inside the Perimeter

fall/winter 2017/18

The Centre for the Universe

Physics haiku

Innovation150 wraps up

Black holes, dark matter, and quantum sneak peeks

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

inside the Perimeter

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WHERE GOLD IS FORGED

We live in a golden age of discovery of the cosmos – quite literally.

Gold is among the elements blasted out of a kilonova, the violent merger of neutron stars, observed recently for the first time. And that is only the latest in an unprecedented sequence of discoveries which keep lighting up new corners of the cosmos.

Not only was it a scientific first, but the kilonova event was witnessed in a rich variety of new ways. The newly-operational Virgo gravitational wave detector, added to the two LIGO detectors, enabled scientists to locate the neutron star merger in the sky. Then, using gamma ray and light telescopes, they were able to pinpoint the *exact* location of the merger, 130 million light years away, and to witness it as it unfolded over the next week – from an extremely high-energy burst of gamma rays, to an intense flash of UV light, and then cooler red, infrared light and finally radio waves. Each of these channels of light added its own piece of information to a detailed story of a cosmic cataclysm.

This discovery marks the dawn of multi-messenger astronomy, in which cosmic phenomena can be viewed from many different angles at once, allowing us to test theories and models as never before.

Einstein's discovery that spacetime is curved, that it bends and moves in response to the matter and energy within it, is one of the most remarkable ideas in science. In extreme cases, spacetime curves so strongly that black holes are formed. When two black holes merge, in a swirling dance, ripples in spacetime are sent outward at the speed of light.

That elegantly strange idea spawned a 40-year effort involving over 1,000 scientists from around the world who developed the technology capable of detecting these waves. LIGO is an extraordinary example of the power of collaboration, generating landmark discovery upon landmark discovery. One should not forget, likewise, that Einstein himself was a part of a network of theorists and mathematicians, who helped him develop his ideas.

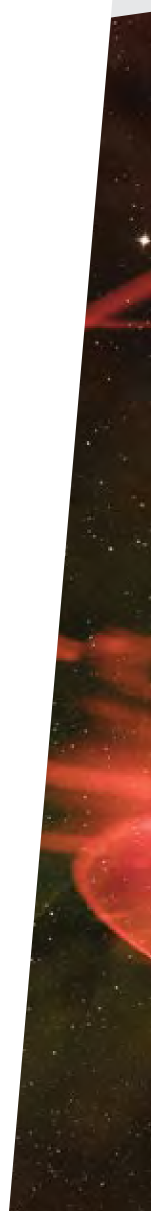
In the two years since LIGO launched, we have learned an enormous amount about black holes and extreme gravitational phenomena. Most exciting of all, the gravitational wave observatories of the future may allow us to detect signals from the birth of the universe.

When LIGO's founders won this year's Nobel Prize, for the detection of gravitational waves, they immediately pointed to the large community that had made its discoveries possible.

Science has an extraordinary way of bringing people together around ideas, creating special communities that are capable of far more than any individual.

That is the motivation behind Perimeter Institute's existence: by creating a community of minds, by challenging each other, by putting ideas into collision, by drawing on one another's strengths and enthusiasm, we can collectively develop new understanding that will ultimately enrich humanity.

Given the many new windows opening on the cosmos, we were recently delighted to announce the launch of a new Centre for the Universe at Perimeter Institute. Its first goal is to design and analyze new observations and experiments, to shed light on key mysteries. In tandem, the Centre will support the intense development and testing of new theoretical ideas and techniques. Centre scientists will interact with and inform the entire Perimeter community about developments in cosmology and the clues they provide. Perimeter Institute provides the ideal environment within which those clues can inform and guide profound new theoretical advances.



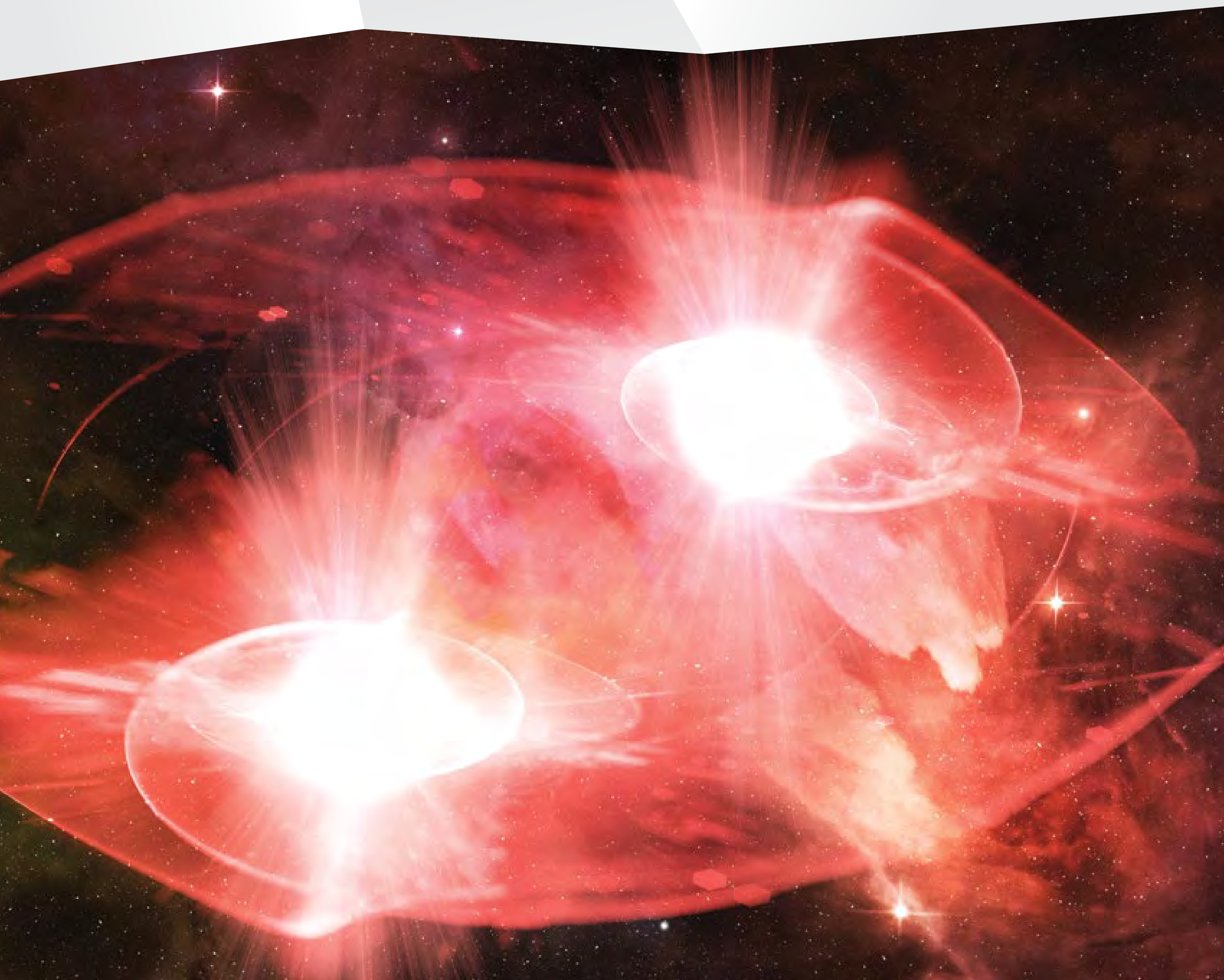
We aim to create a scientific effort characterized, like LIGO's, by focus, excellence, and humility. While drawing strength from Perimeter's greater community, the Centre for the Universe will bring together scientists – particularly young scientists – from around the world, and across the spectrum of physics, to explore fundamental questions in cosmology. What is the nature of the dark energy? What is dark matter? How do black holes really work? How did the universe begin?

These are some of the hardest but most fascinating questions in science. We are fortunate to live at a time when those questions are testable with real observations.

Kilonovas might be the source of planetary volumes of gold, but the real treasure is the human endeavour that enriches our understanding and experience of the world we share. At a moment when society is under myriad stresses, science – built on curiosity, creativity, courage, and collaboration – is delivering more richly than ever. It provides an example that our fractious and divided world can draw inspiration from.

The wonderful promise of the Centre for the Universe – and of Perimeter – is that we can bring people together to raise our game both as scientists and as human beings and, in so doing, help reveal and understand our place in this vast, intriguing, and beautiful cosmos.

– Neil Turok



New faculty to advance quantum matter research

The research pursued by three new faculty members at Perimeter Institute will advance understanding in a highly promising field.

Three exceptional young researchers are joining Perimeter's faculty, where they will bring new expertise to efforts to better understand, and one day exploit, quantum effects and condensed matter.

Beni Yoshida – a former Perimeter postdoctoral researcher and "It from Qubit" Simons Fellow – is already at Perimeter. He will be joined in spring 2018 by Timothy Hsieh, currently a Gordon and Betty Moore Fellow and associate specialist at the Kavli Institute for Theoretical Physics, and Yin-Chen He, a Gordon and Betty Moore Fellow at Harvard University.

All three study various aspects of condensed matter, which is being widely pursued as a solution to many challenges, from computing limits to efficient energy transmission. Together, they will lead the Institute's new Quantum Matter Initiative.

Director Neil Turok described the appointments as a coup for the Institute, providing a leap forward in condensed matter research, one of the fastest-growing areas in physics today.

"Quantum materials are expected to enable entirely new technologies with a host of potential applications," Turok said. "With three exceptional young theorists joining our faculty, each bringing complementary skills and insights, Perimeter is preparing to engage with and support these exciting developments."

Yoshida studied and worked at MIT and Caltech before coming to Perimeter in 2015. A specialist in quantum information theory, condensed matter, and black holes, his current work focuses on topological order and quantum chaos.

For Yoshida, the transition from postdoctoral fellow to faculty member promises exciting potential not just for his research but also for future collaborations. His research lies between three fields – quantum information, condensed matter, and string theory – all of which are represented in Perimeter's faculty.

"This field is relatively young. There are many brilliant young researchers and it's a very energetic field. I want to bring more of those young talents here," he said.

"Perimeter is very interdisciplinary. I can learn from people with diverse interests. Of course, I was very happy to do research as a postdoc, but now I have more opportunity to make contributions to both PI and also to science, by bringing very smart students and postdocs. That's probably most exciting."

Hsieh studied physics and mathematics at Harvard before earning his PhD in physics from MIT in 2015. A prediction he co-authored in 2013 – that a material called tin-telluride is a topological crystalline insulator – was experimentally confirmed by multiple groups and has spawned significant theoretical and experimental interest in its phenomenology.

Hsieh said he was looking forward to exploring quantum materials, entanglement, and dynamics in Perimeter's interdisciplinary environment.

Yin-Chen He is a condensed matter researcher interested in spin liquids, topological phases, and topological phase transitions. He received his PhD from Shanghai's Fudan University in 2014, and prior to moving to Harvard in 2016, worked at the Max Planck Institute in Dresden.

"PI and I share a mutual interest in doing original, path-breaking research rather than following the main trends of the field," He said.

"PI has highly interdisciplinary research fields in theoretical physics, as well as very active research members, and I am very much looking forward to being part of it."

– Tenille Bonoguore

Find out more about the Quantum Matter Initiative, and all of Perimeter's research initiatives, at www.perimeterinstitute.ca/research/research-initiatives.

A UNIVERSE OF IDEAS

Three new fellowships named in honour of some of the 20th century's most prominent cosmologists will attract and support brilliant young scientists at Perimeter's Centre for the Universe.

When asked if he would provide video greetings to celebrate the launch of a new research hub at Perimeter Institute, Stephen Hawking said yes – and went one better.

Hawking also agreed to lend his name to a new research fellowship, to be held by an exceptional young scientist tackling big theoretical questions in cosmology at Perimeter's Centre for the Universe.

In doing so, Hawking joined two other prominent figures – Jim Peebles and the late Yakov Zel'dovich – as namesakes for fellowships at the new Centre, which were officially launched on November 20. Zel'dovich was represented at the launch by his friend and close colleague, Rashid Sunyaev.

"I am honoured to have my name associated with one of the new fellowships," Hawking said. "Cosmology is one of the most exciting fields in science today. We are on the verge of major discoveries about the universe and its origins. I hope and expect many of those discoveries will be made at Perimeter."

By assembling a mix of eminent international leaders and rising young stars, the Centre for the Universe at Perimeter Institute will be an international focal point for research into black holes, the big bang, dark matter, dark energy, and other basic questions in cosmology.

The Centre is founded in partnership with the Canadian Institute for Theoretical Astrophysics (CITA) and the Dunlap Institute at the University of Toronto, the University of Waterloo, Queen's University, SNOLAB, and York University – institutions involved in some of today's most important astronomical experiments, including the Square Kilometer Array, the Event Horizon Telescope, and the Canadian Hydrogen Intensity Mapping Experiment (CHIME).

"The exploration of our universe is a wonderful adventure that will certainly not end for a very long time," said Peebles. "The new Peebles Fellows, Zel'dovich Fellows, and Hawking Fellows at Perimeter will help explore these questions. As a Canadian, I am particularly happy this will happen in Canada, at the Perimeter Institute."

Stephen Hawking and 2015 Nobel laureate Art McDonald will serve as Scientific Patrons for the Centre, with a steering committee that includes Perimeter Faculty members Asimina Arvanitaki, Avery Broderick, Luis Lehner, Ue-Li Pen, and Kendrick Smith.

New Faculty member Neal Dalal will also be joining the effort. He recently joined Perimeter from the University of Illinois at Urbana-Champaign, where he has pioneered several tests of the nature of dark matter using cosmological data. After receiving his PhD from the University of California, San Diego, Dalal held fellowships at Princeton's Institute for Advanced Study and CITA. His research probes the fundamental physics of cosmology, the structure of the universe, and the formation of galaxies – often bridging theory, data analysis, and observation.

That theme of bridge-building drives the Centre's vision. Its principal goal is to design and analyze new observations and experiments to shed light on key mysteries. In tandem, the Centre will support the intense development and testing of new theoretical ideas and techniques.

"We are fortunate to live in a golden age of discovery of the universe," said Neil Turok, Director of the new Centre.

"Cosmology has always provided some of science's biggest conundrums. Now, it is providing many of the most important clues which are guiding the future development of fundamental physics. The new fellowships at the Centre of the Universe, named for Hawking, Peebles, and Zel'dovich, will attract top talent to Perimeter. Centre scientists will interact with and inform the entire Perimeter community as we seek solutions to our deepest questions about the universe. I firmly believe we are on the threshold of revolutionary advances."

– Colin Hunter

Things didn't go so smoothly at the big bang...

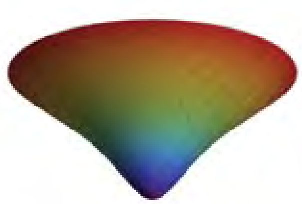
A decades-old description of the big bang may not hold up to mathematical scrutiny, according to recent work co-authored by researchers from Perimeter Institute and the Albert Einstein Institute.

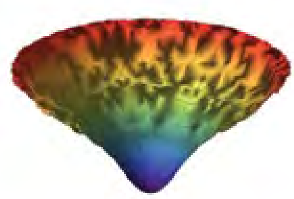
The big bang is one of science's great mysteries, and it seems the plot has thickened thanks to recent research that refutes prevailing theories about the birth of the universe.

A classical description of the big bang implies a singularity: a point of infinite smallness, at which Einstein's theory of gravity – general relativity – breaks down. To tackle this problem, two proposals were put forward in the 1980s: the "no-boundary proposal" by Stephen Hawking and James Hartle, and Alexander Vilenkin's theory known as "tunnelling from nothing."

Each proposal attempted to describe a smoother beginning to spacetime using quantum theory. Rather than the infinitely pointy needle of the classical big bang, the proposals described something closer to the rounded tip of a well-used pencil.

While this view has spawned much research, new mathematical work suggests such a smooth beginning could not have given birth to the ordered universe we see today.





A paper, co-authored by Perimeter Institute researchers Neil Turok and Job Feldbrugge, with Jean-Luc Lehners of the Albert Einstein Institute in Germany, points out mathematical inconsistencies in the "no-boundary" and "tunnelling" proposals.

"The beginning of our universe – if there is one – is one of the big open questions in theoretical physics," said Feldbrugge, a PhD student at Perimeter Institute. "The no-boundary proposal by Hartle and Hawking and others is an elegant proposal to model the big bang using quantum gravity. Using a new mathematical technique, we can now rigorously investigate this proposal and see what kind of universe it predicts."

Turok says the previous models were "beautiful proposals seeking to describe a complete picture of the origin of spacetime," but they don't hold up to this new mathematical assessment.

"Unfortunately, at the time those models were proposed, there was no adequately precise formulation of quantum gravity available to determine whether these proposals were mathematically meaningful," Turok said.

The paper, "No smooth beginning for spacetime," demonstrates that a universe emerging smoothly from nothing would be "wild and fluctuating," strongly contradicting observations, which show the universe to be extremely uniform across space.

"Hence the no-boundary proposal does not imply a large universe like the one we live in, but rather tiny curved universes that would collapse immediately," said Lehners, a former Perimeter postdoc who leads the theoretical cosmology group at the Albert Einstein Institute.

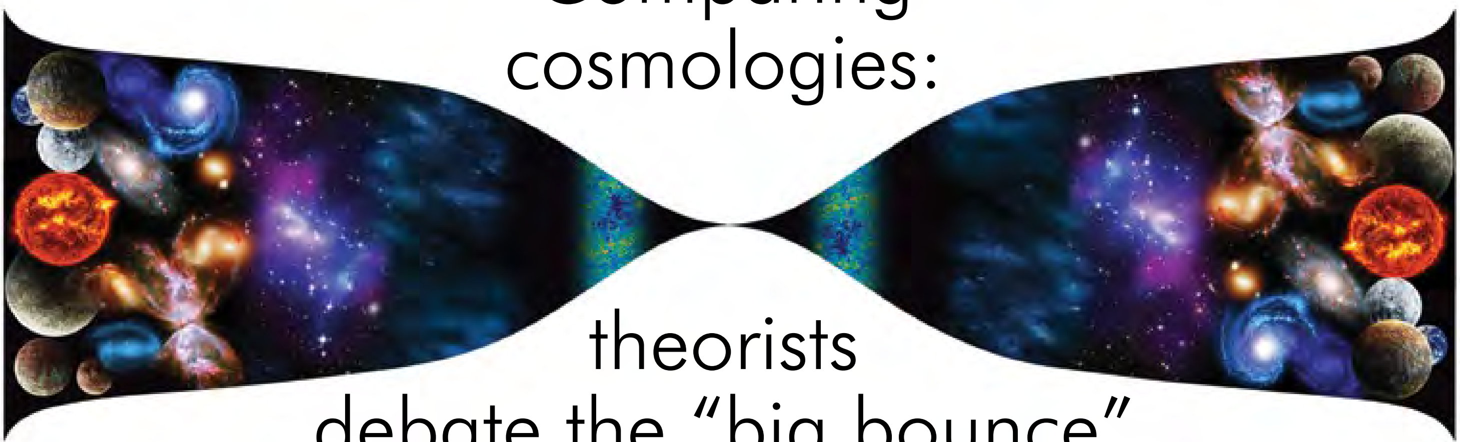
Turok, Lehners, and Feldbrugge reached this result by revisiting the foundations of the field. They found a new way to use powerful mathematics developed over the past century to tackle one of physics' most basic problems: how to connect quantum physics to gravity. The work builds on previous research Turok conducted with Steffen Gielen, a postdoc at the Canadian Institute for Theoretical Astrophysics and at Perimeter, in which they replaced the concept of the "classical big bang" with a "quantum big bounce."

Turok, Lehners, and Feldbrugge are now trying to determine what mechanism could have kept large quantum fluctuations in check while allowing our large universe to unfold. The new research implies that "we either should look for another picture to understand the very early universe, or that we have to rethink the most elementary models of quantum gravity," said Feldbrugge.

"Uncovering this problem gives us a powerful hint," added Turok. "It is leading us closer to a new picture of the big bang."

– Colin Hunter

Comparing cosmologies: theorists debate the "big bounce"



In standard cosmology, the universe starts with a big bang. An emerging idea replaces the bang with a "bounce" between a shrinking former universe and our currently expanding one. "Bounce Scenarios in Cosmology," a workshop held at Perimeter in June, brought together proponents of various scenarios to compare approaches, discuss broad concepts, and ponder the role of quantum mechanics in the universe's first moments. Inside the Perimeter *asked four workshop participants for their perspectives.*

Inside the Perimeter: What do you see as the greatest weakness in the big bang theory?

Jean-Luc Lehners, Albert Einstein Institute: The greatest weakness, and at the same time the greatest opportunity, is the big bang itself. At the big bang, the model breaks down, as physical quantities such as the density and the curvature of space and time become infinite. This means that we cannot trust the equations anymore, and a better model is needed. Bringing quantum theory and gravitational physics together in order to address this challenge is seen by many, including myself, as the most interesting problem in theoretical physics.

Inside: What is meant by the term "bounce scenarios"?

Abhay Ashtekar, Pennsylvania State University: In any physical theory, if you try to push it beyond its domain of validity, it gives nonsensical answers. Usually when this happens, then one doesn't take that theory very seriously in that domain. That is its limit. General relativity predicted singularities, in particular the big bang as the most spectacular of them, but for some reason, people take it seriously. The bounce scenario, for me, is a scenario in which one is going beyond Einstein, beyond general relativity, thereby avoiding the big bang, and replacing the big bang with something where physics does not break down. To me, that really involves some quantum mechanical aspects.

Inside: Which paradigm for the early universe do you think shows strongest potential? Why?

Mairi Sakellariadou, King's College London: At this point, I do not believe that there is enough evidence to favour a particular scenario. Different quantum gravity proposals offer appropriate frameworks to build cosmological models. We are still at the stage of extracting their distinct predictions and confronting them with currently available data, while also trying to better understand their conceptual underpinning.

Inside: Why is it important to come together in a forum like this to discuss these ideas?

Martin Bojowald, Pennsylvania State University: The question of what might replace the big bang singularity requires us to handle quantum spacetime at very high densities. There is no reliable intuition that could guide us. It is a complicated problem in which promising ideas have often encountered unexpected obstacles. It is good to see how other approaches have dealt with such issues, or what additional difficulties they might suggest.

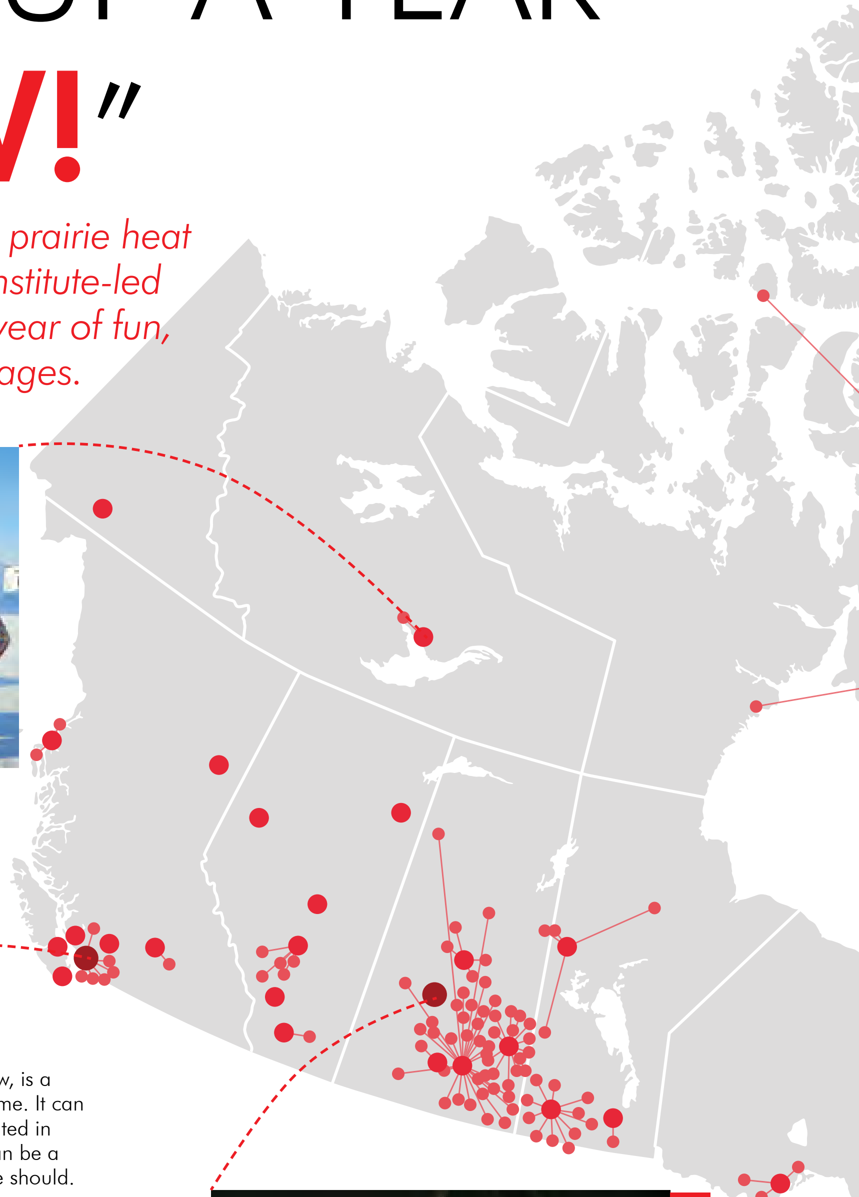
– Tenille Bonoguore

This is a condensed version of a story published on www.insidetheperimeter.ca. Read the full Q&A at www.insidetheperimeter.ca/theorists-debate-big-bounce.

Find out more about all Perimeter conferences at www.perimeterinstitute.ca/conferences.

WINDING UP A YEAR OF "**WOW!**"

From mountain passes and ice roads to prairie heat and blazing fall colours, the Perimeter Institute-led Innovation150 partnership delivered a year of fun, fascinating science to Canadians of all ages.



Crew member Nick Butts, pictured second from left with his fellow Power of Ideas tour staff in Yellowknife, NWT, shares his top moments from across Canada:

YELLOWKNIFE, NWT

1. We had the chance to go dog sledding in Yellowknife, piled five people to a sled, under the brightest northern lights I've ever seen.

2. In Weymouth, Nova Scotia, one student threw his arms in the air as he left the exhibit and said, "After five years of searching, I finally found what I want to do with my life!" I just wonder how many more had similar experiences without us even knowing.

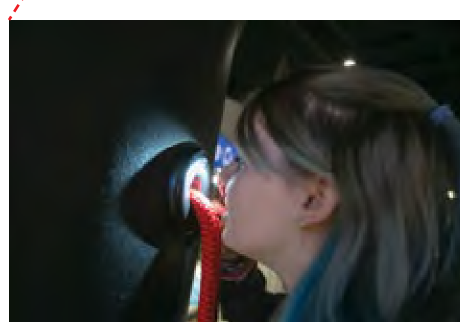
3. Touring SNOLAB was awesome. Fun fact: there lies the deepest flushable toilet in the world.

VANCOUVER, BC

"Innovation, in my view, is a process, not an outcome. It can be learned and cultivated in our society. Anyone can be a part of it and everyone should. It actually defines who we are, and where we are going."

– Neil Turok, launching the six-stop "We Are Innovators" tour in Vancouver in January

SASKATCHEWAN



"There was so much energy in the building! Students got hands-on with technologies they would otherwise not have access to, and teachers got that spark to keep going and take risks in classroom learning. The impact is huge."

– Jenna Crossman, teacher at Carlton Comprehensive Public High School, Prince Albert, Saskatchewan

The three-month "Innovation Festival: Saskatchewan" featured the Power of Ideas tour, the Canada Wide Science Fair, the Vancouver Aquarium's AquaVan 150 "wet lab," "QUANTUM: The Exhibition," and events across the province.

BY THE NUMBERS:

5 major innovation festivals

180+ communities

100,000+ Power of Ideas attendees

2.4+ million online clicks, shares, and likes

Supported by the federal government through Canadian Heritage, Innovation150 was delivered through a partnership between Perimeter Institute, Actua, the Institute for Quantum Computing at the University of Waterloo, the Canadian Association of Science Centres and its members, Ingenium, and collaborations in every province and territory.

Find more stories of innovation, tour highlights, and more at www.innovation150.ca.

The Power of Ideas hit its most easterly point – St. John's, Newfoundland – in time for Science Literacy Week in September.

"Science is fun and it should be fun. You can set yourself up for a career in science that is only limited by your imagination and energy."

– Nobel Prize laureate and Perimeter Board member Arthur B. McDonald speaking at his former high school, the Sydney Academy

As grand prize winners of the "In Every Class" contest, Cathedral High School was transformed into a science wonderland for a day.

"You never know who wants to be a scientist. And things like this, they might create future scientists."

– Sophia Lim, Grade 12 student, Cathedral High School

DEMOCRACY AND **SCIENCE** NEED EACH OTHER TO **THRIVE**

Perimeter Faculty member Lee Smolin discusses the intersection of the two practices, and why Canada is an ideal locus for scientific research. This piece first appeared in Maclean's.

We live in a world of uncertainty. Our decisions – long-term or spur-of-the-moment – are always made with incomplete information. We can never fully anticipate, with perfect certainty, the outcome of our decisions or the unintended consequences. But because we must act with some degree of confidence, we are very good at fooling ourselves into a sense of certainty. Worse, we are good at fooling others.

For most of human history, progress of all kinds was slow because ideas and practices that were helpful in the short run got locked in and blocked further insights. This lasted until the invention of practices that allowed groups of people to efficiently discover and root out error.

The two most important of these practices are science and democracy. Not surprisingly, they have a close association. Democracy and science need each other, as they are based on the same principles.

The tools of scientists' trade allow them to discover and correct errors; science makes progress when mistakes are corrected. Indeed, scientists make mistakes all the time, but we also strive to correct these errors using the best available evidence. As Richard Feynman said, "Science is the organized skepticism in the reliability of expert opinion."

And he might equally have been talking about democracy. The principles of a democratic society recognize that those in positions of power will, despite what are generally their best and most sincere efforts, make mistakes. That is why we need freedom of the press, freedom of speech, and the rights of citizens, defended by an array of judicial procedures with many checks and balances – all practices that help a society root out errors.

Ultimately, the practice of science and democracy share a common set of ethical principles. First, if people of good faith can apply rational argument and publicly available evidence to reach a conclusion, that conclusion should be considered valid – that is, until new information demands the issue be reconsidered. Second, if no such consensus can be reached by people of good faith who base rational argument on available evidence, society must allow – even encourage – diverse conclusions. Diversity of ideas, which we rightly cherish here in Canada, is good for a society as long as it is not at odds with reason and evidence.

Scientists know even the best ideas will eventually need to be updated by new insights, and will be, from time to time, replaced by revolutionary new conceptions. Similarly, democratic governance gives people the power to vote a government out of office when its effectiveness diminishes or when events show that its election was a mistake. Societies that can admit error know in their bones that the future will be a better place, based on increased knowledge and deeper insights.

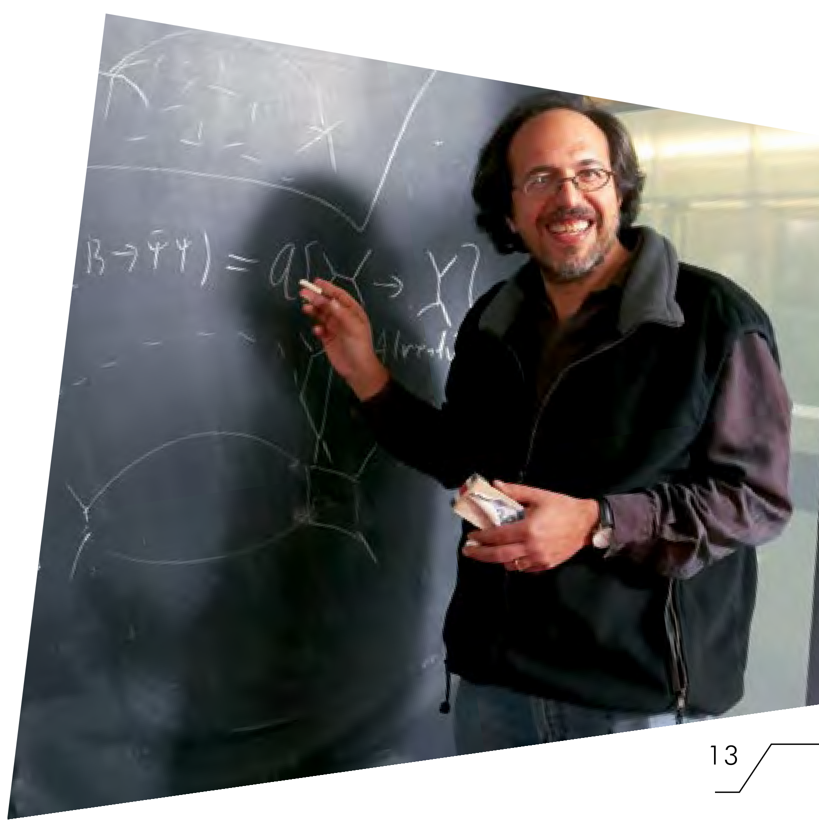
Problems are unavoidable; a healthy society can recognize and solve unexpected problems. Democracy, like science, must be evidence-based if it is to succeed.

In Canada, we see the intersection of these two related ideals at work. Canada will never be the most populous country in the world, but with its diverse, highly educated population – full of immigrants who are open to new lives and are welcomed into an optimistic society – it can, if it chooses, become a leading country scientifically. To do so, Canada needs to increase its investment in science to the level of other first-world democracies and use that investment to support risk-takers who have the ambition, creativity, and boldness to make the big discoveries on which scientific progress depends.

Science could truly thrive in Canada because science is the one true society of immigrants. People from every country, religion, race, gender, and sexual orientation are welcome to join in the shared adventure of a life searching for truth, within a community defined by a commitment to know more about nature. Science is, indeed, a purely immigrant society, because no one is born a scientist; everyone joins by the conscious adoption of the principles of honesty and respect for the evidence.

What better home for science could there be than Canada, a country defined by openness, diversity, and tolerance within a shared adventure to build and explore our shared human future?

– Lee Smolin



NEW EXPERIMENT REVEALS WHAT DARK MATTER ISN'T

Science often progresses not in leaps and bounds, but by inching slowly towards the truth. When looking in the obvious places yielded no results, theorists proposed a novel way to look for dark matter by repurposing existing neutrino experiments.

We know it exerts a gravitational tug and is five times more abundant than regular matter. Beyond that, details are sketchy. Researchers still don't know what dark matter is, but that's not for lack of trying.

In the 1970s, astrophysicist Vera Rubin noticed that the edges of galaxies rotated much faster than expected, given the amount of matter visible at their centres. The conclusion: there must be some unseen matter holding the galaxies together.

The discovery set in motion a scientific treasure hunt to detect this mysterious dark matter. After detailed sky surveys ruled out the possibility that dark matter could simply be normal, less luminous matter – like black holes, neutron stars, or cold clouds of gas – researchers flipped the scale of the problem from astrophysics to particle physics.

Since then, the theory that dark matter must be some as-yet-undiscovered particle that interacts with regular matter via gravity (and possibly the weak force) has dominated. Extensive experimental searches were carried out to find these hypothetical particles, usually called "weakly interacting massive particles" or "WIMPs."

Direct detection experiments, located deep underground to filter out the myriad other particles streaming in from space, look for evidence of dark matter particles bumping into regular matter. Other experiments rely on indirect detections by hunting for particles and radiation produced when dark matter particles collide or decay in outer space. Researchers have even tried to produce dark matter particles in the lab by colliding protons together at extremely high energies.

Every single one of them has come up empty.

THINKING OUTSIDE THE BOX

By the mid-2000s, the research community was restless about the lack of detections. "People had been searching for WIMPs for a while, and hadn't seen anything," says Brian Batell, an Assistant Professor at the University of Pittsburgh and former Perimeter Institute postdoc. "So some people started thinking a little bit more broadly – a little bit outside the box."

Their creative thinking was spurred, in part, by intriguing satellite measurements at the time that indicated an unexpectedly high number of positrons (the positively-charged counterpart to the electron) coming from the centre of our galaxy.

Highly magnetized, spinning neutron stars called pulsars can produce positrons, but there is uncertainty about both the number of pulsars in the galaxy and how many positrons they create. Another theory also fit the data: could it be that dark matter particles were colliding, annihilating, and producing positrons in the process? The answer was yes – but only if the dark matter particles were light enough.

"At the time, it was not even clear whether there were any particle physics models that could provide such light [dark matter] candidates," says Perimeter Institute Associate Faculty member Maxim Pospelov. "Everyone was talking about particles five orders of magnitude heavier." (One of the early pioneers of the light dark matter models was Celine Boehm of Durham University, a 2016/17 Emmy Noether Visiting Fellow at Perimeter.)

From a detection point of view, the possibility that dark matter could be much lighter than conventional WIMP models came with an upside.

"It turns out that, from the experimental perspective, it would be very interesting if dark matter particles are light because then we can kinematically access them," says Batell. (Simply put, it's much easier to produce lighter particles than heavy ones.)

"We have accelerator experiments. We can collide particles and some energy and produce other particles. So if dark matter happens to be light, we could actually do experiments to try to produce those particles and detect them," he says.

Theorists dug into the problem and showed that not only were there plausible models of light dark matter, but that those models came with some interesting characteristics. "When there is light dark matter, there must also be a light particle that mediates interactions between dark matter and Standard Model matter," explains Pospelov.

A "DARK FORCE"?

According to the Standard Model of particle physics, mediators are particles that carry the forces between the other particles. For example, photons (the quantum particle of light) carry, or mediate, the electromagnetic force that acts on charged particles like electrons and protons.

The possibility of a mediator particle for dark matter, then, carried an intriguing correlation: perhaps dark matter could interact more than just gravitationally, through some new, long-range "dark force." Though it might sound like something straight out of a science fiction novel, the existence of a dark force fit well into theories describing the production of dark matter in the early universe.

Experimental searches were carried out in search of a "dark photon," a hypothetical particle that would be an ideal mediator for dark matter particles. In many cases, physicists suspected, it would be easier to detect the dark photon than the light dark matter particles themselves.

But, as with the search for WIMPs, the hunt for dark photons kept coming up empty.

It might sound frustrating, but the meandering process of putting forth a hypothesis for a dark matter candidate, carrying out a set of experiments to test the hypothesis, and either ruling it out or – as every researcher hopes – finding evidence to support it, is simply the process of science.

"The scientific method has demonstrated its power time and time again," says Batell. "Unfortunately, there is no guarantee we will ever discover dark matter. On the other hand, there is no other method to make progress on the basic question. The nature of dark matter is one of the outstanding mysteries in physics, and we are obliged as scientists to explore and experimentally test, to the extent of our abilities, all motivated ideas and hypotheses."

Of course, building a new detector or experiment to test every possibility is both costly and time-consuming. Could there be a way to explore new dark matter theories more efficiently?

NEW EXPERIMENTAL POSSIBILITIES

In 2009, Batell, then a postdoc at Perimeter Institute, published a paper with Pospelov and University of Victoria Associate Faculty member Adam Ritz. In it, they proposed that rather than looking for a mediator particle, it could be possible to directly detect light matter particles by using existing experiments designed to study neutrinos.

Located deep underground, these "fixed target" accelerators fire an intense, energetic beam of particles, such as protons, into a target made of beryllium or other materials. The collisions between the protons and nucleons in the target produce pions, which then decay into neutrinos. The neutrinos travel through several metres of earth into a detector filled with mineral oil or heavy water and lined with light-sensitive devices to detect collisions between the neutrinos and the nuclei of the material inside the detector.

"What we realized is one can use the very same scheme to produce light mediators that, say, decay to a pair of dark matter particles," says Pospelov. "And dark matter particles would fly into the detector and scatter off. So we would be able to search for light dark matter in neutrino experiments."

It was an elegant idea. The accelerator experiments would be complementary to other direct detection setups, such as those at SNOLAB in Sudbury, Ontario, that are tuned towards searching for higher-mass, lower-energy dark matter thought to exist throughout the galaxy.

"Direct detection experiments are good at searching for heavy dark matter particles, but not so good at searching for light dark matter particles," explains Batell. By attempting to create the light dark matter particles using the accelerator, the particles "can be very high energy, and they can easily scatter with the particles in the detector," he says – which would leave a striking signature.

THEORY MEETS EXPERIMENT

Around the time that Batell, Pospelov, and Ritz published their paper, several experiments designed to study neutrino oscillations happened to be winding down their runs. The community held a meeting, gathering experimentalists and theorists to brainstorm ways to re-use the high-precision instruments.

Experimentalists from Fermilab's MiniBooNE neutrino experiment attended a talk from Batell detailing the trio's dark matter proposal. MiniBooNE (the "BooNE" stands for Booster Neutrino Experiment) was on the verge of completing its 10-year run studying neutrino oscillations and neutrino mass, and the team was intrigued by the idea of repurposing their experiment. A collaboration was born.

Reusing an existing experiment, rather than building something from the ground up, has some advantages: it's significantly less expensive and allows for more flexibility determining the experimental trajectory.

But repurposing a neutrino experiment also has downsides. One of those is the neutrinos themselves, which could mask the faint signal of dark matter. "Most of the time, these experiments are tuned to increase the neutrino output," says Pospelov. "But for us, because we are looking for something else, the neutrino would be a background."

To solve this problem, the team devised a way to reconfigure the accelerator. Rather than directing the beam of protons into the beryllium target, they used magnets to steer the beam directly into the iron "beam dump" (used to dump the excess protons at the end of a neutrino experiment). The iron quickly absorbs the mesons that produce the neutrinos, reducing the neutrino flux by 50 times.

From November 2013 to September 2014, the MiniBooNE team ran the accelerator in its new configuration, looking for a specific interaction where a dark matter particle scatters with a mineral oil atom in the detector, kicking out a nucleon in the process.

The theorists involved – including Batell, Ritz, and Ritz's PhD student Patrick deNiverville at the University of Victoria – broke with convention and worked closely with the experimental side of the team to develop a suite of simulation and analysis tools that can be carried forward to similar dark matter searches.

"Entering the experimental collaboration is not quite like entering a medieval order," says Pospelov with a chuckle. "It's a different world with the experimental physicists."

For example, proprietary information is rare in the realm of theoretical physics, but experimentalists cannot disclose their data before the results are published.

The results, in this case, resembled those of the many experiments that came before it: no signal was detected over the background. Dark matter, for now, remains elusive.

THE SEARCH CONTINUES

Pospelov and Batell acknowledge that finding dark matter would have been a stroke of immense luck. "Looking for dark matter in a fairly specific place – yeah, if you find it in that place, that would of course be a super pleasant surprise," says Pospelov. "That didn't happen. But it's a process, right?"

Regardless of a detection, or lack thereof, MiniBooNE represents an important step forward for dark matter searches, stresses Batell. "It's an important result because it's kind of the first dedicated experiment of this type that has looked for light dark matter," he says.

Pospelov believes the intersection of theory and experiment will continue to propel the search for dark matter forward. "These two things together – theorists proposing new signatures and experimentalists looking for new applications of their apparata – these things have come together in the last decade and actually made a difference in this field."

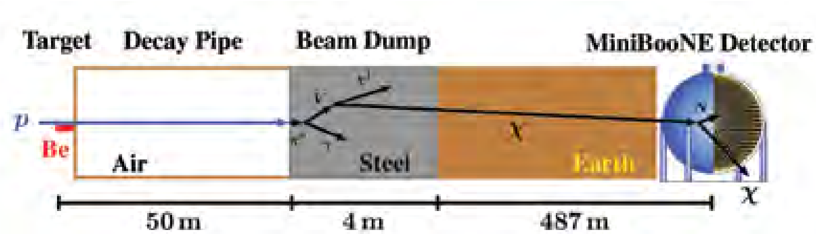
The team will continue running the experiment in order to look at several other possible ways light dark matter could leave its mark – for example, scattering with electrons, or breaking up a nucleus to release a shower of particles.

Each channel they examine holds promise in some way: either the highly sought-after positive detection, or the less glamourous, but still crucial, progress toward ruling out what dark matter could be.

"We can put a limit on the variety of different models of light dark matter," says Batell. "So we learned something: we learned what dark matter is not, for the time being."

– Stephanie Keating

A schematic illustration of the dark matter search using the MiniBooNE detector: the proton beam is steered around the beryllium target and directly into the steel "beam dump."



All eyes on the sky

With the arrival of multimessenger astronomy, physicists can probe the universe like never before.

The signals came within two seconds of each other: first, a gravitational wave, then a gamma-ray burst. Shortly afterward, an urgent message went out to observatories around the world.

Seventy telescopes – 63 on Earth, located on every continent, and seven more in space – turned to focus on the small region of space from which the signals appeared to originate.

What they saw starting on August 17 was astounding – despite the fact that witnessing such an event had been clearly predicted. Two neutron stars – the first at 1.6 solar masses, the second at 1.1 solar masses, each packed into regions more compact than an average city – had collided 130 million light years away.

It was the birth of real-time, multimessenger astronomy, a transformative advance that Perimeter Institute strong gravity researcher Luis Lehner has long been anticipating. Indeed, Lehner's models of extreme cosmic events helped experimentalists work out what to look for in the first place.

Over several days, astronomers were able to record all of the cosmic reverberations from the collision, from gravitational waves and gamma-ray bursts right down the spectrum to radio waves. The results also revealed that heavy metals are born in the maelstrom of cosmic cataclysms.

"This is all just the beginning – the very first event. To have, in the first event, everything come out like this, it's just very exciting," Lehner said.

Now, with multimessenger astronomy moving from theory to reality, scientists have a whole new way to probe the universe. "You actually get to ask questions about our universe in gravitational and electromagnetic waves. It's opening the door to amazing physics," Lehner says.

The results, Lehner explained, finally allow scientists to make a direct connection between gamma-ray bursts – long considered a mystery – and the violent collision of compact objects: "Connecting these electromagnetic events, which we have been following for a long time, to what happens at the inner core of the galactic engine, is just amazing. It's mind-boggling."

But that's not the only new window opening on the cosmos:

CHIME: When the Canadian Hydrogen Intensity Mapping Experiment (CHIME) radio telescope in British Columbia switches on this fall, it is expected to detect hundreds of rare and mysterious flickers from space called fast radio busts (FRBs). Until now, we've only seen 26 of them. The flood of data expected from CHIME is expected to surpass that in a matter of days.

Wrangling with that torrent of data – a petabyte every day – is a prime challenge for Perimeter cosmologist Kendrick Smith, who is working on both CHIME's cosmology and FRB teams. Along with Perimeter Associate Faculty member Ue-Li Pen and a small team of Perimeter PhD students and postdocs, the researchers have helped design algorithms that will sift through the data in real time. "It's going to be a game-changing experiment," says Smith.

EHT: In November, the Event Horizon Telescope (EHT) receives the final dataset from the 2017 observation run and can start piecing together the first image of a black hole. The global network of radio telescopes is taking aim at two black holes: Sagittarius A*, the supermassive black hole at the heart of the Milky Way, and the black hole at the centre of the M87 galaxy.

All of the data recorded at EHT sites are shipped to two central processing facilities at MIT and the Max Planck Institute for Radio Astronomy, where the signals are combined. But there has been a very terrestrial lag in proceedings: observations from the South Pole Telescope were taken months ago, and were then essentially iced in until the southern summer made travel to Antarctica possible.

When the final data arrives, Perimeter Associate Faculty member Avery Broderick and Perimeter's EHT Initiative will play a key role in piecing together that first image, and working out what it says about the physics of black holes. "For the first time, we're going to be able to check, validate, or maybe even invalidate, ideas about how black holes operate in practice," Broderick says.

– Tenille Bonoguore

Fundamental physics has entered its most exciting period in decades, driven by theory and torrents of new data from the EHT and other experiments. Find out more about Perimeter's new Centre for the Universe on page 7 or visit www.perimeterinstitute.ca/centre-universe.

BIG IDEAS ABOUT NOT-SO-BIG EXPERIMENTS

It sounds like the setup to a corny physics joke: What do you get when you invite a bunch of experimentalists to a theoretical physics institute?

The answer, if all goes according to plan, is "a whole lot of new ideas."

That theory was put to the test during Perimeter's "Experimental Techniques in Table-Top Fundamental Physics" conference in August, which saw dozens of experimentalists and theorists interact in hopes of generating new ideas to probe the frontiers of their respective fields.

It is part of a broader program that is picking up steam. The past several decades have seen incredible advances in the precision with which small-scale, or "table-top," experiments (which can range from actual table-top size to the size of a room) can measure certain properties of nature.

These advances, explained Savas Dimopoulos, the Archimedes Chair (Visiting) at Perimeter and co-organizer of the conference, are expected to have broad applicability, from particle physics and quantum computing to probing the nature of dark matter.

And there's a substantial bonus: table-top experiments can help bridge the gap between major experimental efforts, such as the Large Hadron Collider, which often have long timelines and big budgets.

"Most particle physics in the last half-century was done in colliders, and these are typically enormous experiments," explained Dimopoulos. "The time between colliders is usually three decades, and so the question is: can we learn things in the intervening time? The answer is yes, and small-scale experiments are where the action will be, where the new discoveries will be made for the next two to three decades."

By bringing together theorists (who have a wealth of ideas to test) with experimentalists (who have the equipment and know-how to do so), the conference organizers hoped to facilitate interactions that will lead to new searches and fresh discoveries.

"The science of theoretical physics – of physics – cannot exist without theory. It also cannot exist without experiments. So the two go hand-in-hand," said Asimina Arvanitaki, the Stavros Niarchos Foundation Aristarchus Chair in Theoretical Physics at Perimeter Institute, and another co-organizer of the conference.

The realms of experiment and theory, she said, were not always as disparate as they tend to be today. "But as knowledge increases, the amount of things you need to know to do theory well, or to do experiment well, becomes bigger and bigger," she said. "People became more specialized."

While specialization has merits, the biggest discoveries tend to come from the unexpected intersections between fields. That's why the conference organizers ensured specialists had plenty of time to interact with peers outside their specific subfields, with a mutual understanding that no questions are too simple.

"Each of us has to be open to hearing something stupid," joked Arvanitaki. "This is how you make progress."

Using table-top experiments for fundamental physics is a relatively new practice, with new questions and ideas emerging at an accelerating pace.

Yannis Semertzidis, Director of the Centre for Axion and Precision Physics Research in Korea, said, "It's really the enthusiasm that is very important. One technique hits a wall and then we do something else differently. Smart people can't sit around doing nothing. New techniques come along day after day. It's very exciting."

For Dimopoulos, one particularly exciting avenue to investigate is the search for the elusive dark matter believed to make up the majority of the universe. He and Arvanitaki are exploring, for example, whether relatively small and inexpensive experiments could determine whether dark matter may actually be a wave instead of a particle, and whether cutting-edge experiments may be able to detect its signature.

Other experiments, both proposed and under way, are tackling a number of fundamental questions at the heart of physics, such as the perplexing puzzle of why the universe contains more matter than antimatter.

By gathering such a diverse group – both in terms of specialty and geography – the organizers aimed to not only spark progress on these questions, but also to prompt questions no one has yet thought to ask.

"I would like this conference to be a catalyst for interactions that may lead to completely new searches and, down the line, completely new discoveries," said Dimopoulos.

– Stephanie Keating and Colin Hunter

UPCOMING CONFERENCES

Conferences are continually being added. Check www.perimeterinstitute.ca/conferences for the latest.

Gauge Theory, Geometric Langlands, and Vertex Operator Algebras

March 22-24, 2018

This workshop will explore the relation between boundary conditions in four-dimensional gauge theory, the Geometric Langlands program, and Vertex Operator Algebras.

Searching for New Particles with Black Hole Superradiance

May 9-11, 2018

This workshop will bring together theorists, data analysts, and observers in particle physics, gravitational wave astronomy, strong gravity, and high energy astrophysics to explore the signatures of black hole superradiance and to study the current and future possibilities of searching for new particles with black holes.

Foundations of Quantum Mechanics

July 30-August 3, 2018

The foundations of quantum mechanics have been revitalized in the past few decades from several directions, and this workshop will bring together researchers who have made substantial contributions to these recent developments.

SWINGING FOR THE FENCES

Classically, you never get a black hole without a singularity, but might you get a singularity without a black hole? That turns out to be a slightly more open question.

In gravitational physics, where spacetime can be pictured in terms of curves and wells, you can think of a singularity as a bottomless pit.

Surrounding that pit is a region where spacetime is so distorted that it loses contact with the rest of the universe. In classical physics, we can't see inside and nothing can come back to us – not even light. That barrier is known as the event horizon, or a black hole.

While it's common to think of the black hole as the bottomless pit and the event horizon as the boundary around it, that's wrong. The black hole acts like a fence around the singularity, hiding it from view and preventing it from affecting the rest of the universe.

It also serves as a glaring beacon for researchers wanting to know how the universe works, says Perimeter Faculty member and strong gravity researcher Luis Lehner.

"The word singularity is just code for '*our physics broke here*,'" he says. Just because we can't see over the fence doesn't mean there isn't something interesting happening on the other side.

But what if there was no black hole fencing off the singularity? What if the singularity were, in the parlance of the field, naked? A naked singularity is one with no horizon to hide it, one we can observe from the outside – and one that can affect the rest of the spacetime.

"A naked singularity could have literally any effect on us," says Lehner. "It probably wouldn't destroy the universe. But we can't say 'oh, definitely not.' And that loss of predictability is unsettling."

The end of "censorship"

Naked singularities are so unsettling that in 1969 the great theorist Roger Penrose conjectured that all singularities (except the singularity known as the big bang) are covered by black holes, and that naked singularities are impossible.

Across the intervening decades, this "cosmic censorship" conjecture has remained unproven, even as the circumstantial evidence supporting its existence (in our four observable dimensions, at least) has grown.

So far, the tiny handful of possible counterexamples have been carefully designed and physically implausible. New work by Lehner, Pau Figueras of Queen Mary University of London, and Markus Kunesch and Saran Tunyasuvunakool of the University of Cambridge, changes that.

The paper "End Point of the Ultraspinning Instability and Violation of Cosmic Censorship," published recently in *Physical Review Letters*, shows that if black holes in six dimensions spin fast enough, their spin would distort them so much that, in places, their size would shrink to zero, uncovering the singularity within.

The good news for our universe is the "six-dimensional" part: we observe our universe to have four dimensions, three of space and one of time.

It is believed that most black holes spin; in four dimensions, that spin has a maximum speed. Thus, a spinning 4D black hole would distort and change from a sphere to an oblate form: squished at the top and bottom and bulging along the equator. The faster the spin, the greater this pancaking effect. But the math saves us: in four dimensions, even a black hole with maximal spin does not expose its singularity.

So how does that relate to new work about six-dimensional black holes? The journey is long and weaves in and out of work done at Perimeter Institute.

In four dimensions, black holes are like bells. If you perturb one – if you give it a nudge – it will ring down until it's quiet. In the early 1990s, Durham professor Ruth Gregory (now a Visiting Fellow at Perimeter) collaborated with Raymond Laflamme (now a Perimeter associate faculty member) to investigate black holes extended across one more spatial dimension, taking the theory to five dimensions.

Gregory and Laflamme discovered that, in five dimensions, a class of black hole does not become quiet. Instead, some of its tones become intense and then continue to get louder. Meanwhile, the "bell" itself can deform, violently.

It took almost 20 years before researchers were able to work out what happened after that point. In 2011, work by Lehner and Perimeter Distinguished Visiting Research Chair Frans Pretorius revealed the final fate of these strangely unquiet 5D black holes.

The role of beads and donuts

If you think of a black hole in 4D as roughly the shape of a ball, then you can picture a black hole in 5D as a series of balls stacked on top of each other – as a string with some thickness. Indeed, 5D black holes are sometimes called black strings.

The Gregory-Laflamme work from the 1990s showed that perturbed black strings would deform. The 2011 Lehner-Pretorius work showed how that deformation would behave: the string begins to vary in thickness, developing a bulge in the middle and at each end, with a thinner thread connecting them (a bit like beads on a string).

In six dimensions, a spinning black hole is unstable. It distorts into a series of toruses connected by thin films. These films can even "pop," creating a naked singularity.

The distortion continues and each thread becomes unstable, creating smaller beads along it; then the thin thread between each small bead creates tiny beads, and so on, until the thread size shrinks to zero – and breaks. When the thread breaks, the singularity inside the black string is exposed.

The 2011 work showed that naked singularities are possible, at least in 5D. It was the first example of a naked singularity that came naturally out of a simulation without the need for fine tuning. The work pointed to rich physics hiding in higher dimensions.

Now, in 2017, Lehner and colleagues have simulated black holes in six dimensions. At high spin, such holes start as six-dimensional spheres, then spin into 6D disks, which then develop structures – like a series of donuts connected by thin films. As in the 5D beads-and-string case, the process repeats: the film between the donuts bunches, thins, and finally breaks. In short, this new work again found naked singularities.

Does that mean we could have naked singularities in our universe? Maybe, and maybe not. It depends on whether spacetime is truly four dimensional, as we observe it to be, or if it has higher hidden dimensions, as string theory suggests.

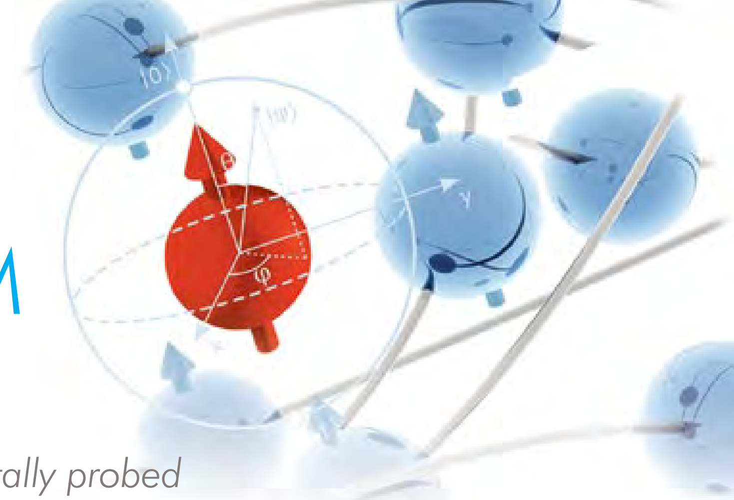
If the higher dimensions are purely mathematical, then this work is simply academic. If these higher dimensions are a physical part of our spacetime, however, then the naked singularities might be real too. But whether higher dimensions are real or not, Lehner's work has developed tools and ideas that can be used to push gravitational theory forward.

– Erin Bow

Videos demonstrating the concepts:

In 5D: In 6D:

SNEAKING A PEEK AT THE QUANTUM WORLD



For the first time, researchers have experimentally probed topological order and its breakdown. The work could open the way for new approaches to quantum computation.

Topological matter has been hailed as a potential solution to everything from power transmission to quantum computing. What makes it special – and difficult to study – is quantum.

At a certain point, the long-range entanglement that gives topological matter its special properties breaks down, or decoheres, and it becomes boring old normal matter. This leaves quantum matter researchers facing quite a puzzle: can you identify, let alone observe, the phases [see footnote 1] of quantum topological matter without destroying the entanglement that bestows its unique properties?

Now, there is an answer: yes, you can. The trick, it turns out, is to have the system do the hard work for you.

In a paper published recently in *Nature Physics*, a team of theorists and experimentalists in China and Canada created a small topological system that, when manipulated slowly enough, revealed its own phases. The researchers also observed the transformation as quantum entanglement broke down.

While the team did its experiment using a nuclear magnetic resonance (NMR) machine, they expect that their approach could also work in other physical systems for quantum computers, such as superconductors, and that it could serve as a potential system for quantum memory.

Co-author and former Perimeter postdoctoral fellow Yidun Wan said the results surpassed even the research team's expectations. "This is something we didn't quite expect to happen, to observe the breakdown of entanglement so nicely," said Wan, who is now a professor at Fudan University.

What made it particularly surprising is that the team initially didn't set out to do any of this at all.

One question leads to another

Since topological phases were first put forward as something of a mathematical oddity in the 1970s, they've become a hotbed of research activity (and the basis for the 2016 Nobel Prize in Physics).

The China-Canada research team initially set out to find out if two mathematical tools used in topology theory – the S matrix and the T matrix – are actually physical effects that can be experimentally observed.

The S and T matrices are considered one of the most fundamental fingerprints of topological order. They essentially map out what happens when a quantum system is put through a particular transformation. Because topological systems have unique properties, each system's S and T matrices will be different as well.

Each matrix plots out "anyonic" statistics that represent the behaviour of anyons (an exotic kind of quasiparticle) in a system: the S matrix shows what happens when a quantum system that is mapped onto a torus (which looks like a donut) is rotated; the T matrix defines that same toric system when it is sheared.

In their first experiment, the team used an NMR simulator to show that, indeed, the S and T matrices do provide fundamental signatures of topological order. They sent the paper to *Nature Physics* for consideration, noting that the result "opens up new future avenues toward identifying more generic topological orders based purely on experimental measurements."

One of the reviewers sent back a number of pointed questions, chief among them: why didn't they push the work further?

"The reviewer's comments were illuminating," said Wan, who spent the last year of his Canadian postdoctorate working on the research. "We decided to challenge ourselves and try to observe the breakdown of topological order. We redesigned the experiment completely."

The resulting experiment, and the subject of the new paper, goes well beyond verifying the S and T matrices as an observable fingerprint for topological order.

Now, the matrices have been used to probe topological order itself, mapping out the phases of a system right up to the point where entanglement breaks down, all with minimal theoretical input at the start.

Mapping a quantum system

The researchers essentially launched a voyage of discovery. When studying a quantum system, researchers usually calculate the

[1] The phases in normal matter – solid, liquid, gas, plasma – are dictated by temperature. Topological systems also have something called phases, but these are dictated by other factors. At each quantum phase, a topological system obeys specific rules or symmetries. Under certain external pressures, these factors can be altered, and the system can be made to flip from one phase to another. This is called a phase transition.

system's energy interactions and all of its ground states before starting their experiments. This team took a different route.

Theory told them that the system they were simulating – a particular kind of topological code called a Z2 toric code, which is the simplest example of topological order – has four ground states, but they didn't know what quantum phase those states belonged to. That's largely because of the quirks of quantum matter.

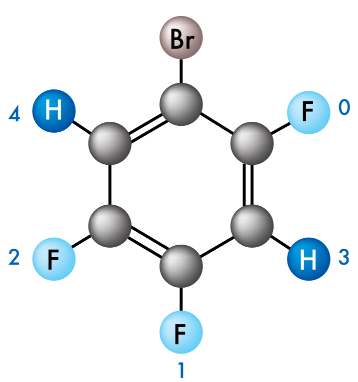
Quantum systems are described using something called a Hamiltonian. The Hamiltonian is like a map of the energy interactions inside the quantum system. The ground state of a quantum system is the lowest energy it can have while still maintaining its particular Hamiltonian.

But ground states can take different forms, because a system's Hamiltonian "map" can be configured in different ways: two nuclear up-spins could produce the same Hamiltonian as two down-spins. These alternate versions are called "degenerate ground states," and they are potentially powerful for quantum memory.

The team decided to use what they had just learned about S and T matrices to see if a simple topological system could essentially identify its own degenerate ground states.

They designed an experiment using the "adiabatic method," which posits that, if you move slowly enough, you can manipulate a quantum system without disrupting its quantum-ness. (The idea was first proposed in 2008 as a potential avenue for creating quantum memory.) They were essentially sneaking up on a quantum system.

The experiment



The simulated qubits are labelled 1 through 4, with the observer qubit labelled "0".

The five-qubit experiment was carried out using a two-dimensional compound called 1-bromo-2,4,5-trifluorobenzene.

The nuclear spins of two protons and two fluorine atoms were numbered one through four, each serving as a single quantum bit, or "qubit." A third fluorine atom acted as the observer. (The bromine and carbon-12 nuclei have spins of zero, so cannot be detected by the NMR machine.)

Experimentalist Zhihuang Luo, then a PhD student at the University of Science and Technology of China, used radio-frequency pulses to manipulate the spins of the qubit. Going slowly, he put the four-qubit system through a series of transformations.

Then, using measurements from the probe qubit, the team developed an algorithm that allowed them to recover the S and T matrices and get a peek at what was happening inside the system as it moved.

"It was difficult. The sample is a liquid crystal that is very sensitive to temperature," said Luo, who is now a postdoctoral researcher at the Institute for Quantum Computing. "A tiny fluctuation – even 0.1 degree Kelvin – would lead to a large change of the system's parameters. That decoherence effect is serious."

Thanks to the observer qubit, the experimentalists were able to monitor the effects of the transformation, and then to recover the S and T matrices from the data, all without destroying the system's entanglement (or, more technically, without collapsing the wave function).

It seems that sneaking up works. At a critical point, there was a sudden jump and change in the S and T matrices. The system had revealed its information.

A first step

The results paint a striking picture: the four degenerate ground states in the Hamiltonian were clearly identified as time evolved, and then the entanglement collapsed. "Our results open up novel avenues toward identifying more generic topological phases purely based on experimental measurements, and open the doors to many applications, like fault-tolerant quantum computation," Luo said.

The experiment shows that, with current technology, researchers can not only identify phases of matter; they can also probe the system in its "phase space," right up to the point where the long-range entanglement collapses.

This work, Wan said, shows that the idea of using degenerate ground states as quantum memory is sound. It could also be used to identify topological orders in realistic materials, where researchers usually do not have prior knowledge of the topological orders to be discovered, nor their ground states.

The researchers said the work also promises to be a better method of characterizing topological order. The standard method – if anything can be called "standard" in this area of physics – is to use entanglement entropy [see footnote 2]. But this has an inherent flaw: with entanglement entropy, different phases often have the same value. It does not tell you what is happening within a system, because all the phases look alike.

By being able to distinguish between phases, the S and T matrices provide a window to observe quantum behaviour. It could even be used to simulate a quantum computing proposal called anyon braiding, which forms another plank of Wan's research.

"This is the first time a topological order has been simulated and identified knowing only the approximate Hamiltonian, without any prior knowledge of the ground states," Wan said.

"The method is here. It's not only scalable but also applicable to quantum simulators other than NMR simulators. And it becomes more reliable as the system grows. All that is needed now is the technology with which to create it. We need more qubits."

– Tenille Bonoguore

[2] Entanglement entropy is associated with the information you lose when you isolate a region to study its properties. By "cutting out" part of the system to study, you inevitably lose information about hidden quantum links; this missing information corresponds to entropy.

PHYSICS HAIKU

APPRAISAL

DO WE ALL MATTER?
if $E = mc^2$
WE MUST ALL MATTER.

—ANONYMOUS

PI

Three point one four one
Five nine two six five three five
Eight nine and SO ON.

—COLIN HUNTER, PI communications director

STRING THEORY

What's on the outside
DOESN'T COUNT, mom always said.
Wrong, wrong, wrong, wrong, WRONG.

—TENILLE BONOGUORE, PI sr. science writer

SPOOKY

up here, up there? FINE.
tilted here means up there too?
THAT'S ENTANGLEMENT.

—RONAK SONI, PI Visiting Graduate Fellow

in theory

consider the COW
as a sphere in a vacuum.
Draw the FBD*

—STEPHANIE KEATING, PI Science Writer

*FREE BODY DIAGRAM

EXCITED DEUTERIUM

Charged in company
Strongly bound and EXCITED
Our love is pion

—NITICA SAKHARWADE, PI PhD Student

SHAPE SHIFTER

Shifty neutrino
ELECTRON, MUON, or TAU?
who are you today?

—AURORA IRELAND, PSI student

Noethers Theorem

Nature never rests.
Yet change ceases if you wield
Symmetry's power.

—FLORIAN HOPFMULLER, PI PhD Student

Physics fuels friendships at summer "boot camp"

High-schoolers from across the globe dive deeply into science together at Perimeter's International Summer School for Young Physicists.

When you're a teenager with an interest in quantum physics or general relativity, finding other teens who share your passions can be a tall order.

That is, unless you're lucky enough to be accepted to the International Summer School for Young Physicists (ISSYP), an intensive physics boot camp that each year brings together 40 teens and immerses them in Perimeter Institute's unique environment for two weeks.

For many, ISSYP marks the first time they can dive deeply into conversations about physics and science with like-minded peers.

"What surprised me was the amount of time that people can spend talking about physics," remarked Zhanna Klimanova, an 18-year-old CEGEP (Quebec's pre-university college program) student from Montreal. "I can do it for hours, but I'm usually cut off by, you know, the 10-minute mark. Here, it's the complete opposite."

Physics may be an easy conversation starter, but the diversity of the group ensured there was much, much more to talk about. Selected from a pool of more than 400 applicants, half of the 40 chosen students are Canadian. The others hailed from 13 other countries, including China, Greece, Germany, India, Slovakia, South Africa, and the US. The group is split evenly between female and male students.

"Not every country does things the same way, from the way we go to school, to the way we learn physics," said AJ Loy, a 16-year-old from Singapore. "It's been interesting being able to talk and share experiences with everybody."

Fostering that kind of connection is one of the goals of ISSYP, where social activities and field trips are interspersed with lectures and talks from eminent physicists. Keynote sessions included an address on the state of physics from Perimeter Director Neil Turok, a talk on causality from quantum physicist Robert Spekkens, and a question-and-answer session with Perimeter researchers about life as a physicist.

A perennial ISSYP favourite is the trip to SNOLAB, a physics laboratory located two kilometres underground within an active mine in Sudbury, Ontario. The lab is home to the 2015 Nobel Prize in Physics, awarded jointly to Arthur B. McDonald for the discovery that neutrinos have mass.

Before touring the facilities, which are now used for dark matter detection experiments, visitors must shower and don special suits to protect the sensitive equipment. "That was like, from a different world," said 17-year-old Sophia Chavele-Dastamani from Athens, Greece, as she described the trip to SNOLAB. "It was like I landed in a sci-fi movie."

Chavele-Dastamani heard about ISSYP through a student advisor and was drawn by the chance to learn more about topics her school didn't cover. While the physics lessons were rewarding, the depth of the connections she made surprised her.

"Everyone is so helpful," she said. "It might be midnight in the residence, and they might be explaining calculus to me – it's things I haven't done in school. But at the same time, they're not snobby with me for not knowing it. They're actually helping me."

The first half of the program focuses on getting the students up to speed with core topics in theoretical physics: a banquet of ideas that the teens eagerly devoured. "I was ecstatic because all the topics were the ones that I wanted to know. There's quantum mechanics, special relativity, general relativity, and black holes," said Anwyn Woodyatt from Qualicum Beach, BC, who graduated from Grade 12 before coming to ISSYP.

Her favourite was the hands-on lesson that explored concepts of curved spacetime and general relativity using simple materials like beach balls and masking tape. "You take a piece of tape, and you're not expecting it to explain the universe to you. That one really opened my mind. I think we all walked out of there really, really excited to learn more the next day."

In the second week, students got a taste of what research is like as they worked in small groups with mentors to explore current problems in theoretical physics. On the final day of the program, they presented their work on topics ranging from quantum gravity and quantum computing to holography and cosmology at a poster session (similar to those seen at scientific conferences) in Perimeter's atrium.

Chavele-Dastamani plans to share her newfound knowledge with the nuclear physics club that she runs at her high school in Athens. "I want to help them understand this," she says. "Even if they don't understand the math, it's very easy to understand on a theoretical level."

In addition to binders full of notes, an international network of friends, and selfies with the Nobel Prize medal at SNOLAB, alumni take home a renewed sense of confidence and possibility.

For George Mo, who is 16 and going into Grade 12 at Bayview Secondary School in Richmond Hill, Ontario, the most powerful lesson was the power of physics itself.

"The world is so complex. Just by using these math principles, we can discover so many things," he said. "It makes me wonder if there's so much more that can be done – so many more things to be developed – and it's just really cool."

– Stephanie Keating

Calling all high school physics aficionados!
Applications for the 2018 edition of ISSYP open in December, and close March 31.

www.issyp.ca

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DO WE NEED TO KEEP TALKING ABOUT **WOMEN IN SCIENCE?**

Science is meant to be a meritocracy, but anecdotes and evidence indicate that the field – and physics in particular – is not living up to its own standards.

Let us take it as given that women have the talent and ability to study physics and pursue research at the highest levels. Let us also take it as given that the vast majority of people would agree with the previous statement.

Was there, then, still a need for the "Women in Physics Canada" conference, held at the Institute for Quantum Computing in Waterloo, Ontario, in July? From discussions held during the three-day gathering of students, postdocs, and professors, it seems the answer is both "yes" and "no."

Yes, there is a need for women scientists to know the issues they face are not unique nor individual. A legacy of sexism lingers in physics, affecting how students are treated, which people are promoted, how letters of recommendation are written. Even gender-neutral policies can have unintended detrimental impacts on women.

Things start to fray early: data from the US shows a steep drop in women's participation in physics, starting with the transition from high school (where girls make up half of the enrollment in science and math classes) to university and graduate school (where women make up around 20 percent of physics undergrad and PhD classes). It unravels further when physicists seek tenure: around 16 percent of faculty positions are held by women in the US, but predominantly at the assistant and adjunct professor levels.

On the other hand, no, this is not just a conversation for women. As Serge Villemure, Director of Scholarships and Fellowships at Canada's Natural Sciences and Engineering Research Council (NSERC), said on the opening day: equity is "not just an issue for those affected by it. It is an issue for everyone. It is a social issue."

Discrimination runs counter to the meritocratic ideal of science itself. If the practice of science largely supports "the establishment," society risks blocking brilliant thinkers who could make great contributions to the field.

So how, exactly, does one unpick discrimination from the fabric of science?

The case for systemic change

For cosmologist and former Perimeter postdoc Chanda Prescod-Weinstein, the solution requires systemic change. Encouraging minorities to enter, and stay in, the field will not dismantle the barriers they face; supporting individuals will not ensure others won't end up needing the same supports.

She's seen it play out in her own career. A physicist at the University of Washington, Seattle, Prescod-Weinstein also dedicates time to sitting on committees and promoting equal opportunity in science for all minorities. She sees both her science and her activism as integral to her work, but they are not rewarded equally: she often gets flak for focusing on something other than publishing. "Hiring committees are telling me to stop doing so much additional stuff," she said during a panel on diversity in science.

Villemure, from NSERC, said it was a common bind. The "publish or perish" mentality that currently dictates success in science does not allow for other modes of work and other priorities, and self-selects for a certain kind of person. "We need to make changes in how excellence in research is defined," he said.

For example, an idea floated at NSERC is to rely less on lists of publications, and instead ask researchers to only highlight their most influential papers and then also outline other contributions they make to the field, such as mentoring, science and mathematical promotion, outreach activities, and so on.

Villemure said targets and quotas could also be considered as part of the solution, along with other measures such as implicit bias training, gendered language awareness building, and breaking down the myth that scientific career paths have to be linear: "Targets and quotas change the culture faster than without them. We need to stop being hesitant. We need to be proactive."

But affirmative action policies that mandate greater equality are not a panacea. Research suggests that quotas and affirmative action policies have helped white women a lot more than they have helped women of colour. (Indeed, the relative privilege of women among other minorities was a recurring theme throughout the conference. Calls for the gender equality movement to act as an umbrella community for other minorities – such as disabled and trans people, or people of colour – were roundly endorsed by participants.)

"The gap between white women and other women has increased," said Shohini Ghose, a physics professor at Wilfrid Laurier University and director of the Laurier Centre for Women in Science. "[These policies] are perfectly well intentioned, but they haven't thought about the fact not every woman is the same."

There are avenues opening up to promote and enact institutional change. The Athena SWAN network in Britain and related SAGE program in Australia promote gender equality, and award accreditation denoting the level achieved (similar to how the LEED system accredits environmentally friendly construction). These accreditation levels can also be tied to other forms of accountability, such as funding renewals. Perimeter has implemented a series of initiatives to support women at various stages of their careers, named after the influential physicist and mathematician Emmy Noether.

But an institute-by-institute approach cannot dismantle the discrimination that, some assert, is enmeshed in the practice of science itself.

Meanwhile, in the classroom…

Young women attending WIPC shared their own stories of bias and inequality. Undergraduate students Claire Leuty and Lindsay Babcock said the overwhelming majority of their science and math classmates at the University of Waterloo were male – and that had a tangible impact.

"I feel like, when you are stuck on something and you go ask for help, you're just perpetuating this idea that girls can't do math," Leuty said. And while many of her physics professors actively encourage women to stay in the field, other male professors have been condescending towards female students.

There was, however, an unexpected if somewhat uncomfortable advantage: male first-year undergrads often can't find older students to help them, because the older, male students were busy helping the first-year females.

"It is creepy, but you've got to take advantage of what you have," Babcock said. "If we're struggling in other areas because we have disadvantages because we're female, you might as well take what you can get."

Their offers of assistance, however, were mostly rebuffed. "When it's the other way around, when we try to help somebody else, they don't take us seriously," Leuty said.

Their complaints are not imagined, research shows. While explicit bias has become frowned upon and/or downright illegal in modern society, implicit bias is a harder knot to unravel.

That's because most people aren't aware of the internal biases they hold. Implicit bias comes out in unexpected ways: such as associating "science" with one gender and "arts" with another, or labelling one teacher "tough" but the other "mean."

In her conference presentation, University of Waterloo Centre for Teaching Excellence instructional developer Crystal Tse discussed a study of science faculty members that found faculty favoured male applicants more than female, offering better feedback, more support, and encouraging them to ask for more money in job negotiations. The bias was consistent across male and female faculty. Such "unseen" biases can leave individuals uncertain of their value or worth. It can be hard to work out if the good or bad things in your career are happening because of your ability, or because of the categories you can be slotted into.

And being aware of a stereotype can lead you to fall prey to it: pressure to disprove a bias can actually impede your ability to do so (something known as stereotype threat). Simply pointing out the reality of implicit bias is not enough to overcome it, Tse warned. "We know from the literature that a lot of diversity training does not work. It actually backfires," she said.

What is required is not a single element of training, but an ongoing diversity training program such as the University of Michigan's Diversity, Equity, and Inclusion workshops and its Advance program, that brings the issue to the fore and keeps it top-of-mind.

An individual's choice

Another example of bias could be the decision to schedule a "work-life balance" panel as part of the Women in Physics Canada conference.

Proponents of such panels point out that all people – men and women – juggle the pressures of career, family, and life. Openly discussing these stresses can help people feel less alone, provide coping strategies, and encourage individuals to find whatever kind of "balance" that best suits them.

Opponents, however, counter that such discussions – almost exclusively held during women's conference or "women's sessions" at larger gatherings – sustain, rather than address, the academic and societal structures that disadvantage women.

By holding these panels, they say, you imply that the best approach is to "help the women," rather than addressing the systematic problems that leave people needing such panels.

This became a hot and somewhat contentious issue at the conference's work-life balance panel.

One panellist – former IQC postdoc Krister Shalm, who is now a researcher at the US National Institute of Standards and Technology – said people's unintentional tendency to hire people like themselves had created a field filled with "white, male workaholics."

"Physics is very macho. We need to really rethink how we work. We can't do that without greater diversity," he said. At NIST, he's trying to help undo the tangle. "I want to hire people that are different from me. They will bring different values and different skills, and will be different kinds of role models."

Other panellists suggested a more individualistic approach: control what you can, set your own limits, and define your own success. "There's no right answer. What you want out of your career is going to be your measure of success," said career coach Jen Schrafft.

Added IQC postdoc and new mom Razieh Annabestani: "Different people have different definitions of 'work' and 'life.' What helped me a lot was to get away from this reverence of tough competition."

The discussion illuminated a fraught dichotomy: defining your own measure of success is all well and good for creating a greater level of personal equanimity, but it does not change the prerequisites for a job promotion. You still need to play the game to score a big win.

For Ghose, who was not on the panel, the whole concept of "balance" is misleading. Career success requires dedication and sacrifice. So does a family. Most people wax and wane between the two, she said, often vacillating between extremes, and that is okay. To hold up an arbitrary and often-unachievable ideal of "balance" mostly makes people feel inadequate.

But there's a deeper problem when these panels are largely directed at women, she warned. "There's an historical inability to view women apart from their family," she said. "Historically, men can be seen in just a professional light, but women cannot. These panels hark back to those standards."

Short term, the panels share stories and strategies for surviving an imperfect system. But survival today won't dismantle the barriers for minority scientists tomorrow. Much better, said Ghose, would be to disrupt the status quo and create an environment in which "balance" wasn't a discussion point for anyone.

A woman's place

It could all be enough to leave heads spinning. Thankfully, the attendees were physicists and physics students, who are well accustomed to probing complexity. They finished the three-day conference not dismayed by the issues, but invigorated by the robust discussions.

Physics undergrad Amy McAllister said she'll be going back to the University of Lethbridge with a renewed sense of purpose. Before now, she shared any apprehensions about her field with friends studying arts.

"Before I came here, it was something that was holding me back," she said on the final day. "I didn't feel like I could talk to anybody about it. But now I know there are people that are like-minded; it makes me empowered to keep going and pursue my field."

At the conference's welcome session, local Member of Parliament Bardish Chagger – herself a science grad from the University of Waterloo – set the tone as she looked into the auditorium of women scientists. "One day, this is what I believe our offices and our labs will look like," she said.

As the event wound up two days later, University of Toronto professor and active conference participant A.W. Peet summed up the prevailing atmosphere in one tweet: "If the students at #WIPC2017 are the future of physics in Canada, I'm in. All in."

– Tenille Bonoguore

Forces of nature: Women who changed physics

People of PI:

Bridge-builder Bianca Dittrich

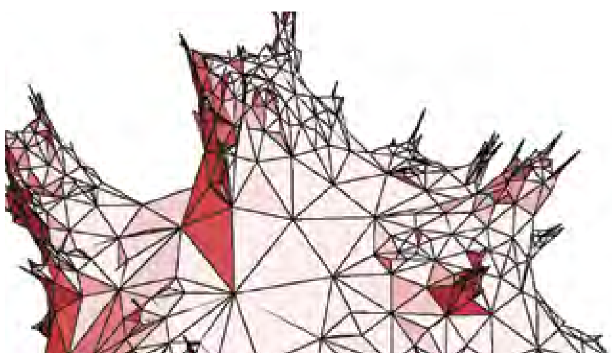
People kept telling Bianca Dittrich to turn back. She ignored them, and is breaking new ground on one of physics' most challenging problems.

Bianca Dittrich's path was neither easy nor obvious. Growing up in East Germany in a time of political turmoil, she took an early interest in history. The wealth of stories told from various perspectives was intriguing but their subjectivity troubled her: all stories, in the end, were coloured by interpretations.

Science offered a more objective means to learn about the world. She considered a career in geo-ecology, a field that also appealed to her love of nature and the environment. Her parents, meanwhile, encouraged her to choose an "employable" career in medicine or to focus on her athletic talents with competitive tennis.

But Dittrich sought wider horizons. "In some sense, I wanted, always, to know everything," she said. Theoretical physics offered the best promise of fulfilling that quest. "Physics is very powerful in explaining many phenomena with few principles."

Friends and peers cautioned against her choice. "Everyone told me I won't get a job doing physics," she said. What's more, the problem she found most intriguing, quantum gravity, was widely considered one of the most difficult topics in theoretical physics. "Everyone tells you that you should not do quantum gravity."



Dittrich uses mathematical methods to construct spacetime from the ground up.

Unfazed by her critics, Dittrich pressed on – not knowing if it would work out, but determined to try.

Though Dittrich is humble about her accomplishments, she distinguished herself as a rising research star from the very start. After completing her PhD in Germany, she came to Perimeter Institute as a postdoctoral fellow and next was awarded a prestigious European Union Marie Curie Fellowship.

In 2009, she received a grant from the Max Planck Society in Germany to build a research group at the Albert Einstein Institute. Perimeter recruited her as a faculty member and she came to Waterloo in 2012. Today, she is a highly respected researcher working on uniting two great theories of physics: quantum mechanics and general relativity.

The two theories have been at odds for nearly 100 years. At the heart of the disagreement is the nature of the fabric of the universe itself. In general relativity, spacetime is smooth and continuous. If you were to zoom in with a microscope to arbitrarily small distances, it should look the same as it does when you zoom out for the larger view. But in quantum theory, at the level of subatomic particles, spacetime is discrete and granular, like pixels in a photograph.

In spearheading the Discretuum to Continuum Initiative at Perimeter, Dittrich is leading efforts to develop the mathematical tools that will be used to bridge the two theories.

Still, not everything has to be difficult. When asked where she gets her best ideas as she grapples with one of physics' thorniest challenges, she shrugged. "In the shower," she said. "Or in the bus stop."

– Stephanie Keating

Read more profiles of Perimeter researchers at www.insidetheperimeter.ca/discover/people-of-pi.

CANADA AS A HAVEN FOR INNOVATION

In a keynote address to the Canadian Science Policy Conference, Neil Turok highlighted Canada's role as an "innovation nation."

While delivering a keynote address to more than 600 scientists, public servants, and policymakers in Canada's capital, Perimeter Director Neil Turok suddenly broke into dance.

His improvised jig happened while big screens on either side of him showed a rapid-fire montage of great Canadian innovations, accompanied by a funky beat. The little dance was a physical embodiment of the positive spirit and optimism that resonated throughout his entire presentation, titled "We Are Innovators," at the Canadian Science Policy Conference on November 1.

"We must build on Canada's strengths as a haven of hope, where young people are enabled to dream and to create," Turok said. "We live in times of global instability, but we must not be frozen with fear, because such moments bring great opportunities."

Such sentiments permeated the three-day conference at Ottawa's Shaw Centre, which examined Canada's role on the world stage as a beacon of diversity, critical thinking, and evidence-based science policy-making.

Turok's presentation was part of the Perimeter-led Innovation150 collaboration for Canada's sesquicentennial, and has been seen by thousands in venues across Canada (see pages 10-11 for more on Innovation150).

Nobel laureate and Perimeter Board member Art McDonald introduced Turok, describing the talk as a reminder of the importance of "evidence-based decision-making being central to our government's agenda." Canadian Science Minister Kirsty Duncan and Chief Science Advisor Dr. Mona Nemer were among the many representatives of the federal government in attendance.

Turok shared stories from his childhood in South Africa (where his parents were jailed alongside Nelson Mandela for fighting apartheid), his formative years as a curious scientist-to-be, his research into the beginnings of the universe, and his efforts to make Perimeter and Canada havens for reason and science in a troubled world.

Turok explored these ideas further the next day as featured speaker at an annual thought-leadership event organized by Finance Canada at a packed Library and Archives Theatre in Ottawa. The session, webcast to federal employees across Canada, included portions of Turok's "We Are Innovators" talk, as well as a Q&A between him and John Knubley, Deputy Minister of Innovation, Science, and Economic Development Canada.

"We are fortunate to live in a country where diversity is cherished and collaboration is normal," he said. "We can make it a place, maybe even the place, where young people have all the space and the support they need to re-imagine and improve the world."

– Colin Hunter

UNLEASHING INNER SCIENTISTS

How Perimeter Institute's annual summer camp for teachers is transforming classrooms around the world

Children are natural scientists. In kindergarten, they will happily explore ideas that make adults minds reel – from the warping of space to the direction of time. By the time most of those children grow up and start learning physics – usually in high school – their minds are much less open.

The task of reigniting that innate curiosity often falls to teachers who are overworked and under-resourced. Before teachers can engage their students, they have to find a way to energize themselves.

For many, that means having a well-earned vacation over the summer. Last July, 44 educators from the around the globe took a very different approach: they dove into cutting-edge theoretical physics at Perimeter's EinsteinPlus summer school for teachers.

They arrived with an inkling that something big was coming their way. They departed with goodie bags full of science demonstrations, a network of peers spanning the globe, and a rejuvenated sense of wonder and purpose.

"It really helps me re-engage with the toughest, most interesting bits of physics," said Jon Clarke, a former high school teacher who now runs professional development sessions for science teachers in the United Kingdom. "It is intense. This is hard work to be here, but very enjoyable hard work."

Through a series of workshops, science seminars, evening discussions, and craft nights, the teachers explored deep science, from gravity and general relativity to the Event Horizon Telescope (EHT) and particle physics. They did it from both sides of the pedagogical equation, performing the experiments first as students, then putting on their teacher hats for deeper discussions about the lessons.

For Mara Anderson, a teacher from Maryland, US, the format takes physics concepts that seem unapproachable and presents them in a way that can engage a science-shy teen.

But that was not the most powerful lesson. Far more important, she said, is the scientific approach itself. Anderson was particularly taken with the "knowledge building" approach, in which students lead their own exploration, guided by teachers. "That's how you want people to approach the universe – it's what scientists do," she said.

Add in some hands-on lessons that urge students to predict what will happen in an experiment, carry out the test, and then explain what actually did occur, and you have a powerful combination.

Inevitably, some of your predictions will turn out to be wrong – many scientists joke about how they are wrong most of the time – but for those not used it, error can be difficult to stomach.

"I hate it at first. I hate being wrong," Anderson said. Science forces you to confront that feeling, and to keep going. "It's not going to go away. You work to be less wrong next time. Science teaches skills and research techniques that … are more important than the equations."

Itumeleng Molefi, a high school science teacher in Carnarvon, South Africa, started incorporating "knowledge building" into his own lesson plans after attending CERN's High School Teacher program in 2016, where he also did a Perimeter Institute workshop.

As a result, he noticed his students exploring scientific models and probing them in greater depth. It liberated them to look for clues, rather than answers. He particularly wants to bring the new EHT astronomy lessons back to South Africa, where a network of radio telescopes (which rely on the same physics principles as the EHT) is being built as part of the Square Kilometre Array.

"We've got this incredible project right there in the country, but so few people know about it, so few teachers know about it, so few students know about it. This is a good way to demonstrate it," he said.

The value of this goes beyond the classroom, said Amber Henry, a former high school teacher who in 2016 became the education and outreach coordinator for the Laser Interferometer Gravitational-Wave Observatory (LIGO) in Hanford, Washington, US.

Science, she said, makes people better citizens. They can analyze rhetoric, assess public policy, and make more informed decisions. And it can help students understand the complexities of the world they live in. "There's all this physics we use every day in everything we do that they have never heard of, and they will never hear of [it] unless they hear it in a high school classroom," she said.

Henry's role at LIGO takes her into all kinds of classrooms – from kindergarten to Grade 12 – where she runs workshops and lessons about cutting-edge physics. The funny thing is, her high school classes are much more daunting than kindergarten visits.

Kids, she said, get it. "They're born scientists. They ask questions constantly – it's what they do," Henry said. "When you get them as high-schoolers, they've had that scientist beat out of them through the education system. They've been jaded, so now you have to find a new way to get them back."

Through EinsteinPlus, the teachers now have a series of activities that invite childlike curiosity, and aim to keep the students – and their teachers – inspired. It's a powerful boost, said Clarke: "The facilitators are such engaged, enthusiastic people – they really want to share with us. And that gets me fired up to go share it again."

– Tenille Bonoguore

The 2017 EinsteinPlus program was supported by Maplesoft.

Teachers: Want to supercharge your science teaching? Applications for EinsteinPlus 2018 open December 8, 2017 and close April 2, 2018. To find out more and to submit your application, visit **www.einsteinplus.ca**.

LIEUTENANT GOVERNOR CHAMPIONS EMPOWERMENT THROUGH SCIENCE

Ontario Lieutenant Governor Elizabeth Dowdeswell works with Perimeter to support education and equality in science.

When Elizabeth Dowdeswell became the Lieutenant Governor of Ontario, she broke with tradition: instead of immediately declaring a focus area for her mandate as the Queen's representative in the province, she instead set out to listen to the stories, concerns, and ideas of Ontarians. The themes that emerged were ones of storytelling, social cohesion and sustainability, and Ontario's place in the world.

As Canadians have looked back and forward during this sesquicentennial year, she said, it's clear that scientific literacy is an essential component of a stable and successful society. With that in mind, Dowdeswell engaged with the Perimeter community twice this year to get a better sense of the issues affecting scientists and teachers.

In July, Dowdeswell – who worked as a teacher and university instructor earlier in her career – met with participants in Perimeter's EinsteinPlus program for high school teachers. She spent the morning with 44 educators as they playfully grappled with ways to understand, then teach, quantum mechanics, general relativity, and more.

"One of the reasons I came was to thank these teachers for what they are doing, and also to encourage them to keep doing it, because scientific literacy is so important," Dowdeswell said.

"It is fundamental to our growth and maturity as a country. It's not that kids will necessarily grow up doing some science, although some will – and very effectively. It's that the whole process of science is one of critical thinking, of problem solving – a process that is applicable to any number of future careers and just involvement as a citizen."

That visit to Perimeter inspired Dowdeswell to invite a group of Perimeter researchers, staff, and Leadership Council members to visit her at Queen's Park in November for a private discussion on the advancement of women in science.

Perimeter guests were treated to a behind-the-scenes tour of the Legislative Assembly and a crash course on Canada's political system (which proved fascinating to many of PI's international scientists) before engaging in dialogue with the Lieutenant Governor, who invited them to share their experiences as women in science.

The conversation spanned a range of topics, including the feeling of "impostor syndrome" that plagues many scientists, the importance of having women as role models, and the effects of diversity on scientific research.

"This was such a wonderful opportunity to be with a group of women who are associated with science, to talk about the little things that matter and the big things that matter," said Dowdeswell. "It ranged all the way from what we need to think about with respect to our education system and how we approach science as individuals, but most of all it was just an informal opportunity for people to tell me their stories."

For some researchers, having a government official take an active interest in the affairs of scientists was a rare but welcome experience. "Inviting academics here, and being curious about what they have to say – I have never seen this anywhere," said Emanuela Dimastrogiovanni, an Emmy Noether Visiting Fellow at Perimeter.

Dowdeswell sees part of her role as Lieutenant Governor to be the province's "storyteller-in-chief," and she intends to keep conversations about diversity and education in science flowing. "I always love to come to Perimeter because it's one of those places that is full of wonder, full of intense activity, bright and engaging minds in a magnificent space," she said in July.

"A place like Perimeter illustrates Ontario in the world so well. It's a place that attracts the best, a place dedicated to improving humanity – what could be better than that?"

– Colin Hunter and Stephanie Keating

HISTORY IN THE MAKING

After a half-century watching breakthrough after breakthrough, Australian historian and science-fan Gary Brown lends his support to future advances he won't be around to see.

It was a spring night in the regional Australian town of Albury, and seven-year-old Gary Brown stood on the grass, looking up at the sky. Above him, amid the smudge of the Milky Way and the static pricks of the Southern Cross, a light steadily tracked across the night sky.

Sixty years later, Brown still remembers watching Sputnik 1 – the first artificial satellite – pass overhead. "There wasn't any trouble seeing it," he recalled. "It was quite bright, and it moved fast."

Already the kind of kid who pestered his family with questions – Why does the sun shine? What are stars? – he seemed destined for a career in science. Except for one hitch.

"Unfortunately, I have a complete lack of talent with mathematics," Brown said with humour from his home in Canberra. "At high school, I was almost always near the top in science and near the bottom for maths. That's not sustainable to do science."

So he doubled down on humanities and became a military historian, eventually going to work at the Australian Parliament, where he provided advice and reports to sitting politicians about defence and national security. It was a challenging job, one that required him to spend years wading through the lesser aspects of humanity. "It's not a savoury subject. Sometimes you had to swallow hard," he noted.

All the while, he maintained a lifelong enthusiasm for science, filling a chunk of his living room bookshelf with popular science books and keeping abreast of developments thanks to one of the perks of his job: access to the parliamentary library. In the age before the internet, the library's subscriptions to various science journals were a valuable resource for an avid science fan.

"I had the good fortune to live through an age of discovery. In 1950, when I was born, we knew almost nothing about the solar system," he said. "All that changed virtually while I watched."

But that explosion in knowledge has brought us to something of a precipice. Modern technology – based in large part on last century's theoretical physics breakthroughs – is reaching its limits. To go further, we must discover new physics.

And that is what brought Brown to Perimeter Institute as a legacy donor.

"We can't rely forever on technologies that consume irreplaceable resources or foul our nest," he said. "To get really new tech, we need new science. That means fundamental research, most of which will produce precisely nothing. That's just the way of it with fundamental research. You've got to explore an idea to know if it's rubbish or not."

While Australia has its fair share of philanthropists – whom Brown applauds – few put their money into the kind of fundamental research that could transform society.

Canada has a larger population, giving it a greater base for philanthropy, and the distinct advantage of sitting next to a great pool of wealth and talent in the US.

So Brown has made a pledge to Perimeter in his will in the hope that his donation, along with many others, can help the Institute make transformative breakthroughs.

"Places like Perimeter are not opposed to new ideas. They don't close their eyes and close their ears. I think that's really important," he said.

"I really wish there were more institutes like this. It seems highly successful at attracting eminent thinkers. Hopefully, something truly significant will emerge from Perimeter to take us forward."

– Tenille Bonoguore

$\int$ Part of (the) = Σquation^2

Perimeter's fundraising efforts recently passed an important milestone – since 2014, more than $25 million has been raised from the private sector in support of our research, training, and outreach efforts.

Here is a salute to some of the visionary donors who have stepped forward to make this happen.

Davide Gaiotto, Stacey Krembil, Mark Krembil, Linda Krembil, Kevin Costello, and Robert Krembil: The Krembil Foundation supports the Krembil Galileo Galilei Chair, held by Davide Gaiotto, and the Krembil William Rowan Hamilton Chair, held by Kevin Costello.

Maria Antonakos (Strategic Philanthropic Partnerships, Perimeter Institute), Patrice Merrin (Co-Chair, Perimeter Leadership Council), Asimina Arvanitaki (Stavros Niarchos Foundation Aristarchus Chair), and Heather Clark (Director of Advancement, Perimeter Institute)

Subir Sachdev, Neil Turok (Director, Perimeter Institute), and Harbir Chhina (Executive Vice-President & Chief Technology Officer, Cenovus Energy; Member, Perimeter Leadership Council): Cenovus Energy supports the Cenovus Energy James Clerk Maxwell Chair (Visiting), held by Subir Sachdev.

Michael Duschenes (Managing Director and Chief Operating Officer, Perimeter Institute), Clayton Riddell, Pedro Vieira, and Mike Lazaridis (Founder and Board Chair, Perimeter Institute): Clay Riddell supports the Clay Riddell Paul Dirac Chair, held by Pedro Vieira.

Thomas MacMillan (former President and CEO, Gluskin Sheff), Freddy Cachazo, and Jeff Moody (President and CEO, Gluskin Sheff; Perimeter Board Member): Gluskin Sheff supports the Gluskin Sheff Freeman Dyson Chair, held by Freddy Cachazo.

Sherry Shannon-Vanstone (Co-Chair of the Emmy Noether Council) and Anne-Marie Canning (supporter of Emmy Noether Initiatives)

Avery Broderick, Catherine (Kiki) Delaney (Member, Perimeter Leadership Council), and Ian Delaney: The Delaneys support the Delaney Family John Archibald Wheeler Chair, held by Avery Broderick.

Paul Genest (Senior Vice President, Power Corporation Canada) and Neil Turok

Peter Godsoe (Perimeter Board Member Emeritus), Shelagh Godsoe, and Mike Lazaridis: The Godsoes support the Peter and Shelagh Godsoe Family Foundation Award for Exceptional Emerging Talent.

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An ever-growing group of both public and private donors has helped make Perimeter what it is today: a world-leading centre for fundamental research, scientific training, and educational outreach. We are deeply grateful to all our supporters.

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EMMY NOETHER CIRCLE

Emmy Noether was a brilliant scientist whose work underpins much of modern physics. Perimeter's Emmy Noether Initiatives – funded by Emmy Noether Circle donors – support and encourage women in science.

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This list reflects gifts received between August 1, 2016 and October 23, 2017, and multi-year commitments of $50,000 and more.

CAN YOU DECODE THE UNIVERSE?

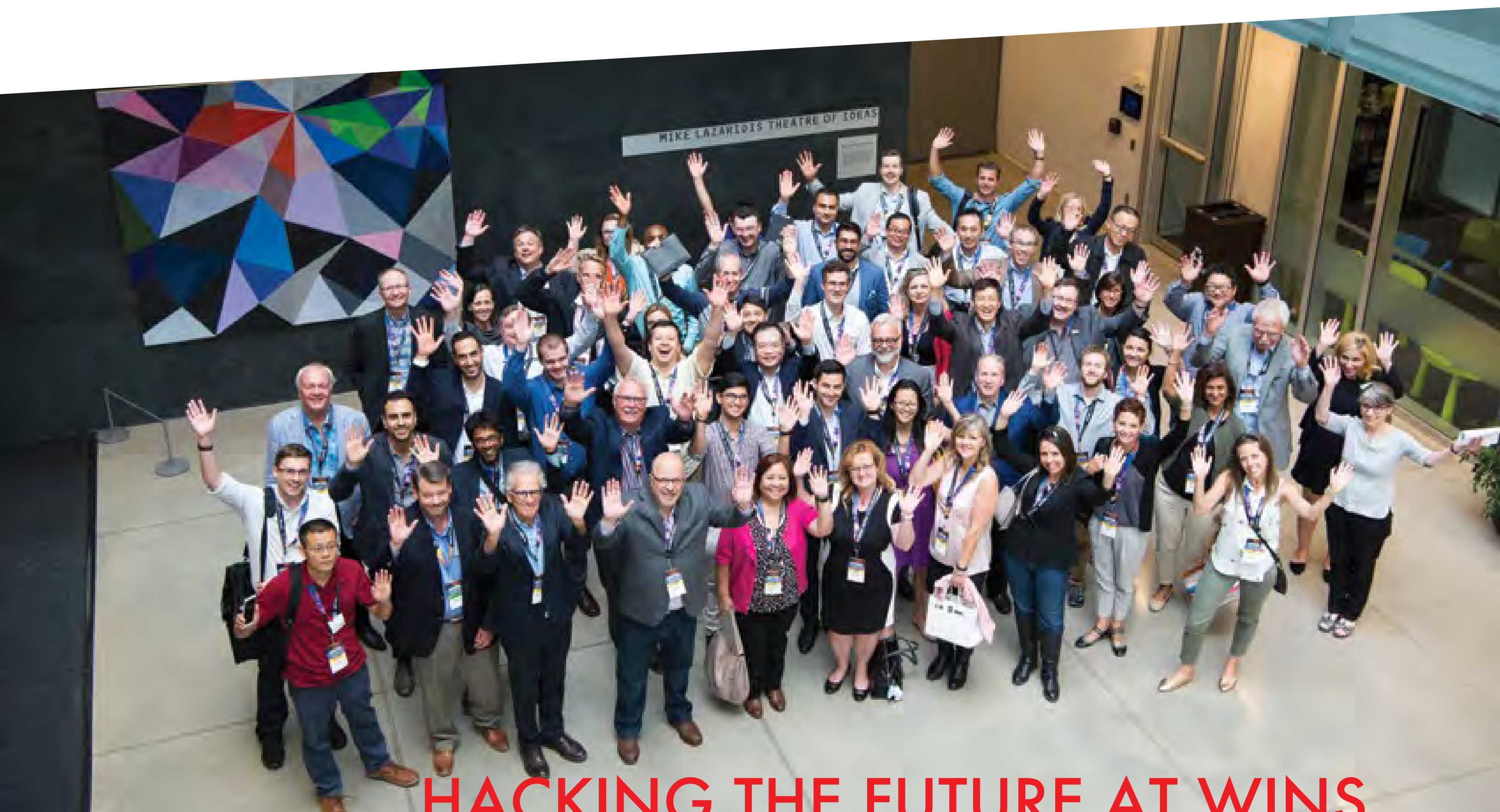
Hidden on this blackboard is one of the most iconic equations in physics. Can you spot it?
Hint: This illuminating equation is contained in one area of the board. *See the answer on page 45.*

Onsager Prize for Subir Sachdev shows condensed matter matters

Cenovus Energy James Clerk Maxwell Chair (Visiting) Subir Sachdev has won the prestigious 2018 Lars Onsager Prize from the American Physical Society for his many contributions to the theory of quantum phase transitions, quantum magnetism, and fractionalized spin liquids, and for his leadership in the physics community. Sachdev, who is also the Herchel Smith Professor of Physics at Harvard University, has been driven throughout his career to understand the properties of quantum matter, and his diverse ideas have led to key experimental tests that are helping us better understand this exotic, and enormously promising, realm.

PI's training programs lauded for being a "talent magnet"

Tackling some of the most radical ideas in the universe instills a combination of creative and rigorous thinking – skills that also enable physicists to excel at areas from high finance to high tech and medicine to media. So it's fitting that in October, Perimeter won the "Labour" award from the Creative Destruction Lab (CDL) in Toronto for its efforts to train the scientists of the future. "They recognized that being useful does not always mean you can make a product with it now, or even in the near future, and that recruiting and training young minds from all over the world has a huge benefit," said Perimeter's Director of Academic Programs, James Forrest. "I think that we were basically recognized for becoming such an effective talent magnet."



HACKING THE FUTURE AT WINS

The 2017 Waterloo Innovation Summit (WINS) explored issues around disruptive technology, adaptation, and policy. The summit – co-chaired by Perimeter Board member Michael Serbinis – brought dozens of thought leaders to Canada's top tech ecosystem for three days of keynotes, workshops, and hard-hitting discussions. While they were here, attendees toured Perimeter and heard from Perimeter Founder Mike Lazaridis on the importance of setting – and maintaining – an early lead in technological revolutions.

A world of opportunity

A number of Perimeter researchers journeyed to Brazil this year to share cutting-edge physics with exceptional young minds – and their teachers. Led by Pedro Vieira, the Clay Riddell Paul Dirac Chair at Perimeter, the team delivered workshops and mini-courses at the South American Institute for Fundamental Research (SAIFR). Topics included machine learning and cosmology; a high school teacher workshop; and the PI-SAIFR "Journeys into Theoretical Physics" school for undergraduates.

New chair supports Raymond Laflamme's pioneering research

When Raymond Laflamme stepped down after 15 years as the director of the Institute for Quantum Computing (IQC) at the University of Waterloo this past summer, he said he was excited to devote himself fully to research again. A new $8 million research chair at the University of Waterloo will enable him to do just that. The Mike and Ophelia Lazaridis John von Neumann Chair in Quantum Information will support Laflamme's groundbreaking work on quantum error correction. Laflamme is an associate faculty member at Perimeter, a fellow of the Royal Society of Canada, a recipient of the Queen Elizabeth II Jubilee Medal, and winner of this year's CAP-CRM Prize in Theoretical and Mathematical Physics.

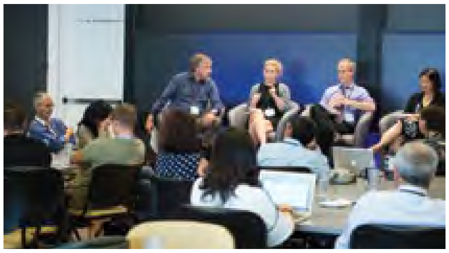
Perimeter's workplace culture earns an A+

The stunning architecture, the excellent espresso, and the buzz of the coolest ideas in the universe all help. But ultimately it's Perimeter's community that makes it special. That's why the Institute recently garnered top marks from its employees, earning Perimeter an Employee Recommended Workplace Award from *The Globe and Mail* and Morneau Shepell for mid-size Not-For-Profit/Government organizations. "It shows we have an environment where people know that we are there for them, to support them throughout their work life, and that's our ultimate goal," said Sheri Keffer, Perimeter's Director of People and Culture.

PI postdoc wins Sofja Kovalevskaja Award

Can Darwin's theory of evolution offer new avenues of discovery, as a tool of prediction? Perimeter Institute postdoctoral researcher Matteo Smerlak hopes to find out, thanks to a €1.65 million, five-year Sofja Kovalevskaja Award from the Alexander von Humboldt Foundation to explore the mathematics of evolutionary dynamics. "Evolutionary theory is really a statistical theory. It's much more about statistical patterns than particular, observable outcomes," Smerlak said. It's the second year in a row that a Perimeter postdoc has won a Sofja Kovalevskaja Award, following Michal Heller's win last year. Former PI postdoc David (Doddy) Marsh is also among the six winners for 2017.

Powerful discussion about the future of energy



How will today's frontier scientific research affect Canada's long-term energy future? Participants from diverse backgrounds – including machine learning, nanomaterials, biomimicry, and science fiction – grappled with this question at the Frontier Science Roundtable. Co-hosted by the Waterloo Global Science Initiative (WGSI), Natural Resources Canada, and the Waterloo Institute for Sustainable Energy (WISE), the roundtable met at Perimeter to discuss ideas around both physical and theoretical energy frameworks, as well as the policy and funding ecosystems needed to realize opportunities for a sustainable future.

PI summer students receive parliamentary visit

The Honorable Bardish Chagger, MP for the riding of Waterloo, Leader of the Government in the House of Commons, and Minister of Small Business and Tourism, stopped by Perimeter in August to chat with PI's summer students. Minister Chagger asked the students about their studies, career aspirations, and their experience working at PI. The students were hired through the Canada Summer Jobs Program with Employment and Social Development Canada to contribute to a number of Perimeter departments, including IT, Academic Programs, Educational Outreach, and Scientific Administration.

Answer for the hidden formula from page 42:

$$\partial_\mu F^{\mu\nu} = \mu_0 J^\nu$$

This equation is one-half of Maxwell's equations (written using tensor notation), combining Gauss' law and Ampere's law. Maxwell's iconic set of equations forms the foundation of our understanding of electromagnetic radiation, optics, and electric circuits.

The other half of Maxwell's equations combines Faraday's law and Gauss' law for magnetism:

$$\partial_\mu\left(\tfrac{1}{2}\epsilon^{\mu\nu\gamma\delta} F_{\gamma\delta}\right) = 0$$

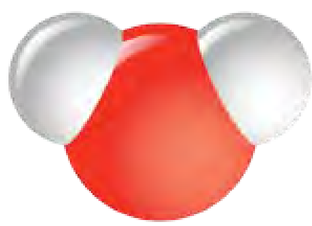
These young scientists were among nearly 500 guests who visited Perimeter on September 16, 2017, as part of Doors Open Waterloo Region, which was themed around "Identity and Innovation." Perimeter staff, scientists, and volunteers were on hand to give 26 tours (including six accessible tours) of the Institute's award-winning facilities.

IS IT TRUE THAT EVERY SNOWFLAKE IS DIFFERENT?

And if they are all different, how come?

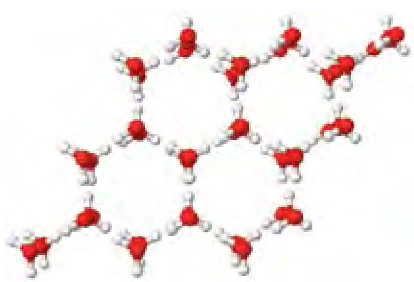
Most of us have heard that no two snowflakes are alike. But how could we possibly know that for sure? Surely, no one has examined every snowflake that has ever fallen and compared them, right?

That's technically true, but Wilson Bentley tried pretty hard to do just that. Born in Vermont in 1865, Bentley became fascinated with snow crystals after receiving a microscope for his 15^{th} birthday, and in 1885, he created the first photograph of a snowflake. As you'd imagine, the process was quite tricky – snowflakes melt if you bring them inside – so he set up his microscope and camera outside in the cold.



Despite the chilly working conditions, Bentley eventually photographed over 5,000 snowflakes – and no two looked exactly alike!

You might think that a sample of a few thousand flakes doesn't prove that all of the snowflakes that have fallen are unique, and you'd be right. To prove this, we have to use some physics.



Let's start with water, the basis of all snowflakes. A water molecule is made of two hydrogen atoms and one oxygen atom. It's shaped like a "V," with the two hydrogen atoms separated by an angle of 104.5 degrees. The interesting thing about a water molecule is that it is a polar molecule. This means that even though the whole molecule is electrically neutral (it has an equal number of protons and electrons), the side with the hydrogen atoms has a slight positive charge, and the other side has a slight negative charge.

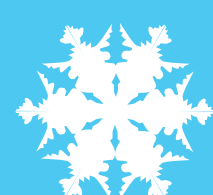
Since opposite charges attract and like charges repel, when multiple water molecules group together, the slightly positive hydrogen atoms in one molecule tend to be attracted to the slightly negative oxygen atoms in another. This process, known as "hydrogen bonding," orders the molecules into a hexagonal pattern as water cools down to form ice. This is why snowflakes always have six arms!

A snowflake starts when water droplets freeze onto a particle of dust or pollen. It begins forming as a small hexagonal crystal of ice, and then grows larger as it travels through the atmosphere. The points of the hexagon stick out a little bit further than the sides, meaning there's more of a chance for a water molecule to latch on at those points. The arms start to grow, and stick out a little further, giving them more opportunity to attract nearby water molecules. This carries on until the snowflake gets too heavy to be carried by the wind, and then it falls to the ground.

Each snowflake is shaped by the temperature, humidity, and air currents it encounters as it travels through the atmosphere: no two crystals will follow the exact same path, so it's extremely unlikely to find two snowflakes that look exactly alike.

What's more, even supposing you did find two seemingly identical snowflakes, they probably aren't the same on an atomic level. Why's that? Well, about one in every 5,000 water molecules will contain at an isotope of hydrogen – just like a normal hydrogen atom, but with a bonus neutron in the nucleus – rather than a regular old hydrogen atom. Plus, one in 500 molecules will contain an oxygen atom with two extra neutrons. The chances of those slightly different molecules being in the exact same place in two different flakes are mind-bogglingly, vanishingly tiny!

– *Stephanie Keating*



Try it yourself!

If you live in a climate that has snow, you can study snowflake shapes yourself. All you need is a piece of cardboard, a piece of black felt or velvet, a magnifying glass, and a snowy day.

Secure the felt or velvet onto the cardboard with tape or glue, and then place the board into the freezer or in a box outside. After about 15 minutes, remove the cold board and take it outside to catch some snowflakes. Examine each one with your magnifying glass. If you have a digital camera, try taking some photos of the flakes. Otherwise, sketch the basic shapes that you see. Can you find any that look the same?

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

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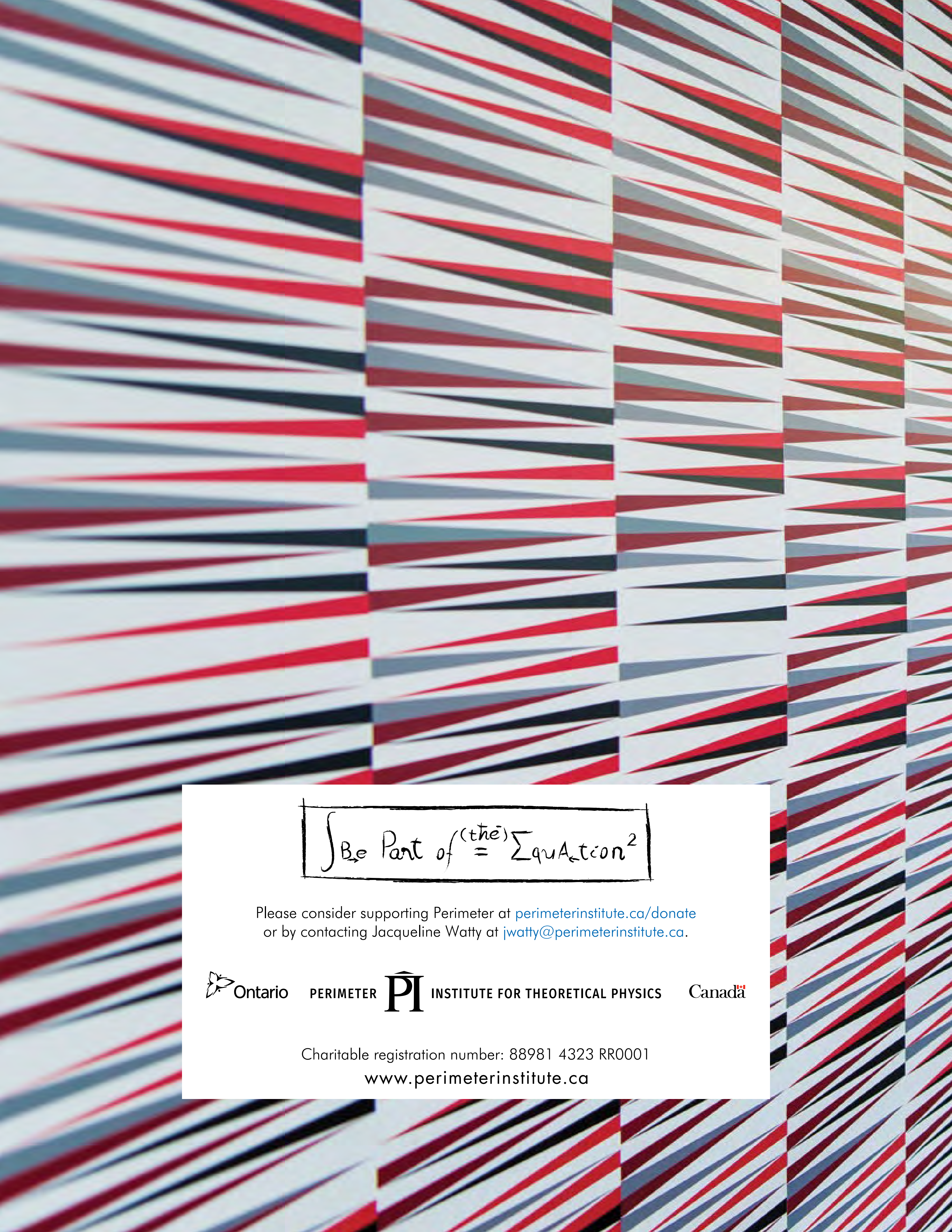

$\int$ Be Part of $\overset{(\text{the})}{=}$ ΣquAtion^2

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