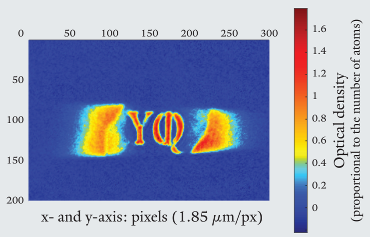
YALE QUANTUM INSTITUTE ANNUAL REPORT

2020

On the cover

At first glance the YQI logo seems straightforward, however it contains a few hidden meanings. The Q and I are stacked on top of one other to evoke the superposition of state like a on/off button, and the feline-like tail of the Q hints at Schrödinger's cat. But this year, our logo gets atomized!



YQI investigator Nir Navon's group focuses on the quantum many-body problem. They devised a program known as quantum simulation, in which well-controlled quantum systems can be used to investigate prototypical quantum many-body models. These quantum simulations consists of quantum matter cooled down to "ultracold" scales.

Ultracold quantum matter is a fascinating platform to conduct this program. Researchers can control the laser traps in which the atoms are confined, the interactions between particles, or subject them to effective gauge fields. These ultracold atoms offer a "magnifying glass" to study phenomena that are hard to measure in other many-body systems. For instance, while inter-particle spacing in an electron gas is at the angstrom scale, their atoms are typically separated by micron-scale distances, making it relatively easy to probe their ultracold quantum matter, down to the single particle constituent. Out-of-equilibrium solid-state systems often relax on very short time scales (femtoseconds or less). However, in these ultracold systems they can persist for much longer (sometimes seconds), offering a new window into the poorly understood territory of far-from-equilibrium quantum dynamics.

Jere Mäkinen, a YQI Fellow in Navon's group, with the help of group members Yunpeng Ji, Franklin Vivanco, Gabriel Assumpcao, and Grant Schumacher, used this platform to create images made by absorption imaging of ultracold fermions, at temperatures of a few tens of nano Kelvins, with a new optical system allowing it to traps atoms in arbitrary geometries. Jere recreated for us the YQI logo, used as a cover for this report. The background image is the optical table used to create the trap. The front cover shows the table when the lasers are on – and the lights off – while the back cover shows the table with the lasers off and the lights on.

YQI Executive Team

DOUGLAS STONE
Deputy Director
Carl Morse Professor of Applied Physics and Physics

FLORIAN CARLE
Institute Manager
Benjamin Franklin College Fellow

RACQUEL MILLER
Event Coordinator

Director's Word

Robert Schoelkopf

Sterling Professor of Applied Physics and Physics

Entering the sixth year since its founding, the Yale Quantum Institute is fully engaged in its mission to support research and training in quantum science at Yale.

This was a banner year for quantum science at Yale and at the YQI. The university science strategy committee has designated quantum information science and quantum materials as a top priority for growth and recommended significant growth in the number of faculty working in these areas across multiple physical science and engineering departments at Yale. Initial gifts to help fund this initiative have been pledged and the University has engaged in a planning exercise for a new state-of-the-art physical science and engineering building, with a site in the Science Hill area as the proposed location. With the onset of the coronavirus pandemic, we have all been concentrating on maintaining research continuity and supporting all of the members of our community as best we can in a socially-distanced mode. Although the pandemic will introduce some delays in all of our plans, the University remains committed to the priorities articulated in the strategy for quantum science and engineering, and we are continuing to advance the planning and lay the groundwork for rapid progress when the immediate crisis has passed. The YQI and our members stand ready and will play a key role in the next phase of growth in this research, engineering and teaching activity at Yale.

This year YQI welcomed to our membership six additional faculty members for a 5-year term (see page 11), bringing to 23 the numbers of faculty members working under the Institute umbrella. We have broadened our research portfolio by including members from the Chemistry department and from areas of physics focused on fundamental topics, such as the origin of dark matter.

The Institute hosted more than 80 events in the past year to engage the scientific community working on quantum science and information, and to train a growing population of undergraduate and graduate students responding to the promise of 21st century quantum science. These events included cutting-edge research seminars and symposia in QSTEM by visiting scientists, tutorials on relevant topics in quantum science and information, professional and workforce training, and interdisciplinary Yale team meetings to formulate and execute research programs to advance the field.

YQI and Yale have played a key role in serving the workforce needs of the exploding field of QIS, sending many of our trainees to top QS research universities such as Caltech, ETH, Harvard, Max Plank Institute, and industrial labs such as IBM, Google, Microsoft…

In addition YQI has hosted or participated in many outreach events to educate the general public and interested government and business leaders. Our most ambitious project, organized by Institute Manager Florian Carle, is Quantum Week at Yale (see page 20). This event, now scheduled for spring of 2021, will involve more than 20 events all over campus in collaboration with 16 departmental and institute partners to encourage anyone, from interested novice to quantum expert, to celebrate and learn more about quantum.

Yale and YQI are playing a key organizational role in a consortium of universities, national laboratories, and industrial partners in the tri-state area responding to the US National Quantum Initiative. If successful Yale would play a leading role in a new 125M$ research hub that will span the range of quantum physics, quantum sensing, quantum information science and technology activities, and engage fully with the computer science, materials science and engineering activities related to the Second Quantum Revolution.

We invite you to learn more about our work and programs through this annual report, and to share our optimism for new scientific and technological advances for the benefit of mankind, once our current challenges are behind us.

Stay safe,

About the Institute

Home of everything quantum at Yale

Life as we now know it would not be possible without several profound scientific and technological revolutions over the last century: the Industrial Revolution, the internal combustion engine, the telephone, and, most recently, the Digital Revolution which ushered in computers, cellular phones, and the Internet. This transformative period was made possible by the understanding of the fundamental laws of the atom, and of light, embodied in quantum theory which was developed in the first half of the 20th century. At the onset of the 21st century, we are on the brink of a new quantum revolution – and Yale is paving the way.

Our faculty members, spanning the departments of Physics, Applied Physics, Computer Science, and Electrical and Mechanical Engineering, are making scientific breakthroughs that would have been unimaginable only a few decades ago. The Yale Quantum Institute was formed in 2015 to advance the progress in fundamental and applied quantum science at Yale and in the broader community of researchers across the globe. Yale has particular expertise in the theoretical and experimental development of new technologies to store and process quantum information. The goal is to better understand the fundamental quantum laws of our universe, and to harness the unique features of quantum mechanics for novel sensors, secure communications, and eventually, the realization of large-scale quantum computers. We now know that by employing a kind of massive parallel processing, computers based on "quantum bits" can address problems that would otherwise remain forever beyond the reach of our current computers. These problems include basic algorithms underlying secure communication on the internet, as well as quantum simulations of new materials, complex optimization problems, and improved machine learning. As with conventional computers, the true scope of their utility will only be discovered once they are built.

Beginning with pioneering work on macroscopic quantum coherence in the 80's, to the realization of today's quantum information processors, Yale professors are renowned for their leadership in the Quantum Revolution. In the past fifteen years, under the leadership of Devoret, Girvin, and Schoelkopf, the Yale superconducting science and technology team, comprising more than fifty researchers, has demonstrated several milestones in quantum computing including the development of the first solid state quantum information processors based on superconducting electronics. Together, the members of YQI are pursuing the collective goal of turning quantum physics into practical technologies and advancing our fundamental understanding of quantum science and engineering. We welcome researchers from around the world to visit and participate in this intellectual adventure.

YQI by the numbers in 2019

Events Hosted	86
Faculty Members	23
Postdocs & Research Assistants	73
Graduate Students	108
Staff Members	2
Publications	171
Citations *Data: Scopus, Jan 2020*	15,123

Mission & Programs

The institute acts an intellectual hub for quantum information science and engineering, and of quantum science more generally, through fostering collaboration and welcoming world leaders in the field.

The Yale Quantum Institute was founded to enhance Yale's leadership in the field of quantum science and technology. It serves as a forum to bring together experimental and theoretical researchers at Yale in the fields of quantum information science and engineering, quantum control, quantum measurement, and quantum many-body physics and chemistry. The Institute also runs an active visitors program to bring quantum scientists from leading institutions worldwide, and hosts conferences and workshops in sub-fields relating to its core mission.

The past two decades have seen breakthroughs in both the theory and the practice of quantum science. The properties of superposition and entanglement, once thought of as paradoxical and counter intuitive, are understood now as unique resources. Recent progress in the laboratory allows unprecedented control over individual quantum objects, whether they are naturally occurring microscopic systems like atoms, or macroscopic man-made systems with engineered properties.

These advances may soon enable us to: perform otherwise intractable computations, ensure privacy in communications, better understand and design novel states of matter, and develop new types of sensors and measurement devices. Today, a new discipline is emerging which combines physics, chemistry, electrical engineering, mathematics, and computer science to further the basic understanding of the quantum world, and to develop novel information processing devices and other quantum-enabled measurement and sensing technologies.

Colloquia & Seminar Series

Every academic year, the Institute presents an exciting series of technical seminars and colloquia from experts in the field of quantum information science, quantum control, quantum measurement, and quantum many-body physics. Speakers are proposed by members of the Yale Quantum Institute community and approved by a selection committee. The talks are attended by a diverse cross section of the university ranging from undergraduates to emeritus professors.

Venue for quantum information events

The Institute hosts many seminars, presentations, group meetings and other events in the field of quantum information science and engineering. YQI is also the organizer of the annual Yale Science and Engineering Forum. In 2017, we welcomed the workshop Majorana Fermions & Beyond, and in 2019, the symposium Mesoscopic Quantum Physics & Beyond. All interested students, professors and staff from Yale or other academic institutions are welcome to attend our events.

Women in Quantum Information Group

The aim of WIQI is to promote an inclusive environment for women in the field by creating a platform where young women scientists can voice concerns and seek advice. Moreover, we also seek to increase retention of female students in quantum science through activities such as lunches, panels, and workshops focused on quantum science.

Visitors Program

The Yale Quantum Institute opens its doors to world leaders in quantum information science for sabbatical visits to Yale. These visiting scientists can focus on their research in close proximity to YQI's professors and students at our 17 Hillhouse Avenue location. This program could be expanded to encourage more long-term collaborations by welcoming visitors for longer periods (month, semester, sabbatical year).

YQI Fellowship

In keeping with the mission of the Institute to facilitate research and teaching of quantum physics, the YQI Fellowship Program provides funding for recent Ph.D. recipients to join any YQI faculty member's group for a 2-year period. YQI Fellows are young researchers who have demonstrated excellent research ability in their prior work and exceptional promise for future leadership in their field of quantum science. Apply at **quantuminstitute.yale.edu/apply**.

Distinguished lecturer series

YQI awards the title of Distinguished Lecturer to recognize a researcher whose work significantly advances quantum science, with emphasis on the areas of mesoscopic physics, nanoscience, quantum information, quantum computing and related theoretical and mathematical topics. Annually, a Distinguished Lecturer will be invited to visit the Yale Quantum Institute to deliver one or more lectures about their work and how it has advanced our understanding of quantum science.

Networking and professional development

We offer a selection of presentations to help students and postdocs with career development, job searching, and networking. For this series, we bring in Yale alumni to share their career experiences, answer questions on working in their industry, and offer an opportunity for attendees to build a career network. Speakers in this series have included noted scientists, industry leaders, and legal advisors.

Physics Open Mic

An informal, bi-monthly lecture series by and for graduate students and postdocs to share their love and enthusiasm for physics while practicing their communication skills in a relaxed setting.

A Look back

In the next few pages, we look back at the news and achievements of the YQI community during the year 2019

Charles Ahn, recently **named as the John C. Malone Professor of Applied Physics**, researches the fabrication and characterization of the physical properties of materials.

Victor Batista, was **appointed as the John Randolph Huffman Professor of Chemistry**. His research focuses on the development of rigorous and practical methods for simulations of quantum processes in complex systems, as well as applications studies of photochemical processes in proteins and semiconductor materials.

Jeffrey Brock was **named dean of the Yale School of Engineering and Applied Science**. He will encourage the university to leverage dynamic collaborations between faculty members in biomedical engineering; computer and data science; environmental engineering; and quantum science, engineering, and materials.

Hui Cao, newly **named as the John C. Malone Professor of Applied Physics and of Physics**, focuses her research on mesoscopic physics and nanophotonics.

Meng Cheng's whose main field of research is quantum condensed matter theory, with a particular focus on the topological phases of matter, was **awarded a 2019 Sloan Research fellowship**.

Physics and applied physics professor Jack Harris, whose innovative research helped to advance the new field of quantum opto-mechanics, **won a Vannevar Bush Faculty Fellowship**.

Yale student Gabriel Mesa **joins alumni in supporting Connecticut's youngest inventors**. "I looked at the physics lab and Yale Quantum Institute, but I was also drawn to the richness of the humanities and my ability to do both."

Yale made more than $4 million in new investments in core facilities that support science and engineering research. Ben Myers, **newly hired as the director of research cores** under the Provost's Office, will provide additional coordination and support to the cores.

Nir Navon was **awarded a 2019 Sloan Research fellowship** for his work on probing the behaviors of interacting quantum particle assemblies using highly-controllable ultra-cold quantum matter.

After nearly 40 years at Yale (beginning with his time as a graduate student), President Peter Salovey says he is still impressed with the ways in which Yale and New Haven neighbors unite to improve their city and **lauds a three-centuries-old partnership for the benefit of New Haven.**

Ramamurti Shankar, recently **appointed as the J.W. Gibbs Professor of Physics**, researches theoretical condensed matter physics and quantum field theory.

2019 saw the launch of a new program to **support women in quantum information to increase retention** of female students and promote an inclusive environment for women in the field.

Yale and New Haven Usher in a Quantum Revolution

Yale President Peter Salovey sent this note to all members of the Yale community

This year I will celebrate my thirty-eighth year as a New Haven resident. I have seen many exciting changes come to the Elm City, including wonderful restaurants, stores, and arts and cultural opportunities. In recent years, a number of entrepreneurs have recognized what many of us have long known—that New Haven is a great place to live, work, and do business. And the cutting-edge companies they have built are helping to transform our city.

Earlier this year, we celebrated the opening of Quantum Circuits Inc. (QCI), a startup founded by a team of Yale investigators. QCI promises to further enhance New Haven's reputation as a hub for technology and innovation. Connecticut Governor Ned Lamont SOM '80 was on hand for the ribbon-cutting, and he expressed enthusiasm about the way "high-tech pioneers" like QCI are contributing to our state and communities. QCI currently employs twenty scientists and engineers with plans to expand.

QCI exemplifies how Yale-led research helps to create jobs and opportunities in New Haven. Startups with ties to Yale employ over 1,000 people in the city. In recent years, 130 companies, based on Yale discoveries, have been established in partnership with Yale's Office of Cooperative Research. Many ventures have been launched by Yale faculty, alumni, and students. Recent high-tech companies that call New Haven home are developing cancer therapies, antibiotics, and new green technologies based on Yale research. They enrich our city and neighborhoods, and their discoveries are making a difference around the world.

Yale has long been at the forefront of quantum research. The Yale Quantum Institute, founded in 2014, brings together more than 120 physicists, engineers, computer scientists, materials scientists, and other researchers to study quantum information, computation, measurements, and sensing. Important related research at the university involves designing and elucidating novel properties of quantum materials. Quantum science may help us build more advanced computers, secure our communications, create improved sensors, and even solve the puzzle of how the universe began. Medicine, national defense, artificial intelligence, and economics could benefit from such advances. In recognition of the field's growing importance, last year Congress passed the bipartisan National Quantum Initiative Act, authorizing $1.2 billion for quantum science research and education over five years.

The first rudimentary electronic quantum processor was invented at our university, and Yale investigators are working on the basic science and technology needed to develop the world's first practical quantum computer, which would be far faster and more powerful than today's supercomputers and able to solve problems at an unprecedented scale. Now they may be one step closer to achieving that goal. In February, Yale faculty members Robert Schoelkopf, Michel Devoret, Liang Jiang, and Steve Girvin announced a new breakthrough in efforts to build a quantum computer. By developing a "universal entangler," the team has created "a valuable building block for universal quantum computation," according to findings published in the journal Nature.

Today we are at the beginning of a new era for science at Yale—and for our home city. As one of the world's leading research universities, Yale has a responsibility to pursue bold research that benefits humanity. Quantum science—one of five areas for top-priority investment identified by the University Science Strategy Committee—exemplifies the promise and potential of Yale's scientific leadership.

Exciting discoveries require vision, imagination, commitment, and resources. That is why Yale's historic commitment to science is important. By investing in great ideas, in people, and in our communities, we also invest in the future. Innovation at Yale is good for our city and state today, and it is absolutely essential to our well-being tomorrow. On behalf of future generations, we have an obligation to carry this promising work forward.

Six Yale faculty members join YQI

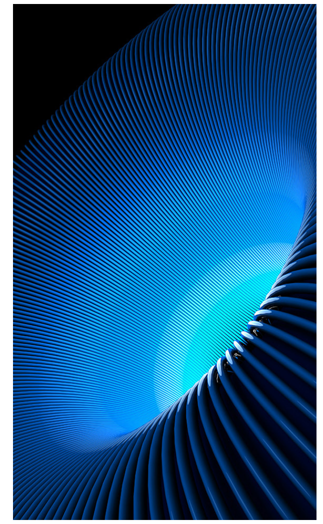
We are delighted to welcome six new YQI members for the next 5-year term of the Yale Quantum Institute.

Sean Barrett, Professor of Physics
Victor Batista, John Randolph Huffman Professor of Chemistry
Meng Cheng, Assistant Professor of Physics
David Moore, Assistant Professor of Physics
Reina Maruyama, Associate Professor of Physics
Karsten Heeger, Professor of Physics, YQI Ex-Officio member.

By including more members from the Chemistry and Physics departments, **we hope to continue our actions to encourage interdepartmental collaboration and foster a stimulating research environment**.

If you are a faculty member and want to be considered to become a YQI member, please contact one of the current members.

A tool for identifying phases of matter



Even if you're not a physicist, phases of matter … really matter.

They're the distinct physical forms taken on by all the "stuff" in the universe, from icebergs to ozone, and now Yale scientists have developed a more accurate way to help classify some of them.

The findings appear in a recent study published in the journal Physical Review Letters and a follow-up work published in Physical Review B.

The fundamental phases of matter — solid, liquid, and gas — are well known. But there are many other phases, including ones that emerge when matter is chilled or heated to extreme temperatures. Extreme heat, for example, can create plasma phases by breaking down the individual atoms in a substance. Extreme cold, on the other hand, down to nearly absolute zero, triggers an array of quantum phases in which particles interact in entirely new ways.

Understanding the intricacies of these phases could unlock breakthroughs in quantum computing and materials science. In fact, some of these phases could be used as quantum hard drives that will store quantum information. That's why scientists are actively seeking new approaches to characterize and classify them.

More than a decade ago, Caltech physicists Alexei Kitaev and John Preskill and concurrently Michael Levin along with Xiao-Gang Wen at MIT pioneered a new diagnostic tool — called topological entanglement entropy — for identifying whether a phase of matter is topological. Topology explains why you can turn a doughnut shape into a coffee cup shape by simply deforming its surface. Topologically speaking, a coffee cup is the same as a doughnut because they both have one hole.

Topology is particularly important in quantum research, because the robust properties of topological phases establish a measure of stability within the highly delicate, and unpredictable, world of quantum physics. Similar to the doughnut example in which the number of holes doesn't change under smooth deformations, topology appears in the patterns of quantum entanglement in a topological phase. The principle of topological entanglement entropy can detect such patterns.

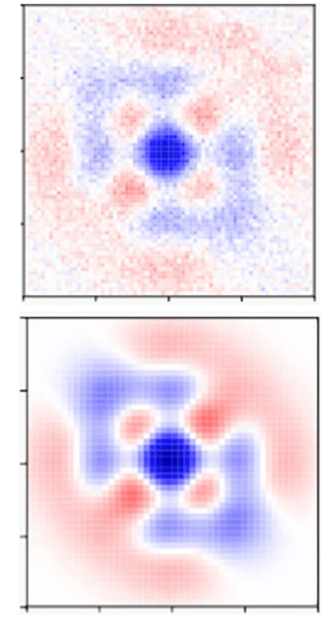
A team of Yale researchers led by physicist Meng Cheng found a discrepancy in the principle that could lead to a false result. The team included graduate student Arpit Dua and postdoctoral associate Dominic Williamson.

"Because of its fundamental nature, this principle has been used extensively in the literature on topological phases," Dua said.

The culprit, Dua said, is a specific kind of hidden string order that crops up in parts of the phase of matter. The researchers' first study points out the discrepancy, explains why it occurs, and offers a way to correct for the error — thus making the principle more accurate. In the second study, the researchers look at an important class of phases where the discrepancy occurs, phases that could be used for making quantum hard drives. The researchers discuss a quantity that can be used to classify these phases, a quantity that is robust to the presence of the hidden string order that affects topological entanglement entropy.

"Topological phases represent an important class of phases of matter," Dua said. "Their study and methods for diagnostics are important, and identifying the right diagnostic tools is fundamental."

Jim Shelton for Yale News



Yale researchers create a 'universal entangler' for new quantum tech

One of the key concepts in quantum physics is entanglement, in which two or more quantum systems become so inextricably linked that their collective state can't be determined by observing each element individually. Now Yale researchers have developed a "universal entangler" that can link a variety of encoded particles on demand.

The discovery represents a powerful new mechanism with potential uses in quantum computing, cryptography, and quantum communications. The research is led by the Yale laboratory of Robert Schoelkopf and appears in the journal Nature.

Quantum calculations are accomplished with delicate bits of data called qubits, which are prone to errors. To implement faithful quantum computation, scientists say, they need "logical" qubits whose errors can be detected and rectified using quantum error correction codes.

"We've shown a new way of creating gates between logically-encoded qubits that can eventually be error-corrected," said Schoelkopf, the Sterling Professor of Applied Physics and Physics at Yale and director of the Yale Quantum Institute. "It's a much more sophisticated operation than what has been performed previously."

The entangling mechanism is called an exponential-SWAP gate. In the study, researchers demonstrated the new technology by deterministically entangling encoded states in any chosen configurations or codes, each housed in two otherwise isolated, 3D superconducting microwave cavities.

"This universal entangler is critical for robust quantum computation," said Yvonne Gao, co-first author of the study. "Scientists have invented a wealth of hardware-efficient, quantum error correction codes — each one cleverly designed with unique characteristics that can be exploited for different applications. However, each of them requires wiring up a new set of tailored operations, introducing a significant hardware overhead and reduced versatility."

The universal entangler mitigates this limitation by providing a gate between any desired input states. "We can now choose any desired codes or even change them on the fly without having to re-wire the operation," said co-first author Brian Lester.

The discovery is just the latest step in Yale's quantum research work. Yale scientists are at the forefront of efforts to develop the first fully useful quantum computers and have done pioneering work in quantum computing with superconducting circuits.

Additional authors of the study are Kevin Chou, Luigi Frunzio, Michel Devoret, Liang Jiang, and Steven Girvin. The research was supported by the U.S. Army Research Office.

Jim Shelton for Yale News

Physicists can predict the jumps of Schrödinger's cat (and finally save it)

This was the single most-read Yale News story of 2019.

Yale researchers have figured out how to catch and save Schrödinger's famous cat, the symbol of quantum superposition and unpredictability, by anticipating its jumps and acting in real time to save it from proverbial doom. In the process, they overturn years of cornerstone dogma in quantum physics.

The discovery enables researchers to set up an early warning system for imminent jumps of artificial atoms containing quantum information. A study announcing the discovery appears in the June 3 online edition of the journal Nature.

Schrödinger's cat is a well-known paradox used to illustrate the concept of superposition — the ability for two opposite states to exist simultaneously — and unpredictability in quantum physics. The idea is that a cat is placed in a sealed box with a radioactive source and a poison that will be triggered if an atom of the radioactive substance decays. The superposition theory of quantum physics suggests that until someone opens the box, the cat is both alive and dead, a superposition of states. Opening the box to observe the cat causes it to abruptly change its quantum state randomly, forcing it to be either dead or alive.

The quantum jump is the discrete (non-continuous) and random change in the state when it is observed. The experiment, performed in the lab of Yale professor Michel Devoret and proposed by lead author Zlatko Minev, peers into the actual workings of a quantum jump for the first time. The results reveal a surprising finding that contradicts Danish physicist Niels Bohr's established view — the jumps are neither abrupt nor as random as previously thought.

For a tiny object such as an electron, molecule, or an artificial atom containing quantum information (known as a qubit), a quantum jump is the sudden transition from one of its discrete energy states to another. In developing quantum computers, researchers crucially must deal with the jumps of the qubits, which are the manifestations of errors in calculations.

The enigmatic quantum jumps were theorized by Bohr a century ago, but not observed until the 1980s, in atoms. "These jumps occur every time we measure a qubit," said Devoret, the F.W. Beinecke Professor of Applied Physics and Physics at Yale and member of the Yale Quantum Institute. "Quantum jumps are known to be unpredictable in the long run."

"Despite that," added Minev, "We wanted to know if it would be possible to get an advance warning signal that a jump is about to occur imminently."

Minev noted that the experiment was inspired by a theoretical prediction by professor Howard Carmichael of the University of Auckland, a pioneer of quantum trajectory theory and a co-author of the study.

In addition to its fundamental impact, the discovery is a potential major advance in understanding and controlling quantum information. Researchers say reliably managing quantum data and correcting errors as they occur is a key challenge in the development of fully useful quantum computers.

The Yale team used a special approach to indirectly monitor a superconducting artificial atom, with three microwave generators irradiating the atom enclosed in a 3D cavity made of aluminum. The doubly indirect monitoring method, developed by Minev for superconducting circuits, allows the researchers to observe the atom with unprecedented efficiency.

Microwave radiation stirs the artificial atom as it is simultaneously being observed, resulting in quantum jumps. The tiny quantum signal of these jumps can be amplified without loss to room temperature. Here, their signal can be monitored in real time. This enabled the researchers to see a sudden absence of detection photons (photons emitted by an ancillary state of the atom excited by the microwaves); this tiny absence is the advance warning of a quantum jump.

"The beautiful effect displayed by this experiment is the increase of coherence during the jump, despite its observation," said Devoret. Added Minev, "You can leverage this to not only catch the jump, but also reverse it."

This is a crucial point, the researchers said. While quantum jumps appear discrete and random in the long run, reversing a quantum jump means the evolution of the quantum state possesses, in part, a deterministic and not random character; the jump always occurs in the same, predictable manner from its random starting point.

"Quantum jumps of an atom are somewhat analogous to the eruption of a volcano," Minev said. "They are completely unpredictable in the long term. Nonetheless, with the correct monitoring we can with certainty detect an advance warning of an imminent disaster and act on it before it has occurred."

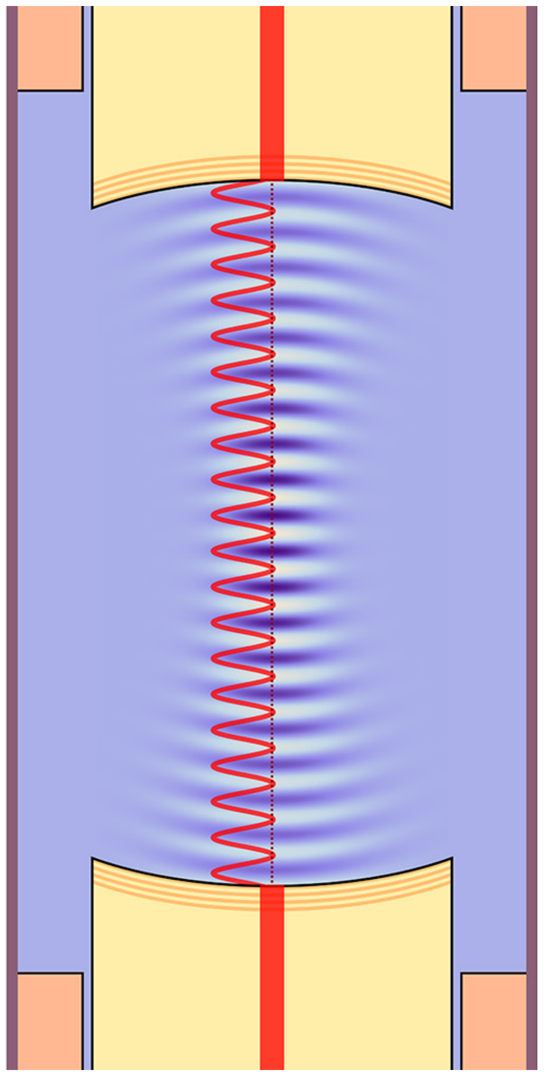
Additional co-authors of the study include Robert Schoelkopf, Shantanu Mundhada, Shyam Shankar, and Philip Reinhold, all of Yale; Ricardo Gutiérrez-Jáuregui of the University of Auckland; and Mazyar Mirrahimi, from the French Institute for Research in Computer Science and Automation.

The research was supported by the U.S. Army Research Office.

The new study is the latest step in Yale's quantum research work. Yale scientists are at the forefront of efforts to develop the first fully useful quantum computers and have done pioneering work in quantum computing with superconducting circuits.

Jim Shelton for Yale News

New experiment dives into quantum physics in a liquid



The space between two optical fibers (yellow) is filled with liquid helium (blue). Laser light (red) is trapped in this space, and interacts with sound waves in the liquid (blue ripples).

For the first time, Yale physicists have directly observed quantum behavior in the vibrations of a liquid body.

A great deal of ongoing research is currently devoted to discovering and exploiting quantum effects in the motion of macroscopic objects made of solids and gases. This new experiment opens a potentially rich area of further study into the way quantum principles work on liquid bodies.

The findings come from the Yale lab of physics and applied physics professor Jack Harris, along with colleagues at the Kastler Brossel Laboratory in France. A study about the research appears in the journal Physical Review Letters.

“We filled a specially designed cavity with superfluid liquid helium,” Harris explained. “Then we use laser light to monitor an individual sound wave in the liquid helium. The volume of helium in which this sound wave lives is fairly large for a macroscopic object — equal to a cube whose sides are one-thousandth of an inch.”

Harris and his team discovered they could detect the sound wave’s quantum properties: its zero-point motion, which is the quantum motion that exists even when the temperature is lowered to absolute zero; and its quantum “back-action,” which is the effect of a detector on the measurement itself.

The co-first authors of the study are Yale postdoctoral fellows Alexey Shkarin and Anya Kashkanova. Additional authors are Charles Brown of Yale and Jakob Reichel, Sébastien Garcia, and Konstantin Ott of the Kastler Brossel Laboratory.

Jim Shelton for Yale News

Retaining non-traditional students in STEM classrooms

“The most important thing is to believe in your students. Once you believe that all students can succeed, and that it is worth your time to help them succeed, everything else is a detail,” said Andrew Houck, professor of electrical engineering and principal investigator in the Houck Lab for Quantum Computing and Condensed Matter Physics with Microwave Photons at Princeton University.

Houck will visit Yale on Thursday, Jan. 31 and Friday, Feb. 1 to present seminars for the Poorvu Center’s Diversity and Education Series and the Quantum Institute’s Colloquium Series. Houck and his colleagues are responsible for redesigning the first-year curriculum at Princeton’s School of Engineering and Applied Science after analyzing the negative impacts of attrition rates of under-represented students in the school.

“There are three reasons I can think of to strive for a more diverse student body,” said Houck. “The first is selfish; I want to see great scientific breakthroughs and engineering innovations in my lifetime. If we are systematically missing out on exceptional people, we are systematically missing out on a huge number of discoveries that could have been. The second is about community; people with different perspectives recognize and approach problems differently, and our community is more robust due to this variety. The third is moral; education is a powerful mechanism for change, and we are participating in an injustice if we are biased in providing access to a high-quality education.”

Working with Houck to organize the visit were Mitchell Smooke, acting dean of the School of Engineering and Applied Science; Steve Girvin, the Eugene Higgins Professor of Physics and professor of applied physics; Florian Carle, manager of the Yale Quantum Institute; and Nancy Niemi, director of faculty teaching initiatives at the Poorvu Center. The collaborative two-day visit is part of the larger Diversity and Educations Series sponsored by the Office of the Provost and the Poorvu Center for Teaching and Learning. Houck’s experience with introducing an alternate path for first-year requirements that teaches the necessary math and physics skills in the context of engineering examples drew the attention of the group.

“Everyone who is capable of benefiting from university education should be able to do so,” said Girvin, who also served as deputy provost for research for 10 years and worked to build a collaborative approach to scientific excellence.

The Poorvu Center seminar, “Improving access with an application-focused approach to engineering requirements,” will focus on the strategies Houck used to improve student retention and student affect. Houck plans to “discuss [Princeton’s] new courses as well as the process of developing and introducing the new curriculum.”

“We aim to work with colleagues from varied disciplines, in part by inviting them to campus to discuss issues of inclusion in curriculum, instruction, and in program development. We learn a great deal from their experiences at other institutions,” said Niemi. “Andrew has helped Princeton improve their Freshman Scholars Institute and the overall curriculum at the School of Engineering and Applied Science by striving for inclusion in the classroom and lab.”

Similar to Princeton’s Freshman Scholars Institute, Yale launched the First-year Scholars program in 2013. FSY is a “summer bridge program for incoming first-years who are the first in their families to attend college, had low-income backgrounds growing up, or otherwise come from segments of the population who might not traditionally have had access to elite institution.” The program has helped the university expand the socio-economic diversity of incoming classes. Current Yale first-years set a record for socio-economic diversity with 20% receiving federal Pell Grants and 18% representing first-generation college students in their families.

“Like all Yale students, First-year Scholars are very bright, but they may not have had the advantages some students had in terms of preparation for college,” said Girvin. “For example, the summer opportunity to strengthen their foundation in mathematics can be crucial to success in the STEM courses at Yale.”

“Summer programs play an important role in increasing retention of non-traditional students; they facilitate the creation of a strong community and prepare students for both the curricular rigor and the everyday rhythm of college life,” said Houck. “But, we have also found that summer programs alone were not sufficient at Princeton, and it took curricular innovation in the academic year to make significant strides in retaining non-traditional students.”

Patrick C. O’Brien for Yale News

YQI is pleased to present to the public programs of high quality and substantial content, inviting them to learn and reflect about this exciting new area of science and technology.

Outreach programs

Artist in Residence Program

Central to our outreach efforts is the Artist-in-Residence Program. Each year, the Institute welcomes an artist for a year-long residency in which they produce quantum science-based artwork and visuals, and participate in a series of public talks to explain their work and the science behind it. One of the goals of this program is to bridge the humanities-science divide. The artists are rigorously selected by YQI Institute Manager Florian Carle based on the quality and presentation of their work, and their background and experiences.

In 2018, we welcomed visual artist Martha Lewis who collaborated with YQI researchers to create several quantum-inspired art pieces. The artworks were featured in a series of public talks relating the work to quantum physics, discussing how to better use colors in scientific publications, and how art can offer ways of looking at problems that are wobbly and uncertain, as an alternative to strict scientific guidelines for testing theories about the universe. The artworks were featured in a series of public talks relating the work to quantum physics and a discussion of how art can offer an alternative lens through which to examine "wobbly and uncertain" scientific problems as opposed to the strict scientific guidelines that are used for testing theories about the universe.
The highlight of the year was the interactive and immersive installation "I'll be your qubit!" where the visitor was invited to experience the world within a quantum circuit, artistically transposed to the human scale.

In 2019, we continued exploring art as a medium to increase our understanding and discourse of quantum physics by welcoming Spencer Topel; a musician and artist working with sound installations, and performances. We proposed an ambitious project: a live concert where Spencer, and two graduate students, Kyle Serniak and Luke Burkhart, "played" sound generated by the operation of quantum computers prototypes cooled to nearly absolute zero, as if they were instruments in an orchestra. This live performance was be the first of its kind, attracting the interest of scientists in the quantum community for the technical challenge, and of the public for the novel soundscape that was produced. Read more about Quantum Sound on page 22.

We continue to collaborate with Martha and Spencer, and are always on the lookout for artists interested in our program. Visit **art.quantuminstitute.yale.edu** for more information.

Public Conversations

Our newest outreach program is public conversations; two or three people chatting on a somewhat general topic that allows the conversation to flow from one idea to another depending on the interest of the participants and of the audience.

The panels consist of a mix of YQI members and non-physicists to reduce jargon and make sure concepts are explained in layman terms. These public conversations are informal events and the audience is encouraged to take part in the conversation by asking questions or sharing ideas and comments.

Events in this series included a conversation between sound artist Spencer Topel & YQI manager Florian Carle on experimental quantum music; a conversation between science writer Philip Ball, and YQI members Steve Girvin and Douglas Stone on quantum weirdness and the second quantum revolution; and a conversation between Law professor Paul Kahn and YQI member Michel Devoret on how to talk about quantum physics to a general audience.

Nontechnical talk Series

Working at the intersection of science and the humanities, YQI organizes non-technical talks to engage the public and try to calm science and, more specifically, quantum physics phobia. These talks seek to communicate the excitement of scientific exploration and educate the audience about the role that science plays in our daily life. At the time of this report, we have organized ten non-technical talks that attracted 644 attendees, indicating a great need for and interest in this type of programming.

The goal of this series is to present a new perspective on quantum physics and science using music, art, dance, crochet, board games, or literature as a conduit to learning about quantum physics, as well as other topics in science, engineering, and mathematics. These events are accessible to a wide audience and have attracted a diverse group including Yale undergrads, professors, staff and their children, as well as high school students and other Greater New Haven residents.

These talks are co-sponsored by **The Franke Program in Science and the Humanities**.

353

attendees to our public events in 2019

Quantum Week at Yale

Spring 2021

Quantum science and engineering is one of five top priority areas identified in the University's Science Strategy Report, recommending to extend the Yale Quantum Institute (YQI) to a university-wide initiative. To celebrate this, YQI has partnered with departments and centers across campus to bring you quantum events all week long to share our excitement for quantum science!

Quantum Week at Yale is created by Florian Carle for the Yale Quantum Institute.

quantum.yale.edu

Understanding Quantum

Understanding the Quantum Information Revolution
@ Linsly-Chittenden Hall

Lab tour lead by WIQI group
@ Becton Center

A Quantum Physicist walks into a bar
@ Gryphon's Pub

Quantum Reads
@ Bass Library

Display on online Resources for quantum research
@ CSSSI Library

Display takeover
@ Ground Café at the CEID

Entrepreneurship

Job Search Strategies for Quantum Careers
@ Office of Careers Strategy

Company Intelligence and Market Research Sources for Quantum
@17 Hillhouse - Library Classroom 07

Quantum Start with Tsai CITY: a creative tensions talk
@ Yale Quantum Institute

Open House
@ Quantum Circuit Inc.

Art & Quantum

Display of a manuscripts and rare books on quantum physics and fundamental physics
@ Beinecke Library

Draw me a quantum computer
@ Yale Quantum Institute

Meeting the universe halfway
@ Center for Collaborative Art and Multimedia

Screening of Coherence
@ Whitney Humanities Center

Superconductive Jewelry Collection
@ Yale Quantum Institute

Quantum and the Arts
@ Robert B. Haas Family Arts Library

For Researchers

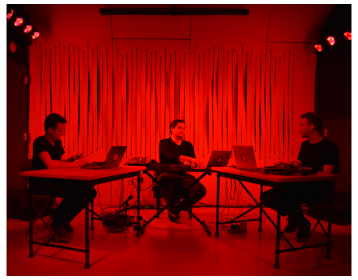
Women in Quantum Information Lunch
@ Yale Quantum Institute

Fundamental science applications of quantum
@ Wright Lab

Physics Open Mic
@ Yale Quantum Institute

Outreach programs

Yale science hits the stage with 'Quantum Sound'



> This all came together because what we're doing with these sounds is so similar to what we do daily in the lab… That's the only way it could ever work.
>
> **KYLE SERNIAK**
> Quantum Researcher

Creative team of Quantum Sound
Performer and composer
Spencer Topel
Performers
Luke Burkhart & **Kyle Serniak**
Producer and light design
Florian Carle

Here's a little-known fact about quantum computing: It sounds remarkably warm.

While much of the focus in quantum research has been on the race to build a useful quantum computer, one that far outstrips the computing power of traditional computers, a contingent from the Yale Quantum Institute (YQI) also has a second quantum endeavor in the works. They're turning their data into an acoustic performance this Friday night, June 14.

"Quantum Sound," part of the International Festival of Arts and Ideas, is set for two sold-out shows at 8 and 10 p.m. at Firehouse 12, on Crown Street. The 10 p.m. show will be broadcast live on WPKN radio. There's also talk of putting out an entire album of quantum sounds.

"We purposely avoided the term 'quantum music,'" said sound artist and composer Spencer Topel, who took on the challenge proposed by YQI manager Florian Carle to play superconducting instruments during a year-long artistic residency at the institute. Topel is a researcher and designer working with acoustics and sound, and his work has appeared in major venues and concert halls around the world, including Lincoln Center and Carnegie Hall.

"We'll be introducing the audience to the quantum systems we use and talk about how they are precursors to quantum computers. These systems generate data that we then use to create sonic signals," Topel said. "We follow this presentation with a 40-minute performance consisting of a controlled improvisation that we composed collaboratively over the last three months or so."

The "we" Topel mentioned are his bandmates — Yale physics graduate students Kyle Serniak and Luke Burkhart. Serniak, a long-time guitarist, came on board after hearing Topel give a presentation about his previous work; Burkhart, who has experience singing in musical theater, joined quickly thereafter.

For the Quantum Sound gig, this intrepid trio will perform the first-ever concert created from the measurements of internal operations of superconducting quantum devices. Their instruments — the superconducting quantum devices — are housed in special refrigerators that Yale researchers use to chill things down to near absolute zero for experiments.

Oh, and the fridges all have nicknames: Audiences may get to hear data coming live from JPC, Blue, or Lazarus.

The students' experiments record electrical signals coming from the fridges, which Topel and his crew have spent months sampling — or as Topel says, "sonifying" them.

This is the crucial component of Quantum Sound, according to Carle, who will be giving the quick primer on quantum computing before the concerts. The team is adamant that the sounds being produced remain faithful to the characteristics of the actual data.

Topel said the concerts will open with sonification of the raw data with minimal processing. He, Burkhart, and Serniak will gradually slow down and mix the live signals to produce an artistic narrative that relates to the way quantum information is stored in qubits — electrical circuits printed on sapphire — deep inside the fridges during experiments.

The range of sounds includes moments of intense noise, intercut by melodies that are by turns diatonic, ominous, or almost imperceptible. Other moments sound reminiscent of winter landscape, populated by winds blowing through a mountain pass and looming storms. At times there's a comforting flutter that brings warmth to the listener. Topel calls this a "wobble," and it is created by the quantum "noise" that exists within the signal.

Understanding the interplay of elements within the fridges is what Quantum Sound, and quantum research, are all about, Serniak explained. "This all came together because what we're doing with these sounds is so similar to what we do daily in the lab," he said. "The parallels are there, so the sounds can be true to the physics. That's the only way it could ever work."

Burkhart had a similar reaction to the project. "When we heard the sounds corresponding to different qubit states, it clicked for me that the project was truly an interpretation of the science through sound," he said.

Still, there is also a performance aspect of Quantum Sound.

At a recent rehearsal in a conference room at the Yale Quantum Institute, Topel, Carle, Serniak, and Burkhart gathered around a white table laden with laptop computers, sound boards, and a whole mess of wires.

"Can you guys send me some test tones?" Topel asked, as they settled into the rehearsal.

Soon they were jamming. Topel orchestrated as they each worked a board. Serniak bobbed his head; so did Burkhart. Topel worked his board with a flourish as if he were playing a Hammond organ.

They stopped after perhaps eight minutes and compared notes. "Hmm. That's great. Let's try it again," Topel suggested. "Remember to punch it in. If there's a section change, you just have to own it."

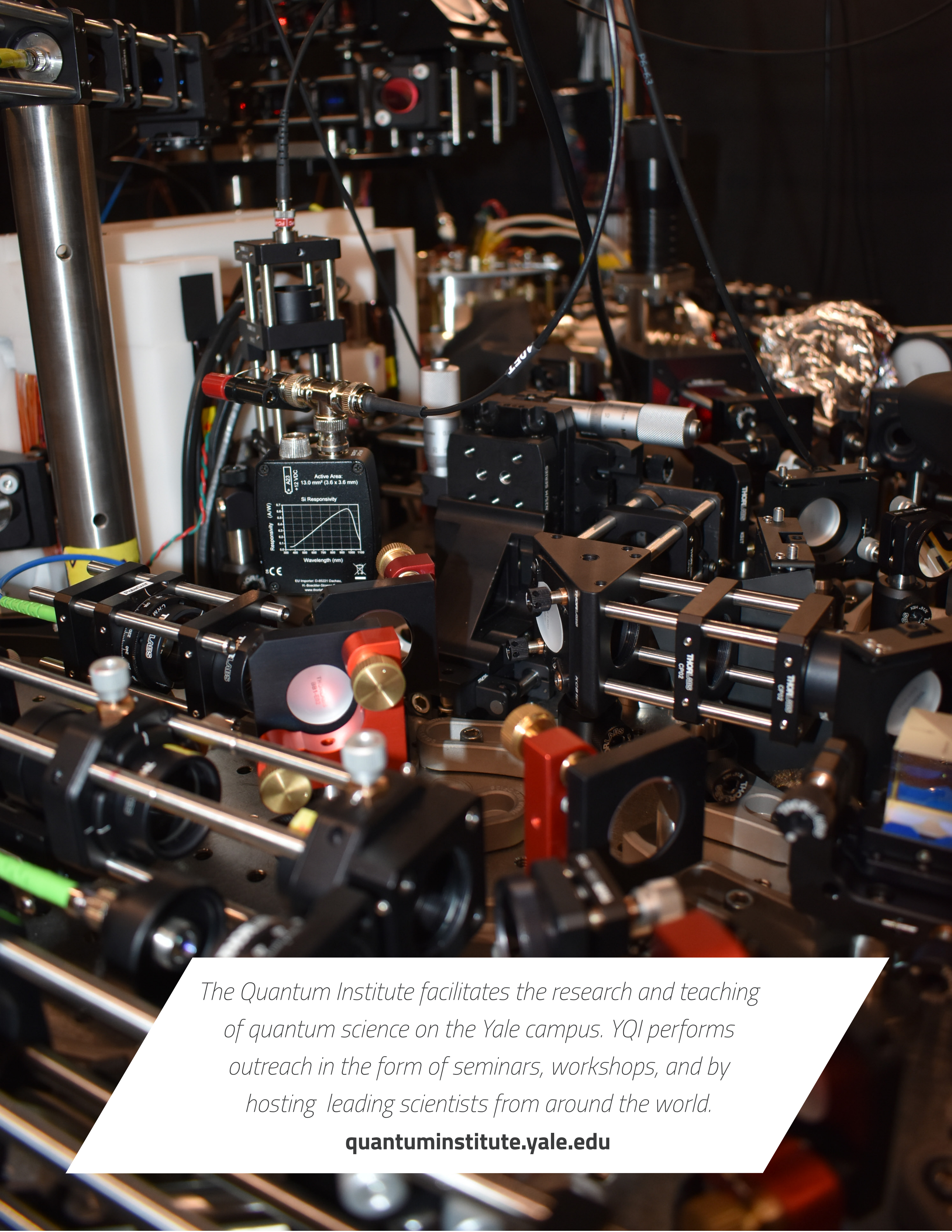
Burkhardt offered an example. "Yes, that's better," Topel said. "Just so it has presence."

They played on for another four hours, experimenting with pitch and determining which riffs make sense, making sure the data is not corrupted with audio artifacts that would have no physical significance in the signal.

"The idea here is seeing if we can use these systems as musical instruments, in order to get at new sounds and behaviors," Topel said.

More details about the science behind the performance and audio clips are available at **art.quantuminstitute.edu**.

Jim Shelton for Yale News



The Quantum Institute facilitates the research and teaching of quantum science on the Yale campus. YQI performs outreach in the form of seminars, workshops, and by hosting leading scientists from around the world.

quantuminstitute.yale.edu