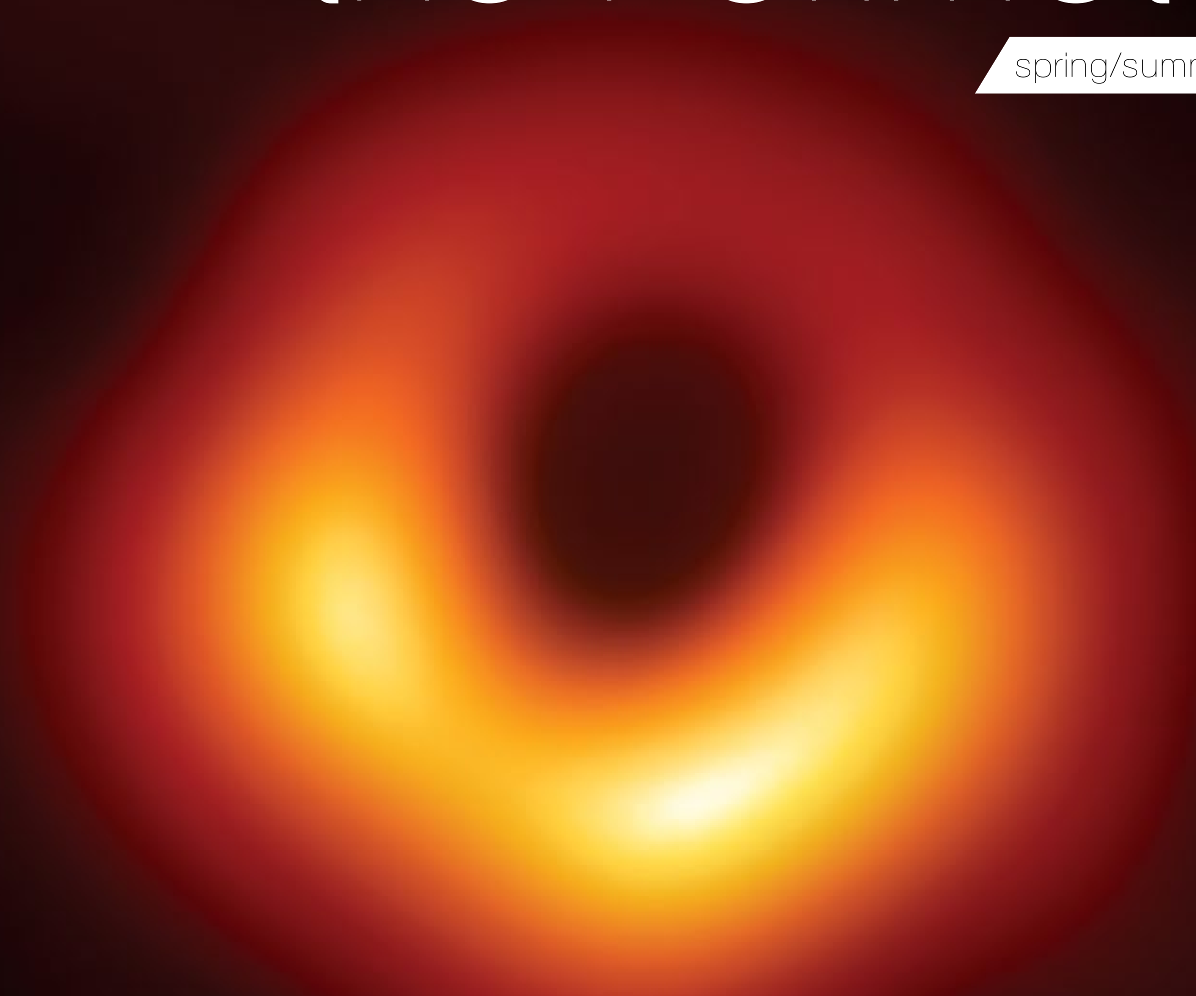
inside the Perimeter

spring/summer 2019



THE UNSEEABLE

PERIMETER PI INSTITUTE FOR THEORETICAL PHYSICS

inside the Perimeter

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First image of a black hole,
by Event Horizon Telescope Collaboration

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IN THIS ISSUE

THREE WORDS TO BUILD THE FUTURE ON

If I had to sum up Perimeter Institute in three words – which is the sort of thing I've had to do a surprising number of times since becoming Perimeter's Director in February – they'd be these: Simplicity. Clarity. Audacity.

I first heard about Perimeter back in the fall of 2000, when I met the Institute's founding donor, Mike Lazaridis. Mike, in those days, was fresh from the launch of the BlackBerry, and he was moving fast. Within a few years, he and his team would take the BlackBerry from high-tech pager to the world's first full-fledged smartphone.

In short, I met Mike at what had to be an exciting time for him. But he didn't want to talk about smartphones. He wanted to talk about breakthroughs.

His BlackBerry, he said, was based on physics breakthroughs from 50 years ago, 100 years ago, 150 years ago. Breakthroughs in electromagnetism, in quantum theory, in many fields of physics. What drove the men and women who made those breakthroughs? Certainly not the quest for smartphones. No, they couldn't have even conceived of such devices. They were doing something far simpler, and far more exciting: they were trying to understand how the universe works.

Mike put a question to me: What about the next breakthroughs, the ones that will shape the lives of our children, our grandchildren, and our grandchildren's grandchildren? He believed that, with the right investment and a bold mission, we could strategically make those breakthroughs more likely.

He wanted to launch a new theoretical physics institute.

This institute, he said, would bring together some of the best minds in the world, tackling the deepest and most difficult problems in physics. It would be free-standing. It would do away with the usual academic system, which makes so many scientists go for the safe bets. It would seek nothing less than breakthroughs.

For Mike, it was an investment in our collective future: a long-range investment, but a smart one, whose benefits would pay out over many generations.

One thing that really stood out from our conversation was when Mike said, "We're going to do something special here, for Canada and for the world. And we have to get it right."

I was struck by the simplicity, the clarity, the audacity of his vision.

Simplicity. Clarity. Audacity. Those are the hallmarks of a powerful idea. As a scientist, I know how precious ideas like that really are.

As I went home to Montreal, my conversation with Mike played over and over in my mind. Two days later, I found myself emailing to say, "I'm in. How can I help?" Soon after, I left my position at McGill and joined Perimeter as one of its founding faculty members.

Nineteen years later, the power of Mike's idea has never left me, and it has never left Perimeter. It guided Neil Turok as he led Perimeter brilliantly over the past 10 years, bringing every aspect of our research, training, and outreach to the next level.

It still inspires me and will inform everything I do as Director.

Perimeter's a special kind of place. We don't have any laboratories or any equipment more complicated than blackboards and computers. We like to say we run mostly on chalk and coffee. Yet Perimeter researchers have developed theories and tools behind headlining discoveries over the past decade.

Frameworks developed by Perimeter scientists were used at the Large Hadron Collider when it detected the Higgs boson, and they are still in use. Perimeter scientists were involved in the detection of gravitational waves and proposed groundbreaking ways to use this new eye on the universe. Still others have been pioneers in the theory behind the fast-emerging technology of quantum computing. Earlier this year, Perimeter scientists played a crucial part in the detection of fast radio bursts at the new CHIME telescope. And now we've helped capture humanity's first glimpse of a black hole.

As you'll read on page 16, Associate Faculty member Avery Broderick was key to the landmark black hole image produced by the Event Horizon Telescope (EHT).

A leader in bringing together this international collaboration, Avery and his Perimeter team developed some of the crucial models and techniques that went into the EHT's image, and he will be a leader in analyzing the data in the months and years to come.

It's the same in many fields. At Perimeter, we don't run the telescope – we develop the ideas that guide what the telescope should look for. We don't run the particle detectors – we help make sense of the data they collect. We don't build quantum computers – we develop ideas that will bring the coming quantum age to fruition.

Scientific exploration pays off. Like the men and women whose physics breakthroughs long ago power our smartphones today, at Perimeter we are trying to understand how nature works at its deepest levels. We aim to accelerate the pace of discovery into the fundamental workings of space, time, matter, and information.

I think back to Mike's words, 19 years ago, and see that Perimeter has indeed become a special place, a beacon of excellence, and we want to preserve that. We are an example to the world, and we will continue to lead. We did get it right. But we're going to make it even better.

And so, with simplicity, clarity, and audacity, we will keep exploring.

– Robert C. Myers

THE MYERS EFFECT

World-renowned string theorist Robert Myers takes over from Neil Turok as Director of Perimeter Institute.

Almost 20 years ago, string theorist Robert Myers took a leap of faith. The tenured professor at McGill University quit his job, packed up his family, and set off to join a fledgling physics institute that didn't yet have an office, let alone a building.

Perimeter Institute was not much more than an idea, and Myers was one of its founding faculty members. Now, Myers has taken another leap as he becomes the Director of the Institute he helped shape.

Perimeter Founder Mike Lazaridis announced the appointment at a special event in February.

"In many ways, Rob represents the beating heart of Perimeter," said Lazaridis, who first pitched the idea of joining Perimeter to Myers at a breakfast meeting in a Waterloo diner.

"He was a founding faculty member, taking an enormous risk in coming on board when the Institute was an ambitious – some might say audacious – idea. People noticed, and many scientists have followed his lead."

Myers has played an integral part in the Institute's development, helping select its areas of research focus, recruiting scientists, mentoring students, and serving as Faculty Chair. All the while, he continued his own research, earning repeated recognition on the list of the world's most influential scientists.

"Don't let his modesty fool you," Lazaridis added. "As a scientist, he is a giant."

The choice of Myers as Director brought greetings and approval from scientists around the world, but it was as a colleague and friend that Myers took the stage at the announcement.

The son of a Canadian biochemist and an immigrant Dutch national who spent several years in a concentration camp, Myers embraces – and in many ways embodies – the Canadian spirit of Perimeter.

"What my mom learned and passed on to her four sons was a boundless optimism, a conviction that things can change for the better – that we can change things for the better," he told the crowd of researchers, students, and dignitaries.

"Perimeter has become a global leader, yet it remains very Canadian: a generous and optimistic place that draws in people and ideas from around the world."

Myers' own research focuses on foundational questions in quantum theory and gravity. His contributions span a broad range, from quantum field theory to gravitational physics, black holes, and cosmology. Several of his discoveries, such as the "Myers effect" and "linear dilaton cosmology," have been influential in seeding new lines of research.

Along with the directorship, Myers now holds the BMO Financial Group Isaac Newton Chair in Theoretical Physics, a prestigious position supported by a $4 million gift made to the Institute by BMO Financial Group in 2010.

But he is equally respected for his efforts to support and encourage young scientists, including the 140-plus postdocs, PhD candidates, and master's students he has supervised and mentored over the years. Working with them, he said, has been a highlight of his career so far.

"You're awesome," he said, smiling up to the young researchers lining the Perimeter atrium balcony. "When I talk about the future, you're the ones we're counting on. When you leave here, you'll join more than a thousand other young researchers who have trained here. They – and you – are the future, and the best measure of our success."

"I know Rob Myers will maintain Perimeter's high standard of research excellence and provide stellar training experiences for the next generation of critical thinkers in an environment of equality and opportunity. Keep up the amazing work."

– The Hon. Kirsty Duncan, Canadian Minister of Science and Sport

"Perimeter and Quantum Valley are helping create the technology of tomorrow. On behalf of the Government of Ontario, my congratulations to Rob and Perimeter on this important appointment."

– The Hon. Todd Smith, Ontario Minister of Economic Development, Job Creation and Trade

Myers takes over as Director from cosmologist Neil Turok, who will stay at Perimeter as a full-time researcher and head of the Institute's Centre for the Universe.

"It's been the privilege of a lifetime to work with such an incredible team and for such a wonderful community," said Turok, who acknowledged Myers as his closest advisor during his tenure as Director. "The Institute could not be in safer hands. This is a wonderful day for us all."

For Myers, though, the event celebrating his appointment was just the beginning.

"Everybody in this room who knows me knows three things about me: I like to learn, I like to listen, and I like to work hard. In this job, I'll be doing plenty of all three," he said. "So, my friends – let's get to work."

– Tenille Bonoguore

"Rob Myers has been an extremely influential voice in theoretical physics and I believe he will be a great leader of the Perimeter Institute."

– Edward Witten, 2012 Breakthrough Prize laureate and professor at the Institute for Advanced Study

"Perimeter is fortunate to have a respected, dedicated scientist and likable person like Rob Myers as its new Director. What an excellent choice."

– Donna Strickland, 2018 Nobel laureate and professor at the University of Waterloo

"Rob Myers is a visionary physicist, a natural leader, and a great guy. I'm confident that, with Rob's guidance, PI will soar to even greater heights."

– John Preskill, Richard P. Feynman Professor of Theoretical Physics at the California Institute of Technology

People of PI:

Beauty seeker Chong Wang

For condensed matter theorist Chong Wang, the messy challenges of complex quantum systems can reveal an irresistible beauty.

When talking about condensed matter, the potential technological spin-offs often get the most attention. After all, the field holds out the promise of loss-free energy transmission, room-temperature superconductors, scalable quantum computers, and more.

For budding theoretical physicists, though, condensed matter research can be a hard sell. The problem looks ugly, the challenges are difficult to explain, and the sheer complexity of many-body quantum systems is too tough for our best supercomputers to simulate.

But if you stick with it, says condensed matter theorist Chong Wang, something amazing can emerge: beauty.

It took some time for Wang to see that allure himself. As a child, he liked science and math but felt no particular affinity for one thing. By high school, in his home town of Zunyi, China, he was leaning toward studying string theory. It wasn't until late in his undergrad studies, at the Hong Kong University of Science and Technology, that he got deep enough into condensed matter research to realize that he found it absolutely fascinating.

Part of the problem, he notes in retrospect, is that to fully appreciate condensed matter, you need to first understand it. And that isn't easy.

Unlike cosmology or string theory, in which a budding scientist can grab hold of simple and fascinating problems to pursue, in condensed matter "it takes some effort to actually understand the question," Wang says.

"I don't know if 'acquired taste' is the right word," he laughs. "It was only at my later stage of college that I realized that condensed matter physics, very often, is about the study of the emergence of beauty. This idea of beauty emerging out of ugliness, that really drove me into the field."

From Hong Kong he went to MIT for his PhD, to Harvard as a postdoc, and has now come to Perimeter Institute as a faculty member. He is part of a growing focus on "quantum matter" at the Institute, joining other promising young researchers busy probing nature's quirkier building blocks.

The strangeness of condensed matter

Condensed matter and many-body quantum physics encompass some of the strangest phenomena in some of nature's most complex systems.

Traditionally, scientists figure out how a complex system works by calculating one small part and extrapolating across the whole. Just as a baker making various kinds of cookies would start with a basic recipe then mix in different flavours, a scientist assessing a complex quantum system might first work out what the individual particles are doing and extrapolate that across the system to form a base. Then, they'd start adding "real world" effects between the particles, like attraction, repulsion, and interference, to slowly build complexity into their calculations.

However, that approach doesn't work for the systems Wang studies. These systems are simply too weird, the emergent behaviours too strange, to understand by incrementally adding complexity. Instead, they must be approached on their own terms, he says.

"Experimentalists see weird behaviours from those materials all the time," Wang says. "Many of the phenomena are poorly understood by theorists, actually."

One phenomenon scientists do understand quite well – at least in its most basic aspects – is called the "fractional quantum Hall effect." For Wang, it provides the perfect example of condensed matter's strange allure.

To see the effect in action, a layer of electrons is placed in a strong magnetic field. The fundamental laws of physics dictate that electrons cannot split into smaller particles – but the fractional quantum Hall effect appears to break that law. When placed in a strong enough magnetic field, the electrons in this thin "soup" can behave, collectively, as if they have been split.

"If you put zillions and zillions of electrons together and they move collectively, then the collective motion behaves as if it's a one-third electron, or one-fifth electron," Wang explains. "You never understand [this behaviour] from a single electron point of view. It's the emergence of the many-particle motion. It's a very weird behaviour, but it's also a very simple pattern."

The math structure that governs this kind of emergent behaviour is called topological quantum field theory, which Wang describes as "one of the most beautiful math structures out there."

"What's particularly intriguing about this final picture is that it looks completely different from your microscopic building block, where you think of electrons moving independently," he says. "It's a complicated, messy problem, but very often at the end, a very beautiful picture emerges. It's a miracle that simplicity can ever emerge from something so complex."

His research probes some of the stranger regimes in many-body quantum physics, such as quantum spin liquids, topological insulators, quantum Hall effects, quantum phase transitions, and their connections to modern aspects of quantum field theory like anomalies and dualities.

Unlocking these puzzles is a challenge, but it's also a huge opportunity for Wang and his colleagues in Perimeter's Quantum Matter Initiative as theory and experiment push each other to better understand nature.

"For a theorist, your daily life has two goals: one is to get the most beautiful structure for your theory; the other is to try to explain the most puzzling experiment," he says. "Very often, the two goals run in parallel, but occasionally, they meet. Then something awesome happens."

– Tenille Bonoguore

MERA AND HOLOGRAPHY – OR MAYBE NOT

*For a decade, physicists have been asking a tantalizing question: could a mathematical tool lifted from condensed matter physics be the unlikely key to a better understanding of holography? Now the answer is at hand – **and it's not what anyone expected**.*

Call it a twist ending. Since 2009, experts have been debating whether a tensor network called MERA could be the key to a better understanding of the holographic principle – the deep mystery that proposes connections between field theory and quantum gravity.

The question was: if MERA is a key, then how does the key fit? Phrased more technically, experts were debating the exact relationship between MERA and holography. Two camps developed two theories about that relationship – call them option A and option B. Now, a pair of Perimeter researchers has provided a definitive answer.

They picked option C.

Introducing MERA

Faculty member Guifre Vidal and postdoctoral researcher Ash Milsted are experts in MERA. Milsted is the first postdoc hired under the Tensor Networks Initiative, Perimeter's five-year push into tensor networks. Now finishing his postdoctoral fellowship – and soon off to a second postdoc at Caltech – he's worked on developing MERA and other tensor network formalisms and applying them to a large number of other research areas, particularly in high energy physics.

Vidal is the researcher who originally developed MERA, which stands for "multi-scale entanglement renormalization ansatz." MERA is a mathematical structure that brings the tools of the renormalization group to bear on entangled quantum systems.

To take that piece by piece: the renormalization group is a set of tools that allow you to go from high energy physics to low energy physics. "It's one of the most important ideas of the 20th century," says Vidal. "It connects physics at one length scale to another length scale."

Entanglement, meanwhile, is a uniquely quantum kind of correlation, in which two or more particles are intertwined, such that the quantum state of each particle cannot be described independently of the state of the other.

Entangled particles don't just come in pairs: they come in systems, and some of the systems are big. These systems can't be understood piece by piece: that would be like trying to understand an image by understanding each pixel, or trying to understand a sentence by understanding each letter. As with the image or the sentence, in certain highly entangled systems, all the interesting stuff is in the relationships between the parts.

Since Vidal introduced it in 2005, MERA has become the tool of choice for understanding not just highly entangled quantum matter, but a variety of other complex systems. It's used in machine learning, in describing exotic states of matter, and in field theory, just to name a few.

The tool's power goes back to a key insight Vidal had when developing it: he added an extra dimension to an older framework and used it to encode entanglement at different length scales. This was the origin of MERA, with its M for "multi-scale."

MERA meets holography

Vidal's seminal papers on MERA were published in 2007 and 2008. In 2009, another physicist named Brian Swingle noticed the parallels between the way MERA makes complex problems more tractable by adding a dimension and the way string theory does the same through its holographic principle.

The holographic principle says that certain kinds of field theories are exactly equivalent to certain kinds of gravitational theories in one more dimension. Also known as AdS/CFT, holography is central to the study of string theory and certain branches of field theory and gravity, and it has surprising uses far beyond them. The more Swingle looked, the deeper and more profound the parallels between MERA and holography seemed.

A community of research sprang up to build on Swingle's initial insight. The researchers involved hoped that MERA would prove to be the formalism that could chop the complex mathematics of holography into manageable pieces, where calculations can actually be performed. In the parlance of the field: it was hoped that MERA would prove to be a lattice realization of AdS/CFT.

Lattice = progress

A realization, says Vidal, is simply a concrete version of something – "the way you might see 'happiness' realized in a little kid playing." A lattice realization is one that can be considered piece by piece, rather than needing to be tackled as a whole.

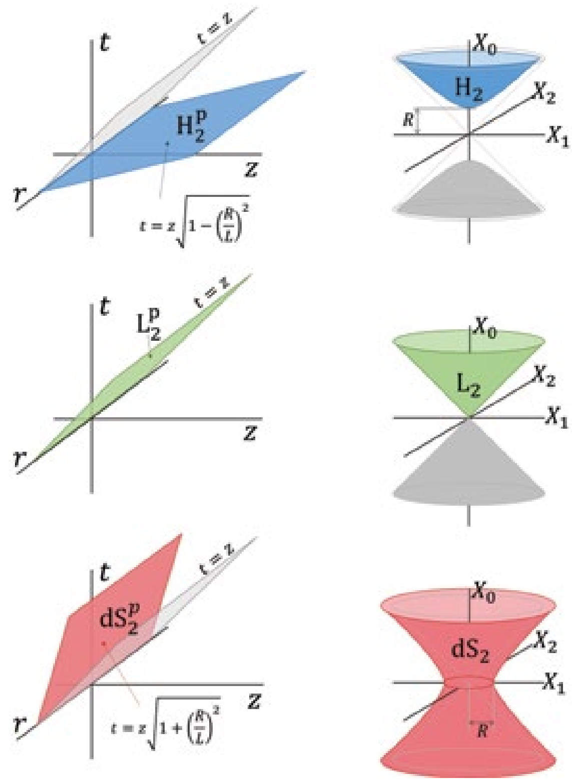
Finding a lattice realization of holography would be a huge step forward. Milsted explains: "It would be a computational framework to answer questions. Sometimes just thinking is not good enough. You need to also be able to calculate things. If you can turn these abstract ideas in AdS/CFT into some lattice simulation, then you can put actual numbers in your computer. Then, you are forced to be really concrete – forced to work out exactly what you mean."

"Once you have chopped AdS/CFT into pieces, you can look at the pieces and ask questions," says Vidal. "AdS/CFT can be very abstract. There are no experiments – the energies are too high to experiment with – so it's possible to get lost in a castle of conjectures. It's very useful to be able to chop the big construction into small pieces to understand what you meant in the first place."

Option A, option B – none of the above

With the motivation strong and the connection widely sensed, the open question seemed to be exactly how to make sense of MERA in the holographic setting – whether it represented a theory of gravity in hyperbolic space as proposed by Swingle, or a field theory in de Sitter spacetime as proposed by Cedric Beny: whether it was option A or option B.

Now, after 10 years of debate, Vidal and Milsted finally have a definitive answer. MERA corresponds to neither hyperbolic space nor de Sitter spacetimes, but to a light cone geometry. It's option C.



Three candidate geometries for MERA – hyperbolic (blue), light cone (green), and de Sitter (red).

As a bonus – or a consolation prize – Milsted and Vidal developed two variants of MERA, one for use in option A and one for use in option B. "So everyone can be happy," says Vidal.

One might naively expect this breakthrough to rapidly advance the progress of holography. "Yes, I'd expect that too," says Vidal. "But it might not be quite that simple."

Though this new work finally establishes how to interpret MERA geometrically from a CFT perspective, researchers are still uncertain about how this new interpretation relates to the geometry of AdS/CFT. It looks as if the relationship is not as straightforward as previously believed.

"One of the implications of our work is that these tensor networks are not necessarily related to AdS/CFT. We're not saying they're not; we're saying 'where is this relationship?'" says Milsted.

"What our results show is what the exact relationships between the MERA and the CFT side of the story are," adds Vidal. "It's for the experts in AdS/CFT to find the gravitational side of the story."

Clearly, the long and twisting tale of MERA and holography is not over yet.

– Erin Bow

NEW SIMONS EMMY NOETHER FELLOWS ANNOUNCED

Perimeter welcomes the next group of Simons Emmy Noether Fellows – eight talented physicists spanning a range of specialties.

Physics is diverse and so are the people who do it. Eight new visiting fellows from four continents will come to Perimeter Institute in 2019/20 to research everything from black holes and dark matter to quantum field theories and the development of new mathematical tools.

Yet for all their varied research and backgrounds, the physicists do have something in common: they are all women.

They will come to Waterloo as part of the Simons Emmy Noether Fellows Program, which honours the legacy of Emmy Noether, a brilliant scientist who made indelible contributions to the landscape of physics and mathematics. The fellowships offer rich collaboration opportunities, with additional logistical support ranging from teaching buyouts with home institutions to accommodation and childcare assistance.

Sayantani Bhattacharyya is a professor of physics at the School of Physical Sciences, National Institute of Science Education and Research, in Orisha, India. Her current research centres on the study of black holes in large spacetime dimensions. While at Perimeter, Bhattacharyya plans to apply fluid dynamical analysis around the concept of entropy to higher derivative theories of gravity.

Cecilia Chirenti is a strong gravity theorist based at Universidade Federal do ABC in Brazil. Her research focuses on gravitational waves, the perturbative analysis of background spacetimes, and the properties of quasinormal modes of black holes, neutron stars, and other exotic objects. Chirenti is also a member of the 3G Science Case Team for third-generation gravitational wave detectors.

Lavinia Heisenberg is a theoretical physicist and cosmologist based at ETH Zurich. Her research investigates generalizations of gravity theory and the interplay between particle physics and cosmology, with a focus on the fundamental properties of field theories of spacetime.

Wei Li is a professor at the Institute of Theoretical Physics, Chinese Academy of Sciences. Her research explores the quantum gravity aspects of string theory and the mathematical physics that arises in string theory, quantum field theory, and quantum gravity in general.

Katherine (Katie) Mack is an astroparticle physicist based at North Carolina State University whose research focuses on new approaches to the fundamental nature of dark matter. A member of the CYGNUS dark matter detector collaboration, she is particularly interested in investigating the small-scale behaviour of dark matter and how we can use it to illuminate dark matter's fundamental nature.

Catherine Meusburger is a quantum gravity theorist based at Friedrich-Alexander University Erlangen-Nürnberg. Her research focuses on topological quantum field theories with defects and Kitaev lattice models, with a particular interest in how these theories relate to quantum gravity.

Monika Mościbrodzka is an assistant professor in the Department of Astrophysics at Radboud University who works on imaging the event horizons of black holes, strong gravity, accretion physics, and numerical methods in physics and astrophysics. A member of the Event Horizon Telescope collaboration, she has done extensive work in theoretical black hole physics modelling.

Sylvie Paycha is a professor in the Department of Mathematics at the University of Potsdam, on leave from the University Clermont-Auvergne, working at the interface of mathematics and physics. Her research centres on regularization and renormalization methods, with particular focus on an algebraic approach to locality she recently developed with collaborators.

These fellowships are supported by The Simons Foundation and its mission to advance the frontiers of research in mathematics and the basic sciences.

BECOMING NOETHER

*The giants of science are mostly male. But not all of them – and that discovery can prove deeply revelatory, writes **Sonali Mohapatra**.*

It's 2 pm on a Wednesday. At Perimeter Institute, that means colloquium time, and if you're a certain sort of nerd, that's exciting. The Time Room is packed. Typically, the colloquium is on some recent cutting-edge bit of science, but today is a little different. Yvette Kosmann-Schwarzbach is giving a talk: "Emmy Noether's two theorems, a hundred years later."

I've gone through a tough time recently and have started having doubts about academia. It feels like I've opened Pandora's box: a single doubt unleashes a swarm of doubts about my abilities as a physicist, threatening to engulf.

It is in this mood that I sit now, listening to an amazing woman scientist talk about another amazing woman scientist: The "mother" of modern algebra. The inventor of Noether's theorem almost a century ago. The discoverer of symmetries and conserved charges. The master of group theory. The one without whom modern physics could not be where it is now. The one of whom there are only a few black-and-white photographs. The one hidden in plain sight – the name universally known among physicists, the gender far less so.

Goosebumps rise on my arm.

As an aspiring scientist growing up in India, meddling around with makeshift labs, cutting out newspaper clippings on black holes and spacetime, I was much influenced by the stories of great scientists who had shaped the history of physics. The scientist in my head – the one I romanticized being – looked like the caricature in every book or movie: an eccentric white man with a shock of white hair that crackled like electricity. I forced my size three feet into his size nine shoes, and those of Dirac, Newton, Pauli, Heisenberg, Schrödinger, Bose. In my mind, I strolled, shapeless in my own clothes, while figuring out the geometry of the world. I stumbled onto gravity and held on tight.

But often, the image wavered. I could find no reference to my struggles in any of my heroes' narratives. They were not constrained by what their gender "could" and "could not" do. They never had periods; their thighs did not chafe under dresses during physics class. They were not asked, again and again, if they "really" intended to become a physicist.

My heroes wrote of physics as a seductress, a flighty, elusive temptress who brought the universe into play. I wanted to write of her in that romantic way too, but I was unfortunately mostly straight. I didn't have a language for my passion.

I first heard the word "Noether" one fine afternoon in a dusty undergraduate class in the jungles of Mohanpur, India. I automatically attached "him" to the name. Noether's theorems were everywhere. I named them, used them many times in my calculations, without knowing that behind them was someone who had looked like me in her figure and – maybe – in her brain. Who had achieved what I yearned to.

Four years later, in 2015, when I was a master's student at Perimeter, Emmy Noether's gender was revealed to me. I felt a peculiar shame. How happy I could have been, I thought, if I'd known.

Now, four years later still, I'm back as a visiting researcher, rediscovering Emmy Noether's legacy in a colloquium.

Professor Kosmann-Schwarzbach brings a dispassionate, raw energy to the room. When she whispers, the whole room leans forward imperceptibly to hear. She's been researching Noether for years. She talks about Noether's contributions. Were they original? What did Noether uncover about the energy conservation problem in general relativity? What did she write in her letters? What was her family like? Kosmann-Schwarzbach talks with the authority born of a lifetime of scholarly pursuits.

The room disappears before my eyes, and I am a *flâneuse*, walking along in Noether's (size three?) shoes, her stiff dresses. I see myself poring over Hilbert's notes. I am in the room in 1915 when Klein and Hilbert invite Noether to Göttingen in the hope that her expertise on invariant theory will help them understand some of the implications of Einstein's newly formulated theory of general relativity. I am in the room in 1916 when there are flurried exchanges of letters between Einstein and Hilbert. In one, Hilbert encloses a note from Noether to Einstein. I am right there when Einstein writes back to ask for a clarification and says: "Of course, it would be sufficient if you ask Fräulein Noether to clarify this for me."

Her first year in Göttingen and already an expert! It must have been stormy, the day in 1918 when Noether solved a central problem arising in general relativity – one on which the whole theory turned, really – and proved the theorems that would be known by her name. She proved and vastly generalized a conjecture made by Hilbert concerning the nature of the law of conservation of energy and how it must be phrased generally through group theory. A triumphant moment.

But then the story took a turn.

Time passed. Noether's seminal paper was never much mentioned again, either by her or by others. Weyl, who performed similar computations to hers, only referred to her in a footnote in his third and subsequent editions. Even though Courant and Markow knew about her work and referred to her briefly in their writings, it is not obvious that this knowledge was transferred down to Rumer. He cited Weyl but not Noether. Never Noether! And neither did Fock.

Here Kosmann-Schwarzbach pauses and asks, "Was it because she was a woman? Or because she was Jewish?"

Emmy Noether never wrote another paper on the symmetries in general relativity. Rather, she focused on algebra. Papers by other philosophers "proved" the same generalizations without glancing at Noether's 1918 papers to learn that she had already proved them long before!

How did she feel then, I wonder? Did she even care? How did the other hardships in her life as a Jew during one of the most dangerous eras in human history transform her? Did she mourn the family members she lost? Did her work become her faith, keep her sane? How did she feel when her gender was bandied about as a reason to not appoint her at the university? Did she laugh when Hilbert, in support of her appointment to the university, argued that Noether's sex should not be an argument against her? ("After all, we are a university, not a bathhouse," he indignantly told the administration, to no avail.) Or did she struggle privately with her anger, as so many of us do?

Today, in our memories, Emmy Noether does not need to be a vocal feminist. She does not need to have done more for women. She is quite enough in the fact that she existed and she changed the course of humanity. She is quite enough in the fact that she never let societal expectations of her gender confine her. She is now rightly considered as one of the greatest mathematicians in history. That is enough. Or it should be.

Why do we care, in the end, about credit? Why do we need – why do I need – to see the person behind the idea? Because when we do, we see a glimmer of possibilities for ourselves. Emmy Noether is a hero for her work. But even more so, in this moment, for herself: a person sharing some of my characteristics, who allows me to envision physics as my own world. She makes me accept myself. I am not a colonizer. I belong here.

Sonali Mohapatra was a Perimeter Scholars International master's student in 2014/15 and is now pursuing her PhD at the University of Sussex.

FURTHER EXPLORATION:

Why did Noether's theorems fly under the radar so long? Mathematician Yvette Kosmann-Schwarzbach set out to find an answer. She spoke with Perimeter's Stephanie Keating at InsideThePerimeter.ca.

SEEING THE UNSEEABLE

After decades of speculation, theory, and indirect observation, we finally have visual proof: black holes exist.

The first image of a black hole, released by the Event Horizon Telescope, or EHT, is truly astonishing. This is the black hole at the hub of the M87 galaxy, containing more mass than six billion suns, located more than 50 million light years away.

The round black shadow against a swirl of brilliant light is the silhouette of the event horizon itself. Ten years in the making, it is the highest resolution image in the history of science.

The image is a triumph, but it is not an end. As we explore in this special issue, this is just the beginning.

Seeing the unseeable

Humanity's first look at a black hole has been released by the Event Horizon Telescope collaboration, a globe-spanning consortium of researchers from Perimeter Institute and a dozen partner organizations.

After nearly two decades of intense theoretical research and technical ingenuity spanning continents and cultures, researchers from the Event Horizon Telescope (EHT) collaboration have shared humanity's first look at a black hole.

"We have gone right to the edge of the event horizon, and seen the point of no return," said EHT researcher Avery Broderick, who holds the Delaney Family John Archibald Wheeler Chair at Perimeter Institute. "This is an extraordinary moment in science."

The image reveals the black hole – an incredibly massive and compact object with gravity so intense that even light cannot escape – at the heart of the Messier 87 (M87) galaxy in the Virgo galactic cluster.

The M87 black hole resides 55 million light years from Earth and has a mass 6.5 billion times that of our Sun. Black holes are believed to be the core gravitational engines of most galaxies, including our own Milky Way.

The EHT's observations and resulting image match theoretical predictions with incredible precision. Those predictions date back to Albert Einstein, whose theory of general relativity predicted the bending of light and spacetime by black holes.

The landmark image is the result of a worldwide collaboration of more than 200 researchers from 13 partner organizations – with Perimeter Institute comprising the Canadian contingent – and dozens of affiliate organizations.

"Perimeter is proud to be a partner in this remarkable international collaboration," said Perimeter Institute Director Robert Myers. "Giving us the first-ever picture of a black hole is a spectacular achievement. It inspires us all as to what an extraordinary place the universe really is and how much there is to discover in it."

Broderick, an associate faculty member at Perimeter Institute and the University of Waterloo (an EHT affiliate organization), was among four EHT researchers who announced the discovery during a press conference on April 10 at the National Press Club in Washington, DC.

Broderick and members of Perimeter's Event Horizon Telescope Initiative devised a number of key predictive models and simulations that guided the development of the EHT and conducted analysis on the vast amounts of data obtained through the EHT's observations. A 2014 conference at Perimeter was also one of the key early meetings of the scientific partners behind the EHT.

The image shows a bright circular ring of superheated gas circling the dark patch where the event horizon – the black hole's point of no return – absorbs anything that crosses it, creating a black shadow or silhouette.

"This shadow, caused by the gravitational bending and capture of light by the event horizon reveals a lot about the nature of these fascinating objects and allowed us to measure the enormous mass of M87's black hole," said Heino Falcke, chair of Radboud University's EHT Science Council.

Creating the EHT was a formidable challenge that required upgrading and connecting a worldwide network of eight pre-existing telescopes deployed at a variety of high-altitude sites. These locations included volcanoes in Hawaii and Mexico, mountains in Arizona and the Spanish Sierra Nevada, the Chilean Atacama Desert, and Antarctica.

The EHT observations use a technique called very-long-baseline interferometry (VLBI), which synchronizes telescope facilities around the world and exploits the rotation of our planet to form one huge, Earth-sized telescope observing at a wavelength of 1.3 mm. VLBI allows the EHT to achieve an angular resolution of 20 micro-arcseconds – a resolution great enough to read the fine print on a dime in South Africa from a vantage point in New York City.

The telescopes contributing to this result were ALMA, APEX, the IRAM 30-metre telescope, the James Clerk Maxwell Telescope, the Large Millimeter

Telescope Alfonso Serrano, the Submillimeter Array, the Submillimeter Telescope, and the South Pole Telescope. Petabytes of raw data from the telescopes were combined by highly specialized supercomputers, hosted by the Max Planck Institute for Radio Astronomy and MIT Haystack Observatory.

While capturing an image of a black hole is a milestone achievement in itself, the greater scientific value comes from having a powerful new tool for understanding the universe's most mysterious and powerful phenomena. On the day of the announcement, the EHT collaboration published six papers in *The Astrophysical Journal Letters*, with many more already in process.

"We now have exceptionally strong evidence for the link between supermassive black holes and the centres of active galaxies – this is how black holes shape our universe on galactic scales," said EHT project director Sheperd S. Doeleman of the Harvard Smithsonian Center for Astrophysics. "Breakthroughs in technology, connections between the world's best radio observatories, and innovative algorithms all came together to open an entirely new window on black holes and the event horizon."

The release of the landmark image marks a tipping point for astronomy that will open new research paths and enable innovations and technologies.

"This first image doesn't represent the end of an endeavour, but the beginning of an era," said Broderick.

"We are now entering an era of empirical strong gravity research – something that just two decades ago was firmly the purview of science fiction. Just as understanding electromagnetism made the information age possible, thoroughly understanding gravity will launch the gravitational age, with benefits we have only begun to imagine."

– Colin Hunter

Members of the EHT Collaboration briefed members of the US Congress on the discovery. From left: Sera Markoff, Avery Broderick, Dan Marrone, Sheperd Doeleman, with France Córdova, Director, National Science Foundation.

A moment to remember

When Ian Delaney, chairman of both Westaim Corporation and the Ontario Air Ambulances Services Co., heard the Event Horizon Telescope (EHT) was releasing the first-ever image of a black hole, he paused his busy day.

For the last two years, the Delaney Family Foundation has supported Avery Broderick's research through the Delaney Family John Archibald Wheeler Chair in Theoretical Physics. Kiki Delaney, Ian's wife, has also been a member of Perimeter's Leadership Council since 2011.

"I was on a business call. I put it on hold to catch the news conference," Ian Delaney says.

He had suspected, from the build-up to the announcement, that the EHT team would be releasing a groundbreaking image. Now, amid a consortium of hundreds of researchers, Broderick was one of just four EHT leaders on the podium, describing to international media how his theoretical models had been instrumental in the collaboration's ability to understand what they were seeing.

"It's yet another confirmatory piece of why, and how, Perimeter works. It's a terrific model for Canada," Delaney says.

Delaney is optimistic that the image – an incredible scientific achievement in its own right – will also be a launchpad for future breakthroughs.

"When you see the physical confirmation of mathematical theory, and what must happen at a black hole event horizon, it's quite a good stepping stone," he says.

"You've still got the great huge questions. Avery deals in the theoretical physics of the very, very large. Elsewhere at Perimeter Institute, you have people dealing with the theoretical physics of the very, very small. And the two don't agree. We know there's much to be discovered, and much to be learned."

– Stephanie Keating

"My family are great believers in the concept of Perimeter Institute. It's leading edge. Canada's contribution here is dramatic."

– Ian Delaney, whose family supports Avery Broderick's Chair

"We felt the weight of history"

Avery Broderick reflects on the 20-year project that went from audacious idea to globe-stopping announcement.

Two decades ago, I was among a ragtag group of dreamers who yearned to do something not just scientifically interesting, but brand new. We staked our careers and reputations on an endeavour we believed would someday bear fruit.

That endeavour would become the Event Horizon Telescope (EHT), an interconnected array of telescopes around the world, linked with split-second precision, with a shared goal: to capture humanity's first glimpse of a black hole.

In the beginning, the EHT was just a bold idea, and the risk was palpable. A newly minted PhD at the time with an enviable research job, I also had a burgeoning family to care for. I was faced with a choice: to stick with the safety of the familiar or gamble on the possibility of participating in something profound. At the same time, I was being scouted for lucrative opportunities outside of science.

It was Perimeter's Latham Boyle, then a fellow postdoc, who reminded me that we give our children more than money. We teach them a sense of what is truly fulfilling and important. The EHT gamble stood to pay dividends beyond the monetary. For Latham's insight, I remain forever grateful.

On April 5, 2017, after years of intense work and against steep odds, the EHT's eight interconnected telescopes around the globe finally turned toward the supermassive black hole in M87. By then, our once-ragtag group had grown to an international collaboration of 200. Through the months of analytical work that followed – endless teleconferences, work sessions, coding, blunders and successes, conflicts and resolutions, writing papers – the result became clear: an ominous shadow encircled by a bright ring, exactly as predicted, depicting a never-before-seen monster in the night. All that remained was to share our joy with the world.

Just 12 months after that observation, on April 10 of this year, I had the great honour of joining my colleagues and friends Shep Doeleman, Dan Marrone, and Sera Markoff onstage, on behalf of the entire EHT collaboration, at Washington's National Press Club to unveil the image of the M87 black hole.

I did not relish the thought of appearing before millions. But standing alongside my colleagues to present our results in April was, and remains, a humbling experience. We felt the weight of history on that stage. It is estimated that 4 billion people – half the Earth's population – have now seen the M87 image. It is a rare and precious occasion when humanity turns its collective gaze toward something so positive, so emblematic of the power of human ingenuity and cooperation.

That image, a gravitational behemoth 55 million light years from home, represented a culmination, a vindication, and a new beginning. Nothing could have fully prepared us for the press conference and what followed: interviews, congressional testimony, celebrations, even moments of unexpected celebrity. The world awoke to the first image of a black hole splashed in vivid colour across the front pages of practically every newspaper around the globe.

I still find myself filled with a panoply of emotions: pride in the work, joy in the sharing, relief in seeing many early predictions come to pass. And immense gratitude. I'm grateful to the young scientists with whom I worked night and day, to all the EHT collaborators both sung and unsung, to the partner organizations.

And I am inestimably grateful to my family, and to all of the families of the EHT, who have supported us and sacrificed with us. The EHT has been omnipresent for our spouses and children. My kids' crayon drawings of black holes are posted on my office wall and remind me every day of their support, which means more than I can express.

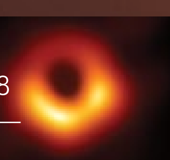
By April 11, the day after the announcement in Washington, I was already getting restless. The wanderlust that sparked the EHT project 20 years ago is still with us.

The EHT will continue to grow for years to come: adding data collected in 2018, then from additional telescopes to be added to the network in 2020 and 2021; expanding in bandwidth; and extending to even shorter wavelengths and hence higher resolutions. It will move to space-based observations. We will replace black hole portraiture with black hole cinema. Even the minor results will only appear so in comparison; the EHT is a transformative instrument, not an incremental advance.

M87 will always be our first direct window onto the event horizon. It is now firmly ensconced in the collective human ethos. But this is just the beginning.

We are already journeying to the next horizon, and we invite the world to join the adventure.

Avery Broderick holds the Delaney Family John Archibald Wheeler Chair at Perimeter Institute.



NSF Diamond Achievement Award celebrates groundbreaking image

The National Science Foundation (NSF) announced a new award – the NSF Diamond Achievement Award – which this year will go to the international team of researchers who captured the first-ever image of a black hole.

Awarded at the discretion of the NSF Director, the award recognizes the highest possible level of achievement or contributions made to NSF's mission by private citizens or organizations.

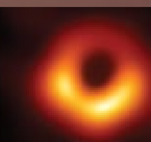
"This groundbreaking accomplishment seemed the perfect research to launch our NSF Diamond Achievement Award," said NSF Director France Córdova of the work done by the Event Horizon Telescope collaboration.

"It's emblematic of why NSF exists. We enable scientists and engineers to illuminate the unknown and to reveal the subtle and complex majesty of our universe."

"It is a rare and precious occasion when humanity turns its collective gaze toward something so positive, so emblematic of the power of human ingenuity and cooperation."

– Avery Broderick, Delaney Family John Archibald Wheeler Chair in Theoretical Physics at Perimeter Institute

Hilary Gauld-Camilleri



Black holes as tools

Multimessenger astronomy is here. What are researchers doing with it?

Since its arrival two years ago, gravitational wave multimessenger astronomy has treated physicists to a smorgasbord of tantalizing observational data. We've watched black hole mergers, linked gamma ray bursts to neutron star collisions, and seen gold created through cosmic cataclysms.

Yet the bounty has created more questions than it has answered. Which, for scientists, is just perfect. There are few things in science more delectable than an open question. An open question within reach of an answer? Well, that's downright irresistible.

What is the interior of a neutron star like, and what can that tell us about nuclear physics? Can we use black holes as massive particle colliders? What is dark matter? How are black holes born?

The answers, it seems, might be found by considering black holes not just as something to be studied, but as a tool to be harnessed.

It's a new approach that has been a century in the making. The two key pillars of modern physics – the theory of general relativity and quantum mechanics – were developed in the early 20th century. While each theory has been shown to be exquisitely accurate in its respective realm, neither works with the other.

The quest to unite them took an unexpected turn in 1974, when cosmologist Stephen Hawking realized that, thanks to quantum effects, black holes emit black body radiation. Suddenly, black holes became a key part of the effort to unite quantum mechanics and gravity.

Now, thanks to the arrival of multimessenger astronomy – which uses multiple telescopes and observatories to record the same astrophysical event using gravitational waves and different wavelengths of light – scientists are revealing deep truths about the universe at a (relatively) breakneck pace.

So far, astrophysics has been the immediate winner. But big benefits are also expected for nuclear physics (thanks to the ability to probe the inner workings of high-density stars), early universe cosmology (third-generation detectors could see all – yes, *all* – black hole collisions in history), and particle physics (where theorists are proposing creative theories to obtain information about dark matter).

This mix of theory and experiment is enough to throw physicists into a veritable feeding frenzy. Or it would be, if the work wasn't quite so exacting, methodical, and very, very deliberate.

It's all in the timing

When Luis Lehner was an undergrad student in Argentina in the 1990s, he assumed that his decision to specialize in general relativity would be an on-ramp to physics' slow lane. Back then, any experimental application for this work was more than 20 years away; for many of his peers, that was too long a wait.

In grad school, he decided to specialize in numerical relativity. This sub-branch of general relativity uses simulations to work out how gravity behaves in extreme situations.

Fast forward two decades and the pace is anything but slow. It turns out those extreme regions are extremely versatile, scientifically.

On the experimental side, the Laser Interferometer Gravitational-Wave Observatory (LIGO), the Canadian Hydrogen Intensity Mapping Experiment (CHIME), the Event Horizon Telescope, and other experiments mean things that were theorized or presented as observational puzzles – gravitational waves, fast radio bursts, and the shadow of a black hole – are now logged in data records.

Meanwhile, theoretical physicists are pushing deeper into uncharted territory by linking specialties that were once deemed separate. Cosmology and astrophysics now overlap with particle physics, quantum field theory, and more.

The result for Lehner is that he has become a leading figure in one of science's fastest developing fields, his work split between the immediate and the eventual: he helps decipher the observational data streaming in from today's experiments, while developing predictions to be pursued by experiments decades, or even generations, from now.

"I know how long it takes to come up with the models that will be used in the future," says Lehner, who is Faculty Chair at Perimeter Institute and the theorist-in-residence for the Gravitational Wave International Committee.

"I'm anxious today for an answer I know will be needed 20 years from now. If we don't start today, we might miss that boat. Important opportunities could slip by."

There are big questions on the menu: Are primordial black holes the seeds of today's supermassive black holes? Why do the black hole mergers we've detected involve objects with low spin or randomly oriented spins? Where does our theory of gravity break down – and what will replace it?

Unsurprisingly, young researchers are scrambling to get a seat at the table. Lehner is there to welcome them with open arms. After all, the challenges ahead are too big for one specialty.

"These are fields that have advanced for a long time independently. Now we have a multitude of messengers from different sources that require expertise in all of them," says Lehner.

"Coming together in a multidisciplinary way is crucial, not only to address some of the challenges but also to bring in the next generation of people who can talk more than one language on this front."

The field is setting a demanding pace. The Advanced LIGO and VIRGO gravitational wave detectors are running, and it is hoped the Kamioka Gravitational Wave Detector (KAGRA) in Japan will come online later this year. In a decade or so, the space-based gravitational wave telescope LISA will be launched. By that time, the third generation of Earth-based detectors should almost be ready.

"There will be this passing of the baton, where we're running this relay in which every new runner – every new experiment – is going to be much faster and much stronger than the previous one," Lehner says. "Eventually, we're going to be able to probe much more deeply both individual events and multiple events."

The success of gravitational wave detectors has reinvigorated a field that, just a few decades ago, looked relegated to theory for theory's sake. And this, says Lehner, is just the beginning.

"There's a larger front here at Perimeter where people are looking at common ground in creative or unexplored corners. If they pan out, there will be a really high pay-off."

Superradiance and the hunt for axions

Hawking radiation showed that black holes could be used as particle accelerators. Particle physicist Asimina Arvanitaki, who holds the Stavros Niarchos Foundation Aristarchus Chair at Perimeter, is working out ways to put that idea into practice.

In a paper published in 2010, Arvanitaki and collaborators including Sergei Dubovsky outlined how black holes could be used to detect a hypothetical particle called the axion, thought to be a candidate for dark matter. The idea centres on a process called superradiance.

Superradiance is a feedback loop consisting of two ingredients: a rotating black hole and a boson particle that is ultralight and has a Compton wavelength as big as the black hole. (Yes, such a thing may exist.)

It all starts if – or when – a black hole spontaneously emits this boson. Thanks to its wavelength matching the size of the black hole, the particle absorbs some of the black hole's rotational energy. This is the start of stimulated emission, explains Arvanitaki, where the black hole keeps making more and more of these particular bosons.

Because bosons can occupy the same quantum state, a cloud of particles forms around the black hole. The bigger the cloud, the more energy it can siphon from the black hole, which makes the cloud even bigger.

But the phenomenon has an inherent instability: the loss of energy slows down the black hole's rotation. When the black hole's rotational frequency drops enough to match the oscillation frequency of the cloud, the instability no longer holds and the phenomenon shuts off.

While the notion of superradiance was first put forward in the 1960s, it was Arvanitaki and Dubovsky who extended the idea and proposed that the bosons in superradiance could be a candidate for axions. (That paper now has more than 500 citations.)

Should such a particle exist, it is a promising candidate for dark matter.

"It sounds like something out of science fiction books. It looks like an atom in the sky and it does all sorts of weird things," says Arvanitaki.

"The great thing about this is it's actually embedded in the theory of general relativity. There is no magic that needs to happen. The particle doesn't even need to be cosmologically abundant; if it exists in the fundamental theory, then the black hole will take care of the rest.

"These are the best type of ideas – the ones where you say, 'Why didn't people think about this 40 years ago?'"

Thanks to multimessenger astronomy, the hunt for axions is within reach – and it's gaining interest. When Perimeter Institute held a superradiance workshop in 2018, more than 30 theorists and experimentalists came from around the world to explore possible collaborations. Some participants were experimentalists from LIGO.

The gravitational wave detectors can already detect "monochromatic" gravitational waves (waves of a single wavelength), which are the kind that would come from superradiance. However, LIGO's data analysis must be modified to seek the "fingerprint" of superradiance: unlike the decreasing frequencies of neutron star spins, the properties of a superradiance signal would drift up and grow with time.

So now, Arvanitaki and others are talking with experimentalists to find ways to incorporate the axion search criteria into current facilities.

"The tools are there; they just need to tweak them in a way to be more targeted to this idea," says Arvanitaki. "The question is, how do you optimize those tools to look for this?"

While the idea is well motivated, Arvanitaki notes that there is no way to guarantee discovery. "It's a high-risk, high-reward game," notes Arvanitaki. "Most of the time you'll fail, but the one time that you will succeed is going to be groundbreaking, because we'll be discovering something completely new about the world as we know it."

Beyond black holes

Black holes aren't the only massive and mysterious objects in our universe that can serve as tools. Many scientists find another object just as intriguing, and it comes with a huge benefit: you can actually see it.

Neutron stars are the remnants of collapsed massive stars. These objects are ultradense – their cores compressed to the density of atomic nuclei – and have extremely strong gravitational fields.

That makes them particularly interesting for physicists like Huan Yang. The general relativity specialist has had a front row seat in the rise of multimessenger astronomy, collaborating with experimentalists at LIGO to perform instrumental noise analysis before earning his PhD at Caltech in 2013.

"The neutron star collisions are the giant colliders of our universe," says Yang, who is now a faculty member at the University of Guelph and associate faculty at Perimeter.

"At the starting point, everybody was trying to figure out how to observe these kinds of things. Now, the focus of the area has shifted to, 'how do we learn physics from these events?' It gives us data that we cannot obtain from our Earth-bound experiments."

There's a slight problem, though. We actually know very little about neutron stars and virtually nothing about their inner workings, because we don't know the neutron star equation of state.

Equations of state detail how an elastic material gets deformed by pressure. For a neutron star, the equation of state will outline how gravity compresses and deforms the star, and through that scientists can work out the star's radius and inner structure.

"We have some [neutron star] models when the density is not very high, but deep in the star, the density is really high and basically all our models fail," Yang says. "By detecting these events, we will learn nuclear physics."

To get that information, we need to get a clearer view of neutron star mergers. Thankfully, Yang and collaborators like Perimeter Faculty member William East are working on that, too.

Gaps left to fill

Like Lehner, East uses numerical relativity to understand strong gravity. He co-organized the superradiance conference with Arvanitaki and has worked with Lehner and Yang to study neutron star mergers, black hole magnetospheres, and ways to distinguish between low-mass black hole mergers and neutron star mergers.

His goal is as simple as it is bold: "I just want to understand all of the interesting phenomena that happen in this new regime that we're just beginning to glimpse."

Neutron star mergers are a perfect example of the gaps left to fill. Today's detectors can pick up the gravitational waves that are flung out just before a merger; telescopes and radio telescopes can record the electromagnetic radiation issued after a merger. But the point of cataclysm? Well, we just can't see it yet.

"At the most violent and exciting part, when the [neutron] stars start to smash together, that's when the frequency becomes too high for LIGO to see the gravitational waves," East explains.

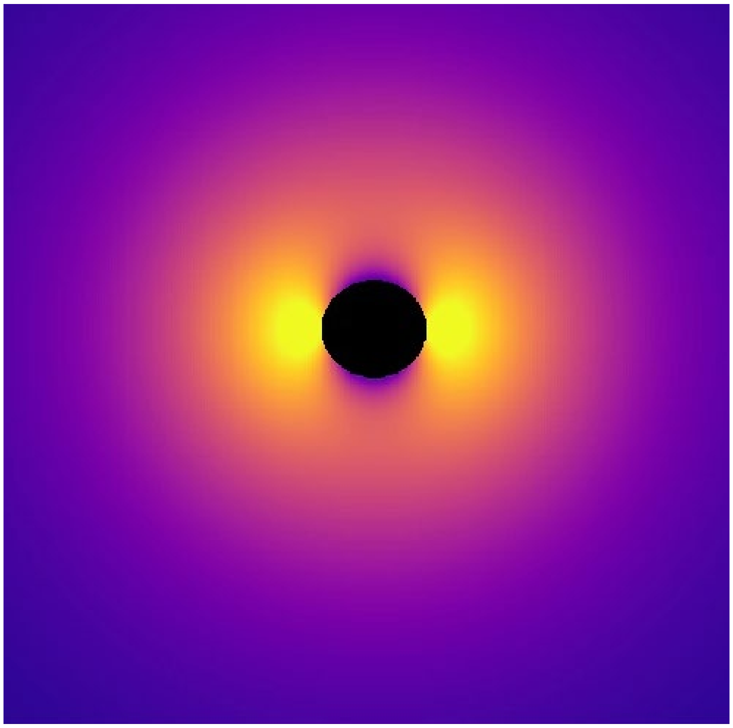
"There's a lot of interesting science you could do if you could actually detect that merger and post-merger. These stars smash into each other and we don't know: Did they immediately form a black hole? Do they form this very hot, perturbed star that's oscillating at high frequencies? We don't really know at all."

How these objects end up on a collision course is also something of a mystery. While the mergers we've seen so far involve objects that spin toward each other in a shrinking circular orbit, East wants to know if a different kind of merger exists: "eccentric" mergers of objects whose orbital paths look more like overlapping ovals.

For these systems, the gravitational wave signal would look like a burst every time the objects had a close encounter. "This [gravitational wave burst] would be the smoking gun that you have this other class of binaries that were formed in this different way," he says.

What's so interesting about eccentric mergers? They could show how some pairs end up bound to each other, which could provide clues about the environment each object came from.

The spin of neutron stars could also give some indication of how these binaries form. The binary neutron stars that we've seen in our own galaxy – pairs that won't merge for a very long time – do have low spins, and the one merger of neutron stars that we've observed through multimessenger astronomy was also consistent with low-spin stars.



In this still from a simulation, a cloud of ultralight particles accumulate around a black hole as it spins down. (Image: William East and Frans Pretorius)

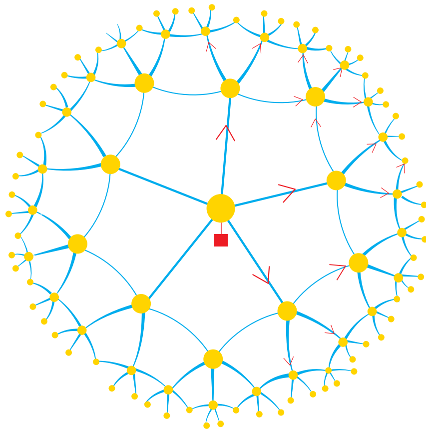
But the data from that merger did not rule out the possibility that the merging stars had significant spin. How would a rapidly spinning neutron star change the merger dynamic? To know that, we again need to see the moment of impact.

East isn't impatient, though. As he points out, a few years ago we'd seen nothing. Some of these questions could be answered within years; others will take decades or longer. Balancing the two is part of the appeal of multimessenger astronomy – as is the very real likelihood that fresh mysteries are just around the corner.

"I think the really exciting possibility is that there will be some surprises, things we weren't expecting," says East. "Since this is a completely new way of looking into the universe, I think it would be weird if we already anticipated everything that is out there."

– Tenille Bonoguore

AN EXPERIMENTAL TEST OF QUANTUM INFORMATION SCRAMBLING



Perimeter Faculty member Beni Yoshida and colleagues successfully simulated the process of quantum information scrambling inside a black hole.

In early 2017, while seeking his first faculty position, Beni Yoshida visited the University of California, Berkeley, for an interview. Though he ultimately joined Perimeter Institute's faculty as one of the first hires tied to the Institute's Quantum Matter Initiative, the interview in California sparked exciting new research on quantum information scrambling, published recently in *Nature*.

During that interview, Yoshida met Norman Yao, a Berkeley faculty member, and they got talking about a protocol for reconstructing quantum states that Yoshida was working on with Alexai Kitaev, a long-time professor at Caltech. Yao and Yoshida quickly deduced that this protocol could be used as an experimental verification tied to a concept called quantum information scrambling.

A collaboration was born.

A hot topic

Quantum information scrambling is an area of considerable interest in physics right now for both theorists and experimentalists. In essence, it concerns the dispersal of local information through a physical system via chaotic dynamics.

Imagine you have a localized quantum bit, or qubit, with a known state. As that qubit interacts with other qubits, delocalizes, and interacts with more and more qubits in the broader system, it becomes increasingly difficult to track what happens to it. Quantum information scrambling studies how this spread of information occurs.

Quantum information theorists like Yoshida are interested in using this scrambling to understand how quantum entanglement is generated in actual quantum systems – a vital ingredient to the error correction required to build a full-scale quantum computer.

Condensed matter physicists are interested in quantum information scrambling as a new paradigm to understand a long-standing question concerning thermalization phenomena in isolated quantum systems (i.e., how these systems reach equilibrium).

And high-energy physicists working on black holes are perhaps even more interested: recent studies have shown that a black hole scrambles quantum information very quickly – in the fastest possible manner allowed in nature – suggesting that quantum information scrambling is the property that makes black holes distinct from ordinary quantum systems.

Confronting the black hole information paradox

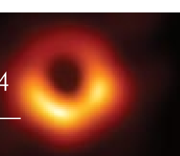
In 2007, quantum information theorists John Preskill and Patrick Hayden published a seminal paper about the black hole information paradox, which posits that physical information could permanently disappear in a black hole.

One concrete way of checking whether a black hole is destroying quantum information would be to throw something into a black hole and try to recover it. If that recovery was successful, it would provide strong evidence that no information had been erased.

If quantum mechanics is to be believed, the information that has fallen into a black hole *can* be reconstructed, but only after the black hole has shrunk to nearly half its original size. This takes an inordinate amount of time. In the case of a black hole with the mass of our Sun, it would take approximately 10^{67} years.

There is, however, a clever way to avoid this conclusion using Hawking radiation, the content emitted by black holes as they shrink. It may be possible to retrieve the information thrown into the black hole significantly faster by measuring weak entanglements between the black hole and the Hawking radiation it has already emitted. The Hayden-Preskill paper outlined a thought experiment in which you use this subtle entanglement structure to reconstruct the information that entered the black hole initially.

It's a beautiful paper, says Yoshida, but it has two important drawbacks. First, the Hayden-Preskill paper used a crude approximation of black hole dynamics called "random unitary evolution."



"Basically, you imagine all the quantum mechanical time evolutions which are mathematically possible, and you pick one of them at random," says Yoshida. "But most of them do not actually occur in real physical systems."

Working from this random unitary evolution framework, Hayden and Preskill proved that reconstructing the information from the black hole is indeed possible. "But they didn't tell us how to do that," says Yoshida. That's the second drawback. "In fact, some people conjectured that the reconstruction is computationally difficult, even if you have access to a super-powerful quantum computer."

Out-of-time-order correlations

In a 2016 paper, Yoshida and colleagues proposed a resolution to the first drawback using something called "out-of-time-order correlation (OTOC) functions" that involve measuring observable physical properties in the present, then the future, then reversing to measure them in the present again, and then returning to the future for one more measurement. These measurements are purely theoretical, of course – a mathematical tool that is receiving great attention.

The OTOC quantifies the effect of how small perturbations spread at later times. When the physical system undergoes chaotic dynamics, the OTOC function decays to a small value, which is a signature of quantum information scrambling.

Yoshida and his colleagues showed that quantum information scrambling is what makes the Hayden-Preskill finding possible. "If this out-of-time-order correlation function decays to a small value, then mathematically you can prove that there exists a procedure to reconstruct the quantum state," says Yoshida. It's counterintuitive, but the chaotic dynamics of a black hole actually make it possible to reconstruct quantum states.

A crucial new insight

The OTOC decay acts as a signal that quantum information scrambling is happening. Unfortunately, a poorly executed experiment – one where the time reversal was imprecise, for example, or an experiment with lots of noise and decoherence – would result in a similar signal. They needed a method that would result in the decay of the OTOC correlation function, while also showing that quantum mechanics was followed properly and the experiment was performed precisely.

That's where Yoshida's work with Kitaev comes in. They had developed a rather simple protocol for reconstructing quantum states from an entangled black hole by measuring the outgoing Hawking radiation on its two sides. This work proposed a resolution to the second drawback of the Hayden-Preskill paper, concerning how to reconstruct the quantum states – but with a bonus.

"By running our protocol for actual quantum systems, we can check two things: does the out-of-time-order correlator decay to a small value and also does the system evolve according to quantum mechanics?" explains Yoshida. "We can immediately check these two things. That's why this protocol is useful for experimental demonstration of quantum information scrambling."

And that's why Norman Yao got so excited. Yoshida and Yao wrote another paper aimed at explaining the potential of the protocol as an experimental probe of quantum information.

A theorist in an experimentalist's world

Chaotic systems are extremely sensitive to even the smallest perturbations, so OTOCs are prone to noise and decoherence. As such, experiments on quantum information scrambling require the type of precise control over quantum systems afforded by ion traps. Yoshida and Yao contacted Christopher Monroe at the University of Maryland's Joint Center for Quantum Information and Computer Science, home to arguably the best ion trap system in the world.

Operating on a seven-qubit trapped ion quantum computer, Monroe and his colleagues implemented Yoshida and Kitaev's protocol and measured a reconstruction fidelity of approximately 80 percent. According to the study by Yao and Yoshida, this means that at least half of the quantum state was scrambled quantum mechanically and the other half decayed by decoherence and errors. Nevertheless, that was enough to demonstrate that genuine scrambling had occurred in a three-qubit quantum circuit.

Yoshida is not an experimentalist. "I didn't touch the apparatus," he says, laughing. But in addition to doing the theoretical work that underpinned the experiment, he spent a lot of time discussing how to engineer the actual quantum chaotic dynamics that would scramble quantum information in a way that worked for the ion trap in question.

It was an exciting result, with potential implications not only for black hole research – Yoshida dreams of his protocol being run on a micro black hole at a high-energy supercollider someday, though not likely in his lifetime – but also in quantum information and condensed matter physics.

"We engineered the dynamics, but we want to take some material and study its dynamics, measure out-of-time-order correlators, and so on. That's the next step," says Yoshida. "This experiment has short-term goals, intermediate goals, and very long-term goals, so I feel like it's an interesting thing to look at."

But Yoshida knows his strengths, and he isn't about to ditch theory for experiment.

"I have nice motivation to think about experimental observations which actually tie into very, very fundamental questions in quantum gravity," he says. "It's really nice that these kinds of deep, deep questions are actually connected to physical, experimental realizations. Both fields can motivate each other."

– Mike Brown

The power of resolution

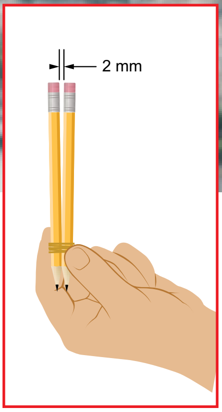
When it comes to telescopes, is bigger always better? This simple exercise illustrates the role that a telescope's diameter plays in its ability to see objects that appear small in the sky.

Using only a couple of pencils or playing cards and two small flashlights (your cellphone will work, too), you can get a sense for what happens when you look at light through different sized openings.

- Take two pencils and use a rubber band to tie them together near the tips. You could also tape two playing cards together in a very narrow "V" shape.
- Tape two small flashlights together and put them in a distant corner of the room. You can also use two cellphone flashlights placed very close together (ideally no more than a couple of centimetres apart).
- From the other side of the room (about 6 metres or more away), hold the pencils right against one eye and look through the gap at the two light sources.
- Start at the narrow end of the gap. How do the lights appear when the opening is very small? Can you differentiate between both lights? How does the image change when you look through a wider opening?

What you probably noticed was that when the gap between the pencils was very, very small, the two light sources appeared to be blurred together, with bands of shadow and light on either side of them. As you look through a larger gap, the lights should begin to separate into two easily distinguishable sources.

This is similar to what happens when a telescope looks at, for example, a pair of distant stars that appear close together in the sky. If the telescope isn't big enough, separate stars will appear blurred together as one. This is known as a telescope's "resolving power": the ability to distinguish between objects or to see detail in an object.



That's why, when it comes to telescopes, bigger is always better: just as a larger opening allowed you to see the two lights more clearly, a larger diameter enables a telescope to resolve more distant objects.

The Event Horizon Telescope was created to look at extremely compact astrophysical sources – black holes (which, astrophysically speaking, are compact) – located very far away. To accomplish this remarkable feat, the collaboration needed to create a telescope with incredible resolving power, which meant a telescope with an incredibly large diameter.

In fact, they needed a telescope bigger than any previously built. They needed a telescope the size of the Earth.

So, they flipped the problem, and turned the Earth into a telescope by linking radio telescopes across the globe. Using a technique called "very-long-baseline interferometry," along with some clever imaging algorithms, the linked telescopes could act as one giant observatory to produce the image of the supermassive black hole at the heart of the M87 galaxy.

– Stephanie Keating

For teachers: *Visit resources.perimeterinstitute.ca to explore and download all of Perimeter's free in-class teaching resources, including a lesson on the Event Horizon Telescope.*

“Portrait of Stephen Hawking”

In memory of our friend and supporter Stephen Hawking (1942–2018), Perimeter commissioned the artist known as Seth to create this portrait. It now hangs, fittingly, at the edge of the Black Hole Bistro.

Seth, who lives in nearby Guelph, Ontario, is internationally known for his *New Yorke*r covers and his tragicomic graphic novel *It's a Good Life, If You Don't Weaken*. He is also a fan of physics. According to the artist, “All I wanted of the portrait was that it have dignity and possibly some elegance. These would be, in my opinion, the two traits most evident in the subject himself.”

In conversation with

ROGER PENROSE

Sir Roger Penrose shares advice for young scientists and his thoughts on visual representation in mathematics, going against the grain, and more.

Most colloquia held at Perimeter Institute take place in one of the classrooms, like the bright and airy Space Room, which can hold about 50 people, or the tiered Time Room, with a capacity of around 60. But when Sir Roger Penrose gave a talk during his April visit to Perimeter Institute, even the Mike Lazaridis Theatre of Ideas, with its 205 seats, was not quite enough to contain the faculty, postdocs, students, and staff who were eager to hear him speak.

Penrose, who is the Emeritus Rouse Ball Professor of Mathematics at the University of Oxford and an Emeritus Fellow of Wadham College, also had lunch with Perimeter graduate students and held a discussion about the future of physics during his four-day visit.

Inside the Perimeter sat down with him to ask what advice he would offer to budding scientists, find out his favourite shape, and more.

Inside the Perimeter: You were a member of Perimeter's Scientific Advisory Committee in the Institute's early years. What are your impressions of Perimeter today?

Roger Penrose: I find a lot of excitement amongst students and people here, which I find very refreshing. I was in there right at the beginning, and it was really very exciting to find out what people were doing, and how it developed from year to year, and trying to have maybe a little bit of influence on the way it should go. I think it's come along amazingly. It's a wonderful place.

Inside: You spent a good deal of time here talking with the graduate students. What can you hope to impart to the next generation of scientists?

RP: People think in different ways, and to give a general piece of advice about how to think about things is probably not a good idea. But what I would say is: do what you find exciting and do what you find beautiful. Simply do what you find exciting in the physics, what you find fascinating.

Myself, I have certain views about things – not all of them conventional views. So I suppose it also helps people to think a little bit outside the box.

Inside: Was there something that inspired you at the beginning of your career that you've always remembered?

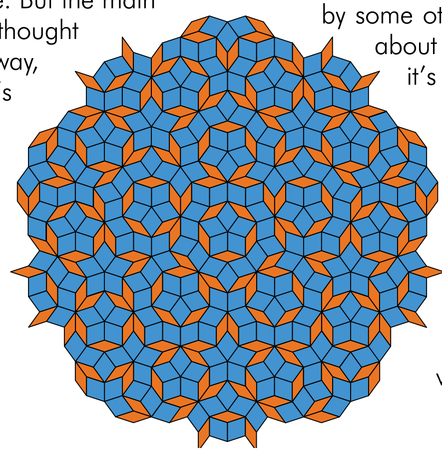
RP: One particular thing I remember was, you see, my father had a telescope that was brass, with a long tube. He took me outside and I was looking at the moon and things like that. And then he showed me Saturn.

I'd seen many pictures of Saturn, but just to see it there as something real – that had a big impression on me, that you can see these things which you may just see in books otherwise.

Inside: Your visual representations of your work are quite well known. How do pictorial representations help you conceptualize your ideas?

RP: I've always been a very visual person. I studied mathematics as an undergraduate and I was quite surprised when I got to university. I found more different ways of thinking about thinking than I'd experienced before. But the main division, I found, was whether people thought visually or not; it's quite surprising, in a way, that mathematicians don't, very much. It's not the way it's done. I guess thinking a little bit differently is helpful in a way, because then I can go on routes which other people haven't gone on.

Of course, you've got to be good at other things, too, like being able to solve equations and so on. But I've found it useful, with certain types of equations, representing these with little diagrams, too. And that I find much easier to manipulate.



A Penrose tiling (P3) using thick and thin rhombi. Note the aperiodic structure, shared by all Penrose tilings. This particular Penrose tiling exhibits exact five-fold symmetry.

Inside: Do you have a favourite shape?

RP: I don't think I have a favourite shape, no. Some of them are more interesting than others. I've played around with things with five-fold symmetry, pentagons and pentagonal stars and things like that, but I wouldn't say they're my favourite shapes particularly.

There are some very interesting configurations. One of them that I found very useful is a four-dimensional one: these things called Clifford parallels. You have a sphere, and circles drawn on the sphere, but the sphere has to be a sphere in four dimensions. It's not an ordinary sphere that you'd normally visualize. In this sphere in four dimensions, you have these circles which go around and they link each other and make a very symmetrical pattern. But to get a picture of that, you've got to project it into three dimensions, and these make very intriguing configurations. So that's one of my favourite configurations, if you like.

Inside: Some of your work has challenged the status quo of some widely accepted theories. Why is it important to consider unconventional ideas or have the courage to go against the grain?

RP: It's an intriguing issue. I mean, should one be trying to argue against things which are usually well established? You see, where I think you're going to raise issues is [that] there may be parts of theory which seem to be necessarily there, but are they that well established?

You see, there is a thing which is accepted as part of cosmology, which you'll find in all the books, whether they're popular books or technical books. In the first very, very tiny fraction of a second – 10^{-32} seconds, roughly – we're supposed to be in this thing called inflation, which was a huge expansion and it went on within this tiny fraction of a second and you have to cook up a special theory to make it work. And it doesn't really, in my view, work even then.

But on the other hand, it's there for a purpose – you need something. If you don't have the inflationary theory, you've got to replace it with something else. It needs to be replaced by some other picture, and I have a sort of scheme about what sort of a picture that might be, and it's different from the conventional view.

So if there's something which one might feel is in need of replacement or in need of change, in need of some modification, it's because it has some awkwardness, not just that it's "strange." You see, quantum mechanics is strange, but there's lovely strange aspects of quantum mechanics that completely verify it. Fine, that's the way nature works. You've got to get used to it.

But there's certain aspects of it which are not just that. They don't seem to make sense in a more serious way. In the case of the inflationary model, I worry about things which don't seem to make sense, and one has to have a way of explaining in some other way the good things it does.

Inside: So it's all part of the scientific process?

RP: Yes. I think questioning them is certainly good. Even just as part of understanding. It's a good thing to be suspicious of, say, quantum mechanics, and then it's a part of understanding the theory as it is, and coming to terms with it. The questioning is important.

– Stephanie Keating

This interview has been edited and condensed for clarity.

CHARTING A NEW COURSE FOR LOW-ENERGY QCD

The theory that governs the interactions of quarks and gluons inside atoms has long been an intractable mathematical snarl. Perimeter Faculty member Jaume Gomis is on a quest to change that.

QCD "An ode to Richard Feynman" by Nikk Valentine/Flickr

GOMIS GETS CAP-CRM PRIZE

Jaume Gomis is the winner of the prestigious 2019 CAP-CRM Prize in Theoretical and Mathematical Physics. The award, presented by the Canadian Association of Physicists (CAP) and the Centre de recherches mathématiques (CRM), recognizes Gomis "for his broad range of important contributions to string theory and strongly coupled gauge theories, including the pioneering use of nonlocal observables, the exact computation of physical quantities in quantum field theory, and the unravelling of the nonperturbative dynamics of gauge theories."

CENTRE DE RECHERCHES MATHÉMATIQUES

Jaume Gomis takes a pen and rolls it across his desk. This leading mind in quantum field theory is turning his attention (briefly) to experiment.

"You probably have a good intuition for this," he says. "For example, you know that the pen will go in the direction you push it. It will go faster if you push it harder. It might skitter as the cap catches."

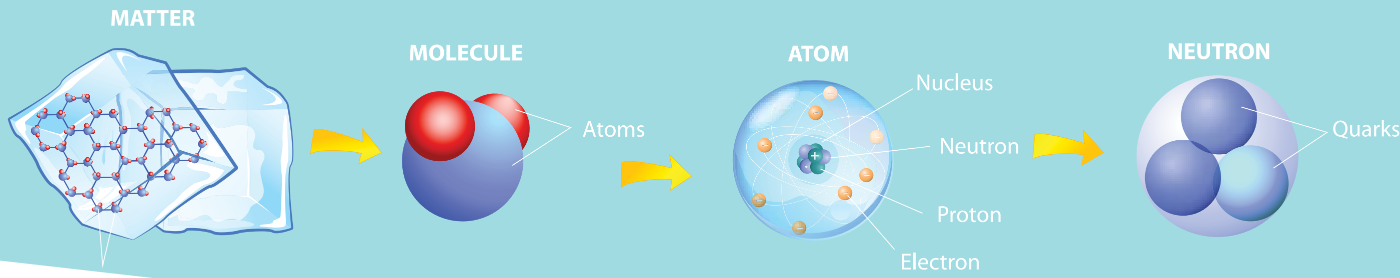
It does, and then crashes into a pile of papers. All of that was predictable. Almost nothing else in Gomis' research works this way.

Gomis, one of Perimeter's senior faculty members, studies the physics of objects that are much smaller and, in principle, simpler than pens: the quarks and gluons that make up the protons and neutrons of everyday matter. The behaviour of the pen is governed (roughly) by the laws of classical mechanics. The behaviour of quarks and gluons is governed by the laws of something called quantum chromodynamics, or QCD.

But while predicting the behaviour of the pen is high school physics, predicting the behaviour of the quarks is extremely difficult – often impossible. We can do it for quarks interacting over very short distances, or at very high energies, where quantum effects are tame. But at the lower energies and larger scales we can actually observe on Earth, the surprising and non-classical behaviour of quantum mechanics reigns. [Why is low-energy QCD in such a snarl? See sidebar at right.]

Gomis describes the way our classical approaches and intuition fail. "It's as if, instead of sliding across the table with a bit of skittering, the pen ran off to Las Vegas to form a band," he says. "What's happening here is that strong quantum effects reorganize the quarks and gluons into systems whose dynamics are entirely different than the ones we see at high energies."

When it comes to QCD at everyday energies, our intuition is not a reliable guide and our calculations from first principles fail us. This is a situation Gomis is determined to change, and in what's already being called a major step forward for the field, he's having some success.



Gomis is working with a particular subset of QCD known as QCD3. The "3" refers to the number of dimensions in the theory: two of space and one of time. That's obviously different than a theory of QCD for all four dimensions of the known universe, but it's not as impractical as it sounds: many real-world condensed matter systems are best described using QCD3. That includes several types of condensed matter whose properties could be useful in quantum computing.

That makes what Gomis did next both a theoretical leap forward and a practical advance that's sure to catch the eye of experimentalists. By deploying a variety of recent developments from the forefront of particle physics, condensed matter physics, and pure mathematics, Gomis developed a new mathematical formulation of QCD3 that can be used to predict the dynamics of systems at low energies.

Asked to dive deeper into the principles that guided his reformulation of QCD3, Gomis demurs. "It's extremely technical," he says. "Call it an educated guess."

It was clearly a very, very educated guess. But that leads to a question: how does Gomis know his guess was right?

It turns out that quantum chromodynamics makes a handful of predictions that are the same at all energies and all length scales. These calculated results, known technically as "anomalies," can act as fixed stars, making sure the theory is on the right course.

Here's how. Remember that physicists have long been able to work with high-energy QCD; it's the low-energy counterpart that has been the problem. To check his theory, Gomis first used the existing high-energy QCD3 and calculated the theory's anomalies. Then, with some trepidation, he used his reformulated low-energy QCD to calculate the same anomalies. Because anomalies are the same at high energies as at low energies, he knew the calculations should match.

And they did. "It was the most beautiful thing, the most astonishing thing," Gomis says. The anomalies at low energy lined up with those from high energy like stars with a star chart.

This work is considered a breakthrough in the subfield and it has opened new lines of research by both Gomis and the community. There have been further insights and conjectures on the low-energy dynamics of QCD theories, including concrete predictions for the low-energy dynamics that can now begin to be tackled by large-scale computer simulations.

With the "stars" aligned and the work ongoing, it seems that in the long quest for a workable version of low-energy QCD, Jaume Gomis has set a promising course.

– Erin Bow

The problem with low-energy QCD

Low-energy QCD is in such a snarl because, in the parlance of the field, it is non-perturbative.

Most everyday physics is perturbative. Practically speaking, that means we can make rough calculations based on approximations and then dial in on more correct answers through a series of small corrections. To perturb something is to give it a little knock. If you bump into a swinging pendulum, the resulting motion would probably be a swing with a wobble in it. If you wanted to describe the motion mathematically, you could get close by writing down the well-known equations for the basic swing and then adding a bit of math to represent the wobble. The pendulum has been perturbed, and perturbative methods can be applied.

A non-perturbative pendulum would be a different story. The wobble would likely be bigger than the swing, and the resulting motion a complex mixture of both. In any calculation, both the wobble and the swing (and any other complicated factors) would have to be included from the beginning. Describing the dynamics of this pendulum is obviously much, much more challenging than describing the dynamics of a perturbative pendulum.

Many non-perturbative physics problems have not been solved analytically at all. This is particularly true of problems that are far from the classical realm, where quantum effects rule. Low-energy QCD is a morass of such problems – which makes charting a course through it particularly hard.

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Unity seeker
Elise LePage

For Elise LePage, studying physics feeds a deep desire to tease out nature's unifying principles.

Shortly before sunset, Elise LePage unshouldered her heavy backpack and dropped it to the mossy forest floor. Having found a suitable spot to set up camp for the night, she unpacked the simple tarp she used as shelter on her journey.

She knew she was somewhere in Vermont, somewhere along a 430-kilometre path known, fittingly, as the Long Trail. She also knew the remaining daylight would afford some time to read her tattered copy of Kurt Vonnegut's *Breakfast of Champions* before darkness enveloped the forest and unveiled a canopy of stars stretched between horizons.

She felt simultaneously connected to the Earth and afloat in the vastness of the universe. That feeling – the sense of a connectivity between all things great and small – had been on her mind. The hike made her feel it in her bones.

It was the summer of 2016, and LePage was barely 20 at the time. She had only recently realized, mostly by accident, that the study of physics could feed her desire to tease out nature's unifying principles.

She can pinpoint that realization to a single moment. It was during spring break of her second year at Hamilton College in New York and LePage was reading a book loaned to her by a friend: Manjit Kumar's *Quantum: Einstein, Bohr, and the Great Debate About the Nature of Reality*.

At the time, LePage was a geoscience major who had only taken an introductory physics class to meet a curriculum requirement. After reading the book, she switched majors. "The book showed me that physics goes beyond the Newtonian mechanics we learned in high school," recalls LePage, who grew up in Massachusetts. "I'm drawn to fundamental questions."

The allure of deep questions inspired her to apply for Perimeter Scholars International (PSI), where she is now earning a master's degree with a focus on the interplay between pure mathematics and physics. That interplay, she believes, "will shed light on the answers" to some of the most fundamental questions in physics.

"Ideally, I would like to come up with a theory to unify general relativity and quantum mechanics," she says, half-jokingly.

She realizes that's a lofty goal – perhaps the loftiest, most sought-after goal of contemporary theoretical physics – but she also believes it is possible, and she wants to play her part.

"I'm not sure I'll be the one to single-handedly unite the theories," she clarifies, "because I consider physics to be more of a group effort than that. I'd like to at least make significant contributions in the right direction, though. I'll hopefully find some pieces of the puzzle."

Equipping brilliant young minds with the tools they'll need to solve difficult puzzles – whether as lifetime physicists or in other careers – is the goal of PSI. Students are encouraged to work tenaciously and collaboratively toward solutions.

LePage and her colleagues in the 10th class of PSI must work together to thrive – not just in the classroom, but as peers on a shared adventure. Some go running together. Some go rock climbing. They cook and eat together, sharing cuisines from their respective home countries. And in between classes, most can be found playing a pattern-recognition card game called Set, often with a competitive zeal bordering on obsession.

They do these things together because theoretical physics is really, really hard. It helps to lean on one another for advice, support, and a sense of unity.

The challenge of it all doesn't deter LePage. Her ongoing search for unity – whether through complex physics research or camping under the stars – is what keeps her curious, keeps her motivated, keeps her moving.

The path is not always well illuminated, and it is rarely straight. But LePage knows that progress on even the most daunting challenges is made one step at a time.

– Colin Hunter

Embracing the **challenge**

Nearly 200 high school students at Perimeter Institute's annual "Inspiring Future Women in Science" event heard that adversity and failure can be the most powerful drivers of future success.

When Cather Simpson speaks to audiences about the advantages of being a woman in science, one comment always gets a laugh: "No line-ups for the bathroom."

Sure enough, it elicited plenty of giggles from the nearly 200 high school students sitting in Perimeter Institute's theatre for the annual "Inspiring Future Women in Science" event on March 7.

The punchline, of course, makes light of an unfunny reality: women have been historically under-represented in the STEM fields (science, technology, engineering, and mathematics).

Making headway toward correcting that imbalance is the goal of "Inspiring Future Women in Science," held this year on the eve of International Women's Day. While there is no quick fix to remedy the entrenched biases and systemic barriers affecting women in science, the annual event aims to give tangible support to young women as they begin to chart their post-secondary careers.

Such encouragement was in great supply from successful women from various sectors who delivered keynote addresses and met with attendees in the "speed mentoring" sessions.

"I used to think that being smart was the most important thing about being a scientist," Simpson told attendees. "But now I know the most important thing is persistence and drive."

Simpson is a laser scientist and founder of the University of New Zealand's Photon Factory, which applies ultrashort laser pulses for fundamental research, with applications to the agriculture industry. While her "Top 10 Reasons to be a Woman in Science" list is tongue-in-cheek, it also underscores the message that incredible opportunities await young women willing to work through periods of adversity and failure.

That notion of embracing failure was a recurring theme in the keynote talks of the event. Each of the speakers encouraged the students to consider failure as an opportunity to learn and grow.

Varuna Prakash recalled the shame and disappointment she felt when, after being a straight-A student in high school, she struggled to earn Cs and Ds during her first year of an engineering degree at the University of Toronto.

"I felt like a complete failure, and felt a deep sense of shame, like I had let down everyone who had great expectations for me," recalled Prakash. "But having this failure, and having it so early in my career, was one of the best things that could have happened to me."

Prakash used the disappointment as an opportunity to pivot into a different branch of engineering, which she found much more interesting and satisfying. From there, she went on to medical school and has since worked for the World Health Organization and Massachusetts General Hospital. "I wouldn't be here today if I hadn't failed so spectacularly back then," she said.

For the teens in the audience – and those watching the keynote addresses via live webcast – the event was a chance to hear that even the most successful women battled insecurities and barriers in high school and beyond.

"Something that I heard that resonated was that it's okay to fail," said 16-year-old Raelyn Marshall, a Grade 11 student at St. Marys District Collegiate and Vocational Institute in St. Marys, Ontario. "It's okay to not do everything perfect, to learn from everything."

For Deirdre Finnigan, a 17-year-old Grade 12 student from St. John's College in Brantford, Ontario, the event provided reassurance that it's okay to be unsure of your career aspirations.

"A lot of (the mentors) didn't know what they wanted to do at all in high school, and a lot of them applied to everything," she said.

"I thought it was interesting that a lot of them ended up doing something they had no idea they would end up doing. I don't know exactly what I want to do, but they were helpful in showing me that it doesn't really matter if I know or not what I want to do right now – that I'll get there."

– Colin Hunter

FURTHER EXPLORATION:

Watch the IFWIS keynotes on Perimeter's YouTube channel
www.youtube.com/PIOutreach

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Martin Lipman / NSERC

ANNA GOLUBEVA WINS NSERC BRASSARD PRIZE

Perimeter PhD student Anna Golubeva is honoured for her interdisciplinary research.

Perimeter PhD student Anna Golubeva, a recent recipient of the prestigious Vanier Canada Graduate Scholarship, has won this year's Gilles Brassard Doctoral Prize for Interdisciplinary Research from the Natural Sciences and Engineering Research Council of Canada (NSERC).

Golubeva works with Perimeter Associate Faculty member Roger Melko on applying machine learning methods to problems in complex quantum many-body systems.

Golubeva came to Perimeter from Germany in 2016 to take part in Perimeter Scholars International (PSI), the Institute's one-year master's program. She approached Melko and expressed an interest in computer simulation techniques for condensed matter systems. That led to a collaboration between the two for her PSI essay research project.

Impressed with the quality of Golubeva's work, Melko offered her a position as a PhD student in his research group. She accepted, choosing Melko's group over several other academic offers and industry positions.

"PSI brought me to Canada. My current supervisor, Roger Melko, and Perimeter Institute made me choose to stay in Canada for my PhD," she says.

"Canada excels in embracing diversity, both in science and in general."

The NSERC Gilles Brassard Doctoral Prize for Interdisciplinary Research, established in 2012 by Gilles Brassard (winner of the 2009 Gerhard Herzberg Canada Gold Medal for Science and Engineering), is awarded annually to an outstanding recipient of an NSERC Vanier Canada Graduate Scholarship who best exemplifies interdisciplinary research.

"Anna was well aware of the current revolution that machine learning is precipitating in the world of information technology, and she and I began discussing early on the prospects for using machine learning in my own line of physics research. Such a perspective and outlook is rare among students of her age," Melko says.

NSERC Interim President Digvir Jayas congratulates Anna Golubeva at the award ceremony in Ottawa.

Golubeva got her start studying biophysics during her undergraduate degree, where she built a base of knowledge spanning physics, biology, chemistry, and even some medicine.

At Perimeter, she set her sights on theoretical physics. Still, she says, "I remained true to my belief in interdisciplinary science. Nature is not split into subfields of biology, physics, mathematics – it's all one. Our understanding of nature can be advanced when we step over the boundaries between these academic fields."

Her current research is a true blend of subfields. "Machine learning is a tool from the field of artificial intelligence, which has its roots somewhere between neuroscience and computer science, but is now rapidly spreading through all possible branches of science and industry," Golubeva explains.

"Adapting machine learning as a tool for theoretical physics was a novelty a few years ago – now, it's a whole new field of theoretical physics, which has a strong representation at Perimeter through the Perimeter Institute Quantum Intelligence Lab."

But when Golubeva began to apply the methods to problems in physics, she had a realization.

"[Machine learning] was driven by industry applications, and so it is completely lacking theoretical foundation. We don't fully understand it. How can I apply it as a scientific tool if I don't know exactly where I can expect reliable results?"

She decided to flip the problem. "It very naturally suggested the other direction – to apply my knowledge and methods from theoretical physics to study machine learning. We're using physics to develop machine learning, and we use machine learning to solve problems in physics."

The techniques, she notes, could be coupled with quantum computing in the future to tackle currently intractable quandaries. "There are a lot of problems in physics that we theoretically, in principle, know how to solve – but because the problem is so complex, and scales exponentially with the system size, we would need about 10,000 years of computer time to solve it with normal, classical computers."

For Golubeva, receiving the prize adds tangible, meaningful support at a critical early career stage. "It's a confirmation that strengthens my belief and enhances my motivation to carry on my work."

"Anna is one of a very few bold young researchers charting the boundaries between artificial intelligence and fundamental theoretical physics," says Melko. "I am delighted to see the Gilles Brassard Prize go to such a deserving student and am personally thrilled to have a front-row seat to the exciting developments coming out of Anna's new interdisciplinary field of research."

– Stephanie Keating

UPCOMING CONFERENCES

Perimeter Institute knows that a lively program of conferences and workshops is essential to maintaining a dynamic scientific atmosphere. Don't miss your chance to register for these upcoming conferences:

QFT for Mathematicians
June 17-28, 2019

Machine Learning for Quantum Design
July 8-12, 2019

Bootstrap 2019
July 15-August 2, 2019

Boundaries and Defects in Quantum Field Theory
August 6-9, 2019

Dynamics and Black Hole Imaging
August 12-23, 2019

Cosmological Frontiers in Fundamental Physics 2019
September 3-6, 2019

Simplicity III
September 9-12, 2019

Emmy Noether Workshop: The Structure of Quantum Space Time
November 18-22, 2019

Indefinite Causal Structure
December 9-13, 2019

Quantum Gravity 2020
July 13-17, 2020

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

A quick **quantum** history of the light bulb

It might be an icon of old-school invention, but the light bulb is a quantum device. A tour through its history can double as a history of quantum mechanics.

Unimaginably powerful quantum computers, unbreakable quantum encryptions, ultraprecise quantum sensors. When we think quantum technology, we think exotic. But though we're learning to harness the quantum properties of the world in new ways, the deeper truth is that the world has always been quantum.

Even that icon of old-school invention – the light bulb – is a quantum technology. In fact, a tour through the history of the light bulb can double as a tour through the history of science, where small puzzles can lead to big breakthroughs and esoteric little observations can – given enough time – light up the whole world.

Old-school bulbs: The dawn of the quantum world

The first light bulbs were incandescent, which is a physicist's way of saying that they glow because they are hot, and hot things glow.

In fact, all hot things glow in the same way. Heat something – embers, glass, clay, steel, the little wire filament in a light bulb, anything – to 800°C, and it will glow red. Heat it to 1,100°C, and it will be yellow. 1,300°C, white.

Why should everything at the same temperature emit the same colour light? Physicists love a good phenomenological question, and at the end of the 19th century, this one was all the rage.

The best scientific models of the day said that the energy of the glow should be smeared evenly across all frequencies. This seemed reasonable but resulted in a nonsensical prediction. At the high end of the spectrum, the frequencies are closer together. If each frequency got an equal smear of energy, then the high end of the spectrum would have more energy – and a run-of-the-mill toaster would produce blinding ultraviolet light and deadly X-ray radiation.

That's not what's happening – good news for those who like toast, but bad news for 19th century physics. The problem came to be called "the ultraviolet catastrophe."

Enter Max Planck. Unlike most people who remake science, Planck was no hip young thinker: he was in his forties, with a comfortable position at the University of Berlin and a membership in the Prussian Academy. He was a leading mind in thermodynamics, a branch of physics that defines the relationship between heat and other forms of energy. The ultraviolet catastrophe should have been right up his alley.

But, like everyone else, he couldn't make a model that worked. Like everyone else, he struggled with it for years.

Planck had built a career by clarifying the subtleties of the Second Law of Thermodynamics, which states that entropy always increases. He believed that the Second Law was rigorously true in all circumstances, but not everyone at the time thought so.

Ludwig Boltzmann had developed a model of heat in gases that chopped the gas up into molecules and then considered their average position and velocity using statistics. He'd even written a statistical version of the Second Law, in which entropy increases on average, but may decrease temporarily because of momentary fluctuations. Planck hated it. He wasn't even convinced that atoms and molecules existed.

So it must have been with desperation that Planck turned to Boltzmann's method to tackle the ultraviolet catastrophe. As Boltzmann had chopped gas up into atoms, Planck sliced energy up into packets, and he used Boltzmann's statistical approach to calculate how small these packets could be. It turned out that they did, in fact, have a minimum size.

This was – and is – the solution to the ultraviolet catastrophe: energy doesn't get smeared evenly across all frequencies, because energy isn't something you can evenly smear. At small scales, it's lumpy, coming in bits, which Planck dubbed "quanta" – the Latin word for packet. It was the dawn of quantum mechanics.

Every time you flip on an old-school incandescent bulb, you are lighting the bridge between the 19th century and the quantum age.

Fluorescent bulbs: New lines of light

Fluorescent light bulbs embody an entirely different quantum principle: spectral lines.

When light passes through a glass prism, it is split into what most of us call a rainbow and scientists call a spectrum. In the early 1800s, a young glassmaker named Joseph von Fraunhofer was studying this effect when he discovered something that would shape the course of science for centuries to come.

The story behind Fraunhofer being around to make his discovery is so unlikely it's almost a fairy tale. The youngest son of a glassmaking family, Joseph was orphaned when he was just 11. His guardians sold him into a prestigious apprenticeship cutting vases and decorative mirrors. But young Joseph hated it because it wasn't scientifically interesting and he was not allowed to continue his studies or read his books on optics. That might well have been the end of it – one more talented mind lost to poverty and chance – but for the master glassmaker's house collapsing... with Joseph inside.

The story goes that Joseph's rescue was aided by none other than the prince of Bavaria, Maximilian IV. The support of Prince Maximilian allowed the teenager to leave his apprenticeship and buy new tools. Fraunhofer became a researcher, a producer of lenses for telescopes, and an expert in the refraction of light.

To aid his research, Fraunhofer invented a grating that separated colours in a more reliable way than a prism. His aim was to reliably produce the same specific colour so that he could study the way it bent in different kinds and shapes of glass. But what he discovered in his mapping of the colours of sunlight was something brand new: a series of dark lines, spread across the spectrum like a barcode printed over a rainbow.

They came to be called the Fraunhofer lines.

Like most glassmakers, Fraunhofer died young, poisoned by the heavy metal toxins of his craft. But Fraunhofer lines did not die with him. They were rigorously studied, and, in 1860, Gustav Kirchhoff and Robert Bunsen finally cracked their secret.

They discovered that when light passed through a gas containing, say, iron, the gas absorbed some specific blue and green lights to create black lines in the spectrum. If the same gas was burned, it created lines of those specific colours. Each element had a unique barcode – a unique set of spectral lines.

Suddenly, spectral lines could be used to tell what things were made of. Suddenly, we could study the composition of the Sun!

But working out why different elements have different spectral barcodes took another 50 years and a scientific revolution.

In 1913 – almost 100 years after Fraunhofer mapped his lines – Niels Bohr introduced the first quantum model of the atom.

In it, electrons made "quantum leaps" from one energy level to another, emitting or absorbing light at certain wavelengths – or colours – as they did so. This handful of distinct energy levels and transitions between them gives each element its unique set of spectral lines.

The barcode, it turns out, is quantum. Which brings us back to fluorescent lighting.

Inside a fluorescent light bulb is a source giving off ultraviolet radiation. Coating the inside of the light bulb are phosphors, which can absorb those ultraviolet bits of light, bumping their electrons up several steps to very high energy levels. As the electrons fall back down, they emit a series of different coloured lights, a barcode that when added together happens to look white.

So when you turn on a fluorescent light bulb, you have your hands on another technology that traces its roots to a young and meticulous researcher noticing something odd.

LEDs: Quantum roots and quantum branches

In 1900, Planck proposed that light comes in packets called quanta. In 1905, Einstein defined how electrons can absorb or emit these packets of light via the photoelectric effect. In 1916, Bohr put these two ideas together to create the first quantum model of the atom. The three discoveries, together, are called "the old quantum mechanics."

As physics was turning itself inside out, so was the western world. World War One raged from 1914 to 1918. One of the soldiers in that war was a French student from an aristocratic family. His name was Louis Victor Pierre Raymond de Broglie, and he would eventually be the seventh Duke de Broglie and a prince of the realm. But when war broke out, he joined the French army and became a wireless operator, stationed at the Eiffel Tower – by then a wireless telegraph transmitter as well as a landmark.

The posting away from the horrors of the trenches was a lucky break for the young Louis – and perhaps for physics. He came to know radio waves and their technical problems intimately. He had the time and connections to read about modern physics and to learn that light could be both a particle and a wave.

De Broglie survived the war and turned to the study of physics. In a groundbreaking doctoral thesis, he asserted that, just as light could have the particle-like properties of matter, matter – specifically electrons – could have the wave-like properties of light.

Matter as wave: it was astonishing, but it was true. The new quantum mechanics was born.

After that, things happened fast. There came Dirac and his wave equation; Heisenberg and Schrödinger and their formulations of wave mechanics; then Bloch with his quantum understanding of solids. Bloch's understanding gave Schottky footing for models of the strange conducting and insulating properties of materials we now call semiconductors.

From there came the engineers (and more physicists), harnessing the quantum properties of semiconductors to make devices in a wave of innovation that went on for decades. One of these devices was the light-emitting diode, or LED.

LED light bulbs – lit, as one might guess, by LEDs – stand at one branch tip of a tall tree of technological innovation, all of it rooted in theoretical physics. The roots, too, branch out and go deep – one can trace them through famous names and obscure ones, through light bulb moments and odd little observations. Nor are light bulbs unique: almost every technology of the last century has its roots in basic research – research with no obvious or immediate benefit.

We know this. But sometimes it's interesting to think about the history of science that's at our fingertips when we flip on a light.

– Erin Bow

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STEPHEN HOUGH, PIANO
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LEONARD ELSCHENBROICH, CELLO
& ALEXEI GRYNYUK, PIANO
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Talking about support for science

Ted Hewitt, the inaugural chair of the Canada Research Coordinating Committee, visited Perimeter to gather perspectives on the nation's support for scientists, scholars, and students. He quizzed a number of researchers and staff on their work and their ideas to invigorate research in Canada. Hewitt, who is also the president of the Social Sciences and Humanities Research Council, is seen here with Perimeter Director of External Relations and Public Affairs John Matlock and Managing Director and Chief Operating Officer Michael Duschenes.

New chapter for Women in Communications and Technology

Nobel laureate Donna Strickland, a pioneer in the field of pulsed lasers and a professor at the University of Waterloo, shared her personal journey from early career to receiving the Nobel Prize in Physics at the kickoff event for the Women in Communications and Technology Waterloo Regional Chapter. The event took place at Perimeter Institute in April.

Teacher Network educators honoured for outstanding pedagogy

Two educators in Perimeter's Teacher Network have been recognized for exceptional STEM teaching practices. Sarah Torrie was awarded the Canadian Association of Physicists (CAP) Award for Excellence in Teaching High School/ CEGEP Physics (Ontario), while Karen Kennedy-Allin received the 2019 Prime Minister's Award for Teaching Excellence. Kennedy-Allin, who is the Saskatchewan regional coordinator of Perimeter's Teacher Network and a former facilitator for Perimeter's EinsteinPlus teachers' camp, also won the CAP Award for Excellence in Teaching in 2017. Both prizes recognize innovative teaching methods and commitment to promoting physics at the high school level.

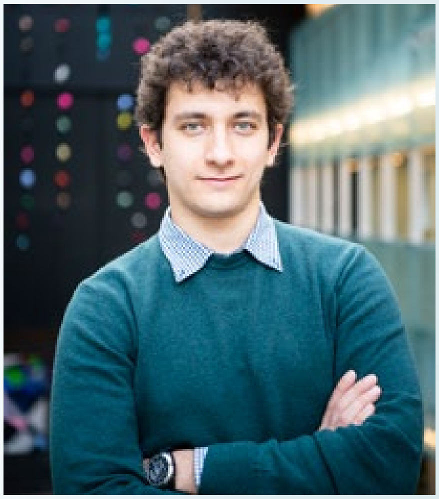
Postdoctoral researcher wins Dieter Rampacher Prize

Earning a PhD is a remarkable achievement that reflects years of dedication and effort – and it's not one that many 23-year-olds have already crossed off their "to do" lists. But that's just what Lena Funcke did. Now a postdoctoral researcher at Perimeter, Funcke is the recipient of this year's Dieter Rampacher Prize, awarded by the Max Planck Society each year to one of its youngest PhD candidates for outstanding doctoral work.

Robert Myers receives UW Science Alumni Award

It's been a big year for Robert Myers. Not only was he named Perimeter's new Director, he also received the Distinguished Alumni Award from the University of Waterloo Science Faculty. The award honours alumni who have distinguished themselves as outstanding professional and personal achievers in their chosen fields.

Perimeter cosmologists continue winning streak



For the fifth time in the five-year history of the Buchalter Cosmology Prize, the awards have recognized research by Perimeter Institute scientists. Postdoctoral researcher Davide Racco was among the first-prize winners for work completed during his PhD at the University of Geneva, while Perimeter Associate Faculty member Matthew Johnson was awarded third prize (marking Johnson's second recognition with the award, following his third-prize win in the inaugural competition).

Perimeter donors named to the Order of Canada

Two of Perimeter's supporters, Joanne Cuthbertson and Charlie Fischer, have been appointed to the Order of Canada. Cuthbertson is a Perimeter Board member and co-chair of Perimeter's Leadership Council. Together, the pair support the Joanne Cuthbertson and Charlie Fischer Graduate Student Award at Perimeter Institute. Presented by the Governor General, the Order of Canada is one of the country's highest honours, reserved for those whose service shapes our society. Cuthbertson and Fischer, who are based in Calgary, Alberta, were named "for their generosity and their commitment to improving the quality of life for people in their community."

TMMC Cambridge supports STEM at Perimeter

Toyota Motor Manufacturing Canada Inc. (TMMC) is proud to support Perimeter's STEM training, particularly for girls from Grade 5 and up. Their $25,000 donation was recently presented by TMMC President Fred Volf to Jacqueline Watty of Perimeter's Advancement team.

CCAE awards

Perimeter Institute carried a win streak forward after a resounding debut last year at the Canadian Council for the Advancement of Education awards, this year taking home awards for initiatives in publications and educational outreach. The annual Prix d'Excellence awards recognize outstanding achievements in educational advancement across Canada.

Perimeter's *Inside the Perimeter* magazine (fall/winter 2018/19 issue) took home silver in the "Best Print Magazine" category, while the bronze in "Best Use of Multi-Media" went to Perimeter's educational outreach interactive website, QuantumToCosmos.ca.

Canada School of Public Service visits Perimeter

Rising leaders in Canada's public service visited Perimeter in April to learn about the Institute. The assistant deputy ministers from Ottawa spoke with Perimeter Director Robert Myers, plus other researchers and administrative members, on the value of basic research and Perimeter's commitment to training and outreach.

Lei Yang receives Vanier Scholarship

Congratulations to Lei Yang, a PhD candidate at the University of Waterloo and Perimeter Institute, on receiving one of this year's NSERC Vanier Canada Graduate Scholarships. Her work in condensed matter physics may have application to the increase in speed and miniaturization of semiconductor electronic devices. Yang is working under the supervision of Anton Burkov, and the topic of her thesis is "using duality to investigate the effects of interactions between electrons in topological quantum materials."

Perimeter DVRCs named as Highly Cited Researchers

Two Perimeter Distinguished Visiting Research Chairs made the "Highly Cited Researchers" list for 2018. The annual list, compiled by Clarivate Analytics, recognizes exceptional researchers whose papers rank in the top one percent of citations for their field. Ashvin Vishwanath (Harvard University) made his second consecutive appearance on the list in 2018. Joining him for the first time was Leon Balents (Kavli Institute for Theoretical Physics).

Government of Canada invests in growing Quantum Valley

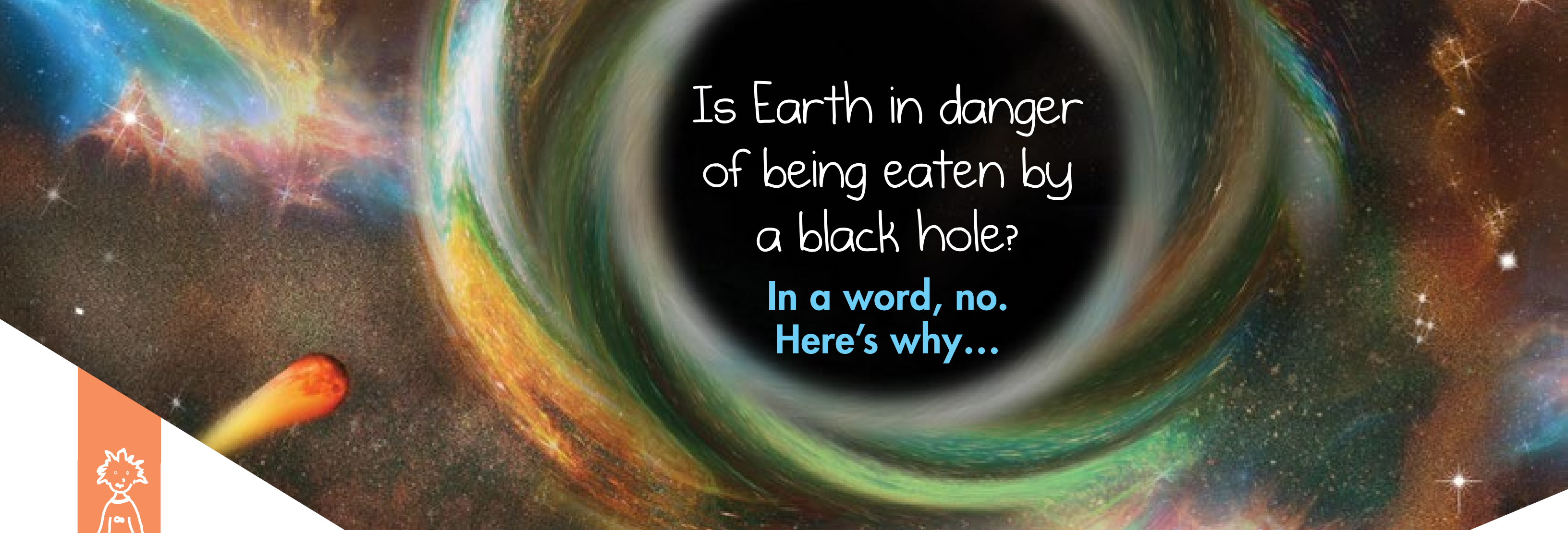
Nearly 20 years ago, Perimeter Institute, and later the Institute for Quantum Computing, were the first seeds planted in what has become a flourishing quantum ecosystem. The Government of Canada recently gave a boost to this "Quantum Valley" with a $41 million investment in one Waterloo-based not-for-profit and three start-up companies for projects that bolster quantum-related technologies and skills development.

John Brodie Prize goes to Hugo Marrochio

PhD student Hugo Marrochio is the recipient of this year's John Brodie Memorial Prize. The prize is awarded annually by Perimeter Institute in honour of John Brodie, one of the first postdoctoral researchers at Perimeter. Marrochio is completing his PhD under the supervision of Robert Myers, studying the role of quantum information concepts in the AdS/CFT correspondence, with a focus on properties of quantum complexity in high energy physics.

Visit with The Honourable Todd Smith

Perimeter recently welcomed Ontario Minister of Economic Development, Job Creation and Trade, The Honourable Todd Smith. Following an introduction to the Institute, the Minister toured other Quantum Valley locations to discuss the role of talent and innovative thinking that keeps Ontario competitive. The Minister is seen here with Perimeter Director Emeritus Neil Turok, Nobel Prize winner Donna Strickland, and Board Chair Mike Lazaridis.



PI KIDS ARE ASKING

Is Earth in danger of being eaten by a black hole?

In a word, no. Here's why...

You've seen them in science fiction and popular culture: black holes as "cosmic vacuum cleaners," sucking in planets, stars, and other space debris on a wanton path of destruction.

But what if I told you that the Earth's moon could be replaced by a black hole of the same mass (say, by some trickster alien race) and not a whole lot would change for us? Life on Earth would carry on pretty much as normal.

Black holes, it turns out, aren't all that scary.

That's because they don't have any sort of special "suction" power to gobble up matter. Their only pulling force comes from plain old gravity, the same force that keeps the moon in orbit and keeps us stuck to the Earth. The strength of the gravitational force between two objects only depends on their masses (bigger mass equals a stronger force) and the distance between them (smaller distance equals a stronger force) – so replacing our moon with an equal mass black hole wouldn't increase the gravitational force. That moon-mass black hole would be all but invisible to us, so we wouldn't have the moon lighting up most nights, but its gravitational effect on Earth would be just like the moon's, pulling water around in tides as Earth turns.

Black holes are still some of the most intriguing objects in the universe, though.

Here's what we know so far: a black hole is a thing that is so dense, with so much mass packed into a small space, that it warps spacetime around it to an extreme degree. Now, Earth warps spacetime, too (and so do you, at least a teensy bit), but black holes warp it so much that nothing can escape once it has entered – not even light, the fastest and, indeed, "lightest" thing in the universe. That "point of no return" is known as the black hole's event horizon. Once a photon passes the event horizon, as far as we know, it is lost forever; light can't pass through black holes or be reflected by them. That's why black holes are, well, black. Really, really black.

Any amount of mass could get turned into a black hole if you squished and compressed it enough. To turn the moon into a black hole, you'd have to squeeze it to about the size of a grain of sand. There are a few ways we think real black holes are created. One of those ways is when a very massive star runs out of fuel to power its fusion and gravity overcomes the other forces as the core collapses. Black holes formed in this manner are known as "stellar mass" black holes.

There are also supermassive black holes, which (as you probably guessed) are much larger, weighing in at millions or billions of times the mass of our Sun. Astronomers aren't sure how supermassive black holes are made, but they suspect it is tied to galaxy formation, since supermassive black holes are found at the centres of galaxies.

Finally, miniature or micro black holes (much smaller than stellar mass black holes) are hypothesized to exist, but so far, we haven't found them. They would require outside pressure to form, since their masses are too small for gravity alone to create them. The universe was very dense in its early stages, so scientists think it would have been an ideal place for these sorts of black holes to form.

Some theories also suggest that micro black holes could be formed during particle collisions at accelerators like the Large Hadron Collider. In fact, many people were frightened that the Large Hadron Collider could destroy the world with these micro black holes. We've already learned that black holes don't have special suction powers, but miniature black holes are harmless for another reason.

Physicist Stephen Hawking argued that – thanks to quantum mechanical effects that come into play on very tiny scales – black holes can actually lose mass in a process known as "Hawking radiation." It would take stellar mass and supermassive black holes more than a septillion years to lose all their mass (that's many times the age of the universe!) via Hawking radiation, but micro black holes (if they exist) would evaporate almost instantly.

There is still a lot to learn about black holes, and scientists are discovering more every day. Experiments like the Event Horizon Telescope are sure to shed more light on these fascinating dark objects.

– Stephanie Keating

Learn more:

Watch a video by *MinutePhysics* about how we know black holes exist at youtube.com/watch?v=sglqRwvaBw4

Webcomic *xkcd* takes a look at a hypothetical lunar black hole at what-if.xkcd.com/129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