News & Events in Physics

PETER FISHER, SCOTT HUGHES GIVE TALKS TO MIT ALUMNI, PARENTS AND FRIENDS

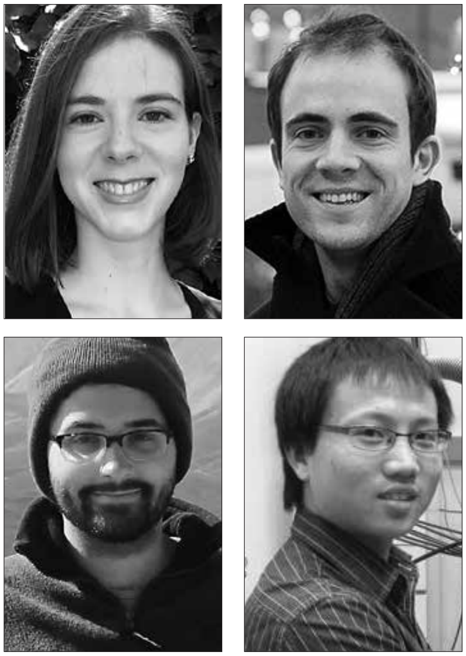
Scott Hughes travels to Palo Alto and London
Professor of Physics **Scott Hughes** gave talks in Palo Alto, CA, and London, UK. He spoke on October 20, 2015, at the Stanford Park Hotel in Palo Alto on "Black Holes and Gravitational Waves: Two Amazing Consequences of Einstein's General Relativity." On May 16, 2016, Scott gave a talk on "Gravitational-Wave Astronomy: Opening Einstein's Ears," in London. His talk described the quest to measure gravitational waves and use them to understand our universe, from the earliest predictions of their existence through indirect confirmation in nature, to the recent discovery of the waves generated by the merger of two black holes.

Peter Fisher travels to China
Physics Department Head **Peter Fisher** gave talks for the MIT clubs in Beijing and Hong Kong on December 10 and 14, 2015, respectively. For both events, the title of his talk was "Big Bangs and Little Bumps: The Story of Dark Matter." Peter gave out "dark matter" boxes that were translated into Chinese. MIT Club of Beijing member **Helene Ponty** and MIT Club of Hong Kong members **Louis Chong** and **Henry Lam** welcomed and introduced Peter. *(E. McGrath)*

2016-2019 PAPPALARDO FELLOWSHIPS IN PHYSICS COMPETITION

The **MIT Pappalardo Fellowships in Physics**, a leading postdoctoral fellowship program of the international physics community, completed its 17th annual competition in January 2016 with the acceptance of four fellows for the 2016-2019 fellowship cycle. Arriving this fall are **Rachel Carr** (experimental nuclear and particle physics), a 2015 PhD from Columbia University; **Richard Fletcher** (atomic physics), a 2016 PhD from the University of Cambridge; **Carl Rodriguez** (theoretical astrophysics), a 2016 PhD from Northwestern University; and **Sanfeng Wu** (experimental condensed matter physics), a 2016 PhD from the University of Washington, Seattle.

Detailed biographies, including research descriptions and selected publications for all Pappalardo Fellows (current and former), are available at *web.mit.edu/physics/research/pappalardo/index.html*. The MIT Pappalardo Fellowships in Physics program was initiated, and is sustained, by funds generously provided by **A. Neil and Jane Pappalardo**. *(C. Breen)*



Clockwise from top left: Rachel Carr, Richard Fletcher, Sanfeng Wu, and Carlos Rodriguez.

Scientists make first direct detection of gravitational waves

By Jennifer Chu, MIT News Office

LIGO signal reveals first observation of two massive black holes colliding, proves Einstein right.

ALMOST 100 YEARS AGO TODAY, Albert Einstein predicted the existence of gravitational waves—ripples in the fabric of space-time that are set off by extremely violent, cosmic cataclysms in the early universe. With his knowledge of the universe and the technology available in 1916, Einstein assumed that such ripples would be "vanishingly small" and nearly impossible to detect. The astronomical discoveries and technological advances over the past century have changed those prospects.

Now for the first time, scientists in the LIGO Scientific Collaboration—with a prominent role played by researchers at MIT and Caltech—have directly observed the ripples of gravitational waves in an instrument on Earth. In so doing, they have again dramatically confirmed Einstein's theory of general relativity and opened up a new way in which to view the universe.

But there's more: The scientists have also decoded the gravitational wave signal and determined its source. According to their calculations, the gravitational wave is the product of a collision between two massive black holes, 1.3 billion light years away—a remarkably extreme event that has not been observed until now.

The researchers detected the signal with the Laser Interferometer Gravitational-wave Observatory (LIGO)—twin detectors carefully constructed to detect incredibly tiny vibrations from passing gravitational waves. Once the researchers obtained a gravitational signal, they converted it into audio waves and listened to the sound of two black holes spiraling together, then merging into a larger single black hole.

"We're actually hearing them go thump in the night," says Matthew Evans, an assistant professor of physics at MIT. "We're getting a signal which arrives at Earth, and we can put it on a speaker, and we can hear these black holes go, 'Whoop.' There's a very visceral connection to this observation. You're really listening to these things which before were somehow fantastic."

After a decades-long quest, The MIT-Caltech collaboration LIGO Laboratories has detected gravitational waves, opening a new era in our exploration of the universe.

By further analyzing the gravitational signal, the team was able to trace the final milliseconds before the black holes collided. They determined that the black holes, 30 times as massive as our sun, circled each other at close to the speed of light before fusing in a collision and giving off an enormous amount of energy equivalent to about three solar masses—according to Einstein's equation $E=mc^2$—in the form of gravitational waves.

"Most of that energy is released in just a few tenths of a second," says Peter Fritschel, LIGO's chief detector scientist and a senior research scientist at MIT's Kavli Institute for Astrophysics and Space Research. "For a very short amount of time, the actual power in gravitational waves was higher than all the light in the visible universe."

These waves then rippled through the universe, effectively warping the fabric of space-time, before passing through Earth more than a billion years later as faint traces of their former, violent origins.

"It's a spectacular signal," says Rainer Weiss, a professor emeritus of physics at MIT. "It's a signal many of us have wanted to observe since the time LIGO was proposed.

MIT LIGO team faculty and senior researchers, left to right: David Shoemaker, Rainer Weiss, Matthew Evans, Erik Katsavounidis, Nergis Mavalvala, and Peter Fritschel.

It shows the dynamics of objects in the strongest gravitational fields imaginable, a domain where Newton's gravity doesn't work at all, and one needs the fully non-linear Einstein field equations to explain the phenomena. The triumph is that the waveform we measure is very well-represented by solutions of these equations. Einstein is right in a regime where his theory has never been tested before."

"Magnificently in alignment"

The first evidence for gravitational waves came in 1974, when physicists Russell Hulse and Joseph Taylor discovered a pair of neutron stars, 21,000 light years from Earth, that seemed to behave in a curious pattern. They deduced that the stars were orbiting each other in such a way that they must be losing energy in the form of gravitational waves—a detection that earned the researchers the Nobel Prize in physics in 1993.

Now LIGO has made the first direct observation of gravitational waves with an instrument on Earth. The researchers detected the gravitational waves on September 14, 2015, at 5:51 a.m. EDT, using the twin LIGO interferometers, located in Livingston, Louisiana and Hanford, Washington.

Each L-shaped interferometer spans 4 kilometers in length and uses laser light split into two beams that travel back and forth through each arm, bouncing between precisely configured mirrors. Each beam monitors the distance between these mirrors, which, according to Einstein's theory, will change infinitesimally when a gravitational wave passes by the instrument.

"You can almost visualize it as if you dropped a rock on the surface of a pond, and the ripple goes out," says Nergis Malvalvala, the Curtis and Kathleen Marble Professor of Astrophysics at MIT. "[It's] something that distorts the space time around it, and that distortion propagates outward and reaches us on Earth, hundreds of millions of years later."

Last March, researchers completed major upgrades to the interferometers, known as Advanced LIGO, increasing the instruments' sensitivity and enabling them to detect a change in the length of each arm, smaller than one-ten-

Photo: Bryce Vickmark

thousandth the diameter of a proton. By September, they were ready to start observing with them.

"The effect we're measuring on Earth is equivalent to measuring the distance to the closest star, Alpha Centauri, to within a few microns," Evans says. "It's a very tough measurement to make. Einstein expected this to never have been pulled off."

Nevertheless, a signal came through. Using Einstein's equations, the team analyzed the signal and determined that it originated from a collision between two massive black holes.

"We thought it was going to be a huge challenge to prove to ourselves and others that the first few signals that we saw were not just flukes and random noise," says David Shoemaker, director of the MIT LIGO Laboratory. "But nature was just unbelievably kind in delivering to us a signal that's very large, extremely easy to understand, and absolutely, magnificently in alignment with Einstein's theory."

For LIGO's hundreds of scientists, this new detection of gravitational waves marks not only a culmination of a decades-long search, but also the beginning of a new way to look at the universe.

"This really opens up a whole new area for astrophysics," Evans says. "We always look to the sky with telescopes and look for electromagnetic radiation like light, radio waves, or X-rays. Now gravitational waves are a completely new way in which we can get to know the universe around us."

Tiny detection, massive payoff

LIGO research is carried out by the LIGO Scientific Collaboration (LSC), a group of some 950 scientists at universities around the United States, including MIT, and in 15 other countries. The LIGO Observatories are operated by MIT and Caltech. The instruments were first explored as a means to detect gravitational waves in the 1970s by Weiss, who along with Kip Thorne and Ronald Drever from Caltech proposed LIGO in the 1980s.

"This has been 20 years of work, and for some of us, even more," Evans says. "It's been a long time working on these detectors, without seeing anything. So it's a real sea change and an interesting psychological change for the whole collaboration."

"The project represents a triumph for federally funded research," says Maria Zuber, vice president for research and E. A. Griswold Professor of Geophysics at MIT. "LIGO is an example of a high-risk, high-return investment in discovery-driven science. In this case the investment was major and sustained over many years, with a successful outcome far from assured. But the scientific payoff is shaping up to be extraordinary. While the discoveries reported here are already magnificent, they represent the tip of the iceberg of what will be learned about fundamental physics and the nature of the universe."

The LIGO Observatories are due for more upgrades in the near future. Currently, the instruments are performing at one-third of their projected sensitivity. Once they are fully optimized, Shoemaker predicts that scientists will be able to detect gravitational waves emanating "from the edge of the universe."

"In a few years, when this is fully commissioned, we should be seeing events from a whole variety of objects: black holes, neutron stars, supernova, as well as things we haven't imagined yet, on the frequency of once a day or once a week, depending on how many surprises are out there." Shoemaker says. "That's our dream, and so far we don't have any reason to know that that's not true."

As for this new gravitational signal, Weiss, who first came up with the rudimentary design for LIGO in the 1970s as part of an experimental exercise for one of his MIT courses, sees the tiny detection as a massive payoff.

"This is the first real evidence that we've seen now of high-gravitational field strengths: monstrous things like stars, moving at the velocity of light, smashing into each other and making the geometry of space-time turn into some sort of washing machine," Weiss says. "And this horrendously strong thing made a very tiny effect in our apparatus, a relative motion of 10 to the minus 18 meters between the mirrors in the interferometer arms. It's sort of unbelievable to think about."

This research was funded by the National Science Foundation.

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11TH ANNUAL PATRONS DINNER

The Department celebrated its 11th annual Patrons of Physics Fellows Dinner on April 8, 2016. Over 80 guests gathered in the Green Center's Pappalardo Room. **Peter Fisher**, Physics Department Head, started the evening with remarks about the Department and how important fellowship support is so we can attract the top students and give them freedom to try different research areas. **Tudor Cristea-Platon**, **2015-2016 Whiteman Fellow**; **Libby Tolman**, **2015-2016 Kurt Forrest Fellow**; and **Michael DeMarco**, **2015-2016 Frank Fellow**, were the student presenters. Patron donor **Tom Frank** concluded the evening with remarks on the importance of fellowships. He also spoke about his background from physics to Wall Street and how he values his MIT education in physics. The annual dinner is a great opportunity for the donors to get to know the students who are supported by fellowships. *(E. McGrath)*

From left: Tom Frank '77, PhD '85; Mark Mueller PhD '78; Paul Swartz '73, PhD '79

Dean Michael Sipser (left) catches up with Sam Gasster '77.

15TH ANNUAL PAPPALARDO FELLOWSHIPS IN PHYSICS SYMPOSIUM

The Department's leading postdoctoral fellowship program, the **Pappalardo Fellowships in Physics**, held its 15th annual symposium at the close of the academic year on May 12, 2016. Five fellows from its roster of gifted young physicists gave carefully crafted mini-lectures to members and friends of the MIT physics community.

Pappalardo Symposium Emcee Peter Fisher.

Deftly emceed by Department Head **Peter Fisher**, the symposium was launched with introductory remarks by Prof. **Jesse Thaler**, a theoretical particle physicist who has actively mentored the Pappalardo Fellows and Department postdocs through his ongoing participation in the weekly and monthly Pappalardo Fellowships events.

Dr. **Or Hen** ("From Nuclei to Neutron Stars: Short-range Fermion Correlations") led the Fellows' talks, followed by Dr. **Itamar Kimchi** ("Many-electron Quantum Entanglement"), Dr. **Taritree Wongjirad** ("From Pixels to Neutrinos in the MicroBooNE Experiment"), Dr. **Benjamin Safdi** ("The Milky Way's Gamma-ray Mystery: Dark Matter or Astrophysical Point Sources?"), and Dr. **Inna Vishik** ("A Picosecond in the Life of a Superconductor").

Joining a full house in the Pappalardo Community Room were program founder and benefactor **A. Neil Pappalardo**, along with his son **Michael**, son-in-law **Todd Lemke**, Department friend, alumnus and Meditech, Inc., CEO **Howard Messing** and his wife **Colleen**; as well as longstanding Department friends and supporters alumni **Curt Marble** and **Mark Mueller**.

Videos of this and prior Pappalardo Fellowships symposia are available online at *web.mit.edu/physics/research/pappalardo/videos.html*. For more information on the Pappalardo Fellowships in Physics program, its Fellows, and founders A. Neil and Jane Pappalardo, please visit *web.mit.edu/physics/research/pappalardo/index.html*. *(C. Breen)*

Department Head Peter Fisher (left) with Colleen and Howard Messing.

Neil Pappalardo (center) with Pappalardo Fellows (from left) Or Hen, Guy Bunin, Benjamin Safdi, Inna Vishik, Taritree Wongjirad and Itamar Kimchi.

Symposium introductory speaker Jesse Thaler (left) getting a few tips from Neil.

Neil checking in with Physics Reading Room Assistant Tan-Quy Tran. "Tran" has supported all Pappalardo Fellowships events since the program's launch in 1999.