The Adolph C. and Mary Sprague

MILLER INSTITUTE

for Basic Research in Science

Newsletter
Winter 2017

Ultrafast Manipulation of Materials

Miller Fellow Focus: Cassandra R. Hunt

The fundamental particles that act as the building blocks of the universe are codified in The Standard Model, a sort of periodic table for particle physics. But most objects that are well-described as particles do not claim membership to this exclusive club. An atomic nucleus consists of protons and neutrons, which are actually composite particles made up of quarks and force-mediating gluons that bind them. In materials, collective interactions give rise to new "quasiparticles" which also behave like individual particles in their own right, but with different properties than the fundamental particles that comprise them. Electrons interacting with each other and the surrounding crystal lattice, for example, can appear to weigh more that the bare electron mass, or even appear massless. The coherent, quantized vibrations of atoms in a crystal lattice behave as a bosonic particle, dubbed a "phonon" in analogy with the photon, the particle of light.

A cornerstone of my field, condensed matter physics, is the study of "emergent phenomena": behavior due to the collective interactions of many objects which is distinct from the behavior of the underlying constituents. The idea of emergence applies across many scientific disciplines—the behavior of an ant colony, for instance, would not be predictable from studying a single ant in isolation. Nor the brain from studying a single neuron. In materials, quasiparticle states can be emergent; the fractional quantum

Hall effect is a dramatic example, where electron-like quasiparticles interacting with an external magnetic field behave as though they have just a fraction of an electron charge. Phases of matter can also be the product of emergent behavior. Superconductivity, discussed below, for instance. Or spatially organized states such as charge density waves, where electrons form extended patterns of alternating high and low density. My research utilizes ultrafast laser techniques to study complex and emergent phenomena in materials, with two goals in mind. First, to understand how these states form, and second, to control material behavior with light. Ultrafast manipulation of materials is therefore interesting from a basic research perspective, but also potentially useful for technological applications.

The fundamental timescale which governs quasiparticle and lattice motion is the femtosecond (fs) to picosecond (ps) regime. To give a sense of this scale, light takes about 300 fs to travel the diameter of a human hair. This is far faster than modern electronic devices, which operate in the several GHz (>100 ps) range. Ultrafast lasers, which output pulses of light with <100 fs duration, are uniquely capable of offering a direct, time-resolved glimpse into material behavior. Experiments are typically arranged in a pump-probe scheme: one or more pulses of light are used to excite ("pump") the system, then another pulse or set of pulses measure ("probe") the light-induced state. By repeating this procedure, varying the arrival time between pump and probe, a full "movie" of the system dynamics can be captured, as illustrated in **Figure 1**.

CONTINUED ON PAGE 2 >

Inside this edition:

"It is a joy to interact with the Institute's Fellows, a most brilliant, enthusiastic and diverse group, destined to be the future leaders of science."

- **David Chandler**, *Theoretical Chemist & Physicist, University of California Berkeley, 2016 Miller Senior Fellow, Miller Professor Fall 1991, 1999-2000, National Academy of Sciences.*

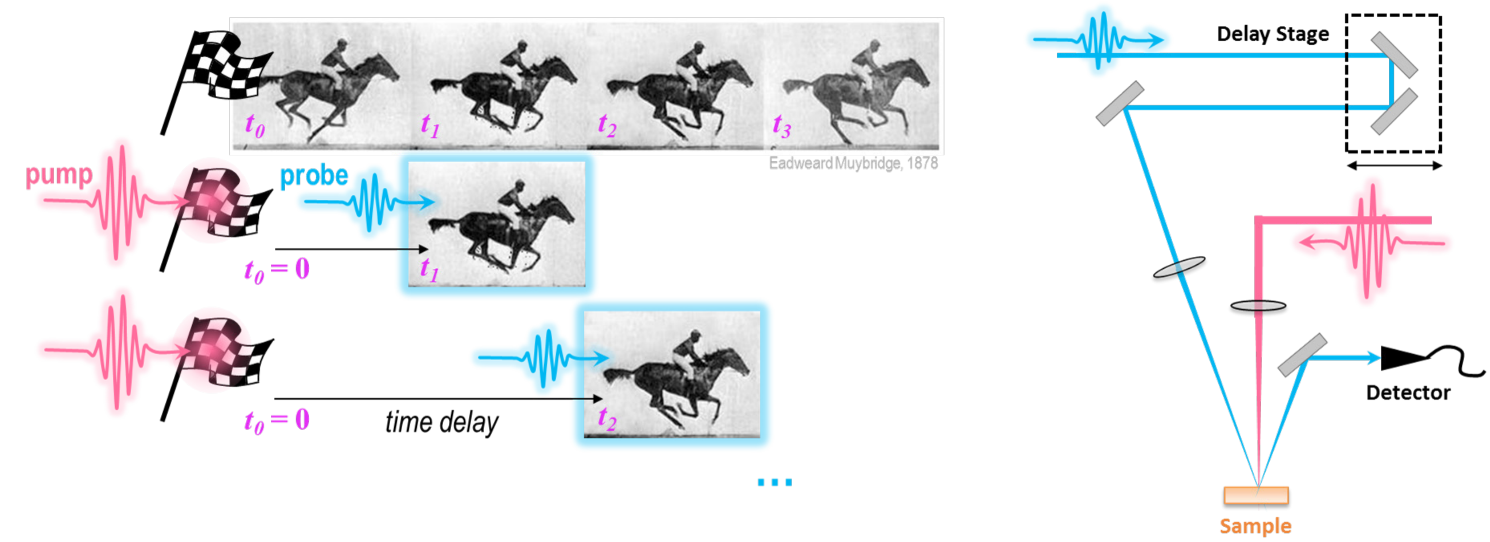

Figure 1. Left: A photo series of a galloping horse and rider, taken in the late 1870's by Eadweard Muybridge, is partially shown above. These photos definitively answered the question of whether all four of a horse's legs left the ground during a gallop. Muybridge captured the horse's motion using a series of cameras in a line that each snapped a shot as the horse rode by. Ultrafast pump-probe measurements capture material dynamics using a different scheme: the system is "pumped" (the horse is set in motion) and the dynamics are "probed" (a single photo is taken) repeatedly, changing the time delay between excitation and probe. This method captures dynamics that happen much faster than modern electronics could record them. **Right:** A basic schematic of a two pulse pump-probe optical set-up. The delay stage changes the path length the probe pulse travels with respect to the pump, setting the time delay between the arrival of each pulse on the sample.

Femtosecond pulse technology advanced rapidly in the 1990's with the development of the self-mode-locking Ti-doped sapphire solid state laser. With a central frequency output in the near-infrared (eV)—higher than the meV energy scale which governs emergent phenomena in many unconventional materials—pulses could be directly utilized to disrupt a system and probe the relaxation dynamics to gain new insight into the equilibrium states from which they arose. In the last few years, attention has begun to shift towards tailoring light excitation. By selecting the appropriate pump pulse parameters—including polarization, duration, intensity, and especially wavelength - a specific material interaction pathway can be targeted while minimizing other unwanted excitations, such as quasiparticle heating. Wavelength selection is achieved by nonlinear light mixing techniques, which though inefficient, can still produce intense, narrowband pulses over a wide frequency range thanks to the large pulse energy capabilities of Ti:Sapphire lasers.

My Ph.D. work showed how light tailored to excite certain phonon modes can support and enhance superconductivity in a group of high-temperature superconductors called cuprates. A superconductor is characterized by two unusual properties: a zero dc resistance state and the "Meissner effect," in which an externally applied magnetic field is expelled from the material on entering the superconducting state. These properties have already been put to use to make powerful electromagnets: for maglev trains, in MRI machines at hospitals, and to steer particle accelerators. Superconductors also make sensitive magnetometers, and show promise in the development of quantum computers and low loss power cables. But superconductors only function at cryogenic temperatures—even so-called "high temperature" superconductors have a superconducting transition temperature, T_c, just above the liquid nitrogen boiling point. Their unique properties arise from a macroscopic realization of quantum physics: a quantum mechanically "coherent" state made up of electrons that pair together to form a quasiparticle called a Cooper pair. Above T_c, the pairs lose their coherence and break apart. For many superconductors, normally repulsively-interacting electrons feel an attraction due to their interaction with the lattice: phonons act as a binding glue that overcomes Coulomb repulsion. In cuprates and other high-temperature superconductors, however, this interaction alone is not strong enough to explain the formation of pairs. The "pairing glue" of cuprates remains unclear, over 30 years after their discovery.

One pathway to understanding the pairing mechanism, and the development of even higher T_c materials, may be to clarify how superconductivity is favored or suppressed by other energetically similar phases. The superconducting regime in cuprates is sensitive to the crystal lattice: small changes in applied pressure, strain or chemical doping can affect T_c, tipping the balance between neighboring spin and charge phases. Using light, we can manipulate the lattice to selectively target electronic phases. Resonant phonon excitation involves triggering lattice motion by pumping with light tuned to the frequency of an infrared-active phonon mode and polarized along the direction of lattice motion.

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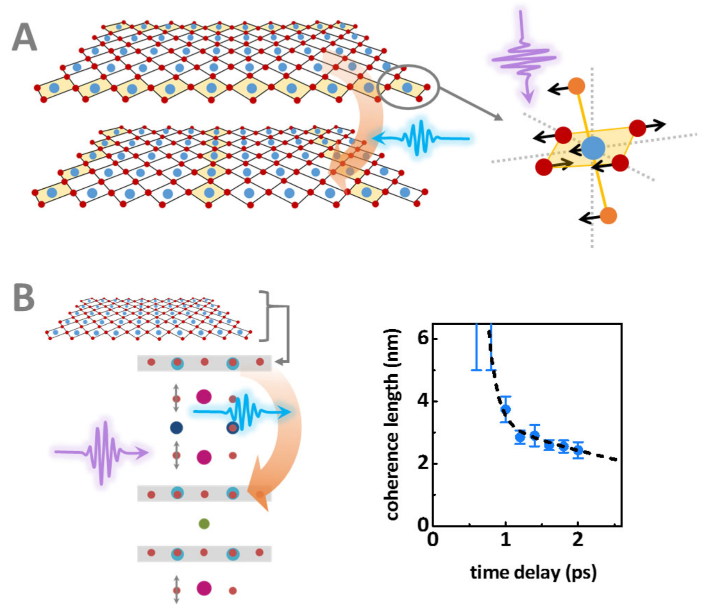

Figure 2. (A) Left: The CuO_2 planes of $La_{1.625}Eu_{0.2}Sr_{0.125}CuO_4$, where charge stripe order (yellow) and superconductivity develop. We probed coherent, superconducting transport between these planes (orange arrow) using time-domain THz spectroscopy. **Right:** The resonant motion of Cu (blue) and O (red/orange) atoms after phonon excitation. **(B) Left**: The $YBa_2Cu_3O_{6.5}$ lattice, which has two CuO_2 planes per unit cell. Arrows depict the resonant O atom motion. **Right:** The coherence length-scale decays with delay time after excitation. The lattice unit cell length is 1.17 nm.

In a lanthanide cuprate $La_{1.625}Eu_{0.2}Sr_{0.125}CuO_4$, a spatial charge stripe order that is supported by the lattice spacing destroys superconductivity. Resonantly driving a Cu-O stretching mode (**Figure 2A**) disrupts the charge ordering and restores superconductivity up to the charge ordering temperature, which is higher than the equilibrium T_c in any related lanthanide superconductor. In another cuprate family, $YBa_2Cu_3O_x$, we resonantly drove oxygen atoms (**Figure 2B**) whose position in the lattice has been shown by pressure and chemical doping studies to be related to T_c. The excitation enhances superconductivity below T_c and, remarkably, appears to induce a superconducting-like state that survives for a few picoseconds even far above T_c (up to room temperature for some compounds). The time evolution shows a relaxation driven by a loss in coherence, offering further support that the light-induced state above T_c involves superconducting pairs, as discussed in our paper published this month in *Physical Review B.* Critical to both these experiments is the ability to drive the materials with high intensity (μJ/pulse) light at a tailored wavelength and polarization. The meV-energy scale of the phonon modes ensures that the light excitation does not break Cooper pairs.

Now at Berkeley, I am working in the lab of Alessandra Lanzara, designing and developing a state-of-the-art system to combine high pulse intensity, tunable wavelength light excitation with angle-resolved photoemission spectroscopy (ARPES). ARPES is a key technique for probing the electronic behavior of materials. The allowed energy states of electrons in a crystal form "bands" as a function of electron momentum. ARPES probes this band structure via the photoelectric effect, illustrated in **Figure 3,** where ultraviolet (UV) light frees electrons from a sample and the angle and energy of a photoemitted electron is mapped to its momentum and energy in the material (ie, the band it originated from).

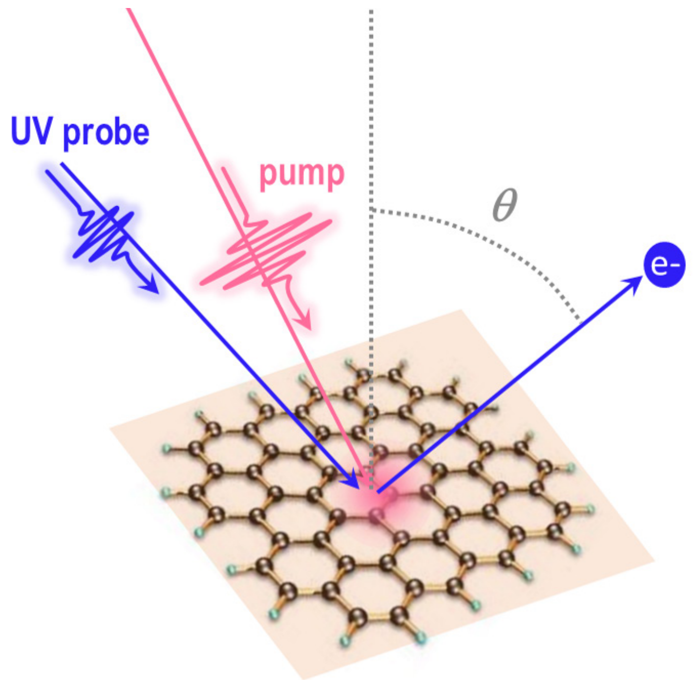

Figure 3. An illustration of pump-probe ARPES, where a sample surface is first pumped with a light pulse, then a UV light probe is used to generate photoemission.

Light has been harnessed to dramatically switch electronic, spin, and lattice behavior in less than a picosecond. Light can also generate states that are fundamentally non-equilibrium, either because they require a driving field, or because they arise from light-matter interactions that cannot be readily duplicated by equilibrium methods. Manipulating superconductivity with resonant phonon pumping is just one example. I am interested in using time-resolved ARPES to manipulate materials with topological band structure, which are intriguing both fundamentally - they host novel quantum states and display some analogues with particle physics phenomena - and for their possible use in spintronic devices. I am also designing experiments to use tailored excitation to understand light-matter interaction in promising candidate materials for next-generation solar cells. Targeted light excitation is a technique still in its nascency and the potential applications for material

CONTINUED ON PAGE 6 >

Miller Institute Announces 2017 Miller Senior Fellowships

The Miller Institute is pleased to announce three new Miller Senior Fellows to join Barbara Meyer and David Chandler. Jennifer Doudna, Alex Filippenko and Christos Papadimitriou will join the Institute in 2017.

The Miller Senior Fellowship program was started in 2008 to recognize the special achievements of an elite subset of the Berkeley faculty, and to create an environment in which the Miller Fellows would benefit from the opportunity for informal interactions with the Senior Fellows. These informal relationships allow the Miller Fellows to gain the kind of perspective seldom available to scientists at the postdoctoral stage of their career.

"I fully support The Miller Institute's commitment to basic research in science. Throughout my career I have focused on the process of discovery and a desire to understand the world. I look forward to collaborating with the other Fellows to exchange ideas and approaches that will allow us to advance vital scientific research."

Jennifer Doudna is a Professor of Chemistry and of Molecular & Cell Biology, a member of the Howard Hughes Medical Institute and the Lawrence Berkeley National Lab. She joined the faculty of UC Berkeley in 2002, the same year she was elected to the National Academy of Sciences. She received her Ph.D. in 1989 at Harvard University with Dr. Jack Szostak. Doudna has been awarded Canada's Gairdner Award for Research on CRISPR, a Breakthrough Prize in Life Sciences, the Gruber Prize in Genetics, the Dr. Paul Janssen Award for Biomedical Research, the Lurie Prize in Biomedical Sciences, and the Eli Lily Award in Biological Chemistry among many others.

Doudna's research focuses on determining the molecular structures of RNA molecules as a basis for understanding their biological function. Her work lays the foundation for understanding the evolution of RNAs and their relationship to the molecules that played a role in early forms of life. Her work is cited so often that The Intellectual Property and Science division of Thomson Reuters named her as a citation laureate for her development of the CRISPR-Cas9 genome-editing method. She will join the Institute in July 2017.

Alex Filippenko is the Richard and Rhoda Goldman Distinguished Professor in the Physical Sciences. His accomplishments, documented in more than 850 research papers, have been recognized by several major prizes, including a share of both the Gruber Cosmology Prize (2007) and the Breakthrough Prize in Fundamental Physics (2015). One of the world's most highly cited astronomers, he is an elected member of the National Academy of Sciences (2009) and the American Academy of Arts and Sciences (2015). He has won the most prestigious teaching awards at UC Berkeley and has also been voted the "Best Professor" on campus a record 9 times. Filippenko was a Miller Research Fellow from 1984-86, and a Miller Professor in both 1996 and 2005.

Filippenko and his collaborators are determining the nature of the progenitor stars and the explosion mechanisms of different types of supernovae and gamma-ray bursts. He is also using supernovae as cosmological distance indicators, and he was a member of both teams that discovered (in 1998) the accelerating expansion of the Universe, probably driven by "dark energy" - a discovery that was honored with the 2011 Nobel Prize in Physics to the teams' leaders. He also works on quantifying the physical properties of quasars and active galaxies, and he searches for black holes in both X-ray binary stars and nearby galactic nuclei. Filippenko will join the Institute in January 2017.

"The Miller Institute provides an amazing opportunity for cross-fertilization as passionate scholars in different disciplines share their ideas with each other."

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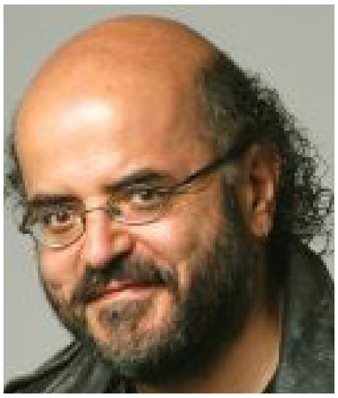

Christos Papadimitriou is the C. Lester Hogan Professor of Electrical Engineering and Computer Science. He received his Ph.D. from Princeton University in 1976 and was awarded a Miller Research Fellowship in 1978-79. He taught at Harvard, MIT, the National Technical University of Athens, Stanford and UCSD before returning to Berkeley in 1996. He is a member of the National Academy of Sciences, a Fellow of the Association for Computing Machinery and the National Academy of Engineering. His awards include the IEEE John von Neumann Medal, the EATCS Award, the Godel Prize and the Knuth Prize. He also held a Miller Professorship in 2005. He will start his Senior Fellowship in January 2017.

Papadimitriou is interested in the theory of algorithms and complexity, and its applications to optimization, control systems, databases, AI, the Internet, game theory, evolution, and the brain. In addition to his prolific academic writings, he is also the author of three novels, including the graphic novel "Logicomix".

On life at Berkeley, Papadimitriou was once quoted saying, "There is a very aggressive form of academic freedom at Berkeley. I first visited as a Miller Fellow in 1978, and it gave me a feeling of extreme freedom: If it feels good intellectually, then you must do it! And do it with passion."

Miller Research Professorship & Visiting Professorship Awards

On December 5, 2016, the Advisory Board of the Miller Institute met to select next year's Professorship awards. The Board is comprised of four advisors external to UCB: Roger Blandford (Stanford University), David Botstein (CALICO), Yun Song (University of Pennsylvania) and Steven Block (Stanford University); and four internal Executive Committee members: Executive Director Jasper Rine (Genetics and Developmental Biology), Stephen Leone (Chemistry/Physics), Roland Bürgmann (Earth & Planetary Science) and Craig Evans (Mathematics). The Board is chaired by Chancellor Nicholas Dirks.

The Miller Institute is proud to announce the awards for Professorship terms during the Academic Year 2017-2018. These outstanding scientists pursue their research, following promising leads as they develop. The Visiting Miller Professors join faculty hosts on the Berkeley campus for collaborative research interactions.

Ronald Amundson, Miller Professorship, UC Berkeley Department of Environmental Science, Policy, and Management.

Naomi Ginsberg, Miller Professorship, UC Berkeley Departments of Chemistry / Physics.

Thomas Griffiths, Miller Professorship, UC Berkeley Department of Psychology.

Michael Jordan, Miller Professorship, UC Berkeley Departments of Statistics / EECS.

Richmond Sarpong, Miller Professorship, UC Berkeley Department of Chemistry .

Joss Bland-Hawthorn, Visiting Miller Professor in the Dept. of Astronomy . Host: Christopher McKee. Home institution: University of Sydney.

Joel Blum, Visiting Miller Professor in the Dept. of Earth & Planetary Science. Host: Donald DePaolo. Home institution: University of Michigan.

Peter Bühlmann, Visiting Miller Professor in the Dept. of Statistics. Host: Peter Bickel. Home institution: ETH Zurich, Switzerland.

Sylvie Corteel, Visiting Miller Professor in the Dept. of Mathematics. Host: Lauren Williams. Home institution: Universite Paris.

Laurent Excoffier, Visiting Miller Professor in the Dept. of Integrative Biology. Host: Montgomery Slatkin. Home institution: University of Bern, Switzerland.

Shana Kelley, Somorjai Visiting Miller Professor in the Dept. of Chemistry. Host: Christopher Chang. Home institution: University of Toronto.

Mohamed Noor, Visiting Miller Professor in the Dept. of Integrative Biology. Host: Michael Nachman. Home institution: Duke University.

Thomas Pollard, Visiting Miller Professor in the Dept. of Molecular & Cell Biology. Host: David Drubin. Home institution: Yale University.

Talat Rahman, Visiting Miller Professor in the Dept. of Physics. Host: Steven Louie. Home institution: University of Central Florida.

Edward H. Sargent, Somorjai Visiting Miller Professor in the Dept. of Chemistry. Host: Peidong Yang. Home institution: University of Toronto.

Mark Thiemens, Visiting Miller Professor in the Dept. of Chemistry. Host: Kristie Boering. Home institution: UC San Diego.

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control are only beginning to be explored. This is a thrilling time to be at Berkeley as a Miller Fellow and I am excited to continue contributing to this rapidly growing field.

Cassandra Hunt originally hails from the suburbs of St. Louis, Missouri. She completed her B.S. in physics at the Massachusetts Institute of Technology (MIT) and her Ph.D. in condensed matter physics at the University of Illinois at Urbana-Champaign (UIUC) under the supervision of Laura Greene. During her Ph.D., she spent four years in Hamburg, Germany, working at the Max Planck Institute for the Structure and Dynamics of Matter in the lab of Andrea Cavalleri. In her free time, Cassi enjoys running in the hills of Tilden Park, cheesy movies, and volunteering for youth science outreach.

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Fall Reception 2016

In the News

(see more past & current Miller Institute News: miller.berkeley.edu/news)

Jiaxing Huang (Miller Fellow 2004 - 2007) has been elected a recipient of **Humboldt Research Award** in recognition of lifetime achievements in materials chemistry, processing and manufacturing.

David Milstein (Visiting Miller Professor 2006) has been awarded the prestigious **2016 Eni Award** for his research into innovative, efficient and environmentally-compatible catalytic reactions.

Gabor Somorjai (Miller Professor 1977 - 1978, Miller Senior Fellow 2009 - 2014) wins prestigious **2016 Richards Medal**.

Three former Miller members among **2016 AAAS** Fellows:

- **Mary Kay Gaillard** (Miller Professor 1987 - 1988, 1996) recognized for her scientifically distinguished achievements in particle physics.
- **Jonathan Feng** (Miller Fellow 1995 - 1997) honored for his contributions in theoretical particle physics, astroparticle physics, and cosmology.
- **Mark Kirkpatrick** (Miller Fellow 1983 -1985, Visiting Miller Professor 2009) recognized for his scientific achievements in biological sciences.

Gibor Basri (Miller Professor 1997 - 1998) wins **Sagan Prize.** Astronomer honored for contributions to his field.

Stephen Leone (Visiting Miller Professor 1990, Miller Professor 2010, Advisory Board Member 2015 - Current) has received the **2017 ACS Ahmed Zewail Award** in Ultrafast Science and Technology.

Thi (Kelly) Nguyen (Miller Fellow 2016 - 2019) has been recognized with two Early Career Awards: **The Genes Early Career Research Award** & **The 2016 RNA Society Scaringe Young Scientist Award.**

Three former Miller members share **$1.7 Million from the Federal Government's BRAIN Initiative:**

- **Marla Feller** (Miller Fellow 1994 - 1996) - to develop a high-speed volumetric multiphoton microscope for the study of developing neural circuits in the retina.
- **Mikhail Shapiro** (Miller Fellow 2011 - 2013) - to study molecular functional ultrasound for non-invasive imaging and image-guided recording and modulation of neural activity.
- **Ehud Isacoff** (Miller Professor 2013) - to develop novel tools for cell-specific imaging of functional connectivity and circuit operations.

Marvin Cohen (Miller Professor 1969 - 1970, 1976 - 1977, 1988) has been awarded the **2017 Franklin Medal** "for making possible atomic-scale calculations of the properties of materials so detailed that new materials and their mechanical, thermal, electrical and optical properties can be predicted in agreement with experiments."

Sarah Keller (Somorjai Visiting Miller Professor 2016) has been awarded the **2017 Avanti Award** from the Biophysical Society for "outstanding contributions to our understanding of lipid biophysics."

Richard Henderson (Visiting Miller Professor 1993) is awarded the **Copley Medal 2016** in recognition of his fundamental and revolutionary contributions to the development of electron microscopy of biological materials.

Gifts to the Miller Institute

The Miller Institute gratefully acknowledges the following contributors to the Miller Institute programs in 2016. These generous donations help support the Miller Research Fellowship program, the general programs of the Institute, and the Gabor A. and Judith K. Somorjai Visiting Miller Professorship Award (SVMP). (*= 5 years of giving)

Make A Gift

Donations can be made by going to:
Give to CAL for the Miller Institute
miller.berkeley.edu/gift

Gold Circle ($10,000 and above)

Ian Agol & Michelle McGuinness

Patrons of the Miller Knot ($5000 - $9999)

Anonymous: "In honor of Vincent Racaniello, Ph.D., Virologist. Though probably having no direct connection to UC Berkeley, through his podcasts showed me the importance of Basic Science Research funding."
*Jasper Rine

Leadership Circle ($2500 - $4999)

Barbara Meyer (The Byron R. Meyer Living Trust)

Director's Circle ($1000 - $2499)

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Fall Dinner 2016

Birth Announcements

Nicholas Piro (Miller Fellow 2009-2012) & his wife Christine welcomed their second son, Oliver Nicholas Piro, born May 2016.

Greg Bowman (Miller Fellow 2011-2014) & his wife Angela welcomed their daughter, Claire Aislong Bowman, born August 2016.

August Johansson (Miller Fellow 2010-2013) & his wife Miriam Kjellgren announced the birth of their son, Ivo Alexander Tage, born August 2016.

Jason Stajich (Miller Fellow 2006-2009) & his wife Amy Steelman announced the birth of their daughter, Lucy, born September 2016.

Gokhan Barin (Miller Fellow 2013-2016) & his wife Ebru Unel-Barin announced the birth of their daughter, Beren, born November 2016.

Ray Jayawardhana (Miller Fellow 2000-2002) & his wife Kathryn Simms announced the birth of their son, Tehan Jayawardhana, born November 2016.

The Miller Institute is "dedicated to the encouragement of creative thought and the conduct of research and investigation in the field of pure science and investigation in the field of applied science in so far as such research and investigation are deemed by the Advisory Board to offer a promising approach to fundamental problems."

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