PERIMETER PI INSTITUTE FOR THEORETICAL PHYSICS

2011 ANNUAL REPORT

Vision

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

CONTENTS

This report covers the activities and finances of Perimeter Institute for Theoretical Physics for the period August 1, 2010 to July 31, 2011.

BACKGROUND AND PURPOSE

Perimeter Institute for Theoretical Physics was founded in 1999, in Waterloo, Ontario, Canada. Its mission is to create and sustain a world-leading centre for foundational theoretical physics research, training, and educational outreach, fostering scientific excellence and stimulating breakthroughs.

Perimeter is rapidly emerging as one of the world's leading centres of theoretical physics. It is now home to more than 150 researchers, ranging from Masters students to eminent senior scientists such as Distinguished Research Chair Stephen Hawking. Perimeter houses the world's largest group of independent postdoctoral researchers in theoretical physics and receives well over 600 applications per year for the ten or so postdoctoral fellowships awarded at the Institute annually. Over 1,000 researchers from around the world visit Perimeter each year, making the Institute a global hub for the interchange of ideas.

Why theoretical physics? Because it is a cornerstone of modern quantitative science, on which so much else rests. The goal of the field is to understand how the universe works at the most fundamental level. Theoretical physics continues to spin off key ideas to fields ranging from astrophysics to chemistry, from engineering to computer science. And it seeds innovation: theoretical ideas have time and again inspired the development of new technologies, and thereby created new industries. One breakthrough in theoretical physics can literally change the world.

Perimeter is not just about research. Brilliant young people are the lifeblood of science, and so the Institute has developed innovative and highly sought-after scientific training programs, including the Perimeter Scholars International program. Since sharing the excitement and wonder of science feeds the soil in which new talent can grow, the Institute also conducts extensive, award-winning outreach to students, teachers, and the general public.

MESSAGE FROM THE BOARD CHAIR

In my high school electronics shop, Mr. Micsinszki had one rule. If you wanted to use a piece of machinery, you had to read the manual first. Then he would ask you questions about how to use the instrument, and if you answered correctly, you were allowed to open the box. By the time summer came, I had opened every box in that laboratory. A lot of ideas came out of those boxes.

Perimeter's scientists are reading the manual for the universe itself. This manual – physics – underlies all the technologies of our modern world. The BlackBerry, for example, is theoretical physics in a box: it's the commercialization of breakthroughs made by physicists like Maxwell and Hertz, more than a hundred years ago.

The other thing I learned from Mr. Micsinszki was vision. In his class, I was excited to be building computers and learning how they worked. He told me to be careful not to focus too narrowly. "In the future," he said, "electronics, computers, and wireless are all going to combine, and that's going to be the next big thing."

That too is something I often remember: If you only work to solve today's problems, you'll never find tomorrow's solutions.

In that spirit, I'd like to salute our partners. This year, the Government of Canada and the Province of Ontario announced renewed support of $50 million each for the Perimeter Institute.

Private partners, too, have been both generous and visionary. I think particularly of the BMO Financial Group, which this year gave Perimeter the largest gift it's ever made to support science: $4 million to establish the BMO Financial Group Isaac Newton Chair in Theoretical Physics. Xiao-Gang Wen of MIT, an internationally renowned theorist, will become the first Chairholder.

"This visionary place, and the people who enable it to thrive, are models to be emulated as we strive to strengthen a quality of life for all Canadians that is second to none.... This organization is a place of boundless potential.... That is why the Government of Canada has steadfastly supported the work of the Perimeter Institute."

– The Honourable Jim Flaherty, Minister of Finance

Times are hard and in such times it's tempting to think small. Our partners are leading the way by thinking big.

At Perimeter, we're also thinking big and building strategically for the future. The bold, asymmetric lines of the just-completed Stephen Hawking Centre embody this. Here, some of the brightest talents in the field will be trained and do research, looking at the universe from entirely new angles, in spaces designed to be stimulating. In the Sky Room, the circular skylight encourages all to look beyond the usual horizons.

Many people work to expand Perimeter's horizons. As Chair of Perimeter's Board, I'd like to express my gratitude to Don Campbell, who retired this year after seven years of wise guidance and truly dedicated service on the Board. I would also like to welcome new Board member Barbara Palk, who recently retired as President of TD Asset Management Inc. and is a trustee of Queen's University. Lastly, I wish to thank members of Perimeter's Leadership Council for their generous support and their committed efforts to widen our circle of friends throughout Canada and beyond.

Perimeter is truly a shared enterprise – all of us have a stake in it and all will share in the fruits of the breakthroughs that I have no doubt will happen here. Together, we're building an engine of discovery, which will power game-changing ideas and technologies. There's a feeling in the air that the boxes are opening – and what's inside is amazing.

– Mike Lazaridis

MESSAGE FROM THE INSTITUTE DIRECTOR

Can one speed the rate of discovery in a field as foundational as theoretical physics, through a strategic intervention? Or are such basic discoveries completely unpredictable, made by solitary geniuses whose emergence is essentially random?

Here at Perimeter, we believe that the answer to the first question, as ambitious as it seems, is yes. One *can* create an institution deliberately designed to foster new breakthroughs. That was the thinking behind our creation of the stunning new Stephen Hawking Centre (SHC): it is our version of the Starship Enterprise, enlarging Perimeter's space in ways both physical and metaphorical. Perimeter is now the largest independent theoretical physics institute in the world – and has an exceptionally bold statement of vision and faith in a field that has, over and over again, unlocked fundamental discoveries that enabled us to see the world anew, and brought literally every modern technology in their wake.

Perimeter is designed as an institute to attract new talent, and provide an inspiring environment and culture which will encourage its scientists to pursue radically new approaches to the most basic questions. We didn't get to the moon, after all, by waiting for it to happen.

Over the past year, we have worked intensively to prepare and present our application for renewed funding to the Governments of Ontario and Canada. We were delighted that both levels of government demonstrated their confidence in our strategy and our track record of success by renewing their investments. We offer our profound appreciation to the leaders who made these farsighted decisions in challenging economic times.

Perimeter is in the end all about people and recruitment is one of the most important parts of my own job. It was a thrill to announce the appointment of Xiao-Gang Wen as the inaugural BMO Financial Group Isaac Newton Chair in Theoretical Physics. Xiao-Gang is one those rare talents whose insights open up whole new fields. He did just that when he discovered topological order, a novel concept which has already led to a deeper understanding of phenomena which were thought to be well understood, such as superconductivity, and which holds the promise of an entirely new paradigm for describing and predicting the behavior of quantum materials. His work is bold, interdisciplinary, and far-reaching: precisely the kind of research to which Perimeter aspires. Xiao-Gang will join us from MIT next fall: he is already closely involved in building our research effort at Perimeter.

We were also delighted to welcome as new faculty members Guifre Vidal and Sung-Sik Lee, who are helping to make Perimeter a new force in condensed matter physics. Guifre is a world leader in the application of quantum information concepts to the study of quantum entanglement in condensed matter systems. And Sung-Sik is a pioneer of the application of advanced concepts such as holography to the description of real quantum systems.

Philip Schuster and Natalia Toro, two of the brightest young talents in particle physics, are building Perimeter's links to the watershed experiments now underway at the Large Hadron Collider and other leading laboratories. Next year, they will be joined by several more outstanding junior faculty recruits: Itay Yavin (in particle physics), Avery Broderick (in black hole astrophysics), and Bianca Dittrich (in quantum gravity).

Eight senior theorists from around the world accepted visiting Distinguished Research Chairs at Perimeter: James Bardeen, Ganapathy Baskaran, James Gates, Gerard 't Hooft, Frans Pretorius, Eva Silverstein, Paul Steinhardt, and Senthil Todadri. They join Perimeter's 19 current DRCs. Collectively, they represent an incredible array of scientific expertise and will, no doubt, enormously enrich our research community.

We were extremely pleased to receive a major grant of $2 million from the John Templeton Foundation, to build a major new program linking several of our most ambitious frontier areas of research: quantum foundations and information, foundations of cosmology, and emergence of spacetime.

Inside, the new SHC is deliberately playful, with unexpected angles and sightlines, bold shots of colour, and stunning overviews of Silver Lake. Already, we researchers are enjoying working together in its think spaces, scribbling on the specially treated "transparent boards," and working in our offices in full view of the outside world. It is a glimpse of the excitement of physics made visible.

It is a great pleasure to see the new building named for Stephen Hawking, my friend and colleague. Stephen is an icon in our field: he is as inspiring as his research is ambitious. By naming our new wing in his honour, we pledge ourselves to that ambition and inspiration. Within the Stephen Hawking Centre, we hope to train the future leaders of our field. We will also inform, educate, and excite millions of people about the power of physics. And we will do ambitious research into the deepest questions in physics, combining intellectual daring with uncompromising rigour.

We look to change the world.

– Neil Turok

SEEKING NEW ANSWERS TO BIG QUESTIONS

What really happened at the Big Bang? What are the basic building blocks of nature and what holds them together? Are space and time granular? Can we harness the power of quantum mechanics to build quantum computers? What accounts for the properties of materials – exactly how do electrons flow in solids and what makes superconductors? What is causing the accelerating expansion of the universe? Are there entirely new states of matter and energy we have not yet discovered?

BY THE NUMBERS

In 2010-11, Perimeter's research community included ...

15 full-time Faculty

14 Associate Faculty

27 Distinguished Research Chairs

43 Postdoctoral Researchers

24 PhD students

35 Masters students

Answering questions like these does much more than satisfy our curiosity. It drives the science, experiments, and technologies of tomorrow. Theoretical physics is perhaps the highest-impact, lowest-cost area of basic research. Its discoveries have seeded innovations across fields from mechanical engineering to wireless communication, and from electronics to power generation. Radio, television, semiconductors, computers, cell phones, lasers, fibre optics, holography, the Internet, GPS, solar cells, and diagnostic imaging – they are all rooted in breakthroughs made by theoretical physicists.

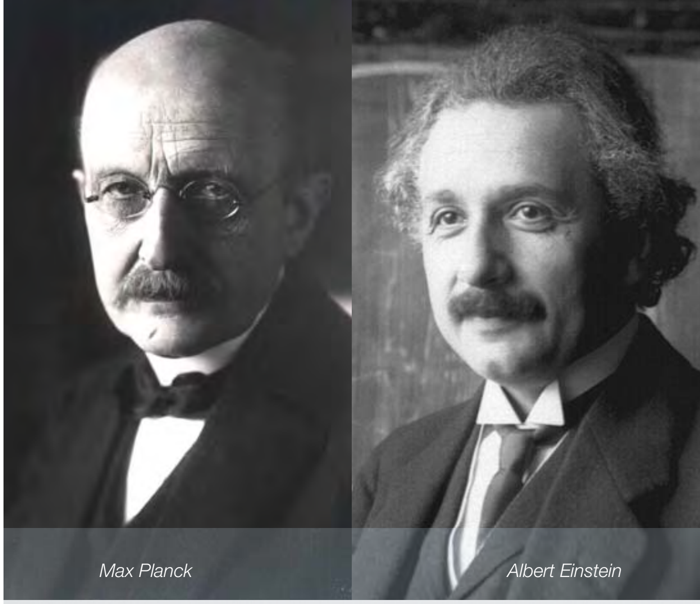
At Perimeter, our goal is to make breakthroughs in our understanding of quantum theory and spacetime, drawing on insights from the full spectrum of physics, from particles to the universe.

Perimeter's eight research fields have been chosen strategically, to form a complementary whole combining our most important insights into the basic laws governing the universe, from subatomic scales, to the table-top scales of condensed matter systems, to the description of the entire cosmos. The Institute's choice of complementary disciplines is unique worldwide; its emphasis on ambitious, unconstrained scientific enquiry has led to a vibrant, growing research community.

A consistent theme running through the research highlights of the past year is the interrelationship between theories about the largest structures in the universe and the smallest. A system with microscopic quantum entanglement may become a platform for quantum computing. Techniques developed by quantum information scientists may help produce telescopes that see farther and deeper into the cosmos. Mathematical models of multidimensional black holes reveal striking parallels to classical fluid dynamics. New cosmological observations can help test theories about the Big Bang itself, when the physics of the highest conceivable energies and the tiniest distances were probed.

A second theme in our past year's research is contact with experiment. Powerful new experimental tools are meeting new theories and ideas. Theory is helping to guide experiment and experimental data is challenging theory. The synergy has put the world of physics on the brink of major advances, with Perimeter researchers among those at the forefront.

These cross-pollinations – between fields, between theory and experiment – are no coincidence. Discoveries often result from collisions and Perimeter is explicitly structured to foster the interplay of ideas between different fields. As the highlights on the following pages demonstrate, this collaborative, multi-disciplinary approach is paying off.



Max Planck *Albert Einstein*

A QUANTUM LEAP

In physics, a small idea can have big consequences.

At the end of the nineteenth century, scientists were hard at work trying to understand the way things glow when heated, a phenomenon called black body radiation. Light was known to move as a wave – as Maxwell had discovered – and it was thought that a light wave, of any wavelength, could carry an arbitrary amount of energy. Unfortunately, this theory totally failed to explain the observed black body radiation.

Finally, in 1900, German physicist Max Planck successfully matched theory to experiment by proposing that light does not come in a smooth wave; instead, it is absorbed and emitted in little packets of energy. Light waves were seen to be made up of "quanta" (derived from the Latin word "quantum," meaning "how much"), each carrying a fixed energy which depends on their wavelength.

Within five years, Einstein and others had taken Planck's notion much farther – reimagining the quantum of light as a particle called a photon. It was the beginning of a new field: quantum mechanics, the fundamental science behind everything from transistors to lasers to modern microscopes. Quantum mechanics catalyzed breakthroughs in virtually every other science, from genetics to modern chemistry. It is still opening doors to discovery, from quantum computing to quantum biology.

COSMOLOGY AND GRAVITATION

Physicists at Perimeter combine recent developments at the interface of fundamental physics and astrophysics to shed light on some of the major puzzles in the field: What is causing the observed cosmic acceleration? What is the nature of dark matter? What can be learned from the microwave background and large-scale structure observations about theories of fundamental physics? Is inflation the correct paradigm of early-universe cosmology? What drives some of the most energetic events in nature? What happens in the vicinity of black holes, and how do they behave in more than three dimensions?

IS THE CONVENTIONAL PICTURE OF THE EARLY UNIVERSE CORRECT?

At the centre of modern cosmology is the theory of cosmological inflation – the idea that the early universe experienced a brief burst of accelerated expansion. Recently, Faculty member **Latham Boyle** and Distinguished Research Chair (DRC) **Paul Steinhardt** proposed an observational test that could confirm this theory beyond a reasonable doubt.

The test involves the Cosmic Microwave Background (CMB), ancient radiation that permeates every corner of the cosmos. It was generated when the universe was a mere few hundred thousand years old. Cosmologists can infer detailed information about the first instants after the Big Bang by studying variations in the CMB. If inflation is correct, the universe would have "stretched" by an enormous factor during the early burst of expansion, and then "unstretched" by precisely the same factor during the billions of years since. Forthcoming CMB observations will yield independent estimates for both the "stretch" and "unstretch" factors. Boyle and Steinhardt argue that if these estimates match one another, it will amount to persuasive evidence that the theory of inflation is really on the right track.

WHAT HAPPENS WHEN SINGULARITIES ARE NOT HIDDEN BEHIND BLACK HOLES?

What happens inside a black hole stays inside a black hole. Or so one might hope.

A hypothesis called "cosmic censorship" addresses the question of how the extreme conditions within a black hole can exist in a universe whose physical laws they seem to defy.

A black hole contains a "singularity" – a region with energy density so high, it tears up spacetime itself and Einstein's equations cease to be valid. The effects of such singularities would be felt across the universe, were they not hidden inside black holes. Black holes "censor" singularities, enabling outside observers to do meaningful physics without having to deal with the chaotic effects within.

In the early 1990s, **Ruth Gregory** (now at Durham University, and recently appointed as a Visiting Fellow at Perimeter) and **Raymond Laflamme** (now an Associate Faculty member at Perimeter) found that black holes are sometimes unstable and that singularities may not always be so censored. Their analysis led to a long-standing question about the nature and evolution of black hole instability.

Associate Faculty member **Luis Lehner** and DRC **Frans Pretorius** have now beautifully resolved this question.

Their work draws on, and contributes to, string theory and multi-dimensional models of the universe. They build on the Gregory-Laflamme instability, which describes the state of multidimensional holes known as "black strings." Their simulations show how an unstable black string in five dimensions evolves in a fractal manner. First, a thick string evolves into a sequence of nearly spherical black holes connected by thin strings; each thin string becomes unstable and evolves to a sequence of smaller, self-similar spherical black holes connected by even thinner strings. The final state violates cosmic censorship, creating new challenges for developing a model of the universe that allows for singularities and conventional physics to interact.

One surprising result of this new model is that a very similar fractal pattern appears in classical physics, in the way low-viscosity fluids form droplets. This strange parallel may help physicists reconcile our familiar world with the counterintuitive extremes of black holes.

HAS OUR UNIVERSE EVER COLLIDED WITH ANOTHER?

Postdoctoral Researcher **Matthew Johnson** has developed and carried out the first systematic search for evidence of whether our observable universe has collided with others.

The theory of cosmological inflation suggests that our observable patch of the universe is contained within an expanding bubble – one of many effervescing in a cosmic cauldron. If our bubble collided with another in the past, the collision should have left a distinctive mark in the Cosmic Microwave Background. This would make it possible to detect evidence of a past collision through observation today – the cosmological equivalent of checking for car damage after a fender bender.

Johnson and his colleagues developed a general algorithm for searching the CMB for signatures of bubble collisions. An analysis of the most recent CMB data was inconclusive, but they plan to use new data from the European Space Agency's Planck satellite to test the bubble collision hypothesis more stringently in the coming year.

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PROFILE: LUIS LEHNER

My passion is what you could call "extreme gravity," involving interactions of massive objects at high speeds. I grew up on the plains of Argentina and few who know me would be surprised to learn that gravity often played a role in my childhood. For instance, while horseback riding when I was nine, a spooked horse, a soccer goal post, and I all combined to produce an intense collision, a fall, and an impromptu nose job!

My goal is to understand how gravity behaves in even more extreme situations, involving neutron stars, or black holes, which we believe are very important to forming and shaping galaxies. Events such as the merging of two black holes should produce detectable ripples in the fabric of spacetime – these ripples would carry crucial information about the systems that created them, and the behaviour of spacetime itself.

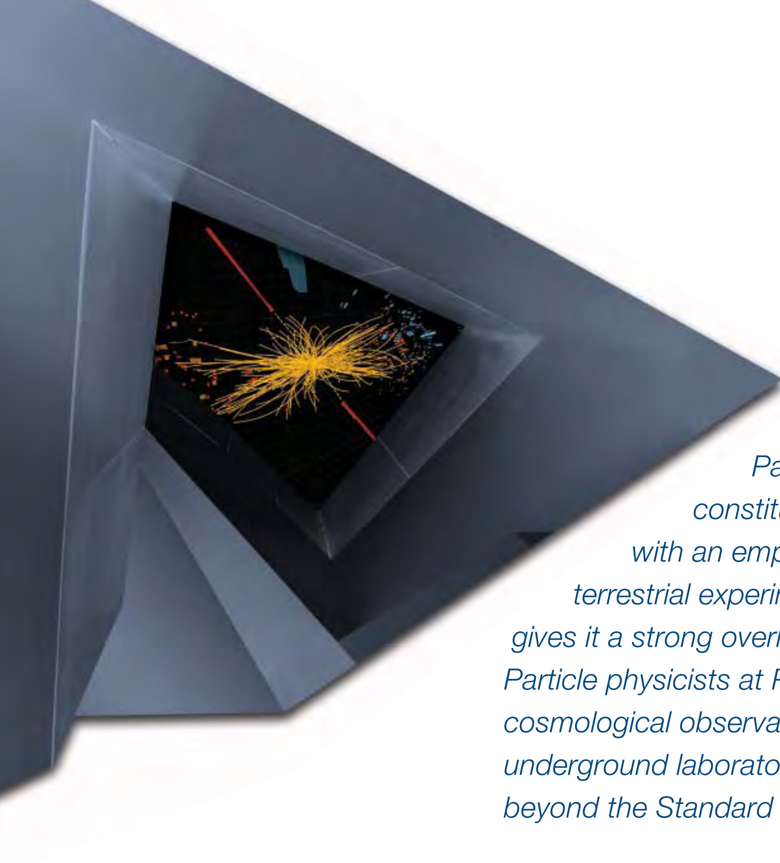
We expect to detect gravitational waves using highly sensitive detectors within the decade. When we do, an era of gravitational wave astronomy will begin, allowing us to peek deep into systems that are impossible to study with current instruments. It promises to revolutionize our understanding of astrophysics, gravity, and even cosmology by confronting theoretical predictions with observations.

I develop such predictions using complex simulations to faithfully model systems of interest. Recently, for example, my collaborators and I demonstrated that as binary black holes come together, they induce very powerful electromagnetic jets. By observing and comparing gravitational and electromagnetic signals, we will get a much richer picture, giving us clues as to the validity of general relativity and providing guidance on how to go beyond it.

Perimeter's environment and research areas are ideal for interacting with others, and stimulating thinking outside the usual boxes. This encourages me to venture beyond my comfort zone, which I greatly enjoy – it's a very lively and energizing atmosphere.

– Luis Lehner

Associate Faculty member Luis Lehner was recently elected a Fellow of the American Physical Society and a Fellow of the Canadian Institute for Advanced Research.



PARTICLE PHYSICS

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

WHY DOES DARK ENERGY DOMINATE OUR UNIVERSE?

There is clear evidence that our universe is expanding faster and faster. Scientists don't know why. The theory of general relativity can only account for it if there is something in the universe that has bizarre properties, such as negative pressure. For want of a better name, this something is known as "dark energy." But the Standard Model of particle physics can't account for dark energy. Yet there is more dark energy in the universe than anything else. We appear to be entering what scientists call "a new epoch of dark-energy domination."

Now, Associate Faculty member **Cliff Burgess** and his student **Leo van Nierop** may have unravelled this enigma, which has long vexed both the cosmologists who observe the accelerated expansion and the particle physicists working to explain it.

The researchers began with ideas taken from string theory which predict two things: the existence of more than the standard three spatial dimensions and the existence of multi-dimensional surfaces called "branes," on which elementary particles might be trapped. Building on these models, the researchers developed the first systematic tools that show how branes that span any number of spatial dimensions curve their environment. These new tools show how the extra dimension can curve in a way that looks like dark energy. This not only might explain the current accelerated expansion of the universe, but also another period of accelerated expansion that is believed to have happened in the very early universe – the epoch of cosmic inflation.

CAN PERIMETER PHYSICISTS BRIDGE THE WORLDS OF THEORY AND EXPERIMENT?

Physics advances through the interplay of theory and experiment – theorists' ideas spark new forms of experimentation and experimentalists' data lead to new theoretical models. Despite this symbiotic relationship, few physicists straddle the worlds of experiment and theory. Faculty members **Philip Schuster** and **Natalia Toro** are rare exceptions.

Schuster and Toro have shown leadership in proposing and helping to secure funding for APEX, the A-Prime Experiment based at the Jefferson Laboratory in Virginia. They are co-spokespersons for the experiment, which seeks to find new very weak forces. Such "dark forces" are predicted by some theories of dark matter that were proposed by Associate Faculty member **Maxim Pospelov**, Distinguished Research Chair **Nima Arkani-Hamed**, and others. These theories attempt to explain a puzzling excess of antiparticles bombarding the Earth from space.

Schuster and Toro also work closely with experimental collaborators, helping to develop new theoretical tools to interpret the results from the Large Hadron Collider at the European Organization for Nuclear Research (CERN). In particular, their "simplified models" proposal provides a more model-independent framework for extracting the theoretical implications of observations from the collider. This framework is now routinely adopted by collaborators on major collider experiments, including the ATLAS and CMS experiments at the LHC in CERN.

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R. Essig, P. Schuster, N. Toro, and B. Wojtsekhowski ,"An Electron Fixed Target Experiment to search for a new vector boson A' decaying to e^+e^-," *J. High Energy Phys.* 1102:009 (2011), arXiv:1001.2557.

Multiple authors, "Search for a new gauge boson in the A' Experiment (APEX)," arXiv:1108.2750.

"The laws of nature are turning out to be miraculous, much more beautiful than you had any right to expect, symmetrical, economical. They could have turned out to be like the tax code. Nobody knows why they didn't turn out to be messy. I don't think people appreciate this fact about the universe."

– Latham Boyle, Faculty member

PROFILE: GANAPATHY BASKARAN

Physics caught me slowly and unaware, when I had no aims and ambitions.

In India when I was young, it was customary in poor families to stop education at middle school. My parents valued education, though; my dad flooded our house with books.

As a physics undergraduate, I remember learning Ole Rømer's method of measuring the speed of light by observing eclipses of Jupiter's moons. Rømer's method was clever, simple, and gave the first quantitative and accurate value of an incomprehensibly large speed. I was fascinated.

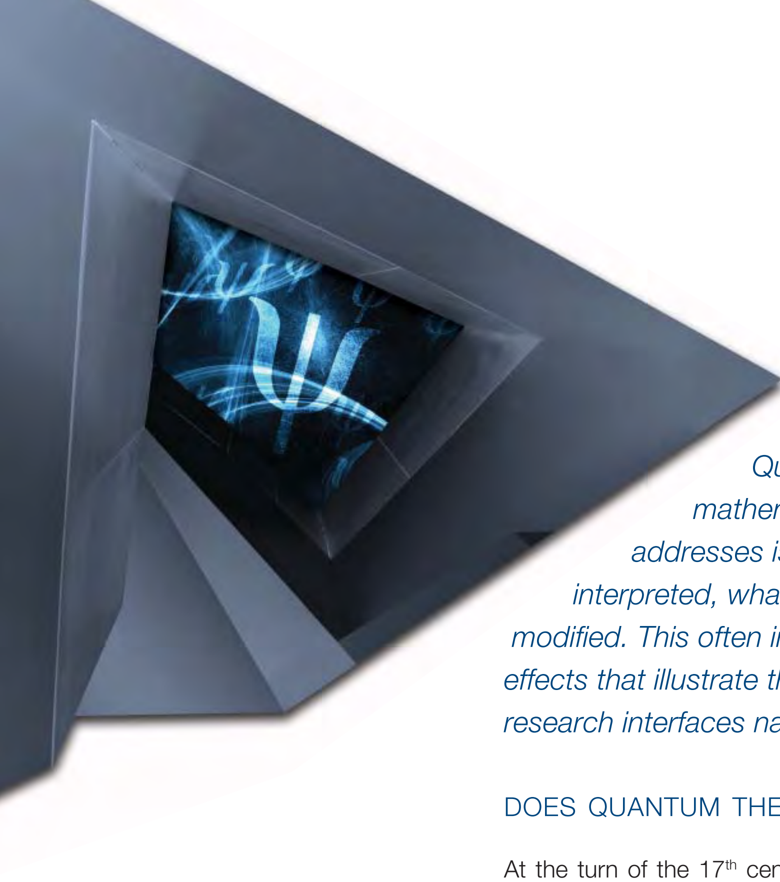
During my graduate studies in Madurai and Bangalore, I was drawn to condensed matter physics. Now I try to develop a theory of matter on the level of atoms and molecules, which obey the strange laws of quantum mechanics. In particular, I study how novel quantum properties emerge in strongly interacting materials. I look at experimental results, develop mathematical models, suggest solutions, and often rely on intuition and educated guesses to make predictions.

I am obsessed with the idea of a superconductor that works at room temperature. Such a material would revolutionize our technological world on a scale equivalent to the invention of the transistor. Doing this kind of science, an exploration into the quantum world is humbling, regardless of momentary successes. I feel that understanding the scientific secrets of this universe will make a better world, not only from a material point of view but also from what one may call a spiritual angle.

At Perimeter, human thought, bounded by experiments, nature, logic, aesthetics, and beauty, flow freely. I am happy and excited to have a scientific home in Waterloo.

– Ganapathy Baskaran

Distinguished Research Chair Ganapathy Baskaran is an Emeritus Professor at the Institute of Mathematical Sciences, Chennai, where he founded the Quantum Science Centre. He is the recipient of many honours, including the S. S. Bhatnagar Award and the Alfred Kasler ICTP Prize.



QUANTUM FOUNDATIONS

Quantum foundations concerns the conceptual and mathematical underpinnings of quantum theory. Research addresses issues such as how quantum theory should be interpreted, what deeper principles underlie it, and how it might be modified. This often involves the search for, and analysis of, novel quantum effects that illustrate the theory's peculiar properties. Quantum foundations research interfaces naturally with quantum information and quantum gravity.

DOES QUANTUM THEORY NEED TO BE THIS COMPLICATED?

At the turn of the 17th century, physicists faced a phenomenon that seemed counterintuitive, puzzling, and an affront to established science. German astronomer Johannes Kepler had observed that planets move in elliptical paths rather than in circles. Furthermore, their speed varied in ways that defied the contemporaneously understood laws of nature. Kepler developed revolutionary new laws of planetary motion that seemed to fly in the face of reason, but that accurately explained important aspects of how the universe worked.

It would take many decades before Isaac Newton refined and expanded on Kepler's laws to create a universal law of gravitation. Newton provided deeper understanding of why the planets move the way they do.

In the 20th century, Albert Einstein changed the game again, placing gravity in the context of a warped spacetime continuum. He enthralled and befuddled the scientific world and society at large, but his ideas were ultimately vindicated by experiments.

Over time, Newton's, Kepler's, and even Einstein's once abstruse and revolutionary ideas have become the stuff of straightforward high school physics. Today, quantum theory is similar to planetary motion four centuries ago – difficult to understand, a challenge to intuition, and also the best known theory for predicting the behaviour of atoms, electrons, and a host of other quantum particles. It has helped scientists develop everything from the transistor to the laser. But the axioms of quantum theory are mathematical, abstract, and very difficult to reconcile with everyday experience.

Where do these axioms come from? Why is quantum theory the way it is? How can it make the journey from complicated, evolving laws into something universal – and more universally understood?

In the last few years, Perimeter scientists have been trying to develop natural principles from which the math of quantum theory follows. Postdoctoral Researcher **Markus Mueller** (along with collaborator Lluis Masanes), Senior Postdoctoral Fellow **Giulio Chiribella** (in collaboration with Mauro D'Ariano and Paulo Perinotti), and Faculty member **Lucien Hardy** have each developed separate schemes for such principles.

This work helps provide a better means for talking and thinking about quantum theory. For instance, quantum equations rely on complex numbers – numbers that have a real component and an imaginary component. While complex numbers may appear inconveniently complicated, their use actually reflects a deep, beautiful, and very simple postulate of quantum theory: simply that the state of a system having two parts can be determined by making separate measurements on each of the parts. This postulate is common to all three Perimeter researchers' sets of natural principles.

Creating a common, straightforward language does more than make quantum theory more accessible. It also helps advance toward the field's overarching goals, such as creating a theory of quantum gravity.

IN QUANTUM PHYSICS, DOES REALITY MATTER AS MUCH AS BELIEF?

Quantum theory is, at its heart, about calculating probabilities.

In the classical world, people deal with probabilities continually – games of chance, weather forecasts, playing the stock market, and many other everyday experiences involve some calculation of odds. In general, though, classical physics provides the opportunity to reach a concrete outcome – we flip a coin, look out the window, check an investment statement – and probabilities turn into certainties.

Such observational confirmations lead to the reasonable assumption that probabilities say something about reality – even if there is a 60 percent chance of rain and the sun is shining, we tend to believe that the forecast still speaks to a verifiable combination of humidity, regional cloud cover, air currents, and temperature.

Alternative interpretations of statistics, though, can also be highly useful, particularly in the realm of quantum theory. The Bayesian approach, for instance, interprets probabilities not as assertions about reality, but as reflections of our incomplete knowledge and "degrees of belief." The percentage chance of precipitation will almost never tell you, for example, whether it is actually raining or not. It will, however, affect your choice of whether to pack an umbrella.

Faculty member **Robert Spekkens** and collaborator Matthew Leifer have made important strides in applying Bayesian approaches to quantum theory, where circumstances are often expressed exclusively in terms of probability. Their analogue to a weather forecast is a "quantum conditional state" whose specific properties can only be expressed in terms of likelihood, not actuality. By treating the equations describing these states as a form of incomplete knowledge, they hope to make it simpler to conceptualize and investigate the causal structures underlying quantum systems.

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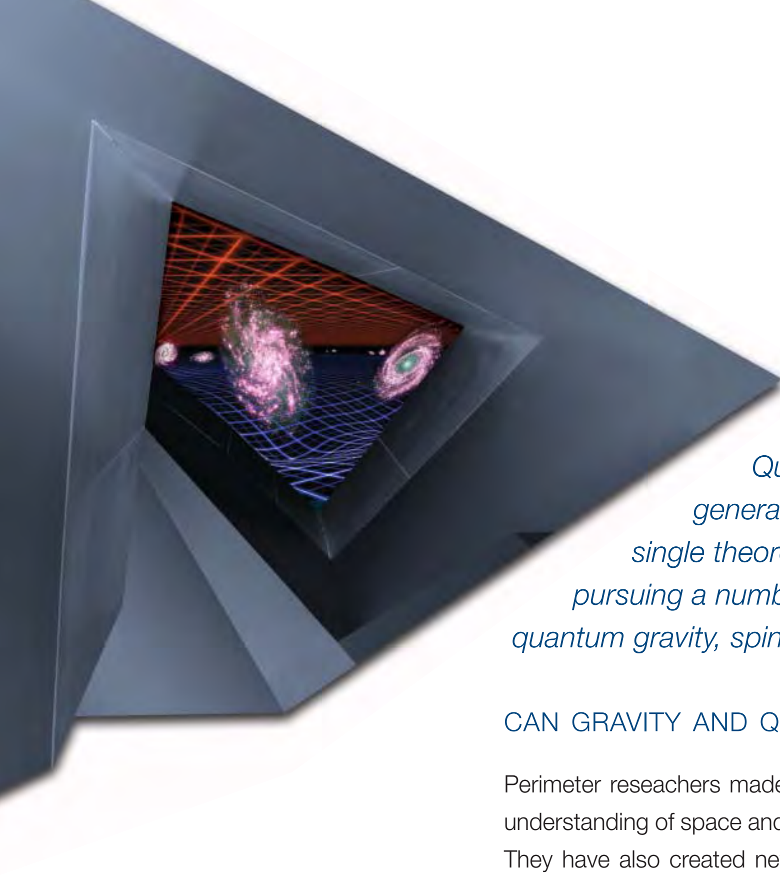

QUANTUM GRAVITY

Quantum gravity is concerned with unifying Einstein's general theory of relativity with quantum theory to create a single theoretical framework. At Perimeter, researchers are actively pursuing a number of approaches to this problem including loop quantum gravity, spin foam models, emergent gravity, and causal set theory.

CAN GRAVITY AND QUANTUM PHYSICS COEXIST?

Perimeter reseachers made strides in several directions over the past year, seeking to take our understanding of space and time beyond Albert Einstein's special and general theories of relativity. They have also created new models that express the hypothesis that space and time have an atomic structure.

Many Perimeter researchers have been particularly focused on approaches to quantum gravity that are classed together as being "background independent." Background independence embraces one of the basic principles of Einstein's general theory of relativity: that space and time are relational. They have no fixed, absolute structure to serve as a static background for doing physics. Instead, space and time exist in a dynamically evolving network of relationships.

Theorists at Perimeter make use of a multiplicity of approaches in order to winnow out the best model of a given phenomenon. Several different background-independent approaches, though, converge on a common, if surprising, hypothesis: space and time must have an atomic structure.

According to this hypothesis, at a miniscule level – 20 orders of magnitude smaller than the atomic nuclei of matter – the smoothness of space breaks into discrete units. The phenomenon is analogous to the way water appears to flow continuously even though it is actually made up of vast numbers of individual molecules. It has led Perimeter researchers to some of the most enticing and important questions facing theoretical physics today:

1. What are the atoms of space and time? What laws do they satisfy?
2. How does the apparent smoothness of space and time emerge from their atomic structure?
3. How do the known laws of physics emerge as approximations of the fundamental laws obeyed by the atoms of spacetime?
4. Are there observations and experiments by which the atomic structure of space and time could be confirmed and studied?

The answer to the fourth question turns out to be an emphatic yes. While the scale of the atomic structure of space and time might seem inconceivably small, it appears possible that spacetime atoms – or at least their effects – might be observed.

It is an ironic rule of doing physics that observation of smaller phenomena demands larger tools. Searching for evidence of the atomic structure of spacetime requires the biggest observational instrument in existence: the universe itself. When light and cosmic rays travel for hundreds of millions or even billions of years across the universe, the tiny effects of atomic spacetime become amplified to the point where observations can detect them. While no spacetime atomic effects have yet been observed, there is optimism that current and emerging technology will have the required sensitivity to do so in the near future.

CAN OTHER DISCIPLINES HELP SOLVE THE PUZZLES OF QUANTUM GRAVITY?

Perimeter members have also found new ways to address questions of quantum gravity by adopting and adapting methods from other fields, including condensed matter physics and quantum computing. This has led them to an approach called "quantum graphity," which is providing new tools to understand how physical laws and phenomena like gravity emerge as a result of the specific geometry of spacetime.

Last year, Faculty members **Laurent Freidel** and **Lee Smolin** developed an entirely new physics principle, known as the Principle of Relative Locality. This innovation was the result of a collaboration with visiting researchers Giovanni Amelino-Camelia and Jerzy Kowalski-Glikman.

Relative locality deepens Einstein's relativity principle by theorizing that each observer constructs a unique version of spacetime that is dependent on his or her point of observation. According to this principle, different universes may also be constructed from observations using light of different wavelengths. In related work, Freidel and Smolin also showed how to test this new hypothesis experimentally using observations of gamma ray bursts.

WHAT IF SIZE REALLY DOESN'T MATTER?

Another remarkable development was the discovery of a new formulation of Einstein's general theory of relativity called Shape Dynamics. One of the basic results of the general theory concerns the relativity of simultaneity. This says that the notion of what is happening "right now" at a distant location depends on the observer. Shape Dynamics reveals that there is in general relativity a preferred notion of time and simultaneity, which is determined by the motions of matter all over the universe. When this is taken into account, the equations of general relativity have a new property, which is that the size of objects no longer has meaning – all that is measurable is shapes. This remarkable insight was the result of a collaboration of young theorists: PhD student **Sean Gryb** and Postdoctoral Researcher **Tim Koslowski**, together with visiting PhD student **Henrique Gomes**.

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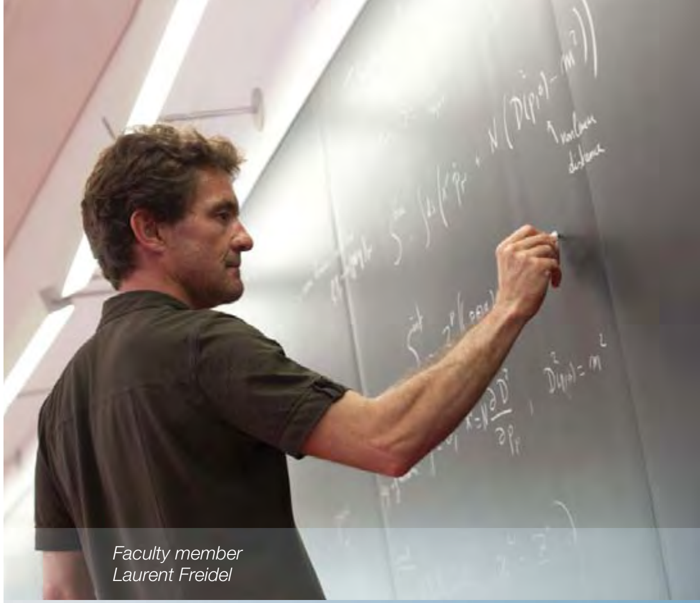


Faculty member Laurent Freidel

FACULTY

Latham Boyle

Freddy Cachazo

Laurent Freidel

Jaume Gomis

Daniel Gottesman

Lucien Hardy

Fotini Markopoulou

Robert Myers

Philip Schuster

Lee Smolin

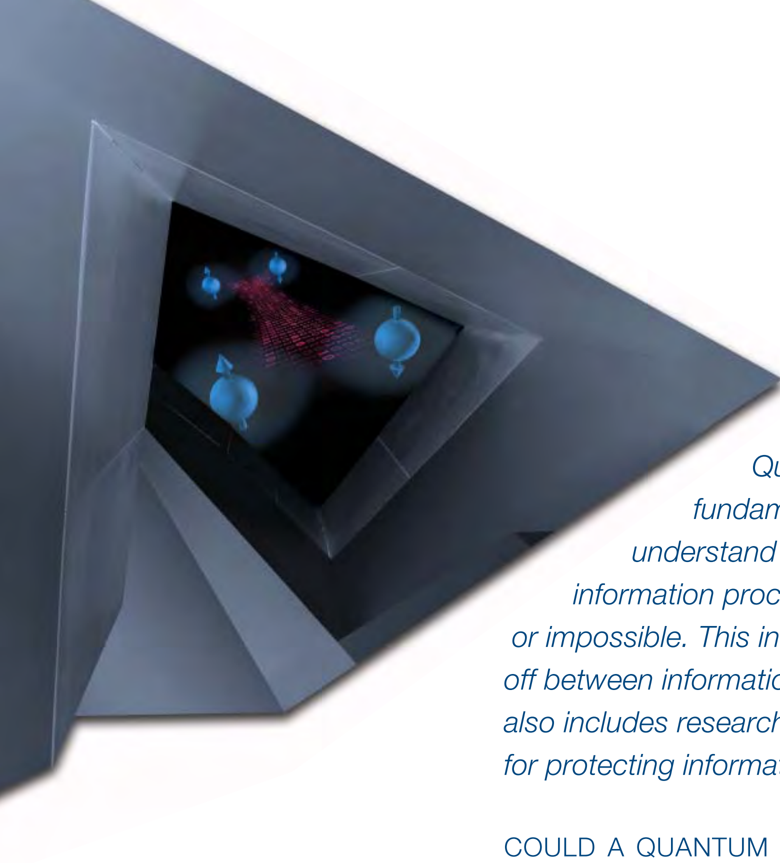
Robert Spekkens

Natalia Toro

Neil Turok

Guifre Vidal

Pedro Vieira



QUANTUM INFORMATION

Quantum mechanics redefines information and its fundamental properties. Perimeter scientists work to understand the properties of quantum information and study which information processing tasks are now feasible, and which are infeasible or impossible. This includes quantum cryptography, which studies the trade-off between information extraction and disturbance, and its applications. It also includes research in quantum error correction, which develops methods for protecting information against decoherence.

COULD A QUANTUM COMPUTING PLATFORM EXIST IN NATURE?

Postdoctoral Researcher **Akimasa Miyake** may have found a naturally occurring platform for a scalable quantum computer.

Quantum computers rely on entangled particles in order to process information. Entanglement occurs when particles – subatomic, atomic, or molecular – physically interact with one another in ways that give them common quantum properties. Not all entangled states are the same, though. Some occur naturally. Others must be painstakingly created. Some states work for quantum computing. Others do not.

Measurement-based quantum computation requires a system of entangled particles in a special condition known as a "universal resource state." Researchers used to think that this state could only be achieved through difficult, artificial means and by exercising painstaking control over the particles in a quantum system.

Miyake showed that quantum systems with universal resource states could occur naturally. He was studying a quantum model that had previously been of interest primarily to condensed matter physicists and that shares some properties with known real-world systems. He found that this theoretical model could act as a universal resource state, raising the hope of finding a naturally-occurring material with the same property.

CAN QUANTUM COMPUTING HELP BUILD BETTER TELESCOPES?

One surprising by-product of quantum computing may be better telescopes.

One of the primary areas of study for quantum information researchers concerns moving quantum states around and protecting them against errors. A branch of telescopy called interferometry relies on those same capacities. An interferometer consists of an array of two or more telescopes, all collecting electromagnetic radiation from the same target of observation. When observers combine these readings, the discrepancies from one location to another create interference patterns that can be decoded into an ultra-high resolution image. Increasing the distance between dishes increases the resolution. Because radiowaves are abundant, interferometry in this part of the electromagnetic spectrum can effectively function according to the laws of classical physics.

For optical wavelengths, though, photons arrive only rarely, which makes the quantum nature of the light important. To build an optical interferometer, one must move photonic information from one place to another while preserving each photon's quantum nature – exactly the kind of task performed by quantum information researchers. Such information generally gets lost when it travels any great distance, limiting the resolution of current optical interferometers.

Faculty member **Daniel Gottesman**, IQC Faculty member Thomas Jennewein, and Postdoctoral Researcher **Sarah Croke** have proposed a way to use "quantum repeaters" to extend the distance over which quantum information can be communicated. Quantum repeaters are still in development, but one day, they may be incorporated into the design of telescopes to allow observations with much higher angular resolution than today's best telescopes.

CAN A QUANTUM COMPUTER LEARN FROM ITS MISTAKES?

One mistake leads to another. Nowhere is this truer than in the world of computers. Nowhere is it more difficult to deal with than in the world of quantum computers. In a quantum system, once erroneous information is introduced, it is nearly impossible to rectify.

There are two ways to deal with quantum computing errors. One is to prevent them from happening in the first place, which can only be done in very specific circumstances. The other is to build in the capacity to correct errors as they occur. This option offers more flexibility, but error correction on a quantum level has a difficulty that makes it akin to magic.

One approach to building fault-tolerant quantum computers is to use "magic states," which contain important steps of the computation in a separate package. A magic state is difficult to create, but once it's made, it can be inserted easily into any ongoing computation. Since the magic state is self-contained, it can be tested and discarded if it contains mistakes. Creating and comparing multiple copies of a magic state, a process known as "distillation," can make it possible to identify and remove errors before they infect the main computation.

This year, a team of students and postdocs working with Associate Faculty member **Raymond Laflamme** successfully achieved magic state distillation, an important step toward fault tolerant quantum computing.

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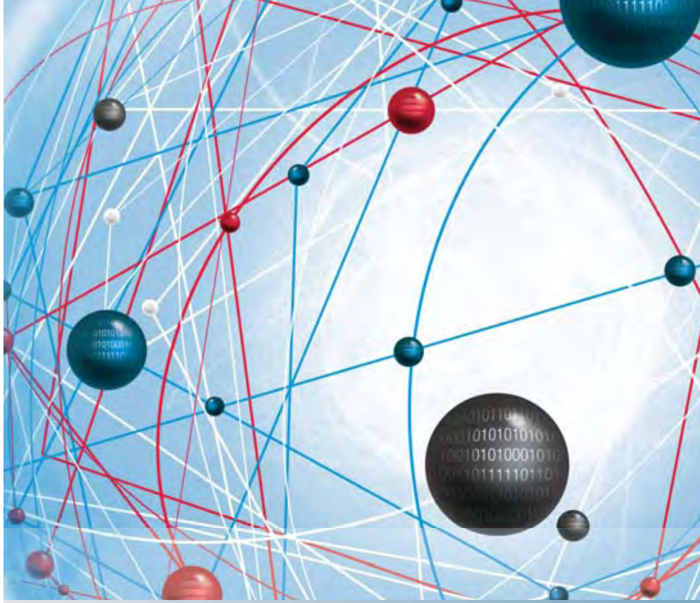
A. M. Souza, J. Zhang, C. A. Ryan, and R. Laflamme, "Experimental magic state distillation for fault-tolerant quantum computing," *Nature Comm*. 2, 169 (2011), arXiv:1103.2178.



ASSOCIATE FACULTY

(cross-appointed with other institutions)

Niayesh Afshordi
(University of Waterloo)

Alex Buchel
(University of Western Ontario)

Cliff Burgess
(McMaster University)

Richard Cleve
(University of Waterloo)

David Cory
(University of Waterloo)

Adrian Kent
(University of Cambridge)

Raymond Laflamme
(University of Waterloo)

Sung-Sik Lee
(McMaster University)

Luis Lehner
(University of Guelph)

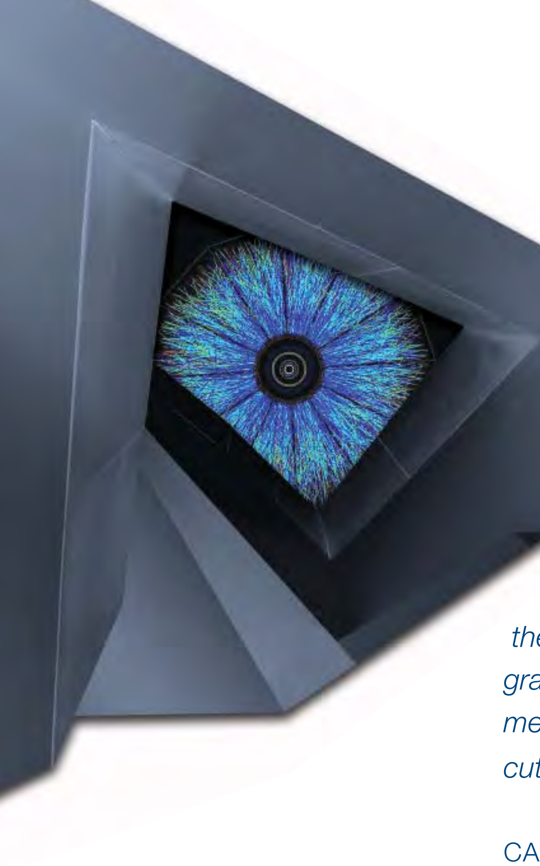
Michele Mosca
(University of Waterloo)

Ashwin Nayak
(University of Waterloo)

Maxim Pospelov
(University of Victoria)

Thomas Thiemann
(Max Planck Institute for Gravitational Physics)

Itay Yavin
(McMaster University)



STRING THEORY

String theory is a theoretical framework aimed at producing a unified description of all particles and forces in nature. It is based on the idea that at very short distances, all particles should be seen as one-dimensional objects or "strings." String theory has strong connections to other research areas, including quantum gravity, particle physics, and cosmology, as well as mathematics. Notably, members of the string research area at Perimeter are leading the world in the cutting-edge area of advanced field theory methods.

CAN SIMPLER EQUATIONS LEAD TO A MORE SOPHISTICATED UNDERSTANDING OF PARTICLE PHYSICS?

To find out what's inside a piñata, one makes it collide with a stick. In a similar vein, to reveal the basic building blocks of matter, particle accelerators like the Large Hadron Collider (LHC) smash subatomic particles together at very high speeds. With the piñata, the stick does not produce any candy that was not there already; by contrast, particles in an accelerator collide, bounce off each other, and emit or absorb additional new particles in a process called scattering.

As the most powerful particle accelerator on the planet, the LHC is the focal point for physicists around the world. Many feel that it will bring breakthroughs in our understanding of the universe's first moments, as well as what matter is made of, and even why matter exists at all.

In order to answer such questions, particle theorists need to be able to precisely calculate what our current theories predict about what should be seen, which experimentalists check against the actual data from high energy particle collisions. "Scattering amplitudes" are precise theoretical predictions about the probabilities for obtaining various outgoing particles when a given set of incoming particles collide.

When experimental results conform to theorists' predictions, that's good. But when something unexpected happens instead, that's even better – it means scientists have discovered something new about physics.

While traditional methods for calculating predictions for simple processes of a few particles bouncing off one another are fairly straightforward, they are hopelessly complex for describing processes with a great morass of particles all crashing together at once. Yet this is exactly the situation at the LHC. Thus, over the past several years, theorists have been pushing hard to develop a range of techniques aimed at better understanding both how to compute scattering amplitudes and what they actually tell us.

In the past year, Perimeter scientists have made great strides in this quest.

Since 2003, Faculty member **Freddy Cachazo** has been a leader in this effort, and has discovered much simpler methods for calculating scattering amplitudes that have become widely adopted by theorists and experimentalists.

Recently, Cachazo *et al.* found that the equations used to predict the results of complex collisions were analogous to a much more straightforward mathematical problem: finding the volume of a class of geometric objects called polytopes. While calculating polytope volumes is still complicated, it is far simpler than the usual methods of modelling particle collisions. The discovery of this relationship means that even very precise calculations can be greatly simplified.

The principles underlying this work are profound and hint at a new understanding of the fundamental structure of the universe. Well beyond their immediate utility to experimentalists, they are providing an entirely new approach to understanding fundamental physical properties. Cachazo is now pursuing this deeper theoretical understanding with collaborators including Perimeter Distinguished Research Chair **Nima Arkani-Hamed** of the Institute for Advanced Study.

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.

Senior Postdoctoral Fellow **David Skinner** and collaborators have taken another geometric approach to simplifying calculations of scattering amplitudes. Several years ago, Luis Alday and Juan Maladacena conjectured a relationship between scattering amplitudes for strongly coupled interactions and complex objects known as Wilson Loops, but it remained unproven. (Wilson loops represent the flux of the strong nuclear force fields through various geometrical areas.) Soon after, the conjecture was extended to all ranges of coupling but it remained a conjecture. Now, using ideas from an area of mathematics called twistor theory, Skinner and colleagues have proven the conjecture precisely.

In the same way a major snarl can be untangled by breaking it down into several smaller knots, Skinner's equations can break a complex several-particle collision into collisions of fewer particles that can be modeled more easily. It is a crucial new technique with wide implications for the work of other Perimeter researchers, such as Faculty member **Pedro Vieira**, and well beyond.

These recent discoveries are likely to be of enormous significance. Not only do they allow physicists to calculate complex physical processes relevant to real experiments, but they also enable them to tackle fundamental questions about the structure of spacetime itself.

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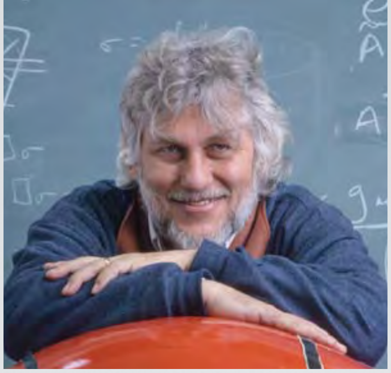
M. Bullimore and D. Skinner, "Holomorphic Linking, Loop Equations and Scattering Amplitudes in Twistor Space," arXiv:1101.1329.



PROFILE: WILLIAM UNRUH

In these days of economic crisis, many governments around the world are losing sight of the importance of fundamental, curiosity-driven research. They are much more likely to support research if it promises to solve immediate problems – not recognizing that addressing short-term issues often requires thinking about long-term problems.

Perimeter, by contrast, acts as a refuge, a supportive environment where people can carry out long-term fundamental research. For example, I do research on the relationship between gravity and quantum mechanics, asking questions such as, "Why do black holes evaporate by emitting quantum radiation?" When Stephen Hawking discovered this phenomenon, it was treated as highly mysterious and believed to be unique to black holes. In 1981, I argued that this phenomenon is far from unique and that black holes in fact behave analogously to water waves at a river mouth. In both cases, incoming waves become amplified when they interact with outflowing energy. We can use similar equations to describe both situations.

Identifying analogues between seemingly unrelated systems like these can help explain the physical properties of one system in terms of the other. Not only do waves in a flowing fluid help us understand black holes, but black holes also help us understand the behaviour of waves in the ocean.

Perimeter resists doing only immediately relevant research, which makes it an island of sanity. It gives researchers like me the freedom to solve problems for the knowledge they give of how our world operates, whether in the far reaches of space or understanding our immediate world from a totally different direction.

– William Unruh

Distinguished Research Chair William Unruh is a Professor of Physics at the University of British Columbia who has made seminal contributions, including the discovery of the Unruh effect. He is the recipient of many honours and awards, including the Canadian Association of Physicists Medal of Achievement and the Canada Council Killam Prize.

Detail of "Branch," Shirley Wiitasalo, 1994, Perimeter Institute Collection.

HONOURS, AWARDS, AND MAJOR GRANTS

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

- 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"
- 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
- Faculty member Lee Smolin and Associate Faculty member Richard Cleve were inducted as Fellows of the Royal Society of Canada
- 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
- 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
- Director Neil Turok and Faculty member Lee Smolin were awarded a $2 million grant from the John Templeton Foundation to create a new program, The Templeton Frontiers Program at Perimeter Institute
- 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 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
- Associate Faculty member Niayesh Afshordi received a $150,000 Early Researcher Award from Ontario's Ministry of Research and Innovation
- Director Neil Turok was named to the Science, Technology and Innovation Council (STIC), the Government of Canada'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)
- 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 for his project, "Physical and cosmological consequences of the hypotheses of the reality of time"
- Faculty members Lee Smolin and Laurent Freidel, with colleagues, 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
- Postdoctoral Researcher Matthew Johnson was co-awarded an FQXi grant of US$112,331 for "Detecting signatures of eternal inflation using WMAP and Planck data"
- Senior Postdoctoral Fellow Giulio Chiribella was selected by the American Physical Society as an APS highlight for his paper, "Informational derivation of quantum theory"

PERIMETER DRC YAKIR AHARANOV WINS NATIONAL MEDAL OF SCIENCE

In November 2010, President Barack Obama presented the National Medal of Science to Perimeter Institute Distinguished Research Chair Yakir Aharanov. The award is the highest honour bestowed on scientists by the United States government.

Professor Aharanov is best known for the discovery of the Aharanov-Bohm effect, a quantum phenomenon which fundamentally advanced modern physics by demonstrating that potentials, not forces, were the most appropriate language in which to describe the quantum world. The implications of the Aharanov-Bohm effect are still being probed by scientists more than 50 years after its discovery.

Photo credit: Ryan K. Morris/National Science & Technology Medals Foundation

Left to right: Director Neil Turok, Professor Xiao-Gang Wen, President and CEO of BMO Financial Group William Downe, and Perimeter Board Chair Mike Lazaridis

RECRUITMENT

IN 2010-11…

- *Philip Schuster, Natalia Toro, and Guifre Vidal joined Perimeter as full-time Faculty members*
- *Sung-Sik Lee and Itay Yavin joined Perimeter as Associate Faculty members jointly appointed with McMaster University*
- *8 new Distinguished Research Chairs were appointed*
- *11 new Postdoctoral Researchers were recruited*

THE BMO FINANCIAL GROUP ISAAC NEWTON CHAIR IN THEORETICAL PHYSICS

World-leading condensed matter theorist **Xiao-Gang Wen** has been recruited from MIT to become the inaugural BMO Financial Group Isaac Newton Chair in Theoretical Physics at Perimeter Institute.

In 2010, a leadership gift of $4 million from BMO Financial Group enabled the Institute to create the first of a projected five Perimeter Research Chairs, designed to attract distinguished research leaders from around the world. They will be named for the legendary scientists whose insights helped define modern physics: Newton, Bohr, Dirac, Einstein, and Maxwell.

Wen is a global leader in the quest to discover new forms of matter. In 1989, he introduced the notion of topological order, enabling physicists to describe a new class of matter – topological matter – which exhibits quantum entanglement properties at macroscopic scales. This breakthrough opened up major new research directions and topological matter is now one of the most active research areas in condensed matter physics. Wen himself has subsequently made major discoveries in the new field that he created, notably the discovery of "topological insulators," which show strong promise for use in quantum computers. Wen's continued research has implications well beyond his own field, advancing quantum information science, high-energy physics, mathematics, and even the development of new models of the universe. The BMO Isaac Newton Chair, which Wen will hold, is the first chair to be named for Newton worldwide.

"My research is very interdisciplinary, which helps me find totally new topics – unexplored areas of physics that no one has touched before. It fits Perimeter's philosophy and research model very well."

– Xiao-Gang Wen

FACULTY

Perimeter welcomed several new faculty members in 2010-11.

Particle physicists **Natalia Toro** and **Philip Schuster** both joined Perimeter in September 2010 as junior faculty members. Toro is an expert in dark forces that couple very weakly to ordinary matter, and has played a major role in developing simplified models and integrating new techniques into experiments at the Large Hadron Collider. Schuster specializes in particle theory, with an emphasis on physics beyond the Standard Model. He too has close ties to experimental physics, including work at the LHC. Toro and Schuster are co-spokespeople for the APEX experiment, a search for weakly interactive dark forces at the Thomas Jefferson National Accelerator Facility in Virginia.

Guifre Vidal joined Perimeter 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 of Mathematics and Physics. 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.

Davide Gaiotto is widely considered one of world's most talented young theorists in the vital area of strongly quantum-correlated systems. Working at the interface of quantum field theory and string theory, he has made several major discoveries, for which he received the 2011 Gribov Medal of the European Physical Society. He will join Perimeter from the Institute for Advanced Study in Princeton in spring 2012.

Bianca Dittrich will join Perimeter in 2012 from the Albert Einstein Institute in Potsdam. A young leader in quantum gravity, she recently developed a computational framework for gauge invariant observables in canonical general relativity. In 2007, she received the Otto Hahn Medal of the Max Planck Society, which recognizes outstanding young scientists.

THE TEMPLETON FRONTIERS PROGRAM AT PERIMETER INSTITUTE

The John Templeton Foundation recently awarded $2 million to the Institute to create the Templeton Frontiers Program at Perimeter Institute. The program aims to catalyze path-breaking research in three areas at the heart of Perimeter's research: quantum foundations and information, foundational cosmology, and the emergence of spacetime. The grant will support several exceptional young postdoctoral researchers, in addition to research projects, conferences, lectures, and visits by Distinguished Research Chairs working in these fields.

ASSOCIATE FACULTY

In addition to full-time faculty, Perimeter often works with nearby universities to make joint hires through its Associate Faculty program, enabling the Institute to recruit top scientific talent to Canada and to spread the benefit among multiple institutions. In 2010-11, Perimeter made three such joint appointments, increasing the Institute's research strength in key areas.

Astrophysicist **Avery Broderick** will join Perimeter's faculty in September 2011 in a joint appointment with the University of Waterloo. Broderick has recently been part of an international effort to produce and interpret horizon-resolving images of supermassive black holes, studying their dynamics and the nature of gravity in their vicinity.

Particle physicist **Itay Yavin** focuses on the search for physics beyond the Standard Model, particularly the nature of dark matter and the origin of electroweak symmetry breaking. He joined Perimeter in July 2011 in a joint appointment with McMaster University.

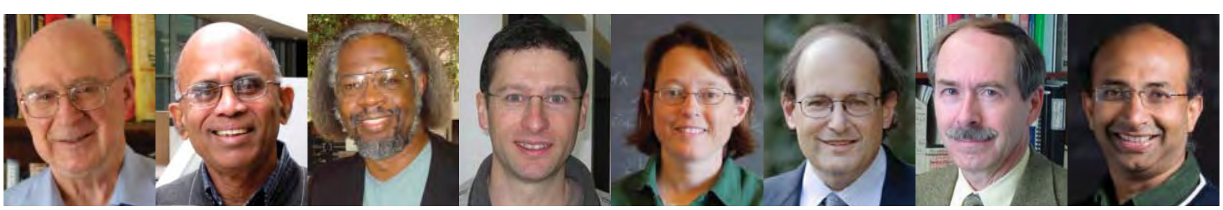
Sung-Sik Lee joined Perimeter's faculty in July 2011. He is a condensed matter theorist whose research focuses on strongly interacting quantum many-body systems using quantum field theory, as well as the intersections between condensed matter and high energy physics.

"I'm thrilled to be joining such an innovative and lively research environment. Perimeter recognizes the importance of ideas that cut across conventional disciplinary boundaries, a notion that underpins much of my research. The Institute is also quickly amassing a first-rate group of condensed matter researchers that I'm excited to work with."

– Sung-Sik Lee, Associate Faculty member

DISTINGUISHED RESEARCH CHAIRS

Quantum theory suggests a particle can be in two places at one time. Perimeter's unique Distinguished Research Chairs (DRCs) program offers leading scientists an analogous opportunity. While retaining permanent positions at their home institutions, DRCs visit the Institute for extended periods each year, becoming part of Perimeter's community in all respects: conducting research, collaborating with colleagues, organizing conferences, teaching in the PSI program, and contributing to outreach programs.



James Bardeen | Ganapathy Baskaran | S. James Gates | Frans Pretorius | Eva Silverstein | Paul Steinhardt | Gerard 't Hooft | Senthil Todadri

Perimeter's DRCs include luminaries such as **Stephen Hawking**, **Nima Arkani-Hamed**, **Leonard Susskind**, **Mark Wise**, and **Ignacio Cirac** from across the entire spectrum of theoretical physics. Their presence sparks new ideas and collaborations, and greatly enhances Perimeter's resident research community. This year, eight new DRCs were appointed, bringing the total to 27.

Postdoctoral Researchers Alioscia Hamma and Astrid Eichhorn
Photo credit: Scott Norsworthy

POSTDOCTORAL RESEARCHERS

Many of the great discoveries in physics were made by surprisingly young scientists. With this in mind, Perimeter provides its postdoctoral researchers with exceptional opportunities to maximize their research potential at a pivotal stage in their careers. They infuse the Institute's research environment with energy and vivacity, offering consistently fresh perspectives.

Perimeter is home to the largest group of independent theoretical physics postdoctoral researchers in the world (43 in 2010-11). As full partners in Perimeter's research community, postdocs pursue independent research programs and are encouraged to invite scientific collaborators, travel, and organize conferences.

This year's 11 new appointees were chosen from more than 600 applicants, joining Perimeter from top institutions including Harvard, Caltech, Princeton, Hebrew University, ETH Zurich, and the Kavli Institute for Theoretical Physics (Santa Barbara). Working at Perimeter has launched many successful careers; last year, departing postdoctoral researchers obtained excellent positions at the Albert Einstein Institute (Potsdam), Los Alamos National Laboratory, the Indian Institute of Science (Bangalore), and other leading institutions.

DISTINGUISHED RESEARCH CHAIRS

Dorit Aharonov, Hebrew University

Yakir Aharonov, Chapman University & Tel Aviv University

Nima Arkani-Hamed, Institute for Advanced Study

Neta Bahcall, Princeton University

James Bardeen,* University of Washington

Ganapathy Baskaran,* Institute of Mathematical Sciences (Chennai)

Juan Ignacio Cirac, Max Planck Institute of Quantum Optics, Garching

Gia Dvali, New York University and CERN

S. James Gates,* University of Maryland

Stephen Hawking, University of Cambridge

Patrick Hayden, McGill University

Christopher Isham, Imperial College London

Leo Kadanoff, University of Chicago

Renate Loll, Utrecht University

Malcolm Perry, University of Cambridge

Sandu Popescu, University of Bristol

Frans Pretorius,* Princeton University

Subir Sachdev, Harvard University

Ashoke Sen, Harish-Chandra Research Institute

Eva Silverstein,* Stanford University

Paul Steinhardt,* Princeton University

Leonard Susskind, Stanford University

Gerard 't Hooft,* Utrecht University

Senthil Todadri,* Massachusetts Institute of Technology

William Unruh, University of British Columbia

Xiao-Gang Wen, Massachusetts Institute of Technology

Mark Wise, California Institute of Technology

** Indicates DRC appointed in 2010-11*

Sir Roger Penrose with members of the Perimeter Scholars International Class of 2011

RESEARCH TRAINING

PERIMETER SCHOLARS INTERNATIONAL

BY THE NUMBERS

- *31 Masters students in PSI Class of 2011*
- *4 MSc students*
- *24 PhD students*
- *7 courses*

Perimeter Scholars International (PSI) is the Institute's Masters program, which brings highly talented university graduates from around the world to the cutting edge of theoretical physics in one academic year.

The program is structurally innovative, with courses taught in three-week modules by Perimeter faculty and other top lecturers from around the world, providing a broad range of expertise and perspectives. Students not only experience the full spectrum of theoretical physics, but also learn practical skills such as computer-based model development, independent thinking, and collaborative problem solving. In the latter part of the program, students defend original research theses, many of which are later accepted for publication. The program is run in partnership with the University of Waterloo, which confers a Masters degree on completion of the program.

"PSI gave me the opportunity to learn from a global community of physicists, as well as the freedom to let my interests guide and inspire me, all within Perimeter's incredibly focused research atmosphere."

– Lauren Greenspan, PSI Class of '11

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perimeter scholars international™

In 2010-11, 31 students from 15 countries completed PSI. Notably, 14 of this year's graduates are women, reflecting the Institute's strong commitment to cultivating gender diversity in the field. Fifteen 2010-11 graduates are now pursuing their PhDs in Canada, 12 with Perimeter Faculty and Associate Faculty members. Others have gone on to excellent programs at Columbia University, Stony Brook, UC Santa Cruz, and elsewhere.

A donation from the Kitchener-Waterloo Community Foundation — The John A. Pollock Family Fund helped to support the PSI program in 2010-11.

COURSES

In addition to the PSI curriculum, Perimeter presents topical courses on current topics for resident researchers and students, as well as those of surrounding universities. Last year, resident and visiting scientists offered seven courses, enhancing and complementing the course offerings of universities across the region. Highlights included "Spacetime, Quantum Mechanics and Scattering Amplitudes" taught by DRC Nima Arkani-Hamed (IAS) and Faculty member Freddy Cachazo; "Scattering Amplitudes from Single-Cuts" taught by Simon Caron-Huot (IAS); and "Introduction to Tensor Network Algorithms" taught by Postdoctoral Researcher Robert Pfeifer. As with all Perimeter research happenings, these courses are available to the wider scientific community through PIRSA, Perimeter's online video archive (www.pirsa.org).

PHD STUDENTS

Faculty supervised 24 PhD students over the past year (with three completed), all of whom will receive their degree from a partnering university where the faculty member has an affiliation. Perimeter's rich environment offers students unparalleled opportunities to interact with research leaders from around the world and to develop further career opportunities. All of this year's graduates obtained competitive postdoctoral fellowships at international institutions, including NASA, MIT, and the Max Planck Institute for Gravitational Physics.

UNDERGRADUATE RESEARCH

Postdoctoral researchers are encouraged to develop mentoring skills while enhancing their own research by developing two- to four-month summer research projects suitable for undergraduates. Last summer, seven talented undergrads from around the world got an opportunity to become members of Perimeter's research community, developing their research skills and absorbing the rich variety of talks, conferences, and happenings at Perimeter.

PSI 2010-11 FACULTY

John Berlinsky, Director

Nima Arkani-Hamed, Institute for Advanced Study (IAS)

Carl Bender, Washington University

Latham Boyle, Perimeter Institute

Freddy Cachazo, Perimeter Institute

David Cory, Perimeter Institute & Institute for Quantum Computing, University of Waterloo

François David, Institute of Theoretical Physics, CEA-Saclay

Jaume Gomis, Perimeter Institute

Daniel Gottesman, Perimeter Institute

Ruth Gregory, Durham University

Leo Kadanoff, University of Chicago

Luis Lehner, Perimeter Institute & University of Guelph

Renate Loll, Utrecht University

John McGreevy, Massachusetts Institute of Technology

Scott Noble, Center for Computational Relativity and Gravitation, Rochester Institute of Technology

Tamar Pereg-Barnea, California Institute of Technology

Michael Peskin, SLAC National Accelerator Laboratory

Veronica Sanz, York University

Ben Schumacher, Kenyon College

Philip Schuster, Perimeter Institute

Sarah Shandera, Perimeter Institute

Eric Sorensen, McMaster University

Robert Spekkens, Perimeter Institute

Andrew Tolley, Case Western Reserve University

Natalia Toro, Perimeter Institute

Neil Turok, Perimeter Institute

Pedro Vieira, Perimeter Institute

Konstantin Zarembo, NORDITA

Participants at "Integrability in Scattering Amplitudes II" conference

RESEARCH EVENTS

CONFERENCES, WORKSHOPS, AND SUMMER SCHOOLS

There is no substitute for the intense focus and unexpected human interactions at scientific gatherings. Time and again, discussion, debate, and unexpected ideas catalyze new insights and discovery.

Perimeter's flexibility enables it to rapidly identify and capitalize on promising new areas, and the Institute is often the first in the world to host a conference on an emerging area or new discovery.

In 2010-11, Perimeter held 12 timely, focused conferences and workshops, attended by over 600 scientists from around the world. By strategically choosing areas where a conference or workshop is likely to have significant outcomes, Perimeter aims to accelerate progress and act as a major node of exchange for groundbreaking research.

Last year, Perimeter launched a new conference venture aimed at combining the benefits of conferences and workshops with those of extended research collaborations. The first two such hybrid programs – one on early universe cosmology, another on astrophysical signatures of gravitational and electromagnetic waves – were both highly successful and follow-up events are expected in coming years.

"The conference on Holographic Cosmology v2.0 was one of the most stimulating meetings I have been to in recent years. I particularly enjoyed the discussions during and after the talks with participants from fields ranging from cosmology to quantum information. It is very interesting to see these different fields have become linked through the holographic principle."

– Erik Verlinde, Institute for Theoretical Physics, University of Amsterdam

BY THE NUMBERS

In 2010-11 …

- *Hosted 12 timely, focused conferences and workshops, attended by 653 scientists from around the world*
- *Partnered on 10 joint workshops and conferences with other institutions*
- *Presented 263 scientific talks, all made available online at www.pirsa.org*

COLLOQUIA AND SEMINARS

Perimeter provides a rich environment for knowledge exchange, with 233 seminars and 30 colloquia held over the last year. The Institute hosts eight active weekly seminar series, fostering collaboration with researchers around the globe.

Speakers of the past year included Yakir Aharonov (Chapman and Tel-Aviv Universities), Patrick Hayden (McGill University), Renate Loll (Utrecht University), William Unruh (University of British Columbia), Erik Verlinde (University of Amsterdam), Sandu Popescu (University of Bristol), Sir Anthony Leggett (University of Illinois), Andreas Albrecht (University of California), Robert Brandenburger (McGill University), and many more.

PERIMETER INSTITUTE RECORDED SEMINAR ARCHIVE

Scientists and students all over the world can access over 5,800 talks, lectures, and colloquia online via the Perimeter Institute Recorded Seminar Archive (PIRSA) at www.pirsa.org. PIRSA has become an important resource for the international community and site traffic continues to rise year over year. Last year, more than 50,000 unique visitors from 151 countries accessed nearly 500,000 pages on PIRSA. In 2010-11, recording and archiving technologies were substantially upgraded to enhance image quality and make PIRSA more accessible.

CONFERENCE HIGHLIGHTS

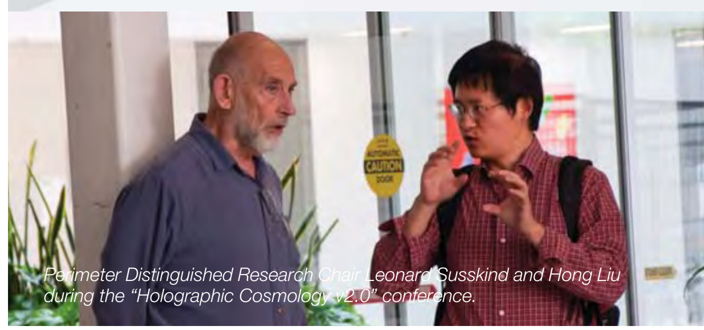
Participants at "Women in Physics Canada"
Photo credit: Peter Kovacs, courtesy of the Institute for Quantum Computing

WOMEN IN PHYSICS CANADA

Perimeter and the Institute for Quantum Computing co-organized Canada's first-ever conference aimed at addressing the pronounced gender imbalance in physics, and encouraging female undergraduates and recent graduates to continue their scientific careers. With talks and workshops from both early career and senior physicists, it provided inspiration and information, as well as initiating the creation of a peer support network, all of which are important to young physicists' continuing success.

FUNDAMENTAL ISSUES IN COSMOLOGY

Over 100 string theorists and cosmologists, from students to luminaries, met in summer 2011 to tackle major unresolved questions about the early universe. Two conferences – "Holographic Cosmology v2.0" and "Challenges for Early Universe Cosmology" – were held a month apart, with collaborative research time between the gatherings. The program exemplified Perimeter's interdisciplinary and innovative approach to stimulating progress in the field, and by all accounts was a major success. Plans are underway for a follow-up gathering next year at the Stanford Institute for Theoretical Physics.



Perimeter Distinguished Research Chair Leonard Susskind and Hong Liu during the "Holographic Cosmology v2.0" conference.

Participants at "IGST 2011"

RESEARCH LINKAGES

BY THE NUMBERS

In 2010-11 …

- *over 1,000 scientists visited Perimeter to do research and attend conferences*
- *13 Affiliate members joined Perimeter, bringing the total to 105*

VISITOR PROGRAM

Fresh voices invigorate discussion. Over the last year, Perimeter's lively scientific visitor program brought 416 scientists for research visits (in addition to over 600 conference participants). Coming to Perimeter provides visiting scientists with time, space, and ample opportunities to attend conferences and talks, exchange ideas, and spark new collaborations with colleagues. In 2010-11, four appointments were made to the new Visiting Fellows program, which will bring accomplished researchers to the Institute for extended research stays of up to six months while keeping positions at their home institutions.

AFFILIATES

Through the Institute's Affiliate member program, select faculty from Canadian universities are invited to make regular visits to the Institute, attending seminars, conferences, and other events, and working with resident researchers. Affiliates enrich Perimeter's community, helping to build regional and national research links between Perimeter and other Canadian universities. In 2010-11, 13 new Affiliate members joined, bringing the total membership to 105.

NATIONAL LINKAGES

Modern physics is inherently collaborative – the big questions are so complex that they can rarely be answered by a single researcher, or even by a single institution. Collaboration is vital and sharing intellectual wealth enriches all.

Perimeter aims to serve as a hub for theoretical physics in Canada. In addition to long-standing and productive ties with the Institute for Quantum Computing at the University of Waterloo, Perimeter partners with regional universities, including McMaster, Guelph, and Western, via cross-appointments, adjunct appointments, joint postdoctoral fellowships, and graduate training. The Institute also provides unique resources and leadership to the national scientific community through conferences, workshops, and courses.

Perimeter has forged strong ties with other research organizations across the country, including the Canadian Institute for Theoretical Astrophysics (CITA), Canadian Institute for Advanced

Research (CIFAR), the Fields Institute, SNOLAB, Centre de Recherches Mathématiques, Pacific Institute for Mathematical Sciences, and Mathematics of Information Technology and Complex Systems (MITACS) research networks.

Last year, Perimeter established an agreement with TRIUMF, Canada's national particle and nuclear physics laboratory in British Columbia, to facilitate research visits and build new bridges between the worlds of theory and experiment. Through such partnerships, Perimeter benefits from and contributes to Canada's diverse and dynamic research community.

INTERNATIONAL LINKAGES

Perimeter maintains links with research institutions around the world. The innovative new Unification of Fundamental Forces and Applications (UNIFY) partnership, joins Perimeter with partners in Europe and the US, and will combine topical conferences with training in *Mathematica* computational software, plus an array of opportunities for PhD students, postdoctoral researchers, and senior scientists. In June 2011, the Institute joined the international HoloGrav Network to further interdisciplinary research in the cutting-edge area of gauge/gravity duality.

Perimeter has strengthened links to leading observational and experimental centres in recent years. In 2011, for example, Perimeter and CITA together became the first Canadian members of the international Laser Interferometer Gravitational Wave Observatory (LIGO) Scientific Collaboration, opening exciting opportunities for the upcoming era of gravitational wave astronomy.

Organizers from "PI-CITA Day 2011"

A COLLISION OF MINDS

Since 2007, researchers from Perimeter and the Canadian Institute for Theoretical Astrophysics (CITA) have gotten together regularly to share new ideas in common fields of interest — black holes, Big Bang nucleosynthesis, dark matter, and so on — through a series of informal talks followed by discussion.

The success of PI-CITA Days motivated the creation of PI-ATLAS Days in 2009. These meetings bring physicists from all over southwestern Ontario together to discuss the current status of searches at the ATLAS experiment and the Large Hadron Collider. Tau identification, baryogenesis, and exotic signals in the data all figure into the mix. Perhaps most important, it brings theorists and experimentalists together for an active and ongoing exchange of ideas.

BY THE NUMBERS

In 2010-11, Perimeter Outreach ...

- *Reached over 160,000 Canadian high school students*
- *Developed 2 new in-class and web-based educational resources*
- *Presented 8 public lectures by world renowned scientists*
- *Brought 40 budding physicists from across Canada and around the world to ISSYP*
- *Gave presentations to over 1,000 students across Canada*

OUTREACH

To shape our future wisely, we all need to understand and value science. From the technologies we use daily in all walks of life to the methods we use to discover new knowledge, the fruits of science are all around us. And science isn't just a spectator sport – everyone can share in the joy and excitement of the universe's mind-bending mysteries.

At Perimeter, outreach is a core part of our mission. The Institute has developed a comprehensive array of materials and programs, each tailored for specific audiences: students, teachers, and the general public. The Outreach team, which includes two staff scientists, works with leading scientists and educators to ensure that all materials and programs are accurate, cutting edge, and engaging.

INSPIRING YOUNG PEOPLE

It is crucial to connect students with science early and often. Inspiring young people about science is valuable in its own right and it also fosters key skills: thinking independently, asking questions, devising solutions, and conducting rigorous, open testing of ideas. Best of all, it unlocks the joy of solving challenging intellectual problems.

Perimeter Outreach aims to kindle sparks of discovery with thoughtfully designed programs for students at various levels. For junior high school grades, inspirational materials and presentations are designed to get students excited about modern science, followed by more in-depth content and programs for high school students.

"I can safely say it was the best two weeks of my life.... Because of ISSYP, I'm now absolutely sure that I want to take up a career in physics."

– Anna O'Grady, ISSYP 2011

INTERNATIONAL SUMMER SCHOOL FOR YOUNG PHYSICISTS

This year's edition of the International Summer School for Young Physicists (ISSYP) brought 40 top high school students from around the world to Perimeter – 21 Canadians, plus 19 international students from 12 countries – for two intense weeks of physics and fun. Nearly 500 students have participated in ISSYP since its launch in 2003.

ISSYP provides a unique opportunity for exceptional students to "live science" for a few weeks at an age when they are weighing career directions. In addition to learning sessions, they meet with leading scientists, tour research labs, and forge lasting friendships amid a spirit of camaraderie that models the true nature of scientific research. ISSYP has helped launch many scientific careers.

In addition to ISSYP, three one-day *GoPhysics!* camps were held across the country, giving a snapshot of the ISSYP experience to approximately 25 students at a time.

TAKING THE SHOW ON THE ROAD: PHYSICA PHANTASTICA

Last year, over 1,000 students throughout Ontario and Canada got excited about physics through entertaining and accessible Physica Phantastica presentations. Physica Phantastica seeds scientific literacy and creativity among grades 7 to 12, illuminating connections between the scientific enquiry into the forces governing the universe and the discovery of new knowledge and technologies.

BANKING ON YOUNG SCIENTISTS

This year, the RBC Foundation pledged a generous gift over four years to support International Summer School for Young Physicists (ISSYP).

RBC's gift has enabled Perimeter to bring outstanding international students to ISSYP, and to hire a master teacher to refresh its curriculum and develop accompanying hands-on experiments. One of the most exciting is a lab unit demonstrating the photoelectric effect, through which electrons are ejected from a metal when it is exposed to light. Students can vary the colour of the light and measure the energy of the emitted electrons. Plotting out the results leads intuitively to the equations governing the photoelectric effect – letting students discover for themselves the cornerstone idea of quantum mechanics. This seminal experiment, and the equation for which Einstein won the Nobel Prize, are now within easy reach of high school students.

PARTNERING WITH TEACHERS

Many of the ideas of modern physics are difficult to understand, let alone teach to high school students. The annual EinsteinPlus National Teachers' Workshop (E^+), brings approximately 40 high school teachers from Canada and abroad to Perimeter for a one-week intensive workshop to learn effective ways to convey key concepts. Teachers are introduced to in-class resources and encouraged to give feedback on resources in development, helping to ensure they are useful and engaging in the classroom.

E^+ alumni form the core of Perimeter's Teacher Network, a peer-to-peer training program that includes over 80 teachers throughout Ontario and across the country who are trained on sharing Perimeter's resources with fellow educators in their home districts. The Network greatly extends the reach of our Outreach program: in 2010-11, Network teachers delivered 60 workshops to 1,300 educators, who in turn reached over 58,000 Canadian high school students.

"The information and resources from Perimeter are outstanding.... It is essential that teachers and students continue to receive the latest research information and this is the best source I have come across."

– Chris Copley, teacher, Nepean, Ontario

BY THE NUMBERS

In 2010-11, Perimeter Outreach ...

- *Held EinsteinPlus teacher training camp for 39 teachers*
- *Delivered 60 peer-to-peer workshops to 1,300 educators across Canada through the Perimeter Teacher Network*

Teachers at EinsteinPlus 2011

Perimeter held its first Perimeter Teacher Network conference in October 2010. In *The Power of Ideas* contest, teachers told us about the creative ways they integrate Perimeter's resources in their classrooms and winning entries were shared with the rest of the Perimeter Teacher Network. Outreach staff also presented 15 on-location workshops at teacher conferences to over 1,250 educators across Canada.

INSPIRATIONS AND EXPLORATIONS

Without theoretical physics, there would be no computers, Internet, DVDs, cellphones, video games, or texting. By making connections like these between everyday life and physics, *Inspirations* content aims to intrigue and motivate junior high school students to continue with math and science in senior grades.

Perimeter's classroom resources have been used by over 500,000 students across Canada to date

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In 2010-11, Perimeter produced two new *Inspirations* modules, combining online and in-class components tied to *Alice and Bob in Wonderland*, a popular series of 60-second animations which entertain while introducing deep ideas about the universe.

Explorations modules, aimed at senior high school students, delve deeper into more challenging ideas and technical content, providing excellent preparation for post-secondary education in math, science, and engineering. Three *Explorations* modules have been produced to date: *The Mystery of Dark Matter, The Challenge of Quantum Reality,* and the popular *Planck's Constant* LED activity. A new module on particle physics will be released in early 2012.

Teacher feedback indicates Perimeter resources are used and re-used in the classroom. Activities from The Challenge of Quantum Reality *and* Measuring Planck's Constant *have been integrated into Ontario's official grade 12 physics textbook.*

CUT FROM THE SAME FABRIC

When high school teacher Laura Pankratz attended the 2010 EinsteinPlus Teachers' Workshop, she was already familiar with one of Perimeter's hands-on resources – a stretchy piece of fabric used to illustrate gravitational warping of spacetime as described in the special theory of relativity.

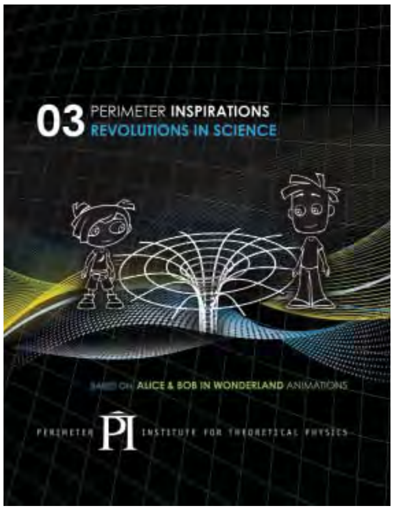
One of the other participants had a fresh idea, though – rather than create a depression in the fabric to simulate gravitational attraction, why not create a peak to demonstrate a repulsive force such as that caused by an electrostatic charge? It was a simple but original idea that expanded the fabric's pedagogical potential.

The idea stayed with Pankratz, who is a science curriculum assessor for the Government of Alberta. Months later, at the Alberta Teachers' Association Science Council Conference, Pankratz used the fabric to illustrate how it could be used more broadly to teach students about fields and atomic models.

The fabric – and its expanded use – has now found its way into the hands of students in Alberta classrooms, just one example of how Perimeter's impact extends far beyond its original activities.

ONLINE RESOURCES

For online explorers, Perimeter's Outreach website is a treasure trove. *Alice and Bob in Wonderland*, a series of short animations, shows how deceptively simple questions lead to deep science, emphasizing the importance of curiosity and critical thinking for younger viewers. Interactive and immersive features like *The Power of Ideas* explore some of the universe's deepest mysteries as fun and compelling stories. In 2010-11, in addition to enhancing online materials, Outreach expanded its use of social media and held several webinars in order to engage as many people in as many ways as possible.



The production of the new Inspirations *module,* Revolutions in Science*, was supported by The Cowan Foundation.*

Over 160 public lectures, 3 Inspirations *and 3* Explorations *modules, 37* Virtual ISSYP *sessions, and 32* Meet a Scientist *interviews are all available online at pitp.ca/outreach.*

SCIENCE FOR ALL: COMMUNICATING WITH THE GENERAL PUBLIC

The search for life on other planets. The latest dispatches from the quantum world. The impact of revolutions in space, nuclear, genetic, and computing technology. These were just a few of the subjects covered in eight fascinating and accessible talks in Perimeter's flagship Public Lecture Series, presented by Sun Life Financial, in 2010-11. Featuring luminaries like Sir Roger Penrose, Frank Wilczek, and Freeman Dyson, the lectures consistently draw capacity crowds of over 600.

Public Lectures and other content, such as the Institute's full-length documentary on quantum science, *The Quantum Tamers: Revealing Our Weird & Wired Future*, are broadcast on public television through a strategic partnership with TVO. Lectures are also available for download on Perimeter's and TVO's websites, and through iTunes University. In fact, TVO's most-downloaded science podcast last year was "Quantum Life," a lecture given by MIT scientist Seth Lloyd on the fascinating ways that nature appears to harness quantum phenomena in living systems.

THE WATERLOO GLOBAL SCIENCE INITIATIVE

The Waterloo Global Science Initiative (WGSI) is an independently funded, non-profit partnership between Perimeter Institute and the University of Waterloo. Founded in 2009, WGSI's mandate is to present a biennial event illuminating scientific and technological solutions to key challenges.

In June 2011, Perimeter hosted the Equinox Summit: Energy 2030, which brought together scientists, next-generation leaders, policy experts, and entrepreneurs to discuss potential solutions for electricity production, storage, and distribution. At its conclusion, participants assembled a shortlist of potentially transformative technologies and a roadmap to a lower-carbon, more electrified future. These will be expanded into the *Equinox Blueprint*, and presented to international science and technology leaders in industry and government.

AN INTERNATIONAL RESOURCE

In additional to making most of the Institute's resources freely available online, Outreach staff frequently present workshops at international gatherings. Last year, these included a "mini-EinsteinPlus" workshop at CERN in Switzerland for 40 European teachers from 30 countries, and presentations to the Physics Teaching Resource Agents' (PTRA) annual Summer National Leadership meeting in Omaha, Nebraska.

High-quality journalism is also vital to increasing scientific literacy, so Perimeter provides information and professional development opportunities to Canadian and international media. The Institute is also a sponsor of the Science Communication Program at the Banff Centre, a Charter Member of the Science Media Centre of Canada, and maintains close ties with the Canadian Science Writers Association and the World Federation of Science Journalists.

MUSIC OF THE SPHERES

"I've never met a physicist who didn't love music, or some other kind of art. Music nourishes my scientific work – creativity is creativity, after all."

– Raymond Laflamme, Associate Faculty member and Director, Institute for Quantum Computing, University of Waterloo

Cultural events complement the Institute's research and outreach activities, and provide a way to connect with the community at large. Generously supported by the Kitchener and Waterloo Community Foundation – Musagetes Fund, Event Horizons programming presents innovative works by renowned artists designed to stimulate and enthrall.

Pianist Yuja Wang's performance was one of the highlights of the 2010-11 Perimeter Classical World Artists series.

CITIZEN SCIENCE

Every year, Perimeter brings an all-star line-up of scientists and thinkers to a local 600-seat auditorium to give free public lectures. And every year, every one of those lectures sells out, usually in minutes. (Freeman Dyson's talk this year sold out in 90 seconds.) In the audience, high school students rub shoulders with doctors and lawyers, Perimeter staff and researchers, homemakers and seniors.

"There's huge excitement about science out there. All kinds of people are passionate and curious, and hungry for new ways to learn about cutting-edge science," says Renée Ellis, Perimeter's public events producer.

When programming the Public Lecture Series, Ellis looks for excellent science communicators able to convey fascinating ideas. "The audience wants to be stretched," she advises speakers. "Stretch them out, bring them back, and stretch them out again. Science is exciting. Get excited."

The Perimeter Public Lecture series is presented through the generous support of Sun Life Financial.

Esra Khaleel, an AIMS graduate, is currently finishing a graduate degree in nuclear physics at Stellenbosch University in South Africa.

GLOBAL OUTREACH

While the influence of science in seeding new technologies is evident, it shapes the world in other ways. It is a powerful unifying force for humanity, cutting across cultures, languages, and religious differences in ways which few other human activities can.

Perimeter's Global Outreach initiative seeks to promote scientific talent and the emergence of centres of scientific excellence in the developing world. By sharing knowledge and expertise, and cultivating collaborative relationships, the Institute is working to build research capacity around the world and also to strengthen Canadian research by drawing talented researchers here.

The first focus is on Africa: Perimeter is proud to partner with the African Institute for Mathematical Sciences (AIMS). Founded in 2003 by Perimeter Institute Director Neil Turok, AIMS is a globally recognized centre of excellence for graduate education and research based in Cape Town, South Africa. AIMS' mission is to rapidly and cost-effectively expand Africa's scientific and technological capacity by providing advanced training to exceptional graduates. Outstanding lecturers from around the world train students to become independent thinkers with the advanced skills needed in many sectors.

"Just think what will happen if Africa does for science what it has done for music, for literature, and for art. Not only Africa, but the world could be transformed."

– Neil Turok, Perimeter Institute Director and AIMS Founder

Since 2003, AIMS has graduated over 360 students – more than a third of them women – who are already making a substantial difference to the development of science across the continent. With plans for 15 centres across Africa by 2021, the AIMS-Next Einstein Initiative (AIMS-NEI) is developing a new generation of outstanding African problem-solvers who will become leaders across a range of key sectors, including medicine, energy, business, and technology.

Perimeter Scholars International graduate Bruno Le Floch (standing) teaching at AIMS-South Africa

Last year, Perimeter offered assistance in planning and launching the new AIMS-Sénégal centre and helped to attract major support from private and public institutions in Canada and abroad. The governments of Sénégal and Ghana have each provided more than $1 million dollars in support, plus land donations for new centres in their respective countries. Perimeter also helped secure $2 million from Google and over $1 million from Canadian universities and the private sector for student scholarships through the "One for Many" campaign.

In 2010, AIMS-NEI and Director Neil Turok were honoured with the 2010 World Innovation Summit for Education (WISE) Award, which recognizes initiatives that have transformative educational impact.

Professor Vincent Rivasseau, President of the AIMS-Sénégal Foundation, University of Ottawa President Allan Rock, and Perimeter Director Neil Turok sign "One for Many" agreement which will provide scholarships for AIMS students.

FORGING THE FUTURE

AIMS has transformed the lives of hundreds of scholars – not only the Africans who have graduated from the program, but also the international scientists who have taught and mentored there. Here are just two stories of the last year:

Esra Khaleel, who grew up in Darfur, a Sudanese city dominated by war and poverty, spent a year at the AIMS centre in South Africa and is now completing a PhD in nuclear physics.

Bruno Le Floch, a graduate of Perimeter's PSI program, decided to spend a year in South Africa tutoring AIMS students before starting his PhD. Many of the students he met have difficult pasts but bright futures. Their stories have become part of his education – something he couldn't have experienced anywhere else.


Photo credit: Shail Gil

FACILITY

Perimeter Institute is located in the heart of Waterloo, Ontario, Canada. Approximately an hour from Toronto, Waterloo and its surrounding region are home to two universities and over 400 high tech companies. The Institute overlooks Silver Lake in Waterloo Park and is a ten-minute walk from its experimental partner institute, the Institute for Quantum Computing at the University of Waterloo, as well as Wilfrid Laurier University.

The facility includes both private and collaborative research spaces, and also features a two-storey library and a 200-seat theatre. Presentation spaces have recently upgraded multimedia technologies, allowing scientific talks to be shared online with the international research community via the Perimeter Institute Recorded Seminar Archive (www.pirsa.org).

BY THE NUMBERS

The Stephen Hawking Centre (SHC) *has nearly doubled Perimeter's physical space. Here's a breakdown, by the numbers:*

Researchers the SHC can accommodate: *up to 150*

Floor space added: *55,000 ft²*

New seminar and meeting rooms: *6*

Chalkboards: *A great many*

Right angles: *Very few*


Photo credit: Scott Norsworthy

THE STEPHEN HAWKING CENTRE

The spectacular, just-completed Stephen Hawking Centre (SHC) is the only physics research centre in the world to which the great cosmologist has lent his name. Designed by Governor General Award-winning Teeple Architects, the SHC incorporates numerous elements to optimize research and encourage spontaneous exchanges at every level: abundant natural light, alcoves for discussion, windows that can be written upon as well as traditional chalkboards, and a welcoming bistro at the building's heart. At the same time, it provides contemplative spaces needed for intense solitary concentration.

*Photo credit:
Scott Norsworthy*

"It is inspiring to see that this building is so beautiful and that it welcomes the public in the way that it does."

– Frank Wilczek, 2004 Nobel Prize winner

The SHC has nearly doubled Perimeter's physical size, as well as its research and training capacity, making it the largest centre for theoretical physics research in the world.

The expansion project included major upgrades to the Institute's library, online resources, and technology infrastructure. Perimeter has launched a major research-technology infrastructure program, led by Erik Schnetter, a physicist and expert in the development of scientific computing platforms. Through customized computational tools, access to high performance computing, telepresence technology for long-distance collaboration, and high quality video capture and archiving of all scientific events, the Institute aims to be a leader in the use of information technology to support research.

Ontario's Ministry of Research and Innovation and the Government of Canada via the Canada Foundation for Innovation provided a total of $20.8 million toward the expansion, supplemented by private funds raised by the Institute.

A REFLECTIVE VIEW

For us, this was a project of a lifetime: to envision a physical space and building form that could simultaneously reflect, enhance, and inspire some of the most amazing, cutting-edge research and scientific collaboration in the world.

We designed the Stephen Hawking Centre at Perimeter Institute to be as innovative and as bold as the research. We like to think we succeeded in providing a felt architectural space that reflects the immense complexity of the scientific research artfully and beautifully.

It is a thrill to experience the completed centre – it feels as if the passion and science of the researchers is expressed in the form and light, the space and the openness of the mass and structure. This facility will always be a source of great pride, inspiration, and accomplishment for our office.

– Stephen Teeple and Bernard Jin,
Teeple Architects

Photo credit: NASA, ESA, HEIC and The Hubble Heritage Team (STScI/AURA)

ADVANCING PERIMETER'S MISSION

Perimeter Institute's overarching goal is to achieve scientific breakthroughs that will transform our future.

This bold venture was initially seeded by major gifts from visionary philanthropists and generous public support from local, regional, provincial, and federal governments. Since then, donations from many individuals, corporations, and foundations – as well as continuing support from all levels of government – have helped Perimeter grow to become one of the world's leading centres for theoretical physics, a remarkable accomplishment for an institution that is only a decade old.

It was 1999 and Mike Lazaridis was considering ways in which a single philanthropic investment might change the world.

For him, the target for that investment was clear: it had to be theoretical physics. The capital costs are modest, because the human mind is both the most powerful piece of scientific equipment we possess and the least expensive to operate.

Moreover, what other field has the history of transforming the world as physics has? What other field has the near certainty of doing it again?

Lazaridis' vision quickly attracted public and philanthropic support, and Perimeter grew rapidly.

Perimeter has set even more ambitious goals for the future. To reach them, advancement efforts are seeking to broaden the Institute's base of private support among individuals, corporations, and foundations.

With this expanded support, Perimeter will:

- Build a critical mass of scientific talent, capable of fostering fundamental breakthroughs in our understanding
- Attract and train the world's brightest young research talents
- Build its innovative educational outreach programs, informing and inspiring students, teachers, and the general public with the power and importance of scientific ideas

PERIMETER INSTITUTE LEADERSHIP COUNCIL

The Perimeter Institute Leadership Council is a group of prominent individuals who volunteer their time, offer their guidance, and act as ambassadors to the business and philanthropic communities on Perimeter's behalf. Led by Board Chair Mike Lazaridis and Vice-Chair Cosimo Fiorenza, the Leadership Council was established in early 2010. In the 2010-11 fiscal year, the Council opened some exciting doors for Perimeter.

We are honoured to have this exceptional group of volunteers on board, and we would like to thank the Leadership Council for their support and hard work.

PERIMETER INSTITUTE LEADERSHIP COUNCIL

Mike Lazaridis, O.C., O.Ont.
Council Co-Chair
Founder and Chair, Board of Directors, Perimeter Institute
Board Vice-Chair and Chair, Innovation Committee, Research in Motion Ltd.

Cosimo Fiorenza
Council Co-Chair
Vice-Chair, Board of Directors, Perimeter Institute
Vice-President and General Counsel, Infinite Potential Group

Alexandra (Alex) Brown
President, Aprilage Inc.

David Caputo
Co-Founder, President and CEO, Sandvine

Savvas Chamberlain, C.M.
CEO and Chairman, Exel Research Inc.

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Catherine A. (Kiki) Delaney, C.M.
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Farsad Kiani
President and CEO, The Ensil Group of Companies

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Co-Founder and CEO, Linacare Cosmetherapy Inc.

Michael Lee-Chin, O.J.
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Gerry Remers
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Maureen J. Sabia, O.C.
Chairman of the Board, Canadian Tire Corporation Ltd.

Kevin Shea
Chair, Ontario Media Development Corporation

LEADERSHIP COUNCIL MEMBER SAVVAS CHAMBERLAIN

Savvas Chamberlain is a scientist and inventor who turned his deep expertise in CCD image sensors (the kind of sensors inside high-end digital cameras) into a company called DALSA. Today, DALSA is part of Teledyne, and is a global leader in high performance imaging and semiconductors. DALSA's image sensors are used around the world, from postal sorting halls to hospital X-ray suites – they're even inside NASA's Mars Rovers.

It wouldn't have happened without physics: CCDs, a type of semiconductor, were invented by theoretical physicists Willard Boyle (a Canadian) and George Smith from Bell Labs, who were awarded the 2009 Nobel Prize for their work. The connection is even deeper, as CCDs rely on the photoelectric effect, described by Albert Einstein in 1905.

"The work I've done in my career has been at the cutting edge of technology – and I am aware that not so long ago the science behind it was just math and sketches on a chalkboard," says Chamberlain. "I am eager to see what today's chalkboards will look like when they too come to life."

Savvas Chamberlain and his wife, Christine, are among Perimeter's donors, and Savvas is a new member of the Perimeter Leadership Council.

The video display wall (featuring Christie® MicroTiles®) which graces the entrance of the new Stephen Hawking Centre was provided by Christie Digital Systems Canada Inc.
Photo credit: Scott Norsworthy

THANKS TO OUR SUPPORTERS

Perimeter Institute's public-private partnership unites government, individuals, corporations, and foundations in a shared venture to enable scientific breakthroughs, nurture scientific talent, and share scientific discovery with the broader public.

We are deeply grateful to all of our supporters.

FOUNDING DONORS

Mike Lazaridis
Jim Balsillie
Doug Fregin

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The above reflects gifts pledged August 1, 2010-December 31, 2011.

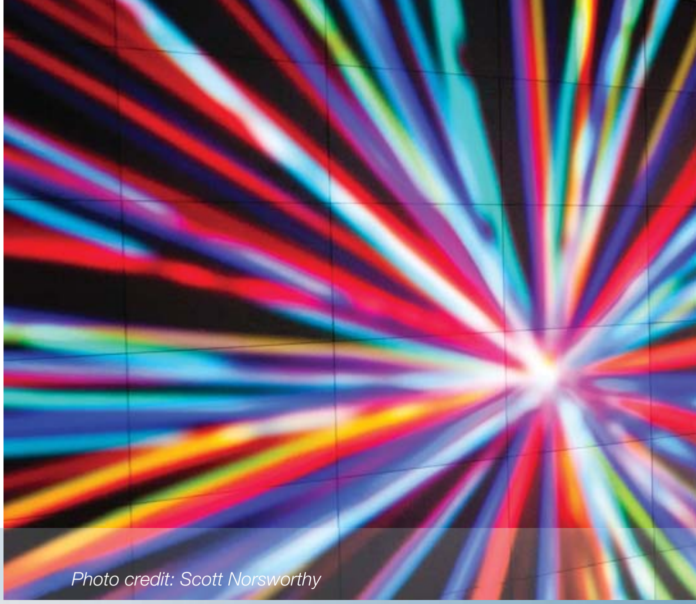


Photo credit: Scott Norsworthy

THE BMO FINANCIAL GROUP ISAAC NEWTON CHAIR IN THEORETICAL PHYSICS

In seeking to become the world's leading centre in the field, Perimeter is growing strategically. The keystone of its scientific growth – supporting it from above – will be the establishment of five Chairs, to be named for scientists whose insights defined modern physics: Isaac Newton, James Clerk Maxwell, Albert Einstein, Niels Bohr, and Paul Dirac.

Each Chair will be filled by a world-leading scientist in the appropriate field. They will attract others: senior and junior faculty, postdocs and students, anchoring exceptional research teams.

This year, Perimeter established and filled the first Chair: The BMO Financial Group Isaac Newton Chair in Theoretical Physics at Perimeter Institute. BMO's $4 million investment was the largest single donation it has made to support science and technology in Canada, and the largest corporate donation Perimeter has received to date.

Xiao-Gang Wen, one of the world's top condensed matter theorists, has been recruited from MIT as the first Chairholder. He is expected to arrive at Perimeter in the coming year.

GOVERNANCE

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

Financial planning, accountability, and investment strategy are carried out by the Board's Investment and Finance & Audit Committees. The Board also forms other committees as required to assist it in discharging its duties. Reporting to the Board of Directors, the Institute's Director is a pre-eminent scientist responsible for developing and implementing the overall strategic direction of the Institute. The Chief Operating Officer (COO) reports to the Director and is in charge of day-to-day operations. Support for the COO is provided by a team of administrative staff.

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

The Scientific Advisory Committee (SAC), composed of eminent scientists drawn from the international community, is an integral oversight body, created to assist the Board of Directors and the Director to ensure objectivity and a high standard of scientific excellence.

BOARD OF DIRECTORS

Mike Lazaridis, O.C., O.Ont., Chair, is Founder, Board Vice-Chair and Chair, Innovation Committee of Research In Motion Limited (RIM). A visionary, innovator, and engineer of extraordinary talent, he was instrumental in launching the smartphone revolution with the BlackBerry®. He is the recipient of many technology and business awards, and the Order of Canada.

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

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 his senior roles within the CSA, Dr. MacLean has extensive experience with NASA and the International Space Station. He is also 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.

SCIENTIFIC ADVISORY COMMITTEE

Michael Peskin, Chair, SLAC National Accelerator Laboratory (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 to 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 Department 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.

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 many contributions included 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. Professor Preskill is a past Sloan Research 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 the 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.

FINANCIALS

MANAGEMENT DISCUSSION AND ANALYSIS OF FINANCIAL RESULTS

RESULTS OF OPERATIONS

The 2011 fiscal year saw Perimeter Institute continue to make good progress on all initiatives in its Five Year Plan, with investment in its core mission areas of research, training, and outreach continuing to be the largest area of expenditure at 76%.

Scientific research costs (52%) incurred during the year supported the growing complement of research staff and related activities, while research training costs (9%) reflect a growing body of students enrolled in the Perimeter Scholars International and PhD programs. Outreach activities (14%) included the delivery of educational programs and development of pedagogical material. In alignment with the Five Year Plan, certain outreach initiatives (such as the production of a festival) are executed on a biennial basis, which is portrayed in the reduced costs of the current year compared to the past year.

Indirect research and operations expenses continued to be closely monitored and kept at 24% of the total operating expenditures of the Institute, covering the costs of core support areas including administration, information technology, and facilities. Costs pertaining to the Institute's advancement activities (which yielded over $4.9 million in donations and pledges over the course of the year) were also included in this category. In accordance with Perimeter's revenue recognition policy, only donations received are included as revenue in the financial statements.

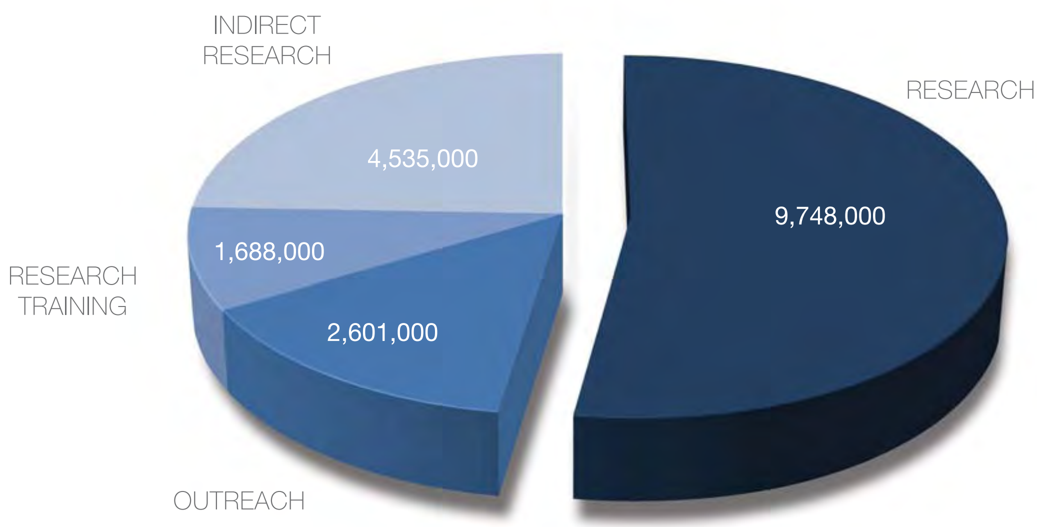
Continued public support was demonstrated in the 2011 fiscal year through funding by the Governments of Canada and Ontario of both operational activities as well as construction and infrastructure costs of the Stephen Hawking Centre at Perimeter Institute.

Renewed ongoing funding commitments were secured in 2011 with announcements of commitments by both the federal and provincial governments for a combined multi-year investment of $100 million, reinforcing the strong public-private partnership dedicated to supporting Perimeter's scientific research, training, and outreach.

Perimeter's investment strategy, strong oversight, and portfolio management allowed its endowment fund to continue its upward momentum, gaining well over 9% or $20.9 million in 2011.

OPERATING EXPENDITURE SUMMARY

For the year ended July 31, 2011



BALANCE SHEET

The balance sheet reflects an exceptionally strong working capital position. This position allows Perimeter to act quickly on targets of opportunity, giving the Institute a considerable competitive advantage in accelerating its research and outreach goals.

The progress made during the year leading to the final stages of the facility expansion project was clearly demonstrated with a $17.3 million increase over prior year to Property and Equipment.

Although bank indebtedness was incurred during the last quarter of the fiscal year, this credit was strategically used as a temporary measure, while consciously targeting optimization of working capital.

The endowment fund primarily allows for the accumulation of private funds to address the future needs of Perimeter Institute. The $220 million fund consists of a portfolio mix of domestic equities, international equities, fixed income, and alternative investments specifically designed in accordance with the Institute's risk return objectives.

RISKS AND UNCERTAINTIES

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

New funding commitments of $50 million from the Government of Canada ending March 31, 2017 and $50 million from the Government of Ontario ending July 31, 2021 reinforce Perimeter's strong collaboration with public partners and the value they see in investing in the Institute.

While the most recent multi-year government commitments totalling $100 million demonstrate that the Institute is perceived by government as an excellent investment, no guarantees of future funding beyond the above commitments exist.

Perimeter Institute is also seeking to expand its sources of funds from the private sector through an ambitious advancement initiative designed to raise yearly operating funds for the Institute, as well as double long-term endowment assets over the coming years.

Private sector donations are either utilized as contributions towards operational expenditures or are protected in an endowment fund, in accordance with donor requests. The endowment fund is designed to maximize growth and minimize risk in order to contribute to the strongest possible long-term financial health of the Institute. Although the endowment is invested in a diversified portfolio and managed by an active investment committee of experts, market values do vary over time.

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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 the 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 the 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

Zeifmans LLP is a member of Nexia International, a worldwide network of independent accounting and consulting firms.

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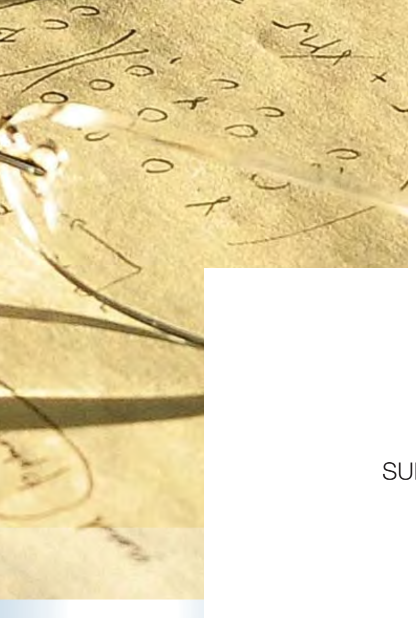

PERIMETER INSTITUTE

(Incorporated Under the Laws of Canada Without Share Capital)

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	$ 577,000	$ ---
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 balance		
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

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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

LOOKING AHEAD: PRIORITIES AND OBJECTIVES FOR THE FUTURE

In the coming year, the Institute will continue to advance its core mission and goals, based upon the following strategic objectives:

Deliver world-class research discoveries by continuing to focus on advancing fundamental research across Perimeter's eight identified areas, encouraging complementary and multidisciplinary approaches, and instilling a collaborative atmosphere which maximizes cross-fertilization of ideas and increases the probability of breakthroughs.

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

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

Generate a flow-through of the most promising talent by recruiting top-calibre postdoctoral researchers, facilitating researcher engagements with experimental and observational centres, attracting and training brilliant young graduate students through the PSI program and recruiting the best for further PhD training, and providing research training opportunities to promising undergraduate students.

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

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

Increase Perimeter's role as Canada's focal point for foundational physics research by continuing to develop national and international relationships, maximizing technologies allowing remote participation, and fostering research interaction opportunities between Faculty members and Affiliates across the country.

Host timely, focused conferences, workshops, seminars, and courses focusing on cutting-edge topics, as well as an active seminar program.

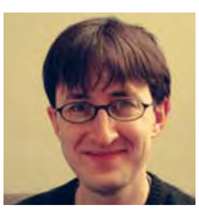
Engage in high impact outreach by communicating the importance of basic research and the power of theoretical physics to general audiences, providing unique opportunities and high quality resources to educators and students.

Continue to build on Perimeter's highly successful public-private partnership funding model.

APPENDICES

FACULTY

Neil Turok (PhD Imperial College London, 1983) joined the Institute as its Director in 2008. After a postdoc in Santa Barbara and an Associate Scientist position at Fermilab, he moved to Princeton where he was Professor of Physics. In 1997, he assumed the Chair of Mathematical Physics at the University of Cambridge. In addition to Sloan and Packard Fellowships, he won the 1992 James Clerk Maxwell medal. In 2008, he was named a Canadian Institute for Advanced Research (CIFAR) Fellow in Cosmology and Gravity. Turok's work focuses on developing fundamental theories of cosmology and new observational tests. His predictions for the correlations of the polarization and temperature of the cosmic background radiation, and of the galaxy-cosmic background correlations induced by dark energy have been confirmed. With Stephen Hawking, he discovered instanton solutions describing the birth of inflationary universes. His work on Open Inflation forms the basis of the now-popular "multiverse" paradigm. With Paul Steinhardt, he developed 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, Turok founded the African Institute for Mathematical Sciences (AIMS) in Cape Town, South Africa. In 2008, he was awarded the TED Prize and a "Most Innovative People" award at the World Summit on Innovation and Entrepreneurship (WSIE). Among his many honours, he holds the Medaille de l'Ordre National du Lion, Sénégal's highest recognition, awarded for his role in creating the new AIMS-Sénégal centre.



Latham Boyle (PhD Princeton, 2006) joined the Institute as a junior Faculty member in 2010. From 2006 to 2009, he held a Canadian Institute for Theoretical Astrophysics (CITA) Postdoctoral Fellowship; he is also a Junior Fellow of the Canadian Institute for Advanced Research (CIFAR). Boyle has studied what gravitational wave measurements can reveal about the universe's beginning; with Paul Steinhardt, he derived "inflationary bootstrap relations" that – if confirmed observationally – would provide compelling support for the theory of primordial inflation. He co-developed a simple algebraic technique for understanding black hole mergers and recently constructed the theory of "porcupines": networks of low-frequency gravitational wave detectors that function together as gravitational wave telescopes.

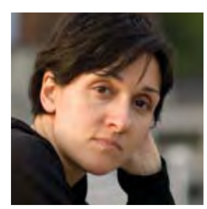
Freddy Cachazo (PhD Harvard, 2002) has been a Faculty member at Perimeter since 2005. From 2002 to 2005, he was a Member of the School of Natural Sciences at the Institute for Advanced Study in Princeton. Cachazo is one of the world's leading experts in the study and computation of scattering amplitudes in quantum chromodynamics (QCD) and N=4 super Yang-Mills (MSYM) theories. In 2007, he was awarded an Early Researcher Award and, in 2009, he was awarded the Gribov Medal of the European Physical Society.

Laurent Freidel (PhD L'École Normale Supérieure de Lyon, 1994) joined Perimeter Institute in September 2006. Freidel is a mathematical physicist who has made many notable contributions in the field of quantum gravity; he possesses outstanding knowledge of a wide range of areas including integrable systems, topological field theories, 2d conformal field theory and quantum chromodynamics. Freidel has held positions at Pennsylvania State University and L'École Normale and has been a member of France's Centre National de la Recherche Scientifique (CNRS) since 1995. Freidel is also the recipient of several awards including two ACI-Blanche grants in France.

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

Daniel Gottesman (PhD Caltech, 1997) joined Perimeter's faculty in 2002. From 1997 to 2002, he 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). 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 (PhD Durham University, 1992) joined Perimeter as a Faculty member in 2002, having previously held research and lecturing positions at various European universities including the University of Oxford, La Sapienza University, the University of Durham, the University of Innsbruck, and the National University of Ireland. In 1992, he found a very simple proof of non-locality in quantum theory which has become known as Hardy's theorem. He currently works on characterizing quantum theory in terms of operational postulates and applying the insights obtained to the problem of quantum gravity.



Fotini Markopoulou (PhD Imperial College London, 1998) joined the Institute 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 Pennsylvania State University (1997-1999). 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 currently holds an Alexander von Humboldt Fellowship for Experienced Researchers at the Albert Einstein Institute in Germany.

Robert Myers (PhD Princeton, 1986) is one of the leading theoretical physicists working in string theory in Canada. After attaining his PhD, he was a postdoctoral researcher at the (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 2001. Among Myers' many honours, he received the Herzberg Medal in 1999 for seminal contributions to our understanding of black hole microphysics and D-branes, won the 2005 CAP-CRM Prize, and is a Fellow of the Cosmology and Gravity program of the Canadian Institute for Advanced Research (CIFAR).

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

Lee Smolin (PhD Harvard, 1979) is one of Perimeter Institute's founding Faculty members. Prior to joining Perimeter, Smolin held postdoctoral positions at the Institute for Advanced Study, the Institute for Theoretical Physics (Santa Barbara), and the Enrico Fermi Institute at the University of Chicago, and was a professor at Yale, Syracuse, and Pennsylvania State Universities. Smolin's research is centred on the problem of quantum gravity, with particular focus on loop quantum gravity and deformed special relativity, though his contributions span many areas. Smolin's many honours include the Majorana Prize, the Klopsteg Memorial Award, and election as a Fellow of both the American Physical Society and the Royal Society of Canada.

Robert Spekkens (PhD University of Toronto, 2001) joined Perimeter's faculty in 2008, after holding a postdoctoral fellowship at Perimeter and an International Royal Society Fellowship at the University of Cambridge. His research is focused upon identifying the conceptual innovations that distinguish quantum theories from classical theories and investigating their significance for axiomatization, interpretation, and the implementation of various information-theoretic tasks. He is a previous winner of the Birkhoff-von Neumann Prize of the International Quantum Structures Association.

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

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

Pedro Vieira (PhD École Normale Supérieure Paris and the Centro de Fisica do Porto, Universidade do Porto, 2008) joined Perimeter in 2009 from the Max Planck Institute for Gravitational Physics (Albert Einstein Institute), where he was a Junior Scientist from 2008 to 2009. Vieira's research concerns the development of new mathematical techniques for gauge and string theories, ultimately aiming at the solution of a realistic four-dimensional gauge theory. His research interests also include the related areas of the AdS/CFT correspondence and theoretical calculations of scattering amplitudes.

ASSOCIATE FACULTY

Niayesh Afshordi (PhD Princeton, 2004) is jointly appointed with the University of Waterloo. He was the Institute for Theory and Computation Fellow at the Harvard-Smithsonian Center for Astrophysics from 2004 to 2007, and a Distinguished Research Fellow at Perimeter Institute from 2008 to 2009. Professor Afshordi joined Perimeter as an Associate Faculty member in 2010. He specializes in interdisciplinary problems in fundamental physics, astrophysics, and cosmology. In 2010, he was awarded a Discovery Accelerator Supplement from the Natural Sciences and Engineering Research Council of Canada (NSERC).

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

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

Richard Cleve (PhD University of Toronto, 1989) joined Perimeter's faculty in 2004, jointly appointed with the Institute for Quantum Computing (IQC), where he holds the IQC Endowed Chair in Quantum Computing. Prior to coming to Waterloo, he was a postdoctoral fellow at Berkeley's International Computer Science Institute and then a Faculty member in the Department of Computer Science at the University of Calgary. 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, winner of the CAP-CRM Prize in Theoretical and Mathematical Physics, and an elected Fellow of the Royal Society of Canada.

David Cory (PhD Case Western Reserve University, 1987) is jointly appointed with the Institute for Quantum Computing and the Department of Chemistry at the University of Waterloo. He held research positions at the University of Nijmegen in The Netherlands, the National Research Council at the Naval Research Laboratory in Washington, D.C., and MIT. He also led research and development activities in nuclear magnetic resonance at Bruker Instruments. Since 1996, Cory has been exploring the experimental challenges of building small quantum processors based on nuclear spins, electron spins, neutrons, persistent current superconducting devices and optics. In 2010, he was named the Canada Excellence Research Chair in Quantum Information Processing. Cory chairs the advisory committee for CIFAR's Quantum Information Processing program.

Adrian Kent (PhD Cambridge, 1996) is jointly appointed with the University of Cambridge. Prior to joining Perimeter's faculty, he was an Enrico Fermi postdoctoral fellow at the University of Chicago, a member of the Institute for Advanced Study, and a Royal Society University Research Fellow at the University of Cambridge. Kent's research focuses on the foundations of physics, quantum cryptography, and quantum information theory, including the physics of decoherence, novel tests of quantum theory and alternative theories, and new applications of quantum information.

Raymond Laflamme (PhD Cambridge, 1988) is a founding Faculty member of Perimeter Institute and founding Director of the Institute for Quantum Computing, where he is jointly appointed. He held research positions at UBC and Peterhouse College, University of Cambridge before moving to Los Alamos Research Laboratory in 1992, where his interests shifted from cosmology to quantum computing. Since the mid-1990s, Laflamme has elucidated theoretical approaches to quantum error correction. Laflamme is the Director of QuantumWorks, Canada's national research consortium on quantum information science, and has been Director of the Quantum Information Processing program at the Canadian Institute for Advanced Research (CIFAR) since 2003, and a CIFAR Fellow since 2001. He also holds the Canada Research Chair in Quantum Information.

Sung-Sik Lee (PhD Pohang University of Science and Technology, 2000) is jointly appointed with McMaster University. 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. 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 (PhD University of Pittsburgh, 1998) began a joint appointment with Perimeter and the University of Guelph in 2009. He held postdoctoral fellowships at the University of Texas at Austin and the University of British Columbia, and was a member of Louisiana State University's faculty from 2002 to 2009. Lehner's many honours include the Honor Prize from the National University of Cordoba, Argentina, a Mellon pre-doctoral fellowship, the CGS/UMI outstanding dissertation award, and the Nicholas Metropolis award. He has been a PIMS fellow, a CITA National Fellow, and a Sloan Research Fellow, and he is currently a fellow of 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 (DPhil University of Oxford, 1999) is jointly appointed with the University of Waterloo. He is a founding member of Perimeter Institute, and co-founder and Deputy Director of the Institute for Quantum Computing. Mosca has made major contributions to the theory and practice of quantum information processing, particularly in the areas of quantum algorithms, techniques for studying the limitations of quantum computers, quantum self-testing and private quantum channels. Mosca's numerous academic honours include Canada's Top 40 Under 40 (2010), the Commonwealth Scholarship, the Premier's Research Excellence Award, and a Canada Research Chair in Quantum Computation. He was named a Canadian Institute for Advanced Research (CIFAR) Fellow in 2010.

Ashwin Nayak (PhD University of California, Berkeley, 1999) is also appointed at the University of Waterloo and the Institute for Quantum Computing. He has held positions at DIMACS Center (Rutgers University), AT&T Labs-Research (California Institute of Technology), and the Mathematical Sciences Research Institute, Berkeley. Nayak was a recipient of an Early Researcher Award from Ontario's Ministry of Research and Innovation in 2006 and a Discovery Accelerator Supplement from the Natural Science and Engineering Research Council (NSERC) of Canada in 2008.

Maxim Pospelov (PhD Budker Institute of Nuclear Physics, Russia, 1994) is jointly appointed with the University of Victoria and became an Associate Faculty member at Perimeter in 2004. He previously held research positions at the University of Quebec at Montreal, University of Minnesota, McGill University, and University of Sussex, UK. 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 (PhD RWTH Aachen University, 1993) is jointly appointed with the Max Planck Institute for Gravitational Physics in Germany. 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.

Itay Yavin (PhD Harvard, 2006) is jointly appointed with McMaster University and joined Perimeter as an Associate Faculty member in particle physics in 2011. From 2006 to 2009, he was a Research Associate in the Department of Physics at Princeton University. Prior to coming Perimeter, he was a James Arthur Postdoctoral Fellow at the Department of Physics at New York University. Yavin's research focuses on particle physics and the search for physics beyond the Standard Model. In particular, he is interested in the origin of electroweak symmetry breaking and the nature of dark matter. Most recently, he has worked on interpreting puzzling data coming from experiments looking for dark matter in the lab.

POSTDOCTORAL RESEARCHERS, 2010-11

Marcus Appleby
Brian Batell
Joseph Ben Geloun
Hector Bombin
Valentin Bonzom
Marc Casals
Giulio Chiribella
Lukasz Cincio
Roger Colbeck
Sarah Croke
Eleonora Dell'Aquila
Adrienne Erickcek
Åsa Ericsson
Cecilia Flori
Travis Garrett
John Giblin Jr.
Simone Giombi
Razvan Gurau
Alioscia Hamma
Chad Hanna
Janet Hung
Zhengfeng Ji
Matthew Johnson
Tim Koslowski
Louis Leblond
Jean-Luc Lehners
Pier Gian Luca Porta Mana
Nicolas Menicucci
Markus Mueller
Akimasa Miyake
Leonardo Modesto
Alberto Montina
Joao Penedones
Robert Pfeifer
Josef Pradler
Natalia Saulina
Amit Sever
Sarah Shandera
Yanwen Shang
David Skinner
Misha Smolkin
Michael Trott
Tom Zlosnik

SCIENTIFIC VISITORS

** indicates Distinguished Research Chair*
*** indicates longer-term Visiting Researcher*

Please note that researchers who made multiple visits are listed only once.

Dmitry Abanin, Princeton University

Emil Akhmedov**, Institute for Theoretical and Experimental Physics

Andreas Albrecht**, University of Chicago

Emanuele Alesci, Institut für Theoretische Physik III, Erlangen

Yacine Ali-Haimoud, California Institute of Technology (Caltech)

Rouzbeh Allahverdi, University of New Mexico

Jan Ambjorn, Utrecht University

Giovanni Amelino-Camelia, Sapienza University of Rome

Luigi Amico, Università di Catania

Mustafa Amin, Massachusetts Institute of Technology (MIT)

Mohamed Anber, Canadian Institute for Theoretical Astrophysics (CITA)

Matthew Anderson, Louisiana State University

Dionysios Anninos, Harvard University

Philip Argyres, University of Cincinnati

Nima Arkani-Hamed*, Institute for Advanced Study (IAS)

Jonathan Arons, University of California, Berkeley

Michele Arzano, Institute for Theoretical Physics, Utrecht University

Sujay Ashok, The Institute of Mathematical Sciences, Chennai

Amjad Ashoorioon, Uppsala University

Joonwoo Bae, Korea Institute for Advanced Study (KIAS)

Neta Bahcall*, Princeton University

Yang Bai, SLAC National Accelerator Laboratory

Dave Baker, University of Michigan

Cosimo Bambi, Institute for the Physics and Mathematics of the Universe (IPMU)

Julian Barbour, independent

Neil Barnaby, University of Minnesota

Howard Barnum, Los Alamos National Laboratory

Jonathan Barrett, Royal Holloway, University of London

Itzhak Bars**, University of Southern California

Ganapathy Baskaran*, Institute of Mathematical Sciences

Benjamin Basso, Institute for Advanced Study (IAS)

Andreas Bauswein, Max Planck Institute for Astrophysics, Munich

Rob Beezer, University of Puget Sound

Viacheslav Belavkin, University of Nottingham

Ido Ben-Dayan, Ben-Gurion University of the Negev

Carl Bender, Washington University

Dionigi Benincasa, Imperial College London

Francesco Benini, Princeton University

Jacob Biamonte, University of Oxford

Eugenio Bianchi, Centre de Physique Théorique, Marseille

Robin Blume-Kohout, Los Alamos National Laboratory

Nate Bode, California Institute of Technology (Caltech)

Sergio Boixo, Harvard University

Steve Boughn, Haverford College

Jacob Bourjaily, Institute for Advanced Study (IAS)

Patrick Brady, University of Wisconsin-Milwaukee

Robert Brandenberger, McGill University

Sergey Bravyi, IBM T. J. Watson Research Center

Anne Broadbent, Institute for Quantum Computing/University of Waterloo

Avery Broderick, Canadian Institute for Theoretical Astrophysics (CITA)

Adam Brown, Princeton University

Brielin Brown, University of Virginia

Johannes Brunnemann, University of Hamburg

Michel Buck, Kings College London

Timothy Budd, Utrecht University

Oliver Buerschaper, Max Planck Institute of Quantum Optics, Garching

Mathew Bullimore, University of Oxford

Chris Byrnes, Universitat Bielefeld

Mariano Cadoni, University of Cagliari/INFN

Xian Camanho, University of Santiago de Compostela

Lorenzo Campos, Venuti ISI, Turin

Simon Caron Huot, Institute for Advanced Study (IAS)

Horacio Casini, Centro Atomico Bariloche

Pablo Cerda, Max Planck Institute for Astrophysics, Munich

Oscar Chacaltana, University of Texas at Austin

Zackaria Chacko, University of Maryland

Claudio Chamon, Boston University

Shih-Hung Chen, Arizona State University

Xie Chen, Massachusetts Institute of Technology (MIT)

Xingang Chen, University of Cambridge

Fang Chen, McGill University

Paul Chesler, Massachusetts Institute of Technology (MIT)

Hillary Child, Kenyon College

Neil Christensen, University of Wisconsin-Madison

Yi-Zen Chu, Arizona State University

Ignacio Cirac*, Max Planck Institute of Quantum Optics, Garching

James Cline**, McGill University

Bob Coecke, University of Oxford

Patrick Coles, Carnegie Mellon University

Samuel Colin, Griffith University

Fabio Costa, University of Vienna

Sera Cremonini, DAMTP, University of Cambridge

Giacomo D'Ariano, University of Pavia

Naresh Dadhich, Inter University Centre for Astronomy and Astrophysics

Alex Dahlen, Princeton University

Kari Dalnoki-Veress, McMaster University

Saurya Das, University of Lethbridge

Arundhati Dasgupta, University of Lethbridge

François David, CEA, Saclay

Anne Davis, University of Cambridge

Henrique de Andrade Gomes, University of Nottingham

Andre de Gouvea, Northwestern University

Francesco De Martini, Sapienza University of Rome

Claudia de Rham, University of Geneva

Nikolay Dedushenko, Bogolyubov Institute for Theoretical Physics, Kiev

Lidia del Rio, ETH Zurich

Jennings Deskins, Kenyon College

Jacobo Diaz-Polo, Pennsylvania State University

Keith Dienes, National Science Foundation

Bianca Dittrich, Max Planck Institute for Gravitational Physics

Fay Dowker, Imperial College London

James Drummond, Laboratoire d'Annecy-le-Vieux de Physique des Particules

Guillaume Duclos-Cianci, Université de Sherbrooke

Maite Dupuis, École Normale Supérieure de Lyon

Cora Dvorkin, University of Chicago

William Edwards, University of Oxford

Astrid Eichhorn, Institute for Theoretical Physics, University of Jena

Glen Evenbly, University of Queensland

Dmitri Feldman, Brown University

Laura Felline, Università di Cagliari

Yuan Feng, University of Technology, Sydney

Andrew Fitzpatrick, Boston University

Anthony Fradette, University of Victoria

Eduardo Fradkin, University of Illinois, Urbana-Champaign

Sebastian Franco, Kavli Institute for Theoretical Physics (KITP)

Marcel Franz, University of British Columbia

Liang Fu, Harvard University

Abhijit Gadde, State University of New York at Stony Brook

Davide Gaiotto, Institute for Advanced Study (IAS)

Chad Galley, California Institute of Technology (Caltech)

Jose Tomas Galvez Ghersi, Universidad Nacional de Ingenieria, Lima

Inaki Garay, Universität Erlangen, Institut für Theoretische Physik III, Erlangen

Silvano Garnerone, University of Southern California

Jerome Gauntlett, Imperial College London

Jack Gegenberg, University of New Brunswick

Ghazal Geshnizjani, State University of New York at Buffalo

Christian Gogolin, University of Potsdam

Gerald Goldin, Rutgers University

Cesar Gomez, Instituto de Física Teórica

Joaquim Gomis, Universidad de Barcelona

Gabriela Gonzalez, Louisiana State University

Megan Gralla, University of Chicago

Sam Gralla, University of Chicago

Ruth Gregory, Durham University

Benjamin Grinstein, University of California, San Diego

Nikolay Gromov, Kings College London

Yuval Grossman, Cornell University

Zheng-Cheng Gu, Kavli Institute for Theoretical Physics (KITP)

Amir Hajian, Canadian Institute of Theoretical Astrophysics (CITA)

Gabor Halasz, University of Cambridge

Andrew Hamilton, University of Colorado

Masanori Hanada, University of Washington, Seattle

Esther Hanggi, ETH Zurich

Juho Happola, Aalto University and University of Helsinki

John Harnad, Concordia University

James Hartle, University of California, Santa Barbara

Sean Hartnoll, Stanford University

Patrick Hayden*, McGill University

Simeon Hellerman, Institute for the Physics and Mathematics of the Universe (IPMU)

Frank Hellman, Albert Einstein Institute (AEI)

Johannes Henn, Humboldt University of Berlin

Christopher Herzog, Princeton University

Andrew Hodges, University of Oxford

Jason Hofgartner, University of Waterloo

Gil Holder, McGill University

Richard Holman, Carnegie Mellon University

Shaun Hooper, University of Western Australia

Sabine Hossenfelder, NORDITA (Nordic Institute for Theoretical Physics)

Taylor Hughes, University of Illinois, Urbana-Champaign

Viqar Husain, University of New Brunswick

Chantal Hutchison, University of Waterloo

Nabil Iqbal, Massachusetts Institute of Technology (MIT)

Mark Jackson, Leiden University

Karan Jani, Pennsylvania State University

Romuald Janik, Jagiellonian University

Thomas Janka, Max Planck Institute for Astrophysics, Munich

Peter Janotta, Universität Würzburg

Dileep Jatkar, Harish-Chandra Research Institute

Kristan Jensen, University of Victoria

Christopher Jillings, SNOLAB

Juan Jottar, University of Illinois

Leo Kadanoff*, James Franck Institute

Catherine Kallin, McMaster University

Jared Kaplan, Stanford University

Andrey Katz, University of Maryland

Louis Kauffman, University of Illinois at Chicago

Patrick Kerner, Max Planck Institute for Astrophysics, Munich

Justin Khoury, University of Pennsylvania

Michael Kiermaier, Princeton University

Yong Baek Kim, University of Toronto

Gen Kimura, Advanced Industrial Science and Technology/Research Center for Information Security

William Kinney, State University of New York at Buffalo

John Klauder, University of Florida, Gainesville

Aleksandra Klimek, University of Warsaw

Frans Klinkhamer, University of Karlsruhe

Robert Koenig, California Institute of Technology (Caltech)

Joachim Kopp, Fermilab

Ryszard Kostecki, University of Warsaw

Anna Kostouki, Kings College London

Jurek Kowalski-Glikman, University of Wroclaw

Martin Kruczenski, Purdue University

David Kubiznak, University of Cambridge

Vincent Lam, University of Queensland

Rafael Lang, Columbia University

Guilhem Lavaux, University of Illinois

Bruno Le Floch, École Normale Supérieure

Matthew Leifer**, University College London

Rob Leigh**, University of Texas at Austin

Stefano Liberati, SISSA

Steve Liebling, Long Island University

Zoltan Ligeti, Lawrence Berkeley National Laboratory

Chunshan Lin, McGill University

Fu-Sin Ling, Universite Libre de Bruxelles

Etera Livine, École Normale Supérieure de Lyon

Renate Loll*, Utrecht University

Andrea Lommen, Franklin & Marshall College

Maxim Lyutikov, Purdue University

Elena Magliaro, Pennsylvania State University

Frederic Magniez, Université Paris Diderot, Paris 7

Kendall Mahn, TRIUMF

Seth Major, Hamilton College

Juan Maldacena, Institute for Advanced Study (IAS)

Dmitry Malyshev, New York University

Matilde Marcolli, California Institute of Technology (Caltech)

Owen Maroney, University of Sydney

Joseph (Joe) Marsano, University of Chicago

Lionel Mason, University of Oxford

Samir Mathur, Ohio State University

Luca Mazzucato, State University of New York at Stony Brook

John McGreevy, Massachusetts Institute of Technology (MIT)

David McKeen, University of Victoria

Noppadol Mekareeya, Imperial College London

Kristen Menou**, Columbia University

Jacob Miller, Franklin W. Olin College of Engineering

Joseph Minahan, Uppsala University

Djordje Minic, Virginia Tech

Mozhgan Mir, Ferdowsi University

Guy Moore, McGill University

Bernhard Mueller, Max Planck Institute for Astrophysics, Munich

Jonas Mureika, Loyola Marymount University

David Neilsen**, Brigham Young University

Kin-Wang Ng, Stanford University

Piero Nicolini, Institute for Theoretical Physics, Goethe University Frankfurt

Theo Nieuwenhuizen, University of Amsterdam

Scott Noble, Rochester Institute of Technology

Brien Nolan, Dublin City University

Denjoe O'Connor**, Dublin Institute for Advanced Studies

Sam Ocko, Massachusetts Institute of Technology (MIT)

Stephan 'Jay' Olson, University of Queensland

Jonathan Oppenheim, University of Cambridge

Garnet Ord, Ryerson University

Alessio Orlandi, University of Bologna

Adrian Ottewill, University College Dublin

Yaron Oz, Tel Aviv University

Carlos Palenzuela, Canadian Institute of Theoretical Astrophysics

Ivan Panfilov, Taras Schevchenko National University of Kyiv

Kyriakos Papadodimas, CERN

Manu Paranjape, University of Montreal

Filippo Passerini, Humboldt University, Berlin

Marcin Pawlowski, Institute of Theoretical Physics and Astrophysics, University of Gdansk

Roger Penrose, University of Oxford

Tamar Pereg-Barnea, California Institute of Technology (Caltech)

Hagai Perets, Harvard-Smithsonian Center for Astrophysics

David Perez-Garcia, Universidad Complutense, Madrid

Paolo Perinotti, Universita degli Studi di Pavia, Italy

Malcolm Perry*, DAMTP, University of Cambridge

Michael Peskin, SLAC National Accelerator Laboratory

Robert Pfeifer, University of Queensland

Dan Phillips, University of California, Davis

Federico Piazza, APC France

Levon Pogosian, Simon Fraser University

David Poland, Harvard University

Giuseppe Policastro, École Normale Supérieure

Sandu Popescu*, University of Bristol

Erich Poppitz, University of Toronto

Daniele Pranzetti, CPT, Marseille

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CONFERENCES AND WORKSHOPS, 2010-11

Integrability in Scattering Amplitudes II
September 15-16, 2010

IR Issues and Loops in de Sitter Space
October 27-30, 2010

PI-ATLAS LHC Day
December 7, 2010

PI-CITA Day 2011
February 15, 2011

New Frontiers in Quantum Foundations, CUPI 2011
March 9-11, 2011

Integrability in Scattering Amplitudes III
March 11-12, 2011

Back to the Bootstrap
April 12-14, 2011

4-Corner Southwest Ontario Condensed Matter Symposium
April 26, 2011

Conceptual Foundations and Foils for Quantum Information Processing
May 9-13, 2011

PI-ATLAS LHC Day 2011
May 11-12, 2011

Cosmological Frontiers in Fundamental Physics 2011
June 14-17, 2011

Microphysics in Computational Relativistic Astrophysics
June 20-25, 2011

Holographic Cosmology v2.0
June 21-24, 2011

Fundamental Issues in Cosmology
June 20-July 16, 2011

Challenges for Early Universe Cosmology
July 12-16, 2011

Women in Physics Canada
July 19-21, 2011

COURSES, 2010-11

Space-time, Quantum Mechanics and Scattering Amplitudes

Instructors: Nima Arkani-Hamed, Institute for Advanced Study and Distinguished Research Chair, and Freddy Cachazo, Perimeter Institute

August 23-27, 2010

Viewable at: http://www.pirsa.org/C10018

Scattering Amplitudes from Single-Cuts

Instructor: Simon Caron-Huot, Institute for Advanced Study

September 13, 14, and 17, 2010

Viewable at: http://www.pirsa.org/C10021

An Invitation to Causal Sets

Instructors: Rafael Sorkin, Perimeter Institute, and Fay Dowker, Imperial College London

October 18-22, 2010

Viewable at: http://www.pirsa.org/C10020

Introduction to the de Broglie-Bohm Theory

Instructor: Samuel Colin, Griffith University

February 22, 24, and 28, 2011

Viewable at: http://www.pirsa.org/C11001

Higher Spin Theories and Holography

Instructor: Simone Giombi, Perimeter Institute

March 24, 25, 28, and 29, 2011

Viewable at: http://www.pirsa.org/C11003

Topos Theory as a Mathematical Universe

Instructor: Cecilia Flori, Perimeter Institute

April 29, May 3 and 6, 2011

Introduction to Tensor Network Algorithms

Instructor: Robert Pfeifer

June 1, 10, 15, and 17, 2011

Viewable at: http://www.pirsa.org/C11007

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Association pour la Promotion Scientifique de l'Afrique, "Afrique: le choix de la science, l'exemple de l'initiative AIMS" conference

Science Expo

Canadian Association of Physicists, CAP Award for Excellence in Teaching High School

University of Alberta, Lake Louise Winter Institute

Youth Science Canada, International Summer School for Young Physicists Award

Ontario Association of Physics Teachers, OAPT Conference 2011

TRIUMF, "Physics at the Dawn of the LHC Era" workshop

York University, "PI-ATLAS LHC Day"

University of Lethbridge, African science conference bursary

The Banff Centre, Science Communications Program Scholarship

University of Waterloo, "Black Holes VIII" conference

Clemson University, "New Frontiers in Quantum Foundations, CUPI 2011" conference

The Fields Institute for Research in Mathematical Sciences, "Connections in Geometry and Physics 2011" conference

University of Victoria, "From Black Holes to Hydrodynamics: a Symposium Celebrating the 80th Birthday of Werner Israel"

University of Sherbrooke, "11th Canadian Summer School on Quantum Information"

University of Waterloo, "31st International Workshop on Bayesian Inference and Maximum Entropy Methods in Science and Engineering"

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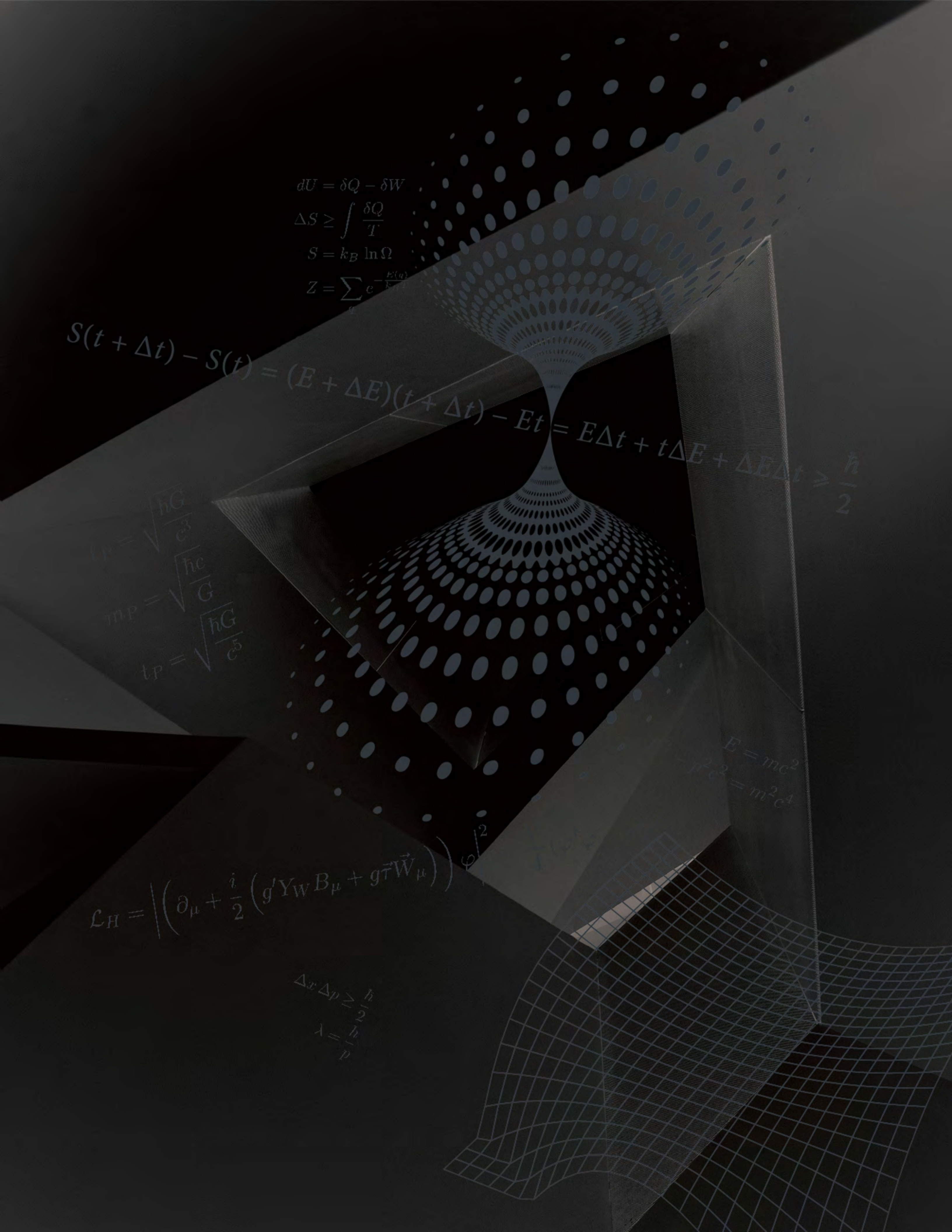
$dU = \delta Q - \delta W$
$\Delta S \geq \int \frac{\delta Q}{T}$
$S = k_B \ln \Omega$
$S(t + \Delta t) - S(t) = (E + \Delta E)(t + \Delta t) - Et = E\Delta t + t\Delta E + \Delta E\Delta t \geq \frac{\hbar}{2}$
$m_P = \sqrt{\frac{\hbar c}{G}}$
$t_P = \sqrt{\frac{\hbar G}{c^5}}$
$E = mc^2$
$\mathcal{L}_H = \left| \left(\partial_\mu + \frac{i}{2} \left(g' Y_W B_\mu + g \vec{\tau} \vec{W}_\mu \right) \right) \varphi \right|^2$
$\Delta x \Delta p \geq \frac{\hbar}{2}$
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