billion years ago where, according to Einstein's theory, the size of the universe was zero and its density and temperature, as well as the curvature of spacetime, were infinite.

The breakdown of the equations obstructs any attempt to understand exactly what happened at the big bang. Did the universe begin at the big bang? If so, how and why? If not, what came before?

In recent years, Richard P. Feynman Chair **Paul Steinhardt** and **Neil Turok**, Perimeter Director and Mike and Ophelia Lazaridis Niels Bohr Chair, along with their collaborators, have been developing new approaches to these questions based upon the hypothesis that, at its root, fundamental physics should not have a scale.

In a recent series of papers, they have uncovered a range of new cosmological solutions in which a contracting universe passes through an exotic anti-gravity phase before starting its expansion.

In very recent work, Turok and **Steffen Gielen** of Imperial College (and formerly a postdoctoral fellow at Perimeter) have shown how the Feynman path integral for quantum gravity may be calculated in these cosmological settings, giving a precise quantum description of what they term "a perfect bounce." They explain how one can consistently describe the quantum passage of a universe through a cosmological singularity. This work opens the way to a new class of theoretical models, which may in time be capable of explaining the Planck satellite's remarkable findings in a compelling and unique way.

A surprising spinoff of Gielen and Turok's work was their realization that the very early universe, even in the most conservative picture, must have contained shocks – abrupt jumps in the density of the fluid of radiation which filled space at that time. Fortunately, Associate Faculty member **Ue-Li Pen**, based at the Canadian Institute for Theoretical Astrophysics and an expert in computational hydrodynamics, was on hand to help work out the details. These shocks might have a number of important consequences, from helping to explain the preponderance of matter over antimatter in today's universe, to the existence of cosmic magnetic fields, to the generation of primordial gravitational waves which may be detectable in future experiments.

References:

K. Smith et al., "Planck 2015 Results. XVII. Constraints on primordial non-Gaussianity," arXiv: 1502.01592.

I. Bars, P. Steinhardt, and N. Turok, "Local Conformal Symmetry in Physics and Cosmology," *Phys. Rev. D* 89 043515 (2014), arXiv:1307.1848.

S. Gielen and N. Turok, "A Perfect Bounce," arXiv:1510.00699.

U. Pen and N. Turok, "Shocks in the Early Universe," arXiv:1510.02985.

PERIMETER FACULTY

Dmitry Abanin (on leave)

Asimina Arvanitaki

Latham Boyle

Freddy Cachazo, Gluskin Sheff Freeman Dyson Chair in Theoretical Physics

Kevin Costello, Krembil William Rowan Hamilton Chair in Theoretical Physics

Bianca Dittrich

Laurent Freidel

Davide Gaiotto, Krembil Galileo Galilei Chair in Theoretical Physics

Jaume Gomis

Daniel Gottesman

Lucien Hardy

Luis Lehner

Robert Myers

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

Philip Schuster

Kendrick Smith

Lee Smolin

Robert Spekkens

Paul Steinhardt, Richard P. Feynman Chair in Theoretical Physics (Visiting)

Natalia Toro

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

Guifre Vidal

Pedro Vieira, Clay Riddell Paul Dirac Chair in Theoretical Physics

Xiao-Gang Wen, BMO Financial Group Isaac Newton Chair in Theoretical Physics

STRONG GRAVITY

From the big bang to neutron stars and black holes, Perimeter research into strong gravity explores cosmic cataclysms powerful enough to warp the fabric of spacetime. These areas of space where gravity is extremely strong serve as a natural experiment where researchers can theoretically "test" the validity of our current theory of gravity (Einstein's general relativity) and investigate alternative theories. Perimeter researchers also seek to understand and characterize the ways that curved or dynamical spacetimes are connected to other fundamental questions of physics.

THE MULTIMESSENGER PROMISE

The direct detection of gravitational waves by the Advanced LIGO experiment is the beginning of a revolution, one that will vastly deepen our understanding of the most weird and wonderful objects in the universe – black holes and neutron stars – and their interactions.

Most astronomy today is electromagnetic, done with telescopes that look at light. But whether it is gamma ray, X-ray, or infrared, what we detect is all part of the same spectrum.

Now, thanks to the detection of gravitational waves, we can start probing the universe with a different sense. We can listen, as well as look. A new generation of gravitational wave detectors is coming online to listen for ripples in the fabric of spacetime. Astrophysicists hope that this global network of detectors will allow us to spot colliding black holes, or collapsing binary neutron star systems.

This gravitational data will be particularly powerful and interesting if we can combine it with electromagnetic data from traditional telescopes, an idea that goes by the name "multimessenger astronomy."

Faculty member **Luis Lehner** is one of those giving careful thought to what multimessenger astronomy could teach us. For example, in recent work, Lehner and collaborators studied the collision of two neutron stars. It is known that these stars collapse and blow off their outer shells. It's an incredibly violent process that creates some of the heaviest atoms in the universe – elements too heavy to be created even in the furnace of the hottest stars. Many of these atoms are unstable and, as they decay, they produce a characteristic electromagnetic signal.

Using complex simulations, Lehner et al. showed that certain details about the collapse would affect the quantity and kind of heavy atoms created, which in turn would affect the electromagnetic signal the decaying elements emit.

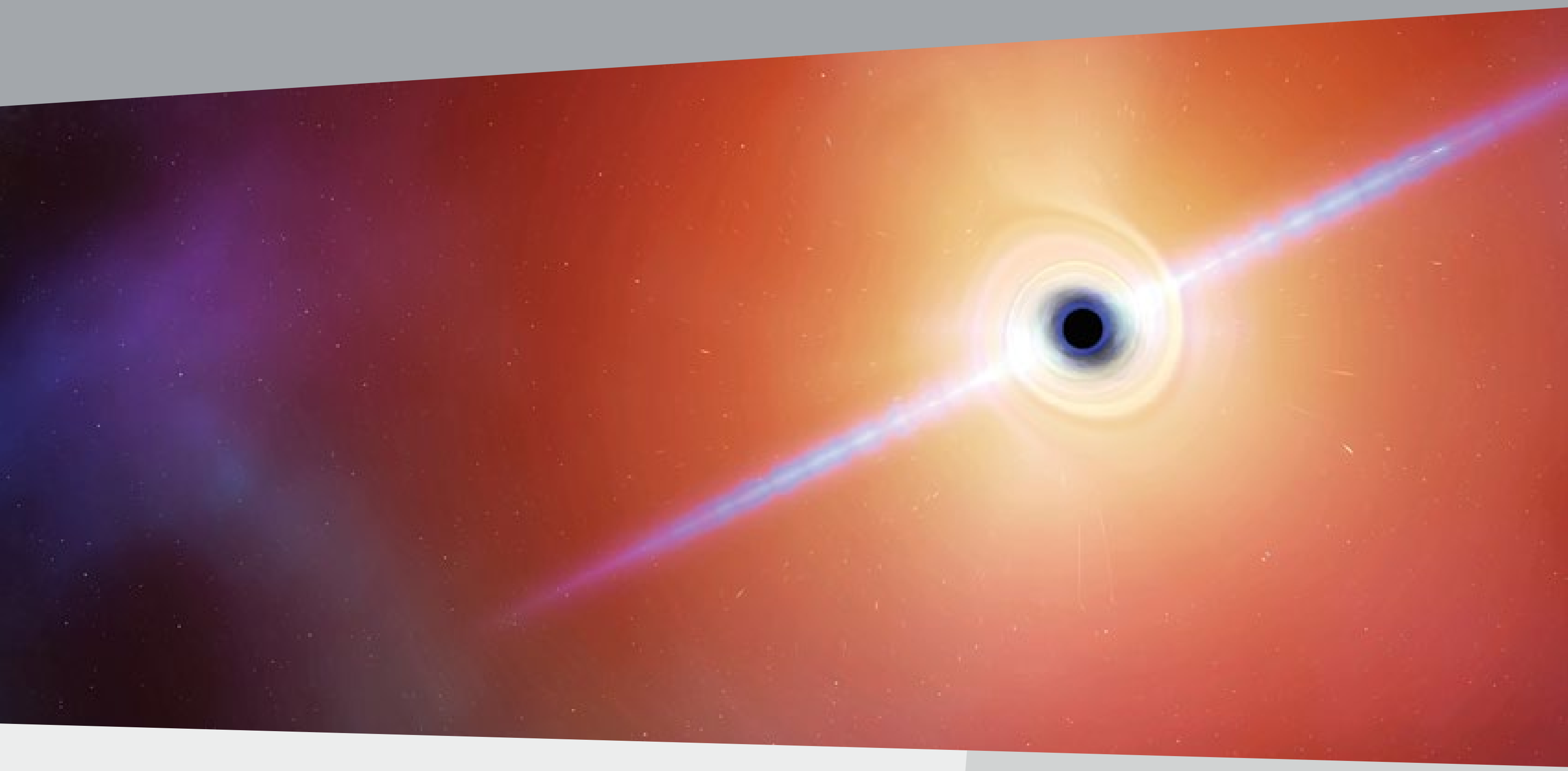
By looking at both that electromagnetic signal from the decaying elements and the gravitational signal from the colliding stars at the same time, astrophysicists will learn far more about the details of neutron star collapse than they could learn from either signal in isolation. Two senses are better than one.

THE BLACK HOLE TEST

For physicists interested in putting Einstein's general relativity to the test, there is nothing better than a black hole.

Black holes have the twin virtues of being extraordinarily simple solutions to Einstein's equations and of being the place where Einstein's predictions about gravity differ most sharply from Newtonian ideas about gravity. If we could see a black hole clearly, we could see whether general relativity holds up in extreme conditions.

Through the work of people like Perimeter Associate Faculty member **Avery Broderick**, such a close-up look at black holes is



becoming possible. Broderick is one of the lead researchers on the Event Horizon Telescope (EHT) project. The EHT is a global network of radio telescopes that is slowly producing remarkably detailed pictures of the black hole at the heart of our galaxy, and of the black hole at the heart of the nearby M87 galaxy.

With this new data, researchers are beginning to validate the stories we tell about black holes. For instance, the EHT team published a careful study of the luminosity of the M87 black hole. The goal of the study was to tell whether the object has a hidden surface, or if it has the kind of event horizon that black holes have long been said to have. The conclusion? There is no surface. Other EHT projects have studied the growth of black holes, the structure of their magnetic fields, and the origins of their mysterious jets.

In addition to analyzing data, theorists like Broderick are identifying what kinds of data would distinguish a black hole obeying the laws of general relativity from a black hole doing something slightly different. In other words, researchers are learning what to look for, as well as learning how to look. All in all, it seems the age of black hole observation may be beginning.

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Ue-Li Pen (Canadian Institute for Theoretical Astrophysics/University of Toronto)

Maxim Pospelov (University of Victoria)

Itay Yavin (McMaster University)

CONDENSED MATTER

The challenge of condensed matter physics can be summed up in a single observation: the behaviour of a system with many particles can be very different from that of its component particles. Condensed matter physicists study these many-body systems, especially those that are in a condensed state. At Perimeter, researchers tackle such fundamental issues as the nature of superconductors or the possible different phases of matter, as well as cutting-edge questions such as whether we can describe gravity as a property of a material, or tailor an exotic form of quantum matter for use inside quantum computers.

THE THEORY OF (QUANTUM) EVOLUTION

For decades, physicists have thought of "quantum-ness" as something seen only on microscopic scales or in very cold systems. Quantum phenomena such as superposition and entanglement typically cancel out in large systems through processes called "dissipation" (random interactions between the system being studied and the rest of the laboratory) and "thermalization" (internal mixing and interactions of the system itself).

Thanks to recent experimental progress, it is now possible to create, manipulate, and study artificial quantum many-body systems where dissipation is almost zero and in which quantum effects can persist over long times. Now, theorists predict that, in the presence of disorder, thermalization may also be evaded and such systems may no longer obey the conventional laws of statistical mechanics.

In these so-called localized many-body systems, quantum effects are seen in systems with a large number of particles, evolving dynamically over a long time. The strange behaviour of such systems may be important, even useful, in the design of various proposed quantum technologies. As a result, the problem of understanding how quantum systems evolve has come to the fore.

In 2013, Faculty member **Dmitry Abanin**, postdoctoral researcher **Zlatko Papić**, and **Maksym Serbyn** (then a graduate student at MIT and a Perimeter visitor) fuelled a breakthrough by developing a theory that explains the breakdown of statistical mechanics in localized many-body systems, and replaces it with new laws of quantum dynamics. This is a general result that can be applied to any strongly disordered experimental quantum many-body system.

Over the past few years, their work has been remarkably influential, stimulating a huge amount of new research on many-body localization (and the consequent avoidance of thermalization) in the international condensed matter community. For example, the Kavli Institute for Theoretical Physics in California recently ran a program that brought together researchers from around the world to brainstorm on these new ideas and their implications.

Perimeter researchers remain at the forefront of these exciting developments, in exploring the laws governing the dynamics of quantum many-body systems. Within the past year, Abanin and Papić have worked with other researchers to take their ideas even further. Their recent papers have provided new insights into largely unexplored questions about many-body localization, such as whether it can occur in systems with no disorder.

It's one important step toward the quantum leap we need.

GETTING TO THE HEART OF ENTANGLEMENT

Quantum entanglement is increasingly emerging as a common theme connecting quantum information, condensed matter, and quantum gravity. But understanding quantum entanglement remains a significant challenge.

Entangled particles become intertwined – or correlated – and stay that way, even after they are widely separated in space. Perimeter Faculty member **Guifre Vidal** is a pioneer of tensor networks, a new language for describing the behaviour of highly entangled quantum systems. Vidal was the first to apply ideas of quantum information to quantum lattice systems, which play a crucial role in understanding many-particle quantum behaviour in condensed matter physics.

Tensor networks also provide a way to better investigate emergence, a separate but related aspect of many-body physics in which the collective dynamics of a system produce higher-level properties – just as individual water molecules, operating in tandem, ultimately form complex waves in the ocean.

In the last decade, tensor networks have revealed a startling range of applicability. Beyond understanding nature on its own quantum terms, tensor network states may well play a central role in the description of systems relevant to new quantum technologies.

A key element in Vidal's ongoing work is the multi-scale entanglement renormalization ansatz (MERA), a tensor network he proposed in 2005 that exploits the spatial structure of entanglement to produce a computationally tractable, efficient description of ground states, even at a quantum critical point.

As a powerful and universal tool for understanding quantum systems, MERA has attracted wide interest. For example, it is currently being scrutinized by string theorists as a lattice realization of the holographic principle, and is also being used by researchers in quantum information, condensed matter, statistical mechanics, and quantum gravity.

Two recent papers co-authored by Vidal made a breakthrough in our fundamental understanding of tensor networks and provide a new perspective into ideas of entanglement. The insight allows the MERA formalism to be extended to classical statistical systems. The papers also provide a first principles derivation, making MERA much more accessible to researchers in other fields.

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Guifre Vidal and colleague Juan Maldacena (IAS)

SEIZING OPPORTUNITY

Truly new ideas often fall outside established frameworks, yet they are exactly the ones which can most benefit from an intense, cross-disciplinary boost.

Recognizing this, Perimeter launched several multi-year initiatives to gather emerging and senior scientists across fields in order to accelerate progress in promising areas.

Tensor networks, for example, are a powerful new set of numerical approaches for describing strongly entangled quantum many-body systems that is proving widely useful in many areas of physics.

The five-year Tensor Networks Initiative, led by Perimeter Faculty member **Guifre Vidal**, includes Faculty member **Bianca Dittrich**, Director's Fellow **Zheng-Cheng Gu**, and Associate Faculty member **Roger Melko**, whose collective expertise spans quantum information, quantum gravity, high-energy theory, and condensed matter theory.

This year, the program brought together subject leaders from Perimeter and around the world for workshops and conferences, including the Mathematica Summer School on entanglement, and the "Quantum Information in Quantum Gravity" conference series.

Learn more about Tensor Networks and other Perimeter Special Initiatives at: www.perimeterinstitute.ca/research.

PARTICLE PHYSICS

Particle physics explores nature's constituents and interactions at the most fundamental level. As such, it has strong overlaps with string theory, quantum gravity, and cosmology. At Perimeter, particle physics researchers often compare theoretical ideas with both astrophysical observations and Earth-bound experiments like the ones carried out at the Large Hadron Collider (LHC), and study how such results can help us map the physics beyond the Standard Model.

DARK MATTER AS CRACKS IN THE GLASS

Dark matter is four times as common as ordinary matter, and yet we know almost nothing about it. The leading hypothesis is that, like ordinary matter, dark matter is made of particles. But what if it doesn't resemble our traditional ideas of matter at all?

Perimeter Associate Faculty member **Maxim Pospelov** and collaborator Andrei Derevianko of the University of Nevada are investigating that possibility.

Instead of particles, picture a field with cracks in it, like broken safety glass. The field itself might be undetectable, the way perfectly clear glass is invisible. But the cracks are different. Just as cracks in glass can be seen, cracks in the field can, perhaps, be detected.

The researchers contend that we might be able to detect them with instruments we already have: atomic clocks, laser interferometers, and gravitational wave detectors.

This take on dark matter is known as topological dark matter, and the cracks themselves are generically called topological defects (TDs). You can think of these TDs as a stationary backdrop to the universe, with Earth crashing through at speeds of about 300 kilometres per second.

When an atomic clock crosses a TD, Pospelov and Derevianko contend, it would either slow down or speed up, depending on the nature of the interaction. If one had a network of atomic clocks, an encounter with a TD would look like a wave of such out of sync events, which should be detectable.

Pospelov and Derevianko have even been able to calculate details about what such a wave would look like if the GPS satellites surrounding Earth encountered a TD: the on-board clocks would shift in a characteristic order determined by their orbital positions, over a span of about three minutes.

Initial experiments are already underway. Whether they can spot topological dark matter, only time will tell.

A GRAVITATIONAL ATOM IN THE SKY

If dark matter is a particle, then what kind of particle is it? It turns out, that's not a small question.

Faculty member **Asimina Arvanitaki** recently explored a scenario in which black holes could actually provide clues to the identity of dark matter.

Suppose, she argued, that a particle's size – or, more technically, its Compton wavelength – is comparable to that of a black hole. Such a particle can become bound by the intense gravity of the black hole, dragged by its rotating spacetime into a kind of lockstep – a process originally theorized by, and eventually named after, astrophysicist Roger Penrose.

Bound together by the Penrose process, the particle and the black hole become what Arvanitaki calls a "gravitational atom in the sky." The notion poses intriguing possibilities in the hunt for nature's underlying building blocks, including dark matter.

As the incredible forces of the black hole wreak havoc on the surrounding spacetime, a process called superradiance causes the number of particles to grow very quickly – exponentially – in the orbit around the black hole, extracting energy and angular momentum from the black hole.

Particles can transition between energy states, producing gravitons (similar to how transitions of electrons in atoms can produce photons – the process by which a laser works). Pairs of particles can also annihilate, transforming into a pair of gravitons – one of which is absorbed by the black hole, the other escaping it. Both phenomena create a signal that could be detected on Earth: gravitational waves.

Arvanitaki believes this process may allow researchers to diagnose the presence of a particle called the QCD axion, a hypothetical elementary particle that is considered by many to be a potential candidate for dark matter.

WHAT ABOUT THE DARK SIDE?

Dark matter is thought to comprise a quarter of the mass in the universe, yet remains mysterious. There is abundant indirect evidence for its existence, yet it has never been directly detected, since it does not interact with ordinary matter except through gravity. But what if it interacts with itself? There could conceivably be an entire dark sector of physics, ruled by forces that we cannot feel. If there were such unknown forces, could we find out?

Perimeter Faculty members **Philip Schuster** and **Natalia Toro** are leading figures in the quest to discover dark matter. Working with Perimeter postdoctoral researchers **Eder Izaguirre** and **Gordan Krnjaic**, they proposed an elegant set of experiments using “low energy” accelerators to search for dark matter as well as so-called “dark forces,” as-yet undetected forces.

Their work opened a new subfield, and hundreds of scientists are searching for new forces and for dark matter through a dozen different high-energy and nuclear physics experiments. Schuster and Toro themselves have helped bring three experiments from the blackboard to the beamline: APEX, of which they are spokespeople, and HPS and BDX, of which they are founding leaders. They also have other exciting new proposals to search for dark matter in the pipeline.

This approach to particle physics is complementary to that pursued at the LHC, and every bit as fundamental. Anything these experiments discover will be paradigm-shifting.


Natalia Toro and Philip Schuster

“I was very drawn by all the other people around. It’s a very energetic, active, hardworking group, really trying to do something big. I view a lot of the work we do here as really paving the way for the next generation of big science.”

– Natalia Toro

“This place is all about trying to make discoveries. That means we all try to push ourselves, and each other, to not just work on things that were maybe popular five years ago, or the latest elaboration of an idea. We’re really pushing each other to do something new, to make a new discovery.”

– Philip Schuster

This year, Natalia Toro and Philip Schuster jointly won the prestigious New Horizons in Physics Prize from the Breakthrough Prize Foundation for their ground-breaking approach to new physics searches at the Large Hadron Collider, and for spearheading new searches for dark matter.

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QUANTUM FIELDS AND STRINGS

Quantum field theory is the modern paradigm with which we understand particle physics, condensed matter systems, and many aspects of early-universe cosmology. It is used to describe the interactions of elementary particles, the dynamics of many-body systems, and critical phenomena, all with exquisite accuracy. Perimeter researchers are producing world-leading advances in quantum field theories.

String theory is a theoretical framework that was proposed as a unified description of all particles and forces in nature, including gravity. It is based on the idea that, at very short distances, all particles should in fact be seen to be extended one-dimensional objects – that is, "strings." Modern string theory has grown to be a broad and varied field of research with connections to and implications for quantum gravity, particle physics, and cosmology, as well as mathematics.

FINISHING THE QUILT

One of the most basic questions in string theory is what happens when strings interact. One fruitful way of tackling that question has been to turn it into one of topology. Picture a single closed string, like a tiny vibrating loop of energy. In the same way a point moving through space traces a straight or curvy line, that string moving through space draws a cylinder that resembles a kind of wobbly drinking straw. In the parlance of string theory, this surface is known as the string's world sheet.

As the string begins to interact with other strings and with its environment, it creates more complex topologies and more complex world sheets, which require more complex calculations.

Pedro Vieira, Perimeter's Clay Riddell Paul Dirac Chair, is engaged in an ambitious, long-term research project to simplify these calculations and bring the string interactions into analytic reach for the first time. He's had many collaborators, most recently including Perimeter PhD students **Lucia Cordova** and **Joao Caetano** and postdoctoral researchers **Benjamin Basso**, **Shota Komatsu**, and **Amit Sever**.

The basic thrust of the research has been to learn first to cut the complex topologies into pieces, and then to patch those pieces back together – string theory as quilting. The researchers learned to cut the topologies describing closed strings (or loops) into hexagons and the open strings as pentagons. They then developed mathematics that allow them to stitch these pieces back together, thus creating arbitrarily large and complex world sheets.

There has always been a risk that this program could fail at the last minute – that the behaviour of the world sheets at the points where they are mathematically cut and stitched could be just too complex to manage. But this year, the research program passed that major milestone and the various pieces were at last put together.

This is a major result, which may well have long-term impact on both string theory and particle physics.

IS QUANTUM FIELD THEORY A STRING THEORY IN DISGUISE?

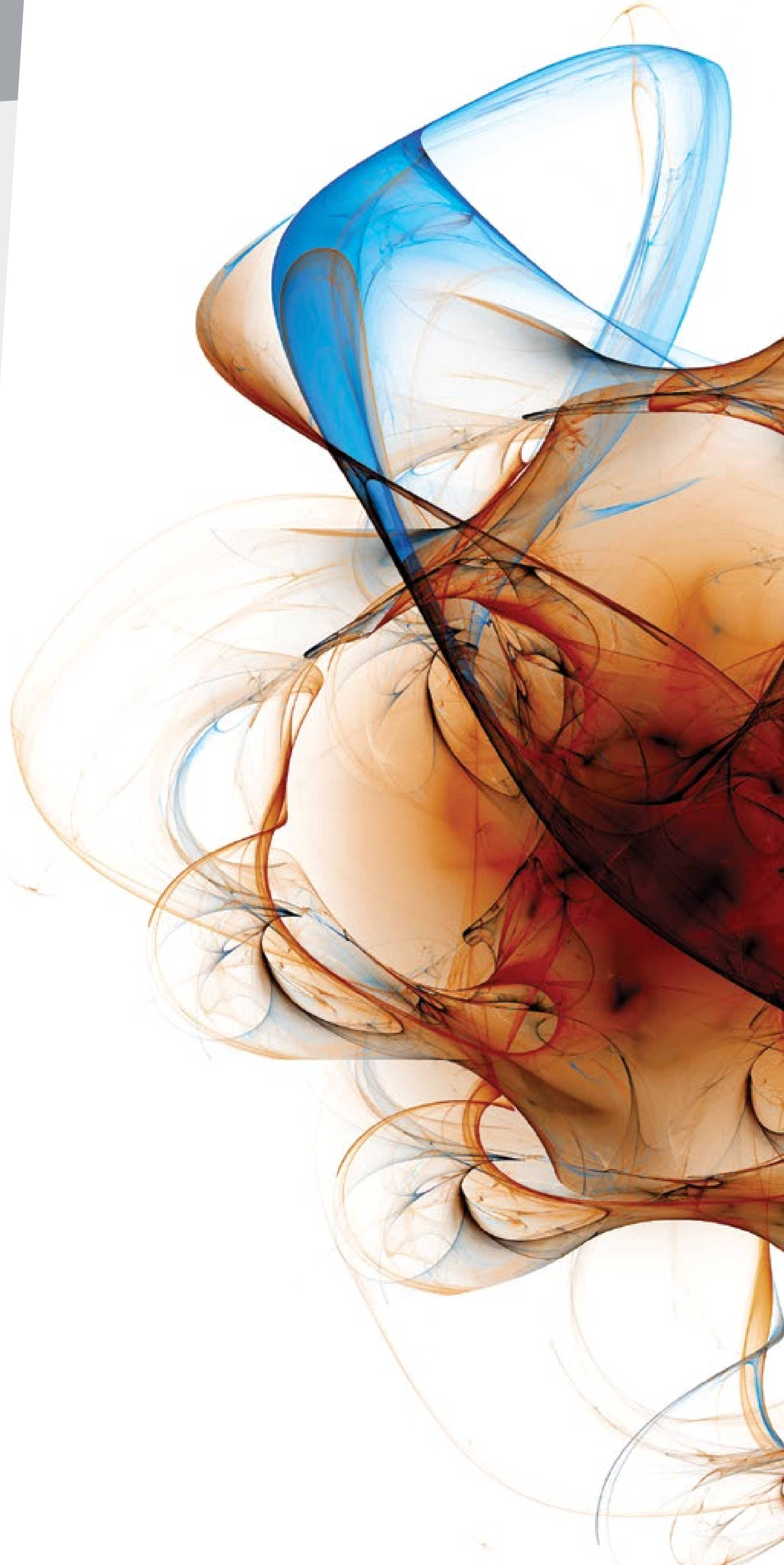
Quantum field theory (QFT) is the backbone of our best models of the universe. Any theory that aspires to go deeper and become unified with Einstein's theory of gravity must, at some limit, be able to be represented by a QFT.

String theory was developed to do just this. At the heart of string theory is the idea that all the different kinds of particles in the universe are made out of the same basic object, an extended string, just in different vibrational modes. This is both a bold and beautiful idea.

However, in string theory, there is a limit in which the strings shrink and become point-like. In this limit, they can be represented by a QFT. This is an intriguing hint that string theory may provide the desired unification, but more evidence is needed before it can be taken to be a unified theory of nature.

In December of 2014, Perimeter researchers **Freddy Cachazo** (Gluskin Sheff Freeman Dyson Chair), **Song He** (postdoctoral fellow), and **Ellis Yuan** (Perimeter and University of Waterloo graduate student) showed that a large variety of well-known QFTs (including Einstein gravity and electromagnetism) can be described directly in terms of a novel kind of "big" string – that is, not in the limit when the strings become point-like.

What is now known as the Cachazo-He-Yuan formulation takes the scattering amplitudes (quantities used for computing the outcomes of a particle collider experiment) of quantum field theories and expresses them as interactions on a two-dimensional plane, where one-dimensional strings move in time (one more dimension).



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QUANTUM GRAVITY

Quantum gravity aims to complete the revolution in physics Einstein started, by unifying the general theory of relativity with quantum theory into a single theoretical framework. Perimeter researchers are actively pursuing a number of approaches to this problem, including loop quantum gravity, spin foam models, asymptotic safety, emergent gravity, string theory, and causal set theory. The search for quantum gravity overlaps with other areas such as cosmology, particle physics, and the foundations of quantum theory.

THE EMERGENCE OF SPACE AND TIME FROM ATOMS OF QUANTUM GEOMETRY

We know that air and metals are not smooth. The properties that distinguish gases from liquids, and both from solids, are emergent from the complicated motions and interactions of myriads of atoms.

It has long been hypothesized that space and time are also made up of vast numbers of fundamental "atoms of quantum spacetime." What we call space and time would then be emergent from the interactions of those atoms.

For theorists, a central challenge has been to develop techniques by which the properties of classical spacetime, and in particular the equations of general relativity, can be derived from the fundamental dynamics of these atoms of quantum spacetime.

Major progress toward this goal has been made by Faculty member **Bianca Dittrich**, who has been leading the development of a new paradigm for the analysis of the large-scale behaviour of quantum spacetime, which she calls "boundary coarse graining."

With collaborators (including Perimeter graduate students **Sebastian Mizera** and **Sebastian Steinhaus**), she has successfully applied this new paradigm to a series of model quantum spacetimes of increasing complexity and dimension. They have also discovered a new "phase" of quantum spacetime. The researchers are now poised to apply their techniques to fully realistic models of four-dimensional quantum spacetime.

A FRESH LOOK AT STRING THEORY AND SPACETIME

Perimeter Faculty member **Laurent Freidel** and collaborators have proposed a new approach to string theory, with startling implications about the nature of space and time.

They used a newly discovered principle, called relative locality, to reimagine string theory. Relative locality asserts that whether two events occurring far from an observer are coincident depends not just on the motion of the observer (as in Einstein's relativity theory), but also on the energy of light used to observe the events.

The principle – proposed by Freidel, Perimeter Faculty member **Lee Smolin**, and collaborators – implies that that the structure of space and time depends on the energy of the probes we use to observe it.

By applying it to string theory, Freidel and collaborators have posited a radically new picture of both spacetime and string theory, in which a fundamental string moves in a novel quantum geometry they call modular spacetime.

This new work gives theorists a deeper understanding of some of the symmetries and dualities of string theory, such as the Born duality under which the dynamics of a system can be expressed in terms of position or momentum.

TIME COMES FIRST

Before quantum theory and general relativity can be combined, one key issue must first be clarified: the two theories have different conceptions of time.

Perimeter Faculty member **Lee Smolin** is developing a new approach to that unification by considering time as fundamental to the expression of the laws of physics. This rests on three key suppositions: that causal relations and the flow of moments are fundamental aspects of reality; that irreversibility is fundamental, so events cannot be turned back; and that the laws of nature are not static, but themselves evolve in time.

Smolin developed this framework in a series of papers which culminated in two books – *The Singular Universe and the Reality of Time* and *Time Reborn*. He has followed that with a new formulation of quantum spacetime, created with University of Edinburgh cosmologist Marina Cortês, called energetic causal sets. (This builds upon earlier work on other causal set models done by Perimeter researchers **Rafael Sorkin** and **Cohl Furey**.)

In a series of three papers, Smolin and Cortês developed their theory analytically and by numerical simulation, and discovered an application to spin foam models (which are realistic models of quantum geometry). The work received the inaugural Buchalter Prize, which was created "to stimulate ground-breaking theoretical, observational, or experimental work in cosmology that challenges, extends, or illuminates current models and/or helps explain the cosmic expansion from first principles."

In further work, together with Perimeter postdoctoral researcher **Henrique Gomes**, they showed that general relativity can be extended naturally to a theory that is irreversible in time – a finding that may be tested in cosmological observations.

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QUANTUM FOUNDATIONS

The study of quantum foundations concerns the conceptual and mathematical underpinnings of quantum theory. Research in quantum foundations at Perimeter Institute aims to refine and reformulate quantum theory in ways that express its true nature and structure. Research in this field is closely tied with work in quantum gravity and quantum information.

QUANTUM CAUSE AND EFFECT

Correlation does not imply causation. That's a caution drilled into scientists and statisticians alike. If you have only two variables, A and B, and they seem to rise and fall together, it does not necessarily mean that A effects B or B effects A. They could merely share a common cause. Unless you can actively experiment on the system, it is impossible to tell a cause-effect relation from a common-cause relation. Hence the caution.

But the caution now needs to be updated. Recent research from Perimeter and the Institute for Quantum Computing (IQC) says that in a quantum world, certain kinds of correlations *can* imply causation.

The research is both theoretical and experimental. Perimeter Faculty member **Robert Spekkens** and PhD student **Katja Ried** worked with Max Planck Institute scientist Dominik Janzing from the theoretical end. They considered the situation of an observer who takes two measurements of a quantum variable – say, the polarization of a photon – at two different points in time. The observer does not know if she is measuring the same photon twice (that is, if she is measuring a cause-effect relationship) or if she is measuring each of a pair of entangled photons (that is, if she is measuring a common-cause relationship). The theorists' crucial insight was that the correlations observed in the cause-effect case have a different pattern than those arising from a common cause according to quantum theory, allowing them to tell the two scenarios apart.

The theory became reality at IQC, where Kevin Resch's group built a circuit wherein the experimenter herself does not know the causal relation. Just as the theorists predicted, the patterns of correlations revealed which causal structure was realized.

The take-away message is that correlation does not imply causation unless it's quantum. This discovery has both foundational significance and the potential for applications to quantum technology.

QUESTIONING WEAK VALUES

New work by Perimeter postdoctoral researcher **Joshua Combes** and Chris Ferrie of the University of New Mexico asserts that a key technique used to probe quantum systems may not be so quantum after all.

The technique in question is called "weak measurement," and it works something like this. Perhaps you want to measure the spin of some particles. You would prepare particles in some particular state – say spin up, throwing away the data from particles that are spin down. This is called "pre-selection." Later, you would detect the particles in a final state, again throwing away spin-down particles. This is called "post-selection."

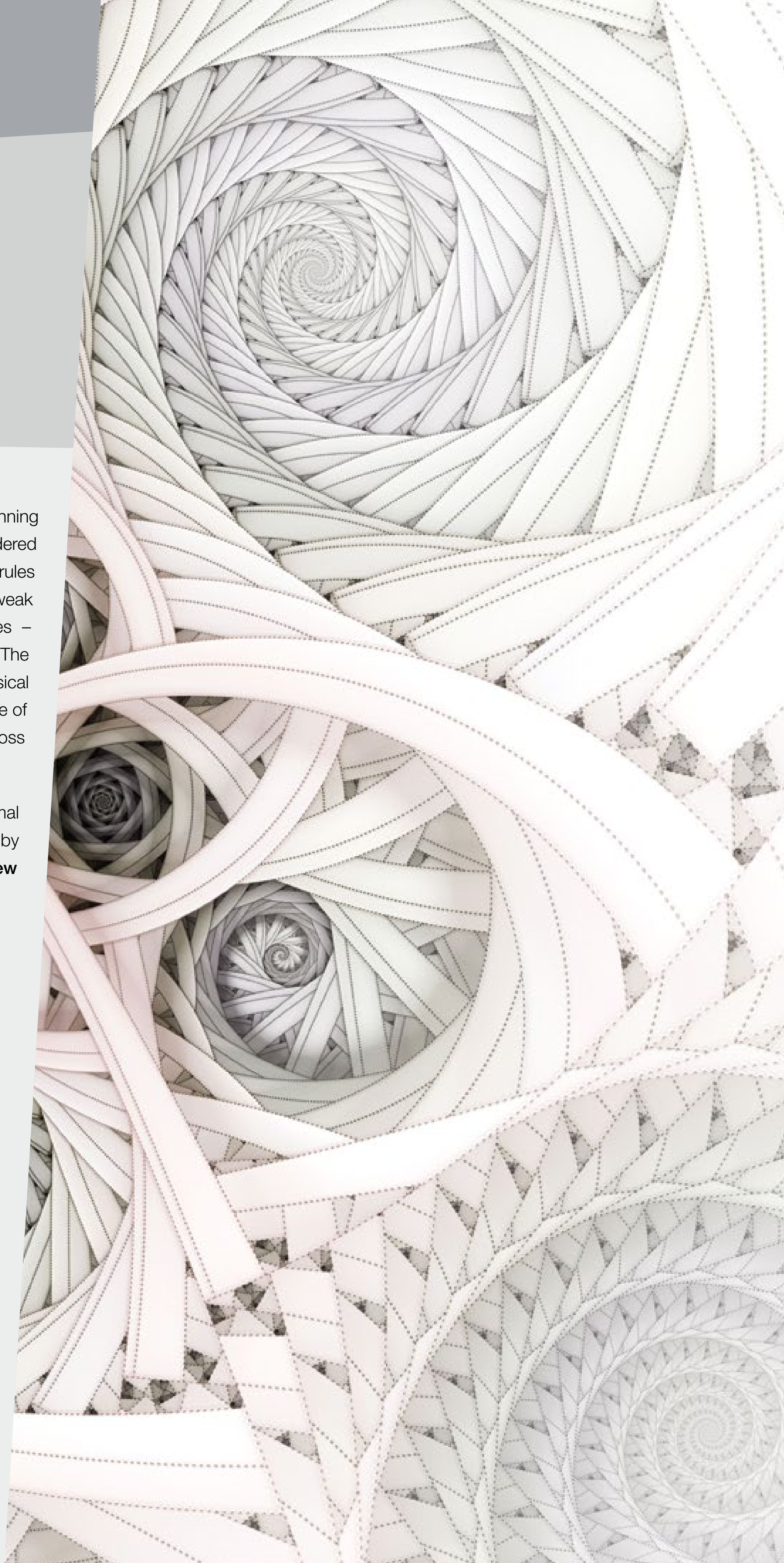
You also make a measurement in between. In order to minimize disturbances to the system, you measure that spin as gently – as weakly – as possible, and average over a large number of trials.

Combining pre-selection, post-selection, and weak measurement gives an unexpected result, which can be glimpsed in the title of the landmark 1988 paper by Yakir Aharonov (now a Perimeter Distinguished Visiting Research Chair) et al., "How the measurement of a component of the spin of a spin-½ particle can turn out to be 100." This odd outcome – a measurement that should be +½ or -½ turning out to be 100 – is called a "weak value," and it is thought to be an important new window into the quantum world.

But could weak values have a purely classical analogue? That's the question Combes and Ferrie set out to answer.

Where Aharonov et al. considered spinning particles, Combes and Ferrie considered flipping coins. By combining the same rules of pre-selection, post-selection, and weak measurement, they replicated weak values – even though coins are clearly not quantum. The "weak value" in this case is an artifact of classical statistics and classical disturbances. The title of their paper: "How the result of a single coin toss can turn out to be 100 heads."

The provocative work generated six formal comments in rebuttal and a related paper by Perimeter postdoctoral researcher **Matthew Pusey**.

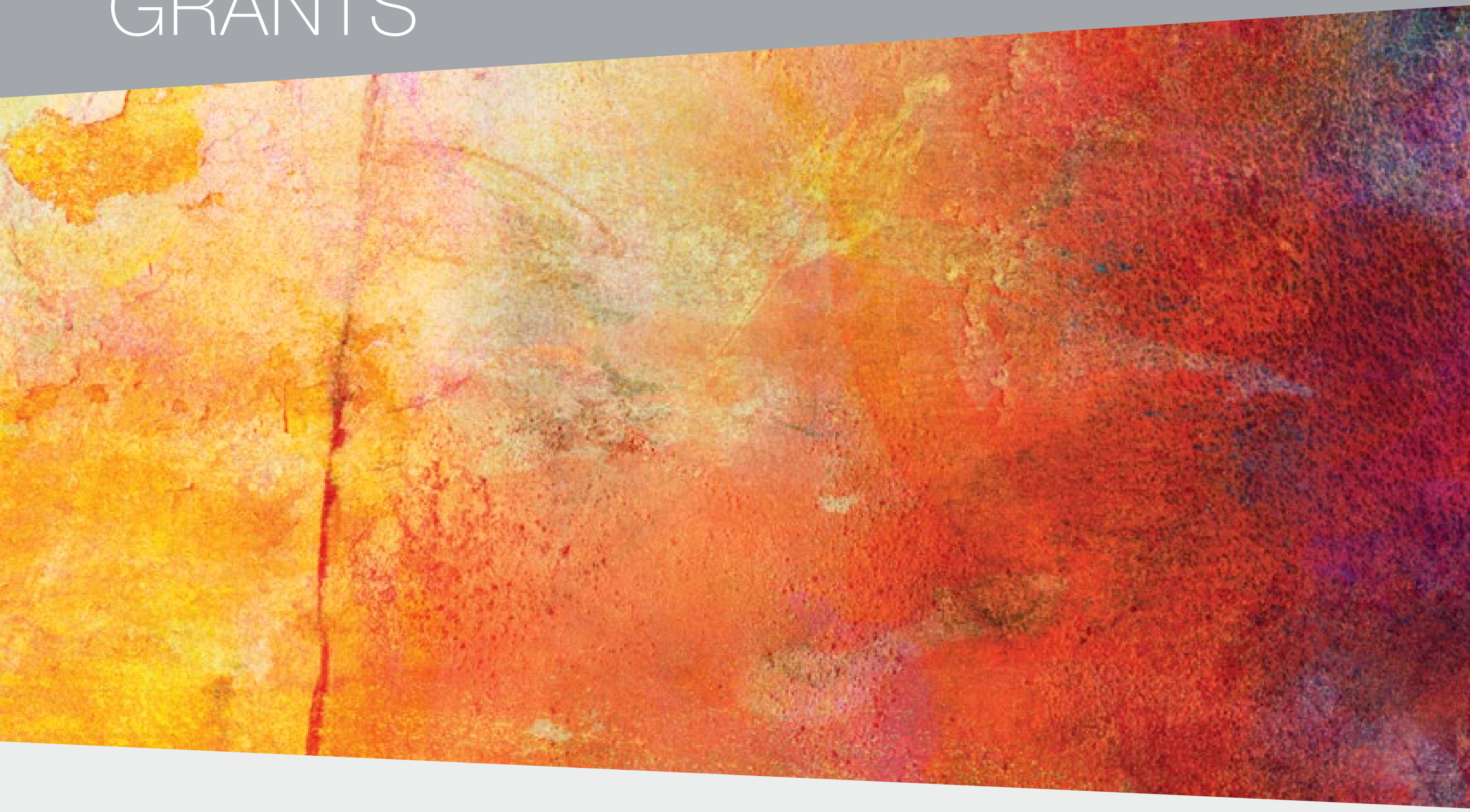


References:

K. Ried, M. Agnew, L. Vermeyden, D. Janzing, R.W. Spekkens, and K.J. Resch, "A quantum advantage for inferring causal structure," *Nature Phys.* 11, 414-420 (2015) doi:10.1038/nphys3266.

C. Ferrie and J. Combes, "How the Result of a Single Coin Toss Can Turn Out to be 100 Heads," *Phys. Rev. Lett.* 113, 120404 (2014).

HONOURS, AWARDS, AND MAJOR GRANTS



- Faculty members **Philip Schuster** and **Natalia Toro** were awarded the 2015 New Horizons in Physics Prize by the Breakthrough Prize Foundation, valued at US$100,000.

- **Pedro Vieira**, the Clay Riddell Paul Dirac Chair in Theoretical Physics at Perimeter Institute, received a 2015 Sloan Research Fellowship, valued at US$55,000.

- **Neil Turok**, Perimeter Director and Mike and Ophelia Lazaridis Niels Bohr Chair in Theoretical Physics, was elected as a Fellow of the Royal Society of Canada.

- For the second year in a row, Faculty member **Robert Myers** was named to the "World's Most Influential Scientific Minds" list by Thomson Reuters. Perimeter Distinguished Visiting Research Chair **Juan Ignacio Cirac** was also named to the 2015 list.

- **Pedro Vieira** was awarded the prestigious 2015 Gribov Medal by the European Physical Society, making him the third Perimeter faculty member to win since 2009.

- Faculty member **Lee Smolin** and his collaborator, Marina Cortês, were awarded the inaugural Buchalter Cosmology Prize by the American Astronomical Society, while Faculty member **Luis Lehner** and Associate Faculty member **Matthew Johnson** were among the prize's third place winners.

- **Neil Turok** was awarded an honorary doctorate degree by Stellenbosch University in South Africa.

- Visiting Fellow **Eduardo Martin-Martinez** was awarded a 2015 John Charles Polanyi Prize from the Council of Ontario Universities, valued at $20,000.

- Former postdoctoral researcher **Joseph Ben Geloun** received the 2015 Young Scientist Prize in Mathematical Physics from the International Union of Pure and Applied Physics, for work completed during his time at Perimeter.

- Three Perimeter researchers were awarded Early Researcher Awards worth $140,000 each by the Province of Ontario:
  - Faculty member **Philip Schuster**
  - Faculty member **Kendrick Smith**
  - Associate Faculty member **Itay Yavin**

- Associate Faculty member **Avery Broderick** is a co-investigator on a US$6.5 million National Science Foundation grant to support the Event Horizon Telescope experiment.

- Perimeter scientists obtained more than $3.7 million in research grants from agencies including the Natural Sciences and Engineering Research Council of Canada, the Simons Foundation, the John Templeton Foundation, and the Foundational Questions Institute.

A VERY GOOD YEAR

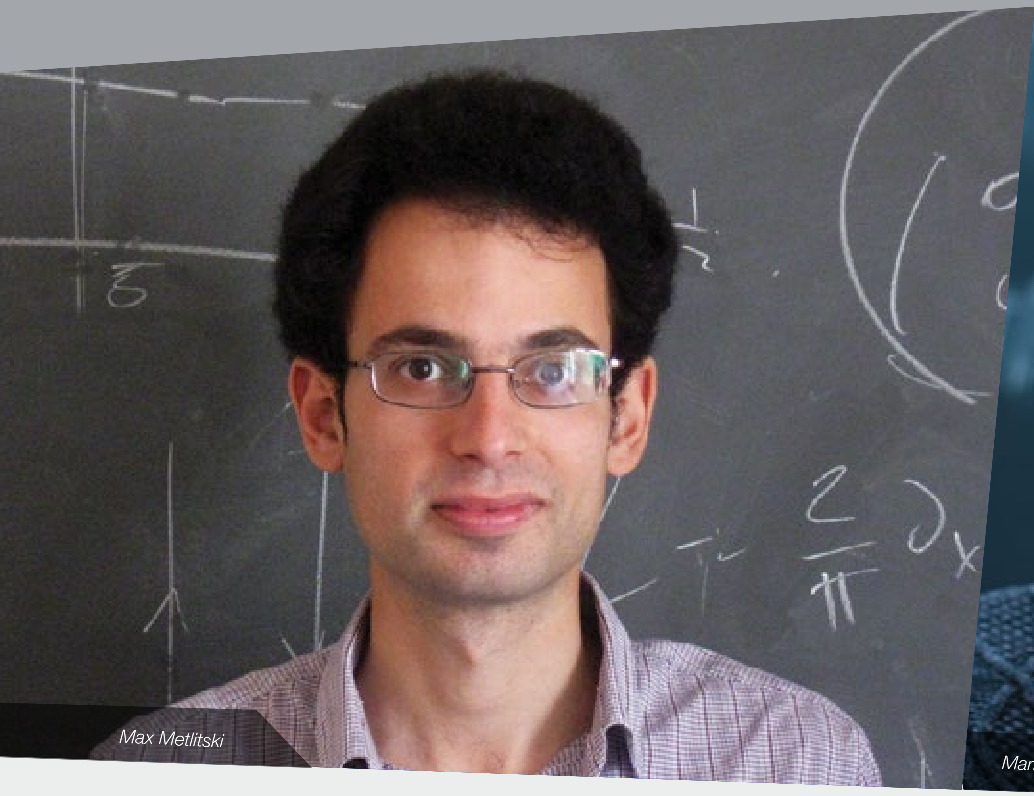
It's been a very good year for **Pedro Vieira**, who won two major awards – a Sloan Fellowship and the Gribov Medal – and was appointed as the Clay Riddell Paul Dirac Chair in Theoretical Physics at Perimeter Institute.

Sloan Research Fellows are widely viewed as people to keep an eye on: 42 have gone on to win Nobel Prizes. The Gribov Medal is given once every two years by the European Physical Society for outstanding work by physicists under the age of 35.

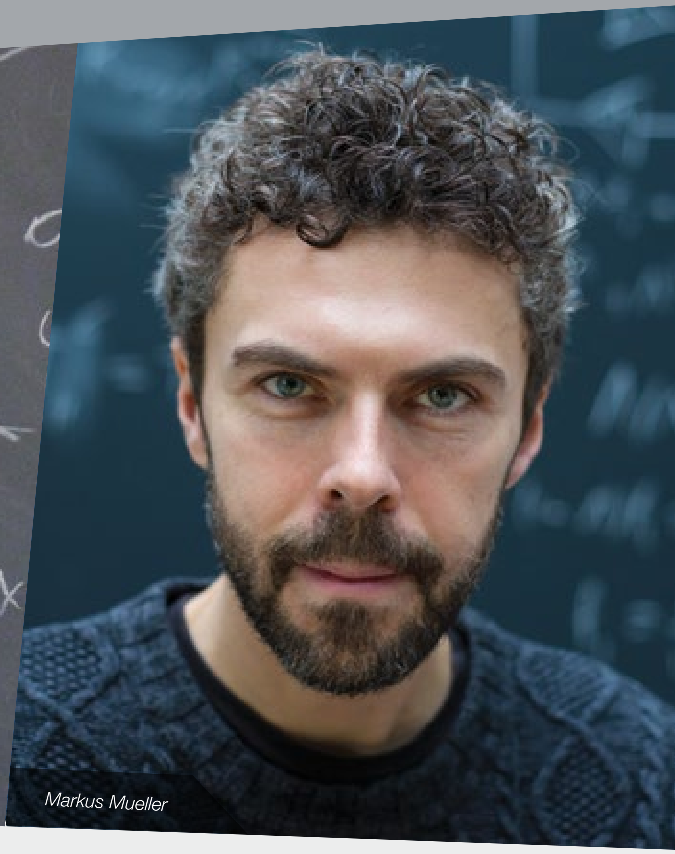
The awards recognize Vieira's work developing exact techniques for solving gauge theories and string theories – and, in doing so, tackling the toughest and most long-standing set of problems in quantum field theory.

By using a mathematical technique called holography, Vieira has opened a path to a richer conceptual and practical understanding of quantum field theory – the language in which particle physics, condensed matter physics, and much of cosmology is written.

RECRUITMENT



Max Metlitski



Markus Mueller

The most powerful scientific equipment on the planet isn't a particle accelerator or a space vehicle: it's the human mind.

The best way to spur breakthroughs is to bring brilliant people together. Perimeter assembles great minds, challenging them to pursue the most ambitious questions within a vibrant, collaborative environment.

Perimeter has become the world's largest independent centre for theoretical physics, a community of extraordinary researchers with the freedom and focus to tackle the deepest questions. In 2014/15, Perimeter welcomed leading scientists across the full spectrum of theoretical physics, with emphasis on areas of growing strength, such as condensed matter and mathematical physics.

PERIMETER RESEARCH CHAIRS

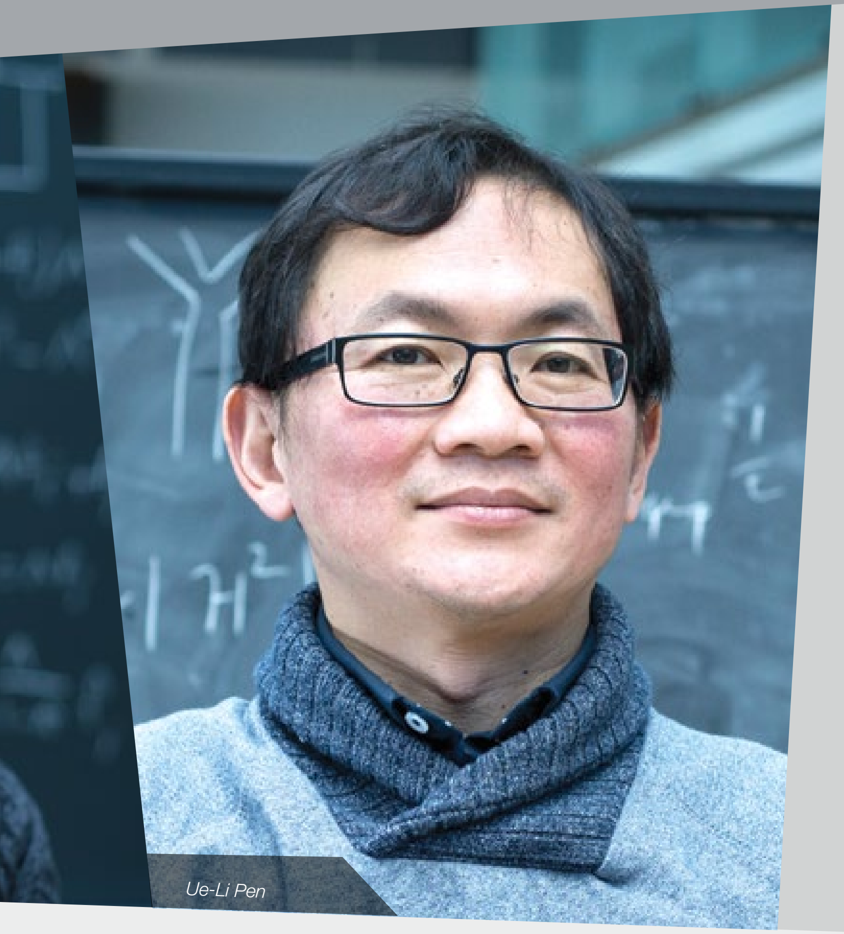
The Perimeter Research Chairs program was designed to assemble world-leading scientists in strategically chosen fields, attracting and retaining top scientists around whom the Institute can build "powerhouse" research groups and ultimately make rapid progress on key problems. Envisioned as the most prestigious chairs in theoretical physics worldwide, they are named for the legendary scientists whose insights helped define the field.

Since Xiao-Gang Wen was appointed as the BMO Financial Group Isaac Newton Chair in Theoretical Physics in 2012, the program has appointed a total of eight top international scientists as Chairs.

Over the past year, Perimeter welcomed **Kevin Costello** as the Krembil William Rowan Hamilton Chair, the fifth Perimeter Research Chair, and appointed three new Chairs: **Freddy Cachazo** as the Gluskin Sheff Freeman Dyson Chair; **Pedro Vieira** as the Clay Riddell Paul Dirac Chair; and **Paul Steinhardt** as the Richard P. Feynman Chair (Visiting).

To help fund the new Chairs, Perimeter attracted investments totalling $3.3 million from Gluskin Sheff + Associates, the Riddell Family Charitable Foundation, and Cenovus Energy – the latter of which will support **Subir Sachdev**'s Chair, now known as the Cenovus Energy James Clerk Maxwell Chair (Visiting).

Freddy Cachazo is a world leader in the study and computation of scattering amplitudes in gauge theories, such as quantum chromodynamics (QCD) and N=4 super Yang-Mills (MSYM) theories, and in Einstein's gravity theory. A faculty member since 2005, he has won many honours and awards, most recently the 2014 New Horizons in Physics Prize from the Fundamental Physics Prize Foundation.


Ue-Li Pen

PI BY THE NUMBERS

Perimeter is the world's largest theoretical physics community

24 faculty, including eight Perimeter Research Chairs

17 associate faculty cross-appointed with partner universities

44 Distinguished Visiting Research Chairs

22 Visiting Fellows

59 postdoctoral researchers

71 graduate students[1]

[1] This includes 42 PhD students and 29 Perimeter Scholars International master's students. All numbers reflect the Perimeter community as of July 31, 2015.

Pedro Vieira, who joined Perimeter's faculty in 2009, develops new mathematical techniques for gauge and string theories, ultimately aiming at the solution of a realistic four-dimensional gauge theory. He also works in the related areas of the AdS/CFT correspondence and theoretical calculations of scattering amplitudes. This year, he was awarded both a Sloan Research Fellowship and the Gribov Medal of the European Physical Society.

Paul Steinhardt is a renowned cosmologist whose research also spans particle physics, astrophysics, condensed matter physics, and geoscience. In recent years, he co-developed the "cyclic theory" of the universe with Neil Turok. As the Richard P. Feynman Chair, he will spend three months a year at Perimeter, in conjunction with his positions as the Albert Einstein Professor in Science at Princeton University and Director of the Princeton Center for Theoretical Science.

FACULTY

In 2014/15, in addition to its success in appointing Perimeter Research Chairs, the Institute recruited **Max Metlitski**, an outstanding young Canadian researcher, to its faculty from the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara, where he has been a Postdoctoral Research Associate since 2011. Metlitski's work has contributed to the theory of quantum criticality in metals and to the understanding of topological phases in the presence of interactions, and his arrival will add to Perimeter's growing strength in condensed matter physics. Since 2013, he has won the Hermann Kummel Early Achievement Award in Many-Body Physics, the Nevill F. Mott Early Career Prize of the International Conference on Strongly Correlated Electron Systems, and the William L. McMillan Award.

ASSOCIATE FACULTY

Complementing the full-time faculty, Perimeter partners with Canadian universities to attract and retain top scientific talent through its Associate Faculty program. Associates spend up to 50 percent of their time at Perimeter, in addition to teaching and conducting research at a partner university. By providing unique opportunities at both Perimeter and its partner institutes, the program brings many highly respected international scientists to Canada.

In 2014/15, Perimeter made three associate faculty appointments, including the Institute's first joint hires with the University of Toronto.

Emmy Noether Fellow Sarah Shandera

Alexander Braverman began a joint appointment with Perimeter and the University of Toronto in July 2015, having spent the last decade as a member of the faculty at Brown University. Braverman specializes in several areas with applications to mathematical physics, a rapidly expanding area at Perimeter. His work covers algebraic geometry, representation theory, number theory, and the geometric Langlands program.

Markus Mueller is a mathematical physicist, jointly appointed with Western University, where he holds the Canada Research Chair in the Foundations of Physics. Previously at the Institute for Theoretical Physics at the University of Heidelberg, Mueller's work intersects with quantum information and quantum foundations, with particular interests in statistical physics, generalized probabilistic theories, and algorithmic information theory.

Ue-Li Pen is a theoretical astrophysicist who studies systems where basic physical effects can be isolated from astronomical complexities. His research interests include 21cm cosmology, high-performance computing simulations, gravitational waves, pulsars, and radio interferometry. He is jointly appointed with the Canadian Institute for Theoretical Astrophysics at the University of Toronto, where he has been Associate Director since 2009.

DISTINGUISHED VISITING RESEARCH CHAIRS

Perimeter's unique Distinguished Visiting Research Chairs (DVRC) program brings world-leading scientists to the Institute for extended research visits. DVRCs are appointed to renewable three-year terms, while retaining permanent positions at their home institutions.

DVRCs contribute to life at the Institute in many ways – from conducting research, giving seminar talks, and collaborating with colleagues, to organizing conferences, teaching in the PSI master's program, and participating in outreach activities. For DVRCs, time spent at Perimeter is highly productive, since they are free from their usual teaching and administrative duties.

This year, Perimeter appointed four new DVRCs and renewed nine more. The Institute now has 44 DVRCs spanning every branch of theoretical physics, including luminaries such as Gerard 't Hooft, Nima Arkani-Hamed, Gabriela González, and Leonard Susskind. (For the full list of DVRCs, see page 35.)

"Science is a very social thing. Belonging is really important…. When you see other people make it, you feel less this weight of people saying women can't do it. It helps remove this drain on your resources. Here I am. I worked hard. You can do it too."

– 2015 Emmy Noether Fellow Sarah Shandera

TIME TO FOCUS ON A BIG, DARK MYSTERY

Perimeter is challenging the under-representation of women in physics through its Emmy Noether initiatives, named for the great 20th century mathematician who overcame many obstacles to have enduring impact on mathematics and physics. Backed by the Emmy Noether Circle – donors and leaders who champion women in science – the initiatives aim to provide strategic boosts that will make a difference.

The Emmy Noether Visiting Fellowship Program, for example, brings promising young scientists to Perimeter, enabling them to focus intensively on research, away from the usual responsibilities of their home faculty positions.

Rachel Rosen, one of this year's Emmy Noether Fellows and an assistant professor of theoretical physics at Columbia University, spent four months here in 2015, investigating a new approach to one of the biggest mysteries in physics.

In the 1990s, researchers discovered that the universe is not only expanding, but doing so at an accelerated rate. The mysterious force pushing spacetime apart is dubbed "dark energy."

Rosen's approach to dark energy, called "massive gravity," seeks to modify general relativity to yield a theory consistent with observations that can also explain the accelerated expansion. Even if it's not the full answer, Rosen believes it may yield productive insights.

Rosen describes the Emmy Noether Fellowship as a fantastic experience, adding, "It is a great opportunity to be interacting with so many people without being constrained by the usual responsibilities."

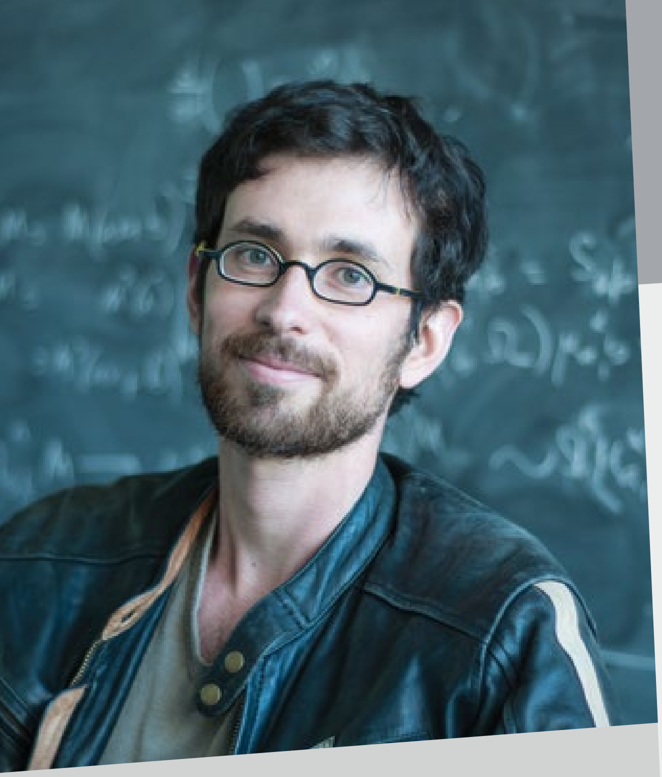
EMMY NOETHER FELLOWSHIP

VISITING FELLOWS

Fashioned after the successful DVRC model, the Visiting Fellows program brings researchers of great promise 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 of up to six months each year.

The program continued to grow this year, as Perimeter appointed eight new Visiting Fellows and renewed one more. The Institute now has 22 Visiting Fellows spanning a wide range of expertise.

Emmy Noether Fellow Rachel Rosen



POSTDOCTORAL RESEARCHERS

Many of the most important discoveries have been made by young scientists. Einstein's theory of special relativity, Heisenberg's uncertainty principle, and Dirac's prediction of antimatter were all made before those scientists turned 30.

The Institute taps the creativity and intellectual energy of young scientists. It's the world's largest community of independent theoretical physics postdoctoral researchers. This year, 18 new postdocs joined Perimeter, with 17 more recruited for next year.

Here, postdocs are independent, with the time and scope to pursue novel, ambitious research. As full members of the research community, they can invite collaborators, travel, give talks, and organize conferences and workshops.

FREEDOM OF DISCOVERY

The world usually doesn't present itself declaring "I'm physics" or "I'm biology." Ideas feed into one another, and I go where curiosity takes me.

So far, that's included macroeconomics, evolutionary biology, and ecology, on top of my usual work probing gravitational physics. There's no grand strategy. Once something's interesting, I make it part of my research.

Many collaborations were born at the Santa Fe Complex Systems Summer School in 2013. I went on a whim, and found myself surrounded by scientists from all different disciplines. It quickly became apparent that theoretical physicists were the most flexible. We were jumping between more projects, because math and its abstractions can be used in so many different contexts. We also tend to simplify any problems, which is an attitude as much as a skill.

You realize you really can help, in many different ways. It was really empowering, and it took me in entirely unexpected directions.

Complex problems underscore that disciplinary boundaries don't really make sense. Crossing them is essential to save the phenomena from academic idiosyncrasy. I try to do that. Scientifically and intellectually, I feel more complete, and more creative too.

– Matteo Smerlak, Perimeter postdoctoral researcher

"What brought me to Perimeter is seeing the unity across physics disciplines. Perimeter is clearly excellent in all the research areas it covers, but what is really special about it is that it is much more than a mere sum of its parts."

– Michal Heller, Perimeter postdoctoral researcher

Training at Perimeter develops skills that translate to discovery and innovation in physics and beyond. This year, despite an extremely competitive worldwide academic market, three departing postdocs accepted tenure-track faculty positions, while several others obtained prestigious positions at top international institutions.

"Perimeter Institute is today, in my opinion, the place where the boldest challenges in physics can be undertaken with the true hope of an answer."

– Joseph Ben Geloun,
Perimeter postdoctoral researcher, 2010-13,
and winner of the 2015 IUPAP Young Scientists Prize
for work done at Perimeter

DISTINGUISHED VISITING RESEARCH CHAIRS

* Indicates DVRC appointed in 2014/15

** Indicates Templeton Frontiers Program DVRC

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
Ganapathy Baskaran, Institute of Mathematical Sciences, Chennai
Patrick Brady, University of Wisconsin-Milwaukee
Alessandra Buonanno, Max Planck Institute for Gravitational Physics (Albert Einstein Institute) and University of Maryland, College Park
Juan Ignacio Cirac, Max Planck Institute of Quantum Optics
Savas Dimopoulos, Stanford University
Lance Dixon, Stanford University
Matthew Fisher, University of California, Santa Barbara
S. James Gates, Jr., University of Maryland, College Park
Alexander Goncharov, Yale University
Gabriela González, Louisiana State University
Duncan Haldane, Princeton University
Patrick Hayden, Stanford University
Joseph Incandela*, University of California, Santa Barbara
Ted Jacobson, University of Maryland, College Park
Shamit Kachru, Stanford University
Leo Kadanoff, University of Chicago
Adrian Kent, University of Cambridge
Renate Loll, Radboud University, Nijmegen
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
Peter Shor, Massachusetts Institute of Technology
Iakov (Yan) Soibelman*, Kansas State University
Dam Thanh Son, University of Chicago
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, University of California, Berkeley
Zhenghan Wang, Microsoft Research Station Q
Steven White, University of California, Irvine
Mark Wise, California Institute of Technology
Matias Zaldarriaga*, Institute for Advanced Study

RESEARCH TRAINING

AN ONLINE INTRODUCTION

I wasn't that good at science to begin with. I was 10 or 11 years old, and I didn't want to embarrass myself or my parents because of my poor academic performance. So I tried to pursue it for myself.

I found it really interesting. Someone told my mom we should meet Ramachandra Subramanyam, who tutored students at the Centre for Fundamental Research and Creative Education (CFRCE) in my hometown of Bangalore.

At the CFRCE, I got involved in increasingly difficult physics, using PIRSA [the Perimeter Institute Recorded Seminar Archive] and watching PSI lectures along the way. I came to Perimeter to present a paper at "LOOPS 13." A year later, I finished high school and came here to do my master's.

It has been a dream come true, honestly. It has led me to learn unhindered, at a pace which I couldn't practically muster before. I'm now doing my PhD in quantum gravity with Lee Smolin, who is very amenable to allowing his students to pursue their own ideas.

– Vasudev Shyam, Perimeter PhD student

In 2014/15, Vasudev Shyam was the recipient of an Honorary Scholarship Award in the PSI program, supported by Brad and Kathy Marsland and Margaret and Larry Marsland.

In 2015/16, he will be supported in his doctoral studies with the inaugural Peter and Shelagh Godsoe Family Foundation Award for Exceptional Emerging Talent.

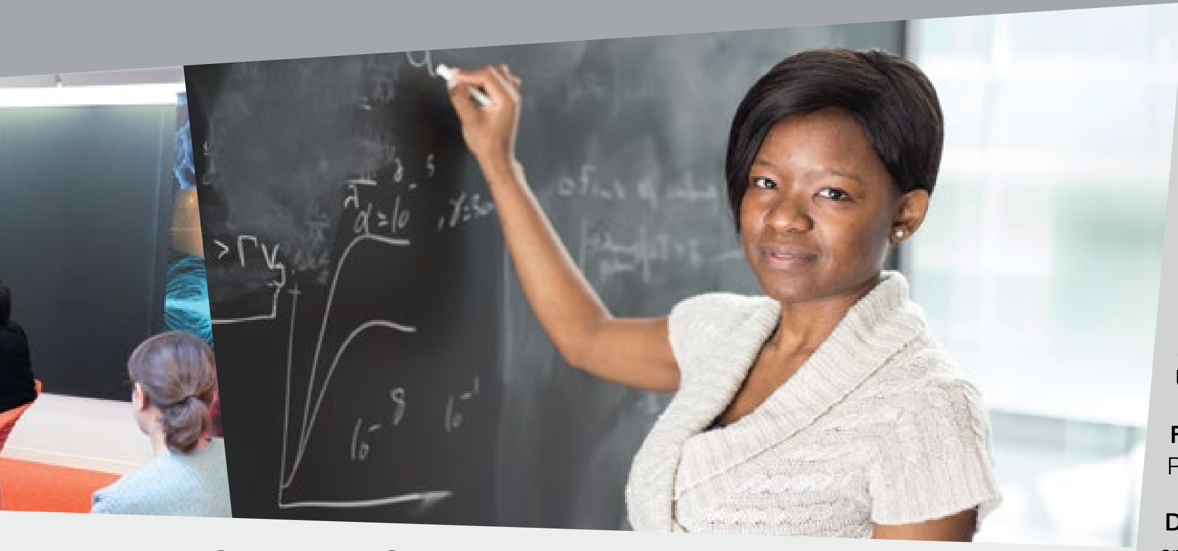
PERIMETER SCHOLARS INTERNATIONAL

Perimeter understands that brilliant young people are not just the future of physics, but also a crucial element in any dynamic scientific community. It was with that in mind that the Institute created its master's program, Perimeter Scholars International (PSI), in 2009, and it has been attracting exceptional university graduates from across Canada and around the world ever since.

PSI brings these promising students to the cutting edge of theoretical physics in one academic year. The innovative curriculum features three-week modules taught by Perimeter faculty and other top international lecturers, with tutorial support from postdoctoral-level PSI Fellows and graduate teaching assistants. Students are exposed to the full spectrum of theoretical physics, while learning skills that will serve them well in both academia and industry – such as independent thinking, collaborative problem solving, and computer-based model development. Upon completion of the program, students receive a master's degree from the University of Waterloo and a PSI certificate.

In 2014/15, PSI trained 31 students from 16 countries. Eleven of this year's graduates – more than one-third of the class – are remaining in Canada for their doctoral studies, eight of them with Perimeter faculty. Many others have gone on to top international institutions, including the University of Oxford, Stanford University, and the University of California, Berkeley. PSI continues to grow in prestige and competitiveness. For the incoming 2015/16 class, Perimeter received 472 applications from 76 countries, up 29 percent over the previous year.

The PSI program was generously supported in 2014/15 by: The Bluma Appel Community Trust, Burgundy Asset Management Ltd., The Savvas Chamberlain Family Foundation, Joanne Cuthbertson and Charlie Fisher, The Ira Gluskin and Maxine Granovsky Gluskin Charitable Foundation, The Scott Griffin Foundation, The Hellenic Heritage Foundation, The Kitchener and Waterloo Community Foundation – The John A. Pollock Family Fund, Margaret and Larry Marsland, Brad and Kathy Marsland, and Scotiabank.



PHD STUDENTS

Perimeter's PhD program continues to grow, bringing top students not only to Perimeter, but also to the Canadian partner universities where they ultimately receive their degrees. Much of the program's growth can be attributed to the pool of highly talented graduates provided by the PSI program. Seven PhD students supervised by Perimeter faculty graduated from partner universities in 2014/15, and at year's end, Perimeter had 42 PhD students in residence. Three additional PhD students were supervised by Perimeter associate faculty while in residence at partner universities. During their time at Perimeter, PhD students receive unparalleled opportunities to interact with international scientific leaders and develop their careers in a supportive, collaborative environment.

In 2014/15, the Ira Gluskin and Maxine Granovsky Gluskin Charitable Foundation generously supported an Honorary Scholarship Award for a female PhD student through the Emmy Noether Circle.

VISITING GRADUATE FELLOWS

Perimeter's Visiting Graduate Fellows program allows advanced PhD students from around the world to spend several months at the Institute. These young researchers benefit from and enrich Perimeter's vibrant research community, while interacting with leading researchers in their field at a pivotal time in their training. Perimeter hosted 21 Visiting Graduate Fellows in 2014/15.

UNDERGRADUATE RESEARCH

Perimeter's Undergraduate Student program exposes select undergraduate students to high-level research through two- to four-month projects with Perimeter postdoctoral researchers. The promising young students receive an unparalleled preview of life as a physicist, while the postdoctoral researchers accrue valuable mentoring experience. This year, Perimeter provided research training to four exceptional undergraduate students from top institutions, including the Massachusetts Institute of Technology, the University of Alberta, and the University of Cambridge. The program also acts as a means of attracting talent to the Institute. Alumni of this program who have returned to Perimeter include PSI student **Shreya Prasanna Kumar**, PhD student **Dalimil Mazac**, and postdoctoral researcher **Matteo Smerlak**.

PSI FACULTY, 2014/15

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

Anton Burkov, University of Waterloo

Freddy Cachazo, Perimeter Institute

David Cory, Perimeter Institute and Institute for Quantum Computing (IQC)/University of Waterloo

François David, Institute of Theoretical Physics/CEA-Saclay

Bianca Dittrich, Perimeter Institute

Joseph Emerson, IQC/University of Waterloo

Marcel Franz, University of British Columbia

Davide Gaiotto, Perimeter Institute

Jaume Gomis, Perimeter Institute

Stefania Gori, Perimeter Institute

Daniel Gottesman, Perimeter Institute

Ruth Gregory, Durham University

Alioscia Hamma, Tsinghua University

Lucien Hardy, Perimeter Institute

Kurt Hinterbichler, Perimeter Institute

Gordan Krnjaic, Perimeter Institute

David Morrissey, TRIUMF

Brian Shuve, Perimeter Institute

Kendrick Smith, Perimeter Institute

Miles Stoudenmire, Perimeter Institute

Neil Turok, Perimeter Institute

Pedro Vieira, Perimeter Institute

RESEARCH EVENTS

BY THE NUMBERS

In 2014/15, Perimeter ...

Held 15 conferences and workshops, attended by 873 scientists from around the world

Presented 325 scientific talks (283 seminars and 42 colloquia)

Partnered on eight joint workshops and conferences held at Perimeter and sponsored an additional 11 off-site workshops and conferences (10 in Canada)

Delivered four courses to researchers and students from surrounding universities

Hosted 250+ scientists for "Convergence," a new kind of physics conference providing a "big picture" overview of fundamental physics and its future

The history of physics is one of discussion, debate, and collaboration. Major breakthroughs in quantum physics, for example, can be traced to the famous Fifth Solvay Conference in 1927, where 17 of the 29 scientists in attendance had or would soon receive Nobel Prizes – Einstein, Bohr, Curie, Heisenberg, and Schrödinger among them.

Perimeter's renowned conference program seeks to build on this tradition. Topics are selected for potentially significant outcomes, often at interfaces between different disciplines, or between theory and experiment. The Institute's flexibility allows it to rapidly identify and capitalize on promising new areas, and Perimeter is often the first in the world to host a conference on an emerging field or new discovery. In the wake of the BICEP2 claim of gravitational wave detection in 2014, for instance, Perimeter was the first North American institution to gather experts to analyze it, raising doubts that were later validated.

SEMINARS AND COLLOQUIA

Seminars and colloquia given by resident and visiting scientists are an important part of the intellectual life of the Institute, sharing cutting-edge discovery and fostering collaboration across fields.


Participants at "Convergence" conference

In the past year, Perimeter hosted 325 scientific talks (283 seminars and 42 colloquia). Talks were given by a number of Distinguished Visiting Research Chairs, such as **Nima Arkani-Hamed**, **Abhay Ashtekar**, **James Bardeen**, **Savas Dimopoulos**, **S. James Gates Jr.**, **Matilde Marcolli**, **Barbara Terhal**, **Senthil Todadri**, **Bill Unruh**, **Ashvin Vishwanath**, **Steven White**, and **Mark Wise**.

ONLINE VIDEO ARCHIVE

Nearly all talks held at Perimeter are recorded and can be viewed in the Video Library section of Perimeter's website or through the Perimeter Institute Recorded Seminar Archive (PIRSA) at www.pirsa.org. This free, searchable, and citable video archive of seminars, conferences, workshops, and courses was developed by the Institute to share knowledge with the international scientific community, and has become an important and widely used resource for the field.

During 2014/15, Perimeter's video archive was accessed by 82,845 unique visitors from more than 170 countries, accounting for 628,796 page views.

CONVERGING ON IDEAS

"You can see all kinds of discussions going on in the corridor on the latest topics in physics, which is just what you would hope would happen at a conference like this."

– Art McDonald, 2015 Nobel Prize laureate in Physics and Perimeter Board member

"These are amazing times for physics," said Perimeter Institute Director Neil Turok as he opened "Convergence," this year's five-day gathering of more than 250 theorists, experimentalists, and alumni from 17 countries. "Many of us believe physics is poised for a new revolution."

Recent triumphs in physics – like the 2012 discovery of the Higgs boson – have been spectacular, but long-standing challenges and puzzling data remain.

"Convergence" asked everyone to look across the field as a whole in a bid to uncover, and potentially begin to solve, some of them.

The interplay of theory and experiment quickly emerged as a touchstone throughout the talks, roundtables, and occasionally feisty question periods. Experts in one field were introduced to the latest ideas and challenges in many others, from the hunt for exoplanets and gravitational waves to the potential parallels between strange metals and black holes.

Breakthroughs tend to happen at the broken places – the places where things don't quite add up. And that's why, in this environment, "I don't know" was not just an acceptable answer – it was the most exciting one.

"Convergence" was presented by BMO Financial Group.

LINKAGES

VISITOR PROGRAM

At Perimeter, researchers are encouraged to interact with colleagues working across the spectrum of theoretical physics. But this goes well beyond the Institute's resident scientists. Each year, Perimeter hosts hundreds of top scientists from across Canada and around the world, providing them with the time and space necessary to attend conferences and talks, exchange ideas, and begin new collaborations.

In 2014/15, Perimeter hosted 450 visiting scientists (for a total of 530 research visits), including 32 Distinguished Visiting Research Chairs and 12 Visiting Fellows. The rest were short-term visitors – a strategic mix of affiliates, collaborators, potential recruits, and seminar and colloquia speakers – many of whom were exposed to Perimeter's unique environment for the first time. In the past year, visits ultimately led to new appointments at all levels – including, notably, Faculty member **Max Metlitski** and Associate Faculty members **Markus Mueller** and **Ue-Li Pen**. (Refer to page 70 for a complete list of visitors.)

DRAWING GLOBAL STRANDS OF SCIENCE TOGETHER

Perimeter has formal partnership agreements with:

Centro de Fisica do Porto, University of Porto, Portugal

Fields Institute for Research in Mathematical Sciences, University of Toronto, Canada

Institute of Mathematical Sciences, Chennai, India

International Centre for Theoretical Physics – South American Institute for Fundamental Research, Sao Paulo, Brazil

International Solvay Institutes, Brussels, Belgium

International School for Advanced Studies (SISSA), Trieste, Italy

TRIUMF, Vancouver, Canada

Weizmann Institute of Science, Rehovot, Israel

AFFILIATES

For more than a decade, Perimeter's Affiliate program has been making crucial connections in Canada's foundational physics research community, bringing select researchers from across the country to Perimeter for regular informal visits. Affiliates gain access to an active community of scientists spanning the spectrum of physics, while Perimeter strengthens its connections with more than 25 of Canada's top research centres. In 2014/15, Perimeter appointed nine new Affiliates and renewed an additional 89 through 2017, bringing the total number of Affiliates to 113. (Refer to page 74 for a complete list.)

COLLABORATIONS AND PARTNERSHIPS

Collaboration is more essential to physics than ever. Perimeter's partnerships with leading centres in Canada and abroad reinforce its role as a global research hub and provide the Institute's researchers with crucial collaboration opportunities.

In 2014/15, Perimeter renewed productive partnerships with the International School for Advanced Studies (SISSA), International Centre for Theoretical Physics – South American Institute for Fundamental Research, and University of Porto through 2016, 2019, and 2020, respectively. Perimeter also strengthened ties in the international physics community with informal partnerships through the Institute's faculty, which now include the Event Horizon Telescope, Large Hadron Collider, Thomas Jefferson National Accelerator Facility, Canadian Hydrogen Intensity Mapping Experiment, Square Kilometre Array, and TRIUMF, among others.

FIELDS-PERIMETER INSTITUTE AFRICA POSTDOCTORAL FELLOWSHIP

Perimeter and The Fields Institute for Research in Mathematical Sciences at the University of Toronto have partnered to fund four one-year joint postdoctoral fellowships for African nationals who have recently completed their PhDs. This year, **Prince Osei** of Ghana, whose research concerns quantum gravity and mathematical physics, was selected as the third fellow.

TRI-INSTITUTE SUMMER SCHOOL ON ELEMENTARY PARTICLES

The Tri-Institute Summer School on Elementary Particles (TRISEP), a two-week summer school in particle physics for graduate students and postdoctoral researchers, is a partnership between Perimeter, TRIUMF, and SNOLAB. In July 2015, Perimeter hosted the third annual summer school, with topics including cosmology, the Standard Model, astroparticle physics, and modern amplitude techniques. The school's lecturers also included Perimeter researchers **Natalia Toro** and **Song He**, as well as Distinguished Visiting Research Chair **Matias Zaldarriaga**.

THE WATERLOO GLOBAL SCIENCE INITIATIVE

The Waterloo Global Science Initiative (WGSI) is an independently funded, non-profit partnership between Perimeter Institute and the University of Waterloo. WGSI's mandate is to promote dialogue on complex global issues and to catalyze the long-range thinking necessary to advance ideas, opportunities, and strategies for a secure and sustainable future. It seeks to fulfill this mandate through its Summit Series, Blueprints, and related impact activities.

In 2014/15, the WGSI team continued to distribute the *Learning 2030* Blueprint and wrapped up related impact activities. Building on the successes of the 2011 and 2013 summits, planning is underway for the next summit in 2016, which will explore scientific and technological approaches aimed at decreasing reliance on non-renewable energy sources and improving the well-being of those who lack reliable access to energy.

GLOBAL OUTREACH

Perimeter's Global Outreach initiative seeks to provide expertise and guidance to emerging scientific centres of excellence around the world, acting as a resource as they write their own success stories. To date, these efforts have largely focused on the African Institute for Mathematical Sciences – Next Einstein Initiative (AIMS-NEI), a project founded by Perimeter Director Neil Turok in 2003 to establish a pan-African network of centres providing advanced mathematical and scientific education to exceptional African graduates.

In 2014/15, Perimeter continued to leverage the expertise of both its research and administrative staff in support of the flourishing AIMS-NEI network, which opened its fifth centre in the fall of 2014, in Tanzania. Perimeter staff assisted with a successful $25 million proposal to the MasterCard Foundation, and shared expertise in preparations for both the launch of AIMS-Tanzania and the inaugural Next Einstein Forum, to be held in Senegal in 2016. Perimeter researchers also continue to be involved in teaching at AIMS centres.

A GROWING QUANTUM VALLEY

Today's computers are digital. They process information in binary "bits" of ones and zeros. But for decades theorists have forecast the creation of a new kind of computing, one that harnessed quantum mechanics to compute in much richer and more powerful ways.

That reality is now upon us. Labs around the world – including at Perimeter's experimental partner, the Institute for Quantum Computing at the University of Waterloo – have made quantum computations happen.

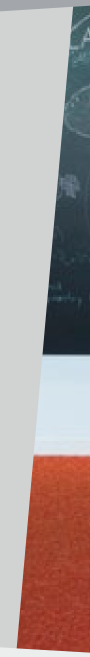
Currently, the systems are still fragile, but there has been enormous recent progress in building technology that will lead to scalable, fault-tolerant quantum computers. Research milestones are being passed faster than anyone dared hope even a few years ago.

Quantum Valley is emerging in Waterloo Region, covering the full spectrum from deep discovery and training, to experimental labs, technology development, and even start-up companies. Commercial development is being fuelled in part by Quantum Valley Investments, a venture capital firm led by Perimeter Founder Mike Lazaridis.

Perimeter is the wellspring of this ecosystem, attracting outstanding research talent helping to seed Canada's Quantum Valley.

A long-hypothesized age is dawning, and it may well shape the future.

EDUCATIONAL OUTREACH AND PUBLIC ENGAGEMENT



"I've learned how much I don't know, and I've realized that's not an obstacle. It encourages me to learn more."

– Lola Hourihane, ISSYP 2015 participant

"Until you've actually been at the EinsteinPlus week, you cannot comprehend just how incredibly useful it will be directly in your classroom."

– Miles Hudson, EinsteinPlus 2015 participant

What is the universe made of? What are the forces within it? How did it begin, and how does it evolve?

People from all walks of life – moms and dads, entrepreneurs and academics, children and CEOs – are fascinated by questions that physics seeks to answer. In seeking those answers, the discoveries of physics have led to scientific advances and technologies that have changed the world. Inevitably, they will again.

Perimeter's outreach efforts engage and inspire students, teachers, and the public, helping to build a new generation of scientific explorers.

This year, from the popular Public Lecture Series to the International Summer School for Young Physicists (ISSYP), teacher resources, and monthly "Slice of PI" dispatches, Perimeter made science more accessible than ever.

BY THE NUMBERS

In **2014/15**, Perimeter ...

Reached over **1 million** Canadian students with resources and programs

Presented **130** workshops to **3,000** educators

Gave **18** Physica Phantastica presentations to **2,400** Canadian students

Drew more than **250,000** online viewers for the Perimeter Public Lecture Series

EINSTEINPLUS

Preparing kids for the future starts with top-quality science educators. Each summer, high school teachers from around the world and across Canada converge at Perimeter for the EinsteinPlus Teachers' Camp. This year's one-week summer workshop immersed 45 participants in modern physics – 23 Canadian teachers spanning eight provinces, and 22 international teachers from 11 countries. Together, they learned and shared effective strategies for teaching key concepts in modern physics, and were introduced to Perimeter's educational resources and hands-on classroom techniques. Surveys of past participants indicate that they view the experience as a top-calibre professional development opportunity, adding that it reignites their passion for physics.

ISSYP class of 2015

THE INTERNATIONAL SUMMER SCHOOL FOR YOUNG PHYSICISTS

It's a summer's dream come true for science kids.

Each year, 40 young people who love science – half Canadian and half international – are chosen to come to Perimeter for two heady weeks of nonstop talks, mentoring sessions with scientists, tours of experimental facilities like SNOLAB and the Institute for Quantum Computing, and a poster session modelled after a science conference, attended by the whole PI community. There's even time for a little backyard physics and bonding in the summer sun.

For many, it's life-altering – follow-up surveys indicate that over 70 percent credit ISSYP with inspiring them to pursue a career in math or physics.

This year was the 13th installment of ISSYP, with 20 Canadians from seven provinces and 20 international students from 12 countries, including equal representation of males and females.

The 2014/15 edition of ISSYP was made possible by the continued generous support of Presenting Partner, RBC Foundation, and additional supporters: The Boardwalk, Deloitte, Vicki Saunders, and Toyota Motor Manufacturing Canada Inc.

TWIN PASSIONS – PETER BOYCE II

In 2007, Peter Boyce II followed his passion for physics to the International Summer School for Young Physicists (ISSYP). Later, as an undergrad at Harvard, he added a new passion: technology.

Now, he's combined both by specializing in computer science and entrepreneurship. He co-founded Rough Draft Ventures, an initiative backing the most talented university entrepreneurs, and works with General Catalyst Partners, helping to open the venture capital firm's New York office.

Peter remembers ISSYP as "easily one of the best summers I've ever had" and credits it with helping set him on his current path: "It helped me realize where I wanted to go to school and gave me a real taste of what college would be like. ISSYP gave me a great sense of the diversity of people I'd get to study alongside. It was the first time I was exposed to folks from all over the world united by a passion for math and physics."

"This is what is happening in science right now. This is where the excitement is."

– Stacey Harvey, EinsteinPlus 2014 participant

IN-CLASS RESOURCES

Every science teacher strives to share the spark of scientific inspiration – but physics can be challenging.

Perimeter aims to help. Produced with the input of working physics educators and scientists, Perimeter's educational modules are the Institute's primary means of introducing elementary and high school students to modern physics. Although Canadian students remain Perimeter's primary focus, these resources have been deployed in over 60 countries worldwide. Feedback indicates that they are used and re-used in classrooms, multiplying their impact over time.

Over the past year, the Institute converted its existing resources for digital distribution and created three new e-modules: *Black Holes*, *The Physics of Innovation*, and *Contemporary Physics*. Two e-courses on modern physics were also completed to support top math and physics students with advanced lessons to prepare them for university-level physics.

With Ontario's Ministry of Education, Perimeter also launched an exciting partnership that will support the creation of new resources to reach even more young minds: an integrated suite of materials for Grades 5-12 on science, technology, and math.

TEACHER NETWORK AND ON-LOCATION WORKSHOPS

The Perimeter Teacher Network, consisting of teachers from across Ontario and Canada, equips educators with classroom resources and techniques to share modern science concepts effectively. Network members are trained by Perimeter Outreach staff and then go on to conduct training workshops in their home districts, using the Institute's resources.

This year, Network members gave 104 workshops to over 2,000 educators, ultimately reaching 150,000 students with cutting-edge STEM (science, technology, engineering, and mathematics) education.

Four Teacher Network camps trained 445 teachers this year – in Waterloo (two), Calgary, and Vancouver – and Institute staff held an additional 27 on-location workshops at conferences in Canada and abroad.

PUBLIC LECTURE SERIES

Perimeter's flagship Public Lecture Series continues to be one of the Institute's most popular programs. In 2014/15, Perimeter presented eight accessible, engaging lectures to packed audiences in the Mike Lazaridis Theatre of Ideas. In addition, all lectures are now webcast to online audiences around the world through Perimeter's website and presenting media partners, including *Maclean's*, CBC, *National Post*, *Scientific American*, and *Cosmos*.

All lectures are professionally recorded, webcast live, and available for on-demand playback through Perimeter's website, YouTube channel, and via media partners, with over 235,000 views in 2014/15. The Institute has also considerably extended the reach of the talks with advance trailers and marketing, as well as supplementary online chats with Perimeter researchers.

The 2014/15 season presented engaging talks on scientific topics ranging from interstellar voyaging to the unusual properties of water. Highlights included Kendrick Smith's "State of the Universe" address on cosmology in the 21st century, Amanda Peet's explanation of string theory using Lego, and Cenovus Energy Maxwell Chair Subir Sachdev on quantum entanglement and superconductivity.

The 2014/15 Perimeter Institute Public Lecture Series was presented by Sun Life Financial.

ABORIGINAL ENGAGEMENT

In the past year, Perimeter continued its partnership with Actua, one of Canada's leading STEM outreach organizations for youth, particularly among Aboriginal Canadians.

Perimeter Outreach staff trained Actua associates from across the country on Perimeter resources; the Actua associates then delivered the content to Aboriginal students during the summer months. Perimeter and Actua also began strategizing to expand their collaborative reach to Aboriginal communities across Canada tied to the Canada 150 celebrations in 2017.

Perimeter partners reached more than 1,000 Aboriginal youth with the Institute's resources.

"It's largely because of the researchers at Perimeter Institute that I chose to become a physicist."

– Ash Arsenault, ISSYP 2008 participant

CULTURAL EVENTS

Art and science share natural symmetries, each pushing us to move beyond the familiar and explore the possible. Cultural events are an important part of life at Perimeter, complementing research and outreach activities, and connecting the Institute to the community.

This year's Classical World Artists series brought luminaries like Christian Tetzlaff, the Sitkovetsky Trio, Avi Avital, and Benedetto Lupo to the Mike Lazaridis Theatre of Ideas. Just down the road, the Stratford Festival and Perimeter co-hosted an evening of readings and discussion of *Copenhagen*, Michael Frayn's seminal play imagining a meeting between Niels Bohr and Werner Heisenberg.

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

MEDIA COVERAGE

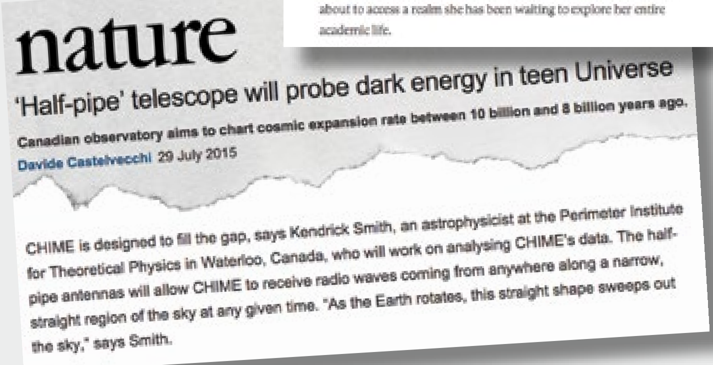
Perimeter shares the excitement of theoretical physics with media around the world, and has become a go-to source of insight, commentary, and high-quality content related to theoretical physics. This year, the Institute received major coverage in national and international media, including *The Globe and Mail*, *Nature*, *Forbes*, *Maclean's*, *The New York Times*, *The Guardian*, CBC, *Wired*, and many more outlets.

THE GLOBE AND MAIL*

After two years lying dormant, the Large Hadron Collider again revs up

Asimina Arvanitaki was just a small child growing up in Greece when plans were first being drawn up for the Large Hadron Collider. By the time its powerful proton beams were switched on for the first time in 2008, she had a newly minted PhD from Stanford University.

But only now, as a 35-year-old faculty member at the Perimeter Institute for Theoretical Physics in Waterloo, Ont., is Dr. Arvanitaki about to access a realm she has been waiting to explore her entire academic life.



nature

'Half-pipe' telescope will probe dark energy in teen Universe

Canadian observatory aims to chart cosmic expansion rate between 10 billion and 8 billion years ago.

Davide Castelvecchi 29 July 2015

CHIME is designed to fill the gap, says Kendrick Smith, an astrophysicist at the Perimeter Institute for Theoretical Physics in Waterloo, Canada, who will work on analysing CHIME's data. The half-pipe antennas will allow CHIME to receive radio waves coming from anywhere along a narrow, straight region of the sky at any given time. "As the Earth rotates, this straight shape sweeps out the sky," says Smith.

The New York Times

Black Hole Hunters

Aiming to make the first portrait of the hungry monster at the center of our galaxy, astronomers built "a telescope as big as the world."

Dennis Overbye
OUT THERE JUNE 8, 2015

"If Einstein was wrong, how would we know?"

AVERY BRODERICK, A THEORIST AT THE PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Later on, a real earthquake sent the astronomers running from their breakfasts down in Serdan.

In late March, Dr. Doeleman's collaborators were camped out on similarly uncomfortable mountains in Chile, Hawaii, California, Arizona and Spain, waiting for his signal, based on weather forecasts and the state of their equipment — all the accouterments of that spider silk — to begin observing. All the telescopes would point in unison at M87, and then at the galactic center.

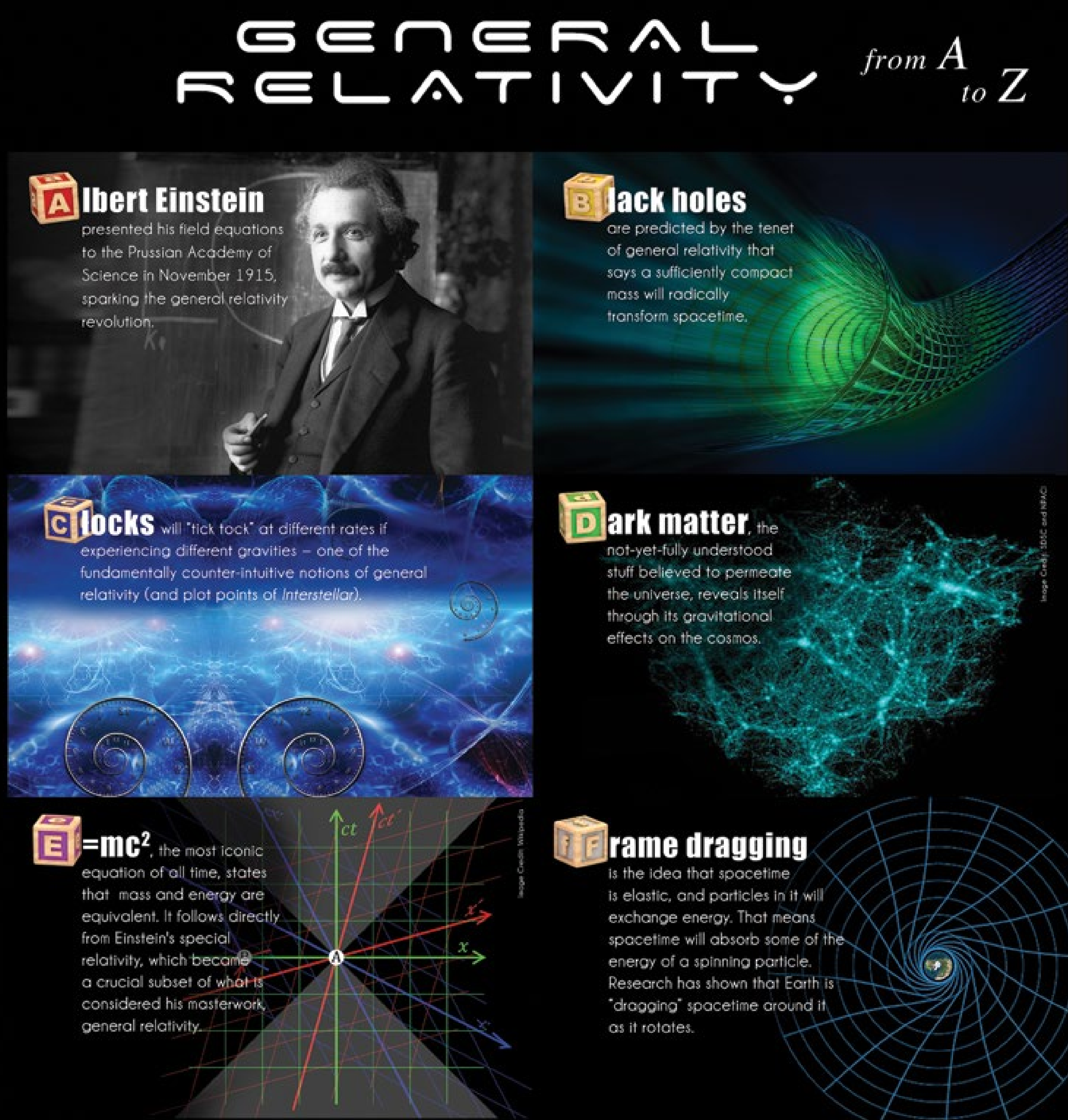
When it works well, this ganging up on the cosmos is "boring, in a good way," Dr. Doeleman said one night that was anything but boring, explaining that the observations best proceed automatically while the astronomers all hold their breath.

DIGITAL AND SOCIAL MEDIA OUTREACH

Who wouldn't want to know general relativity from A to Z, science fictions that became fact, profiles of the pioneering women of physics, or what we know about black holes so far?

Perimeter Institute aims to be the leading source of fascinating, accurate, and shareable physics content online. Over the past year, innovative digital media outreach initiatives such as the monthly "Slice of PI" series (fun and sharable science content) helped attract large new audiences. YouTube subscribers more than doubled, and Perimeter's social media following grew by 90 percent.

SLICE OF PI



ADVANCING PERIMETER'S MISSION

"We felt a resonance with Perimeter Institute because it was evident to us that they shared our belief that Canadian institutions can be among the best in the world at what they do. It all starts with attracting and developing world-class talent."

– Jeremy Freedman, President and Chief Executive Officer, Gluskin Sheff + Associates, supporter of the Gluskin Sheff Freeman Dyson Chair in Theoretical Physics

Breakthroughs are made through a combination of intellect, imagination, and inspiration. At Perimeter Institute, these are the same qualities that inspire our valued supporters.

Perimeter is a collaborative entity, in every sense. A non-profit research institute and registered charity, Perimeter's operations are supported through a successful public-private partnership, combining investments from the Governments of Ontario and Canada with corporate, foundation, and individual donations.

Together, we are partners in the pursuit of world-leading scientific inquiry. Our supporters understand that today's fundamental discoveries will power tomorrow's technological advances.

Contributions big and small are powering great science, and will one day enable great leaps in human understanding.

PERIMETER INSTITUTE LEADERSHIP COUNCIL

The Leadership Council is comprised of prominent individuals who volunteer their time, offer guidance, and act as ambassadors for Perimeter to the business and philanthropic communities. This exceptional group helps Perimeter grow strategically and internationally.

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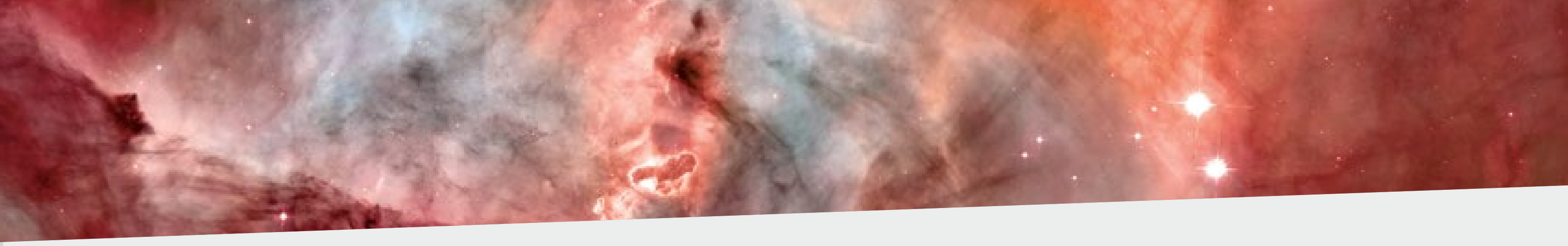

SUBIR SACHDEV, CENOVUS ENERGY JAMES CLERK MAXWELL CHAIR

When liquid nitrogen spills during his October 2014 public lecture at Perimeter – creating a hissing cloud of vapour onstage – **Subir Sachdev** has to laugh.

That's what happens, he quips, when you have "theorists doing an experiment."

As a theorist, Sachdev prefers the blackboard to the lab, but he wants to show the audience some of the remarkable, real-world properties of superconducting materials.

He uses the liquid nitrogen to supercool a piece of superconducting material, allowing him to "levitate" a small magnetic cube. It's a small-scale demonstration of principles that could revolutionize transportation, efficient energy transmission, medical technology, and more.

One of the world's leading minds in superconductivity, Sachdev has uncovered intriguing connections to string theory and black holes, making him the perfect candidate to hold a visiting research chair at Perimeter Institute.

In June 2015, Sachdev became the Cenovus Energy James Clerk Maxwell Chair in Theoretical Physics at Perimeter Institute (Visiting), a position which allows him to split his time between Perimeter and Harvard University.

Supported by Cenovus Energy, the position enables Sachdev to spend extended periods at Perimeter to conduct research and collaborate with peers across a number of disciplines.

"Our company believes in innovation," said Harbir Chhina, Executive Vice-President of Oil Sands Development for Cenovus Energy. "We believe in fundamental research. The calibre of people at Perimeter is going to lead to advancements that will change our nation, change our world, and help us understand the universe better."

Cenovus Energy James Clerk Maxwell Chair (Visiting) Subir Sachdev gave one of the year's most entertaining public lectures on the challenge and promise of superconductors.

ADVANCING INNOVATIVE THINKING

"I want to understand the structure of spacetime and how the physics we experience can be translated into mathematical terms."

– Freddy Cachazo, Gluskin Sheff Freeman Dyson Chair in Theoretical Physics

FREDDY CACHAZO, GLUSKIN SHEFF FREEMAN DYSON CHAIR

Finance and physics are both mathematical fields, but it isn't a knack for numbers that drew Gluskin Sheff + Associates Inc. to Perimeter Institute. It's the shared ethos of innovation.

Founded in 1984, the wealth management firm prides itself on leadership and innovative thinking – and it's the reason the firm's President and CEO, Jeremy Freedman, saw Perimeter Institute as a natural partner.

"At Gluskin Sheff, we see ourselves as innovators, and we're proud to be associated with Perimeter Institute because Perimeter is a global leader and innovator as well," says Freedman. "We believe Canadian institutions can be as good as anyone in the world – Perimeter has proven that, and we believe Gluskin Sheff is proving that too."

The Chair is named for Freeman Dyson, one of the 20th century's most distinguished physicists – and **Freddy Cachazo** appears to be following a similar trajectory. Still in his thirties, Cachazo has already won the 2014 New Horizons in Physics Prize, as well as the Gribov and Rutherford medals. His elegant mathematical ideas have already been adopted for interpreting data emerging from state-of-the-art experiments, including CERN's Large Hadron Collider, and will have enduring significance in the search for a unified description of nature's physical laws.

The Gluskin Sheff Freeman Dyson Chair in Theoretical Physics at Perimeter Institute is supported by Gluskin Sheff + Associates' $2 million donation, matched by Perimeter Institute.

PEDRO VIEIRA, CLAY RIDDELL PAUL DIRAC CHAIR

Clayton (Clay) Riddell is an entrepreneurial leader who invests in change.

He began his career as a geologist with a multinational oil company before starting his consulting practice and then launched Paramount Resources Ltd. in 1978.

With a grounding in the sciences and a keen interest in fostering innovation and the next generation of scientific leaders, it was natural for Riddell to support the research of Perimeter Faculty member **Pedro Vieira**, a rising star in mathematical physics, by funding the Clay Riddell Paul Dirac Chair in Theoretical Physics.

Vieira is renowned for his innovative use of string theory tools to tackle long-standing problems in physics.

"Just 15 years since Perimeter's inception, the Institute's scientific excellence at global levels is outstanding. I attribute this to the smart vision, strong leadership, and successful partnerships behind the Institute," Riddell said.

"I'm confident in Perimeter's national role in accelerating research and discovery, and that is why our family foundation is investing through the Institute's unique Chairs program."

The Clay Riddell Paul Dirac Chair in Theoretical Physics at Perimeter Institute is supported by the Riddell Family Charitable Foundation's $1 million donation, matched by Perimeter Institute.

BLAZING A TRAIL

She's the most influential scientist you've never heard of.

Emmy Noether's work over a century ago has shaped modern physics, computer science, and branches of mathematics. Noether's theorem is used in every branch of physics, from quantum field theory to the understanding of black holes, to the prediction of new particles, including the discovery of the Higgs boson. Yet during her lifetime, she was unable to get a paid position in her native Germany because she was a woman, and much of her enormously influential work was published by her mentor and colleague David Hilbert for the same reason.

This remarkable woman is a fitting namesake to Perimeter's Emmy Noether initiatives, backed by a committed group of funders and champions of women in science called the **Emmy Noether Circle**.

In the past year, Emmy Noether initiatives have supported six Emmy Noether Visiting Fellowships, four master's and PhD students, and 200 female high school students at the annual "Inspiring Future Women in Science" event.

As the Emmy Noether Circle grows, it will provide even more opportunities for women in physics.

THE EMMY NOETHER COUNCIL

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

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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 the Institute's operations. Support is provided 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 Director.

The Scientific Advisory Committee (SAC), comprised of eminent international scientists, offers independent scrutiny and advice, helping to ensure objectivity and a high standard of excellence in all of Perimeter's activities.

BOARD OF DIRECTORS

Mike Lazaridis, O.C., O.Ont., is Managing Partner and Co-Founder of Quantum Valley Investments (QVI), which he and Doug Fregin established in Waterloo. In March 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 more than a decade's 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 both the Royal Societies of London and Canada, and has been named to 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 McMaster University, the University of Windsor, and Laval University. 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 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 March 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.

Kevin Lynch, P.C., O.C., is a distinguished former public servant with 33 years of service with the Government of Canada. Most recently, Dr. Lynch served as Clerk of the Privy Council, Secretary to the Cabinet, and Head of the Public Service of Canada. Prior roles included Deputy Minister of Finance, Deputy Minister of Industry, and Executive Director (Canada, Ireland, Caribbean) of the International Monetary Fund. He is presently the Vice-Chair of BMO Financial Group.

Art McDonald, C.C., was Director of the Sudbury Neutrino Observatory (SNO) experiment for over 20 years, and is Emeritus Professor at Queen's University. In 2015, he shared the Nobel Prize in Physics and the Breakthrough Prize for the SNO experiment that showed neutrinos have mass. Professor McDonald has received numerous 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.

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 currently 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

Perimeter Institute's Scientific Advisory Committee (SAC) provides key support in achieving the Institute's strategic research objectives, particularly in the area of recruitment.

Renate Loll, Radboud University, Nijmegen (2010-Present), Chair

Professor Loll is Professor of Theoretical Physics at the Institute for Mathematics, Astrophysics, and Particle Physics of the Radboud University in Nijmegen, Netherlands. Her research centres on quantum gravity, the search for a consistent theory that describes the microscopic constituents of spacetime geometry and the quantum-dynamical laws governing their interaction. She has made major contributions to loop quantum gravity and, with her collaborators, has proposed a novel theory of quantum gravity via "Causal Dynamical Triangulations." Professor Loll heads one of the largest research groups on non-perturbative quantum gravity worldwide and is the recipient of a prestigious personal VICI-grant of the Netherlands Organization for Scientific Research. In 2015, she was installed as a member of The Royal Netherlands Academy of Arts and Sciences.

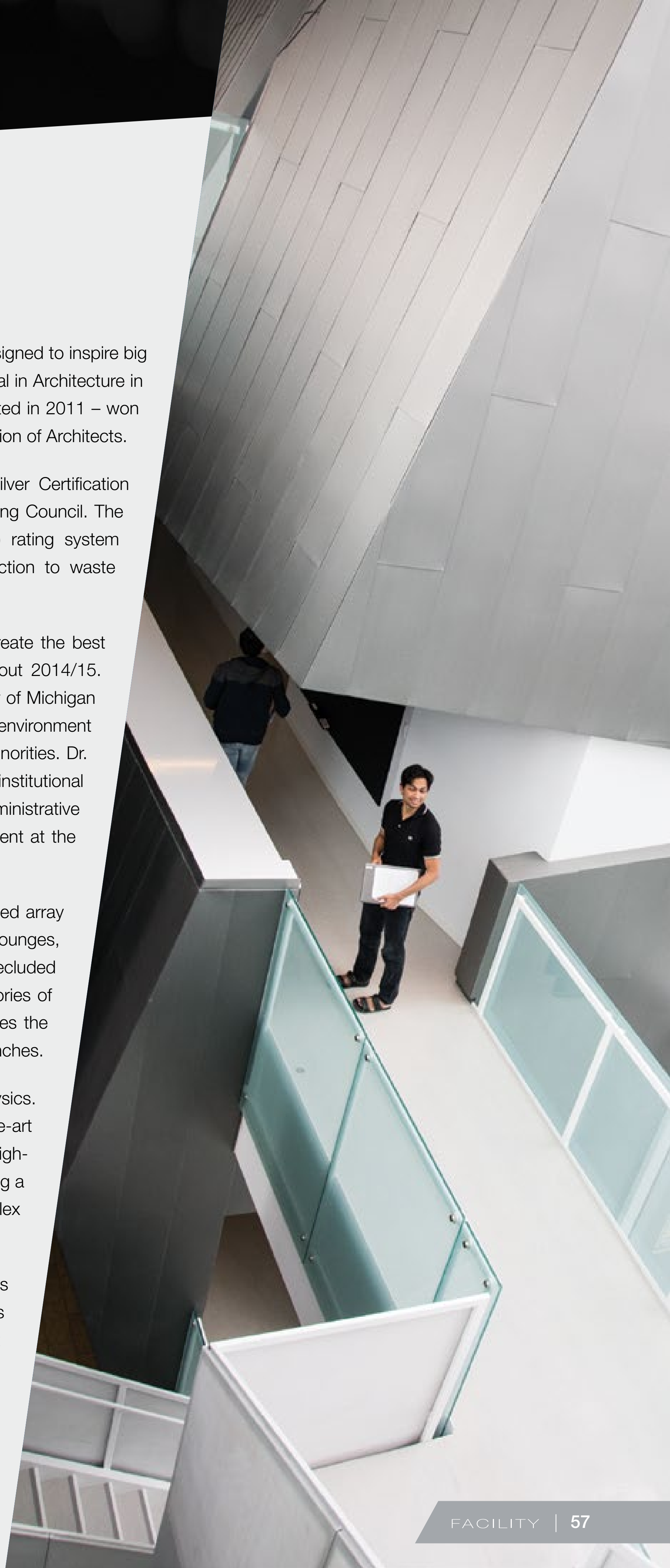
Ganapathy Baskaran, Institute of Mathematical Sciences, Chennai (2013-Present)

Professor Baskaran is Emeritus Professor at the Institute of Mathematical Sciences, Chennai, in India, where he founded the Quantum Science Centre. He has made important contributions to the field of strongly correlated quantum matter. His primary research focus is novel emergent quantum phenomena in matter, including biological ones. He is well known for his contributions to the theory of high temperature superconductivity and for discovering emergent gauge fields in strongly correlated electron systems. He predicted p-wave superconductivity in Sr_2RuO_4, a system believed to support Majorana fermion mode, which is a popular qubit for topological quantum computation. In recent work, he predicted room temperature superconductivity in optimally doped graphene. From 1976 to 2006, Dr. Baskaran contributed substantially to the Abdus Salam International Centre for Theoretical Physics in Trieste, Italy. He is a past recipient of the S.S. Bhatnagar Award from the Indian Council of Scientific and Industrial Research (1990); the Alfred Kasler ICTP Prize (1983); Fellowships of the Indian Academy of Sciences (1988), the Indian National Science Academy (1991), and the Third World Academy of Sciences (2008); and the Distinguished Alumni Award of the Indian Institute of Science, Bangalore (2008).

Mark Wise, California Institute of Technology (2013-Present)

Professor Wise is the John A. McCone Professor of High Energy Physics at the California Institute of Technology. He has conducted research in elementary particle physics and cosmology, and shared the 2001 Sakurai Prize for Theoretical Particle Physics for the development of the "Heavy Quark Effective Theory" (HQET), a mathematical formalism that enables physicists to make predictions about otherwise intractable problems in the theory of the strong interactions of quarks. He has also published work on mathematical models for finance and risk assessment. Professor Wise is a past Sloan Research Fellow, a Fellow of the American Physical Society, and a member of the American Academy of Arts and Sciences and of the National Academy of Sciences.

FACILITY



BEYOND BRICKS AND MORTAR

Perimeter's iconic, award-winning building was custom-designed to inspire big ideas. The original building won a Governor General's Medal in Architecture in 2006. The Stephen Hawking Centre – an addition completed in 2011 – won a 2012 Design Excellence Award from the Ontario Association of Architects.

In 2015, the Stephen Hawking Centre attained LEED Silver Certification after an independent review by the Canadian Green Building Council. The Leadership in Energy and Environmental Design (LEED) rating system takes into account everything from design and construction to waste management, energy use, and plant selection for gardens.

But Perimeter is much more than a building. Efforts to create the best environment for breakthrough science continued throughout 2014/15. Perimeter hosted Abigail Stewart, Director of the University of Michigan ADVANCE Program, which seeks to improve the campus environment for all faculty, particularly women and underrepresented minorities. Dr. Stewart delivered a colloquium outlining the process of institutional change, and met with members of Perimeter's faculty and administrative staff for a wide-ranging discussion on areas for improvement at the Institute.

The facility melds form and function with its carefully curated array of private places and collaborative spaces. Quiet nooks, lounges, and alcoves provide areas for small meetings and secluded contemplation. The two-storey library houses vast repositories of physics knowledge. The bustling Black Hole Bistro provides the perfect venue for spontaneous discussions and working lunches.

Scientific computing is crucial to modern theoretical physics. Because it is so important, Perimeter offers a state-of-the-art computational environment that includes access to high-performance computing and dedicated IT services, including a scientific computation expert able to design and run complex simulations in consultation with researchers.

With enough space to accommodate 250 researchers and students, Perimeter is the largest theoretical physics research centre in the world. In a physical environment that encourages deep thinking and lively exchanges of ideas, Perimeter is actively working to create an equally nourishing working environment to encourage and support great scientists and their work.

FINANCIALS

RESULTS OF OPERATIONS

Continued strong public and private support – along with prudent, strategic spending – allowed Perimeter Institute to further strengthen its financial positon in the 2014/15 fiscal year and remain firmly on track to achieve its long-term goals.

The Institute continued to spend strategically on its core mission. In keeping with Perimeter's growth plans, investment in scientific personnel and support of research programs increased by more than 12 percent.

Perimeter's innovative research training programs – which aim to produce the next generation of leading physicists and provide highly skilled problem solvers and creative thinkers to the wider innovation ecosystem – accounted for approximately seven percent of annual expenditures. Perimeter Scholars International and the PhD program, which are delivered in collaboration with university partners, continued to attract highly talented graduates from around the world.

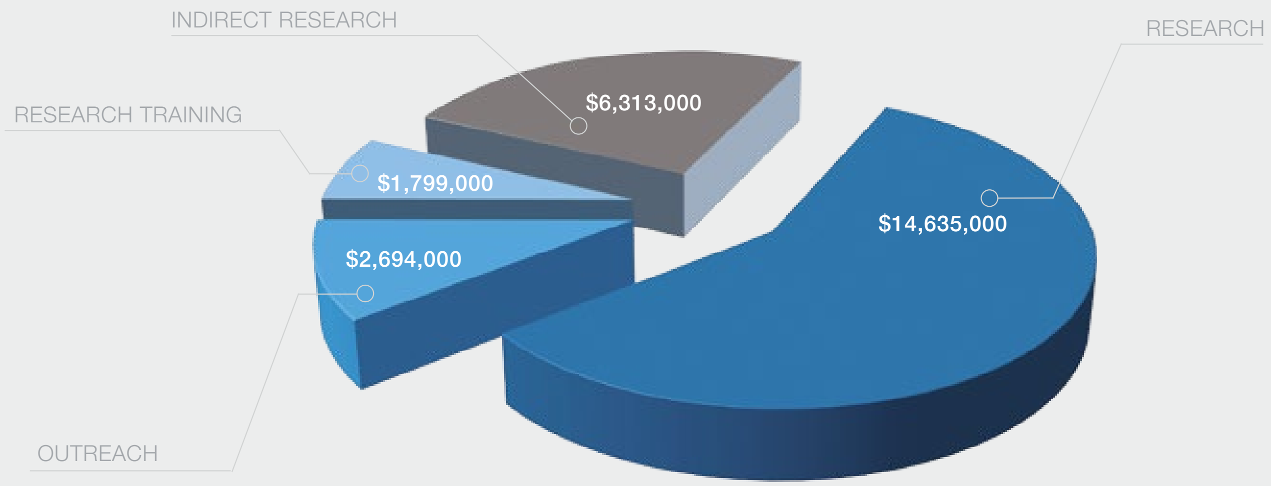
Educational outreach remained a key component of Perimeter's mandate in 2014/15. The Institute invested approximately 11 percent of its annual expenditures in inspirational programs and products for students, teachers, and the general public.

Indirect research and operating expenditures cover the costs of core support areas, including administration, advancement, information technology, and facilities. As a percentage of total expenditures, spending in this area remained consistent with the prior year, demonstrating effective cost management while building a world-class research centre.

Perimeter Institute completed its 2014/15 fiscal year with revenues exceeding expenditures by $28 million. Factors contributing to this strong outcome included success in obtaining new research grants, traction gained by Perimeter's private-sector fundraising campaign, and investment returns that exceeded 10 percent. Surpluses are prudently managed to further strengthen the Institute's long-term financial position.

OPERATING EXPENDITURE SUMMARY

For the year ended July 31, 2015



FINANCIAL POSITION

Perimeter Institute strengthened its working capital position. This position provides the Institute with near-term flexibility so it can react to targeted research opportunities that may present themselves.

The endowment fund primarily allows for the accumulation of private funds to address the Institute's future needs.

The $303 million in this fund 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.

RISKS AND UNCERTAINTIES

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

Funding commitments of $50 million from the federal government and $50 million from the provincial government (both up for renewal in 2017) reinforce Perimeter's strong collaboration with public partners and the value they see in investing in the Institute.

The multi-year government commitments totalling $100 million clearly demonstrate that the Institute is an excellent and strategic government investment.

Perimeter Institute is innovatively seeking to expand its sources of funds from the private sector to raise yearly operating funds for the Institute, as well as increase endowment assets over the coming years.

Private sector donations, in accordance with donor requests, are either utilized as contributions toward operational expenditures or protected in an endowment fund. The endowment fund is designed to maximize growth and minimize risk in order to contribute to the strongest possible long-term financial health of the Institute. However, investment returns are 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.

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REPORT OF THE INDEPENDENT AUDITORS ON THE SUMMARY FINANCIAL STATEMENTS

To the Directors of
Perimeter Institute

The accompanying summary financial statements, which comprise the summary statement of financial position as at July 31, 2015 and the summary 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, 2015. We expressed an unmodified audit opinion on those financial statements in our report dated December 11, 2015. Those financial statements, and the summary financial statements, do not reflect the effects of events that occurred subsequent to the date of our report on those financial statements.

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

Management's Responsibility for the Summary Financial Statements

Management is responsible for the preparation of a summary of the financial statements in accordance with Canadian accounting standards for not-for-profit organizations.

Auditor's Responsibility

Our responsibility is to express an opinion on the summary 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 summary financial statements derived from the audited financial statements of the Institute for the year ended July 31, 2015 are a fair summary of those financial statements, in accordance with Canadian accounting standards for not-for-profit organizations.

Zeifmans LLP
Chartered Accountants
Licensed Public Accountants

Toronto, Ontario
December 11, 2015

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T: 416.256.4000

NEXIA INTERNATIONAL

PERIMETER INSTITUTE
Summarized Statement of Financial Position
as at July 31, 2015

		2015		2014
ASSETS				
Current assets:				
Cash and cash equivalents	$	9,230,000	$	15,958,000
Investments		302,796,000		264,333,000
Government grants receivable		4,671,000		5,680,000
Other current assets		706,000		809,000
		317,403,000		286,780,000
Property and equipment		46,412,000		49,457,000
TOTAL ASSETS	$	363,815,000	$	336,237,000
LIABILITIES AND FUND BALANCES				
Current liabilities:				
Accounts payable and other current liabilities	$	1,095,000	$	1,692,000
TOTAL LIABILITIES		1,095,000		1,692,000
Fund balances:				
Invested in capital assets		46,399,000		49,974,000
Externally restricted		117,866,000		121,873,000
Internally restricted		188,840,000		78,840,000
Unrestricted		9,615,000		83,858,000
TOTAL FUND BALANCES		362,720,000		334,545,000
	$	363,815,000	$	336,237,000

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PERIMETER INSTITUTE
Summarized Statement of Operations and Changes in Fund Balances
For the Year Ended July 31, 2015

	2015	2014
Revenue		
Government grants	$ 21,548,000	$ 19,526,000
Research grants	3,073,000	1,850,000
Donations	2,691,000	761,000
	27,312,000	22,137,000
Expenses		
Research	14,635,000	13,002,000
Research training	1,799,000	2,034,000
Outreach and science communications	2,694,000	3,112,000
Indirect research and operations	6,313,000	5,770,000
	25,441,000	23,918,000
Excess of revenue over expenses (expenses over revenue) before amortization, gain on disposal of property and equipment and investment income	1,871,000	(1,781,000)
Amortization	(2,941,000)	(3,838,000)
Gain on disposal of property and equipment	111,000	
Investment gain	29,134,000	41,635,000
Excess of revenue over expenses	28,175,000	36,016,000
Fund balances, beginning of year	334,545,000	298,529,000
Fund balances, end of year	$ 362,720,000	$ 334,545,000

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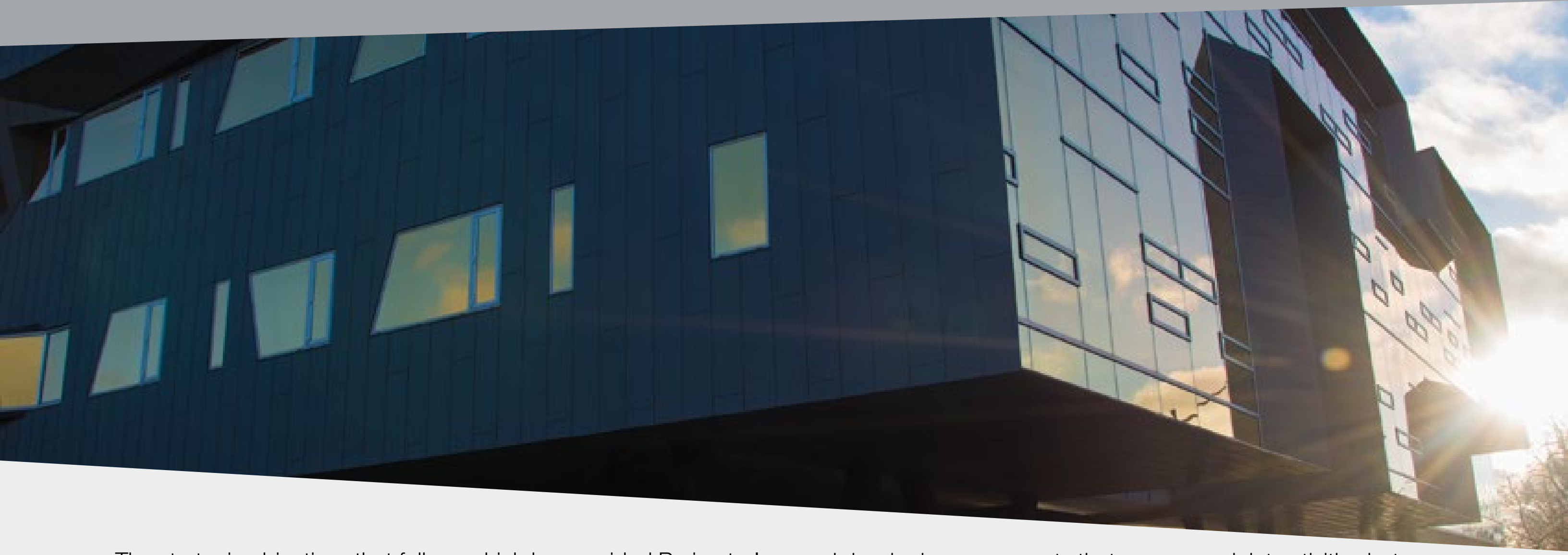
LOOKING AHEAD: PRIORITIES AND OBJECTIVES FOR THE FUTURE



The strategic objectives that follow, which have guided Perimeter's institutional strategy for more than five years, are currently in review. In the coming year, the Institute will revise these objectives as necessary to reflect its growing international stature and new opportunities to be a leader in fundamental science. The advancement of Perimeter's core mission will continue to inform every facet of the Institute's research, training, and outreach efforts.

Deliver world-class research discoveries by continually seeking to advance fundamental research across Perimeter's areas of focus, encouraging complementary approaches and a collaborative atmosphere which maximizes cross-fertilization and the probability of breakthroughs.

Become the research home of a critical mass of the world's leading theoretical physicists by continuing to recruit top talent, offering second-to-none research opportunities, and fostering cooperative links throughout the Canadian and international research community.

Generate a flow-through of the most promising talent by recruiting the world's top postdoctoral researchers, facilitating researcher engagement with experimental and observational centres, attracting and training brilliant young graduate students through the Perimeter Scholars International program and retaining the best for further PhD studies, and providing research training opportunities to promising graduate and undergraduate students on a visiting basis.

Become the second research home for many of the world's outstanding theorists by continuing to recruit top scientists to the Distinguished Visiting Research Chairs program, attracting Visiting Fellows and Emmy Noether Fellows of exceptional calibre, and developing agreements that encourage joint activities between researchers at Perimeter and leading centres throughout the world.

Act as a hub for a network of theoretical physics and math centres around the world, seeking partnership and collaboration opportunities that can help accelerate the creation of centres of excellence in math and physics.

Increase Perimeter's role as Canada's focal point for foundational physics research by continuing to develop national and international partnerships, leading in the development of the Quantum Valley ecosystem, and fostering research interaction opportunities between Perimeter researchers and affiliates across the country.

Host timely, focused conferences, workshops, seminars, and courses on cutting-edge topics, making the majority freely available online for the broader scientific community.

Engage in high-impact outreach by communicating the importance of basic research and the power of theoretical physics to general audiences, while also providing unique opportunities and high-quality resources to educators and students in Canada and abroad.

Create the world's best environment and infrastructure for theoretical physics research, training, and outreach by providing an inspiring physical space, cutting-edge information technology, and high-quality professional support.

Continue to build on Perimeter's highly successful public-private partnership funding model by broadening the Institute's donor base, both in Canada and internationally.

APPENDICES

FACULTY

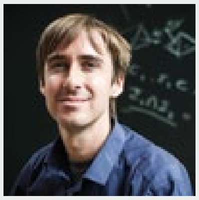
Neil Turok (PhD Imperial College London, 1983) was Professor of Physics at Princeton University and Chair of Mathematical Physics at the University of Cambridge before assuming his current position as Director of Perimeter Institute. In 2013, he was re-appointed for a second term and additionally awarded the Mike and Ophelia Lazaridis Niels Bohr Chair in Theoretical Physics at the Institute. 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 recently confirmed. With Stephen Hawking, he discovered instanton solutions describing the birth of inflationary universes. His work on open inflation forms the basis of the widely discussed multiverse paradigm. With Paul Steinhardt, he developed an alternative, cyclic model for cosmology, whose predictions are so far in agreement with all observational tests. 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 in 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 five centres – in South Africa, Senegal, Ghana, Cameroon, and Tanzania – and has become Africa's most renowned institution for postgraduate training in mathematical science. For his scientific discoveries and his work founding and developing AIMS, Turok was awarded a TED Prize in 2008. He has also been recognized with awards from the World Summit on Innovation and Entrepreneurship and the World Innovation Summit on Education.

Dmitry Abanin (PhD Massachusetts Institute of Technology, 2008) joined Perimeter in 2012 after postdoctoral positions at Harvard University and the Princeton Center for Theoretical Science. Abanin is a leading young condensed matter theorist whose research has focused on developing a theoretical understanding of Dirac materials, focusing on quantum transport of charge and spin and finding new ways of controlling their electronic properties. Some of his theoretical work has been experimentally confirmed by groups at Harvard University, the University of Manchester, Columbia University, the University of California, Riverside, the Max Planck Institute, and elsewhere. In 2014, he received a Sloan Research Fellowship.

Asimina Arvanitaki (PhD Stanford University, 2008) joined Perimeter's faculty in 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 precision level. Arvanitaki also works on theoretical challenges raised by experimental results, such as a model of particle physics influenced by string theory called "split SUSY."

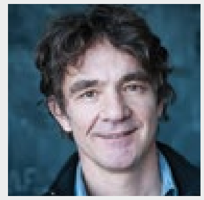
Latham Boyle (PhD Princeton University, 2006) joined the Institute's faculty in 2010. From 2006 to 2009, he held a Canadian Institute for Theoretical Astrophysics Postdoctoral Fellowship; he was also a Junior Fellow of the Canadian Institute for Advanced Research. Boyle has studied what gravitational 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. In collaboration with his student 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), and a New Horizons in Physics Prize from the Fundamental Physics Prize Foundation (2014).



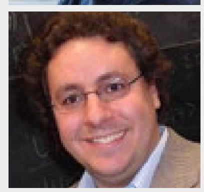
Kevin Costello (PhD University of Cambridge, 2003) joined Perimeter in August 2014 from Northwestern University, where he had been a faculty member since 2006. He is the Krembil William Rowan Hamilton Chair in Theoretical Physics. Previously, he was a Chapman Fellow at Imperial College London (2003-05) 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. Costello's previous honours include an Alfred P. Sloan Research Fellowship and several prestigious grants from the National Science Foundation in the United States.

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 and has constructed new realizations of quantum geometry. Dittrich has received the Otto Hahn Medal of the Max Planck Society, which recognizes outstanding young scientists, and an Early Researcher Award from Ontario's Ministry of Research and Innovation.

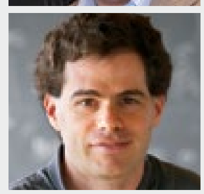


Laurent Freidel (PhD L'École Normale Supérieure de Lyon, 1994) joined Perimeter Institute first as a visitor in 2002 and then as faculty in 2006. Freidel is a mathematical physicist who has made many notable contributions in the field of quantum gravity, developing spin foam models, among other things. He has also introduced several new concepts in this field, such as group field theory, relative locality, and most recently, 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.

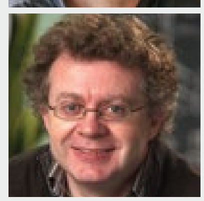
Davide Gaiotto (PhD Princeton University, 2004) joined Perimeter in 2012 and holds the Krembil Galileo Galilei Chair in Theoretical Physics. Previously, he was a postdoctoral fellow at Harvard University from 2004 to 2007 and a long-term Member at the Institute for Advanced Study in Princeton from 2007 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).



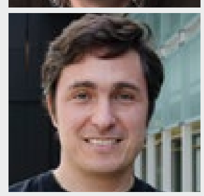
Jaume Gomis (PhD Rutgers University, 1999) joined Perimeter Institute in 2004, declining a European Young Investigator Award by the European Science Foundation to do so. Prior to that, he worked at the California Institute of Technology as a Postdoctoral Scholar and as the Sherman Fairchild Senior Research Fellow. His main areas of expertise are string theory and quantum field theory. In 2009, Gomis was awarded an Early Researcher Award from Ontario's Ministry of Research and Innovation for a project aimed at developing new techniques for describing quantum phenomena in nuclear and particle physics.



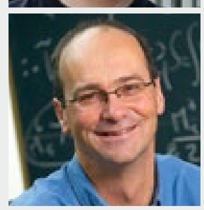
Daniel Gottesman (PhD California Institute of Technology, 1997) joined Perimeter's faculty in 2002. From 1997 to 2002, he held postdoctoral positions at the Los Alamos National Laboratory, Microsoft Research, and the University of California, Berkeley (as a long-term CMI Prize Fellow for the Clay Mathematics 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, the University of Durham, the University of Innsbruck, and the National University of Ireland. In 1992, he found a very simple proof of non-locality in quantum theory which has become known as Hardy's theorem. He has worked on characterizing quantum theory in terms of operational postulates and providing an operational reformulation of quantum theory. He is currently working on reformulating general relativity in operational terms as a stepping stone en route to finding a theory of quantum gravity.



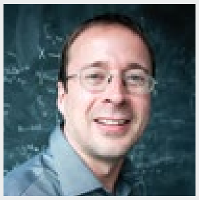
Luis Lehner (PhD University of Pittsburgh, 1998) began a joint appointment with Perimeter and the University of Guelph in 2009 and became a full-time faculty member at Perimeter in 2012. He previously held postdoctoral fellowships at the University of Texas at Austin and the University of British Columbia, 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.



Robert Myers (PhD Princeton University, 1986) is one of the leading theoretical physicists working in string theory 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 moving to Perimeter in 2001. He has made seminal contributions to our understanding of black hole microphysics and D-branes. Among Myers' 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. He was named on Thomson Reuters' list of the "World's Most Influential Scientific Minds" in 2014 and 2015.

Subir Sachdev (PhD Harvard University, 1985) joined Perimeter in 2014 and holds the Cenovus Energy James Clerk Maxwell Chair in Theoretical Physics at Perimeter Institute (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 US National Academy of Sciences, and he was a Perimeter Distinguished Visiting Research Chair from 2009 to 2014.

Philip Schuster (PhD Harvard University, 2007) joined Perimeter's faculty in 2010. He was a Research Associate at SLAC National Accelerator Laboratory from 2007 to 2010. Schuster's area of specialty is particle theory, with an emphasis on physics beyond the Standard Model. He has close ties to experiment and has investigated various theories that may be discovered at experiments at the Large Hadron Collider (LHC) at CERN. With members of the Compact Muon Solenoid experiment at the LHC, he developed methods to characterize potential new physics signals and null results in terms of simplified models, facilitating more robust theoretical interpretations of data. He is also a co-spokesperson for the APEX collaboration at the Thomas Jefferson National Accelerator Facility in Virginia. With Natalia Toro, he was awarded the 2015 New Horizons in Physics Prize by the Breakthrough Prize Foundation.



Kendrick Smith (PhD University of Chicago, 2007) joined Perimeter in 2012 from Princeton University, where he was the Lyman P. Spitzer Postdoctoral Fellow since 2009. 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 CHIME and the Planck collaboration. He was also involved in the start-up phase of the major Hyper-Suprime Cam project at the Hawaii-based Subaru telescope. 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 180 papers have generated over 16,300 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.

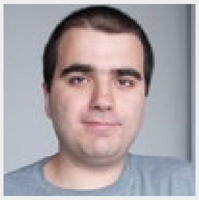
Robert Spekkens (PhD University of Toronto, 2001) joined Perimeter's faculty in 2008, after holding a postdoctoral fellowship at Perimeter and an International Royal Society Fellowship at the University of Cambridge. His field of research is the foundations of quantum theory, where he is known for his 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 previous winner of the Birkhoff-von Neumann Prize of the International Quantum Structures Association.

Paul Steinhardt (PhD Harvard University, 1978) is the Richard P. Feynman Chair in Theoretical Physics at Perimeter Institute (Visiting) and the Albert Einstein Professor in Science at Princeton University, where he is also the Director of the Princeton Center for Theoretical Science. Steinhardt's research spans problems in particle physics, astrophysics, cosmology, condensed matter physics, and geoscience. He is one of the original architects of the inflationary theory of the universe, having constructed the first viable models and shown they can generate density variations that could seed galaxy formation. He was also the first to show that quantum fluctuations make inflation eternal, which ultimately leads to a multiverse. With Neil Turok, he later developed the "cyclic theory" of the universe, which proposes that the universe underwent repeated periods of contraction and expansion punctuated by a big bounce; the theory generates similar density variations, but avoids the multiverse and its associated problems. He is also known for his work on dark energy and dark matter, including theories of "quintessence" and self-interacting dark matter. In condensed matter physics, Steinhardt invented the theoretical concept of quasicrystals with his student Dov Levine, and has subsequently worked to illuminate many of their unique properties. More recently, he organized a team that discovered the first natural quasicrystal and later established its origin by leading an expanded team on a geological expedition to the Kamchatka Peninsula in 2011. He is co-inventor of the first three-dimensional icosahedral photonic quasicrystal, along with a new class of photonic materials called hyperuniform disordered solids.

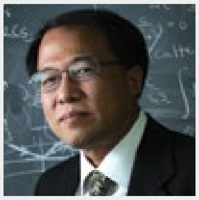
Natalia Toro (PhD Harvard University, 2007) joined Perimeter in 2010 after completing a postdoctoral fellowship at the Stanford Institute for Theoretical Physics. Toro has developed a framework for few-parameter models of possible new physics signals and has played a major role in integrating new techniques, called "on-shell effective theories," into the program of searches at the Compact Muon Solenoid experiment at the Large Hadron Collider at CERN. She is an expert in the study of dark forces that couple very weakly to ordinary matter and is co-spokesperson for APEX, an experiment searching for such forces at the Thomas Jefferson National Accelerator Facility. With Philip Schuster, she was awarded the 2015 New Horizons in Physics Prize by the Breakthrough Prize Foundation.

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. In 2015, he was awarded both a Sloan Research Fellowship and the Gribov Medal of the European Physical Society.



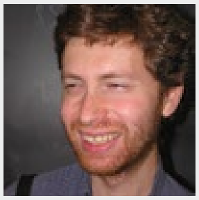
Xiao-Gang Wen (PhD Princeton University, 1987) joined Perimeter's faculty in 2012 as the BMO Financial Group Isaac Newton Chair in Theoretical Physics. Widely recognized as one of the world's leaders in condensed matter theory, he pioneered the new paradigm of quantum topological order, used to describe phenomena from superconductivity to fractionally charged particles, and he has invented many new mathematical formalisms. Wen authored the textbook *Quantum Field Theory of Many-body Systems: From the Origin of Sound to an Origin of Light and Electrons*. He was previously a Distinguished Moore Scholar at the California Institute of Technology and the Cecil and Ida Green Professor of Physics at the Massachusetts Institute of Technology, as well as one of Perimeter's own Distinguished Visiting Research Chairs. He is also a Fellow of the American Physical Society.



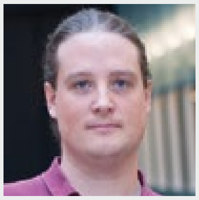
ASSOCIATE FACULTY

Niayesh Afshordi (PhD Princeton University, 2004) is jointly appointed with the University of Waterloo. He was the Institute for Theory and Computation Fellow at the Harvard-Smithsonian Center for Astrophysics from 2004 to 2007 and a Distinguished Research Fellow at Perimeter Institute from 2008 to 2009. Afshordi began his appointment as an associate faculty member in 2009. He specializes in interdisciplinary problems in fundamental physics, astrophysics, and cosmology. In 2010, he was awarded a Discovery Accelerator Supplement from the Natural Sciences and Engineering Research Council of Canada. In 2011, he won the Vainu Bappu Gold Medal from the Astronomical Society of India, as well as an Early Researcher Award from the Ontario Ministry of Research and Innovation.

Alexander Braverman (PhD Tel Aviv University, 1998) joined Perimeter in July 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. 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 has recently been part of 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 Ontario's 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.

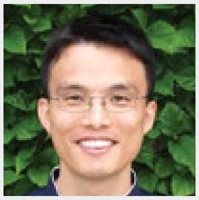
Cliff Burgess (PhD University of Texas at Austin, 1985) joined Perimeter's faculty as an associate member in 2004 and was jointly appointed to McMaster University's faculty in 2005. Prior to that, he was a Member in the School of Natural Sciences at the Institute for Advanced Study in Princeton and a 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 a member of 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 chairs the advisory committee for the Quantum Information Processing program at the Canadian Institute for Advanced Research. He is a Fellow of the American Physical Society and a Fellow of the Royal Society of Canada.

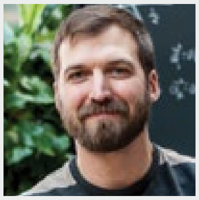
James Forrest (PhD University of Guelph, 1994) joined Perimeter in 2014 as the Institute's Academic Programs Director and an associate faculty member. He is jointly appointed at the University of Waterloo, where he's been a professor since 2000. His research focuses on the physics of soft matter on the 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.

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 spanning 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.

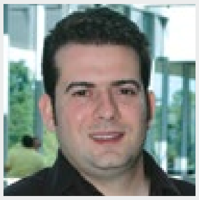
Raymond Laflamme (PhD University of Cambridge, 1988) is a founding faculty member of Perimeter Institute and founding Director of the Institute for Quantum Computing, where he is jointly appointed. He held research positions at the University of British Columbia and Peterhouse College, University of 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. With colleagues, he founded Universal Quantum Devices, a start-up commercializing spin-offs of quantum research.



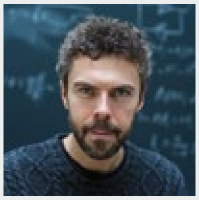
Sung-Sik Lee (PhD Pohang University of Science and Technology, 2000) joined Perimeter in 2011 in a joint appointment with McMaster University, where he is an Associate Professor. He previously worked as a postdoctoral researcher at the Pohang University of Science and Technology, the Massachusetts Institute 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 an Early Researcher Award from Ontario's Ministry of Research and Innovation, the International Union of Pure and Applied Physics Young Scientist Prize in Computational Physics from the Council on Computational Physics, 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 and Deputy Director of IQC. Mosca has made major contributions to the theory and practice of quantum information processing, including several of the first implementations of quantum algorithms and fundamental methods for performing reliable computations with untrusted quantum apparatus. His current research interests include quantum algorithms and complexity, and the development of cryptographic tools that will be safe against quantum technologies. Mosca's numerous academic honours include Canada's Top 40 Under 40 award (2010), the Premier's Research Excellence Award (2000-05), Fellow 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).



Markus Mueller (PhD Technical University of Berlin, 2007) joined Perimeter in July 2015, jointly appointed with Western University, where he holds the Canada Research Chair in the Foundations of Physics. Prior to that, he was a Junior Research Group Leader at the Institute for Theoretical Physics at the University of Heidelberg, and held postdoctoral positions at Perimeter Institute, the University of Potsdam, and the Max Planck Institute for Mathematics in the Sciences. Mueller is a mathematical physicist working in quantum information and quantum foundations, with particular interest in statistical physics, generalized probabilistic theories, and algorithmic information theory.

Ue-Li Pen (PhD Princeton University, 1995) joined Perimeter in December 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 Associate Director since 2009. 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 and an Adjunct Professor at the Tata Institute for Fundamental Research in India.

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.

Itay Yavin (PhD Harvard University, 2006) began a joint appointment with Perimeter and McMaster University in 2011. Previously, he was a Research Associate at Princeton University and a James Arthur Postdoctoral Fellow at New York University. Yavin's research focuses on particle physics and the search for physics beyond the Standard Model. Among his recent proposals is a new experiment to search for new particles with fractional charges at the Large Hadron Collider. He is now leading a collaboration looking to make this experiment a reality.

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
Maria Antonakos

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, 2014/15

** Indicates PSI Fellow*
*** Indicates Templeton Frontiers Program Postdoctoral Fellow*

Tibra Ali*
Wolfgang Altmannshofer
Denis Bashkirov
Agata Branczyk*
Daniel Brod
Christopher Brust
Juan Carrasquilla
Anushya Chandran
Lukasz Cincio
Joshua Combes
Yanou Cui
Denis Dalidovich*
Tobias Fritz**
Martin Ganahl
Henrique Gomes
Stefania Gori
Stephen Green
Gus Gutoski
Song He
Michal Heller
Kurt Hinterbichler**
Philipp Hoehn
Mike Hogan
Eder Izaguirre
Tim Johannsen
Hee-Cheol Kim
Heeyeon Kim
Isaac Kim
Shota Komatsu
Peter Koroteev
Ryszard Kostecki
Gordan Krnjaic
David Kubiznak*
Ipsita Mandal
David Marsh
Jia-Wei Mei
Flavio Mercati**
Yasha Neiman
Matthew Pusey
C. Jess Riedel
Aldo Riello
Julian Rincon
Dine Ousmane Samary
Luiz Santos
Brian Shuve
Matteo Smerlak
Edwin (Miles) Stoudenmire
Matt von Hippel
Yidun Wan
Yuan Wan
William Witczak-Krempa
Daniel Wohns*
Elie Wolfe
Gang Xu*
Huan Yang
Shuo Yang
Peng Ye
Jie Zhou
Huangjun Zhu

SCIENTIFIC VISITORS, 2014/15

** Indicates Distinguished Visiting Research Chair*
*** Indicates Visiting Fellow*

Scott Aaronson, Massachusetts Institute of Technology (MIT)

Niloufar Afsari, University of Toronto

Yakir Aharonov*, Chapman University and Tel Aviv University

Aris Alexandradinata, Princeton University

Murad Alim, Harvard University

John-Mark Allen, University of Oxford

Jan Ambjorn, University of Copenhagen/Niels Bohr Institute

Giovanni Amelino-Camelia, Sapienza University of Rome

Abhay Ashtekar*, Pennsylvania State University

Benjamin Assel, King's College London

Miriam Backens, University of Oxford

Yuntao Bai, Princeton University

Leon Balents*, University of California, Santa Barbara

Guillermo Ballesteros, Heidelberg University

Ning Bao, California Institute of Technology (Caltech)

Yaneer Bar-Yam, New England Complex Systems Institute

Ben Baragiola, University of New Mexico

Jacob Barandes, Harvard University

Julian Barbour, University of Oxford

James Bardeen*, University of Washington

Till Bargheer, Institute for Advanced Study (IAS)

Maissam Barkeshli, Microsoft Research Station Q

Alexandre Barreira, Durham University

John Barrett, University of Nottingham

Jonathan Barrett**, University of Oxford

Itzhak Bars, University of Southern California

Masha Baryakhtar, Stanford University

Ganapathy Baskaran*, Institute of Mathematical Sciences, Chennai

Benjamin Basso, École Normale Supérieure (ENS)

Nick Battaglia, Princeton University

Matthew Baumgart, Carnegie Mellon University

Melanie Becker, Texas A&M University

Christopher Beem, Institute for Advanced Study (IAS)

Jibril Ben Achour, University of Paris VII

Ariel Bendersky, Institute of Photonic Sciences (ICFO)

Nathan Benjamin, Stanford University

Joshua Berger, SLAC National Accelerator Laboratory

David Berman, Queen Mary University of London

Gary Bernstein, University of Pennsylvania

Joe Bhaseen, King's College London

Atri Bhattacharya, University of Arizona

Nadir Bizi, Pierre and Marie Curie University

Nikita Blinov, TRIUMF

Robin Blume-Kohout, Sandia National Laboratories

Celine Boehm, Durham University

Hector Bombin, University of Copenhagen

James Bonifacio, University of Oxford

Valentin Bonzom, University of Paris 13

Patrick Brady*, University of Wisconsin-Milwaukee

Joseph Bramante, University of Notre Dame

Robert Brandenberger, McGill University

Nikolas Breuckmann, RWTH Aachen University

Alyson Brooks, Rutgers University

Adam Brown, Stanford University

Olivier Brunet, Lycée Vaucanson

Matthew Buckley, Rutgers University

Oliver Buerschaper, Free University of Berlin

Philip Bull, University of Oslo

Mathew Bullimore, Institute for Advanced Study (IAS)

Philipp Burda, Durham University

Juan Campuzano, University of Illinois at Chicago

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

Sylvain Carrozza, Aix-Marseille University/Centre of Theoretical Physics (CPT)

Shira Chapman, Tel Aviv University

Benoit Charbonneau, University of Waterloo

Edgardo Cheb-Terrab, Maplesoft

Chien-Yi Chen, Brookhaven National Laboratory

Gang Chen, University of Toronto

Ji-Yao Chen, Tsinghua University

Yanbei Chen, California Institute of Technology (Caltech)

Meng Cheng, Microsoft Research Station Q

Aleksey Cherman, University of Minnesota

Giulio Chiribella**, University of Hong Kong

Emily Cliff, University of Oxford

Adrian Clough, Swiss Federal Institute of Technology (ETH), Zurich

Andrew Coates, University College London

Mattia Colombo, University of Nottingham

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CONFERENCES AND WORKSHOPS, 2014/15

PI Days
October 22-23, 2014

EHT 2014
November 10-14, 2014

Mathematical Physics Workshop
November 14-16, 2014

Superluminality in Effective Field Theories for Cosmology
April 9-11, 2015

(Mock) Modularity, Moonshine, and String Theory
April 13-17, 2015

Superstring Perturbation Theory
April 22-24, 2015

PI Day
April 28, 2015

4 Corners Southwest Ontario Condensed Matter Physics Symposium 2015
April 30, 2015

PI-CITA Day 2015
May 1, 2015

Information Theoretic Foundations for Physics
May 11-15, 2015

Flux Tubes
May 13-15, 2015

GAP 2015: Geometry and Physics
May 25-30, 2015

Preparing for the High-Luminosity Run of the LHC
June 8-9, 2015

Convergence
June 20-24, 2015

TRISEP 2015
July 6-17, 2015

COURSES, 2014/15

Fundamentals of Astrophysics
Instructor: Niayesh Afshordi, Perimeter Institute and University of Waterloo
September 23-December 11, 2014
Viewable at: http://pirsa.org/C14039

Entanglement Entropy and the Area Law
Instructor: Rafael Sorkin, Perimeter Institute
October 7-28, 2014
Viewable at: http://pirsa.org/C14040

Higher-Spin Gravity: One Learner's Perspective
Instructor: Yasha Neiman, Perimeter Institute
May 4-8, 2015
Viewable at: http://pirsa.org/C15029

Unruh-DeWitt Detectors in RQI: From the Basics to Frontiers
Instructor: Shih-Yuin Lin, National Changhua University of Education
May 25-26, 2015
Viewable at: http://pirsa.org/C15028

SPONSORSHIPS, 2014/15

"5th IUPAP International Conference on Women in Physics," Wilfrid Laurier University

"5th Nanoscale Magnetic Resonance Imaging (NanoMRI) Conference," Institute for Quantum Computing/University of Waterloo

"Contextuality and Non-Locality as Resources for Quantum Information," University of British Columbia

"Isham at 70: Modern Issues in Foundations of Physics," Imperial College London

"Lake Louise Winter Institute 2015," University of Alberta

"PQCrypto 2014," University of Waterloo

"Progress in Ab Initio Techniques in Nuclear Physics," TRIUMF

"Searches for New Phenomena at the Upgraded LHC," TRIUMF

"Testing Gravity 2015," Simon Fraser University

"Theory Canada 10," University of Calgary

"Women in Physics Canada 2015," University of Toronto

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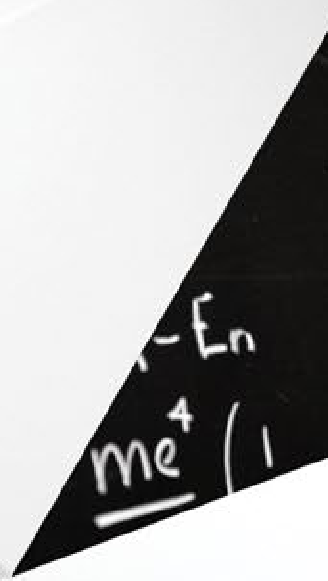

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