inside the Perimeter

fall 2013

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Nearly 25,000 people came to the BrainSTEM: Your Future is Now Festival, held September 30 to October 6, 2013.

Front cover: Glowing plasma balls represented the spark of scientific discovery during Perimeter Institute's BrainSTEM Festival.

inside the Perimeter

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IN THIS ISSUE

Question Everything

It's a wonderful time to be a physicist. The greatest-ever microscope – the Large Hadron Collider – and the greatest-ever telescope – the Planck Satellite – have revealed the cosmos on scales a billion times smaller than an atom and 10 trillion times larger than the solar system.

The Higgs boson was predicted by theorists nearly half a century ago, based on known principles of quantum theory, relativity, and symmetry in particle physics. And the LHC, the greatest experimental device of all time, found the Higgs exactly where it was supposed to be.

Likewise, the Planck satellite has made the most detailed snapshot to date of the oldest light in the universe, revealing the pattern of density and temperature variations coming out of the big bang. The data lines up exactly with theoretical predictions.

Never before have we had such a complete picture of our universe.

And yet … these amazing achievements represent a profound challenge. You see, the results from both the LHC and the Planck experiments were actually much simpler than most theorists were predicting. For many, this is a deeply vexing situation.

For the last few decades, theorists have built an extravaganza of models. Each one has new fields and particles beyond the Higgs. These models were built to address deep puzzles in the Standard Model, like the complex pattern of particles and forces, and why mass scales in particle physics are so much smaller than the Planck mass, which characterizes gravity. The models range from supersymmetry to grand unified theories to superstring and M theory. Each one involves adding many extra ingredients, and many free parameters, to the particles, forces, and fields we know.

Cosmologists have focused on the idea of inflation, which says that just after the big bang, the universe underwent super-rapid expansion, snapping in an instant into a huge region that could evolve into the cosmos we see all around us. Inflation has never meshed very well with physics beyond the Standard Model, but it provided a generous framework for model-building, and literally thousands of models of inflation have been built.

The goal, in each case, was to unify and simplify the picture. But in every case, the new models turned out to have many more bells and whistles than the models they replaced. Ultimately, with the realization that string theory is really a vast landscape of models rather than a unified theory, the suggestion arose that inflation might have exploded the universe into a "multiverse" within which every possible string theory model was realized. Unfortunately, neither string theory nor inflation came up with any kind of prediction as to which particular universe within this multiverse we would be likely to find ourselves in.

Many theorists expected that Planck and the LHC would reveal new physics, pointing the way to some particular models in the landscape and regions in the multiverse. Instead, both have revealed the minimal, "vanilla" universe characterized by the simplest conceivable properties. Many model-builders are walking around with long faces, because their models, where they made interesting predictions beyond the minimal story, have been ruled out.

The universe has spoken, and I believe it is telling us that our theories are too complicated. We need new, more powerful principles and mathematical laws that reflect nature's extraordinary simplicity.

Should we be worried or elated by this challenge?

History points at the answer, for physics has faced a similar situation before. In 1900, Lord Kelvin, one of the greatest scientists of his day, gave a speech in which he claimed that physics had already discovered the basic principles – mechanics, electromagnetism, and thermodynamics – needed to explain everything that needed explaining. Henceforth, science would mostly be a matter of working out the details in various complicated situations, dotting the i's and crossing the t's. Presciently, he noted various small "clouds" on the horizon – like the difficulty in reconciling Maxwell's theory of light with the theory of heat, or of building consistent models of the atom – but he hoped future developments would clear them away.

Within two decades, those clouds had unleashed the thunderstorms of relativity and quantum mechanics, which totally revised our picture of the physical world. Each was a revolution in thought, a new way of seeing things. Together, they brought in their wake all of the key technologies of the 20th century – transistors, lasers, X-rays, computers – and led to transformative discoveries in every science, from astronomy to zoology.

Recently, we held two events here at Perimeter that threw the opportunity before us into sharp relief.

BrainSTEM was a science communication festival that brought nearly 25,000 students and members of the public here to view amazing exhibits and events that showcased emerging technologies – from cloaking devices to wireless electricity.

Such events, while unusual for a scientific institution, are a regular part of life at Perimeter. They are an expression of our deep commitment to education and communication that inspires and draws people – especially young people – into science.

Concurrent with BrainSTEM, we held a conference focused on the future of secondary school education. The Equinox Summit: Learning 2030 brought educators, students, and innovators from around the world to Perimeter with a mandate of imagining and designing a school for the 21st century. It was hosted by the Waterloo Global Science Initiative (WGSI), a non-profit partnership between Perimeter and the University of Waterloo that was created to promote global dialogue and propose solutions to complex issues involving science and society.

It is very clear that in education, as in physics, great changes are coming, and a radical rethinking is required. Rote learning, exams, rigid curricula – these things make little sense in a world flooded with information.

One of the experts at the summit gave the shocking statistic that two-thirds of high school students are intellectually disengaged. The numbers are even worse when it comes to science.

I believe we have failed to communicate the meaning of the Higgs discovery and the Planck data: the universe is simple! And beautiful! We can grasp and understand it. We should draw strength from these achievements. They tell us about who we are and what we can be. And, best of all, the best is yet to come. Yet many young people are saying, "It's great the Higgs has been discovered and the universe mapped, but what does it mean to me, to my future?"

Imagine – young people who travel in cars and planes, whose many devices are literally extensions of themselves, wonder what relevance science has to them!

Our world has never needed deep, imaginative, critical thinkers more.

We need people, especially young people, to appreciate the significance of the amazing discoveries that have been made, and to see them not as a conclusion or endpoint, but a starting place.

Their starting place.

In physics, the recent discoveries point to a need to re-examine our most basic assumptions.

What better place in the world than Perimeter to work on new and more powerful principles? From its inception, Perimeter has emphasized foundational ideas. Its welcoming, youthful, open community, supporting collaboration and cross-fertilization of ideas, has made it a haven for theorists worldwide who want to focus on the fundamentals.

The way forward is clear. Question everything. Acknowledge the shortcomings of current approaches. Think from the ground up.

Opportunities don't get any better than this.

- Neil Turok

Guiding Growth: Perimeter Welcomes Scientific Advisory Committee Members

Eminent scientists Ganapathy Baskaran (The Institute of Mathematical Sciences, Chennai) and Mark Wise (California Institute of Technology) were recently appointed to Perimeter Institute's Scientific Advisory Committee (SAC), joining current committee Chair Renate Loll. SAC members are distinguished scientists from the international physics community whose advice helps the Institute achieve the highest standards of scientific excellence in its research and training initiatives.

Perimeter Inks Two International Partnerships

Perimeter Institute has signed agreements to encourage scientific exchange with a pair of international partners: The Scuola Internazionale Superiore di Studi Avanzati (SISSA) in Trieste, Italy, and the Weizmann Institute of Science in Rehovot, Israel. These agreements facilitate research visits and promote scientific collaboration between the institutes. The Weizmann Institute of Science will also work with Perimeter to develop educational outreach programming, an area of particular focus at both institutes.

Flexing the TRISEP

PI · SNOLAB · TRIUMF TRISEP

TRIUMF, Canada's national laboratory for nuclear and particle physics, and SNOLAB, Canada's underground science laboratory specializing in neutrino and dark matter physics, have teamed up with Perimeter Institute. Together, these institutes host a new international summer school for graduate students and postdoctoral researchers on hot topics in particle physics. The Tri-Institute Summer School on Elementary Particles (TRISEP) features leading particle physicists lecturing on collider physics, neutrino physics, dark matter, Monte Carlo techniques, and physics beyond the Standard Model.

Seven Perimeter Researchers Primed for Discovery

NSERC CRSNG

The Natural Sciences and Engineering Research Council of Canada (NSERC) has awarded seven Discovery Grants to Perimeter researchers this year. Faculty members Dmitry Abanin, Davide Gaiotto, Natalia Toro, and Xiao-Gang Wen, and Associate Faculty members Matthew Johnson, Sung-Sik Lee, and Roger Melko received grants totalling $1.79 million (over three- to five-year terms). In addition to their core grants, two Perimeter faculty members received Discovery Accelerator Supplements, valued at $120,000 over three years: Wen for his program on "Highly Entangled Quantum Matter," and Gaiotto for his program, "Investigations in Quantum Field Theory."

Perimeter Resources Go Global

Perimeter Institute's educational outreach team visited Singapore this summer as part of the Institute's effort to share its expertise and award-winning modern physics resources internationally. The Perimeter team went at the invitation of Singapore's Ministry of Education, and delivered a keynote address and three days of workshops at the country's National Physics Education Seminar. In all, over 100 teachers were trained in innovative classroom techniques and the use of Perimeter's modern physics resources.

Eugenio Bianchi Wins Inaugural Bronstein Prize

Perimeter Postdoctoral Researcher Eugenio Bianchi was recognized by his peers in loop quantum gravity (LQG) with the inaugural Bronstein Prize. The Prize recognizes high-quality scientific results in LQG, creativity and originality, and the significance of results to the field as a whole. Bianchi received the award during the "Loops 13" conference at Perimeter Institute in July (see page 25). The Bronstein Prize is named in honour of Matvei Petrovich Bronstein, the first person to emphasize that quantum gravity requires a deep revision of classical spacetime concepts. Bianchi was cited "for his insightful contributions to black hole entropy, the discrete geometry of quantum spacetime and the propagation of gravitons thereon, and for his inspiring enthusiasm and collaborative spirit."

David Skinner Wins Best Paper Prize

Perimeter Visiting Fellow David Skinner won *Journal of Physics A*'s "Best Paper Prize" for 2013 with collaborator Lionel Mason. The paper, titled "Amplitudes at weak coupling as polytopes in AdS_5," came from research Skinner conducted as a Perimeter postdoctoral fellow. The prize is awarded on the basis of excellence, novelty, achievement, and potential impact. Perimeter researchers have now won this prize two consecutive years; in 2012, Perimeter Faculty member Pedro Vieira and Senior Postdoctoral Fellow Amit Sever shared the prize with collaborators for their paper, "Y-system for scattering amplitudes."

Neil Turok Wins Lane Anderson Award

Perimeter Director Neil Turok was awarded the Lane Anderson Award for his book *The Universe Within: From Quantum to Cosmos* – the companion volume to his CBC Massey Lectures, published by the House of Anansi Press. The award honours excellence in Canadian science writing, and judges praised *The Universe Within*'s blend of science and inspiration.

Advancing Perimeter's Mission

Perimeter has welcomed Jonathan Braniff as its first Chief Advancement Officer (CAO). Braniff now leads the Institute's long-term private fund development strategy, raising awareness and support for Perimeter's research, training, and outreach activities. Braniff has helped organizations across the globe raise over $300 million from individuals, corporations, foundations, trusts, and governments. Most recently, he served as Vice President of Advancement for the University of Windsor.

Searching for the Next Einstein: AIMS Opens New Centre in Cameroon

AIMS NEI

The African Institute for Mathematical Sciences (AIMS) recently opened its fourth centre for excellence in Cameroon. AIMS is a pan-African network of centres offering advanced training in mathematics to exceptional African graduates, with the goal of training the world's next Einstein in Africa through the Next Einstein Initiative. AIMS-Cameroon joins centres already active in Ghana, Senegal, and South Africa.

Fourth PSI Class Graduates

Perimeter Scholars International (PSI), the Institute's master's program, awarded 29 students University of Waterloo MSc degrees in June, the fourth class in the program's history. Nearly all of the graduates are heading on to earn a PhD at institutions including Oxford, Cambridge, the Massachusetts Institute of Technology (MIT), and the California Institute of Technology (Caltech). Several PSI graduates will pursue their doctoral studies here at Perimeter.

Brains on ICE

In early August, guidance counsellors and Careers teachers from across Ontario gathered at Perimeter for BrainSTEM ICE (Instructional Camp for Educators), an interactive workshop that gave teachers tools for inspiring students to pursue careers in STEM fields (science, technology, engineering, and mathematics). Over two intense days, 48 educators focused on exploring innovative career options and the skills required to excel in them, to give students considering a STEM-based career an advantage. At the conclusion of BrainSTEM ICE, participants were invited to join the Perimeter Institute Teacher Network to share Perimeter resources with their peers across the province.

Summer Science

Perimeter's annual International Summer School for Young Physicists (ISSYP) brought 40 high school students from 12 different countries to Waterloo to give their careers in physics a supercharged start. ISSYP brings exceptional students to Perimeter every summer to learn about modern physics, meet scientists, tour research labs, and forge lasting friendships. Over 70 percent of alumni surveyed credit ISSYP with inspiring them to pursue careers in math and science.

ISSYP was generously supported in 2012/13 by RBC Foundation.

Freedom to Ask the Deepest Questions

Templeton Frontiers Program Postdoctoral Fellow Flavio Mercati and former Perimeter postdoc Tim Koslowski, along with co-investigator Julian Barbour, were awarded a $140,000 grant by the Foundational Questions Institute (FQXi) for their project "Information, Complexity, and the Arrow of Time in Shape Dynamics." Thirty-seven recipients were chosen from roughly 200 applicants, with several Perimeter connections among other awardees: Visiting Fellows Jonathan Barrett and Giulio Chiribella, Affiliate Joseph Emerson, and Distinguished Visiting Research Chairs Patrick Hayden and Adrian Kent all received FQXi grants this year.

Brodie Award Winners

This year's John Brodie Memorial Award was given to João Caetano and Jonathan Toledo for their paper "χ Systems for Correlation Functions." The award is given each year to a graduate student – in this case a pair – in honour of one of Perimeter's first postdoctoral researchers. Caetano and Toledo are supervised by Perimeter Faculty member Pedro Vieira, who said that the award "is meant to reward brilliance, but also independence, and this work is a perfect example that combines both." Caetano and Toledo's prize-winning work in string theory attempts to extend a system for understanding the correlations between three operators into a system for understanding the correlations between four operators. They ended up with a powerful new system that should work for any number of operators.

Ghost in the Nobel

This year's Nobel Prize in Physics – given to Francois Englert and Peter Higgs – was an occasion for great joy. In the 1960s, Higgs and Englert predicted that the vacuum was permeated by something that came to be called the Higgs field. It was the interaction of elementary particles with that field, they argued, that distinguishes particles from each other and gives them mass. A field like the Higgs can only be detected via its ripples, and it took decades of work before a ripple in the Higgs field – a Higgs boson – was finally found at CERN's Large Hadron Collider.

It was a landmark moment in physics, and well worth celebrating.

But even as the physics community fêted this year's laureates, it also paused to remember someone who couldn't be included. As Professor Englert said during a press conference at the Free University of Brussels, "Of course I am happy to have won the prize – that goes without saying. But there is regret, too, that my colleague and friend, Robert Brout, is not there to share it."

The Nobel Prize is only awarded to living persons, and Brout died in 2011; he would likely have shared in the prize if he were alive today.

In the early 1960s, Brout and Englert worked together to apply quantum field theory to elementary particle physics. In a groundbreaking 1964 paper, they used this new marriage of ideas to show how some particles acquire mass. The paper was followed a few weeks later by an independent paper from Higgs on the same subject. The hunt for the Higgs boson can be traced back to those two papers.

Professor Brout was for many years an honoured presence at Perimeter, visiting frequently from 2005 on. He gave many talks at Perimeter and continued doing groundbreaking research, both independently and in collaboration with Perimeter scientists, until he fell ill in 2009.

Brout was a wide-ranging and prolific scientist, who did work in field theory, elementary particle physics, lattice gauge theory, general relativity, black hole physics, and cosmology. Aside from his work on the origin of mass, he will be remembered for developing the idea of inflation (again, with Englert) and relating it to the emergence of the universe itself from a quantum fluctuation.

Perimeter salutes all three of these pioneers – Brout, Englert, and Higgs – and the hundreds of other scientists who so triumphantly connected forward-looking theory to the engines of experiment.

- Erin Bow

Editor's Note: Interested readers can find talks given by Robert Brout on PIRSA.org, Perimeter's online archive of past talks and courses.

Remind Me … What's The Higgs Again?

Quick recap: in July 2012, the physics community rejoiced when the two experiments at CERN's Large Hadron Collider both verified that they had spotted a new particle – the long-sought Higgs boson. It was the last undiscovered particle predicted by the Standard Model.

The Standard Model of particle physics is a powerful, comprehensive theory that explains all known particles and their complex interactions. According to it, there are six quarks, three electron-like particles, three neutrinos, and a handful of force-carrying bosons, such as the photon. Though it's not a theory of everything – it leaves gravity out of the mix, for a start – the Standard Model is a well-tested, highly successful theory, one of the great triumphs of modern physics.

The Higgs is central to the Standard Model. Early in the 1960s, physicists were struggling to understand why elementary particles such as quarks and electrons have mass. A deep look at the mathematical symmetries governing the known particles led them to propose the existence of what came to be called "the Higgs field." This field interacts with particles through a process called the "Higgs mechanism" to give them mass.

The Higgs boson is just a ripple in the Higgs field. Though the field is the more central matter, the boson is the only part of the field that we can detect. It's analogous to the way we can't feel the air, but can feel the wind. But without the air, we'd be in trouble. Without the Higgs mechanism, all particles would be massless, like the photon. We ourselves would not exist.

THE BALLAD OF

Alice & Bob

A QUANTUM LOVE STORY

BY COLIN HUNTER

Like most fairy tales, this one begins with "Once upon a time" and ends with "happily ever after." Unlike most fairy tales, this one has lasers. And it's true.

Once upon a time, in a land called Waterloo, there lived Alice and Bob, who were forbidden from meeting face-to-face.

Alice sat alone, locked in her third-storey room, forever staring out a window. She wondered if Bob, trapped in his own room a few miles away, was gazing back. He was.

Alice and Bob had eyes for each other. In fact, they *were* eyes for each other.

Each was a glass-and-gadgetry cyclops – a high-tech receiver of messages made of light – each unblinkingly awaiting messages beamed through the air.

Bob was holed up in a place called Perimeter Institute, in the office of his master – a quantum information scientist. Alice was marooned at the Institute for Quantum Computing a few miles across the land of Waterloo.

Whispering sweet nothings over the phone or Internet simply wouldn't work. Eavesdroppers – particularly a nosy little nuisance named Eve – could be anywhere, seeking gossip or worse.

Alice and Bob could only talk to one another if they were absolutely positive no one else was listening.

Lucky for Alice and Bob, their creators had figured out a way.

Those scientists knew that the particles of light, or photons, always exhibited a telltale property called polarization. They also knew that photons were so tiny and frail that even the mere act of looking at them would noticeably alter the polarization.

For Alice and Bob, this was great news. It meant each could receive a blast of laser light from a source in between , which sat on a rooftop at the local university. The light contained "entangled" photons, with matching polarizations.

That meant that, if nobody was eavesdropping in between, Alice and Bob would receive blasts of light with matching polarizations. If Alice got a blast of light with polarizations that she translated into, say, a binary pattern of 0101110, Bob could expect to get the same.

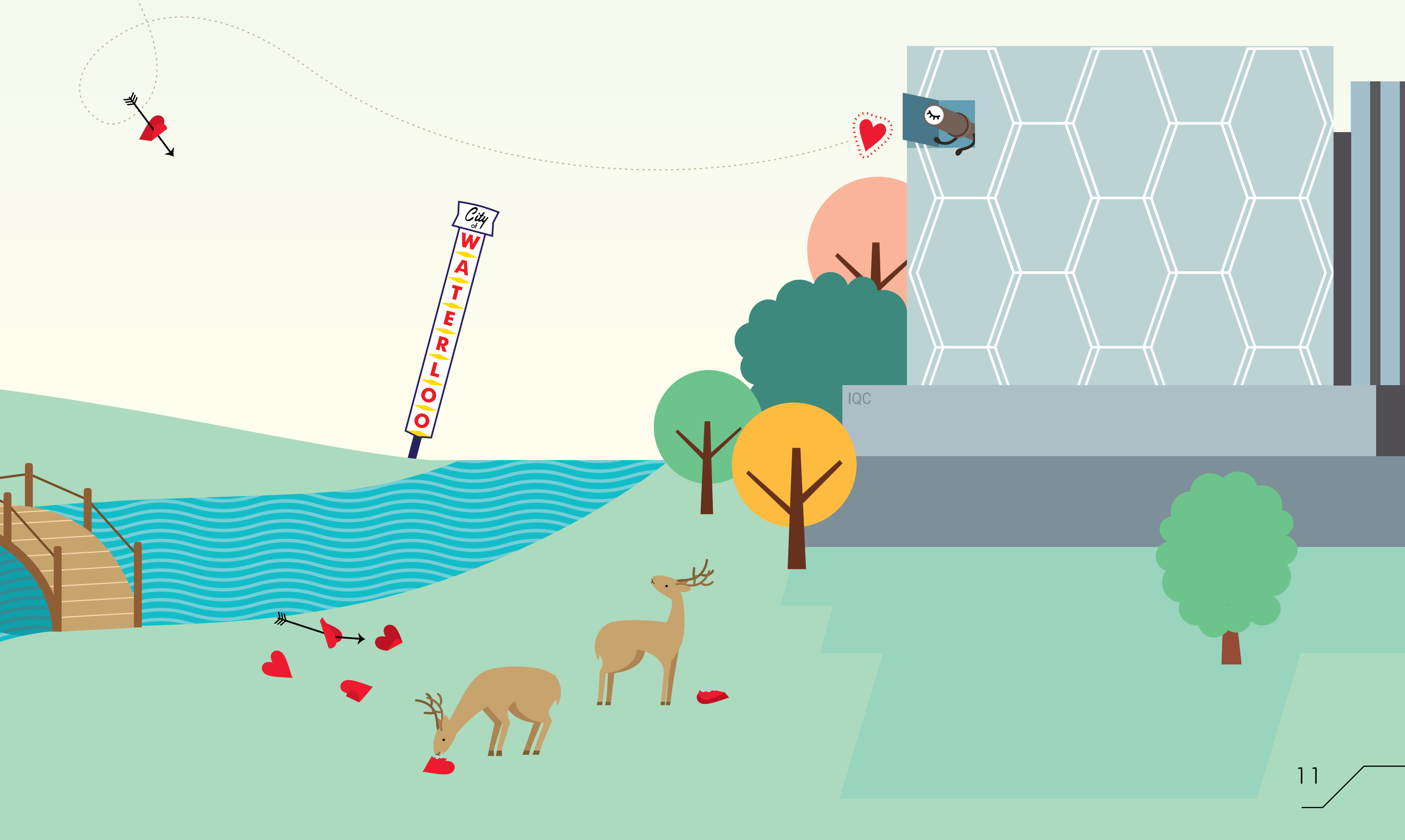
If there was a mismatch, Alice and Bob would know that someone between them was trying to snoop. If that happened, they'd keep exchanging laser blasts until they received matching, un-snooped-upon ones.

Only when Alice and Bob agreed their laser blasts were identical did they use the binary patterns as "keys" to safely scramble and unscramble secret messages.

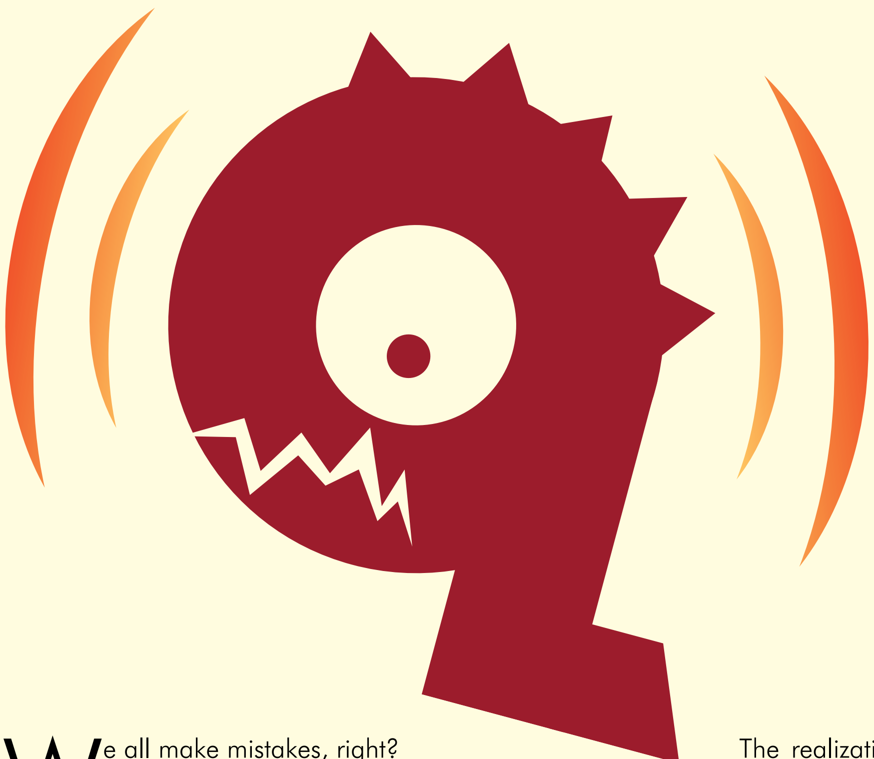
The scientists called it quantum key distribution. Alice and Bob called it a perfect connection in imperfect times.

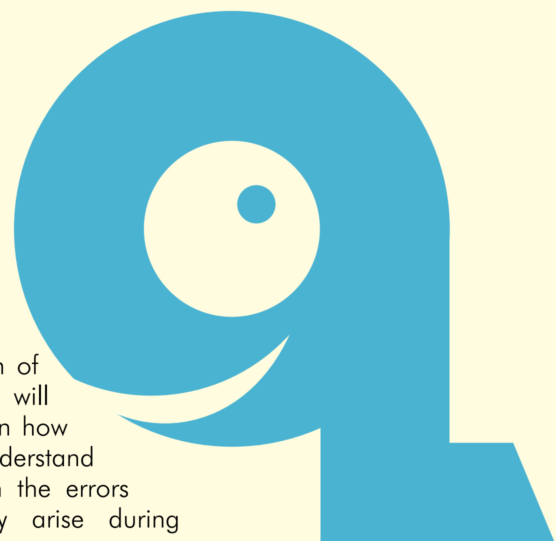
One night, using an unsnooped key to encode her secret message, Alice wrote to Bob: "You're more special than relativity."

And they exchanged entangled photons happily ever after.



Chill Out, Qubits! Quantum Refrigerator Gives Fired-Up Qubits a Time Out





We all make mistakes, right?

Even things at the tiny atomic scale – the quantum building blocks of nature – are prone to goof-ups.

Errors at these scales are why it's so tricky to build a quantum computer. Wrangling and controlling quantum particles to perform computation is difficult because those particles are so unfathomably small and susceptible to disturbance.

The exciting promise of quantum computing – ultra-powerful processing that capitalizes on quantum phenomena like superposition and entanglement – is what drives Perimeter research in quantum information.

Processors that function according to quantum laws have the potential to be vastly more powerful than even today's most complex supercomputers. As opposed to present-day computers, which process bits of zero or one, quantum computers will use quantum bits (or qubits) that behave in uniquely quantum ways, enabling them to be in "superpositions" of both zero *and* one simultaneously. This allows a tremendous – even exponential – boost in computing power, which promises to drastically change how we work, communicate, and live.

The realization of that promise will hinge partly on how researchers understand and deal with the errors that inevitably arise during quantum computation.

To err is quantum. So how do we proceed?

Perimeter Faculty member Daniel Gottesman is working on answers, and he recently made some important progress.

The trick isn't to eliminate errors – they'll always happen, even in classical computing – but to figure out viable work-arounds that ensure the error rate remains below an acceptable threshold.

In a recent paper titled "Quantum Refrigerator," Gottesman and collaborators Michael Ben-Or (Hebrew University of Jerusalem) and Avinatan Hassidim (Bar-Ilan University, Google) proposed a system that gives misbehaving qubits, a chance to chill out.

Quantum error correction techniques often require that new qubits – called ancilla qubits – be introduced to a computation to measure information about the errors.

Usually, performing this measurement scrambles up the ancilla qubits, making them essentially useless after only a single measurement.

Gottesman and collaborators, however, devised a model in which ancilla qubits can be effectively reset (and therefore used again) by shunting them into a "refrigerator" where they can unscramble.

Think of a quantum computer as a children's choir. When all the components are working in harmony, the resulting beauty is greater than the sum of its parts. Mistakes happen when individual members get too rambunctious. But if those problematic participants can be given a "time out" in a quiet room nearby, they can simmer down and return to the choir once they're ready to behave.

In Gottesman's model, the fired-up qubits (that is, those with elevated entropy) are sent off to a kind of "storage house," where some qubits will naturally cool down from their excited state thanks to a process called spontaneous emission, in which an atom spits out a photon.

At this stage, qubits can also undergo a process called algorithmic cooling, which essentially shuffles around the amount of excitement or entropy within the system – keeping the chilled-out qubits at hand while sending the hyperactive ones off for more cooling.

After these processes, some of the ancilla qubits are sufficiently chilled out to be sent back into the quantum computation to perform error correction.

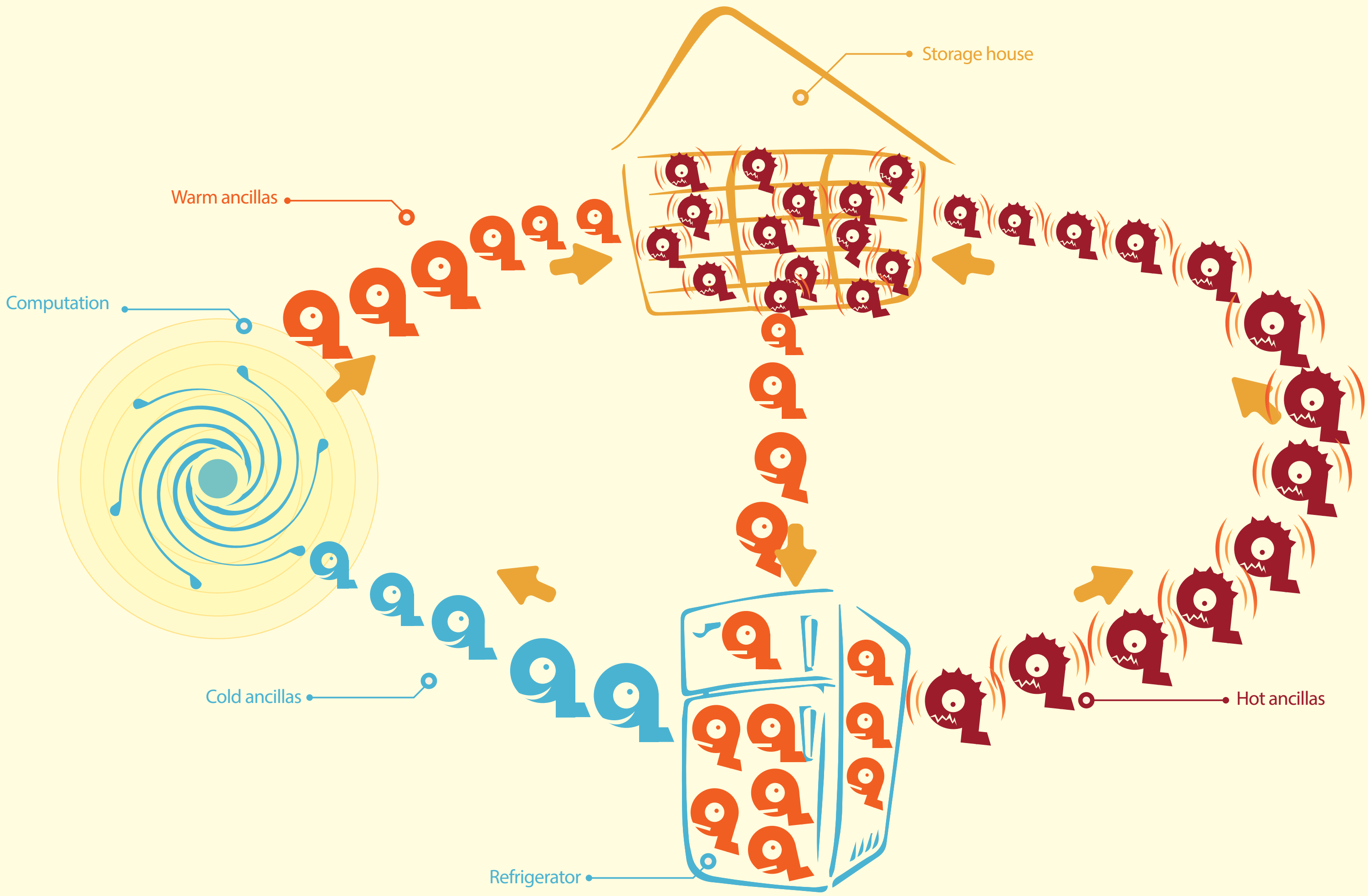
It's a continual loop of heating and cooling that allows for quantum error correction to be performed longer and more reliably than in the past.

The "quantum refrigerator" proposed by Gottesman and collaborators is, therefore, an important step closer to fault-tolerant error correction, which will be essential to a stable quantum processor.

As experimentalists develop the potential hardware for practical quantum processors, error correction protocols like those developed by Gottesman will prove essential in making the computer perform valuable operations.

"I'm interested in the question, 'If we build a quantum computer, what will we be able to do with it?'" says Gottesman. "We're trying to figure out both the power and the limits of quantum computation."

- Colin Hunter



Alice and Bob in Space!

Alice and Bob – long separated by the cruel need to test quantum cryptography – are about to be pulled still further apart.

The fault lies with a team of researchers, including Perimeter Associate Faculty member Raymond Laflamme, Perimeter Affiliate researcher Thomas Jennewein, and many collaborators from Perimeter's sister institute, the Institute for Quantum Computing (IQC). Some years ago, the team began to brainstorm ways in which quantum mechanics and the principles of quantum information could be tested using space-based programs.

From these brainstorming sessions came the plan for a small satellite – about the size of a box of files – which would contain one half of a quantum key distribution (see The Ballad of Alice and Bob, pages 10-11). This year, the federal government gave a green light to begin developing the microsatellite for a future launch.

So, Bob is off to space. Alice will remain on the ground – as will a source of entangled photons. Researchers are eager to know if the "quantumness" of photon entanglement persists at larger distances.

It's possible – though unlikely – that it won't. Quantum mechanics has never been tested at scales longer than a 140-odd kilometres. It's also never been tested in a varying gravitational field. A satellite exchanging signals with a station on the ground would set both of these important precedents.

So, even though quantum mechanics is the most thoroughly tested theory in the history of physics, leaving the earth with it will be – so to speak – a final frontier.

This is particularly interesting because we know quantum mechanics is incomplete, in the sense that it is not yet unified with the theory of gravitation, general relativity. At longer scales and in varying gravitational fields, we might see interactions between gravity and quantum mechanics. If so, a satellite-based platform may prove ideal for measuring the effects of such interactions, or at least putting an upper bound on how strong its effects might be. The experiments might even be able to distinguish between competing theories of how gravity and quantum mechanics interact.

The satellite experiments have implications for quantum computing as well. Quantum mechanics is often thought of as governing the world of the small; at everyday scales, quantum effects smooth out and become invisible, and it is as if we live in a classical world. What quantum information has taught us is that "quantum = small" is not quite right. We've learned instead that quantum effects show up in systems that are *isolated* from their surroundings. When things are small, it is easy to isolate them, but it should in principle be possible to build an isolated system that's large.

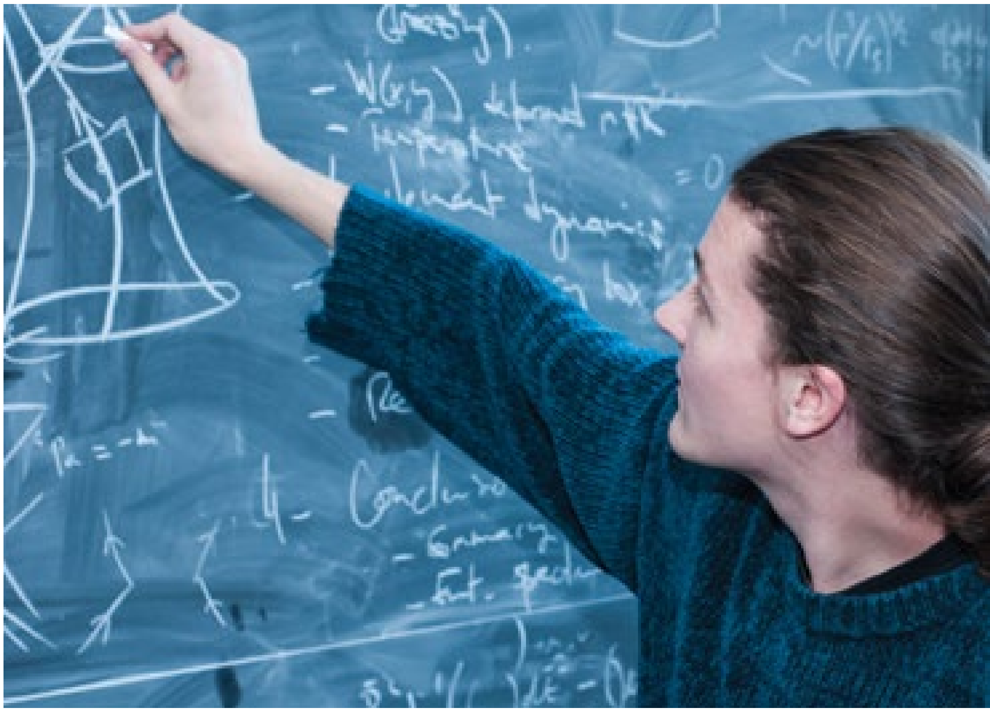
Building a large system that exhibits quantum effects is one of the challenges we must overcome to build a quantum computer. Building a large quantum system in the form of an earth-to-satellite network is not only a step toward proving that quantum mechanics is valid at large scales, but also an important demonstration that practical-sized quantum computers are possible.

The Bob-in-space satellite will be developed by a team of academic researchers and private partners. A launch is at least a few years away.

- Erin Bow

Perimeter Postdoc Charts New Route to Classic Landmark

In the quest to bridge the gap between the physics of the very large and the very small, Perimeter Postdoctoral Researcher Steffen Gielen and collaborators achieved an important milestone that brings to mind the adage "what's old is new again."



The team's research, culminating in a *Physical Review Letters* paper, reached a nearly century-old cosmological equation. It's a result that might seem, at first glance, somewhat unremarkable.

"If you showed the last equation in our paper to a cosmologist, he wouldn't be too impressed because it's the most basic equation of cosmology," said Gielen. "You'd find it on page one of a cosmology textbook."

But that equation – a description of an empty universe first put forward 89 years ago by pioneering physicist Alexander Friedmann – is exactly what the researchers were hoping for.

The equation, in this context, is remarkable because of *how they reached it*.

Coming up with the fundamental equation through a different avenue of investigation – the avenue of quantum gravity – is an achievement with important implications.

Quantum gravity research seeks to unify the physics of the big, as described by Einstein's general relativity, with the physics of the tiny, which is described by quantum mechanics. Both theories have decades of experimental verification, but they don't play nicely with each other; a new theory that unifies them is among the grandest goals of contemporary physics.

Research in "background-independent" quantum gravity, like the work done by Gielen and collaborators, is one of several approaches that aim to unify these pillars of physics. So when Gielen and collaborators arrived at a foundational equation of cosmology through what's called the "group field theory" approach to quantum gravity, they were justifiably "quite excited."

By reaching the Friedmann equation, which describes a bare-bones, homogeneous model of the universe (think of it like a blackboard with nothing written on it), the researchers demonstrated the potential for compatibility between quantum mechanics and general relativity.

Results of this sort could lead to a better understanding of the beginnings of the universe, since the big bang exemplifies an instance of the apparent incompatibility between general relativity and quantum mechanics.

The paper in *Physical Review Letters* is the result of a year's worth of collaborative research in Canada and Germany (and plenty of Skype chats). Gielen teamed with Daniele Oriti and Lorenzo Sindoni, both of the Max Planck Institute for Gravitational Physics (Albert Einstein Institute), where Gielen held a postdoctoral position before joining Perimeter in January 2012.

Their finding opens the door to follow-up research – already under way by Gielen and collaborators – applying their approach to more complex models of the universe, taking into account factors like matter and perturbations.

That is, having demonstrated a principle with a theoretical "empty" universe, they will now fill their universe with stuff and see if their predictions hold true.

"The real universe isn't exactly homogeneous – it has structure, galaxies, planets, everything," Gielen explained. "The standard theories of cosmology give us good explanations for these, so we need to explain things like that within the quantum gravity framework."

The result outlined in *Physical Review Letters* represents a significant step in that direction, and a tantalizing glimpse at the future of quantum gravity research.

"The great potential that this has is to give us a much clearer connection between quantum gravity and cosmology," Gielen said. "These are two big research areas at Perimeter. With them, we can really study things like the big bang and understand what's going on."

- Colin Hunter

The Case of the Shrinking Proton

How big is the proton? We're not sure; it seems to be shrinking.

Before 2010, the size of the proton was so well defined and agreed upon that it joined the speed of light and the charge of the electron on the list of known quantities.

But then, an international team announced a new measurement of the proton radius. Where the old measurement was 0.8768 femtometres, the new one was 0.841 femtometres. The difference is only a quadrillionth of an inch, but the relative shift is huge – far larger than can be explained by experimental uncertainty.

So what happened? Theorists such as Perimeter Associate Faculty members Itay Yavin and Maxim Pospelov have an intriguing idea – one that posits a new force of nature.

Some background will lay the groundwork for this idea. You can think of the proton not as a point, but almost as a cloud of charge. By "size of the proton," in this case, researchers mean the width of that cloud. "Charge radius" is the technical term. The oldest and simplest method of measuring the proton's charge radius is to scatter electrons off of protons; bombarding subatomic particles with smaller particles has been the standard way of measuring their size for nearly a century. The second method of measuring charge radius is to infer it from a careful measurement of the energy levels of hydrogen – and this is where things begin to get particularly interesting.

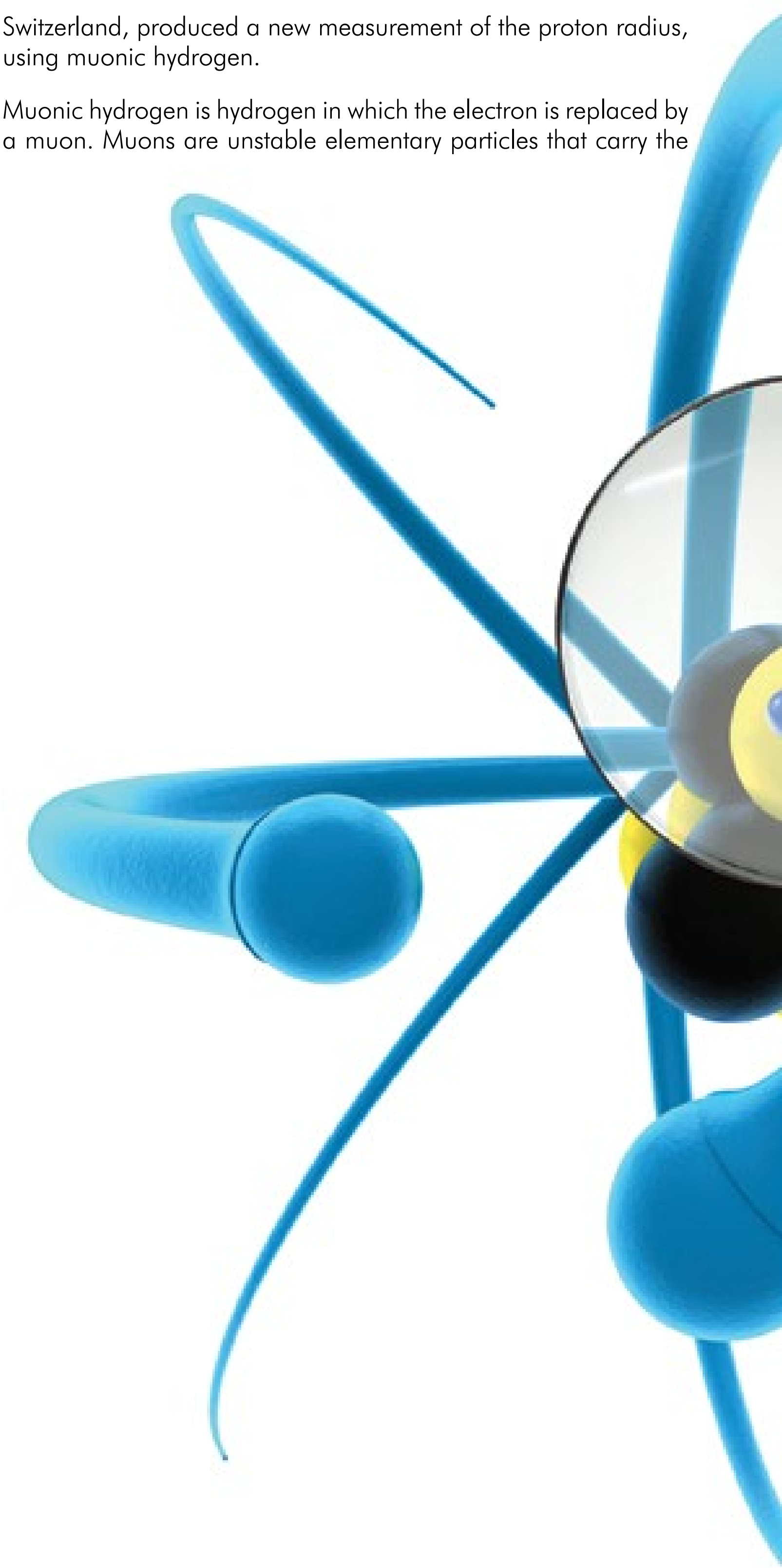
Hydrogen is the simplest atom in nature: a bound state of a single proton and a single electron. The electron in hydrogen can exist in one of several energy levels – sometimes known as atomic orbitals. All atoms have energy levels, but because the hydrogen atom is such a simple, clean system, its energy levels can be observed very precisely.

The energy levels of hydrogen tell us that the charge of the single proton in its core is spread out. Think of it this way: orbiting a cloud is different than orbiting a point, even if they both have the same charge. Different sizes and densities of cloud give different orbits – and that idea can be turned around. Different orbits, carefully observed, can be used to infer the size of the cloud. That's what researchers are doing when they measure the charge radius of the proton via measurement of hydrogen energy levels.

For decades, these two measurements – the electron bombardment method and the hydrogen energy level method – gave the same value (within experimental error) for the charge radius of the proton. The methods are independent, and they cross-check each other so beautifully that the physics community's confidence in them was incredibly high. The charge radius of the proton was considered a settled question.

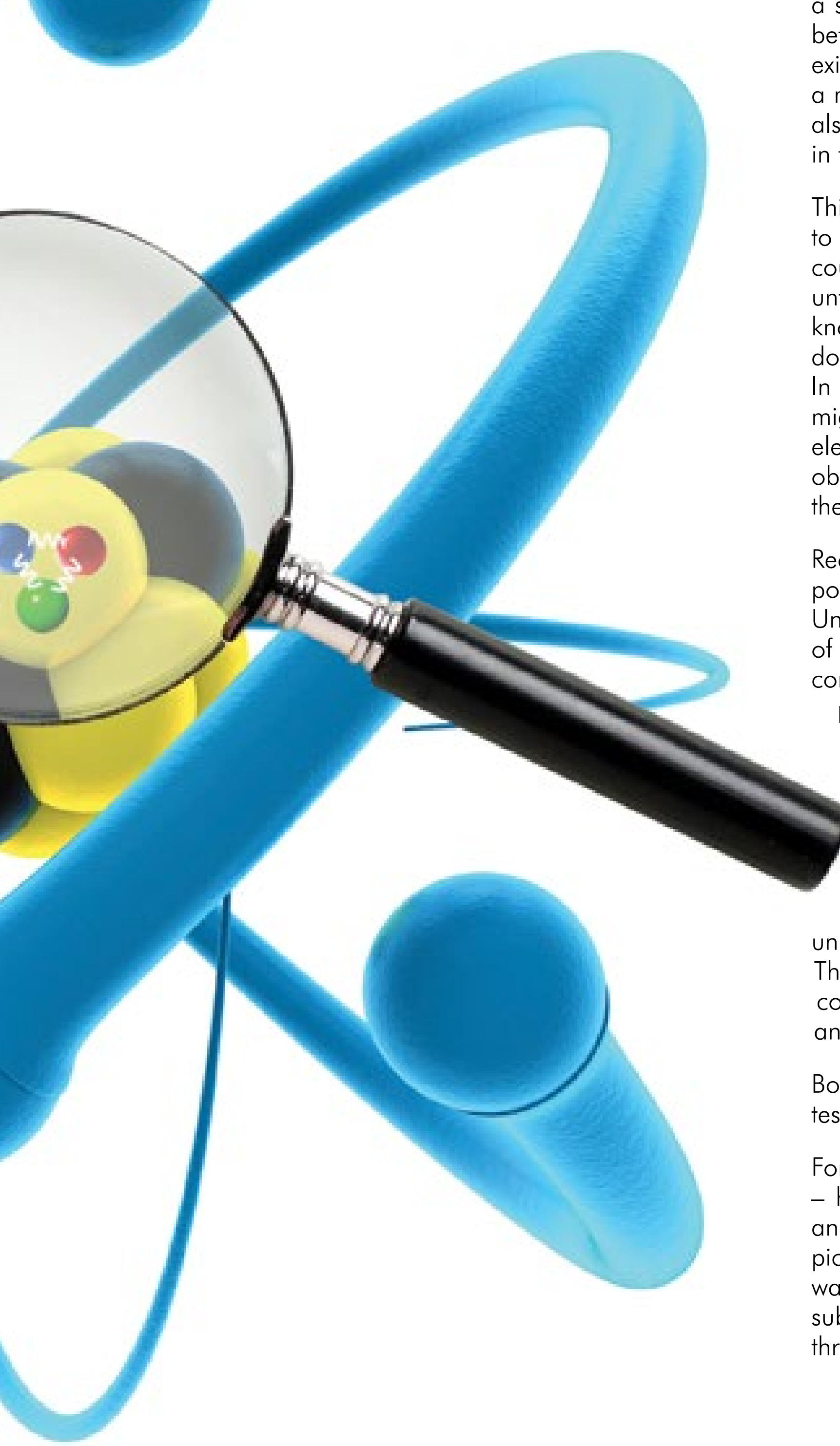
Then came 2010. A team of more than 30 researchers, led by Randolf Pohl and working at the Paul Scherrer Institute in Switzerland, produced a new measurement of the proton radius, using muonic hydrogen.

Muonic hydrogen is hydrogen in which the electron is replaced by a muon. Muons are unstable elementary particles that carry the



same charge as the electron, but are 200 times heavier. Like ordinary hydrogen, muonic hydrogen will have energy levels. But, because the muon is 200 times heavier than the electron, its orbit is 200 times smaller than that of the electron in normal hydrogen. The muons get so close to the proton that they almost drag through its charge cloud.

As you might imagine, this should make the effect of the cloud's size on the muon's orbit much stronger than its effect on the electron's orbit. Using muons, Pohl and his collaborators reasoned, should therefore give a more precise measure of the cloud's size. Their goal was to add a few more decimal places to a well-known number.



Instead, they emerged from their lab having seemingly shrunk the proton.

This new-ish finding still puzzles the research community. "It's certainly possible that there's an answer within the Standard Model," says Yavin. "There may be subtle quantum electrodynamic effects that could clear the whole matter up, for instance. Still, it is worth considering whether new physics could be the explanation."

By new physics, in this case, Yavin means a new force of nature. In 2011, Yavin and David Tucker-Smith of the Institute for Advanced Study wrote a short paper on muonic hydrogen measurement. They proposed that a new force could lead to a slightly stronger attraction between muons and protons than between electrons and protons. Specifically, they posited the existence of a new force-carrying particle with a mass of about a megaelectron volt, or MeV. Interestingly, this new force could also explain a different puzzle – the long-standing discrepancy in the measurement of the muon's gyromagnetic ratio.

This proposal is not without its problems. It's easy for researchers to posit a new force carrier that doesn't affect electrons – it might couple to mass rather than charge, leaving electrons mostly untouched because they are so light. However, researchers also know (from experiments not discussed here) that the new force doesn't couple to neutrons either, and neutrons do have mass. In order to leave neutrons untouched, the new force carrier might couple to charge rather than mass – which would put electrons back into the mix. Mass and charge are the only two obvious channels for interaction, so it's difficult to imagine how the new force carrier might work.

Recently, this was addressed by Pospelov, working with two postdocs, Brian Batell at Perimeter and David McKeen at the University of Victoria. The researchers found that a certain type of dark photon can provide the required force while staying consistent with the rest of the Standard Model. The dark photon is the hypothetical carrier of the equally hypothetical dark electromagnetic force – a sort of mirror version of electromagnetism that would affect dark matter the same way electromagnetism affects ordinary matter.

Dark photons and dark electromagnetism are a fairly new way some theorists are thinking about dark matter – that mysterious stuff that makes up 25 percent of the universe, though not a particle of it has ever been found. The specific kind of dark photon described by Pospelov and collaborators might be a bridge between the dark matter world and the ordinary world, which is a tantalizing idea.

Both Yavin and Pospelov have suggested experiments that would tests their ideas.

For the moment, the radius of the proton – once so certain – has become an open puzzle. It will take more experiments and more thought before the physics community has a clearer picture of what is behind the discrepancy between the different ways of measuring the proton's radius. It might be nothing: a subtle effect of something well known. But it might be the crack through which the light gets in.

- Erin Bow

Dark Matter in the Dumps?

When searching for treasure, sometimes the best place to look is the dump.

A team of Perimeter researchers is on the hunt for one of the most sought-after treasures in science: dark matter, the invisible fabric that makes up most of the universe. And they hope to find it at the dump.

More specifically, they want to look for dark matter at an electron-beam dump – the place where unwanted energy is sent to fizzle out after particle accelerator experiments.

It is generally accepted that dark matter represents the majority of the total mass in the universe; cosmology would essentially fall apart without it. But since we can't directly see dark matter – it neither emits nor absorbs light – its make-up remains mysterious.

Faculty members Natalia Toro and Philip Schuster, with postdoctoral researchers Eder Izaguirre and Gordan Krnjaic, propose that dark matter might lurk just beyond where other particles go to die.

Particle accelerator experiments blast billions and billions of energetic electrons at focused points in order to measure and interpret the scattering from collisions.

After an experiment, all that energy needs to be safely dissipated, so it's shunted off to the "dump." This dense layer of material (often in layers of copper, aluminum, and beryllium) fizzles the energy like a wet blanket as electrons repeatedly interact with the atoms that make up the dump, losing energy each time.

But could, the researchers wondered, some unusual particles produced in electron collisions interact so weakly with other particles that they might zip right through the dump and be detected on the other side? Might those peculiar survivors be part of the elusive dark matter?

"There are unexplored possibilities for dark matter there," says Schuster.

Experiments designed to directly detect dark matter typically look for relatively heavy particles (up to roughly 1,000 times the weight of a proton), since the most popular hypothesis suggests that dark matter is made up of weakly interacting massive particles, or WIMPs.

But it's conceivable that dark matter consists of much lighter particles, each just a fraction of the mass of a proton. This postulated stuff is called "light dark matter" (not without a hint of irony).

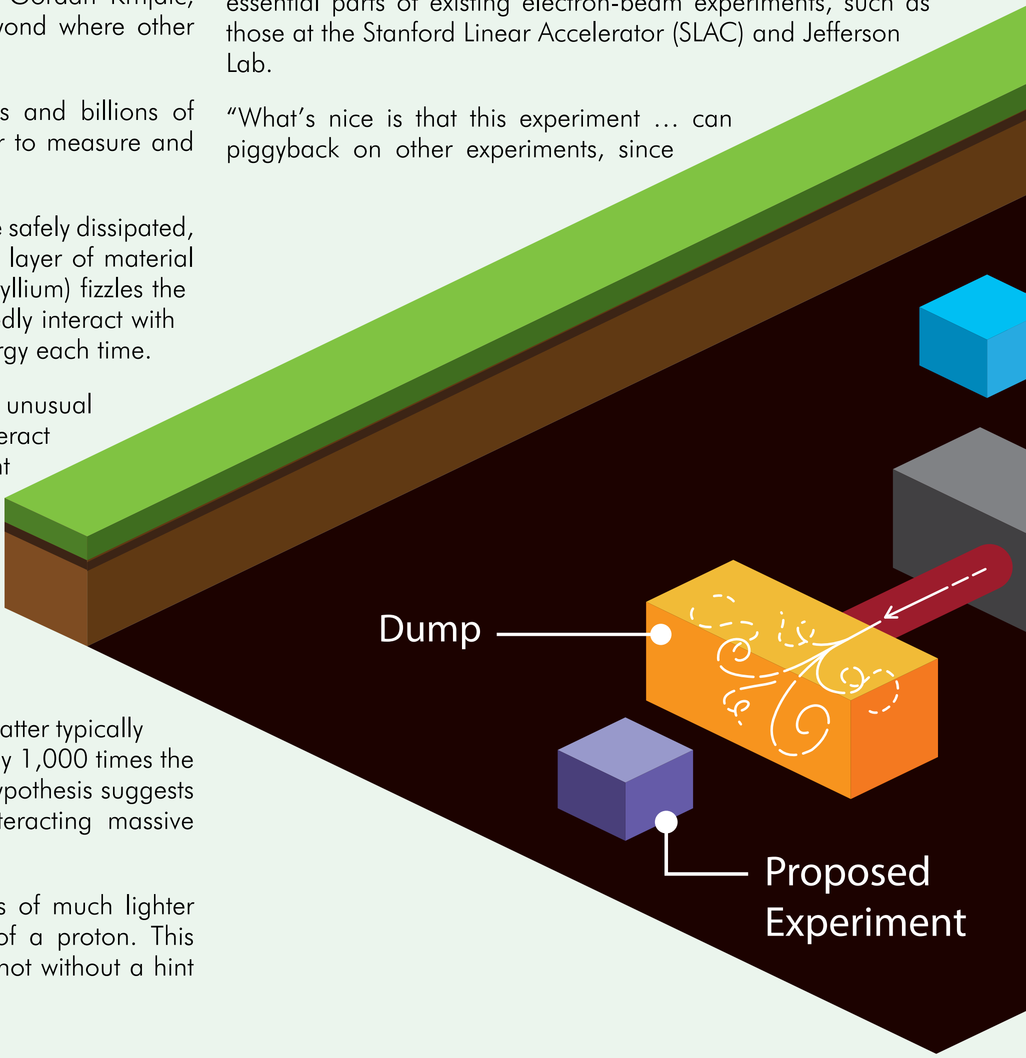
If dark matter particles in the galaxy are indeed such lightweights, they wouldn't collide against other particles with much oomph, making them tough to detect with conventional deep-underground particle-colliding methods.

Hence the dump. Behind an electron beam dump, any dark matter produced would be very energetic and much easier to see. The team realized that any such particles detected on the far side of the dump would represent a significant discovery – possibly the first-ever laboratory detection of dark matter.

The dump is also an ideal place to hunt for dark matter because there is relatively little background "noise" (the constant bombardment of cosmic radiation, for example).

The best part is that such an experiment can be carried out relatively easily and inexpensively, since it requires equipment no larger than a typical refrigerator, and dumps are already essential parts of existing electron-beam experiments, such as those at the Stanford Linear Accelerator (SLAC) and Jefferson Lab.

"What's nice is that this experiment … can piggyback on other experiments, since



what we want to do is all behind the dump, and nobody else wants to use that space," says Schuster.

In fact, a follow-up paper written by Schuster and former Perimeter Scholars International master's student Miriam Diamond re-examined a decade-old experiment at SLAC to determine whether its dump would have been viable for carrying out a dark matter experiment. Sure enough, the paper concluded, it would have. That SLAC experiment can be seen as a proof-of-concept for this new method of looking for particles beyond electron beam dumps.

The next step, of course, is to actually carry out the experiment. While that's not exactly an easy process – it will require an international collaborative effort with a team of experimentalists, not to mention digging a ditch to get behind a beam dump – it is certainly feasible, for a fraction of the cost of most high-energy physics experiments.

The Perimeter researchers believe the first stages of the experiment – and, perhaps, a discovery of great significance – are possible within the next five years.

Actually detecting dark matter would "make our picture of the universe significantly more complete," Schuster says.

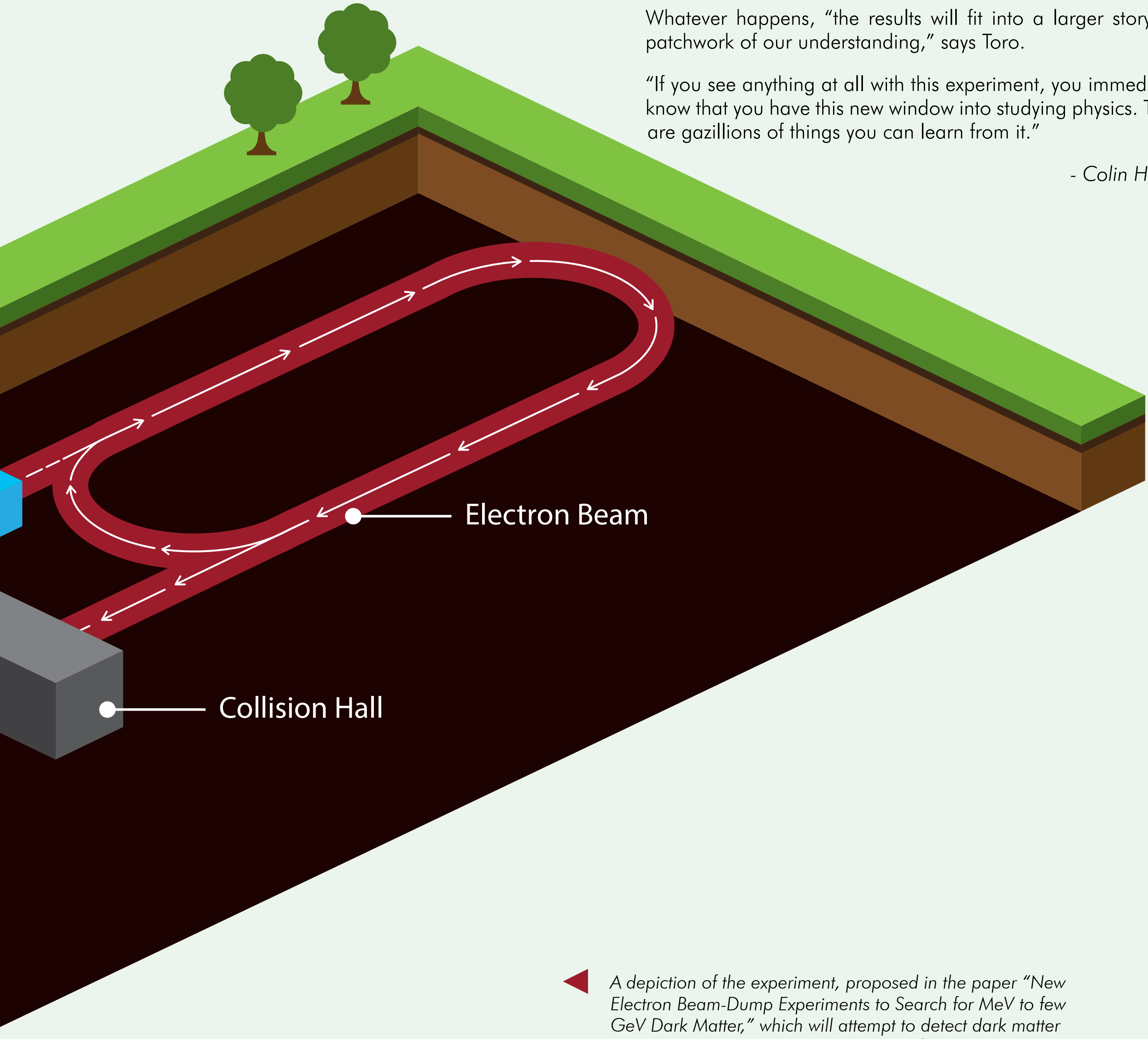
Of course, it's entirely possible that the experiment won't find dark matter. Perhaps dark matter is, as many theories suggest, relatively heavy and thus not detectable through this method.

Failing to detect dark matter would not, however, be a failure of the experiment. Exploring the far side of the dump could turn up nothing, or it could yield a wholly unexpected treasure.

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

"If you see anything at all with this experiment, you immediately know that you have this new window into studying physics. There are gazillions of things you can learn from it."

- Colin Hunter



A depiction of the experiment, proposed in the paper "New Electron Beam-Dump Experiments to Search for MeV to few GeV Dark Matter," which will attempt to detect dark matter particles just past the dump at the end of an underground particle accelerator

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FAST TRACK COMMUNICATION

Can apparent superluminal neutrino speeds be explained as a quantum weak measurement?

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Abstract
Probably not.

PACS numbers: 03.65.Ta, 03.65.Xp, 14.60.Pq

Conference participants at "Emergence and Entanglement II"

EMERGENCE AND ENTANGLEMENT II

May 6-10, 2013

This past spring, 40 brilliant physicists from around the world converged on Perimeter Institute to figure out what's the matter – specifically, what's the quantum matter.

Few areas in physics are leaping ahead as quickly as our understanding of quantum matter – that is, matter that exhibits quantum effects not just a few particles at a time, but billions of atoms at a time, at the scale of tables and chairs. While most states of matter are described by the patterns of their atoms or electrons, quantum states of matter are described by patterns of quantum properties, particularly entanglement. It's like describing a city not in terms of the layout of its streets, but in terms of the ideas being exchanged in phone calls.

Describing the properties of quantum matter has long been mathematically daunting. But, in the last few years, new understandings of how properties of matter emerge from patterns of entanglement have allowed researchers to classify the exotic phases of quantum matter. A new mathematical language for talking about long-range entanglement has emerged in the form of tensor networks.

Building on the success of the first "Emergence and Entanglement" workshop held at Perimeter in 2010, this invitation-only event covered the latest developments in this exciting field. Panelists included eight of Perimeter's Distinguished Visiting Research Chairs, making it one of the largest single gatherings of these top international minds. Researchers from the fields of condensed matter, quantum information, computational physics, and string theory all contributed to this interdisciplinary discussion.

Check perimeterinstitute.ca for conference updates

Upcoming Conferences

PI-UIUC 2013
Thursday, November 7, to Friday, November 8, 2013

WATERLOO SOFT MATTER THEORY
Thursday, December 5, 2013

Conference participants at "The Quantum Landscape"

THE QUANTUM LANDSCAPE

May 27-31, 2013

Over the course of five days in May, more than 40 researchers from around North America, Europe, and Asia gathered at Perimeter Institute to discuss the blueprint for how we understand nature at its most fundamental level: quantum mechanics.

There's no question quantum mechanics is mathematically coherent – beautiful, even – and the most well-tested and verified theory in the history of physics.

Whether quantum mechanics is the fundamentally *correct* description of nature, however, remains uncertain. We know at least that it is incomplete, because it cannot explain gravity. Several competing theories attempt to unify quantum theory and gravity, but none is conceptually well-defined and empirically tested, and none rigorously explains cosmological data.

Alternatives to quantum theory have been increasingly explored in recent decades, partly in the hope of resolving these problems, and partly with the aim of better understanding quantum theory itself. One outcome of this exploration is a suite of strong experimental tests that could, in principle, distinguish between competing alternatives. In parallel with theoretical developments, advances in matter interferometry and other areas have also made new tests possible. The result is a new landscape of possible theories, of which quantum theory is only one region. The new tests are useful in marking the edges of this map.

The conference brought together theorists working on possible extensions and new realist formulations of quantum theory with experimentalists looking to test quantum theory against possible generalizations. Counterpoint was provided by researchers who have proven strong new constraints on the possibility of extending quantum theory, and theorists with arguments against extending or reformulating quantum theory.

This may well have been the first major conference on generalizations from quantum theory, and it is safe to say it won't be the last.

Conference participants at "Cosmological Frontiers in Fundamental Physics"

COSMOLOGICAL FRONTIERS IN FUNDAMENTAL PHYSICS

July 8-11, 2013

These are exciting times for cosmology, as new experimental data is unveiling our universe in unprecedented detail. The excitement was palpable this past summer when dozens of the world's leading cosmologists convened at Perimeter Institute for the "Cosmological Frontiers in Fundamental Physics" conference, to talk about the latest developments in the fast-changing field.

Holographic cosmology, eternal inflation, inflationary cosmology, primordial magnetic fields, string cosmology – the conference covered all this ground and more.

This year, two of the main areas of focus were the implications of the cosmic microwave background data from the Planck satellite, which just came in this May, and developments in massive gravity, which has seen a resurgence of interest due to progress overcoming some of its traditional problems.

This year's conference was the seventh in a series of workshops jointly organized by the International Solvay Institute, the APC (University of Paris VII), and Perimeter Institute.

LOOPS 13

July 22, 2013

Perhaps the largest-ever conference on quantum gravity – an area of research that aims to reconcile quantum mechanics with general relativity – unfolded at Perimeter Institute over five days this past summer.

Quantum gravity aims to unify Einstein's vision of spacetime as a dynamical object with the realization that fundamental physics, and hence spacetime, has to be quantum. It's a fast-changing field from which new ideas and discoveries are emerging every day. So the timing was right for Perimeter to host a Loops conference, which is held every two years at one of several different institutions.

There were 194 total participants and a rich diversity of approaches, nationalities, and ages, ranging from 17 to 75. The conference also featured 21 plenary talks that highlighted the most important recent developments in quantum gravity research, and 133 parallel session talks that ran in four separate venues. And, to keep things lively, there were soccer and foosball tournaments. All told, Loops 13 was the biggest and most complex conference ever put on at Perimeter, casting new light on one of the most important and fast-evolving topics in science.

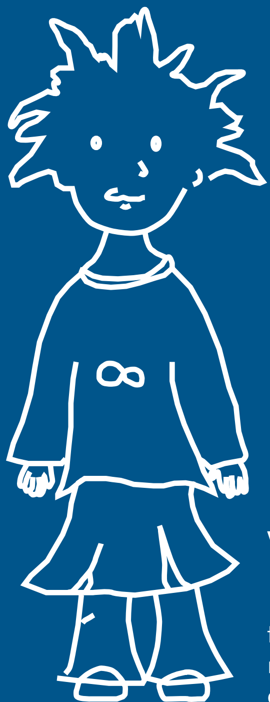
Former Perimeter postdoc and Loops 13 participant Simone Speziale (in yellow) uses bodily movements to serve as "guest conductor" during a piece by the TorQ Percussion Ensemble. The Toronto-based quartet performed sonic experiments in time and space during their sold-out concert at the Loops 13 conference, titled "A Shift in Time."

NEWTONIAN STUDIES OF BLACK-HOLE STARS MEET GENERAL RELATIVITY EFFECTS

August 19-30, 2013

Roughly a dozen top experts in black hole physics from North America and Europe came together at Perimeter this summer for a highly focused conference in the field of strong gravity. The researchers discussed the phenomena associated with how black holes – the gravitational powerhouses of the universe – interact with material sources through long time scales. The assembled scientists were particularly interested in exchanging ideas about the best known techniques and methodologies for accurately analyzing such systems. Conference organizer Luis Lehner and collaborator Enrico Barausse (Institut d'Astrophysique de Paris) shared a post-Newtonian-based formalism they recently developed, which accounts for an improved treatment of black hole effects on matter. Participant Enrico Ramirez-Ruiz (University of California, Santa Cruz) shared his approach to sophisticated simulations that account for microphysics. One of the aims of this unique conference was to combine such innovative research efforts into a unified approach to many important astrophysical phenomena.

PI KIDS ARE ASKING



Ryan, who is 11, recently visited the doctor with a fever. Ryan reports the doctor said the thermometer "took a picture of my temperature." That seemed weird to Ryan, who asks: "How can you take a picture of your temperature?"

We're guessing from your question, Ryan, that you already know heat is motion – that your temperature ultimately measures how much the atoms that make up your body are jiggling. The faster those atoms are going, the higher your temperature. This is why you can make your hands warmer by rubbing them together – it gets the atoms wiggling around faster.

So when you think of heat as atoms moving, it does seem weird to think you can "take a picture" of it. What are we missing?

In a word: light. Warm things glow. Think of the glowing burner on an electric stove, or the glow of molten lava. What's happening is that the vibration – the wiggling – of the charged particles caused by heat creates an electromagnetic wave. And "an electromagnetic wave" is just a technical term for light.

So, you're glowing because you're warm. Specifically, you give off light in the infrared part of the spectrum, which isn't quite visible to our eyes (infrared wavelengths are a little bit longer than those our eyes can detect). The infrared glow humans give off is invisible to other humans – though it shows up on thermal cameras, and certain animals can see it. Ear thermometers can see it too.

How do we get from seeing light to measuring temperature? Well, the really interesting thing about warm things glowing is that the colour of the glow depends on exactly how warm the warm thing is. "Red-hot," for example, is not just a turn of phrase. Things begin to glow dull red at 525°C.

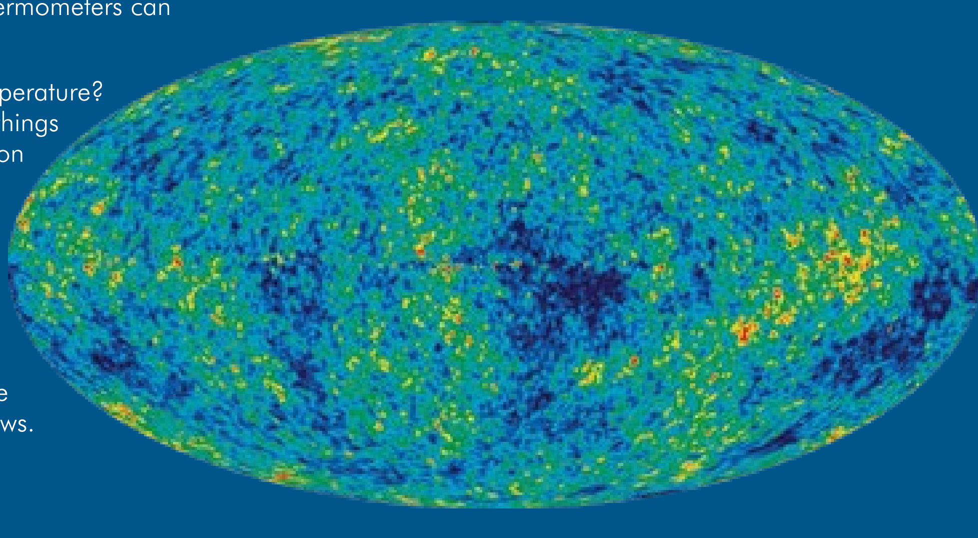
Physicists use this connection between temperature and colour to learn about the universe in many surprising ways. For example, did you know that you can take the temperature of the sky? Because, guess what? The sky glows.

Even when you look beyond the stars, beyond the distant galaxies, beyond the quasars, even when you look at the most distant emptiness you can find, the sky glows. Its average colour is way, way down below what humans can see, with wavelengths 10,000 times longer than the wavelengths of visible light. But nevertheless, it glows.

This glow, called the cosmic microwave background, is proof that, very far away and very long ago, the entire universe was very hot. It's the most direct proof we have that the universe began with a big bang. There are specialized telescopes and satellites – think of them as the world's best ear thermometers – that have taken a picture of this glow and measured its temperature. Measuring this temperature and the tiny variations in it has taught us a lot about the universe, including its age: about 13.8 billion years.

So taking a picture of temperature is not just possible – it's pretty cool.

- Erin Bow



Igniting Curiosity: BrainSTEM Draws Thousands

The BrainSTEM: Your Future is Now Festival welcomed scientific explorers of all ages to Perimeter Institute through the first week of October.

Attendance at the festival was close to 25,000 – including nearly 2,500 high school students – over the exciting week of activities. Visitors chatted with Perimeter scientists, talked to a robot, tried on an invisibility cloak, explored wireless electricity, and discovered a range of emerging technologies made possible by STEM fields (science, technology, engineering, and math).

The sold-out public lecture series featured fascinating talks by James Grime, Raymond Laflamme, and Lucy Hawking. Science comedian Brian Malow had packed crowds laughing at "Science in the Club."

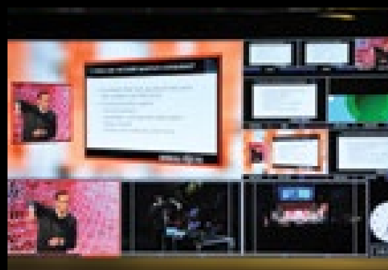
"BrainSTEM showcased the amazing things that can happen when curiosity and imagination are combined with scientific exploration and the entrepreneurial spirit," says Greg Dick, Perimeter's Director of Educational Outreach. BrainSTEM highlights are featured on the Perimeter Institute website.

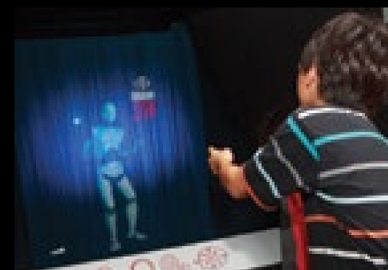
Federal Economic Development Agency for Southern Ontario | Agence fédérale de développement économique pour le Sud de l'Ontario | Canada | Ontario

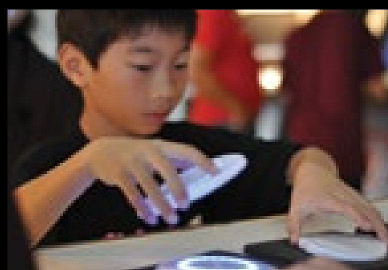
Sun Life Financial | tvo makes you think | Toyota Motor Manufacturing Canada Inc. | Waterloo Region Record Community Partnerships Program | Linamar Power to Perform

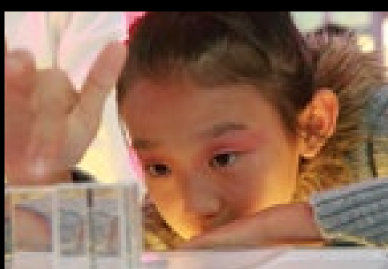
BRAINSTEM
a story in images



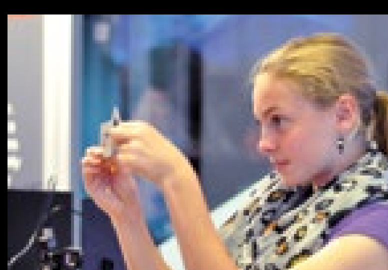
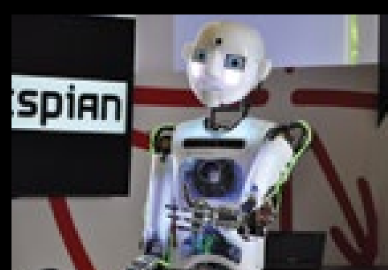



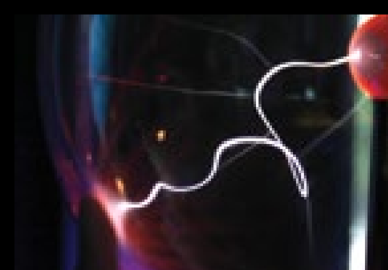
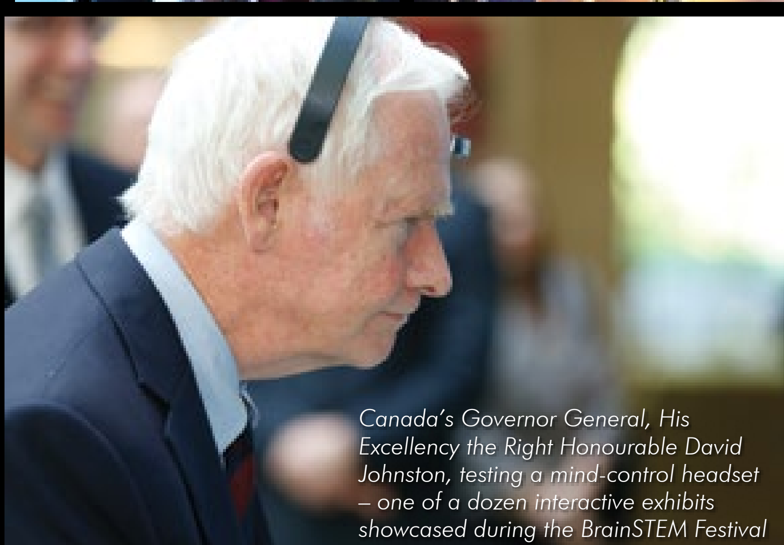




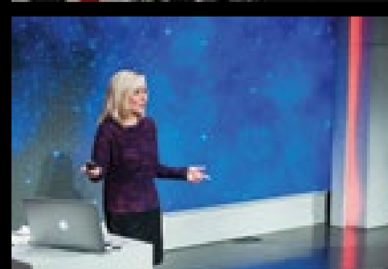
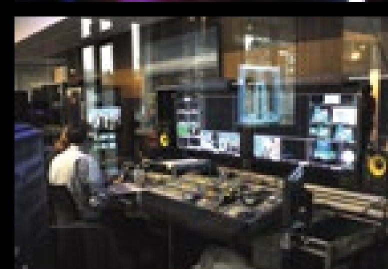
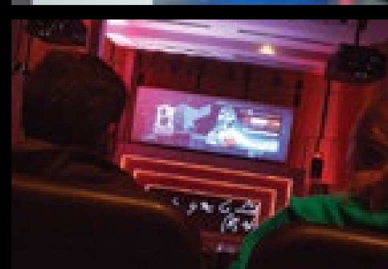





Canada's Governor General, His Excellency the Right Honourable David Johnston, testing a mind-control headset – one of a dozen interactive exhibits showcased during the BrainSTEM Festival



Science
Question
tvokids.com
#BrainSTEM

Celebrating Imagination and Creativity

James Grime demonstrated this original Enigma Machine, used to encrypt German messages during the Second World War, in his BrainSTEM public lecture.

"Imagination is the fuel of science."

With those six words, Lucy Hawking spoke volumes.

That inspiring idea – that great discoveries and innovations are the products of imagination – resonated through all three public lectures during Perimeter's BrainSTEM: Your Future is Now Festival.

Speakers in the series were Hawking, quantum information pioneer Raymond Laflamme, and codebreaking expert James Grime.

Hawking, daughter of cosmologist and Perimeter Distinguished Visiting Research Chair Stephen Hawking, spoke about incredible scientific discoveries sparked by pure curiosity.

Laflamme explained how scientists at Perimeter and the Institute for Quantum Computing (of which he is Executive Director) are developing technologies barely conceivable a generation ago.

Laflamme provided a guided tour of the counterintuitive phenomena of quantum mechanics, such as quantum superposition and entanglement, and how they are being harnessed to build new technologies of unprecedented power and precision.

"Suddenly, with quantum mechanics, we are able to do something we're not able to do in the classical world," he said. "We are now making our first steps in a technological revolution."

As Laflamme's talk looked to the remarkable technologies of the future, James Grime's focused on a game-changing piece of technology from the past.

Grime brought to Perimeter an original Enigma Machine, a 77-year-old device used by the German military to create secret messages during the Second World War.

He explained how the ingenious English mathematician Alan Turing cracked the seemingly unbreakable German codes and, in the process, created the blueprint for the general-purpose computer.

The innovations of Turing and the other codebreakers at England's Bletchley Park are believed to have shortened the Second World War by roughly two years.

"It's an example of using your brains to save people's lives," Grime said. "It's brains over bullets."

Hawking's lecture featured video greetings from her father, who issued a challenge to young people that echoed the theme of the whole BrainSTEM Festival: "Can you imagine a future that no one else has thought of?"

- Colin Hunter

Lucy Hawking addressing a packed house at the BrainSTEM Festival

Hawking's lecture was presented by Sun Life Financial.

Skills for the Journey: A New Perimeter Resource Debuts

Any way you slice it, success in the 21st century will require creativity, critical thinking, entrepreneurial spirit, and technical skills. Perimeter's newest resource for high school students, *Career Moves: Skills for the Journey*, offers students opportunities to build these skills within the STEM disciplines (science, technology, engineering, and mathematics).

Career Moves, tailored towards students in Ontario's Grade 10 Careers course, is the result of extensive collaboration between Perimeter's Outreach team and the professional educators helping Ontario students choose a career path. The resource is designed to empower students and excite them about what they can achieve through science and innovation.

The resource was unveiled during the BrainSTEM: Your Future is Now Festival (see page 27) by the Honourable Gary Goodyear, Minister of State for the Federal Economic Development Agency for Southern Ontario (FedDev Ontario), with observations from Kitchener-Waterloo Member of Parliament Peter Braid. The *Career Moves* resource, as well as the BrainSTEM Festival, were made possible through the support of FedDev Ontario.

"Our goal is to give students the best tools possible to fuel curiosity, exploration, and innovation," said Greg Dick, Perimeter's Director of Educational Outreach. "Students who are passionate about STEM subjects will be ready to face the challenges and opportunities of the 21st century. Our resources are designed to inspire students and build a smarter, more prosperous future for the world."

Career Moves is the ninth in-class kit developed by Perimeter Institute, joining a series of multimedia resources developed specifically for teachers that use cutting-edge physics research from Perimeter scientists. The just-released resource was made available to guidance counsellors and classroom teachers during BrainSTEM ICE (see page 8), who described it after the workshop as "an easy-to-integrate tool for any educator interested in empowering their students to explore 21st century skills," "an excellent pedagogical experience," and as emphasizing "essential skills and entrepreneurship."

The resource is currently available to teachers across Canada on the Perimeter Institute website.

- Phil Froklage

Federal Economic Development Agency for Southern Ontario
Agence fédérale de développement économique pour le Sud de l'Ontario

The Honourable Gary Goodyear (left) remarks on the importance of STEM education in Ontario.

"I Found the Place": A Young Talent Joins PSI

Jacob Barnett, sprinkled in chalk dust, scrawls complex equations on a floor-to-ceiling blackboard.

No matter how many vexing physics topics he tackles – general relativity, strong gravity, field theory – one class of problems remains just beyond his reach: the ones at the top of the blackboard.

At 15 years old, Jacob just isn't as tall as most of his scientific peers at Perimeter Institute. But like his older colleagues, Jacob's desire and ability to decode the deepest mysteries of the universe are boundless.

Still a year shy of eligibility for a driver's license, Jacob is studying in Perimeter Scholars International (PSI), an innovative and intensive theoretical physics program that draws exceptional young minds from around the world to Perimeter, allowing them to learn from leading minds in fields spanning cosmology, quantum information, mathematical physics, and other areas at the forefront of science.

He and his parents spent months touring some of the most renowned universities in North America and abroad, looking for the perfect place for Jacob to pursue his training and, ultimately, PhD. He had received offers from top universities, and his heart was set on Cambridge until he set foot inside Perimeter.

"This was very obviously the place where theoretical physics is conducted," says Jacob. "Everyone here is very into what they're doing and very successful at it. And there are equations on the windows, blackboards, everywhere."

In that sense, Perimeter instantly felt like home.

By age 12, Jacob had converted his bedroom into a physics lab, complete with glass-top desks on which he perpetually scrawled equations.

He received his first research grant that same year, which led to the publication of his first academic paper, "Origin of maximal symmetry breaking in even PT-symmetric lattices," in a leading physics journal.

It's serious physics. To Jacob, in a very real sense, it's child's play. He does physics because he absolutely loves it, and always has.

"I've been looking at the world very interestingly for as long as I can remember," says Jacob.

His family recalls that, as a baby, Jacob would spend countless silent hours watching the interplay of light and shadows in their Indiana home, quickly learning to tell the time – precise to the minute – simply by knowing the sun's position in the sky.

While still in diapers, he'd empty cereal boxes of their contents – not merely for the bliss of making a mess, but to calculate with decimal-point accuracy the volume of each box. While buckled up in his car seat as a toddler, he'd rhyme off the address of every house they drove past, then mentally add up those numbers and blurt out their sum.

Before he could talk, he strung elaborate matrices of yarn around his family's kitchen – geometric patterns that his parents later realized were equations in a kind of parallel mathematics that he had invented.

As if entangled in one of those complex spiderwebs of yarn, the story of Jacob's genius is intertwined with the story of his autism.

At first a bubbly and affectionate toddler, Jacob suddenly retreated into silence, spending years uncommunicative and seemingly detached from reality. Special education teachers urged his parents, Kristine and Michael Barnett, to lower their expectations for Jacob, warning that he might never speak or learn to tie his shoelaces.

Unwilling to accept the grim prognosis, Kristine pulled her son from preschool and committed to a home-schooling approach that focused on nurturing Jacob's interests, like weather patterns and starry nights.

His prodigious spark became fully evident when, before he was even old enough for kindergarten, Jacob piped up during a public astronomy lecture and, to the amazement of everyone in attendance, correctly pointed out that the moons of Mars are oval-shaped because their mass is too small for gravity to pull them into spheres.

The more Jacob studied physics, the more he emerged from the inner exile of autism.

At age 8, he began auditing physics and mathematics courses at Indiana University-Purdue University Indianapolis, and was fully enrolled and taking graduate-level courses by 12.

Having completed most of the advanced physics courses available there, Jacob turned his gaze to obtaining a full-fledged PhD at a top-tier institution.

He accompanied his mother on an international book tour – she recently published *The Spark: A Mother's Story of Nurturing Genius* – visiting universities and research institutions along the way.

The final stop of the book tour was this past June in Toronto, giving Jacob a chance to attend a colloquium about quantum gravity at the nearby Perimeter Institute.

Afterward, he said to his mother, "I found the place."

In August 2013, Jacob and 30 other students started the PSI program, studying under world-leading researchers from Perimeter and around the world.

To ensure Jacob was up for the challenge, Perimeter researchers assigned him several graduate-level course modules as homework, which he quickly completed.

Since he had not yet finished his bachelor's degree, Jacob is taking PSI as part of a University of Waterloo undergraduate "Independent Studies" program, which will take two years to complete – the first year as part of PSI and the second year conducting research supervised by a professor. After that, he will be ready to pursue doctoral studies.

Perimeter Academic Program Director John Berlinsky says Jacob's track record and proven grasp of advanced topics in theoretical physics made him an ideal candidate for the PSI program, which, over four years, has resulted in 125 top students from 37 countries graduating with University of Waterloo MSc degrees.

"The PSI program is custom-designed to allow graduate students to explore the full spectrum of theoretical physics," says Berlinsky. "Jacob was clearly ready for this experience."

Jacob hasn't yet decided what his long-term research focus will be – whether quantum gravity, string theory, cosmology, or particle physics – and that, he says, is part of the fun.

"There are so many areas I'm interested in. Physics is the foundation for understanding nature and the universe. I want to try it all, figure out my specialty, then go for it."

- Colin Hunter

Canada's Governor General, His Excellency the Right Honourable David Johnston, visits the 2013/14 class of Perimeter Scholars International (PSI), an innovative graduate program run in partnership with the University of Waterloo.

Envisioning the High School of the Future

Albert Einstein struggled in high school.

His problem wasn't a lack of intelligence – clearly – but a lack of *interest*.

Like so many high school students before and since, Einstein was put off by an educational system that valued rote memorization and strict authoritarianism over experiential learning.

A lot has changed since Einstein's day, but much remains the same.

Research indicates that two-thirds of students become intellectually disengaged during high school, their potential untapped by a system that fails to inspire them to learn.

That the high school class of 2030 is predicted to have 43 million dropouts globally is evidence that secondary education is in need of new ideas, new approaches, and a new beginning.

To begin that task, the Equinox Summit: Learning 2030 brought 33 education innovators from six continents to Perimeter Institute from September 29 to October 3. Their collective mission: to share the best educational practices and ideas from around the world and draft a blueprint for a new, more effective kind of high school.

It was the second such summit – the first, in 2011, focused on sustainable energy – hosted by the Waterloo Global Science Initiative (WGSI), a non-profit partnership between Perimeter Institute and the University of Waterloo. WGSI was created to promote dialogue and propose solutions to complex global issues.

This year's summit sought to re-imagine what high school should be like by the year 2030 – the year that children born in 2013 will graduate high school.

"We brought together people from all over the world, with expertise in some of the best practices we've been able to identify," said Michael Brooks, a British science journalist who served as curator for the summit. "By getting them together in one room to share these ideas, we are aiming for something more than the sum of the parts – solutions that we can apply globally."

Summit participants from vastly different social and economic backgrounds explored ideas of secondary education reform that have proven successful, sustainable, and economical, and have the potential to go global.

A principal from Singapore who has pioneered innovative approaches to technology in the classroom, for instance, brainstormed with an educator from Uganda who manages a school network in poor rural areas. High school students joined in the discussions to provide first-hand accounts of what inspires them – and what discourages them – in present-day high schools.

Bringing together experts from such diverse backgrounds, of course, did not result in an immediate consensus.

"It felt like we climbed a mountain that first day, because everyone had such radically different philosophies and visions for education," said Julie Wright, general manager of WGSI. "But we had a magic moment where everyone actively decided to set aside their differences and work collectively toward a shared vision for the future."

The goal was not to outline a specific curriculum for the future, but to lay the groundwork for a new education system that will adequately prepare young people for a world defined by rapid technological and social change.

The old "factory" model of education – in which an authoritarian teacher prescribes information to be memorized for exams – doesn't work in an era of information overload, when the answer to practically any question is a few keystrokes away.

What's needed are the skills to sift through vast amounts of data, think critically and creatively, extract meaningful information, and use it wisely.

The goal, as Einstein would say later in his life, is not merely to teach pupils, but to "provide the conditions in which they can learn."

The summit's four days of intense discussions culminated in a set of broad recommendations, which will be fleshed out in a more comprehensive Equinox Blueprint document, due out in early 2014. Those recommendations include: focusing on learners' rights, training a new kind of educator, shifting the focus from "knowing" to "doing," eliminating year-end exams, and rebuilding the "learning ecosystem."

Jennifer Groff, an educational researcher and Vice President of Learning at the US-based non-profit Learning Games Network, explained some of the summit's recommendations.

"The learner has the right to pursue their intrinsic motivations," said Groff. "They need the freedom to fail. We need to get rid of these monolithic exams at the end of the year. That doesn't mean there should be no way of measuring learning, but we need to rethink how we capture the *understanding* of learning."

John Baker, CEO of Kitchener-based educational software company Desire2Learn, applauded the efforts of summit participants to chart a new path for secondary education.

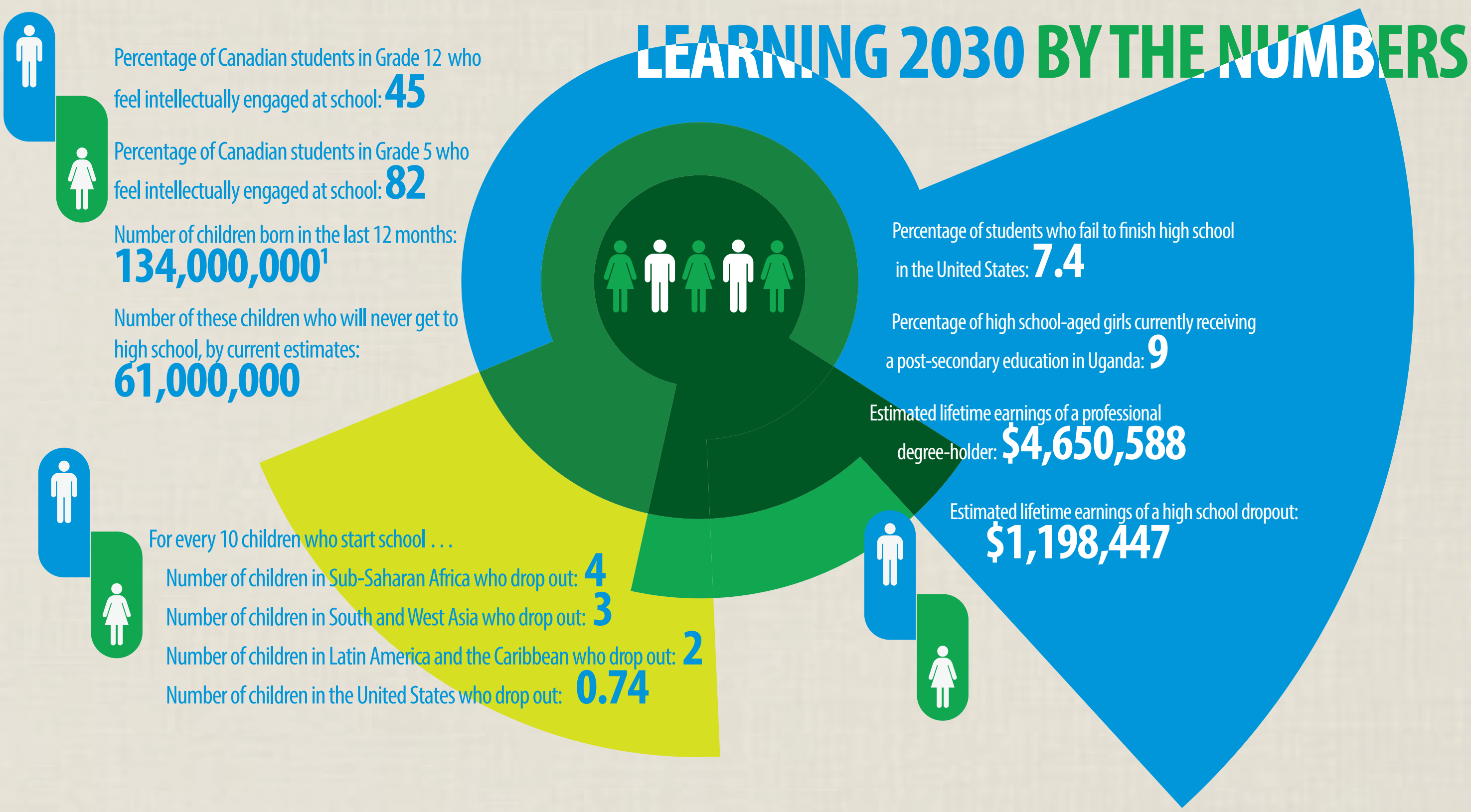
"There have been all these pockets of innovation and great ideas around the world, but no one until now that has been pulling them together into a blueprint for the future," said Baker. "We are at the very beginning of a sea change that is happening and we have to accelerate the change. We're not yet giving students all the tools they'll need."

The Equinox Blueprint, now being drafted by summit leaders, will be sent to education officials, governments, and policy-makers around the globe, with the goal of sparking fundamental changes in secondary education worldwide.

Brooks is optimistic that the Blueprint's recommendations will ultimately result in a vastly different, vastly improved education system – one that will prepare the newborns of today to become the productive and prosperous high school graduates of 2030.

"The work is just beginning," he said. "We are very much at the start of this journey."

- Colin Hunter



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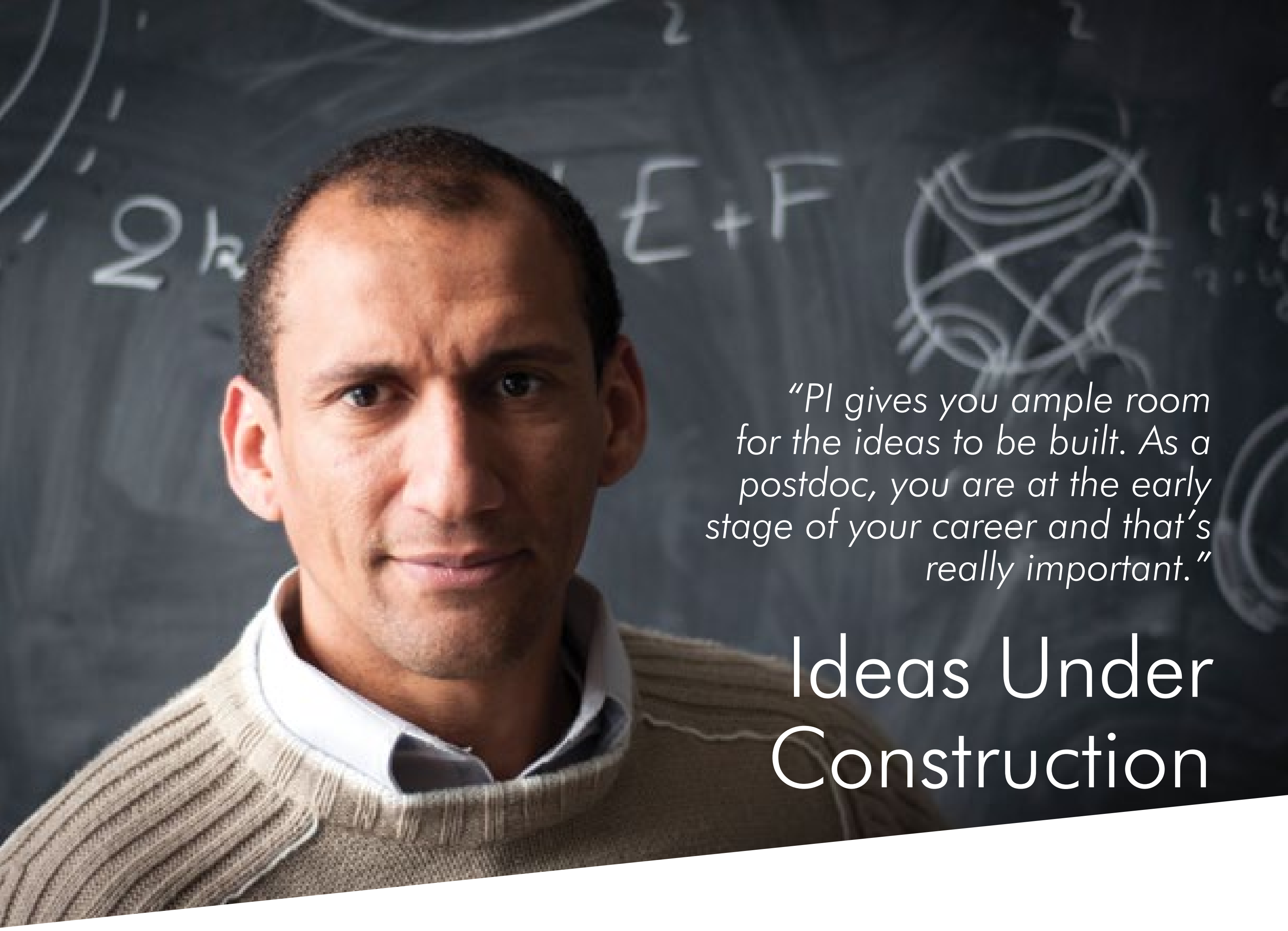
WGSI
Waterloo Global Science Initiative

[1] Based on 19.15 births per 1,000 total population, which is a medium variant per UN prediction of 2010-15 average global birth rate



"PI gives you ample room for the ideas to be built. As a postdoc, you are at the early stage of your career and that's really important."

Ideas Under Construction

When Joseph Ben Geloun thinks back to his arrival at Perimeter Institute in May 2010, he remembers himself as a young man eager to know everything, but not yet sure of who he was as a scientist. He'd already earned his PhD in Benin and completed a one-year postdoctoral fellowship at the National Institute for Theoretical Physics in South Africa, and he viewed Perimeter as a "bold, challenging place" where he could grow.

"I thought that it would be an amazing place to come and try to draw on the knowledge of bright minds – the brightest minds, maybe," remembers Ben Geloun. "I was trying to enrich myself, and I thought that Perimeter was the best place. And it turned out to be the case. But what was surprising for me was that at the end of my stay, I was able to share knowledge with those bright minds too."

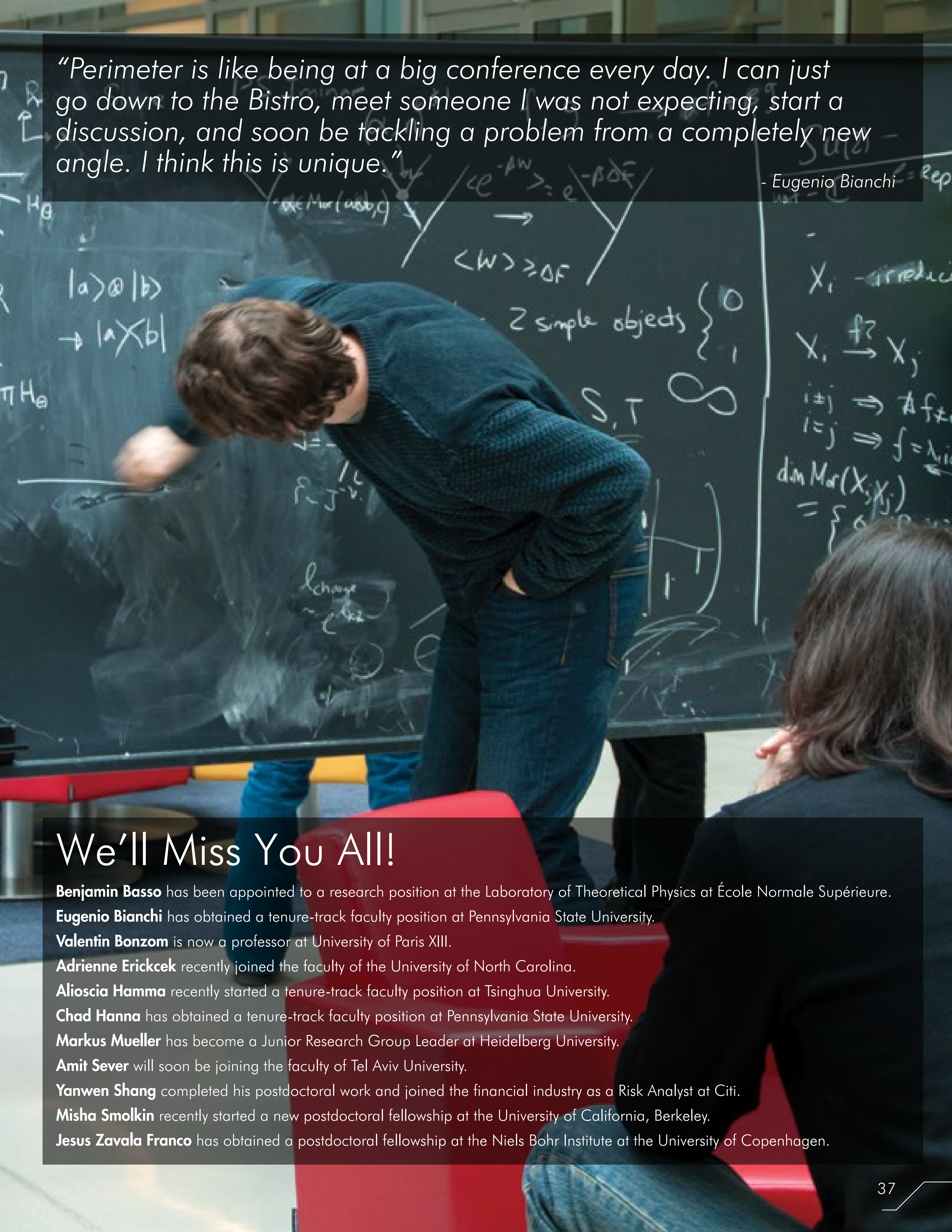
A lot can change in three-and-a-half years. As he prepares to leave Perimeter at the end of November, Ben Geloun is more confident in himself as a scientist. He understands his "own peculiar skills" and how they can be used to greatest effect within a collaborative research group. He knows what it means to pursue a research program, adapt, and explore directions that may not have been obvious at the outset.

With Perimeter Visiting Fellow Vincent Rivasseau, he has developed a physically and mathematically consistent model, called the Ben Geloun-Rivasseau (BGR) model, which generates infinitesimally tiny grains, called quanta, of four-dimensional spacetime. The BGR model predicts that these quanta likely "clump together" and it appears to work on several distance scales. The hope is that this model may ultimately provide a mechanism for understanding how the smooth spacetime geometry we experience at macroscopic scales could emerge from such quanta. This would be a major step forward in the search for a quantum theory of gravity, the "holy grail" of modern physics.

Ben Geloun's next stop is Germany. He's obtained a Humboldt Research Fellowship and will be taking up a postdoctoral position at the Max Planck Institute for Gravitational Physics (Albert Einstein Institute) in Potsdam-Golm. Eventually, he hopes to land a job at the University of Dakar in his home country of Senegal, where he can mentor a group of young theoretical physicists. But he will always be grateful to Perimeter for nurturing him in the early days of his career.

"PI gives you ample room for the ideas to be built. As a postdoc, you are at the early stage of your career and that's really important," reflects Ben Geloun. "I understand myself better now. I have new challenges of what I want to achieve in my future projects. And that's beyond my wildest expectations."

- Mike Brown



"Perimeter is like being at a big conference every day. I can just go down to the Bistro, meet someone I was not expecting, start a discussion, and soon be tackling a problem from a completely new angle. I think this is unique."

- Eugenio Bianchi

We'll Miss You All!

Benjamin Basso has been appointed to a research position at the Laboratory of Theoretical Physics at École Normale Supérieure.

Eugenio Bianchi has obtained a tenure-track faculty position at Pennsylvania State University.

Valentin Bonzom is now a professor at University of Paris XIII.

Adrienne Erickcek recently joined the faculty of the University of North Carolina.

Alioscia Hamma recently started a tenure-track faculty position at Tsinghua University.

Chad Hanna has obtained a tenure-track faculty position at Pennsylvania State University.

Markus Mueller has become a Junior Research Group Leader at Heidelberg University.

Amit Sever will soon be joining the faculty of Tel Aviv University.

Yanwen Shang completed his postdoctoral work and joined the financial industry as a Risk Analyst at Citi.

Misha Smolkin recently started a new postdoctoral fellowship at the University of California, Berkeley.

Jesus Zavala Franco has obtained a postdoctoral fellowship at the Niels Bohr Institute at the University of Copenhagen.

Paying it Forward

Lucas Hackl graduated from Perimeter's PSI master's program in 2011. Instead of going straight on to a PhD, he chose to spend two years helping to bring scientific training to the developing world.

After graduation, Hackl spent a year as a tutor for the African Institute for Mathematical Sciences (AIMS) in Senegal. AIMS was founded in Cape Town, South Africa, in 2003 by Perimeter Director Neil Turok, and is now globally recognized for excellence in postgraduate education and research.

"I first heard of AIMS by watching Neil Turok's speech for the TED Prize," he says. "I liked the idea of creating centres of excellence … bringing world-class science to Africa."

AIMS-Senegal was new at the time, having just been established in 2011, so there were plenty of interesting challenges for Hackl to address. "Being involved in shaping the educational system at the institute was hard work," recalls the 24-year-old Hackl, a native of Germany.

"Besides teaching every day, it takes a lot of time to establish the evaluation standards, the support systems for students struggling with the language, and so on." But his efforts paid dividends far beyond what he could have imagined: "It was incredibly rewarding to see progress: excellent students getting excited about advanced mathematics."

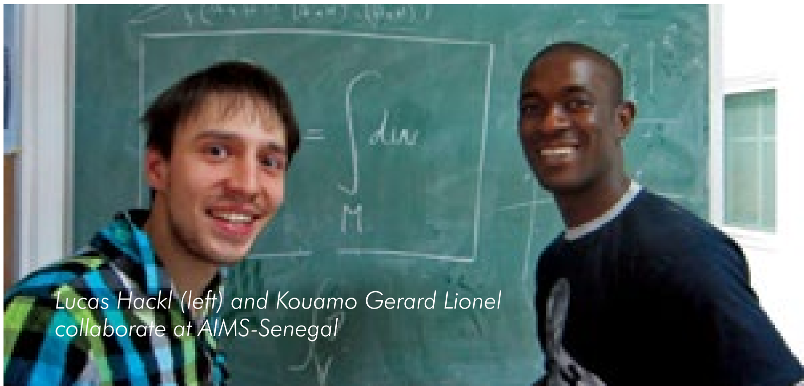
After leaving AIMS, Hackl took on an internship at Berlin's Global Public Policy Institute. He worked on a three-month study submitted to the German government on fragile developing countries, researching places like the Democratic Republic of the Congo, Iraq, and post-revolutionary Egypt.

Although such work might seem like a far cry from the intensive training of PSI, Hackl was pleasantly surprised to discover that his physics education came in handy in ways he hadn't fully anticipated: "I found that it's more important to be able to approach problems in the right way than to have a huge body of knowledge. I was surprised by how quickly I could jump in and do the kind of work that the others appreciated; there are great synergies to be found between natural scientists and international policy-makers."

Now, Hackl is beginning a PhD in physics, studying loop quantum gravity through an informal collaboration between Pennsylvania State University and the Centre de Physique Théorique at Marseille, France. "It's very exciting for me," he says. "It's great to be working with two of the most important centres in this field, and to be able to stay in contact with them. I can't wait to get started."

This year, Hackl has been collaborating with Perimeter Institute on a program aimed at helping Perimeter alumni remain connected and collaborative after graduation. "It would be great to stay in touch, and do it a little more formally than just regular Google Hangouts and Facebook groups. It would be nice to have something organized, with the support of Perimeter. The reaction so far has been really positive – people are telling me they are very interested in reuniting. My hope is that it can spark that PSI experience from time to time, even if for just a conference or a few days."

- Phil Froklage



Lucas Hackl (left) and Kouamo Gerard Lionel collaborate at AIMS-Senegal

A Gift for the Future, a Bridge to the Past

A new scholarship at Perimeter supports the brightest young minds in physics in honour of the first scientist in history. Two new foundations have teamed up to help Perimeter bring in new talent and train the next generation of scientific leaders. The Savvas Chamberlain Family Foundation and the Hellenic Heritage Foundation have each donated $50,000 to create the Anaximandros Scholarship at Perimeter Institute.

The scholarship aims to carry forward the scientific tradition launched by Anaximandros, the ancient Greek philosopher believed to have been the first scientist in history. It will provide $10,000 annually toward supporting a student of Hellenic or Greek-Cypriot heritage enrolled in Perimeter Scholars International, the Institute's master's program.

Established in 2011, the Savvas Chamberlain Family Foundation invests in organizations working to make Canada a more civilized, gentle, and caring society. It has already disbursed over $1 million to support education, the arts, culture, music, health and welfare, and the environment.

"Technology impacts business productivity, the economy, and the lives of everyone in Canada," said Dr. Savvas Chamberlain. "Theoretical physics is where technological innovation begins, but much of this science is very long-term. It takes time and vision to see major results. Our foundation is drawn to Perimeter because of its independence. The goals, priorities, and objectives of the Institute stay focused from year to year, which is the only way to make progress on the biggest, oldest problems in the field: with unswerving determination."

Established in Toronto in 1996, the Hellenic Heritage Foundation promotes Hellenic heritage, culture, and education in Canada. So far, they've raised over $5.5 million to support an array of initiatives, including a Chair of Modern Greek Studies, numerous fellowships and scholarships, and projects supporting seniors, youth education, and cultural events in the community.

"We're thrilled to be partnering with Perimeter Institute," said George Raios, President of the Hellenic Heritage Foundation. "Anaximandros was a fitting choice for the name of this scholarship; the Hellenic community has a long history of contributing to breakthroughs in science, and we're pleased that this scholarship will help the next generation carry on that tradition."

Perimeter's Chief Advancement Officer, Jonathan Braniff, said, "It is gratifying to see more people and organizations coming forward who understand that fundamental science is the key to improving every aspect of the world around us – from the environment, to health, to business, and even culture. Through the Anaximandros Scholarship, the Savvas Chamberlain Family Foundation and the Hellenic Heritage Foundation have forged a bridge from our scientific past to our future. We're deeply grateful for their support."

- Phil Froklage

HELLENIC HERITAGE FOUNDATION

Savvas Chamberlain FAMILY FOUNDATION

The First Scientist

Anaximandros (c.610-c.546 BC Miletus), also referred to as Anaximander, was one of the earliest Greek philosophers and proponents of science. His quest was to find natural explanations for phenomena that previously had been explained with appeals to supernatural powers.

Anaximandros had a particular interest in the origins of the universe. He believed that the universe is boundless and infinite. With his assertion that physical forces, rather than supernatural means, create order in the universe, Anaximandros can be considered the first physicist.

He has been called the father of astronomy, and cosmology, because he was the first thinker to use mathematical proportions to map the heavens. He was also the first to draw a map of the known world, which was later refined by travellers and other scholars.

Anaximandros' lasting influence comes from his insistence on rational explanations of the world. With this basic principle of scientific reasoning, he was able to develop theories much more accurate than those of his contemporaries: that man originated from another animal, that motion was connected to properties in the world (such as hot and cold), and other visionary scientific ideas.

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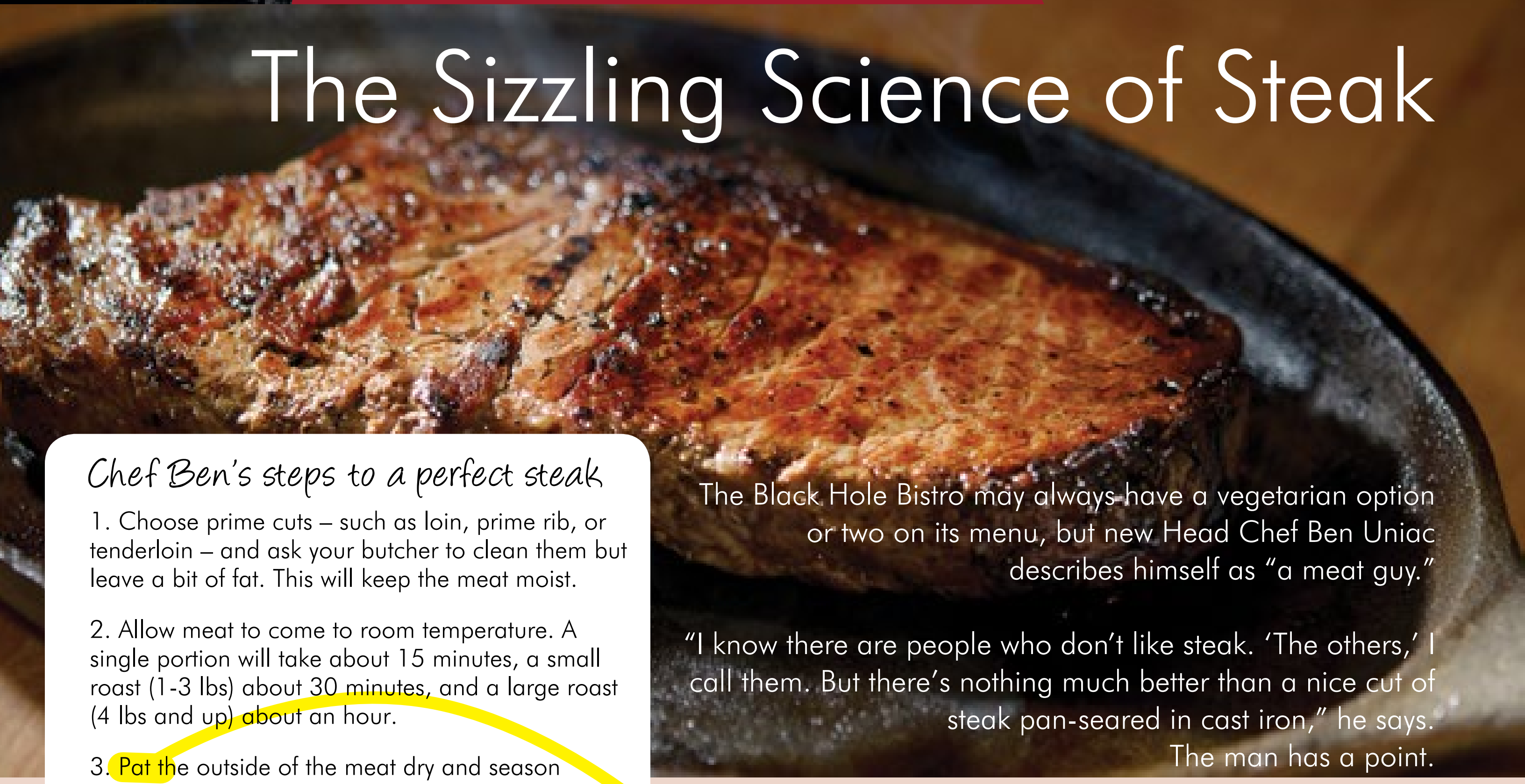
The Sizzling Science of Steak



The Black Hole Bistro may always have a vegetarian option or two on its menu, but new Head Chef Ben Uniac describes himself as "a meat guy."

"I know there are people who don't like steak. 'The others,' I call them. But there's nothing much better than a nice cut of steak pan-seared in cast iron," he says. The man has a point.

Chef Ben's steps to a perfect steak

1. Choose prime cuts – such as loin, prime rib, or tenderloin – and ask your butcher to clean them but leave a bit of fat. This will keep the meat moist.

2. Allow meat to come to room temperature. A single portion will take about 15 minutes, a small roast (1-3 lbs) about 30 minutes, and a large roast (4 lbs and up) about an hour.

3. Pat the outside of the meat dry and season generously with salt and pepper.

4. Heat a cast iron or thick-bottom pan over high heat until slightly smoking, and drizzle high smoking-point oil such as canola, safflower, or grape seed.

5. Sear the meat until dark golden on both sides (for a steak) or all sides (for a roast).

6. Place steak or roast on roasting rack (roasting pan or baking sheet with a rack) so that the meat is not sitting directly on the pan or tray.

7. Smother meat with compound butter, which is butter mixed with your favourite combination of herbs and spices. Mine is garlic, lemon zest, fresh thyme, rosemary, and parsley. The butter will melt through the meat as it cooks, and add to the crust on the steak.

8. Place in a 225°F oven until a meat thermometer piercing the centre of the meat gives the reading you want: 125°F for rare, 135-140°F for medium rare, 150°F for medium well, or 160°F for well done. The cook time will vary from 10 to 20 minutes for a single steak, one to two hours for a small roast, and two-plus hours for a large roast.

9. Allow your meat to rest, loosely covered with foil, for roughly half the cooking time to a maximum of 30 minutes (for example, a steak cooked for 10 minutes should rest for five minutes). This allows the juices to reabsorbed into the meat before you slice it.

10. Enjoy with a delicious Côtes du Rhône red wine, or whatever your favourite red may be.

If a steak is wet or is being cooked in liquid, it will not reach the right temperature for browning. All the (heat) energy being pumped into the meat from the pan will go first to boosting the water on the steak through the phase transition from liquid to steam, and the whole steak-water system will stay at 212°F until that transition is complete – after which you'll have a dried-out piece of shoe leather for dinner. This is also why the meat in the oven is lifted from the bottom of the pan: it will sit in its juices otherwise.

The notion that meat is seared in order to seal in juice is widespread, but incorrect. It's actually all about enhancing flavour. Searing meat jumpstarts one of the great processes in food: a complicated chain of events known collectively as the "Maillard reaction." In the Maillard reaction, which occurs most readily between 300°F and 500°F, amino acids and simple sugars naturally present in the meat react with each other to form new compounds. In steaks, they form more than 600 compounds, which is what gives the crust on a seared steak such an incredible richness of flavour.

How can you tell the Maillard reaction is happening? In a word: colour. The various compounds produced in the Maillard reaction reveal themselves in arrays of rings that reflect light as brown, from tan to deepest caramel. Black bits, however, are just carbon, and they mean you've burnt your dinner.

Why cook steak in two steps? First, it lets you cook steak through without burning the outside. Second, it makes your steak more tender. Meat contains several proteins, and the one that makes it "tough" is collagen. Between 140°F and 150°F, the long, stringy collagen molecules slowly disintegrate. They form a gelatin, which then dissolves into the juice of the meat. Physicists, especially the high-energy lot, are used to lightning-fast reactions, but this is organic chemistry, and it takes a while. The relatively cool oven gives it the time it needs.

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