
# 2010-11 Annual Report to Industry Canada

Covering the Objectives, Activities and Finances
for the period August 1, 2010 to July 31, 2011 and
Statement of Objectives for Next Year and the Future

Submitted by: Neil Turok, Director
to the Hon. Christian Paradis, Minister of Industry
and the Hon. Gary Goodyear Minister of State (Science and Technology)

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*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.*

## Executive Summary

Perimeter Institute's overarching aim is to create and sustain a world-leading centre for foundational theoretical physics research, training, and outreach, fostering scientific excellence and stimulating major breakthroughs. During 2010-11, the Institute met or exceeded targeted outcomes under each of the Objectives set out last year. Its successes provide compelling evidence that the Institute's strategic planning has been both sound and effective, and that it is on track to achieve its long-term goals.

## Achievement Highlights, 2010-11

- ✓ Obtained funding renewals of $50 million from the Governments of Canada and Ontario, and attracted over $5 million in private funding.[1]

- ✓ Received top marks in an independent review from KPMG, reflecting the findings of a panel of independent international scientific experts and stakeholders.

- ✓ Executed a major facility expansion, the Stephen Hawking Centre at Perimeter Institute, on schedule and on budget.

- ✓ Produced research discoveries of international impact and importance. [2]

- ✓ Recruited world-leading theorist Xiao-Gang Wen from MIT as the BMO Financial Group Isaac Newton Chair in Theoretical Physics, plus three new Faculty members, three Associate Faculty members, and eight internationally eminent scientists as visiting Distinguished Research Chairs.

- ✓ Hired 11 postdoctoral researchers in 2010-11 and recruited 15 postdoctoral researchers for 2011-12 from a field of over 600 applicants, the largest in the Institute's history.

- ✓ Trained 31 students through Perimeter Scholars International (PSI) graduate research training program and completed training of 3 PhD students, in conjunction with surrounding universities.

[1] Perimeter Institute is currently completing a five-year grant agreement with the Government of Canada through Industry Canada, which provided the Institute with $50 million for the period 2008-2012.

[2] PI researchers produced 263 research papers during the one-year period August 1, 2010 –July 31, 2011. Each publication has been counted only once, regardless of how many Perimeter Institute researchers collaborated on it.

- ✓ Hosted 416 visiting scientists for a total of 439 scientific visits, including 380 short-term scientific visitors, 11 long-term Visiting Researchers, 15 Distinguished Research Chairs, and four Visiting Fellows.

- ✓ Held 12 timely, focused conferences and workshops, attended by 653 scientists from around the world, plus 263 scientific talks.

- ✓ Provided logistical and practical support to the African Institute for Mathematical Sciences-Next Einstein Initiative (AIMS-NEI), and helped secure new funding commitments of over $6 million.

- ✓ Held the inaugural Waterloo Global Science Initiative (WGSI) conference, *Equinox Summit: Energy 2030*, to generate effective new ideas on using science to advance our capabilities in energy generation.

- ✓ Delivered engaging and popular lectures and broadcast programs to audiences of over 1 million locally, nationally and internationally through partnership with TVO.

- ✓ Developed new in-class and online educational resources for students and teachers—PI educational modules have been used by over 500,000 students across Canada to date.

- ✓ Reached over 160,000 Canadian high school students in 2010-11 via PI's outreach programs, resources, teacher training, and the International Summer School for Young Physicists camp.

## Overview of Perimeter Institute

Theoretical physics seeks to understand what the universe is made of, and the forces that govern it, at the most basic level. Because the field is so fundamental, just one major discovery can literally change the 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 technologies. Theoretical physics is the lowest-cost, highest-impact field of science.

Located in Waterloo, Ontario, Perimeter Institute for Theoretical Physics (PI) was founded in 1999, the first attempt in history to strategically accelerate discovery in this most basic area of science. Supported through a visionary funding model, it unites public and private partners, and the world's best scientific minds, in a shared quest to achieve the next breakthroughs, which will transform our future.

As of July 31, 2011, the PI community has grown to include:

- 15 full-time Faculty
- 14 Associate Faculty
- 27 Distinguished Research Chairs
- 43 Postdoctoral Researchers
- 27 Graduate students
- 37 Masters level students participating in Perimeter Scholars International

As a major research hub, PI's conference and visitor programs bring over 1,000 scientists to the institute annually, catalyzing new research collaborations and discoveries across the spectrum of fundamental physics.

Science is essential to our society and our future. Thus, an integral part of Perimeter's mission is educational outreach to teachers, students and the general public. PI'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.

*"...What may be the most ambitious intellectual experiment on Earth."*
– New Scientist

## Statement of Objectives for 2010-11

**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 create the world's best environment and infrastructure for theoretical physics research and outreach**

**Objective 4:** **To generate a flow-through of the most promising talent**

**Objective 5:** **To become the second 'research home' for many of the world's outstanding theorists**

**Objective 6:** **To act as a hub for a network of theoretical physics centres around the world**

**Objective 7:** **To increase PI's role as Canada's focal point for foundational physics research**

**Objective 8:** **To host timely, focused conferences, workshops, seminars and courses**

**Objective 9:** **To engage in high impact outreach**

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

# Objective 1: To deliver world-class research discoveries

## Summary of Achievements

- Advanced fundamental research through 263 high calibre papers during 2010-11: Since inception, PI researchers have produced 1692 papers appearing in 50 journals, which have attracted 34,629 citations to date[3], attesting to the importance and long-term impact of PI research
- Received top marks in an independent review conducted by KPMG for Industry Canada, reflecting the findings of a panel of international scientific experts and numerous stakeholders

## Highlights

## KPMG Audit

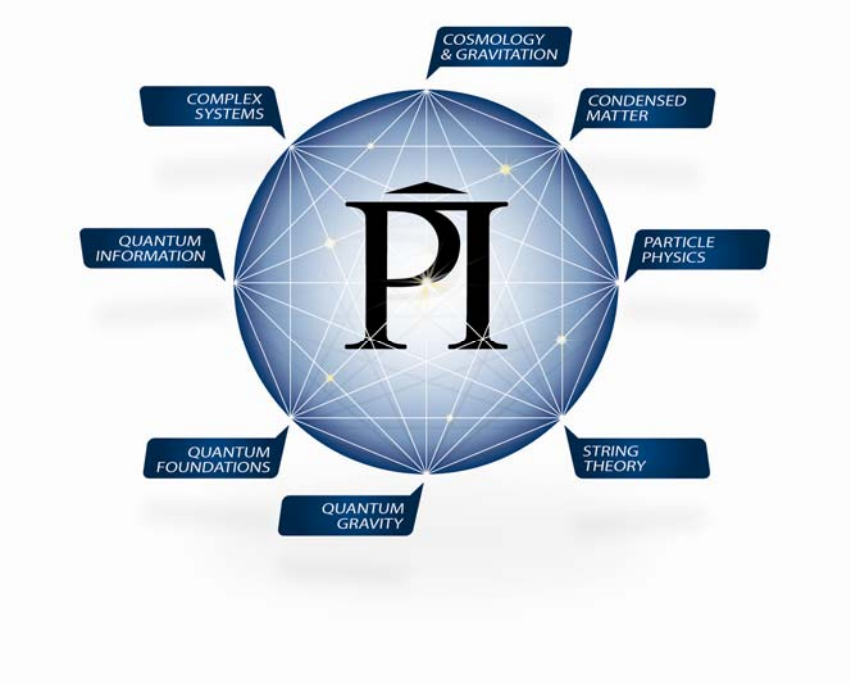
*"Research conducted within PI's core fields are of great importance and of consequence to testing the understanding of existing theories, developing new approaches, and creating new linkages that allow wider application. The research is creating the kind of highly innovative and challenging advances in theoretical physics that PI seeks to create. Some of the research is reaching groundbreaking, revolutionary, and transformative levels and international experts have strong positive opinions of both the research and PI researchers."*

–KPMG Evaluation Report, 2011

In 2010-11 KPMG conducted an independent third party assessment of PI's research and operations for Industry Canada. This thorough review, which included an expert panel of 19 independent international scientists, determined that virtually every aspect of Perimeter Institute's research, programs and operations is of the highest international calibre. It provides strong evidence that PI has created an institution capable of achieving its high scientific aspirations.

[3] According to Google Scholar and Spires databases, as of July 31, 2011. Each PI publication is counted only once, regardless of how many PI researchers were co-authors.

## Research




Over the course of the year, PI continued to foster collaborative, interdisciplinary approaches to some of the most challenging problems in the field and produced numerous results of international impact and importance, thereby meeting the targeted outcomes. The Institute continues to prioritize ambitious, 'risky' but potentially high payoff research over predictably 'safe,' incremental science.

The schematic representation above depicts PI's research space, which fosters novel insights, or 'sparks,' between strategically interconnected areas. Perimeter's set of research areas is unique worldwide, comprising a whole far greater than the sum of its parts. By actively promoting the constant interchange of ideas, discoveries in one field can catalyze new ideas in others, accelerating the process of discovery.

Several notable examples of research from the past year are outlined below

**"AdS/QHE: Towards a Holographic Description of Quantum Hall Experiments," Allan Bayntun (McMaster University), C.P. Burgess (McMaster University and Perimeter Institute), Brian P. Dolan (National University of Maynooth and Dublin Institute), Sung-Sik Lee (McMaster University and Perimeter Institute) *New J. Phys*. 13 (2011) 035012 [arXiv:1008.1917]**

The discovery in the mid-1990s that strongly interacting non-gravitational systems are precisely equivalent to certain gravitational systems – known as the Anti-de Sitter/Conformal Field Theory (AdS/CFT) correspondence – was the biggest breakthrough in theoretical physics in decades. Among other things, it opens up the promise that well-developed tools used for understanding the gravitational

properties of black holes can be used to understand more prosaic situations where electrons interact very strongly within condensed matter systems.

The program for seeking points of contact between these new theoretical ideas and real condensed matter systems is only a few years old and is still in the process of determining which gravitational systems may be useful for understanding which condensed matter experiments. This paper argues that the experimental systems for which AdS/CFT techniques are most likely to be useful are quantum Hall materials. The evidence for this is the rich set of symmetries that these systems are experimentally found to enjoy, which remain poorly understood within traditional approaches because of their emergent nature. The paper shows that these symmetries arise quite generically within the AdS/CFT formulation, suggesting that this is the natural framework for their explanation. Establishing a quantitative connection between AdS/CFT methods and a real condensed matter system such as this could provide the first observational test of string theory. The paper shows that the simplest version successfully 'postdicts' a scaling exponent measured in experiments, but also predicts a host of new kinds of exotic experimental phenomena for 'bosonic' quantum Hall systems, should these be manufactured. The paper has been followed up by both string theorists and condensed matter physicists, and the search continues, both at PI and elsewhere, for more robust comparisons between AdS/CFT theory and observations in these systems. This research is by nature interdisciplinary, involving expertise in condensed matter physics, string theory and quantum field theory. PI's unique interdisciplinary research environment was crucial in providing the expertise and depth in AdS/CFT methods, in bringing together the researchers involved, and in freeing up their time to work on the research.

**"Testing Inflation: A Bootstrap Approach," Latham Boyle (Perimeter Institute and CITA) and Paul Steinhardt (Princeton University)** ***Phys. Rev. Lett.*** **105:241301, 2010 [arXiv:0810.2787]**

Cosmologists sometimes give the impression that inflation has been firmly established and that our remaining task is just to determine which particular model of inflation is correct. Perimeter faculty member Latham Boyle and collaborator Paul Steinhardt (who was recently appointed as a Perimeter Distinguished Research Chair) instead adopt the viewpoint that establishing the correctness of inflation remains a vital problem, and they present a new test which forthcoming cosmological observations will make feasible and which could establish inflation beyond a reasonable doubt.

When we observe the large-angle directional dependences in the cosmic microwave background radiation, we are really measuring fluctuations in the primordial density field. The inflationary explanation for the origin of these primordial fluctuations focuses on the ratio of two (time-dependent) length scales: namely the wavelength of the fluctuation itself and the Hubble radius. According to inflation, a given fluctuation was generated at a very early moment (the 'horizon exit') when this ratio was one to one: unity. Then, between horizon exit and the end of inflation, the ratio was 'stretched' by a large factor. Finally, between the end of inflation and today, the ratio 'unstretched' by precisely the same factor, returning to unity. Boyle and Steinhardt point out that forthcoming cosmological observations will yield independent estimates for both the stretch and unstretch factors described

above. If these two estimates agree with each other, it will provide extremely specific and convincing evidence for the basic premise of inflation.

**"Black Strings, Low Viscosity Fluids, and Violation of Cosmic Censorship," Luis Lehner (University of Guelph and Perimeter Institute), Frans Pretorius (Princeton University), *Phys. Rev. Lett*. 105:111101, 2010**

This worked studied the instability of black holes in higher dimensions. Previous analysis had uncovered a class of black holes would be unstable, but could not decipher what the end state of the system would be. This problem was open for almost two decades, until this work resolved it. This paper showed that the unstable black holes lead to a naked singularity thus presenting a first generic violation of cosmic censorship. Furthermore, it illustrated that the system undergoes a complex behaviour, acting qualitatively as a low viscosity fluid stream. Thus, it further opened new connections to dualities between the behaviour of gravity and field theories. Next steps are to further explore the correspondence with fluid behaviour and dualities. Perimeter's environment was key in bringing Pretorius and Lehner together to work on this project, as both were teaching in the PSI program.

**"Large Dimensions and Small Curvatures from Supersymmetric Brane Back-reaction," C.P. Burgess (Perimeter Institute and McMaster University), L. van Nierop (McMaster University) *Journal of High Energy Physics* 1104:078, 2011 [arXiv:1101.0152]**

The accelerating universe proposed by most current cosmologies presents several challenges to the predictions obtained from other areas of physics. One particular long-standing puzzle is why the curvature associated with the accelerated expansion of the universe is so small compared with the large expected quantum energy of the vacuum. New calculations by Perimeter faculty member Cliff Burgess and his student Leo van Nierop may provide the key to unravelling this problem.

Burgess and van Nierop took as a starting point the observation that well-explored theories of quantum gravity (such as string theory, for example) predict more than three dimensions of space and often also predict the existence of surfaces, called 'branes,' in these dimensions on which all known particles are trapped. The researchers set out to understand how the size and shape of the observed universe (and of any extra dimensions) respond to the presence of any branes that are present. The result was the first systematic calculational tools for predicting how branes that span an arbitrary number of space dimensions affect the size and shape of the universe.

Furthermore, these new tools may show how the universe can accelerate. In particular, they show how and when the large quantum vacuum energy can curve the extra dimensions without unacceptably curving the three large spatial dimensions we observe. If these results hold, they will be the first known example where the small curvatures observed to be associated with the dark energy density can be consistent with the size of known quantum fluctuations.

**"First Observational Tests of Eternal Inflation," Stephen M. Feeney (University College London), Matthew C. Johnson (Perimeter Institute), Daniel J. Mortlock (Imperial College London), Hiranya V. Peiris (University College London) [arXiv:1012.1995]**

Inflation has been the predominant theory to explain the initial conditions of the universe for the past 30 years. However, inflationary models generically have an eternal regime that predicts a complex structure of spacetime on scales much larger than our observable horizon. Therefore, one of the outstanding questions in cosmology has been whether we can ever test eternal inflation. This question is also directly relevant to quantum gravity and string theory, as well quantum foundations, when it comes to the quantum interpretations in an eternally inflating spacetime. This work provides a concrete way to test possible observational signatures of eternal inflation in the cosmic microwave background observations, which could in turn provide a novel way to understand the physics of the early universe. The work was very well received by the cosmology community and widely covered in the popular press. More precise analysis is underway using the upcoming Planck data that can significantly sharpen these constraints.

**"An Electron Fixed Target Experiment to Search for a New Vector Boson A' Decaying to e+e," Rouven Essig (SLAC), Philip Schuster (Perimeter Institute and SLAC), Natalia Toro (Perimeter Institute and Stanford University), Bogdan Wojtsekhowski (Jefferson Lab), *Journal of High Energy Physics* 02(2011)009 [arXiv:1001.2557]; and "Search for a new gauge boson in the A' Experiment (APEX)" Multiple authors [arXiv:1108.2750]**

Dark matter is one of the central enigmas confronting theoretical physics. It is thought to comprise far more of the universe than the 'ordinary' atomic matter with which we are familiar. While not directly visible (and therefore 'dark'), there is strong evidence for its existence through such astronomical observations as gravitational lensing and in the fact that visible matter does not comprise sufficient mass (and thus gravity) to account for the existence of galaxies, which are held together through gravity. Though there is a wide range of evidence for the gravitational interaction of dark matter, the ways in which it interacts apart from gravity are not well understood. It may be that dark matter interacts with itself via some 'dark force' or forces. If so, such forces would likely be mediated (as all forces other than gravity are known to be mediated) by some kind of particle, a new gauge boson, sometimes called a 'dark photon.'

Perimeter faculty members Philip Schuster and Natalia Toro are working closely with experimentalists to design and optimize experiments to look for evidence of dark forces. Their paper proposing such an experiment led to the launch of the APEX experiment at Jefferson Lab in the United States. The above paper reports on APEX's recently completed test run, confirming that the full experiment should be able to search over a large range of mass and couplings, with a sensitivity unrivalled by other experiments to date. This should allow APEX to investigate new forces beyond the Standard Model that have been invoked to explain a variety of dark matter related anomalies. Schuster and Toro's work on the search for dark forces has provoked wide interest and support, and several other experiments on the same lines will begin operations early in 2012.

**"Forward-backward asymmetry in t-tbar production from flavour symmetries," Benjamin Grinstein (University of California, San Diego), Alexander L. Kagan (Cincinnati University and Weizmann Institute), Michael Trott (Perimeter Institute), Jure Zupan (Cincinnati University), *Phys. Rev. Lett. 107:012002,* 2011, DOI: 10.1103/PhysRevLett.107.012002 [arXiv:1102.3374]**

The CDF experiment at Fermilab has been studying proton-antiproton collisions at very high energies for many years, testing the Standard Model of particle physics and searching for phenomena that cannot be explained by this otherwise very successful theory. They recently found such a phenomenon: a small change in the distribution of top quarks and top antiquarks when these are pair-produced in the experiment. The observed distribution disagrees with what the Standard Model predicts at a level that is statistically uncomfortable, raising the question of how the theory would have to be modified in order to explain what is seen. The result could well provide the first glimpse of the theory that could displace the Standard Model as the paradigm for how physics works at the smallest distances that can be studied. The paper provides a systematic study of the constraints that restrict what might be responsible and presents several well-motivated examples of theories that can describe the observations. With these in hand it is possible to predict how the Large Hadron Collider at CERN can be used to test the various possibilities. The paper has been very well received and has already accumulated an unusually large number of citations.

**"Reformulating and reconstructing quantum theory," Lucien Hardy (Perimeter Institute) [arXiv:1104.2066]**

The usual axioms of quantum theory are highly abstract, and a longstanding problem in the foundations of quantum theory has been to provide an alternative set of more natural postulates from which the usual mathematical axioms of quantum theory follow. Significant progress in this field has been made recently using ideas from quantum information. In this 170-page paper, Hardy provides a set of five very natural postulates from which the usual mathematical axioms of quantum theory follow. These postulates are couched in operational terms applying to a very general probabilistic circuit framework and constitute arguably the most natural way of obtaining the usual mathematical axioms of quantum theory provided to date. A number of groups around the world continue to work on this problem, and PI is well represented here as postdoctoral researchers Giulio Chiribella and Markus Mueller are working on related ideas. The topic of reconstructing quantum theory from natural postulates was one of the major themes at the very successful conference "Conceptual Foundations and Foils for Quantum Information Processing" held at PI in May 2011, which was attended by over 100 researchers from around the world.

**"Formulating Quantum Theory as a Causally Neutral Theory of Bayesian Inference," R. W. Spekkens (Perimeter Institute) and M. S. Leifer (University College London) [arXiv:1107.5849]**

The quantum mechanical universe is inherently uncertain – but does that uncertainty reflect an uncertain reality, or incomplete knowledge? "Uncertain reality" is the prevailing answer, but it is not the

only one. Perimeter faculty member Rob Spekkens and former Perimeter postdoc Matt Leifer have published new results reformulating quantum theory in terms of Bayesian inference. This work is a significant step forward in a broader research program (also pursued by Perimeter Senior Researcher Christopher Fuchs) which seeks to resolve the conceptual difficulties of quantum theory by interpreting quantum states as states of incomplete knowledge, expressing the degrees of belief of an agent.

Bayesian inference is a method of statistical inference which is used to update an agent's state of uncertainty in the light of new evidence. The goal of using Bayesian inference is usually finding a conditional probability: that is, the probability of an event assuming a particular set of circumstances. For instance, it is Bayesian inference that lets us calculate the probability of rain at a temperature of 25 degrees with 75% humidity. Spekkens and Leifer show that conditional probability has a quantum analog: the quantum conditional state. They also show that (as in classical Bayesian inference) quantum Bayesian inference is blind to whether two things happen at the same time or at different times, so far as the rules concerning how we propagate beliefs are concerned. This permits them to unify descriptions of quantum experiments involving two systems at a single time with the descriptions of experiments involving a single system at two times. The new formulation allows a cleaner separation of those aspects of quantum theory that concern mere updating of incomplete knowledge and those aspects that concern the underlying causes and effects, allowing us to better focus our attention on the latter.

**"Einstein Gravity as a 3D Conformally Invariant Theory," Henrique Gomes (University of Nottingham), Sean Gryb (Perimeter Institute and University of Waterloo), Tim Koslowski (Perimeter Institute), *Class. Quant. Grav*. 28:045005, 2011 [arXiv:1010.2481]; "The Link between General Relativity and Shape Dynamics," Henrique Gomes (University of Nottingham), Tim Koslowski (Perimeter Institute) [arXiv:1101.5974]; and "The gravity/CFT correspondence," Henrique Gomes, Sean Gryb, Tim Koslowski, Flavio Mercati [arXiv:1105.0938]**

A new formulation of general relativity which has great promise to address some of the key unsolved issues in classical and quantum gravity was invented by two young PI theorists (postdoctoral researcher Tim Koslowski and PhD student Sean Gryb) and a young colleague, Henrique Gomes (doctoral candidate at the University of Nottingham and a PI visiting researcher). This discovery was made during a visit by Gomes to PI. These papers show that general relativity can be formulated as a theory with a physical and invariant notion of time, and with a new symmetry, which is invariant under changing the volume of objects (called local scale invariance). By showing that general relativity has hidden within it a preferred notion of time, this formulation resolves the knotty problem of time in classical and quantum cosmology. This approach also opens a new approach to the duality between gravity and conformal field theory posited by the very influential AdS/CFT duality.

**[1] "The principle of relative locality," Giovanni Amelino-Camelia (Università "La Sapienza" Roma), Laurent Freidel (Perimeter Institute), Jerzy Kowalski-Glikman (University of Wroclaw), Lee Smolin (Perimeter Institute), *Phys. Rev. D.* [arXiv:1101.0931]; [2] "Relative locality and the soccer ball problem," Giovanni Amelino-Camelia (Università "La Sapienza" Roma), Laurent Freidel (Perimeter Institute), Jerzy Kowalski-Glikman (University of Wroclaw), Lee Smolin (Perimeter Institute), *Phys. Rev. D*. [arXiv:1104.2019]; and [3] "Gamma ray burst delay times probe the geometry of momentum space," Laurent Freidel (Perimeter Institute), Lee Smolin (Perimeter Institute) [arXiv:1103.5626]**

A new principle of physics which leads to a novel approach to experimental tests of quantum theories of gravity was invented at PI in fall 2010. This new principle, called the "Principle of Relative Locality," extends and deepens Einstein's formulation of special relativity. Just as the notion of space was shown by Einstein to be observer dependent, giving rise to a notion that spacetime is invariant and universal, this new principle posits that the description of events taking place in spacetime depends on the position of an observer and the energy that observer uses to detect distant events. There is a new invariant arena for physics, which is a phase space. This principle was discovered during an intensive two-week collaboration in October 2010 between PI Faculty members Laurent Freidel and Lee Smolin and visiting colleagues Giovanni Amelino-Camelia of the University of Rome and Jerzy Kowalski-Glikman of the University of Wroclaw, and was presented in [1] (see above). The authors also recently showed in [2] (see above) that an issue common to attempts to modify relativity theory to incorporate quantum gravity does not afflict this new framework. In [3], Freidel and Smolin showed that the new principle can be used to make predictions for delays in the time of arrival of photons from very distant gamma ray bursts. These delays are found to be energy dependent and may exist at a level of sensitivity where they can be bounded or discovered by observations by the Fermi gamma ray observatory. (For a review of the prospects for such experiments see "Prospects for constraining quantum gravity dispersion with near term observations," Giovanni Amelino-Camelia, Lee Smolin, Phys.Rev.D80:084017, 2009 [arXiv:0906.3731]).

**"Longer-Baseline Telescopes Using Quantum Repeaters," Daniel Gottesman (Perimeter Institute), Thomas Jennewein (Institute for Quantum Computing, University of Waterloo), Sarah Croke (Perimeter Institute) [arXiv:1107.2939]**

One goal in designing telescopes is to optimize resolution, allowing the telescope to see structures with a small apparent size. The resolution of a telescope with a single large mirror is limited by the size of the mirror. One approach to improving resolution beyond that is to do interference measurements between light arriving at two or more separate telescope dishes. Resolution is then limited by the distance between the telescopes rather than the size of the individual mirrors (although the sensitivity to faint objects is still limited by size, since that determines how much light they collect). Radio telescopes can perform interference between telescopes arbitrarily far away because the radio waves arriving at the telescopes are basically classical, allowing astronomers to measure the signal at each telescope and then compare at their leisure. However, for optical wavelengths, photons arrive only rarely, making the quantum nature of the light important. To build an optical interferometer, one must therefore bring the photons together while preserving their quantum nature. This is difficult to do, limiting the size of

current optical interferometers to a few hundred meters.

The task of moving quantum states around and protecting them against errors has been extensively studied in the field of quantum information. PI faculty member Daniel Gottesman, IQC faculty member Thomas Jennewein, and PI postdoc Sarah Croke have proposed a way to apply these quantum information ideas to solve the problem of building optical interferometers with distant telescopes. The necessary technology of quantum repeaters is still in development, but one day, it can be incorporated into the design of telescopes to allow new observations with much higher angular resolution than the best present-day telescopes.

**"Quantum computational capability of a two-dimensional valence bond solid phase," A. Miyake (Perimeter Institute),** ***Annals of Physics,*** **March 2011, DOI: 10.1016/j.aop.2011.03.006 [arXiv:1009.3491]**

PI postdoctoral researcher Akimasa Miyake has proven that an idealized material known as the AKLT model is a universal resource for measurement-based quantum computation. Measurement-based quantum computation is an approach to building a quantum computer where one does all the entanglement first, creating a large entangled state that need not depend on the computation to be performed. Certain entangled 'resource' states are universal, meaning that by performing different possible sequences of measurements, you can get results that correspond to the answers to arbitrary quantum computations. The usual resource states used for measurement-based quantum computation are artificial and could only be produced by a system with a significant degree of control over quantum systems. The AKLT model (named after the initials of its discoverers) is a system that had been previously studied by condensed matter physicists seeking to understand its highly-quantum nature. Miyake showed that the AKLT model has the right kind of entanglement to act as a universal resource state for measurement-based quantum computation. This raises the possibility that one could find a real physical system which naturally produces the right kind of entangled state without any human intervention. The AKLT model defines a very precise form for the interactions between the particles composing it, but Miyake and other researchers are currently investigating whether his result still holds true if the interactions are changed slightly from the exact form specified by the AKLT model.

**"A Note on Polytopes for Scattering Amplitudes," N. Arkani-Hamed (Institute for Advanced Study), J. L. Bourjaily (Institute for Advanced Study, Princeton University), F. Cachazo (Perimeter Institute), A. Hodges (University of Oxford), J. Trnka (Institute for Advanced Study, Princeton) [arXiv:1012.6030]**

To determine the fundamental building blocks of matter, accelerators such as the Large Hadron Collider (LHC) at CERN smash together particles at extremely high energies, measuring the resulting scattering processes to infer the underlying physics. Scattering amplitudes are precise calculations of the scattering processes expected when particles collide at given energies. Observational results of scattering experiments are compared against these predictions in order to search for deviations, which may signal

new physical processes. However, many important physical processes are so complicated that calculating scattering amplitudes using traditional methods was practically infeasible. Perimeter faculty member Freddy Cachazo and his collaborators have been leading a worldwide effort to bring these calculations under better control and have introduced new methods that significantly simplify scattering amplitude calculations. The surprising simplicity of these methods may well hint at a new understanding of the underlying physics. Cachazo's achievements in this area have been recognized with the 2009 Gribov medal of the European Physical Society and the 2011 Rutherford Medal of the Royal Society of Canada.

In this work, Cachazo *et al* show that the calculation has a geometric interpretation and is equivalent to computing the volume of certain geometric objects called polytopes. Just as one can compute areas of a complicated shape by splitting it into triangles, one can compute the volume of a polytope by breaking it into tetrahedrons. This insight will further simplify scattering amplitude problems. In addition to their immediate utility to experimentalists, these new methods are providing insights of deep theoretical importance.

**"The Complete Planar S-matrix of N=4 SYM as a Wilson Loop in Twistor Space," L. Mason (University of Oxford), D. Skinner (Perimeter Institute), *JHEP* 1012:018, 2010 [arXiv: 1009.2225]**

One of the basic tools for studying physical theories was introduced by Feynman in the form of a diagrammatic set of rules called Feynman rules. These rules allow us to understand the behaviour of quarks and gluons at very high energy or very small distances (much smaller than a proton). At low energies or large distances (the size of the nucleus of an atom), another quantity, introduced by Wilson, known as the Wilson loop must be used. In 2007, Alday and Maldacena conjectured that in a special theory, known as N=4 super-Yang-Mills, Feynman diagrams and Wilson loops are related. Since then, discovering how to make this connection work precisely became a 'Holy Grail' of this field. The answer is provided in the present work, in a surprising combination of modern ideas (loop integrands) and classic constructions (Penrose's twistor space).

## Honours, Awards and Major Grants

Many PI researchers received national and international recognition for their work in 2010-11. Notable among these were the following:

- Faculty member Lee Smolin and Associate Faculty member Richard Cleve were inducted as Fellows of the Royal Society of Canada (RSC), Canada's highest academic honour

- Associate Faculty member Niayesh Afshordi won the Professor M. K. Vainu Bappu Gold Medal from the Astronomical Society of India (ASI) for his contributions to our understanding of the dark universe

- Faculty member Freddy Cachazo won the 2011 Rutherford Memorial Medal in Physics from the Royal Society of Canada, which honours outstanding research in any branch of physics by younger scientists

- Associate Faculty member Luis Lehner was awarded a Discovery Accelerator Supplement (DAS) from the Natural Sciences and Engineering Research Council of Canada (NSERC) of $120,000 (2011-2014), in addition to a core grant of $280,000 over five years (2011-2016)

- Associate Faculty member Niayesh Afshordi received a $150,000 Early Researcher Award from Ontario's Ministry of Research and Innovation

- Associate Faculty member Cliff Burgess was awarded an NSERC Discovery grant of $375,000 (2010-2015), within the top tier of awards given to theorists in subatomic physics

- Associate Faculty member Maxim Pospelov was awarded an NSERC Discovery grant of $395,000 (2006-2011), within the top tier of awards given to theorists in subatomic physics

- Distinguished Research Chair Yakir Aharonov was awarded the highest honour bestowed on scientists by the United States government, the National Medal of Science, presented by President Barack Obama in November 2010

- Distinguished Research Chair Sandu Popescu won the John Stewart Bell Prize for his enormous contributions to the field of quantum mechanics

- Distinguished Research Chair Leo Kadanoff was awarded the 2011 Isaac Newton Medal of the Institute of Physics "for inventing conceptual tools that reveal the deep implications of scale invariance on the behaviour of phase transitions and dynamical systems"

- Director Neil Turok was named to the Science, Technology and Innovation Council (STIC), the government's advisory body on science, technology and innovation issues

- Associate Faculty member Cliff Burgess was invited by NSERC to serve on the committee drafting Canada's national five-year plan for subatomic physics (2012-2017)

- Associate Faculty member Luis Lehner was elected as a Fellow of the American Physical Society for his "important contributions to numerical relativity, most notably in the areas of black hole simulations, general relativistic magnetohydrodynamics, and algorithm development"

- Associate Faculty member Luis Lehner was named a Fellow of the Canadian Institute for Advanced Research (CIFAR) Cosmology and Gravitation program

- Postdoctoral Researcher Adrienne Erickcek was awarded a CIFAR Junior Fellowship

- Associate Faculty member Adrian Kent was awarded a Research Fellowship by the Leverhulme Trust for his project, “Mathematical Characterization of Quantum Reality”

- Associate Faculty member Maxim Pospelov was awarded a Gordon Godfrey Visiting Fellowship at the University of New South Wales, Sydney, Australia

- Associate Faculty member Michele Mosca was named to Canada’s Top 40 Under 40 by *The Globe and Mail*

- Faculty member Lee Smolin was awarded a Foundational Questions Research Institute (FQXi) grant of US$47,500 for the project “Physical and cosmological consequences of the hypotheses of the reality of time”

- Faculty members Lee Smolin and Laurent Freidel, with colleagues Giovanni Amelino-Camelia and Jerzy Kowalski-Glikman, won second prize in the 2011 Gravity Research Foundation essay competition for “Relative Locality: A Deepening of the Relativity Principle”

- Senior Researcher Christopher Fuchs was selected as the 2011 Clifford Lecturer at Tulane University, an honour which has previously been bestowed upon Fields Medallists and other distinguished mathematicians; he gave a week-long series of talks in the spring of 2011

- Postdoctoral Researcher Matt Johnson was co-awarded an FQXi grant of US$112,331 for “Detecting signatures of eternal inflation using WMAP and Planck data”

- Postdoctoral Researcher Giulio Chiribella was selected by the American Physical Society as an APS highlight for his paper, “Informational derivation of quantum theory”

- Graduate student Hoan Dang won a Vanier Canada Graduate Scholarship, which provides $50,000 per year over three years to students who demonstrate both a high standard of scholarly achievement and leadership skills

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

## Summary of Achievements

- Recruited Xiao-Gang Wen, one of the world's top condensed matter physicists from MIT as the BMO Financial Group Isaac Newton Chair
- Appointed Guifre Vidal as a senior Faculty member, and Philip Schuster and Natalia Toro as junior Faculty members, bringing the full-time Faculty to 15
- Appointed Sung-Sik Lee and Itay Yavin as Associate Faculty members working jointly with McMaster University, bringing the part-time Associate Faculty to 14
- Recruited Bianca Dittrich and Davide Gaiotto as junior Faculty members to begin in 2012, as well as Avery Broderick as an Associate Faculty member jointly appointed with the University of Waterloo, to arrive fall 2011
- Hired 11 postdoctoral researchers in 2010-11 and recruited 15 postdoctoral researchers for 2011-12 (see Objective 4)
- Appointed eight new PI Distinguished Research Chairs (see Objective 5)

## Highlights

*"It is clear that PI has been able to attract top talent from around the world at all levels, including Faculty, Associates and Affiliates, post-doctoral fellows (PDFs), students and Distinguished Research Chairs."*

–KPMG Evaluation Report, 2011

## The Perimeter Research Chairs

In 2010-11, the Institute launched the Perimeter Research Chairs program, designed to attract stellar, senior research leaders to Perimeter and Canada. There will be five prestigious chairs in total, named for legendary scientists whose insights helped define modern physics: Neils Bohr, Paul Dirac, Albert Einstein, James Clerk Maxwell, and Isaac Newton.

In November 2010, PI announced the creation of the BMO Financial Group Isaac Newton Chair in Theoretical Physics at Perimeter Institute and recruited Xiao-Gang Wen, a world-leading condensed matter theorist at MIT, as the first Chairholder. Together with recent hires Guifre Vidal and Sung-Sik Lee,

Dr. Wen will form the core of the Institute's fast-growing research team in condensed matter. International searches to identify suitable candidates for the remaining Perimeter Research Chairs are ongoing, as are efforts to secure further endowment support for them.

**Xiao-Gang Wen** received his PhD from Princeton University in 1987, under the supervision of Edward Witten. 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 invented many new mathematical formalisms. He authored the textbook *Quantum Field Theory of Many-body Systems: From the Origin of Sound to an Origin of Light and Electrons*. Dr. Wen is currently the Cecil and Ida Green Professor of Physics at MIT, a Distinguished Moore Scholar at Caltech, a fellow of the American Physical Society, and one of Perimeter's own Distinguished Research Chairs. He will join PI in summer 2012.

## Faculty Recruitment

Three outstanding new Faculty members arrived at PI in 2010-11, and one more will arrive in 2012. These hires reflect a strategic balance between accomplished senior theorists and junior scientists of extraordinary potential. The hiring of two female faculty members, Natalia Toro and Bianca Dittrich, signals PI's commitment to increasing gender diversity within the field.

**Guifre Vidal** joined PI as a senior Faculty member in May 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. Dr. Vidal received his PhD in 1999 from the University of Barcelona, and completed postdoctoral fellowships at the University of Innsbruck and the Institute for Quantum Information at Caltech. Dr. Vidal works at the interface of quantum information and condensed matter physics. His past honours include a Marie Curie Fellowship, awarded by the European Union, and a Sherman Fairchild Foundation Fellowship.

**Natalia Toro** joined PI in September 2010 as a junior Faculty member in particle physics. She completed her PhD at Harvard in 2007 and held a postdoctoral fellowship at Stanford University's Institute for Theoretical Physics (SITP). Dr. Toro has developed a framework for "simplified" 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 (CMS) 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 in Virginia.

**Philip Schuster** joined PI in September 2010 as a junior Faculty member in particle physics. He completed his PhD in 2007 at Harvard University and was a Research Associate at SLAC National Accelerator Laboratory from 2007-2010. Dr. 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 a variety of theories that may be discovered at new experiments at the LHC. In collaboration with experimentalists at the LHC, he developed methods to characterize potential new physics signals in a physically transparent manner that makes it easier to identify the underlying theory explaining these signals. He is also a co-spokesperson for the APEX collaboration at the Thomas Jefferson Laboratory.

**New Faculty Recruited for 2011-12:**

**Bianca Dittrich** will join PI's faculty in 2012. She received her PhD from the Max Planck Institute for Gravitational Physics in 2005, under the supervision of Thomas Thiemann, one of Perimeter's Associate Faculty members. She currently leads the Max Planck Research Group "Canonical and Covariant Dynamics of Quantum Gravity" at the Albert Einstein Institute in Potsdam, Germany. Dr. 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. Dr. Dittrich is a recipient of the Otto Hahn Medal of the Max Planck Society (2007), which recognizes outstanding young scientists.

**Davide Gaiotto** will join PI in spring 2012 from the Institute for Advanced Study in Princeton, where he has been a long-term Member since 2007. Dr. Gaiotto received his PhD from Princeton University in 2004 under the supervision of Leonardo Rastelli and was a postdoctoral fellow at Harvard from 2004-2007. Dr. Gaiotto works at the interface of quantum field theory and string theory, and has already achieved several important advances. In 2009, for example, he presented a new way of constructing and studying supersymmetric gauge theories which has led to novel techniques for probing the quantum dynamics of gauge theories. Widely considered to be one of the most talented young theorists in his field worldwide, Dr. Gaiotto, the recipient of the 2011 Gribov Medal of the European Physical Society, was recruited to PI over multiple competing offers, including Stanford. His recruitment is expected to greatly strengthen PI research in the increasingly important area of strongly quantum-correlated systems.

## Associate Faculty Recruitment

In 2010-11, PI co-hired three Associate Faculty members in astrophysics, condensed matter physics, and particle physics. The Associate Faculty program enables PI to recruit top scientific talent to Canada and to "spread the benefit" by jointly appointing them with surrounding universities. The Institute is now investigating additional opportunities with several institutions.

**Sung-Sik Lee** joined PI's faculty in July 2011 in a joint appointment with McMaster University. Dr. Lee completed his PhD in 2000 at the Pohang University of Science and Technology (POSTECH) in South Korea. He works in theoretical condensed matter physics, focusing 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, endeavouring 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.

**Avery Broderick** will join PI's faculty in September 2011 in a joint appointment with the University of Waterloo. He completed his PhD at Caltech in 2004, and held postdoctoral positions at the Institute for Theory and Computation at the Harvard-Smithsonian Center for Astrophysics (2004-2007) and the Canadian Institute for Theoretical Astrophysics (2007-2011). Dr. 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 a handful of supermassive black holes. With these, Dr. Broderick and his collaborators study how black holes accrete matter, launch the ultra-relativistic outflows observed, and probe the nature of gravity in their vicinity.

**Itay Yavin** joined Perimeter in July 2011 in a joint appointment with McMaster University. Dr. Yavin completed his PhD in 2006 at Harvard University under the supervision of PI Distinguished Research Chair, Nima Arkani-Hamed, after which he was a Research Associate in the Department of Physics at Princeton University (2006-2009) and a James Arthur Postdoctoral Fellow at New York University. Dr. Yavin is a particle physicist whose research focuses on the search for physics beyond the Standard Model, particularly 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.

# Objective 3: To create the world's best environment and infrastructure for theoretical physics research, training, and outreach

## Summary of Achievements

- Completed construction of the Stephen Hawking Centre at Perimeter Institute, on time, on budget, and on track to attain LEED Silver certification for environmentally sustainable building
- Planned and implemented first phases of a comprehensive upgrade to Perimeter's IT systems, realizing efficiencies and working towards providing state-of-the-art research tools and support services
- Created a unique hybrid research/IT position to provide specialized scientific computing resources to researchers and recruited a research technology specialist from within the physics community
- Renovated and expanded the library and its reference collections

## Highlights

*"The unique research environment created by PI has contributed in part to fostering this cutting edge research."*

–KPMG Evaluation Report, 2011

## The Stephen Hawking Centre at Perimeter Institute

Over the last year, Perimeter executed a major expansion project, completing the Stephen Hawking Centre at Perimeter Institute on time and on budget. The Canada Foundation for Innovation (CFI) and Ontario's Ministry of Research and Innovation (MRI) provided a total of $20.8 million toward the expansion, which was matched by private contributions. Designed by Governor General Award-winning Teeple Architects, the 55,000 square foot addition has nearly doubled the Institute's research and training capacity, and it can now accommodate up to 250 scientists and research trainees. The expansion has been named Ontario's first-ever "Gold Seal" project, a national award for excellence in project management and workmanship. It is on track to attain LEED Silver certification, recognizing environmentally sustainable building practices.

## Expansion of IT Services and Infrastructure

Perimeter has developed a comprehensive, multi-year strategy to upgrade its IT infrastructure. The plan's first phases were executed in 2010-11, including the following:

- Upgraded the server environment, outsourced email and PI's IT help desk systems
- Retrofitted the existing wing so that the entire building can support state-of-the-art IT infrastructure for scientific computing, visualization, and remote research collaborations
- Upgraded video capture technology for the Perimeter Institute Recorded Seminar Archive (PIRSA), which is being comprehensively overhauled (projected completion 2011-12)
- Began a website consolidation project in preparation for a new website launch (expected completion 2011-12)

## Scientific Computing Specialist

In late 2010, Perimeter appointed Dr. Erik Schnetter as its Research Technologies Group Lead. Dr. Schnetter is a former Assistant Research Professor at the Center for Computation & Technology, Department of Physics & Astronomy at Louisiana State University. With a background in both physics research and the development of innovative and effective computational research platforms, he is uniquely positioned to steer Perimeter's efforts to become a leader in the use of scientific computing in fundamental theoretical physics research. Dr. Schnetter will work with the IT team over the next year to develop and implement a research technology program to support computationally-intensive research and facilitate long-distance research collaborations.

## Library Expansion

In 2010-11, Perimeter's Library continued to expand on several fronts as part of a comprehensive strategy to become a well-resourced centre for resident and visiting researchers. Its physical space was significantly enlarged to provide more study space, resource collections were expanded, and access to journals and other electronic references was enhanced. Over the year, the Library added 978 new texts, bringing the total to 4,779 in the print collection (5,189 items in all formats), a 62% increase over the last two years. The library is well on track to achieve its goal of housing over 5,000 volumes by 2014, with a well-rounded collection of new and classic reference texts covering the full spectrum of the Institute's subject areas and supporting disciplines.

# Objective 4: To generate a flow-through of the most promising talent

## Summary of Achievements

- Trained 31 students from 15 countries through the Perimeter Scholars International (PSI) graduate research training program
- Hired 11 postdoctoral researchers in 2010-11 and recruited an additional 15 for 2011-12
- Trained 24 PhD students and four MSc students (in addition to those in the PSI program)
- Provided research training to nine undergraduate students

## Highlights

*"A high quality training environment is in place wherein PI is improving students' research programs through their ability to produce better quality and quantity of publications and presentations, increased numbers of collaborations, and exposure to a combination of disciplines and fields. Because of PI's training, the likelihood of a student pursuing further training and eventually an academic research career is higher."*

–KPMG Evaluation Report, 2011

## Perimeter Scholars International (PSI)

In 2010-11, the PSI program trained 31 students (17 men, 14 women) from 15 countries. This Masters level program designed to attract highly talented university graduates from around the world and bring them to the cutting edge of theoretical physics in one academic year. The program is highly competitive, and the quality of students very high. In 2010-11, for example, several student research theses were accepted for publication at competitive international venues. For 2011-12, 37 students from 20 countries, including 11 women, have been accepted from a field of 280 applicants from 65 countries. The quality of students is again very high; all six entering Canadian students, for example, hold competitive NSERC scholarships.

The PSI syllabus is structurally innovative, with courses taught in three-week modules by PI Faculty and other top lecturers from around the world. Support and continuity is provided by several full-time postdoctoral level Tutors and several PhD students, who serve as teaching assistants.

PSI is fulfilling its major strategic objective, which is to bring graduates with high scientific potential to PI and Canada and to select the best among them for continued training. Fifteen of the 2010-11 graduates (48%) are pursuing their PhDs in Canada, 12 with PI Faculty and Associate Faculty members. Others have gone on to excellent programs at Columbia University, Stonybrook, UC Santa Cruz, and elsewhere. Even

alumni continuing their training abroad continue to maintain ties; for example, two students who have returned to Europe for their PhD studies will be returning to PI for regular visits to collaborate with Canada Excellence Research Chair and PI Associate Faculty member David Cory.

## Postdoctoral Researchers

Eleven postdoctoral researchers joined PI in 2010-11, and an additional 15 have been recruited for 2011-12, meeting the Institute's goal of maintaining the number of postdoctoral researchers at approximately steady state. The applicant pool for 2011-12 (631) was the largest in the Institute's history, representing a 20% increase over last year. The number and quality of applicants attest to the Institute's reputation internationally and enable PI to accept only top-calibre research talent.

PI hosts the largest group of independent postdoctoral researchers in theoretical physics in the world[4] and encourages these early-career scientists to pursue novel, ambitious lines of research. The Institute strives to offer an exceptional research training environment. Its success in this regard is demonstrated by the success of its postdoctoral researchers in obtaining faculty positions at reputable international institutions. In 2010-11 despite an extremely competitive worldwide market for academic positions, six departing postdoctoral researchers obtained faculty positions at international institutions,[5] while the remainder obtained continuing postdoctoral fellowships or positions in industry.

## PhD Students

Perimeter had 24 PhD students in residence at the end of 2010-11, exceeding its target of 21. Over the last year, three doctoral students supervised by PI Faculty graduated from PI's partner universities, and all obtained competitive postdoctoral fellowships at international institutions, including NASA, MIT, and the Max Planck Institute for Gravitational Physics.[6]

## Undergraduate Student Program

In 2010-11, Perimeter trained nine undergraduate students through this program, its highest total to date. Undergraduates are exposed to high-level research through two- to four-month research projects with PI postdoctoral researchers, who also gain valuable mentoring experience. The program has also helped attract talent to PI and to Canada, as several alumni later applied to the PSI Masters program.

[4] There were 43 postdoctoral researchers at PI at the end of 2010-11.
[5] Aninda Sinha at the Indian Institute of Science; Parampreet Singh at Louisiana State University; Philip Goyal at the State University of New York (SUNY), Albany; Takuya Okuda at the University of Tokyo; Andrew Tolley at Case Western Reserve University; and Sarah Shandera at Pennsylvania State University.
[6] Sean Gryb, Utrecht University; Isabeau Premont-Schwartz, Max Planck Institute for Gravitational Physics; Chanda Prescod-Weinstein, postdocs at Observational Cosmology Lab of NASA's Goddard Space Flight Center, then MIT.

# Objective 5: To become the second 'research home' for many of the world's outstanding theorists

## Summary of Achievements

- Appointed eight leading scientists as PI Distinguished Research Chairs, bringing the total to 27
- Initiated the new Visiting Fellows program and appointed four Fellows
- Hosted 416 visiting scientists for a total of 439 scientific visits, including 380 short-term scientific visitors, 11 long-term Visiting Researchers, 15 Distinguished Research Chairs, and four Visiting Fellows

## Highlights

## Distinguished Research Chairs Program

The Perimeter Distinguished Research Chairs (DRC) program is unique worldwide. While retaining permanent positions at their home institutions, DRCs are appointed for three-year terms, during which they visit PI for extended periods to do research, collaborate, and participate in all facets of life at PI. These world-leading scientists, such as Stephen Hawking, Nima Arkani-Hamed, Leonard Susskind, and Ignacio Cirac, span an enormous range of expertise and greatly enhance PI's research environment.

In 2010-11, 15 DRCs, including luminaries such as Xiao-Gang Wen, Renate Loll, and Neta Bahcall, made a total of 24 visits, collaborating with PI researchers, co-organizing conferences and workshops, participating in the outreach program, and lecturing on the PSI program. In 2010-11, PI appointed eight new Distinguished Research Chairs, meeting its target for the year and bringing the current total to 27 of a projected 30 at final steady state (see Appendix B, PI Distinguished Research Chairs).

The new appointments include the following:

**James Bardeen** (PhD Caltech, 1965) is an Emeritus Professor of Physics at the University of Washington in Seattle who has made major contributions in general relativity and cosmology. His recent research focuses on improving calculations of the generation of gravitational radiation from merging black hole and neutron star binaries. Dr. Bardeen received his PhD from Caltech under the direction of Richard Feynman.

**G. Baskaran** (PhD Indian Institute of Science Bangalore, 1976) is an Emeritus Professor at the Institute of Mathematical Sciences, Chennai in India, where he founded the Quantum Science Centre. 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. 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).

**S. James Gates** (PhD MIT, 1977) 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 has made numerous contributions to supersymmetry, supergravity, and superstring theory. 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 currently serves on the U.S. 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.

**Gerard 't Hooft** (PhD University of Utrecht, 1972) 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. 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).

**Frans Pretorius** (PhD University of British Columbia, 2002) is a Professor of Physics at Princeton University. His primary field of research is general relativity, specializing in numerical solution of the field equations. He also designs algorithms to efficiently solve the equations in parallel on large computer clusters, and software to manipulate and visualize the results. Among his honours, Dr. Pretorius was awarded an Alfred P. Sloan Research Fellowship in 2007 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.

**Eva Silverstein** (PhD Princeton, 1996) is a Professor of Physics at Stanford University and the Stanford Linear Accelerator Centre (SLAC). Dr. Silverstein's major contributions include predictive new mechanisms for inflationary cosmology; mechanisms for singularity resolution in string theory; a novel duality in string theory between extra dimensions and negative curvature; extensions of the AdS/CFT correspondence; and simple mechanisms for stabilizing the extra dimensions of string theory. She is a former MacArthur Fellow and past recipient of a Sloan Research Fellowship.

**Paul Steinhardt** (PhD Harvard, 1978) is the Albert Einstein Professor in Science and Director of the Princeton Center for Theoretical Science at Princeton University. 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. Dr. Steinhardt is a Fellow in the American Physical Society (APS) and a member of the National Academy of Sciences.

**Senthil Todadri** (PhD Yale, 1997) is an Associate Professor of Physics at the Massachusetts Institute of Technology (MIT). Dr. Todadri's research interests are in condensed matter theory, and 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. He is a past Sloan Research Fellow and winner of a Research Innovation Award from the Research Corporation for Science Advancement.

## Visiting Fellows Program (New Initiative)

In January 2011, following the successful blueprint established with the DRC program, PI launched a new Visiting Fellows program to bring accomplished researchers to the Institute on a regular basis. Like DRCs, they are appointed for three-year terms and maintain their positions at their home institutions. They will come to PI for extended research visits of up to six months each year, collaborating with PI's research community and participating in conferences and workshops. PI appointed the following as the first four Visiting Fellows:

**Jonathan Barrett** is an EPSRC Fellow and Lecturer in Mathematics at Royal Holloway, University of London. He works in the areas of quantum foundations and quantum information, with a particular focus on cryptography and aspects of quantum non-locality. Recently, he has been investigating information processing in formalisms more general than quantum theory.

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

**Vincent Rivasseau** is a Professor at Université Paris-Sud XI, Laboratoire de physique théorique, in Orsay, France. His specialty is constructive quantum field theory and renormalization. He is currently working on non-commutative quantum field theory and on the group field theory approach to quantum gravity. Chief Editor of the Annales Henri Poincaré, Professor Rivasseau is also involved with the African Institute for Mathematical Sciences-Next Einstein Initiative and is a Founder of AIMS-Sénégal.

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

## Visitor Program

In 2010-11, PI hosted 416 visiting scientists for a total of 439 scientific visits, including 380 short-term scientific visitors and 15 PI Distinguished Research Chairs, meeting targeted objectives.[7] Eleven senior Visiting Researchers accepted PI's invitation to work at Perimeter during leaves of absence from their home universities.

[7] There were 24 visits by 15 DRCs in 2010-11, including 21 research and conference visits, and three visits from DRCs who came to lecture in the PSI program.

# Objective 6: To act as a hub for a network of scientific training centres around the world

## Summary of Achievements

- Partnered on ten joint workshops and conferences held at PI and other institutions, and sponsored an additional eight off-site conferences, workshops, and symposia
- Established five new partnerships, including the first Canadian membership in the LIGO Scientific Collaboration and a major four-year international research and training partnership (UNIFY)
- Provided extensive assistance to the African Institute for Mathematical Sciences-Next Einstein Initiative (AIMS-NEI)
- Director Neil Turok and AIMS-NEI were honoured with the 2010 World Innovation Summit for Education (WISE) Award, which recognizes outstanding educational initiatives that are having a transformative impact on societies

## Highlights

## Collaborations and Partnerships

In 2010-11, PI continued to strengthen existing partnerships within Canada and abroad. These partnerships increasingly solidify the Institute as a global hub for theoretical physics, while providing scientific opportunities for PI's scientists.

A snapshot of these activities includes:

- **"PI-ATLAS LHC Days"** (Dec. 7, 2010, May 11-12, 2011): this ongoing series of meetings between scientists at PI and the Canadian Institute for Theoretical Astrophysics (CITA) provides linkages to efforts at the LHC
- **"Integrability in Scattering Amplitudes"** (September 15-16, 2010 at PI, and March 11-12, 2011 at the Institute for Advanced Study): workshops held at PI and the Institute for Advanced Study (IAS) brought together top researchers to work intensively on problems relevant to major experimental efforts to determine the fundamental constituents of matter
- **"PIAF Workshop Brisbane"** (December 1-3, 2010): the Perimeter Institute-Australia Foundations (PIAF) collaboration has provided a major stimulus to the field of quantum foundations since 2008; this year's workshop (held at Griffith University) focused on the interface between quantum foundations and cosmology
- **"PI-CITA Day 2011"** (February 15, 2011): an ongoing series of meetings between researchers at PI and the Canadian Institute for Theoretical Astrophysics (CITA)

- **"New Frontiers in Quantum Foundations, CUPI 2011"** (March 9-11, 2011): a new conference (held at Clemson University) aimed at further strengthening quantum foundations
- **"Connections in Geometry and Physics, GAP 2011"** (May 13-15, 2011): The third in a series of conferences (held this year at the Fields Institute) was co-organized by PI Faculty member Robert Myers
- **"Cosmological Frontiers in Fundamental Physics 2011"** (June 14-17, 2011): The fifth conference in an ongoing partnership with the Laboratoire Astroparticule et Cosmologie (APC) and the Solvay Institute (Brussels), held this year at APC in Paris
- **"Holographic Cosmology v2.0"** (June 21-24, 2011): The follow-up to a 2009 workshop held at PI was jointly organized with the Stanford Institute for Theoretical Physics

PI also co-sponsored an additional eight off-site conferences, workshops, and symposia throughout Canada, including:

- "Physics at the Dawn of the LHC Era" (January 27-29, 2011), held at TRIUMF in Vancouver, BC
- "Lake Louise Winter Institute 2011" (February 20-26, 2011), held at the University of Alberta
- "Theory Canada 6" (June 10-12, 2011), held at Memorial University in Corner Brook, Newfoundland
- "11th Canadian Summer School on Quantum Information" (June 16-17, 2011), held at the Centre de Recherches Mathématiques, Université de Montréal

## New Partnerships

PI concluded five new partnership agreements in 2010-11, each of which holds excellent scientific and strategic potential.

### Unification of Fundamental Forces and Applications (UNIFY)

Launched in June 2011, the UNIFY partnership, joined PI with seven institutional partners spanning three continents.[8] UNIFY will provide an innovative annual two-month research and training program centred on current research topics. The first month will provide advanced training and research opportunities to PhD students and postdoctoral researchers, while the second is aimed at senior researchers. PI will co-organize the inaugural 2011 program, which will rotate locations. The partnership will also facilitate exchange visits by postdoctoral and senior scientists. Overall, PI has committed to 100 research months abroad using existing research grants (at no additional cost to PI) and will host visitors for the equivalent of 72 research months (funded by the European Union). This major four-year international collaboration

[8] Humboldt-Universität zu Berlin, Commissariat à l'Énergie Atomique et aux Énergies Alternatives – Saclay (France), Universidade do Porto (Portugal), Institute for the Physics and Mathematics of the Universe (IPMU) at the University of Tokyo, California Institute of Technology (Caltech), the Yang Institute for Theoretical Physics at the State University of New York (SUNY).

was awarded 400,000 Euros from a European Union granting agency, with approximately 150,000 Euros allocated to the PI node.

### LIGO

In June 2011, PI and the Canadian Institute for Theoretical Astrophysics signed an agreement to become the first Canadian members of the Laser Interferometer Gravitational Wave Observatory (LIGO) international scientific collaboration. The agreement enables PI researchers to participate in the analysis of LIGO data and facilitates research visits. Given the high potential of gravitational wave physics to provide new insights on several fronts, this agreement furnishes significant new scientific opportunities.

### TRIUMF

In July 2011, PI signed a one-year renewable agreement with TRIUMF, Canada's leading experimental centre for subatomic physics, based in British Columbia. The agreement will facilitate a two-way flow of faculty and postdoctoral researchers between the two centres for two- to four-week visits, and should increase engagement of PI theorists with experimentalists in Canada.

### Abdus Salam International Centre for Theoretical Physics (ICTP) Partnership

In April 2011, PI signed a one-year, renewable memorandum of understanding with the Abdus Salam International Centre for Theoretical Physics (ICTP) to facilitate research visits and collaboration on workshops in areas of mutual interest.

### HoloGrav Network

In 2011, Perimeter became an associate member of the HoloGrav Network, an international network including 15 partner organizations in 13 countries across Europe, as well as associates in 12 countries throughout Europe, Asia, and North America. The HoloGrav Network focuses on furthering research on the interdisciplinary aspects of gauge/gravity duality, including its applications across particle, nuclear, condensed matter, and gravitational physics, primarily through student exchanges, workshops, conferences, and summer schools.

## Global Outreach

Perimeter Institute's Global Outreach initiative shares expertise (not funding), in order to help catalyze the growth of scientific centres of excellence around the world. The current focus of Global Outreach efforts is the African Institute for Mathematical Sciences-Next Einstein Initiative (AIMS-NEI), a pan-African initiative to establish a network of centres providing advanced mathematical and scientific education to exceptional African graduates. AIMS was founded in 2003 by PI Director Neil Turok and, in 2010, AIMS-NEI and Dr. Turok were honoured with the 2010 World Innovation Summit for Education (WISE) Award, which recognizes initiatives that have transformative educational impact.

Many Perimeter employees contributed to Global Outreach efforts in 2010-11. Examples of this assistance include the following:

- Prepared a successful proposal which garnered $2 million from Google
- Obtained $1.12 million in support from five Canadian universities and private sector partners for the "One for Many" campaign to provide scholarship funds for AIMS students[9]
- Helped prepare the AIMS-NEI business plan and recruit an Executive Director
- Helped obtain support from the Government of Sénégal (1 million euros, plus a parcel of land valued at a similar amount) and provided significant logistics support for the new AIMS-Sénégal centre (opening fall 2011)
- Helped obtain support from the Ghanaian government (US$1.5 million), plus a 20-acre parcel of land donated by a diaspora organization, the Saltpond Redevelopment Institute, for AIMS-Ghana (projected to open in late 2012)

The Global Outreach initiative has opened a conduit between PI and Africa. Researchers and students have gone to AIMS as tutors and lecturers, and four AIMS graduates have entered the PSI program over its first three years, a number expected to grow as more AIMS centres open.

[9] The University of Ottawa and the University of Guelph have committed $250,000 each, while Simon Fraser University, the University of Victoria and the University of Waterloo have committed $100,000 each. The Université de Paris Sud pledged $70,000, and Waterloo-based Research in Motion committed $250,000.

# Objective 7: To increase PI's role as Canada's focal point for foundational physics research

## Summary of Achievements

- Conducted joint faculty searches with the University of Waterloo and McMaster University, resulting in the recruitment of three new Associate Faculty members (see Objective 2)
- Partnered with the University of Waterloo to deliver the PSI Masters program and involved faculty from several Canadian universities as lecturers and thesis supervisors[10] (see Objective 4)
- Appointed 13 new Affiliate members, bringing the total to 105 at the end of 2010-11
- Partnered on 10 joint workshops and conferences held at PI and other institutions, and sponsored an additional eight off-site conferences, workshops, and symposia (see Objective 6)
- Held seven advanced courses open to students at surrounding universities (see Objective 8)
- Commenced expansion of IT infrastructure, which will enhance virtual research and training (see Objective 3)

## Highlights

*"Perimeter Institute has succeeded in increasing Canadian research capacity in theoretical physics,*

–KPMG Evaluation Report, 2011

PI has become a hub of theoretical physics in Canada. In 2010-11, the Institute continued to provide unique resources to the national scientific community through courses, seminars, and workshops (see Objective 6), and attracted top students to Canada through the PSI program (see Objective 4). Perimeter continued to cultivate strategic partnerships at all levels, including joint recruitment (see Objective 2), co-organization of conferences (see Objective 6), and recruitment of new members of PI's Affiliate program (see below).

## Engagement with Experimental Centres

In 2010-11, PI increased engagement with experimental and observational centres, in line with targeted outcomes. Of particular note, PI and the Canadian Institute for Theoretical Astrophysics (CITA) became the first Canadian members of the LIGO international collaboration, opening up significant opportunities

[10] Matthew Choptuik, University of British Columbia; Kari Dalnoki-Veress, McMaster University; Veronica Sanz, York University; Erik Sorenson, McMaster University

for engagement with this key experimental effort (see Objective 6). PI also concluded a new formal agreement with TRIUMF, Canada's National Laboratory for Particle and Nuclear Physics (see Objective 6), and held discussions with the SNOLAB experimental particle physics laboratory, which will continue in the coming year. The Institute continues to deepen its relationship with the Institute for Quantum Computing (IQC) at the University of Waterloo and is launching a new joint recruitment effort in quantum information in the coming year.

## Affiliate Member Program

In 2010-11, Perimeter added 13 new Affiliate members, exceeding targeted outcomes and bringing the total to 105. Affiliates are select researchers at Canadian universities who are invited for regular informal visits to PI for scientific collaboration and the opportunity to be involved in the Institute's research activities. The program continues to strengthen regional and national research linkages between Perimeter and the Canadian scientific community, while in turn enriching PI research (see Appendix C, PI Affiliates).

# Objective 8: To host timely, focused conferences, workshops, seminars and courses

## Summary of Achievements

- Held 12 timely, focused conferences and workshops, attended by 653 scientists from around the world
- Partnered on ten joint workshops and conferences with university partners (see Objective 6)
- Presented 263 scientific talks (233 seminars, 30 colloquia)
- Delivered seven courses to researchers and students from surrounding universities
- Continued to develop PIRSA (Perimeter Institute Recorded Seminar Archive) as a leading international archival resource (see Objective 3)

## Highlights

*"PI has created an international hub for the gathering of researchers, facilitating stimulating formal and informal discussion and collaboration that is inviting and productive."*

–KPMG Evaluation Report, 2011

*"Recognizing the importance of a dynamic program in the dissemination of research outcomes, PI has encouraged, and been successful at, research dissemination activity over and above typical academic activities. In-person and on-line seminars, workshops, colloquia, exchange programs are all key mechanisms in helping PI to achieve this."*

–KPMG Evaluation Report, 2011

## Conferences and Workshops

Perimeter held 12 conferences and workshops in 2010-11 and continued to act as a major global node of exchange for cutting-edge research in theoretical physics, meeting targeted outcomes. The slight decrease in the overall number of conferences held this year reflects the Institute's strategy of very carefully selecting topics with exceptional potential for stimulating significant outcomes and closely monitoring expenses to ensure excellent value.

The Institute hosted a number of groundbreaking conferences in the past year, including the following:

- **"Integrability in Scattering Amplitudes II"** (September 15-16, 2010): This workshop, and a follow-up at the Institute for Advanced Study (IAS) in March, 2011, brought together the top researchers worldwide working on scattering amplitudes in N=4 SYM for a productive series of working sessions and presentations that generated major new results of international importance.
- **"Conceptual Foundations and Foils for Quantum Information Processing"** (May 9-13, 2011): This conference brought together 108 students and researchers for 29 invited talks, including some from founders of the field, such as DRC Sandu Popescu. It exemplified the cross-fertilization of ideas, examining how ideas from quantum information are leading to exciting new results in quantum foundations. (All talks are viewable at http://pirsa.org/C11006.)
- "**Women in Physics Canada"** (July 19-21, 2011): This was the first-ever conference aimed at trying to address the gender imbalance in the field by supporting the country's female physics students, and featured talks from early career and senior scientists.

## The Hybrid Program (New Initiative)

PI ran two Hybrid programs in 2010-11. A new initiative in 2010-11, the program aims to provide an integrated approach to focused research problems. Each hybrid program combines extended research visits, workshops, and talks, and spans weeks or even months. It is intended to amplify scientific outcomes by combining the benefits of longer-term collaborative work with the intense, multiple interactions of conferences that often spark new research directions.

The first, organized by Associate Faculty member Luis Lehner, brought together 12 international scientists to develop gravitational and electromagnetic wave astrophysical signatures, which are key to current and upcoming gravitational wave experiments. Work among key players is ongoing, and a follow-up conference is planned for late 2012 or early 2013.

The second hybrid program, "Fundamental Issues in Cosmology" (June 20-July 16, 2011), brought together leading string theorists and cosmologists to discuss unresolved questions about the cosmology of the early universe. The program was bookended by two conferences held a month apart ("Holographic Cosmology v2.0" and "Challenges for Early Universe Cosmology"), with informal collaboration time in between. More than 100 scientists participated in all, including many luminaries. The program exemplified PI's approach – highly interdisciplinary, with fresh ideas contributed from many areas, and encouragement of participation by students and early-career researchers as well as senior scientists. The Stanford Institute for Theoretical Physics, which partnered with PI in organizing the program, plans to host a follow-up workshop next year.

## Seminars and Colloquia

Perimeter held 233 seminars and 30 colloquia in 2010-11. In line with targeted objectives, the number of external speakers invited to present seminars in each research area was reduced slightly to allow for

more focused research time, while the number of distinct seminar series increased, reflecting the expanded scope of PI research. Particularly notable from the past year were talks by DRCs Yakir Aharonov, Patrick Hayden, Renate Loll, and William Unruh.

## Perimeter Institute Recorded Seminar Archive (PIRSA)

All talks held at PI can be viewed online on PIRSA, the Perimeter Institute Recorded Seminar Archive at www.pirsa.org. This permanent, free, searchable and citable archive of video recorded seminars, conferences, workshops, and courses was developed by Perimeter Institute to share knowledge with the international scientific community. It has become an important scientific resource for the field, as evidenced by the continued rise in site traffic year over year.

During the reporting period, 51,132 unique visitors from 151 countries accessed PIRSA, a 14% increase over the same period last year. New and returning users are also accessing PIRSA more frequently, as demonstrated by the 31% increase in the number of visits over last year, representing 490,304 page views. With recent and upcoming improvements to the archive (see Objective 3), this traffic is expected to rise.

## Courses

In addition to three-week courses held through the PSI program, the Institute offered PI resident researchers and students seven focused mini-courses in 2010-11. Given by both resident and visiting scientists, topical courses are open to students of surrounding universities and thereby enhance their course offerings. Highlights included “Space-time, Quantum Mechanics and Scattering Amplitudes” taught by DRC Nima Arkani-Hamed (IAS) and Faculty member Freddy Cachazo (August 2010), “Scattering Amplitudes from Single-Cuts” taught by Simon Caron-Huot (IAS) (September 2010), and “Introduction to Tensor Network Algorithms” (June 2011) taught by PI Postdoctoral Researcher Robert Pfeifer.

# Objective 9: To engage in high impact outreach

## Summary of Achievements

- Reached over 160,000 Canadian high school students in 2010-11 via all of PI's outreach programs
- Developed two new in-class and web-based educational resources; cumulatively, PI classroom resources have been used by over 500,000 students across Canada to date
- Held the inaugural conference of the Waterloo Global Science Initiative (WGSI), *Equinox Summit: Energy 2030* to generate ideas on how science can address current energy challenges
- Held the 9th annual International Summer School for Young Physicists (ISSYP); held three one-day *Go Physics!* camps; and gave six *Physica Phantastica* presentations to over 1,000 students across Canada
- Held one week-long EinsteinPlus teacher training camp, and delivered on-location teacher workshops to over 1,250 educators across Canada and internationally
- PI Teacher Network Associates delivered 60 peer-to-peer workshops to 1,300 educators across Canada
- Received an Honourable Mention in the International Science & Engineering Visualization Challenge of the American Association for the Advancement of Science and the U.S. National Science Foundation for *Everyday Einstein: GPS & Relativity*

## Highlights

*"PI's engagement in high impact communications and outreach goes beyond that of a typical research institution. Respondents reported that the products are in-depth and vibrant, influencing the awareness, interest and desire of target audiences to learn more about modern science.*

–KPMG Evaluation Report, 2011

## Programs and Resources for Teachers

### EinsteinPlus National Teachers' Workshop

In July 2011, Perimeter welcomed 39 high school teachers (31 Canadians and eight international teachers) for its annual EinsteinPlus National Teachers' Workshop (E+). This intensive, one-week workshop is PI's primary hub for engaging Canada's physics educators. It provides teachers with effective methods for teaching key concepts in modern physics and introduces them to PI's in-class resources. Teachers in turn provide feedback on PI resources, which is critical to ensuring they meet teacher needs and have an impact in the classroom, and E+ alumni form the core of the Teacher's

Network (see below). Surveys show that E+ provides highly enjoyable, top-calibre professional development and is a very effective vector for distribution of PI educational resources.

## On-location Teacher Workshops

Presentations at educational conferences and gatherings are an efficient means of increasing the reach and visibility of Perimeter's outreach programs in Canada and abroad. In 2010-11, outreach staff delivered 15 on-location workshops at teacher conferences nationally, exceeding targeted outcomes and reaching over 1,250 educators.[11] Outreach staff again presented workshops internationally at the Physics Teaching Resource Agents' (PTRA) annual Summer National Leadership meeting, and a 'mini-EinsteinPlus' at CERN in Switzerland for 40 European physics teachers from 30 countries. Since new resources are being developed for younger grades, the outreach team also held several events in 2010-11 to expand contacts among elementary and junior high school teachers.[12]

## PI Teacher Network

Comprised of select alumni from EinsteinPlus and PI's on-location teacher workshops, PI's Teacher Network includes over 80 teachers across Canada who are trained on sharing the Institute's resources with fellow educators in their home districts. The Network has become a key means of scaling PI's impact across the country: in 2010-11 Network Associates delivered 60 workshops to 1,300 educators, thereby reaching 58,500 Canadian high school students. In October 2010, the Institute hosted its first PI Teacher Network conference, bringing 20 Network Associates to PI for a two-day training session which provided opportunities for Network members to share strategies and delivery methods they use when conducting workshops on PI resources. Feedback indicated that the conference was very successful, and it is planned that it will become a regular biennial event.

## Educational Resources

### *Perimeter Inspirations* and *Explorations*

Perimeter's in-class educational modules have cumulatively reached over 500,000 students across Canada to date. They are the Institute's primary means of introducing Canadian high school students to modern physics. They are produced with the input of working physics educators to ensure they are genuinely useful to teachers, and feedback indicates that they are used and re-used. Indeed, significant

[11] PI's outreach team presented workshops at the following conferences: Science Teachers' Association of Ontario (STAO), Ontario Association of Physics Teachers (OAPT), and British Columbia's Science Teaching Catalyst Conference.

[12] In September 2010, PI hosted a Professional Development day for regional elementary school teachers; in November 2010, PI hosted 78 teachers for a teacher talk by Dr. Eric Mazur (Harvard University); in May 2011, Perimeter staff spoke to 30 grade 6-8 teachers at McMaster University.

parts of *The Challenge of Quantum Reality* and *Measuring Planck's Constant* resources have even been deeply integrated into Ontario's sole grade 12 physics textbook.

*Perimeter Inspirations* show the connections between everyday life and fundamental physics, and are aimed at motivating junior high school students to continue with math and science in senior grades. Of special note, *Everyday Einstein: GPS & Relativity* was awarded an Honourable Mention in the prestigious 2011 International Science & Engineering Visualization Challenge of the American Association for the Advancement of Science (AAAS) and the US National Science Foundation (NSF). In addition, Perimeter ran *The Power of Ideas* Teacher Contest, ultimately recognizing two outstanding submissions for their creative integration of the resource into their teaching and sharing these highly effective techniques throughout PI's Teacher Network.

In 2010-11, Perimeter completed two new *Inspirations* resources:

- Classroom materials and a DVD tied to *Alice and Bob in Wonderland,* a popular series of 60-second animations introducing profound ideas about the universe
- *Alice and Bob – Revolutions in Science*, a pedagogically rich teacher's kit examining the thinking processes that led to three revolutions in science: the quantum atom, $E=mc^2$, and Einstein's gravity

Work on a new *Perimeter Explorations* module on particle physics commenced in 2010-11 and is slated for completion in 2012. *Perimeter Explorations* are more advanced in-class modules for senior high school students which convey challenging concepts in highly visual and hands-on ways. Three such modules have been produced to date: *The Mystery of Dark Matter, The Challenge of Quantum Reality,* and the popular *Planck's Constant* LED activity.

# Student Programs and Products

## International Summer School for Young Physicists (ISSYP)

The 2010 edition of the International Summer School for Young Physicists (ISSYP) brought 40 top Canadian and international students[13] to PI for two weeks of intensive instruction in modern physics, plus mentoring sessions and lab tours. For the third year running, a program highlight was the visit to SNOLAB, an underground particle physics facility located in a decommissioned mine.

Since 2003, ISSYP has been a pillar of PI's outreach efforts. The program is highly selective, and chooses students with demonstrated scientific potential – just 8% of applicants were accepted in 2010-11. By providing a first-hand view of leading-edge research at an age when students are actively weighing career directions, PI strives to develop new talent for the field and for Canada. New skills and lasting friendships were formed amid a spirit of camaraderie that models the true nature of scientific research.

[13] ISSYP 2010 participants included 21 Canadians from eight provinces and 19 international students from 12 countries.

Follow-up metrics indicate that it is effective; every year, numerous ISSYP alumni do enter science, many at Canadian universities.

Numerous program enhancements were made in 2010-11, facilitated by a gift from the RBC Foundation (see Objective 10). An experienced high school physics teacher was hired as an Educational Consultant to assess the program and develop refinements. In addition, ISSYP's rich course content is being consolidated into a modern physics textbook, which will significantly extend the program's reach.

In addition to ISSYP, *GoPhysics!* is a one-day program which gives a snapshot of the ISSYP experience to approximately 25 students at a time. Given by Teacher Network Associates and Perimeter's outreach staff scientists, it is designed to get more high-potential senior high school students excited about physics. In 2010-11, three *Go Physics!* Camps were held across Canada (in Waterloo, Calgary, and Halifax); six are planned for 2011-12.

## *Physica Phantastica* Presentations

*Physica Phantastica* presentations illustrate the connections between foundational science and the technological devices that enhance day-to-day life with images and animations that make abstract ideas come alive. In 2010-11, the series continued to provide entertaining and accessible introductions to modern physics to over 1,000 students across the country, and by request to several adult audiences including RIM, ARC, Sun Life Financial, and a group of Canada's leading Chief Information Officers. (While the Institute will continue providing these presentations to interested adult audiences as time permits, the focus will remain on students in grades 7 to 12).

## Aboriginal Engagement

In 2010-11, Perimeter's outreach staff held meetings with educators and students on Manitoulin Island, with Waterloo Region District School Board officials, and with the Chancellor of Nipissing University. These meetings indicated that to effectively engage Aboriginal students and teachers, significant tailoring of current resources, and an effective delivery strategy are required. Further research and consultation will be undertaken to develop these.

## Online Resources

In 2010-11, PI's outreach website was enhanced, preparations were started for a major website overhaul in 2011-12, and the use of social media was significantly expanded. Putting high-quality offerings online allows PI to scale its reach and impact; thus, most outreach resources are available online, including *Perimeter Inspirations* and *Explorations*, *Virtual ISSYP,* over 30 *Meet A Scientist* video interviews, and past Public Lectures, which are now also available through iTunes University.

In 2010-11, the outreach team conducted three webinars with students and educators in Toronto, Fort Hope, and Whale Cove, Nunavut. Webinars are a low-cost means of extending PI's reach and have the further benefit of enabling PI researchers to participate in outreach while reducing demands on their time. Response to the webinars was highly positive, and they appear to be an efficient and cost-effective way of communicating with the expanding Teacher Network, as well as students in remote communities.

# Programs for the General Public

## Waterloo Global Science Initiative (WGSI)

WGSI is an independently funded, non-profit partnership between Perimeter Institute and the University of Waterloo whose mandate is to advance dialogue and catalyze the long-range thinking necessary to drive scientific and technological solutions to key social, environmental, and economic challenges.

From June 5 to 9, 2011, the Waterloo Global Science Initiative (WGSI) hosted its inaugural event, *Equinox Summit*, at Perimeter Institute. The event focused on energy solutions and brought together scientists, next-generation leaders, and policy experts to discuss potential solutions for electricity production, storage, and distribution. At the Summit's conclusion, participants presented the Equinox Communiqué, a shortlist of potentially transformative technologies and a roadmap for a lower-carbon and electrified future. This will be expanded into the Equinox Blueprint, to be presented at the American Association for the Advancement of Science (AAAS) meeting in Vancouver in February 2012, and later distributed to science and technology leaders throughout industry and government.

Perimeter's public broadcast partner, TVO, filmed five nights of *The Agenda With Steve Paikin* live from the Summit and shared several debates, plenary sessions, public lectures, and panel discussions online and on-demand. Major international media organizations, including *Nature*, *Scientific American*, and the BBC, reported on the proceedings, and Perimeter staff shared the results of the Summit with over 700 delegates at the World Conference of Science Journalists (see below).

## Public Lecture Series

Perimeter continued its flagship Public Lecture Series in 2010-11 with eight accessible, engaging talks on compelling scientific topics (plus three lectures presented in conjunction with the Waterloo Global Science Initiative). The series is extremely popular, and the 600 tickets for each lecture are distributed within minutes (the lectures are free, but require tickets ordered via Perimeter's website). Highlights included Sara Seager (MIT), who spoke on "Exoplanets and the Search for Habitable Worlds," Freeman Dyson (Institute for Advanced Study) on "Living Through Four Revolutions," Seth Lloyd (MIT) on "Quantum Life," and Sir Roger Penrose (University of Oxford) on "Twistors and Quantum Non-Locality."

Through PI's partnership with TVO, select talks are broadcast as part of TVO's "Big Ideas" series, along with other PI content such as the "Hawking at the Perimeter" special and *The Quantum Tamers* documentary. Lectures are also available for download on Perimeter's website and on iTunes University. TVO reports that they are among its most popular content and, indeed, TVO's most-downloaded science podcast was a PI Public Lecture given by MIT scientist Seth Lloyd.

## Media Engagement and Professional Development

Perimeter Institute seeks to raise scientific literacy in Canada and beyond, and high quality science journalism is an important means to achieving this. As such, PI has developed strong relationships with several science media partners. In March 2011, students from Laurentian University's Graduate Program in Science Communication toured PI, spoke with staff in Perimeter's outreach department, and met with award-winning science writer Marcus Chown before his Public Lecture. The Institute is a program sponsor of the Science Communication Program at the Banff Centre and a Charter Member of the Science Media Centre of Canada. In June 2011, Perimeter staff and scientists attended the World Conference of Science Journalists in Doha, Qatar, where they contributed to three conference sessions.[14]

Perimeter continued to receive positive national and international media coverage in 2010-11 from numerous media outlets. Among the highlights were the following:

- In September 2010, Paul Wells, Senior Columnist for *Maclean's* magazine, published a feature article entitled "Mind-bending mysteries at the Perimeter Institute" in the magazine's "Rethink Issue" after a month-long visit to PI
- In October 2010, BBC's long-running science documentary program Horizon aired "What Happened Before The Big Bang?", featuring PI scientists Neil Turok, Lee Smolin, Parampreet Singh, and Distinguished Research Chair Leonard Susskind
- In January 2011, CBC Radio One's national current affairs program, *The Current*, aired an episode featuring Perimeter Board Chair Mike Lazaridis, Director Neil Turok, Faculty member Latham Boyle, and Associate Faculty member Raymond Laflamme on the topic of innovation and the importance of theoretical physics

[14] These included a panel on prospective upcoming research highlights in physics and how best to report them, featuring Associate Faculty member Raymond Laflamme; a session outlining the outcomes of the *Equinox Summit*; and a plenary session produced by PI on science as a force for positive change in Africa to address the continent's development challenges.

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

## Summary of Achievements

- Obtained a funding commitment from the Government of Canada of $50 million beginning in 2012-13
- Obtained a funding commitment from the Province of Ontario of $50 million beginning in 2011-12
- Hired a Director of Advancement to oversee the Institute's efforts to attract private donors
- Obtained a $4 million gift from BMO Financial Group to endow the first Perimeter Research Chair, as well as other private sector investments ranging from $75,000 to $500,000

## Highlights

## Renewal of Public Funding

In the last year, Perimeter submitted proposals for renewed funding to both its provincial and federal government partners. Both proposals were successful; the Government of Canada pledged $50 million beginning in 2012-13, and the Government of Ontario pledged $50 million beginning in 2011-12.

## Leadership Council

In October 2010, PI formed a Leadership Council of 21 influential leaders, primarily from the private sector, to assist with advancement efforts. Members volunteer their time, offer guidance, and act as ambassadors in the business and philanthropic communities on PI's behalf, widening the circle of contacts PI can engage as partners in the coming years.

## Private Sector Support

To support its rapid growth and ensure the Institute's long-term sustainability, Perimeter has been actively seeking private support, and 2010-11 was its most successful year to date in this respect. In summer 2011, PI hired a Director of Advancement, Maria Antonakos, to lead PI's small advancement team.

In November 2010, BMO Financial Group announced a $4 million gift to partially endow the BMO Financial Group Isaac Newton Chair in Theoretical Physics at Perimeter Institute, the first of five projected Perimeter Research Chairs. The investment was both the largest corporate donation in PI's

history and the largest single donation BMO has ever made to support science in Canada. World-leading condensed matter physicist Xiao-Gang Wen was recruited from MIT to become the first Chairholder (see Objective 2).

In addition, PI welcomed the following private sector support:

- The RBC Foundation, which pledged $400,000 to strengthen Perimeter's annual International Summer School for Young Physicists
- Christie Digital, which donated leading-edge visual display systems worth approximately $500,000 for the new Stephen Hawking Centre
- Sun Life Financial, which gave $100,000 to sponsor PI's 2010-11 Public Lecture Series; this funding has been renewed for 2011-12
- The Cowan Foundation, which gave $75,000 over three years to help support the creation of three *Perimeter Inspirations* in-class resources(see Objective 9)
- Private donors pledged $10,000 in support of Perimeter Scholars International (PSI)
- In celebration of the grand opening of the Stephen Hawking Centre, Leadership Council members, PI Board members, and senior management made personal commitments of over $400,000

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

Summarized Financial Statements of

**PERIMETER INSTITUTE**

Year Ended July 31, 2011

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, 2011, 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, 2011. We expressed an unmodified audit opinion on those financial statements in our report dated December 2, 2011. 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 generally accepted accounting principles. 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 audited financial statements in accordance with Canadian generally accepted accounting principles.

*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, 2011 are a fair summary of those financial statements, in accordance with Canadian generally accepted accounting principles.

Zeifmans LLP

Toronto, Ontario
December 5, 2011

Chartered Accountants
Licensed Public Accountants

## PERIMETER INSTITUTE

Summarized Statement of Financial Position
as at July 31, 2011

| | 2011 | 2010 |
|---|---|---|
| **ASSETS** | | |
| Current Assets: | | |
| Cash and cash equivalents | $ 1,082,000 | $ 5,063,000 |
| Investments | 218,970,000 | 209,003,000 |
| Government grants receivable | 2,145,000 | 3,611,000 |
| Other current assets | 2,168,000 | 1,170,000 |
| | 224,365,000 | 218,847,000 |
| Other receivable | --- | 30,000 |
| Property and equipment | 55,489,000 | 38,197,000 |
| **TOTAL ASSETS** | $ 279,854,000 | $ 257,074,000 |
| **LIABILITIES AND FUND BALANCE** | | |
| Current liabilities: | | |
| Bank overdraft | $ 571,000 | $ --- |
| Bank indebtedness | 1,330,000 | --- |
| Accounts payable and other current liabilities | 6,168,000 | 4,917,000 |
| **TOTAL LIABILITIES** | 8,075,000 | 4,917,000 |
| Fund balances: | | |
| Invested in capital assets | 53,536,000 | 38,114,000 |
| Externally restricted | 100,128,000 | 136,180,000 |
| Internally restricted | 78,840,000 | 77,410,000 |
| Unrestricted | 39,275,000 | 453,000 |
| **TOTAL FUND BALANCES** | 271,779,000 | 252,157,000 |
| | $ 279,854,000 | $ 257,074,000 |

On behalf of the Board:

_____ Director

_____ Director

ZEIFMANS LLP
CHARTERED ACCOUNTANTS

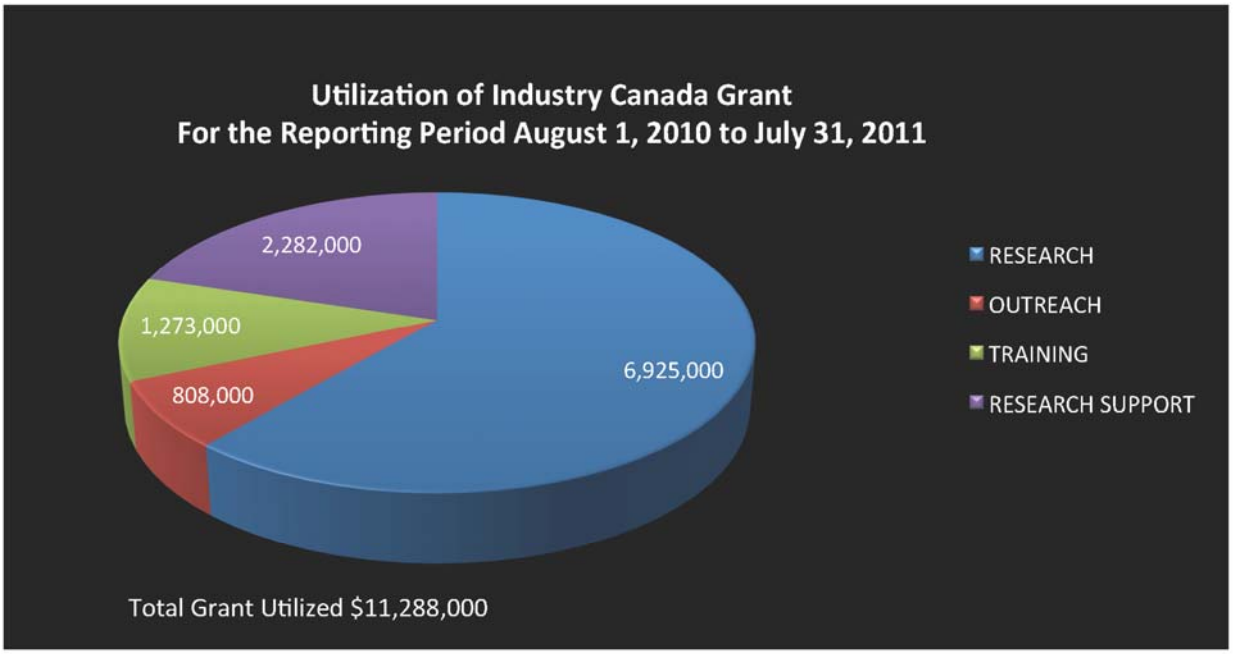
## PERIMETER INSTITUTE

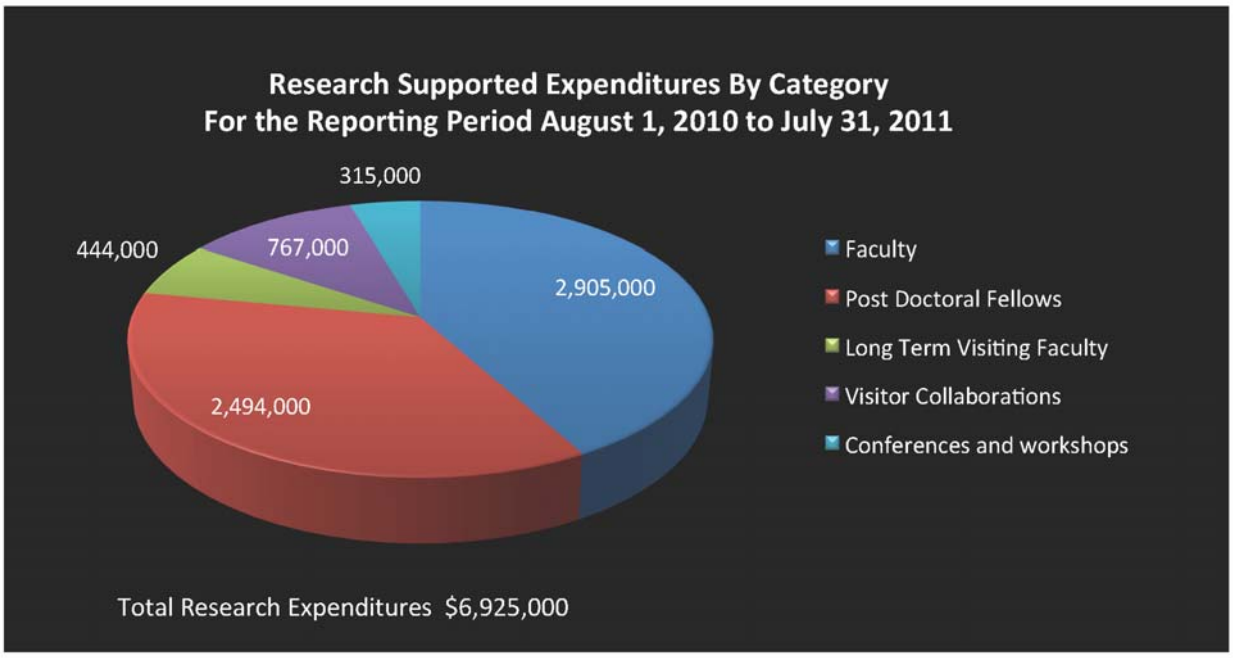
Summarized Statement of Operations and Changes in Fund Balances
For the Year Ended July 31, 2011

| | 2011 | 2010 |
|---|---|---|
| **Revenue:** | | |
| Government grants | $ 18,190,000 | $ 18,073,000 |
| Other income | 425,000 | 435,000 |
| Donations | 212,000 | 626,000 |
| | 18,827,000 | 19,134,000 |
| **Expenditures:** | | |
| Research | 9,748,000 | 9,858,000 |
| Research training | 1,688,000 | 1,450,000 |
| Outreach and science communications | 2,601,000 | 3,149,000 |
| Indirect research and operations | 4,535,000 | 4,415,000 |
| **Total Operating Expenditures** | 18,572,000 | 18,872,000 |
| Excess of revenue over expenditures before investment income and amortization | 255,000 | 262,000 |
| Amortization | (1,573,000) | (1,656,000) |
| Investment income | 20,940,000 | 11,374,000 |
| Excess of revenue over expenditures | 19,622,000 | 9,980,000 |
| Fund balances, beginning of year | 252,157,000 | 242,177,000 |
| Fund balances, end of year | $ 271,779,000 | $ 252,157,000 |

ZEIFMANS LLP
CHARTERED ACCOUNTANTS

## Expenditures by Activity



## Criteria Applied to Eligible Activities

Perimeter Institute uses 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. Tools used to measure outcomes, results, and impacts include:

## Performance Monitoring – Internal

- Annual reports on research activity submitted to the Director by all researchers for evaluation
- Annual reports on research activity submitted to the Director by all research groups for evaluation
- Ongoing monitoring of publication and citation records
- Monthly updates and monitoring of progress of all scientific programs
- Post-conference reports and evaluation
- Annual evaluation of all scientific programs
- Mid-term researcher performance reviews
- Postdoctoral Researcher and junior Faculty mentorship program
- Visitor research activity reports and ongoing tracking of all output
- Monitoring of Postdoctoral Researchers' post-PI placement success
- Monitoring of international researcher presence and impact through collaborations and invitations to lecture
- Internal review and evaluation of all outreach programs and products

## Performance Monitoring – External

- The Scientific Advisory Committee provides ongoing scrutiny of the Institute's performance and submits reports and recommendations to the Board and Director. Committee members are listed in Appendix E.
- Review by the Scientific Advisory Committee of all Faculty and Associate Faculty hires, renewals, and promotions
- Peer review of publications
- Performance audits as per granting 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, PI Board of Directors).

Financial planning, accountability, and investment strategy are carried out by the Board's Investment Committee and its Finance and Audit Committee. The Board also forms other committees as required to assist it in discharging its duties. Reporting to the Board of Directors, the Executive 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 Executive Director and is in charge of day-to-day operations of the Institute. Support for the COO is provided by a team of senior directors and administrative staff.

The Institute's resident scientists play an active role in scientific operational issues via participation on various committees in charge of scientific programs. Committee chairs report to the Executive Director.

The international Scientific Advisory Committee (SAC) is an integral oversight body, deliberately created to assist the Board of Directors and Executive Director to ensure objectivity and a high standard of

scientific excellence. The SAC meets regularly and submits detailed reports with recommendations to the Board and Executive Director following each meeting. The SAC is composed of eminent scientists drawn from the international community (see Appendix E, SAC Members).

## Financial – Investment and Management of Funds

The Board of Directors of Perimeter Institute is supported in fulfilling its fiduciary responsibilities with respect to financial management 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.

## Objectives for 2011-12

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 on track to achieve its long-term goal: to create and sustain a world-leading centre for foundational theoretical physics research, training, and outreach that will promote scientific excellence and stimulate breakthroughs.

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.

## Statement of Objectives, 2011-12

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

Objective 4: To generate a flow-through of the most promising talent

Objective 5: To become the second 'research home' for many of the world's outstanding theorists

Objective 6: To act as a hub for a network of theoretical physics centres around the world

Objective 7: To increase PI's role as Canada's focal point for foundational physics research

Objective 8: To host timely, focused conferences, workshops, seminars, and courses

Objective 9: To engage in high impact outreach

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

# Appendices

Note: Appendices include individuals who held a position with the Institute for any period between August 1, 2010 and July 31, 2011. Unless otherwise noted, they were still serving in the capacity listed at the end of the fiscal year.

# Appendix A: Perimeter Institute Faculty

## Faculty

**Neil Turok** is the Director of Perimeter Institute for Theoretical Physics in Waterloo, Ontario, Canada. He earned his PhD at Imperial College, London, in 1983, after which he held a postdoctoral fellowship in Santa Barbara. After his time in Santa Barbara he became an Associate Scientist at Fermilab before moving to Princeton University, where he became Professor of Physics in 1994. In 1997, he was appointed to the Chair of Mathematical Physics in the Department of Applied Mathematics and Theoretical Physics (DAMTP) at the University of Cambridge. In October 2008, he joined Perimeter Institute as its Director. Among his many honours, Professor Turok was awarded Sloan and Packard Fellowships and the 1992 James Clerk Maxwell medal of the UK Institute of Physics. In 2009, he was named a Canadian Institute for Advanced Research (CIFAR) Fellow in the Cosmology and Gravity program. Professor Turok has worked in a number of areas of theoretical physics and cosmology, focusing on developing fundamental theories and new observational tests. Highlights of his research include showing how the polarization and temperature anisotropies of the cosmic background radiation would be correlated, developing a key test for the presence of the cosmological constant, formulating the Hawking-Turok instanton solutions describing the birth of inflationary universes, and advancing a cyclic model for cosmology, according to which the big bang is explained as a collision between two 'brane-worlds' in M-theory. Born in South Africa, Professor Turok founded the African Institute for Mathematical Sciences (AIMS) in Cape Town in 2003, a postgraduate educational centre that supports the development of mathematics and science across the African continent. For this work and his contributions to theoretical physics, he was awarded the TED Prize and a "Most Innovative People" award at the 2008 World Summit on Innovation and Entrepreneurship (WSIE).

**Latham Boyle** joined PI as a junior Faculty member in 2010. He received his PhD in physics in 2006 from Princeton University, under the direction of Paul Steinhardt. From 2006 to 2009, Dr. Boyle held a Canadian Institute for Theoretical Astrophysics (CITA) Postdoctoral Fellowship; he is also a Junior Fellow of the Canadian Institute for Advanced Research (CIFAR). Dr. Boyle has studied what gravitational wave measurements can teach us about the beginning of the universe; with Paul Steinhardt, he derived a series of "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** has been a Faculty member at PI since 2005. He received his PhD in 2002 from Harvard University and, from 2002 to 2005, he was a Member of the School of Natural Sciences at the Institute for Advanced Study in Princeton, New Jersey, USA. Dr. Cachazo is one of the world's leading experts in the subject of the study and computation of scattering amplitudes in quantum chromodynamics (QCD) and N=4 super Yang-Mills (MSYM) theories. In 2007, he was awarded an Early Researcher Award for his project "Taming the Strong Interactions: Perturbative and Non-Perturbative Methods." In 2009, he was awarded the Gribov Medal of the European Physical Society, "for work that has led to significant simplifications in the calculation of scattering amplitudes in both gauge theories and gravity ones."

**Laurent Freidel** received his PhD from L'École Normale Supérieure de Lyon in 1994. He has made many notable contributions in the field of quantum gravity and joined Perimeter Institute in September 2006. Dr. Freidel is a mathematical physicist with outstanding knowledge of a wide range of areas including integrable systems, topological field theories, 2d conformal field theory and QCD (quantum chromodynamics). He has authored or co-authored over 40 publications, many of which are known among fellow researchers for offering particularly complete, detailed arguments. Dr. Freidel is also the author or co-author of several significant papers on spin foam models – higher-dimensional diagrams that operate as models of the quantum geometry of spacetime in loop quantum gravity. He also contributes to further research on the low energy limit of spin foam models including new proposed formulations and coupling to matter. Dr. Freidel has held positions at Penn State University and L'École Normale and has been a member of France's Centre National de la Recherche Scientifique (CNRS) since 1995. Dr. Freidel is also the recipient of several awards, including two ACI-Blanche grants in France.

**Jaume Gomis** received his PhD from Rutgers University in 1999, then worked at the California Institute of Technology as a Postdoctoral Scholar and as the Sherman Fairchild Senior Research Fellow. In 2004, Dr. Gomis was awarded a European Young Investigator Award by the European Science Foundation, which he declined in order to join Perimeter Institute that same year. His main areas of expertise are string theory and quantum field theory. In 2009, Dr. Gomis was awarded an Early Researcher Award from the Ministry of Research and Innovation of Ontario for his project "New Phases of Matter and String Theory," aimed at developing new techniques for describing quantum phenomena in nuclear and particle physics.

**Daniel Gottesman** received his PhD in 1997 from the California Institute of Technology, where he was a student of John Preskill. He then held postdoctoral positions at Los Alamos National Lab, Microsoft Research, and UC Berkeley (as a long-term CMI Prize Fellow for the Clay Mathematics Institute). Dr. 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 3,500 citations to date. He is also a Fellow in CIFAR's Quantum Information Processing program.

**Lucien Hardy** received his PhD at Durham University in 1992 under the supervision of Euan Squires. Prior to his arrival at PI, he held research and lecturing positions at various European universities including the University of Oxford (1997-2002), La Sapienza University, Rome, Italy (1996-1997), the University of

Durham, UK (1994-1996), the University of Innsbruck, Austria (1993-1994), and the National University of Ireland (1992-1993). While in Rome, he collaborated on an experiment to demonstrate quantum teleportation. 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.

**Fotini Markopoulou** received her PhD from Imperial College in 1998 under the supervision of Christopher Isham. She joined PI as one of its first Faculty members in 2001, prior to which she held postdoctoral positions at the Albert Einstein Institute (2000-2001), Imperial College London (1999-2000), and Penn State University (1997-1999). Dr. Markopoulou is a past recipient of First Prize in the Science and Ultimate Reality Young Researchers Competition in honour of J.A. Wheeler (2001). She has been a visiting professor at MIT (2008) and currently holds an Alexander von Humboldt Fellowship for Experienced Researchers at the Albert Einstein Institute in Germany.

**Robert Myers** is one of the leading theoretical physicists working in the area of string theory in Canada. He received his PhD from Princeton University in 1986, after which he was a postdoctoral researcher at the (now) Kavli Institute for Theoretical Physics at the University of California, Santa Barbara. He moved to McGill University in 1989, where he was a Professor of Physics until moving to Perimeter Institute in the summer of 2001. Currently, he also holds an Adjunct position in the Department of Physics and Astronomy at the University of Waterloo. Dr. Myers was awarded the Herzberg Medal in 1999 by the Canadian Association of Physicists for seminal contributions to our understanding of black hole microphysics and D-branes. He won the 2005 CAP-CRM Prize, Canada's top prize in theoretical and mathematical physics, awarded by the Canadian Association of Physicists and the Centre de Recherches Mathématiques. In 2006, he was elected a Fellow of the Royal Society of Canada. Dr. Myers is also a Fellow of the Cosmology and Gravity program of the Canadian Institute for Advanced Research. From 2001 to 2005, he was a founding member on the scientific advisory board of the Banff International Research Station. Dr. Myers also serves on the editorial boards of the research journals *Annals of Physics* and *Journal of High Energy Physics*.

**Philip Schuster** joined PI in 2010 as a junior Faculty member in the particle physics program. Dr. Schuster completed his PhD in 2007 at Harvard University under the supervision of Nima Arkani-Hamed and was a Research Associate at SLAC National Accelerator Laboratory from 2007 to 2010. Dr. 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 a variety of theories that may be discovered at new experiments at the Large Hadron Collider (LHC) at CERN. In collaboration with members of the Compact Muon Solenoid (CMS) experiment at the LHC, he developed a set of methods to characterize potential new physics signals and null results in terms of 'simplified models,' making it easier to provide more robust theoretical interpretations of data. He is also a co-spokesperson for the APEX collaboration, which is developing an electron fixed-target experiment designed to search for new forces at the GeV-scale with unrivalled sensitivity and which recently completed a successful test run at the Thomas Jefferson National Accelerator Facility in Virginia.

**Lee Smolin** is one of Perimeter Institute's founding Faculty members. After acquiring an undergraduate degree in Natural Philosophy from Hampshire College, he received his PhD from Harvard University in 1979, after which he held postdoctoral positions at the Institute for Advanced Study, Princeton, the Institute for Theoretical Physics, Santa Barbara, and the Enrico Fermi Institute at the University of Chicago. He was a professor at Yale, Syracuse, and Penn State Universities and has held various visiting positions at Imperial College London, and the Universities of Oxford, Cambridge, Rome, Trento, and SISSA in Italy. Professor Smolin's research is centered on the problem of quantum gravity, and was one of the initiators of two research programs: loop quantum gravity and deformed special relativity. He has also contributed to cosmology, the foundations of quantum mechanics, astrophysics, philosophy of science and, recently, economics, and his papers have generated over 6,390 citations to date. His three non-technical books, *The Life of the Cosmos*, *Three Roads to Quantum Gravity*, and *The Trouble With Physics*, explore philosophical issues raised by developments in modern physics and cosmology. They have been widely read by the public and translated into over 20 languages. In 2007, Professor Smolin was awarded the Majorana Prize and, in 2009, he was given the Klopsteg Memorial Award from the American Association of Physics Teachers for his "extraordinary accomplishments in communicating the excitement of physics to the general public." Professor Smolin is an elected Fellow of the American Physical Society and, in 2010, was elected as a Fellow of the Royal Society of Canada.

**Robert Spekkens** received his PhD from the University of Toronto in 2001 and subsequently held a postdoctoral fellowship at Perimeter Institute and an International Royal Society Fellowship at the University of Cambridge. He joined PI's faculty in 2008. Dr. Spekkens' 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. He is a previous winner of the Birkhoff-von Neumann Prize of the International Quantum Structures Association.

**Natalia Toro** joined PI in 2010 as a junior Faculty member in the particle physics program. She completed her PhD at Harvard in 2007 under the supervision of Nima Arkani-Hamed, a Distinguished Research Chair at Perimeter Institute, and subsequently completed a postdoctoral fellowship at Stanford University SITP. Dr. 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** joined PI as a senior Faculty member in May 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. Dr. Vidal received his PhD in 1999 from the University of Barcelona, under the supervision of Professor Rolf Tarrach. He did three-year postdoctoral fellowships at the University of Innsbruck in Austria and the Institute for Quantum Information at Caltech before joining the University of Queensland. Dr. Vidal works at the interface of quantum information and condensed matter physics.

He uses 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** joined PI in 2009 from the Max Planck Institute for Gravitational Physics (Albert Einstein Institute) in Potsdam, Germany, where he was a Junior Scientist from 2008 to 2009. Dr. Vieira completed his PhD at the École Normale Supérieure Paris and the Centro de Fisica do Porto, Universidade do Porto, under the supervision of Vladimir Kazakov and Miguel Sousa Costa. Dr. Vieira's research concerns the development of new mathematical techniques for gauge and string theories, ultimately aiming toward the solution of a realistic four-dimensional gauge theory. Using integrability techniques, he and his collaborators have recently made significant progress in computing, for the first time, the exact (planar) spectrum of a remarkable holographic duality between a theory of gravity and field theory known as the AdS/CFT correspondence. This work may yield new insights into both gauge theories and quantum gravity, and for theoretical calculations of scattering amplitudes in particle physics.

## Associate Faculty

**Niayesh Afshordi** (jointly appointed with the University of Waterloo) completed his PhD at Princeton under the supervision of David Spergel in 2004. 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. In 2010, Professor Afshordi joined PI as an Associate Faculty member, in a joint appointment with the Department of Physics and Astronomy at the University of Waterloo. Professor Afshordi specializes in interdisciplinary problems in fundamental physics, astrophysics, and cosmology, with particular focus on observational findings that can help address problems in fundamental physics. In 2010, Professor Afshordi was awarded a Discovery Accelerator Supplement from the Natural Sciences and Engineering Research Council of Canada (NSERC), one of only eight awarded across Canada in physics. His 28 peer-reviewed publications have attracted over 900 citations to date.

**Alex Buchel** (jointly appointed with the University of Western Ontario) received his PhD from Cornell in 1999. He was a Postdoctoral Researcher at the Institute for Theoretical Physics, UCSB, US from 1999 to 2002 and a Research Fellow at the Michigan Center for Theoretical Physics, University of Michigan from 2002 to 2003. He joined PI as an Associate Faculty member in 2003. Professor Buchel's research efforts focus on understanding the quantum properties of black holes and the origin of our universe, as described by string theory. Additionally, he is involved in developing analytical tools in string theory that could shed new light on strong interactions of subatomic particles. In 2007, Professor Buchel was awarded an Early Researcher Award from Ontario's Ministry of Research and Innovation.

**Cliff Burgess** (jointly appointed with McMaster University) received his PhD from the University of Texas at Austin in 1985 under the supervision of Steven Weinberg. From 1985 to 1987, he was a Member in the School of Natural Sciences at the Institute for Advanced Study in Princeton, New Jersey, and from 1987 to 2005, he was a Faculty member at McGill University, where he was named James McGill Professor in 2003. In 2004, he joined PI's faculty as an Associate member and was jointly appointed to McMaster University's faculty in 2005. Over two decades, Professor 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. He has authored several authoritative reviews of effective field theories, as well as numerous book and encyclopedia chapters, and has co-authored a graduate text on the Standard Model. From 2005 to 2007, Professor Burgess held a Killam Fellowship. In 2008, Professor Burgess was elected a Fellow of the Royal Society of Canada and, in 2010, he won the CAP-CRM Prize in Theoretical and Mathematical Physics, Canada's highest honour in theoretical physics.

**Richard Cleve** (jointly appointed with the University of Waterloo) received his PhD from the University of Toronto in 1989, specializing in computational complexity and cryptography. He completed a postdoctoral fellowship at Berkeley's International Computer Science Institute from 1988 to 1990 and joined the Faculty in the Department of Computer Science at the University of Calgary in 1990. In 2004, Professor Cleve joined PI and the Institute for Quantum Computing (IQC), where he holds the IQC Endowed Chair in Quantum Computing. He is cross-appointed as a Professor in the School of Computer Science at the University of Waterloo. Professor Cleve has made numerous important contributions to quantum algorithms and information theory. He is a Founding Fellow of the Canadian Institute for Advanced Research (CIFAR) Quantum Information Processing program and a team leader at QuantumWorks, Canada's national research consortium on quantum information science. He is a Founding Managing Editor of the journal *Quantum Information & Computation*. In 2008, Professor Cleve was awarded the Canadian Association of Physicists-Centre de Recherches en Mathématiques Prize in Theoretical and Mathematical Physics for his seminal contributions in quantum information science, and he was elected as a Fellow of the Royal Society of Canada in 2010.

**David Cory** (jointly appointed with the Institute for Quantum Computing and the Department of Chemistry at the University of Waterloo) received his PhD in physical chemistry from Case Western Reserve University in Cleveland, Ohio. He held postdoctoral fellowships at the University of Nijmegen, The Netherlands, and at the National Research Council at the Naval Research Laboratory in Washington, D.C. He was also a senior scientist at Bruker Instruments and led their research and development activities in nuclear magnetic resonance. In 1992, he joined the Department of Nuclear Science and Engineering at MIT. Since 1996, Professor 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. From 2009 to 2010, Professor Cory was a Visiting Researcher at PI and, in 2010, he was named the Canada Excellence Research Chair in Quantum Information Processing. Professor Cory chairs the advisory committee for CIFAR's Quantum Information Processing program.

**Adrian Kent** (jointly appointed with the University of Cambridge) received his PhD from the University of Cambridge in 1996. Prior to joining PI's faculty, he was an Enrico Fermi postdoctoral fellow at the University of Chicago, a member of the Institute for Advanced Study in Princeton, New Jersey, and a Royal Society University Research Fellow at the University of Cambridge. His research is focused on the foundations of physics, quantum cryptography, and quantum information theory, including the physics of decoherence and its implications for fundamental physics, novel tests of quantum theory and alternative theories, new cryptographic applications of quantum information, and new scientific applications of quantum information. He co-edited *Many Worlds? Everett, Quantum Theory and Reality,* published by Oxford University Press in 2010.

**Raymond Laflamme** (jointly appointed with the Institute for Quantum Computing, University of Waterloo) is a founding Faculty member of Perimeter Institute. He completed his PhD at the University of Cambridge under the direction of Stephen Hawking. From 1988 to 1990, he held a Killam postdoctoral fellowship at UBC and then a research fellowship at Peterhouse College, University of Cambridge. From 1992 to 2001, Professor Laflamme worked as a research scientist at Los Alamos Research Laboratory, where his interests shifted from cosmology to quantum computing. Since the mid-1990s, Professor Laflamme has elucidated theoretical approaches to quantum error correction. In work with Emmanuel Knill, he gave conditions for quantum error correcting codes and established the fault-tolerance threshold, thereby showing that quantum computing systems could be useful even in the presence of noise. He then went on to perform the first experimental steps toward a demonstration of quantum error correction. With colleagues, he developed a blueprint for a quantum information processor using linear optics, and devised and implemented new methods to make quantum information robust against corruption in both cryptographic and computational settings. In 2001, Professor Laflamme was attracted back to Canada to become a founding member of Perimeter Institute and the founding Director of the Institute for Quantum Computing (IQC). Professor Laflamme is the Director of QuantumWorks, Canada's national research consortium on quantum information science, and has been Director of the Quantum Information program at the Canadian Institute for Advanced Research (CIFAR) since 2003, and a CIFAR Fellow since 2001. Professor Laflamme holds the Canada Research Chair in Quantum Information and is a Professor in the Department of Physics and Astronomy at the University of Waterloo.

**Sung-Sik Lee** joined PI's faculty in July 2011 as an Associate Faculty member in theoretical condensed matter physics jointly appointed with McMaster University. Dr. Lee completed his PhD in 2000 at the Pohang University of Science and Technology (POSTECH) in South Korea, under the supervision of Professor Sung-Ho Suck Salk. He worked as a postdoctoral researcher at POSTECH, MIT, and the Kavli Institute for Theoretical Physics (Santa Barbara) before joining McMaster as an Assistant Professor in 2007. Dr. 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, among other things, 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.

**Luis Lehner** (jointly appointed with the University of Guelph) received his PhD from the University of Pittsburgh in 1998 under the direction of Jeffrey Winicour. He held postdoctoral fellowships at the University of Texas at Austin (1998-2000) and the University of British Columbia (2000-2002), and was an Assistant Professor of Physics at Louisiana State University from 2002 to 2006, before becoming an Associate Professor there from 2006 to 2009. He is currently an Adjunct Professor at LSU. Professor Lehner received the Honor Prize in 1993 from the National University of Cordoba, Argentina; held a Mellon pre-doctoral fellowship in 1997; won the CGS/UMI outstanding dissertation award and the Nicholas Metropolis award in 1999; and was a PIMS fellow from 2000 to 2002 and a CITA National Fellow in 2001-2002. He was an Alfred P. Sloan Fellow from 2003 to 2005 and is currently a fellow of CIFAR, the Institute of Physics, and the APS. He is also an editorial Board member of *Classical and Quantum Gravity* and *Papers in Physics*.

**Michele Mosca** (jointly appointed with the University of Waterloo) obtained his DPhil in 1999 from the University of Oxford. He is a founding member of Perimeter Institute, and co-founder and the Deputy Director of the Institute for Quantum Computing. Professor Mosca has made major contributions to the theory and practice of quantum information processing, particularly in the areas of quantum algorithms, techniques for studying the limitations of quantum computers, quantum self-testing and private quantum channels. Together with collaborators at Oxford, he realized several of the first implementations of quantum algorithms using nuclear magnetic resonance. He has made major contributions to the phase estimation approach to quantum algorithms, including the hidden subgroup problems, and quantum searching and counting. In the area of quantum security, he helped define the notion of private quantum channels and develop optimal methods for encrypting quantum information using classical keys. Professor Mosca has won numerous academic awards and honours, including the Commonwealth Scholarship, the Premier's Research Excellence Award (2000-2005), and a Canada Research Chair in Quantum Computation (2002-2012). He has also been a Fellow of the Canadian Institute for Advanced Research (CIFAR) since 2010.

**Ashwin Nayak** (also appointed at the University of Waterloo) received his PhD in Computer Science from the University of California, Berkeley, in 1999. Subsequently, he held positions at DIMACS Center (Rutgers University), AT&T Labs-Research, the California Institute of Technology, and the Mathematical Sciences Research Institute, Berkeley. Professor Nayak is an associate professor in the Department of Combinatorics and Optimization, and a member of the Institute for Quantum Computing at University of Waterloo. Professor Nayak was a recipient of an Early Researcher Award from the Ministry of Research and Innovation of Ontario in 2006, and a Discovery Accelerator Supplement from the Natural Science and Engineering Research Council (NSERC) of Canada in 2008.

**Maxim Pospelov** (jointly appointed with the University of Victoria) received his PhD from the Budker Institute of Nuclear Physics, Russia, in 1994. He was the NATO Science Fellow at the University of Quebec in Montreal (1996-1998), a Research Associate at the University of Minnesota (1998-2001), a Visiting Scientist at McGill University (2001-2002), and an Advanced PPARC Research Fellow at the University of Sussex, UK (2002). In 2002, he joined the Department of Physics and Astronomy at the University of Victoria and was cross-appointed to PI's faculty in 2004. Professor Pospelov works in the

area of particle physics and has recently made detailed studies of Catalyzed Big Bang Nucleosynthesis (CBBN), a novel idea which he proposed to alleviate persistent discrepancy of theoretical predictions and experimental observations of lithium abundance in the universe.

**Thomas Thiemann** (jointly appointed with the Max Planck Institute for Gravitational Physics, Germany) received his PhD from RWTH Aachen University in 1993. His research centres on non-perturbative quantum field theory, in particular quantum gauge field theory and quantum gravity; non-perturbative aspects of quantum string theory; constructive and algebraic quantum field theory; Euclidean quantum field theory and its connection with statistical mechanics; semiclassical quantum field theory; and non-perturbative approximation methods. He is the author of *Modern Canonical Quantum General Relativity*.

**Itay Yavin** (jointly appointed with McMaster University) joined Perimeter as an Associate Faculty member in particle physics in 2011, with a joint appointment at McMaster University. Dr. Yavin completed his PhD in 2006 at Harvard University under the supervision of PI Distinguished Research Chair Nima Arkani-Hamed. After completing his PhD, he joined the Department of Physics at Princeton University as a Research Associate from 2006 to 2009. Prior to coming to PI, Dr. Yavin was a James Arthur Postdoctoral Fellow at the Department of Physics at New York University. Dr. 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: PI Distinguished Research Chairs

**Dorit Aharonov** is a Professor in the Department of Computer Science and Engineering at Hebrew University in Jerusalem. She has made major contributions to the theoretical foundations of quantum computation, in particular in the context of understanding and counteracting the effects of 'noisy' environments on delicate quantum systems performing computations, the identification of a quantum to classical phase transition in fault tolerant quantum computers, the development of new tools and approaches for the design of quantum algorithms, and the study of ground states of many-body quantum Hamiltonians for various classes of Hamiltonians, from a computational complexity point of view. In 2006, she was awarded the Krill Prize for excellence in scientific research.

**Yakir Aharonov** is a professor of theoretical condensed matter physics at Chapman University and Professor Emeritus at Tel Aviv University, as well as a Patron of Perimeter Scholars International. 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 Masters 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.

**Neta Bahcall** is the Eugene Higgins Professor of Astrophysics at Princeton University. She is an observational cosmologist who has pioneered quantitative approaches to the understanding of astronomical data. These methods have enabled her to achieve key insights into such fundamental questions as the large-scale structure, mass, and fate of the universe, galaxy formation, the nature of quasars, and dark matter.

**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.

**G. 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 temeperature 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).

**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 recently 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.

**Gia Dvali** is a Professor at New York University's Center for Cosmology and Particle Physics and a member of the Theory Division at CERN, in Switzerland. Professor Dvali investigates fundamental questions at the intersection between particle physics and cosmology, including large extra dimensions, quantum gravity, and the very early universe.

**S. James Gates** 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 exit purely as four-dimensional constructs similar to the standard model of particle physics. He is a past recipient of the Public Understanding & Technology Award from the American Association for the Advancement of Science (AAAS) and the Klopsteg Award from the American Association of Physics Teachers. 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 currently 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.

**Stephen Hawking** is the Emeritus Lucasian Professor of Mathematics at the Department of Applied Mathematics and Theoretical Physics at Cambridge. In his work, Dr. 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. Stephen Hawking has published three popular books; his best seller *A Brief History of Time* has

sold over 30 million copies worldwide and is the most popular scientific book of all time. 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** holds the Canada Research Chair in the Physics of Information at McGill University. His research focuses on finding efficient methods for performing the communication tasks that will be required for large-scale quantum information processing. This includes the development of methods for reliably sending quantum states through 'noisy' media and for protecting quantum information from unauthorized manipulation. He has also applied these techniques to the question of information loss from black holes. Among Dr. Hayden's honours, he is a past Alfred P. Sloan Foundation Fellow and Rhodes Scholar.

**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.

**Christopher Isham** is a Senior Research Investigator and Emeritus Professor of Theoretical Physics at Imperial College London. He is a former Senior Dean of the College. Dr. Isham has made many important contributions in the fields of quantum gravity and the foundations of quantum mechanics. Motivated by the "problem of time" in quantum gravity, he developed a new approach to quantum theory known as the "HPO formalism" that enables the theory to be extended to situations where there is no normal notion of time (such as in Einstein's theory of general relativity). Since the late 1990s, Dr. Isham has been developing a completely new approach to formulating theories of physics based on the mathematical concept of a "topos." This gives a radically new way of understanding the traditional problems of quantum theory as well as providing a framework in which to develop new theories that would not have been conceived using standard mathematics. From 2001 to 2005, Dr. Isham was a member of Perimeter Institute's Scientific Advisory Committee; in 2005, he was the Chair of the Committee.

**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 National Medal of Science (US), 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. Dr. Kadanoff is a lecturer for Perimeter Scholars International.

**Renate Loll** is a Professor of Theoretical Physics and a member of the Institute for Theoretical Physics in the Faculty of Physics and Astronomy at Utrecht University. 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. She is also a lecturer for Perimeter Scholars International.

**Malcolm Perry** is a Professor of Theoretical Physics in the Department of Applied Mathematics and Theoretical Physics at the University of Cambridge and a Fellow of Trinity College, Cambridge. His research centres upon general relativity, supergravity, and string theory. Dr. Perry has made major contributions to string theory, Euclidean quantum gravity, and our understanding of black hole radiation. With Perimeter Institute Faculty member Robert Myers, he developed the Myers-Perry metric, which shows how to construct black holes in the higher spacetime dimensions associated with string theory. Dr. Perry’s honours include a Sc.D. from the University of Cambridge. He has also lectured in the PSI program.

**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 an Alfred P. 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.

**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).

**Subir Sachdev** of Harvard University 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. His 1999 book, *Quantum Phase Transitions*, has been described as "required reading for any budding theorist."

**Ashoke Sen**, of the Harish-Chandra Research Institute in Allahabad, India, is a pioneering string theorist whose many contributions include the famous Sen Conjecture, as well as major insights about string dualities and entropy in black holes.

**Eva Silverstein** is a Professor of Physics at Stanford University and the Stanford Linear Accelerator Centre (SLAC). Dr. Silverstein's major contributions include predictive new mechanisms for inflationary cosmology, which helped motivate a more systematic understanding of the process and the role of UV-sensitive quantities in observational cosmology; mechanisms for singularity resolution in string theory; a novel duality in string theory between extra dimensions and negative curvature; extensions of the AdS/CFT correspondence to more realistic field theories (with applications to particle physics and condensed matter model building) and to landscape theories; and simple mechanisms for stabilizing the extra dimensions of string theory. She is a former MacArthur Fellow and past recipient of a Sloan Research Fellowship.

**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.

**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.

**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.

**Xiao-Gang Wen** is the Cecil and Ida Green Professor of Physics in the Department of Physics at MIT, and is also a member of the faculty of Perimeter Scholars International (PSI). He has proposed novel theories about condensed matter physics, the nature of space-time, and superconductivity. His recent book, *Quantum Field Theory of Many-Body Systems*, explores many-particle quantum mechanics.

**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.

**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 Alfred P. Sloan Foundation 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: Perimeter Institute Affiliate Members

| Name | Institution | Research Area |
|---|---|---|
| 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/CITA | Cosmology |
| Ivan Booth | Memorial University | General Relativity |
| Vincent Bouchard | University of Alberta | String Theory |
| Robert Brandenberger | McGill University | Cosmology |
| Gilles Brassard | University of Montreal | Quantum Information |
| Anne Broadbent | University of Waterloo/IQC | Quantum Information |
| Anton Burkov | University of Waterloo | Condensed Matter |
| Bruce Campbell | Carleton University | String Theory |
| Hilary Carteret | University of Calgary | Quantum Information |
| Jeffrey Chen | University of Waterloo | Condensed Matter |
| Andrew Childs | University of Waterloo/IQC | Quantum Information |
| Matthew Choptuik | University of British Columbia | Numerical General Relativity |
| Dan Christensen | University of Western Ontario | Quantum Gravity |
| James Cline | McGill University | Cosmology, Particle Physics |
| Alan Coley | Dalhousie University | General Relativity |
| 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 | String Theory |

| Name | Institution | Research Area |
|---|---|---|
| Rainer Dick | University of Saskatchewan | Particle Physics |
| Joseph Emerson | University of Waterloo/IQC | Quantum Foundations |
| James Forrest | University of Waterloo | Polymer Physics |
| Marcel Franz | University of British Columbia | Condensed Matter |
| Doreen Fraser | University of Waterloo | Philosophy |
| Valeri Frolov | University of Alberta | Quantum Gravity, Cosmology |
| Andrei Frolov | Simon Fraser University | Cosmology |
| Jack Gegenberg | University of New Brunswick | Quantum Gravity |
| Stephen Godfrey | Carleton University | Particle Physics |
| Thomas Gregoire | Carleton University | Particle Physics |
| John Harnad | Concordia University | Mathematical Physics |
| Jeremy Heyl | University of British Columbia | Astrophysics |
| Bob Holdom | University of Toronto | Particle Physics |
| Mike Hudson | University of Waterloo | Cosmology |
| Viqar Husain | University of New Brunswick | Quantum Gravity, Cosmology |
| Thomas Jennewein | University of Waterloo/IQC | Quantum Information |
| Catherine Kallin | McMaster University | Superconductivity Theory |
| Joanna Karczmarek | University of British Columbia | String Theory |
| Spiro Karigiannis | University of Waterloo | Differential Geometry |
| Gabriel Karl | University of Guelph | Particle Physics |
| Achim Kempf | University of Waterloo | Quantum Information |
| Yong Baek Kim | University of Toronto | Condensed Matter |
| Pavel Kovtun<br>(until January 31, 2011) | University of Victoria | String Theory |

| Name | Institution | Research Area |
|---|---|---|
| David Kribs | University of Guelph | Quantum Information |
| Gabor Kunstatter | University of Winnipeg | Quantum Gravity,<br>Quantum Mechanics |
| Kayll Lake | Queen's University | General Relativity |
| Sung-Sik Lee<br>(until June 30, 2011) | McMaster University | Condensed Matter |
| 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 |
| Norbert Lutkenhaus | University of Waterloo/IQC | Quantum Information |
| Alexander Maloney | McGill University | String Theory |
| Robert Mann | University of Waterloo | Quantum Gravity,<br>String Theory |
| Gerard McKeon | University of Western Ontario | Particle Physics |
| Brian McNamara | University of Waterloo | Cosmology |
| Roger Melko | University of Waterloo | Condensed Matter |
| Volodya Miransky | University of Western Ontario | Quantum Information |
| Guy Moore | McGill University | Particle Physics |
| Ruxandra Moraru | University of Waterloo | Pure Math |
| David Morrissey | TRIUMF Canada | Particle Physics |
| Norman Murray | University of Toronto/CITA | Astrophysics |
| Wayne Myrvold | University of Western Ontario | Philosophy |
| Julio Navarro | University of Victoria | Cosmology |
| Elisabeth Nicol | University of Guelph | Condensed Matter |

| Name | Institution | Research Area |
|---|---|---|
| Garnet Ord | Ryerson University | Quantum Foundations |
| Maya Paczuski | University of Calgary | Quantum Information |
| Don Page | University of Alberta | Cosmology |
| Prakash Panangaden | McGill University | Quantum Foundations |
| Manu Paranjape | University of Montreal | Particle Physics |
| Amanda Peet | University of Toronto | High Energy Physics |
| Ue-Li Pen | University of Toronto/CITA | Cosmology |
| Harald Pfeiffer | University of Toronto/CITA | Numerical General Relativity |
| 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 | Gravitational Physics |
| Erich Poppitz | University of Toronto | High Energy Physics |
| David Poulin | University of Sherbrooke | Quantum Foundations |
| Robert Raussendorf | University of British Columbia | Quantum Information |
| Ben Reichardt | University of Waterloo | Quantum Information |
| Kevin Resch | University of Waterloo/IQC | Quantum Information |
| Adam Ritz | University of Victoria | Particle Physics |
| Moshe Rozali | University of British Columbia | String Theory |
| Barry Sanders | University of Calgary | Quantum Information |
| Veronica Sanz | York University | Particle Physics,<br>High Energy Physics |
| Kristin Schleich | University of British Columbia | General Relativity |
| Achim Schwenk | TRIUMF Canada | Particle Physics |

| Name | Institution | Research Area |
|---|---|---|
| Douglas Scott | University of British Columbia | Cosmology |
| Sanjeev Seahra | University of New Brunswick | Cosmology, Quantum Gravity |
| Gordon Semenoff | University of British Columbia | String Theory |
| Kris Sigurdson (until May 1, 2011) | University of British Columbia | Cosmology, Particle Physics |
| John Sipe | University of Toronto | Quantum Foundations, Condensed Matter |
| Philip Stamp | University of British Columbia | Cosmology |
| Aephraim Steinberg | University of Toronto | Quantum Optics |
| Alain Tapp | University of Montreal | Quantum Information |
| James Taylor | University of Waterloo | Cosmology |
| Mark Van Raamsdonk | University of British Columbia | String Theory |
| Johannes Walcher | McGill University | String Theory |
| Mark Walton | University of Lethbridge | String Theory |
| John Watrous | University of Waterloo | Quantum Information |
| Steve Weinstein | University of Waterloo | Quantum Foundations |
| Lawrence Widrow | Queen's University | Astrophysics |
| Frank Wilhelm | University of Waterloo/IQC | Quantum Information, Condensed Matter |
| Don Witt | University of British Columbia | Particle Physics, String Theory |
| Bei Zeng | University of Guelph | Quantum Information |

# Appendix D: Perimeter Institute Board of Directors

**Mike Lazaridis**, **O.C., O.Ont., Chair**, is Founder, President and Co-CEO of Research In Motion Limited (RIM). A visionary, innovator, and engineer of extraordinary talent, he is the recipient of many technology and business awards, and the Order of Canada. At RIM, Mr. Lazaridis leads R&D, product strategy, and manufacturing for the world-renowned BlackBerry® wireless solution.

**Donald W. Campbell** is the senior strategy advisor at Davis LLP. Prior to joining Davis, he was Executive Vice-President of CAE Inc., where he led the company's world-wide government procurement activities. Mr. Campbell joined CAE after a distinguished career with Canada's Department of Foreign Affairs and International Trade, including serving as Canada's Ambassador to Japan.

**Cosimo Fiorenza**, **Vice Chair**, is the Vice-President and General Counsel of the Infinite Potential Group. He is actively involved at several public and private non-profit and charitable institutions in addition to Perimeter Institute, including the Law Society of Upper Canada, the Centre for International Governance Innovation, the Institute for Quantum Computing, and several private family foundations. Mr. Fiorenza holds a degree in Business Administration from Lakehead University and a law degree from the University of Ottawa.

**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 C.A. 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.**, 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.

**Steve MacLean** is President of the Canadian Space Agency (CSA). A physicist by training, in 1983 he was selected as one of the first six Canadian astronauts and he has participated in missions on the Space Shuttles Columbia (1992) and Atlantis (2006) to the International Space Station. In addition to senior roles within the CSA and extensive experience with NASA and the International Space Station, he is a strong supporter of science literacy and child education.

**Barbara Palk** recently retired as President of TD Asset Management Inc., one of Canada's leading money management firms, and as Senior Vice President of TD Bank Financial Group. She is a Fellow of the Canadian Securities Institute, a CFA Charterholder, and a member of the Toronto Society of Financial Analysts. Ms. Palk is Vice-Chair of the Board of Trustees of Queen's University and the Chair of its Investment Committee, and a member of the Boards of the Shaw Festival and Greenwood College

School. She is a recipient of the Ontario Volunteer Award and was honoured by the Women's Executive Network in 2004 as one of Canada's Most Powerful Women: Top 100 in the Trailblazer category.

**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. John has served on many hospital boards throughout Canada and has also been a director on many university and college boards.

# Appendix E: Perimeter Institute Scientific Advisory Committee

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

**Michael Peskin, Chair,** Stanford Linear Accelerator Center (2008-Present)
Professor Peskin's research interests include all aspects of theoretical elementary particle physics, but particularly the nature of new elementary particles and forces that will be discovered at the coming generation of proton and electron colliders. He was a Junior Fellow at the Harvard Society of Fellows from 1977 to 1980 and was elected to the American Academy of Arts and Sciences in 2000. He is co-author of a popular textbook on quantum field theory.

**Gerard Milburn, Chair**, University of Queensland (2007-10)
Professor Milburn's research interests include quantum optics, quantum measurement and stochastic processes, quantum information and quantum computation. He has published over 200 papers in international journals, with over 6,000 citations. He is also the author or co-author of several books, two of which seek to explain quantum phenomena and their potential for a general audience.

**Abhay Ashtekar**, Pennsylvania State University (2008-10)
Professor Ashtekar is Eberly Professor of Physics and the Director of the Institute for Gravitational Physics and Geometry at Pennsylvania State University. As the creator of Ashtekar variables, he is one of the founders of loop quantum gravity. He has written a number of descriptions of loop quantum gravity that are accessible to non-physicists.

**Sir Michael Berry**, University of Bristol (2009-Present)
Sir Michael Berry is Professor Emeritus at Bristol University. He has made numerous important contributions to semi-classical physics (asymptotic physics, quantum chaos) applied to wave phenomena in quantum mechanics and other areas such as optics. Among other work, he is well known for the Berry phase, a phenomenon which has found applications in atomic, condensed matter, nuclear, and elementary particle physics, as well as optics. He was elected a fellow of the Royal Society of London in 1982 and was knighted in 1996. Professor Berry's previous honours include the Dirac Medals of both the Institute of Physics (1990) and the ICTP (1996), the Lilienfeld Prize (1990), the Wolf Prize (1998), and the London Mathematical Society's Polya Prize (2005).

**Matthew Fisher**, California Institute of Technology (2009-Present)
Professor Fisher is a condensed matter theorist whose research has focused on strongly correlated systems, especially low dimensional systems, Mott insulators, quantum magnetism and the quantum Hall effect. He 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. In 2003, he was elected as a Member of the American Academy of Arts and Sciences. Professor Fisher has over 150 publications.

**Brian Greene**, Columbia University (2010-Present)
Professor Greene is a Professor of Mathematics and Physics at Columbia University, where he is co-Director of the Institute for Strings, Cosmology, and Astroparticle Physics (ISCAP). Professor Greene has made groundbreaking discoveries in superstring theory, exploring the physical implications and mathematical properties of the extra dimensions the theory posits. His current research centres on string cosmology, seeking to understand the physics of the universe's first moments. Professor Greene is well known for his work on communicating theoretical physics for general audiences, and his books include *The Elegant Universe*, which has sold more than a million copies worldwide; *The Fabric of the Cosmos*, which spent six months on the New York Times Best Seller List; and *Icarus at the Edge of Time, A Children's Tale*. A three-part NOVA special based on *The Elegant Universe* won both the Emmy and Peabody Awards.

**Gerard 't Hooft**, Utrecht University (2008-10)
Professor 't Hooft's research focuses on gauge theories in elementary particle physics, quantum gravity and black holes, and fundamental aspects of quantum physics. In addition to the Ben Franklin Medal, Professor 't Hooft's contributions to science have been recognized with many awards, including the 1999 Nobel Prize in Physics, with the citation "for elucidating the quantum structure of electroweak interactions in physics."

**Igor R. Klebanov**, Princeton University (2007-10)
Professor Klebanov's research has touched on many aspects of theoretical physics and is presently centered on relations between superstring theory and quantum field theory. He is currently Thomas D. Jones Professor of Mathematical Physics at Princeton University. He has made many highly regarded contributions to the duality between gauge theories and strings.

**Renate Loll**, Utrecht University (2010-Present)
Professor Loll is a Professor of Theoretical Physics and a member of the Institute for Theoretical Physics in the Faculty of Physics and Astronomy at Utrecht University. Her research centres on quantum gravity, the search for a consistent theory that describes the microscopic constituents of spacetime geometry and the quantum-dynamical laws governing their interaction. She has made major contributions to loop quantum gravity and, with her collaborators, has proposed a novel theory of quantum gravity via 'Causal Dynamical Triangulations.' Professor Loll heads one of the largest research groups on non-perturbative quantum gravity worldwide and is the recipient of a prestigious personal VICI-grant of the Netherlands Organization for Scientific Research. Professor Loll is a Perimeter Institute Distinguished Research Chair and is also a lecturer in the Perimeter Scholars International program at the Institute.

**John Preskill**, California Institute of Technology (2009-Present)
Professor Preskill is the Richard P. Feynman Professor of Theoretical Physics and the Director of the Institute for Quantum Information at the California Institute of Technology (Caltech). Until the mid-1990s, Professor Preskill's research focused on elementary particles, cosmology, and gravitation. His many contributions include work on superheavy magnetic monopoles in the early universe which led to the inflationary universe, the proposal that axions may comprise the universe's cold dark matter, and

the theory of local discrete symmetries. Since the mid-1990s, his research has focused on mathematical issues related to quantum computation and quantum information theory. Among his numerous honours, Professor Preskill is a past Alfred P. Sloan Fellow, a two-time recipient of the Associated Students of Caltech Teaching Award, and an elected Fellow of the American Physical Society. He was also the Morris Loeb Lecturer at Harvard University in 2006.

**David Spergel**, Princeton University (2009-Present)
Professor Spergel is the Charles Young Professor of Astronomy at Princeton, as well as the Chair of the Department of Astrophysical Sciences. He is known for his work on the Wilkinson Microwave Anisotropy Probe (WMAP) mission. Professor Spergel is a MacArthur Fellow as well as a member of the US National Academy of Sciences. He is currently the chair of the Astrophysics Subcommittee of the NASA Advisory Council. He was co-awarded the 2010 Shaw Prize in Astronomy, along with Charles L. Bennett and Lyman A. Page Jr., for his leadership of the WMAP experiment, which has enabled precise determinations of the fundamental cosmological parameters, including the geometry, age, and composition of the universe.

**Erik Peter Verlinde**, University of Amsterdam (2010-Present)
Professor Verlinde is a Professor of Theoretical Physics at the Institute for Theoretical Physics at the University of Amsterdam. Professor Verlinde is world renowned for his many contributions, including Verlinde algebra and the Verlinde formula, which are important in conformal field theory and topological field theory. His research centres on string theory, gravity, black holes, and cosmology. He recently proposed a holographic theory of gravity which appears to lead naturally to the observed values of dark energy in the universe.

**Birgitta Whaley**, University of California, Berkeley (2010-Present)
Professor Whaley is a Professor in the Department of Chemistry at the University of California, Berkeley, where she is Director of the Berkeley Quantum Information and Computation Center. Professor Whaley's research centres on understanding and manipulating quantum dynamics of atoms, molecules, and nanomaterials in complex environments to explore fundamental issues in quantum behaviour. She has made major contributions to the analysis and control of decoherence and universality in quantum information processing, as well as to analysis of physical implementations of quantum computation. Professor Whaley is also known for her theory of molecular solvation in nanoscale superfluid helium systems. Current research includes theoretical aspects of quantum information science, quantum simulation of exotic topological phases, and exploration of quantum effects in biological systems.