2013/14 Annual Report to Industry Canada

Covering the Objectives, Activities, and Finances
for the period August 1, 2013 to July 31, 2014 and
Statement of Objectives for Next Year and the Future

Submitted by: Neil Turok, Director
to the Hon. James Moore, Minister of Industry
and the Hon. Ed Holder, Minister of State (Science and Technology)

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 Institute is now one of the world's leading centres in theoretical physics, if not the *leading centre."*
– Stephen Hawking

Theoretical physics is the lowest-cost, highest-impact field of science. It seeks to understand the universe at the most basic level: what it is made of, the forces that govern it, and the potential it holds. Because the field is so fundamental, each new advance literally changes our world. The discovery of electromagnetism, for example, led to radio, X-rays, and all wireless technologies, and in turn catalyzed breakthroughs in all the other sciences. The discovery of quantum mechanics led directly to semiconductors, computers, lasers, and a nearly infinite array of modern electronics.

Located in Waterloo, Ontario, Perimeter Institute for Theoretical Physics was founded in 1999, as an unprecedented effort to strategically accelerate discovery in this most basic area of science. Its visionary funding model unites public and private partners, and some of the world's best scientific minds, in a shared quest to achieve the next breakthroughs, which will transform our future.

As of July 31, 2014, the Perimeter community has grown to include:

- 22 faculty
- 14 associate faculty
- 42 Distinguished Visiting Research Chairs
- 14 Visiting Fellows
- 44 postdoctoral researchers
- 73 graduate students[1]

Perimeter has become a major hub for the exchange of new ideas. Its conference and visitor programs bring approximately 1,000 scientists to the Institute annually, catalyzing collaborations and discoveries across the whole spectrum of fundamental physics.

Breakthroughs in physics are essential to our society and our future. Understanding the role of science in all of our lives is more important now than ever; thus, an integral part of Perimeter's mission is educational outreach to teachers, students, and the general public. The Institute's 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.

[1] This includes 42 PhD students and 31 Perimeter Scholars International (PSI) master's students.

AN ACCELERATOR OF DISCOVERY

150+ SCIENTISTS IN RESIDENCE conducting research

10 MAJOR PRIZES AND HONOURS awarded to Perimeter scientists in 2013/14

1,000+ VISITING INTERNATIONAL SCIENTISTS annually

2,900+ PAPERS appearing in 100+ journals with **90,000+** citations since 2001

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

15 YEARS after its creation, Perimeter has been ranked **#2** IN SCIENTIFIC EXCELLENCE in the world in theoretical physics

>4+ MILLION STUDENTS reached since 2003

10,000+ EDUCATORS trained through Perimeter workshops since 2003

500 TOP HIGH SCHOOL STUDENTS from **44** COUNTRIES have attended the International Summer School for Young Physicists since 2003

90 COUNTRIES have broadcast *The Quantum Tamers*, a documentary on the new science of quantum computing

Perimeter is currently home to
73 PHD & MASTER'S STUDENTS and
44 POSTDOCTORAL RESEARCHERS

Perimeter Scholars International (PSI) master's program
155 GRADUATES from **48** COUNTRIES since **2009**

THE COMMERCIALIZATION CATALYST OF QUANTUM VALLEY

Contents

Preface

Today, Perimeter Institute stands in a remarkable position. It is well-placed, I believe, to lead a coming revolution in fundamental physics.

Over the last two decades, and especially in the last two years, three very powerful clues have emerged pointing to a new paradigm.

First, we have discovered that 70 percent of the energy in the universe is in dark energy: the energy present in the vacuum of empty space when all particles and forms of radiation are removed. Since the early 20th century, we have understood that many fields – the electric field, the gravitational field, Dirac's electron field, and so on – can travel as waves through empty space. In fact, particles and radiation are just ripples in these fields. With the advent of quantum theory, we learned that even in the vacuum, every field is constantly fluctuating, and each possible wave in every field contributes to the energy of the vacuum. When you add up all of these contributions, you get a huge number, vastly exceeding the vacuum energy which was measured in the late 1990s from measurements of the expansion rate of the universe, and subsequently confirmed in several ways. There are two possibilities: either we need a new theory of quantum fields and the vacuum, or there must be additional fields cancelling the effects of the fields we already know. Both possibilities are extremely exciting.

The second clue is the Higgs boson, detected at the Large Hadron Collider in 2012. Its discovery was both a spectacular success for basic theory and a huge challenge for the future. The Higgs was found just where it was predicted to be – that's the triumph – but, according to the most popular theories, it was expected to be accompanied by a slew of other particles, none of which have so far been found. This has raised doubts over most of the theories developed over the last several decades. Somehow, nature has found a simpler way of governing itself than we so far understand.

The third clue is the picture of the cosmic microwave background, the radiation which emerged from the big bang, showing us the structure of the universe on very large scales. The Planck satellite's map, released last year, provides an exquisitely detailed picture. Remarkably, the entire pattern, representing the primordial structure in the universe as it emerged from the big bang, can be described to good accuracy with just one number, representing the level of fluctuations on every visible scale. The universe, on the largest scales, is one of the simplest things we know! But so far, just as for the Higgs boson and particle physics, the theories we have do not explain this stunning simplicity.

These observations are the best clues we've had for a very long time. And they are all pointing to a new paradigm for fundamental physics. Perimeter has the right combination of expertise and imagination to take advantage of these clues and forge a new understanding of nature. Throughout history, such radical advances have led to new technologies and transformational progress for society. What I mean by "the right combination" of expertise is a critical mass of singular minds – people able to reframe questions in entirely new ways, people with the skill and talent to illuminate new territories with their answers.

Over the last five years, Perimeter has succeeded in gathering together many such singular minds. This year, for example, we welcomed Kevin Costello to Perimeter as the inaugural Krembil Foundation William Rowan Hamilton Chair in Theoretical Physics. Kevin is a pure mathematician who has surprised leading physicists by bringing powerful new mathematical tools to bear on quantum field theory, our most basic framework for physical theories, and in so doing simplifying and extending our understanding of nature at its most basic level.

This year, we also welcomed Asimina Arvanitaki, another young pathbreaker. In her field of particle physics, the trend since the 1940s has been to build bigger and bigger colliders in order to probe higher and higher energies. But there are clear limitations to this approach – as they become more and more powerful, the colliders become more and more expensive, and take longer and longer to build. Asimina has taken a different path, using extreme precision, not energy, as the probe of new physics. She has designed elegant and ingenious experiments to look for gravitational waves and hypothetical particles called axions, and she has used the observed properties of black holes to infer limits on such particles in the universe.

Perimeter was launched with the vision of understanding and harnessing the power of the quantum world on everyday scales. Quantum theory, developed in the 1920s, enabled us to conceive of and design the transistor, the backbone of every modern computer, smartphone, and electronic device. Likewise, the quantum properties of light are the basis for the laser, now used in every digital hard drive and every projector.

Moore's Law, according to which the number of transistors one can fit on a microprocessor chip doubles every two years, has held for decades, powering the exponential growth of the digital electronics, communications, and information industries. But Moore's law will come to an end when the size of a transistor shrinks to the size of the atom. In this regime, one can no longer use a transistor as a "tap" controlling the flow of electricity. Instead, one has to describe nature in its own, much more subtle, quantum terms. The good news is that, according to quantum theory, much more powerful technologies are possible. Quantum electronics will make today's digital devices seem like abacuses. Quantum devices will enable us to gather, store, and process information on an almost inconceivable scale.

PI is part of remarkable community here in Waterloo. Our theorists interact with experimentalists such as those at Institute for Quantum Computing and the new Quantum-Nano Centre at the University of Waterloo, and where there are efforts like the Quantum Valley initiative to translate the scientific discoveries into commercial quantum technologies. In the last several years, we have seen rapid progress toward building quantum computers, quantum sensors, and quantum communication technologies.

In becoming a world-leading hub for the theoretical research that underpins these technologies, Perimeter has become the catalyst for a quantum revolution in Canada, with enormous commercialization and economic growth opportunities. We are truly fortunate to be part of an ecosystem where fundamental ideas are being translated into the technology of the future.

– Neil Turok, Director

Executive Summary

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

Each of the Objectives set out in last year's Corporate Plan plays a part in the Institute's comprehensive long-term strategy for achieving this ambitious goal. In 2013/14, the Institute 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.

Achievement Highlights, 2013/14

Advancing Fundamental Research

- ✓ Produced research discoveries of international impact and importance

- ✓ Perimeter Faculty members Robert Myers and Subir Sachdev were named among the "world's most influential scientific minds," as were Distinguished Visiting Research Chairs Lance Dixon and Dam Thanh Son

- ✓ Sample research highlights include the following:
    - Quantum computing holds promise for tremendous advances in fields spanning communications, cryptography, medicine, and beyond. Unlocking that promise requires research bridging theory and experiment to realize practical quantum computers. One key is developing methods to overcome the errors that inevitably arise in fragile quantum systems. Postdoctoral researcher Hector Bombin introduced a new approach that may make detecting errors in a quantum computation more efficient.
    - Faculty member Dmitry Abanin and postdoctoral fellow Zlatko Papić discovered that applying an electric field across the surface of two stacked sheets of graphene – a crystalline form of carbon just one atom thick – could produce "non-Abelian anyons." Such particles could be used to make qubits, the fundamental "bits" of quantum computers. Several experimental groups around the world are following up this theoretical discovery in the lab, with promising early results.
    - Perimeter Faculty members Philip Schuster and Natalia Toro are engaged in the search for dark matter, which is believed to account for the majority of all mass in the universe, even though it has never been directly detected. They proposed a novel search approach, seeking evidence for dark matter in the electron beam dumps at high energy particle accelerators.

- ✓ PI researchers won numerous national and international awards and honours, including:
    - o Faculty member Freddy Cachazo was awarded a $100,000 New Horizons in Physics Prize by the Fundamental Physics Prize Foundation, the top prize worldwide for young theoretical physicists, making Perimeter the only institution to have won two
    - o Faculty member Dmitry Abanin was awarded a Sloan Research Fellowship
    - o Associate Faculty member Roger Melko was named to the Canada Research Chair in Computational Quantum Many-Body Physics (Tier 2)
    - o Perimeter researchers were awarded four Early Researcher Awards from the province of Ontario
    - o Director Neil Turok was elected as a Fellow of the Royal Society of Canada
    - o Director Neil Turok won the 2013 Lane Anderson Award for Canadian science writing for his book, *The Universe Within: From Quantum to Cosmos*
    - o Director Neil Turok was awarded honorary doctorate degrees by Rhodes University and Nelson Mandela Metropolitan University, both in South Africa, and Saint Mary's University in Halifax

- ➢ Perimeter scientists were awarded $2.2 million in research grants

Attracting the Brightest Minds

- ✓ Recruited leading international scientists Kevin Costello and Subir Sachdev as Perimeter Research Chairs, as well as one new full-time faculty member and two associate faculty members

- ✓ Re-appointed Director Neil Turok to a second five-year term commencing October 2013 and named him the Mike and Ophelia Lazaridis Niels Bohr Chair in Theoretical Physics

- ✓ Appointed 11 eminent international scientists as Distinguished Visiting Research Chairs

- ✓ Appointed a new Academic Programs Director

- ✓ Hired 16 postdoctoral researchers in 2013/14; recruited 21 more for 2014/15

Training the Scientists of the Future

- ✓ Trained 31 students from 16 countries through the Perimeter Scholars International (PSI) master's program

- ✓ Provided advanced training to 45 PhD students in conjunction with surrounding universities

- ✓ Seven 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 844 scientists from around the world
- ✓ Partnered on eight joint workshops and conferences held at Perimeter and co-sponsored an additional 12 off-site workshops and conferences
- ✓ Presented 286 scientific talks
- ✓ Hosted 424 visiting scientists to do collaborative and individual research
- ✓ Shared the Institute's scientific events virtually with over 75,000 visitors from 171 countries
- ✓ Provided expertise and assistance to the African Institute for Mathematical Sciences – Next Einstein Initiative (AIMS-NEI)

Inspiring Through Outreach

- ✓ Reached over 1 million students through Perimeter programs and in-class resources, bringing the total to more than 4 million students to date
- ✓ Completed BrainSTEM – a FedDev Ontario-funded project which included a science festival, educator workshops, and a classroom resource – to foster 21st century STEM skills, reaching nearly 2 million people in total
- ✓ Created new classroom resources, *Our Expanding Universe* and *Career Moves: Skills for the Journey*, and launched international distribution partnerships
- ✓ Substantially and successfully expanded digital and social media communications
- ✓ Neil Turok's book, *The Universe Within: From Quantum to Cosmos,* based on his 2012 CBC Massey Lectures, was awarded the Lane Anderson Prize for outstanding popular science writing
- ✓ Hosted the 12th International Summer School for Young Physicists (ISSYP) and gave 18 Physica Phantastica presentations – reaching 5,500 students across Canada
- ✓ Delivered 90 workshops to over 2,000 educators across Canada and abroad, ultimately reaching more than 150,000 students

- ✓ Held the Equinox Summit: Learning 2030 to envision the high school of the future, and summarized findings and recommendations in the *Equinox Blueprint*

- ✓ Received major coverage in national and international media, including *Nature*, CBC, *Maclean's* magazine, BBC News, TVO, *The Globe and Mail*, *Scientific American*, *Wired*, and more

- ✓ Delivered 10 public lectures to capacity audiences on-site, and an expanding online audience through the Perimeter Public Lecture Series, presented by Sun Life Financial

Creating an Optimal Research Environment

- ✓ Continued to foster a climate of collaboration, exchange, and gender equity

- ✓ Enhanced Perimeter's website and IT systems, providing state-of-the-art computing and research resources to scientists

Growing the Public-Private Partnership

- ✓ Attracted over $5.1 million in new commitments from individuals, corporations, and foundations, including $4 million from the Krembil Foundation

- ✓ Formally launched the Emmy Noether Circle to provide focused support to women in physics

- ✓ Launched the Annual Fund and Alumni Programs, aimed at cultivating individual donors

- ✓ Worked with partners at all levels of government to provide insight and guidance on science-related public policy initiatives

- ✓ Continued to act as a catalyst for the emerging Quantum Valley ecosystem

Statement of Objectives for 2013/14

Objective 1: To deliver world-class research discoveries

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

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

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

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

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

Objective 7: To host timely, focused conferences, workshops, seminars, and courses

Objective 8: To engage in high impact outreach

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

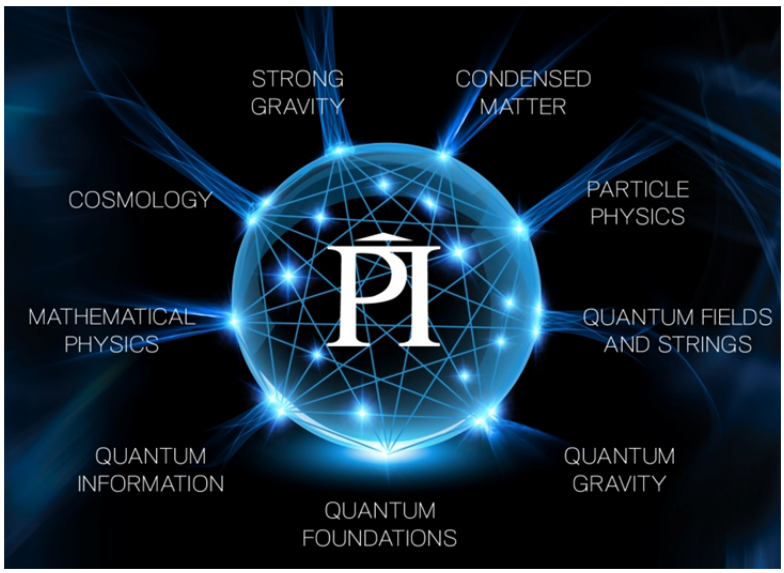
Objective 10: To continue to build on Perimeter's highly successful public-private partnership funding model

Objective 1: To deliver world-class research discoveries

Summary of Achievements

- Advanced fundamental research through 413 high calibre papers
- Since inception, PI researchers have produced 2,961 papers appearing in nearly 150 journals, which have attracted over 90,000 citations to date, attesting to the importance and long-term impact of PI research

Highlights



Research

Perimeter Institute's overriding goal is to foster breakthroughs. To that end, it prioritizes foundational research across a strategically chosen set of research fields and promotes a dynamic interchange of ideas among them.

This approach is paying off – for physics and for Canada. Objective, third party studies indicate that Perimeter scientists are doing high-quality, high-impact research, and that the Institute is contributing significantly to increasing Canada's standing in the global scientific community.[2]

[2] See, for example, "Mapping Scientific Excellence," a 2013 study which ranked Perimeter second in the world in theoretical physics, and fifth overall in physics and astronomy; and a 2011 study by Thomson Reuters ranking national citation impact in physics, which showed that Canada's scientific impact in physics has risen dramatically

This year, four Perimeter scientists were named among the "world's most influential scientific minds," in a recent study authored by Thomson Reuters: Perimeter Faculty Chair **Robert Myers**; **Subir Sachdev**, the James Clerk Maxwell Chair in Theoretical Physics at Perimeter Institute (Visiting); and Distinguished Visiting Research Chairs **Lance Dixon** and **Dam Thanh Son**.[3] The study analyzed 11 years of citation data to identify scientists whose publications ranked in the top one percent most-cited in their fields, thereby having the greatest impact on the future direction of those fields.

In science, the ultimate test of all theory is experiment; thus, it is noteworthy that Perimeter's connections to major experimental efforts throughout the world continued to increase in 2013/14. Perimeter scientists are linked to many of the world's most important experimental efforts, including the Event Horizon Telescope (EHT), the Institute for Quantum Computing (IQC) at the University of Waterloo, the Large Hadron Collider (LHC) at CERN, the Planck satellite, the Canadian Hydrogen Intensity Mapping Experiment (CHIME), the Stanford National Linear Accelerator (SLAC), the Sudbury Neutrino Observatory (SNOLAB), the Thomas Jefferson National Accelerator Facility (JLab), TRIUMF, the Wilkinson Microwave Anisotropy Probe (WMAP), and more. A list of these connections may be found in Appendix F. The Institute also hosted several conferences directly aimed at forging connections between theorists and experimentalists, including the first conference in the world on the BICEP2 gravitational wave experiment (see Objective 7).

Scientists at Perimeter pursue creative, interdisciplinary approaches to some of the most challenging problems in fundamental physics. Representative examples from 2013/14 are outlined below.

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since Perimeter's inception. In 2010, Canada ranked first in physics citation impact; without Perimeter, Canada would have ranked fourth.

[3] "The World's Most Influential Scientific Minds: 2014", Thomson Reuters, http://thomsonreuters.com/articles/2014/worlds-most-influential-scientific-minds-2014

Quantum Information

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

Keeping Qubits in Line

Building a quantum computer – one that can outstrip its classical counterparts at important information-processing tasks – is no easy task.

Harnessing and controlling quantum "bits" of information – atoms, electrons, photons or other particles – is a bit like wrangling the rambunctious singers in a children's choir. Synchronizing and conducting them is tricky, but once they lock into the desired groove, the resulting harmony can be greater than the sum of its parts.

Of course, if one or two children drop out of key or forget a line, their mistakes will be drowned out by the majority of others remaining in sync.

In quantum computation, achieving such harmony requires researchers to anticipate and account for similar hiccups – the inevitable errors that occur when dealing with such tiny, fragile bits. Like a choir recital, a quantum computation cannot be expected to go perfectly; the trick is to keep the errors in check, such that the end result is still a success.

Such is the goal of fault-tolerant quantum computation: to achieve the correct result, even when errors pop up (and add up) during the course of the computation.

Current fault-tolerant techniques involve adding extra quantum bits (qubits) for encoding – to build in redundancies. But this approach drastically increases the ultimate cost and difficulty of building a quantum computer.

Perimeter Institute Faculty member **Daniel Gottesman** has proposed a unique solution to this problem that uses only slightly more qubits than would be needed in a perfect quantum computer.

Though the protocols proposed by Gottesman are still not fully practical, they crucially demonstrate that fault-tolerant computation may not require many extra qubits. This research also demonstrates the

properties an error-correcting code should have in order to use qubits efficiently – a crucial component making quantum computers a reality.

Finding Harmony in Noise

Hector Bombin, a postdoctoral researcher at Perimeter Institute, is particularly interested in fault-tolerant techniques called topological quantum memories, which are generally considered among the most promising approaches to quantum error correction.

For quantum computers to become a practical reality, researchers will need to find ways to perform quantum operations with "noisy" (or error-prone) components and hardware. Researchers must bridge theory and experiment, translating what is mathematically possible on paper to something that can actually be built and reliably operated.

Bombin's key innovation is the introduction of a new kind of topological memory that, unlike conventional quantum error correction techniques, does not require multiple rounds of measurements to detect errors in a quantum computation.

With less time devoted to the error-detection process, fewer errors are allowed to accumulate. To revisit the metaphor of the children's choir: the conductor gets a couple of misbehavers in line quickly and launches everyone into song before the rest of the singers have a chance to get fidgety and distracted.

Quantum computing holds promise for tremendous advances in fields spanning communications, cryptography, medicine, and beyond. Unlocking that promise requires intense research, bridging theory and experiment, into the properties and potential applications of quantum information.

References:

D. Gottesman (Perimeter Institute), "Fault-Tolerant Quantum Computation with Constant Overhead," arXiv:1310.2984.

H. Bombin (Perimeter Institute), "Gauge Color Codes," arXiv:1311.0879.

H. Bombin (Perimeter Institute), "Single-shot fault tolerant quantum error correction," arXiv:1404.5504.

Mathematical Physics

In mathematical physics, new problems in physics give rise to new mathematics to solve them and new mathematics open doors to new understanding of the physical universe. Newton invented modern calculus because he needed it to understand mechanics – and calculus went on to redefine all of physics. The development of quantum theory in the 20th century both spurred and was spurred by advances in mathematical fields such as linear algebra and functional analysis. Perimeter's mathematical physics researchers continue this grand tradition.

Seeing Deeper into Quantum Gravity by Zooming Out

Understanding the interplay of quantum mechanics and gravity at short distances would a breakthrough in modern physics. However, the traditional techniques for treating fundamental forces quantum mechanically cannot be straightforwardly applied to gravity, despite their successful application to other forces, like electromagnetism or the weak force. New, innovative approaches to the problem of quantum gravity are needed.

One such approach is loop quantum gravity (LQG). This ambitious research program treats spacetime itself like a quantum mechanical system, and one of the most interesting features of the theory is that space and time are quantized. In other words, space and time are made up of discrete, fundamental building blocks. The short distance behaviour of gravity would be governed by their dynamics.

This is a compelling picture of spacetime at short distances. If it is correct, a successful, microscopic, quantum mechanical theory of spacetime should also reproduce the well-known properties of classical spacetime at long distances, which is governed by Einstein's theory of relativity. However, this is no easy task, as tracking the dynamics of each individual spacetime quantum to understand gravity over large distances would be like tracking the movement of each atom in a cup of water to understand its fluid motion; it is both inefficient and impossible!

Physicists have more effective means of treating systems with a large number of constituents, and Perimeter Faculty member **Bianca Dittrich** has been developing such techniques for loop quantum gravity. In LQG, spacetime is represented by quantum states, and Dittrich is employing coarse graining methods to extract the relevant, collective properties of many states at once. By essentially zooming out, she has better understood the set of quantum states that are allowed by the theory. This set encodes the possible solutions of the theory, providing insight into the structure of spacetime in LQG. For example, with these tools, Dittrich has uncovered a new possible vacuum state of LQG. Such a vacuum state determines important properties of the theory.

This is a large step towards a full understanding of LQG. In fact, it is expected that these results will allow researchers to understand the long-distance behaviour of LQG, and help quantum gravity researchers achieve their ultimate goal, which is to make testable predictions from this exciting theory.

Quantum Field Theory on a Sphere

Quantum field theory is the language that describes all many body interactions in nature, be it particles in a collider or materials on a laboratory bench. In some systems, the interactions between the component parts are weak, and there quantum field theory is well understood. However, many systems interact strongly, and when it comes to strongly interacting systems, quantum field theory begins to fall apart.

In other words, if quantum field theory is a language, then we're missing the words and the grammar that describe everything from the everyday workings of protons to the exotic behaviours of superconductors. It would be as if biology could describe everything except mammals. This is – obviously – a problem.

Perimeter Faculty member **Jaume Gomis** is one of the many people trying to make sense of this puzzle – looking for a new dictionary of what's technically called strongly coupled quantum field theory.

This year he's made some progress by changing the space in which he's looking. Many field theories describe the flat space in which we live: that is, a space in which a pen drawing a straight line on paper will never come back to where it started. Gomis transformed these theories into theories which describe a spherical space, where the space looks less like a piece of paper than a soccer ball.

By putting field theory on a sphere, Gomis found, he could get a better view on it. It isolates certain interesting variables mathematically, and makes certain observables better defined. (An observable is something about a system that can be measured, and which gives some insight into the system's state. Temperature, for instance, is an observable.) Specifically, Gomis discovered that by using spherical partition functions, you can compute one such observable exactly, no matter how strong the coupling is. Being able to compute something exactly at arbitrary coupling is, as Gomis notes, "very special, very rare."

So far as we know, we do not actually live on a soccer ball, and the field theory Gomis is working with not quite as complex as the one we will need to truly write a new dictionary for strongly coupled quantum field theory. But, as Gomis says, "this work helps us develop insights into what kinds of beasts might live at strong couplings."

References:

B. Dittrich (Perimeter Institute) and S. Steinhaus (Perimeter Institute), "Time evolution as refining, coarse graining and entangling," arXiv:1311.7565.

B. Dittrich (Perimeter Institute) and M. Geiller (Pennsylvania State University), "A new vacuum for Loop Quantum Gravity," arXiv:1401.6441.

B. Dittrich (Perimeter Institute), "The continuum limit of loop quantum gravity – a framework for solving the theory," arXiv:1409.1450.

E. Gerchkovitz (Weizmann Institute of Science), J. Gomis (Perimeter Institute), and Z. Komargodski (Weizmann Institute of Science), “Sphere Partition Functions and the Zamolodchikov Metric,” arXiv:1405.7271.

Cosmology

Cosmologists at Perimeter Institute seek to uncover the distant history and constituents of our universe and decode the rules that govern its origins and evolution. These researchers look for answers to some of the most enduring questions in physics, at scales and energy levels that could never be simulated in an earth-bound lab. Cosmology is intrinsically connected to other branches of research at Perimeter, including particle physics, quantum fields and strings, and strong gravity.

Understanding the Early Universe (or Universes)

It is one of the most enduring questions in science: how did the universe begin?

Cosmology is, in a sense, a kind of time travel, as researchers peer nearly 14 billion years into the past to understand the birth, infancy, and growth of our universe.

With telescopes of unprecedented precision scanning the distant reaches of the cosmos, and theorists decoding the mathematical structures of reality, these are exciting times for cosmology.

The universe does not give up its secrets easily, however, and the process of discovery requires tackling questions from many angles, collaborating, seeking repeatable results, and always remaining open to new possibilities.

Case in point: the announcement last March that the Antarctic-based BICEP2 (Background Imaging of Cosmic Extragalactic Polarization) experiment may have detected primordial gravitational waves sparked much excitement among cosmologists and the science media.

The BICEP2 result seemed to constitute a major breakthrough in cosmology – an apparent confirmation of the theory of inflation, which posits a moment of extreme expansion of the universe a tiny fraction of a second after the big bang. But some members of the cosmological community believed it was premature to declare that the BICEP2 results – the detection of "B-mode" polarization in the cosmic microwave background – were caused by gravitational waves.

Just weeks after the announcement, Perimeter Institute hosted the world's first major conference on the subject, "Implications of BICEP2."

Amid all this buzz, new collaborative research emerged attempting to interpret the BICEP2 data, its possible interpretations, and its relation to other theoretical and experimental investigations.

Perimeter researchers **Latham Boyle**, **Kendrick Smith**, and **Neil Turok** were among the co-authors of a paper that carefully analyzed the compatibility between the BICEP2 findings and previous data from the Planck satellite, and discovered a surprising statistical tension between them.

The researchers quantified the extent to which the tension may be alleviated by modifications to the current Standard Model, and propose a novel test that will be able to check the correctness of one such modification in the future.

Their paper also indicated how future experiments should shed new light on the BICEP2 results – which is precisely what happened six months later, when the Planck satellite indicated that cosmic dust, not gravitational waves, could account for some of the intriguing spacetime "ripples" that were attributed to gravitational waves in March.

A Scientific Test for the Multiverse

Such continued experimental advances, driven and interpreted by theoretical research, allow us to peer deeper into our universe's distant past.

But perhaps "our universe" does not sufficiently convey the full extent of reality. Perhaps our universe is just one bubble in a frothing sea of universes, as suggested by the increasingly prevalent multiverse hypothesis.

Proposed barely a decade ago as a consequence of what we think we know about cosmic inflation, the multiverse hypothesis has drawn criticism for being closer to metaphysics than true science. Even if other universes exist outside our own, critics say, how could we possibly know, since they are beyond the limits of our observation?

Perhaps other universes occasionally bump up against ours and leave an observable trace, suggest Perimeter researchers **Matthew Johnson** and **Luis Lehner**.

Using computer simulations, the researchers created a scenario in which another universe collides with ours, leaving a tell-tale "bruise" on the cosmic microwave background (or CMB, the earliest light in the universe).

Their paper on the subject marks the first time anyone has produced a direct, quantitative set of predictions for a collision between two inhabitant universes in the multiverse.

That is, they have moved the multiverse hypothesis from the realm of metaphysics into the domain of testable, empirical science. If we are living in just one universe of many, we may now have a way to tell.

References:

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Strong Gravity

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

Could Black Holes Have Hair?

All black holes with the same mass and spin, general relativity assures us, look exactly the same. This is true even if they are formed in entirely different ways, or made of entirely different material. The short-hand version of this is one of the odder truisms in physics: black holes have no hair.

If a hairy black hole were found, it would be proof that general relativity was incorrect.

New research from Perimeter Associate Faculty member **Avery Broderick**, Associate Postdoctoral Researcher **Tim Johannsen**, and collaborators is aimed at checking whether black holes could have hair – thereby putting general relativity to the test.

The team began by trying to decide what hairy black holes would look like. The researchers tweaked the equations of general relativity to allow for hairy black holes, and then used complex computer models to generate images of what such holes would look like. Then, they examined these images, searching for features caused by their alterations of general relativity, rather than factors such as the size, spin, or the exact process by which matter fell into the black holes.

They found that altering GR would alter the shape of the shadow cast by the event horizon.

The team compared the real image data from the black hole Sag A* with the lineup of black hole mugshots generated by their models. This allows them to put limits on how big a tweak to general relativity would be allowed by the data – how hairy black holes could possibly be.

So far, the team can rule out big effects – black holes can't have a mop of hair like Einstein's – but not small ones. The real importance of this work is that it's a proof of concept: it shows definitely that physicists can use black holes as natural experiments to test ideas about spacetime.

Turbulent Black Holes

Can gravity become turbulent? The conventional answer is "no," but new Perimeter research may have you buckling your seatbelt.

In physics, a duality is pair of theories which are mathematically equivalent, even though they appear to be describing different things using different languages. Dualities are powerful ways of generating new approaches to difficult problems and producing fresh insights into old fields. One such duality is the gravity/fluids duality, which asserts that gravitational fields can be described with the language of fluid dynamics.

The gravity/fluids duality is not new work – it's been developing over the past six years. But hidden at the heart of it is a tension. If gravity can be treated as a fluid, then what about turbulence?

The conventional wisdom is that gravity is described by a set of equations that are so different from fluid dynamics equations that there would not be turbulence under any circumstances.

This research was done by Perimeter postdoctoral fellow **Huan Yang**, Faculty member **Luis Lehner**, and CITA postdoctoral fellow Aaron Zimmerman. Lehner highlights the emerging paradox: "Either there was a problem with the duality and gravity really can't be fully captured by a fluid description, or there was a new phenomenon in gravity and turbulent gravity really can exist."

The researchers set out to find out which. Specifically, they studied non-linear perturbations of black holes. Gravitational systems are rarely analyzed at this level of detail, as the equations are fiendishly complex. But, knowing that turbulence is fundamentally non-linear, the team decided a non-linear perturbation analysis was exactly what was called for.

They were stunned when their analysis showed that spacetime around fast-spinning black holes does become turbulent. "We have gone from a serious doubt about whether gravity can ever go turbulent, to pretty high confidence that it can," says Lehner.

So if your travels take you to the vicinity of a black hole, be sure to buckle up.

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Condensed Matter

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

Dialling in on qubits

There are two kinds of particles in our three-dimensional world: fermions (such as electrons), where two identical particles can't occupy one state, and bosons (such as photons), where two identical particles actually want to occupy one state. In three dimensions, fermions are fermions and bosons are bosons, and never the twain shall meet.

But in condensed matter, there's an exception. The wonder material graphene is a crystal from of carbon that's only one atom thick. From the perspective of the particles and charges within it, graphene doesn't have three dimensions – it has two. It's effectively a tiny two-dimensional universe, and in that universe, new phenomena can occur. Fermions and bosons can meet halfway – becoming anyons, which can be anywhere in between fermions and bosons.

Perimeter postdoctoral fellow **Zlatko Papić** and Faculty member **Dmitry Abanin** are investigating the properties of graphene, looking for a particular kind of anyon called non-Abelian anyons. Non-Abelian anyons are important because they can be used in the making of qubits.

Qubits are to quantum computers what bits are to ordinary computers: both a basic unit of information and the basic piece of equipment that stores that information. A way of building stable q-bits has been urgently sought for a decade.

Papić and Abanin hope that the strange properties of graphene's pocket universe may allow non-Abelian anyons, and thus qubits, to emerge. Specifically, they investigated what happens when two sheets of graphene laid one on top of another and the resultant bilayer graphene is placed in a strong perpendicular magnetic field. They discovered that applying an electric field across the surface of bilayer graphene, one can tune the material to – in theory – produce non-Abelian anyons.

Three experimental groups are now following up on the work, using this unique experimental knob to dial in on qubits. Early results seem promising. With Abanin and Papić's knob, we are tuning up, perhaps, for a new world of quantum computers.

Waiter, there's a black hole in my condensed matter …

Subir Sachdev (the James Clerk Maxwell Chair in Theoretical Physics at Perimeter Institute), **William Witczak-Krempa** (a Perimeter postdoctoral fellow), and Erik Sørensen (a faculty member at McMaster University) are condensed matter physicists. They study exotic but tangible systems, such as superfluids. And their latest paper about one such system has a black hole in it.

Black holes are a fairly exotic ingredient in condensed matter papers. Normally, condensed matter physicists add a far more conventional (though still imaginary) ingredient to their models: something called "quasiparticles." Using the quasi-particle approach, physicists describe the behaviour of materials as if electrons or other particles were moving freely around inside them. But there have always been a handful of systems which can't be described by quasi-particles – and the broad problem modelling them has been stumping condensed matter physicists for decades.

So Witczak-Krempa and Sachdev decided to try something new. They studied one of the simplest no-quasiparticles systems, a quantum phase transition between a superfluid and an insulator. They used one of the basic tools of string theory – holography – to turn that quantum field theory which describes that system into a theory of gravity with one extra dimension.

To study the system at a temperature other than zero, they had to add a black hole.

Witczak-Krempa admits it's unorthodox. "Most condensed matter people would go: 'Why is there a black hole in this paper?' It's crazy. But what's even crazier is that this mathematical machinery works quite well. It gives you answers that make a lot of sense."

Witczak-Krempa and Sachdev were able to compare their string-theory-flavoured results with the results of a more traditional simulation of the system carried out by Sørensen. It's the first time results from a traditional large-scale condensed matter simulation have been compared to results from the new string theory approach.

The proof of the pudding: The two results matched.

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Z. Papić (Perimeter Institute and Institute for Quantum Computing) and D.A. Abanin (Perimeter Institute and Institute for Quantum Computing), "Topological Phases in the Zeroth Landau Level of Bilayer Graphene," *Phys. Rev. Lett.* 112, 046602 (2014), arXiv:1307.2909.

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Particle Physics

Particle physics is the science which identifies nature's constituents and interactions at the most fundamental level, with an emphasis on comparing theoretical ideas with both terrestrial experiments and astrophysical observations. This mandate gives it a strong overlap with string theory, quantum gravity, and cosmology. Particle physicists at Perimeter identify how cosmological observations and experiments at Earth-based accelerators and underground laboratories constrain the theoretical possibilities for physics beyond the Standard Model.

Seeking Nature's Hidden Building Blocks

The Standard Model of particle physics is the master theory that describes all the elementary particles and their interactions. Since being finalized in the 1970s, the Standard Model has had huge success in predicting the results of particle physics experiments, culminating last year with the discovery of the Higgs boson, the last of the 17 particles predicted by the model to be observed.

But though the Standard Model is widely celebrated as "the theory of (almost) everything," that "almost" is important. The model does not account for gravity, dark matter, or dark energy, among other things. Physicists are therefore eager to find any cracks in the model to be filled with new discoveries. This past year, the LHC experiment at CERN observed what may be such a crack when the rate at which they measured semileptonic decays of B-mesons differed slightly from the rate predicted by the Standard Model.

Perimeter researchers **Itay Yavin** and **Maxim Pospelov**, with collaborators, have demonstrated that this deviation may be the result of a new force acting on the muon and tau leptons, and the muon and tau neutrinos. If this deviation is indeed the sign of new physics beyond the Standard Model, this explanation is perhaps the most natural. The researchers were able to identify additional rare decays where this new force should make itself known. The tests proposed include measurements of the properties of muon and tau leptons.

Also, importantly, the new force will contribute to the process of muon pair-production by muon neutrinos, which is an extremely rare process first observed 25 years ago at CERN and Fermilab.

The work on fully exploring this piece of long-forgotten experimental data, as well as on prospects of detecting this process again in the upcoming neutrino experiments is ongoing at Perimeter, and has led to follow-up work published in *Physical Review Letters*.

Dark Matter in the Dumps?

Two other Perimeter researchers, **Philip Schuster** and **Natalia Toro**, are engaged in the search for the most pervasive, yet most elusive, stuff of the universe. Dark matter is generally believed to account for

the majority of all mass in the universe, even though it has never been directly detected or measured (it neither emits nor absorbs light, hence the name).

Finding it, argue Schuster and Toro, might require looking where particles typically go to die: an electron beam dump.

Particle accelerator experiments blast billions of energetic electrons at focused points in order to measure and interpret the ensuing subatomic shrapnel. All of that energy needs to be safely diffused after the experiment, so it is shunted off to a dump – a dense block of metal that absorbs most of the particles and tamps down the energy they carry.

It's possible, Schuster and Toro argue, that some unusual particles interact so weakly with others that they might just zip through the dump and be detected on the other side. If so, such particles could be candidates for dark matter.

A beam dump is an ideal place to search for dark matter, they argue, because there is very little background "noise" (such as the typical bombardment of cosmic radiation), thanks to its shielded, underground location.

The researchers are working closely with collaborators at particle accelerator facilities to implement the proposed experiment (and they have already demonstrated the feasibility of such an experiment at the Stanford Linear Accelerator, or SLAC).

Although it's quite possible such an experiment will find no dark matter (the experiment would only detect lightweight, weakly interacting particles), it will regardless clarify our understanding of nature's building blocks.

"The results will fit into a larger story – the patchwork of our understanding," says Toro.

References:

W. Altmannshofer (Perimeter Institute), S. Gori (Perimeter Institute), M. Pospelov (Perimeter Institute), and I. Yavin (Perimeter Institute), "Dressing $L_\mu - L_\tau$ in Color," arXiv:1403.1269.

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Quantum Fields and Strings

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

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

A Bridge Between Strings and Fields

What happens when two or more particles meet?

It's perhaps the most fundamental question in particle physics. To answer it, physicists calculate what are technically known as scattering amplitudes, which give the probability for each possible outcome.

Historically, calculating scattering amplitudes has been cumbersome, requiring researchers to take into account every possible result of an interaction individually and add together all those possibilities, to make even the simplest prediction. In many cases, the complexity of these calculations made them impossible.

Fortunately, the last decade has seen dramatic progress – much of it based at Perimeter – in the way scattering amplitudes are understood and calculated. This is particularly true of the scattering of massless "force-carrying" particles, such as photons, gluons, and gravitons, moving in our familiar four-dimensional (three dimensions plus time) space.

Perimeter Faculty member **Freddy Cachazo**, postdoctoral fellow **Song He**, and PhD student **Ellis Yuan** wondered if the new methods of calculating scattering amplitudes had to stop at four dimensions. They embarked on a program of research to examine whether the new techniques can be applied to the scattering of particles in other kinds of spaces.

The researchers found that the new understandings of scattering can indeed be extended to higher dimensions. They wrote a very compact formula for the scattering of massless scalars, gluons, and gravitons, which is valid in any number of dimensions. This includes the 10- and 11-dimensional spaces often described by string theory.

The new formula builds some surprising bridges between the string theory and more work-a-day quantum field theory. It even implies existence of a string-theory-like description of pure quantum field theory.

This is exciting new work at the foundation of mathematical physics. It has inspired 42 follow-up papers so far, leading to advances in quantum field theory, string theory, and even pure mathematics.

Kicking a Quantum Clock

Systems that are far from equilibrium are difficult to understand. For instance, consider clocks. Describing the way the pendulum swings in a ticking clock is fairly easy. Describing the pendulum swing of a stopped clock, easier still. But what if you kicked the clock? Could you then predict the swing of the pendulum as the clock wobbled and toppled and crashed to the floor?

The kicked clock embodies the challenge of studying systems far from equilibrium. Suffice it to say, it's hard. Add a quantum twist to it, and it's harder still. Physicists have made some progress, but are still searching for broadly applicable theoretical techniques – or, ideally, a set of universal principles – for describing far-from-equilibrium systems. Now it appears that Perimeter researchers may have found one such principle.

Perimeter Faculty member **Robert Myers**, Associate Faculty member **Alex Buchel**, and PhD student **Anton van Neikerk** decided to look at far-from-equilibrium systems through the one of the lenses of string theory, technically known as the AdS/CFT correspondence. AdS/CFT says some quantum field theories – which would usually be the go-to language in which quantum systems are described – can instead be translated into a very different language: a language of gravity.

Specifically, AdS/CFT shows that a quantum system falling toward equilibrium can also be described as a hollow shell of energy collapsing to form a black hole. That sounds like an unnecessary complication, but it actually makes the system easier to describe mathematically.

At first using this black-hole approach, the researchers were able calculate how much energy is added to the system after it is given a (mathematical) kick of various strengths. Even better, the researchers – this time including Myers, Sumit Das, and Perimeter PhD student **Damian Galante** – were able to generalize this result. They extracted from the string theory approach one simple behaviour of a system falling toward equilibrium, which holds true for a broad class of systems.

The researchers published papers on this topic in *Physical Review Letters* in 2013/14, and work is ongoing.

References:

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Quantum Gravity

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

The Pull to Unification

Much like our everyday experience of gravity itself, the field of quantum gravity tends to pull things together.

Think of how gravity unites two very different things – your feet and planet Earth, for instance – in a way that seems completely natural, even if you don't fully understand the forces at play.

Quantum gravity research also aims to unify disparate things: the theory of the extraordinarily small (quantum mechanics) with the theory of the extraordinarily massive (general relativity). The missing puzzle piece in our understanding of nature lies between these fields, in the realm of things that are very heavy yet very small (such as black holes or the big bang singularity). This is the realm of quantum gravity research.

Because the phenomena under consideration are so foreign to our everyday experience – and so difficult to measure experimentally – a wide range of theoretical research is under way in hopes of sharpening our understanding of the field.

Perimeter Faculty member **Laurent Freidel**, for example, has recently conducted research that makes a major advance on an old topic – namely, the relationship between gravity and thermodynamics suggested by Stephen Hawking's discovery that black holes are hot.

The possibility of a deep link between gravity, quantum physics, and thermodynamics has been a subject of much interest since the 1970s. Freidel's work extends the correspondence in two important ways: first, to situations that are out of thermodynamic equilibrium (previous studies treat black holes as being in equilibrium), and second, it demonstrates that the correspondence extends to general spacetimes.

Freidel's innovative approach was to posit a screen – a kind of membrane stretched through spacetime – to show that, as spacetime evolves in time (according to Einstein's equations) the matter in the membrane obeys the laws of non-equilibrium thermodynamics.

How Time Flies

Whereas Freidel's work looks at processes that unfold over time, Perimeter postdoctoral researcher **Flavio Mercati** has recently tackled the question of why time itself unfolds the way it does.

Mercati, with collaborators Julian Barbour and Tim Koslowski, posited a new explanation of the so-called "arrow of time," which describes the universal progression from past through present to future.

Exactly *why* time should fly straight ahead like an arrow has been the subject of much investigation and debate. The arrow of time is often explained by the so-called "past hypothesis," which presumes that the universe began with a very special low-entropy state – a tidy scenario in which the baby universe was neatly ordered before getting progressively messier.

But observations suggest that our universe actually started quite messily (a "plasma soup" close to thermal equilibrium), then evolved into the beautifully ordered structures we now see, such as galaxies and solar systems.

Mercati and co-authors argue that a more tenable explanation of the arrow of time is, therefore, based on complexity.

The model Mercati and collaborators studied exhibits an irreversible growth of complexity in all its solutions, which implies that the flow of time streams necessarily from past to future.

Research programs like Freidel's and Mercati's are crucial components in a multi-faceted approach to quantum gravity – bridging once-disparate fields and ideas – in the search for a cohesive, unified understanding of our universe on the tiniest and grandest scales.

References:

L. Freidel (Perimeter Institute), "Gravitational Energy, Local Holography and Non-equilibrium Thermodynamics," arXiv:1312.1538.

"A Gravitational Origin of the Arrows of Time," J. Barbour (College Farm and University of Oxford), T. Koslowski (University of New Brunswick), and F. Mercati (Perimeter Institute), arXiv:1310.5167.

Quantum Foundations

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

Extending Noether's Theorem

Noether's theorem is one of the best known and most powerful mathematical tools in physics, showing that every symmetry in the laws of motion implies a conservation law. For instance, the fact that physical laws do not change over time implies conservation of energy, and that they are the same everywhere implies conservation of momentum.

Noether's theorem is important not only because of the insight it gives into conservation laws, but also as a practical calculation tool. It is widely used, for instance, when the evolution of a system is too complicated to solve exactly, or some of the details of the dynamics are unknown. In these cases, it allows researchers to use the symmetries of the dynamics to still derive strong constraints on the system's evolution despite these limitations.

Despite its widespread use, however, Noether's theorem is deficient in two respects. First, it applies only to systems that are not interacting with their environments. Second, even in the case of isolated systems, it does not capture all of the consequences of symmetries.

In a recent paper, Perimeter Faculty member **Robert Spekkens** and graduate student Iman Marvian extend Noether's theorem. They derive measures of the extent to which a quantum state breaks a given symmetry and demonstrate that such measures are non-increasing under laws of motion respecting that symmetry, even if the system interacts with its environment. In the case of isolated systems, this yields new conservation laws.

This result is of immediate interest to physicists, but also has many practical applications in emerging quantum technologies. It can, for instance, be used in measuring quantum coherence, deriving model-independent bounds on the performance of quantum amplifiers, and assessing quantum schemes for achieving high-precision standards.

The authors' work in deriving various interesting measures of asymmetry is based on ideas from quantum information theory. This is an outstanding example of the value of supporting quantum information theory within a broader framework of theoretical physics research, as Perimeter Institute has done since inception.

The Whys of Quantum Mechanics

Quantum mechanics works. The trouble is that no one knows *why* it works. Contrast this with special relativity, which is built up from just two fundamental principles about the nature of physical laws and the speed of light. If quantum mechanics does have such fundamental principles underlying it, we don't yet know what they are.

This becomes a problem when physicists try to extend or generalize quantum theory beyond quantum mechanics. Since we don't have the underlying principles of quantum mechanics, we also don't know which parts of it are fundamental, and which parts are artifacts of the way we've constructed the story. When we strike out from the known in quantum theory, it's not clear what direction we should take.

Perimeter postdoctoral researcher **Ryszard Kostecki** is hoping to find that direction, and ultimately derive the structure unifying quantum mechanics and nonperturbative quantum field theory from conceptually meaningful principles of information theory.

In this recent work, Kostecki investigated a connection between how quantum states change when you make measurements, and how probability measures change when you gain knowledge. More technically, he reconsidered the idea that Lüders' rule, central to quantum mechanics, is the analog of Bayes' rule, central to probability theory.

In recent decades, researchers have discovered that Bayes' rule can be derived as a special case of a more general, and information theoretic, principle. Called the constrained maximization of relative entropy, it states that, when we learn something new, our new state of knowledge should agree with this information, while being maximally noncommittal to everything else.

So, Bayes' rule has an underlying principle: maximum entropy. Kostecki and his collaborators proved that Lüders' rule can also be derived from this principle. This turns the conceptual analogy between Bayes' rule and Lüders' rule to an exact mathematical property: they are two cases of a single unifying principle. The next step is to investigate other special cases of this principle, as potential new forms of quantum information dynamics.

The attempt to build quantum theory from the ground up, on the model of probability theory, is a very large project. But any success Kostecki and his colleagues have would also have a very large payoff: making quantum theory mathematically more general and conceptually clearer.

References:

I. Marvian (Perimeter Institute, Institute for Quantum Computing, and Center for Quantum Information Science and Technology, University of Southern California) and R.W. Spekkens (Perimeter Institute), "Extending Noether's theorem by quantifying the asymmetry of quantum states," *Nature Comm.* 5, 3821 (2014), arXiv:1404.3236.

F. Hellman (Albert Einstein Institute and Potsdam Institute for Climate Impact Research), W. Kamiński (Perimeter Institute and Institute for Theoretical Physics at the University of Warsaw), and R.P. Kostecki (Perimeter Institute), “Quantum collapse rules from the maximum relative entropy principle,” arXiv:1407.7766.

Honours, Awards, and Major Grants

- Faculty member Freddy Cachazo was awarded a $100,000 New Horizons in Physics Prize by the Fundamental Physics Prize Foundation.

- Faculty member Dmitry Abanin received a $50,000 2014 Sloan Research Fellowship.

- Faculty member Guifre Vidal received an $835,000 Simons Foundation Grant as part of the Tensor Network Group within the "Simons Collaboration on the Many Electron Problem."

- Founder and Board Chair Mike Lazaridis was elected as a Fellow of the Royal Society (UK).

- Director Neil Turok was elected as a Fellow of the Royal Society of Canada.

- Director Neil Turok won the 2013 Lane Anderson Award for Canadian science writing for his book, *The Universe Within: From Quantum to Cosmos*.

- Director Neil Turok was awarded honorary doctorate degrees by Rhodes University and Nelson Mandela Metropolitan University, both in South Africa, and Saint Mary's University in Halifax.

- Associate Faculty member Roger Melko was named to the Canada Research Chair in Computational Quantum Many-Body Physics (Tier 2).

- Faculty member Guifre Vidal and Associate Faculty member Roger Melko received a $454,000 grant from the John Templeton Foundation for their project, "Simulating Emergence in Quantum Matter."

- Xiao-Gang Wen, the BMO Financial Group Isaac Newton Chair in Theoretical Physics, obtained a grant of $452,000 from the John Templeton Foundation for his project, "Emergence of elementary particles and fundamental laws from quantum entanglements."

- Distinguished Visiting Research Chairs Leon Balents, Joel Moore, Senthil Todadri, and Ashvin Vishwanath were elected Fellows of the American Physical Society.

- Templeton Frontiers Fellow Flavio Mercati received a $140,000 grant from the Foundational Questions Institute (FQXi) for his project, "Information, Complexity, and the Arrow of Time in Shape Dynamics." Other FQXi grant recipients with Perimeter connections included Distinguished Visiting Research Chairs Adrian Kent ($72,500) and Patrick Hayden ($127,000), and Visiting Fellows Giulio Chiribella ($48,000) and Jonathan Barrett ($120,000).

- Templeton Frontiers Postdoctoral Fellow Flavio Mercati was a fourth prize winner in the Foundational Questions Institute (FQXi) essay contest.

- Then-Postdoctoral Researcher Eugenio Bianchi received the inaugural Bronstein Prize "for his insightful contributions to black hole entropy, the discrete geometry of quantum spacetime and the propagation of gravitons thereon, and for his inspiring enthusiasm and collaborative spirit."

- Visiting Fellow David Skinner received a 2013 "Best Paper Prize" from the *Journal of Physics A* for his paper, "Amplitudes at weak coupling as polytopes in AdS_5."

- Associate Graduate Student Lauren Hayward was named one of "Canada's future leaders of 2014" by *Maclean's* magazine.

- Four Perimeter researchers were awarded Early Researcher Awards worth $140,000 each by the Province of Ontario:
    - Krembil Galileo Galilei Chair in Theoretical Physics Davide Gaiotto
    - Faculty member Dmitry Abanin
    - Faculty member Bianca Dittrich
    - Faculty member Natalia Toro

- Perimeter scientists were awarded NSERC Discovery Grants totalling $790,000 (over five-year terms), as follows:
    - Faculty member Jaume Gomis: $300,000 ($60,000/year over five years)
    - Faculty member Robert Myers: $350,000 ($70,000/year over five years)
    - Faculty member Kendrick Smith: $140,000 ($28,000/year over five years)

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

Summary of Achievements

- Re-appointed Neil Turok to a second five-year term as Director
- Recruited Kevin Costello and Subir Sachdev as the fourth and fifth Perimeter Research Chairs
- Appointed Asimina Arvanitaki as a full-time faculty member, bringing the total to 22
- Jointly appointed Raffi Budakian and James Forrest as associate faculty members, bringing the total to 14
- Appointed Zhengcheng Gu as the inaugural Director's Fellow

Highlights

Director Re-appointed

Since his arrival from the University of Cambridge in 2008, Neil Turok has led the Institute's strategic growth and development, helping Perimeter increase rapidly in both size and international stature. Highlights of his first term included numerous recruitment successes,[4] the establishment of the Distinguished Visiting Research Chairs program, the creation of the Perimeter Scholars International (PSI) master's program, and the arrival of the first Perimeter Research Chairs, Xiao-Gang Wen and Davide Gaiotto. In October 2013, Turok began a second five-year term as Perimeter director, following unanimous support for renewal from the Institute's Board of Directors.

Perimeter Research Chairs

The Perimeter Research Chairs program was designed to attract world-leading scientists in strategically chosen fields to Perimeter's faculty. The Institute targets researchers in the most productive phases of their careers to act at the nuclei of "powerhouse" research groups, supporting them with the necessary resources to make rapid progress on key problems.

Already, this approach has paid dividends. The recruitment of Xiao-Gang Wen, the BMO Financial Group Isaac Newton Chair in Theoretical Physics, was an important factor in attracting Dmitry Abanin, Raffi Budakian, Sung-Sik Lee, Roger Melko, and Guifre Vidal to Perimeter's faculty. In only a couple years, the Institute has become one of the top international destinations for condensed matter researchers.

The Perimeter Research Chairs are envisioned as the most prestigious chairs in theoretical physics in the world, each named for a legendary scientist whose insights helped define modern physics. Each

[4] Since Turok's arrival, Perimeter has recruited 15 new faculty and nine associate faculty.

recruitment success constitutes a major talent gain for Canada. Over the past year, Perimeter exceeded its goals for the program, demonstrating the traction it has already gained in the wider physics community.

In November 2013, Perimeter partnered with the Krembil Foundation to create two new endowed chairs: the Krembil Galileo Galilei Chair in Theoretical Physics and the Krembil William Rowan Hamilton Chair in Theoretical Physics.

Davide Gaiotto, widely regarded as the leading young quantum field theorist worldwide, is the inaugural Galileo Chair. Perimeter has recruited Kevin Costello, one of the world's best young mathematicians, for the Hamilton Chair; he will arrive from Northwestern University in August 2014 and lead Perimeter's expansion into mathematics and mathematical physics.

Lastly, in February 2014, Perimeter appointed Subir Sachdev as the James Clerk Maxwell Chair in Theoretical Physics, on a visiting basis. He is the fifth Perimeter Research Chair, joining Wen, Gaiotto, Costello, and Turok.

New Perimeter Research Chair Recruits in 2013/14:

Kevin Costello (PhD University of Cambridge, 2003) will join the Institute in August 2014 from Northwestern University, where he has been a faculty member since 2006. He will be the inaugural Krembil Foundation 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 recently authored *Renormalization and Effective Field Theory*, a pathbreaking 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.

Subir Sachdev (PhD Harvard University, 1985) became the James Clerk Maxwell Chair in Theoretical Physics at Perimeter Institute in February 2014 (on a visiting basis). 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.

Faculty

Perimeter's full-time faculty is comprised of eminent senior scientists and leading young researchers from across the spectrum of theoretical physics. In addition to its recruitment successes with the Perimeter Research Chairs, the Institute appointed an outstanding new faculty member, Asimina Arvanitaki, in March 2014. This brings Perimeter's faculty to 22, in line with targeted objectives.

New Faculty Appointment in 2013/14:

Asimina Arvanitaki (PhD Stanford University, 2008) joined Perimeter's faculty in March 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. She pioneered the use of optically levitated dielectric objects to detect gravitational waves. Arvanitaki also works on theoretical challenges raised by experimental results, such as a model of particle physics influenced by string theory called "split SUSY."

Associate Faculty

Through its associate faculty program, Perimeter seeks to attract and retain top scientific talent through joint appointments with Canadian university partners. Associate faculty spend up to 50 percent of their time at Perimeter, in addition to teaching and conducting research at the partner university.

The program has succeeded in bringing highly respected international scientists to Canada by highlighting the unique opportunities afforded by both Perimeter and its partner institutes.[5] Each such recruitment success further enhances the country's growing strength in fundamental physics, while also making both Perimeter and its institutional partners more attractive destinations for outstanding junior faculty, postdoctoral researchers, and graduate students.

In 2013/14, in line with targeted objectives, Perimeter appointed two new associate faculty members, Raffi Budakian (with the Institute for Quantum Computing at the University of Waterloo) and James Forrest (also at the University of Waterloo), both condensed matter physicists. The Institute now has 14 associate faculty.[6] In addition, a search was conducted for a joint hire with the University of Toronto's Department of Mathematics, which would mark Perimeter's first joint appointment with Toronto, one of the country's most prestigious universities. The Institute expects to make a hire in 2014/15.

[5] In recent years, Perimeter has succeeded in attracting a number of top researchers from established faculty positions in the US, including Luis Lehner (Louisiana State University), David Cory (Massachusetts Institute of Technology), and, most recently, Raffi Budakian (University of Illinois at Urbana-Champaign).

[6] Associate faculty are appointed for fixed terms ranging from three to seven years. No associate faculty members completed their terms in 2013/14.

New Associate Faculty Appointments in 2013/14:

Raffi Budakian (PhD University of California, Los Angeles, 2000) joined Perimeter in June 2014, jointly appointed with the Institute for Quantum Computing at the University of Waterloo, where he holds the Nanotechnology (WIN) Endowed Chair in Superconductivity. Budakian comes to Waterloo from the University of Illinois at Urbana-Champaign. Prior to joining the faculty there, he held research positions at the University of California, Los Angeles, and the IBM Almaden Research Center in San Jose. Budakian 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.

James Forrest (PhD University of Guelph, 1994) joined Perimeter in February 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.

Director's Fellow

The Director's Fellowship is a new position that supports 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. Zhengcheng Gu joined Perimeter as the inaugural Director's Fellow in October 2013.

Zhengcheng Gu (PhD Center for Advanced Study, Tsinghua University (CASTU), 2007) arrived at Perimeter in the fall of 2013 following a one-year visit to the California Institute of Technology (Caltech). Prior to that, he held postdoctoral fellowships at the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara, and the Massachusetts Institute of Technology (MIT). Gu's research area is the theoretical study of topological phases in strongly correlated quantum systems. He has developed new analytical and numerical methods to explore and understand the emergence of topological phases in strongly correlated quantum systems. He is also interested in the experimental realization of topological phases in cold atom and solid state systems. Recently, Gu applied the concept of topology to high energy physics and quantum gravity.

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

Summary of Achievements

- Hired 16 postdoctoral researchers in 2013/14 and recruited 21 more for 2014/15
- Seven departing postdoctoral researchers obtained tenure-track faculty positions
- Appointed James Forrest as the new Academic Programs Director
- Successfully ran fifth year of the Perimeter Scholars International (PSI) master's program for 31 students
- Provided ongoing training for 42 PhD students
- Brought 24 Visiting Graduate Fellows to the Institute
- Provided research training to eight undergraduate students

Highlights

Postdoctoral Researchers

In 2013/14, Perimeter appointed 16 postdoctoral researchers and recruited an additional 21 for 2014/15, exceeding targeted outcomes. Perimeter received 735 applications for its 2014/15 postdoctoral fellowships, the largest applicant pool in its history, attesting to the Institute's international reputation.

Perimeter is known internationally for its exceptionally supportive and stimulating environment, in which postdocs have full research independence and are encouraged to pursue novel, ambitious lines of research. The Institute offers collaboration opportunities second to none through numerous strategic partnerships, including agreements with observational and experimental centres like TRIUMF, CERN, and the Institute for Quantum Computing at the University of Waterloo (see Objective 6). Perimeter also leverages its partnerships to offer joint postdoctoral positions to some top candidates.[7]

Training at Perimeter pays off. In 2013/14, despite an academic market that remains extremely competitive worldwide, seven departing postdoctoral researchers obtained tenure-track faculty positions: Eugenio Bianchi (Pennsylvania State University), Valentin Bonzom (University of Paris 13), Nikolay Bobev (Institute of Theoretical Physics at Katholieke Universite Leuven), Alioscia Hamma (Tsinghua University), Chad Hanna (Pennsylvania State University), Chris Laumann (University of Washington), and Amit Sever (Princeton University). Several other departing postdocs obtained prestigious positions in academia and industry.[8]

[7] In 2013/14, Perimeter offered three such positions, all joint with the Institute for Quantum Computing at the University of Waterloo.

[8] For example, Ajay Singh became a Risk Manager at Polar Securities in Toronto.

New Academic Programs Director

After more than five years running Perimeter's Academic Programs department, John Berlinsky departed in June 2014 to take on a new position as Deputy Director of the Kavli Institute for Theoretical Physics in Santa Barbara, California. Perimeter appointed James Forrest as its new Academic Programs Director in February 2014, allowing for a five-month hand-off period.

Forrest is a distinguished soft condensed matter physicist whose appointment is expected to strengthen ties with a crucial academic partner. While retaining his position at the University of Waterloo, he will oversee Perimeter's PSI master's program, PhD program, Visiting Graduate Fellows, and undergraduate program. He comes to Perimeter with a wealth of experience in graduate education, including four years as the Director of the Guelph-Waterloo Physics Institute and two years as the Associate Dean of Research in the Faculty of Science at the University of Waterloo. Forrest was also appointed as an associate faculty member (see Objective 2).

Perimeter Scholars International (PSI) Master's Program

- In 2013/14, the PSI program trained 31 students, nine of them women, from 17 countries

Perimeter Scholars International (PSI) is a master's level program that attracts highly talented university graduates from around the world, bringing them to the cutting edge of theoretical physics in one academic year. The innovative curriculum features three-week course modules taught by some of the world's top lecturers.[9] Six postdoctoral-level PSI Fellows and several graduate teaching assistants provide students with tutorial support throughout the year. Upon completion of the program, students receive a master's degree from the University of Waterloo.

PSI brings graduates with high scientific potential to Canada, and Perimeter selects the best among them for continued doctoral training. Eleven students – approximately 35 percent of the 2013/14 class – are remaining in Canada to pursue their doctoral studies, eight of them at Perimeter. Many others will be pursuing their PhD studies at top international institutions, including the University of Cambridge, Princeton University, Harvard University, and Stanford University.

The PSI program also strengthens Perimeter's ties with its regional partners, with faculty from nearby universities participating in teaching and research project supervision. This year, all PSI classes were also made available to non-Perimeter graduate students who obtained special permission, thereby enriching graduate course offerings throughout the region.[10]

[9] In 2013/14, the PSI faculty comprised 13 Perimeter faculty members, one Perimeter postdoctoral researcher, and nine other international scientists.

[10] In 2013/14, 18 students from surrounding universities enrolled in PSI courses.

The PSI program continues to grow in prestige, competitiveness, and reach. For the upcoming 2014/15 class, Perimeter received 366 applications from 63 countries, up five percent over last year.[11]

PhD Students

- 42 PhD students were in residence at Perimeter in 2013/14
- Three PhD students graduated and all obtained competitive postdoctoral fellowships

The PhD program continues to grow as planned, in part because the Institute recruits top PSI graduates for continued studies with Perimeter faculty. At year's end, Perimeter had 42 students in residence, 25 of whom had received their master's degree through the PSI program. In addition, six students were supervised by Perimeter associate faculty while in residence at our partner universities.

Since Perimeter is not a degree-granting institution, the PhD program brings top students not only to Perimeter, but also to the partner universities from which they receive their degrees, constituting a significant talent gain for Canada.

Three PhD students supervised by Perimeter faculty graduated from partner universities in 2013/14 and all obtained competitive postdoctoral fellowships.

Visiting Graduate Fellows

- Perimeter hosted 24 Visiting Graduate Fellows for a total of 26 visits in 2013/14

The Visiting Graduate Fellows program brings advanced PhD students from around the world to spend several months at the Institute, enabling them to join Perimeter's research community and interact with leading researchers at a pivotal time in their research training. Now in its third year, the program met its targeted outcome of maintaining three to four Visiting Graduate Fellows in residence at any given time.

Undergraduate Students

- Perimeter provided research training to eight exceptional undergraduates from top institutions

The Undergraduate Student program exposes promising undergraduates to high-level research through two- to four-month projects, while giving Perimeter's postdoctoral researchers valuable mentoring experience. The program also acts as a means of attracting talent to the Institute – its alumni include PSI student Emily Adlam, PhD Student Dalimil Mazac, and postdoctoral researcher Matteo Smerlak.

[11] 30 students from 16 countries have been accepted for the 2014/15 class, including six women.

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

Summary of Achievements

- Appointed 11 leading scientists as Distinguished Visiting Research Chairs and renewed five more, bringing the total to 42
- Appointed five accomplished researchers as Visiting Fellows and renewed four more, bringing the total to 14
- Welcomed two early-career researchers as the inaugural Emmy Noether Fellows and recruited five more
- Hosted 424 visiting scientists for a total of 465 visits

Highlights

Distinguished Visiting Research Chairs

- Appointed 11 new DVRCs and renewed five more,[12] bringing the total to 42
- 30 DVRCs made a total of 46 visits in 2013/14

Perimeter's unique Distinguished Visiting Research Chairs (DVRC) program has developed into one of the Institute's most successful – a strategic and cost-effective means of bringing world-leading scientists to Perimeter for extended periods. DVRCs are appointed to renewable terms of three to four years, while retaining permanent positions at their home institutions.

Perimeter's DVRCs – including such luminaries as Stephen Hawking, Yakir Aharonov, Renate Loll, and Paul Steinhardt – collectively span an enormous range of expertise (see Appendix B: Distinguished Visiting Research Chairs). They visit Perimeter for extended periods to do research, collaborate, and participate in all facets of life at the Institute. S. James Gates Jr., for example, gave a very well received talk to end Perimeter's 2013/14 Public Lecture Series.

For DVRCs, time spent at Perimeter is highly productive, since they are free from their usual administrative and teaching duties. In turn, their presence as conference participants, seminar and colloquia speakers, PSI lecturers, and collaborators greatly enhances Perimeter's research environment and inspires its resident community.

With 42 DVRCs by the end of 2013/14, Perimeter has now exceeded its steady state goal for the program, and the DVRC community is as active as ever, having collectively made 46 visits over the past

[12] James Bardeen, Ganapathy Baskaran, Frans Pretorius, Gerard 't Hooft, and Senthil Todadri all renewed their terms through 2017.

year. Four of the new DVRCs are women, demonstrating the Institute's commitment to combatting the field's traditional gender imbalance at even the highest levels of achievement.

New Distinguished Visiting Research Chair Appointments in 2013/14:

Abhay Ashtekar (PhD University of Chicago, 1974) 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, and a Fellow of both the American Physical Society and the 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 (PhD Harvard University, 1994) 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.

Patrick Brady (PhD University of Alberta, 1994) 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 (PhD University of Pisa, 1996) is a Professor of Physics at the University of Maryland, College Park, and she will begin a new appointment in September 2014 as Director of the Astrophysical and Cosmological Relativity division of the Max Planck Institute for Gravitational Physics (Albert Einstein Institute) in Potsdam, Germany. She is also a member of the Maryland Center for Fundamental Physics, the Joint Space-Science Institute, and the LIGO Scientific Collaboration. 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.

Savas Dimopoulos (PhD University of Chicago, 1978) 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 (PhD Princeton University, 1986) is a theoretical particle physicist and a Professor at Stanford University. He has made groundbreaking 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.

Gabriela González (PhD Syracuse University, 1995) is a Professor of Physics and Astronomy at Louisiana State University and is 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 Penn State University before joining LSU in 2001. In 2007, she was awarded the Edward A. Bouchet Award by the American Physical Society.

Shamit Kachru (PhD Princeton University, 1994) 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.

Matilde Marcolli (PhD University of Chicago, 1997) 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 (PhD Massachusetts Institute of Technology, 2001) 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.

Barbara Terhal (PhD University of Amsterdam, 1999) 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 (CIFAR).

Visiting Fellows

- Appointed five new Visiting Fellows and renewed four more, bringing the total to 14
- Eight Visiting Fellows made a total of nine visits in 2013/14

The Visiting Fellows program is an important means of bringing accomplished researchers to Perimeter on a regular basis. Much like DVRCs, Visiting Fellows span a wide range of expertise, are appointed to renewable terms, and retain their positions at their home institutions while coming to Perimeter for extended research visits (of up to six months each year).

The program has continued its rapid growth in 2013/14, exceeding targeted objectives by attracting five new Visiting Fellows and renewing an additional four.[13] Two of the new fellows are outgoing Perimeter postdoctoral researchers, allowing the Institute to maintain productive ties with its promising young researchers while also building relationships with the top international institutions where these Visiting Fellows are based.

New Visiting Fellow Appointments in 2013/14:

Eugenio Bianchi (PhD Scuola Normale Superiore, Pisa, 2010) 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.

Vitor Cardoso (PhD Instituto Superior Técnico, 2003) is an Assistant Professor at the Instituto Superior Técnico (IST) in Lisbon, Portugal, 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 and Gulbenkian Scholarships.

Zohar Komargodski (PhD Weizmann Institute of Science, 2008) 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.

Chris Laumann (PhD Princeton University, 2010) 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.

Thomas Vidick (PhD University of California, Berkeley, 2011) 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

[13] The Visiting Fellows whose terms were renewed are Jonathan Barrett, Ruth Gregory, Etera Livine, and Kris Sigurdson.

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.

Emmy Noether Fellows (new initiative)

In 2013, Perimeter launched the Emmy Noether Fellows program, named for Amalie (Emmy) Noether, an influential German mathematician known for her groundbreaking contributions to abstract algebra and theoretical physics. Despite being described as the most important woman in the history of mathematics by Albert Einstein, Noether faced many obstacles as a woman in a male-dominated field. This program aims to provide an early-career boost to emerging stars in fundamental physics.

Unlike the DVRC and Visiting Fellows programs that encourage multiple visits over renewable terms, Emmy Noether Fellows spend up to one year pursuing their research in Perimeter's dynamic scientific environment while on leave from their home institutions. Fellows span a wide range of expertise, take part in conferences and workshops, and generally enjoy the freedom to focus fully on their research at a crucially important stage in their young careers.

In 2013/14, Perimeter welcomed Claudia de Rham and Sara Pasquetti as its inaugural Emmy Noether Fellows, and recruited five more Fellows for 2014/15.

New Emmy Noether Fellow Recruits in 2013/14:

Alejandra Castro is an assistant professor at the University of Amsterdam, specializing in new approaches toward classical and quantum gravity. Her work seeks to explain the microscopic origin of black hole thermodynamics and the emergence of spacetime in quantum gravity.

Claudia de Rham is an assistant professor at Case Western Reserve University. She is a cosmologist working on very early universe cosmology and dark energy. Her recent work includes giving the graviton a mass. This has led to new developments in theories which modify gravity at large distances and could play a crucial role in understanding the nature of dark energy and tackling the cosmological constant problem.

Belén Paredes is a junior professor at Madrid's Institute for Theoretical Physics (IFT), UAM-CSIC, whose research interests include novel phases of matter, quantum entanglement, and engineering quantum matter for quantum information processing.

Sara Pasquetti is a lecturer at the University of Surrey. Her research interests lie at the interface between physics and mathematics. In particular, Pasquetti is interested in the relation between gauge theories, conformal field theory (CFT), and geometry. In recent years, she has combined supersymmetric localization and topological string methods to develop new tools for the study of supersymmetric gauge theories in various dimensions, in the presence of defect operators and CFT correlators.

Catherine Pépin is a permanent researcher at France's Institut de Physique Théorique, CEA-Saclay, with a focus on emergent quantum phenomena. In particular, her recent work has examined zero-temperature phase transitions (called quantum critical points) in heavy fermion systems and high-temperature superconductors.

Silke Weinfurtner is a Royal Society Research Fellow and Nottingham Research Fellow at the University of Nottingham, specializing in questions of quantum gravity, strong gravity, and condensed matter physics. Much of her research focuses on the quest to design and carry out table-top experiments to explore quantum gravity.

Kathryn Zurek is an associate professor in the University of Michigan's physics department, where she works at the interface of particle physics, cosmology, and astrophysics. Her work examines new data emerging from particle collider facilities, as well as the astrophysical search for dark matter and physics beyond the Standard Model.

Visitor Program

- Hosted 424 visiting scientists for a total of 465 visits, exceeding targeted objectives[14]
- Twelve long-term Visiting Researchers came to work at Perimeter during leaves (e.g., sabbaticals) from their home institutions

Perimeter Institute's active visitor program enables its resident scientists to stay abreast of recent developments, exchange ideas, and spark new collaborations. Visitors, meanwhile, benefit from having the time and space for the intense, sustained work required to tackle tough problems. The program is also a recruitment aid, showcasing Perimeter's vibrant research environment and the excellent administrative support that enable scientists to maximize their productivity. In the past year, visits by potential recruits have led to new appointments at all levels, notably including Perimeter Research Chairs Kevin Costello and Subir Sachdev, as well as Faculty member Asimina Arvanitaki.

[14] This number includes 374 short-term visitors, 30 Distinguished Visiting Research Chairs, and eight Visiting Fellows.

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

Summary of Achievements

- Provided expertise in support of the African Institute for Mathematical Sciences – Next Einstein Initiative (AIMS-NEI)
- Partnered on eight workshops and conferences with national and international partners and sponsored an additional 12 off-site scientific gatherings (see Objective 7)
- Welcomed the inaugural Fields-Perimeter Africa Postdoctoral Fellow
- Held the Equinox Summit: Learning 2030 to envision the high school of the future, and summarized its findings and recommendations in the *Equinox Blueprint*

Highlights

Collaborations and Partnerships

Perimeter pursues relevant institutional partnerships with leading centres in Canada and abroad, in order to strengthen its position as a global research hub and open up collaboration opportunities for its scientists. Current partners include, among others, the Centre for Theoretical Cosmology at the University of Cambridge, the Weizmann Institute of Science, and TRIUMF, Canada's national laboratory for particle and nuclear physics.

In 2013/14, Perimeter strengthened ties in the international physics community through a number of ongoing partnerships, both formal and informal.

Fields-Perimeter Institute Africa Postdoctoral Fellowship

Perimeter has partnered with The Fields Institute for Research in Mathematical Sciences at the University of Toronto to fund four one-year joint postdoctoral fellowships for African nationals who have recently completed their PhD. In 2013/14, Perimeter welcomed Dine Ousmane Samary from Benin as the first such fellow, conducting research in quantum gravity and splitting his time between Toronto and Waterloo. The second fellow, Cyril Batkam of Cameroon, will arrive in fall 2014.

Tri-Institute Summer School on Elementary Particles (TRISEP)

Perimeter partnered with fellow Canadian institutes TRIUMF and SNOLAB to convene the Tri-Institute Summer School on Elementary Particles (TRISEP), a two-week summer school for graduate students and postdoctoral researchers on hot topics in particle physics. The second edition of TRISEP took place June

1-14, 2014, at SNOLAB in Sudbury, covering topics from physics beyond the Standard Model, to neutrino physics and dark matter.[15]

The Waterloo Global Science Initiative (WGSI)

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

In 2013/14, the WGSI team met its targeted objectives, hosting the Equinox Summit: Learning 2030, which envisioned a high school of the future that engages and empowers critical thinkers.

- From September 28 to October 3, 2013, held concurrently with the BrainSTEM: Your Future Is Now Festival (see Objective 8), the Equinox Summit: Learning 2030 brought delegates from six continents to Perimeter to discuss the shifting needs and opportunities in high school education.
- Throughout Learning 2030, presenting media partner TVO broadcast five episodes of *The Agenda with Steve Paikin* from Perimeter, featuring panel discussions with Summit participants.
- At the World Literacy Summit in Oxford in April 2014, the WGSI team released the *Equinox Blueprint: Learning 2030*, summarizing the Summit's findings and recommendations; nearly 1,000 copies have been distributed to international media, policymakers, and education influencers (as of May 2014).
- An interactive website (learning2030.org) was launched to allow education communities around the world to share and discuss their stories, challenges, and successes with education reform.

In addition to these formal collaboration agreements, Perimeter hosted several important international conferences, most notably "Implications of BICEP2" on April 4, 2014, the first major conference held to discuss the implications of the possible detection of primordial gravitational waves. Perimeter hosted more than 80 theoretical physicists and observational cosmologists for a one-day workshop to discuss the results.[16] Perimeter researchers Neil Turok, Latham Boyle, Kendrick Smith, and David Marsh were among the first scientists to publish papers in response to the BICEP2 findings, further evidence that the Institute is a hub for cutting-edge research.

Global Outreach – AIMS-NEI

Perimeter's Global Outreach initiative provides expertise (not funding) to assist in the growth of scientific centres of excellence around the world. The current focus of these efforts is the African Institute for Mathematical Sciences – Next Einstein Initiative (AIMS-NEI). This is a pan-African project

[15] Art McDonald, a member of Perimeter's Board of Directors, delivered the keynote address, while Perimeter Faculty member Kendrick Smith was one of the school's lecturers.

[16] Distinguished Visiting Research Chairs Nima Arkani-Hamed, James Bardeen, and Eva Silverstein were among those in attendance.

founded by Perimeter Director Neil Turok in 2003 to establish a network of centres providing advanced mathematical and scientific education to exceptional African graduates.

In 2013/14, Perimeter continued to leverage the expertise of both its research and administrative staff in support of the flourishing AIMS-NEI network.

- Several Perimeter researchers taught at AIMS centres.
- Perimeter staff assisted with the preparation of a major funding proposal to the MasterCard Foundation, with a decision expected in fall 2014.
- Perimeter staff provided administrative expertise in planning the start-up of both AIMS-Cameroon (launched February 2014) and AIMS-Tanzania (slated to launch October 2014).
- Perimeter Director Neil Turok participated in the launch of AIMS-Cameroon in February 2014, and Perimeter leveraged its contacts to help ensure the attendance of Fields Medallist Cedric Villani, Nobel Laureates David Gross and Klaus von Klitzing, and former Governor General of Canada Michaëlle Jean.
- In March 2014, owing to the popularity of his initial 2008 TED Prize wish, Turok was invited to deliver an update on the progress of AIMS-NEI at the TED 2014 conference in Vancouver.
- Perimeter co-hosted a 10^{th} anniversary celebration for AIMS in Ottawa to raise awareness among the Canadian government and other potential supporters.

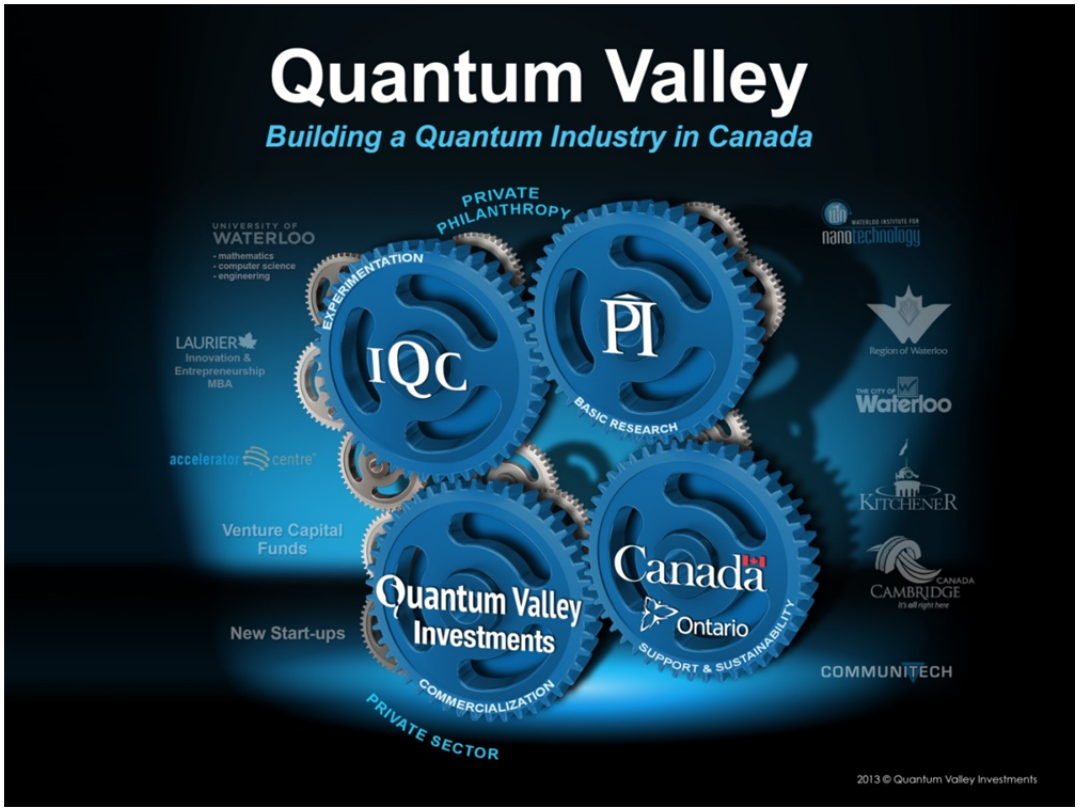
Objective 6: To increase Perimeter's role as Canada's focal point for foundational physics research

Summary of Achievements

- Appointed four new Affiliates from across the country and renewed an additional 16, giving the Institute 120 Affiliates in total from across Canada
- Continued to work with regional partners to foster the Quantum Valley ecosystem
- Strengthened ties with experimental and observational centres in Canada and internationally
- Appointed two new associate faculty members with 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[17] (see Objective 3)
- Hosted eight joint workshops and conferences with regional and national academic partners, and sponsored an additional 12 (see Objective 7)

Highlights

Commercialization Catalyst for Quantum Valley



[17] These included Anton Burkov, University of Waterloo; Andrew Childs, University of Waterloo; Joseph Emerson, Institute for Quantum Computing at the University of Waterloo; and Robert Mann, University of Waterloo.

Quantum information processing, or quantum computing, is one of the fastest moving fields in science, seeing rapid progress from theory to prototype components and devices. It is now widely believed that quantum technologies will transform society much as the first wave of classical computers did. In the next two decades, experts believe quantum devices will begin to revolutionize areas as disparate as digital currency, oil exploration, and non-invasive medical diagnostics.

Perimeter has helped position Canada as a leader in the quantum race; the Institute's creation was a landmark step in the formation of the quantum ecosystem – dubbed "Quantum Valley" – that has emerged in Waterloo Region. Perimeter researchers do the crucial theoretical work that underpins the entire field, acting as a commercialization catalyst for a quantum revolution in Canada. The Institute's scientists work closely with experimentalists at IQC, and many of the field's pioneers are located at one or both of these centres.

In 2013/14, Perimeter continued to work closely with other key players in Waterloo Region[18] to ensure Canada remains at the forefront of international efforts to create new quantum industries, which will in turn spark major job and value creation. In particular, recruitment efforts have emphasized quantum specialists like Subir Sachdev, the James Clerk Maxwell Chair in Theoretical Physics; Associate Faculty member Raffi Budakian (see Objective 2); Distinguished Visiting Research Chair Barbara Terhal; Visiting Fellows Chris Laumann and Thomas Vidick (see Objective 4); and numerous postdoctoral researchers.

Engagement with Experimental Centres

Experiment is the ultimate test of all theory. For this reason, Perimeter has continued to expand and deepen its ties to experimental centres in 2013/14.

The Institute for Quantum Computing (IQC), which Perimeter helped establish at the University of Waterloo in 2002, remains Perimeter's primary experimental partner. IQC is led by Raymond Laflamme and Michele Mosca, both of whom are associate faculty members at Perimeter, and many more PI researchers are cross-appointed at IQC.[19]

Perimeter scientists are also connected to many major experimental efforts throughout the world. Associate Faculty member Avery Broderick is a member of the Event Horizon Telescope (EHT) project, which is working to directly observe the immediate environment of a black hole for the first time. Faculty members Philip Schuster and Natalia Toro have extensive experimental connections, including at the Large Hadron Collider (LHC) at CERN. Faculty member Kendrick Smith, meanwhile, works on a

[18] 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 venture capitalists (such as Quantum Valley Investments, Mike Lazaridis' latest venture).
[19] Associate Faculty members Raffi Budakian and David Cory are jointly appointed at IQC, as are postdoctoral researchers Gus Gutoski, Zhengfeng Ji, Keith Lee, Zlatko Papic, and Huan Yang. Faculty member Dmitry Abanin and Senior Research Affiliate Steve MacLean are associates at IQC, and the institutes share a number of affiliates as well.

number of experimental collaborations aimed at measuring the cosmic microwave background (CMB), including the Planck satellite and the Hyper-Suprime Cam (HSC) project at the Subaru telescope.

Other experimental centres Perimeter has ties to include the Stanford National Linear Accelerator (SLAC), Sudbury Neutrino Observatory (SNOLAB), Thomas Jefferson National Accelerator Facility (JLab), TRIUMF, and more (see Appendix F: Perimeter's Research Ties to Experiment).

Lastly, Perimeter connects with experiment through its conference program, with several conferences in 2013/14 revolving directly around experimental findings and challenges.[20]

Affiliate Members

Since shortly after Perimeter's creation, the Institute's Affiliate program has been a crucial means of connecting the foundational physics research community across Canada. Affiliates are select researchers, from universities and research institutions across the country, who are invited to Perimeter for regular informal visits.

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

In 2013/14, Perimeter appointed four new Affiliates and renewed an additional 16 through 2016, ensuring this vibrant community of scientists will continue to enrich the Institute's research environment. Perimeter now has 120 Affiliates, exceeding targeted objectives (see Appendix C, Affiliate Members).

[20] These included "Implications of BICEP2" (April 4, 2014), "Low Energy Challenges for High Energy Physicists" (May 26-30, 2014), and "International Workshop on Quantum LDPC Codes" (July 14-16, 2014). For further details, refer to Appendix F: Perimeter's Research Ties to Experiment.

Objective 7: To host timely, focused conferences, workshops, seminars, and courses

Summary of Achievements

- Held 17 conferences and workshops, attended by 844 scientists from around the world
- Presented 286 scientific talks (247 seminars and 39 colloquia)
- Partnered on eight joint workshops and conferences held at Perimeter and sponsored an additional 12 off-site workshops and conferences (see Objective 6)
- Launched "PI Days," internal workshops designed to build research connections within the Perimeter community
- Delivered four courses to researchers and students from surrounding universities

Highlights

Conferences and Workshops

- Held 17 focused conferences and workshops, exceeding targeted objectives[21]
- Hosted the world's first international conference to examine and interpret the important BICEP2 results, "Implications of BICEP2"

Perimeter has built an internationally renowned conference program by selecting topics with high potential for stimulating significant outcomes. This year, 844 scientists attended Institute conferences and workshops, demonstrating its role as a major node of exchange for theoretical physics. The conference program also strengthens Perimeter's ties to institutional partners; this year, the Institute

[21] These included: (1) "Newtonian Studies of Black Hole Stars Meet General Relativity Effects;" (2) "Cosmology and Strong Gravity Workshop;" (3) "Physics Around Mirror Symmetry;" (4) "PI-UIUC Joint Workshop on Strongly Correlated Quantum Many-Body Systems;" (5) "Waterloo Soft Matter Theory;" (6) "PI Day;" (7) "Emergence in Complex Systems;" (8) "Implications of BICEP2;" (9) "Renormalization Group Approaches to Quantum Gravity;" (10) "Supersymmetric Quantum Field Theories in Five and Six Dimensions;" (11) "4 Corner Southwest Ontario Condensed Matter Physics Symposium 2014;" (12) "Compute Ontario Research Day 2014;" (13) "Quantum Many-Body Dynamics;" (14) "Quantum Gravity Day;" (15) "Low Energy Challenges for High Energy Physicists;" (16) "New Ideas in Low Energy Tests of Fundamental Physics;" and (17) "International Workshop on Quantum LDPC Codes."

partnered on eight workshops and conferences with national and international partners[22] and sponsored an additional 12 off-site scientific gatherings.[23]

Selected conference highlights:

- **"Implications of BICEP2"** (April 4, 2014): In March 2014, the research team behind the Antarctica-based BICEP2 (Background Imaging of Cosmic Extragalactic Polarization) telescope announced the detection of what appeared to be primordial 'B-mode' polarization in the earliest light of the universe, the cosmic microwave background (CMB). Just a few weeks later, Perimeter Institute hosted the world's first international conference on the subject. Fruitful exchanges and discussion of the importance of technical factors and "foregrounds" led many to urge caution in interpreting the results. Indeed, follow-up data from the Planck satellite revealed in September that cosmic dust in the interstellar medium may have caused the effects initially attributed to gravitational waves.

- **"Low Energy Challenges for High Energy Physicists"** (May 26-30, 2014): Perimeter hosted a conference to help spark fruitful collaboration between high-energy and condensed matter physicists. "Low Energy Challenges for High-Energy Physicists" brought approximate 40 high energy physicists together with leading condensed matter theorists. Their goal: to unite, focus and inspire a new community, bent on tackling some of the most interesting problems in modern physics. "The speakers were impressively knowledgeable and the participants were excitedly working to develop new ideas," commented one attendee. "This was one of the most engaging and inspiring conferences I've ever been to."

- **"PI Day"** (Jan. 30, 2014): A special one-day internal conference in which Perimeter researchers shared their latest research, issued "challenges" to one another, and sparked new collaborations. "The purpose is that people can interact with each other, provoke each other, and one discipline can present challenges to other disciplines," explained Perimeter Director Neil Turok. "That's often where the most exciting progress in physics comes from: when people

[22] These included: (1) "Newtonian Studies of Black Hole Stars Meet General Relativity Effects," with CIFAR; (2) "PI-UIUC Joint Workshop on Strongly Correlated Quantum Many-Body Systems," with the University of Illinois; (3) "Waterloo Soft Matter Theory," with the University of Waterloo; (4) "Implications of BICEP2," with CIFAR; (5) "Renormalization Group Approaches to Quantum Gravity," with the Templeton Foundation; (6) "Compute Ontario Research Day 2014," with SHARCNET; (7) "New Ideas in Low Energy Tests of Fundamental Physics," with TRIUMF; and (8) "International Workshop on Quantum LDPC Codes," with the Institute for Quantum Computing and the Templeton Foundation.

[23] These included: (1) "Qcrypt 2013," Institute for Quantum Computing; (2) "Canada America Mexico Graduate Student Conference," University of Waterloo; (3) "2013 Canadian Undergraduate Physics Conference (CUPC)," McMaster University; (4) "Lake Louise Winter Institute 2014," University of Alberta; (5) "15th Canadian Conference on General Relativity and Relativisitic Astrophysics," University of Winnipeg; (6) "GAP 2014," University of British Columbia; (7) "String Math 2014," University of Alberta; (8) "Theory Canada 9," Wilfrid Laurier University; (9) "14th Canadian Summer School on Quantum Information and the 11th Canadian Quantum Information Student Conference," University of Guelph; (10) "2014 CAP Congress," Laurentian University; (11) "Quantum Computing, Algebra, and Combinatorics," University of Waterloo; and (12) "13th International Conference on Unconventional Computation and Natural Computation," Western University.

with different perspectives – often *very* different perspectives – interact, give each other a hard time, and maybe help each other do something even more interesting." With 98 participants, the day was considered so successful that it was decided to hold PI Days twice annually going forward.

- **"New Ideas in Low Energy Tests of Fundamental Physics"** (June 16-19, 2014)**:** The purpose of the workshop was to bring together members of theoretical and experimental communities interested in finding new fundamental applications to continuing advancement of new high-precision tools in atomic, nuclear, and optical physics. The conference attracted 55 participants from around the world, who unanimously said the conference was illuminating and fruitful.

Seminars and Colloquia

Seminars and colloquia foster collaboration and share knowledge from leading international researchers, invigorating the Institute's research community and further establishing Perimeter as a global epicentre for theoretical physics. In 2013/14, Perimeter held a total of 286 talks (247 seminars and 39 colloquia), exceeded targeted outcomes. Particularly notable talks were given by Gilles Brassard (co-founder of quantum cryptography, University of Montreal), S. James Gates Jr. (member of President Barack Obama's Council of Advisors on Science and Technology), and Robbert Dijkgraaf (Director, Institute for Advanced Study).

Courses

When possible, Perimeter seeks to share the expertise of its resident and visiting scientists by having them present topical courses on cutting-edge areas. University-level credit courses are open to students of all Ontario universities, while non-credit mini-courses serve students at PI and surrounding universities.

In 2013/14, Perimeter offered four advanced, for-credit courses: "Introduction to Effective Field Theories," taught by Associate Faculty member Cliff Burgess; "Quantum Field Theory for Cosmology" and "General Relativity for Cosmology," both taught by Canada Research Chair for the Physics of Information and PI Affiliate Achim Kempf; and "Topics in QFT on Flat and Curved Spacetime," taught by Ugo Moschella from the University of Insubria, Como. In addition, Distinguished Visiting Research Chair Ted Jacobson presented the mini-course, "Spacetime Approach for Force-Free Magnetospheres."

Online Video Archive

- Over 75,000 unique visitors from over 170 countries accessed Perimeter's video archive, with 764,186 page views, up four percent from 2012/13

Nearly all talks held at Perimeter are recorded and can be viewed online on the Perimeter Institute Recorded Seminar Series (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 science community. It has become an important resource for the field, as evidenced by the continued rise in site traffic every year. Notably, a substantial portion of the traffic for these videos now comes from the Video Library section of the Perimeter Institute website, a new portal for accessing this content that was made available in 2013/14.

Objective 8: To engage in high impact outreach

Summary of Achievements

- Reached more than 1 million students through Perimeter programs and in-class resources, bringing the total to more than 4 million students to date
- Completed BrainSTEM, a FedDev Ontario-funded project which included a science festival, educator workshops, and a classroom resource, to foster 21st century STEM skills, reaching nearly 2 million people in total
- Hosted the 12th International Summer School for Young Physicists (ISSYP) and gave 18 Physica Phantastica presentations – reaching over 5,500 students across Canada
- Delivered 90 workshops to over 2,000 educators across Canada and abroad, ultimately reaching more than 150,000 students
- Launched international distribution partnerships to share Perimeter educational resources across the UK (with the Institute of Physics) and the US (with Physics Teacher Resource Agents)
- Presented 10 engaging public lecture to capacity audiences on-site and online
- Director Neil Turok won the 2013 Lane Anderson Award for Canadian science writing for his book, *The Universe Within: From Quantum to Cosmos*

Highlights

Student Programs and Products

International Summer School for Young Physicists (ISSYP)

- Hosted the 12th edition of ISSYP for 40 top Canadian and international students[24]

The International Summer School for Young Physicists (ISSYP) is a pillar of Perimeter's outreach efforts. The program brings Canadian and international students with demonstrated scientific potential to Perimeter for a two-week immersion in modern physics, including mentoring sessions with resident researchers and lab tours of the Institute's experimental partners. By providing a first-hand experience of cutting-edge research at an age when students are actively weighing career directions, Perimeter is developing new talent for the field and for Canada. Follow-up metrics indicate that over 70 percent of ISSYP alumni credit the program with inspiring them to pursue a career in math or physics.

The 2013/14 edition of ISSYP was made possible by the generous support of the RBC Foundation (see Objective 10).

[24] This included 20 Canadians from seven provinces and 20 international students from 13 countries. An emphasis is placed on ensuring an even gender split – 20 boys and 20 girls.

BrainSTEM

- Successfully completed BrainSTEM, a FedDev Ontario-funded suite of activities, exceeding all targets

The BrainSTEM initiative, funded by the Federal Economic Development Agency for Southern Ontario (FedDev Ontario) was created to foster 21st century STEM (Science, Technology, Engineering, Mathematics) skills and entrepreneurial thinking among youth. The project was an unqualified success, engaging 400,000 students in classrooms, 5,000 teachers, 25,000 parents and children, and 1.5 million viewers on television and online. The integrated suite of activities and products included the following:

- *Career Moves – Skills for the Journey*: an in-class French and English STEM skills resource for students and teachers, featuring 15 student-centred activities, video content, and 200 GB of resource material shared across southern Ontario
- The Un-Conference Summit: a gathering of YouTube's most respected and successful science communicators, educators, and entrepreneurs, all sharing ideas about how to engage worldwide audiences through digital communications
- Training Workshops: the BrainSTEM Instructional Camp for Educators (BrainSTEM ICE), which, coupled with the Career Moves package, provided unparalleled training for teachers to engage students with vital STEM skills
- BrainSTEM: Your Future is Now Festival, an on-site and online interactive celebration of the STEM skills and entrepreneurial spirit that will be crucial for success in the 21st century

Aboriginal Engagement

- Reached more than 1,000 Aboriginal youth with Perimeter resources

In 2013/14, 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 Outreach staff trained Actua associates from across the country on Perimeter resources; the Actua associates then delivered the content to Aboriginal students during the summer months.

Programs and Resources for Teachers

Teacher Network

- Teacher Network members delivered 90 workshops to over 2,000 educators, ultimately reaching 150,000 students

The Perimeter Teacher Network, comprising more than 50 teachers from across Ontario and Canada, trains educators on Perimeter's modern physics classroom resources and technique. Network members are trained by Outreach staff and go on to conduct resource training workshops in their home districts, building the capacity of educators to share modern science with their students. Teachers are trained all of Perimeter's in-class kits, including Perimeter *Explorations*, *Inspirations*, *Investigations*, and BrainSTEM's *Career Moves – Skills for the Journey*.

On-location Teacher Workshops and Conference Presentations

- Outreach staff delivered 18 on-location workshops at teacher conferences in Canada and abroad, reaching more than 1,000 educators, exceeding targeted outcomes[25]

Presentations at major educational conferences and gatherings are a cost-effective means of increasing the visibility of outreach products and programs, both within Canada and abroad. In particular, Perimeter's outreach team has tried to engage grade 9 and 10 teachers, given the expansion of the Institute's resources in recent years to include younger students.

Educational Resources

Perimeter Inspirations, Explorations, and *Investigations*

- Created a new *Inspirations* resource, *Our Expanding Universe*, for release in Fall 2014
- Developed French version of the popular BrainSTEM resource

Produced with the input of physics educators and scientists, in-class modules are the Institute's primary means of introducing Canadian high school students to modern physics. 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 high school students and motivate them to continue with math and science in senior grades. This year's *Inspirations* module, entitled "The Expanding Universe" shares cutting-edge cosmology research and concepts (such as the Planck satellite) with students in grades 7 through 12. ***Explorations*** modules deliver more challenging ideas and technical content to senior high school students, preparing

[25] In 2013/14, Perimeter staff presented at annual conferences including: Science Teachers Association of Ontario (Toronto, Canada); Ontario Secondary Counsellors Association (Toronto, Canada); American Association of Physics Teachers Winter Meeting (Orlando, USA); American Association of Physics Teachers Summer Meeting (Minneapolis, USA);The Association for Science Education (Birmingham, UK); National Science Teachers Association (Boston, USA); Ontario Association of Physics Teachers (Hamilton, Canada); Physics Teachers Resource Agents (Minneapolis, USA); High School Teachers Program at CERN (Geneva, Switzerland).

them for post-secondary education in math, science, and engineering. ***Investigations*** modules are simple, classroom-ready demonstrations or lab activities.

International Distribution

All Perimeter resources, both physical copies and online, will continue to be offered free to Canadian educators, but are also now available to international teachers through Perimeter's online store as part of a cost-recovery strategy.

In 2013/14, Perimeter ramped up its efforts to distribute educational resources internationally, as well as to provide crucial training on the use of these resources. In addition to the training they provided at the on-location presentations noted above, Perimeter's Outreach team launched formal international distribution partnerships to share Perimeter resources across the UK (with both the Institute of Physics and the Science Learning Centres) and the US (with Physics Teacher Resource Agents).

Lastly, Perimeter and Canada's Department of Foreign Affairs, Trade and Development (DFATD) are laying the groundwork for more international engagement and impact. This will include joint communications on talent mobility/recruitment opportunities in Canada and sales/distribution of Perimeter's educational outreach resources abroad.

Online Resources

Publishing high-quality resources online allows Perimeter to scale its reach and impact. Most Outreach content is available online, including *Virtual ISSYP*, over 30 *Meet A Scientist* video interviews, and an archive of past Public Lectures.

Over the past year, a project was launched to divide Perimeter's large, full-kit classroom resources into more accessible e-modules for distribution online. In line with targeted objectives, Perimeter also co-created, in partnership with TVO, seven short interstitial videos called "I Wonder Why," in which children pose scientific questions to experts, as part of the BrainSTEM activities in fall 2013. These videos were aired on television and hosted online, with a reach of 500,000 viewers.

Digital and Social Media Outreach

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

During 2013/14, Perimeter substantially increased its digital and social media outreach efforts, through enhanced use of its Facebook and Twitter channels, a major increase in video creation/sharing through its YouTube channel, and new digital media outreach initiatives including the successful Slice of PI (fun and sharable monthly science content).

Slice of PI:

Launched in March 2014 (in celebration of "Pi Day," March 14), monthly "Slices of PI" present accessible content to a growing list of e-subscribers, through targeted outreach to physics/science influencers (Physics Today, Physics is Awesome, etc.), and through organic social media sharing (Facebook, Twitter, Google+, etc.).

- Successful examples included:
    - **What Great Scientists Did When They Weren't Doing Great Science** (an infographic describing the hobbies of great physicists): 41,000 page views on Perimeter Institute website, featured on CBC News website (1.3 million unique page views), shared on Huffington Post Canada (334,000 unique page views) and Yahoo! News Canada (255,000 unique page views)
    - **Physics of Summer** (a visual list of physics facts about summer): Shared by Buzzfeed Science with 136,000 page views, shared by Physics is Awesome to 144,000 followers, shared on It's Okay to be Smart with 2,700 likes and re-blogs

Video:

In 2013/14, Perimeter Institute significantly increased its YouTube channel content, resulting in large viewership growth and a subscriber base nearing 4,000. The channel had 244,000 video views during 2013/14, an increase of 716% over last year, and an increase of 1,673 subscribers during 2013/14. User engagement increased as well, with a 78% increase in commenting.

- Successful examples:
    - **Putting the Multiverse to the Test** (interview with PI Associate Faculty member Matthew Johnson): 124,700 views
    - **Schrodinger's Cat (Sort of) Explained**: 17,700 views
    - **The Most Important Woman in the History of Mathematics** (about Emmy Noether): 7,200 views

Social Media:

Perimeter's Twitter following increased by roughly 1,900 followers during the 2013/14 Fiscal Year – the fastest period of growth since the account's creation. This is the result of daily content sharing, increased quality of content, live-tweeting during Public Lectures and other events, and targeted influencer outreach.

- Perimeter's Facebook page gained roughly 2,100 new fans during the 2013/14 Fiscal Year – the fastest period of growth since the account's creation

Programs for the General Public

Public Lecture Series

Perimeter's flagship Public Lecture Series, presented by Sun Life Financial, continued to be extremely popular, with (free) tickets snapped up very quickly after being made available.

In 2013/14, the Institute presented 10 accessible, engaging talks on scientific topics – spanning quantum mechanics, black holes, dark matter, laser science, and more – meeting targeted objectives. The series also featured a panel discussion, presented in conjunction with *Maclean's* magazine, in which emerging scientists discussed the future of physics. Importantly, the June 2014 talk by Sylvester James Gates Jr. was webcast live – a pilot project for online streaming of the lectures which has since been adopted for all future lectures. By webcasting the lectures, and providing additional interactive content including live chats and live-tweeting, the lectures can reach wider audiences than ever before.

BrainSTEM: Your Future is Now Festival

- Nearly 25,000 students and families attended the BrainSTEM: Your Future is Now Festival

Over a week in the fall of 2013 (Sept. 30-Oct. 6, 2013), the Institute hosted BrainSTEM: Your Future is Now Festival. This onsite and online event was created to inspire young people to pursue STEM fields (science, technology, engineering, mathematics) and to celebrate the entrepreneurial spirit that will be crucial for success in the 21st century. The festival connected technological innovations to the scientific breakthroughs that make them possible, and featured dozens of interactive exhibits, building tours, public lectures, science comedy shows, and more.

Media Coverage

Perimeter has continued to actively share the wonder and discovery of theoretical physics with major media. In 2013/14, the Institute received major coverage in both national and international media, including *Nature*, CBC, Discovery News, and many more. Highlights included:

- "Waterloo think tank gets even smarter," by Ivan Semeniuk, in *The Globe and Mail*[26]
- "Waterloo Gets Physical," by Hannah Hoag, in *Nature*[27]
- "Five people who are changing how we do physics: Nurturing the next Einsteins," by Hamish Johnston, in *Physics World*[28]
- "Albert Einstein's hobbies and those of 9 other physicists revealed," by Emily Chung, on CBC.ca[29]

[26] November 16, 2013 edition, http://www.theglobeandmail.com/news/national/waterloo-think-tank-gets-even-smarter/article15474330/
[27] October 3, 2013 edition, http://www.nature.com/naturejobs/2013/131003/pdf/nj7469-129a.pdf
[28] October 3, 2013 edition, http://iopscience.iop.org/pwa/full/pwa-pdf/26/10/phwv26i10a42.pdf

- "Will science burst the multiverse's bubble?" by Ian O'Neill, in Discovery News[30]

[29] July 19, 2014 edition, http://www.cbc.ca/news/technology/albert-einstein-s-hobbies-and-those-of-9-other-physicists-revealed-1.2711586

[30] July 18, 2014 edition, http://news.discovery.com/space/will-science-burst-the-multiverses-bubble-140718.htm

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

Summary of Achievements

- Launched a series of internal showcases of Perimeter research, with the goal of further strengthening the research community and sparking new collaborations
- Moved forward on work to improve the climate for women at Perimeter
- Expanded library collections, including electronic access to key journals
- Enhanced the functionality of the website and introduced an intranet portal

Highlights

Building a Climate of Collaboration and Exchange

Historically, many of the great breakthroughs in science have come from collaborations across the boundaries of disciplines. Perimeter was designed to foster such collaborations: even the architecture reflects this. As the Institute has grown, it has become increasingly important to put in place programs that nurture such cross-disciplinary collaborations and exchanges.

In January 2014, Perimeter held an informal one-day showcase of ongoing research programs and collaborations being undertaken by Perimeter's own community, with the goal of strengthening that community and sparking new exchanges across disciplines. "PI Day" featured talks from each physics area. There were 98 participants, ranging from senior faculty to postdoctoral fellows and students. The event was considered so successful that it was decided to hold PI Days twice a year, and to launch more focused one-day workshops on (for example) Quantum Gravity, or Cosmology and Strong Gravity.

To foster community and collaboration at the faculty level, Perimeter instituted a lunch series at which a faculty or associate faculty member gives a brief presentation on his or her work, and then leads a discussion and question period. Hosted by Perimeter's director Neil Turok, and held monthly from October to June, each lunch attracts 15-20 people.

A new lunch series was also initiated for postdoctoral researchers to discuss their work, connect with others outside their areas, and gain a better idea of the breadth of research across the Institute. Eleven such lunches were held in 2013/14, with approximately 30 in attendance at each.

Promoting Gender Equity

Perimeter is committed to addressing the gender imbalance in physics, both at the Institute and on a larger scale.

On the home front, Perimeter is in the middle of a multi-year process which examines – and aims to improve – the climate for women in physics at the Institute. In May 2013, at Perimeter's invitation, a four-woman team of senior scientists from the American Physical Society's (APS) Committee on the Status of Women in Physics conducted a two-day site visit. The team's mandate was to examine the climate for women at Perimeter and recommend changes, with a goal of creating greater gender equity throughout the Institute.

In 2013/14, Perimeter continued to work with experts to refine the committee's recommendations[31] and develop strategies for implementing them. In particular, Perimeter sought consultation with experts from University of Michigan's ADVANCE and STRIDE programs, who are developing a suite of best practices in regard to hiring, recruitment, and retention for women in the sciences. This work is ongoing.

E-Journal Access and Library Collections

An in-house library is essential to building Perimeter's research and learning communities. In 2013/14, 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 64 new texts, bringing the total to 5,256 in the print collection (5,719 in all formats), with additional electronic subscriptions to 115 journals that researchers and students can access on-site and remotely.

IT Systems Upgrades and Initiatives

In 2012, Perimeter launched a redesigned website. In 2013/14, Perimeter continued to improve on this new platform, providing enhanced functionality and usability, including the following:

- Improved French translation functionality on Perimeter's public website
- Enhanced e-commerce capabilities to support international sales of the Institute's educational outreach resources via the Institute's website (see Objective 8)
- Improved capabilities to support online donations (see Objective 10)

Planned upgrades to IT infrastructure to optimize research and realize administrative efficiencies continued, in line with targeted objectives. These included the implementation of new library collections-management systems, new conference calling services, and development of new resource management systems for room booking and related services. In spring 2014, Perimeter initiated a new intranet portal project, which should allow for streamlined reporting, and reduce redundant inputting of information.

[31] These included, among other things, fostering more regular and informal feedback and peer advice for PhD students and junior research staff; determining whether unconscious biases are directing female researchers disproportionately to PSI Fellow teaching roles among postdoctoral fellows; and continued training in diverse hiring practices.

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

Summary of Achievements

- Attracted over $5.1 million from individuals, corporations, and foundations
- Obtained pledges for additional major gifts from Gluskin Sheff ($2M) and Peter Godsoe ($500,000); now working closely with each to finalize support
- Expanded the Corporate Partners, Emmy Noether Circle, and Friends and Alumni programs
- Expanded Perimeter's network of advocates and supporters in the financial and philanthropic communities across Canada and the United States
- Successfully concluded the FedDev Ontario YSTEM-funding BrainSTEM suite of activities, bolstered by additional corporate support
- Hired a Director of Major Gifts

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. Investment from all levels of government helped establish Perimeter and sustained support from the public sector has been critical to the Institute's success to date. These partnerships are also pivotal in establishing Canada as the world's Quantum Valley, ready to reap the benefits of the next great technological revolution.

2013/14 marked the second year of five-year, $50 million funding agreements with both the Government of Canada and the Province of Ontario. Perimeter continues to utilize best practices in financial management, to fulfill all its reporting requirements, and to meet or exceed targeted objectives.

Perimeter completed the FedDev Ontario-funded BrainSTEM suite of activities, with support from additional corporate sponsors. The BrainSTEM initiative, created to foster 21st century STEM (Science, Technology, Engineering, Mathematics) skills and entrepreneurial thinking among youth, was an unqualified success, engaging 400,000 students in classrooms, 5,000 teachers, 25,000 parents and children, and 1.5 million viewers on television and online.

The Institute continued to work with partners at all levels of government to provide insight and guidance on science-related public policy initiatives. Perimeter contributed substantively to the consultation process for *Seizing Canada's Moment: Moving Forward in Science, Technology and Innovation.* Staff provided briefings to key ministries, agencies, and government leaders at Perimeter, in Ottawa, and in Toronto. Perimeter leaders, including Chief Operating Officer Michael Duschenes and

Director Neil Turok, have lent their expertise via talks and meetings with Industry Canada Officials (at its Distinguished Speaker Series), Deputy Ministers (at the Canada School of Public Service's Deputy Minister Seminar Series), and regional leaders (at the Canada's Technology Triangle International Dinner and Reception).

Private Partners

Private partners who share and invest in Perimeter's vision are crucial to the Institute's ability to attain and sustain global leadership in theoretical physics research, training, and outreach over the long term. Through their support, private donors demonstrate their commitment to fundamental science as a driver of next-generation science and technology, and ultimately societal well-being.

Perimeter's long-term Advancement strategy encompasses both high net worth individuals, foundations whose missions align with Perimeter's, corporations, and individuals who want to share in the joy and excitement of discovery. Efforts to date have focused primarily on prospects with highest potential return, though efforts to raise awareness and widen Perimeter's base of support expanded substantially in 2013/14.

In 2013/14, Perimeter attracted more than $5.1 million in private-sector support, including $4 million from the Krembil Foundation to create a pair of Perimeter Research Chairs for world-leading scientists Davide Gaiotto (The Krembil Foundation Galileo Chair in Theoretical Physics) and Kevin Costello (The Krembil Foundation William Rowan Hamilton Chair in Theoretical Physics). Notably, this is the first time the Krembil Foundation has invested outside of healthcare.

In addition, Perimeter Institute secured support from a variety of corporations, foundations, and individual supporters, including the following:

- **Emmy Noether Circle and Council:** Perimeter's initiative to foster and support female physicists gained significant momentum and support. Perimeter hosted an event in celebration of International Women's Day, attended by members of the Emmy Noether Council, donors, prospects, and a panel of influential women from a variety of backgrounds (physics, banking, mining, technology, etc.). The Emmy Noether initiatives attracted new gifts from Deloitte, Scotiabank, the Beatrice Snyder Foundation, and individual donors.
- **The Perimeter Director's Circle:** Donors in this circle have given gifts of $1,000 or more to the Institute. Membership in this circle grew this past year to reach 34 supporters, many of whom have made multi-year pledges.
- **BrainSTEM:** In addition to the funding from FedDev Ontario, the BrainSTEM suite of resources and educational outreach activities was supported by corporate donors including Linamar Corporation, Toyota Motor Manufacturing Canada Inc., Drake Entertainment, Desire2Learn, and Maplesoft.

Perimeter Institute's Advancement department continued to identify and cultivate prospective private donors. These new prospects were largely identified and cultivated through a number of special events, such as speaking engagements and public events at Perimeter, across Canada, and internationally.

- November 2013: Director Neil Turok was the keynote speaker at a "Ramsay Talk" event attended by donors and top prospects in Toronto.
- December 2013: COO Michael Duschenes and Director Neil Turok delivered the keynote speeches at the Canadian Technology Triangle's annual dinner, attended by hundreds of leaders from Ontario's high-tech and political sectors.
- November 2013 and April 2014: Perimeter representatives had meetings regarding possible collaborations with leaders at Goldman Sachs, IBM, and the New York Academy of Sciences.
- October 2013 and April 2014: Neil Turok addressed the at METal event in Los Angeles, followed by meetings with Elon Musk (CEO SpaceX, Tesla Motors) and David Fransen (Consul General, Los Angeles).
- May 2014: In conjunction with Communitech, Perimeter hosted 15 delegates from Nova Scotia – representing both the Premier's office and the province's top academic institutions – as well as 10 local business and academic leaders.

Annual Fund and Alumni Program

This year, Perimeter has launched new Annual Fund and Alumni Programs aimed at cultivating individual donors. This involved building a comprehensive campaign focused on engaging Perimeter alumni across the globe and motivating regional friends of the Institute to become entry-level donors.

Efforts to raise broader awareness and support included creative pieces distributed through social media like "Slices of Pi" (see Objective 8), increased outreach to Perimeter alumni, and improved online donation capabilities, which resulted in a substantial increase in the number of online donations over last year.

Major Gifts Director Appointed

In March 2014, Perimeter recruited Andrea Grimm as Director of Major Gifts. Grimm has over 25 years of experience in the development sector. She was recently the Chief Development Officer for the Alzheimer Society of Canada, and has held key roles advancing education, research, and health. She served as the Principal Gift Officer for a $400 million campaign for McMaster University and has also had leadership roles with the Canadian Cancer Society and the United Way of St. Croix, among others.

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

Summarized Financial Statements of

PERIMETER INSTITUTE

Year Ended July 31, 2014

ZEIFMANS LLP
CHARTERED ACCOUNTANTS

ZEIFMANS
LLP
CHARTERED ACCOUNTANTS

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REPORT OF THE INDEPENDENT AUDITORS ON THE SUMMARY FINANCIAL STATEMENTS

To the Directors of
Perimeter Institute

The accompanying summary financial statements, which comprise the summary statement of financial position as at July 31, 2014 and the summary statement of operations and changes in fund balances for the year then ended, are derived from the audited financial statements of Perimeter Institute (the "Institute") for the year ended July 31, 2014. We expressed an unmodified audit opinion on those financial statements in our report dated December 12, 2014. Those financial statements, and the summary financial statements, do not reflect the effects of events that occurred subsequent to the date of our report on those financial statements.

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

Management's Responsibility for the Summary Financial Statements

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

Auditor's Responsibility

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

Opinion

In our opinion, the summary financial statements derived from the audited financial statements of the Institute for the year ended July 31, 2014 are a fair summary of those financial statements, in accordance with Canadian accounting standards for not-for-profit organizations.

Zeifmans LLP

Toronto, Ontario
December 12, 2014

Chartered Accountants
Licensed Public Accountants

PERIMETER INSTITUTE

Summarized Statement of Financial Position
as at July 31, 2014

	2014	2013
ASSETS		
Current Assets:		
Cash and cash equivalents	$ 15,958	$ 11,774
Marketable securities	264,333	232,514
Government grants receivable	5,680	2,321
Other current assets	809	1,599
	286,780	248,208
Property and equipment	49,457	52,808
TOTAL ASSETS	$ 336,237	$ 301,016
LIABILITIES AND FUND BALANCE		
Current liabilities:		
Accounts payable and other current liabilities	$ 1,692	$ 2,487
TOTAL LIABILITIES	1,692	2,487
Fund balances:		
Invested in capital assets	49,974	52,319
Externally restricted	121,873	126,801
Internally restricted	78,840	78,840
Unrestricted	83,858	40,569
TOTAL FUND BALANCES	334,545	298,529
	$ 336,237	$ 301,016

ZEIFMANS LLP
CHARTERED ACCOUNTANTS

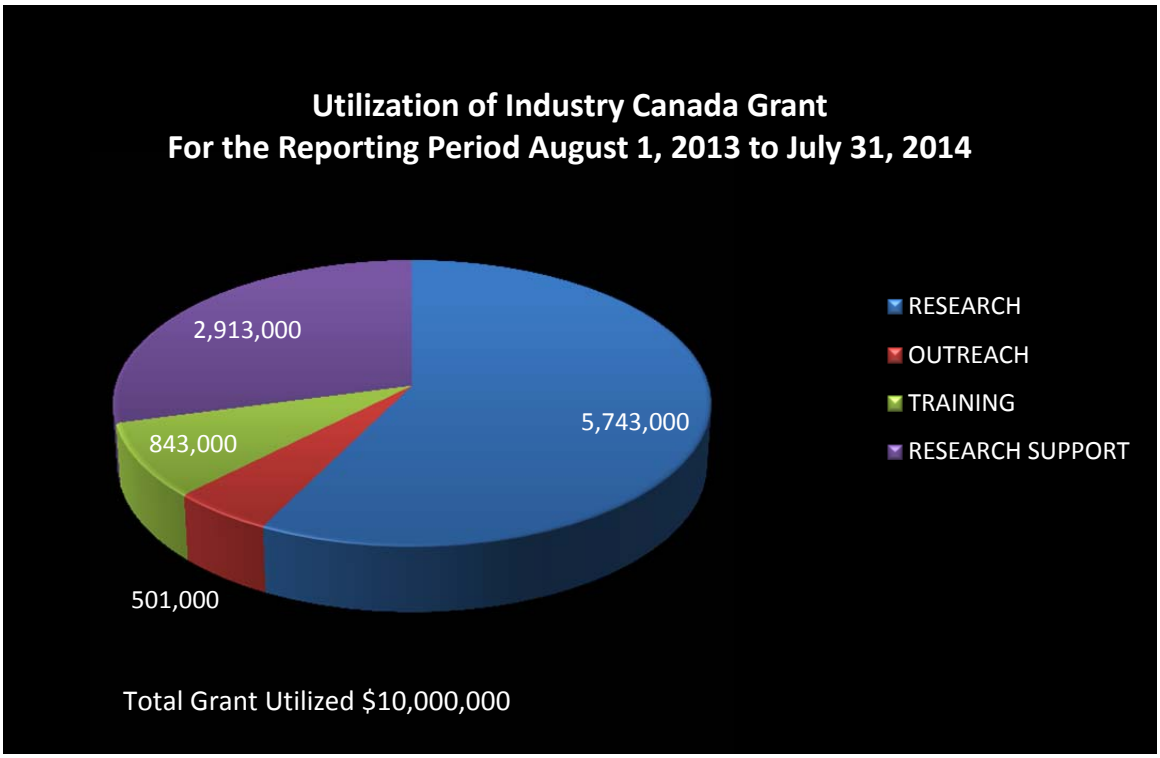
PERIMETER INSTITUTE

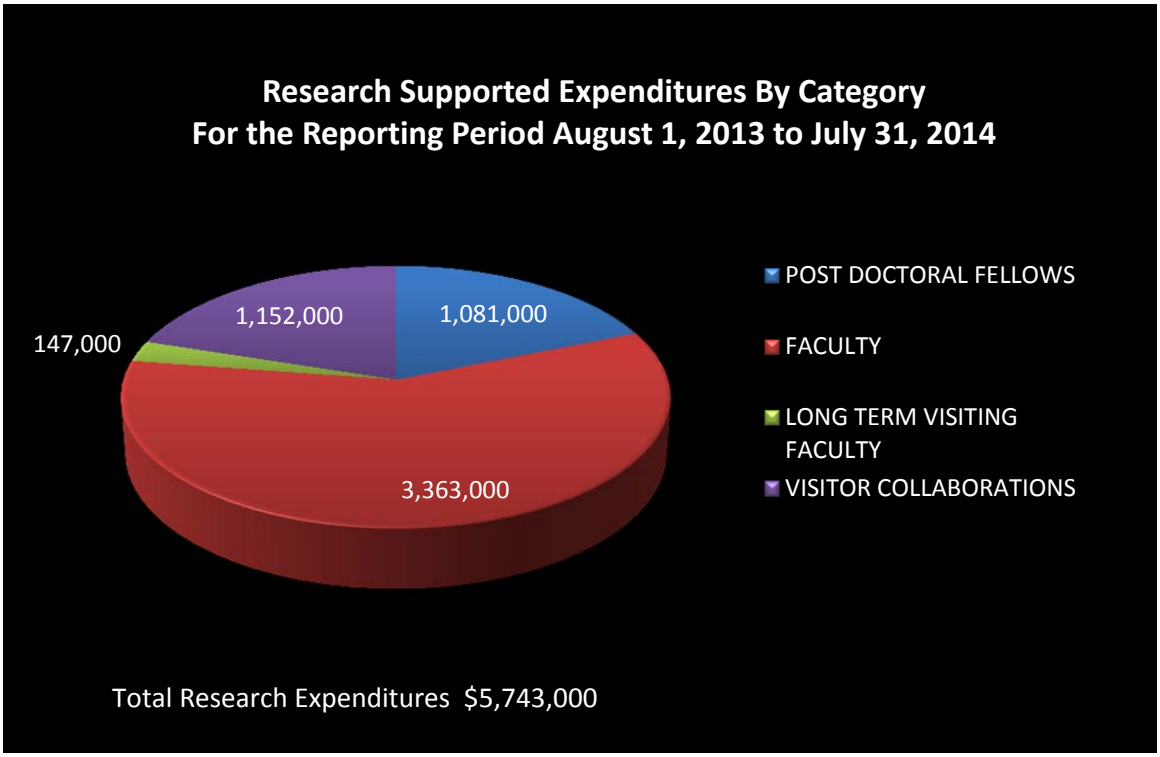
Summarized Statement of Operations and Changes in Fund Balances
For the Year Ended July 31, 2014

	2014	2013
Revenue		
Government grants	$ 19,526	$ 23,837
Other income	1,424	1,446
Donations	761	909
	21,711	26,192
Expenditures		
Research	12,517	11,913
Research training	2,034	1,983
Outreach and science communications	3,171	3,080
Indirect research and operations	5,770	5,697
	23,492	22,673
Excess of revenue over expenditures (expenditures over revenue) before investment and amortization impacts	(1,781)	3,519
Amortization	(3,838)	(4,129)
Investment income	41,635	29,372
Excess of revenue over expenditures	36,016	28,762
Fund balances, beginning of year	298,529	269,767
Fund balances, end of year	$ 334,545	$ 298,529

ZEIFMANS LLP
CHARTERED ACCOUNTANTS

Expenditure of Industry 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 initiatives to measure outcomes, results, and impact include:

Performance Monitoring – Internal

- Annual reports on research activity submitted to the director by all faculty and associate faculty members for evaluation
- Annual performance reviews of all research 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 fellow mentorship program
- Monitoring of postdoctoral fellows' 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 E for a list of SAC members)
- Review of faculty hires and promotions by Scientific Advisory Committee
- Peer review of publications
- 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 D: 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 Chief Operating Officer (COO) reports to the Director and is in charge of day-to-day operations. Support to the COO is provided by a team of senior 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 and report to the Director.

The Scientific Advisory Committee (SAC), comprised of eminent international scientists (see Appendix E: Scientific Advisory Committee), offers independent scrutiny and advice, helping to ensure Perimeter's activities meet high standards of scientific excellence. Members serve three-year terms and participate in regular meetings held at the Institute to thoroughly review PI's scientific, training, and educational outreach programs, after which the Chair writes a report to the Board of Directors and the Institute Director.

Objectives for 2014/15

Statement of Objectives, 2014/15

The successes outlined in the preceding pages provide strong evidence that the Institute's strategic planning has been both sound and effective, and that it is well 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 research breakthroughs that will transform our future.

In the coming year, the Institute will continue upon its present course in order to advance its core mission and goals, based upon the following strategic objectives.

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

Appendices

Note: Where applicable, appendices reflect the Perimeter community as of July 31, 2014.

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. 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 were 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 (CIFAR) Fellow in Cosmology and Gravity and a Senior Fellow of Massey College in 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 four centres – in South Africa, Senegal, Ghana, and Cameroon – 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 (WSIE) and the World Innovation Summit on Education (WISE).

Dmitry Abanin (PhD Massachusetts Institute of Technology, 2008) joined Perimeter in 2012 from Harvard University, where he had been a postdoctoral fellow since 2011. Previously, he was a Research Scholar at the Princeton Center for Theoretical Science from 2008 to 2011. 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, University of Manchester, Columbia University, University of California, Riverside, the Max Planck Institute, and elsewhere.

Asimina Arvanitaki (PhD Stanford University, 2008) joined Perimeter's faculty in March 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. She pioneered the use of optically levitated dielectric objects to detect gravitational waves. Arvanitaki also works on theoretical challenges raised by experimental results, such as a model of particle physics influenced by string theory called “split SUSY.”

Latham Boyle (PhD Princeton University, 2006) joined the Institute as a junior faculty member in 2010. From 2006 to 2009, he held a Canadian Institute for Theoretical Astrophysics (CITA) Postdoctoral Fellowship; he is also a Junior Fellow of the Canadian Institute for Advanced Research (CIFAR). 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 recently constructed the theory of ‘porcupines’: networks of low-frequency gravitational wave detectors that function together as gravitational wave telescopes.

Freddy Cachazo (PhD Harvard University, 2002) has been a faculty member at Perimeter 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 quantum chromodynamics (QCD) and N=4 super Yang-Mills (MSYM) theories. His many honours include an Early Researcher Award (2007), the Gribov Medal of the European Physical Society (2009), the Rutherford Memorial Medal in Physics from the Royal Society of Canada (2011), and the Herzberg Medal (2012).

Bianca Dittrich (PhD Max Planck Institute for Gravitational Physics, 2005) joined Perimeter’s faculty in January 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. In 2007, Dittrich received the Otto Hahn Medal of the Max Planck Society, which recognizes outstanding young scientists.

Laurent Freidel (PhD L’École Normale Supérieure de Lyon, 1994) joined Perimeter Institute in September 2006. Freidel is a mathematical physicist who has made many notable contributions in the field of quantum gravity; he possesses outstanding knowledge of a wide range of areas including integrable systems, topological field theories, 2D conformal field 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 (CNRS) since 1995. Freidel is also the recipient of several awards, including two ACI-Blanche grants in France.

Davide Gaiotto (PhD Princeton University, 2004) joined Perimeter in May 2012. 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 several major conceptual advances that have potentially

revolutionary implications. 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 (2012).

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 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 40 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 (CIFAR) and a Fellow of the American Physical Society (APS).

Lucien Hardy (PhD University of Durham, 1992) joined Perimeter's faculty in 2002, having previously held research and lecturing positions at various European universities including the University of Oxford, Sapienza University of Rome, the University of Durham, the University of Innsbruck, and the National University of Ireland. In 1992, he found a very simple proof of non-locality in quantum theory which has become known as Hardy's theorem. He currently works on characterizing quantum theory in terms of operational postulates and applying the insights obtained to the problem of quantum gravity.

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

Robert Myers (PhD Princeton University, 1986) is one of the leading theoretical physicists working in string theory in Canada. After attaining his PhD, he was a postdoctoral researcher at the Institute for Theoretical Physics at the University of California, Santa Barbara, and a Professor of Physics at McGill University, before moving to Perimeter in 2001. He has made seminal contributions to our understanding of black hole microphysics and D-branes. Among Myers' many honours, he has received the 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 (CIFAR).

Subir Sachdev (PhD Harvard University, 1985) became the James Clerk Maxwell Chair in Theoretical Physics at Perimeter Institute in February 2014 (on a visiting basis). 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.

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 (CMS) 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.

Kendrick Smith (PhD University of Chicago, 2007) joined Perimeter in September 2012 from Princeton University, where he was the Lyman P. Spitzer Postdoctoral Fellow since 2009. Prior to that, he held the PPARC Postdoctoral Fellowship at the University of Cambridge from 2007 to 2009. Smith is a cosmologist with a foot in the worlds of both theory and observation. He is a member of several experimental teams, including the WMAP collaboration, which won the 2012 Gruber Cosmology Prize, as well as QUIET 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 is currently on a one-year leave of absence to participate in the start-up phase of the major Hyper-Suprime Cam project at the Hawaii-based Subaru telescope, after which he will bring full data rights to Perimeter. Smith 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 research positions at the Institute for Advanced Study, the Institute for Theoretical Physics at the University of California, Santa Barbara, the Enrico Fermi Institute at the University of Chicago, Yale University, Syracuse University, and Pennsylvania State University. Smolin's research is centred on the problem of quantum gravity, with particular focus on loop quantum gravity and deformed special relativity, though his contributions span many areas. His papers have generated over 6,400 citations to date and he has written four non-technical books. Smolin's many

honours include the Majorana Prize (2007), the Klopsteg Memorial Award (2009), 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 research is focused upon identifying the conceptual innovations that distinguish quantum theories from classical theories and investigating their significance for axiomatization, interpretation, and the implementation of various information-theoretic tasks. Spekkens is a previous winner of the Birkhoff-von Neumann Prize of the International Quantum Structures Association.

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 upcoming searches at the Compact Muon Solenoid experiment at the Large Hadron Collider (LHC) 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.

Guifre Vidal (PhD University of Barcelona, 1999) joined Perimeter's faculty in 2011 from the University of Queensland in Brisbane, where he was an Australian Research Council Federation Fellow and Professor in the School of Mathematics and Physics. He did postdoctoral fellowships at the University of Innsbruck in Austria and the Institute for Quantum Information at the California Institute of Technology before joining the University of Queensland. Vidal works at the interface of quantum information and condensed matter physics, using tensor networks to compute the ground state of quantum many-body systems on a lattice and to issue a classification of the possible phases of quantum matter or fixed points of the renormalization group flow. His past honours include a Marie Curie Fellowship, awarded by the European Union, and a Sherman Fairchild Foundation Fellowship.

Pedro Vieira (PhD École Normale Supérieure Paris and the Theoretical Physics Center at University of Porto, 2008) joined Perimeter in 2009 from the Max Planck Institute for Gravitational Physics (Albert Einstein Institute), where he was a Junior Scientist 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 related areas of the AdS/CFT correspondence and theoretical calculations of scattering amplitudes. "Y-system for scattering amplitudes," a paper by Vieira and his collaborators, won the 2012 Best Paper Prize from the Institute of Physics (IOP) and the Editorial Board of *Journal of Physics A*. He also won an Early Researcher Award in 2012.

Xiao-Gang Wen (PhD Princeton University, 1987) joined Perimeter's faculty in May 2012. Widely recognized as one of the world's leaders in condensed matter theory, he pioneered the new paradigm of quantum topological order, used to describe phenomena from superconductivity to fractionally charged particles, and he has invented many new mathematical formalisms. Wen authored the textbook *Quantum Field Theory of Many-body Systems: From the Origin of Sound to an Origin of Light and*

Electrons. He was previously a Distinguished Moore Scholar at the California Institute of Technology and the Cecil and Ida Green Professor of Physics at the Massachusetts Institute of Technology, as well as one of Perimeter's own Distinguished Visiting Research Chairs. He is also a Fellow of the American Physical Society.

Associate Faculty

Niayesh Afshordi (PhD Princeton University, 2004) is jointly appointed with the University of Waterloo. He was the Institute for Theory and Computation Fellow at the Harvard-Smithsonian Center for Astrophysics from 2004 to 2007 and a Distinguished Research Fellow at Perimeter Institute from 2008 to 2009. Afshordi began his appointment as an associate faculty member in 2010. 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 (NSERC).

Avery Broderick (PhD California Institute of Technology, 2004) began a joint appointment with Perimeter and the University of Waterloo in 2011. He previously held postdoctoral positions at the Institute for Theory and Computation at the Harvard-Smithsonian Center for Astrophysics (2004-07) and the Canadian Institute for Theoretical Astrophysics (2007-11). Broderick is an astrophysicist with broad research interests, ranging from how stars form to the extreme physics in the vicinity of white dwarfs, neutron stars, and black holes. He has recently been part of an international effort to produce and interpret horizon-resolving images of supermassive black holes, studying how black holes accrete matter, launch the ultra-relativistic outflows observed, and probe the nature of gravity in their vicinity.

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

Raffi Budakian (PhD University of California, Los Angeles, 2000) joined Perimeter in June 2014, jointly appointed with the Institute for Quantum Computing at the University of Waterloo, where he holds the Nanotechnology (WIN) Endowed Chair in Superconductivity. Budakian comes to Waterloo from the University of Illinois at Urbana-Champaign. Prior to joining the faculty there, he held research positions at the University of California, Los Angeles, and the IBM Almaden Research Center in San Jose. Budakian 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) is jointly appointed with the Institute for Quantum Computing and the University of Waterloo. He held research positions at the University of Nijmegen in The Netherlands, the National Research Council at the Naval Research Laboratory in Washington, D.C., and the Massachusetts Institute of Technology. He also led research and development activities in nuclear magnetic resonance at Bruker Instruments. 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 (CIFAR).

James Forrest (PhD University of Guelph, 1994) joined Perimeter in February 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 August 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 cosmologist, whose interdisciplinary research seeks to understand how the universe began, how it evolved, and where it is headed. To this end, he designs data analysis algorithms to confront fundamental theory with observations of the cosmic microwave background radiation. In 2012, Johnson was awarded a New Frontiers in Astronomy and Cosmology grant from the University of Chicago and the John Templeton Foundation.

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 Research 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, 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 using quantum field theory, as well as the intersections between condensed matter and high energy physics. His recent work has included using gauge theory as a lens through which to examine the phenomenon of fractionalization, efforts to apply the AdS/CFT correspondence from string theory to quantum chromodynamics and condensed matter, and building a non-perturbative approach to understanding unconventional metallic states of matter.

Roger Melko (PhD University of California, Santa Barbara, 2005) joined Perimeter in September 2012, while retaining his appointment with the University of Waterloo, where he has been since 2007. Prior to that, he was a Wigner Fellow at Oak Ridge National Laboratory (2005-07). Melko is a condensed matter theorist who develops new computational methods and algorithms to study strongly correlated many-body systems, focusing on emergent phenomena, ground state phases, phase transitions, quantum criticality, and entanglement. Among his honours, he has received an Early Researcher Award, the International Union of Pure and Applied Physics Young Scientist Prize in Computational Physics from the Council on Computational Physics, and the 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 at the University of Waterloo. He is a founding member of Perimeter Institute, as well as co-founder and Deputy Director of the Institute for Quantum Computing. 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 (CIFAR) since 2010, Canada Research Chair in Quantum Computation (2002-12), and University Research Chair at the University of Waterloo (2012-present).

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

Itay Yavin (PhD Harvard University, 2006) began a joint appointment with Perimeter and McMaster University in 2011. Previously, he was a Research Associate at Princeton University and a James Arthur Postdoctoral Fellow at New York University. Yavin's research focuses on particle physics and the search for physics beyond the Standard Model. In particular, he is interested in the origin of electroweak

symmetry breaking and the nature of dark matter. Most recently, he has worked on interpreting puzzling data coming from experiments looking for dark matter in the lab.

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 Professor Aharonov 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, a previous long-term visitor at PI, and a lecturer for the Perimeter Scholars International master's program. Professor Arkani-Hamed has developed theories on emergent extra dimensions, 'little Higgs theories', and recently proposed new models that can be tested using the Large Hadron Collider (LHC) at CERN in Switzerland. In 2012, he 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, and a Fellow of both the American Physical Society and the 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. Dr. Bardeen received his PhD from Caltech under the direction of Richard Feynman.

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

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 a Professor of Physics at the University of Maryland, College Park, and she will begin a new appointment in September 2014 as Director of the Astrophysical and Cosmological Relativity division of the Max Planck Institute for Gravitational Physics (Albert Einstein Institute) in Potsdam, Germany. She is also a member of the Maryland Center for Fundamental Physics, the Joint Space-Science Institute, and the LIGO Scientific Collaboration. 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.

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 groundbreaking 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. He has over 160 publications.

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. Dr. 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 (AAPT), and the US National Medal of Science. Dr. 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 is 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 Penn 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, Professor 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. Professor Hawking 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. Professor 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 Dr. Hayden's honours, he 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.

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.

Leo Kadanoff is a theoretical physicist and applied mathematician based at the James Franck Institute at the University of Chicago. He is a pioneer of complexity theory and has made important contributions to research in the properties of matter, the development of urban areas, statistical models of physical systems, and the development of chaos in simple mechanical and fluid systems. He is best known for the development of the concepts of 'scale invariance' and 'universality' as they are applied to phase transitions. More recently, he has been involved in the understanding of singularities in fluid flow. Among Dr. Kadanoff's many honours, he is a past recipient of the US National Medal of Science, the Grande Medaille d'Or of the Académie des Sciences de l'Institut de France, the Wolf Foundation Prize, the Boltzmann Medal of the International Union of Pure and Applied Physics, and the Centennial Medal of Harvard University. He is also a past President of the American Physical Society.

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'. Dr. 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.

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. He is a past recipient of the Adams Prize (Cambridge) and the Clifford Patterson Prize of the Royal Society (UK).

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, in 2007, Dr. Pretorius was awarded a Sloan Research Fellowship and was the 2010 recipient of the Aneesur Rahman Prize for Computational Physics of the American Physical Society. He is also a Scholar in the Canadian Institute for Advanced Research (CIFAR) Cosmology and Gravity program.

Peter Shor is the Morss Professor of Applied Mathematics at MIT. 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).

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.

Paul Steinhardt is the Albert Einstein Professor in Science and Director of the Princeton Center for Theoretical Science at Princeton University. Dr. Steinhardt is a Fellow in the American Physical Society (APS) and a member of the National Academy of Sciences. He shared the P.A.M. Dirac Medal from the International Centre for Theoretical Physics for the development of the inflationary model of the universe, and the Oliver E. Buckley Prize of the APS for his contributions to the theory of quasicrystals. His research interests include particle physics, astrophysics, cosmology, and condensed matter physics. Recently, with Neil Turok, he has developed a cyclic model for cosmology, according to which the big bang is explained as a collision between two 'brane-worlds' in M-theory. In addition to his continued research on inflationary and cyclic cosmology, Steinhardt has been one of the developers of a new class of disordered 'hyperuniform' photonic materials with complete bandgaps, and he conducted a systematic search for natural quasicrystals that has culminated in discovering the first known example. He is currently organizing an expedition to Far Eastern Russia to find more samples and study the local geology where they are found.

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, Professor Susskind has also made seminal contributions to particle physics, black hole theory, and cosmology. His 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, Dr. '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). Dr. '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 (CIFAR).

Senthil Todadri is an Associate Professor of Physics at the Massachusetts Institute of Technology (MIT). Dr. 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. Dr. 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.

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. Dr. 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 on an indefinite leave. 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. Dr. 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 C: Affiliate Members

Name	Institution	Research Area(s)
Ian Affleck	University of British Columbia	Condensed Matter
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 Waterloo/Institute for Quantum Computing (IQC)	Quantum Information
Anton Burkov	University of Waterloo	Condensed Matter
Bruce Campbell	Carleton University	Particle Physics
Benoit Charbonneau	St. Jerome's University/University of Waterloo	Mathematical Physics
Gang Chen	University of Toronto	Condensed Matter
Jeffrey Chen	University of Waterloo	Condensed Matter
Andrew Childs	University of Waterloo/IQC	Quantum Information
Kyung Soo Choi	University of Waterloo/IQC	Quantum Information
Matthew Choptuik	University of British Columbia	Strong Gravity
Dan Christensen	Western University	Quantum Gravity
Aashish Clerk	McGill University	Condensed Matter

Name	Institution	Research Area(s)
James Cline	McGill University	Cosmology, Particle Physics
Alan Coley	Dalhousie University	Strong Gravity
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
Andrei Frolov	Simon Fraser University	Cosmology
Valeri Frolov	University of Alberta	Cosmology, Quantum Gravity
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, Quantum Computation
Florian Girelli	University of Waterloo	Quantum Gravity, Applied Math
Stephen Godfrey	Carleton University	Particle Physics
Thomas Gregoire	Carleton University	Particle Physics
John Harnad	Concordia University	Mathematical Physics

Name	Institution	Research Area(s)
Jeremy Heyl	University of British Columbia	Astrophysics
Gilbert Patrick Holder	McGill University	Astrophysics
Bob Holdom	University of Toronto	Particle Physics
Michael Hudson	University of Waterloo	Cosmology
Viqar Husain	University of New Brunswick	Cosmology, Quantum Gravity
Thomas Jennewein	University of Waterloo/IQC	Quantum Information
Catherine Kallin	McMaster University	Condensed Matter
Joanna Karczmarek	University of British Columbia	Quantum Fields and Strings
Spiro Karigiannis	University of Waterloo	Mathematical Physics, Differential Geometry
Mikko Karttunen	University of Waterloo	Condensed Matter, Biology
Achim Kempf	University of Waterloo	Quantum Information
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, Quantum Mechanics
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
Norbert Lütkenhaus	University of Waterloo/IQC	Quantum Information

Name	Institution	Research Area(s)
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
Gerry McKeon	Western University	Particle Physics
Brian McNamara	University of Waterloo	Cosmology
Volodya Miransky	Western University	Quantum Information
Guy Moore	McGill University	Particle Physics
Ruxandra Moraru	University of Waterloo	Mathematical Physics, Pure Math
David Morrissey	TRIUMF Canada	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
Arun Paramekanti	University of Toronto	Condensed Matter
Manu Paranjape	University of Montreal	Particle Physics
Amanda Peet	University of Toronto	Quantum Foundations, Quantum Fields and Strings
Ue-Li Pen	University of Toronto/CITA	Cosmology
Alexander Penin	University of Alberta	Condensed Matter, Particle Physics

Name	Institution	Research Area(s)
Tamar Pereg-Barnea	McGill University	Condensed Matter
Harald Pfeiffer	University of Toronto/CITA	Strong Gravity
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
Moshe Rozali	University of British Columbia	Quantum Fields and Strings
Barry Sanders	University of Calgary	Quantum Information
Veronica Sanz-Gonzalez	York University	Particle Physics, High Energy Physics
Kristin Schleich	University of British Columbia	Strong Gravity
Achim Schwenk	Darmstadt University of Technology	Particle Physics
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

Name	Institution	Research Area(s)
John Sipe	University of Toronto	Condensed Matter, Quantum Foundations
Philip Stamp	University of British Columbia	Cosmology
Aephraim Steinberg	University of Toronto	Quantum Information
Alain Tapp	University of Montreal	Quantum Information
James Taylor	University of Waterloo	Cosmology
Andre-Marie Tremblay	University of Sherbrooke	Condensed Matter
Mark Van Raamsdonk	University of British Columbia	Quantum Fields and Strings
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
Frank Wilhelm-Mauch	University of Waterloo/IQC	Condensed Matter
Don Witt	University of British Columbia	Particle Physics, Quantum Fields and Strings
Bei Zeng	University of Guelph	Quantum Information

Appendix D: Board of Directors

Mike Lazaridis, O.C., O.Ont., Chair, is the Founder of BlackBerry (formerly Research In Motion Limited) and recently founded the Quantum Valley Investment Fund to provide financial and intellectual capital for the development and commercialization of quantum physics and quantum computing breakthroughs. A visionary, innovator, and engineer of extraordinary talent, he transformed the communications industry with the development of the BlackBerry®. He is the recipient of many technology and business awards, a Fellow of the Royal Society of Canada, and a recipient of both the Order of Ontario and the Order of Canada.

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

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

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

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

Art McDonald has been the Director of the Sudbury Neutrino Observatory (SNO) experiment for over 20 years. He holds the Gordon and Patricia Gray Chair in Particle Astrophysics at Queen's University and works on the new SNO+ and DEAP experiments at the international SNOLAB, researching an accurate measurement of neutrino mass and seeking to observe directly dark matter particles making up a large fraction of the universe. Professor McDonald has received numerous awards for his research, including the 2011 Henry Marshall Tory Medal from the Royal Society of Canada and the 2007 Benjamin Franklin Medal in Physics, alongside researcher Yoji Totsuka. He was named an Officer of the Order of Canada in 2007.

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

Michael Serbinis is the founder and CEO of The Everlong Project, a new digital health startup launching 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 $110M in sales in its very first year, becoming the only global competitor to Amazon's Kindle with 20 million customers in 190 countries. He is currently the founder of Three Angels Capital, a member of the Board of Trustees at the Ontario Science Centre, and a member of YPO. He holds a BSc in engineering physics from Queen's University and an MSc in industrial engineering from the University of Toronto.

Appendix E: 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 (2010-Present), 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.' Professor Loll heads one of the largest research groups on non-perturbative quantum gravity worldwide and is the recipient of a prestigious personal VICI-grant of the Netherlands Organisation for Scientific Research.

Ganapathy Baskaran, Institute of Mathematical Sciences, Chennai (2013-Present)
Professor Baskaran is an Emeritus Professor at the Institute of Mathematical Sciences, Chennai in India, where he recently founded the Quantum Science Centre. He has made important contributions to the field of strongly correlated quantum matter. His primary research focus is novel emergent quantum phenomena in matter, including biological ones. He is well known for his contributions to the theory of high temperature superconductivity and for discovering emergent gauge fields in strongly correlated electron systems. He predicted p-wave superconductivity in Sr_2RuO_4, a system believed to support Majorana fermion mode, which is a popular qubit for topological quantum computation. In recent work, he predicted room temperature superconductivity in optimally doped graphene. From 1976 to 2006, Dr. Baskaran contributed substantially to the Abdus Salam International Centre for Theoretical Physics in Trieste, Italy. He is a past recipient of the S.S. Bhatnagar Award from the Indian Council of Scientific and Industrial Research (1990); the Alfred Kasler ICTP Prize (1983); Fellowships of the Indian Academy of Sciences (1988), the Indian National Science Academy (1991), and the Third World Academy of Sciences (2008); and the Distinguished Alumni Award of the Indian Institute of Science, Bangalore (2008).

Mark Wise, California Institute of Technology (2013-Present)
Professor Wise is the John A. McCone Professor of High Energy Physics at the California Institute of Technology. He has conducted research in elementary particle physics and cosmology, and shared the 2001 Sakurai Prize for Theoretical Particle Physics for the development of the 'Heavy Quark Effective Theory' (HQET), a mathematical formalism that enables physicists to make predictions about otherwise intractable problems in the theory of the strong interactions of quarks. He has also published work on mathematical models for finance and risk assessment. Dr. 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 F: Perimeter's Research Ties to Experiment

Perimeter scientists are connected to many of the world's most important experimental efforts. This is a representative sample of such involvement from Perimeter faculty members and associate faculty members.

- **Dmitry Abanin** works directly with several leading groups of graphene experimentalists, including those headed by Philip Kim and Amir Yacoby (the Harvard graphene groups)[32] and by Alberto Morpurgo (the Geneva graphene group).[33] He also works with an experimental group in Munich on questions related to cold atoms and many-body dynamics.
- **Asimina Arvanitaki** is part of the ARIADNE collaboration (Axion Resonant InterAction DetectioN Experiment) which is looking for axion mediated interactions in matter.
- **Avery Broderick** is a member of the Event Horizon Telescope project (http://www.eventhorizontelescope.org), 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 (https://uwaterloo.ca/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.
- **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 startup commercializing spinoffs of quantum information research.
- **Maxim Pospelov** is an associate member of the BaBar collaboration (http://www.slac.stanford.edu/BFROOT), which studies the physics of b-quarks and other intermediate mass particles. He also directly collaborates with experimental physicists at TRIUMF (http://www.triumf.ca) and Fermilab (http://www.fnal.gov).
- **Philip Schuster and Natalia Toro** work jointly, and have extensive connection 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 (http://home.web.cern.ch/topics/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.[34] They are spokespeople for APEX.

[32] Refer to http://kim.physics.harvard.edu and http://yacoby.physics.harvard.edu.
[33] Refer to http://dpmc.unige.ch/gr_morpurgo.
[34] 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[35] and the ground-based CAPMAP and QUIET CMB experiments.[36] He is also involved in the HSC survey (http://subarutelescope.org/Projects/HSC/HSCProject.html), a new experiment to observe distant galaxies using the Subaru telescope.
- **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 (http://recast.it), 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.[37]

Perimeter also connects to experiment through its conference program, with several conferences in 2013/14 revolving directly around experimental findings and challenges. These included:

- **"Implications of BICEP2"**: In March, the cosmic microwave background experiment BICEP 2 announced that it had detected primordial gravitational waves. In April, Perimeter hosted the first conference on the implications of this result, bringing the BICEP experimental team together with other experimentalists and with theorists.[38]
- **"Low Energy Challenges for High Energy Physicists"**: This May conference united experimentalists from particle physics with experimentalists from condensed matter physics, and theorists interested in both.[39]
- **"International Workshop on Quantum LDPC Codes"**: This high-level workshop brought together theorists, experimental physicists, and computer scientists interested in leading-edge problems in quantum information, specifically in the field of quantum error correction.[40]

[35] Refer to http://map.gsfc.nasa.gov and http://www.cosmos.esa.int/web/planck.
[36] Refer to http://cfcp.uchicago.edu/research/projects/capmap.html and http://quiet.uchicago.edu.
[37] For more on RECAST, refer to http://arxiv.org/abs/1010.2506.
[38] For more information, refer to http://www.perimeterinstitute.ca/conferences/implications-bicep-2.
[39] For more information, refer to http://www.perimeterinstitute.ca/conferences/low-energy-challenges-high-energy-physicists.
[40] For more information, refer to http://www.perimeterinstitute.ca/conferences/international-workshop-quantum-ldpc-codes.

Appendix G: Media Highlights

In 2013/14, Perimeter Institute received coverage in both national and international media, including *The Globe and Mail*, *Wired.com, Maclean's*, TVO, CBC, BBC News, *Nature*, and *Scientific American*, among others. Highlights are included below.

Outlet	Headline	Date	Summary
GlobeAdvisor.com, *Report on Business – The Globe and Mail*	How can Canada produce more creative business thinkers?	August 8, 2013	Neil Turok was interviewed as part of the Canada Competes project, which aims to take the debate on Canada's global competitiveness further by asking influential Canadians to offer solutions to several of the concerns that are keeping us from performing at our full potential.
***Wired Science* – Wired.com**	Is That Quantum Computer for Real? There May Finally Be a Test	August 23, 2013	This article discusses the current state of quantum computation with Daniel Gottesman of Perimeter Institute quoted on computation by teleportation, developed in 1999.
Maclean's	Jacob Barnett, boy genius	September 1, 2013	As a result of Paul Wells' three-day visit to Perimeter, *Maclean's* published a five-page article on Jacob Barnett and his intriguing personal story, including his diagnosis with autism, how his mother encouraged him to pursue his gift, and how he ultimately ended up attending Perimeter Institute in the Perimeter Scholars International program. This article was supplemented with online rich media and a subsequent live-chat with Paul Wells, Jacob, and Kristine Barnett.
Maclean's	Perimeter Institute and the crisis in modern physics	September 5, 2013	As a follow-up to Paul Wells' article on Jacob Barnett, this *Maclean's* website blog entry focuses on Neil Turok's interview on the future of theoretical physics and the positioning of Perimeter Institute as a leader in theoretical physics research.
Nature	Did a hyper-black hole spawn the Universe?	September 13, 2013	This article discusses speculation that the universe formed from the debris ejected when a four-dimensional star collapsed into a black hole with reference to Niayesh Afshordi, an astrophysicist at PI.
Nature	Rethinking Particle Dynamics	October 1, 2013	This article identifies scientists working to improve on Richard Feynman's representations of particle interactions with reference to PI's Freddy Cachazo and his research into scattering amplitudes in 'supergravity.'
CTV National News	15-year-old Jacob Barnett: One of the world's most promising	October 1, 2013	CTV National News produced a television segment, and subsequent online feature, on Jacob Barnett and his intriguing personal

	physicists		story.
The Agenda with Steve Paikin	Scientific Literacy for All	October 2, 2013	Live from Perimeter Institute, *The Agenda* examined science without the fear of failure. The panel included Neil Turok, Director of Perimeter Institute.
Physics World	Five People Who Are Changing How We Do Physics: Nurturing the next Einsteins	October 3, 2013	The *Physics World* 25th Anniversary edition features Neil Turok as a top innovator in education and physics in the world.
The Agenda with Steve Paikin	The Challenge of Big Science	October 29, 2013	From the massive postwar effort to put a man on the moon, to the mapping of the human genome, incredible scientific progress has been made through large-scale national or international efforts. But in the age of sovereign debts and shrinking coffers, do we have the political and social will to continue building particle colliders and solving the remaining mysteries of science? This panel discussion included Neil Turok, Director of Perimeter Institute.
Globe and Mail	Waterloo think tank gets even smarter	November 16, 2013	This *Globe and Mail* article by Ivan Semeniuk put the $4-million Krembil Foundation Chairs in the context of a series of high-profile hires by the Perimeter Institute. The online version of the article was featured on the *Globe*'s homepage and the Canada News page.
***Globe and Mail* – supplement**	New model encourages scientists to communicate, work together	November 29, 2013	CFI's special Innovation Report featured comments from PI's Neil Turok on encouraging research activity and stimulating greater science communication involving stakeholders, academia, and the public.
Science News (i09)	Slow, cold start to universe suggested	January 31, 2014	PI's Niayesh Afshordi provides comment on Christrof Wetterich's proposal that fundamental particles become heavier over time while gravity weakens, suggesting a period in the formation of the universe where it inflated but did not expand.
BuzzFeed	If famous physicists had logos	February 3, 2014	"Listicle" of 20 physics logos credited to Prateek Lala and Perimeter Institute.
Fast Company Design	50 rock star logos for physicists	February 5, 2014	Gallery of 50 physics logos credited to Prateek Lala and Perimeter Institute
The Wall Street Journal	Discovery Bolsters Big-Bang Theory	March 17, 2014	*The Wall Street Journal* interviewed Neil Turok about the BICEP2 experiment, the implications for cyclical models, and need for caution.
BBC News	Stephen Hawking 'wins inflation debate'	March 18, 2014	BBC Radio 4 reported that Stephen Hawking had claimed victory in a bet he has with Neil Turok. Both Hawking and Turok were interviewed, with Turok sharing details of a bet that is not over yet.

BuzzFeed	14 Science Facts To Make You Smarter This Summer	June 23, 2014	BuzzFeed's list of fun summer science facts, some of which were relayed from the Institute's June Slice of PI, *The Physics of Summer*. Perimeter Institute is referenced at the end of the list.
CBC.ca **Syndicated by Yahoo! Canada, *Huffington Post Canada*, and e! Science News**	Albert Einstein's hobbies and those of 9 other physicists revealed	July 19, 2014	This article showcases the July Slice of PI, "What Great Scientists Did When They Weren't Doing Great Science." The article discusses the current edition and idea behind the Slice of PI series with PI's Colin Hunter.