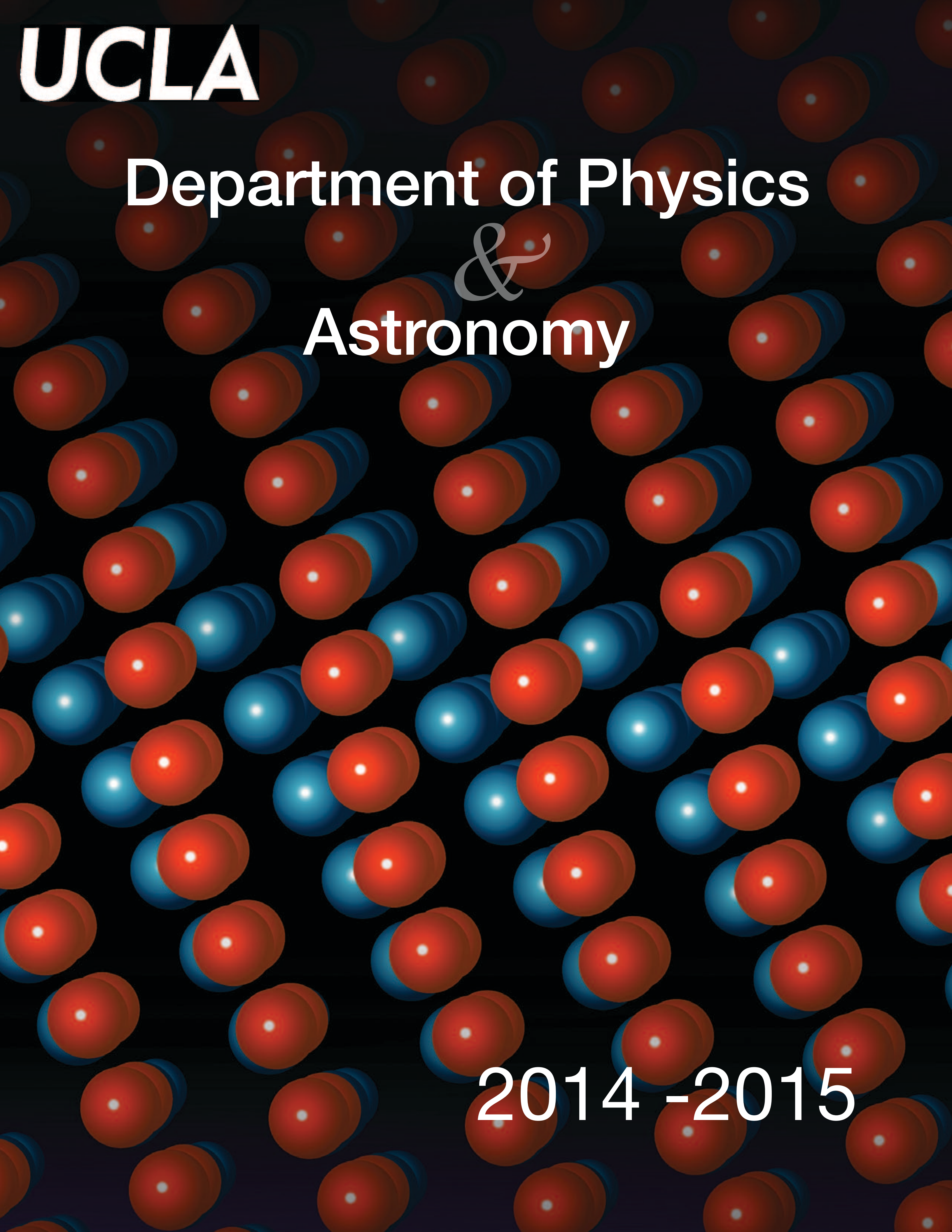
UCLA

# Department of Physics & Astronomy



2014 -2015

UCLA Physics and Astronomy Department
2015
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*Jean Turner*

Chief Administrative Officer
*Will Spencer*

Feature Article
*Jianwei (John) Miao*
*Pietro Musumeci*
*Chris Regan*

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# DEPARTMENT OF PHYSICS & ASTRONOMY

# 2014 - 2015 Annual Report

University of California, Los Angeles

# CHAIR'S MESSAGE

Jean Turner,
Chair

It is my pleasure as Chair to present the 2014-15 Annual Report of the UCLA Department of Physics and Astronomy. With over 60 faculty members and now with more than 700 graduate students and majors, the Department is an active, vibrant research environment. With this report, we aim to communicate some of the news and accomplishments of faculty, staff, and students of the Department during the past year.

One of the highlights of the year was the announcement that our colleague Claudio Pellegrini, Distinguished Professor Emeritus, was named the 2015 recipient of the Enrico Fermi Presidential Award. This award, consisting of a medal and honorarium awarded by the Department of Energy, and is one of the government's oldest and most prestigious awards for scientific achievement. Claudio founded the accelerator effort at UCLA nearly twenty years ago; this highly successful group now includes former chair James Rosenzweig and Pietro Musumeci.

We are delighted to note the approval by University of California President Janet Napolitano of the Mani L. Bhaumik Presidential Endowed Chair in Theoretical Physics. This term chair, made possible by the generosity of Mani Bhaumik, enables the recruitment of talented young theorists to the Department with the promise of support for their research during the early career period.

In other news we are pleased to report a number of prizes, awards, and fellowships received by our faculty this year. Andrea Ghez was awarded the Bakerian Medal of the Royal Society, which she received in London in October 2015. Smadar Naoz was awarded the Annie Jump Cannon Award, given annually by the American Astronomical Society in recognition of outstanding research by a young female astronomer. Smadar was also awarded a Sloan Fellowship. Wes Campbell and Rahul Roy received NSF CAREER awards for early career research. Michael Gutperle and Steve Furlanetto were awarded Simons Fellowships in Theoretical Physics.

The Division of Astronomy and Astrophysics marked two major milestones this academic year. The Galactic Center Board of Advisors held a kickoff dinner for the campaign for the UCLA Galactic Center Group, led by Andrea Ghez. Planning for accommodation of the expanding group within the Department is ongoing, and parallels efforts to support development for the Keck Observatory and the new Thirty Meter Telescope. The second milestone event occurred in June, when the Infrared Laboratory marked its 25th anniversary. The commemoration of this event, and the birthday of its Director, Ian McLean, took place at the faculty center over two days. Visitors and friends had the opportunity both to see the laboratories and to celebrate the Infrared Lab's instruments, including instruments at Keck and on the SOFIA airborne observatory, which have enabled major scientific discoveries.

The Department lost two faculty members in 2015, David Cline and Byron Wright. David Cline, a member of the Experimental Elementary Particle group, was influential in steering the Department toward its successful efforts in accelerator physics and astroparticle physics and supported the Infrared Laboratory. Byron Terry Wright, who contributed to the Manhattan Project and did early work at CERN, helped design the modern upper division laboratories in the Department that have become so integral to our undergraduate program, and also served as Associate Dean of the Graduate Division. Memorials to both David and Byron are included in this report.

Two new faculty members are joining the Department in 2015-16. Paul Hamilton is the newest member of the Atomic, Molecular, and Optical (AMO) Physics group. Paul comes to UCLA from a postdoctoral fellowship at Berkeley. He uses atom interferometry to make precision measurements of fundamental physical quantities and with these methods has put significant constraints on the properties of a dark matter candidate. Shenshen Wang joins the Biophysics/Soft Condensed Matter area in January 2016. Shenshen comes to us from a postdoctoral fellowship at MIT, where she has worked on applying condensed matter techniques to immunology, with specific applications to the delivery methods for AIDS drugs. We are excited to have these very talented young physicists joining our ranks.

Another enterprise of which we are extraordinarily proud is the annual Exploring Your Universe (EYU) outreach event. Founded and run by the graduate students of Astronomy and Astrophysics, this event has grown to encompass all of the sciences. EYU is a day of demonstrations, hands-on activities, and lectures, centered around the Court of Science, with focus on science for the community, for families and children. In 2014 EYU had a record attendance of more than 5500 participants. We hope for even greater numbers of attendees this November.

I close this message with an expression of appreciation to all of our alumni and supporters. We are enormously grateful to you for your continued interest in the Department and its work, and we welcome our alumni to visit us on campus. We especially appreciate the generosity of those who are able to give back, whether they are in the form of contributions to the Chair's discretionary fund, or for support student groups and undergraduate research, or for gifts targeted to a specific purpose. We value your ongoing partnership as we can continue to explore the frontiers of human understanding, to disseminate our findings to the community, and to educate the future scientific leaders of our society.

Ian McLean
Vice Chair Astronomy

# NEW FRONTIERS IN ELECTRON AND X-RAY IMAGING

*Recent years have witnessed a revolution in the development of ground-breaking electron and X-ray imaging methodologies, enabling cutting-edge research across several disciplines. UCLA physicists are at the frontiers of this imaging revolution.*

## Atomic Resolution Electron Tomography

In his famous "There's plenty of room at the bottom" lecture in 1959, Richard Feynman challenged the physical science community saying "It would be very easy to make an analysis of any complicated chemical substance; all one would have to do would be to look at it and see where the atoms are… I put this out as a challenge: Is there no way to make the electron microscope more powerful?" More than 50 years later, UCLA physicists made a breakthrough to address Feynman's challenge. In 2012, Jianwei (John) Miao and collaborators demonstrated for the first time electron tomography at 2.4 Å resolution using Au nanoparticle (Fig. 1a). Individual atoms were observed inside the nanoparticle and several 3D grains were identified at atomic scale resolution. This work was published in Nature and a Science online news article wrote, "Superman has nothing on Jianwei Miao, at least in the vision department."

After this ground-breaking work, Miao and co-workers applied this 3D imaging method to observe nearly all the atoms in a Pt nanoparticle and image the 3D core structure of edge and screw dislocations at atomic resolution (Fig. 1b). This work was again published in Nature, accompanied by a New and View article.

**Nature** produced a video featuring the paper by Miao and co-workers, which has been viewed over 900,000 times on **YouTube. (www.youtube.com watch?v=yqLlgIaz1L0).**

More recently, Miao and collaborators reported, for the first time, the determination of the 3D coordinates of thousands of individual atoms and a point defect in a material with a precision of ~19 picometer, where the crystallinity of the sample is not assumed. From the coordinates of these individual atoms, they measured the atomic displacement field and the full strain tensor with a 3D resolution of 1 nm and a precision of 10-3, which was published in Nature Materials. The ability to precisely localize the 3D coordinates of individual atoms in materials without assuming crystallinity will find important applications in materials science, nanoscience, physics, chemistry and biology.

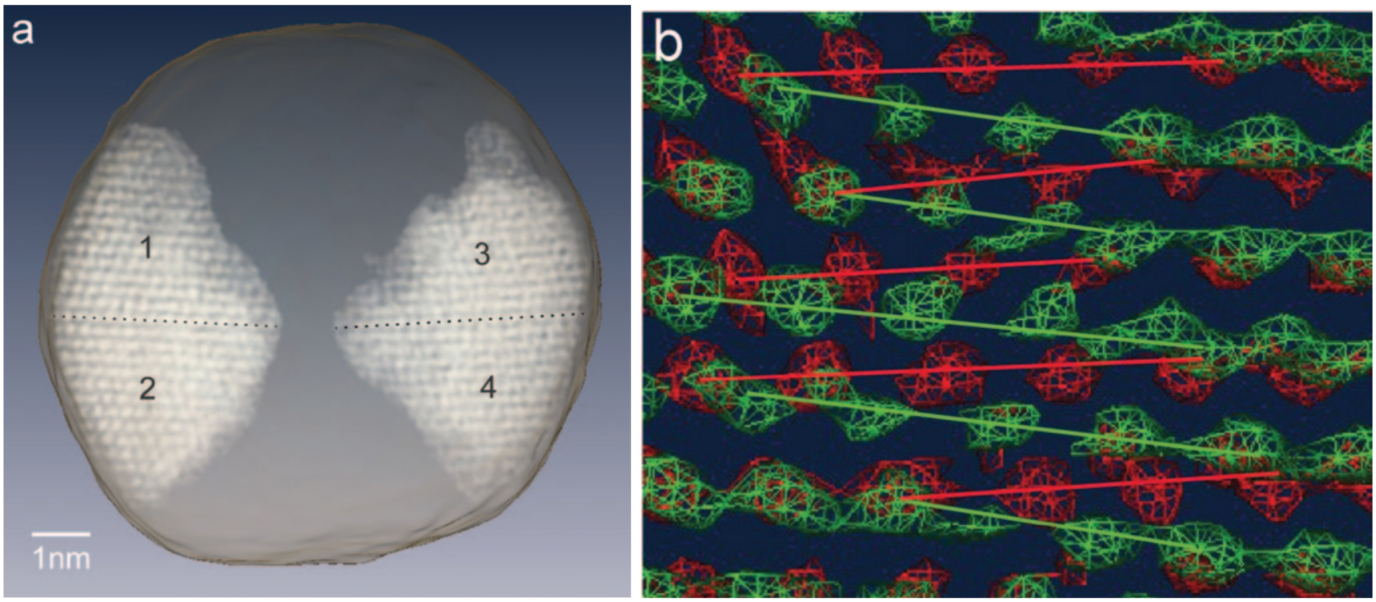



Fig.1: 3D atomic resolution electron microscopy. a, 3D identification of four twin grains inside the Au nanoparticle at atomic scale resolution. b, 3D imaging of the core structure of a screw dislocations at atomic resolution. The zigzag pattern is a characteristic feature of a screw dislocation.

# In Situ Transmission Electron Microcopy

Since Ruska's pioneering work in the 1930's, scientists have been working to improve the capabilities of the transmission electron microscope (TEM). Now 2D atomic-resolution TEM imaging of suitable samples is routine and researchers are turning their attention to new frontiers. John Miao and co-workers have been demonstrating 3D atomic resolution imaging. Alternatively, the new dimension might be time, allowing TEM to look beyond still images of static systems and into dynamic processes where the sample under observation is physically evolving during the measurement period.

Chris Regan is working in this developing area, broadly termed in situ (or sometimes operando) electron microscopy. Among the numerous challenges in situ researchers face, one of the most insidious is radiation damage. The penetrating, high-energy electron beam used to form TEM images can alter the sample: the act of observing a dynamic process can easily disturb that same process. For this reason Regan has focused his attention on systems that can be cycled, e.g. rechargeable batteries (Fig. 2) or computer memory. In a cyclic process, irreversible beam-induced effects are easily identified.

**Ernst Ruska** won the Nobel Prize in Physics 1986 for his work in electron optics including the design of the first electron microscope.

Recently Regan and his graduate student Billy Hubbard led a team that demonstrated an important first in the study of next-generation, non-volatile digital memory. The semiconductor industry is currently exploring alternatives to the now-ubiquitous flash memory, for flash has reached its scaling limit. A leading contender to replace flash is ReRAM, or resistive random access memory. In ReRAM the flash transistor (i.e. the element that records the digital "1" or "0") is replaced by a molecular-scale mechanical switch. The switch is fabricated with two, dissimilar metal electrodes sandwiching a thin, insulating layer. Applying a voltage causes metal atoms to leave one electrode, burrow through the insulator, and eventually form a filamentary electrical connection between the electrodes. This connection represents the "1", or ON state. Reversing the voltage causes the filament to disconnect, putting the memory element in the "0", or OFF state. Despite numerous attempts, this switching process had not previously been imaged.

The main difficulty arises because the molecular-scale switch is, by construction, buried inside a dense solid. To address this challenge Regan and Hubbard designed and built clean, microfabricated ReRAM elements which are topologically identical to real devices, and yet still allow good imaging access. Their 2015 Nano Letter, "Nanofilament Formation and Regeneration During Cu/Al2O3 Resistive Memory Switching," describes their innovative "slant-vertical" design, and presents the first time-resolved, nanometer-scale imaging of functioning ReRAM devices over numerous switching cycles. To more completely address the poor theoretical understanding of the ReRAM switching physics, Regan's group is currently extending these measurements to include high-speed cycling with a variety of metal/insulator chemistries.

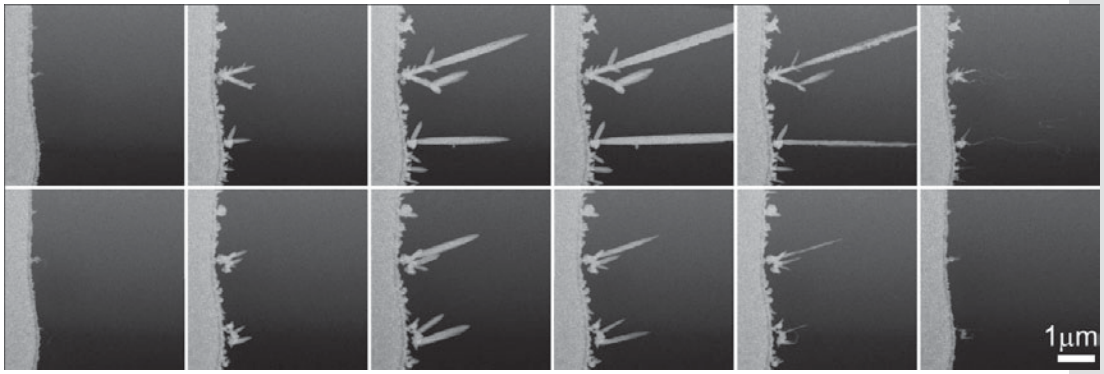



Fig. 2: Two consecutive cycles of lead dendrite formation and dissolution from an aqueous solution of lead nitrate. The time series proceeds from left to right, first along the top row and then along the bottom. Dendrites such as these cause an important failure mode in all types of rechargeable batteries. The dendrites here are single crystals and repeatedly grow from distinct nucleation sites on the gold electrode (seen on the left side of the images). These data are part of the first-ever video observations of dendrite growth with transmission electron microscopy.

# Time-Resolved Ultrafast Electron Imaging: Diffraction and Microscopy

The main goal for time-resolved electron diffraction and microscopy is to obtain real time resolution of atomic motion –one of the great open challenges in modern science– which promises the possibility to understand at the most basic levels various processes in the study of molecules, materials, and biological systems. The progress in ultrafast laser technology has enabled the generation of optical pulses of time duration comparable to the time-scale of atomic motion (<100 fs or 0.1 trillionth of a second). But optical laser pulses can only give indirect information on the sample structural dynamics, and x-ray photons or electrons are required to resolve spatially atomic motion. Various schemes that take advantage of the ultrashort laser pulses to generate bursts of x-rays or electrons suitable for ultrafast probing of materials have been developed.

At UCLA Pietro Musumeci's group pioneered a new technique termed ultrafast electron diffraction (UED) based on a compact source of relativistic electrons to directly investigate materials with atomic spatio-temporal resolution (Fig.3). Due to the large difference between in cross sections, probing with 1 million of electrons is equivalent (i.e. yields the same number of scattered particles) to a probe pulse of 1 trillion of x-ray photons. The strong interaction of charged particles with matter makes electrons the preferred choice to study thin layers, surface effects, or gas phase samples, whenever the number or the density of scattering centers is limited. The main results obtained at UCLA in this field include the optimization of an RF photoinjector-based electron source for this application, the first demonstration of a time-resolved diffraction study using MeV electrons, the development of RF-streaked UED, time-resolved electron shadowgraphy, and the introduction of time-stamping techniques to overcome timing jitter problems.

Following up from these results on diffraction, the UCLA group has made important steps towards applying the technology of ultrafast MeV electrons for real-space (as oppose to reciprocal space) imaging. The next frontier in TEMs is to improve its temporal resolution to ultrafast time scales in order to study the dynamics of microscopic processes in real time (<1ps). At UCLA we are working on the possibility of using high brightness beams from RF photoinjector in a TEM column to capture in a single shot images of 10-nanometer-sized objects within 10 picoseconds ($10^{-11}$ seconds) – about 1000 times faster than the highest-speed microscopes in operation today, enabling the study of ultrafast physical phenomena as for example the propagation of pressure shock waves in a metal structure. The UCLA proposal shows that an electron microscope driven by a photoinjector gun using special quadrupole magnet lenses has the potential to capture an image of a test pattern of few nanometer-sized bars within 10 picoseconds, beating current designs for time-resolved microscopy by many orders of magnitude.

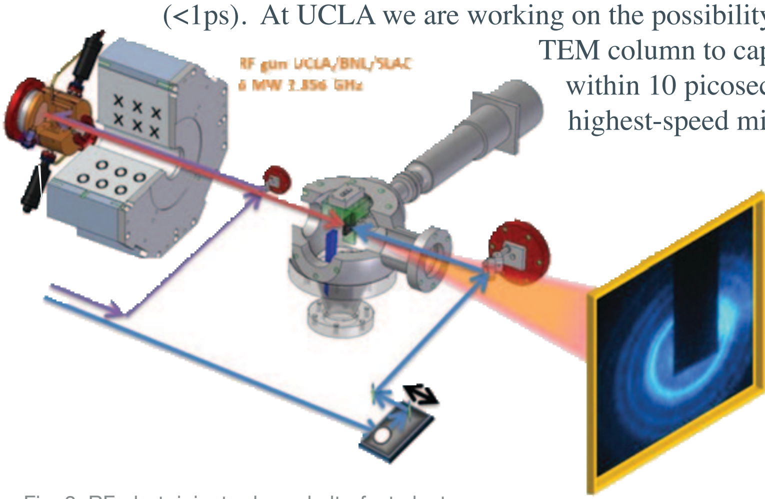



Fig. 3. RF photoinjector based ultrafast electron diffraction setup at UCLA Pegasus Laboratory.

# Diffractive Imaging with Coherent X-rays

Recently, the X-ray science community has witnessed two revolutionary developments. First, large-scale coherent X-ray sources, such as X-ray free electron lasers (XFELs) and diffraction-limited storage rings, have been under rapid development worldwide, of which UCLA physicists (including Claudio Pellegrini and James Rosenzweig) have played a pioneering role. Furthermore, tabletop coherent X-ray sources based on high harmonic generation have advanced rapidly, significantly increasing access to ultrafast coherent X-ray beams for applications in nano and materials science. Second, a new approach to X-ray crystallography, known as coherent diffractive imaging (CDI) or lensless imaging, was first demonstrated by Miao in 1999 that enables structural determination of non-crystalline specimens and nano-crystals with a resolution limited only by the spatial frequency of the diffracted waves (Fig. 4). Over the past few years, powerful new CDI methods have been developed and applied to image a broad range of samples. The combination of these ground-breaking coherent X-ray sources and powerful diffractive imaging methods has opened up new research frontiers of interdisciplinary science that are not attainable by conventional X-ray crystallography.

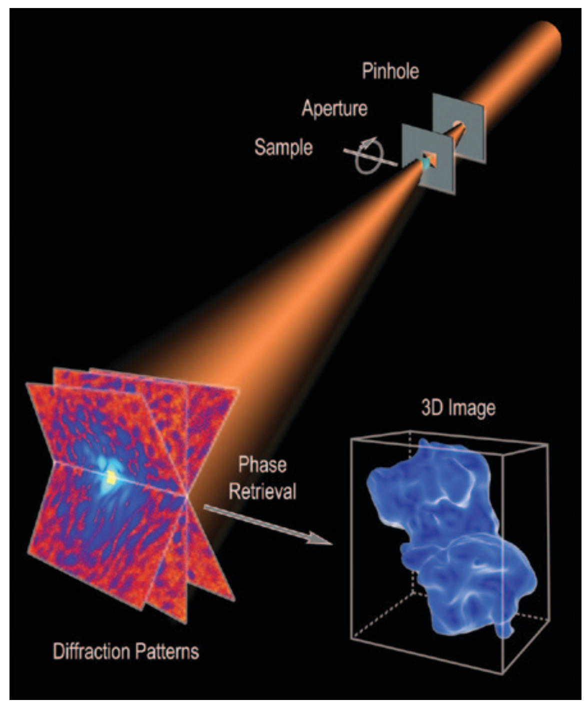



Fig. 4. Schematic layout of CDI. A coherent wave illuminates a non-crystalline specimen or nano-crystal, the far-field diffraction pattern is measured by a detector. If the diffraction pattern is oversampled, the phase information can be directly recovered from the diffracted intensity using iterative algorithms.

In CDI, a coherent wave illuminates an object and the diffracted wave field in the far-field is proportional to the Fourier transform of the object. While the magnitude squared of the Fourier transform can be measured as an intensity by a detector, the phase information is lost, which constitutes the phase problem. For a non-crystalline specimen or nano-crystal, the diffraction pattern is continuous and can be sampled at a frequency finer than the Nyquist interval (the inverse of the specimen size). When the number of independently sampled intensity points is larger than the number of unknown variables associated with a specimen, the phase information is in principle encoded inside the diffraction intensity and can usually be retrieved by iterative algorithms.

By using this powerful oversampling phasing method, various CDI methods have been developed, including plane-wave CDI, Bragg CDI, ptychographic CDI, reflection CDI, Fresnel CDI, and sparsity CDI. These CDI methods have been used to study a broad range of samples in physics, chemistry, materials science, nanoscience, geology, and biology (Fig. 4). Recently, Miao and collaborators published an article in Science, reviewing this rapidly growing and interdisciplinary field.

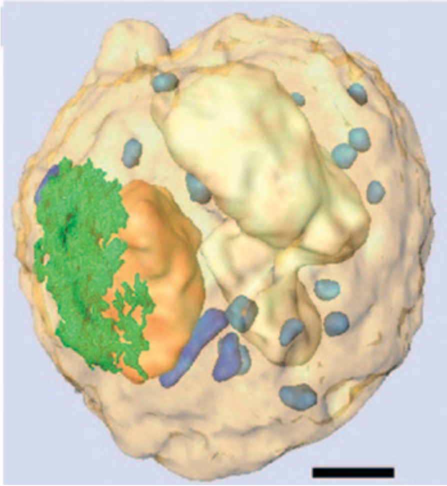
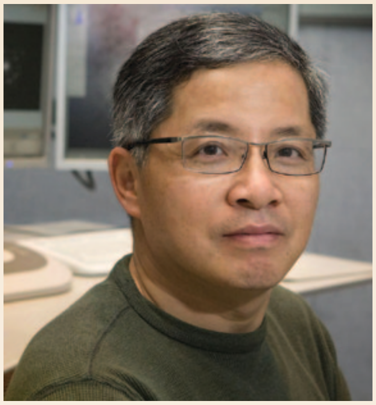


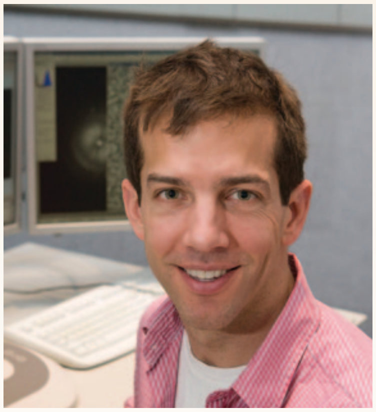
Fig. 5. CDI reveals the 3D cellular organelles inside the yeast spore cell, showing nucleus (orange), ER (green), vacuole (white), mitochondria (blue), and granules (light blue). (Scale bar: 500 nm)

# UCLA physicists at the frontiers in electron and X-ray imaging



**JIANWEI (JOHN) MIAO:** Professor Jianwei (John) Miao is an internationally renowned pioneer in the development of novel imaging methods with X-rays and electrons. Miao performed a seminal experiment on extending X-ray crystallography to allow structural determination of non-crystalline specimens in 1999. This method, known as coherent diffraction imaging (CDI), has been broadly implemented using synchrotron radiation, high harmonic generation, optical lasers, and electrons. It was also one of the major justifications for the construction of X-ray free electron lasers worldwide. Moreover, Miao has also pioneered a general electron tomography method for 3D imaging of local structures at atomic resolution. He achieved electron tomography at 2.4 Å resolution in 2012 and imaged for the first time the 3D core structure of edge and screw dislocations at atomic resolution in 2013. More recently, he determined the 3D coordinates of thousands of individual atoms in materials with a precision of 19 picometers.

**PIETRO MUSUMECI:** Professor Pietro Musumeci's main interests lie in taking advantage of the tremendous progress of laser technology in the last few decades to provide high quality, ultra-short particle beams from compact accelerators for a variety of applications. His expertise spans from laser acceleration (plasma beatwaves and world-record acceleration achieved in an IFEL), FEL physics (strong tapering, superradiant and nonlinear FEL regime studies) as well as advanced beam physics with experimental investigations on high brightness beam production (photocathode physics, magnetic and RF bunching). In 2005-2006 he led the commissioning of the first ever Italian RF photoinjector, at the SPARC facility in Frascati and since 2007 he directs the UCLA PEGASUS laboratory experimental efforts, with the goal of building an advanced photoinjector facility suited to for basic beam research and application of ultrafast electron beams to imaging by diffraction and microscopy.



**CHRIS REGAN:** Associate Professor Chris Regan's group researches the electrical, thermal, optical, chemical, and mechanical properties of nanomaterials. His group uses in situ transmission electron microscopy to study dynamics in active devices of all types, ranging from incandescent nanolamps to wet electrochemical cells.

In 2014, UCLA launched the $4.2 billion Centennial Campaign to celebrate the anniversary of its founding in 2019, and to raise support for our faculty and students in our next 100 years. We greatly appreciate the generous support of our alumni and friends. If you are able to give back to UCLA Physics and Astronomy, please consider giving to the following high-priority areas:

**Chair's Discretionary Fund**
An unrestricted gift of any size helps the Chair meet the department's most pressing needs.

**Endowed Chairs**
Endowed Chairs help recruit and retain the highest caliber faculty, and allow faculty to undertake innovative research not supported by federal grants.

**Prize Postdoctoral Fellowships**
Due to lack of federal funding, there is a critical need to attract top post-doctoral researchers with a competitive and prestigious prize.

**Undergraduate Scholarships & Graduate Fellowships**
Scholarships support the most deserving graduate and undergraduate students based on merit, financial need, or a combination of both. Student support has a tremendous impact on our students' lives and future careers.

**Lab Equipment Upgrades**
Investment in highly technical lab equipment can help our faculty and students perform cutting-edge research for years to come.

**Public Outreach Support**
You can have a major impact on the department's ability to engage the public in science education by supporting the Astronomy Live! graduate student outreach group and upgrades to the UCLA Planetarium.

We invite our alumni to reconnect with UCLA Physics and Astronomy by attending public lectures, visiting campus for a lab tour or planetarium show, and letting us know about your career path after UCLA.

If you are interested in reconnecting with the department, or in learning more about how you can make a difference for our faculty and students, please contact Brooke Sanders at 310-794-9045 or bsanders@support.ucla.edu.

## Donor Impact: Dr. Mani L. Bhaumik

Dr. Mani L. Bhaumik has always been passionate about "the logic of science and the beauty of math."

*Dr. Mani L. Bhaumik has always been passionate about "the logic of science and the beauty of math."*

A scientist, entrepreneur and philanthropist, Bhaumik recently established the Mani L. Bhaumik Presidential Endowed Chair in Theoretical Physics in the Department of Physics and Astronomy. His gift will support the recruitment of an exceptional faculty member to bolster the UCLA theoretical physics group.

Bhaumik grew up in a rural village in West Bengal, India, in the midst of the struggle for Indian independence. He credits his father, a schoolteacher and revolutionary, with inspiring him to succeed in his studies. His success earned him a scholarship at Calcutta University for graduate studies under the renowned Professor Satyendranath Bose of the Bose-Einstein fame. Bhaumik went on to become the first student to receive a Ph.D. from the Indian Institute of Technology Kharagpur.

Bhaumik came to UCLA in 1959 as a postdoctoral scholar on a Sloan Foundation fellowship . His village raised the money for his airfare, and he recalled arriving in Los Angeles with "three dollars in my pocket." In 1961, he joined the Quantum Electronics Division at Xerox Electro-Optical Systems as a laser scientist. Subsequently, he became Director of the Laser Technology Laboratory of the Northrop Grumman Corporation.

Throughout his career, Bhaumik has made significant scientific contributions to the development of high-power lasers, including presenting the first evidence that excimer lasers—used in Lasik eye surgery today—could have sufficiently high efficiency for practical applications.

The help he received from others early in his career inspires his philanthropy.

"I thought I should establish the endowed chair for two reasons: I would not be who I am today without the people who paved the way before me," he said. "As a scientist, I understand the importance of supporting basic research, especially theoretical physics that is at the foundation of all sciences."

In addition, as a member of the Division of Physical Sciences Board of Advisors and a long-time supporter of Professor Zvi Bern's distinguished research group on quantum gravity, Bhaumik has witnessed the effects of significant cuts in government-funded grants on the ability of faculty to pursue "outside-the-box" research that could lead to pioneering discoveries.

Bhaumik hopes his gift will inspire others to support UCLA Physics and Astronomy. "I consider UCLA my home, and I also want people to learn more about science," he said. "Every moment of the day, we are touched by science and technology. I believe that we physicists can do a better job of showing how technology spawned by physics

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Our alumni and friends' generosity in 2014-2015 academic year has had an extraordinary impact on the Department of Physics and Astronomy. We would especially like to thank our leadership donors for their past and ongoing support:

**Ronald and Jeryl Abelmann**
Rudnick-Abelmann Endowed Fund

**Cyrus and Melissa Arman**
**Diana Arman**
Moossa J. Arman Physics Colloquia Endowed Fund

**Mani Bhaumik**
Zvi Bern Postdoctoral Research Fund
Mani L. Bhaumik Presidential Endowed Chair in Theoretical Physics
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**Estate of Nina Byers**
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Binder Postdoctoral Fellowship

**Enrichetta, Beverly, & Anthony Gangi Estate**
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**Chuck Lorre Family Foundation/Big Bang Theory Cast and Crew**
The Big Bang Theory Scholarship Fund

**Ralph and Shirley Shapiro**
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**Ken and Eileen Kaplan**
Ken and Eileen Kaplan Student Support and Travel Awards

**Richard B. Kaplan and Rosamond Westmoreland**
Alice Shapley Research Fund
Richard B. Kaplan Endowed Graduate Award in Astrophysics
Ultramet Nanotech Endowed Fund to support the Center for Biological Physics



*Gifts for the Academic Year July 1, 2014– June 30, 2015*

**Michael and Gretchen Kriss**
Michael and Gretchen Kriss Teaching Assistant Award
Physics and Astronomy Capital Support

**Arthur E. Levine and Lauren B. Leichtman**
Arthur Levine and Lauren Leichtman Fund in Astrophysics
Lauren B. Leichtman and Arthur E. Levine Astrophysics Endowed Chair
UCLA Galactic Center Group Fund

**Jerry Magnin**
UCLA Galactic Center Group Fund

**Janet Marott**
Janet Marott Student Travel Awards
UCLA Galactic Center Group Fund

**Helen Nefkens**
Bernard M. Nefkens Memorial Fund

**Howard and Astrid Preston**
Howard and Astrid Preston Graduate Colloquium Fund
Preston Family Endowed Graduate Fellowship in Astrophysics
Physics and Astronomy Capital Support
UCLA Galactic Center Group Fund

**Rasmussen Family Trust**
Robert A. Rasmussen (PhD 1961) Endowment

**Shirley Saxon**
David Saxon Physics Graduate Fellowship Fund

**Robert and Jane Schneider**
Physics and Astronomy Graduate Award

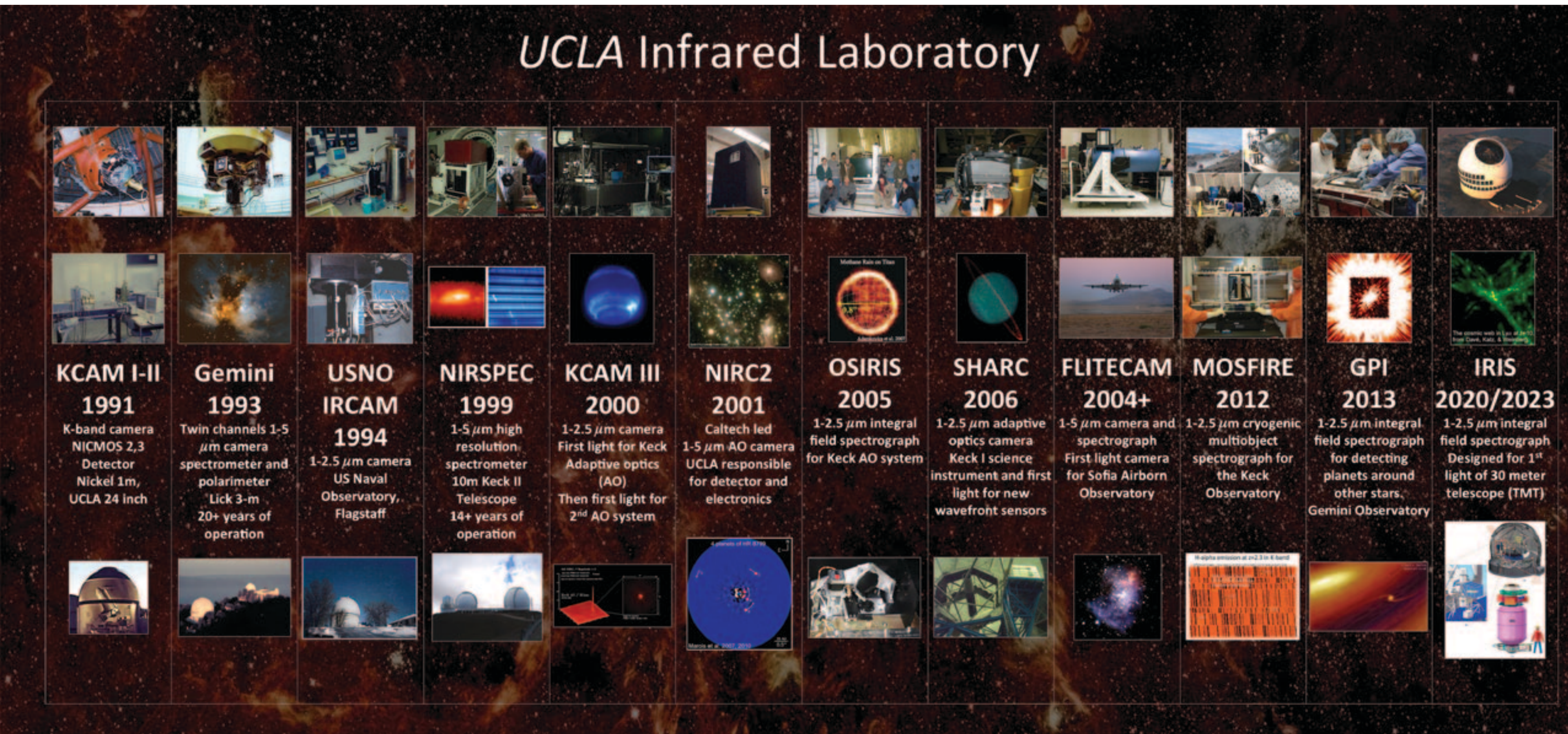
**Dorothy P. Wong**
Eugene Y. Wong Physics Graduate Fellowship

**Guy Weyl**
Department of Physics & Astronomy  Undergraduate Scholarship

# Infrared Laboratory Group:

## Ian McLean, James Larkin and Mike Fitzgerald

UCLA's Infrared Laboratory for Astrophysics (IR Lab) was founded in 1989 when Professors Becklin and McLean joined the faculty at UCLA, and the official opening of the IR Lab took place in the fall of 1990. Professors Larkin and Fitzgerald joined the group in 1997, and 2010 respectively, and Professor Becklin retired in 2005. Since its inception, the IR Lab group has developed and supplied state-of-the-art infrared cameras and spectrometers to many observatories, most especially the twin 10-meter telescopes of the W. M. Keck Observatory on Mauna Kea, Hawaii. UCLA led or contributed to all four of the infrared instruments in current use at the Keck Observatory (NIRSPEC, NIRC2, OSIRIS, and MOSFIRE). These instruments have resulted in many hundreds of research papers, and facilitated numerous discoveries. Each instrument is developed for open use by the community in order to maximize scientific return. During the past year the IR Lab continued to support delivered instruments, advance the design of an infrared imaging spectrograph (IRIS) for the 30-meter telescope currently under construction, work on detector upgrades for the OSIRIS instrument at Keck Observatory, and develop a proposal to upgrade the NIRSPEC instrument. In addition, we celebrated our 25th anniversary!



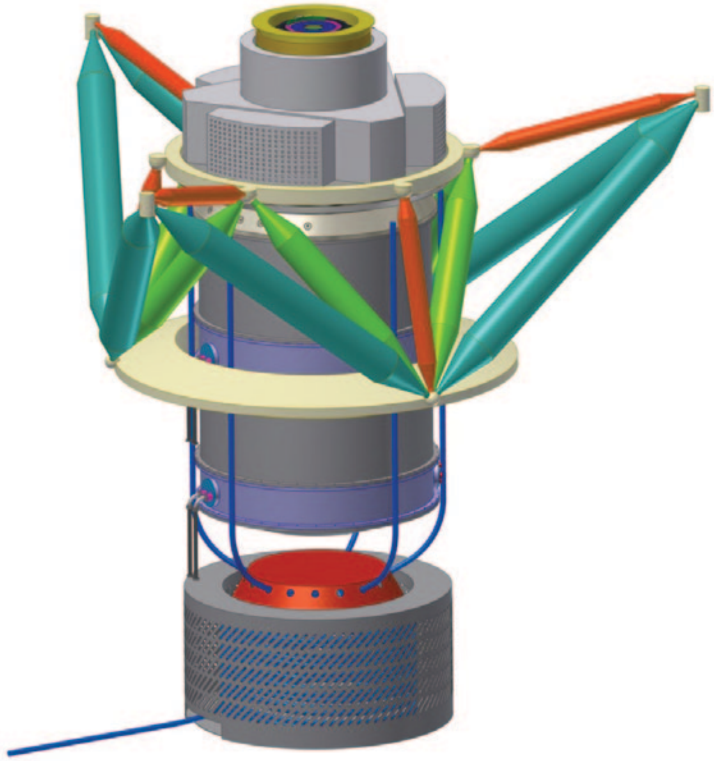

To acknowledge this milestone the IR Lab hosted an open house for the department on June 18, followed by a science conference on June 19, featuring our collaborators and many of our past graduate students. At the original opening in 1990 our guests of honor were Dr. Kadri Vural (Teledyne Imaging Sensors), the Dean of Physical Sciences Clarence Hall, and Dr. Roberto Peccei, Chair of Physics and later Vice Chancellor for Research at UCLA. For the 25th anniversary we were fortunate to have again Dr. Vural (now retired), as well as the current president of Teledyne Imaging Sensors, Dr. James Beletic. Our current Dean, Joe Rudnick, opened the conference by reminiscing that he was the chair of Physics in 1989 who supported the hiring of two infrared astronomers in a bold move to develop a niche for UCLA in the coming "Keck era."

From the beginning, the IR Lab's goals were to advance infrared astronomy in the new era of very large telescopes by developing unique instrumentation using the latest digital imaging devices. More expensive and harder to produce than visible light cameras, the best infrared detectors had a format of 256 x 256 pixels in 1990. Today, sensitive IR detectors with 2048 x 2048 pixels are standard, and 16 megapixels will soon be available. Our emphasis has always been on the delivery of complete scientific instruments to the telescope. For the past 25 years, the Lab has maintained an outstanding track record for producing well-built instruments. Our first contribution

(KCAM) was a simple infrared camera for the 1-m telescope at Lick Observatory; it was demonstrated during the official opening of the lab in November 1990. A unique twin-channel camera for the Lick 3-m telescope followed in 1993. Today, as already mentioned, the IR Lab can proudly claim to have led or collaborated in all four of the currently operational infrared instruments at the W.M. Keck Observatory (WMKO). In addition, UCLA provided two cameras (KCAM III and SHARC) to support commissioning of the adaptive optics (AO) systems on both Keck telescopes. Adaptive optics provides a way to compensate for atmospheric turbulence in real time. The lab has also contributed instruments to the US Naval Observatory, Flagstaff, Arizona, the Gemini South 8-m telescope, Chile, and NASA's Stratospheric Observatory for Infrared Astronomy (SOFIA), which operates from the Armstrong Aircraft Operations Facility in Palmdale, California. Current and future projects include upgrades to the existing OSIRIS and NIRSPEC instruments at Keck Observatory, and the development of a large and very powerful infrared imaging spectrograph for the Thirty Meter Telescope (TMT).

To date, the IR Lab has produced 17 PhD students. All our graduate students have gone on to very successful careers. In fact, one of the guest speakers at the 25th anniversary conference was Dr. Bruce Macintosh. Bruce was the first graduate from the IR Lab in 1994. He is now a professor at Stanford University, and is the Principal Investigator for the Gemini Planet Imager (GPI), to which UCLA also contributed by providing the infrared imaging spectrograph (PI: James Larkin). GPI has been in the news lately because it was used to discover a hot Jupiter-like planet around a young nearby star.

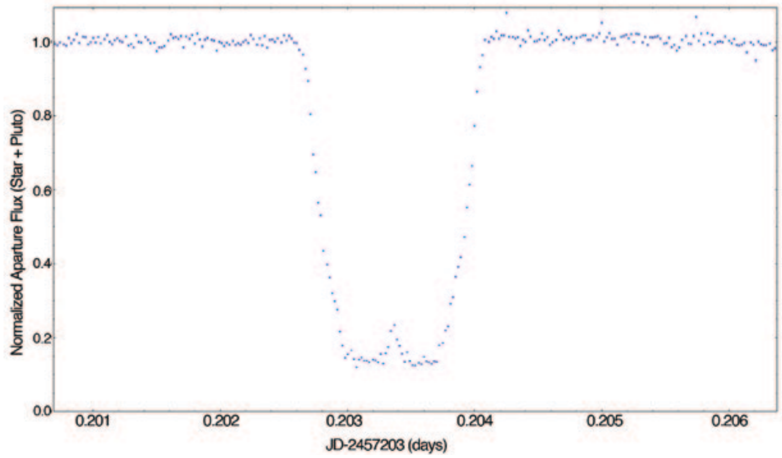
During the current reporting period, the Lab ramped up the NSF-funded detector upgrade for the OSIRIS spectrograph on Keck (PI: James Larkin). In addition, private funding from the Moore foundation is enabling a major redesign and upgrade of the imager section of OSIRIS (PI: Michael Fitzgerald). This second upgrade will follow on after the spectrograph is modified. Work also continued on the preliminary design of IRIS, the Infra-Red Integral-field Spectrograph for the Thirty Meter Telescope (TMT). Professor James Larkin is principal investigator of the international team tasked with building this huge, adaptive-optics-based instrument. IRIS will provide unprecedented detail on objects ranging from the solar system to the galactic center to the high redshift universe.



The IRIS spectrograph (approximately 4 meters tall) being developed for the Thirty Meter Telescope.

Following its commissioning on NASA's Stratospheric Observatory for Infrared Astronomy (SOFIA) last year, our FLITECAM instrument (PI: Ian McLean) was taken through a rigorous acceptance and physical audit, resulting in formal delivery to NASA on May 7, 2015. SOFIA was deployed to New Zealand for one month beginning on June 13, and FLITECAM was scheduled for two flights, the most important of which occurred on June 29/30. On that date, Pluto passed in front of a relatively bright star, occulting its light, and casting a small shadow on Earth for a short period of time. SOFIA was able to fly out of Christchurch, New Zealand to intercept the track of this shadow. Four cameras on board captured the occultation event, but only FLITECAM provided infrared data. The shape of the light curve provides information about haze in Pluto's thin atmosphere. What made this event so important was the imminent arrival of NASA's New Horizons spacecraft at Pluto two weeks later on July 14. UCLA graduate student Sarah Logsdon was on board SOFIA to operate FLITECAM for the successful obsevations of Pluto. UCLA engineer Chris Johnson created a photo-journal of the southern deployment that can be seen at http://irlab.astro.ucla.edu/flitecam/newzealand/

In collaboration with Keck Observatory, the IR Lab prepared and submitted a proposal to the National Science Foundation to upgrade NIRSPEC (PI: Michael Fitzgerald). UCLA also contributed software expertise to the Keck Cosmic Web Imager (KCWI), which is led by Caltech. Finally, Professor Fitzgerald hosted a TMT second-generation planet imager mini-workshop at UCLA in May 2015.




UCLA graduate student Sarah Logsdon (far right) with other observers on board SOFIA looking at the light curve as Pluto passes in front of a bright star on June 30, 2015.

**Ian McLean** continued as Vice Chair for Astronomy through Summer 2015, Director of the Infrared Lab, and Associate Director for the University of California Observatories (UCO). After six years as head of the Astronomy Division, McLean stepped down on September 30, 2015. During this reporting period, McLean supported graduate students Sarah Logsdon and Emily Martin. McLean's research includes the study of the coolest sub-stellar objects known as brown dwarfs, as well as star formation in the local and high-redshift universe. He uses the NIRSPEC and MOSFIRE instruments at the Keck Observatory, and the FLITECAM instrument on NASA's SOFIA.

**James Larkin** focuses on the early development of galaxies like our own Milky Way. Using his instrument OSIRIS at the Keck Telescopes. He and his former graduate student Shelley Wright (now a faculty member at University of California, San Diego) measure the internal motions of galaxies more than 9 billion light years away at a time soon after their formation. A primary goal of this research is to learn when and how these vast structures began to mature into the stable rotating disk galaxies we see in the Universe today. As a byproduct of these measurements they are also able to identify black holes growing at the galaxy centers and can measure the composition of the gas going into the early generations of stars. Larkin's effort to construct the Gemini Planet Imager spectrograph was assisted by graduate student Jeffrey Chilcote. Jeff is now a postdoctoral researcher at the University of Toronto. Larkin also supports graduate student Anna Boehle, who is working on the OSIRIS upgrade and imaging spectroscopy of nearby active galaxies.

**Mike Fitzgerald** studies the relationship between exoplanets and dusty circumstellar debris disks, which act as tracers of planet formation processes. He has applied the NIRC2 camera and the Keck AO system to search for faint emission from planets and disks around nearby stars, and has developed similar techniques for the Gemini Planet Imager (GPI). He has worked with former graduate students Jeffrey Chilcote and Thomas Esposito, and current students Li-Wei Hung, and Pauline Arriaga to develop and apply high-contrast imaging techniques to these systems. He is now applying these methods to observations with the Gemini Planet Imager, and received NSF funding to support this research. Meanwhile, he is also leading the upgrade of the OSIRIS imager for the Keck Observatory and the future upgrade for NIRSPEC. He is also working with the Professor Ghez's group to model the field-dependent aberrations in Keck AO imaging via the AO Optimization project.

# Grism-Lens-Amplified-Survey from Space

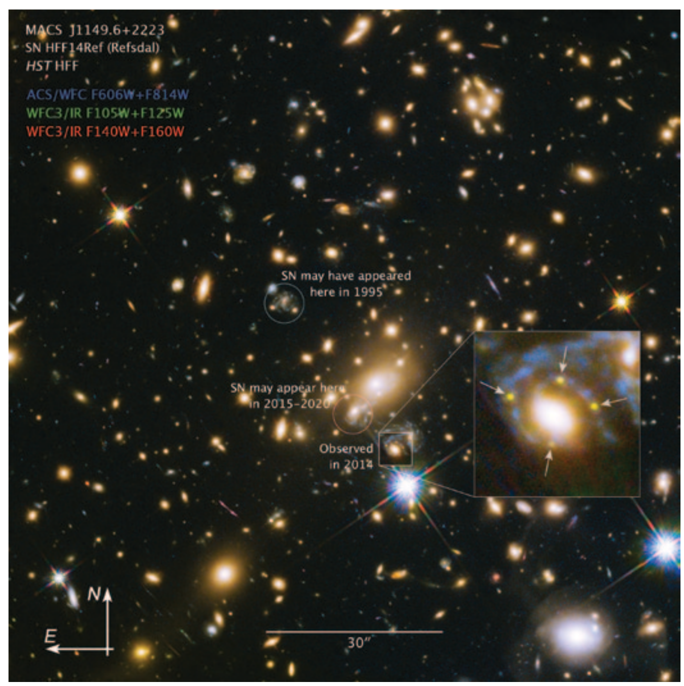
## Tommaso Treu Group

Professor Treu's group has been pursuing three main research areas. The first is a study of distant galaxies, tracing their evolution from the time when the universe was just about to become transparent a few hundred million years after the Big Bang to almost the present day, several billion years later. By combining the power of the Hubble Space Telescope and the magnifying effect of foreground massive clusters of galaxies acting as lenses, GLASS (Grism-Lens-Amplified-Survey from Space; glass.physics.ucsb.edu) is delivering new insights into how galaxies form and evolve. As an additional bonus, the survey is discovering many new supernovae, including the first case of a multiply-imaged one. This rare and exotic phenomenon was predicted more than fifty years ago and finally discovered by the GLASS team. The discovery was published in a special issue of Science celebrating 100 years of general relativity. More information on this discovery is available here: http://hubblesite.org/newscenter/archive/releases/2015/08/image/a/

The GLASS team is led by Professor Tommaso Treu and includes UCLA Professor Matt Malkan and graduate students Charlotte Mason and Xin Wang.

The second main area of activity is concerned with understanding what the universe is made of. We know that the Universe is mostly made of dark matter and dark energy – stuff that does not interact with light and is thus invisible – but we do not know what they are. Prof Treu's group uses very careful measurements of how the trajectory of light in the universe is distorted by the gravitational field of dark energy and dark matter to gather clues to their nature. This innovative method relies on the study of rare astronomical configurations consisting of a supermassive black hole billion of light years away being lensed by a foreground massive galaxy. Finding them is a classic needle in the haystack problem as there is less than one a million chance of finding them at random. Prof Treu's group is leading the way in finding many more as part of the STRIDES collaboration (STRong-lensing Insights into Dark Energy Survey; strides.physics.ucsb.edu). The STRIDES collaboration is led by Treu and includes UCLA graduate students Daniel Gilman and Peter Williams and UCLA postdocs Dr. Adriano Agnello and Dr. Alessandro Sonnenfeld, as well as former UCLA undergraduate, and now CCAP Fellow Dr. Anna Nierenberg.

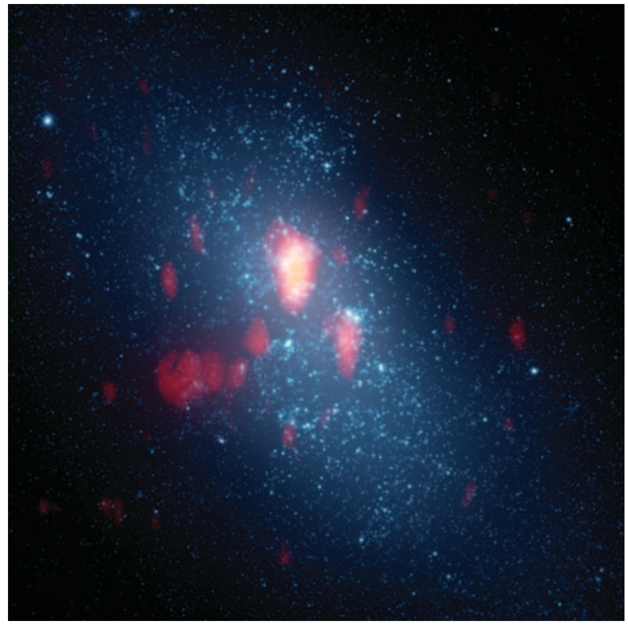
The third main area of activity is the study of supermassive black holes and their evolution across cosmic time. Prof Treu and his group have developed a new method that allows one to measure black hole masses at cosmological distances using the echo of the light emitted by the accretion disk near the black hole, bouncing off clouds of more distant gas. Using this method, Treu and his group have measured masses of several black holes and have learned about the distribution of gas surrounding them. This work was done in collaboration with Dr. Anna Pancoast who just defended her Thesis under the supervision of Professor Treu and is now Einstein Postdoctoral Fellow at Harvard. Treu's group is also using what we are learning with this technique and other measurements in the local universe to study the relative evolution of black holes and their host galaxy. We know that in the local universe bigger galaxies host bigger black holes, with a tight correlation between the mass of the two, but we do not know how this correlation arises. Treu's group is measuring how this correlation evolves with cosmic time and has found that a few billion years ago the correlation was different, with black holes living in smaller galaxies, on average. This work is in collaboration with UCLA Professor Matt Malkan.




Credit: NASA, ESA, and S. Rodney (JHU) and the FrontierSN team; T. Treu (UCLA), P. Kelly (UC Berkeley), and the GLASS team; J. Lotz (STScI) and the Frontier Fields team; M. Postman (STScI) and the CLASH team; and Z. Levay (STScI)

*Dr. Malkan was elected Vice President of a major Division of the International Astronomical Union. Division J, which has about 3000 members, covers "Galaxies and Cosmology" for the IAU.*

# Extragalactic Astronomy



## Jean Turner

Professor Jean Turner has been studying the efficiency of star formation in regions forming super star clusters in local galaxies. The molecular clouds forming these immense clusters are unlike any clouds known in our Galaxy: they are hot, dense, and unusually dusty. Turner employs kinematic methods and high spatial resolution to obtain gas masses since standard techniques for finding mass fail in these clouds. She finds star formation efficiencies that are nearly 100 times higher than in Milky Way gas clouds, and has proposed that the high efficiencies are due to fueling by accretion of circumgalactic streamers of gas. Turner has been using the Submillimeter Array for this work, and is currently obtaining data with the new Atacama Large Millimeter/Submillimeter Array, working in collaboration with students S. Michelle Consiglio and Joe Izaguirre.

# Extrasolar Planetary Science

## Brad Hansen

Brad Hansen continues to study the formation and evolution of planetary systems. Along with former graduate student Ian Crossfield, now a Sagan Fellow at the University of Arizona, and several other collaborators, he is using the Keck telescope to verify transiting exoplanet candidates from the K2 mission. Recent discoveries include the first three planet system unearthed by this mission and a pair of planets very close to a mean motion resonance.

Hansen has also studied the long term secular evolution of planetary systems under the action of tidal evolution. With undergraduate student Jonathan Zink, he finds that the innermost planet of the star 55 Cancri might have had a very dramatic history that includes amplification of orbital eccentricity and inclination and possible mass loss due to a very close approach to the parent star. If true, then this planet offers a unique opportunity to study the stripped core of a planet that was once substantially more massive.

Hansen and collaborators from the University of British Columbia and the Space Telescope Science Institute also recently concluded a study on the cooling of young, hot white dwarfs. By comparing models to observations made by the Hubble Space Telescope, they are able to constrain the rate of neutrino production and cooling, and to test a variety of exotic particle physics models that produce effects at high temperatures (of order a 100 million degrees). The results suggest that standard models of neutrino production fit the data very well and do not require any modifications.

## William Newman

During the past year, Professor Newman has been engaged in several research projects as well as completing a graduate textbook, which is press with Princeton University Press, entitled Mathematical Methods for Geophysics and Space Physics.

It presents a massive updating of materials present in classic textbooks on the topic inasmuch as it explores topics emergent from chaos and complexity theory, with real-world examples drawn from problems which appear in several disciplines, also including planetary science and astrophysics, as well as provide surveys of often overlooked topics---such as inverse theory with roots in astrophysics and geophysics---as well as probability and statistics and numerical analysis.

Professor Newman's paper with former physics graduate student Nathaniel Hamlin addresses numerical issues in solving extreme relativistic magnetohydrodynamic problems that occur in astrophysics (both special and general relativistic environments) and plasma fusion devices.

Hamlin is presently a postdoc at Cornell. His work on pattern formation in statistical physics, with extensions to problems in population biology, offers new insight into the question of observed periodicities in animal populations.

Finally, Professor Newman has found some closed form solutions to a class of analytical mechanics problems that present themselves in application to solar system dynamics (both our own as well as extrasolar planetary systems), and he continues to pursue problems in pattern formation that pertain to observed scalings in cosmological contexts.

# High-Redshift Galaxies

## Alice Shapley Group

A few billion years after the Big Bang, the growth rates of galaxies and the supermassive black holes that they host were at their peak levels. Currently, our knowledge of fundamental galaxy properties is extremely limited during this important epoch. Key questions include: What are the physical processes driving star formation in individual galaxies? How do galaxies exchange gas and heavy elements with the intergalactic medium? How are stellar mass and structure assembled in galaxies (in situ star formation vs. mergers)? What is the nature of the co-evolution of supermassive black holes and galaxies? Starting in spring 2013, Alice Shapley, UCLA graduate student Ryan Sanders, and collaborators at the University of California embarked upon the MOSFIRE Deep Evolution Field (MOSDEF) survey (http://mosdef.astro.berkeley.edu/Home.html) to address these questions. The MOSDEF survey has been awarded 47 nights from 2013-2016 to use the MOSFIRE near-infrared spectrograph on the Keck I telescope (built here at UCLA, with Professor Ian McLean as co-PI).

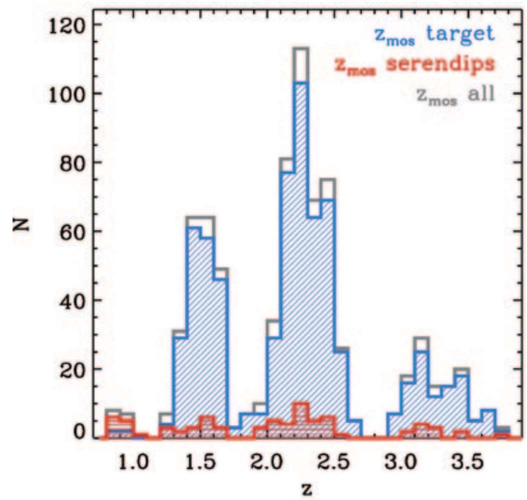



Fig.1: Here we show the histogram of ~900 redshifts collected thus far in the MOSDEF survey. We target multiple redshift windows (i.e., windows of cosmic time) in order to trace the evolution of galaxies.

If we want to learn about photons that were emitted in the optical part of the electromagnetic spectrum in galaxies ~10 billion years ago (i.e., the wavelengths of light that our eyes are sensitive to, and which astronomers typically use to study galaxies in the universe today), we need to turn to the near-infrared. In the time that elapses while these optical photons travel to us through space, the universe expands, and the wavelengths of light stretch by roughly a factor of three into the near-infrared. With MOSDEF, we are collecting near-infrared (i.e., rest-frame optical) spectra and observing the stellar, gaseous and chemical content of ~1500 galaxies when the Universe was only 1.5 to 4.5 billion years old. This sample size represents more than an order of magnitude increase over previous near-infrared spectroscopic surveys of the distant universe. So far, we have obtained spectra for more than ~900 galaxies, and used this amazing dataset to investigate many key questions in the field of galaxy formation and evolution.

Our measurements of the metal content of distant galaxies provide important evidence that the cycle of gas and heavy elements operates in a different manner at high redshift relative to what is observed in the local universe. Observations of a large set of emission lines coming from the stellar nurseries in these distant galaxies constitute a code that we are trying to break to determine the detailed physical conditions under which stars form in the early universe. We are learning about properties such as the density of gas, and the intensity of the radiation field in these early star-forming regions, and how these properties relate to what is observed in star-forming regions today. We have also learned about the nature of dust in ancient galaxies, and how to find the star formation that is obscured by dust clouds. In addition, we are considering various types of motions in distant galaxies. These include the dynamics of rotation, which can be used to estimate galaxy masses, as well as the kinetics of outflows, driven by the energy input from both supernova explosions, and actively accreting supermassive black holes. A sampling of recent MOSDEF publications can be found here: http://mosdef.astro.berkeley.edu/Publications.html

The MOSDEF survey is supported by grants from NSF, NASA, and the Space Telescope Science Institute.

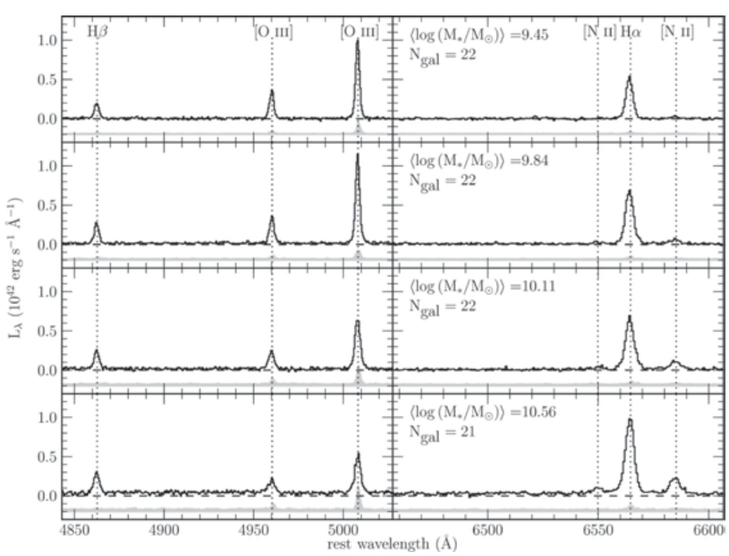



Fig. 2: (From a recent paper in The Astrophysical Journal led by UCLA graduate student Ryan Sanders.) Here we show a set of four stacked spectra of high-redshift galaxies, each consisting of the average of ~22 individual galaxy spectra. The average galaxy mass in each bin increases from the top to bottom row, and it is clear that the pattern of hydrogen, oxygen, and nitrogen emission lines changes systematically as a function of galaxy mass. These emission lines are produced in the star-forming regions of galaxies, and their relative strengths indicate the metal and dust content of these galaxies, as well as the rate at which stars are being formed (and much, much more).

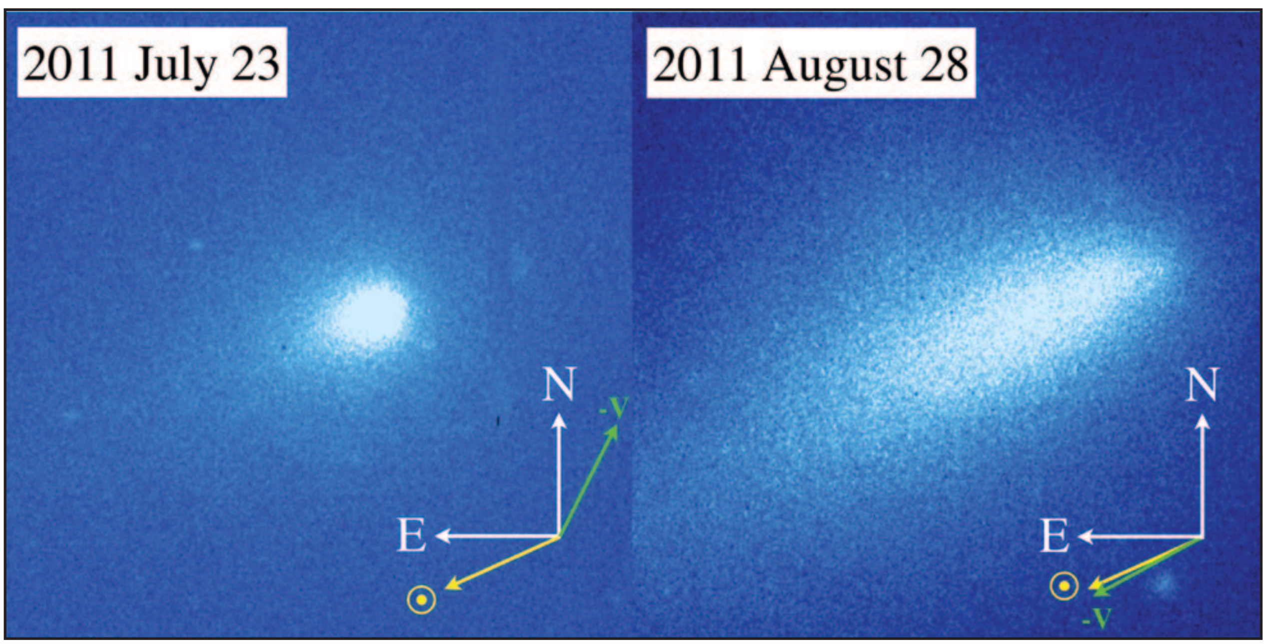
*Dr. Matt Malkan is serving as Convenor for the ISDT (International Science Definition Team) now planning for the Thirty Meter Telescope (TMT). In particular, he and his international collaborators are defining the Key Projects TMT will conduct to understand Supermassive Black Holes in Galaxies.*

# Planetary Science and Astronomy

## David Jewitt

Oort's model for the origin of long-period comets does not fit the dynamical data without the assumption of an arbitrary "fading law", in which comets dim or disappear soon after their first pass through the inner solar system. Posited in 1950, the physical origin of the fading law has never been convincingly established, although conjectures abound. With researcher Jing Li from the Department of Earth, Planetary and Space Sciences, Jewitt has investigated the demise of long period comet C/2010 X1 (Elenin) to try to understand the fading mechanism. At first predicted to become a brilliant near-Sun super-comet, Elenin faded and then disappeared even before reaching perihelion at 0.48 AU from the Sun. The key events occurred inside Earth's orbit, making routine observations with night-time telescopes relatively difficult. Instead, Li and Jewitt used observations from the NASA STEREO sun-observing telescopes to study comet Elenin. The main result is that the half-kilometer scale nucleus completely disintegrated into fragments less than 40 meters across starting at about 0.7 AU from Sun. This distance is too large for solar tides or sublimation stresses to be important but is compatible with rotational bursting driven by outgassing torques on the inbound nucleus. This result, if replicated on other comets, may indicate that rotational instability is the long-sought explanation for Oort's fading law.

David Jewitt: jewitt@ucla.edu
http://www2.ess.ucla.edu/~jewitt




# Planets and Exoplanets

## Jean-Luc Margot

Our research group measures the spin states, shapes, and orbits of planets, satellites, and asteroids. This work allows us to quantify the interior structure of these bodies and the processes that affect them. The goal is to better understand the formation and evolution of habitable worlds.

Last June, our group observed the kilometer-sized asteroid (1566) Icarus at the Arecibo Observatory (Fig. 1). The orientation of the orbit of Icarus changes as a function of time due to general relativity and the fact that the Sun is not a perfect sphere. The change amounts to about 10"/cy, which is easily detectable with the Arecibo radar. Icarus is one of about a dozen objects specifically targeted by our UCLA team to measure these effects.

Graduate student Adam Greenberg has continued to perfect our algorithms for 3D shape reconstruction of asteroids, improving both the speed and the rigor of the modeling procedure. Knowledge of asteroid shapes helps not only with key science questions, but also with trajectory predictions, impact risk assessments, and spacecraft proximity operations.

Postdoc Ashok Verma performed an independent analysis of MESSENGER radio science data to estimate Mercury's gravity field, obliquity, and libration amplitude. These parameters provide key constraints on the interior of the innermost planet.

Motivated in part by the abundance of Earth-like planets in the galaxy, Margot proposed a new course titled 'Search for Extraterrestrial Intelligence: Theory and Applications' that will be offered to undergraduate and graduate students starting in Spring Quarter 2016.

In other areas, Margot developed a quantitative criterion for defining planets (to appear in the Astronomical Journal), debunked the claim of a lunar influence on plant pollination (Journal of Biological Rhythms), and joined NASA's Europa multiple-flyby mission as part of the Gravity Science Working Group.
web site: http://mel.epss.ucla.edu/jlm

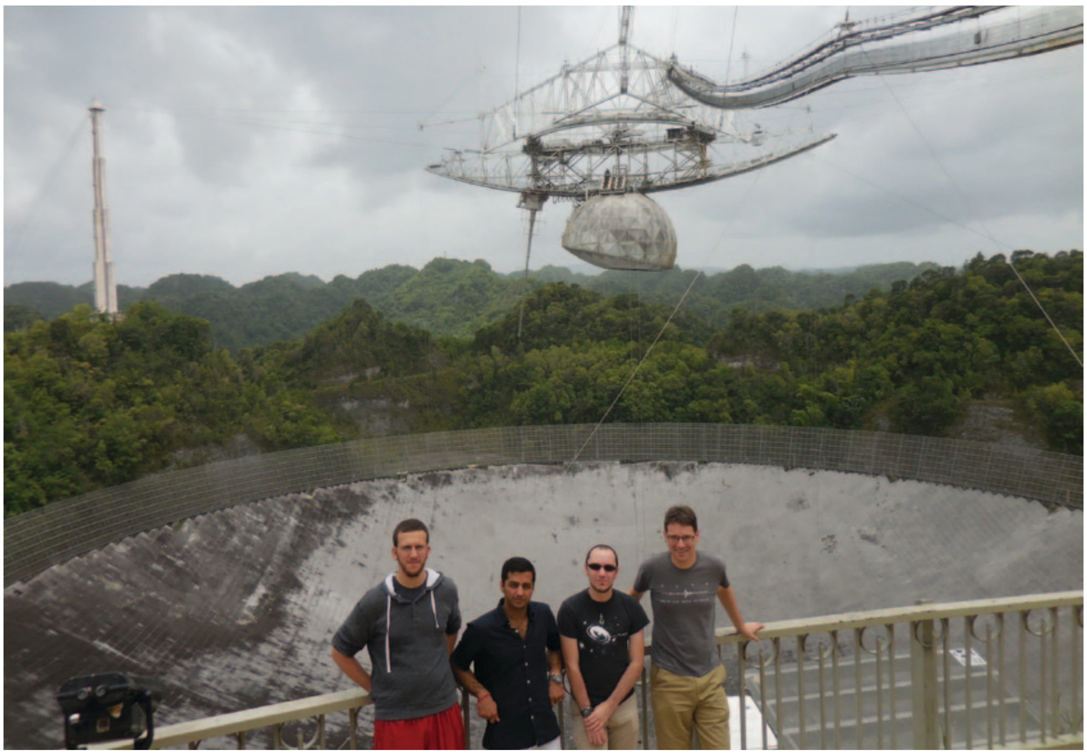


Fig. 1: Adam Greenberg, Ashok Verma, Oliver Bowman, and Jean-Luc Margot at the Arecibo Observatory, the largest telescope on Earth. Margot and his group use the 1,000-foot diameter telescope to measure the 3D shapes of near-Earth asteroids and their trajectories with exquisite precision.

## Research Group: Galactic Center Group

### Andrea Ghez (Director), Tuan Do, Eric Becklin, Mike Fitzgerald, Mark Morris, Smadar Naoz, Shoko Sakai, Gunther Witzel

The mission of UCLA's Galactic Center Group is to transform our understanding of black holes and their role in the Universe with high-resolution observations of the center of our Galaxy. Due to its proximity, the Milky Way's central supermassive black hole and its environs affords us with the unique opportunity to study the fundamental physics of black holes - by opening up new probes of Einstein's theory of General Relativity in regimes that have thus far never been explored - and the role that black holes play in the formation and evolution of galaxies.

In this past year, one of the highest profile areas of Galactic Center research has been work on G2 - the first spatially resolved object to show tidal interactions with the central black hole. G2 was first reported in 2012, by a competing group, to be a gas cloud headed toward the black hole on an extremely radial orbit with the expectation that it would be torn apart (tidally disrupted) when it made its closest approach by the central black hole. It was expected that this event would provide a unique opportunity to study an increase in the accretion flow, leading to tremendous efforts by groups all around the world, using radio, infrared, and x-ray facilities to study the black hole accretion flow response and theoretical studies to understand the origin and nature of G2. Our group had a very different hypothesis early on – (1) that G2 was a star, albeit an unusual star, as the tidal interactions would require it to be 100 times larger than a typical star observed in this region, and (2) that no immediate response would be seen in the accretion flow. Because the emission from the accretion flow is highly variable, one of the first things we did was to develop a statistically rigorous approach to identifying a true second state. This study was carried out in collaboration with UCLA Finance Professor Francis Longstaff and was funded by a UCLA interdisciplinary seed grant (see images). In studies with Keck Observatory and Spitzer space telescope, we have shown that the black hole accretion flow has thus far been unaffected. We have also demonstrated that G2 survived its closest approach, providing strong support for an underlying star. This led us to suggest that G2 is the result of a black hole driven binary star merger. This hypothesis introduces an object that is expected to be large, that has a long lifetime (~106 yr.), avoiding the improbability of the short lifetime (10 yr.) for the gas cloud hypothesis, and that can survive its closest approach to the central black hole. We have also found other similar objects that support this hypothesis. This may provide a clue to some of the other unusual properties that we have observed over the last decade with Adaptive Optics at the Galactic Center and has led to (1) a new collaboration with our newest faculty member Professor Smadar Naoz and graduate student Alexander Stephan to model the viability of the black hole driven binary star mergers (via the Kozai-Lidov effect) to explain G2 and other phenomena (see image) and (2) new graduate student projects to measure the presence of binary stars at the Galactic center (Sam Chappell & Abhimat Gautam) and model the evolution of such systems.

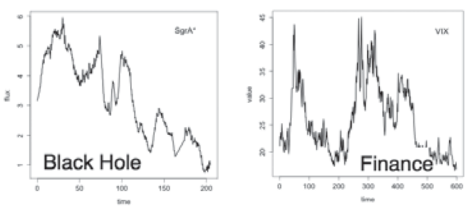



Fig.1: Comparison of the variability of the light coming from the black hole accretion flow with the financial market. The similarity led to a collaboration between the UCLA Galactic Center Group and UCLA Finance Professor Francis Longstaff to develop new tools for astronomical data to detect multiple states building off of analytic methods used in finance (see Meyer, Witzel, Longstaff, Ghez et al. 2014, ApJ, 791, 24 and Witzel, et al. in prep).

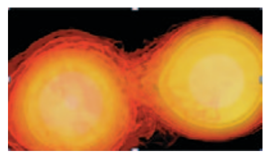
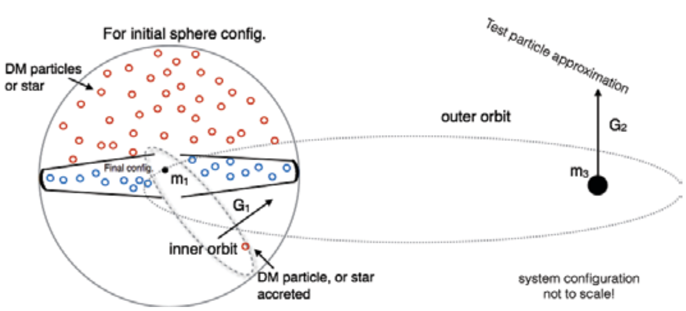


Fig.2: A pair of stars in the process of merging. The UCLA Galactic Center Group has suggested that G2 – the first case of an object being caught in the act of tidally interacting with the central black hole – may be a binary star that has been driven to merge by the black hole (figure is a still from an animation produced by NASA/AEI/ZIB/M. Koppitz and L. Rezzolla).

## Smadar Naoz

Smadar Naoz continues her research on astrodynamics at different scales. In particular, she considers the effects that gravitational perturbations from a far away object has on a relatively tight binary. Recently, she showed, in collaboration with a former student Gongjie Li, from Harvard University, and others, that such mechanism can significantly affect the properties of the stellar population around a supermassive black hole. Specifically, the effect of gravitational perturbations of supermassive black hole binaries on an ambient star cluster may increase the stellar tidal disruption event rate and even lead to a torus-like configuration of stars (or dark matter particles) around one of the black holes (see cartoon). This mechanism causes large elliptical orbits to the stars around one of the supermassive black holes, which ultimately causes the stars to either scatter off the second supermassive black-hole or get tidally disrupted. These effects may be even more prominent in nuclear stellar clusters hosting a supermassive and an intermediate mass black hole.




Applying this mechanism at different scales, Professor Naoz showed that it can lead to the formation of high mass X-ray binaries associated with supernova impostor. X-ray binaries are binary stars that are luminous in X-ray, which is produced when matter is accreting from a donor star to a black hole or a neutron star. On the other hand, supernova impostors are explosions that appear at first to be a type of supernova but evidentially do not destroy their progenitor stars. It was recently claimed that high mass X-ray binaries can undergo a phase of explosions imposing as supernova. However, the dynamics of these systems have not been understood. Naoz suggested that perturbations from a far away star may drive a high mass evolving star onto a neutron star (or black hole) causing an interacting phase of these systems that later can be observed as a high mass X-ray binary and supernova impostor.

# Atomic-Molecular-Optical Physics

## Harnessing quantum interactions for future science and technology

For the majority of the first two centuries of its existence, atomic, molecular, and optical physics (AMO) focused on studying matter at the atomic level. Experiments with higher-resolution spectroscopy of atoms led to the development of the Bohr model and eventually quantum mechanics. Optical interferometry experiments rejected the idea of an ether in favor of Einstein's theory of relativity. And improved, higher-resolution spectroscopy led to the development of Dirac's formulation of relativistic quantum mechanics and eventually the gold standard of all theories, quantum electrodynamics.

In the last quarter century, AMO physicists have been turning the exquisitely precise tools developed to study matter around and are now using them to control matter at the quantum level. The resulting techniques, like laser cooling, have forever altered the course of the field. It is now possible to produce single atoms and ions in single internal and external quantum states and manipulate those states coherently. Ideas that were previously thought to be the realm of thought experiments are now reality. Atoms have been put into superposition of internal and external quantum states (like the famous Schrodinger cat experiment) and the counterintuitive ideas of quantum measurement have been tested and found to be consistent with reality.

In the present day, AMO researchers are focusing on harnessing the power of quantum interactions to improve both technology and fundamental physics knowledge. The laser, a tool developed to study and control atoms, is now commonplace in everything from supermarkets to computer drives to industrial fabrication. The global positioning systems in our cars and phones require exquisite timing and synchronization to function, which they achieve through the use of highly stable atomic clocks. These clocks realize the necessary precision by employing quantum measurement protocols developed in AMO. Mass spectrometers, developed by these early experimenters, are now used in hospitals and crime labs across the world. And, quantum-assisted sensing of magnetic and gravitational fields, again using techniques developed during the AMO revolution, is beginning to be used for everything from locating potential oil and diamond fields to detection of weapons stockpiles. In fact, all totaled, it is estimated that discoveries in quantum physics, such as these, account for 30% of the current US GDP!

On the science side of things, these same techniques have been used to enable the most accurate measurements of the constants of nature, the highest precision tests of quantum electrodynamics, and searches for physics beyond the standard model. These techniques have also been used to confirm our understanding of quantum mechanics and quantum measurement. And, they are now being harnessed to usher in a new generation of measurement techniques that exploit the peculiarities of quantum mechanics to allow for even more precise measurements of the world around us.

Looking forward, the future of the field lies in continuing to harness the power of quantum interactions to improve science and technology. At UCLA we are working towards this by both developing new techniques to harness the power of quantum interactions and by bringing new systems under the same level of quantum control that laser cooling brought to atoms.

## Quantum physics with atoms and molecules

### WES CAMPBELL

Continuous wave (CW) lasers are the enabling technology for producing ultracold atoms through laser cooling and trapping. These pristine samples of slow moving particles are the de facto starting point for both fundamental and applied science when a highly controlled quantum system is required. However, CW laser technology currently limits laser cooling and trapping to a handful of exotic species, excluding highly abundant and chemically relevant atoms such as hydrogen, carbon, oxygen, and nitrogen. Led by postdoc Andrew Jayich, we have recently shown that Doppler cooling and trapping by optical frequency combs may provide a route to trapped, ultracold atoms whose spectra are not amenable to CW lasers. We have been able to laser cool a gas of atoms by driving a two-photon transition with an optical frequency comb, an efficient process to which every comb tooth coherently contributes. We have further extended this direct frequency comb cooling to create a magneto-optical trap, which produces an electromagnetic beaker for confining the laser-cooled atoms for accumulation and study. These results suggest that the wide spectral coverage offered by optical frequency combs could provide a key ingredient for producing trapped, ultracold samples of nature's most abundant building blocks.

Another product of laser cooling, cold trapped atomic ions, have been a center of focus in our group as well. We have created 2D crystals of ytterbium ions (see figure) that contain up to a few hundred ions in a single planar structure that self-organizes to form a regular pattern. We will use these crystals to explore the quantum many-body physics of 2D lattices of spins as well as the classical physics of these novel crystals themselves. Our current focus is on using ultrafast lasers to perform quantum information processing tasks on much smaller collections of ions in this trap. We have also just begun a related project in collaboration with Eric Hudson's group to demonstrate that the radioactive barium-133 isotope, in singly-ionized form, has the potential to surpass all of the naturally-occurring ions as the qubit of choice for the trapped ion quantum information community due to its unique internal structure.

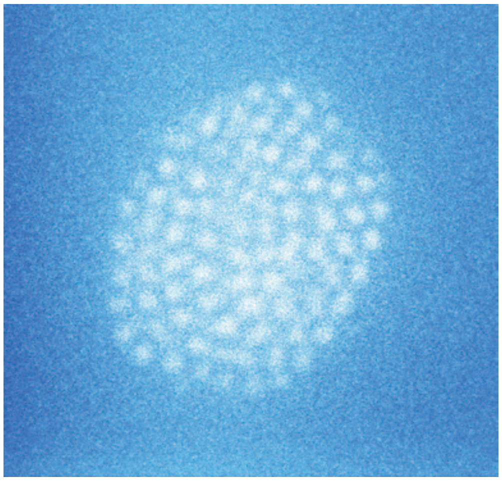


Fig.1: A collection of atoms form a 2D pattern called a Coulomb crystal in a radiofrequency Paul trap. Each atom is at a temperature of only a few millikelvin above absolute zero and glows in the dark when illuminated with light from a laser.

## Hudson lab: Exploring new frontiers in AMO science

Real progress in AMO has come whenever new techniques were developed that extended the precision control offered by the field to new systems. The technique of laser cooling brought the external and internal quantum states of neutral atoms and atomic ions under control roughly three decades ago, enabling a scientific revolution with few parallels. Our research program at UCLA is working to push the techniques of AMO physics to two new, unexplored frontiers: the study of ultracold polar molecular ions and a laser-accessible nuclear transition.

### *The MOTion trap: Ultracold molecular ions*

Without question, the atom has been tamed. With modern AMO techniques it is possible to completely control and manipulate atoms at the quantum level. The same cannot be said, however, of even the simplest molecule, e.g. diatomic molecules made of just two atoms. Because of the extra complexity that comes with a molecular bond -- rotation and vibration of the molecule – molecules have evaded all but a few attempts to domesticate them. Nonetheless, it is expected that if and when molecules are brought under control they will enable a scientific revolution that parallels what transpired when atoms were brought under control, with implications ranging from quantum computation to material science.

At UCLA we are developing a new method that uses ultracold atoms as "ice cubes" to cool trapped molecular ions into their quantum ground state. Simply put, by spatially overlapping a cloud of ultracold, laser-cooled atoms in a magneto-optical trap (MOT) with a molecular ion trap, we have shown that it is possible to quickly cool both the internal and external degrees of freedom of the molecular ion. The technique promises to be robust and simple since it requires only an ion trap and ultracold atom trapping – both proven technologies.

### *Research Highlights from 2014-2015:*

Solving an old mystery: It has been known since the early days of ion trapping that the laws of thermodynamics failed to predict the observed behavior. In two recent papers -- K. Chen, Scott T. Sullivan, Wade G. Rellergert, and Eric R. Hudson, Physical Review Letters 110, 173003 (2013) and K. Chen, Scott T. Sullivan, and Eric R. Hudson, Physical Review Letters 112, 143009 (2014) – we have provided the first complete solution to this old riddle. The coherent micromotion inside of these ion traps precludes the application of equilibrium thermodynamics and has profound implications on the evolution of the system. With this 50-year-old mystery finally solved, ion trapping systems can be optimized more completely for harnessing the power of quantum interactions.

Slowing down to take a better spectrum: This year saw the demonstration of a new technique to improve the resolution of mass spectrometers, which are a critical tool in analyzing the results of our ultracold quantum chemistry experiments. The work, reported in Christian Schneider, Steven J. Schowalter, Kuang Chen, Scott T. Sullivan, and Eric R. Hudson, Physical Review Applied 2, 034013 (2014), used laser cooling to sympathetically cooling ions to ultracold temperatures before injecting them into a mass spectrometer. The technique improved both the resolution and detection efficiency of the mass spectrometer by more than a factor of 10! The APS featured the work in their weekly mailings with a Synopsis, which can be read at: http://physics.aps.org/synopsis-for/10.1103/PhysRevApplied.2.034013\

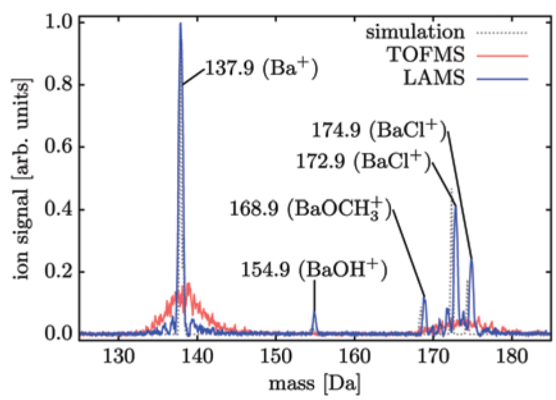



Fig. 2: Mass spectrum of a sample of barium chloride. The red trace shows the mass spectrum recorded with a traditional mass spectrometer, while the red shows the same spectrum with our new technique applied. The individual isotopes are easily distinguished.

### *A nuclear clock*

The technological impact of atomic clocks has been profound, ranging from the successful implementation of global positioning systems and cellular telephones to the synchronization of modern-day electrical power grids. Improved clocks, based on optical frequency standards, are likely to enable several new technologies such as secure data routing, jamming resistant communication, high-resolution coherent radar, and improved global positioning. Furthermore, high-precision clocks have provided a means to probe fundamental issues in physics. For example, atomic clock experiments have provided some of the most stringent tests of General Relativity. Because of these motivations, there is presently enormous effort towards building next-generation atomic clocks. It appears universally recognized that the most promising route to improved clocks uses reference oscillators based on optical transitions. Indeed, several optical atomic clock experiments have already reported better stability than the primary Cesium standard, which keeps time for the nation.

In 2010, we proposed (W.G. Rellergert et al., Phys. Rev. Lett. 104, 200802 (2010)) a novel optical frequency standard based on a high-Q transition in the 229Th nucleus, this "nuclear" clock architecture promises several orders of magnitude improvement in precision over next-generation optical atomic clocks, while simultaneously reducing experimental complexity. This paradigm shift in optical frequency standards is possible because, as indicated by recent data, the 229Th transition has the lowest energy of any known nuclear excitation, making it amenable to study by laser spectroscopy. Furthermore, because nuclear energy levels are relatively insensitive to their environment, the complicated vacuum apparatus of current optical frequency standards can be replaced by a single crystal doped with 229Th atoms.

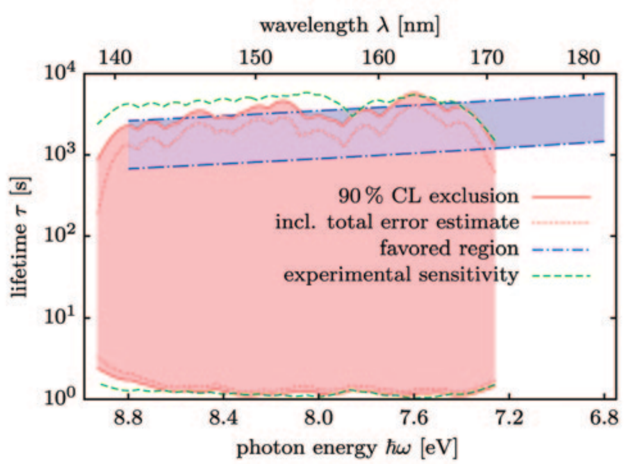



Fig. 3: (color online). The 90% CL exclusion region (red shaded) for the vacuum lifetime The 90% CL exclusion region (red shaded) for the vacuum lifetime τ of the $^{229}$Th isomeric transition as a function of the transition energy ħω. Reduction of the sensitivity by the total error budget (Table II) would reduce the excluded region to the area between the red dotted lines. The experimental sensitivity (green, dashed; see text) and the favored region for the transition (blue shaded area between dash-dotted lines) are also given.

To date, our work has been focused on solving a 40 year old mystery and the most significant experimental challenges for constructing a solid-state optical clock based on the 229Th nuclear transition: determining the nuclear transition frequency.

## *Research Highlights from 2014-2015*

Searching for the nuclear transition with a synchrotron light source: Because the resolution of the previous measurement (7.8 ± 0.5 eV) of the transition frequency is poor by laser spectroscopic standards, it is necessary to better determine the transition energy before a clock can be built. For this purpose, we used the intense, wide-bandwidth VUV light from a synchrotron – the Advanced Light Source (ALS) at Berkeley – to attempt to excite the 229Th nuclei and collect their resulting fluorescence. However, no evidence of the nuclear transition was found in the region where it was thought to exist! Thus, we have recently reported -- Justin Jeet et al., Physical Review Letters 114, 253001 (2015) – an exclusion of a large fraction of the "favored region", i.e. the region of parameter space where the transition was thought to exist.

The remaining, non-excluded, parts of this favored region cannot be accessed with the ALS, so we have just finished constructing a vacuum ultraviolet laser system capable of scanning over the entire region with considerably more flux than the ALS. The search continues!

Results of the first search for the thorium nuclear transition at the ALS. The blue region covers the range of possible transition energy and lifetime of the nuclear transition suggested by previous experimental data. The red region shows our exclusion.

**Give to the UCLA AMO Effort:** AMO physics experiments are typically small-scale experiments that could fit on most tables. However, despite this small scale they can have enormous scientific and technological impact due to the precise nature of the techniques. Unlike larger scale experiments in other fields, the small scale of AMO experiments means that private contributions to research, which can allow us to upgrade equipment or add new capabilities, can have a tremendous impact. If you are interested in making any contribution, large or small, to UCLA's AMO effort please contact us at: eric.hudson@ucla.edu

# BIOPHYSICS

## Arisaka Neurophysics Group

**KATSUSHI ARISAKA**

## The Elegant Mind Club


Fig. 1: Pictures of active members of the Elegant Mind Club, assembled at the 2nd anniversary and Arisaka's birthday party on July 1, 2015.

C. elegans is a well-established model organism whose nervous system consists of a network of only 302 neurons according to a fully mapped Connectome. However, even at the level of the most simple organisms, dynamic neuronal mechanisms for spatial navigation are not yet well understood. In the summer of 2013, an innovative undergraduate science education program named the Elegant Mind Club (http://www.elegantmind.org) was founded, and since that time, ~150 undergrads have participated (See Figure 1). The Club is trying to explore the complete circuit diagrams necessary for spatial navigation, and to identify the biological origins of the networks from the synaptic level, to entire complex systems. To achieve this goal, all possible stimulations (such as temperature gradient, Electric and Magnetic fields and UV/visible/IR photons) have been applied, and behavior of the C. elegans have been observed and analyzed in controlled and experimental conditions. A total of eight posters were presented at the recent International Conference of C. elegans in June 2015, where Karen Jiang, an Elegant Mind Club member, received the award of the best poster presented by an undergraduate.

## Development of advanced optical microscopes

The Arisaka group have also been developing several novel microscope systems to detect fluorescently-labeled ions or proteins in living organisms which directly relate to brain activity. In most cases, a spike neuronal activity (referred to as an action potential) is marked by a characteristic influx of calcium ions into the brain cell. If these calcium ions are marked with some type of fluorescent tag, their influx (and thus activity) will relate directly to an increase in the number of longer-wavelength photons being emitted from the brain cell. Using various microscopy methods of illumination and detection, these photons are detected, and neural activity is in turn analyzed. Based on these principles, two new microscopes have been developed and are now being tested on various live samples.

### *(1) Worm tracker*

The Arisaka lab have created a novel microscope system to track-

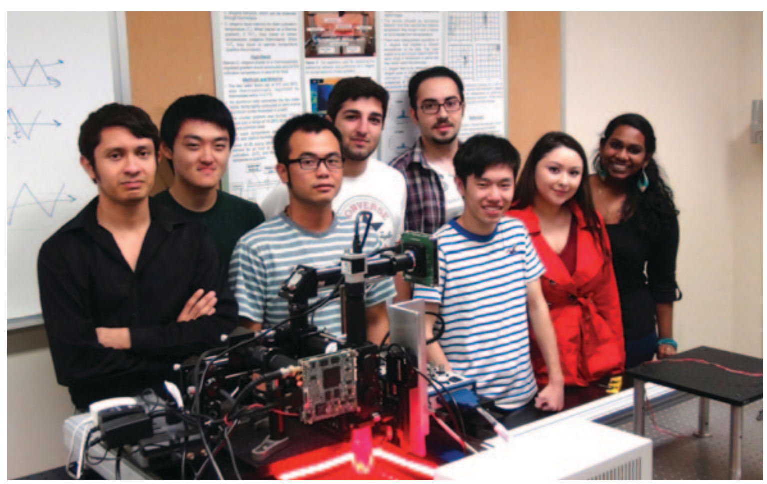


Fig. 2: Members of Elegant Mind Club with Worm Tracker under operation with the Temperature stimulation. Left to Right: Steve Mendoza, Mike Zhuang, Phat Mai, Haik Chatalyan, Shayan Niaki, Brian Lam, Roxana Chavarria, Addelynn Sagadeva.

the motion of a freely-moving C. elegans across a large ~20cm area in real time. The system is equipped with two high-sensitivity scientific CMOS cameras for neural-dynamic observation across two emission wavelength channels. This microscope translates its position on a stable system of linear stages and ball bearing slides, making it the first system of its kind to move three dimensionally around the sample, not vice versa.

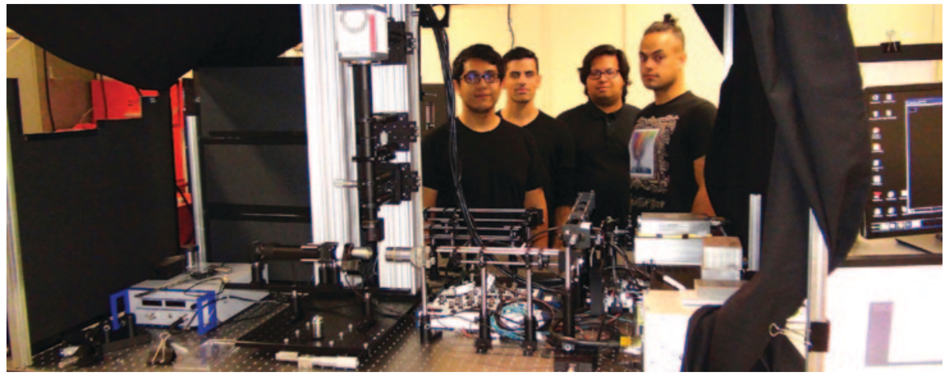


Fig. 3: Members of Elegant Mind Club with Spatial Light Modulator (SLM) – Bessel Beam (BB) microscope. Left to Right: Javier Carmona, Anthony Baldo, Ahis Shrestha, Blake Madruga.

### *(2) SLM-BB*

Sheet-Illumination has been a rapidly advancing field in microscopy for the past several years. The technique's benefits have led to many recent neuroscientific discoveries, and thus opened up sheet illumination as a well-known method in the bio imaging community. The Arisaka group is developing a software-configurable Bessel Beal (BB) sheet illumination microscope based on a spatial light modulator (SLM). Using a SLM provides massive flexibility in the imaging technique, granting the user ability to optimize beam characteristics to image neural activity across multiple spatial and temporal scales. Such open parameter space makes this imaging system suitable for capturing data from many major model organisms in the highest possible resolution, in multiple scientifically relevant ways.

## Nanoscale thermometry

### CHRIS REGAN GROUP

Chris Regan's group has been investigating nanoscale thermodynamics in hot wires. This year they demonstrated a thermometry technique with record-setting spatial resolution.

The physics underlying their technique is the same as that employed by Fahrenheit's glass-bulb thermometer, which uses the calibrated thermal expansion of mercury to indicate temperature. Such a device is too clumsy to map temperature on sub-micron length scales, but thermal expansion is a well-characterized, near-universal property of solids. By measuring thermal expansion, one can turn almost any solid into a thermometer. By measuring thermal expansion precisely and locally, one can turn a solid into many thermometers, so that temperature variations across the solid can be detected. With this approach, scanning the themometer across the device-under-test becomes unnecessary. The device takes its own temperature, functioning as a collection of localized thermometers.

Regan's group implemented this reasoning in an electron microscope, using the electron beam to measure the density of a heated, aluminum wire at fifty-thousand separate locations. The microscale aluminum wire thus became fifty-thousand nanoscale thermometers, each of which was queried individually. Capturing a temperature reading from each, they generated maps, thereby solving a well-known open problem: thermometry with nanoscale spatial resolution.

This technique, described in the February 6, 2015 issue of Science, promises to open new avenues of fundamental research. The ultimate, limiting resolution of their technique is only a few nanometers, which is smaller than the electron and phonon mean-free-paths in many materials. Since electrons and phonons are the main carriers of heat in a solid, this technique should be able to probe the crossover between normal, diffusive thermal transport and ballistic thermal transport. Moreover, in very tiny system it may be possible to see the breakdown of the usual, large-number, statistical assumptions of thermodynamics that allow the classical definition of temperature.

The technique has practical applications as well. Modern

Fig.1: This composite image shows merged density (grey) and temperature (color) maps of a 100 nm-wide polycrystalline aluminum wire. The temperature is computed from the density using aluminum's known thermal expansion. Lower densities appear at crystal-grain boundaries, which are atomic-scale features, and where thermal expansion has caused the aluminum to expand. One end of the wire (green) is near room temperature, and the other (orange) is 160 K warmer.

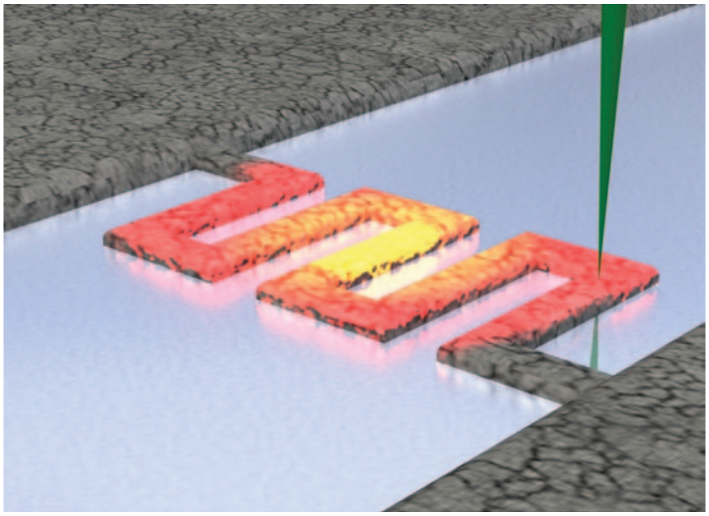


Fig. 2: In this artist's conception of plasmon energy expansion thermometry (PEET), a focused electron beam is shown penetrating a 100-nm wide, aluminum wire atop a thin glass window. The wire is heated by a current passing through it. The wire's temperature is mapped by scanning the electron beam, which has sufficient spatial resolution to detect atomic-scale grain boundaries in the poly-crystalline aluminum.

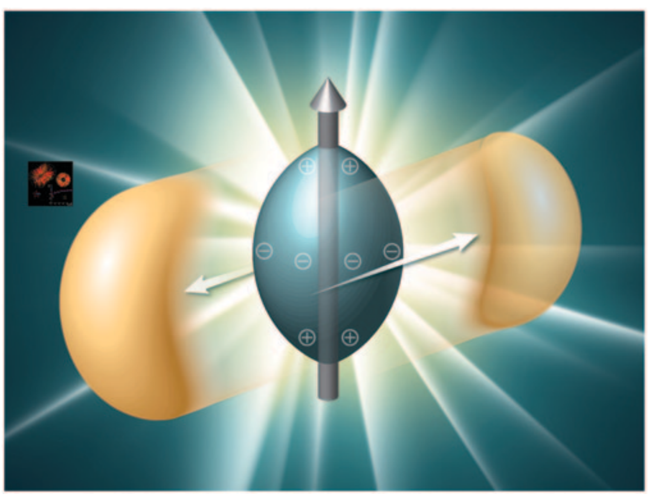
microprocessors have transistors with characteristic feature sizes of only 14 nm, and their performance is deliberately limited to prevent overheating. Currently thermal transport within individual transistors can only be studied numerically. Circuit designers must assume, despite evidence to the contrary, that heat moves at the nanoscale much as it does at the macroscale. In other words, the $300 billion semiconductor industry is designing its flagship devices using physical assumptions that have not been tested at the relevant length scales. With an improved understanding of nanoscale thermal transport, new methods for heat management may unlock better-performing and more efficient microelectronic devices. Regan's group is currently verifying their technique in silicon, and hopes to apply it soon to functioning transistors.

# Experimental Elementary Particles and Nuclear Experimental Physics

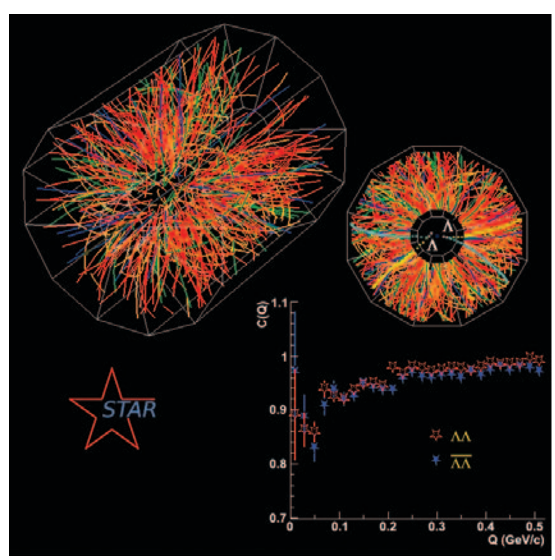
## Nuclear Physics Group

### HUAN HUANG GROUP

The UCLA Nuclear Physics Group (HUANG) has research programs on hot QCD (Quantum ChromoDynamics) matter of quarks and gluons and searches for neutrinoless double-decays. The group plays a leading role in the STAR (Solenoidal Tracker at RHIC) experiment at Brookhaven National Laboratory (BNL) Relativistic Heavy Ion Collider (RHIC). The neutrino program focuses on the CUORE experiment at Gran Sasso National Laboratory in Italy. We will highlight two recent papers from STAR with major contributions from the UCLA group that were published in the Physical Review Letters and were selected as editors' suggestions as well.



The first paper published in Phys. Rev. Lett. 114, 252302 (2015) was about the charge asymmetry dependence of pion elliptic flow and Chiral Magnetic Wave (CMW) phenomenon in heavy ion collisions. The Quark-Gluon Plasma (QGP) created in heavy ion collisions may have a chirality imbalance (unequal number of left- and right-handed quarks) locally due to vacuum transitions. Such chirality imbalance can couple to strong magnetic field (1015 Tesla) generated by the passing of spectator protons in off-center collisions. The dynamics of chirality and magnetic field can lead to chiral magnetic wave where an electric quadrupole may be formed (Figure left). Theoretically it was predicted that the CMW will lead to a charge asymmetry dependence of the pion elliptic flow. We have observed a charge asymmetry dependence of the pion elliptic flow from Au+Au collisions at RHIC and the difference depends on the collision centrality as expected from theoretical calculations. The UCLA group organized a workshop on chirality, vorticity and magnetic field in heavy ion collisions in January 2015 and another one is planned for February 2016.




The second paper published in Phys. Rev. Lett. 114, 022301 (2015) is about the first high statistics measurement of – correlations from Au+Au collisions. Strange baryon (hyperon) interactions play an important role in the equation of state for nuclear matter at high baryon density such as that in neutron stars. But experimental access to multiple strange baryons and their mutual interactions simultaneously has been

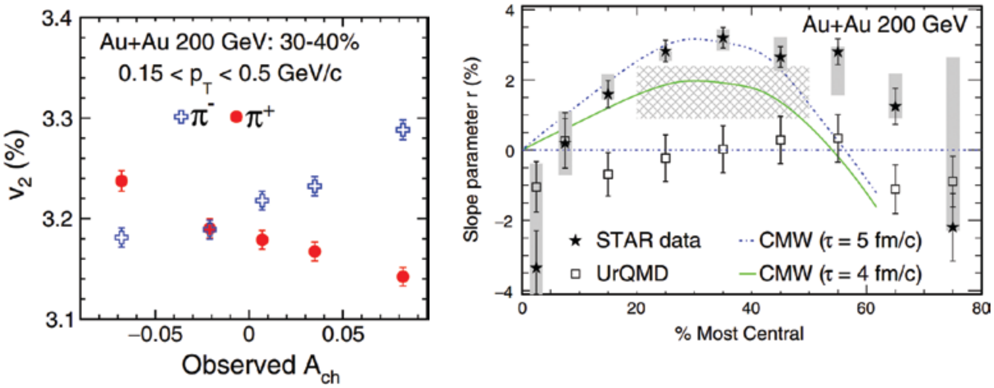



Fig.1: Left- Positive (negative) pion v2 linearly decreases (increases) with the increasing charge asymmetry, which is expected by a CMW model. Right- The slope parameter, r, as a function of centrality for Au+Au collisions with the center-of-mass energy = 200 GeV. Also shown are a conventional model (UrQMD) and the calculation with the CMW with varied duration times.

very limited. In heavy ion collisions many strange baryons are produced in central collisions and through the correlation measurement we can learn about their interaction potential. Our measurement indicated that the – interaction is relatively weak and unlikely to be strong enough to form the stable H particle made of (uuddss) quarks which has been a subject of experimental searches since 1978. We pioneered the use of heavy ion collisions as a hyperon factory to study hyperon interactions. tion of topological excitation of the QCD vacuum, an intrinsic characteristic of the non-Abelian gauge field theory. The UCLA nuclear physics group will continue to explore this physics topic in the coming years.

# Particle Physics Energy Frontier Group

**ROBERT COUSINS, JAY HAUSER, DAVID SALTZBERG**

Researchers: Mikhail Ignatenko, Slava Valuev

## UCLA studying nature at the highest energies

For many years, physicists have been using collisions between particle beams to understand the fundamental physics of our universe at the smallest distances and highest energies. A theory called the standard model emerged in the early 1970s, and since then the theory has withstood all experimental tests with spectacular success. Our UCLA team has participated in experiments that have tried to find deviations from the standard model at the high energy frontier since the 1990s. Rather than finding such deviations, we participated in discoveries that have cemented the standard model: in 1994 the discovery of the heaviest known particle, the top quark, and in 2012 the discovery of the capstone of the standard model, the Higgs boson.

The UCLA group works on the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC), located outside of Geneva, Switzerland. This experiment electronically records details about the type, the direction, and the energy of the many particles that are created in the collision of counter-circulating proton beams.

The study of the LHC collisions is very challenging in many ways: the rate of proton-proton collisions is about a billion per second. Since each collision that is recorded produces about a megabyte of data, to record all the data would require a petabyte per second. To reduce this otherwise unmanageable data flow, a small percentage of collisions that contain interesting features are selected for recording. One of the most robust ways to do this is to select the rare collisions that contain energetic particles of a special type known as muons. The muon particles penetrate matter more easily than any other charged particle, and so the apparatus is built to filter out other particles on the inside of the CMS detector and detect the muons on the outside. From the scale in Fig. 1 it is clear that the system is enormous. The muon detector as a whole is composed of many hundreds of individual detector devices, each having an area between about one-third to five square meters.

Handling all aspects of muon detection is a specialty of the UCLA group. Members of our group lead the CMS muon project, build muon detectors and their electronics, run the apparatus around the clock at the CERN laboratory, and optimize the measurement of the muon particle characteristics. The collisions that contained muons were crucially important for the discovery of the Higgs particle, and for subsequent detailed investigations of its properties such as mass, spin, and couplings.

After the first major running period of the LHC in 2010-2012, the accelerator was shut down for two years while undergoing major renovations to increase its proton-proton energy from 8 to 13 trillion electron volts, and to double the rate of collisions. Meanwhile, the UCLA group led the renovation of part of the CMS muon system that added additional detectors and improved electronics. Starting in 2015, the second LHC run has begun and the accelerator has been ramping up the rate of collisions. Among other analysis topics, the UCLA group has been looking at the rate of production of pairs of very energetic muon particles. A peak in the distribution of Lorentz-invariant mass of muons will indicate the presence and mass of a very short-lived particle that cannot be detected directly. In the past, such peaks have led to very significant discoveries that have resulted in Nobel prizes. In

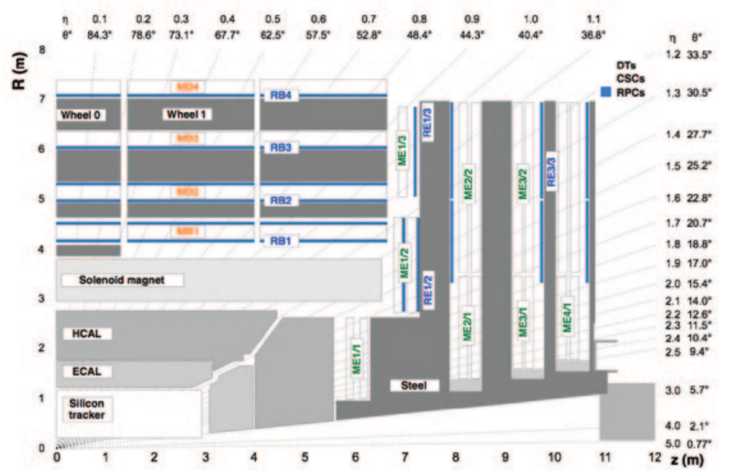



Fig. 1: A quadrant of the CMS detector, emphasizing the three muon detection technologies, Drift Tubes, Cathode Strip Chambers, and Resistive Plate Chambers, that are employed. In addition, a tracker detector, used for precisely measuring the trajectories of charged particles, and two calorimeter detectors (ECAL and HCAL), used for measuring the energies of all non-muon particles, are located closer to the region of proton-proton collisions at the origin (0, 0).

the 2015 data, a first look at this distribution is shown below in Fig. 2. Several theories of physics beyond the standard model predict an additional heavy particle that decays to muon pairs. New postdoc Alice Florent and graduate student Chris Schnaible, shown in Fig. 3, are working on the possible detection of such a particle, known as the Z-prime (Z') which could show up at the high end of this plot once the CMS experiment has collected a sufficient amount of data.

One of the unusual aspects of this science is that the CMS experiment itself is located nine time zones from UCLA. To participate effectively in the daily work of the experiment, many of the researchers are resident in the Geneva area, where they work closely with all of their collaborators at the world's premier particle laboratory, in an atmosphere of tremendous excitement and activity. The professors in the group are at CERN at least during summers, and commute frequently to meetings. With faster computer networks, video conferencing is also used on a daily basis to collaborate with physicists from other institutes on these global experiments. Typical CMS data analysis samples range from terabytes to petabytes in size, and so data analysis jobs are submitted to a sophisticated worldwide LHC computing grid. Graduate students in the group typically spend one or two years at CERN getting intimately familiar with the experiment and the data analysis tools, and when they are up to speed they may return to Los Angeles to finish their work. As the CMS run goes on for several years accumulating a large sample of collisions, and plans are to continue the LHC improvement program even ten or more years from now, our group is considering gradually shifting its center of gravity towards the UCLA campus.

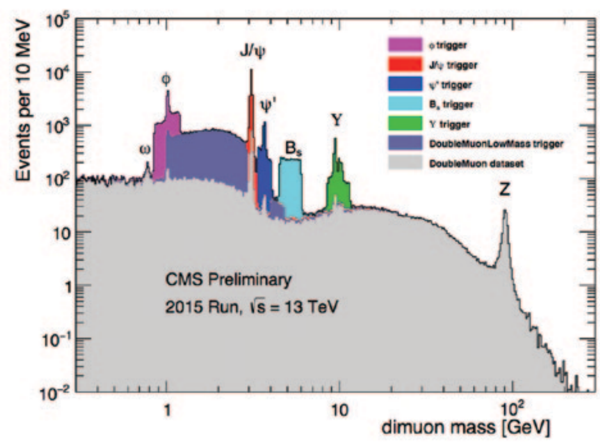



Fig. 2: The Lorentz-invariant mass distribution of pairs of muon particles observed in proton-proton collisions at center-of-mass energy 13 TeV using a small sample of CMS detector data collected in early 2015. Peaks are seen at the masses of particles that decay into muon pairs; several of these represent past Nobel prize-winning discoveries. Additional structure below 10 GeV is due to a variety of collision selection criteria (listed in the figure as triggers).

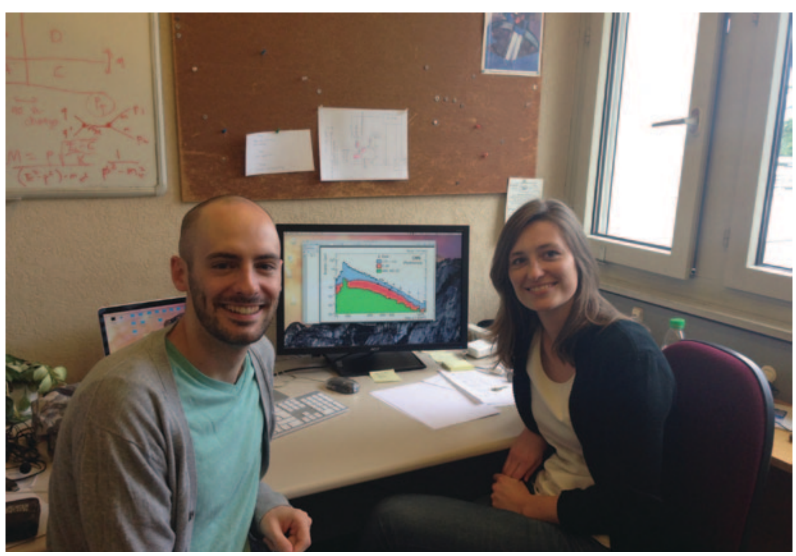


Fig. 3: Two members of the Z-prime search team from UCLA. Pictured from left to right are Chris Schnaible and Alice Florent.

# Bi-Polar Search for Neutrinos

## DAVID SALTZBERG GROUP

Dr. Stephanie Wissel, a postdoctoral scholar in Professor David Saltzberg's research group traveled close to both Poles this year, where she furthered their effort to build neutrino telescopes using Antarctic and Arctic Ice. From November through January, she deployed with UCLA, University of Hawaii, and others as part of a NASA, NSF, and DOE funded team to assemble and launch the ANITA-3 long-duration balloon payload. The apparatus spent 22 successful days aloft making observations.

As summer moved northward, Wissel joined a small team led by former UCLA Ph.D. student, Professor Abigail Vieregg of the University of Chicago, to test a new kind of neutrino telescope. They built and lowered a phased antenna array into the Arctic ice at the NSF Summit Station, located in the center of Greenland. We wish Dr. Wissel the best as she took up a faculty position at Cal Poly in San Luis Obispo for the upcoming academic year.

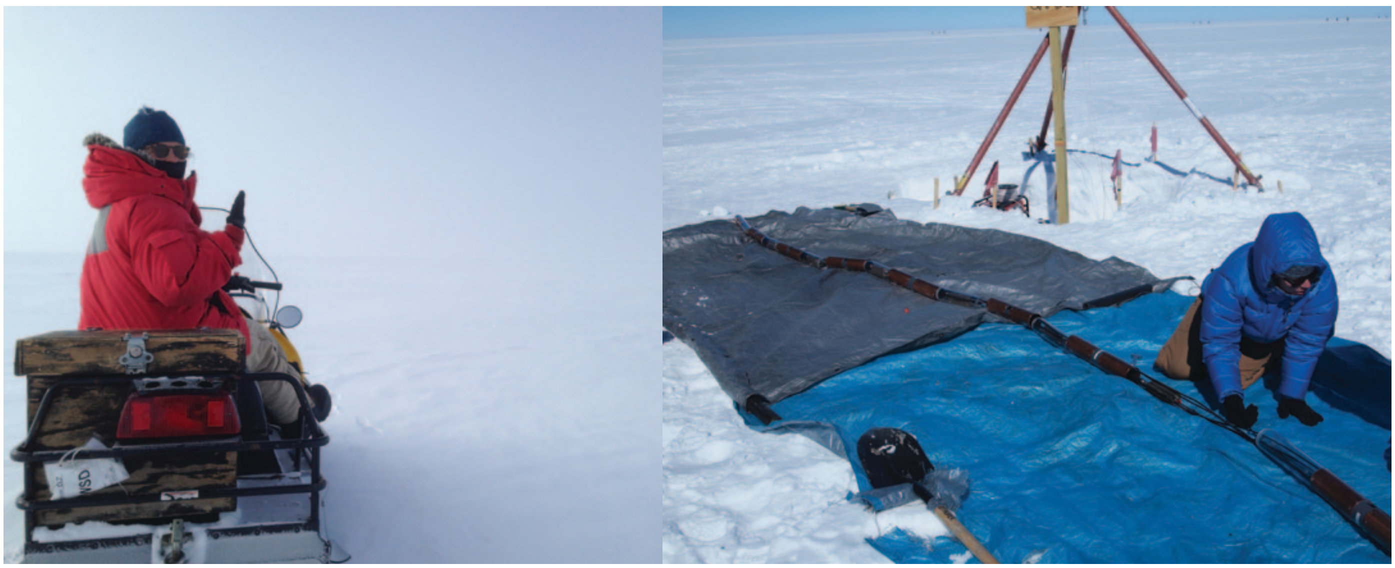


Fig. 1: This academic year, Dr. Stephanie Wissel helped conduct and advance experimental searches for astrophysical neutrinos in both high latitudes: December 2014 on the West Antarctic Ice Sheet Divide (left) and June 2015 in Summit, Greenland (right).

# Hanguo Wang's group Noble Liquid Detector Lab for Rare Event Searches

One of the biggest open questions of modern astrophysics is the nature of an invisible form of matter called dark matter. It is five times more abundant than ordinary matter in the Universe but has so far eluded all direct detection efforts, which has pushed physicists to build more massive and more sensitive detectors.

Hanguo Wang's group participates in two of the major efforts: XENON and DarkSide, both international collaborations utilizing dual-phase (liquid-gas) noble liquid time projection chambers (TPCs). They detect scintillation and ionization signals induced by possible dark matter interactions in a target volume instrumented with highly sensitive photodetectors.

The XENON program, located underground at Gran Sasso National Laboratory (LNGS) in Italy, has been the world leader in direct dark matter detection. The latest iteration, XENON1T, is a fully approved next generation detector with a 3.5 ton liquid xenon target mass. Wang's team is responsible for designing the TPC, designing and testing the photosensor assembly system, and designing and constructing the high voltage feedthrough (HVFT). XENON1T is deep in the construction phase and is expected to start data-taking in late 2015.

The DarkSide program is similar to XENON, but uses liquid argon as the target mass. Hanguo Wang leads a team of graduate students and postdcos that is deeply involved in the DarkSide experiment. The current iteration of the experiment is DarkSide-50, a liquid argon Time Projection Chamber (TPC) with 50 kg active volume, which published its first physics results in Fall 2014, setting the most sensitive WIMP (Weakly Interacting Massive Particle, a well motivated class of dark matter particles) detection limit using an argon target to date. Following the publication, the collaboration installed its calibration insertion system, allowing for detailed studies of the detector response to background radiation and to potential WIMP interactions. Postdoc Yury Suvorov played a key role in the installation process. In March and April of 2015, the UCLA team (composed of Hanguo Wang, postdocs Yury Suvorov and Andrew Renshaw, and graduate students Alden Fan and Yi Wang) worked around the clock and around the world (some of the team were on-site, while others were remote) to replace the target material of the DarkSide-50 detector with underground argon (UAr). In naturally occurring atmospheric argon (AAr), the radioactive Ar-39 contamination is prohibitively high (1 Bq/kg) for large scale Dark Matter detectors, while in UAr the Ar-39 content is drastically reduced, allowing for far more sensitive dark matter searches with an argon target. The installation of UAr in the DarkSide-50 experiment was a major milestone for DarkSide. Immediately following the UAr fill, DarkSide began its second dark matter search campaign. From 70 days of data, DarkSide-50 remained background free and found no potential signal events in the WIMP search region, improving its WIMP sensitivity by a factor of 3. It also made the most sensitive measurement of the Ar-39 level in UAr to date, showing that the isotope is depleted by a factor 1.4 x 10^3 compared to AAr. These results were released to the public in Fall 2015, representing the second major result of the DarkSide-50 experiment. Alden Fan was the principal analyst for the paper, working in close collaboration with the other members of the UCLA team as well members of the DarkSide collaboration around the world. The results pave the way for future multi-ton scale liquid argon dark matter detectors, including DarkSide-20k, a 20 ton detector, and ARGO, a 200 ton detector. The design of the DarkSide-20k detector has begun, with Hanguo Wang playing a central role in the design effort.

In August 2015, Andrew Renshaw began a faculty position at the University of Houston and continues to collaborate on the DarkSide experiment.

# Theoretical Elementary Particles

## ALEXANDER KUSENKO

In a recent paper, which was published and highlighted this year in Physical Review Letters as "Featured in Physics" and "Editor's suggestion", Alexander Kusenko, the UCLA students Louis Yang, and a recent Ph.D. graduate of UCLA Lauren Pearce explored a new phase in the evolution of the universe, which they called a Higgs relaxation. The paper pointed out that the recent measurement of the Higgs boson mass at the LHC implies the possibility of a new epoch in the early universe cosmology, during which the Higgs field undergoes a coherent motion. The epoch of Higgs relaxation occurring at the end of inflation and during the first stages of reheating may be responsible for the observed matter-antimatter asymmetry of the universe. In the papers that quickly followed up on this original idea, it was pointed out that other scalar fields, including an axion can play a similar role as well. This work received a broad coverage in the press with articles in Washington Post, Scientific American, Astronomy Magazine, etc.

Identifying the nature of cosmological dark matter is an important scientific problem. Although we know that most of the matter in the universe is not made of ordinary atoms, the identity of dark matter remains a mystery. One intriguing possibility that has received a lot of attention is that dark matter exhibits an asymmetry similar to the matter-antimatter asymmetry of the universe. Together with two former UCLA students, Kalliopi Petraki (now a faculty member at University of Massachusetts, Amherst) and Lauren Pearce (now a postdoc at University of Minnesota), Alexander Kusenko explored the astrophysical signatures that can help discover this form of dark matter.

Alexander Kusenko is an active participant in the work and the governance of Aspen Center for Physics, where he was elected for a third 5-year term. He also serves as Chair of the Organizing Committee of the Particle Astrophysics and Cosmology Including Fundamental Interactions (PACIFIC) symposium that is held annually at the University of California R. Gump Research Station in French Polynesia. This conference is often attended by some present and former UCLA graduate students and postdocs. In addition, Alexander Kusenko is a member of Kavli Institute for the Physics and Mathematics of the Universe (IPMU) in Japan.

## JOHN CORNWALL

Professor Cornwall is working on long-term projects to understand non-perturbative Quantum Chromodynamics (QCD), the theory of how quarks are permanently confined into observable particles such as protons and neutrons. QCD is a complicated non-linear theory of quantum fields called gluons that bind quarks together; QCD shows asymptotic freedom, a special property that is crucial to understanding confinement and not valid for other theories such as quantum electrodynamics. Earlier, Cornwall and collaborators showed how to remove the ambiguities of QCD coming from gauge transformations of gluons, and more recently Cornwall has shown how to implement dimensional transmutation (elimination of the unobservable coupling of gluons to each other in favor of an observable mass) directly in the equations of motion for the gluon field, a previously unsolved problem. He recently studied a six-dimensional field theory that shares the critical property of asymptotic freedom with QCD, but is otherwise much simpler, and illustrated dimensional transmutation in that theory. In his latest work this year, he has studied in QCD in three dimensions, which has many similarities as well as many differences from QCD in our universe (with four dimensions, three space and one time), and resolved another previously unsolved problem concerning the behavior of gluon propagation.

This year, Cornwall was co-organizer of the international workshop called QCD-TNT4: Unraveling the Organization of the QCD Tapestry.

## CHRISTIAN FRONSDAL

### *1. Formation of a model Black Hole*

The approach to stellar structure based on laboratory science was recommended by the American physicist in Homer Lane in 1875. Polytropic gas spheres have dominated almost all model building since they were first introduced by Emden in 1907. Now Fronsdal (fronsdal.physics.ucla.edu) has proposed somewhat more realistic models based on the van der Waals equation of state. These models, like most actual planets and stars have gaseous atmospheres and a condensed core. With the loss of energy the atmosphere condenses on the surface and the metric turns Schwarzschild in the limit when space empties outside the surface. The condensed core remains physical (there is no horizon), with finite density and increasing pressure, until and if the limit is reached and a Black Hole is formed. Till then remnants of the atmosphere continue to condense on the surface, but nothing "falls into a Black Hole". Greater realism undoubtedly require several phase transitions and, of course, multiple components etc.

### *2. The canonical structure of hydrodynamics*

An action principle formulation of hydrodynamics was created recently (Annual Report 2014). Focusing on canonical structure it can be derived in just a few lines. The equation of continuity can be included among the Euler-Lagrange equations only if the dynamical variables include a density and a scalar velocity potential, which accounts for two degrees of freedom. Ordinary hydrodynamics has 4 degrees of freedom so that only 2 remain to be accounted for. (The usual velocity field, subject to first order equations of motion, has 3 degrees of freedom, with the density that makes 4.) A vector field with just two degrees of freedom was introduced by Ogievetskij and Palumbarinov in 1964; it was introduced into string theory by Kalb and Ramon and it was used by Regge et al (1976) in their work on vorticity. With this bit of insight the Lagrangian for hydrodynamics (fronsdal.physics.ucla.edu) can be written down immediately.

## SERGIO FERRARA

The activity was mostly at the interface between Cosmology and Spontaneously Broken Supersymmetry.

There are important clues that the Universe, described within a Friedmann-Lemaitre-Robertson-Walker framework, underwent an early phase of accelerated expansion that is commonly referred to as inflation. During this epoch, space-time geometry was akin to de Sitter phase, which cannot accommodate unbroken supersymmetry. Supersymmetry breaking is thus central to the picture, which also poses the problem of realizing this type of constructions in supergravity.

The main novelty of the research carried out during the last Academic Year lies in the use, within four-dimensional supergravity, of non-linear realizations of local supersymmetry based on constrained superfields. These can describe incomplete multiplets, where some superpartners are very massive and thus no longer dynamical. In this fashion the goldstino, the Goldstone fermion of supersymmetry, can undergo the superHiggs effect leading to a massive gravitino without being accompanied by scalar superpartners. The first construction of this type, presented in [1], was a supersymmetric extension of the Starobinsky model of inflation. The result was later extended to a wide range of scalar geometries in [2], which also elucidated some links with the string landscape. More recently, the scale symmetry of de Sitter geometry was used to build a supergravity model with merely a positive cosmological constant and an axion-dilaton pair of fields [3].

*[1] I. Antoniadis, E. Dudas, S. Ferrara and A. Sagnotti, The Volkov-Akulov-Starobinsky supergravity, Phys. Lett. B733 (2014) 32 [arXiv:1403.3269 [hep-th]].*

*[2] S. Ferrara, R. Kallosh and A. Linde, Cosmology with Nilpotent Superfields, JHEP 1410 (2014) 143 [arXiv:1408.4096 [hep-th]].*

*[3] S. Ferrara, M. Porrati and A. Sagnotti, Scale invariant Volkov–Akulov supergravity, Phys. Lett. B749 (2015) 589 [arXiv:1508.02939 [hep-th]].*

*Sergio Ferrara was awarded the 2015 Margherita Hack prize, awarded by the Italian Ministry of Arts and Culture and by the National Institute for Astrophysics.*

# Experimental Plasma and Beam Physics

## Inverse Free Electron Laser (IFEL)

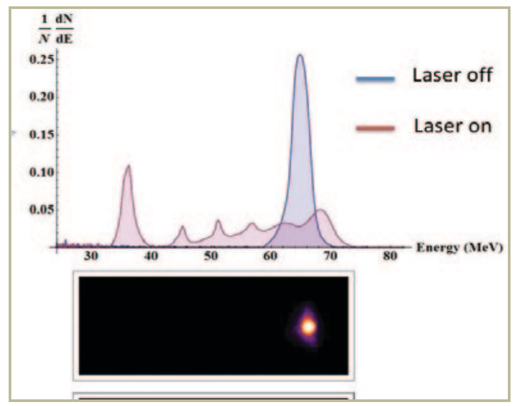
### PIETRO MUSUMECI

Following up the recent success in the demonstration of high gradient high energy gain using the Inverse Free Electron laser (IFEL) accelerator with the Rubicon experiment at Brookhaven National Laboratory (Duris et al. Nat. Comm. 5, 4928, 2014), the Musumeci group has been investigating the possibility of reversing the interaction to extract a large fraction (> 50 %) of the beam energy with possible applications to high efficiency high average and peak power radiation sources. Among different laser-based high gradient accelerators, unique advantages of the IFEL include the fact that the laser-electron interaction happens in vacuum (no plasma or no nearby structures) and there is no need for a tight laser focus (far-field interaction). This implies extended interaction lengths and very high efficiency of energy transfer between the laser and the electrons.

A new mechanism called TESSA (Tapering Enhanced Stimulated Superradiant Amplification) has been identified to describe the physics of high gradient deceleration in a strongly tapered undulator and a first experimental test (the Nocibur experiment) is underway at the Accelerator Test Facility site to demonstrate 40% energy extraction from a relativistic electron beam. Just like in free-electron lasers, the radiation wavelength can be tuned by varying the e-beam energy. Given that typical high power lasers and FELs have efficiency lower than few per cent, such high efficiency calls for various applications of TESSA across all regions of the electromagnetic spectrum, such as high average power visible and near infrared lasers, EUV sources for lithography as well as high peak power sources in the x-ray and in the THz region of the spectrum.

On campus, the exquisite quality of the beams produced at the UCLA Pegasus Laboratory has enabled a new generation of laser-driven dielectric acceleration experiments. Funded by a large Moore foundation collaborative grant including SLAC, Stanford and European National Laboratories and Universities the Musumeci group is using ultrahigh brightness beams to study injection and acceleration of particles in miniaturized laser-driven "accelerator on a chip".

The efforts are directed to increasing the interaction length and obtain higher gradient and energy gains as well as in the generation and characterization of the extreme beam parameters required by these kind of accelerators. Novel beam diagnostics have been developed to measure ultrasmall beam sizes (less than 4 micron across) and sub-10 nm normalized emittances for the sub-pC charge beams generated operating in the "cigar" regime the new Pegasus RF photoinjector (D. Alesini et al. Phys. Rev. ST Accel. Beams 18, 092001, 2015).




## Plasma Advanced Accelerators

### CLAUDIO PELLEGRINI

During the last year I continued my work, supported by a DOE grant and done in collaboration with a UCLA Graduate student, Claudio Emma, and SLAC scientists, for the development of X-ray free-electron laser (XFEL). Our study is mainly focused on methods to increase hundred times the XGEL peak power, from the present level of 20 to 50 GW to about 5 TW. This is an important step for single molecule imaging and nonlinear X-ray science, two areas of great scientific interest and only recently made possible by the X-ray free-electron laser.

The XFEL has been made possible by my pioneering theoretical work and the experimental work done at UCLA by the Pellegrini-Rosenzweig advanced accelerators/plasma group. For this work and my other contributions to accelerator physics I have received the 2014 Enrico Fermi Presidential Award *(http://science.energy.gov/fermi/award-laureates/2010s/pellegrini/)* with the citation "For pioneering research advancing understanding of relativistic electron beams and free-electron lasers, and for transformative discoveries profoundly impacting the successful development of the first hard X-Ray free-electron laser, heralding a new era for science".

I have also given an invited talk at the June 2015 Nobel Symposium on Free-electron Lasers. My talk is available as a Powerpoint presentation and video at the Symposium site
*http://agenda.albanova.se/conferenceDisplay.py?confId=4905* .

# High Energy Density Plasma (HEDP) Physics Group

## CHRISTOPH NIEMANN

### *From bow-shocks in space to collisionless shocks in the laboratory*

Ever since the discovery of the cosmic rays by Victor Hess in 1912 the question of particle acceleration in space has been following generations of physicists. Theoretically proposed mechanisms for these efficient space "accelerators" inserted collisionless shocks into the picture – a type of shock wave that uses the ambient electromagnetic fields as agents for the isotropization of the bulk kinetic energy of plasma flows. These shocks are unlike their hydrodynamic counterparts in which the energy is dissipated through binary particle collisions and therefore the underlying physics is set apart. Magnetized shocks propagate over large distances in space, anywhere around planets magnetospheres or in supernova remnants through tenuous ambient plasmas and magnetic fields. The closest example is the bow shock created by the solar wind impacting Earth's magnetosphere.

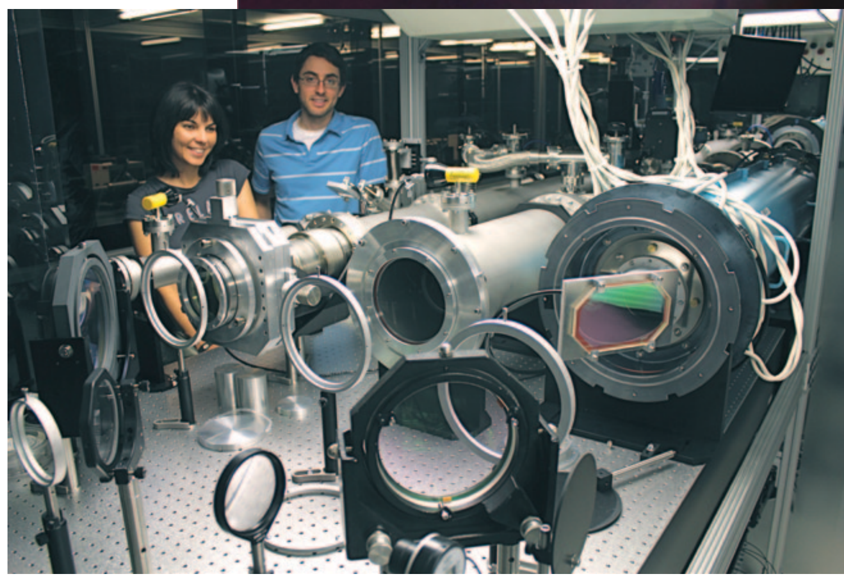


Fig. 1: Fast-shutter photograph of the laser-plasma cloud exploding into the LAPD plasma (left) and photograph of the new high-energy laser system in the STRB.

Well-scaled laboratory experiments can reproduce the physics of collisionless shocks in a controlled setting, despite orders of magnitude difference in spatial and temporal scales. Laboratory experiments can provide insight into the microphysics of shocks that can only be limitedly studied by spacecraft, including the formation of a shock, their dissipation, and the nature of plasma turblence. Such laboratory experiments are challenging, since they must simultaneously provide a highly magnetized plasma and a high-pressure piston.

Professor Christoph Niemann and his team embarked on such a journey with the aid of a new facility, uniquely combining a high-energy kilojoule-class laser and the 20 m long plasma column in the Large Plasma Device (LAPD), both located in the STRB at UCLA. The intense laser beam irradiates a target submerged in the LAPD plasma column and causes an energetic burst of plasma that explodes into the magnetized background at high speed. From the start of its expansion the highly-conducting laser plasma creates a diamagnetic cavity, voided of ambient plasma ions and magnetic fields, which are expelled to the edge of this bubble and generate a compressed magnetic pulse propagating further into the background. Very much like in the case of shocks in space, collisionless coupling between the fast streaming debris ions and the stationary background is facilitated through transverse electric fields (Larmor-coupling fields) setup by their relative ion currents. At some stage in its evolution, with help from Larmor coupling and magnetic instabilities, the energy is transferred to the background until the debris ions stop and the magnetic pulse evolves into a shock that is fully carried by the ambient ions.

The group has recently observed the first collisionless shock propagate across the magnetic field in the LAPD device [C. Niemann et al., Geophys. Res. Lett. 41 (2014)]. Figure 2a shows stack plots of the measured magnetic field for various distances x from the laser target. Each trace shows the typical signature of a diamagnetic laser plasma cavity, including an initial field compression followed by complete field expulsion. The magnetic pulse ahead of the cavity travels at 370 km/s, which is super-Alfvénic (MA = 2.2). The magnetic piston, i.e., the leading edge of the diamagnetic cavity, slows from 500 km/s near the target to 200 km/s in the center of the vessel. About 20 cm from the target, the magnetosonic pulse steepens into a shock and separates from the piston. The measured field compression of a factor of 2 is consistent with the Rankine-Hugoniot jump conditions for a shock. In comparison with expansion into vacuum (Figure 2b), the field compression is significantly larger with the ambient plasma and the leading edge of the magnetic pulse expands faster, indicating that the pulse is carried by ambient ions, which have been accelerated by the piston. Simultaneously, the trailing edge of the pulse (i.e., the piston) moves much slower, indicative of energy transfer to the ambient plasma. The spatial profile (Figure 2c) shows a ramp with a width of a few millimeters, similar to shocks in space. In comparison to earlier times before the shock is formed (blue dashed line in Figure 2c), the structure of the shock shows a significantly steeper and faster ramp, and a much broader, more compressed pulse.

In the future, the group plans to use this new experimental platform to study shocks in different geometries (e.g. so called quasi-parallel shocks along the magnetic field) and the acceleration of particles with relevance to cosmic rays.

The group consists of researcher Carmen Constantin, postdoctoral fellow Derek Schaeffer, and graduate student researchers Erik Everson, Anton Bondarenko, Eric Clark, and Peter Bauer. Undergraduate students Erik Knall and Lucas Hofer were also involved in the experiments. This work is performed in close collaboration with Professor Walter Gekelman's group, the Los Alamos National Laboratory, and the Lawrence Livermore National Laboratory.

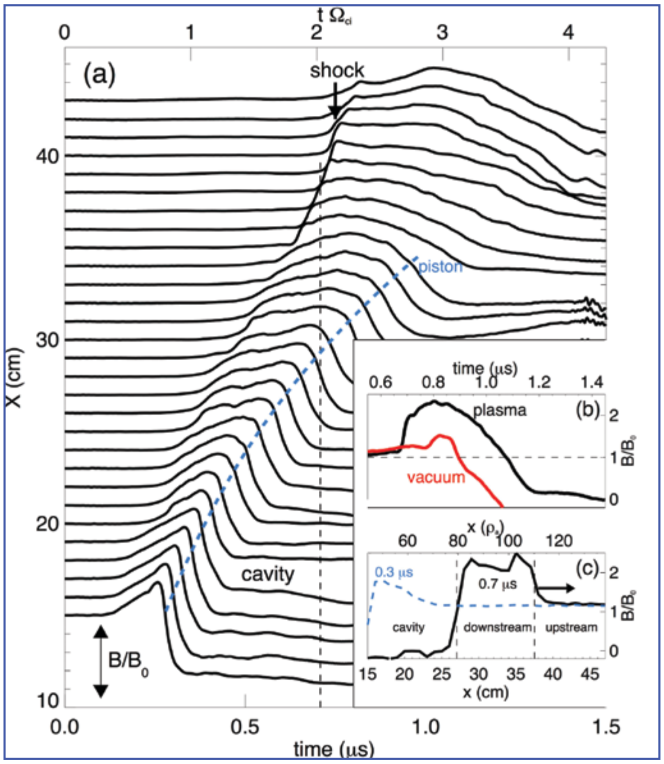



Fig. 2: First observation of a laser-driven magnetized collisionless shock in a laboratory plasma. (a) Stack plots of the magnetic field B as a function of time for various distances from the target. (b) Comparison of B(t) at x = 35 cm with (black) and without (red) the ambient plasma. (c) Structure of the pulse before (t = 0.3 μs) and after a shock is formed (t = 0.7 μs).

# Basic Plasma Physics Experiments

## Investigation of Magnetic Flux Ropes

### WALTER GEKELMAN, TIM DEHAAS, BART VAN COMPERNOLLE, STEVE VINCENA

Magnetic flux ropes are twisted bundles of electrical current and magnetic field, which can exist in magnetized plasmas. There are quite a few situations where multiple flux ropes exist simultaneously. If the magnetic ropes have strong enough magnetic fields they can mutually interact. The interaction results in the ropes twisting about each other, colliding and sometimes merging. In instances when they do collide magnetic field can be partially converted to other forms of energy such as flows, heat, fast particles and waves. Flux ropes routinely occur near the surface of the sun and in all probability every other star. Sometimes large magnetic ropes are ejected from the sun and if the timing and ejection angle is right they may come all the way to the earth where they are detected by probes on satellites. Under the right conditions individual ropes can be subject to the kink instability. The resulting motion can be violent enough to make them collide and produce bursts of magnetic field line. Our group at UCLA has been able to generate flux ropes in a large variety of numbers and sizes and can turn the kink instability on or off depending on the currents within them and the background magnetic field. The experiment can be reproduced millions of times and the electric and magnetic fields, plasma flows, temperature, density and currents can be measured at tens of thousands of spatial locations and time steps. When the ropes collide some of the magnetic field associated with them can be destroyed in process called magnetic field line reconnection. When this occurs magnetic field lines can rapidly diverge from one another and the region where this occurs is called a quasi-seperatrix layer (QSL). A QSL was observed for the first time in our laboratory. When the ropes collide violently the magnetic fields and flows become chaotic. In a recent experiment we made the ropes marginally unstable so the collision was periodic. Figure 1 shows a measurement of the QSL, and the electric currents during one such collision. Probes designed to measure the space charge electric field and calculations of the induced field from the currents allow calculation of the plasma resistivity. When the ropes collide the plasma resistivity to current flow jumps to values hundreds of times greater than what is normal under these conditions. This is the only experiment where this type of measurement of flux ropes is possible. This will lead to a better understanding of how the solar corona is heated and the interpretation of satellite data.


*1. W. Gekelman, E. Lawrence, B. Van Compernolle, "Three-Dimensional Reconnection Involving Magnetic Flux Ropes", Astrophys. Jour, 753, 131, (2012), B. Van Compernolle, W. Gekelman, "Morphology and Dynamics of Three Interacting Kink-Unstable Flux Ropes in a Laboratory Magnetoplasma", Phys. Plasmas, 19, 102102 (2012)*

*2. E. Lawrence, W. Gekelman, "Identification of a Quasi-Seperatrix layer in a Reconnecting Laboratory Magnetoplasma", Phys. Rev. Letters, 103, 105002 (2009)*

*3. W. Gekelman, B. Van Compernolle, T. DeHaas, S. Vincena, "Chaos in Magnetic Flux Ropes", Plasma Phys. and Control. Fusion, 56, 064002 (2014)*

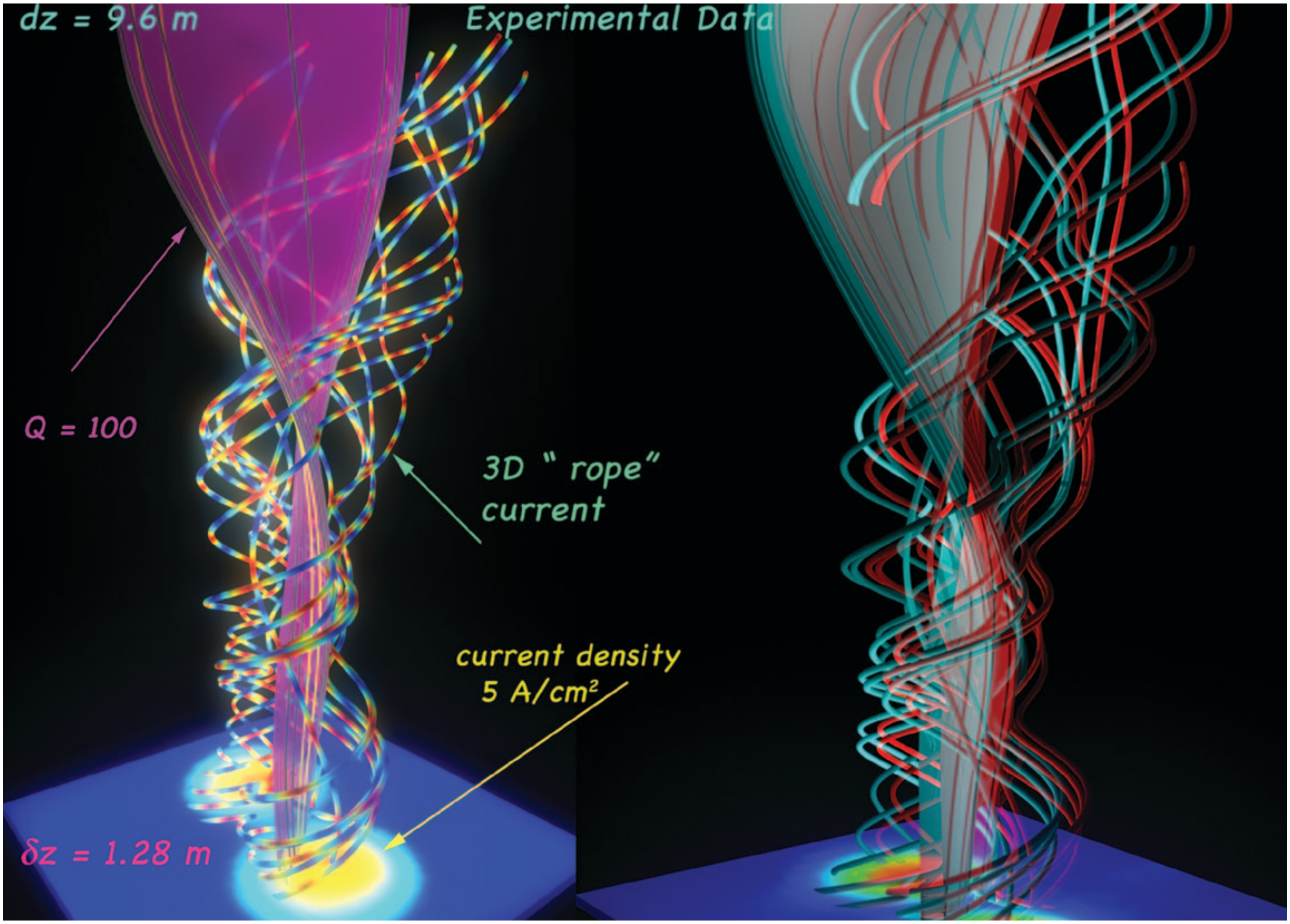



Fig. 1: The left hand (labeled) image is in true color and the right is a 3D anaglyph which must be viewed through a red/cyan pair of glasses. There are readily available in hobby shops. The ropes are generated at z = 0. The current density in a plane at δz = 1.28 m is shown as contours. The 3D currents are rendered as striped tubes. The QSL is midway between the ropes and appear every time they collide. A QSL of 100 means that by the time the field lines have travelled 11 meters to the end of the measurement volume they have separated by a factor of 50.

# Excitation of chirping whistler waves by a helical electron beam

**B. VAN COMPERNOLLE, J. BORTNIK, X. AN, W. GEKELMAN**

A major scientific problem of current interest is the determination of the dominant physical processes that drive the dynamic variability of the outer radiation belt. Resonant interactions between energetic electrons and whistler mode waves are thought to play an essential role. Experiments at LAPD have focused on the excitation of whistler waves by energetic electrons under various plasma and beam conditions. A recent result is the excitation of discrete frequency chirping whistler waves, which have been observed in space for decades known as chorus waves, but have up to now never been observed in the laboratory. The experiment identifies stringent conditions under which the discrete frequency chirping is seen. There is a strong dependence on beam density, plasma density and the guide field profile and magnitude. Examples of the rich variety of beam-generated wave activity is displayed in the spectrograms in the figure. The experiment allows, for the first time, to test under controlled conditions the leading theories in nonlinear whistler wave excitation. Van Compernolle et al, Phys. Rev. Lett. 114, 245002 (2015)

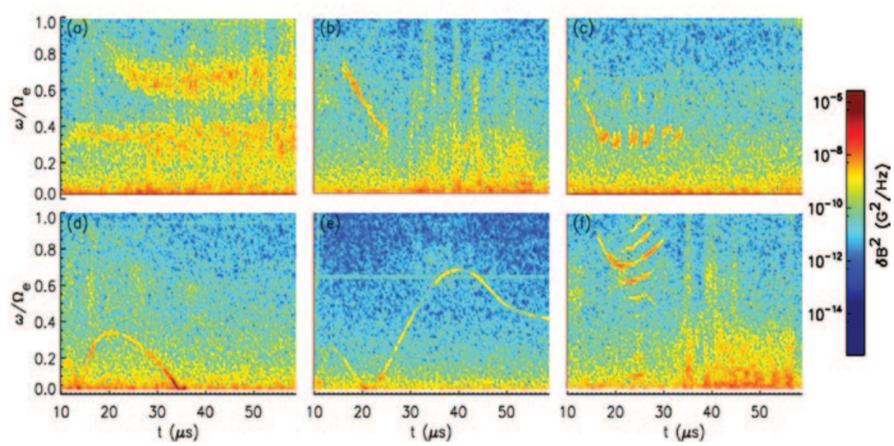



Fig. 1: Examples of spectrograms of whistler wave excitation. (a) broadband waves, (b) falling tone, (c) multiple consecutive chirps, (d) double hook, (e) long rising and falling tone, (f) chirps at multiple frequencies simultaneously.

# Resonant excitation of Alfvén waves by a spiraling ion beam

SHREEKRISHNA TRIPATHI, BART VAN COMPERNOLLE, WALTER GEKELMAN, PATRICK PRIBYL

Interaction of energetic-ions with large magnetized plasmas is a topic of fundamental and practical importance in fusion and space plasma physics. In fusion-grade magnetized plasmas, a variety of Alfvén waves are driven unstable by energetic-ions that are generated in bulk quantities by radio-frequency and neutral-beam-injection sources and as a byproduct of fusion reactions. These energetic-ions interact with Alfvén waves and significantly affect stability and energy-transport in fusion plasmas. In solar-wind and interstellar plasmas, energetic alpha-particles and Cosmic rays are believed to play a special role in the excitation of a number of plasma waves and heating of the ambient plasma. In recognition of this important research area, laboratory plasma experiments are carried out on the LAPD using an intense ion-beam source (25 kV, 10 A) that was developed in-house at the Basic Plasma Science Facility, UCLA.

In a recent laboratory experiment, the ion-source was used to obliquely inject a sub-Alfvénic hydrogen ion beam ($v_b$/vA = 0.2) into an ambient magnetized plasma on the LAPD. The ambient plasma had a mixture of dual-ion species (92% $He^+$ and 8% $H^+$). Measurements of the beam-profile were made at several axial locations in the plasma using a fast-ion collector that confirmed the propagation of a high-quality ion-beam with a helical trajectory. A typical beam profile is shown in Fig. 1(a). Although, a multitude of waves were driven unstable by the ion beam, our primary focus was on exploring the Alfvén wave. In this experiment, spectra of the beam-driven magnetic-fluctuations were recorded using a magnetic-loop probe at thousands of locations in a plane transverse to the ambient-magnetic field $B_{z0}$. The average spectrum of the magnetic-fluctuations over this plane is displayed in Fig. 1(b). Propagation of Alfvén waves in two distinct bands (labeled as LF and HF) is evident from the observed spectrum. This is a characteristic feature of Alfvén frequency spectra in a two ion-species plasma [Vincena, Phys. Plasmas 20, 2013, 012111]. In these experiments, the Doppler-shifted ion cyclotron resonance between spiraling $H^+$ ions and Alfvén waves was identified to be the most effective drive mechanism to excite the HF Alfvén waves. Typical pattern of magnetic-field-vectors of the HF Alfvén wave is shown in Fig. 1(c). As expected for the cyclotron-resonance of the wave with the spiraling ions, the wave-field pattern rotates in an azimuthal direction consistent with the left-handed polarization of the wave. Details of this wave-particle resonance are discussed in a recent publication from our research group.

*Tripathi et. al., Phys. Rev. E 91, 013109 (2015)*

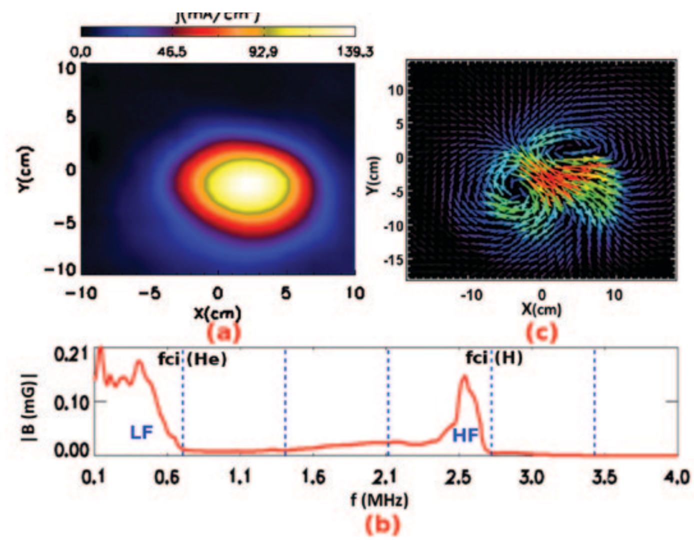



Fig. 1: (a) A fast-ion-collector measured profile of the H+ ion-beam (15 keV, 10 A, $B_{0z}$ » 1.8 kG, 7.5° injection-angle, 53° pitch angle, gyro-radius≈7.9 cm, $n_b$ = 5x$10^9$ $cm^{-3}$, ${}^{n}$LAPD≈$10^{12}cm^{-3}$) in the LAPD plasma. The profile was measured at a 5.0 m distance from the beam-extractor-grid. (b) Spectrum of the beam-driven magneticfluctuations manifests two distinct bands (labeled as "LF" and "HF") of Alfvén wave propagation. (c) Typical pattern of the magnetic-fieldvectors of the HF Alfvén wave evinces the existence of two current channels. The HF Alfvén waves have a left-handed circular polarization.

# Radio Frequency Heating

MICHAEL MARTIN, WALTER GEKELMAN, PATRICK PRIBYL, BART VAN COMPERNOLLE

Radio-frequency (RF) heating is expected to be a vital component of the International Thermonuclear Experimental Reactor (ITER), currently being constructed in the south of France. To achieve fusion conditions, the ITER design team plans on coupling up to 20 MW of RF power into the core of the ITER plasma. However, RF power losses to metal surfaces (e.g. limiters) can significantly reduce heating power delivered to the core plasma as well as cause destruction of vessel wall materials.

In order to study fusion-relevant wave and heating phenomena, a 200 kW RF amplifier has been constructed to launch fast waves in the LAPD plasma. The amplifier operates between 2 – 6 MHz with a 1% duty cycle. A picture of the RF amplifier alone and with the LAPD is shown in figure 1. The entire RF system has recently been used to study the problem above. Detailed two-dimensional measurements of the electric and magnetic fields have been performed using moveable probes both very close to the fast wave antenna and at a limiter several wavelengths away. These types of measurements are necessary for understanding basic physical processes occurring in fusion reactors and for benchmarking RF heating simulations. Figure 2 shows a plot of the plasma potential across the LAPD axis 108 μs into the RF pulse with electric field vectors overlaid. The LAPD offers a unique capability to make detailed measurements that are impossible to make in fusion devices.

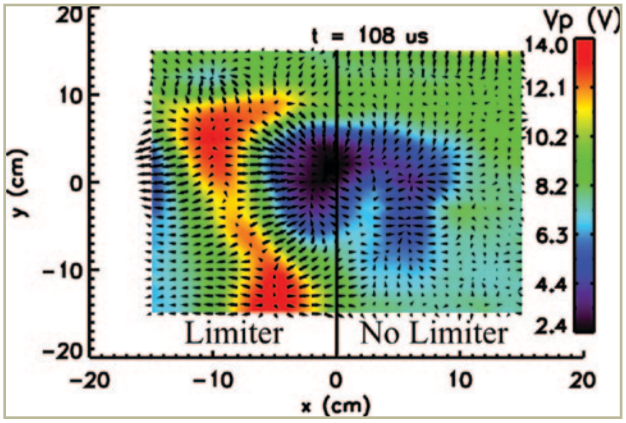



Fig. 2: Plasma potential in a plane across the LAP plasma axis between the antenna and limiter, located 32 cm axially from the limiter. The plasma potential shows a clear outline of the antenna structure (in red). The location of the limiter is indicated in the figure.

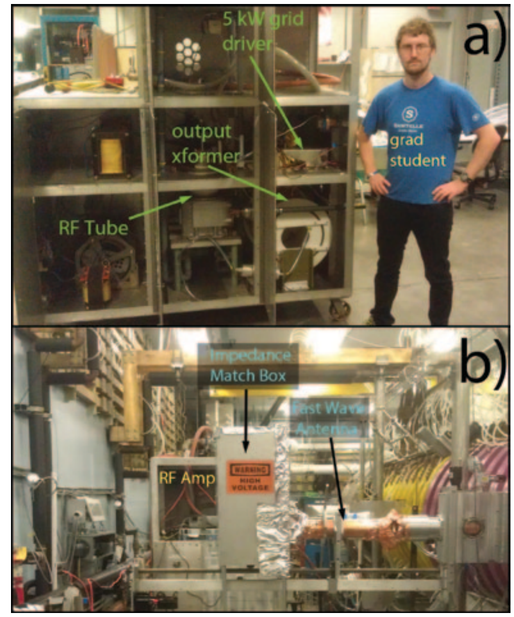



Fig.1: (a) Graduate student Michael Martin standing next to the 200 kW RF amplifier. (b) The RF amplifier driving the fast wave antenna connected to the LAPD.

## Troy Carter

Professor Troy Carter and his group perform research on fundamental processes in magnetized plasmas, in particular waves, instabilities and turbulence. Motivation for their work comes from terrestrial applications of magnetized plasmas, in particular magnetic confinement fusion energy, as well as natural plasmas found in space and astrophysical settings, for example accretion disk plasmas. Experimental work performed by the group makes use of frontier-class facilities, such as UCLA's own Basic Plasma Science Facility and tokamak experiments including the DIII-D experiment operated by General Atomics Corporation in San Diego.

A recent research highlight from the Carter group concerns the observation of a decay instability of Alfvén waves in LAPD. Alfvén waves are low-frequency modes in magnetized plasmas which can play fundamentally important roles in laboratory, space and astrophysical plasmas. In recent experiments, observations consistent with the decay of a single, large-amplitude Alfvén wave have been made, as shown in the Figure. This figure shows the spectrum of magnetic fluctuations in the experiment as the amplitude of the "pump" Alfvén wave is increased (x-axis). Above a threshold amplitude, two new coherent waves appear spontaneously; the waves have frequencies and wavenumbers consistent with a three-wave decay process. The observations, made by postdoc Seth Dorfman, are consistent with a particular theoretically-predicted decay channel (modulational decay) that has never before been documented in a laboratory experiment.

A second research highlight from the group comes from work on the DIII-D tokamak studying important instabilities called Neoclassical Tearing Modes or NTMs. NTMs are macroscopic instabilities of the magnetized tokamak plasma that arise when the plasma pressure is sufficiently large compared to the pressure (or energy density) associated with the confining magnetic field. These instabilities limit the ultimate pressure, and therefore fusion power, obtainable in current and planned fusion experiments such as the ITER device being constructed in Cadarache, France. The instability mechanism for these modes is strongly affected by transport processes: the mode creates a magnetic "island" and the flattening of the pressure profile within the island destabilizes the mode. Graduate student László Bardóczi, working closely with researcher Terry Rhodes, has made measurements of turbulence in the vicinity of NTM islands in DIII-D, demonstrating that the turbulence, and therefore turbulent transport, is modified by the presence of the island. This work will enable better understanding of the role of turbulent transport in the growth and saturation of NTMs, potentially informing strategies to avoid or minimize their impact on tokamak operation.

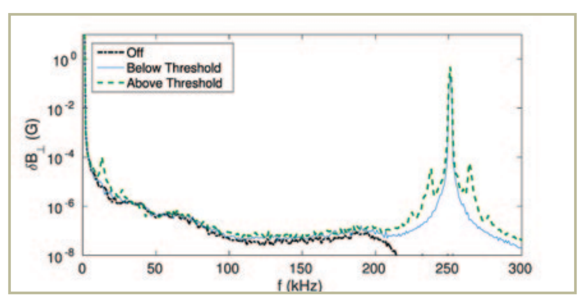



Fig.1: Magnetic fluctuation spectrum in LAPD during experiments in which an Alfvén wave (the pump wave) is launched with increasing amplitude (Antenna Current). Above a threshold amplitude, daughter waves are observed, produced by the decay instability.

# Theoretical Plasma Physics

## George Morales

### *Chaotic fluctuations in the DIII-D tokamak*

A recent publication by Drs. J. Maggs, T. Rhodes and Professor G. Morales [Plasma Phys. Control Fusion 57, 045004 (2015)] has conclusively established that the dynamics responsible for fluctuations in plasma density in the DIII-D tokamak is chaotic. This device is the U.S. flagship for fusion research operated by GA in San Diego. The finding is the result of an unexpected research journey that had its origin in basic heat transport experiments by Maggs and Morales, and their students, in the LAPD device at UCLA, a machine whose geometry and operational parameters are completely different from DIII-D. From the analysis of the basic experiments and subsequent theoretical developments, it was learned that the characteristic signature of chaotic phenomena is an exponential power spectrum that results from individual pulses that have a Lorentzian temporal shape. Furthermore, it was found that the dynamics leading to the observed anomalous transport could be elucidated using the permutation entropy analysis (C-H plane technique) developed by O. Rosso et al. [Phys. Rev. Lett. 99, 154102 (2007)]. This technique is an effective method to identify the various possible dynamical processes (coherent, stochastic, chaotic, fractional Brownian motion). In a characteristic C-H display, the vertical axis corresponds to the Jensen-Shannon complexity, C, and the horizontal axis to the

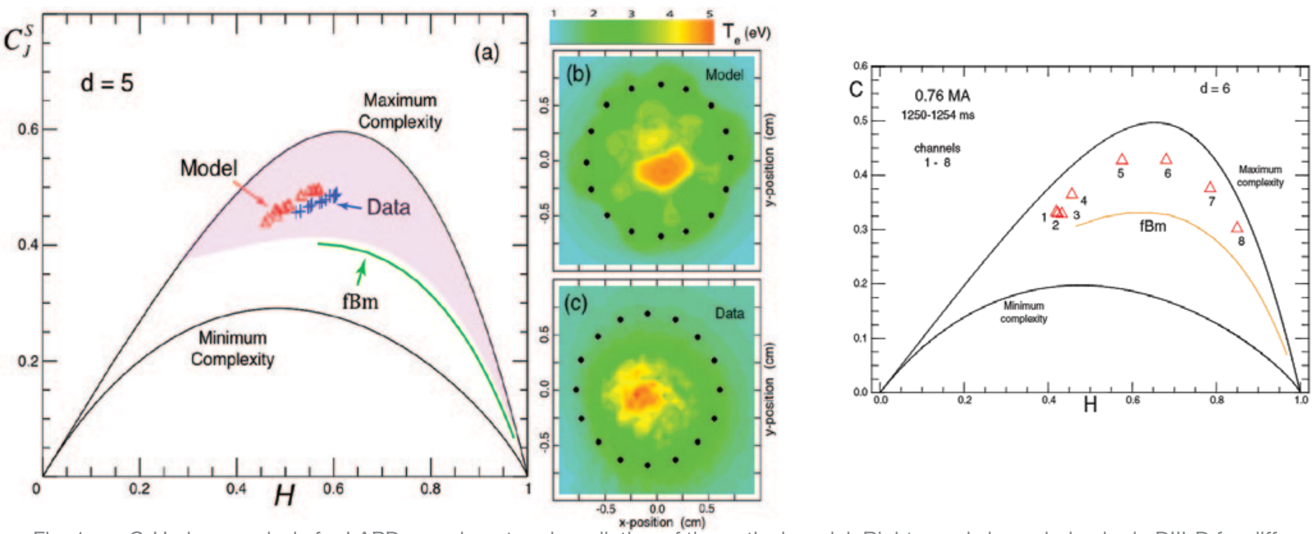



Fig. 1a-c: C-H plane analysis for LAPD experiment and prediction of theoretical model. Right panel shows behavior in DIII-D for different spatial locations.

normalized Shannon entropy, H. These quantities are obtained from the Bandt-Pompe probability distribution [Phys. Rev. Lett. 88, 174102 (2002)]. The analysis methodology developed for the LAPD was applied to the DIII-D and it was found that the behavior of the fluctuations in that seemingly different experiment exhibit the same chaotic behavior as the simple LAPD experiment, as shown in Fig.1.

### *Relaxation of a temperature filament*

In a collaboration with Professor R. Sydora, from the U. of Alberta in Canada, an electromagnetic, 3D gyrokinetic particle code was used to study the relaxation of a magnetized electron temperature filament embedded in a large, uniform plasma of lower temperature. The study provided insight into the role played by unstable drift-Alfvén waves observed in a basic electron heat transport experiment [D.C. Pace et al. Phys. Plasmas 15, 122304 (2008)] in which anomalous cross-field transport has been documented. The simulation exhibits the early growth of temperature-gradient-driven, drift-Alfvén fluctuations that closely match the eigenmodes predicted by linear theory. At the onset of saturation the unstable fluctuations display a spiral

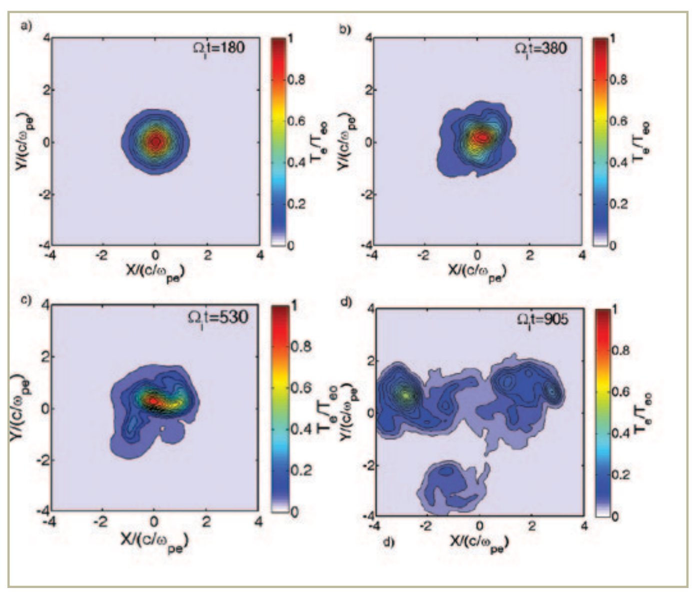



Fig. 2: Color contours of electron temperature across the confinement magnetic field.

spatial pattern, similar to that observed in the laboratory, which causes the rearrangement of the temperature profile. After saturation of the linear instability the system exhibits a markedly different behavior depending on the inclusion in the computation of modes without variation along the magnetic field, i.e., $k_z = 0$. In their absence the initial filament evolves into a broadened temperature profile, self-consistent with undamped, finite amplitude drift-Alfvén waves. But the inclusion of $k_z = 0$ modes causes the destruction of the filament and damping of the drift-Alfvén modes leading to a final state consisting of undamped convective cells and multiple, smaller-scale filaments as illustrated in Fig. 2.

### *Avalanches in magnetized plasmas*

A joint experimental/theory project is underway in collaboration with Dr. B. Van Compernolle to study avalanche phenomena in magnetized plasmas. Avalanches are sudden events that cause major changes over an extended region of a physical system. The origin of avalanches is the presence of a steep gradient in one of the system parameters. Often there is a threshold value for the gradient; when it is exceeded, a complex sequence of processes is triggered whose role is to relax the gradient below the threshold value. In several environments, such as an externally-heated or fueled plasma, the sources reestablish the gradient and further cause it to exceed the threshold value. A sequence of avalanches can then occur, but the actual time of appearance of an individual event displays a marked degree of unpredictability. The behavior is intermittent and causes the parameters of the system to evolve from place to place, i.e., there is an associated "transport" that occurs. The technological breakthrough that makes possible the implementation of an ideal basic configuration for studies of avalanches in magnetized plasmas is a reliable and flexible LaB6 cathode source that has been developed in BaPSF at UCLA. Preliminary results demonstrating an avalanche event have been recently published [B. Van Compernolle et al, Phys. Rev. E. 91, 031102 (2015)] and illustrated in Fig. 3. Associated modeling of the phenomena resulted in an undergraduate thesis for Matt Poulos.

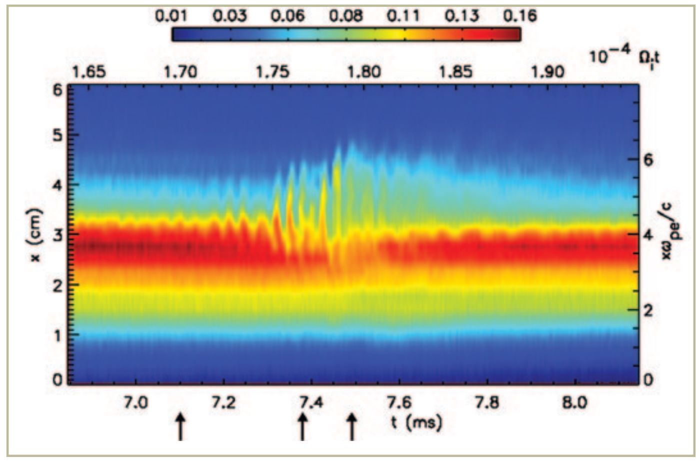



Fig. 3: Radial and temporal behavior of plasma pressure associated with an avalanche event.

## Theoretical and computational plasma Physics

### JENKO GROUP

If driven sufficiently hard, flows in fluids, gases, or plasmas become turbulent. This phenomenon is quite ubiquitous and important, both in nature and in numerous technological applications. From a fundamental point of view, turbulence is a paradigmatic example of nonlinear dynamics in complex systems far from equilibrium. But none of the established statistical theories is able to capture this peculiar state somewhere between order and disorder. Turbulence undoubtedly belongs to the most important unsolved problems of classical physics. One important frontier in this area of research is to understand the turbulent dynamics in plasmas, and this defines a major scientific goal in our group. Below are two recent research highlights. More information is available at: http://www.physics.ucla.edu/~jenko

### *Turbulence in space and astrophysical plasmas*

Recently, the challenging and important question of how energy is actually dissipated by weakly collisional plasma turbulence has emerged as an outstanding unsolved problem in both space and astrophysics, receiving an enormous amount of attention. It applies to a large variety of problems, from the heating of the solar corona and solar wind to predicting the amount of electromagnetic radiation (emitted mainly by electrons) to be expected to come from the massive black hole in our Galactic Center. In this context, the solar wind plays a special role, however, since it can be probed in situ via spacecraft observations.

Thus it comes as no surprise that in a recent review article, it was stated that "the understanding of the small-scale termination of the turbulent energy cascade in collisionless plasmas is nowadays one of the outstanding unsolved problems in space plasma physics." Moreover, recently the THOR (Turbulence Heating ObserveR) project – focused on exactly that issue – has been selected as a candidate for the European Space Agency's next M4 space mission. The scientific team behind this project involves several members of our group, and the physical understanding of turbulent dissipation lies at the very heart of it.

The central problem is to grasp how these virtually collisionless plasmas actually dissipate energy at the tail of the turbulent cascade. It is generally assumed that both linear wave damping, nonlinear phase mixing, and the formation of coherent structures provide important routes to dissipation. In addition, spontaneous magnetic reconnection is thought to be capable of producing energetic, non-thermal particle populations. To assess the relative importance of these effects, one needs to solve numerically the underlying nonlinear kinetic equations, employing the most advanced plasma turbulence codes on some of the largest supercomputers available today. In a recent study with the GENE code [1], which has been developed in our group, simulations at unprecedented numerical resolution have revealed new aspects of the dissipation processes, like the ratio between electron and ion heating (see Fig. 1). Such studies help guide and interpret spacecraft measurements.

## *Turbulence in fusion plasmas*

Another key driver for plasma turbulence research is the quest for fusion energy, a safe, sustainable, and environmentally friendly option to cover the further increasing global energy needs for generations to come. Fusion is the process which powers the stars

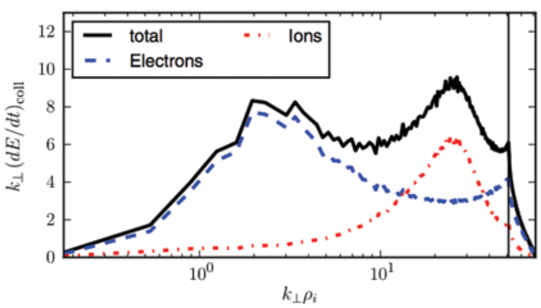



Fig. 1: Collisional dissipation for electrons and ions in high-resolution gyrokinetic simulations of solar wind turbulence. The area under each curve is proportional to the energy dissipation rate.

and enables life on Earth. The idea is to mimic this process by heating a mixture of D and T to extremely high temperatures of more than 100 million degrees, and keeping the resulting plasma away from the material wall with the help of a doughnut-shaped "magnetic cage." Unfortunately, turbulent processes significantly reduce the energy confinement time, an effect which can only be compensated by building bigger, more expensive machines. Thus a key challenge on the road to efficient fusion power plants is to understand, predict, and control turbulence. The success of ITER - the world's flagship project in fusion research, currently under construction in Southern France - hinges on such advances in plasma science. This makes the study of plasma turbulence a very rewarding endeavor with great societal impact.

Over the past 15 years or so, the progress in the area of gyrokinetic simulations of fusion plasmas has been remarkable. While back in the 1990s, turbulent transport has been described by means of scaling laws fitted to existing data, we are now in a position to carry out physically quite comprehensive simulations which can be compared even quantitatively to experimental observations, while unraveling fundamental physical processes (see Fig. 2). An important new frontier of gyrokinetics is a comprehensive description of the plasma boundary. As is widely recognized, many key open issues in fusion research – from the L-H transition and pedestal physics to ELM suppression and plasma-wall interactions – are part of this theme. Moreover, the physical properties of the pedestal are known to determine the overall quality of magnetic confinement to a large degree.

Recently, we were able to carry out the first comprehensive simulation study of an H-mode pedestal, using the gyrokinetic GENE code[2]. We established the importance of turbulence-driving microinstabilities at scales smaller than the ion gyroradius, successfully reproducing the experimentally inferred radial heat fluxes. Based on these findings, we are currently preparing to perform the first "three-scale" turbulence simulations – involving profile scales, ion scales, and electron scales – of edge transport barriers in tokamaks. Here, the overarching goal within the context of fusion research is to capitalize on GENE's outstanding capability to accurately and efficiently describe near-edge plasmas by carrying out simulations of H-mode pedestals with an unprecedented level of realism. This work will provide important clues on how to ultimately attack the problem of constructing a comprehensive, self-consistent, and predictive theory of the L-H transition. This is viewed by many in this field as the holy grail of tokamak confinement.

*[1]: D. Told, F. Jenko, J. M. TenBarge, G. G. Howes, and G. W. Hammett, Physical Review Letters 115, 025003 (2015)*

*[2]: D. R. Hatch, M. Kotschenreuther, S. Mahajan, P. Valanju, X. Liu, F. Jenko, D. Told, T. Gorler, and S. Saarelma, "Microtearing Turbulence Limiting the JET-ILW Pedestal," submitted for publication*

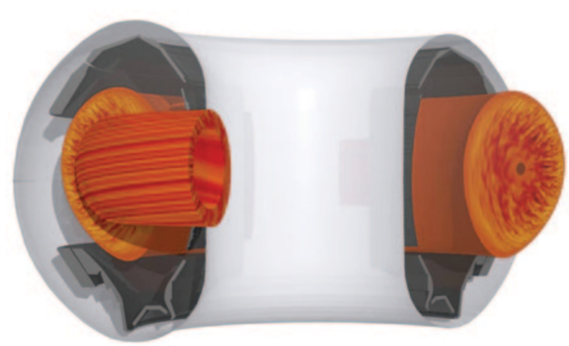


Fig. 2: Gyrokinetic simulation of turbulence in a fusion plasma at about 100 millions degrees, using the GENE code (http://genecode.org). Turbulence induces energy losses and counteracts magnetic confinement. Its control is of vital importance for future fusion power plants.

## Computer Simulations of Plasma Group

**WARREN B. MORI, VIKTOR DECYK, PHIL PRITCHETT**


The Computer Simulations of Plasma Group under the leadership of Professor Warren B. Mori, and Adjunct Professors Viktor Decyk, and Phil Pritchett conducts pioneering work in high-performance computing of complex plasma phenomena. The group is supported by the US Department of Energy (DOE) and the National Science Foundation (NSF). The group is also home to the NSF funded Particle-in-Cell and Kinetic Simulation Software Center (PICKSC (http://www.picksc.idre.ucla.edu)). The mission of PICKSC is to support an international community of PIC and plasma kinetic software developers, users, and educators; to increase the use of this software for accelerating the rate of scientific discovery; and to be a repository of knowledge and history for PIC. The group not only specializes in particle-in-cell (PIC) methods, but also is developing Vlasov Fokker Planck (VFP) techniques. Its codes are used throughout the world and are run on the world's fastest computers.

Besides developing state-of-the-art kinetic simulation software, the group's research is focused on the use of this software to study laser and beam plasma interactions, plasma based accelerator and light sources, space plasmas, Alfvenic plasmas, inertial fusion energy plasmas, and high-energy density science. The group carries out discovery driven research that includes finding solutions for several grand challenge research topics. These include attempting to design next generation accelerators at the energy frontier and for x-ray free electron lasers based on particles surfing on plasma waves. This research requires understanding how intense particle beam or lasers create wakes and propagate through long regions of plasma and how to manipulate the six dimensional phase space of beams of particles surfing on the wake. Another grand challenge is to lasers to drive fusion through inertial confinement. The group has also been studying how lasers evolve as they propagate through mm to cm scale plasmas at the National Ignition Facility (NIF). NIF is the world's largest and most powerful laser. A grand challenge in NIF and IFE research is to unravel the complicated physics behind how a multitude of overlapping high-power laser beams are absorbed, scattered, and deflected as they propagate through centimeters of high-energy density plasmas.

Highlights from this past year include two publications in Nature [1,2]. The group is part of a team that includes experimentalists at UCLA and SLAC. The group simulated parameters of two experiments carried out at SLAC. In one experiment two electron bunches were used. The experiment showed highly efficient transfer of energy from a drive electron beam into a trailing electron beam through the wake created by the drive beam. Results from our simulations were on the cover of the issue of Nature in which the results were published. In the second experiment a single positron bunch was used. The wake created by the leading edge of the bunch was able accelerate positrons in the rear of the bunch forming a monoenergetic positron bunch. These results were also published in Nature.

*Litos et al., Nature 515 92 (2014).*

*Corde et al., Nature 524 442 (2015).*

## Space Plasma Simulation Group (SPSG)

**MAHA ASHOUR-ABDALLA, JEAN BERCHEM, MOSTAFA EL-ALAOUI, ROBERT RICHARD, DAVID SCHRIVER, MENG ZHOU**

The Space Plasma Simulation Group (SPSG) has continued to carry out cutting edge research on a number of different problems in space physics. The overall theme in these projects is to use various types of numerical plasma simulation codes in close coordination with observations made by NASA satellites at the Earth and at other planets. The satellite data is used both to initialize the simulations and to validate the results. The simulations are then used to determine the physical mechanisms that are operating and also to put the single point satellite measurements in a global context.

This has been an exciting year for the SPSG. In March 2015 the Magnetospheric Multiscale Mission (MMS) was launched. This four spacecraft mission will address one of the most critical problems in solar and space physics – the physics of magnetic reconnection. In particular reconnection is generally believed to be the main driver of dynamics in the Earth's magnetosphere. MMS will provide the first up close observations of these phenomena. The SPSG was selected as one part of a theoretical team to work with the experimenters to understand this mechanism.

During the past year we completed development of an entirely new approach to the physics of the magnetosphere and applied it to the problem of magnetospheric reconnection. The breakthrough came by combining a global MHD simulation with an implicit PIC simulation, called iPic3D, which was developed by our collaborator Professor Giovanni Lapenta. The MHD model allows us to realistically include the large-scale interaction with the solar wind and ionosphere in the magnetospheric calculation while the implicit PIC simulation allows us to include small-scale kinetic effects in the critical part of the interaction region. Together with collaborator Ray Walker from the Department of Earth, Planetary, and Space Sciences at UCLA, one of the problems we addressed with this new approach was to determine the dynamics of magnetic reconnection occurring in the magnetotail during a magnetospheric substorm. The simulation box included a region from $-45R_E < X < -15R_E$, $-9R_E < Y < 3R_E$ and $-9R_E < Z < 3R_E$, where $R_E$ = Earth radii = 6371 km. this represents a significant fraction of the magnetotail. The initial and boundary conditions were set by using the MHD results so that the solar wind and ionosphere interactions were included in the simulation.

One of the most important problems in understanding magnetic reconnection is to determine where and when the reconnection occurs. This is the primary goal of the MMS mission. In the electron diffusion region the particles become demagnetized. Most importantly the electron diffusion region is where a fraction of the energy is transferred to the electrons and is where the magnetic field lines are cut and reconnection actually occurs. One of our tasks with our new simulation technique was to figure out how to identify the electron diffusion region. We have considered four approaches that have been suggested for identifying the diffusion region. The first is called slippage. Slippage occurs when one or more of the components of the particle perpendicular velocities differ from the velocity at which magnetized particles move $(\mathbf{E}\times\mathbf{B})/\mathbf{B}^2$ where **E** is the electric field and **B** is the magnetic field. If they are different this represents a candidate region for reconnection. Dissipation in space plasmas is given by the generalized Ohm's Law. The non-ideal terms in the generalized Ohm's law can give us an indication of where the field is not frozen into the flow. The energy that drives reconnection is in the magnetic field. In magnetic reconnection work is done on the particles. The work done on the particles of species s by an electric field, i.e., $\mathbf{j}_s \cdot \mathbf{E}$ where $\mathbf{j}_s$ is the species current density, can be used to identify diffusion regions. Our last indication that a species is not frozen-in is agyrotropy (non-gyrotropy) of the particle distribution in a plane perpendicular to the local magnetic field.

In the upper panel of Figure 1, we show the results of our calculation of the slippage, calculated as the difference between the perpendicular electron velocity and the **ExB** velocity. The largest electron slippage occurs in the small region near the source of the enhanced electron jetting. This is a region of streaming electrons, which is a strong candidate for the electron diffusion region. It is very narrow, only about an ion inertial length or 1500 km. However there are other places where this parameter is enhanced as well and we find no other evidence of reconnection. This means slippage can give false positives. In the second panel from top of Figure 1, we evaluate the use of the non-ideal terms in the Ohm's law to indicate the electron diffusion region. The largest values of the non-ideal terms occur near the region where the electron jetting originates. However again there are regions with little other evidence of reconnection that have enhanced non-ideal Ohm's law terms. In the third panel from top we have used $\mathbf{j} \cdot \mathbf{E}$ in the MHD frame to identify the possible electron diffusion region, $\mathbf{j} \cdot \mathbf{E}$ also is largest near the source of the electron streaming. It is relatively clean in that there are no other regions of enhanced $\mathbf{j} \cdot \mathbf{E}$. Agyrotropy (lower panel) is largest at the same location as the origin of the streaming. It has the same length and width as the narrow region of streaming. It is by far the cleanest indicator of electron diffusion region.

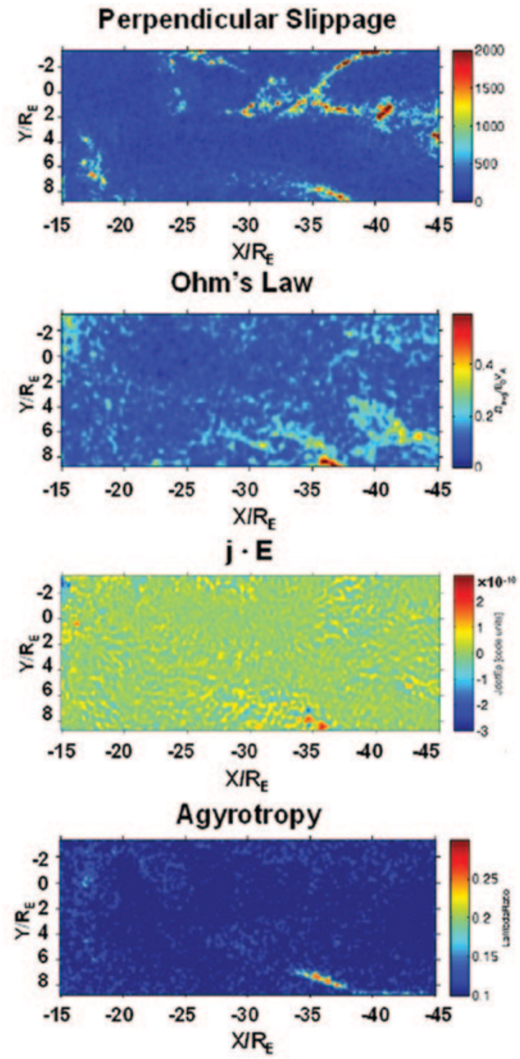



Fig. 1: Shown are different measures of identifying the electron diffusion region including perpendicular slippage (difference in velocity from convection velocity), non-ideal terms in Ohm's law (2nd panel from top), work done by an electric field on the particles, $\mathbf{j} \cdot \mathbf{E}$, third panel from top, and agyrotropy or non-gyrotropy (bottom panel).

All four approaches place the electron diffusion region near the source of the electron flows. Slippage and the non-ideal Ohm's law terms give possible false positive values and as such may be less useful for identifying the diffusion region. The enhanced agyrotropy and the region where the flows start are nearly identical. All the measures are consistent with a long thin diffusion region that is a few $R_E$ in the X direction while only about an ion inertial length in Y. In addition it is very dynamic moving in space.

Members of the SPSG, in collaboration with colleagues from ESA (Noordwijk, The Netherlands), IRAP (Toulouse, France) and APL at the Johns Hopkins University have pursued their investigation of the interaction of solar wind ions with the dayside magnetospheric boundary (magnetopause). They carried out numerical simulation studies of that interaction for southward interplanetary magnetic field (IMF). Results of global MHD simulations in conjunction with large-scale kinetic (LSK) calculations revealed the development of a strong dawn-dusk asymmetry in the ion entry over the high-latitude dayside magnetosphere. This is illustrated in Figure 2, which shows the locations of the solar wind ion crossing a spherical detector used in the simulation. The detector shows that the most energetic ions (red crossings) are precipitating at the lowest latitudes while the less energetic ones (blue crossings) are seen over a large range of high latitudes. This energy dispersion results from the time of flight effect in the entry of the ions accelerated toward Earth by the reconnection process. The detector also reveals a strong asymmetry in the ion precipitation. Most of the precipitation occurs in the morning and pre-noon sectors. This dawn-dusk asymmetry is also visible in the southern hemisphere and has been shown to be consistent with statistical studies of low-altitude spacecraft observations. Analysis of the simulations indicates that the asymmetry results from the dawn-dusk reversal of the electric field associated with the component of the magnetopause current parallel to the magnetic field.

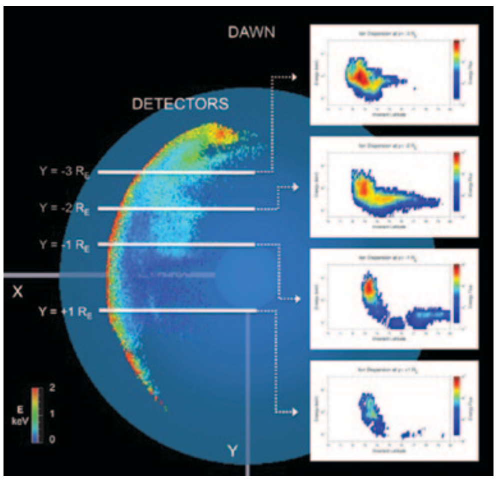



Fig. 2: This figure shows the locations of the solar wind ions crossing a spherical detector (transparent blue sphere) used in the simulation, which is viewed from above the Northern Hemisphere. The solid blue sphere seen inside the transparent one represents Earth. The x-axis is aligned with the Sun-Earth direction and distances are measured in Earth radius (1 $R_E \approx$ 6,371 km or 3,959 mi). The location of each ion crossing has been color coded according to the particle's energy using the scale displayed on the lower-left inside of the figure. The right panels display energy-latitude dispersion plots along virtual trajectories in four planar detectors along the Dawn-Dusk direction (Y = 1, -1, -2, -3 $R_E$) whose locations are represented by the white traces on the spherical detector.

The group has also continued to make progress in understanding Mercury's magnetosphere using a global hybrid simulation that fully resolves the ion gyro-radius. This research effort provides theoretical support for the MESSENGER spacecraft mission, which began orbiting Mercury in March 2011 and crashed into the planet in April 2015. Global kinetic simulations have been carried out to understand the transport and acceleration of heavy ions, i.e., sodium ions (Na+), which originate from the planet's surface. One method of Na+ production occurs when 1-10 keV electrons precipitate and interact with the regolith, ejecting low energy Na+ ions (1-10 eV) from the surface through a process known as electron stimulated desorption (ESD). To examine this process Na+ are launched with initial energy 10 eV into the magnetospheric simulation domain from the planet surface where electron precipitation occurs. A comparison is made between sodium ions measured onboard the MESSENGER spacecraft and simulation results in fig. 3.

The MESSENGER FIPS data on the left was accumulated during 3 Mercury years and shows Na+ density (in $cm^{-3}$ color coded on log scale) altitude vs. local time (LT) in the equatorial region between ± 30° geographical latitude. The simulation results on the right are plotted in the same way as the MESSENGER FIPS data. The white boxed region between 18 and 24 LT shows an observed density enhancement of Na+ in the dusk-nightside, which is in very good agreement with the simulations where it is found that in the nightside-dusk region the ion densities are greatest with particle energies of the order 1-10 keV. This can be explained by considering that when a cold (1-10 eV) sodium ion is produced by electron precipitation (via ESD) at the planetary surface on the nightside, it will move along magnetic field lines out into Mercury's magnetotail. Because of the relatively weak magnetic field and the relatively large sodium mass (22.99 times proton mass), Na+ that reaches the magnetotail become demagnetized and the cross-tail electric field, which is on average directed towards the dusk, accelerates Na+ towards the dusk-nightside flank causing an energetic (> keV) Na+ build up.

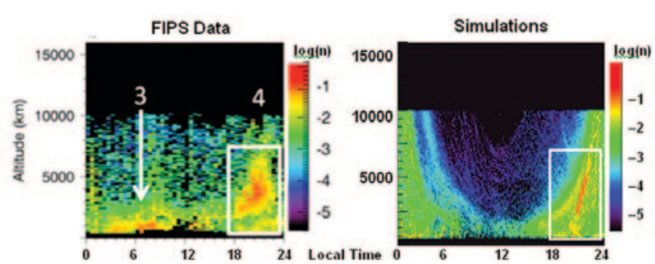



Fig. 3: This figure shows sodium ion measurements from the FIPS instrument onboard the MESSENGER spacecraft on the left compared to results of global kinetic simulations of Mercury's magnetosphere on the right. Shown is altitude versus local time color coded in ion density ($cm^{-3}$). The FIPS data is accumulated over 3 Mercury years worth of MESSENGER orbital data.

## Whistler waves with orbital angular momentum

### R. L. STENZEL AND J. M. URRUTIA

Electromagnetic waves in the low frequency whistler mode regime are investigated experimentally and by digital data superpositions. The new feature of these waves is their helical propagation, i.e., an azimuthal rotation and axial phase propagation. Such waves possess both a linear field momentum and an orbital angular momentum. Helical waves have important applications in laser physics, communication, astronomy and nanotechnology. In plasma physics, one interesting feature is the transverse Doppler effect which can produce a Doppler-shifted cyclotron resonance with energetic electrons, leading to scattering of electrons and possible whistler instabilities. Although wave-particle interactions are known for parallel wave propagation, they have not been recognized for helicon waves whose phase both rotates and propagates. Their phase fronts are helical and their field lines form spirals which propagate like corkscrews (see Fig. 1).

In order to excite waves with angular momentum we developed a novel antenna, consisting of concentric circular arrays of magnetic loops. By introducing a phase shift around the array axis, the waves rotate like a rigid body with integer mode numbers. This forms helicon eigenmodes in unbounded plasmas. When phased radially, spherical waves can be produced. One interesting mode are waves with conical phase fronts propagating at the Gendrin angle which transports wave energy along the ambient magnetic field. It forms a collimated beam of whistler modes. The difference between wave propagation in free space and in anisotropic plasmas has been demonstrated. Different group and phase velocity directions do not allow the formation of Gaussian or Bessel beams in plasmas. Our observations show that helicon wave theory based on free-space propagation has to be revised. The physics of wave excitation from magnetic antennas has been studied. Antenna radiation patterns for phase and energy propagation are different. Receiving and transmitting patterns can differ. Antenna reciprocity and directionality have been explained. Whistler energy focusing is achieved with a circular magnetic line antenna which produces a converging group velocity resonance cone.

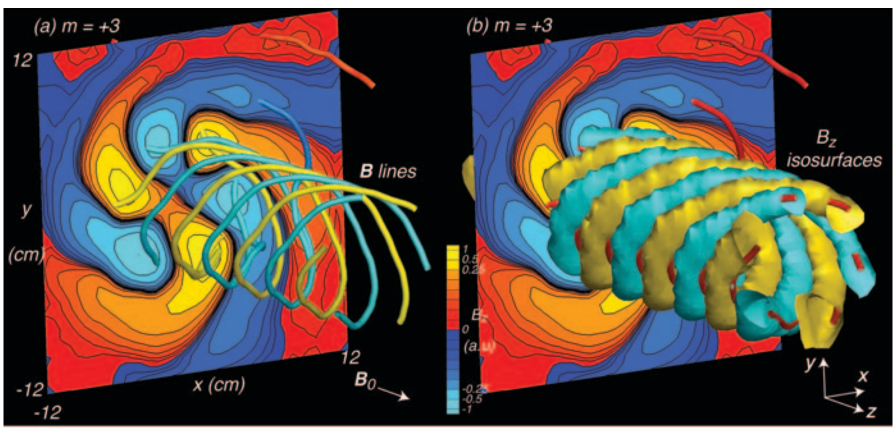



Fig. 1: Topology of an m=3 helicon mode. (a) 2D contour plot of the field component $B_z(x,y)$ and 3D field lines passing through the peaks of $B_z$. The field lines form six nested, left-handed helical screws of alternating directions on a cylindrical surface along $\mathbf{B}_0$. (b) Added to (a) are isosurfaces of $B_z(x, y, z)$ which describe the helical phase fronts of a helicon wave. For m=3 there are three azimuthal wavelengths per circumference in phi and each helix has an axial pitch of three wavelengths, describing the phase relation $cos(mø + kz–wt)$.

These basic studies are relevant to diverse fields in plasma physics such as space plasmas, fusion plasmas and plasma processing applications. They have been disseminated in numerous publications and are described on our website http://www.physics.ucla.edu/plasma-exp/research/Helicons/index.html.

*1. J. M. Urrutia and R. L. Stenzel, Phys. Plasmas 21, 122107 (2014).*

*2. R. L. Stenzel and J. M. Urrutia, Phys. Plasmas 21, 122108 (2014).*

*3. J. M. Urrutia and R. L. Stenzel, Phys. Plasmas 22, 072109 (2015).*

*4. R. L. Stenzel and J. M. Urrutia, Phys. Plasmas 22, 072110 (2015).*

*5. R. L. Stenzel and J. M. Urrutia, Phys. Rev. Lett. 114, 205005 (2015).*

*6. J. M. Urrutia and R. L. Stenzel, Phys. Plasmas 22, 092111 (2015).*

*7. R. L. Stenzel and J. M. Urrutia, Phys. Plasmas 22, 092112 (2015).*

*8. R. L. Stenzel and J. M. Urrutia, Phys. Plasmas 22, 092113 (2015).*

*9. J. M. Urrutia and R. L. Stenzel, "Helicon waves in uniform plasmas. IV. Bessel beams, Gendring beams and helicons," (submitted to Phys. Plasmas 2015.)*

# Experimental Condensed Matter Physics

### STUART BROWN

Electronic correlations in materials are associated with a wide range of phenomena of interest to condensed matter physicists, such as high temperature superconductivity, Mott insulators, and novel ordered and quantum disordered ground states. The diversity of phenomena is typically tunable by chemical or physical methods such as doping or applied pressure or strain, or by applying magnetic fields at low temperatures. In Professor Brown's group, we apply nuclear magnetic resonance methods to systems of interest, such as molecular superconductors, intermetallic heavy fermion compounds, and frustrated quantum magnets. The technique is sensitive to the electronic spin and charge degrees of freedom, for example through the hyperfine interaction, and amenable to the extreme conditions required to explore the range of effects of the correlations.

One of the systems we've been studying recently is an all-organic

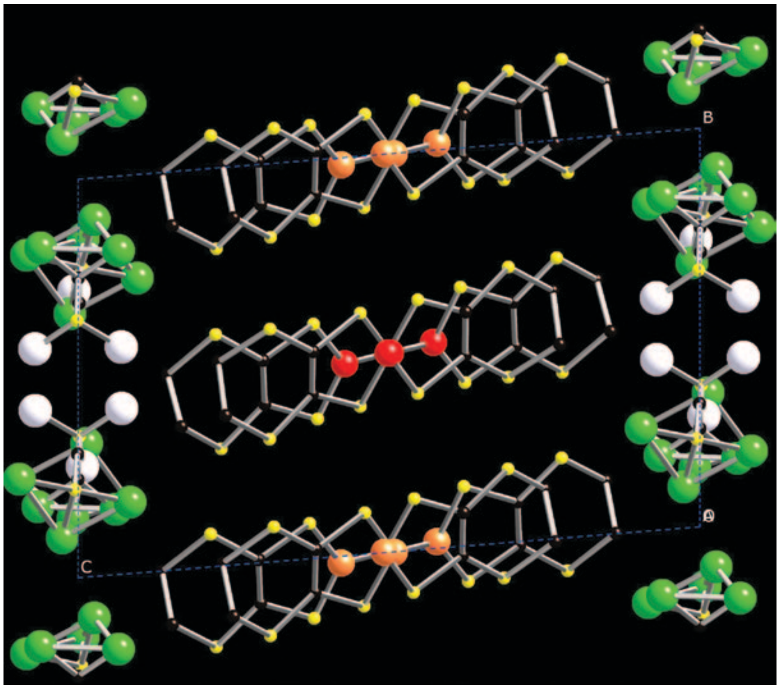



Fig. 1: The layered structure of an all-organic superconductor. The conducting layer is comprised of ET molecules. The insulating layer is made up of the organic molecule X = SF5CH2CF2SO3.

molecular superconductor. One view of the crystal structure is shown in the accompanying Fig. 1. It is composed of two organic molecules which self-assemble into layers. Such a layering effect is a hallmark of molecular superconductors. Typical also, is that only one of the layers contains the mobile carriers. Here, they are confined to the large dimer molecules in the center. One reason that is important is because repulsive interactions between charge carriers tend to be more important in lower dimensions. It is also common that the relative importance of the repulsive interactions can be tuned. In many molecular superconductors, the tuning is done by changing the lattice constant, for example with high pressure. Thus, applied pressure can tune a magnetic insulator to a superconductor at low temperature. The superconductivity is unusual, however, in that it persists only if the spin fluctuations "leftover" from the nearby magnetic state are present. Without spin fluctuations, a conductor would normally exhibit $1/T_1T$ = constant, with $T_1$ the timescale associated with nuclear spin transitions, and T the temperature. The effect is illustrated in Fig. 2, where the blue dots correspond to $1/T_1T$ measured in a compound that undergoes a transition to a superconducting state at T ~ 1 K, and at greater temperatures, a strong T-dependence is seen. One exception is the material shown in Fig. 1, which exhibits no such enhancement in $1/T_1T$ (red dots, Fig. 2). In fact, it was suggested some time ago that charge fluctuations originating with the repulsive interactions could stabilize superconductivity in this compound. This would represent a new route to superconductivity in molecular conductors, and a signature for it would be the absence of the enhanced NMR relaxation characteristic of the presence of spin fluctuations. But is the superconductivity driven by the alternative mechanism? We're not sure, but are exploring methods to confirm it.

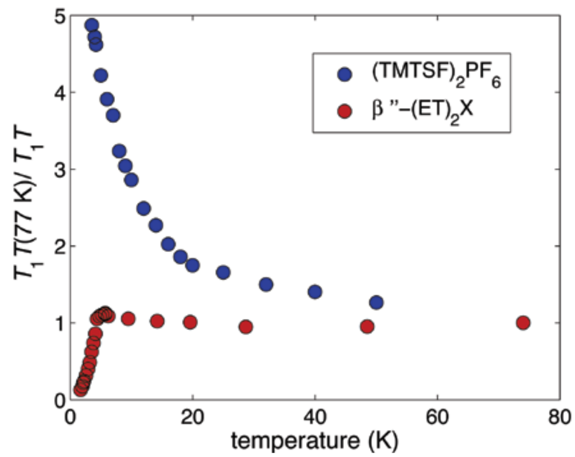



Fig. 2. Well-known temperature-pressurephase diagram of (TMTSF)2PF6.

## HONGWEN JIANG

Professor Jiang's group investigates nano-structured quantum dot devices for storing and manipulating quantum information, encoded in either spin or charge states. This year, in a string of collaborations with a research group at USTC, through multiple trips to China, several experiments were performed.

A crucial requirement for scalable quantum-information processing is the realization of multiple-qubit quantum gates. To date, while there are plenty of experimental demonstrations of gate operation in a single semiconductor quantum dot qubit, there are only two successful demonstrations of two-qubit gates in spin based quantum dot systems while there is none in any charge qubit system. In an experiment, a two-qubit controlled NOT operation is demonstrated in an all-electrically-controlled quantum dot charge-qubit system.[1] The finding appears to against the conventional wisdom that charge qubits are inferior comparing to spin qubits for any semiconducting materials. It was found that, trading shorter dephasing time for faster qubit operation time, charge qubits can perform equivalently well in the two-qubit level.

For qubits, dephasing rate represents a key figure of merit for the material. In another collaboration, the dephasing rates of a graphene quantum dot have been measured, for the first time, using the sensitive dispersive readout of an on-chip superconducting microwave resonator in an integrated graphene-resonator device. Unexpectedly, it is discovered that the rates strongly depend on the number of charges in the dots, and the variation has a period of four charges.[2] The results suggest that this extraordinary property may be caused by the hybrid states of spin and valley degrees, and may provide new means for storing and manipulating quantum information in graphene-based quantum dots.

In another work, a hybrid device with two distant graphene double quantum dots (DQDs) and a microwave resonator was fabricated. A nonlinear response is observed in the resonator reflection amplitude when the two DQDs are jointly tuned to the vicinity of the degeneracy points. This observation can be well fitted by the Tavis–Cummings model which describes two two-level systems coupling with one photonic field. Furthermore, nonlocal coupling of the two distant DQDs, mediated by the photons in the resonator, has been observed by measuring the current cross-correlation noise spectrum.[3] The results contribute to the study of nonlocal transport and future implementations of remote electronic entanglement.

*"Conditional Rotation of Two Strongly Coupled Semiconductor Charge Qubits", Hai-Ou Li, Gang Cao, Guo-Dong Yu, Ming Xiao, Guang-Can Guo, Hong-Wen Jiang, and Guo-Ping Guo, Nature Communications, 15,03633 (2015).*

*"Charge Number Dependence of the Dephasing Rates of a Graphene Double Quantum Dot in a Circuit QED Architecture", G. W. Deng, D. Wei, J. R. Johansson, M. L. Zhang, S. X. Li, H. O. Li, G. Cao, M. Xiao, T. Tu, G. C. Guo, H. W. Jiang, F. Nori, and G. P. Guo, PRL, 115, 126804 (2015).*

*"Coupling two distant double quantum dots with a microwave resonator" , G. W. Deng, D. Wei, S. X. Li, J. R. Johansson, W. C. Kong, H. O. Li, G. Cao, M. Xiao, G. C. Guo, F. Nori, H. W. Jiang, G. P. Guo, Nano Letters, 10,1021 (2015).*

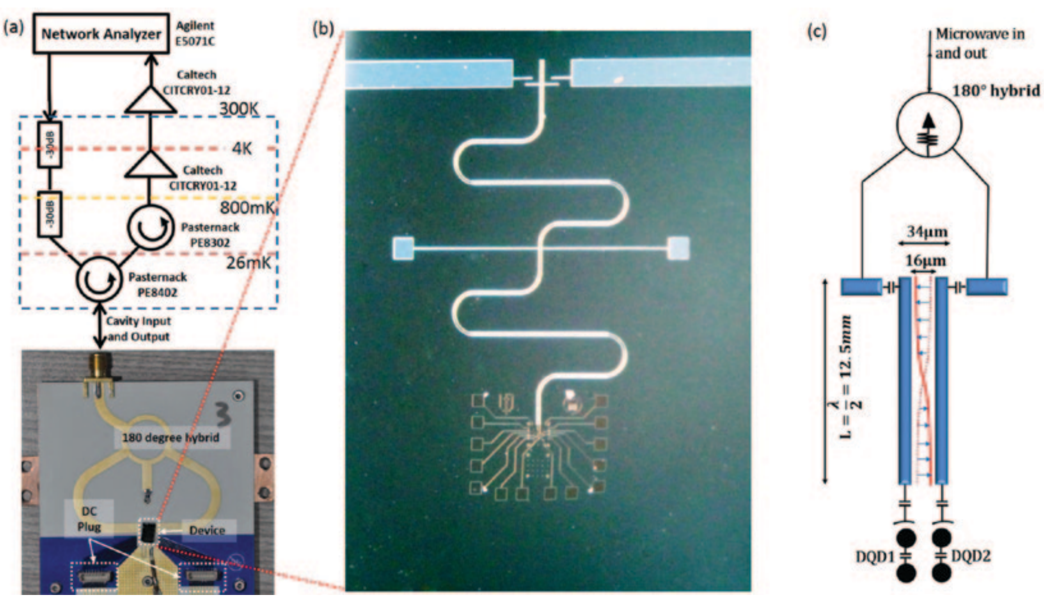


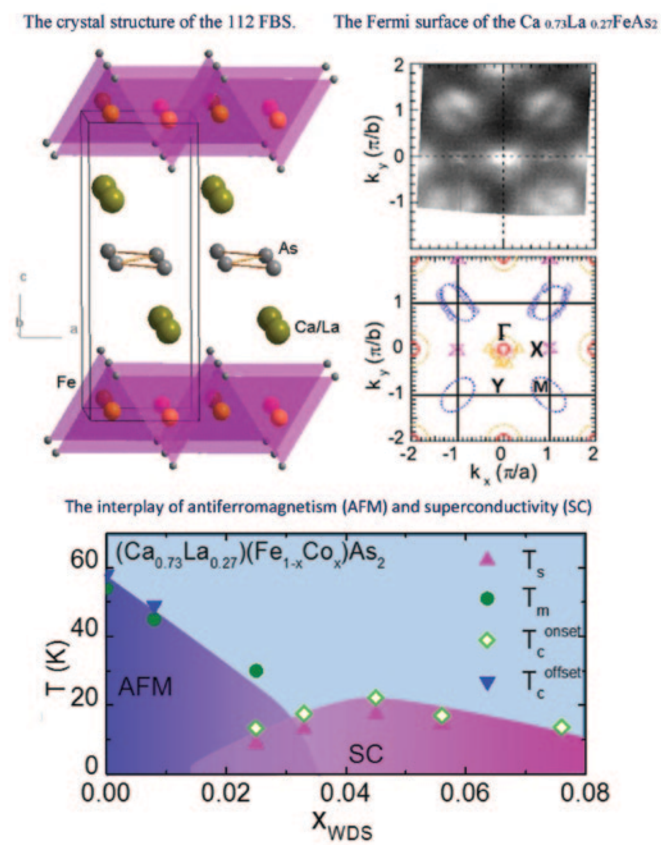

Fig. 1: Layout of the double quantum dot - circuit QED structure.

## Ni Lab Group

### Ni Ni

New materials are the driving force for technology innovations and developing understanding in condensed mater physics. Ni Research Group focuses on the characterization of physical properties and structures of materials through thermodynamic, transport, X-ray and neutron measurements, with an emphasis on the design, synthesis and crystal growth of new materials. The materials of interest spread from intermetallics to oxides, especially superconductors and strongly correlated electron systems showing unusual electronic and magnetic ground states that can be perturbed by chemical doping, applied pressure or magnetic field.

As the second high temperature superconducting systems besides cuprates, new Fe-based superconducting family (FBS) discovered in early 2008 with the highest critical temperature up to 56K has attracted intensive research effort. Although magnetism has been thought to be the death zone for superconductivity (SC), a phenomenon that current can pass the material with no dissipation, high temperature SC in both cuprates and FBS is born out of magnetism. Understanding their interplay is crucial for the discovery of the next generation of high temperature supercon-



ducting materials which may significantly advance the technology applications of supercodncutivity. Ni Research Group focuses on FBS with nontrivial crystal structures and aims at shedding lights on their structure-property relationship and the interplay of magnetism and SC. The newest discovered FBS Ca1−xLaxFeAs2 (CaLa112) crystalizing in the monoclinic lattice with the presence of As chains in the spacer layers, shows SC up to 42 K, the highest bulk Tc among all nonoxide FBS [2]. Graduate student Shan Jiang in Professor Ni's group has unraveled the "parent" phase of the CaLa112 FBS family and demonstrated the existence of metallic spacer layers in this material. Surprisingly, unlike the other FBS, where the "parent" compounds which show structural/magnetic phase transitions have the same number of electrons and holes, the "parent" of the 112 FBS is heavily electron self-doped. By measuring its Fermi surface (collaboration with Chan Liu in SUSTC, China), we attribute this unusual phenomenon to the dual itinerant and localized nature of magnetism in FBS. Furthermore, by electron doping the "parent" compound, a new series of high Tc superconductors is discovered. The work is under review and can be found at arXiv: 1505.05881.

*Professor Ni has received an Early Career Research Award from the U.S. Department of Energy. Currently, the research in the group is supported by both DOE and NSF.*

## Condensed Matter Theory

### ELIHU ABRAHAMS

Elihu Abrahams came to UCLA from Rutgers University at the end of 2009. He is a member of the National Academy of Sciences and the American Academy of Arts and Sciences, and is a Fellow of the American Association for the Advancement of Science and a Fellow of the American Physical Society.

Elihu Abrahams' research is on the application of quantum many-body theory to understand the physical properties of strongly-correlated systems. These are realized in compounds whose behavior is primarily determined by strong electron-electron interactions that dominate the various contributions to the energy of the system. The consequence is the emergence of unexpected phenomena and phase transitions.

Abrahams' most recent research is on the phenomenon of quantum criticality, which is associated with the transformation from one phase to another at the zero of temperature. It is found in many rare-earth and actinide base heavy-fermion metals and is at the forefront of condensed matter research. An essential characteristic of a quantum critical point is that dynamical fluctuations of an order parameter play a key role in determining the behavior in its neighborhood, whereas spatial fluctuations of an order parameter are associated with ordinary thermodynamic phase transitions. Although quantum phase transitions between distinct ground states occur at absolute zero, their effects may be observed over a range of non-zero temperature. Abrahams has collaborated on the development of a new theory of how quantum critical fluctuations affect the electronic properties in heavy-fermion metals.

Among his most recent contributions in this area is "Strong-coupling theory of heavy-fermion criticality", Phys. Rev. B 90, 045105 (2014), in which remarkable agreement has been shown between this "critical quasiparticle theory" and experiment.

Another, related research activity has been on the iron-based superconductors, in which quantum criticality has been related, by Abrahams and collaborators, to strong electron correlations with the consequence that magnetic properties are therefore best understood as arising from interacting quasi-localized spins. This physics is described in the recent research reported in: "Effective Exchange Interactions for Bad Metals and Implications for Iron-based Superconductors", arXiv:1410.8118

### SUDIP CHAKRAVARTY

My research interest involves quantum theory of collective behavior of electronic systems. I am interested in theories of high temperature superconductivity, dissipative quantum systems, quantum phase transition and criticality, localization transition in interacting systems, and the concept of von Neumann entropy in quantum phase transitions. I have written seven papers in the past year. All of them are posted on the arXiv.org. Three of them are already published and the rest are in various stages of revision and submission. One of my students, Arash Bellafard, graduated this year. He received a NIH T32 postdoctoral fellowship and is working in the neurobiology group at UCLA with Professor Alcino Silva where he is poised to make use of the physics ideas (such as criticality in statistical mechanics) he learnt to theory of neural network. My graduate student Antonio Russo received a dissertation year fellowship and should be graduating next year. I have two more graduate students Zhiqiang Wang and Jian Wang.

### *I provide brief highlights of three of my papers.*

(1) Pairing of composite fermions in half-filled Landau level state was reexamined by solving the BCS gap equation with full frequency dependent current-current interactions. Our results show that there can be a continuous transition from the Halperin-Lee-Read state to a chiral odd angular momentum, l=3. This is at odds with the previously established conclusion. As was pointed out, for this pairing there will be chiral Majorana fermion modes on an edge, and correspondingly degenerate states for 2n vortices. For l=3 this will lead to nonabelian statistics. *Z. Wang et al. Annals of Physics, 351, 727 (2014)*

(2) A mechanism was proposed for the tantalizing evidence of polar Kerr effect in a class of high temperature superconductors--the signs of the Kerr angle from two opposite faces of the same sample are identical and magnetic field training is non-existent. The mechanism does not break global time reversal symmetry, as in an antiferromagnet, and results in zero Faraday effect. *G. Sharma et al. arXiv:1503.07174 (submitted to Phys. Rev. Lett.)*

(3) Onsager rule that determines the frequencies of quantum oscillations (an exciting development in the area of high temperature superconductors) in high magnetic fields serves as an anchor point. In its absence it would be very difficult to interpret the experimental results, because for each instance the problem would have to be considered anew. In the mixed-vortex state of the underdoped cuprates, where major consequential discoveries have recently taken place, its validity has been recently questioned. We have shown that this rule actually remains intact to an excellent approximation. Another exceptionally interesting result from our model calculations is that the oscillations ride on top of a field independent density of states for higher fields. This feature appears to be consistent with the recent specific heat measurements published in Nature Communications. *Z. Wang and S. Chakravarty, arXiv:1509.00494.*

Currently I am exploring the recently discovered superconductority at the interface of FeSe/SrTiO3 in excess of 100K . It has rekindled the long standing interest in interfacial superconductivity. In addition, I am collaborating with my former student P. Goswami on the phase diagram of disordered, time reversal invariant topological superconductors in two and three dimensions, an example of which is given below.

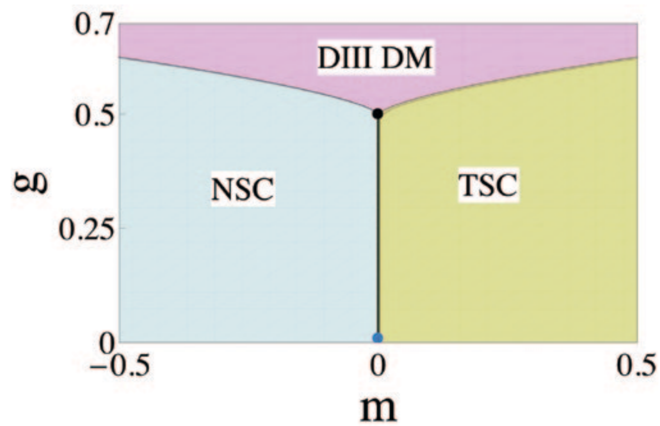



Fig.1: Here g is a suitable coupling constant, m is a mass parameter. NSC is normal superconductor, TSC is a topological superconductor and DIII DM is a diffusive metal in technical language class DIII. The vertical line is a line of quantum criticality.

# Experimental Low Temperature Physics

## GARY WILLIAMS GROUP

Our lab has published papers on several different aspects of superfluidity in liquid helium in 2014-15. One experiment studied superfluid sound propagation in very thin helium films (only 3-5 atomic layers in thickness) that are adsorbed on the outer surface of carbon nanotubes. This work formed the Ph.D. thesis of Dr. Emin Menachekanian, who is now a professor at Santa Monica College. An undergraduate, Vito Iaia, was instrumental in building a new "shaker" mechanism to excite the sound waves, and he won the best paper prize for a paper on this he published in the UCLA Undergraduate Science Research Journal.

Another experiment studied fluctuation-induced changes in thickness of helium films as the temperature increases to within microdegrees of the superfluid phase transtion at 2.176 K. A new effect was observed where the film thickness suddenly increased just above this temperature. We believe this is due to the fact that thermal-wave sound fluctuations can no longer propagate, since helium is just a normal liquid above 2.176 K. This formed the thesis of Dr. John Abraham, who is now at Sandia Laboratories.

The theory of superfluid turbulence in two dimensions was advanced in collaboration with Dr. Andrew Forrester and Dr. Han-Ching Chu, both former graduate students. The turbulent flow in a helium film is due to the excitation of large numbers of quantized vortices in the flow. By applying Andrew and Han-Ching's previous studies of the stochastic dynamics of the vortices, we were able to make the first analytic calculation of the dynamics of a superfluid turbulent cascade.

# Faculty 2014-15

## Professors

Elihu Abrahams (Adjunct)
Katsushi Arisaka
Maha Ashour-Abdalla
William Barletta (Adjunct)
Zvi Bern
Dolores Bozovic
Stuart Brown
Robijn Bruinsma
Troy Carter– Vice Chair of Resources
Sudip Chakravarty
Ferdinand V. Coroniti - Associate Dean of Physical Sciences
Robert Cousins
Eric D'Hoker - Vice Chair of Academic Affairs
Sergio Ferrara
Christian Fronsdal
Steven Furlanetto
Walter Gekelman
Graciela Gelmini
Andrea Ghez
George Grüner
Michael Gutperle
Brad Hansen
Jay Hauser
Kàroly Holczer
Huan Huang
Frank Jenko
David Jewitt
Hong-Wen Jiang
Michael Jura
Per Kraus
Alexander Kusenko
James Larkin - Vice Chair of Astronomy and Astrophysics (as of 10/1/15)
Alexander Levine
Matthew Malkan
Jean-Luc Margot
Thomas Mason
Ian McLean - Vice Chair of Astronomy and Astrophysics (until 9/30/15)
Mayank Mehta
Jianwei Miao
George J. Morales
Warren Mori
Mark Morris
Pietro Musumeci
William Newman
Rene Ong
Vahe Peroomian (Adjunct)
Seth J. Putterman
James Rosenzweig
Joseph A. Rudnick – Senior Dean of Physical Sciences
David Saltzberg
David Schriver (Adjunct)
Alice Shapley
Terry Tomboulis
Tommaso Treu
Yaroslav Tserkovnyak
Slava Turyshev (Adjunct)
Jean Turner – Department Chair
Vladimir Vassiliev
Hanguo Wang (Adjunct)
Gary A. Williams
Edward Wright
Giovanni Zocchi

## Associate Professors

Eric Hudson
Michael Fitzgerald
Christoph Niemann
B. Chris Regan

## Assistant Professors

Wesley Campbell
Paul Hamilton
Gregory Martinez (Adjunct)
Smadar Naoz
Ni Ni
Rahul Roy
Martin Simon (Adjunct)
Lindley Winslow
Shenshen Wang

## Professors Emeriti

Ernest S. Abers
Eric Becklin
Rubin Braunstein
Charles Buchanan
Marvin Chester
W. Gilbert Clark
John M. Cornwall
Robert Finkelstein
George Igo
Steven Moszkowski
C. Kumar N. Patel
Roberto Peccei
Claudio Pellegrini
William E. Slater
Reiner Stenzel
Roger Ulrich
Alfred Wong
Chun Wa Wong
Eugene Wong
Byron T. Wright
Benjamin Zuckerman

# Researchers 2014-15

## Researchers

Jean Berchem
David Brower
Viktor Decyk
Weixing Ding
Mostafa El Alaoui
Samim Erhan
Terry Rhodes
R. Michael Rich
Robert Richard
Lothar Schmitz
Gil Travish
Steven Trentalange
Stephen Vincena

## Associate Researchers

Gerard Andonian
Neal Crocker
Mikhail Ignatenko
Shreekrishna Tripathi
Frank Tsung
Bart Van Compernolle

## Assistant Researchers

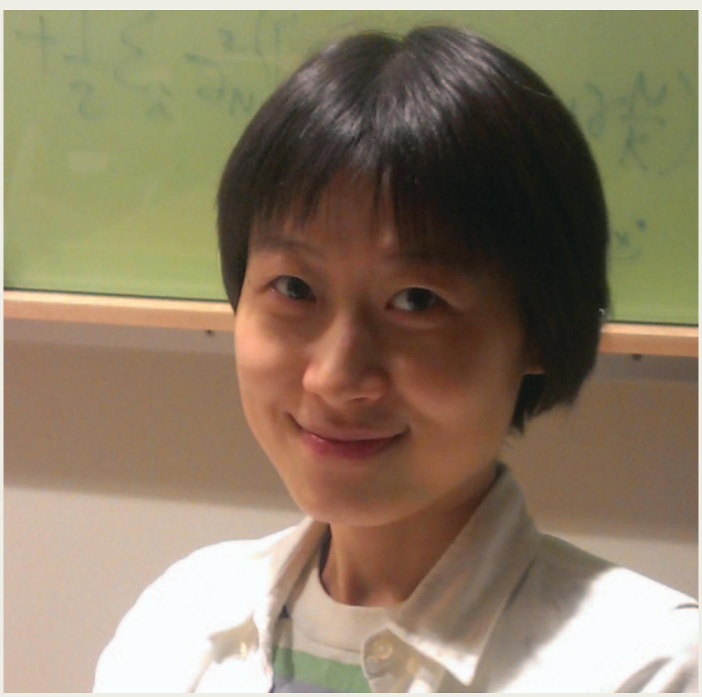
Xiaoping Ding
Tuan Do
Atsushi Fukasawa
Liang Lin
Alexey Lyashenko
Sebastiaan Meenderink
Brian Naranjo
Gregory Rakness
Shoko Sakai
So Takei
John Tonge
Tham Tran
Gang Wang
Gunther Witzel
Jingwen Wu
Jeffrey Zweerink

# New Faculty 2015

## PAUL HAMILTON

We are proud to announce the arrival of a new Atomic, Molecular, and Optical physics professor, Paul Hamilton. Paul received a B.A. in Physics and Astrophysics in 2001, while working with Leon Golub on the development of x-ray telescopes for studying the solar corona. He continued this work for two years at the Harvard-Smithsonian Center for Astrophysics before enrolling in graduate school at Yale University. His Ph.D. thesis, under the supervision of David DeMille, was on a search for the electric dipole moment of the electron using lead oxide molecules in a high temperature vapor cell. Paul then carried out his postdoctoral research at University of California at Berkeley in the group of Holger Müller. At Berkeley, he focused on using atom interferometry to test fundamental physics. Paul's plans in his own group at UCLA are to pursue novel platforms for atom interferometry and using those platforms for new test of physics beyond the standard model.

## SHENSHEN WANG



Shenshen Wang started her scientific journey as a physics major at Nanjing University. She then moved to Hong Kong and obtained an M. Phil. in theoretical physics at Hong Kong University of Science and Technology (HKUST) by studying novel dissipative states in low-dimension electron systems. In 2007 Shenshen arrived at California, where she did her PhD work in theoretical biophysics at UCSD under the supervision of Professor Peter Wolynes where she developed a generic theoretical framework to understand a rich variety of collective phenomena in the eukaryotic cytoskeleton. She moved to MIT in 2012 as a postdoctoral fellow. In collaboration with Professors Arup Chakraborty and Mehran Kardar, Shenshen used computational modeling based on statistical physics to study how the adaptive immune system evolves potent antibodies to fight against rapidly mutating pathogens. She collaborates with chemical and biological engineers and immunologists to deepen our understanding of the immune system using statistical physics methods and discover design principles for better vaccines. Professor Wang will arrive in January 2016.

## DAVID B. CLINE

### December 7, 1933 - June 27, 2015

Distinguished Professor of Physics and Astronomy David B. Cline, a driving force behind experiments aimed at understanding the world of elementary particles and forces, died at UCLA Medical Center on June 27, 2015. He was 81. Cline had an inquisitive and insatiable thirst for knowledge and a remarkable memory. He was dynamic in spirit, and demanding and relentless in pursuing scientific ideas. His creativity, enthusiasm, and passion for new devices and experimental techniques kept him well placed at the forefront of physics research.

Cline received a B.S. and Masters in physics at Kansas State University, earned his Ph.D. in 1965 at the University of Wisconsin under the supervision of William Fry. In the late 1960's, Cline, by then a physics professor at the University of Wisconsin, and his collaborators (including Carlo Rubbia, Alfred Mann and others) performed a series of difficult, innovative experiments to study the weak force at Fermilab outside Chicago. Carlo Rubbia, Peter McIntyre, and David Cline made a radical proposal in a famous 1976 paper to use existing proton accelerators to make antiprotons and collide them head-on with protons. The proposal was first implemented at CERN, resulting in the discovery of W bosons and Z bosons in 1983 by physicists including Cline. This discovery led to the Nobel Prize for Rubbia and Simon van der Meer (the inventor of the methods used to make the antiproton beams). In 1984, Cline co-founded Particle Beam Lasers, Inc., a small company engaged in developing technologies and subsystems to accelerate and control elementary particle beams. Cline served as a director of the company until the time of his death.

Cline moved from Wisconsin to UCLA in 1986, where he promoted new directions of research in the department. In addition to performing research on advanced particle physics accelerators, he recruited the first dedicated accelerator physics faculty member at UCLA, Claudio Pellegrini. Thanks to David Cline, UCLA now has unique, world-class efforts in both accelerator physics and astroparticle physics. In the 1990's, Cline and a few others in the U.S. chose to work on a competing CERN-based effort called the Large Hadron Collider, and he was one of the founders of one of the large detector collaborations known as CMS. In 2012, the CMS collaboration and the ATLAS collaboration announced the discovery at CERN of the Higgs boson, the particle associated with the mechanism giving rise to the masses of the W and Z bosons. Beginning in 1994, Cline organized a biannual conference near UCLA, inviting all the international researchers in this area. This became an extremely popular, major event in the particle and astroparticle physics communities, and the organizing committee is enthusiastically continuing with plans for the twelfth such conference in February 2016. While working on particle and astroparticle physics at UCLA, Cline continued his work on particle beam physics and particle accelerators, leading a group that performed many frontier experiments on advanced accelerators and detectors, in collaboration with Brookhaven National Laboratory.

Cline was preceded in death by his beloved son David Bruce Cline Jr., his parents Ella Mae Cline and Andrew Bruce Cline, and his sister Sandra Cline. He is survived by his children Richard Andrew Cline, Heather Alane Cline, Daphne Aileen Boyle, and Yasmin Cline; and his eight grandchildren Connor, Brendan, and Ryan Boyle; Chiara, Gina, and Ilaria Cline; Myles Cline Cence; and Skye Rose Cline.

*The above memorial is an abbreviated version from a complete Obituary for David Cline of his many contributions to the world of physics. For the full version go to: www.pa.ucla.edu/content/david-b-cline*

## BYRON TERRY WRIGHT

### October 19, 1917 - April 9, 2015

Longtime UCLA Physics Professor Byron Terry Wright died peacefully, surrounded by family, at the home of his daughter in Los Angeles on the evening of April 9th, 2015 at the age of 97. He was born to Wilbur and Dora Thompson Wright on October 19, 1917 in Waco, Texas.

Byron attended Rice University where as a physics undergraduate, the results of his experiment were published as a "Letter to the Editor" in the Physical Review. From 1938 to 1941, he worked at the Radiation Laboratory under Earnest Lawrence while he obtained his PhD at the University of California at Berkeley. In 1941, he was part of a group involved in antisubmarine research at the naval facility in Point Loma, California and his work on an underwater camera led to an unexpected visit to Pearl Harbor on December 24-25th in an unsuccessful attempt to survey the harbor entrance sea floor. In 1942, he was one of many physicists invited to Berkeley to work on a project to determine the feasibility of using a mass spectrometer to produce enriched uranium for an atomic bomb. During the next three years he traveled between Berkeley, Oak Ridge and Los Alamos working on various aspects of what became known as the Manhattan Project. During this period he met and married the love of his life, Lorna Doone Bloemers on October 21, 1944. In 1946, he moved from Berkeley to UCLA along with the Berkeley cyclotron and began his long career as a Physics Professor. Byron was a full professor in physics by 1956. During his career, he was a Fulbright resident scholar (56-57), a Guggenheim Fellow (63-64), and a Ford Foundation Fellow at CERN (63-64). One of his achievements was to initiate construction of equipment in 1949 for a new upper division modern physics lab which is still in use today. His beloved wife of 20 years, Lorna, died on October 21, 1964. After 1972 he became an Associate Dean of the Graduate Division at UCLA where he remained until retiring. Family, travel, and outdoor pursuits (and frequently altogether) filled a big part of his life thereafter. He was a rare person who could simultaneously command true respect and true affection.

In addition to his daughters and their husbands, Carol and Harry Schrauth, Susan and Donald Garrard and Gail and Joel Rosenblum, he is survived by his grandchildren David, Brent, Cynthia, Tyler, Morgan, Corey, Aaron, Lorna, Stephanie and Maegan. Additionally, he has seven great-grandchildren: Tasmine, Akayla, Emily, Michael, Cameron, Lucas and Elliot. A private family celebration was held on May 24th, 2015.

## ASTRONOMY LIVE! & THE UCLA PLANETARIUM

On November 16th, 2014 we hosted the sixth annual Exploring Your Universe (EYU) events. These free public events included talks, demonstrations, exhibits, and hands-on activities from the Departments of Physics and Astronomy, Earth, Planetary and Space Sciences, Atmospheric and Oceanic Sciences, Chemistry, Engineering and Applied Sciences, and the Center for Environmental Implications of Nanotechnology. In addition, EYU 2014 featured an Educators in Science lecture series for local teachers. This event has grown dramatically over the past few years, and EYU 2014 drew approximately 6,000 attendees. Visitors come from all over the Los Angeles area, including many students, staff, and faculty of local schools and UCLA. EYU 2015 promises to be even larger. A new interdepartmental committee was formed in the spring of 2015 to make the planning process easier and more collaborative. The new website is already up and running: http://eyu.astro.ucla.edu/

In 2015, Astronomy Live! hosted a summer observing workshop for high school students here at UCLA for the second year running. 10 local high school juniors and seniors were chosen based on their applications. Over the course of 8 weeks, students learned the basics of observational astronomy. They learned to use the 11-inch and 14-inch telescopes at UCLA, took their own data, and used that data to complete research projects relating to astronomy and astrophysics.

Workshop participants also heard short research talks from graduate students at UCLA. As a part of this program Astronomy Live! was granted three nights on the Lick 1-meter Nickel telescope to observe remotely. During one of these observing runs, the students were able to sit in and even control the telescope. In the process of learning to do data reduction, the workshop participants used reduction scripts written in Python. We hope this workshop will continue to grow in size in future years.

In addition, the UCLA Planetarium has had another very successful year. The graduate student-led planetarium saw 104 shows given over the 2014-2015 school year, with 5,934 attendees - our fourth year with over 5,000 attendees and the largest attendance ever. Shows were given to 58 different schools from the Los Angeles area. Astronomy Live! also played a major role in Exploring Your Universe 2014 and our High School Summer Program.

Drs. Malkan and Sakai continue their active outreach work in the Los Angeles public schools. In 2015 they presented live physics demonstrations to large numbers of students, including the launching of the first annual "Science Slam" at Westwood Charter School. Several Astronomy graduate students also participated in this very successful day-long event.

## **PLASMA FEST:** A CELEBRATION OF UCLA'S EXCELLENCE IN PLASMA RESEARCH


Celebrating the exceptional breadth and depth of UCLA-based research related to the fourth state of matter known as plasma, UCLA hosted Plasma Fest, a day-long symposium on Sept. 22 that was attended by 175 scientists from UCLA and beyond. The event included presentations, a poster session, and discussion groups on a variety of topics, including fusion energy, basic plasma physics, space and astrophysical plasmas, math for plasma science, plasma-based accelerators, plasma-materials interactions, and space propulsion. One main goal was to foster interdisciplinary collaborations in emerging research areas.

Plasma Fest drew 175 attendees from UCLA departments as well as from other campuses across the country.

Plasma Fest was hosted by the Plasma Science and Technology Institute (PSTI), an Organized Research Unit spanning seven UCLA departments in the physical sciences and engineering, which is led by Professor Frank Jenko. It represents the largest university-based plasma research effort in the world and offers unique opportunities in research and education. Visit the PSTI website at http://psti.ucla.edu for more information. Plans are under way to host Plasma Fest again in Fall 2016.

## THE ROYAL SOCIETY OF LONDON'S **BAKERIAN MEDAL**

Professor Andrea Ghez was awarded the Royal Society's 2016 Bakerian Medal. The Royal Society, which is the oldest scientific academy in continuous existence, cited Ghez's "acclaimed discoveries using the techniques of optical astronomy, especially her sustained work on the motions and nature of the stars orbiting the black hole in the centre of our Galaxy." The Bakerian Medal, the Royal Society's premiere prize lecture in the physical sciences, was established by Henry Baker in 1775 and is accompanied by a cash prize of 10,000 pounds (approximately $15,500). Ghez, the Lauren B. Leichtman & Arthur E. Levine Endowed Chair in Astrophysics & Director of the Galactic Center Group, will deliver the award's associated public lecture at the Royal Society in London on April 1, 2016.

Top left: Andrea Ghez received the Bakerian Award at the Royal Society's Premier Awards Dinner, which was held Oct 15, 2015, from Alex Halliday (Vice-President of the Royal Society for Physical Sciences). Above: At the reception prior to the ceremony, Andrea chats with Prince Andrew, Duke of York, who was the event's royal family officiant, about black holes.

## 2015 SLOAN RESEARCH FELLOWSHIPS AWARD

Smadar Naoz was awarded the 2015 Alfred P. Sloan Fellowship for distinguished scientific performance and unique potential for future research. The Fellowship honors outstanding early-career scientists in eight fields. The Alfred P. Sloan Foundation announced the selection of 126 outstanding U.S. and Canadian researchers as recipients of the 2015 Sloan Research Fellowships. Awarded annually since 1955, the fellowships honor early-career scientists and scholars whose achievements and potential identify them as rising stars, the next generation of scientific leaders. Fellows receive $50,000 to further their research.

# PRESIDENT OBAMA NAMES CLAUDIO PELLEGRINI AS A RECIPIENT OF **THE ENRICO FERMI AWARD**

President Barack Obama greets 2014 Enrico Fermi Award recipients Charles Shank, left, and Claudio Pellegrini in the Oval Office, Oct. 20, 2015. (Official White House Photo by Pete Souza)

WASHINGTON – President Obama has named Dr. Claudio Pellegrini and Dr. Charles V. (Chuck) Shank as recipients of the Enrico Fermi Award, one of the government's oldest and most prestigious awards for scientific achievement. The Presidential award carries an honorarium of $50,000, shared equally, and a medal. The award is administered on behalf of the White House by the U.S. Department of Energy.

*"For pioneering research advancing understanding of relativistic electron beams and free-electron lasers, and for transformative discoveries profoundly impacting the successful development of the first hard X-Ray free-electron laser, heralding a new era for science"*

## 'THE BIG BANG THEORY' CREATES A SCHOLARSHIP FOR STEM STUDENTS

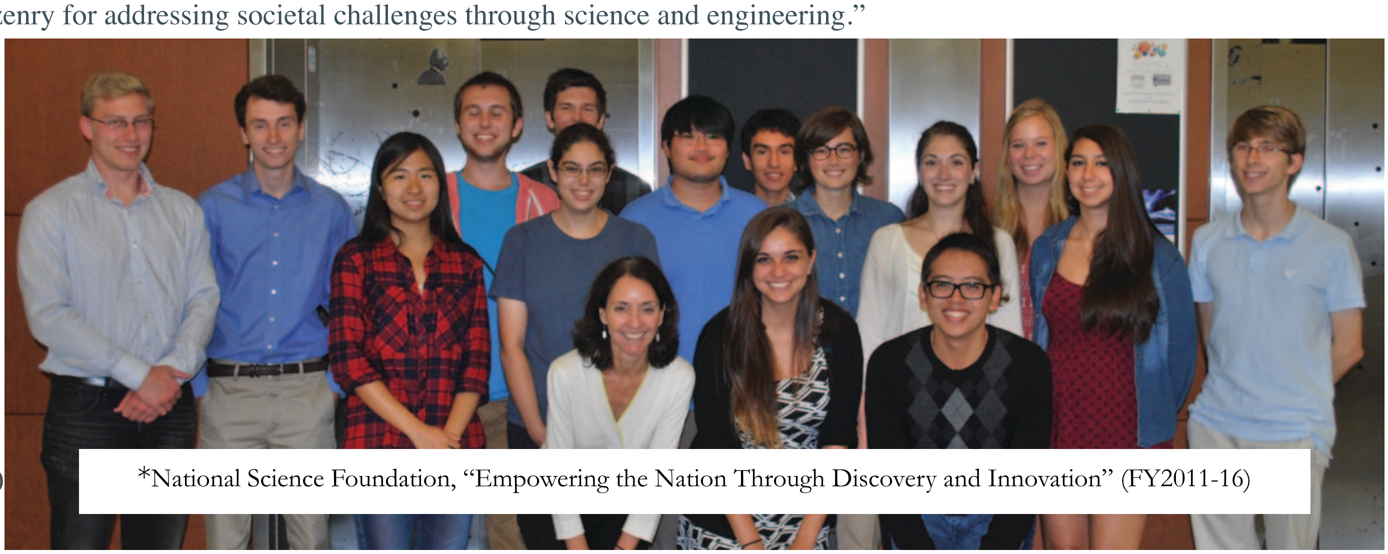
The Chuck Lorre Family Foundation, along with the producers, cast and crew of the hit television show 'The Big Bang Theory' raised over $4 million to endow a major scholarship fund at UCLA to provide financial aid to undergraduate students pursuing degrees in science, technology, engineering and mathematics fields.

Professor David Saltzberg is the show's science consultant.

For the 2015-2016 academic year, 20 Big Bang Theory scholarships will be awarded to low-income students who have earned admission to UCLA. Five additional scholars will be selected each year in perpetuity.

## RESEARCH EXPERIENCE FOR UNDERGRADUATES (REU) 2015

The Physics & Astronomy department hosted its 13th annual Research Experience for Undergraduates Program (REU program) during Summer 2015. A diverse group of fourteen undergraduates came from across the country and California to engage in real frontier level research with a UCLA faculty member for a period of 10 weeks. In this program, students are being trained in the newest lab, computational and theoretical techniques to prepare them for the work of science research. The program has so far hosted 181 students many of whom have then gone on to pursue scientific careers. In so doing, the program addresses key objectives of the NSF's current 5-year strategic plan to "Prepare and engage a diverse STEM workforce motivated to participate at the frontiers and build the capacity of the nation's citizenry for addressing societal challenges through science and engineering."



*National Science Foundation, "Empowering the Nation Through Discovery and Innovation" (FY2011-16)

# KEYNOTE SPEAKER

## 2015 Physics & Astronomy commencement

## Charles F. Kennel

Family and friends gathered at Schoenberg Hall to celebrate the graduation ceremony in honor of the students from the UCLA Department of Physics and Astronomy on June 13, 2015. This was the largest graduating class the Department has had in the last 25-30 years. Department Chair, Jean Turner, welcomed everyone to the commencement celebration, which was followed by a large procession of students onto the stage. The afternoon events flowed flawlessly with student addresses, faculty addresses, outstanding honors and awards amid the cheers and excitement of the graduates. Graduation Day festivities continued on the patio where all enjoyed a light buffet, animated conversation, photo opportunities and emotional goodbyes.

Charles F. Kennel gave the keynote address. Professor Kennel chaired the department from 1983-86 and eventually became the UCLA Executive Vice Chancellor. From 1994-1996 Dr. Kennel served as Associate Administrator at NASA and Director of Mission to Planet Earth, the world's largest Earth Science program. He became the ninth Director of Scripps Institute of Oceanography and Vice Chancellor of Marine Sciences at the University of California, San Diego, serving from 1998-2006. Dr. Kennel was the founding director of the UCSD Environment and Sustainability Initiative. He is a distinguished professor emeritus of atmospheric sciences at Scripps, senior strategist for the UCSD Sustainability solutions Institute, and leads the University of Cambridge/UCSD Global Water Initiative. A member of the National Academy of Sciences, the American Academy of Arts and Sciences, the American Philosophical Society, and the international Academy of Astronautics, Dr. Kennel has served on many national and international boards and committees, including the PEW Oceans Commission. He was a member of the NASA Advisory Council from 19998-2006, and its Chair from 2001-2005. He presently chairs the California Council on Science and Technology and the Space Studies Board of the US National Academy of Sciences.

## AWARDS 2014-2015

### WINSTEIN PRIZE

Peihao Sun

Yi Fei Yan

### RUDNICK-ABELMANN SCHOLARSHIP

Erick Garcia

Bao Minh Thi Hoang

Jesse Santana, Jr.

Joseph Swearngin

### CHARLES GEOFFREY HILTON AWARD

Guachao Sun

### E. LEE KINSEY PRIZE

Peihao Sun

## BACHELOR OF SCIENCE IN ASTROPHYSICS

Saundra Morgan Albers
Lydia Bingley
Patrick Durghalli
Justin William Grace
Manuel Giovanni Gutierrez
Andrew Khannarong Juhasz
Kelly Megan Kosmo
Ronald Alexander Lopez
Joseph Peter Manriquez
Matthew John Richardson
Marcus William Simpson
Guochao Sun
Shea Nelson Thorne

## BACHELOR OF SCIENCE IN PHYSICS

Nicholas Abella Ambrosio
Benham Amlashi
Stephen Matthew Armstrong
Lane Grayson Beale
Nathaniel Ryan Bell
Brandon Robert Berg
Brian James Bleakley
Javier Carmona, Jr.
Joseph Ly Chang
Kacper Dariusz Checinsky
Kunhe Chen
Yuxuan Chen
Tyler Ray Chesebro
Sung Him Chiu
David Mahnyoung Choi
Gale Ivy Dorothy Curry
Nicholas Gordon Dale
Alberto Jose Garcia
Matthew Scott Gong
Chloe Elizabeth Groome
Camilla Dodge Harris
Katherine Lily Heflinger
Lucas Ronald Hofer
Bradley Collin Hooker
Patrick Hovsepian
Nicholas Daniel Hubbard
Vito Mariano Iaia
Grant Frederik Jasmin, Jr.
Zeeshawn Phiroze Kazi
Sami Saad Khamis
Sharareh Koufigar
Dang Nhat Le
David Donggun Lee
Matthew Christopher Lee
Jeovan Max Leon
Preston Kyle Lewis
Andrew Boshi Li
Olivia Elizabeth Liebman
Akshat Mahajan
Janice Lindsey Mallery
Priyank Mehta
Shanil Nikhil Modi
Matthew Joseph Molinare
Andrew James Mott
Richie Singh Nagi
Tam Thien Nguyen
Andrew Edward Olson
David Sal Ortega
Bradley David Parks
Jackie Phuekhunthod
Hanwen Qin
MD Shahedur Rahman
Philipina S. Ramos
Dylan Nathaniel Rees
James Basil Revelino
Derek Allen Rodrigues
Eric Sandouk
Nicolas Andre Searle
Jasmin Hison Shin
Ahis Bhakta Bade Shrestha
Kacie Louise Smith
Coty Dewayne Spence
William Jordan Stalls
Peihao Sun
Joseph Michael Thatcher
Jesus Tejeda
Maxx Isaac Tepper
Jacquelynne Devalcourt Vaughan
Kevin Nicholas Vega
Viet Vo
Anna Li Wang
Hanxiao Wang
Nan Wang
Samuel Linton Watkins
James Thomas Wickham
Michael Wilensky
Hsuan Ming Yu
Deanna Margaret Zapata
Adidlaos Zepeda
Aobo Zhang

## BACHELOR OF ARTS IN PHYSICS

Christopher Minh Dang
Noor Ammar Eltawil
Zaid Eltawil
Jung Huyn Kim
Jeongho Lee
Joanna Lew
Seth David Linker
Xavier Mateo
Izuki Matsuba
Jack Kenneth Stropko
Xavier Mateo
Izuki Matsuba
Jack Kenneth Stropko

## BACHELOR OF SCIENCE IN BIOPHYSICS

Anthony Pablo Baldo
Christopher Carmona
Kevin Yihao Chen
James Philip Earnest
Angelica Lau Jue
Brandon Wey-Hung Liauw
Jie Ma
Daniel Duong Mai
Brittany Helen Strahan
Sarah Weaks Thornton
Alexander Vorperian
Sam Yang

## DOCTOR OF PHILOSOPHY ASTRONOMY

**Frederick Byron Davies**
Advisor: Steven Furlanetto

**Thomas M. Esposito**
Advisor: Michael Fitzgerald

**Shane Franklin Nishi Frewen**
Advisor: Brad Hansen

**Robin Mostardi Rehagen**
Advisor: Alice Shapley

**Nathaniel Robert Ross**
Advisor: Matthew Malkan

## DOCTOR OF PHILOSOPHY PHYSICS

**Scott Bender**
Advisor: Yaroslav Tserkovnyak

**Peter Devore**
Advisor: Eric Hudson

**Joseph Patrick Duris**
Advisor: Pietro Musumeci

**Craig Fogle**
Advisor: Joseph Rudnick

**Zahra Mashhadi Aghajan**
Advisor: Mayank Mehta

**Joshua T. Moody**
Advisor: Pietro Musumeci

**Nathaniel Breckenridge Moore**
Advisor: Walter Gekelman

**Joshua David Nohle**
Advisor: Zvi Bern

**Brendan O'Shea**
Advisor: James Rosenzweig

**Yuxi Pan**
Advisor: Huan Huang

**Thomas Joseph Rehagen**
Advisor: Graciela Gelmini

**Mary Scott**
Advisor: Jianwei Miao

**Eric Hayato Takasugi**
Advisor: David Saltzberg

**Christian Vaca**
Advisor: Alexander Levine

**Feng Zhao**
Advisor: Huan Huang

**Tong Zhou**
Advisor: Stuart Brown

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