2015/16 Annual Report to Innovation, Science, and Economic Development Canada

Covering the Objectives, Activities, and Finances
for the period from August 1, 2015 to July 31, 2016 and
Statement of Objectives for Next Year and the Future

Submitted by Neil Turok, Director
To the Hon. Navdeep Bains, Minister of Innovation, Science, and Economic Development
and the Hon. Kirsty Duncan, Minister of Science

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.

Overview of Perimeter Institute

"Perimeter has successfully positioned Canada as a world leader in theoretical physics research."

– KPMG Review, June 2016

Located in Waterloo, Ontario, Perimeter Institute for Theoretical Physics was founded in 1999 to foster breakthroughs in our understanding of the universe, from the smallest particles to the entire cosmos. Because the field is so fundamental, just one major discovery can literally change our world. Today's theoretical physics is tomorrow's technology. Quantum mechanics, for example, led directly to semiconductors, computers, lasers, and a nearly infinite array of modern electronics.

In just 17 years, Perimeter Institute has delivered one of Canada's biggest research successes in decades: an innovative, world-leading centre of research, training, and educational outreach in the lowest-cost, highest-impact area of science: fundamental physics.

The Institute has attracted some of the world's most brilliant scientists and built a reputation as a major research hub. Approximately 1,000 scientists come to attend conferences or do research each year, catalyzing new collaborations and discoveries. Within this dynamic environment, Perimeter is training the next generation of scientific pioneers through its graduate programs, and the Institute hosts the world's largest community of postdoctoral researchers in the field.

Understanding the role of science in our lives is more important than ever, so an integral part of Perimeter's mission is educational outreach to teachers, students, and the general public. Award-winning programs and resources seek to engage, educate, and inspire, communicating the importance of basic research, the joy of discovery, and the enduring power of ideas.

As an independent, not-for-profit institute, Perimeter's visionary funding model unites public and private partners, and some of the world's best scientific minds, in a shared quest to achieve breakthroughs. With the ongoing support of its partners, Perimeter is helping to catalyze an innovation ecosystem that will bring benefits and prosperity for generations to come.

As of July 31, 2016, the Perimeter community includes:

- 22 full-time faculty, including six Perimeter Research Chairs
- 20 associate faculty, including three Visiting Perimeter Research Chairs
- 49 Distinguished Visiting Research Chairs
- 27 Visiting Fellows
- 58 postdoctoral researchers[1]
- 78 graduate students[2]

[1] This includes full-time postdoctoral researchers, jointly-appointed postdoctoral researchers, and PSI Fellows.
[2] This includes 49 PhD students and 29 Perimeter Scholars International (PSI) master's students.

AN ACCELERATOR OF DISCOVERY

RESEARCH

160+ SCIENTISTS IN RESIDENCE conducting research

12 MAJOR PRIZES AND HONOURS awarded to Perimeter scientists in 2015/16

1,000+ VISITING INTERNATIONAL SCIENTISTS annually

4,000+ PAPERS appearing in 170 journals with 150,000+ citations since 2001

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

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

OUTREACH

20 MILLION STUDENT INTERACTIONS since 2001

20,000+ EDUCATORS trained through Perimeter workshops since 2005

619 TOP HIGH SCHOOL STUDENTS from 50 COUNTRIES have attended the International Summer School for Young Physicists since 2003

65 COUNTRIES have used Perimeter's educational resources

TRAINING

In 2015/16, Perimeter was home to

58 POSTDOCTORAL RESEARCHERS

49 PHD STUDENTS and

29 PSI MASTER'S STUDENTS from 18 COUNTRIES

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Director's Preface

What an extraordinary year it's been – for physics and for Perimeter. In February 2016, the LIGO collaboration announced that they had detected gravitational waves, faint ripples in spacetime from the merger of two black holes. By March, we had learned that the Governments of Canada and Ontario had renewed their investments in Perimeter, with funding renewals that will take us forward through 2022. And in November, we were thrilled to learn that one of our **Distinguished Visiting Research Chairs, Duncan Haldane, a Professor at Princeton, was a co-winner of the 2016 Nobel Prize in Physics.**

Each of these wonderful happenings attest to the incredible power and potential of theoretical physics, and our shared capacity to shape the future for the benefit of humanity through science.

Gravitational waves were a prediction of Einstein's – a stunning example of the power of the human mind to investigate and understand our world. The LIGO experiment was a moonshot – difficult, risky, and hugely ambitious. Ultimately, it was a huge success for science, for spinoff technologies, and for raising humankind's sights. Their wonderful discovery shows what is possible with vision, sustained effort, and committed government support.

Likewise, the Nobel-winning work of Duncan Haldane and his colleagues began in pure theory, but their discoveries turn out to have extraordinary potential – these may well be the materials from which quantum computers are made.

Here at Perimeter, we seek to make breakthroughs of similar magnitude, and to share them for the benefit of the world. We are equally determined to encourage and inspire the next generation of scientists and technologists, who will help to ensure the health and vitality of our economy and our society.

We could not undertake these ambitious pursuits without the visionary and committed support of our public and private partners. The confidence that the Governments of Canada and Ontario have expressed in Perimeter by renewing our funding for a further five years is a huge endorsement of our belief that basic physics advances will be crucial to our collective future.

We are profoundly appreciative of our partnership with the people of Ontario and Canada and their governments. In April, we were delighted to welcome Prime Minister Justin Trudeau for a public announcement of the new federal funding. His passion for physics was well illustrated by his succinct explanation of quantum computing, a video of which went viral online and made an impact around the world. Just a few weeks later, we were similarly pleased to welcome Premier Kathleen Wynne, who met with many members of our community.

Physics discoveries drive progress, and there are enormous opportunities for discovery today. As you will read in these pages, research at Perimeter has never been more exciting. The opportunity Perimeter represents is appreciated globally. Last fall, our external Scientific Advisory Committee, comprising nine eminent scientists from around the world, undertook an extensive review of the Institute. In a glowing report, they stated: "It is difficult to conceive of a research institute of similar scope and size that would

generate as much visibility and impact as does Perimeter Institute…. By lending its support to the Perimeter Institute, the Canadian government takes a lead role in promoting fundamental science and enabling future innovation." A comprehensive five-year audit undertaken by KPMG reached a similar conclusion, stating: "Perimeter has successfully positioned Canada as a world leader in theoretical physics research."

By reaching for the stars, and supporting the most ambitious science, Perimeter has become a magnet for the world's top talent. In April, we appointed Asimina Arvanitaki, a pioneering particle theorist, as the Stavros Niarchos Foundation Aristarchus Chair at Perimeter Institute. Funded by private partners who appreciate the unique opportunity Perimeter represents, Mina's chair is the ninth to be named since 2011. This year, we also appointed one new faculty member, Max Metlitski, and jointly appointed two associate faculty, Huan Yang (with the University of Guelph) and Jon Yard (with the Institute for Quantum Computing at the University of Waterloo). Through such joint appointments, we join forces with the wider Canadian academic community for the benefit of all.

The number of applications for master's or PhD places, or postdoctoral fellowships, and the rate of acceptances of our offers, are among the highest of any institution in the world. In all of our training programs, we seek to draw in exceptional minds, equipping them with the skills and knowledge they need in order to contribute new ideas and discoveries. Above all, we hope to impart Perimeter's ethos, of scientific excellence as a primary means by which we can make unique contributions to advance humanity.

Educational outreach to students, teachers, and the wider public has continued to be an area of special focus and strength at Perimeter. This year, we reached over *one million* students – the vast majority in Canada – through our many educational outreach channels. It remains a top priority of the Institute to engage with and harness the curiosity we all possess, to reach larger and larger audiences, and to deliver quality experiences which have a lasting impact on all.

In this regard, next year is set to be a very special one, as we celebrate Canada's 150th birthday. Perimeter is honoured to have been chosen as the lead partner for the Innovation platform of Canada 150. With our partners, we shall deliver a huge range of activities and events from coast to coast to coast. We look forward to making it a year to remember, as one in which Canada expressed itself as a forward-looking, inclusive society, with knowledge and knowledge-sharing at its heart.

– Neil Turok

Executive Summary

Perimeter Institute's mission is to create and sustain the world's leading centre for theoretical physics research, training, and outreach, fostering excellence and stimulating major scientific breakthroughs.

The objectives set out in last year's Corporate Plan play a part in the Institute's comprehensive long-term strategy for achieving this ambitious goal. In 2015/16, Perimeter made excellent progress, meeting or exceeding major targeted outcomes under all of its objectives. This provides strong evidence that the Institute's strategic planning has been both sound and effective, and that it is on track to achieve its long-term vision.

Two comprehensive, multi-year reviews of Perimeter Institute were conducted in 2015/16, in accordance with the Institute's funding agreement with Innovation, Science, and Economic Development Canada. Both resulted in extraordinarily positive assessments of Perimeter's operations at every level.

The report from Perimeter's Scientific Advisory Committee concluded: "It is difficult to conceive of a research institute of similar scope and size that would generate as much visibility and impact for every dollar invested in it as does the Perimeter Institute."

The independent audit by KPMG concluded: "Perimeter has successfully positioned Canada as a world leader in theoretical physics research."

Achievement Highlights, 2015/16

Of special note, in November 2016, Perimeter Distinguished Visiting Research Chair Duncan Haldane shared the 2016 Nobel Prize in Physics for his pioneering work on exotic phases of matter.

Advancing Fundamental Research

- ✓ Produced research discoveries of international impact and importance
- ✓ Sample research highlights include the following:
    - Showed how to create a highly desirable information-processing gate for optical quantum computation, overturning expectations that this was impossible
    - Developed novel proposals to use existing LIGO data to search for a long-hypothesized particle called the axion

- Working with the Event Horizon Telescope collaboration, showed that strongly ordered magnetic structures exist near black holes – work which will help researchers study how black holes grow and launch powerful jets of radiation and charged particles
- Combined neural networks with Monte Carlo simulations to demonstrate the power of machine learning for condensed matter and statistical physics research, a result with major potential impact for the discovery of new forms of matter

✓ Perimeter researchers received numerous national and international awards and honours, including the following:

- Director Neil Turok won the 2016 John Torrence Tate Award for International Leadership in Physics from the American Institute of Physics.
- Freddy Cachazo, the Gluskin Sheff Freeman Dyson Chair in Theoretical Physics at Perimeter Institute, was awarded the CAP-CRM Prize in Theoretical and Mathematical Physics by the Canadian Association of Physicists and the Centre de recherches mathématiques.
- Associate Faculty member Roger Melko was awarded the CAP Herzberg Medal by the Canadian Association of Physicists.
- Associate Faculty member Markus Mueller won the 2016 Birkhoff-von Neumann Prize of the International Quantum Structures Association.
- Faculty member Robert Myers was named among the "World's Most Influential Scientific Minds 2015," based on a recent study by Thomson Reuters.
- Director Neil Turok was named the 2016 Gerald Whitrow Lecturer of the Royal Astronomical Society.
- Subir Sachdev, the Cenovus Energy James Clerk Maxwell Chair in Theoretical Physics at Perimeter Institute (Visiting), was awarded the Dirac Medal for the Advancement of Theoretical Physics by the University of New South Wales and the Australian Institute of Physics.
- Associate Faculty member Markus Mueller was named to the Canada Research Chair in the Foundations of Physics (Tier 2).
- Postdoctoral researcher Flavio Mercati and his collaborators were awarded the 2015 Buchalter Cosmology Prize by the American Astronomical Society.
- Associate Faculty member David Cory was elected as a Fellow of both the Royal Society of Canada and the American Physical Society.
- Perimeter scientists were awarded $4.7 million in research grants.

Attracting the Brightest Minds

✓ Appointed Asimina Arvanitaki, an outstanding young particle physicist, as the Stavros Niarchos Foundation Aristarchus Chair in Theoretical Physics, the ninth Perimeter Research Chair

- ✓ Welcomed one new full-time faculty member and recruited two part-time associate faculty members, plus a full-time Director's Fellow

- ✓ Appointed five eminent international scientists as Distinguished Visiting Research Chairs, bringing the total to 49, and seven accomplished researchers as Visiting Fellows, bringing the total to 27

- ✓ Welcomed five outstanding early-career researchers as Emmy Noether Visiting Fellows

- ✓ Appointed 19 postdoctoral researchers in 2015/16 and recruited 19 more for 2016/17

Training the Scientists of the Future

- ✓ Trained 29 students from 18 countries (selected from 472 applicants) through the Perimeter Scholars International (PSI) master's program

- ✓ Provided advanced training to 49 PhD students in conjunction with surrounding universities

- ✓ Six departing postdoctoral researchers obtained tenure-track faculty positions

A Global Hub for Scientific Interaction

- ✓ Expanded ties to major experimental efforts throughout the world

- ✓ Held 17 conferences and workshops, attended by 935 scientists from around the world

- ✓ Partnered on eight joint workshops and conferences held at Perimeter and co-sponsored an additional 16 off-site scientific events

- ✓ Presented 322 scientific talks

- ✓ Hosted 430 visiting scientists to do collaborative and individual research

- ✓ Shared the Institute's scientific events virtually with over 108,000 visitors from 170 countries

- ✓ Hosted OpenAccess Energy, the third Summit of the Waterloo Global Science Initiative

- ✓ Provided expertise and assistance to the African Institute for Mathematical Sciences – Next Einstein Initiative (AIMS-NEI) and the International Centre for Theoretical Physics – South American Institute for Fundamental Research (ICTP-SAIFR)

Inspiring Through Outreach

- ✓ Facilitated more than 9.5 million student interactions through Perimeter programs and educational resources, bringing the total to more than 20 million to date

- ✓ Partnered with the Ontario Ministry of Education to produce a suite of integrated educational resources targeting math, science, and technology for students in grades 5 to 8

- ✓ Led the planning and development of Innovation150, a signature initiative of the Canada 150 celebrations to be held throughout 2017

- ✓ Hosted the 14th International Summer School for Young Physicists (ISSYP) and gave 15 Physica Phantastica presentations – reaching more than 4,200 students across Canada

- ✓ Held EinsteinPlus Teachers' Camp for 40 educators from around the world and reached more than 3,000 educators through Teacher Network training camps and workshops

- ✓ Delivered 135 workshops to over 4,000 educators across Canada and abroad

- ✓ Received major coverage in national and international media, including *Scientific American*, *The Globe and Mail*, *Wired*, *The Guardian*, *The Economist*, *Maclean's*, and more

- ✓ Presented eight engaging public lectures to capacity audiences on-site and to expanding audiences online through the Perimeter Public Lecture Series

- ✓ Won the Science in Society Communications Award for the monthly "Slice of PI" series and significantly increased Perimeter's social media impact

Creating an Optimal Research Environment

- ✓ Formed ADVANCE committee to promote diversity and gender balance

- ✓ Supported data visualization tied to the Tensor Network and Event Horizon Telescope Initiatives

Growing the Public-Private Partnership

- ✓ Secured pledges of $50 million each (over five years) from the Government of Canada and the Province of Ontario

- ✓ Finalized a $4 million investment from the Stavros Niarchos Foundation and secured $300,000 investments from both the Daniel Family Foundation and Cenovus Energy, each in support of a Perimeter Research Chair

- ✓ Received positive independent reviews from both the Scientific Advisory Committee and KPMG

Statement of Objectives for 2015/16

Objective 1: Deliver world-class research discoveries

Objective 2: Become the research home of a critical mass of the world's leading theoretical physicists

Objective 3: Generate a flow-through of the most promising talent

Objective 4: Become the second research home for many of the world's outstanding theorists

Objective 5: Act as a hub for a network of theoretical physics and math centres around the world

Objective 6: Increase Perimeter's role as Canada's focal point for foundational physics research

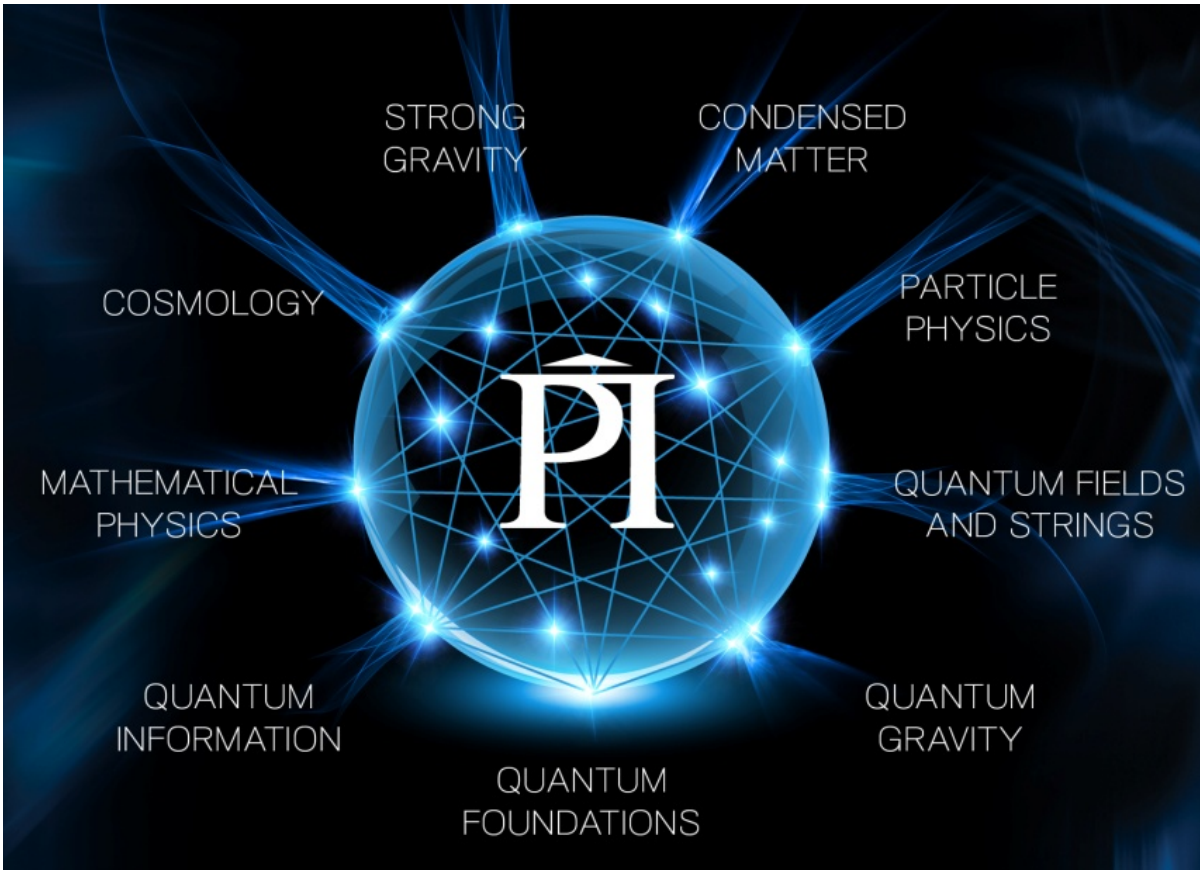
Objective 7: Host timely, focused conferences, workshops, seminars, and courses

Objective 8: Engage in high-impact outreach

Objective 9: Create the world's best environment and infrastructure for theoretical physics research, training, and outreach

Objective 10: Continue to build on Perimeter's highly successful public-private partnership funding model

Objective 1: Deliver world-class research discoveries



Summary of Achievements

- Advanced fundamental research through 453 high-calibre papers[3]
- Since inception, Perimeter researchers have produced more than 4,000 papers appearing in 170 journals, which have attracted more than 150,000 citations to date, attesting to the importance and long-term impact of the Institute's research[4]

[3] This reflects the one-year period from August 1, 2015 to July 31, 2016. Each publication has been counted only once, regardless of how many Perimeter researchers collaborated on it.
[4] This data comes from the Google Scholar and Spires databases.

Research Highlights

At the Quantum Frontier

Early explorations of quantum mechanics in the 20th century unleashed the first quantum revolution – a cascade of discoveries and technologies that included the transistor, the integrated circuit, computers, superconductors, MRIs, digital cameras, modern chemistry, and much more.

Many believe that a second quantum revolution is afoot, based on harnessing subtle and powerful features of quantum mechanics, like superposition (the idea that particles can exist in more than one state at once) and entanglement (which links particles so that they behave in synchrony, even if separated by great distances).

The holy grail of the field of quantum information is the realization of a full scale quantum computer, which could allow us to break unbreakable codes, model complex phenomena, and solve problems previously thought to be unsolvable. Much theoretical research is required, however, before quantum computing technologies can fully emerge.

Perimeter and our nearby experimental partner, the Institute for Quantum Computing (IQC) at the University of Waterloo, have helped make Waterloo into the world's first "Quantum Valley" a global hub of quantum information science spanning theory to experiment and technology development.

For example, Perimeter Faculty member **Daniel Gottesman** is an acknowledged world leader in quantum error correction, the techniques needed to safeguard and verify information amid the errors inherent to quantum computation. Faculty member **Lucien Hardy** has made contributions such as Hardy's Paradox that are foundational to the field. Associate Faculty members **David Cory** and **Raymond Laflamme**, as well as new recruit **Jon Yard** – all jointly appointed at IQC – test and develop new ideas for quantum control, quantum error correction, and frameworks for quantum computing.

As we deepen our understanding of the quantum realm, we will find new ways to apply that knowledge, moving closer to the tangible realization of the next quantum revolution.

The Medium is the Passage

A theoretical doorway to quantum computing long considered closed has been cracked back open by Perimeter postdoctoral researchers **Daniel Brod** and **Joshua Combes**. In two papers published in *Physical Review Letters* and *Physical Review A*, they have revived the idea of creating a type of information-processing gate that is at the top of the wishlist for optical quantum computation.

Working with collaborator Julio Gea-Banacloche, from the University of Arkansas, the researchers offer a concrete example of how to construct a controlled-phase (CPHASE) gate using a cross-Kerr medium (a particular kind of medium that passively permits photons to interact with each other, producing a phase shift).

Current attempts to create CPHASE gates require intense management at each step: to execute complicated control pulses and sequences, and to account for things like error correction. That makes using a Kerr medium attractive, since it doesn't require intense handling at each step.

The researchers showed how a CPHASE gate can be built out of a chain of cross-Kerr "interaction sites" containing one or two atoms which interact with the photons and mediate an effective interaction between them. With many such sites, and photons propagating in opposite directions through the chain, a perfect CPHASE gate can be created. For a dozen or so interaction sites, the gate achieves very high accuracy.

Previous work had indicated such a setup could not withstand real-world effects, so many had assumed it was impossible. This new work does not dispute those earlier findings. Rather, it is based on a different set of assumptions – and, in this instance, proves successful.

That the proposal works with such a small number of resources is encouraging. It is still beyond today's experimental capability to test, but is much closer than similar proposals requiring thousands of optical elements. Brod and Combes hope that, by showing that the scheme is possible in principle, they will breathe new life into a long-dormant avenue of inquiry.

References:

D.J. Brod (PI) and J. Combes (PI and IQC/UW), "Passive CPHASE Gate via Cross-Kerr Nonlinearities," *Phys. Rev. Lett.* 117, 080502 (2016).

D.J. Brod (PI), J. Combes (PI and IQC/UW), and J. Gea-Banacloche (University of Arkansas), "Two photons co- and counterpropogating through ***N*** cross-Kerr sites," *Phys. Rev. A* 94, 023833 (2016).

If it Walks Like a (Quantum) Duck …

If two separate systems are so similar you cannot tell them apart – neither in experiment nor in principle – can they be considered to be physically the same? It turns out that if one adopts the standard notion of physical identity, then, in the quantum universe, the answer is no.

"Noncontextuality" is the idea that, if it walks like a duck, sounds like a duck, and cannot be told apart from a duck in any experiment, then it must be a duck. But recent work devised at Perimeter Institute and tested at the Institute for Quantum Computing has shown that, in quantum mechanics, noncontextuality can fail.

The research, led by Perimeter Faculty member **Robert Spekkens** and University of Waterloo/IQC Faculty member and Perimeter Affiliate **Kevin Resch**, helps to clarify which principles of classical physics fail in a quantum world, and confirms this non-classicality experimentally.

Under quantum theory, two different preparations of a system can return identical results in every conceivable test, and yet any model of the experiment that assigns the systems' well-defined properties *requires* each system to be different. That inherent difference violates the principle of noncontextuality.

Spekkens, Perimeter postdoctoral researcher **Matthew Pusey**, and visiting doctoral student Ravi Kunjwal helped define what a test of noncontextuality could look like. Resch and University of Waterloo doctoral student Michael Mazurek built the complex experiment and ran the tests.

Importantly, the experiment did not assume ideal conditions. While previous attempts to test for the predicted failure of noncontextuality have had to resort to assuming things like noiseless measurements, the Perimeter and IQC teams wanted to avoid such unrealistic assumptions. They designed an experiment that could make meaningful tests of noncontextuality even in the presence of noise, by fighting statistical error with statistical inference.

The results, published in *Nature Communications*, are significant because, for certain kinds of cryptographic tasks and computational tasks, the failure of noncontextuality is the resource that powers quantum-over-classical advantages. Understanding how to contend with noise opens a new range of possibilities for physicists pushing to find – and fully understand – the technological advantages offered by quantum theory.

Reference:

M.D. Mazurek (IQC/UW), M.F. Pusey (PI), R. Kunjwal (Institute of Mathematical Sciences, Chennai), K.J. Resch (IQC/UW), and R.W. Spekkens (PI), "An experimental test of noncontextuality without unphysical idealizations," *Nature Comm.* 7, 11780 (2016).

Exploring Exotic Matter

The promise of quantum matter is hard to overstate.

In the 20th century, our understanding of materials was revolutionized when it was unified with the emerging field of quantum mechanics. This first quantum revolution resulted in much of our current technology, from transistors to solar cells to the touch screen on your iPad.

The 2016 Nobel Prize in Physics was awarded to three researchers – including Perimeter Distinguished Visiting Research Chair **Duncan Haldane** – whose discoveries of topological states of matter in the 1970s and 1980s helped lay the foundation for a second quantum revolution providing new insights into exotic states of matter with powerful properties.

Conventional states of matter are described by the arrangements and symmetries of their atoms. Quantum matter, on the other hand, can only be described by taking into account the correlations between atoms or electrons. This is like describing a city not in terms of its buildings and houses, but the information flows through its fibre optic cables. **Xiao-Gang Wen**, **the BMO Financial Group Isaac Newton Chair**, has made major contributions to this paradigm.

The study of quantum matter requires new mathematical tools and new theoretical understandings. The last decade has been marked by rapid development in both. The immediate payoff is a deeper understanding of phenomena such as superconductivity, but some of the tools and insights developed in relation to quantum matter have had a surprisingly broad effect. For example, tensor networks, a mathematical tool pioneered by Perimeter Faculty member **Guifre Vidal**, are opening new research directions in quantum gravity, high-energy physics, and even mathematics.

Although it began in pure theory, the second quantum revolution is likely to revolutionize the world of materials science and technology, impacting everything from computing and communications to energy transmission and medical technologies.

The race is on to make it happen. Here are just a few ways Perimeter researchers had an impact this year.

Quantum Machine Learning

The study of quantum many-body systems involves what could be nature's most complex object: the electron wavefunction. Using a computer to mathematically represent the wavefunction for a nanometer-sized chunk of dust would require a hard drive containing more magnetic bits than there are atoms in the universe.

To get around this, physicists have a grab-bag of tricks that extract useful properties of some wavefunctions, using only the modest computer hardware currently available. But Associate Faculty member **Roger Melko** is pioneering a different option. He is applying the established success of machine learning to new purposes in quantum many-body physics.

Machine learning refers to a set of algorithms used to extract features from extremely large or complex data sets. It is already prevalent in our daily lives, driving such things as facial recognition capabilities, game self-play, and other tasks in artificial intelligence.

Now, Melko and Perimeter postdoc **Juan Carrasquilla** have combined very modern neural network technology (a class of machine learning algorithm) with Monte Carlo simulations of model Hamiltonians that are of interest in conventional condensed matter physics. This combined Monte-Carlo/machine learning approach was introduced in the preprint "Machine Learning Phases of Matter" (currently under consideration for *Nature Physics*).

The researchers show that standard neural networks can detect conventional phases of matter, and phase transitions, in configurations produced by Monte Carlo simulations. These neural networks can also identify topological phases with no conventional order parameter. Connections between machine learning and tensor networks are also now being explored.

This work was the first to demonstrate the power of machine learning as a basic research tool in the field of condensed matter and statistical physics, and led to Perimeter hosting the first "Quantum Machine Learning" conference, in August, attended by almost 100 people from research and industry.

References:

P. Broecker (University of Cologne), J. Carrasquilla (PI), R.G. Melko (PI and UW), and S. Trebst (University of Cologne), "Machine learning quantum phases of matter beyond the fermion sign problem," arXiv:1608.07848.

K. Ch'ng (San Jose State University), J. Carrasquilla (PI), R.G. Melko (PI and UW), and E. Khatami (San Jose State University), "Machine Learning Phases of Strongly Correlated Fermions," arXiv:1609.02552.

J. Carrasquilla (PI) and R.G. Melko (PI and UW), "Machine learning phases of matter," arXiv:1605.01735.

Advancing the Theory of Topological Insulators

Topological insulators are unusual materials that act like a reverse power cord: they insulate on the inside and conduct electricity on the outside. But there is a crucial difference. Topological insulators are made up of the exact same material throughout.

One of the very few exotic states of matter that emerged from theory and was later confirmed through experiment, topological insulators are believed to hold great promise for quantum computing and no-loss energy transmission. A better understanding of topological insulators is thus of urgent and practical interest.

Perimeter Faculty member **Max Metlitski** has made important progress in this direction. The existing theory of topological insulators described the material in terms of its electrons. Metlitski developed a dual – or equivalent – theory which instead describes topological insulators in terms of vortices of

charge swirling across the surface. In recent work, he was able to extend that theory beyond the surface of the topological insulator and describe the behaviour of the insulating body, or "bulk", of the material as well.

This new description of topological insulators is more powerful than the old one. The previous theory worked only where the electrons on the surface were weakly interacting. This new vortex-based approach can describe strongly interacting electrons as well.

Metlitski's work also resolved a long-standing problem in condensed matter physics involving a system known as a quantum hall fluid. In these fluids, a film of electrons in a strong magnetic field has certain phases which are superconducting. The best existing theory describing the special states of the quantum hall fluid did not include one of the symmetries that quantum mechanics says it should have, and thus was known to be incomplete.

Metlitski and collaborators discovered an unexpected connection between topological insulators and quantum hall fluids in their special superconducting states: the new vortex-based description resolves the problem of the missing symmetry. This work is a major step forward in the theoretical understanding of both topological insulators and superconductors, and holds promise of further progress to come.

Reference:

M.A. Metlitski (PI and Kavli Institute for Theoretical Physics), "S-duality of $u(1)$ gauge theory with $\vartheta=\pi$ on non-orientable manifolds: Applications to topological insulators and superconductors," arXiv:1510.05663.

A New Window to the Cosmos

New eyes are opening on the universe.

Since the dawn of science, astronomy has been defined by light. First came what we could see with our eyes – movements of the moon, stars, and planets – and then what we could see using telescopes, first with visible wavelengths and then more exotic forms of light: x-rays, radio waves, and microwaves. With each wavelength came new and astonishing discoveries, from uncovering black holes to mapping the afterglow of the big bang.

But we were still limited to working with light. Now, finally, that's changing, as we begin to look at the universe through the lens of gravity.

Our current theory of gravity is Einstein's theory of general relativity, which defines how mass causes spacetime to stretch and warp. While most ordinary objects create gentle dimples in spacetime, very massive or very dense objects, like black holes, create more dramatic effects. And a rapid change in a very massive or very dense system, such as two black holes colliding, can create a tsunami of spacetime that ripples outward through the universe in a phenomenon known as gravitational waves. As the waves spread over cosmological distances, the tsunami is diluted to incredibly faint ripples.

In 2015, after decades of effort, a team of scientists working at the Laser Interferometer Gravitational-Wave Observatory (LIGO) detected these ripples in spacetime, from a pair of black holes on a collision course 1.3 billion years ago. At its peak, the merger released more power than all the light radiated by all the stars in the observable universe, yet its effect on Earth, after spreading out over a billion light-years, was tiny: the waves changed the length of the 4 km-long LIGO arms by a mere one-thousandth the width of a single proton. Achieving this detection was a truly great moment in science, equivalent to the day 400 years ago when Galileo first pointed a telescope at the sky.

Collecting the data is the job of sophisticated machines; understanding the data and mapping the course of future observations is the job of the world's leading theorists. Perimeter researchers are leveraging theory to maximize knowledge gains in this new era of discovery, from piecing together the puzzle of "multimessenger astronomy," which combines gravitational wave detections with electromagnetic signals, to, ultimately, turning the lens of gravity inward to test the predictions of general relativity.

Surprise: Gravitational Waves Can be Used to Study Particle Physics

We will presumably learn much about black holes and about general relativity from the next several years of LIGO observations – but that is not all we could learn from such a large dataset. Perimeter Faculty member **Asimina Arvanitaki**, who holds the inaugural **Stavros Niarchos Foundation Aristarchus Chair**, is among those exploring the possibilities for discovery.

Arvanitaki is a leader among a new generation of physicists seeking novel ways to test fundamentals of particle physics outside of large colliders.

In considering what could be learned from the LIGO data, Arvanitaki worked with Perimeter postdoctoral researchers **Masha Baryakhtar** and **Robert Lasenby**, Distinguished Visiting Research Chair **Savas Dimopoulos**, and Visiting Fellow **Sergei Dubovsky** to re-imagine black holes as naturally occurring particle detectors. Using these "detectors," they are developing a new way to search for new types of particles.

A black hole's enormous mass can produce many strange effects on its surrounding spacetime. Among these is superradiance – a process by which energy and angular momentum from the black hole itself is extracted in a runaway process to create clouds of matter particles.

These particles then orbit the black hole in bound states, much as an electron orbits the atomic nucleus. Like electrons, the orbiting particles could jump between energy states. And just as electrons jumping between energy states in an ordinary atom create electrical radiation, or light, particles orbiting a black hole jumping between energy states could create coherent gravitational wave "beams" that could be detected by a gravitational wave detector on Earth, such as advanced LIGO.

Studying these gravitational waves very precisely could reveal all kinds of details about the particle clouds that created them. Arvanitaki and Baryakhtar are particularly interested in advanced LIGO's potential to detect the QCD axion, a particle proposed in the 1970s to explain the smallness of the neutron's dipole moment. For three decades, much experimental effort have been expended, but it has thus far evaded Earth-bound detection. Many researchers consider the axion an ideal candidate particle that could help to solve the mystery of dark matter.

Like much work at Perimeter, theirs bridges several fields of physics that rarely interact: in this case, particle physics, black hole astrophysics, and gravitational wave detection. It is by building such bridges that Perimeter can truly lead the way.

Reference:

A. Arvanitaki (PI), M. Baryakhtar (PI), S. Dimopoulos (Stanford University), S. Dubovsky (New York University), and R. Lasenby (PI), "Black Hole Mergers and the QCD Axion at Advanced LIGO," arXiv:1604.03958.

History in the Making: First Images of Black Holes are Coming

Amazingly, LIGO's signal was not the only landmark breakthrough in the study of strong gravity in 2015/16. In an entirely separate effort, one of the most sophisticated telescopes in the world, the Event Horizon Telescope (EHT), began its effort to take the first true "image" of a black hole – one that can actually show us the shadow of the event horizon itself silhouetted against the brightness of the matter falling toward it.

Associate Faculty member **Avery Broderick**, a member of the Event Horizon Telescope collaboration, is playing a key role in this historic effort. The images he and his collaborators obtain will confirm – or

perhaps even refute – much of what we believe about the nature of black holes and perhaps gravity itself.

Broderick is a world leader in the analysis of raw data. He has developed models and analysis techniques now widely used to extract relevant information from massive amounts of radio telescope data about black holes.

To support this crucial piece of research, Perimeter has launched the **EHT Research Initiative** to develop the necessary cluster of talent that will lead the global effort to analyze and interpret the large influx of data emerging from the EHT. This year, the initiative recruited and hired three postdocs and one student to make rapid progress on key EHT projects.

As the EHT data arrived, these researchers, and others from around the globe, were at last able to examine a real black hole in detail, and begin to validate some of the long-standing theories about these strange objects.

In a landmark result, the team measured the polarization of light just outside the event horizon of Sagittarius A*, the supermassive black hole at the centre of our galaxy, the Milky Way.

Decades of theoretical work, including enormous computer simulations, had painted a picture of how magnetic fields near the black hole horizon contribute to the processes that enable a black hole to grow. In these models, black holes are ringed by strong and stable magnetic vortices, much as bathtub drains are ringed by whirlpools.

The polarization data from the EHT confirmed that these strongly ordered magnetic structures do indeed exist, and provided a first measure of their size. This in turn allows researchers to make major progress in black hole astrophysics, studying both how black holes grow, and how they sometimes launch jets: outflows of radiation and charged particles moving at nearly the speed of light.

This is a first major result from the EHT that advances our knowledge of black hole astrophysics. Given the richness of the EHT data, it will not be the last.

Reference:

M.D. Johnson (Harvard-Smithsonian Center for Astrophysics), A.E. Broderick (PI and UW), et al., “Resolved magnetic-field structure and variability near the event horizon of Sagittarius A*,” *Science*, 350, 1242 (2015), arXiv:1512.01220.

A Holographic Revolution

Black holes are popping up all over. Peer into the theoretical models and you will find black holes hidden in nuclear physics, in high-temperature superconductivity, in fluid mechanics, and even outside physics in the realms of pure mathematics.

These are not literal black holes, of course, but rather useful abstractions which have their origin in a "duality" developed by string theorists. In a duality, two theories which may look very different are shown to be interchangeable, which allows physicists to take tools and insights from one realm and apply them to another.

The particular kind of duality that brings us the black holes goes by the name "holography." Just as a hologram is a two-dimensional image that stores three-dimensional information, holographic dualities add or subtract one dimension. Through holography, physicists can translate hard problems about gravity into simpler ones about particles and fields – or, much more commonly, hard problems about particles and fields into simpler ones about gravity. That's where black holes come in.

Holography is a powerful tool, and over the last ten years it has worked its way into every corner of physics. Following the flow of ideas across theories and up and down the dimensions requires creative thinking and cross-disciplinary skills. It is perhaps not surprising, then, that Perimeter is a place at which holography thrives.

Many Perimeter researchers are using holography for its primary purpose: making better sense of quantum field theory. **Clay Riddell Paul Dirac Chair Pedro Vieira** has used holographic and string theory techniques to find the first exact solutions in four-dimensional Quantum Field Theories (QFTs), while **Krembil Galileo Galilei Chair Davide Gaiotto's** work on QFTs and holography has led to surprising advances in pure mathematics.

What's more, some Perimeter researchers are pushing holography to do far more than tackle problems in QFTs.

A Strange Step for Strange Metals

Subir Sachdev, the **Cenovus Energy James Clerk Maxwell Chair (Visiting)** at Perimeter, pioneered the application of holography to problems in condensed matter.

Sachdev is particularly interested in quantum states of matter. While normal states of matter can be described in terms of the type and location of particles, quantum states of matter must be described in terms of the entanglement between particles. Moving from one to the other is like moving from describing a city in terms of its buildings and streets to describing one in terms of its cell phone traffic.

The scale of the task can be overwhelming. It's one thing to study a pair of entangled particles – quantum theorists are now expert at that – but a condensed matter system can involve vast numbers of particles: some 10^{23} of them in a sample of a few grams.

Sachdev's breakthrough, some years ago, was to use holography to change the entanglement problem into a gravitational one, cracking open several long-standing problems in quantum condensed matter.

This year, Sachdev made major progress while describing the quantum physics of strange metals, a phase of matter which have perplexed physicists for some time – hence their name.

In a paper published in *Physical Review X*, Sachdev showed that a new kind of quantum field theory exhibits holographic behaviour, demonstrating that the unwieldy particle-based description of strange metals was holographically dual with a description of a certain kind of charged black hole. Remarkably, this QFT is able to give insight into the entropy of black holes – a surprising result considering the two topics seem to be worlds apart.

From strange metals to black holes may seem like a step sideways. But Sachdev proves that it is also a major step forward.

Reference:

S. Sachdev (Harvard University, PI, and Kavli Institute for Theoretical Physics), "Bekenstein-Hawking Entropy and Strange Metals," *Phys. Rev. X* 5, 041025 (2015), arXiv:1506.05111.

Finding the Pixels of Spacetime

Holography is usually used to transform a tough problem about particles into an easier one about gravity. But one Perimeter researcher, Faculty member **Bianca Dittrich**, is turning the hologram around.

Dittrich is one of many researchers seeking new connections between general relativity and quantum field theory. These two great theories of modern physics are elegant, successful – and famously incompatible.

Spacetime, according to general relativity, is smooth. It's also continuous – meaning if you were to zoom in on spacetime with an infinitely powerful microscope, it would look the same: smooth. Quantum field theory, on the other hand, describes particles and forces as discrete "packets," requiring spacetime itself to be granular. A theory of quantum gravity would need to link both pictures – be smooth at large scales, but granular at very small ones, something like a photograph made of pixels.

Dittrich uses an approach called loop quantum gravity, which pictures spacetime as a fine mesh of linked spacetime "pixels." She hopes to define the properties a spacetime "pixel" would need to have to be both separate at small scales and smooth when interacting with many other such pixels.

One major challenge is simulating the connections between many of these spacetime "pixels." The pixels are so small that even a tiny chunk of spacetime would contain a boggling number of them, quickly overwhelming the calculations.

Dittrich's innovation: Rather than studying every "pixel" inside of a given chunk of spacetime, she used holography to instead study just its surface– subtracting a dimension and simplifying the problem.

Holography normally applies in a special kind of spacetime known as anti-deSitter (AdS) space, and is known to hold only for infinitely large surfaces. Dittrich and Valentin Bonzom (previously a postdoctoral researcher at Perimeter Institute and now a professor at Université Paris 13) pushed the limits of the theory in both directions, showing that it could also be used in the case of more generic three-dimensional spacetimes with finite boundaries.

The result of their efforts was a much simplified construction of a theory of quantum gravity. It's an open road which invites future travel by Dittrich and others. The next logical – but challenging – step is to extend Dittrich's model one further dimension to the 4D spaces required by many other theories of quantum gravity.

Reference:

V. Bonzom (University of Paris 13) and B. Dittrich (PI), "3D holography: from discretum to continuum," *JHEP* 3, 208 (2016), arXiv:1511.05441.

Honours, Awards, and Major Grants

Many Perimeter researchers have received national and international recognition for their work in 2015/16. Notable among these are the following:

Honours and Awards

- Director Neil Turok won the 2016 John Torrence Tate Award for International Leadership in Physics from the American Institute of Physics.

- Freddy Cachazo, the Gluskin Sheff Freeman Dyson Chair in Theoretical Physics at Perimeter Institute, was awarded the CAP-CRM Prize in Theoretical and Mathematical Physics by the Canadian Association of Physicists and the Centre de recherches mathématiques.

- Associate Faculty member Roger Melko was awarded the CAP Herzberg Medal by the Canadian Association of Physicists, recognizing outstanding achievements by an early-career physicist.

- Associate Faculty member Markus Mueller won the 2016 Birkhoff-von Neumann Prize of the International Quantum Structures Association, awarded every two years for outstanding scientific achievements in the field of quantum structures.

- Perimeter Faculty member Robert Myers was named among the "World's Most Influential Scientific Minds 2015," based on a recent study by Thomson Reuters.

- Director Neil Turok was named the 2016 Gerald Whitrow Lecturer of the Royal Astronomical Society.

- Subir Sachdev, the Cenovus Energy James Clerk Maxwell Chair in Theoretical Physics at Perimeter Institute (Visiting), was awarded the Dirac Medal for the Advancement of Theoretical Physics by the University of New South Wales and the Australian Institute of Physics.

- Associate Faculty member Markus Mueller was appointed to the Canada Research Chair in the Foundations of Physics (Tier 2).

- Postdoctoral researcher Flavio Mercati and his collaborators, Julian Barbour and Tim Koslowski (a former Perimeter postdoctoral researcher), were awarded the 2015 Buchalter Cosmology Prize by the American Astronomical Society for their paper, "Identification of a gravitational arrow of time"; Associate Faculty member Niayesh Afshordi and postdoctoral researcher Elliot Nelson won third place.

- Associate Faculty member David Cory was elected as a Fellow of the Royal Society of Canada.

- Associate Faculty member David Cory was elected as a Fellow of the American Physical Society.

- Faculty member Lee Smolin and co-author Roberto Mangabeira Unger won the Association of American Publishers' 2016 PROSE Award in the cosmology and astronomy category for their book, *The Singular Universe and the Reality of Time*.

- Five Perimeter-authored papers were named "Highlights of 2015" by the *New Journal of Physics*[5]

- Four Perimeter-authored papers were named "Highlights of 2015" by the Editorial Board of *Classical and Quantum Gravity.*[6]

In addition to the honours conferred on Perimeter's resident researchers, many members of Perimeter's extended research community – Distinguished Visiting Research Chairs, Visiting Fellows, and Board members – received major honours this year. These include:

- Board member Art McDonald won the 2015 Nobel Prize in Physics.

- Board member Art McDonald won the 2016 Breakthrough Prize in Fundamental Physics.

- Distinguished Visiting Research Chair Duncan Haldane won the 2016 Nobel Prize in Physics.

- Distinguished Visiting Research Chair Sandu Popescu won the 2016 Dirac Medal in Physics from the Institute of Physics.

- Distinguished Visiting Research Chair Andrew Strominger received the 2016 Dannie Heineman Prize for Mathematical Physics from the American Physical Society.

- Distinguished Visiting Research Chair Juan Ignacio Cirac was named among the "World's Most Influential Scientific Minds 2015," based on a recent study by Thomson Reuters.

[5] They are: "Rethinking Connes' approach to the standard model of particle physics via non-commutative geometry," by Faculty member Latham Boyle and PhD student Shane Farnsworth; "Quantum bootstrapping via compressed quantum Hamiltonian learning," by Associate Faculty member David Cory and his co-authors; "Quantifying spatial correlations of general quantum dynamics," by Associate Faculty member Markus Mueller and his co-author; "Transfer matrices and excitations with matrix product states," by Distinguished Visiting Research Chair Frank Verstraete, Visiting Fellow Jutho Haegeman, and their co-authors; and "Exact parent Hamiltonians of bosonic and fermionic Moore-Read states on lattices and local models," by Distinguished Visiting Research Chair Juan Ignacio Cirac and his co-authors.

[6] They are: "Advanced LIGO," by Cenovus Energy James Maxwell Chair (Visiting) Subir Sachdev, Distinguished Visiting Research Chairs Patrick Brady, Alessandra Buonanno, and Gabriela Gonzalez, and their co-authors; "Testing general relativity with present and future astrophysical observations," by Associate Faculty member Cliff Burgess, Visiting Fellow Vitor Cardoso, and their co-authors; "Characterization of the LIGO detectors during their sixth science run," by Distinguished Visiting Research Chairs Patrick Brady, Alessandra Buonanno, and Gabriela Gonzalez, and their co-authors; and "Asymptotics with a positive cosmological constant: I. Basic framework," by Distinguished Visiting Research Chair Abhay Ashtekar and his co-authors.

- Distinguished Visiting Research Chairs Abhay Ashtekar and Stephen Hawking were elected as Fellows of the International Society for General Relativity and Gravitation.

- Distinguished Visiting Research Chair Renate Loll was installed as a Member of the Royal Netherlands Academy of Arts and Sciences.

- Visiting Fellow Giulio Chiribella was appointed as one of the inaugural Canadian Institute for Advanced Research (CIFAR) Azrieli Global Scholars, recognizing exceptional early-career researchers.

Major Grants

- Postdoctoral researcher Michal Heller was awarded the Sofja Kovalevskaja Award of the Alexander von Humboldt Foundation, valued at €1.65 million.

- Asimina Arvanitaki, the Stavros Niarchos Foundation Aristarchus Chair at Perimeter Institute, received an Early Researcher Award worth $140,000 from the Ontario Ministry of Research and Innovation.

- Associate Faculty member Markus Mueller received a $101,000 USD grant from the Foundational Questions Institute (FQXi) for his project, "Emergent objective reality – from observers to physics via Solomonoff induction."

- Five-Year Senior Postdoctoral Researcher Matthew Pusey was the co-recipient of a $60,000 USD grant from the Foundational Questions Institute (FQXi) for his project, "Observers in Foil Theories."

- Eight Perimeter scientists were awarded Discovery Grants totalling $1,997,000 (over terms of up to five years) from the Natural Sciences and Engineering Research Council of Canada), as follows:
    - Krembil William Rowan Hamilton Chair Kevin Costello: $375,000 ($51,000/year over five years, plus a Discovery Accelerator Supplement of $40,000/year over three years)
    - Faculty member Laurent Freidel: $240,000 ($48,000/year over five years)
    - Faculty member Max Metlitski: $165,000 ($33,000/year over five years, including an Early Career Supplement)
    - Associate Faculty member Alexander Braverman: $150,000 ($30,000/year over five years)
    - Associate Faculty member Raymond Laflamme: $455,000 ($91,000/year over five years)
    - Associate Faculty member Markus Mueller: $145,000 ($29,000/year over five years)
    - Associate Faculty member Maxim Pospelov: $342,000 ($68,400/year over five years)

- PSI Fellow Agata Branczyk: $125,000 ($25,000/year over five years, including an Early Career Supplement)

Objective 2: Become the research home of a critical mass of the world's leading theoretical physicists

Summary of Achievements

- Appointed Asimina Arvanitaki as the Stavros Niarchos Foundation Aristarchus Chair in Theoretical Physics, making her the ninth Perimeter Research Chair
- Obtained a $4 million investment from the Stavros Niarchos Foundation and secured $300,000 investments from the Daniel Family Foundation and Cenovus Energy, ensuring funding for all nine Perimeter Research Chairs
- Welcomed Max Metlitski as a faculty member, bringing the Institute's full-time faculty to 22
- Jointly recruited two new associate faculty members – Huan Yang (with the University of Guelph) and Jon Yard (with the Institute for Quantum Computing at the University of Waterloo) – and renewed three more, which will bring the total to 22
- Recruited William East as the Institute's second Director's Fellow

Highlights

Ninth Perimeter Research Chair Appointed

The Perimeter Research Chairs program was designed to attract and retain world-leading scientists in strategically chosen fields. The Institute offers chairholders a unique opportunity to maximize their potential for major breakthroughs, providing the necessary resources and administrative support to make rapid progress on key problems. They are able to devote themselves fully to their research, free from teaching requirements.

Named for the legendary scientists whose insights helped define modern physics, the Perimeter Research Chairs are envisioned as the most prestigious chairs in theoretical physics worldwide. They are funded through major gifts of up to $4 million, supporting exceptional emerging talent, young faculty reaching their peak years of research productivity, and renowned physics pioneers. The program not only attracts top scientists from other leading international institutions, but also keeps the Institute's own sought-after faculty at Perimeter, recognizing that they routinely receive offers to go elsewhere.

The Perimeter Research Chairs program has continued to flourish over the past year. In April 2016, Perimeter appointed **Asimina Arvanitaki** as the **Stavros Niarchos Foundation Aristarchus Chair in Theoretical Physics**, supported through a $4 million investment from the Stavros Niarchos Foundation. She is the ninth Perimeter Research Chair appointed since the program's creation five years ago.[7]

[7] The others are: Neil Turok, Mike and Ophelia Lazaridis Niels Bohr Chair; Xiao-Gang Wen, BMO Financial Group Isaac Newton Chair (Visiting); Davide Gaiotto, Krembil Galileo Galilei Chair; Kevin Costello, Krembil William Rowan

Arvanitaki is an outstanding young particle physicist known for her potentially paradigm-shifting work designing innovative 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 an experiment that can look for new spin-dependent forces in nature at an unprecedented level of precision.

Arvanitaki also works on theoretical challenges raised by experimental results, such as a model of particle physics influenced by string theory called "split SUSY." Her appointment to this visible and prestigious chair is a significant accomplishment as Perimeter seeks to address the gender imbalance in physics, as noted by Minister of Science Kirsty Duncan at Arvanitaki's appointment ceremony.

In 2015/16, the Institute also obtained $300,000 donations from the Daniel Family Foundation – to support the **Daniel Family Richard P. Feynman Chair in Theoretical Physics (Visiting)**, held by renowned cosmologist **Paul Steinhardt** – and Cenovus Energy – to support the **Cenovus Energy James Clerk Maxwell Chair in Theoretical Physics (Visiting)**, held by pioneering condensed matter physicist **Subir Sachdev**. All nine of the Perimeter Research Chairs are now funded.

New Faculty in Condensed Matter

Perimeter's resident faculty members form the core of its research community. In addition to the Perimeter Research Chairs, faculty range from rising young researchers to eminent senior scientists covering the full spectrum of theoretical physics.

In October 2015, Perimeter welcomed **Max Metlitski**, a leading young researcher in quantum condensed matter, to its faculty. He was recruited to Perimeter from the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara, where he was a Postdoctoral Research Associate from 2011 to 2015. Metlitski has made significant contributions to the theory of quantum criticality in metals and to the understanding of topological phases in the presence of interactions. 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, which recognizes outstanding contributions by a young condensed matter physicist.

The Institute now has now 22 full-time faculty members, in line with targeted objectives.

Two New Associate Faculty Recruits

Through its Associate Faculty program, Perimeter partners with top Canadian universities to bring highly respected international scientists to Canada by highlighting the unique opportunities afforded by both

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Hamilton Chair; Freddy Cachazo, Gluskin Sheff Freeman Dyson Chair; Pedro Vieira, Clay Riddell Paul Dirac Chair; Subir Sachdev, Cenovus Energy James Clerk Maxwell Chair (Visiting); and Paul Steinhardt, Daniel Family Richard P. Feynman Chair (Visiting).

Perimeter and its partner institutes.[8] Associate faculty spend up to 50 percent of their time at Perimeter, in addition to teaching and conducting research at a partner institution.

The Associate Faculty program has helped raise Canada's stature in foundational physics research, while strengthening the Institute's position as a national physics hub. By pairing its strengths with those of its partner institutions, Perimeter is often able to make a more compelling case to potential recruits; each recruitment success, in turn, makes Canada more attractive to outstanding junior faculty, postdoctoral researchers, and graduate students.

In 2015/16, in line with targeted objectives, Perimeter recruited two new associate faculty members: **Huan Yang**, jointly appointed with the University of Guelph, and **Jon Yard**, jointly appointed with the Institute for Quantum Computing and the Department of Combinatorics and Optimization at the University of Waterloo. Both of these joint appointments will bring talented scientists to Canada from positions in the United States.

Yang is a brilliant young theorist who will join Perimeter in the fall of 2017, strengthening the Institute's existing expertise in black holes and gravitational waves, among other areas. He will return to Ontario from Princeton University, where he is a Postdoctoral Research Associate, having previously held a postdoctoral fellowship at Perimeter (2013-16). Yang's research interests include gravitational wave science, black hole astrophysics, quantum optomechanics, quantum measurement theory, and quantum and classical noise in advanced gravitational wave detectors.

Yard, meanwhile, brings expertise in a number of priority areas for the Institute, including quantum information, mathematical fields, quantum fields, and condensed matter. He will join Perimeter in the fall of 2016, having previously held research positions at McGill University (2005), the California Institute of Technology (2005-07), Los Alamos National Laboratory (2007-12), and Microsoft Research (2012-16). With Graeme Smith, Yard received the 2009 Pat Goldberg Memorial Best Paper Award from IBM Research for proving that quantum capacity does not completely characterize the utility of a channel for transmitting quantum information.

Over the past year, Perimeter also renewed the terms of three existing associate faculty.[9] The Institute now has 20 associate faculty.

New Director's Fellow

In 2013, Perimeter created the Director's Fellowship to support path-breaking young researchers in the early part of their careers. Director's Fellows receive mentorship from Perimeter faculty members, while enjoying complete research freedom.

[8] In recent years, Perimeter has attracted a number of top researchers from prestigious positions in the US, including David Cory (Massachusetts Institute of Technology), Raffi Budakian (University of Illinois at Urbana-Champaign), and Alexander Braverman (Brown University).

[9] Associate faculty are appointed for fixed terms ranging from three to seven years. Niayesh Afshordi (University of Waterloo), Cliff Burgess (McMaster University), and Maxim Pospelov (University of Victoria) all renewed their terms through 2023.

In 2015/16, Perimeter recruited William East as the Institute's second Director's Fellow. In order to join Perimeter, he declined the top astrophysics postdoctoral position in the United States, the Einstein Fellowship. He will arrive in the fall of 2016, after a three-year postdoctoral fellowship at the Kavli Institute for Particle Astrophysics and Cosmology at Stanford University.

East will add to the Institute's growing research strength in areas such as black hole physics, gravitational waves, astrophysics, and cosmology. His work is focused on understanding strong-field gravity and relativistic astrophysics, including numerical simulations of compact object mergers, electromagnetic counterparts to gravitational wave sources, relativistic plasma physics and applications to high-energy astrophysics, inhomogenous cosmologies, black hole dynamics, and ultrarelativistic collisions.

Objective 3: Generate a flow-through of the most promising talent

Summary of Achievements

- Appointed 19 postdoctoral researchers in 2015/16 and recruited 19 more for 2016/17
- Six departing postdoctoral researchers obtained tenure-track faculty positions
- Successfully ran the seventh year of the Perimeter Scholars International (PSI) master's program for 29 students and provided ongoing training to 49 PhD students
- Brought 27 Visiting Graduate Fellows to the Institute
- Provided research training to seven exceptional undergraduate students

Highlights

Postdoctoral Researchers

- Continued to host the world's largest group of independent postdoctoral researchers in fundamental physics, with a total of 58 (as of July 2016)[10]
- Welcomed 19 postdoctoral researchers in 2015/16, exceeding targeted objectives
- Recruited 19 postdoctoral researchers from 630 applicants for 2016/17

Perimeter is one of the world's most attractive (and competitive) destinations for postdoctoral researchers, because it offers unique opportunities. Foremost among these is complete research freedom – the chance to pursue their own, ambitious research in a community of top minds. Postdocs can also organize conferences and host collaborators, and develop collaborations with partner experimental and observational facilities, such as TRIUMF, SNOLAB, and the Institute for Quantum Computing at the University of Waterloo (see Objective 6).

Offering these opportunities is strategically wise: these early-career scientists are typically very productive, and motivated to "make their mark" with career-defining work. Indeed, much of the excellent science emerging from Perimeter comes from postdoctoral researchers, often in collaboration with resident faculty.

Training at Perimeter pays off. From 2011 to 2015, upon completion of their terms at Perimeter, 42 percent of postdoctoral researchers went on to faculty/lecturer positions, while 54 percent secured other research positions and four percent obtained jobs outside academia.[11] The past year was no

[10] This includes full-time postdoctoral researchers, jointly-appointed postdoctoral researchers, and PSI Fellows. It does not include associate postdoctoral researchers or self-funded postdoctoral researchers; these are researchers that are part of the Institute's research community, but whose salaries are not paid by Perimeter.
[11] Over this four-year period, 69 postdoctoral researchers completed their terms at Perimeter: 29 now hold faculty/lecturer positions, 37 have other research positions, and three went into industry.

different. Despite an extremely competitive worldwide academic market, six departing postdoctoral researchers obtained tenure-track faculty positions:

- Wolfgang Altmannshofer, University of Cincinnati
- Tudor Dimofte, University of California, Davis
- Stefania Gori, University of Cincinnati
- Song He, Institute of Theoretical Physics, Chinese Academy of Sciences
- Matthew Leifer, Chapman University
- William Witczak-Krempa, University of Montreal

The majority of the remaining departing postdocs have obtained prestigious positions at top international institutions – including the SLAC National Accelerator Laboratory, University of Illinois at Urbana-Champaign, University of Queensland, and University of California, Irvine – while a couple began exciting careers in industry.[12]

Perimeter Scholars International (PSI) Master's Program

- Trained 29 students, nine of them women, from 18 countries, in line with targeted objectives
- Received a 19 percent increase in applications for the 2016/17 PSI class, making PSI one of the most selective master's programs in the world

Perimeter Scholars International (PSI) is a unique master's program that attracts top university graduates from across Canada and around the world, bringing them to the cutting edge of theoretical physics in one academic year. Its immersive curriculum is taught by resident and visiting scientists and covers the spectrum of foundational physics.[13] Designed to shape promising students into emerging researchers, PSI emphasizes continuous problem solving over rote learning and collaboration over competition. Upon completion of the program, students receive a master's degree from the University of Waterloo (since Perimeter is not a degree-granting institution).

One notable innovation this year was the PSI Winter School, a week-long retreat that introduced students (many of whom are international) to the joys of a Canadian winter and to collaborative research. At least two student groups obtained publishable results.

This year, PSI re-tooled its recruitment strategy with improved marketing and early offers to top candidates. Applications for 2016/17 rose 19 percent, and an outstanding incoming class has been selected, comprising 28 students from 20 countries, including seven women. PSI is now one of the most

[12] Gus Gutoski is a researcher at ISARA Corporation, a Waterloo start-up in the quantum computing realm, while Isaac Kim is a researcher at IBM.

[13] In 2015/16, the PSI faculty comprised 21 lecturers, including 12 Perimeter researchers, one Distinguished Visiting Research Chair, two Visiting Fellows, and six other international scientists.

competitive graduate programs worldwide; it was harder to get accepted into PSI last year than Harvard University, Stanford University, and Princeton University.[14]

PSI also strengthens ties with regional academic partners by bringing in top students and enlisting their faculty for research project supervision.[15] PSI courses are made available to non-Perimeter students who obtain permission, thereby enriching graduate course offerings throughout the region as well.

The program not only attracts top students to Canada – it keeps them here. In 2015/16, 11 out of 29 graduates are remaining in Canada for their PhD studies, including five at Perimeter. Others will be pursuing their doctoral degrees at top international institutions, including Princeton University, Stanford University, and the University of Oxford. If past experience holds, still others will go on to found start-ups or work in government service, medicine, or tech-based industries.[16]

PhD Program

- Trained 49 PhD students, in line with targeted objectives[17]

Perimeter's PhD program brings top students not only to Perimeter, but also to the partner universities where they receive their degrees, constituting a significant talent gain for Canada. Students receive first-rate training in a world-class research environment, developing a unique and valuable skill set that includes advanced analytical, problem-solving, and quantitative skills. The Institute's graduates have gone on to many fields of science, as well as government, technology, and finance.[18]

In 2015/16, Perimeter's PhD program continued to grow as planned, in concert with the Institute's expanding faculty and the pool of high-calibre master's graduates emerging from PSI. More than 70 percent of the Institute's PhD students are now graduates of the PSI program.

[14] For the incoming 2016/17 class, there were 561 applications from 79 countries. The program had an extremely high 64 percent acceptance rate from applicants, topping prestigious American institutions such as Harvard University, Stanford University, and Princeton University.

[15] Non-Perimeter faculty who acted as research project supervisors in 2015/16 include: Michel Gingras, University of Waterloo; Achim Kempf, University of Waterloo; Yong Baek Kim, University of Toronto; and Eduardo Martin-Martinez, University of Waterloo.

[16] Examples of past successes outside academia include Arthur Lee (Research Engineer, Institute for Infocomm Research, Singapore), Saurabh Madaan (Data Scientist, Google, San Francisco, USA), Henry Reich (Creator, *MinutePhysics*, Montana, USA), Anabelle Spinoulas (Analyst and Transport Modeller, TransPosition, Brisbane, Australia), Imogen Wright (Co-Founder and Algorithm Developer, Hyrax Biosciences, Cape Town, South Africa), and An Zhou (Quantitative Research Developer, Global Risk Institute in Financial Services, Toronto, Canada).

[17] This number reflects only those PhD students who were resident at Perimeter. Three more studied with Perimeter associate faculty while in residence at partner universities.

[18] Examples of Perimeter alumni who have experienced success outside of academia include Siavesh Aslanbeigi (Manager of Risk Analytics, Scotiabank, Toronto), Jorge Escobedo (Chief Technology Officer, Canopy Labs, Toronto), Cozmin Ududec (Co-Founder and Risk Management Lead, Invenia Technical Computing, Winnipeg), and Alexandre Yale (Senior Data Analyst, Alchemy Worx, Montreal), among others.

Perimeter's PhD students benefit from their intensive training. In 2015/16, six PhD students supervised by Perimeter faculty graduated from partner universities: Ross Diener was hired as a Defence Scientist at Defence Research and Development Canada, while the other five obtained competitive postdoctoral fellowships.[19]

Visiting Graduate Fellows Program

- Hosted 27 Visiting Graduate Fellows for a total of 31 visits, exceeding targeted outcomes

The Visiting Graduate Fellows program brings advanced PhD students from around the world to spend several months at the Institute, enabling them to benefit from – and contribute to – Perimeter's vibrant research environment at a pivotal time in their training. For Fellows, it is an opportunity to interact with leading researchers and attend scientific talks they would not have access to at their home institutions.

Undergraduate Student Program

- Provided research training to seven exceptional undergraduate students from top institutions, exceeding targeted objectives[20]

Perimeter's Undergraduate Student program brings top Canadian and international undergraduates to the Institute to experience high-level research, completing two- to four-month research projects with Perimeter postdoctoral researchers, who in turn gain valuable mentorship experience. The program also functions as a first point of contact with promising students, giving Perimeter a recruiting advantage as they progress through their careers. Alumni of this program who are currently at Perimeter include Five-Year Senior Postdoctoral Researcher Matteo Smerlak and PhD students Dalimil Mazac, Sebastian Mizera, and Nitica Sakharwade. Many others have returned as visitors.

[19] These postdoctoral fellowships will be held at the Institute for Theoretical Physics at the University of Innsbruck, Max Planck Institute for Gravitational Physics (Albert Einstein Institute), University of Cambridge, University of Nottingham, and Institute for Advanced Study.

[20] Students came from the Massachusetts Institute of Technology, University of Waterloo, University of British Columbia, University of Naples Federico II, Yale University, and University of California, Berkeley.

Objective 4: Become the second research home for many of the world's outstanding theorists

Summary of Achievements

- Appointed five leading scientists as Distinguished Visiting Research Chairs and renewed six more, bringing the total to 49
- Appointed seven accomplished researchers as Visiting Fellows, bringing the total to 27
- Welcomed five early-career researchers as Emmy Noether Visiting Fellows and recruited seven more for 2016/17
- Hosted 430 visiting scientists for a total of 485 visits

Highlights

Distinguished Visiting Research Chairs (DVRCs)

- Appointed five new DVRCs and renewed six more,[21] bringing the total to 49 DVRCs at year's end, exceeding targeted objectives
- Welcomed 25 DVRCs for a total of 36 visits

Perimeter's unique Distinguished Visiting Research Chairs (DVRC) program continues to flourish. It is a strategic and cost-effective means of bringing world-leading scientists to Perimeter for extended periods. DVRCs are appointed to renewable three-year terms, while retaining permanent positions at their home institutions.

Collectively, Perimeter's DVRCs – including such luminaries as Nima Arkani-Hamed, Savas Dimopoulos, Gabriela Gonzalez, and Stephen Hawking – span an enormous range of expertise (see Appendix B: Distinguished Visiting Research Chairs). They come to Perimeter to do research, collaborate, and participate in all facets of life at the Institute. In March 2016, for example, newly-appointed DVRC Katherine Freese delivered a popular Public Lecture on "The Dark Side of the Universe."

For DVRCs, time spent at Perimeter is highly productive, as they can focus exclusively on their research, free from teaching and administrative duties. By showcasing the "Perimeter advantage," the program has also facilitated recruitment: Faculty member Guifre Vidal and Perimeter Research Chairs Subir Sachdev and Paul Steinhardt were all DVRCs before taking on larger roles at Perimeter.

Having these top scientists attend conferences, give seminars, and do research with residents energizes and inspires Perimeter's resident community, enhancing the Institute's research environment and

[21] Duncan Haldane, S. James Gates Jr., Sandu Popescu, Peter Shor, and Steven White renewed their terms through 2018, while Stephen Hawking renewed his through 2019.

helping to catalyze new discoveries. In 2015/16, 15 different DVRCs participated in at least one Perimeter conference each.

New Distinguished Visiting Research Chair Appointments in 2015/16:

Dan Freed (PhD University of California, Berkeley, 1985) is the Mildred Caldwell and Baine Perkins Kerr Centennial Professor in the Department of Mathematics at the University of Texas at Austin. His work deals with global issues in geometry, topology, and global analysis, often relating to questions in quantum field theory, string theory, and condensed matter theory. Among his many honours, Freed has been an Alfred P. Sloan Research Fellow, a Guggenheim Fellow, a Simons Fellow in Mathematics, and an IBM Einstein Fellow at the Institute for Advanced Study (IAS). He was named an Inaugural Fellow of the American Mathematical Society in 2012 and was awarded the Senior Berwick Prize of the London Mathematical Society in 2014. He is one of the founders of the IAS/Park City Mathematics Institute, a member of the Scientific Advisory Committee at the Simons Center for Geometry and Physics at Stony Brook, and a Trustee of the Mathematical Sciences Research Institute.

Katherine Freese (PhD University of Chicago, 1984) is the George E. Uhlenbeck Professor of Physics at the University of Michigan, as well as a Guest Professor at Stockholm University. Her research covers a wide range of topics in theoretical cosmology and astroparticle physics; she has been working to identify the dark matter and dark energy that permeate the universe, as well as to build a successful model for the early universe immediately after the big bang. Freese has been a Sloan Foundation Fellow and a Simons Foundation Fellow in Theoretical Physics, and she has been a Fellow of the American Physical Society since 2009. In 2014, she published her first popular science book, *The Cosmic Cocktail: Three Parts Dark Matter*.

Anton Kapustin (PhD California Institute of Technology, 1997) is the Earle C. Anthony Professor of Theoretical Physics and Mathematics at the California Institute of Technology. His main area of research is quantum field theory, with applications to particle physics and condensed matter theory. In 2007, Kapustin and Edward Witten published a pioneering paper tied to the geometric Langlands conjecture.

Nathan Seiberg (PhD Weizmann Institute of Science, 1982) is a Professor at the Institute for Advanced Study in Princeton, whose research focuses on various aspects of string theory, quantum field theory, and particle physics. With collaborators, he has found exact solutions of supersymmetric quantum field theories and string theories, with applications to mathematics. Seiberg's many honours include a MacArthur Fellowship (1996), the Dannie Heineman Prize for Mathematical Physics of the American Physical Society and the American Institute of Physics (1998), the Breakthrough Prize in Fundamental Physics (2012), and The Dirac Medal of the International Centre for Theoretical Physics (2016). He is a Member of the National Academy of Sciences and a Fellow of both the American Physical Society and the American Academy of Arts and Sciences.

Alexander Zamolodchikov (PhD Institute for Theoretical and Experimental Physics, Moscow, 1978) became the inaugural holder of the C.N. Yang/Wei Deng Endowed Chair in Physics and Astronomy at Stony Brook University in 2016. Prior to that, he was a Professor at Rutgers University for 15 years. He is a theoretical and mathematical physicist, known for his contributions to condensed matter physics,

conformal field theory, and string theory. Specifically, Zamolodchikov has made important contributions to integrable quantum field theories, conformal field theories in two spacetime dimensions, and renormalization group in two-dimensional quantum field theories. With collaborators, he received the Dannie Heineman Prize for Mathematical Physics of the American Physical Society (APS) and the American Institute of Physics in 1999 and the Lars Onsager Prize of the APS in 2011. He was elected an APS Fellow in 1999 and inducted into the National Academy of Sciences in 2016.

Visiting Fellows

- Appointed seven new Visiting Fellows for a total of 27, exceeding targeted objectives
- Welcomed 10 Visiting Fellows for a total of 11 visits, ranging from several days to several months

The Visiting Fellows program is another channel through which Perimeter engages with the wider scientific community while diversifying its own. Like DVRCs, Visiting Fellows are accomplished researchers spanning a range of expertise; they are appointed to renewable terms and come to Perimeter for extended research visits while retaining positions at their home institutions.

New Visiting Fellow Appointments in 2015/16:

Neal Dalal (PhD University of California, San Diego, 2002) is an Assistant Professor of Astronomy and Physics at the University of Illinois at Urbana-Champaign. He previously held fellowships at the Institute for Advanced Study in Princeton and the Canadian Institute for Theoretical Astrophysics at the University of Toronto. Dalal is a cosmologist, whose research interests include using astronomy for probing the fundamental physics of the early universe and the formation of cosmic structure on both large and small scales. He also explores the physics of dark matter using millimeter-wave instrumentation to detect gravitational lensing.

Sergei Dubovsky (PhD Institute for Nuclear Research, Moscow, 2001) is an Associate Professor at New York University, who works at the interface of particle theory, cosmology, and string theory, with specific interests in the physics of black holes, axions, and confining strings. In 2014, he received a National Science Foundation CAREER Award for his work, “From the QCD Flux Tubes to Black Holes and Back.”

Maïté Dupuis (PhD École Normale Supérieure de Lyon, 2010) is a Research Assistant Professor at the University of Waterloo, where she previously held a Banting Postdoctoral Fellowship. She is a mathematical physicist, whose research interests include loop quantum gravity, spinfoam models, and non-commutative geometry.

Tobias Fritz (PhD Max Planck Institute for Mathematics, 2010) is a researcher at the Max Planck Institute for Mathematics in the Sciences. He previously held a Templeton Frontiers Program Postdoctoral Fellowship at Perimeter Institute. His research revolves around mathematical structures in mathematical physics and beyond, often building bridges between different areas.

Alejandro Perez (PhD University of Pittsburgh, 2001) is a Permanent Member of the Quantum Gravity group at the Centre of Theoretical Physics at Aix-Marseille University and an Honorary Member of the Institut Universitaire de France. His research concerns the development of the loop approach to quantum gravity, with interests including black holes, quantum physics, and mathematical physics.

Rachel A. Rosen (PhD New York University, 2009) is an Assistant Professor at Columbia University, whose research focuses on quantum field theory, including applications of quantum field theory to cosmology, astrophysics, particle physics, and condensed matter systems. She is best known for her contributions to the theory of massive gravity, resolving a 40-year-old problem in its favour. With Gregory Gabadadze, Rosen has also studied the astrophysics of helium-core white dwarfs, predicted a possible new state of matter in these objects (charged condensates), and made testable predictions for the cooling of such stars.

Sarah Shandera (PhD Cornell University, 2006) is an Assistant Professor at Pennsylvania State University, studying the very early universe as it pertains to both high-energy particle physics and gravity. Her research aims to build consistent models for the early universe and to make predictions for observations that can distinguish between different scenarios. Shandera often works with astrophysicists to understand how to use data from observational surveys to constrain cosmological theories.

Emmy Noether Visiting Fellows

- Appointed five Emmy Noether Fellows in 2015/16, meeting targeted objectives

As part of Perimeter's Emmy Noether initiatives (see Objective 9), the Emmy Noether Visiting Fellows program aims to provide a vital boost to promising women physicists. While on leave from their home institutions, Fellows spend up to one year at Perimeter focusing on their research at a crucial early stage of their careers. They are encouraged to collaborate, participate in conferences and workshops, mentor students, and generally enjoy the Institute's dynamic environment. The program is designed to be flexible and responsive to Fellows' needs, and provides tailored support that ranges from family-friendly housing and assistance with child care to deferments where needed.

In 2015/16, Perimeter welcomed five Emmy Noether Visiting Fellows and recruited seven more for 2016/17.[22] The Institute continues to promote the program with the goal of becoming the leading destination for top female physicists.

Emmy Noether Visiting Fellow Appointments in 2015/16:

Two 2015/16 Emmy Noether Visiting Fellows, **Rachel Rosen** and **Sarah Shandera**, were appointed as Visiting Fellows at the end of their Emmy Noether visits (see above for bios). The other three were:

[22] The Emmy Noether Visiting Fellows who were recruited for 2016/17 are Celine Boehm (Durham University), Radja Boughezal (Argonne National Laboratory), Gemma De las Cuevas (Institute of Theoretical Physics/University of Innsbruck), Mairi Sakellariadou (King's College London), Didina Serban (Institut de Physique Théorique), Sumati Surya (Raman Research Institute), and Bei Zeng (University of Guelph).

Fiona Burnell is an Assistant Professor at the University of Minnesota who works with exotic phases of matter. Her work encompasses topologically ordered phases, such as fractional quantum hall states, and symmetry-protected phases, such as topological insulators.

Barbara Drossel is a Professor in the Institute of Solid State Physics at the Darmstadt University of Technology, specializing in statistical physics and complex systems. Her research interests include both physical systems (such as soft matter, chaos, and pattern formation) and biological systems (such as the modelling of genetic networks, ecosystems, and evolutionary processes).

Katarzyna Rejzner is a Lecturer in mathematics at the University of York, researching the mathematical structures of quantum field theory – particularly its algebraic framework. Her work covers many areas, including operator algebras, infinite dimensional differential geometry, microlocal analysis, non-commutative geometry, renormalization, and quantum gravity.

Visitor Program

- Hosted 430 visiting scientists for a total of 485 visits, including 25 Distinguished Visiting Research Chairs and 10 Visiting Fellows, exceeding targeted objectives

Perimeter's active visitor program brings leading scientists from around the world to deliver talks, attend conferences, and collaborate with resident scientists. Residents benefit from exchanging ideas with visiting scientists, while visitors have the time and space to focus on research, often in collaboration with Perimeter's resident scientists. The program also facilitates recruitment by showcasing the Institute's vibrant research environment. In the past year, visits by potential recruits led to new appointments at all levels – including Associate Faculty member Jon Yard and Director's Fellow William East.

Objective 5: Act as a hub for a network of theoretical physics and math centres around the world

Summary of Achievements

- Hosted OpenAccess Energy, the third Summit of the Waterloo Global Science Initiative
- Selected H. Praise Adeyemo of Nigeria as the fourth Fields-Perimeter Institute Africa Postdoctoral Fellow
- Working to renew partnerships with TRIUMF and SNOLAB to continue the Tri-Institute International Summer School on Elementary Particles (TRISEP)
- Strengthened partnership ties with the International Centre for Theoretical Physics – South American Institute for Fundamental Research (ICTP-SAIFR) in Brazil
- Provided expertise in support of the African Institute for Mathematical Sciences – Next Einstein Initiative (AIMS-NEI) as it opened its fifth AIMS centre and prepared to open its sixth
- Partnered on eight workshops and conferences with national and international partners and sponsored an additional 16 off-site scientific gatherings (see Objective 7)

Highlights

Collaborations and Partnerships

Global engagement permeates nearly every facet of Perimeter's activities, and has been critical to its success. By partnering with leading centres in Canada and abroad, Perimeter provides collaboration opportunities for its scientists while strengthening its position as a global research hub.

In addition to formal institutional partnerships, Perimeter enjoys many productive informal partnerships through its faculty, including at international institutions like the Thomas Jefferson National Accelerator Facility (Jefferson Lab), Canadian Hydrogen Intensity Mapping Experiment (CHIME), Event Horizon Telescope (EHT), Square Kilometre Array (SKA), TRIUMF, and the Large Hadron Collider at CERN.

In 2015/16, Perimeter strengthened a number of ongoing partnerships, both formal and informal.

- Perimeter worked with TRIUMF and SNOLAB towards renewing the partnership agreements sustaining the Tri-Institute Summer School on Elementary Particles (TRISEP).
- The Institute partnered on eight workshops and conferences with national and international partners.[23]

[23] These included: (1) "Cosmic Flows (and Other Novelties on Large Scales)," with the Canadian Institute for Theoretical Astrophysics; (2) "PI-UIUC Joint Workshop on Strongly Correlated Quantum Many-Body Systems 2015," with the University of Illinois at Urbana-Champaign; (3) "Cosmological Frontiers in Fundamental Physics 2016,"

Waterloo Global Science Initiative: OpenAccess Energy

The Waterloo Global Science Initiative (WGSI) is an independently funded, non-profit partnership between Perimeter Institute and the University of Waterloo to promote dialogue and develop solutions to complex global issues.

In April 2016, Perimeter hosted the third WGSI Summit, OpenAccess Energy, in which participants from 24 countries and five First Nations communities discussed how to increase access to sustainable energy in energy-impoverished regions. Public programming and taping of three episodes of TVO's *The Agenda* complemented the main Summit. A follow-up Blueprint document detailing recommendations and implementation ideas arising from the Summit will follow in early 2017.

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. Mathematician H. Praise Adeyemo of Nigeria was recently selected as the fourth fellow; he will be based at the Fields Institute for 2016/17. Adeyemo's research focuses on algebraic geometry and topology.

The 2015/16 Fellow, Prince Osei, will spend a second year based at Perimeter, this time as a regular postdoctoral researcher.

Global Outreach

AIMS-NEI

To date, Perimeter's Global Outreach efforts have largely focused on the African Institute for Mathematical Sciences – Next Einstein Initiative (AIMS-NEI). This project was 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. The AIMS network has grown from a single centre in South Africa to a network of six across the continent. Since it opened, 1,200 students have graduated from AIMS.

In 2015/16, Perimeter continued to leverage the expertise of both its research and administrative staff to assist the AIMS-NEI network.

- AIMS-NEI hosted the Next Einstein Forum in Dakar, Senegal, in March 2016. With over 1,000 participants, including the Presidents of both Senegal and Rwanda, it was the largest scientific gathering ever held in Africa.

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with APC (University of Paris VII) and the International Solvay Institutes; (4) "It From Qubit Summer School," with the Simons Foundation; and (5) "Condensed Matter Physics and Topological Field Theory," (6) "Symplectic Duality and Gauge Theory," (7) "Concepts and Paradoxes in a Quantum Universe," and (8) "Time in Cosmology," all with the John Templeton Foundation.

- The AIMS-NEI Global Secretariat moved from Cape Town, South Africa, to Kigali, Rwanda.
- Perimeter staff shared administrative expertise in the lead-up to the opening of the fifth AIMS centre – AIMS-Tanzania – and helped with preparations for the launch of AIMS-Rwanda, set to open in August 2016.
- Perimeter researchers continue to be involved in teaching at AIMS centres.

South American Partnership Deepens

Perimeter's next area of focus for its Global Outreach efforts is South America and, to that end, the Institute signed a partnership agreement with the International Centre for Theoretical Physics – South American Institute for Fundamental Research (ICTP-SAIFR) in 2015. ICTP-SAIFR, located at the São Paulo State University (UNESP) in Brazil, was founded in 2010 as a regional centre for theoretical physics in South America. The nascent institute has many commonalities with Perimeter, including a number of research areas – condensed matter, cosmology, mathematical physics, particle physics, and string theory among them. Much like Perimeter, ICTP-SAIFR boasts an active visitor program and plays host to seminars, mini-courses, schools, and workshops.

In 2015/16, this international collaboration – officially known as the UNESP-SAIFR-PERIMETER partnership – deepened considerably.

- Pedro Vieira, the Clay Riddell Paul Dirac Chair in Theoretical Physics at Perimeter Institute, has agreed to spend up to six months per year in Brazil, helping to build the centre and establishing a talent conduit for students and researchers between ICTP-SAIFR and Perimeter.
- Other Perimeter faculty have also become involved in ICTP-SAIFR. Freddy Cachazo, the Gluskin Sheff Freeman Dyson Chair in Theoretical Physics, has been a guest lecturer, while Deputy Chair Luis Lehner is a member of ICTP-SAIFR's Scientific Council.
- The agreement encourages joint organization of schools and workshops, as well as scientific exchange visits between faculty, postdoctoral researchers, and students of both institutes. This year, UNESP's Thiago Fleury and Perimeter postdoctoral researcher Shota Komatsu have made multiple visits, with a joint paper forthcoming.
- The institutes are working together on training programs for emerging talent at the graduate and postdoctoral levels in South America. Already, three students have been identified that are planning to attend the PSI program in 2017/18.
- Perimeter staff and researchers visited Brazil and shared their expertise in helping to launch educational outreach programming. Vieira ran a mini-course for high school students and launched "Science in the Pub" talks for the general public, while outreach staff ran programs for high school teachers.
- Plans are in place for a formal ceremony in São Paulo to celebrate this partnership with the Canadian Ambassador to Brazil, taking place in November 2016. A similar event will be held in Canada at a later date.

Objective 6: Increase Perimeter's role as Canada's focal point for foundational physics research

Summary of Achievements

- Deepened ties with experimental and observational centres in Canada and abroad, including launching the Xperimeter program to support collaborations with experimentalists
- Continued to work closely with all relevant partners to foster the Quantum Valley ecosystem
- Appointed seven new Affiliates from across the country and renewed three more, giving the Institute 118 Affiliates in total
- Jointly recruited two associate faculty members with partners at the University of Guelph and the Institute for Quantum Computing at the University of Waterloo (see Objective 2)
- Partnered with the University of Waterloo to hold the PSI master's program and involved faculty from Canadian universities as research project supervisors and lecturers[24] (see Objective 3)
- Hosted eight joint workshops and conferences with national and international academic partners, and sponsored an additional 16 (see Objective 7)

Highlights

Engagement with Experimental Centres

To make breakthroughs, theory must connect with experiment. Recognizing this, Perimeter has established ties with experimental and observational centres around the world, and continued to strengthen these relationships over the past year.

In 2015/16, Perimeter launched the Xperimeter program to enable research visits to and from experimental facilities such as the Large Hadron Collider at CERN, Thomas Jefferson National Accelerator Facility, advanced LIGO, TRIUMF, and SNOLAB. Thus far, the program has seen significant use, and is likely to expand collaborations with experimentalists.

The Institute for Quantum Computing (IQC) at the University of Waterloo is Perimeter's closest experimental partner. IQC is led by Executive Director Raymond Laflamme and Deputy Directors David Cory and Kevin Resch; Laflamme and Cory are associate faculty at Perimeter, while Resch is an affiliate of the Institute. Michele Mosca, who co-founded IQC with Laflamme and remains a key member of its

[24] Lecturers included: Maïté Dupuis, University of Waterloo; Joseph Emerson, Institute for Quantum Computing at the University of Waterloo; David Morrissey, TRIUMF; and Sean Tulin, York University. Research project supervisors included: Michel Gingras, University of Waterloo; Achim Kempf, University of Waterloo; Yong Baek Kim, University of Toronto; and Eduardo Martin-Martinez, University of Waterloo.

faculty, is also an associate faculty member at Perimeter, and many more Perimeter researchers are cross-appointed at IQC.[25]

A few recent examples of research at the theory/experiment interface include the following:

- The Event Horizon Telescope (EHT) is a major international effort that is directly imaging a black hole's event horizon for the first time. Perimeter is tied directly to this effort through Associate Faculty member Avery Broderick. The Institute's Event Horizon Telescope Initiative[26] is building a team of faculty members, postdoctoral researchers, and graduate students to conduct leading-edge analysis of the EHT's data. This year, Broderick and collaborators achieved several important scientific results tied to these efforts (see Objective 1).
- Faculty member Kendrick Smith works on a number of experimental collaborations aimed at measuring the cosmic microwave background (CMB), including the Planck satellite and Canadian Hydrogen Intensity Mapping Experiment (CHIME).
- Asimina Arvanitaki, the Stavros Niarchos Foundation Aristarchus Chair in Theoretical Physics at Perimeter Institute, is working with AURIGA, a gravitational wave detector in Italy, to analyze existing data for evidence of dark matter.
- Faculty member Robert Spekkens and postdoctoral researcher Matthew Pusey recently worked with IQC researchers to prove the failure of noncontextuality in the lab, a significant finding in the quest for quantum technologies (see Objective 1).

As Perimeter scientists deepen connections with experimental and observational efforts throughout the world, such examples will continue to multiply. (For a more comprehensive list, see Appendix G: Research Ties to Experiment.)

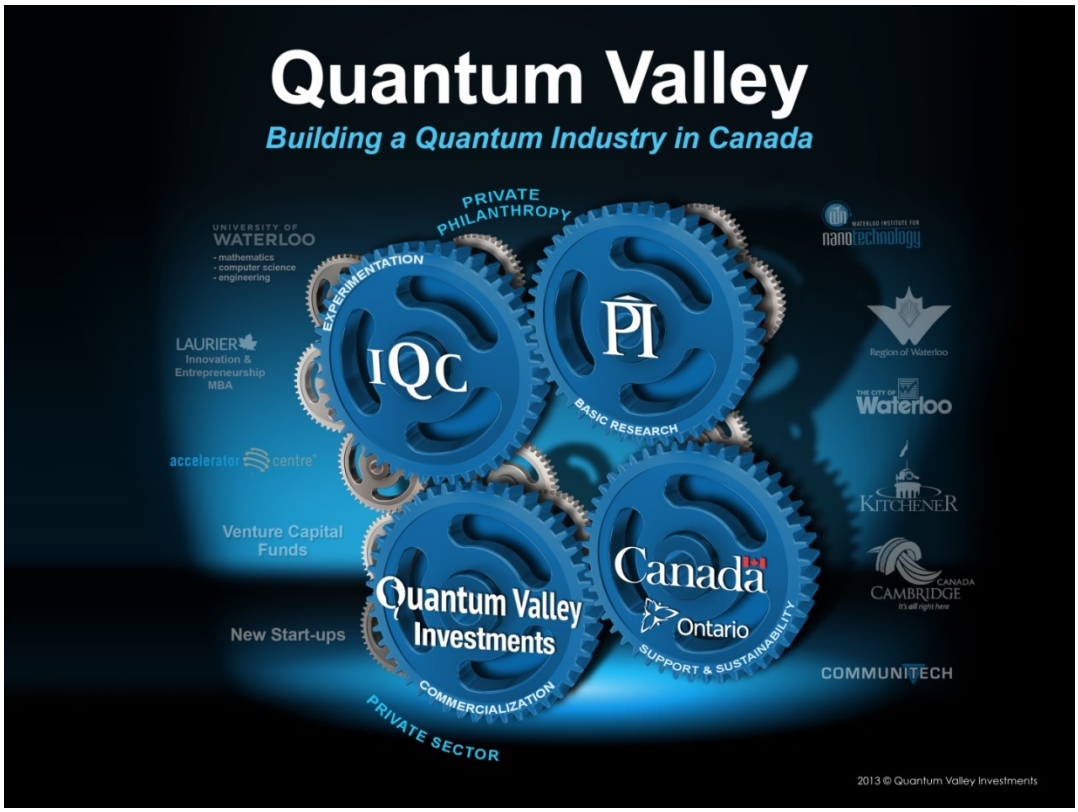
Finally, Perimeter connects with experiment through its conference program, and several conferences this year revolved directly around experimental findings and challenges.[27] The Institute continued to partner with TRIUMF and SNOLAB to hold the Tri-Institute Summer School on Elementary Particles (TRISEP), which held its fourth school in July 2016 at TRIUMF.

[25] Associate Faculty member Raffi Budakian is also jointly appointed at IQC, as are Visiting Fellow Eduardo Martin-Martinez, postdoctoral researcher Dave Touchette, and Associate PhD students Maryam Mirkamali and Paulina Ugalde. Faculty member Dmitry Abanin and Senior Research Affiliate Steve MacLean are associates at IQC, and the institutes share a number of affiliates as well.

[26] The EHT Initiative is led by Associate Faculty member Avery Broderick and Faculty members Luis Lehner and Guifre Vidal.

[27] These included: "Cosmic Flows (and Other Novelties on Large Scales" (August 10-12, 2015), "Condensed Matter Physics and Topological Field Theory" (October 21-24, 2015), "Feedback over 44 Orders of Magnitude: From Gamma-Rays to the Universe" (March 14-16, 2016), "Cosmological Frontiers in Fundamental Physics 2016" (June 14-17, 2016), and "Concepts and Paradoxes in a Quantum Universe" (June 20-24, 2016).

Catalyst for Quantum Valley



In the 20th century, breakthroughs in fundamental physics – transistors, computers, MRI, GPS, wireless communications, smartphones, and much more – led to trillions of dollars of new wealth, and millions of jobs.

Quantum research holds strong promise of a revolution in science and technology on par with – or even surpassing – the information revolution that shaped the 20th century. The 21st century economy will likely rest on innovations emerging from advances in quantum physics, such as quantum computers, sensors, communicators, and new superconductors.

Perimeter is the wellspring of an emerging quantum ecosystem. In 2002, it catalyzed the creation of its experimental partner, the Institute for Quantum Computing at the University of Waterloo. Now, an emerging "Quantum Valley" in the region covers the full spectrum: from deep discovery and training, to experimental labs, technology development, venture capital, an entrepreneurial tech start-up culture, and an abundant supply of young scientific talent. This combination is unparalleled anywhere on the planet, though competition is rising. Countries and companies around the world are investing heavily, creating research centres and hubs, vying to become a quantum valley. Senior government officials and private sector leaders from over 20 countries have expressed interest in emulating Waterloo's model.

In 2015/16, Perimeter continued to work closely with experimentalists at IQC and other key players in Waterloo Region[28] to help ensure Canada remains at the forefront of quantum research, which will ultimately lead to new technologies, jobs, and value creation.

Perimeter also recruited a number of quantum and condensed matter specialists, including Faculty member Max Metlitski; Associate Faculty member Jon Yard; Distinguished Visiting Research Chairs Anton Kapustin and Alexander Zamolodchikov; Emmy Noether Visiting Fellows Fiona Burnell and Barbara Drossel; and numerous postdoctoral researchers.

Affiliates: Uniting the Canadian Physics Community

- Appointed seven new Affiliates and renewed three more through 2018 for a total of 118 Affiliates, in line with targeted outcomes (see Appendix D: Affiliates)

Perimeter's Affiliate program provides a means of connecting the national fundamental physics community by encouraging select researchers from universities and research institutions across Canada to come for regular collaborative visits.

The program enriches both Perimeter and the national physics community. Affiliates gain access to a community of researchers spanning the spectrum of physics, allowing them to explore ideas they might not be exposed to at their home institutions. Meanwhile, Perimeter strengthens its connections to more than 25 of Canada's top research centres and provides resident scientists with new collaboration opportunities.

[28] This includes the surrounding academic community (including the Quantum-Nano Centre, the Waterloo Institute of Nanotechnology, and the University of Waterloo), the region's vibrant start-up community (including Communitech and Universal Quantum Devices), and venture capitalists (such as Quantum Valley Investments).

Objective 7: Host timely, focused conferences, workshops, seminars, and courses

Summary of Achievements

- Held 17 conferences and workshops, attended by 935 scientists from around the world
- Presented 322 scientific talks (294 seminars and 28 colloquia)
- Partnered on eight joint workshops and conferences held at Perimeter and sponsored an additional 16 off-site workshops and conferences
- Delivered four courses to researchers and students from surrounding universities

Highlights

Conferences and Workshops

- Held 17 focused conferences and workshops attended by 935 scientists, exceeding targeted objectives[29]
- Hosted more than 180 scientists for "It From Qubit," a two-week conference and summer school examining the interface between quantum information and high-energy physics

Perimeter's conference program has become internationally renowned by remaining flexible and responsive, prioritizing topics with high potential for stimulating significant outcomes. In 2015/16, 935 scientists from around the world attended Institute conferences and workshops, demonstrating Perimeter's role as a major node of exchange for cutting-edge theoretical physics. The program also strengthens the Institute's ties to partner organizations; this year, the Institute partnered on eight workshops and conferences with national and international partners[30] and sponsored an additional 16 off-site scientific gatherings, exceeding targeted objectives.[31]

[29] These included: (1) "Cosmic Flows (and Other Novelties on Large Scales)," (2) "The Unruh Fest: A Celebration in Honour of Bill Unruh's 70th Birthday," (3) "Quantum Information in Quantum Gravity II," (4) "Mathematica Summer School 2015," (5) "Noncommutative Geometry and Physics," (6) "Renormalization in Background Independent Theories: Foundations and Techniques," (7) "Condensed Matter Physics and Topological Field Theory," (8) "PI-UIUC Joint Workshop on Strongly Correlated Quantum Many-Body Systems 2015," (9) "PI Day" [November 2015], (10) "Feedback over 44 Orders of Magnitude: From Gamma-Rays to the Universe," (11) "Symplectic Duality and Gauge Theory," (12) "Deformation Quantization of Shifted Poisson Structures," (13) "4 Corners Southwest Ontario Condensed Matter Physics Symposium 2016," (14) "Cosmological Frontiers in Fundamental Physics 2016," (15) "Concepts and Paradoxes in a Quantum Universe," (16) "Time in Cosmology," and (17) "It From Qubit Summer School."

[30] These included: (1) "Cosmic Flows (and Other Novelties on Large Scales)," with the Canadian Institute for Theoretical Astrophysics; (2) "PI-UIUC Joint Workshop on Strongly Correlated Quantum Many-Body Systems 2015," with the University of Illinois at Urbana-Champaign; (3) "Cosmological Frontiers in Fundamental Physics 2016," with APC (University of Paris VII) and the International Solvay Institutes; (4) "It From Qubit Summer School," with

Selected conference highlights included:

- **"Cosmological Frontiers in Fundamental Physics 2016"** (June 14-17, 2016): This workshop – the 10th in a series jointly organized by the International Solvay Institutes, APC (University of Paris VII), and Perimeter Institute – focused on next-generation theory, experiments, and observations in both cosmology and strong gravity. In addition to theorists, the 64 participants included experimental and observational physicists from major experimental centres, and the workshop served to encourage new collaborations.

- **"Concepts and Paradoxes in a Quantum Universe"** (June 20-24, 2016): Anchored by quantum pioneer Yakir Aharonov (who is a Perimeter Distinguished Visiting Research Chair), this conference attracted over 50 researchers from around the world to discuss key paradoxes and developments in quantum mechanics from both theoretical and experimental perspectives, with nearly 20 participants spending an entire month at the Institute.

- **"Time in Cosmology"** (June 27-30, 2016): This conference brought together nearly 60 influential contemporary thinkers for critical and focused discussions on key questions pertaining to time. Short talks, panel discussions, and informal interactions sparked new collaborations.

- **"It From Qubit Summer School"** (July 18-29, 2016): As part of a major five-year collaboration funded by the Simons Foundation, this joint summer school and workshop ran for two weeks and brought 188 scientists and students to Perimeter, including many of the most distinguished names in physics. They came to Perimeter to foster communication and collaboration between the quantum information and high-energy physics communities. Due to overwhelming interest, Perimeter set up six satellite schools held simultaneously at the Max Planck Institute for Gravitational Physics (Albert Einstein Institute), University of Amsterdam, Ludwig Maximilian University of Munich, University of Tel Aviv, Massachusetts Institute of Technology, and

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the Simons Foundation; and (5) "Condensed Matter Physics and Topological Field Theory," (6) "Symplectic Duality and Gauge Theory," (7) "Concepts and Paradoxes in a Quantum Universe," and (8) "Time in Cosmology," all with the John Templeton Foundation.

[31] These included: (1) "15th Canadian Summer School on Quantum Information (CSSQI 2015)," Fields Institute for Research in Mathematical Sciences at the University of Toronto; (2) "Workshop on Quantum Marginals and Numerical Ranges," University of Guelph; (3) "Discoveries at the Dawn of LHC Run 2," TRIUMF; (4) "INTRIQ 2015," University of Sherbrooke; (5) "Mann Fest," University of Waterloo; (6) "QIP 2015," Institute for Quantum Science and Technology at the University of Calgary; (7) "Lake Louise Winter Institute 2016," University of Alberta; (8) "Workshop on Quantum Groups in Quantum Gravity," University of Waterloo; (9) "Theory Canada 11," Carleton University; (10) "Information-Theoretic Interpretations of Quantum Mechanics," Western University; (11) "11th Great Lakes Cosmology Workshop: Cosmology and Galaxies," McMaster University; (12) "Relativistic Quantum Information – North 2016," Institute for Quantum Computing at the University of Waterloo; (13) "16th Canadian Conference on General Relativity and Relativistic Astrophysics (CCGRRA 16)," Simon Fraser University; (14) "The 41st International Symposium on Symbolic and Algebraic Computation (ISSAC 2016)," Wilfrid Laurier University; (15) "Women in Physics Canada 2016," University of Saskatchewan; and (16) "Fundamental Science and Society," International Center for Interdisciplinary Science and Education (ICISE), Vietnam.

University of California, Berkeley. This large-scale effort provides an instructive example of how the Institute serves as an international hub for cutting-edge theoretical physics.

Seminars and Colloquia

- Held 322 scientific talks (294 seminars and 28 colloquia), exceeding targeted outcomes

Seminars and colloquia foster collaboration and share knowledge, allowing Perimeter researchers to remain at the cutting edge of research across the spectrum of theoretical physics. The Institute invites both resident and visiting scientists – including Distinguished Visiting Research Chairs, Visiting Fellows, and potential recruits – to share their latest work, thereby enhancing its research environment. In 2015/16, the Perimeter community benefitted from talks by luminaries in all of the Institute's areas of research focus, including DVRCs Nima Arkani-Hamed, Iakov Soibelman, Zhenghan Wang, and Alexander Zamolodchikov.

Courses

- Offered three advanced graduate courses and one non-credit mini-course, meeting targeted objectives[32]

Perimeter shares the expertise of its resident and visiting scientists through advanced graduate courses and non-credit mini-courses on cutting-edge topics. These courses benefit not only Perimeter's resident researchers, but are also open to students of surrounding universities, thereby enhancing their course offerings. The Institute also opens up PSI courses to non-Perimeter students (with special permission) as three-week, non-credit mini-courses.

[32] The graduate courses were: "General Relativity for Cosmology," taught by Perimeter Affiliate Achim Kempf (September-November 2015); "Quantum Many-Body Physics," taught by Perimeter Associate Faculty member Roger Melko (January-March 2016); and "Quantum Field Theory for Cosmology," taught by Perimeter Affiliate Achim Kempf (January-April 2016). The mini-course was: "An Introduction to Julia," taught by Perimeter Research Technologies Group Lead Erik Schnetter (October-December 2015).

Sharing Perimeter Talks and Courses

- Attracted 108,401 unique visitors from more than 170 countries to Perimeter's video archive in 2015/16, accounting for 776,692 page views

Nearly all talks held at Perimeter are recorded and made available via the Perimeter website and 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.

Objective 8: Engage in high-impact outreach

Summary of Achievements

- Facilitated more than 9.5 million student interactions through Perimeter programs and educational resources, bringing the total to more than 20 million to date[33]
- Hosted the 14th International Summer School for Young Physicists (ISSYP) and gave 15 Physica Phantastica presentations – reaching more than 4,200 students across Canada
- Delivered 135 workshops to more than 4,000 educators across Canada and abroad
- Partnered with the Ontario Ministry of Education to produce a suite of integrated educational resources on math, science, and technology for students in grades 5 to 8
- Presented eight engaging public lectures to audiences on-site and online, reaching more viewers than ever before
- Led the planning and development of Innovation150, a signature initiative of the Canada 150 celebrations, with four partner organizations
- Won the Science in Society Communications Award for the monthly "Slice of PI" series and significantly increased Perimeter's social media audience

Highlights

Student Programs and Products

Bringing Young Talent Together at the International Summer School for Young Physicists (ISSYP)

- Held the 14th edition of ISSYP for 40 top students, including 20 Canadians from seven provinces and 20 international students from 15 countries, with equal representation of males and females

The International Summer School for Young Physicists (ISSYP), presented by the RBC Foundation, is a pillar of Perimeter's educational outreach efforts. The program brings talented Canadian and international high school students to Perimeter for two weeks of intensive instruction, including talks from Perimeter faculty, mentoring sessions, and visits to experimental facilities. The program feeds

[33] Perimeter aims to give students multiple opportunities to interact with its resources as they progress through their middle and high school education. These totals reflect individual student interactions with Perimeter programs and resources, not unique students. In 2016, KPMG conducted an evaluation and identified significant increases in how Perimeter educational resources are being shared with educators across the globe. The above numbers reflect those increases (over prior years). Perimeter's methodology for calculating student interactions was updated based on the new KPMG data; additional increases also resulted from improvements to the Institute's delivery approach – including an improved web-based resource centre, a shift in focus from delivering large kits to individual lessons, growth of the Perimeter Teacher Network, and removal of cost barriers for international educators.

students' curiosity and develops crucial collaborative skills, while exposing them – often for the first time – to a community of peers that share their passion for science. Continual evaluation ensures the program is based on sound pedagogy, and follow-up surveys with ISSYP alumni indicate that more than 70 percent credit the program with inspiring them to pursue a career in math or physics.

Inspiring Future Women in Science

- Hosted more than 200 young women from Ontario high schools for the "Inspiring Future Women in Science" conference

As part of its Emmy Noether initiatives, which seek to attract and retain more women in physics, Perimeter has hosted the "Inspiring Future Women in Science" conference for several years, introducing hundreds of high school students with an interest in science to successful women at all stages of their careers. This year's edition welcomed over 200 young women from high schools across Ontario for a day of talks and networking – and a surprise address from Prime Minister Justin Trudeau.

Sharing the Joy of Science with Physica Phantastica

- Delivered 15 Physica Phantastica presentations to more than 4,200 students, exceeding targeted outcomes

Physica Phantastica presentations provide entertaining and accessible introductions to modern physics. These large-scale presentations are generally delivered to audiences of 50-200, and are designed to share the wonder, mystery, and joy of science with students, teachers, and the general public.

Physica Phantastica presentations have traditionally been given to senior high school audiences, but Institute staff introduced them for elementary school audiences in the past year, as part of a larger effort to engage younger students (see below). In order to devote staff time to the development of a travelling science exhibit, the majority of this year's presentations occurred in Ontario, though one session did involve students from Yellowknife, Northwest Territories.

Reaching Underserved Communities through Aboriginal Engagement

- With partners, reached more than 1,000 Aboriginal youth with the Institute's resources

Over the past year, Perimeter continued its partnership with Actua, one of Canada's leading STEM (science, technology, engineering, and mathematics) outreach organizations for youth, particularly among Aboriginal Canadians. Perimeter staff trained Actua associates from across the country on the Institute's resources, and they in turn delivered the content to Aboriginal students during the summer months. Perimeter also strategized ways to expand its reach in Aboriginal and remote communities tied to upcoming Innovation150 activities.

Programs and Resources for Teachers

Teachers Become Students at EinsteinPlus

- Hosted 40 teachers – including 20 Canadians (spanning seven provinces) and 20 international teachers (spanning 10 countries) at EinsteinPlus 2016, meeting targeted objectives

The EinsteinPlus Teachers' Camp is a major hub for Perimeter's engagement with skilled, highly motivated high school science teachers. The one-week summer workshop provides educators with effective methods for teaching key concepts in modern physics, introduces teachers to Perimeter's educational resources, and helps them find creative ways to ignite a passion for physics among their students. Surveys of past participants indicate that they view the experience as a top-calibre professional development opportunity.

The Perimeter Teacher Network

- Delivered 67 workshops to over 1,400 educators – in Canada, the United States, Scotland, Estonia, French Guiana, and elsewhere – through Perimeter's Teacher Network
- Held seven Teacher Network training camps in Durham, Ottawa, Thunder Bay, Waterloo, Saskatoon, Winnipeg, and Vancouver, reaching 667 teachers in total

EinsteinPlus alumni form the core of Perimeter's Teacher Network, a peer-to-peer network of skilled, highly motivated educators who are trained to share Perimeter's proven educational resources and pedagogical strategies with teachers in their home regions. The Teacher Network includes more than 50 teachers from around Ontario and across Canada; together, they broaden the Institute's reach and ensure significantly more teachers and students benefit from Perimeter resources.

On-location Teacher Workshops and Conference Presentations

- Delivered 68 on-location workshops at teacher conferences in Canada, the United States, England, and elsewhere, reaching more than 2,700 educators[34]

Perimeter staff deliver workshops on the Institute's resources to targeted gatherings of educators, particularly at large-scale conferences that significantly increase the reach of Perimeter's educational products in an extremely cost-effective manner. Perimeter strategically targets gatherings of teachers for grades 5 through 12 in both the Canadian and international educational communities.

[34] These included, among others, the annual conferences of the Science Teachers' Association of Ontario (Toronto, Canada), American Association of Physics Teachers (Sacramento, USA), Association for Science Education (Birmingham, UK), National Science Teachers Association (Nashville, USA), Ontario Association of Physics Teachers (Waterloo, Canada), Physics Teachers Resource Agents (Sacramento, USA), and High School Teachers program at CERN (Geneva, Switzerland).

Educational Resources

Product Creation

- Produced an integrated suite of new educational resources on science, math, and technology for students in grades 5 to 8, accelerated with funding from the Ontario Ministry of Education
- Released *Contemporary Physics*, a new module exploring cutting-edge topics such as neutrino physics, black hole science, and gravitational waves

Perimeter has facilitated more than 20 million student interactions to date – including more than 9.5 million in the last year alone – through its educational programs and resources. The Institute has built up a large suite of educational resources for high school students and, in recent years, has begun to expand its products to cover grades 5 to 8 as well. This process has been accelerated by a four-year partnership, formally announced in November 2015, with the Ontario Ministry of Education.

Perimeter resources are produced with the input of working scientists, rigorously tested for classroom use, and are the Institute's primary means for reaching students. Though 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.

The Institute employs a balanced approach to educational product creation. *Inspirations* content aims to intrigue younger students and motivate them to continue with math and science in senior grades, while *Explorations* modules deliver more challenging ideas and technical content to senior high school students, preparing them for post-secondary education in math, science, and engineering.

Online Resources

- Continued to provide an array of high-quality online resources
- Delivered two e-courses, "Quantum Nature" and "Quantum World," for advanced high school math and physics students, helping to prepare them for university-level physics

Publishing high-quality resources online allows Perimeter to scale its reach and impact worldwide, and the Institute has a wealth of content available through its website, including its educational modules, *Virtual ISSYP* content, *Meet A Scientist* videos, and the popular Perimeter Public Lectures.

Perimeter e-modules provide teachers with classroom-ready lessons that include support materials, animations, video clips, and pedagogical instruction via a digital sharing platform. The Institute has also developed e-courses that provide self-guided enrichment opportunities for top math and physics students across Canada and internationally.

Programs for the General Public

Growing Viewership for the Perimeter Public Lecture Series

- Delivered eight public lectures to capacity audiences on-site, with over 320,000 views online, meeting targeted objectives

Perimeter's flagship Public Lecture Series continues to be one of the Institute's most popular programs. This year, Perimeter presented eight engaging lectures on science to capacity audiences in the Mike Lazaridis Theatre of Ideas and through live webcasts to online audiences around the world.

The season presented a compelling array of talks, from dark matter and atomic clocks to climate change and nuclear medicine. Highlights included Nobel laureate Art McDonald explaining how the Sudbury Neutrino Observatory solved a cosmic neutrino mystery, Victoria Kaspi on the cosmic gift of neutron stars, and Neil Turok on "The Astonishing Simplicity of Everything."

The lectures are available online via the Perimeter website, YouTube, and presenting media partners – including *Maclean's*, CBC, *Scientific American*, *The Guardian*, and *Motherboard*, among others. Online viewership continues to grow, and the 2015/16 season has amassed over 320,000 online views to date.

Leading the Innovation150 Partnership

With its track record of producing successful large-scale science festivals, Perimeter was chosen by the Department of Canadian Heritage to lead Innovation150, a signature initiative of Canada's 150th anniversary celebrations to be held throughout 2017.

In 2015/16, Perimeter coordinated this nationwide celebration of Canadian ingenuity with leading outreach partners from across the country, including Actua, the Institute for Quantum Computing (IQC) at the University of Waterloo, the Canadian Association of Science Centres, and the Canada Science and Technology Museums Corporation. Most of the planning and development is complete; delivery will continue throughout 2016/17.

Innovation150 will share Canadian innovations of the past and aim to inspire the next generation of pioneering thinkers. It will include:

- **The Power of Ideas National Tour**, including an immersive, hands-on exhibit and interactive presentation from Perimeter, which will visit 60 communities in all 13 provinces and territories, and be experienced by over 100,000 young people
- Perimeter Director Neil Turok's **"We Are Innovators"** presentation, a highly visual exploration of the roles of curiosity, collaboration, creativity, and courage in innovation, which will be delivered in select cities across Canada throughout 2017

- The **MakerMobile**, including cutting-edge technologies like 3D printing that allow youth to experiment and create their own innovations, which was developed by Actua and will focus on visiting remote and Indigenous communities
- **Quantum: The Exhibition**, an interactive, bilingual, travelling exhibition sharing the wonders of the quantum world and the emerging quantum technologies that will shape our future, which is produced by IQC and will travel to science centres across the country
- Approximately six **Innovation Festivals** that bring together the travelling components of Innovation150 with local activities to showcase innovation and engage entire communities
- The **Innovation150 Digital Hub**, developed by Perimeter and the Canada Science and Technology Museums Corporation as an online nexus with opportunities to explore stories of innovation, share ideas for a brighter future, and participate in exciting contests
- A **Public Awareness Campaign** that engages youth, families, and communities with Innovation150 through integrated promotions, including Public Service Announcement videos in both French and English

An Art-Science Collaboration with the Stratford Festival

Perimeter is continually seeking interesting opportunities to reach new audiences. In September 2015, the Institute co-hosted an event with the Stratford Festival aimed at celebrating the connection between art and science. The event featured a reading of excerpts from Michael Frayn's *Copenhagen*, a play based on a meeting between Niels Bohr and Werner Heisenberg, and a discussion of the work's science and drama between Perimeter Faculty member Lucien Hardy and Stratford's Artistic Director, Antoni Cimolino.

Media Coverage

Perimeter strives to make Canada a world leader in scientific literacy. To this end, the Institute actively shares the wonder and discovery of theoretical physics with major media, both traditional and online.

In 2015/16, the Institute received major coverage in both national and international media, including in-depth stories about Perimeter research, people, and activities in outlets such as *Scientific American*, *The Globe and Mail*, *Wired*, *CTV National News*, *The Guardian*, CBC's *The National*, *The Economist*, *The Washington Post*, *Maclean's*, and many more. Highlights included:

- "General relativity: 100 years old and still full of surprises" by Corey S. Powell in *Popular Science* (October 20, 2015)[35]
    - This long-form article about the continuing importance of general relativity to the study of theoretical physics features Perimeter Faculty member Lee Smolin.

[35] http://www.popsci.com/einsteins-theory-general-relativity-turns-100-and-is-still-full-surprises

- "Scientists detect the magnetic field that powers our galaxy's supermassive black hole" by Rachel Feltman in *The Washington Post* (December 4, 2015)[36]
    - Perimeter Associate Faculty member Avery Broderick is quoted throughout this article about the Event Horizon Telescope's detection of the magnetic field around the supermassive black hole at the centre of our galaxy.
- "The death of general relativity lurks in a black hole's shadow" by Lizzie Wade in *Wired* (January 27, 2016)[37]
    - This article details recent research published by Perimeter Associate Postdoctoral Researcher Tim Johannsen and Associate Faculty member Avery Broderick on the Event Horizon Telescope's ability to help physicists test general relativity in strong gravity situations.
- "Gravitational waves: discovery hailed as the breakthrough of the century" by Tim Radford in *The Guardian* (February 11, 2016)[38]
    - This is a feature about LIGO's historic announcement of the detection of gravitational waves in February 2016. Perimeter Director Neil Turok is quoted at length.
- "'Brilliant' physicist to hold $8-million research chair at Perimeter Institute" by Ivan Semeniuk in *The Globe and Mail* (April 28, 2016)[39]
    - This article pertains to the announcement of the $8 million Stavros Niarchos Foundation Aristarchus Chair in Theoretical Physics at Perimeter Institute, which is held by Perimeter Faculty member Asimina Arvanitaki.

Digital and Social Media Outreach

Perimeter aims to be the leading source of fascinating, accurate, and shareable physics content online. Digital and social media are crucial to this strategy, as they reach all segments of Perimeter's audience: students, teachers, journalists, influencers, policymakers, science enthusiasts, and the research community. This year, the Institute's digital and social media outreach efforts yielded excellent results.

Slices of PI

- Awarded the Science in Society Communications Award by the Canadian Science Writers' Association for "Slices of PI"

"Slices of PI" present fun, accessible content each month to a growing list of e-subscribers and science influencers, and via organic social media sharing. This year, "Slices of PI" were awarded the Science in Society Communications Award by the Canadian Science Writers' Association, and continued to garner

[36] https://www.washingtonpost.com/news/speaking-of-science/wp/2015/12/04/scientists-detect-the-magnetic-field-that-powers-our-galaxys-supermassive-black-hole
[37] https://www.wired.com/2016/01/the-death-of-general-relativity-lurks-in-a-black-holes-shadow
[38] https://www.theguardian.com/science/2016/feb/11/gravitational-waves-discovery-hailed-as-breakthrough-of-the-century
[39] http://www.theglobeandmail.com/news/national/brilliant-physicist-to-hold-8-million-research-chair-at-perimeter-institute/article29795467

significant viewership. Successful examples included “The Ultimate Science Playlist” (13,283 page views) and “Gravitational Waves 101” (11,753 page views and 40,322 video views).

Facebook, Twitter, and YouTube

- Amassed more than 1.3 million views for Perimeter videos on YouTube

In 2015/16, Perimeter continued to expand its social media networks by sharing high-quality, engaging content. Perimeter’s YouTube account saw the largest spike, with 14,578 new subscribers (for a total of 23,447), a 160 percent increase. In the past year, Perimeter videos were viewed over 1.3 million times on YouTube, more than all previous years combined.[40] The Institute’s Facebook page gained roughly 8,000 new fans (for a total of 21,751), a 58 percent increase, while its Twitter account attracted 4,275 new followers (for a total of 15,083), a 40 percent jump.

[40] Examples of particularly successful videos include Neil Turok’s Public Lecture (213,338 views), Perimeter’s forum on gravitational waves (44,385 views), and Canadian Prime Minister Justin Trudeau’s explanation of quantum computing (443,928 views).

Objective 9: Create the world's best environment and infrastructure for theoretical physics research, training, and outreach

Summary of Achievements

- Continued to foster the Emmy Noether initiatives, an array of programs aimed at attracting women into physics and providing appropriate support to help them flourish
- Formed ADVANCE committee to promote diversity and gender balance
- Supported data visualization tied to the Tensor Network and Event Horizon Telescope Initiatives
- Created a new reference book collection for the PSI master's program

Highlights

Emmy Noether Initiatives

Women have historically been underrepresented in physics, particularly at the highest levels of the field. Recognizing that the world's toughest problems won't be solved with half of humanity's brightest minds on the sidelines, Perimeter seeks to be a world leader in combatting this traditional gender imbalance.

The Institute's Emmy Noether initiatives are an array of programs that seek to meaningfully increase the number of women entering physics and flourishing within the field. Named for the pioneering 20th century mathematician who faced – and overcame – many barriers to make crucial contributions to modern physics and mathematics, the Emmy Noether initiatives target women from high school to the senior levels of the field, backed by a group of funders and champions of women in science called the Emmy Noether Circle. Strategic expertise to help drive and promote this mission is provided by the Emmy Noether Council (see Objective 10).

Highlights of the Emmy Noether initiatives in 2015/16 included the following:

- Hosted the "Inspiring Future Women in Science" conference, bringing together more than 200 female high school students to learn about careers in science, technology, engineering, and math (see Objective 8)
- Formed an ADVANCE committee to promote diversity and gender balance in the Institute's recruitment, retention, leadership, and overall climate
- Welcomed five early-career researchers as Emmy Noether Visiting Fellows and recruited seven more for 2016/17 (see Objective 4)

IT Systems Upgrades and Initiatives

Perimeter constantly reviews its physical infrastructure and IT systems to ensure they are leading edge and are helping researchers maximize their productivity. To stay current and realize efficiencies on the administrative side, the Institute upgraded its accounting systems, continued migration of services to the cloud, redesigned its wide area network, upgraded networking equipment, and implemented a new e-commerce system to better manage the sale and fulfillment of educational outreach materials.

Research Technology

- Scientific computing experts supported numerous research projects, including Perimeter's Tensor Network and Event Horizon Telescope Initiatives
- Selected and began implementation of a new Scientific Activity Management System

Perimeter's Research Technology Group includes two physicists whose mandate is to provide specialized scientific computing support to researchers. In 2015/16, they worked with Perimeter scientists to support data visualization for major projects including Perimeter's Tensor Network Initiative, the Event Horizon Telescope Initiative, and the "yt" project, an open science astrophysics initiative. They also launched a Julia programming-language course for researchers to address high-performance numerical and scientific computing requirements. Research technology staff gave talks internally and externally, and co-organized the Compute Ontario Research Day 2015 held at Conestoga College.

Expanding Library Collections

An in-house library is essential to building Perimeter's research and learning communities. In 2015/16, Perimeter continued to expand its library collections, in line with a multi-year strategy to provide resident and visiting researchers with comprehensive research resources. The library added 87 new texts to the main collection, and created a new Perimeter Scholars International master's program reference collection of 215 texts. Library staff also created three instructional videos to help explain library processes. The library now houses 5,582 books (4,287 unique titles) and 5,900 items in total.

Canada 150

In conjunction with the Canadian Science and Technology Museums Corporation, Perimeter completed project planning and technical architecture for the Innovation150 digital hub. The selection processes for web design, web development, web hosting, and CRM/contesting platforms were completed, web functional requirements were completed, and site development was initiated during this period.

Objective 10: Continue to build on Perimeter's highly successful public-private partnership funding model

Summary of Achievements

- Secured pledges of $50 million each (over five years) from the Government of Canada and the Province of Ontario
- Received highly positive ratings in an independent five-year audit performed by KPMG
- Received highly positive evaluation in a four-year review by the Scientific Advisory Committee
- Solidified an $11 million partnership with the Department of Canadian Heritage to lead the Innovation pillar of nationwide Canada 150 celebrations, working with four partner outreach organizations
- Received $6.65 million in private funding revenues
- Raised $5.06 million in new fundraising commitments, including Perimeter Research Chair support from the Stavros Niarchos Foundation, Daniel Family Foundation, and Cenovus Energy

Highlights

Public Partners

Perimeter Institute is funded through an innovative public-private partnership which shares the opportunities and benefits of long-term investment in fundamental research. Perimeter's public partners understand that ongoing, strategic investment in foundational theoretical physics positions Canada and Ontario for success in an extremely cost-effective field – one with an excellent record of attracting talent, advancing human knowledge, and seeding innovation.

In 2015/16, Perimeter welcomed renewed support from both the Government of Canada and the Province of Ontario, and continued to demonstrate excellent return on investment through independent reviews and audits.

Funding Renewals from Canada and Ontario

Sustained support from the public sector has been critical to the Institute's success to date, and both the Government of Canada and the Province of Ontario may justly claim credit for many of the Institute's considerable achievements. The past year was the fourth year of five-year, $50 million funding agreements with both federal and provincial governments that are set to expire at the end of 2016/17.

Recognizing Perimeter as a strategic asset for Canada and Ontario, with the release of their respective budgets in February and March 2016, the Province of Ontario and Government of Canada each pledged additional $50 million investments over five years, beginning in 2017/18. In the months that followed,

the Institute welcomed both Prime Minister Justin Trudeau and Premier Kathleen Wynne to celebrate the renewed investments, and the strong vision for the future that they represent. The federal and provincial leaders, along with key ministers and members of their staff, each had an opportunity to tour Perimeter and meet with students, researchers, and senior leadership to discuss the work being done at the Institute.

By renewing their support, Perimeter's public partners are both recognizing and strengthening the Institute's position as a leader in the global scientific community at a pivotal time in foundational physics, when major discoveries are likely. These cost-effective, high-impact investments are crucial in underpinning Perimeter's flagship public-private partnership, as well as in supporting the first link in the Quantum Valley research and innovation ecosystem that has been established in Waterloo Region.

In line with targeted objectives, Perimeter continues to responsibly steward all public investments using best practices in financial management, while fulfilling its government reporting requirements.

Other Highlights

In addition to securing the new agreements outlined above, Perimeter continued to work with public partners to build on Canada's leadership in science and theoretical physics. Highlights were as follows:

- Provided briefings to leaders across ministries, agencies, and levels of government, including the Prime Minister's Office, Privy Council Office, and with numerous relevant ministers (Navdeep Bains, Minister of Innovation, Science, and Economic Development; Kirsty Duncan, Minister of Science; Bardish Chagger, Minister of Small Business and Tourism and Member of Parliament for Waterloo; etc.)
- Concluded a partnership agreement with the Department of Canadian Heritage to lead the Innovation150 platform tied to Canada's 150th celebrations (see Objective 8)
- Welcomed Ontario Minister of Education Liz Sandals in November 2015 to celebrate a four-year, $2.95 million partnership to make Perimeter's educational resources available to more teachers and students throughout Ontario, particularly in remote areas (see Objective 8)
- Served as a "Nominating Partner" for the inaugural Governor General's Innovation Awards
- Contributed insights on national agendas – such as science and technology, youth, equality, and international development, among others – with partners from Innovation, Science, and Economic Development (ISED), Global Affairs Canada (GAC), the Science, Technology, and Innovation Council (STIC), Canadian Science Policy Conference (CSPC), Public Policy Forum (PPF), Communitech, and other organizations

Independent Reviews Laud Perimeter

In 2015/16, Perimeter continued to demonstrate return on investment for its partners through favourable independent reviews, both from its scientific peers and from professional auditors.

Scientific Advisory Committee Review

In October 2015, Perimeter's Scientific Advisory Committee (SAC) conducted a scientific review of the Institute, assessing its achievements of the last four years and its future prospects. Comprised of eminent international scientists, the SAC offers independent scrutiny and advice, helping to ensure Perimeter's activities meet high standards of scientific excellence (see Appendix F for a list of members). The resulting report was extremely positive, providing excellent validation of the quality and efficacy of the Institute's work:

> *The Perimeter Institute is an extraordinary place with an extraordinary history: what started as the visionary project of a small group of people has in the course of merely 15 years become a world-leading institute for theoretical physics. It has also become a poster child for public-private partnership in research funding, a hub for teachers' education, and a prominent advocate of the value and long-term benefits of fundamental science, in Canada and beyond. Research performed at the Institute has had a significant impact worldwide, and the outstanding quality of its faculty members has been recognized through numerous awards and major international prizes. Perimeter's conference and visitor programs attract scores of excellent scientists from all over the globe, and hundreds of young people compete annually for places in the PSI master's program and for postdoctoral positions at the Institute. Organizationally, the Institute can rely on a dedicated and very well-functioning administration, and on an unrivalled outreach program to further its mission. For an institution dedicated to foundational research to have come this far within such a short time presents a formidable achievement, and an example for the rest of the world to emulate.* ***It is difficult to conceive of a research institute of similar scope and size that would generate as much visibility and impact for every dollar invested in it as does the Perimeter Institute****.*[41]

KPMG Review

As part of Perimeter's ongoing reporting to Canada's Department of Innovation, Science, and Economic Development, KPMG conducted a five-year review of the Institute's research, training, and educational outreach activities. KPMG evaluated performance data, conducted discussions with eminent physicists, and examined feedback from a cross-section of researchers, trainees, partner institutions, outreach audiences, and donors. The resulting report was overwhelmingly positive, commending the Institute for its effectiveness and value for money:

> *PI has achieved great success against its mandate and mission, is viewed very positively by all respondents groups, and is making significant impacts on both science and society. Results in many areas have improved compared to the 2011 evaluation results. Perimeter has successfully positioned Canada as a world leader in theoretical physics research, and its influence on Canada's reputation in foundational theoretical physics is significantly higher than just five years*

[41] "Scientific Review of the Perimeter Institute for Theoretical Physics 2015," Perimeter Institute Scientific Advisory Committee, January 13, 2016.

ago…. Perimeter is now considered to be "the default" when international researchers think about Canadian foundational theoretical physics.[42]

Private Partners

Private partners who share and invest in Perimeter's vision are crucial to the Institute's ability to realize its ambitious goal of long-term global leadership in theoretical physics research, training, and outreach. The Institute's Advancement efforts focus largely on individual philanthropists, corporations, and foundations whose missions align with Perimeter's – whether they share the Institute's spirit of innovation and discovery, its belief in the transformative power of physics, or its conviction that Canada can be a world-leader in fundamental research.

In 2015/16, in line with targeted objectives, the Institute expanded its base of private supporters throughout Ontario, across Canada, and beyond, as outlined below.

Funding the Perimeter Research Chairs

The Perimeter Research Chairs program is a key component of the Institute's strategy for achieving major research breakthroughs (see Objective 2). The Chairs are supported through major gifts of up to $4 million, investments which are crucial in attracting and retaining top international researchers to anchor the Institute's scientific community.

In April 2016, Perimeter announced the appointment of **Asimina Arvanitaki** as the **Stavros Niarchos Foundation Aristarchus Chair in Theoretical Physics**. The Chair was created with a $4 million investment from the Stavros Niarchos Foundation, one of the world's leading private philanthropic organizations. It will support Arvanitaki's research program, as well as foster research and training ties between Perimeter Institute and Greece. Arvanitaki's appointment to this prestigious Chair is a visible demonstration of the Institute's commitment to attracting and retaining women at the highest levels of achievement in the field.

Also in 2015/16, Perimeter secured $300,000 investments from the Daniel Family Foundation and Cenovus Energy – to be paid over three years, beginning in 2015/16. These investments will support the **Daniel Family Richard P. Feynman Chair in Theoretical Physics (Visiting)**, held by renowned cosmologist **Paul Steinhardt**, and the **Cenovus Energy James Clerk Maxwell Chair in Theoretical Physics (Visiting)**, held by pioneering condensed matter physicist **Subir Sachdev**. The Institute has now created and funded nine Perimeter Research Chairs since the program's creation just five years ago.

[42] "The Perimeter Institute for Theoretical Physics: Final Evaluation Report," KPMG LLP, June 7, 2016.

Emmy Noether Initiatives and Funding Circle

Perimeter's Emmy Noether initiatives seek to support women in science at every stage of their careers (see Objective 9). The Emmy Noether initiatives are backed by the Emmy Noether Circle, a group of funders and champions of women in science. Strategic expertise to help drive and promote this mission is provided by the Emmy Noether Council.

The Institute's various Emmy Noether initiatives continued to be a major area of strategic focus in 2015/16. Highlights of these activities included:

- The Emmy Noether Visiting Fellowship program, which welcomed five early-career researchers to Perimeter, with seven more recruited for 2016/17 (see Objective 4)
- The "Inspiring Future Women in Science" conference, which brought over 200 female high school students to Perimeter to learn more about careers in science, technology, engineering, and math (see Objective 8)

Other Activities

Beyond the Perimeter Research Chairs and Emmy Noether initiatives, the Institute continues to seek funding for its world-leading research, training, and educational outreach programs. Highlights of the Institute's fundraising strategy from the past year include the following:

- Perimeter engaged KCI Philanthropy to consult on the planning of a $100 million fundraising campaign, with a $25 million target for its first phase. The strategy includes plans to enhance the Institute's Leadership Council, build a major gift pipeline and a more robust stewardship program, and deepen the philanthropic culture at Perimeter.
- The Institute conducted a study on its US fundraising strategy, resulting in a recommendation to move Perimeter's US "Friends of PI" Foundation from private to public status in 2017. Among other benefits, this will allow Perimeter to accept gifts from Donor Advised Funds, an area of exponential growth in US fundraising.
- Perimeter's Leadership Council – a group of prominent volunteers who act as ambassadors for the Institute in the business and philanthropic communities – welcomed four new members: Donald Campbell, Senior Strategy Advisor at DLA Piper LLP; Harbir Chhina, Executive Vice-President of Oil Sands Development at Cenovus Energy; Brad Marsland, Vice President of Marsland Centre Limited; and Alfredo Tan, Group Director of Global Marketing Solutions at Facebook Canada.
- The Institute held several successful events in the last year, including high-profile speaking engagements and gatherings at Perimeter, across Canada, and internationally.[43] These events

[43] Events included: a tour of Perimeter for prospective donors from Toronto, hosted by Board member Michael Serbinis (November 2015); a celebratory dinner in Calgary for Board member and 2015 Nobel Prize winner Art McDonald, hosted by Perimeter supporters Joanne Cuthbertson, Charlie Fischer, and Clay Riddell (March 2016);

help Perimeter raise awareness and widen its pool of supporters. Perimeter now has networks of potential donors in a number of key Canadian centres – which will be the focus of events in the coming year, tied to Innovation150 – as well as in New York City and Silicon Valley.

and a special announcement of the $4 million investment by the Stavros Niarchos Foundation, in support of the Stavros Niarchos Foundation Aristarchus Chair in Theoretical Physics, held by Asimina Arvanitaki (April 2016).

Overview of Financial Statements, Expenditures, Criteria, and Investment Strategy

Summarized Financial Statements of

PERIMETER INSTITUTE

Year Ended July 31, 2016

Zeifmans

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REPORT OF THE INDEPENDENT AUDITORS ON THE SUMMARIZED FINANCIAL STATEMENTS

To the Directors of
Perimeter Institute

The accompanying summarized financial statements, which comprise the summarized statement of financial position as at July 31, 2016 and the summarized statement of operations and changes in fund balances for the year then ended, are derived from the audited financial statements of Perimeter Institute (the "Institute") for the year ended July 31, 2016. We expressed an unmodified audit opinion on those financial statements in our report dated December 2, 2016. Those financial statements, and the summarized financial statements, do not reflect the effects of events that occurred subsequent to the date of our report on those financial statements.

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

Management's Responsibility for the Summarized Financial Statements

Management is responsible for the preparation of a summary of the 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 summarized financial statements based on our procedures, which were conducted in accordance with Canadian Auditing Standard (CAS) 810, "Engagements to Report on Summary Financial Statements."

Opinion

In our opinion, the summarized financial statements derived from the audited financial statements of the Institute for the year ended July 31, 2016 are a fair summary of those financial statements, in accordance with Canadian accounting standards for not-for-profit organizations.

Zeifmans LLP

Toronto, Ontario
December 2, 2016

Chartered Accountants
Licensed Public Accountants

PERIMETER INSTITUTE
Summarized Statement of Financial Position
as at July 31, 2016

	2016	2015
ASSETS		
Current Assets:		
Cash and cash equivalents	$ 7,127	$ 9,230
Investments	306,393	302,796
Grants receivable	4,170	4,671
Other current assets	1,807	706
	319,497	317,403
Property and equipment	44,607	46,412
TOTAL ASSETS	$ 364,104	$ 363,815
LIABILITIES AND FUND BALANCE		
Current liabilities:		
Accounts payable and other current liabilities	$ 1,315	$ 1,095
TOTAL LIABILITIES	1,315	1,095
Fund balances:		
Invested in capital assets	44,576	46,399
Externally restricted	123,050	117,866
Internally restricted	188,840	188,840
Unrestricted	6,323	9,615
TOTAL FUND BALANCES	362,789	362,720
	$ 364,104	$ 363,815

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PERIMETER INSTITUTE

Summarized Statement of Operations and Changes in Fund Balances
For the Year Ended July 31, 2016

	2016	2015
Revenue		
Government grants	$ 22,794	$ 21,548
Other income	1,855	3,073
Donations	6,479	2,691
	31,128	27,312
Expenditures		
Research	15,403	14,635
Research training	2,145	1,799
Outreach and science communications	4,203	2,694
Indirect research and operations	6,617	6,313
	28,368	25,441
Excess of revenue over expenditures before amortization, gain on disposal of capital assets and investment gain (loss)	2,760	1,871
Amortization	(2,581)	(2,941)
Gain on disposal of property and equipment	---	111
Investment gain (loss)	(110)	29,134
Excess of revenue over expenditures	69	28,175
Fund balances, beginning of year	362,720	334,545
Fund balances, end of year	$ 362,789	$ 362,720

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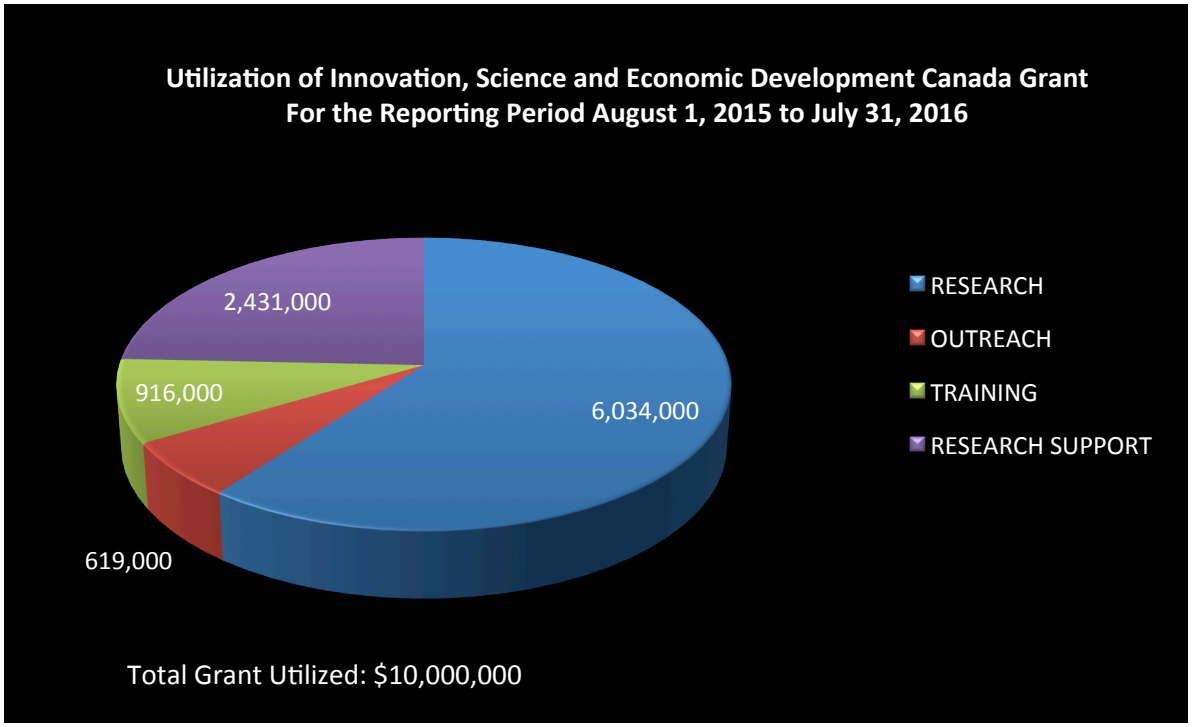
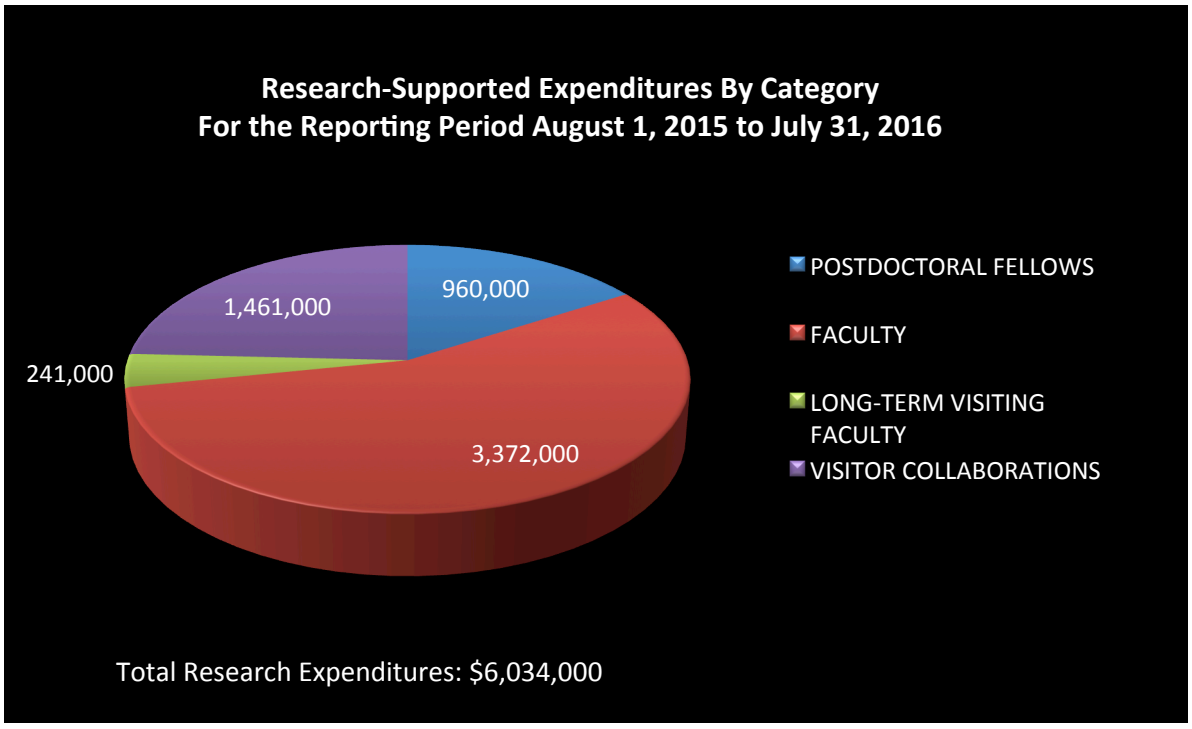
Expenditure of Innovation, Science, and Economic Development Canada Grant





Performance Evaluation Strategy

Scientific

Perimeter Institute has a wide array of performance monitoring and evaluation policies, systems, and processes (both internal and external) that have been developed over the years and are re-evaluated and updated on a regular basis. These mechanisms to measure outcomes, results, and impact include:

Performance Monitoring – Internal

- Annual reports on research activity submitted to the Institute's Director by all faculty and associate faculty members for evaluation
- Annual performance reviews of all staff
- Ongoing monitoring of publication and citation records
- Post-conference reports and evaluation
- Visitor research activity reports and ongoing tracking of all output
- Regular updates and monitoring of progress of all scientific programs
- Mid-term researcher performance reviews
- Postdoctoral researcher mentorship program
- Monitoring of postdoctoral researchers' post-Perimeter placement success
- Monitoring of researchers' international presence and impact through collaborations and invitations to lecture
- Internal review and evaluation process of all outreach programs and products

Performance Monitoring – External

- Regular reporting to international Scientific Advisory Committee (SAC) with subsequent performance assessment and recommendations (see Appendix F for a list of SAC members)
- Review of faculty hires and promotions by Scientific Advisory Committee
- Peer review of publications
- Annual audit of financial statements by an independent auditor
- Other performance audits and reviews in accordance with grant agreements
- External review and evaluation process of all outreach programs and products

Investment Strategy

Public-Private Partnership

Perimeter Institute exists through a cooperative and highly successful public-private approach to investment that provides for ongoing operations while, at the same time, safeguarding future opportunities.

Public partners contribute to research, training, and outreach activities and, in keeping with individual grant requirements, receive ongoing updates, reports, and yearly audited financial statements as required to ensure value for money while remaining aware of the Institute's research productivity and outreach impact.

Private funds from a continuously growing donor base are used, in part, to fund operations, while a portion is protected in an endowment that is primarily designed to receive and increase donated monies by maximizing growth and minimizing risk in order to contribute to the strongest possible long-term financial health of the Institute.

Perimeter Institute continues to be an innovative example of a public-private partnership, uniting government and philanthropists in a common quest to secure the transformative potential of scientific research in Canada.

Governance

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

The Board of Directors is supported in fulfilling its fiduciary responsibilities with respect to financial management of the Institute through two Board committees. The Investment Committee is responsible for overseeing the investment and management of funds received according to a Board-approved investment policy that outlines guidelines, standards, and procedures for the prudent investment and management of funds. The Finance and Audit Committee is responsible for overseeing Perimeter Institute's policies, processes, and activities in the areas of accounting, internal controls, risk management, auditing, and financial reporting. The Board also forms other committees as required to assist it in discharging its duties.

Reporting to the Board of Directors, the Institute's Director is a pre-eminent scientist responsible for developing and implementing the overall strategic direction of the Institute. The Managing Director and Chief Operating Officer reports to the Director and is in charge of day-to-day operations, supported by a team of administrative staff. The Institute's resident scientists play an active role in scientific operational issues via participation on various committees in charge of scientific programs. Committee chairs report

to the Faculty Chair and Deputy Faculty Chair, who assist the Institute's Director with matters such as recruitment, the granting of tenure, and program reviews.

The Scientific Advisory Committee (SAC), comprised of eminent international scientists (see Appendix F: Scientific Advisory Committee), offers independent scrutiny and advice, helping to ensure Perimeter's activities meet high standards of scientific excellence. Members participate in thorough reviews of PI's scientific, training, and educational outreach programs, after which the Chair writes a report to the Board of Directors and the Institute's Director.

Objectives for 2016/17

Statement of Objectives, 2016/17

The successes outlined in the preceding pages provide strong evidence that Perimeter's strategic planning has been both sound and effective, and that the Institute is on track to achieve its paramount long-term goal: to create and sustain the world's foremost centre for foundational theoretical physics research, training, and outreach, fostering scientific excellence and stimulating breakthroughs that will transform our future.

After a comprehensive review, taking into account the Institute's growth over the past several years, Perimeter has established a slightly modified set of strategic objectives to guide its continued development. Perimeter's core mission will continue to inform every facet of the Institute's research, training, and outreach efforts.

Objective 1: Achieve breakthroughs in our understanding of the universe

Objective 2: Create the world's strongest community of theoretical physics researchers

Objective 3: Attract and develop the next generation of brilliant researchers

Objective 4: Attract outstanding visiting scientists

Objective 5: Act as Canada's hub for foundational physics research

Objective 6: Catalyze and support the creation of centres of excellence

Objective 7: Share the transformative power of theoretical physics

Objective 8: Continue to strengthen Perimeter's visionary public-private partnership

Appendices

Note: Where applicable, appendices reflect the Perimeter community as of July 31, 2016.

Appendix A: Faculty and Associate Faculty Members

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, where he also holds the Mike and Ophelia Lazaridis Niels Bohr Chair in Theoretical Physics. 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, a Fellow of the Royal Society of Canada, and a Senior Fellow of Massey College at the University of Toronto. In 2012, Turok delivered the CBC Massey Lectures. The lectures were published as *The Universe Within*, a bestseller which won the 2013 Lane Anderson Award, Canada's top prize for popular science writing. Born in South Africa, Turok founded the African Institute for Mathematical Sciences (AIMS) in Cape Town in 2003. AIMS has since expanded to a network of six centres – in South Africa, Senegal, Ghana, Cameroon, Tanzania, and Rwanda – and has become Africa's 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, as well as the John Torrence Tate Award for International Leadership in Physics from the American Institute of Physics.

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) is the Stavros Niarchos Foundation Aristarchus Chair in Theoretical Physics at Perimeter Institute, where she has been a faculty member since 2014. She previously held research positions at the Lawrence Berkeley National Laboratory at the University of California, Berkeley (2008-11), and the Stanford Institute for Theoretical Physics at Stanford University (2011-14). Arvanitaki is a particle physicist who specializes in designing new experiments to test fundamental theories beyond the Standard Model. These experiments rely on the latest developments in metrology, such as atomic clocks, and the optical trapping and cooling of macroscopic objects. She recently pioneered a new experiment that can look for new spin-dependent forces in nature at an unprecedented level of precision. Arvanitaki also works on theoretical challenges raised by experimental results, such as a model of particle physics influenced by string theory called "split SUSY." In 2016, she received an Early Researcher Award from the Ontario Ministry of Research and Innovation.

Latham Boyle (PhD Princeton University, 2006) joined the Institute's faculty in 2010. From 2006 to 2009, he held a Canadian Institute for Theoretical Astrophysics Postdoctoral Fellowship; he was also a Junior Fellow of the Canadian Institute for Advanced Research. Boyle has studied what gravitational wave measurements can reveal about the universe's beginning. With Paul Steinhardt, he derived "inflationary bootstrap relations" that − if confirmed observationally − would provide compelling support for the theory of primordial inflation. He co-developed a simple algebraic technique for understanding black hole mergers and constructed the theory of "porcupines": networks of low-frequency gravitational wave detectors that function together as gravitational wave telescopes. With Shane Farnsworth, Boyle discovered a reformulation of Connes' non-commutative geometry that greatly simplifies and unifies its axioms, and elucidates its connection to the standard model of particle physics. With Kendrick Smith, he developed the idea of "choreographic crystals" in which the basic elements perform a choreographed dance that can have a much higher symmetry than any instantaneous snapshot reveals. Most recently, with Steinhardt, he has been developing a new approach to Penrose-like tilings and exploring new applications of these structures to physics.

Freddy Cachazo (PhD Harvard University, 2002) is the Gluskin Sheff Freeman Dyson Chair in Theoretical Physics at Perimeter Institute, where he has been a faculty member since 2005. From 2002 to 2005, he was a Member of the School of Natural Sciences at the Institute for Advanced Study in Princeton. Cachazo is one of the world's leading experts in the study and computation of scattering amplitudes in gauge theories, such as quantum chromodynamics and N=4 super Yang-Mills (MSYM), and in Einstein's gravity theory. His many honours include the Gribov Medal of the European Physical Society (2009), the Rutherford Memorial Medal in Physics from the Royal Society of Canada (2011), the Herzberg Medal from the Canadian Association of Physicists (2012), a New Horizons in Physics Prize from the Fundamental Physics Prize Foundation (2014), and the CAP-CRM Prize in Theoretical and Mathematical Physics from the Canadian Association of Physicists and the Centre de recherches mathématiques (2016).

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

aspects of quantum field theory and string theory. He is the author of *Renormalization and Effective Field Theory*, a path-breaking monograph introducing powerful new mathematical tools into the theory of quantum fields. 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, constructed new realizations of quantum geometry, and identified holographic properties of background independent gravity. Dittrich has received the Otto Hahn Medal of the Max Planck Society, which recognizes outstanding young scientists, and an Early Researcher Award from the Ontario Ministry of Research and Innovation.

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

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

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

Daniel Gottesman (PhD California Institute of Technology, 1997) joined Perimeter's faculty in 2002. From 1997 to 2002, he held postdoctoral positions at the Los Alamos National Laboratory, Microsoft Research, and the University of California, Berkeley (as a long-term CMI Prize Fellow for the Clay

Mathematics Institute). Gottesman has made seminal contributions which continue to shape the field of quantum information science through his work on quantum error correction and quantum cryptography. He has published over 50 papers, which have attracted well over 4,000 citations to date. He is also a Senior Fellow in the Quantum Information Processing program of the Canadian Institute for Advanced Research and a Fellow of the American Physical Society.

Lucien Hardy (PhD University of Durham, 1992) joined Perimeter's faculty in 2002, having previously held research and lecturing positions at various European universities, including the University of Oxford, Sapienza University of Rome, University of Durham, University of Innsbruck, and National University of Ireland. In 1992, he found a very simple proof of non-locality in quantum theory which has become known as Hardy's theorem. He has worked on characterizing quantum theory in terms of operational postulates and providing an operational reformulation of quantum theory. He has recently shown how to reformulate general relativity in operational terms. This is seen as a stepping stone en route to finding a theory of quantum gravity.

Luis Lehner (PhD University of Pittsburgh, 1998) began a joint appointment with Perimeter and the University of Guelph in 2009, joined Perimeter as a full-time faculty member in 2012, and became Deputy Faculty Chair in 2014. He previously held postdoctoral fellowships at the University of Texas at Austin and the University of British Columbia, and he was a member of Louisiana State University's faculty from 2002 to 2009. Lehner's many honours include the Honor Prize from the National University of Cordoba, Argentina, a Mellon pre-doctoral fellowship, the CGS/UMI outstanding dissertation award, and the Nicholas Metropolis award. He has been a PIMS fellow, a CITA National Fellow, and a Sloan Research Fellow, and he is currently a Fellow of the Institute of Physics, the American Physical Society, the International Society for General Relativity and Gravitation, and the Canadian Institute for Advanced Research in the Cosmology and Gravity program. Lehner also serves on the Scientific Council of the International Centre for Theoretical Physics – South American Institute for Fundamental Research and the Advisory Board of the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara.

Max Metlitski (PhD Harvard University, 2011) joined Perimeter's faculty in October 2015. He was recruited to Perimeter from the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara, where he was a Postdoctoral Research Associate from 2011 to 2015. Metlitski is a condensed matter physicist whose work has contributed to the theory of quantum criticality in metals and to the understanding of topological phases in the presence of interactions. 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, which recognizes outstanding contributions by a young condensed matter physicist.

Robert Myers (PhD Princeton University, 1986) is one of the leading theoretical physicists working on string theory and quantum gravity in Canada. After attaining his PhD, he was a postdoctoral researcher at the Institute for Theoretical Physics at the University of California, Santa Barbara, and a Professor of Physics at McGill University, before joining Perimeter as one of the founding faculty members in 2001. He was named Faculty Chair in 2010. Myers has made seminal contributions to our understanding of

black hole microphysics, D-branes, and the application of entanglement entropy to holography and renormalization group flows. Among his many honours, he has received the Canadian Association of Physicists' Herzberg Medal (1999), the CAP-CRM Prize (2005), and the Vogt Medal (2012). He is also a Fellow of both the Royal Society of Canada and the Cosmology and Gravity program of the Canadian Institute for Advanced Research. Myers was named on Thomson Reuters' list of the "World's Most Influential Scientific Minds" in 2014 and 2015.

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

Lee Smolin (PhD Harvard University, 1979) is one of Perimeter Institute's founding faculty members. Prior to joining Perimeter, Smolin held faculty positions at Yale University, Syracuse University, and Pennsylvania State University. Smolin's research is centred on the problem of quantum gravity, where he helped to found loop quantum gravity, though his contributions span many areas, including quantum foundations, cosmology, particle physics, the philosophy of physics, and economics. His more than 195 papers have generated over 19,400 citations to date. He has written four non-technical books and co-written a book on the philosophy of time. Smolin's honours include the Majorana Prize (2007), the Klopsteg Memorial Award (2009), the Buchalter Cosmology Prize (2014), and election as a Fellow of both the American Physical Society and the Royal Society of Canada.

Robert Spekkens (PhD University of Toronto, 2001) joined Perimeter's faculty in 2008, after holding a postdoctoral fellowship at Perimeter and an International Royal Society Fellowship at the University of Cambridge. His field of research is the foundations of quantum theory, where he is known for his work on the interpretation of the quantum state, the principle of noncontextuality, the nature of causality in a quantum world, and the characterization of the symmetry-breaking and thermodynamic properties of quantum states as resources. Spekkens co-edited the book *Quantum Theory: Informational Foundations and Foils*. He was awarded the Birkhoff-von Neumann Prize of the International Quantum Structures

Association in 2008, and won first prize in the 2012 Foundational Questions Institute (FQXi) essay contest, “Questioning the Foundations: Which of Our Assumptions are Wrong?”

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.

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 the Ontario Ministry of Research and Innovation.

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

2005, Budakian won a World Technology Award for his work in the detection and manipulation of quantum spins.

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

David Cory (PhD Case Western Reserve University, 1987) joined Perimeter in 2010 and is jointly appointed as a Professor of Chemistry at the University of Waterloo and Deputy Director of Research at the Institute for Quantum Computing. He was previously a Professor of Nuclear Science and Engineering at the Massachusetts Institute of Technology. Since 1996, Cory has been exploring the experimental challenges of building small quantum processors based on nuclear spins, electron spins, neutrons, persistent current superconducting devices, and optics. In 2010, he was named the Canada Excellence Research Chair in Quantum Information Processing. Cory 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 ranging from inflationary cosmology and string theory to numerical relativity and cosmic microwave background radiation data analysis. His research has attracted competitive funding from the Natural Sciences and Engineering Research Council of Canada, the Foundational Questions Institute, and the New Frontiers in Astronomy and Cosmology grant program administered by the University of Chicago.

Raymond Laflamme (PhD University of Cambridge, 1988) is a founding faculty member of Perimeter Institute 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 the CAP Herzberg Medal from the Canadian Association of Physicists, 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 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 (Tier 2). 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. In 2016, he won the Birkhoff-von Neumann Prize of the International Quantum Structures Association for outstanding scientific achievements in the field of quantum structures.

Ue-Li Pen (PhD Princeton University, 1995) joined Perimeter in 2014. He is jointly appointed with the Canadian Institute for Theoretical Astrophysics at the University of Toronto, where he has been a professor since 1998 and 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.

Subir Sachdev (PhD Harvard University, 1985) joined Perimeter in 2014 and holds the Cenovus Energy James Clerk Maxwell Chair in Theoretical Physics (Visiting). He has been a Professor of Physics at Harvard University since 2005. Sachdev has made prolific contributions to quantum condensed matter physics, including research on quantum phase transitions and their application to correlated electron materials like high-temperature superconductors, and he authored the seminal book, *Quantum Phase Transitions*. In recent years, he has exploited a remarkable connection between the electronic properties of materials near a quantum phase transition and the quantum theory of black holes. Sachdev's previous honours include an Alfred P. Sloan Foundation Fellowship and a John Simon Guggenheim Memorial Foundation Fellowship. He is a Fellow of the American Physical Society and a member of the U.S. National Academy of Sciences, and he was a Perimeter Distinguished Visiting Research Chair from 2009 to 2014.

Paul Steinhardt (PhD Harvard University, 1978) is the Daniel Family 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.

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.

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.

Appendix B: Distinguished Visiting Research Chairs

Yakir Aharonov is a professor of theoretical condensed matter physics at Chapman University and Professor Emeritus at Tel Aviv University. He has made seminal contributions in quantum mechanics, relativistic quantum field theories, and interpretations of quantum mechanics. In 1998, he received the prestigious Wolf Prize for his 1959 co-discovery of the Aharonov-Bohm effect. In 2010, US President Barack Obama awarded him the National Medal of Science, the highest scientific honour bestowed by the United States government.

Nima Arkani-Hamed of the Institute for Advanced Study is one of the world's leading particle physicists and a previous long-term visitor at Perimeter. He has developed theories on emergent extra dimensions, "little Higgs theories," and proposed new models that can be tested using the Large Hadron Collider (LHC) at CERN in Switzerland. In 2012, Arkani-Hamed was one of the inaugural winners of the Fundamental Physics Prize.

Abhay Ashtekar is the Eberly Professor of Physics and Director of the Institute for Gravitation and the Cosmos at Pennsylvania State University. As the creator of Ashtekar variables, he is one of the founders of loop quantum gravity. His many research interests include black hole entropy, quantum cosmology and the very early universe, generalizations of quantum mechanics, mathematical aspects of quantum field theory, and many areas of both quantum gravity and general relativity. Among his many honours, Ashtekar has been an Alfred P. Sloan Research Fellow, Honorary Fellow of the Indian Academy of Sciences, President of the International Society for General Relativity and Gravitation (ISGRG), and a Fellow of the ISGRG, American Physical Society, and American Association for the Advancement of Science. In 2007, he was awarded the Distinguished Scholar Prize of the American Chapter of the Indian Association of Physics.

Leon Balents is a Professor of Physics and a Permanent Member of the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara. He researches nearly all areas of condensed matter theory, contributing to the theory of new topological phases of electrons. Balents works on frustrated magnetism (mostly quantum), correlation phenomena in oxide heterostructures, coupled electron dynamics with hyperfine interactions in quantum dots, the quantum Hall effect in graphene, ultra-cold trapped atoms, one-dimensional electron gases, and topological aspects of insulators with strong spin orbit interactions. Balents' past honours include a CAREER Award of the National Science Foundation, Alfred P. Sloan Foundation Fellowship, and Packard Foundation Fellowship. He was elected a Fellow of the American Physical Society in 2013.

James Bardeen is an Emeritus Professor of Physics at the University of Washington in Seattle. He has made major contributions in general relativity and cosmology, including the formulation, with Stephen Hawking and Brandon Carter, of the laws of black hole mechanics, and the development of a gauge-invariant approach to cosmological perturbations and the origin of large-scale structure in the present universe from quantum fluctuations during an early epoch of inflation. His recent research focuses on improving calculations of the generation of gravitational radiation from merging black hole and neutron star binaries by formulating the Einstein equations on asymptotically null constant mean curvature

hypersurfaces. This makes possible numerical calculations with an outer boundary at future null infinity, where waveforms can be read off directly, without any need for extrapolation. Bardeen received his PhD from the California Institute of Technology under the direction of Richard Feynman.

Ganapathy 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, 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).

Patrick Brady is a Professor of Physics and the Director of the Leonard E. Parker Center for Gravitation, Cosmology, and Astrophysics at the University of Wisconsin-Milwaukee. His research interests include the dynamics of gravitational collapse, black holes, the detection of gravitational waves using interferometric gravitational wave detectors, and numerical relativity, including simulation of binary coalescence. Brady received a Research Corporation Cottrell Scholar Award and a Sloan Research Fellowship in 2002, and was made a Fellow of the American Physical Society (APS) in 2010. He has served as Secretary/Treasurer and Vice-Chair of the APS Topical Group in Gravitation and on the Executive Committee of the LIGO Scientific Collaboration. He also has six awards from the National Science Foundation.

Alessandra Buonanno is the Director of the Astrophysical and Cosmological Relativity division of the Max Planck Institute for Gravitational Physics (Albert Einstein Institute) in Potsdam, Germany, and a College Park Professor at the University of Maryland, College Park. Buonanno's research centres around gravitational wave physics and cosmology of the early universe, specifically focused on the analytical modeling of the dynamics and gravitational-wave emission from coalescing black holes, the interface between analytical and numerical relativity, and the search for gravitational waves with ground-based detectors, such as LIGO, GEO600, and Virgo. Buonanno has been a Fellow of the Alfred P. Sloan Foundation and a Radcliffe Fellow at the Radcliffe Institute for Advanced Study at Harvard University. She is currently a Fellow of the International Society on General Relativity and Gravitation and the American Physical Society.

Juan Ignacio Cirac, Director of the Theory Division of the Max Planck Institute of Quantum Optics in Germany, is a leading quantum information theorist whose group received the 2009 Carl Zeiss Research Award. His research aims to characterize quantum phenomena and to develop a new theory of information based on quantum mechanics, work which may ultimately lead to the development of

quantum computers. In 2015, he was named among the "World's Most Influential Scientific Minds," based on a study by Thomson Reuters.

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

Lance Dixon is a theoretical particle physicist and a Professor at Stanford University. He has made ground-breaking contributions to the calculation of perturbative scattering amplitudes and his work has provided a deeper understanding of quantum field theory and led to powerful new tools for computing processes in quantum chromodynamics. Dixon's current research in phenomenology focuses on precision calculation in quantum chromodynamics, as applied to the Large Hadron Collider at CERN, where he spent a sabbatical in 2010 as the LHC began full operations. He also studies the quantum structure of supersymmetric gauge theories and theories of gravity. Dixon is a Fellow of the American Physical Society and a co-recipient of its 2014 J.J. Sakurai Prize.

Matthew Fisher is a condensed matter physicist at the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara. His research has focused on strongly correlated systems, especially low-dimensional systems, Mott insulators, quantum magnetism, and the quantum Hall effect. Fisher received the Alan T. Waterman Award from the National Science Foundation in 1995 and the National Academy of Sciences Award for Initiatives in Research in 1997. He was elected as a Member of the American Academy of Arts and Sciences in 2003 and to the National Academy in 2012. In 2015, he was a co-recipient of the Oliver E. Buckley Condensed Matter Physics Prize of the American Physical Society. He has over 170 publications.

Dan Freed is the Mildred Caldwell and Baine Perkins Kerr Centennial Professor in the Department of Mathematics at the University of Texas at Austin. His work deals with global issues in geometry, topology, and global analysis, often relating to questions in quantum field theory, string theory, and condensed matter theory. Among his many honours, Freed has been an Alfred P. Sloan Research Fellow, a Guggenheim Fellow, a Simons Fellow in Mathematics, and an IBM Einstein Fellow at the Institute for Advanced Study (IAS). He was named an Inaugural Fellow of the American Mathematical Society in 2012 and was awarded the Senior Berwick Prize of the London Mathematical Society in 2014. He is one of the founders of the IAS/Park City Mathematics Institute, a member of the Scientific Advisory Committee at the Simons Center for Geometry and Physics at Stony Brook, and a Trustee of the Mathematical Sciences Research Institute.

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

S. James Gates Jr. is the John S. Toll Professor and Director for the Center for String and Particle Theory at the University of Maryland, College Park. Gates' research has made numerous contributions to supersymmetry, supergravity, and superstring theory, including the introduction of complex geometries with torsion (a new contribution in the mathematical literature), and the suggestion of models of superstring theories that exist purely as four-dimensional constructs similar to the Standard Model of particle physics. He has won the Public Understanding & Technology Award from the American Association for the Advancement of Science (AAAS), the Klopsteg Award from the American Association of Physics Teachers, and the US National Medal of Science. Gates is a Fellow of both AAAS and the American Physical Society, and a past President of the National Society of Black Physicists. In 2011, he was elected to the American Academy of Arts and Sciences. He serves on the US President's Council of Advisors on Science and Technology, the Maryland State Board of Education, the Board of Directors of the Fermi National Laboratory, and the Board of Trustees for the Society for Science and the Public.

Alexander Goncharov is a Professor in the Department of Mathematics at Yale University. Prior to joining Yale's faculty, he was a professor at Brown University, the Max Planck Institute for Mathematics, and the Massachusetts Institute of Technology. Goncharov's research primarily concerns mathematical physics, including arithmetic algebraic geometry and representation theory. He is known for the Goncharov conjecture, which suggests that the cohomology of certain motivic complexes coincides with pieces of K-groups. In 1992, Goncharov won the European Mathematical Society Prize.

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

F. Duncan M. Haldane is the Eugene Higgins Professor of Physics at Princeton University. His research explores strongly interacting quantum many-body condensed matter systems using non-perturbative methods. In particular, his concerns include the entanglement spectrum of quantum states, topological insulators and Chern insulators, and both the geometry and model wave functions of the fractional quantum Hall effect. Haldane is a former Alfred P. Sloan Research Fellow and is currently a Fellow of the Royal Society of London, Institute of Physics (UK), American Physical Society, American Association for the Advancement of Science, and American Academy of Arts and Sciences. Haldane has been awarded the Oliver E. Buckley Condensed Matter Physics Prize of the American Physical Society (1993) and the Dirac Medal of the International Centre for Theoretical Physics (2012).

Stephen Hawking is the Director of Research at the Centre for Theoretical Cosmology at the University of Cambridge. From 1979 to 2009, he was the Lucasian Professor of Mathematics in the Department of Applied Mathematics and Theoretical Physics at Cambridge. In his work, Hawking seeks to better understand the basic laws which govern the universe. With Roger Penrose, he showed that Einstein's theory of general relativity implied space and time would have a beginning in the big bang and an end in black holes. He is known for his popular works on science, including *A Brief History of Time*, which is the most popular scientific book of all time and has sold over 30 million copies worldwide. Hawking has 12 honorary degrees, was made a Companion of the British Empire in 1982, and was made a Companion of Honour in 1989. He is the recipient of many awards, medals, and prizes, and is a Fellow of The Royal Society and a Member of the US National Academy of Sciences.

Patrick Hayden is a Professor of Physics at Stanford University. He is a leader in quantum information science who has contributed greatly to our understanding of the absolute limits that quantum mechanics places on information processing, and how to exploit quantum effects for computing and communication. He has also made some key insights on the relationship between black holes and information theory. Among his honours, Hayden is a past Sloan Research Fellow and Rhodes Scholar. He also held the Canada Research Chair in the Physics of Information at McGill University prior to joining Stanford.

Joseph Incandela is the Pat and Joe Yzurdiaga Chair in Experimental Science and Professor of Physics at the University of California, Santa Barbara. He specializes in high energy experimental physics and has worked on several experiments in his career, including the UA2 experiment at CERN, where he studied W and Z bosons and searched for charged Higgs bosons, and the CDF experiment at the Fermi National Accelerator Laboratory (Fermilab), where he led the construction and design of silicon detectors and co-led the successful search for the top quark using lifetime tagging of b quark jets. More recently, he has served in a number of leadership roles tied to the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider at CERN; he was CMS Spokesperson and, in July 2012, he announced the historic discovery of the Higgs boson. For his leadership roles in CMS, he was awarded a Special Breakthrough Prize in Fundamental Physics from the Breakthrough Prize Foundation in 2013. He was elected a member of the US National Academy of Sciences in 2015.

Theodore A. (Ted) Jacobson is a Professor of Physics at the University of Maryland, College Park. He is a leading researcher in the field of gravitational physics and a devoted and accomplished educator. Jacobson's research has focused on quantum gravity, testing the foundations of relativity theory, and the nature of Hawking radiation and black hole entropy. He has authored more than 100 scientific papers, which have received over 6,800 citations. He is a Fellow of both the American Physical Society and the American Association for the Advancement of Science. In addition, Jacobson has served on the editorial board of *Physical Review D* and as a Divisional Editor for *Physical Review Letters*.

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

models of dark energy or cosmic inflation. Kachru has also made notable contributions to the discovery and exploration of string dualities, to the study of models of supersymmetry breaking in string theory, and to the construction of calculable dual descriptions of strongly-coupled particle physics and condensed matter systems using the AdS/CFT correspondence. Kachru's many honours include a Department of Energy Outstanding Junior Investigator Award, Alfred P. Sloan Foundation Fellowship, Bergmann Memorial Award, Packard Foundation Fellowship, and ACIPA Outstanding Young Physicist Prize.

Anton Kapustin is the Earle C. Anthony Professor of Theoretical Physics and Mathematics at the California Institute of Technology. His main area of research is quantum field theory, with applications to particle physics and condensed matter theory. In 2007, Kapustin and Edward Witten published a pioneering paper tied to the geometric Langlands conjecture.

Adrian Kent is a Reader in Quantum Physics with the University of Cambridge. He has previously held positions as an Enrico Fermi Postdoctoral Fellow at the University of Chicago, a member of the Institute for Advanced Study, and a Royal Society University Research Fellow at the University of Cambridge. Prior to becoming a DVRC, Kent was an associate faculty member at Perimeter Institute. His research focuses on the foundations of physics, quantum cryptography, and quantum information theory, including the physics of decoherence, novel tests of quantum theory and alternative theories, and new applications of quantum information.

Renate Loll is a 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." 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.

Matilde Marcolli is a Professor of Mathematics at the California Institute of Technology, who also holds a Courtesy Appointment at Florida State University and an Honorary Professorship at Bonn University. She is a mathematical physicist whose research interests include gauge theory and low-dimensional topology, algebraic-geometric structures in quantum field theory, and noncommutative geometry with applications to number theory and models of particle physics, quantum gravity, and cosmology. Among her many honours, Marcolli has won the Heinz Maier Leibnitz Prize and the Sofja Kovalevskaya Award, both in 2001, and held many visiting research positions. She has also written four books, most recently *Feynman Motives* in 2009, and edited several others.

Joel Moore is a Professor of Physics at the University of California, Berkeley, studying condensed matter. His research concerns the collective quantum physics of electrons and atoms, including topological insulators and other new states of matter. In particular, Moore studies strongly correlated materials and

devices and uses concepts from quantum information theory to analyze problems in condensed matter. His work has been recognized by a Simons investigatorship, Hellman and JSPS fellowships, and an NSF CAREER award. He serves on the advisory boards of *Physical Review B* and *JSTAT,* and is a Member-at-Large of the APS Division of Condensed Matter Physics.

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

Sandu Popescu is a Professor of Physics at the H.H. Wills Physics Laboratory at the University of Bristol and a member of the Bristol Quantum Information and Computation Group. He has made numerous contributions to quantum theory, ranging from the very fundamental to the design of practical experiments (such as the first teleportation experiment), to patentable commercial applications. His investigations into the nature of quantum behaviour, with particular focus on quantum non-locality, led him to discover some of the central concepts in the emerging area of quantum information and computation. Popescu is a past recipient of the Adams Prize from the University of Cambridge, the Clifford Patterson Medal of the Royal Society (UK), the John Stewart Bell Prize, and the Dirac Medal in Physics from the Institute of Physics.

Frans Pretorius is a Professor of Physics at Princeton University. His primary field of research is general relativity, specializing in numerical solution of the field equations. His work has included studies of gravitational collapse, black hole mergers, cosmic singularities, higher dimensional gravity, models of black hole evaporation, and using gravitational wave observations to test the dynamical, strong-field regime of general relativity. He also designs algorithms to efficiently solve the equations in parallel on large computer clusters, and software to manipulate and visualize the simulation results. Among his honours, Pretorius was awarded a Sloan Research Fellowship (2007) and the Aneesur Rahman Prize for Computational Physics of the American Physical Society (2010). He is also a Scholar in the Canadian Institute for Advanced Research Cosmology and Gravity program.

Nathan Seiberg is a Professor at the Institute for Advanced Study in Princeton, whose research focuses on various aspects of string theory, quantum field theory, and particle physics. With collaborators, he has found exact solutions of supersymmetric quantum field theories and string theories, with applications to mathematics. Seiberg's many honours include a MacArthur Fellowship (1996), the Dannie Heineman Prize for Mathematical Physics of the American Physical Society and the American Institute of Physics (1998), the Breakthrough Prize in Fundamental Physics (2012), and The Dirac Medal of the International Centre for Theoretical Physics (2016). He is a Member of the National Academy of Sciences and a Fellow of both the American Physical Society and the American Academy of Arts and Sciences.

Peter Shor is the Morss Professor of Applied Mathematics at the Massachusetts Institute of Technology. In 1994, he formulated a quantum algorithm for factoring, now known as Shor's algorithm, which is exponentially faster than the best currently-known algorithm for a classical computer. He also showed that quantum error correction was possible and that one can perform fault-tolerant quantum computation on a quantum computer. Shor continues to focus his research on theoretical computer science, specifically on algorithms and quantum computing. Among his many honours, Shor has received the Nevanlinna Prize (1998), the International Quantum Communication Award (1998), the Gödel Prize of the Association of Computing Machinery (1999), and a MacArthur Foundation Fellowship (1999). He is also a Member of the National Academy of Science (2002) and a Fellow of the American Academy of Arts and Sciences (2011).

Iakov (Yan) Soibelman is a Professor of Mathematics at Kansas State University. His research interests include quantum groups, deformation theory, algebraic geometry, topology, symplectic geometry, representation theory, non-commutative geometry, differential equations, mathematical physics, and string theory. In collaboration with Maxim Kontsevich, Soibelman developed new algebraic and geometric methods for studying various aspects of homological mirror symmetry. More recently, they introduced a notion of motivic Donaldson-Thomas invariants and proposed a new type of wall-crossing formulas for such invariants. Soibelman is a member of the American Mathematical Society and the Kiev Mathematical Society, and the founder of the Manhattan Mathematical Olympiad. He is also a past Fellow of the Sloan Foundation and the Clay Mathematics Institute, and has held visiting professorships at numerous prestigious institutions, including Harvard University, the Massachusetts Institute of Technology, and the University of Cambridge.

Dam Thanh Son is a University Professor of Physics at the University of Chicago, a prestigious post that includes appointments at the University's interdisciplinary research institutes, the Enrico Fermi Institute and the James Franck Institute. Son is renowned for his broad research interests; he gained international prominence for his application of ideas from string theory to the physics of the quark gluon plasma. His work encompasses several areas of theoretical physics, including string theory, nuclear physics, condensed matter physics, particle physics, and atomic physics. Among his honours, Son was named an Alfred P. Sloan Foundation Fellow in 2001 and a Fellow of the American Physical Society in 2006.

Andrew Strominger is the Gwill E. York Professor of Physics at Harvard University and Director of the Center for Fundamental Laws of Nature. His research has encompassed the unification of forces and particles, the origin of the universe, and the quantum structure of black holes and event horizons, using a variety of approaches. Among Strominger's major contributions, he is the co-discoverer of Calabi-Yau compactifications and the brane solutions of string theory. With collaborators, he gave a microscopic demonstration of how black holes are able to holographically store information. Strominger's recent research has focused on universal aspects of black holes and horizons, which do not depend on detailed microphysical assumptions.

Raman Sundrum is a Distinguished University Professor at the University of Maryland, College Park, and the Director of the Maryland Center for Fundamental Physics. His research is in theoretical particle physics and focuses on theoretical mechanisms and observable implications of extra spacetime

dimensions, supersymmetry, and strongly coupled dynamics. In 1999, with Lisa Randall, Sundrum proposed a class of models that imagines the real world as a higher-dimensional universe described by warped geometry, which are now known as the Randall-Sundrum models. Sundrum won a Department of Energy Outstanding Junior Investigator Award for 2001/02 and is a Fellow of both the American Physical Society (2003) and the American Association for the Advancement of Science (2011).

Leonard Susskind is the Felix Bloch Professor of Theoretical Physics at Stanford University. Regarded as one of the fathers of string theory, he has also made seminal contributions to particle physics, black hole theory, and cosmology. Susskind's current research centres upon questions in theoretical particle physics, gravitational physics, and quantum cosmology.

Gerard 't Hooft is a Professor at the Institute for Theoretical Physics at Utrecht University. He shared the 1999 Nobel Prize in Physics with Martinus J.G. Veltman "for elucidating the quantum structure of electroweak interactions." His research interests include gauge theories in elementary particle physics, quantum gravity and black holes, and fundamental aspects of quantum physics. In addition to being a Nobel laureate, 't Hooft is a past winner of the Wolf Prize, the Lorentz Medal, the Franklin Medal, and the High Energy Physics Prize from the European Physical Society, among other honours. He is a member of the Royal Netherlands Academy of Arts and Sciences (KNAW) and is a foreign member of many other science academies, including the French Académie des Sciences, the National Academy of Sciences (US), and the Institute of Physics (UK). 't Hooft's present research concentrates on the question of nature's dynamical degrees of freedom at the tiniest possible scales. In his latest model, local conformal invariance is a spontaneously broken symmetry, which may have very special implications for the interactions between elementary particles.

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

Senthil Todadri is an Associate Professor of Physics at the Massachusetts Institute of Technology. Todadri's research interests are in condensed matter theory. Specifically, he is working to develop a theoretical framework to describe the behaviour of electronic quantum matter in circumstances in which individual electrons have no integrity. A prime example is the quest for a replacement for the Landau theory of Fermi liquids that describes many metals extremely successfully, but fails in a number of situations studied in modern experiments in condensed matter physics. He is a past Sloan Research Fellow and winner of a Research Innovation Award from the Research Corporation for Science Advancement.

William Unruh is a Professor of Physics at the University of British Columbia who has made seminal contributions to our understanding of gravity, black holes, cosmology, quantum fields in curved spaces,

and the foundations of quantum mechanics, including the discovery of the Unruh effect. His investigations into the effects of quantum mechanics of the earliest stages of the universe have yielded many insights, including the effects of quantum mechanics on computation. Unruh was the first Director of the Cosmology and Gravity program at the Canadian Institute for Advanced Research (1985-1996). His many awards include the Rutherford Medal of the Royal Society of Canada (1982), the Herzberg Medal of the Canadian Association of Physicists (1983), the Steacie Prize from the National Research Council (1984), the Canadian Association of Physicists Medal of Achievement (1995), and the Canada Council Killam Prize (1996). He is an elected Fellow of the Royal Society of Canada, a Fellow of the American Physical Society, a Fellow of the Royal Society of London, and a Foreign Honorary Member of the American Academy of Arts and Science.

Frank Verstraete is a Professor of Physics at the University of Vienna, where he leads the quantum theory group focused on the study of entanglement in many-body quantum systems. His other research interests include quantum information theory, strongly correlated quantum systems and their numerical simulation, and linear and multilinear algebra. Verstraete also holds a professorship at the University of Ghent and has worked previously with Ignacio Cirac at the Max Planck Institute for Quantum Optics and with John Preskill at the California Institute of Technology. In 2009, he won the Lieben Prize, given annually by the Austrian Academy of Sciences.

Ashvin Vishwanath is an Associate Professor in the Department of Physics at the University of California, Berkeley. His primary field is condensed matter theory, with a focus on magnetism, superconductivity, and other correlated quantum phenomena in solids and cold atomic gases. Vishwanath is particularly interested in novel phenomena, such as topological phases of matter, non-fermi liquids, and quantum spin liquids. He has recently been interested in realizing Majorana and Weyl fermions in solids and in using concepts from quantum information, such as entanglement entropy, to characterize novel phases of matter. His past honours include a Sloan Research Fellowship (2004), the CAREER Award of the National Science Foundation (2007), the Outstanding Young Scientist Award of the American Chapter of Indian Physicists (2010), and the Simons Foundation Sabbatical Fellowship (2012).

Zhenghan Wang is a Principal Researcher at Microsoft Research Station Q on the campus of the University of California, Santa Barbara (UCSB), and a Professor of Mathematics at UCSB. His main interests are quantum topology, mathematical models of topological phases of matter, and their application to quantum computing. Wang and his colleagues at Microsoft have been responsible for many developments, including showing that an anyonic quantum computer can perform any computation that the more traditional qubit quantum computer can. He is currently working on the theoretical foundations of the field of anyonics, broadly defined as the science and technology that cover the development, behaviour, and application of anyonic devices.

Steven White is a Professor in the Department of Physics at the University of California, Irvine. His primary research concerns condensed matter theory with an emphasis on numerical approaches for strongly correlated magnetic and superconducting systems. In 1992, White invented the density matrix renormalization group (DMRG), a numerical variation technique for high accuracy calculations of the low energy physics of quantum many body systems. For his efforts, White has been recognized as a Fellow

of the American Physical Society (1998) and the American Association for the Advancement of Science (2008). In 2003, he won the Aneesur Rahman Prize, the highest honour in the field of computational physics given by the American Physical Society.

Mark 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. 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.

Matias Zaldarriaga is a Professor of Astrophysics at the Institute for Advanced Study who has made many influential and creative contributions to our understanding of the early universe, particle astrophysics, and cosmology as a probe of fundamental physics. Much of his work centres on understanding the clues about the earliest moments of our universe encoded in the cosmic microwave background, the faint glow of radiation generated by the big bang. Early in his career, Zaldarriaga co-wrote computer software known as CMBFAST that has become a standard tool for astronomers interpreting observations of the cosmic microwave background. Among his many honours, he has been awarded Sloan and McArthur Fellowships, the Helen B. Warner Prize of the American Astronomical Society, and the Gribov Medal of the European Physical Society.

Alexander Zamolodchikov became the inaugural holder of the C.N. Yang/Wei Deng Endowed Chair in Physics and Astronomy at Stony Brook University in 2016. Prior to that, he was a Professor at Rutgers University for 15 years. He is a theoretical and mathematical physicist, known for his contributions to condensed matter physics, conformal field theory, and string theory. Specifically, Zamolodchikov has made important contributions to integrable quantum field theories, conformal field theories in two spacetime dimensions, and renormalization group in two-dimensional quantum field theories. With collaborators, he received the Dannie Heineman Prize for Mathematical Physics of the American Physical Society (APS) and the American Institute of Physics in 1999 and the Lars Onsager Prize of the APS in 2011. He was elected an APS Fellow in 1999 and inducted into the National Academy of Sciences in 2016.

Appendix C: Visiting Fellows

Jonathan Barrett is an Associate Professor at the University of Oxford. He works in the areas of quantum foundations, quantum information, and quantum computation, with a particular focus on cryptography and aspects of quantum non-locality. Recently, he has been investigating information processing in formalisms more general than quantum theory.

Eugenio Bianchi is an Assistant Professor of Physics at Pennsylvania State University. He previously held a Marie Curie Postdoctoral Fellowship at the Centre de Physique Théorique de Luminy in France and a Banting Postdoctoral Fellowship at Perimeter Institute. Bianchi's research seeks to understand the quantum nature of spacetime and his work lies at the interface between general relativity, quantum field theory, and thermodynamics. In 2013, he received the inaugural Bronstein Prize for his work in loop quantum gravity.

Fernando Brandão is a Reader at University College London and a Researcher in the Quantum Architectures and Computation Group at Microsoft Research, who will soon be joining the faculty of the California Institute of Technology. His research concerns quantum information, quantum computing, and quantum optics, particularly their interplay with mathematics and computer science in understanding the possibilities and limitations of quantum mechanical systems. Among his honours, Brandão won the Quantum Electronics and Optics Division Prize of the European Physical Society (2009), a QIPC European Quantum Information Young Investigator Award (2013), and the Aspen Center for Physics Block Award (2014).

Vitor Cardoso is a Professor at the Instituto Superior Técnico (IST) in Lisbon, Portugal, a Research Associate at CERN, and an Adjunct Professor of Physics at the University of Mississippi. His research concerns general relativity and black hole physics. Cardoso leads the gravity team at IST's Multidisciplinary Center for Astrophysics (CENTRA), where they are seeking to understand black hole dynamics in generic spacetimes and to discriminate between different gravity theories using gravitational wave observations. Cardoso's many honours include Fulbright (2008) and Gulbenkian (2010) scholarships, and the Ordem de Sant'Iago da Espada (2015).

Giulio Chiribella is an Associate Professor at the University of Hong Kong. His research interests lie in quantum information theory, quantum foundations, and mathematical physics – particularly at the intersection of those fields. Chiribella won the Hermann Weyl Prize (2010) for his work on the application of group theoretical models to the problem of quantum estimation of states and processes. In 2016, he was appointed as one of the inaugural Canadian Institute for Advanced Research Azrieli Global Scholars.

Philippe Corboz is an Assistant Professor in Theoretical Condensed Matter Physics at the Institute for Theoretical Physics at the University of Amsterdam, having completed postdoctoral work at ETH Zurich, the Swiss Federal Institute of Technology, and the University of Queensland. His research interests include condensed matter, computational physics, quantum many-body physics, strongly correlated systems, and computer programming.

Neal Dalal is an Assistant Professor of Astronomy and Physics at the University of Illinois at Urbana-Champaign. He previously held fellowships at the Institute for Advanced Study in Princeton and the Canadian Institute for Theoretical Astrophysics at the University of Toronto. Dalal is a cosmologist, whose research interests include using astronomy for probing the fundamental physics of the early universe and the formation of cosmic structure on both large and small scales. He also explores the physics of dark matter using millimeter-wave instrumentation to detect gravitational lensing.

Fay Dowker is a Professor of Theoretical Physics at Imperial College London and an Affiliate of the Institute for Quantum Computing at the University of Waterloo. Her research interests include quantum gravity, the foundations of quantum mechanics, and causal set theory. Dowker completed her PhD under the supervision of Stephen Hawking and has held previous positions at Queen Mary University of London, Fermilab, the California Institute of Technology, and the University of California, Santa Barbara.

Maïté Dupuis is a Research Assistant Professor at the University of Waterloo, where she previously held a Banting Postdoctoral Fellowship. She is a mathematical physicist, whose research interests include loop quantum gravity, spinfoam models, and non-commutative geometry.

Tobias Fritz is a researcher at the Max Planck Institute for Mathematics in the Sciences. He previously held a Templeton Frontiers Program Postdoctoral Fellowship at Perimeter Institute. His research revolves around mathematical structures in mathematical physics and beyond, often building bridges between different areas.

Jerome Gauntlett is the Head of Theoretical Physics at Imperial College London, having previously held research positions at Queen Mary University of London, the California Institute of Technology, and the University of Chicago. His principal research interests include string theory, supersymmetry, quantum field theory, and black holes. Recently, Gauntlett has been investigating whether string theory techniques can be used to study exotic states of matter that arise in condensed matter physics. He is a Fellow of the Institute of Physics and served as a scientific consultant for the 2014 film *The Theory of Everything*.

Ruth Gregory is a Professor in the Departments of Physics and Mathematical Sciences at Durham University. Her research centres on the interface between fundamental high energy physics and cosmology, including exploring simple braneworld models to determine what physical features they can have. In 2006, she was awarded the Maxwell Medal of the Institute of Physics (UK). Gregory has lectured as part of the PSI master's program since its creation.

Razvan Gurau is a Researcher at the Centre National de la Recherche Scientifique (CNRS) at École Polytechnique in France. His research interests lie in mathematical physics, particularly in both perturbative and non-perturbative aspects of the renormalization of quantum field theories. His work is relevant for physics problems ranging from quantum gravity to condensed matter. For his work in quantum gravity, Gurau won the Hermann Weyl Prize in 2012.

Jutho Haegeman is a postdoctoral researcher at Ghent University, working with Distinguished Visiting Research Chair Frank Verstraete. His research interests concern the description of condensed matter

systems and quantum field theories using tensor network states or related methods. In particular, Haegeman is investigating new ideas and algorithms for extracting the low-energy description of microscopic quantum Hamiltonians using the tensor network philosophy.

Zohar Komargodski is a Senior Scientist in the Department of Particle Physics and Astrophysics at the Weizmann Institute of Science. His work spans quantum field theory, conformal symmetry, supersymmetry, quantum gravity, and particle physics phenomenology. Komargodski is most known for his proof, with Adam Schwimmer, of the "a-theorem," a long-open conjecture of quantum field theory. For this and other work on the dynamics of four-dimensional field theories, Komargodski won the prestigious New Horizons in Physics Prize from the Fundamental Physics Prize Foundation. In addition, he is a recipient of the Gribov Medal of the European Physical Society and an Adjunct Professor of Theoretical Physics at the Niels Bohr International Academy in Denmark.

John Laiho is an Assistant Professor at Syracuse University, having previously held research positions at the Fermi National Accelerator Laboratory (Fermilab), Washington University in St. Louis, and University of Glasgow. Laiho is a theoretical particle physicist, whose research interests include lattice QCD, flavor physics and CP violation, chiral perturbation theory, and lattice gravity.

Christopher Laumann is an Assistant Professor in the Department of Physics at the University of Washington. He previously held postdoctoral positions at Perimeter Institute and Harvard University. Laumann's research primarily concerns condensed matter, quantum information, and quantum computing, with particular interests in disordered systems, topological phases of quantum matter, and spin glasses.

Si Li is a Professor at the Yau Mathematical Sciences Center at Tsinghua University and an Affiliate Member at the Kavli Institute for the Physics and Mathematics of the Universe. He was previously an Assistant Professor at Boston University. Li's research interests centre on the interplay between geometry and physics – specifically algebraic and complex geometry, quantum field theory, and string theory. He was awarded a New World Mathematics Award in 2012 for his doctoral thesis.

Etera Livine is a Researcher for the Centre National de la Recherche Scientifique (CNRS) at the Laboratoire de Physique of the École Normale Supérieure de Lyon, in France. He works in the area of quantum gravity, with a focus on spinfoam models, and he is interested in deriving effective dynamics for quantum cosmology from these models.

Alejandro Perez is a Permanent Member of the Quantum Gravity group at the Centre of Theoretical Physics at Aix-Marseille University and an Honorary Member of the Institut Universitaire de France. His research concerns the development of the loop approach to quantum gravity, with interests including black holes, quantum physics, and mathematical physics.

Rachel A. Rosen is an Assistant Professor at Columbia University, whose research focuses on quantum field theory, including applications of quantum field theory to cosmology, astrophysics, particle physics, and condensed matter systems. She is best known for her contributions to the theory of massive gravity, resolving a 40-year-old problem in its favour. With Gregory Gabadadze, Rosen has also studied the

astrophysics of helium-core white dwarfs, predicted a possible new state of matter in these objects (charged condensates), and made testable predictions for the cooling of such stars.

Sarah Shandera is an Assistant Professor at Pennsylvania State University, studying the very early universe as it pertains to both high-energy particle physics and gravity. Her research aims to build consistent models for the early universe and to make predictions for observations that can distinguish between different scenarios. Shandera often works with astrophysicists to understand how to use data from observational surveys to constrain cosmological theories.

Kris Sigurdson is an Associate Professor in Physics and Astronomy at the University of British Columbia. He works in the areas of particle astrophysics and cosmology, with a focus on dark matter and dark energy. His recent work includes a unified theory for the origin of dark matter and atoms in the early universe and developing, with a Canadian team, a novel new radio interferometer that can make a three-dimensional map of the universe to measure properties of dark energy.

David Skinner is a tenure-track Lecturer at the University of Cambridge. He is interested in mathematical aspects of quantum field theories, particularly their overlap with twistor theory and string theory. Skinner's recent work explores the rich geometric structures present in the scattering amplitudes of four-dimensional gauge theory.

Brian Swingle is a Postdoctoral Research Fellow at Stanford University, having previously held a Simons Fellowship in condensed matter at Harvard University. Swingle works at the interface of quantum matter, quantum information, and quantum gravity; his particular interests include quantum entanglement, strongly correlated systems, spin liquids and the physics of fractionalization, experimental signatures of strongly correlated phases, quantum information and computation, and holographic duality and string theory.

Thomas Vidick is an Assistant Professor in the Department of Computing and Mathematical Sciences at the California Institute of Technology. Vidick's research is centered on problems at the interface of quantum computing, complexity theory, and cryptography. He studies complexity-theoretic aspects of quantum phenomena such as entanglement, and likes to explore the application of ideas from quantum computing to fields as diverse as pseudo randomness, discrete optimization, or functional analysis. In 2011, Vidick won the Bernard Friedman Memorial Prize in Applied Mathematics.

Neal Weiner is a Professor in the Department of Physics and Director of the Center for Cosmology and Particle Physics at New York University. He has broad interests in particle physics and cosmology, with a general focus on physics beyond the Standard Model. In this broad field, his work has included studies of extra dimensional theories (large, small, warped, and flat), supersymmetry, grand unification, flavor, neutrino mass, dark matter, inflation, and dark energy, as well as relationships between the different subjects.

Appendix D: Affiliates

Name	Institution	Research Area(s)
Arif Babul	University of Victoria	Cosmology
Leslie Ballentine	Simon Fraser University	Quantum Foundations
Richard Bond	University of Toronto/Canadian Institute for Theoretical Astrophysics (CITA)	Cosmology
Ivan Booth	Memorial University	Strong Gravity
Vincent Bouchard	University of Alberta	Quantum Fields and Strings
Robert Brandenberger	McGill University	Cosmology
Gilles Brassard	University of Montreal	Quantum Information
Anne Broadbent	University of Ottawa	Quantum Information
Jim Bryan	University of British Columbia	Mathematical Physics
Anton Burkov	University of Waterloo	Condensed Matter
Benoit Charbonneau	University of Waterloo	Mathematical Physics
Gang Chen	University of Toronto	Condensed Matter
Jeffrey Chen	University of Waterloo	Condensed Matter
Andrew Childs	University of Maryland	Quantum Information
Kyung Soo Choi	University of Waterloo/Institute for Quantum Computing (IQC)	Quantum Information
Matthew Choptuik	University of British Columbia	Strong Gravity
Dan Christensen	Western University	Quantum Gravity
Richard Cleve	University of Waterloo/IQC	Quantum Information
James Cline	McGill University	Cosmology, Particle Physics
Alan Coley	Dalhousie University	Strong Gravity

Name	Institution	Research Area(s)
Andrzej Czarnecki	University of Alberta	Particle Physics
Saurya Das	University of Lethbridge	Quantum Gravity
Arundhati Dasgupta	University of Lethbridge	Quantum Gravity
Keshav Dasgupta	McGill University	Quantum Fields and Strings
Rainer Dick	University of Saskatchewan	Particle Physics
Joseph Emerson	University of Waterloo/IQC	Quantum Foundations
Valerio Faraoni	Bishop's University	Cosmology
Marcel Franz	University of British Columbia	Condensed Matter
Doreen Fraser	University of Waterloo	Philosophy
Andrew Frey	University of Winnipeg	Cosmology
Valeri Frolov	University of Alberta	Cosmology, Quantum Gravity
Ion Garate	University of Sherbrooke	Condensed Matter
Jack Gegenberg	University of New Brunswick	Quantum Gravity
Ghazal Geshnizjani	University of Waterloo	Cosmology
Amir Masoud Ghezelbash	University of Saskatchewan	Quantum Gravity
Shohini Ghose	Wilfrid Laurier University	Quantum Information
Florian Girelli	University of Waterloo	Quantum Gravity
Gilad Gour	University of Calgary	Mathematical Physics
Daniel Green	University of Toronto/CITA	Cosmology
Marco Gualtieri	University of Toronto	Mathematical Physics
John Harnad	Concordia University	Mathematical Physics, Quantum Fields and Strings
Igor Herbut	Simon Fraser University	Condensed Matter
Jeremy Heyl	University of British Columbia	Astrophysics

Name	Institution	Research Area(s)
Carl Hoefer	Western University	Philosophy
Gilbert Holder	McGill University	Particle Physics
Bob Holdom	University of Toronto	Particle Physics
Michael Hudson	University of Waterloo	Cosmology
Viqar Husain	University of New Brunswick	Cosmology, Quantum Gravity
Lisa Jeffrey	University of Toronto	Quantum Fields and Strings, Mathematical Physics
Thomas Jennewein	University of Waterloo/IQC	Quantum Information
Catherine Kallin	McMaster University	Condensed Matter
Joel Kamnitzer	University of Toronto	Mathematical Physics
Joanna Karczmarek	University of British Columbia	Quantum Fields and Strings
Spiro Karigiannis	University of Waterloo	Mathematical Physics
Mikko Karttunen	University of Waterloo	Condensed Matter
Achim Kempf	University of Waterloo	Mathematical Physics
Yong-Baek Kim	University of Toronto	Condensed Matter
David Kribs	University of Guelph	Quantum Information
Hari Kunduri	Memorial University	Strong Gravity
Gabor Kunstatter	University of Winnipeg	Quantum Gravity
Kayll Lake	Queen's University	Strong Gravity
Debbie Leung	University of Waterloo	Quantum Information
Randy Lewis	York University	Particle Physics
Hoi-Kwong Lo	University of Toronto	Quantum Information
Michael Luke	University of Toronto	Particle Physics
Adrian Lupascu	University of Waterloo/IQC	Quantum Information

Name	Institution	Research Area(s)
Norbert Lütkenhaus	University of Waterloo/IQC	Quantum Information
Joseph Maciejko	University of Alberta	Condensed Matter
A. Hamed Majedi	University of Waterloo/IQC	Nanotechnology
Alexander Maloney	McGill University	Quantum Fields and Strings
Robert Mann	University of Waterloo	Quantum Fields and Strings, Quantum Gravity
Eduardo Martin-Martinez	University of Waterloo/IQC	Quantum Foundations, Quantum Information
Gerry McKeon	Western University	Particle Physics
Brian McNamara	University of Waterloo	Cosmology
Volodya Miransky	Western University	Quantum Information
Ruxandra Moraru	University of Waterloo	Mathematical Physics
David Morrissey	TRIUMF	Particle Physics
Norman Murray	University of Toronto/CITA	Astrophysics
Wayne Myrvold	Western University	Philosophy
Julio Navarro	University of Victoria	Cosmology
Ashwin Nayak	University of Waterloo	Quantum Information
Elisabeth Nicol	University of Guelph	Condensed Matter
Don Page	University of Alberta	Cosmology
Prakash Panangaden	McGill University	Quantum Foundations
Manu Paranjape	University of Montreal	Particle Physics
Amanda Peet	University of Toronto	Quantum Fields and Strings
Alexander Penin	University of Alberta	Condensed Matter, Particle Physics
Harald Pfeiffer	University of Toronto/CITA	Strong Gravity

Name	Institution	Research Area(s)
Marco Piani	University of Waterloo/IQC	Quantum Information
Levon Pogosian	Simon Fraser University	Cosmology
Dmitri Pogosyan	University of Alberta	Cosmology
Eric Poisson	University of Guelph	Strong Gravity
Erich Poppitz	University of Toronto	Particle Physics
David Poulin	University of Sherbrooke	Quantum Foundations
Robert Raussendorf	University of British Columbia	Quantum Information
Ben Reichardt	University of Southern California	Quantum Information
Kevin Resch	University of Waterloo/IQC	Quantum Information
Adam Ritz	University of Victoria	Particle Physics
Pierre-Nicholas Roy	University of Waterloo	Quantum Information
Moshe Rozali	University of British Columbia	Quantum Fields and Strings
Barry Sanders	University of Calgary	Quantum Information
Kristin Schleich	University of British Columbia	Strong Gravity
Douglas Scott	University of British Columbia	Cosmology
Sanjeev Seahra	University of New Brunswick	Cosmology, Quantum Gravity
Peter Selinger	Dalhousie University	Mathematical Physics
Gordon Semenoff	University of British Columbia	Quantum Fields and Strings
John Sipe	University of Toronto	Condensed Matter, Quantum Foundations
Aephraim Steinberg	University of Toronto	Quantum Information
James Taylor	University of Waterloo	Cosmology
Andre-Marie Tremblay	University of Sherbrooke	Condensed Matter

Name	Institution	Research Area(s)
Sean Tulin	York University	Particle Physics
Johannes Walcher	McGill University	Quantum Fields and Strings
Mark Walton	University of Lethbridge	Quantum Fields and Strings
John Watrous	University of Waterloo	Quantum Information
Steve Weinstein	University of Waterloo	Quantum Foundations
Lawrence Widrow	Queen's University	Astrophysics
Don Witt	University of British Columbia	Particle Physics, Quantum Fields and Strings
Bei Zeng	University of Guelph	Quantum Information

Appendix E: Board of Directors

Mike Lazaridis, O.C., O.Ont., Chair, is Managing Partner and Co-Founder of Quantum Valley Investments (QVI), which he and Doug Fregin established in Waterloo. In 2013, they launched QVI with $100 million to provide financial and intellectual capital for the development and commercialization of quantum physics and quantum computing breakthroughs. QVI aims to help transform ideas and early-stage breakthroughs into commercially viable products, technologies, and services. It is Mr. Lazaridis' latest venture in 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 the Royal Society of London and the Royal Society of Canada, and he has been named to both the Order of Ontario and the Order of Canada. He was listed on the *Maclean's* Honour Roll as a distinguished Canadian in 2000, named as one of *Time*'s 100 Most Influential People, honoured as a *Globe and Mail* Nation Builder of the Year in 2010, and awarded the Ernest C. Manning Principal Award, Canada's most prestigious innovation prize.

Mr. Lazaridis holds an honorary doctoral degree in engineering from the University of Waterloo (where he formerly served as Chancellor), as well as Doctors of Laws from 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 Founding Co-Chair of the Perimeter Leadership Council and a member of the Perimeter Finance Committee. In these

capacities, he regularly assists and supports Perimeter's management team in a variety of contexts including financial, legal, and advancement matters. Mr. Fiorenza is also a member of the Board of Directors of the Institute for Quantum Computing at the University of Waterloo. He holds a degree in business administration from Lakehead University and a law degree from the University of Ottawa. He was called to the Bar in Ontario in 1991.

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

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

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

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

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.

Indira Samarasekera, O.C., is a corporate director and Senior Advisor at Bennett Jones LLP, who recently served as the President and Vice-Chancellor of the University of Alberta (2005-15). She is internationally recognized as a leading metallurgical engineer, and has been appointed an Officer of the Order of

Canada. She is also an elected member of both the Royal Society of Canada and the US National Academy of Engineering. Dr. Samarasekera formerly served as Chair of the Worldwide Universities Network and was a member of Canada's Science, Technology, and Innovation Council. She serves on the boards of the Bank of Nova Scotia, Magna International, and TransCanada Corporation. Dr. Samarasekera has an MSc in mechanical engineering from the University of California and a PhD in metallurgical engineering from the University of British Columbia.

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

Appendix F: Scientific Advisory Committee

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

Renate Loll, Radboud University, Nijmegen (2010-16), Chair
Professor Loll is a 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." 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 Organisation for Scientific Research. In 2015, she was installed as a member of the Royal Netherlands Academy of Arts and Sciences.

Neta Bahcall, Princeton University (2015-16)
Professor Bahcall is the Eugene Higgins Professor of Astrophysics at Princeton University. She is an observational cosmologist who has pioneered quantitative approaches to the understanding of astronomical data. These methods have enabled her to achieve key insights into such fundamental questions as the large-scale structure, mass, and fate of the universe, galaxy formation, the nature of quasars, and dark matter. She is a member of the US National Academy of Sciences and the American Academy of Arts and Sciences, among other honours.

Ganapathy Baskaran, Institute of Mathematical Sciences, Chennai (2013-16)
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, 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).

Edmund Copeland, University of Nottingham (2015-16)
Professor Copeland is a Professor of Physics at the University of Nottingham. He is a particle cosmologist with a particular interest in how the physics of the very early and late universe can be tested by observations on both the largest scales (astronomy) and smallest scales (particle physics) in the

universe. He has been a leader in the quest to obtain successful particle physics-inspired models of inflation, to predict the properties of cosmic strings, and to determine the nature of dark energy. Among his many honours, Copeland has received a Wolfson Research Merit Award from the Royal Society and the 2013 Rayleigh Medal and Prize of the Institute of Physics.

Nigel Hitchin, University of Oxford (2015-16)
Professor Hitchin is the Savilian Professor of Geometry at the University of Oxford. His research interests include differential and algebraic geometry, as well as their interaction with the equations of theoretical physics, and he has made many notable discoveries in these areas. Among his many honours, Hitchin has been awarded the Sylvester Medal of the Royal Society, the Shaw Prize in Mathematical Sciences, and the Senior Berwick Prize and Pólya Prize, both of the London Mathematical Society. He is also a Fellow of both the Royal Society and the American Mathematical Society.

Shamit Kachru, Stanford University (2015-16)
Professor Kachru has been a Professor of Physics at Stanford University since 1999. He is an expert in string theory and quantum field theory, and their applications in cosmology, condensed matter, and elementary particle theory. He has made central contributions to the study of compactifications of string theory from ten to four dimensions, especially in the exploration of mechanisms which could yield string models of dark energy or cosmic inflation. Kachru has also made notable contributions to the discovery and exploration of string dualities, to the study of models of supersymmetry breaking in string theory, and to the construction of calculable dual descriptions of strongly-coupled particle physics and condensed matter systems using the AdS/CFT correspondence. Kachru's many honours include a Department of Energy Outstanding Junior Investigator Award, Alfred P. Sloan Foundation Fellowship, Bergmann Memorial Award, Packard Foundation Fellowship, and ACIPA Outstanding Young Physicist Prize.

Sandu Popescu, University of Bristol (2015-16)
Professor Popescu is a Professor of Physics at the H.H. Wills Physics Laboratory at the University of Bristol and a member of the Bristol Quantum Information and Computation Group. He has made numerous contributions to quantum theory, ranging from the very fundamental to the design of practical experiments (such as the first teleportation experiment), to patentable commercial applications. His investigations into the nature of quantum behaviour, with particular focus on quantum non-locality, led him to discover some of the central concepts in the emerging area of quantum information and computation. Popescu is a past recipient of the Adams Prize from the University of Cambridge, the Clifford Patterson Medal of the Royal Society (UK), the John Stewart Bell Prize, and the Dirac Medal in Physics from the Institute of Physics.

Barbara Terhal, RWTH Aachen University (2015-16)
Professor Terhal has been a Professor of Theoretical Physics at RWTH Aachen University in Germany since 2010. Prior to that, she spent eight years as a research staff member at the IBM Watson Research Center in New York. Terhal's research interests lie in quantum information theory – ranging from quantum entanglement to quantum cryptography and quantum algorithms – and she is currently working on quantum error correction and its realization in solid-state qubits, as well as quantum

complexity theory. She is a Fellow of the American Physical Society and an Associate Member of the Quantum Information Processing program of the Canadian Institute for Advanced Research.

Mark Wise, California Institute of Technology (2013-16)
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. 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.

Appendix G: Research Ties to Experiment

Perimeter scientists are connected to many of the world's most important experimental efforts. The list that follows provides a representative sample of such involvement from Perimeter researchers.

- **Asimina Arvanitaki** is part of the ARIADNE collaboration (Axion Resonant InterAction DetectioN Experiment),[44] which is looking for axion mediated interactions in matter. She has also proposed a number of experimental tests of fundamental physics using optically-levitated sensors, atomic clocks, and nuclear magnetic resonance.
- **Avery Broderick** and **Tim Johannsen** are members of the Event Horizon Telescope project,[45] which is working to directly observe the immediate environment of a black hole for the first time.
- **Raffi Budakian** works with the Institute for Quantum Computing on developing a new class of experimental tools for ultrasensitive detection of electron and nuclear spins.
- **David Cory** works with the Institute for Quantum Computing on the development of quantum sensors and actuators, which probe and control the subatomic world with incredible precision, and will likely form the building blocks of future quantum computers.
- **Matthew Johnson** is a Perimeter cosmologist who analyzes data from experiments measuring the cosmic microwave background, or CMB.
- **Raymond Laflamme** is the director of the Institute for Quantum Computing, where, among several other efforts at the intersection of theory and experiment, he is developing blueprints for quantum information processors such as linear optics quantum computing. Laflamme is also a founder of Universal Quantum Devices (http://uqdevices.com), a start-up commercializing spinoffs of quantum information research.
- **Maxim Pospelov** is an associate member of the BaBar collaboration,[46] which studies the physics of b-quarks and other intermediate mass particles. He also directly collaborates with experimental physicists at TRIUMF and Fermilab, and is part of the Global Network of Magnetometers for Exotic (GNOME) experiment.[47]
- **Philip Schuster** and **Natalia Toro** work jointly, and have extensive connections to experiment. They were the lead developers of the "Simplified Models" approach, which is now the standard way to handle data at the Large Hadron Collider at CERN, in Geneva, Switzerland. They also pioneered new experiments at smaller colliders, including three at the Jefferson Laboratories collider: the Beam Dump eXperiment (BDX), which searches for dark matter, and the A-Prime EXperiment (APEX) and Heavy Photon Search (HPS) experiments, which search for unknown forces.[48] They are spokespeople for APEX.

[44] Refer to http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.113.161801.
[45] Refer to https://perimeterinstitute.ca/research/research-initiatives/event-horizon-telescope-eht-initiative and http://www.eventhorizontelescope.org.
[46] Refer to http://www.slac.stanford.edu/BFROOT.
[47] Refer to http://arxiv.org/abs/1303.5524.
[48] For more information on these experiments, refer to http://arxiv.org/abs/1406.3028, http://arxiv.org/abs/1301.2581, and http://arxiv.org/abs/1310.2060.

- **Kendrick Smith** is a member of several major experimental collaborations aimed at measuring the cosmic microwave background, or CMB. These include the landmark WMAP and Planck satellite experiments[49] and the ground-based CAPMAP and QUIET CMB experiments.[50] He is also part of the Canadian Hydrogen Intensity Mapping Experiment (CHIME),[51] aiming to measure the radio sky using the first large Canadian research telescope in more than 50 years.
- **Robert Spekkens** works with experimentalists at the Institute for Quantum Computing to demonstrate the quantum advantage for inferring causal relations from correlations and to implement robust tests of the quantum phenomenon of contextuality.
- **Itay Yavin** is leading an effort for a new experiment at the Large Hadron Collider to look for new particles with a charge a thousand times smaller than that of the electron. Yavin is also a lead developer of RECAST, a framework which recasts data from the Large Hadron Collider in such a way as to allow for testing of alternative hypotheses and searches for new physics. RECAST is housed at Perimeter.[52]

Perimeter also connects to experiment through its conference program, with several conferences in 2015/16 revolving directly around experimental findings and challenges. These included:

- "Cosmic Flows (and Other Novelties on Large Scales)"
- "Condensed Matter Physics and Topological Field Theory"
- "Feedback Over 44 Orders of Magnitude: From Gamma-Rays to the Universe"
- "Cosmological Frontiers in Fundamental Physics"
- "Concepts and Paradoxes in a Quantum Universe"

[49] Refer to http://map.gsfc.nasa.gov and http://www.cosmos.esa.int/web/planck.
[50] Refer to http://cfcp.uchicago.edu/research/projects/capmap.html and http://quiet.uchicago.edu.
[51] Refer to http://chime.phas.ubc.ca.
[52] For more on RECAST, refer to http://arxiv.org/abs/1010.2506 and http://recast.it.

Appendix H: Media Highlights

In 2015/16, Perimeter Institute received coverage in both national and international media, including *The Globe and Mail*, *The Washington Post*, *Wired, Maclean's*, TVO, CBC, BBC News, *Nature*, and *Scientific American*, among others. Highlights are included below.

Outlet	Headline	Date	Summary
Scientific American	After Einstein, a New Generation Tries to Create a Theory of Everything	August 18, 2015	Feature on research to address problems general relativity cannot solve; shape dynamics – an approach heavily developed at PI – is featured, as is an interview with PI's Lee Smolin
CBC Radio's *Ideas with Paul Kennedy*	Similes and Science, Part 1	September 10, 2015	A radio program that touched on the concepts of imagination and creativity as they relate to physics; the interview was conducted by Paul Kennedy and featured PI's Matthew Johnson and MIT's Sara Seager
The Globe and Mail	Canadian physicist shares Nobel Prize for neutrinos experiment	October 6, 2015	A news article on PI Board member Art McDonald winning the Nobel Prize in Physics; Perimeter's Neil Turok is quoted
CBC *Fresh Air*	Mary Ito with Neil Turok	October 17, 2015	A 12-minute conversation between Mary Ito and Neil Turok on the intersections between theoretical and experimental research (particularly at CERN), and the current "golden age" of physics
Popular Science	General Relativity: 100 Years Old And Still Full Of Surprises	October 20, 2015	PI's Lee Smolin is featured in this long article about the continuing importance of general relativity to the study of theoretical physics
Gizmodo **Also appeared in Gizmodo India**	This Artist Painted Physicists Into a 3D Living Chalkboard	October 21, 2015	An article about the work created by Alexa Meade when she served as Perimeter's Artist-in-Residence; this article also included a PI-branded and produced video
The Globe and Mail	Leveraging the tools of innovation	November 17, 2015	A Q&A with Perimeter Chief Operating Officer and Managing Director Michael Duschenes in a special "Research and Innovation" section of *The Globe and Mail*; Duschenes discusses the innovation chain, which begins with basic research, and PI's place in Quantum Valley
Maclean's	Art McDonald on how to win a Nobel Prize	November 21, 2015	A long-form feature on the life and work of Nobel-winner Art McDonald; Perimeter's Neil Turok is quoted
Macleans.ca	Ten steps to make Canada a leader in science	November 25, 2015	Opinion piece by Perimeter's Lee Smolin on the ten things the Canadian government can do to make Canada a leader in science
Space.com **Also appeared in Live Science**	Turbulent Magnetic 'Perfect Storm' Triggers Hypernovas	December 1, 2015	Article about research that models the creation of a supernova; Perimeter researcher Erik Schnetter is quoted throughout

The Washington Post	Scientists detect the magnetic field that powers our galaxy's supermassive black hole	December 4, 2015	Article about the Event Horizon Telescope's detection of the magnetic field around the supermassive black hole at the centre of our galaxy, quoting Perimeter's Avery Broderick
Motherboard **Also appeared in *Motherboard Canada***	Earth-Sized Telescope Bags Magnetic Fields from the Milky Way's Black Hole Core	December 5, 2015	Article about the Event Horizon Telescope's detection of the magnetic field around the supermassive black hole at the centre of our galaxy; Perimeter's Avery Broderick is quoted throughout
New Scientist	Physicists dream up crystal based on elegant satellite dance	January 15, 2016	Article about recent work on "dynamical" crystals done by Perimeter researchers Latham Boyle and Kendrick Smith; Boyle is quoted throughout
Wired	The Death of General Relativity Lurks in a Black Hole's Shadow	January 27, 2016	Article about recent research published by Perimeter associate postdoctoral researcher Tim Johannsen and Associate Faculty member Avery Broderick on the Event Horizon Telescope's ability to help physicists test general relativity in strong gravity situations
Scientific American	Gravitational Waves Discovered from Colliding Black Holes	February 11, 2016	Article about LIGO's detection of gravitational waves; Perimeter Faculty member Luis Lehner is quoted
Wired	Scientists Spot the Gravity Waves that Flex the Universe	February 11, 2016	Article about LIGO's detection of gravitational waves; Perimeter researcher Avery Broderick is quoted
The Guardian **Also appeared in MSN New Zealand and MSN Philippines**	Gravitational waves: discovery hailed as breakthrough of the century	February 11, 2016	Article about LIGO's detection of gravitational waves; Perimeter Director Neil Turok is quoted
The Globe and Mail	'I felt disbelief.' Physicists open new window on the universe	February 11, 2016	Article about LIGO's detection of gravitational waves; Perimeter researchers Neil Turok and Luis Lehner are quoted
The Globe and Mail	'Brilliant' physicist to hold $8-million research chair at Perimeter Institute	April 28, 2016	Article following the announcement of the $8 million Stavros Niarchos Foundation Aristarchus Chair in Theoretical Physics at Perimeter Institute, which went to PI researcher Asimina Arvanitaki
New Scientist	Bully particle beats up atoms to fix cosmic accounting glitch	June 8, 2016	Article about new research from Perimeter researcher Maxim Pospelov on lithium
New Scientist	Our universe could be reborn as a bouncing baby cosmos	July 11, 2016	Article about new research from Neil Turok and his collaborators on the "big bounce" theory in cosmology; Turok is quoted throughout the story