

# **UCLA** College

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## Physics & Astronomy



Annual Report  
**2016-2017**

UCLA Physics & Astronomy Department  
2016-2017  
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**UCLA** College

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Physics & Astronomy

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2016 - 2017

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Jean Turner, Chair

## Chair's Message

As Chair of the UCLA Department of Physics and Astronomy, I am pleased to present the 2016-17 Annual Report, in which we relate to our alumni and friends the accomplishments of our faculty, staff, and students during the recent academic year.

A highlight of the year was the announcement by the American Astronomical Society of major prizes to two of our faculty members. Eric Becklin, Professor Emeritus, was selected for the Henry Norris Russell Lectureship, awarded annually for lifetime preeminence in astronomical research. Ian McLean was honored with the Joseph Weber Award for Astronomical Instrumentation for the development of instrumentation leading to advances in astronomy. This is well-deserved recognition by the astronomical community of their pioneering efforts in infrared astronomy.

Another notable recognition this year was the election of Claudio Pellegrini, distinguished professor emeritus, to the National Academy of Sciences in recognition of his continuing achievements in original research in the area of relativistic electron beams and free-electron lasers.

Two faculty members joined the Department 2017. Nathan Whitehorn, who studies cosmology and high-energy particles and their astrophysical origins, has worked on projects in Antarctica, including IceCube and the South Pole Telescope. Josh Samani, who received his Ph.D. from UCLA in theoretical physics, joins the faculty as a tenure-track Lecturer, and has already received the 2017 My Last Lecturer Award from the UCLA Alumni Scholars' Club.


June 2017 the department graduated 95 undergraduate students, (71 Physics Bachelors; 14 Astrophysics Bachelors; and 10 Biophysics Bachelors) and 19 Ph.D. students (18 Ph.D.'s Physics; and 3 Ph.D.'s Astronomy). We were especially pleased to have alumnus Barak Bussel, '93, give an inspiring 2017 commencement address. We invite all of our alumni to stay in touch and visit us on campus.

Our graduate students have been exceptionally active in 2016-2017. In January, the Women in Physics organized a Conference for Undergraduate Women in Physics (CUWiP) at the new Luskin Center. CUWiP had an unusually large attendance of 250 undergraduates from colleges across California. Astronomy Live! continues its outreach efforts to local schools and the community, including the annual Exploring Your Universe ("EYU") event, a family-oriented day of activities and lectures. This year's EYU featured an award to astronaut Anna Fisher.

I would like to conclude with by expressing our gratitude to our alumni and supporters. Gifts to the Chair's discretionary fund, student groups and undergraduate research, or to specific research groups truly further our ability our research and education mission. We value your partnership as we continue to explore the frontiers of physics and astrophysics.

James Larkin  
Vice Chair, Astronomy





# PIONEERS OF INFRARED ASTRONOMY HONORED

## ERIC BECKLIN

### **2017 Henry Norris Russell Lectureship by the American Astronomical Society**

Professor Emeritus Eric Becklin has been selected for the Henry Norris Russell Lectureship by the American Astronomical Society. The prize is given annually to an astronomer "on the basis of a lifetime of eminence in astronomical research".

## IAN MCLEAN

### **2017 Weber Prize from the American Astronomical Society**

Professor Ian McLean has been selected to receive the 2017 Weber Prize from the American Astronomical Society (AAS). This prestigious award is given "to an individual, of any nationality, for the design, invention or significant improvement of instrumentation leading to advances in astronomy."

## LIFETIME ACHIEVEMENT PRIZE FROM THE AMERICAN ASTRONOMICAL SOCIETY AWARDED TO ERIC BECKLIN



Over the course of his career, Becklin has produced a remarkable number of trailblazing observational results, covering a wide range of topics, with cutting-edge instrumentation. Not only did these results open whole new avenues of investigation, but they also demonstrated the potential of the infrared regime.





For the past 50 years, Eric Becklin has been a leader in galactic center research. He discovered the galactic center through finding the strong infrared emission of the concentration of stars there, which at the time was quite unexpected. With these observations,

he began a rich field of investigating the astrophysics of galactic nuclei, which included star formation in extreme environments, nuclear star cluster formation and dynamics, and black hole accretion physics. Becklin has led the way with a keen understanding of where progress on key problems could be made and developing the necessary instrumentation. In the 70s, he made early and essential observations for understanding the stars at the center of our galaxy and the extinction of the galactic center. Most recently, he designed a remarkable set of observations with NASA's Spitzer telescope that directly detected SgrA\*, which is the emissive source associated with the accretion flow onto the central black hole. Today, the galactic center is a remarkable laboratory for understanding the physics and astrophysics of black holes thanks to the ground-breaking work of Eric Becklin.

Becklin also has numerous other firsts across the field of astronomy. He discovered the first protostar embedded in its formative dusty cocoon (the Becklin-Neugebauer Object in Orion). He identified one of the first bona fide brown dwarfs, as a companion to a white dwarf in collaboration with UCLA Professor Ben Zuckerman. In addition, he has continuously advanced infrared astronomy beyond these early discoveries, notably by studies of massive star-forming regions, the galactic center black hole and its environs, and the nature of lu-

minous infrared galaxies from near through the far infrared, as well as pioneering explorations of other infrared phenomena.

Becklin's ability also extends to scientific leadership. He has held many inaugural leadership positions including being the first director of both NASA's ground-based Infrared Telescope Facility (IRTF), one of the first dedicated infrared observatories, and NASA's Stratospheric Observatory for Infrared Astronomy (SOFIA), a flying observatory with a large telescope – 2.5 m diameter – aboard a Boeing 747.

Professor Becklin was hired in the late 1980's as the first step in a large initiative at UCLA to invest in Infrared Astronomy to capitalize on UC's co-



Opening of the IR lab in 1990. Eric Becklin, Dean Clarence Hall, and Ian McLean right

ownership of the W. M. Keck Observatory, which hosts the world's two largest telescopes. Becklin was hired with Professor Ian McLean, who formed



Founders of the Intergalactic Center Group (1995): Andrea Ghez, Eric Becklin and Mark Morris



*“The IRTF was unique: it was the only ground-based telescope at that time that could make measurements of Io’s volcanos, especially at 20 and 30 microns: it was very exciting. While the future of infrared astronomy is in observing from space, my time in Hawai‘i was a highlight of my career.” — Eric Becklin*

the UCLA IR Lab with Becklin. The IR Lab has built the majority of the infrared instruments at W. M Keck Observatory and has enabled the department to recruit many other top notch faculty, including Andrea Ghez, who founded the UCLA Galactic Center Group in collaboration with Professor Becklin and Professor Morris in 1995 and whose well-recognized discovery of the supermassive black hole at the center of our galaxy and its unexpected environs has become a key science case for the advancement of Keck Observatory and the future Thirty Meter Telescope. In subsequent years, other faculty members have joined the UCLA IR Lab, including Professor James Larkin, who is currently its Director and Vice Chair of Astronomy, and Professor Mike Fitzgerald. Professor Becklin has been instrumental in propelling UCLA into a leadership position in the field of Astronomy & Astrophysics.

He has a remarkable knack for understanding what is interesting and what is not and has generously mentored and collaborated with multiple generations of students, postdocs and faculty, inspiring them to be the best that they possibly can be. "We are so lucky to have him as our colleague," James Larkin.



April 2005 Eric Becklin, professor of physics and astronomy and chief scientist of the Stratospheric Observatory for Infrared Astronomy (SOFIA), to celebrate his 65th birthday and 40 years in the field.



IR Lab: Ian McLean (left), Eric Becklin, Andrea Ghez, Unknown, James Larkin, Michael Fitzgerald

# AMERICAN ASTRONOMICAL SOCIETY AWARDS

## 2017 WEBER PRIZE TO IAN MCLEAN



Twenty-eight years ago he founded and still directs the UCLA Infrared Laboratory, which has played a major (often lead) role in every infrared instrument at the W.M. Keck Observatory.





Professor Ian McLean has been selected to receive the 2017 Joseph Weber Award for Astronomical Instrumentation from the American Astronomical Society. This prestigious award is given "to an individual, of any nationality, for the design, invention or significant improvement of instrumentation leading to advances in astronomy." For more than forty years, Professor McLean has worked at the forefront of astronomical instrumentation from the early uses of spectropolarimetry in the mid-1970's to the latest in multi-object cryogenic spectrographs. He founded the Infrared Laboratory at UCLA, which has played a major role in every infrared instrument currently at the W.M. Keck Observatory. He has been the mentor for a generation of instrument builders. His latest textbook on electronic imaging remains one of the most authoritative on the subject and his expertise has been invaluable for many international projects.

The coupling of scientific interest and new empowering technology is part of what sets Professor McLean apart. In addition to his instruments, he has over 160 refereed publications and 8500+ citations. His contributions to the field of infrared astronomy began with his dissertation research at the University of Glasgow, in which he developed a dual channel scanning polarimeter for the study of evolved stars. Even as a young instrumentalist, Professor McLean had the foresight to see the scientific possibilities for the new infrared arrays. In 1986 he began construc-

tion of IRCAM-1 for the UKIRT telescope on Mauna Kea. IRCAM-1 served as a forerunner of modern infrared facility instruments and propelled McLean to the University of California and preparations for the Keck Telescope.

The UCLA Infrared Laboratory, established in 1989 under the leadership of Professor McLean, has had a profound effect on the scientific legacy of the Keck Observatory. Three of the four currently operational infrared instruments at Keck were led from the lab (NIRSPEC, OSIRIS, MOSFIRE). All engineering cameras for the Keck adaptive optics systems (KCAM and SHARC) were produced at UCLA. The lab has also designed and delivered facility instruments for the SOFIA airborne observatory, the Naval Research Laboratory, Gemini International Observatory, and Lick Observatory. Two out of the three instruments selected for first light at the Thirty Meter Telescope International Observatory originate from the Infrared Laboratory.

Professor McLean's first instrument for Keck, NIRSPEC (Near InfraRed Spectrograph), was the first of a new generation of cryogenic long-slit spectrographs with both moderate resolution ( $R \sim 3000$ ) and echelle ( $R \sim 25,000$ ) spectroscopic capabilities. Delivered in 1999, NIRSPEC has been used for a remarkable range of discoveries as diverse as Type 1a supernovae and the accelerating universe, distant galaxies of the early universe, the first indications of exoplanetary atmospheres, and defining properties of the supermassive black hole and its stellar cluster at the Galactic Center. It



Professor McLean (left) with former UCLA Ph.D. student Kristen Kulas and Machinist Ted Aliado. They are assembling the very delicate detector system for the MOSFIRE spectrograph.



is not an exaggeration to say that NIRSPEC opened up several new areas of astrophysical investigation.

In his most recent effort, Professor McLean served as the principal investigator of the MOSFIRE (Multi-Object Spectrometer for Infra-Red Exploration) spectrograph for the Keck Telescope. Delivered in 2012, MOSFIRE is the first cryogenic multiobject spectrograph to utilize a reconfigurable slitmask, which can observe the spectra of up to 46 objects simultaneously. Observations of distant galaxies that once took multiple nights can now be achieved in less than an hour. This project was a joint development with Project Scientist Chuck Steidel of Caltech, Harland Epps of UCSC, Keith Matthews of Caltech and a large multi-institution team. MOSFIRE is currently the most requested instrument at the W.M. Keck Telescope.

The Infrared Laboratory has been a rich training-ground for the next generation of infrared instrumentalists. Within the lab, Professor McLean has provided guidance and mentorship for two other faculty members (Larkin and Fitzgerald) and half a dozen postdocs over its 28 years of operations. The Infrared Laboratory has also produced several successful instrumentalists including Bruce Macintosh, the first graduate from the UCLA lab and now a Professor at Stanford and the principal investigator of the Gemini Planet Imager; and Amanda Mainzer, who is now PI of the NEOWISE extended mission for the WISE spacecraft.

Professor McLean's contributions to instrumentation and astronomy are further demonstrated by his service to the community. Within the UC system he is Associate Director for Infrared Instrumentation of the University of California Observatories, and he served for ten years on the Keck Science Steering Committee including as co-chair. He served as the Vice-Chair



Working at the FLITECAM instrument station on board SOFIA are, from left, Sarah Logsdon – UCLA; Ian McLean – UCLA, FLITECAM principal investigator. (NASA/SOFIA/N.Veronico)

for the UCLA Division of Astronomy and Astrophysics for five years. In the broader community, Professor McLean has served as the Chair of the SPIE Instrumentation Organizing Committee and he was President of IAU Commission 25 (Photometry and Polarimetry) and IAU Commission 9 (Instrumentation and Techniques).

Professor McLean's instruments have had a huge scientific impact and continue to have great demand at three observatories (Keck, Lick and SOFIA). His long term legacy of service to the community, founding of the UCLA infrared laboratory, book publishing and student training set him apart as an outstanding astrophysicist and instrumentalist. Professor Ian McLean is extremely deserving of the recognition of the Weber Award for excellence in astronomical instrumentation.

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*"When Eric Becklin and I joined forces in 1989 at UCLA, we had a grand vision of how a laboratory devoted to the development of state-of-the art infrared instruments could enhance the effectiveness of the Keck 10-meter telescopes, and create a major role for UCLA in the Keck community." McLean said. "Today we can look back and see our dreams fulfilled."*

## Donor Impact Story: Benjamin L. Holmes and Carol Scheifele-Holmes

“I paid \$54 my first semester at UCLA and a football ticket was included,” Benjamin L. Holmes, Physics ’59, recalls. “When you think about it, our education was essentially free.”

Holmes and his wife, Carol Scheifele-Holmes, established the Roberto Peccei, Ben Holmes, and Carol Scheifele-Holmes Graduate Fellowship. Known as the Peccei-Holmes Fellowship, their gift honors Professor Roberto Peccei’s achievements in physics and their decades-long friendship. Zahrasadat Alavi, who graduated in June, was named the first Peccei-Holmes fellow.

Looking back on his undergraduate days, Holmes recalls the pressure students felt in lower division physics classes to make it through, but ultimately believes that his education changed his life and laid the foundation for his successful career. The couple also sees UCLA and public education as an asset to society. “Giving back is the right thing to do,” he says.

Holmes and Scheifele-Holmes met and began working at Hewlett-Packard in the 1960s, witnessing the transformation of the company and Silicon Valley. Scheifele-Holmes worked in public relations and marketing and Holmes became general manager of the Medical Products Group and vice president of the corporation. Holmes was responsible for HP’s relations with UCLA and remains involved with UCLA as a member of the Physical Sciences Board of Advisors.

Holmes’ membership in the Kelps, a Bruin men’s spirit organization renowned for game-day pranks, also bonded him to UCLA for life. Holmes remembers a prank that would be impossible today: chartering a helicopter and dropping manure on the University of Southern California’s Tommy Trojan statue.

Holmes advises current UCLA physics and astronomy students that they can achieve anything with a background in physics. Echoing David Packard, he also encourages students to think of “profit as a result, not a goal unto itself” throughout their careers. And “If you make a contribution,” he says, “rewards will come.”



Ben Holmes and Carol Scheifele-Holmes on a trip to Ireland with UCLA Alumni Travel

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We greatly appreciate all gifts to the Department of Physics and Astronomy in the 2016-2017 academic year. Endowed support is critical to our continued success in UCLA's next century, and we would especially like to thank all donors who have established endowments to support our students and faculty.

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# Infrared Laboratory Group.

Ian McLean, James Larkin and Mike Fitzgerald

The UCLA Infrared Laboratory for Astrophysics (IR Lab) group develops state-of-the-art infrared cameras and spectrometers for many observatories, but especially for the twin 10-meter telescopes of the W. M. Keck Observatory on Mauna Kea, Hawaii. Three of the four infrared instruments in current use at the Keck Observatory were under the leadership of IR Lab faculty (NIRSPEC, OSIRIS, and MOSFIRE), and UCLA collaborated with Caltech scientists to produce the fourth instrument (NIRC2). Each instrument is developed for open use in order to maximize scientific return. Consequently, these instruments have facilitated numerous discoveries, and resulted in many hundreds of research papers across the entire Keck community.

During the current reporting period the IR Lab group consisted of three faculty members (McLean, Larkin and Fitzgerald), nine Professorial staff, and five graduate students. Two of our students (Anna Boehle and Sarah Logsdon) received their Ph.D.s in June 2017. Anna was involved in the OSIRIS spectrograph upgrade for Keck Observatory, while Sarah participated in the development and commissioning of FLITECAM on NASA's Stratospheric Observatory for Infrared Astronomy (SOFIA). These projects were completed successfully in 2016. Currently, the IR Lab is involved in two major upgrades for Keck Observatory; the OSIRIS Imager upgrade and the NIRSPEC detector upgrade. Both projects are led by Professor Fitzgerald. UCLA is also the lead institute on the multinational IRIS integral field spectrograph for the proposed Thirty Meter Telescope (TMT). This project is led by Professor Larkin. Last fall, UCLA and Caltech worked together with Keck Observatory to support the repair of MOSFIRE when it was unexpectedly damaged by an incident at the observatory last September. MOSFIRE was successfully returned to service in February 2017. More details are given below.

The Infrared Imaging Spectrograph (IRIS) for the TMT has been lead from the UCLA Infrared Laboratory (PI. Larkin) since 2006. IRIS spans the wavelength range from 0.84-2.4 microns. The instrument combines a set of on-instrument wavefront sensors, a wide-field diffraction limited camera, and an integral field spectrograph (Figure 1). IRIS is an international project with an estimated total budget of \$45 million and major collaborations at UC San Diego, UC Santa Cruz, Caltech, NRC-Victoria and the National Astronomical Institute of Japan (NAOJ). In addition to overall leadership of

the project, UCLA leads the electrical and software systems, and the design of the lenslet array spectrograph. In November, 2016 IRIS went through a formal preliminary review with an international panel of experts. The 2-day review covered all aspects of its mechanical and optical design. The review was deemed very successful, and the project was given approval to continue working on the electrical and software systems as well as carrying out a full cost and schedule review.

IRIS has challenging optics that include collimator and camera systems based on three-mirror-anastigmat (TMA) designs. The spectrograph section provides a base resolving power of  $\sim 4,000$  (8,000 in some modes) and comes with four plate scales (0.004, 0.009, 0.025, 0.050 arcsec per sample). Note how small the pixels are when using a huge telescope like the TMT at its diffraction limit. The imager section provides a relatively large 34 arcsec field of view by using a  $2 \times 2$  grid of  $4K \times 4K$  (H4RG) HgCdTe detectors from Teledyne. The plate scale for imaging is 0.004 arcsec per pixel.

Professor Mike Fitzgerald is leading the replacement of the OSIRIS Imager with a new camera and detector. The aims of this upgrade project are several: Provide stable imaging over

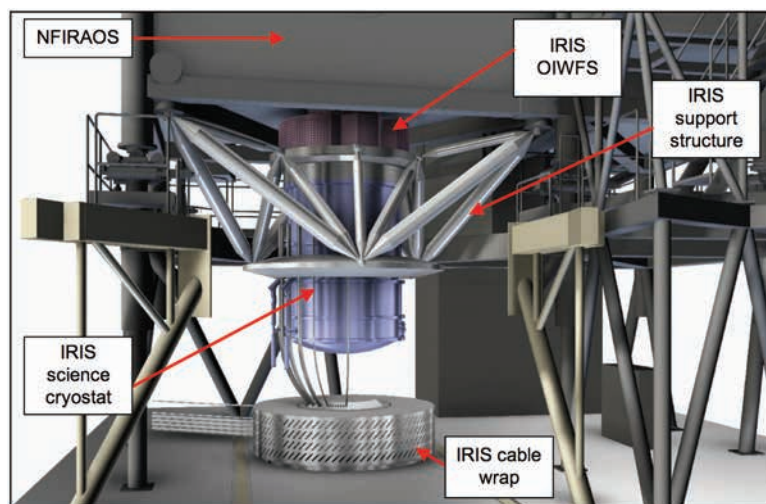


Figure 1. The IRIS instrument shown in-situ mounted to the up-looking port of NFIRAOS (TMT's facility AO system). IRIS mounts through a set of carbon fiber struts and rotates about its vertical axis to track the rotation of the field. The silver cylinder in the lower portion of the image is the IRIS cable services wrap, which is designed to prevent damage to IRIS cables as the cryostat rotates during operations. For scale, the blue dewar is 1.9 meters in diameter.

a 20" x 20" field with fine sampling suitable for astrometry; provide finely sampled PSF references for the spectrometer; improve the sensitivity in the K-band (wavelengths  $\sim 2.2$  micron) over current performance; and enable capabilities for first-light operation of Next Generation Adaptive Optics (NGAO). The Imager upgrade project is primarily funded by the Gordon and Betty Moore Foundation, with cost matching from UCO and UCLA. By June 2017 the project had progressed through fabrication and was in the final stages of integration and testing. Installation at the telescope will begin in September 2017.

Funded by a successful Major Research Instrumentation proposal to the NSF by Keck Observatory, in collaboration with UCLA, Professor Fitzgerald is also leading the upgrade of

design review is scheduled for October 2017, with installation on the telescope by mid-2018.

On September 13, 2016 an incident occurred during testing of the instrument rotator mechanism at the Cassegrain focus of the Keck 1 telescope. Testing of the instrument rotator was being done as part of the telescope control system (TCS) upgrades. MOSFIRE was the instrument mounted on the telescope at the time, and due to an instability in the new software, it was subjected to violent back-and-forth vibration for over two minutes when the rotator's servo loop went into an oscillation mode. When the instrument was used on sky that evening the image quality was two orders of magnitude worse than normal. An emergency project was initiated to reconstitute the original MOSFIRE team (PI: Ian McLean),

identify the problem, and make the necessary repairs. Both UCLA and Caltech received sub-awards from Keck Observatory for this work.

Through a sequence of tests and optical-mechanical analyses, the problem was traced to a single lens of zinc selenide (ZnSe) in the Collimator (Figure 3) that had come loose. Fortunately, the Collimator module is accessible through the rear of the instrument with minimal disturbance to other subsystems. The lens and its cell were removed from MOSFIRE and shipped back to UCLA, where the lens was re-bonded using an improved methodology, and re-aligned in its

cell with our Coordinate Measuring Machine. Post-inspection analysis revealed that despite the apparent violence of the shaking, nothing should have come loose. The fact that the ZnSe lens was able to detach from its cell was traced to bonds that were weaker than expected because the girdle of the lens had been fine polished rather than rough ground, and was therefore different from the test pieces. The remounted lens was successfully re-installed, all other systems were checked, and MOSFIRE was cooled down and re-commissioned on sky in February 2017. Tests showed that the performance of the refurbished MOSFIRE was back to normal. While this was a successful recovery, there was an unavoidable impact on the timelines for the OSIRIS Imager and NIRSPEC upgrade projects.

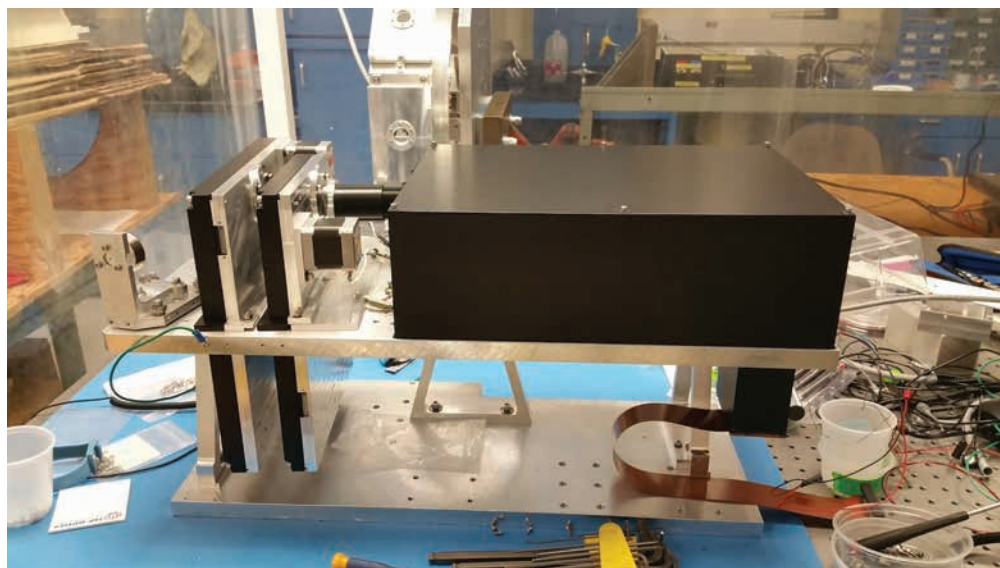


Figure 2. OSIRIS Imager in preparation for shipping to Keck Observatory, August 2017.

NIRSPEC at the Keck Observatory. NIRSPEC was the first cross-dispersed, high-resolution 1-5 micron cryogenic echelle spectrometer on a 10-m class telescope. It was commissioned on Keck II in 1999 (PI: Professor Ian McLean). The upgrade has three main goals. Replace the InSb detector in the spectrograph with an H2RG 5-micron cut-off array; replace the slit-viewing camera optics and detector; and eliminate the obsolete Transputer-based electronics used for both detector and motion control.

Fitzgerald and the IR Lab team have made significant progress in the past year. The new detector head has undergone extensive thermal tuning in our vacuum cryogenic test chamber, and the science grade detectors for the spectrometer and slit-viewing camera were received ahead of schedule. The optical design of the new slit-viewing camera is also nearing completion, and the new filter wheel and detector head required by the more capable slit-viewing camera has matured. Currently, the emphasis is on electronics and software subsystems. A final



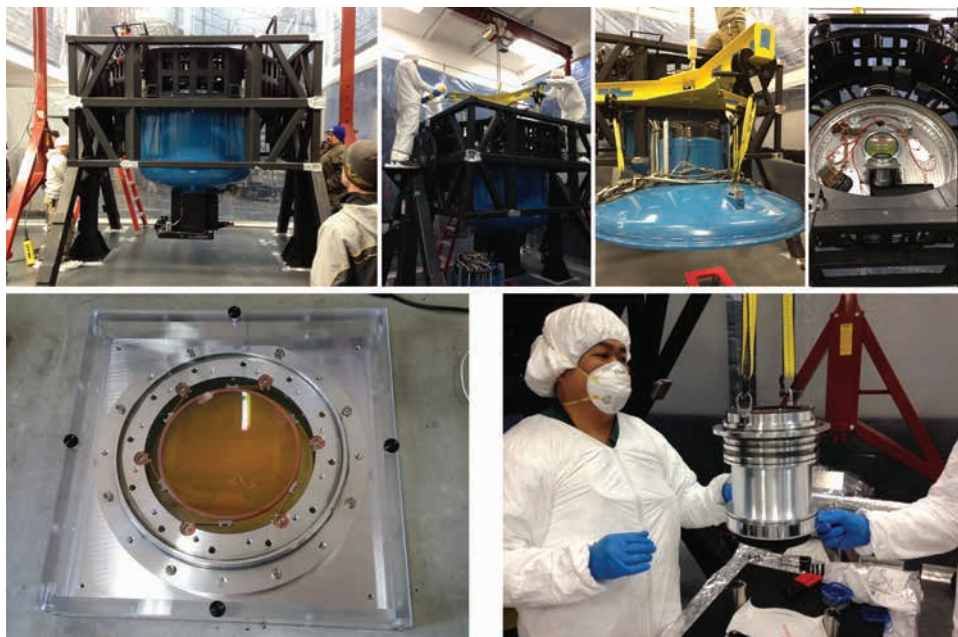


Figure 3. Upper panel. MOSFIRE being opened in the Clean Room on the dome floor of Keck I. Lower pane. The ZnSe lens in its shipping container after re-bonding into its cell at UCLA, and the complete Collimator ready for installation back into MOSFIRE.

**Ian McLean** continued as Director of the UCLA Infrared Lab, and as Associate Director for the University of California Observatories (UCO). He assumed the role of Vice Chair for Academic Affairs on July 1, 2016. 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. He was the principal investigator for all three of these instruments. McLean received the 2016 Maria and Eric Muhlmann Award for innovation in astronomical instrumentation from the Astronomical Society of the Pacific in October 2016, and the American Astronomical Society announced in January 2017 that he is the 2017 recipient of the Joseph Weber Award for Astronomical Instrumentation.

**James Larkin** continued as Vice Chair for Astronomy, and Deputy Director of the Infrared Lab. His research focuses on the early development of galaxies like our own Milky Way. Using his OSIRIS instrument 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 also supported graduate student Anna Boehle, who worked on the OSIRIS upgrade as well as 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 is working with current graduate students Pauline Arriaga and Kevin Stahl 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 detector upgrade for NIRSPEC. He is also working with Professor Ghez's group to model the field-dependent aberrations in Keck AO imaging via the AO Optimization project.

# OBSERVATIONAL COSMOLOGY, GALAXY FORMATION, AND SUPERMASSIVE BLACK HOLES

## Tommaso Treu's Group

Professor Treu's group has been continuing to pursue three major research areas. The first one is galaxy formation and evolution from first light to the present day universe. The second one is observational cosmology, i.e. the measurement of the fundamental constituents of the universe, from the properties of dark matter and dark energy to spatial curvature and neutrino content. The third one is supermassive black holes. Professor Treu's interests are mainly focused on their formation and evolution across cosmic time and the role they play in the evolution of galaxies.

In galaxy formation and evolution, the main results are in the context of the Grism Lens Amplified Survey from Space (GLASS; [glass.astro.ucla.edu](http://glass.astro.ucla.edu)), led by Professor Treu, and including UCLA Professor Malkan, UCLA postdoc Louis Abramson, and UCLA graduate students Xin Wang, Charlotte Mason, and Takahiro Morishita. The team published 12 refereed papers during the period. Highlights include the discovery and spectroscopic confirmation of the faintest galaxy known to date during the so-called epoch of reionization (<https://www.ucdavis.edu/news/astronomers-see-faintest-furthest-galaxy/>). At this epoch, more than 13 billion years ago, the universe undergoes a phase transition. Intergalactic neutral hydrogen that renders the universe opaque to ultraviolet radiation gets ionized by the first galaxies and becomes transparent, thus ending the so-called cosmic dark ages. It is believed that faint galaxies provide the bulk of ionizing radiation to produce this phase transition, but they are generally too faint to be seen. In this case, a cluster of galaxies in the foreground acts as a giant magnifying glass, allowing us to detect and study the faint background galaxy.

In observational cosmology, the group has been working on discovering new gravitationally lensed quasars (instances where multiple images of a quasar are observed due to the

lensing effect of an intervening quasar) to be used as probes of dark energy and dark matter. The team includes UCLA postdoc Simon Birrer, UCLA graduate students Daniel Gilman, Peter Williams, Anowar Shajib, and Xuheng Ding; undergraduate Cicero-Xinyu Lu, as well as former UCLA postdoc Adriano Agnello. One highlight of this work has been the discovery of 11 new lensed quasars forming 4 images, a very rare configuration. Those are the most valuable systems for this work, and they are currently being followed-up via an approved program using the Hubble Space Telescopes. More details can be found at the collaboration website ([strides.astro.ucla.edu](http://strides.astro.ucla.edu)).

In the field of supermassive black holes the two main highlights have been the completion of a major campaign to measure masses of black holes in the local universe using the 3m Shane Telescope at the Lick Observatory (LAMP2016-2017) in collaboration with many astronomers at various UC campuses and elsewhere, and the beginning of a long term campaign using the Gemini 8.2m telescope to measure the mass of a black hole at redshift 2.82, i.e. observed when the universe was just 2 billion years old (i.e. 15% of its present age). The teams includes UCLA Professor Malkan and UCLA graduate student Peter Williams.

Treu was one the Finalist for the 2017 Blavatnik National Awards for Young Scientists (<http://blavatnikawards.org/honorees/national-finalists/>). Fifth year graduate student Charlotte Mason was awarded the 2017 Price Prize by the Center for Cosmology and Astroparticle Physics at Ohio State University. Visiting graduate student Morishita defended his Ph.D. and now works as a postdoctoral scholar at the Space Telescope Science Institute in Baltimore.

## Matt Malkan

### The Universe Going Green

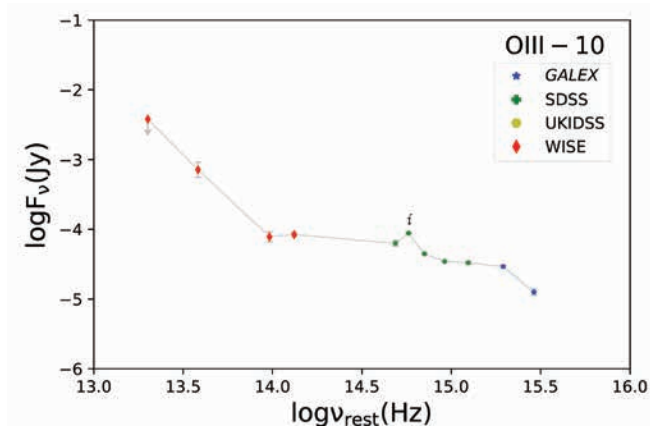
**Detecting the intense green glow from primitive galaxies offers our best view of how the first galaxies evolved**

Professor Matthew Malkan and graduate student Daniel Cohen found that the earliest galaxies were "going green." Last year's Annual Report described how the astronomers discovered a startling thousands of very distant galaxies in which the strongest emission line is from doubly ionized oxygen. Its wavelength of 501nm gives these galaxies their

striking green color. Something unusual was going on in the early generations of star formation, only one or two billion years after the Big Bang. The oxygen atoms in their surrounding gas clouds have lost two electrons, rather than the usual one. Knocking off that second electron requires a lot of energy. This can be done by only extremely energetic photons



(almost into the X-ray range). Few such high-energy photons are produced by the young stars seen today in the Milky Way or any other mature galaxies. To explain this, Malkan and Cohen proposed that the earliest generations of stars must have been substantially hotter than the most massive young stars being formed in the current universe. Their results were reported on by media and internet news outlets around the US and the world, from Science News to the Netherlands and



the Czech Republic. (See for example. <http://www.spaceref.com/news/viewpr.html?pid=50201>)

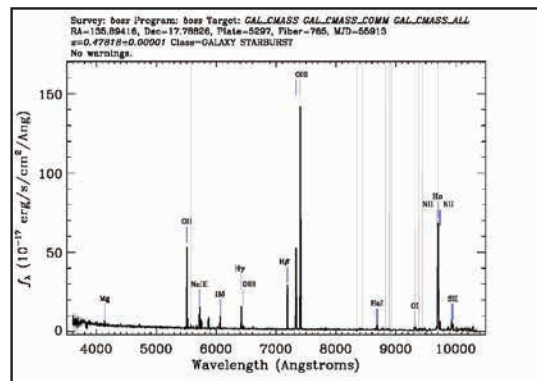
But could such ‘primitive’ young galaxies be found closer to home? Recently, Malkan and visiting Peking University student Zhihui Li found a new way to solve this needle-in-a-haystack challenge. Realizing that the distinctive green emission line would be red-shifted just beyond the wavelengths of visible light, they used digital imaging covering one third of the sky. They searched a catalog of about a billion objects measured in broad-band near-infrared filters, to find those rare galaxies which stand out as being unusually bright just around

# Steven Furlanetto Group

Professor Steven Furlanetto and his research group have continued to build innovative models of the first generations of galaxies in our universe, which appeared over 13 billion years ago, and to apply these models to explain both existing observations and to plan future facilities and observational programs. By comparing their models to measurements from the Hubble Space Telescope, Furlanetto and postdoctoral researcher Jordan Mirocha demonstrated that the most distant observed galaxies (existing just a few hundred million years after the Big Bang) behave similarly to more mature galaxies. However, they also showed that the interaction of these galaxies with the surrounding Universe is even more complicated than previously believed, as these galaxies simultaneously heat and ionize intergalactic gas – gas that provides the fuel for later generations of galaxies. The resulting “reionization” event has long been a prime target for

750nm. The example (left figure) shows the distinctive excess brightness in the “I” (infrared) filter, which Malkan and Li suspected was due to an extraordinarily strong emission line. Sure enough, when they obtained a detailed spectrum of this galaxy (right figure), this infrared excess was indeed found to be from very strong doubly ionized oxygen emission, at a moderate redshift of 0.5 (i.e. at an intermediate lookback time of 5 billion years.)

Their wide-sky search came up with several hundred more examples of primitive galaxies ‘going green’ in the intermediate-age universe. As they had predicted, the gas in these galaxies is depleted in heavy elements compared with the Sun. They have not gone through multiple generations of star birth and death, which enriched the Milky Way in heavy elements. Their very hot young stars are of particular interest, since these may have produced most of the extreme-ultraviolet photons (with energies above 13.6 electron volts) which re-ionized the entire young universe. Malkan is now pursuing observational confirmation of this re-ionization hypothesis by observing the newly discovered green galaxies in the ultraviolet with the Hubble Space Telescope.



observations of early generations of galaxies, and it (along with the heating transition) makes an ideal target for the Hydrogen Epoch of Reionization Array (HERA), a large radio telescope now under construction in South Africa. Furlanetto will help lead the theoretical interpretation of HERA's results, and his group's models are essential to making the most of this innovative telescope. Furlanetto and former UCLA students Fred Davies and Keri Dixon have also studied signatures of this reionization event leftover in the later universe, demonstrating that heretofore puzzling observations of the intergalactic gas offer insight into the reionization process – including both the sources driving it and structures in the gas itself. Furlanetto's program is opening new frontiers to study the earliest luminous sources in our Universe and their impact on galaxy evolution throughout cosmic history.

# HIGH-REDSHIFT GALAXIES

## Alice Shapley's Group

Alice Shapley and her group study key questions in the area of galaxy formation. Specifically, they use the Keck Observatory and space-based telescopes such as Hubble and Spitzer to collect spectra and images of very distant galaxies. These data provide a window  $\sim 10$  billion years into the past, when the Universe was quite young and the galaxies we see around us today were actively forming. Along with her graduate students Ryan Sanders, Xinnan Du, and Michael Topping, and collaborators around the University of California and beyond, Shapley is looking into the ways that gas cycles into and out of galaxies – one of the key processes governing galaxy growth and evolution. Shapley and her group also study the contribution of galaxies to the phenomenon of cosmic reionization – a major phase transition during the first billion years of cosmic time – and the growth of largescale structure in the early universe.

Shapley and her collaborators are busy analyzing the results from the recently-completed MOSFIRE Deep Evolution Field (MOSDEF) Survey (<http://mosdef.astro.berkeley.edu/Home.html>). The MOSDEF Survey is based on 48.5 nights of observations on the Keck I telescope with the MOSFIRE

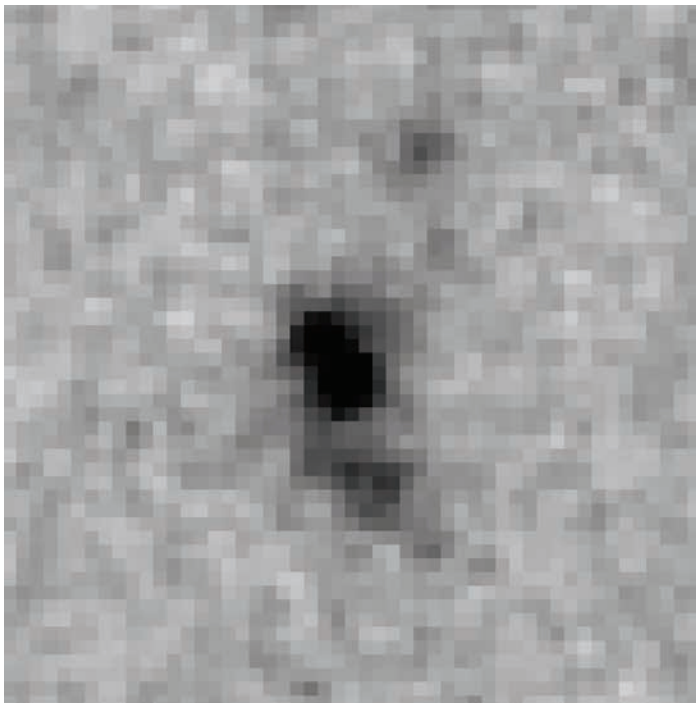


Figure 1. Hubble Space Telescope image of the galaxy GOODS-N-17940. This galaxy is at a redshift of 4.4, and its light has been traveling to us for more than 12 billion years. The HST image spans  $\sim 22,000$  light years on a side, and was taken through a nearinfrared filter, but the photons emitted by the galaxy started out as ultraviolet light. Their wavelengths stretched along with the expansion of the universe as they traveled through cosmic space and time. Shapley and her collaborators measured the heavy element content of GOODS-N-17940 using the MOSFIRE instrument on the Keck I telescope, the most distant such measurement performed to date.

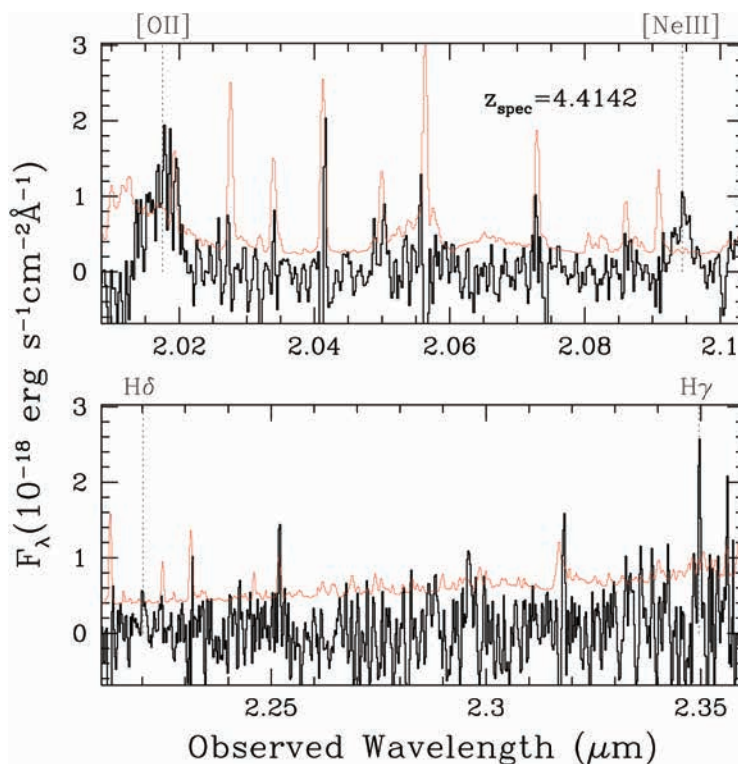


Figure 2. (From Shapley et al. 2017). MOSFIRE spectrum of GOODS-N-17940. Emission lines from oxygen, neon and hydrogen are marked, and the redshift "z" (an indicator of cosmic distance) is indicated as well. The horizontal axis shows wavelength in microns, increasing from left to right, and the vertical axis shows intensity. The oxygen abundance in GOODS-N-17940 is particularly sensitive to the pattern of emission lines observed in this spectrum.

instrument, and provides a census of the fundamental properties of galaxies during the first few billion years after the Big Bang. The basic data collected for the MOSDEF survey are nearinfrared spectra that were emitted as optical radiation  $\sim 10$  billion years ago. These spectra provide a window into the amount of oxygen present in distant galaxies relative to the amount of hydrogen – i.e., the so-called oxygen abundance. The oxygen abundance in interstellar gas provides a measure of the production of heavy elements in stars, the ejection of these heavy elements into the intergalactic medium, and the accretion of pristine hydrogen gas as the galaxy grows. With MOSDEF, Shapley was recently able to obtain the most distant estimate of oxygen abundance in the universe, measured in a galaxy at a redshift of 4.4, observed as it existed over 12 billion years ago (see Figure 1). This distant galaxy is significantly less chemically evolved than our Milky Way galaxy (see Figure 2), but is forming new stars at a rate roughly 100 times as fast! This pioneering result provides a preview of what the upcoming James Webb Space Telescope will measure for comparably and even more distant galaxies in the very early universe, placing important constraints on models of early galaxy formation.

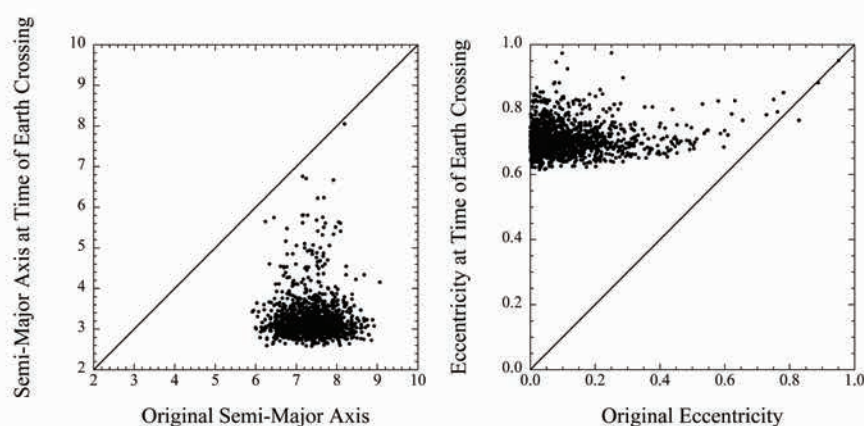
## William Newman

Professor William Newman's astrophysical and planetary science-related research during the past year focused on dynamical issues germane to the evolution of our solar system, with broader implications to extrasolar planetary systems. He, together with his University of Auckland colleague Philip Sharp as well as his Jet Propulsion Laboratory colleague Bruce Bills, returned to a long-standing problem relating to the dynamics of outer solar system planetesimal material, such as comets and their interaction with the gas giants. In recent years, he as well as other groups have demonstrated that around 15% of such planetesimals are injected, due to gravitational forcing from Jupiter and the other Jovian planets, into the inner solar system and go on to cross the orbits of Mars and Earth. On the other hand, the remarkable rarity of collisions by large planetesimals with Earth has resulted in there being only around five large scale events which resulted in the extinction of large numbers of biological species on land and in the oceans. The operative question, then, is why have the orbits of these objects spared us from frequent catastrophic collisions?

We performed very accurate numerical simulations of representative samples of such objects residing initially in the zone between Jupiter and Saturn, as well as planetesimals at much greater distance; we explicitly included the computation of the orbits of Mars and Earth, and their gravitational influence on these interlopers, employing the current positions and velocities of these solar system objects. Our simulations extended over 100's of millions of years and incorporated as many as half a million planetesimals in our simulations. The outcome was that only one planetesimal in 105 would collide with Earth. While this nominally answered our original question and, in the process provides important clues for astrobiologists and extrasolar planetary investigators, it left us with the question of why this happened.

The figure below presents two aspects of the evolution of the elliptical orbits of the planetesimals,

their so-called semi-major axes and their eccentricities. In considering the geometry of ellipses, the latter is a description of their degree of flattening while the former is a measure of their mean distance to the sun. The left-hand panel reveals that the original mean distance to the sun (horizontal axis) is reduced for all planetesimals culminating in their having a smaller mean distance. Meanwhile, the right hand panel reveals that their orbits have become more eccentric. We were able to explain this theoretically employing results from the gravitational three-body problem (Sun, Jupiter, and planetesimal) augmented by the shepherding influence of Saturn, when planetesimals happened to be closer to it than to Jupiter. In essence, the planetesimals that have made their way into the inner solar system, having very high eccentricity orbits, spend almost all of their time in the outer solar system in accord with Kepler's 1st Law, where their interaction with the much more massive gas giants ultimately consumes them or results in their expulsion from the solar system. Moreover, the genericity of our result allows it to be applied to the distant past during the early evolution of our solar system thereby providing a cogent explanation for why the Late Heavy Bombardment predicted by the Nice Model of Solar System Evolution did not in fact take place. Currently, we are making further theoretical inroads on this class of problems with applications both to solar system and large scale stellar environments.



## SUPER STAR CLUSTERS

### Jean Turner

Jean Turner and students S. Michelle Consiglio and Danny Cohen study the gaseous environments of young, presently-forming massive clusters. These so-called "superstar clusters", or SSCs, may eventually become globular clusters. Turner isolated the tiny cloud of molecular gas located within the SSC in the dwarf galaxy, NGC 5253, using images of emission in a

spectral line of carbon monoxide from the ALMA telescope. Cloud "D1", only 15 light years across, still retains its molecular gas in spite of the 2000 windy O stars that have already formed within the cloud. D1 may yet be forming stars. Consiglio has imaged the larger scale molecular environment of NGC 5253 out to ~1000 light years from the galaxy center (shown



in figure), and finds that the formation of its SSCs is driven by the accretion of narrow filaments of gas from outside the galaxy. Cohen has used NIRSPEC with adaptive optics at the Keck telescope to study the chaotic environment surrounding the young SSC in NGC 5253 on  $\sim 5$  light-year scales. He finds that while the stars within the cluster inject large amounts of energy into their surroundings through UV radiation, stellar winds, or supernovae, the end result is a gentle ionized cluster “breeze”, a product of strong gravity and cooling. Ionized gas can slowly escape the cluster, while the clumpy molecular gas is trapped. These results begin to define the process by which huge star clusters can be formed.

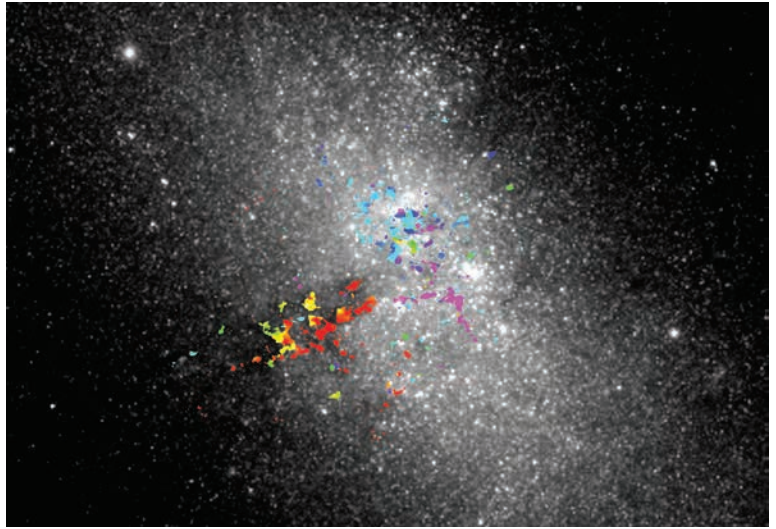


Figure 1. Thin filaments of molecular gas are identified by the Doppler shifts of the carbon monoxide line in dwarf galaxy NGC 5253. In color is the carbon monoxide emission, color-coded by velocity. Red is redshifted relative to the galaxy's systemic velocity, and blue is blueshifted. The prominent foreground filament is thus shown to be accreting onto the galaxy, which is the likely fuel for the many young star clusters forming there.

## PLANETS AND EXOPLANETS

### Jean-Luc Margot

Our research group measures the spin states, shapes, gravity fields, 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.

Graduate student Adam Greenberg completed his thesis work with the largest study ever published of the Yarkovsky effect, a non-gravitational force that affects the orbits of small celestial bodies. For asteroids smaller than 2 km, uncertainties associated with the Yarkovsky effect generally dominate the error budget of trajectory predictions. Adam's 159 detections allowed us to examine the physical properties of asteroids and the Yarkovsky effect in a statistical manner.

NASA's next flagship mission is a mission to Jupiter's satellite Europa. Postdoc Ashok Verma quantified the accuracy with which the gravity field and tidal deformation of Europa can be determined by radio tracking of the spacecraft. His calculations are used to verify that mission science objectives can be met with the proposed trajectory. The tidal signal is

expected to provide definitive evidence for the presence of a subsurface ocean under Europa's icy shell.

Our group quantified the accuracy with which one can test general relativity and measure the oblateness of the Sun by tracking the orbits of asteroids in orbits with large perihelion precession rates (Verma et al., ApJ, 2017). Margot has been accumulating high-precision radar measurements of these asteroids since roughly 2000.

Margot completed a book chapter to appear in *Mercury – The View after MESSENGER*. The article reviews the current state of knowledge about Mercury's interior structure, including radial profiles of the pressure, density, and gravitational acceleration in the core, mantle, and crust.

17 students (Figure 1) took Margot's SETI course and used the Green Bank Telescope to observe 10 planetary systems in the Kepler field, TRAPPIST-1, and LHS 1140. Students wrote Python programs and searched terabytes of data for artificial signals. A two-minute video that describes the student experience has been posted at <http://seti.ucla.edu>. The course will be offered again in Spring 2018.

Margot and EPSS colleague Professor Seulgi Moon organized a trip to view the total solar eclipse and explore the geology of Oregon. 36 participants thoroughly enjoyed the experience.



Figure 1. Spring 2017 UCLA SETI class with Michael Thacher



## RESEARCH GROUP. GALACTIC CENTER GROUP

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

The mission of the 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 (SMBH) and its environs affords us with the unique opportunity to study the fundamental physics of black holes.

With the closest approach of star S0-2 to the Milky Way's black hole in mid 2018, preparation for this exciting event (dubbed GR2018) is in full swing. GR2018 will mark the first test of Einstein's theory of General Relativity (GR) near a supermassive black hole, an important and unexplored regime. At the height of this event, S0-2 will be traveling at a peak speed of 8,000 km/s (4970 mph and  $\sim 3\%$  of speed of light) and changing its velocity by more than 6,000 km/sec over just a few months. This is the first and only star that can

test relativity in the vicinity of a supermassive black hole for the foreseeable future and this event will not occur again for another 16 years. We had a very successful observing season during summer of 2017 and now we are spending most of our time analyzing the data and making sure that we have all the foundations set up for GR2018.

Preparing for GR2018 was the central theme of our science collaboration in December at the 3rd annual GCG Workshop hosted by the Luskin Family and held at the newly opened Luskin Center at UCLA. This is an important meeting for us because it brings together our core collaborators from Keck Observatory, UC Berkeley, Spain, Harvard, TMT, and elsewhere for three days of intense face-to-face discussions. We also held the first ever three-day writing retreat in July at the Keck Observatory Headquarters in Waimea, HI. Being able to concentrate on writing without any distraction turned



The Galactic Center Group outside the W.M. Keck Observatory at the summit of Mauna Kea in Hawaii, 2017 July 20 (photo credit: Andrew Cooper)

out to be more successful than expected and also afforded us the opportunity to further our collaborations with core members outside UCLA and in particular with the W.M. Keck Observatory.

The summer observing run also included a very productive monitoring of the accretion flow onto the supermassive black hole. This included coordinating the following telescopes to capture photons over a large range of wavelengths. W.M. Keck Observatory (near-infrared), the new ALMA telescope (radio), NASA's Spitzer Space Telescope (far-infrared), and NASA's Chandra Space Telescope (x-rays). Dramatic variations were seen (up to a factor of 30 in only 20 minutes). This sheds light on processes close to the Event Horizon of the Black Hole and in particular, those associated with magnetic fields in the plasma where matter is about to fall through the Event Horizon.

Other GCG science highlights include. (1) our postdoc Aurelien Hees' paper on restricting fifth force was chosen as one of the featured articles in Physical Review Letters. In this paper, we used observations of the short-period star S0-2, to search for and to constrain a hypothetical fifth interaction motivated by unification theories and by models of Dark Matter and Dark Energy around the Galactic Center SMBH. (2) A third-year graduate student, Devin Chu, submitted a paper presenting the first limits of the binarity of S0-2 using spectroscopy data. The paper also quantified how a hypothetical binary would affect a measurement of relativistic redshift. (3) Gunther Witzel continued to lead the effort on investigating the intriguing sources G1 and G2, the first objects showing tidal interactions as they came very close to the central supermassive black hole. His paper on these objects revealed that they are stellar merger products. Stellar mergers have been rarely observed in the universe so far, and in this case originate from three body interactions between a binary star system and the central supermassive black hole. (4) We hosted two summer undergraduate students, John Mangian and Joey Marcinik, through the department's NSF

Research and Education for undergraduates program. Both students will be presenting their Galactic Center research results at the winter American Astronomical Society meeting in Washington, DC.

New grants were awarded to our group from the W.M. Keck Foundation and the Heising Simons Foundation for the Galactic Center Orbits Initiative, which has opened up a new approach to studying the physics and astrophysics of black holes.

As part of our community outreach efforts, we co-sponsored UCLA's Exploring Your Universe, an annual family science festival which attracts thousands of attendees each year. The GCG booth at this event answered questions about black holes, laser guide stars, and telescopes, and demonstrated the effects of gravity with a hands on gravity-well experiment. Perhaps, some of these younger audiences will one day join our group!

In other outreach efforts, Ghez participated in the Heising Simons Roundtable on Women in Physics and Astronomy and became a founding member of the resulting Physics & Astronomy Leadership Council. For additional information. <https://www.hsfoundation.org/programs/science/>

In 2016 we launched our Star Society Program which supports our research, education, and public outreach endeavors. The inaugural annual Star Society dinner was held at the Luskin Center on October 13, 2016 and Star Society tour of the Keck Observatory was held in July. If you are interested in helping us succeed in our efforts, please join our team. <http://www.galacticcenter.astro.ucla.edu/contribute.html>

## Smadar Naoz

During this year, Smadar Naoz and her group worked on various theoretical dynamical problems from planets to black holes.

### Throwing Icebergs at White Dwarfs

These "icebergs" caught the attention of the editor of Physics Today who has written a blurb about our research that has appeared on the PT website and will appear in the October print edition. It also featured the July issue of AAS NOVA.

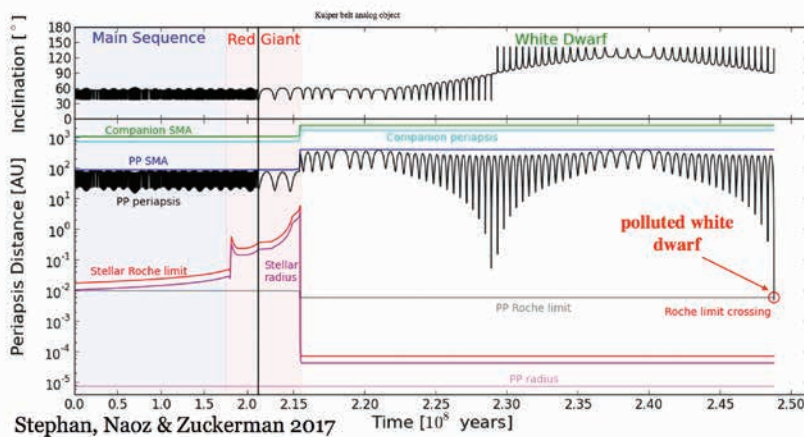
When stars with masses between that of the Sun and about 8 times this mass reach the end of their hydrogen-burning phase, their outer layers are blown off, leaving behind a compact

core, called a white dwarf. The strong gravity of white dwarfs causes elements heavier than hydrogen and helium to rapidly sink to its center leaving an atmosphere that should be free of metallic elements. Thus, it is surprising that about 25–50% of all white dwarfs are observed to have atmospheric pollution by heavy elements. The short timescales for sedimentation of these elements suggest that they were recently accreted by these white dwarfs. In the commonly accepted theory, orbiting asteroid belt that survived the star's evolution, can accrete rather efficiently onto the white dwarf. However, this scenario doesn't explain recent observations that found white dwarfs that accrete larger planetary bodies, as well as icy and volatile material from Kuiper-belt analog objects. How might



you get large or icy objects, which should begin on very wide orbits, close enough to a white dwarf to become disrupted and accrete?

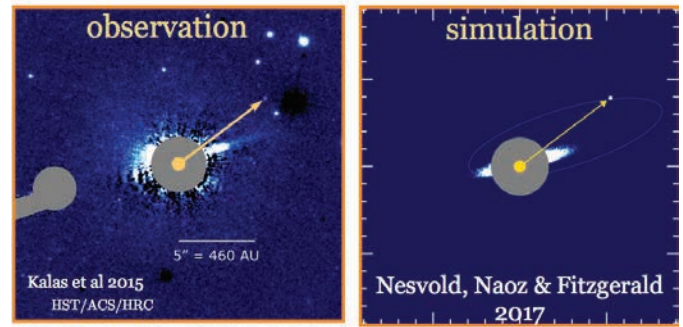
A paper led by UCLA graduate student, Alexander Stephan (Stephan, Naoz & Zuckerman 2017), showed that potential polluters on very wide orbits could achieve highly elliptical orbits and plunge into the white dwarf as a result of gravitational perturbations from a binary companion. These potential polluters have very wide orbits, and thus very cold temperatures; these allow Kuiper-belt objects to retain ice and various volatile materials, thus explaining the peculiar observations. The Figure shows an example of the evolution. Overall the paper analyzed 4500 binary systems at which the primary evolved to a white dwarf. One set of simulations included a Neptune-like planet in orbit around the white dwarf; the other set included a Kuiper-belt object in orbit around the white dwarf. The results of the two sets of simulations are consistent with the observation that about 10% of white dwarf spectra exhibit evidence of volatile species.



## Debris disk analysis suggests rethinking planetary formation

Circumstellar debris disks are produced by the rocky and icy material leftover from the formation of the star and any planets in the system. As the gas slowly evaporates, the dust and debris rotate and collide around the young star until they form a structure like our solar system's Kuiper belt. The architecture of the underlying planetary system can leave a distinct imprint on the morphology of a debris disk and thus the study of these objects provides a rare glimpse to the late stages of planet formation. While models of debris disk morphology are often focused on the effects of a planet orbiting interior to or within the disk, exterior companions have been detected and inferred for several systems. The existence of an interior or exterior perturber in the presence of a debris disk can provide evidence for planet formation.

The current consensus is that planets are formed inside such a vast disk of debris and very close to its central star. However,



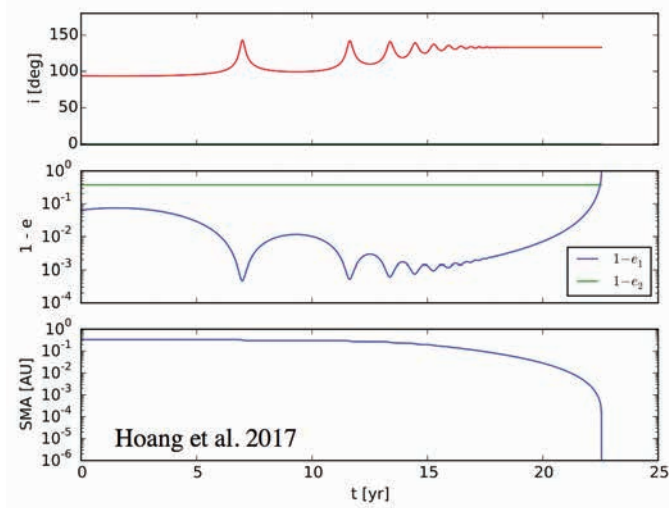
a young, giant planet, called HD 106906b, is 650AU from its host star, and beyond the stars' debris disk observed in the system. The current planet formation theories do not account for a planet beyond its debris disk. Nesvold, Naoz & Fitzgerald 2017, studied the dynamics of HD 106906 debris disk and showed that the far away planet in the system could easily reproduce the main debris disk observed characteristics (see figure). The analysis of the system yields that the planet must have formed in situ, i.e., far from the star, beyond the debris disk, in tension with current planet formation models.

## Old debris disks

In other two studies with collaborators from Harvard and Instituto de Astrofísica, Argentina (Naoz et al. 2017 and Zanardi et al. 2017) we analyzed the dynamics of the long-term evolution of far away test particles under the influence of an eccentric inner giant planet. Most of the studies of the evolution of debris disk focus on the evolution of few to tens of million years. However, debris disks stay put, just like our Kuiper belt. In Naoz et al. (2017) (and Zanardi et al. (2017) we showed that an eccentric inner planet would result in puffing up an exterior disk. Our Hamiltonian formalized yields straightforward calculations for longer timescales that can be achieved with N-body codes.

## Merging black hole binaries in galactic nuclei - LIGO sources

The recent detections of gravitational waves from merging binary black holes (BHs) by the Laser Interferometer Gravitational-Wave Observatory (LIGO) have opened a window of opportunity to observe the Universe in a new and exciting way. The detection of Gravitational-Wave emission by LIGO received the 2017 nobel prize. In a paper led by UCLA graduate student, Bao-Minh Hoang, Naoz and collaborators from Northwestern University and Eötvös University in Hungary (Hoang et al. 2017), Bao-Minh suggested a generic merger scenario. This paper investigates how binary stellar-mass BHs evolves under the gravitational influence of a Supermassive BH (SMBH) in the center of galaxies. Since almost every galaxy has an SMBH in its center, this mechanism is rather generic. Moreover, the SMBH and



its nuclear star cluster act like a gravitational sink, where BHs accumulate. The gravitational perturbations from the SMBH can increase the stellar BH binary eccentricity and can facilitate the merger of the binary (see Figure). The rate estimates are comparable to other suggested dynamically driven BH mergers. Furthermore, the analysis suggests that future LISA observations may help to differentiate between SMBH induced mergers and other mergers scenarios.

## R. Michael Rich Galactic Astronomy

Rich's research program concerns the galactic "geology" of the galactic bulge, which is to infer the galaxy's formation history from the ages, composition, and kinematics of its component field stars and globular clusters. Research in 2016-17 spanned the entire central bulge from the central nucleus, to globular clusters, to the entire stellar field population. Using the nirspec infrared high resolution spectrograph on Keck II, Rich, Nils Ryde (Lund University) and collaborators discovered a star  $\sim 60$  pc from the galactic center with  $[\text{Fe}/\text{H}]=-1$  with composition resembling similar stars in the bulge and halo, important because it is consistent with at least some stars in the center being at least 10 billion years old. Although claims of metal poor stars being found near the galactic center have appeared in the literature, this is the first such star confirmed at high spectral resolution-the gold standard for abundance measurement.



Figure 1. The core of M19 as revealed by the NASA Hubble Space Telescope and WFPC2. M19 has an extended blue horizontal branch and its stars range from 1/100 to 1/10 Solar iron abundance-only the 2nd known cluster to exhibit such a huge abundance range (Johnson, Rich et al. 2016). The helium burning stars on the horizontal branch exhibit a huge range in luminosity, creating an almost "vertical" branch.

The galactic bulge hosts over 100 globular star clusters, many of which have been studied for decades. However, two of the most massive bulge globular clusters have been shown to stand out in remarkable ways. NGC 6273=M19 is the second known galactic globular cluster to exhibit both a blue horizontal branch and a factor of 10 range in iron abundance, like Cen (C. Johnson et al. 2015, 2016). Johnson discovered the cluster while leading a study of the chemical complexity of globular clusters in the bulge. It is suspected that such remarkable globular clusters may be the nuclei of now defunct dwarf spheroidal galaxies. In NGC 6273 we do observe multiple groups of stars with the same iron abundance, but different enhancements in aluminum (produced in massive stars) and lanthanum (produced in so-called AGB stars). Terzan 5 is a similar globular cluster, among the most massive in the Milky Way. Terzan 5 was discovered at Keck II and nirspec to have a wide range in iron abundance (Origlia, Rich et al. 2011). The new research that used both the Keck laser guide star AO system with NIRC2 and the Hubble space telescope, also reveals two main sequence turnoff points. One turnoff with  $[\text{Fe}/\text{H}]=-0.3$  has an age of 12 Gyr, similar to most globular clusters, but a second turnoff at  $[\text{Fe}/\text{H}]=+0.3$  has an age of only 4.5 Gyr (Ferraro, F. et al. 2016). We have no idea why the younger more metal rich population is present. Might this cluster be a building block of the bulge, with the other building blocks subsumed into the field, shortly after birth? Possibly, but no other similar clusters are known in the bulge at present.

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# VERY HIGH ENERGY (VHE) ASTROPHYSICS

Rene Ong, Vladimir Vassiliev



Figure 1. Very Energetic Radiation Imaging Telescope Array System (VERITAS), which is located at the Whipple Observatory in southern Arizona

The VHE astrophysics group led by Rene Ong and Vladimir Vassiliev carries out research in a variety of science topics at the intersection between physics and astronomy. The main focus of their studies involves exploring violent phenomena in the universe, which are capable of producing very high-energy ( $>100$  GeV) photons. Such gamma rays, that have energies 100 billion times greater than optical light, are produced in physics processes far from thermal equilibrium, which take place in the vicinities of supernova remnants (SNRs), pulsars and their nebulae, black holes, such as in centers in active galaxies, and in enigmatic gamma-ray bursts.

At these energies gamma rays can also be created in physics processes beyond the standard model of particle physics, such as from the annihilation of unknown particles comprising the dark matter of the universe or from the evaporation of primordial black holes if they were produced during early stages of universe evolution. Through their interaction with the cosmological low energy (radio through UV) diffuse radiation fields, very energetic photons also provide unique opportunities to probe cosmologically important backgrounds as well as very weak intergalactic magnetic fields.

VHE astrophysics has been greatly advanced by the successful use of the imaging atmospheric Cherenkov technique. VHE gamma rays interacting in the upper atmosphere create

showers of relativistic particles that are beamed towards the ground. These particles emit Cherenkov light that can be detected on the ground by large optical reflectors that focus the light onto imaging cameras. A major benefit of this technique is due to very large area of the Cherenkov light pool on the ground, approximately 100,000 square-meters, compared to the 1 square-meter scale area typical for a satellite instrument. This large collection area enables the detection of very low astrophysical fluxes of gamma rays. In addition, the images of the Cherenkov light in the cameras can be used to accurately reconstruct the direction and energy of the primary gamma

UCLA is a major partner in the Very Energetic Radiation Imaging Telescope Array System (VERITAS), which is located at the Whipple Observatory in southern Arizona and consists of an array of four 12m-diameter imaging atmospheric Cherenkov telescopes. VERITAS has been operating very successfully since 2007 and has detected many dozens of sources and produced a number of important discoveries. In July 2017, an event was held at the Whipple Observatory to celebrate ten years of successful operations. This event highlighted some of the important scientific results of VERITAS and covered plans for the Cherenkov Telescope Array (CTA), the next-generation ground-based gamma-ray observatory. Within the last year, the UCLA group reported

the results from the VERITAS survey of the Cygnus region of the Galaxy at major conferences; a detailed paper has been submitted for publication. Graduate student Alexis Popkow completed her Ph.D. dissertation on the study of the Cygnus region. She is currently a postdoctoral researcher at the University of Hawaii.

The VHE astrophysics group is heavily involved in the plans for CTA, which is expected to have a large telescope array in both the northern and southern hemispheres. CTA will consist of telescopes of three sizes: large ( $\sim 23$  m diameter), medium ( $\sim 10$ - $12$  m diameter) and small ( $\sim 3$  m diameter). The observatory is being proposed by an international consortium of around 1,400 scientists from 32 countries. This consortium is developing all of the key instrumentation for the observatory, including the telescopes, electronics, readout software, and analysis software. Rene Ong has a significant role in the leadership of CTA and is currently serving as Co-Spokesperson of the consortium.

U.S. members of the CTA consortium are working on the development of a two-mirror medium-size telescope. This novel telescope, called the Schwarzschild-Couder Telescope (SCT), is designed to achieve superior performance and wider field of view compared to conventional telescope designs used, for example, by VERITAS. The group organized by Vladimir Vassiliev at UCLA pioneered this new instrumentation development for VHE gamma-ray astronomy and is now leading the effort of more than a dozen institutions to construct a prototype SCT at the VERITAS site location, with support from the NSF and from UCLA. The construction of the prototype SCT is well underway with the main optical structures in place. Figure 1 shows the telescope structure as of July 2017. The mirrors and camera are expected to be integrated into the telescope by late 2017 with first light coming a few months later.

The nature of astrophysical dark matter is one of the most compelling mysteries facing physics and astronomy today. There are strong arguments that a new particle comprises the bulk of the dark matter. One highly motivated candidate is the weakly interacting massive particle (WIMP). Many experiments worldwide are searching for WIMPs utilizing various techniques, among which a unique signature for WIMP annihilation could come from the detection of anti-deuteron particles in the cosmic rays. Astrophysical anti-deuterons have never been detected and so a clear signal of them would be very interesting. A UCLA group led by Rene Ong is working with the other institutions in the U.S., Japan and Italy to develop the first dedicated search experiment for anti-deuterons, called the General AntiParticle Spectrometer (GAPS). An anti-deuteron would be detected in GAPS via signals produced during its passage through an outer time of flight system, followed by its annihilation in a target of Si(Li) detectors.

The GAPS team developed a prototype instrument that had a successful flight in 2012 at the Taiki launch facility of the Japanese Aerospace Exploration Agency in Hokkaido, Japan. The major development over the last year was the approval by NASA of the GAPS construction proposal. This approval provides funding to construct the GAPS science payload for a first balloon flight as early as December 2020. The UCLA group is responsible for the time-of-flight system that measures the velocity and ionization of the anti-deuteron, and provides the master trigger for the experiment. In 2017, the group started intense laboratory work to finalize the design of the detector. Figure 2 shows a concept drawing of the GAPS instrument, illustrating its two major components: the time-of-flight system (blue) and Si(Li) detectors (grey).

The VHE astrophysics group consists of Professors Rene Ong and Vladimir Vassiliev, postdoctoral researcher Ralph Bird, and graduate students Matt Buchovecky, Jamie Ryan, and Brandon Stevenson.

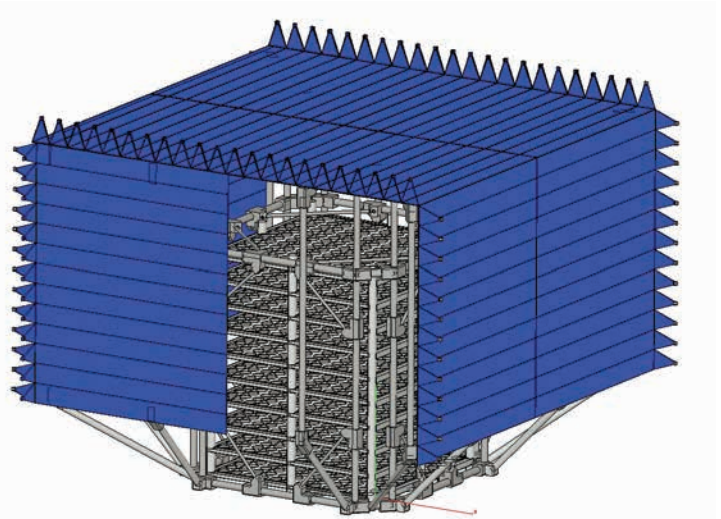


Figure 2. A concept drawing of the GAPS instrument, illustrating its two major components: the time-of-flight system (blue) and Si(Li) detectors (grey).



# MANI L. BHAUMIK INSTITUTE FOR THEORETICAL PHYSICS

## Zvi Bern

Theoretical physicists determine the laws of nature and their consequences by constructing mathematical models of physical systems and solving the equations that underlie those models. At the deepest level, theoretical physicists formulate the laws that govern the world in which we live, providing a basis for our technology, and perhaps even more importantly to satisfy the human thirst for knowledge about the universe we live in.

A year ago the Mani L. Bhaumik Institute for Theoretical Physics at UCLA was founded with a nearly unanimous positive vote of the faculty. In today's environment, with tight government funding in fundamental theoretical research, only those universities with institutes can compete to attract the best minds and most exciting theoretical research. The Bhaumik Institute starts from a solid foundation of exciting programs in the Department of Physics & Astronomy. A primary goal is to maintain and expand this excellence, starting in theoretical elementary-particle physics and issues related to the unification of forces and matter. Concurrently, it also support, as best as possible, junior faculty members in all sub-disciplines of theoretical physics.

A primary goal of the Institute is to provide an exceptional environment for theoretical physics research. The Institute provides support for postdoctoral researchers and graduate students. The Institute also runs a robust visitor program, and host workshops, conferences and public lectures on cutting-edge topics.

The Bhaumik lecture series brings distinguished lecturers to present cutting edge ideas. In the past year there were lectures from Nima Arkani-Hamed (IAS, Princeton), Sudip Chakravarty (UCLA), Claudio Pellegrini (UCLA), and Frank Wilczek (MIT, Nobel Laureate) on latest ideas on the unification of fundamental forces, superconductivity, the X-ray lasers, and basic questions in quantum field theory and quantum mechanics. Our line-up for the upcoming year includes Edward Witten and Kip Thorne. Edward Witten is among the most famous theoretical physicists around. Kip Thorne (Nobel Laureate 2017) is not only known for his work on General Relativity, including early theoretical work for the

LIGO gravitational wave detector, but for having written a script that led to the movie "Interstellar." Both these Bhaumik Lectures will be a treat. The Institute also hosts a quarterly lunchtime lecture series by faculty speakers from around the Department. Following its success, this year there will also be an analogous lecture series for graduate students and postdoctoral researchers.

A primary mission of the Institute is to help recruit the best faculty, postdoctoral researchers and graduate students. We are delighted to have been able to attract an outstanding young person, Thomas Dumitrescu, to join our faculty, starting in July 2018. The Bhaumik Institute was crucial for his successful recruitment. Thomas is currently a postdoc at Harvard. He is a leading expert in quantum field theory, which is a unifying language that pervades many areas of modern theoretical physics. He is broadly interested in all aspects of quantum field theory, from foundational questions about the space of all consistent theories to applications in particle and condensed matter physics, cosmology, as well as string theory, and mathematical physics. The Department is excited to have him join the faculty.

The Institute is currently remodeling the fourth floor of the Physics and Astronomy Building to include a new discussion area. In the modern era, with instantaneous global communication one might think that a gathering place for theorists to discuss the latest developments is a thing of the past. But, in fact, it is just as true today that the life-blood of theoretical physics is face-to-face interactions. Every great theoretical physics institute has a great discussion area. Nothing beats a good set of old-fashioned blackboards!

The Institute would not have been possible without the generous support of Dr. Mani L. Bhaumik. The Department sincerely thanks him for his vision and understanding of the importance of theoretical physics, not only to UCLA, but more generally for all of humanity. We hope that other like-minded individuals will see the wisdom of supporting a theoretical physics institute at UCLA and help contribute to its expansion.

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*The Institute will be an exciting place for  
our students, faculty and postdocs. The  
future has never been brighter!*



## The Miao Group

### Deciphering 3D chemical order/disorder and material properties at the single-atom level

Perfect crystals are rare in nature. Real materials often contain crystal defects and chemical order/disorder such as grain boundaries, dislocations, interfaces, surface reconstructions and point defects. Such disruption in periodicity strongly affects material properties and functionality. Despite rapid development of quantitative material characterization methods, correlating three-dimensional (3D) atomic arrangements of chemical order/disorder and crystal defects with material properties remains a challenge. On a parallel front, quantum mechanics calculations such as density functional theory (DFT) have progressed from the modelling of ideal bulk systems to modelling "real" materials with dopants, dislocations, grain boundaries and interfaces; but these calculations rely heavily on average atomic models extracted from crystallography. To improve the predictive power of first-principles calculations, there is a pressing need to use atomic coordinates of real systems beyond average crystallographic measurements. In combination of state-of-the-art electron microscopy and powerful data analysis and 3D reconstruction algorithms, Professor Jianwei (John) Miao led an international team including postdocs (Yongsoo Yang and Jihan Zhou) and graduate student (AJ Pryor) from UCLA that determined the 3D coordinates of 6,569 Fe and 16,627 Pt atoms in a FePt nanoparticle, and correlated chemical order/disorder and crystal defects with material properties at the single-atom level. They identified rich structural variety with unprecedented 3D detail including atomic composition, grain boundaries, anti-phase boundaries, anti-site point defects and swap defects. They showed that the experimentally measured coordinates and chemical species with 22 picometre precision can be used as direct input for DFT calculations of material properties such as atomic spin and orbital magnetic moments and local magnetocrystalline anisotropy. This work combines 3D atomic structure determination of crystal defects with DFT calculations, which is expected to advance our understanding of structure-property relationships at the fundamental level. This paper is published in *Nature* and has attracted considerable media attention [Y. Yang et al., *Nature* 542, 75-79 (2017)].

### Correlative cellular imaging with functionalized nanoparticles

Precise localization of nanoparticles within a cell is crucial to the understanding of cell-particle interactions and has broad applications in nanomedicine. In collaboration with scientists from the Advanced Light Source at LBNL and Brazilian Center for Energy and Materials, Professors Miao and Jose Rodriguez, postdocs (Marcus Gallagher-Jones and

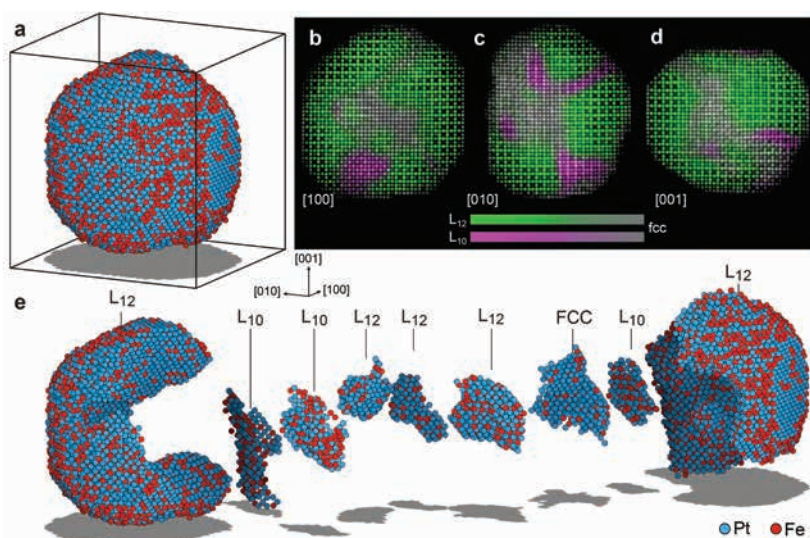


Figure 1. 3D determination of chemical order/disorder of a FePt nanoparticle at the single-atom level using atomic electron tomography. a, Overview of the 3D positions of 6,569 Fe atoms in red and 16,627 Pt atoms in blue. b, The nanoparticle consists of 9 grains with different chemical order/disorder. c, 2D projections of the experimental 3D atomic model.

Carlos Sato Baraldi Dias) and graduate students (AJ Pryor, Mike Lo and Lingrong Zhao) from UCLA have performed a proof-of-principle experiment for imaging individual functionalized nanoparticles within a mammalian cell by correlative microscopy. Using a chemically-fixed HeLa cell labeled with fluorescent core-shell nanoparticles as a model system, they implemented a graphene-oxide layer as a substrate to significantly reduce background scattering. They identified cellular features of interest by fluorescence microscopy, followed by scanning transmission X-ray tomography to localize the particles in 3D, and ptychographic coherent diffractive imaging of the fine features in the region at high resolution. By tuning the X-ray energy to the Fe L-edge, they demonstrated sensitive detection of nanoparticles composed of a 22 nm magnetic Fe<sub>3</sub>O<sub>4</sub> core encased by a 25-nm-thick fluorescent silica (SiO<sub>2</sub>) shell. These fluorescent core-shell nanoparticles act as landmarks and offer clarity in a cellular context. Their correlative microscopy results confirmed a subset of particles to be fully internalized, and high-contrast ptychographic images showed two oxidation states of individual nanoparticles with a resolution of ~16.5 nm. The ability to precisely localize individual fluorescent nanoparticles within mammalian cells will expand our understanding of the structure/function relationships for functionalized nanoparticles. This work is published in *Scientific Reports* [M. Gallagher-Jones et al., *Sci. Rep.* 7, 4757 (2017)].

# ATOMIC-MOLECULAR-OPTICAL PHYSICS

## Quantum Physics with Atoms and Molecules

Eric Hudson, Wes Campbell, and Paul Hamilton

The hallmark of modern atomic, molecular, and optical (AMO) physics is the fact that laboratory experiments can now control samples of atoms and molecules so well that incredibly delicate and tiny effects can become readily apparent, and even dominate the behavior of these samples. The AMO research at UCLA has been focused on developing the tools to broaden the reach of these techniques for control and making measurements that take advantage of this control to tease out miniscule effects from atoms, molecules, and nuclei.

### Keck: Dark matter search with cold atoms

Eric Hudson and Paul Hamilton group

We now know that the visible mass in the universe (made of things like atoms, electrons, protons, etc.) is only a small fraction of the total mass. The remainder is a mysterious substance we simply call “dark matter,” because it seems to interact with regular matter only through gravity. One promising candidate for dark matter is called a sterile neutrino, a hypothetical particle that interacts with normal matter, but so weakly that it has so far gone unnoticed. We are working to build a sensitive detector of sterile neutrinos using a small cloud of laser cooled radioactive atoms. If a decay emits a sterile neutrino, its fingerprint should be visible on the rest of the pieces that fly off the decaying atom. This work is funded by the W.M. Keck Foundation and is a collaboration with UCLA colleagues Hanguo Wang and Peter Smith as well as collaborators at Temple University and the University of Houston.

### MOTion

Eric Hudson group

Ultracold molecules are slippery fish to catch, and controlling them is even more challenging. One approach is to work with charged molecules, which can be levitated in space by ion traps. Some co-trapped atomic ions can then be used as a refrigerator to cool the molecule’s motion, producing a pristine sample with a high degree of control. We introduce laser-cooled neutral atoms into the same volume and can cool

the internal states of the molecular ions through collisions. Excitingly, we have also been able to observe chemical reactions that bend the rules that govern reactions under less strict control. We have used this reactor to synthesize the first mixed hypermetallic oxide,  $\text{BaOCa}^+$ , by driving a reaction through a typically unlikely pathway. The ultracold system allows us to thread the needle in ways that are typically beyond reach, which opens up a whole new world of chemical possibility.

### A single-atom gyroscope

Paul Hamilton and Wes Campbell group

Quantum sensors offer orders of magnitude of improvement over their classical counterparts, and the exploding field of atomic matter-wave sensors is making rapid progress toward next generation detectors of acceleration, rotation, gravity, and possibly gravitational waves. Charged atoms offer an exciting alternative to neutrals since they can be controlled and isolated from their environment with exquisite precision in a small package. We are working on demonstrating the first matter-wave inertial sensor made from ions. Using quantum-mechanical effects, a single ion will be put in two places at once and each part will orbit an ion trap with one going clockwise and the other orbiting in the counterclockwise direction. By recombining the two parts at the end, we can determine if the lab rotated around the ion while it was orbiting (hint – it does, of course!). This sort of “quantum Foucault pendulum” may prove to be a practical sensor in applications such as navigation without GPS.

### A new freeze ray

Wes Campbell group

A laser that produces many colors can do so in a way that makes what is called an optical frequency comb – a sort of ruler for measuring optical frequencies. We have recently been applying the light from optical frequency combs directly to atoms and ions to manipulate their motion. For atoms that require extreme ultraviolet light that is not available in laser form, the use of optical frequency combs can open the door to laser cooling these species, which include H, C, O, and N. When an optical frequency comb is used to laser cool a trapped atomic ion, we find that it gives rise to a comb of stable oscillation amplitudes and behaves as an acoustic laser (a “phonon laser” or, as we prefer, a “PhASER”). The ion’s motion in the trap can be amplified by the applied light in a phase-coherent way, and we have verified phaser action by acoustic injection locking. An immediate practical implication



The MOTion. A linear radio frequency ion trap is co-located with a Ca magneto-optical trap. A time-of-flight mass spectrometer is radially integrated for ion identification.

of this process is that ions do not get “boiled out” of the trap by the laser light, which opens the door to difficult species and potential laser cooling of  $\text{He}^+$ , an enticing species for precision measurements.

## Radioactive quantum computing

Wes Campbell and Eric Hudson group

Trapped ions can be isolated from their environment better than any other laboratory quantum system, a feature that is typically quantified in terms of a parameter called coherence time. The particular structure of the trapped ion one might use in a quantum computer or quantum simulator dictates not just its coherence time, but also its ease of use. Finding a species that has both long coherence and is easy to use, however, has been difficult. We have recently abandoned the atoms that occur naturally in favor of a synthetic isotope of barium, and have trapped and spectroscopically characterized  $^{133}\text{Ba}^+$ . This “Goldilocks qubit” so far looks to have both long coherence and ease of use, and we have recently demonstrated coherent operations on the ground-state hyperfine clock qubit, which is predicted to have extremely good coherence properties. The radioactivity of  $^{133}\text{Ba}$  can be managed using techniques we have developed, and we expect the community to adopt this approach as the practicality of quantum devices becomes more important.

## Dark magnetic fields

Paul Hamilton group

What happens if you build some of the most sensitive magnetic sensors in the world and then stick them inside shields that block out all magnetic fields? As crazy as this may seem, we have done just this with a worldwide collaboration called GNOME (Global Network of Optical Magnetometers). As far as we know dark matter barely interacts with normal matter—it can fly right through both us and magnetic shields without a problem. But, in some proposed models, the dark



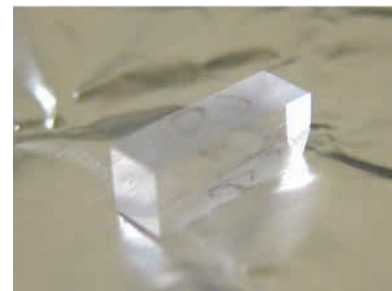
Best Friends. Two  $^{133}\text{Ba}^+$  ions being simultaneously laser-cooled in an ion trap. By coupling their internal state qubits to the collective motion of both ions, quantum computations can be performed using the phonons as a quantum data bus between qubits.

matter may slightly tip the direction atoms are spinning, effectively mimicking a magnetic field that passes through all shielding. By comparing signals across the world we will know if a wall of dark matter were to sweep across the Earth. The key to doing this is being able to compare the timing of measurements across the globe—something now easy with GPS technology. In the future we plan on correlating our measurements with those from other experiments, for example our acceleration measurements from matter-wave interferometry or gravitational wave signals from LIGO.

## A nuclear clock

Eric Hudson group

Atomic clocks are the most accurate and precise measuring devices ever made, allowing measurements of time with 18 significant digits. At this level of scrutiny, tiny changes in things such as the fundamental constants of physics may be observable. By comparing two clocks that are sensitive to these constants in different ways, a change in a fundamental constant will cause the clocks to get out of sync. We are working to develop a stable, precise clock based on nuclear physics in the  $^{229}\text{Th}$  nucleus. This species has a nuclear transition at an anomalously low energy, which should allow us to excite it using laser photons. There are many groups worldwide searching for this same transition at the moment, and our approach has already put tight constraints on the remaining search space. Practical aspects of this transition are also predicted to be substantial, where a solid crystal could be used to host the clock instead of a complicated vacuum apparatus.



One of the thorium-229 doped crystals we have produced. Only three have ever been created.

## Laboratory Interstellar Medium

Eric Hudson and Wes Campbell group

Chemical reactions between prevalent species such as hydrocarbons are surprisingly poorly understood. The ideal experiment for illuminating a reaction would be able to investigate every possible input state for the reaction. This type of experiment is by definition very cold since it involves single quantum states in systems where the splittings between energy states can be very small. We are investigating the type of low-temperature, gas-phase hydrocarbon chemistry that takes place in the space between stars with the goal of pinning down difficult reaction rates. By using an ion trap with  $\text{C}^+$  ions that are cooled by  $\text{Be}^+$ , we can use a cryogenic buffer-gas beam to introduce cold reactants that show measurable reaction rates even for single  $\text{C}^+$  ions. We have recently observed reactions with hydrogen and water molecules, and

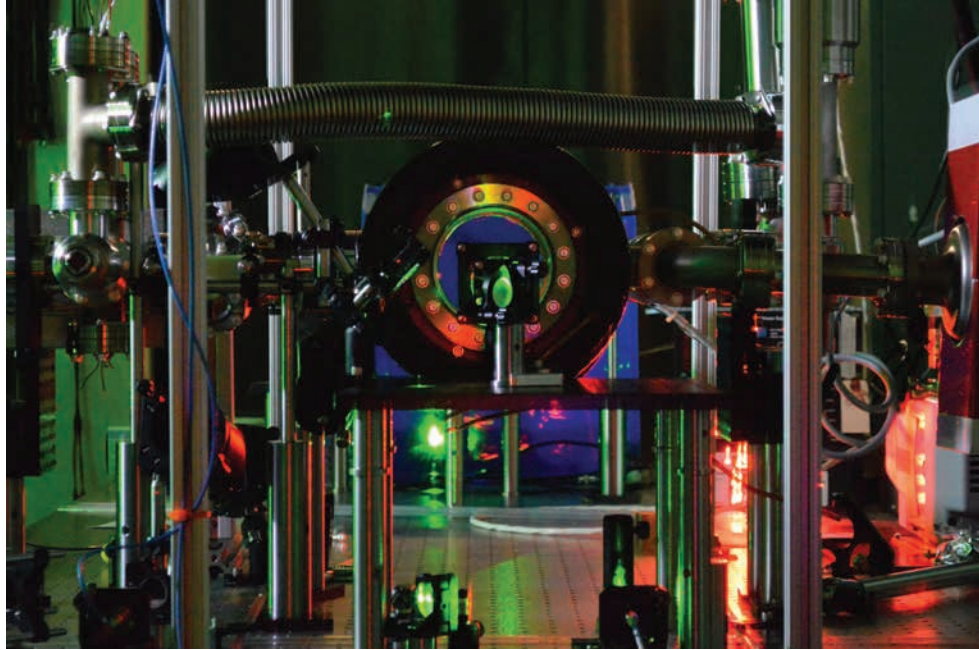


anticipate that this device will be sufficiently general to allow it to study the ion chemistry of the interstellar medium.

## Matter-wave interferometry

Paul Hamilton group

One of the fundamental predictions of quantum theory is that matter will have wave-like properties. This is a well-verified claim that has allowed researchers to create devices called matter-wave interferometers. These devices function on the principle that electrons and atoms can be in multiple places at the same time. We are working toward performing matter-wave interferometry in a standing wave made of light, where an acceleration of the device will manifest itself as oscillations in the positions of cold ytterbium atoms in the light wave. There are also clever ways that the same technology can actually be made sensitive to new forces from candidate theories of dark matter and dark energy, where we will be using cold atoms to probe the fundamental physics questions most-closely associated with fields such as cosmology and elementary particle physics.



Some of the vacuum system, magnetic coils, lasers, and optics used to trap ytterbium atoms.

## NEUROPHYSICS

### Elegant Mind Club: Finding Physics through *C. elegans*

Katsushi Arisaka

*Why are we here?* In order to answer this complex question using fundamental physical principles, the Arisaka group transformed their research direction from particle physics to neurophysics in 2013. A new interdisciplinary lab, named the Elegant Mind Club (<http://www.elegantmind.org/>), was formed by various STEM undergraduate students to test their own scientific hypothesis in a hands-on laboratory setting. Each year, more than 50 students join, collaborate, and form balanced research teams. Currently, over 300 diverse students of varying interests and educational backgrounds have contributed uniquely to the optimization of each aspect of the laboratory's research aims, forming the largest undergraduate laboratory group on UCLA's campus today.

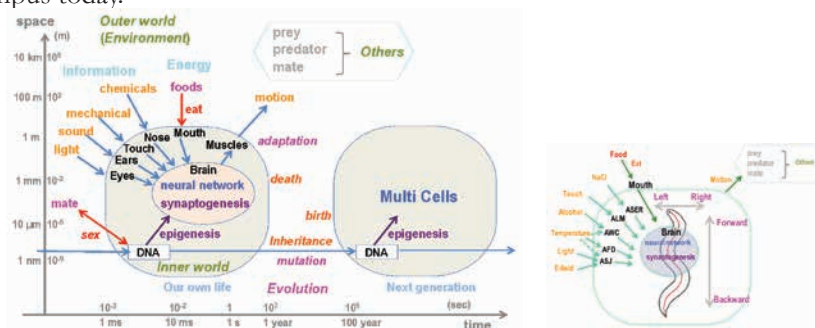


Figure 1. (Left) A conceptual diagram of the development and evolution of multi-cellular life through space-time, inspired by particle physics' Feynman Diagram. (Right) The simple concept applied to *C. elegans* which navigate space-time to survive based on external stimulation received by single specialized neurons, such as ASER in case of NaCl, ALM for touch, and AWC for Alcohol. The organism's motional states are also extremely simple: forward or backward locomotion while swinging the head left and right.

**What is life?** Complex multicellular life has continued and honed itself evolutionarily over billions of years. Inspired by the Feynman Diagram, Figure 1 (left) visualizes the range of biological processes and interactions that take place in multicellular life, which span enormous scales of space-time. Life exists from nanometer (molecular structure) to kilometer (visual environment) spatial scales, and from millisecond (molecular interaction) to millennia (evolution) temporally. *C. elegans* was selected as a model system to due to its simple neural network of 302 neurons, whose genetic infrastructure and connectome is well-established. Figure 1 (right) provides a conceptual diagram of the nematode's activity in three fundamental principles. (1) external stimuli are perceived by sensory neurons, (2) pre-existing motion state is modulated accordingly (3) to obtain nearby food (*E. coli*), or to escape from predators. The simplicity of motion confers an ideal opportunity to educate students on the basic principles of physics that govern fundamental aspects of life in the above three steps.



Figure 2. Five dedicated Elegant Mind Club lab spaces, spread over Knudsen Hall. (Top-left) the Central lab for group meetings, microscope training and data analysis. (Bottom-center) The worm tracking microscope in the tracker lab, presented by Steve Mendoza, Etta D'Orazio (President of the Elegant Mind Club), and Phat Mai.

The lab has been constructed to observe *C. elegans*' behavior to multiple physical stimulations, such as gradients of temperature, humidity, electric/magnetic fields, and UV/visible/IR photons. Five dedicated laboratory spaces have been successfully developed as shown in Figure 2. (1) Central Lab (top-left) as a large office space for meetings, training with microscopes, and data analysis, (2) Biology Lab for sample preparation and culturing/strain preservation, (3) Behavior Lab to observe worm navigation under various stimulations, (4) Tracking Lab to track worms with neuron observation, and (5) Microscopy Lab (bottom-right) to observe neurodynamics under 2D / 3D navigation.

The goal of the Elegant Mind Club is to supply undergraduate students with the opportunity to design novel experiments based on their own hypotheses, and test them. Experimental design, data taking, analysis, and interpretation should be completed by the students; from scratch to their own publication. Through 2016-2017, six science groups

(Temperature, E-field, B-field, Light, Chemicals, and 3D Motion) obtained high quality data containing discoveries beyond those stated in current publications. Students are currently writing their first papers, which are to be submitted to refereed journals by the end of 2017. Each year in May, the UCLA Undergraduate Research Center organizes a campus-wide science poster day. From 2014-2017, the Elegant Mind Club presented the largest number posters for a single lab: 8, 8, 16 and 26 posters each year. It demonstrates that the Elegant Mind Club has become the largest-scale undergrad research lab on UCLA's campus, and it is still growing.

The core of the Elegant Mind Club are the advanced optical microscopes which were designed to rapidly image the organism's entire brain in three dimensions. Several senior students designed and constructed novel, advanced microscopy tools supported by NSF and NIH. Figure 3 (Left/Center) is the Bessel Beam sheet-illumination microscope which can scan a complete *C. elegans* brain at



50 volumes/s; an order of magnitude faster than any previously published (or commercial) 3D sheet illumination microscope system. On the right side is a 3D worm tracking microscope which can observe the 3D unconstrained motion of worms from three directions.

These advanced microscope systems have been all designed, constructed and operated solely by undergraduate students, including Blake Madruga, Javier Carmona, Joseph Thatcher and Steve Mendoza. Sophisticated analysis software was developed by Ahis Shrestha, Suying Jin, Chris Dao and many others. Figure 4 shows the 3D motion *C. elegans* observed by the 3D motion tracking microscope, under a blue light stimulation for photo avoidance reflex in three dimension. It verifies our novel model of 3D locomotion based on 4 SMD neurons acting as CPG.

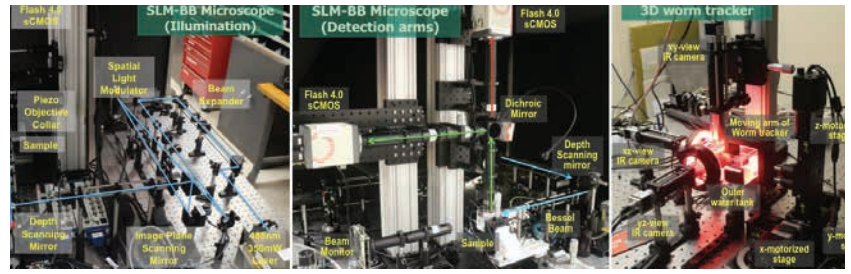


Figure 3. (Left) The SLM-based Bessel beam microscope. (Left) The beam starts from a DPSS laser, and is then phase modified by an SLM to form a Bessel beam by a computer-generated holographic transfer function. (Center) The detection arms of SLM-BB microscope. (Right) 3D Unconstrained motion tracking system for *C. elegans*.

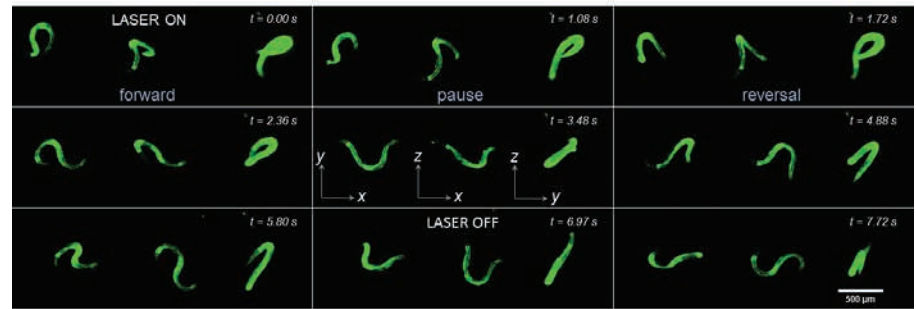


Figure 4. 3D motion of *C. elegans* is observed by the 3D motion tracking microscope. The 3D images show a series of complex avoidance reflex, caused by a blue laser (405 nm) stimulation at  $t = 0$  second.

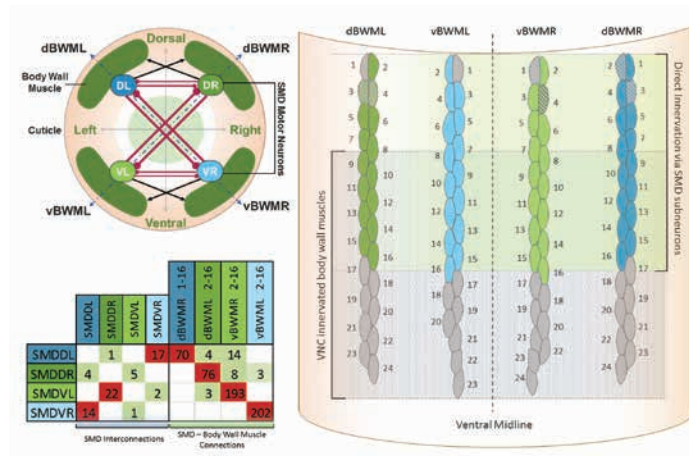


Figure 5. Our new model of 3D locomotion, based on the four SMD neurons acting as a CPG, and controlling the motion of each quadrant of muscles along the body.

## Mayank Mehta Neurophysics group

Neurons are large, tree-like structures with extensive, branch-like dendrites (See figure 1) spanning  $>1000$  mm, but a small  $\sim 10$ -mm soma. Dendrites have synapses that receive inputs from other neurons, and the electrical activity of dendrites determines synaptic connectivity, neural computations, and learning. The prevailing belief has been that dendrites are passive; they merely send synaptic currents to the soma, which integrates the synaptic inputs to generate an all or none

electrical impulse, called an action potential or somatic spike, thought to be the fundamental unit of neural computation. While plenty of evidence supports these ideas, the functioning of dendrites, which constitute more than 90% of neural tissue, has never been directly tested measured during behavior. This is because traditional electrodes, which puncture the dendrite to measure dendritic voltages in vitro, do not work in vivo due to constant movement of the brain that kills the punctured



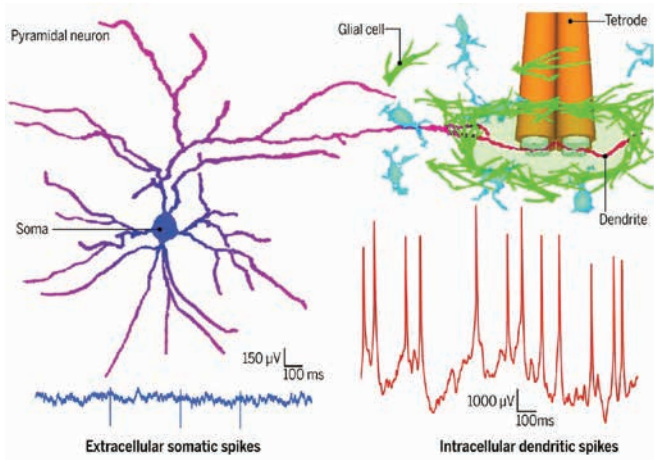


Figure 1. Top left shows a typical neuron with small soma (blue) and extensive dendrites (red). Top right shows the tetrode (gold) and glial cells (green) that trap a dendritic branch. Bottom left shows typical spikes from the soma, which occur rarely ( $\sim 1/s$ ). Bottom right shows membrane potential from one branch of the dendrite, showing broad, dendritic spikes that occur more frequently ( $\sim 10\text{Hz}$ ).

dendrites. Hence, the voltage dynamics of distal dendrites, constituting the vast majority of neural tissue, has remained entirely unknown during natural behavior. Using a novel technique, involving a close combination of experimental and mathematical methods, we measured the voltages of dendrites during natural behavior for the first time. We found that the dendrites are not passive, but they generate their own spikes. In fact, the dendrites generate nearly ten times more spikes than the well studied somatic-spikes. This means that for the past hundred years, we have missed more than 90% of neural spikes. Finally, the dendritic computations are not just digital, but a mixture of analog and digital. These measurements are unprecedented, they resolve many long-standing paradoxes, and they fundamentally change our understanding of how the brain works. The paper received extensive media coverage and ranked as within top 1-5% of all papers (<https://www.altmetric.com/details/17170980#score>).

Jason J. Moore, Pascal M. Ravassard, David Ho, Lavanya Acharya, Ashley L. Kees, Cliff Vuong, Mayank R. Mehta, 'Dynamics of cortical dendritic membrane potential and spikes during natural behavior'. <http://science.sciencemag.org/content/355/6331/eaaj1497>

## PHYSICS OF HEARING

### Dolores Bozovic

The Bozovic laboratory explores the nonlinear dynamics of hair cells, in an attempt to elucidate how the auditory system achieves its sensitivity of detection. It has long been known that the hair cells of the inner ear utilize an active process to amplify incoming signals. In vitro, the hair bundles – actin filled stereocilia that protrude from the surface of the cell – exhibit spontaneous limit cycle oscillations. These innate movements have been shown to expend energy, confirming the existence of an internal active mechanism. A number of questions remain regarding if and how such oscillations could be utilized in vivo. In particular these oscillations are quite noisy, and occur at frequencies that are significantly lower than the detection range in vivo. Therefore, we explored how noisy nonlinear oscillators mode-lock to frequencies higher than their internal clocks. We used magnetic nanoparticles to stimulate the bundles without an imposed mechanical load, and measured the evoked response. We observe regions of high-order synchronization, analogous to in dynamical systems literature. Surprisingly, we found significant areas of overlap occur between the Arnold Tongues, with the bundles showing an intermittent flicker between different winding numbers. We demonstrated that an ensemble of spontaneous oscillators, exhibiting high-order sync, could be entrained to detect signals significantly above the characteristic frequencies of the individual cells.

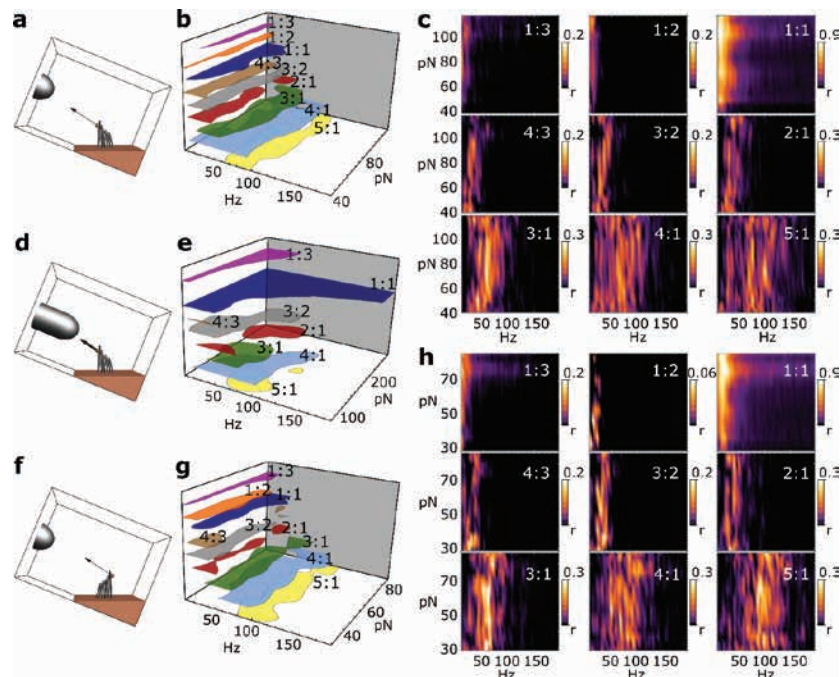


Figure 1. Multi-mode synchronization of hair bundles. Schematics of bundle stimulation (a) toward or (f) away from the tallest row of stereocilia. (c) and (h) present degree of synchronization for various modes. (d) Schematics of high-amplitude bundle deflection toward the tallest row of stereocilia. (b), (e), and (g) display overlaid regions of maximal n:m synchronization. Figure from Levy et al., Sci. Rep., 6, 39116 (2016).

# EXPERIMENTAL ELEMENTARY PARTICLES AND NUCLEAR EXPERIMENTAL PHYSICS

## Nuclear Physics Group Huan Huang Group

The UCLA Nuclear Physics Group has research programs on studies of hot QCD (Quantum Chromo Dynamics) matter of quarks and gluons and on searches for neutrinoless double beta decays. The UCLA group has been a leading university group in the STAR (Solenoidal Tracker at RHIC) experiment at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL). The neutrino program centers on the CUORE (Cryogenic Underground Observatory for Rare Event) experiment at the Gran Sasso National Laboratory in Italy.

The STAR experiment at BNL has accomplished a very successful run in 2017 achieving all data-taking goals. The focus of the run 2017 is on polarized p+p collisions at a center-of-mass energy of 510 GeV. One major scientific goal of the run is to measure a sign change in the Silvers function, which describes the quark structure of the proton. The STAR Forward Meson Spectrometer (FMS) is essential for the measurement of Drell-Yan processes where a quark and anti-quark pair annihilates to produce an electron and positron pair. The lead glass detector used for the FMS suffered major radiation damage in previous high luminosity p+p runs. Dr. Stephen Trentalange and his team designed and built an UV-ray system to cure the radiation damage for lead glass modules in real time during the run 2017. The system worked very well and ensured the success of the experimental program.

The STAR collaboration also achieved a major scientific milestone for the measurement of Lambda polarization from gold+gold collisions with beam energies ranging from 7.7 to 200 GeV. The quark-gluon plasma drop formed in high-energy nucleus-nucleus collisions carries orbital angular momenta. Such angular momenta may transfer to the spin of produced particles so that the spin orientation of the particles may prefer one special orientation to the other possible directions. STAR measured the polarization of Lambda hyperons with respect to the event reaction plane defined by the beam momentum and the impact parameter vectors. Estimate of the vorticity of the quark-gluon plasma drop indicates that gold+gold collisions at RHIC have created the most vortical fluid ever observed in nature. The STAR discovery has been published in Nature 548, 62 (2017) as a cover story.

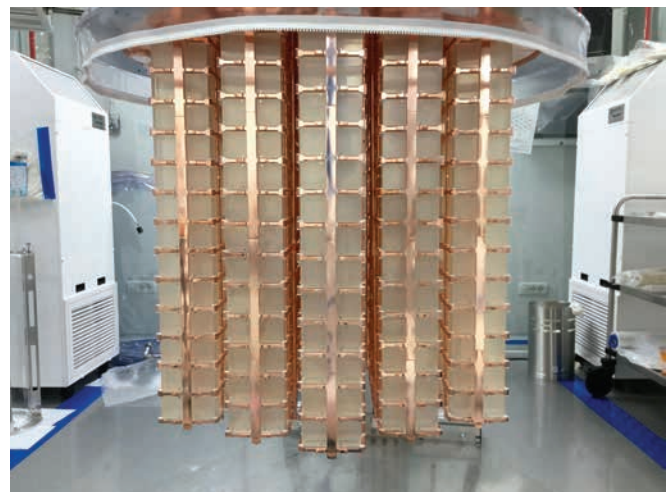
The CUORE experiment completed the detector construction and commissioning. Physics data-taking commenced in April 2017. Shown in the picture are towers of Tellurium dioxide crystals, which operate as bolometer detectors. These towers are cooled inside a large dilution refrigerator to a working temperature of about 10 mK. Initial analyses of data from an approximately three-week period of physics running indicated that CUORE has achieved the expected background level of

0.01 count/keV/kg/year in the region of interest. The first publication of CUORE physics result is expected by the end of 2017.

The Nuclear Physics Group continues to provide training for many undergraduate students. Undergraduate students Haochen Yan (UCLA), Antonett Nunez-del Prado (REU 2017 from Florida) and Jacob Bryon (UCB) will present their results at a NSF sponsored CEU (Conference Experience for Undergraduates) poster session at the Division of Nuclear Physics Conference in the fall 2017 at Pittsburgh, Pennsylvania.



Cover story in Nature 548, 62 (2017)



Shown here are towers of Tellurium dioxide crystals, which operate as bolometer detectors.



# QCD AND NUCLEAR THEORY

## Zhongbo Kang

The main research interests of Professor Kang's group are perturbative Quantum Chromo Dynamics (QCD) and strong interactions, and their applications in high energy nuclear and particle physics. Our recent research efforts have been focused on three topics: (a) QCD collider physics, (b) hadron physics, (c) heavy ion physics. Our research is relevant for all existing and planned experiments in high-energy nuclear and particle physics ranging from JLab-12 to the LHC.

**QCD Collider Physics.** Our main focus along this direction is to apply perturbative QCD and effective field theory techniques to understand jets, jet substructure, and heavy flavor production in high energy physics. High energy jets of collimated hadrons are naturally produced at high energy colliders, especially at the LHC, the current highest energy hadron collider in the world. Jets and their internal substructures have emerged as an ideal testing ground to study the fundamental properties of QCD, and have provided promising new analysis tools for searches of new physics beyond the Standard Model. Our research is to improve the perturbative QCD computations, to explore new opportunities, and to understand and interpret the latest experimental data at the LHC. We recently developed a new theoretical framework to study jet substructure observables in inclusive jet measurements, i.e. fully consistent with the way in which jet substructure experimental measurements are usually performed, and thus facilitates a direct comparison with the ever more precise data on jet physics at the LHC. The work was published in JHEP 1611, 155 (2016). Utilizing such a novel framework, we proposed a new method to explore the production mechanism of heavy quarkonia (e.g.  $J/\psi$ ), by studying distribution and polarization of  $J/\psi$  mesons produced in an energetic jet at the LHC. This research was published in Phys. Rev. Lett. 119, 032001 (2017), and has received great attention from the experimental side at the LHC (e.g. LHCb and ALICE).

**Hadron Physics.** Our main focus along this direction is QCD structure of the nucleon and spin physics. The

fundamental laws of QCD are elegantly concise; however, understanding the structural complexity of nucleons in terms of quarks and gluons governed by those laws is one of the most important challenges facing modern nuclear physics, and is also the major driving force for the JLab and RHIC programs, as well as the future Electron Ion Collider. The central mission is to obtain a three-dimensional description of nucleon structure from vast experimental data. We recently developed a theoretical framework to systematically study the transverse momentum distribution of hadrons inside the jet in proton-proton collisions. Utilizing such a framework, we computed the so-called Collins azimuthal asymmetries of hadrons inside the jet in transversely polarized proton-proton collisions. Our work was published in Phys. Lett. B 774, 635 (2017), in which a remarkable agreement between our theory and recent experimental data from RHIC was shown. Such an agreement demonstrates for the first time the universality of Collins fragmentation function between different scattering processes, which is one of the hottest topics in spin physics community.

**Heavy Ion Physics.** Our main focus along this direction is hard scattering in nucleus and heavy ion collisions. Ordinary nuclear matter is predicted to go through a phase transition to a completely new state under extremely high temperature and density. Such a new state of hot and dense matter of deconfined quarks and gluons, the quark-gluon plasma, should have existed about few micro-second after the Big Bang, and have also been recreated in ultra-relativistic heavy ion collisions at both RHIC and LHC. The overarching goal of heavy ion physics is to explore the properties of this hot and dense QCD matter. We recently developed an effective field theory to study the interaction of collinear light and heavy quarks with hot QCD matter, which successfully described the suppression of heavy flavor mesons and inclusive jets in heavy ion collisions measured at the LHC. Our work was published in Phys. Lett. B 769, 242 (2017) and JHEP 1703, 146 (2017). These results have received great attention from

heavy ion community, and we were invited to present overview talks in several conferences.

The grant proposal made to the NSF by Zhongbo Kang was approved for a three-year period until 2020. Dr. Maarten Buffing from DESY Theory Group joined Professor Kang's group in September 2017. In May 2017, Professor Kang successfully organized and hosted "Topical Workshop on QCD Structure of Nucleons in the Modern Era" at UCLA with the support from Mani L. Bhaumik Institute for Theoretical Physics.

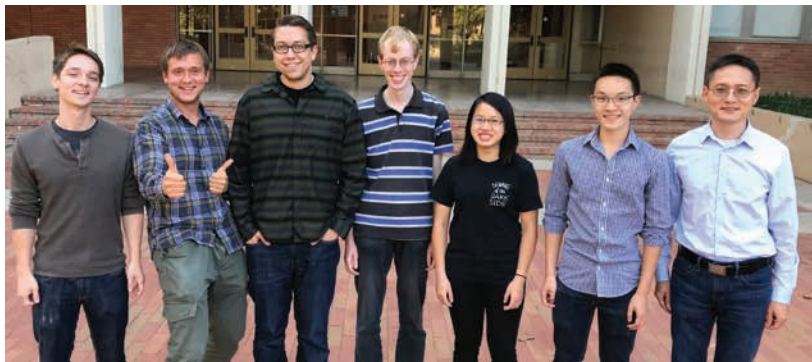


Figure 1. From left to right: John Terry, Yaroslav Balytski, Jared Reiten, Martinus Buffing, Xin Yi Ling, Douglas Wong and Zhongbo Kang.



# CERN'S LARGE HADRON COLLIDER

Michalis Bachtis, Robert Cousins, Jay Hauser, David Saltzberg

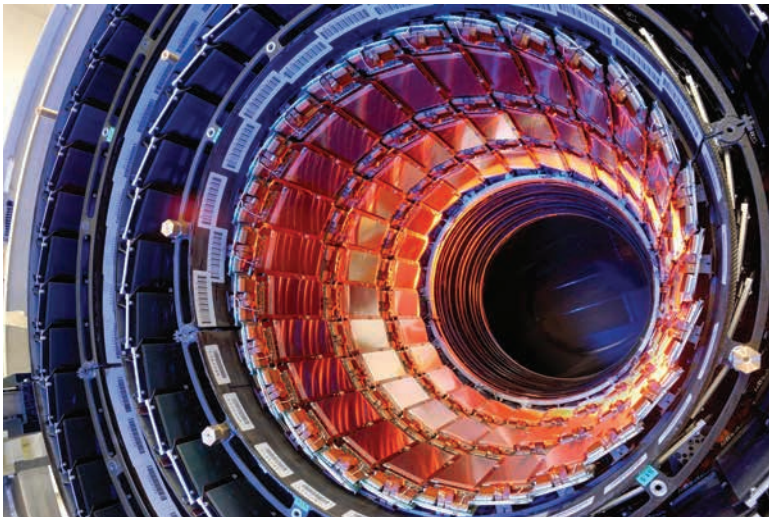
## UCLA group leads analyses of recorded data while operating the CMS detector and planning major future improvements

The UCLA group performing research with the CMS detector at CERN's Large Hadron Collider, for many years led by senior Professors Bob Cousins, Jay Hauser and David Saltzberg, continues to accumulate a wide variety of accomplishments by members based both at UCLA and at CERN. A crucial step for ensuring the health of the group was the arrival of Assistant Professor Michalis Bachtis, which was breaking news in last year's annual report. As the CMS collaboration of some two thousand physicists celebrated its twenty-fifth year, a significant fraction of the effort is now focused on designing improvements ("upgrades" in CERN parlance) to nearly all aspects of the experiment's experimental facilities in order to maintain frontier research capability for another twenty years. Thus the UCLA group, like all of CMS, is simultaneously carrying out three broad functions: the physics analyses of the large data sets already recorded in past years and recent months; the operation of the CMS detector to record more data to increase sensitivity to potential discoveries; and the conception, design, and prototyping of upgrades to the detector. In this year's report, we mention physics analyses (discussed in more detail in past reports) and focus on the fast-moving upgrade activity.

Physics Analyses. Postdoc Alice Florent (featured in last year's report) led the CMS effort to search for new forces of nature via observation of heavy new particles decaying to two muons. Meanwhile Michalis Bachtis and postdoc Simon Regnard are performing a parallel search in which the decay products are the bosons (W and Z) associated with the weak force. Postdoc

Nick McColl (also featured last year) has shepherded his UCSB Ph.D. thesis research through the long process to become a refereed publication by the CMS Collaboration. Meanwhile multiple graduate students are pursuing various topics in their theses, to be featured in future reports; an example is Cameron Bravo who, after learning about the remarkable prediction of a state called the sphaleron in a graduate course taught by Professor Graciela Gelmini, is initiating the search for such states at the LHC. In addition to the various specific analyses pursued by the UCLA group, senior researcher Slava Valuev has served CMS in a high-level physics analysis coordination position, in charge of planning and detailed oversight of some fifty analysis groups in CMS.

CMS detector upgrades. UCLA's detector work continues to have a strong focus on the muon detection systems, for which Professor Jay Hauser is completing multi-year service as overall CMS manager. As the LHC beam intensity grows higher and higher, the particle detectors and their associated electronics systems must be serviced or replaced. The first phase of upgrade to the muon system was successfully completed. The second phase requires adding new detectors with new technologies. Graduate students Riju Dasgupta and Chris Schnaible, working with Bob Cousins, have performed detailed studies on how neutrons made in LHC collisions degrade existing detectors, in order to project future performance. Graduate student Cameron Bravo, postdoc Nick McColl, engineer Andrew Peck, and David Saltzberg are building a new set of muon chambers based on a new technique for CMS, gas electron multiplication (GEM). These GEM detectors are finely segmented and fast, allowing CMS to collect muon data with the upcoming high event rates. This new technology may even extend muon coverage down to angles closer to the high-activity beamline than ever before achieved. A crucial part of the electronics systems (called the Level-1 Trigger) uses custom high-speed circuits to identify interesting collisions in real time and store them for data analysis. Postdoc Simon Regnard, engineer Andrew Peck, and Michalis Bachtis are building a new muon L1 Trigger system deploying a new method to identify muons in real time and measure their momenta with better precision than the current system. The new algorithms are implemented in high-end industrial programmable chips (FPGAs). A new L1 Trigger electronics card featuring a large FPGA with an input/output bandwidth of about a trillion bits per second is under design.



The central part of the CMS tracker barrel – just some of the 200 square metres of silicon in the complete detector (Image: Maximilien Brice/CERN)

# RADIO DETECTION OF HIGH ENERGY PARTICLES

David Saltzberg

In December 2016, the ANITA experiment launched its fourth major flight around Antarctica to search for ultra-high energy neutrinos, as part of NASA's sub-orbital scientific ballooning program. Postdoctoral Scholar Ben Strutt joined us immediately after defending his Ph.D. from the University College London and within days was on "the ice" at McMurdo Station. Graduated UCLA Physics undergraduate, Nan Wang ('15), joined the experiment for a full year to help build the instrument – first in Palestine, Texas at the Columbia Scientific Ballooning Facility, and then during a full season on the ice.

Nearly all experiments need an emulated signal to calibrate and test with. So immediately after the balloon launch, Nan

and Ben hopped on a plane operated by the U.S. Air National Guard for the National Science Foundation's U. S. Antarctic Program bound for the West Antarctic Ice Sheet (WAIS) Divide. They immediately set up UCLA's remote UHF pulser station aimed at the ANITA flying up to 600 km away at 120,000 feet. Ben and Nan returned safely after living in sleeping in tents on the Antarctic Ice Sheet for three weeks having successfully sent nearly a million pulses recorded by the payload.

Nan has since become a Ph.D. student in physics at Stanford University. Ben is in the throes of analyzing the ANITA flight data for a neutrino signal, using our best dataset yet.

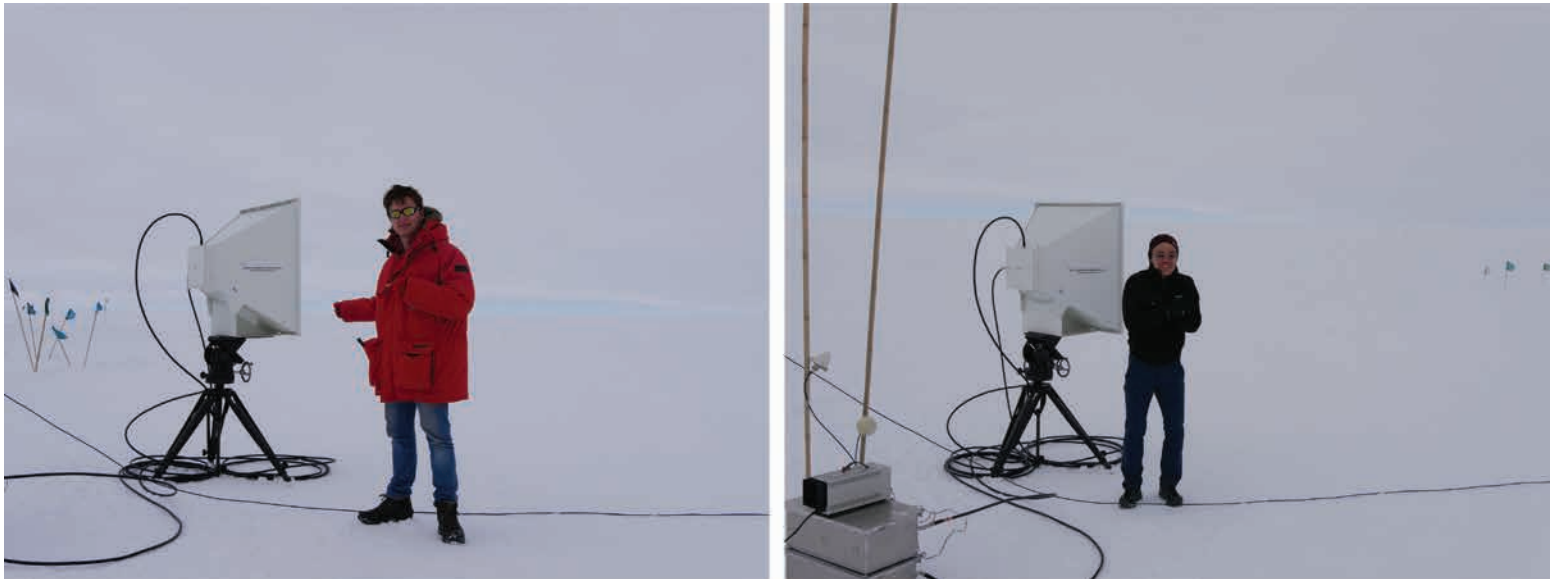


Figure 1. At a remote site on the West Antarctic plateau, postdoc Ben Strutt (left) and graduated-undergraduate Nan Wang (right) operated the UCLA ground pulser to emulate impulsive neutrino events for the ANITA payload drifting by.

# NOBLE LIQUID DETECTOR LAB FOR RARE EVENT SEARCHES

## Hanguo Wang's Group

Dark matter, as an invisible form of matter, constitutes five times more abundant than the ordinary matter (atoms, humans, planets, etc.) in our universe. So far, evidence of the existence of dark matter all comes from its gravitational effect, while its nature still remains as a puzzle. One method to tackle dark matter is to build a terrestrial detector directly searching the signal when dark matter is passing through and interacting with the target medium, and derive its properties from the detected signals. This is the so-called “dark matter direct detection” and has been performed with different experimental technologies by physicists around the world for more than two decades. Among all the direct detection experiments in the world, Professor Hanguo Wang's group participates in two of the major efforts: DarkSide and XENON, both are international collaborations utilizing dual-phase (liquid and gas phases) noble liquid time projection chambers (TPCs) technique, in which scintillation and ionization signals induced by potential dark matter interactions with target medium can be detected simultaneously with highly-sensitive low-radioactive photon-sensors.

The DarkSide program, using liquid argon as the target medium, had published the world's first dark matter search results using low-radioactive argon from underground sources, and now continues to pursue the dark matter puzzle with the next-generation experiment employing 20-ton target mass of underground argon, named as “DarkSide-20k”, a collaboration consisting of 79 institutions from 15 different countries. Liquid argon as target medium has the advantageous ability of dramatically rejecting  $\beta/\gamma$  background events with pulse shape discrimination, and simultaneously scaling up to a large-size detector at a relatively low cost. But the argon we will employ in DarkSide-20k as target medium is not extracted from atmosphere, where there is too much  $^{39}\text{Ar}$ , a cosmogenic  $\beta$  emitter that will generate overwhelming background signals. Under this circumstance, the DarkSide collaboration has successfully extracted argon from underground sources, where  $^{39}\text{Ar}$  is depleted by at least a factor of 1400. Therefore, liquid argon TPC with underground argon is believed to be one of the most promising technique capable of in background-free operation reaching to the ultimate limit of dark matter direct detection, the so-called “neutrino floor”, where signals from coherent neutrino-nucleon scatters become dominant and it's even harder to distinguish any potential dark matter signal from them.

The DarkSide-20k TPC will be immersed in the Liquid Scintillator Veto (LSV) detector, which will then be immersed in the Water Cherenkov Veto (WCV) tank, as shown in Figure 1.

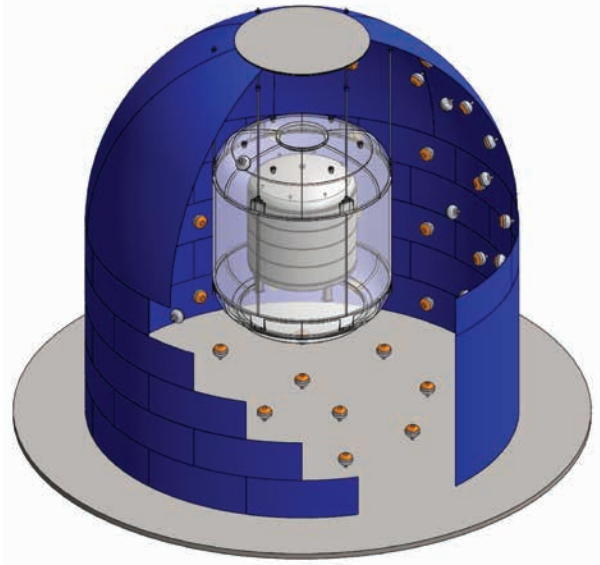


Figure 1 Sketch of DarkSide-20k experiment, from outside to inside: WCV, LSV and TPC (cryostat).

The LSV can mainly detect neutrons from detector and environmental material, hence actively tag and remove corresponding signals from neutrons in the TPC (active veto), since such kind of signal has the same feature as that of dark matter events, and becomes the major background in our case. The WCV can detect and tag cosmogenic muons when they pass through water and generate Cherenkov light, hence remove muon-generated background events in the TPC. The DarkSide-20k experiment will be operated in LNGS (Laboratori Nazionali del Gran Sasso), Italy, overburdened by  $\sim 1400\text{m}$  of rocks to shield the cosmic rays.

Professor Wang's group is responsible for design and construction of the argon handling and cryogenics system, as well as design of the TPC for DarkSide-20k. Professor Wang is serving as a L1 project manager and a member of the technical board. The baseline design of DarkSide-20k cryogenics system is completed, while two major crucial components need prototyping for validation. Professor Wang is leading the efforts with postdoctoral researchers Dr. Yury Suvorov, Dr. Xiang Xiao and Dr. Yi Wang to construct them at UCLA and deliver first to CERN (the European Organization for Nuclear Research), Geneva for the initial test.

As the core of the entire cryogenics system, the liquid argon condenser has been prototyped in full size and tested in our lab early this year (Figure 2, left). Its performance reached the goal of design needed by the system, indicating that this condenser is already capable of being directly used in DarkSide-20k. Another key component is the gaseous argon circulating pump, whose design is being finalized jointly by a commercial company and the UCLA team, dedicated to the ultra-high reliability required by DarkSide-20k. We plan



to test the prototype cryogenics system at CERN to validate the overall design in April 2018. On the other hand, in summer 2017, we built a stand-alone liquid argon system with the ability for various tests at our lab (Figure 2, right). This unique system will be used to test various TPC components for DarkSide-20k at liquid argon temperature and is also very useful for graduate and undergraduate students to study the noble liquid techniques for direct dark matter searches.

The XENON program, similarly to DarkSide, utilizes liquid xenon as the target medium, and has been one of the top runners in the competitive field of dark matter direct detection for years. The current phase XENON1T, with 1-ton liquid xenon as sensitive target, is the first ton-scale dark matter detector in the world. Professor Wang's group is responsible for design and fabrication of the photomultiplier tube assembly system, as well as design and fabrication of the high voltage feedthrough. XENON1T collaboration released its first dark matter search results in May, 2017, which is once

again one of the most stringent exclusion limits on dark matter direct detection up to date, keeping XENON program still at the leading edge in the field.

The XENON1T detector is being upgraded to XENONnT and we just received NSF approval for the DarkSide-20k construction. The UCLA team will be actively participating in these two very challenging complementary experiments.

Former visiting graduate student Dr. Yi Wang graduated at the Institute of High Energy Physics of the Chinese Academy of Sciences, China, and joined in Professor Wang's group as a postdoctoral researcher in July, 2017. Former postdoctoral researcher Dr. Yury Suvorov accepted the offer from University of Naples, Italy, and started working as an assistant Professor in October, 2017.



Figure 2. Left: Picture of the full-size prototype of liquid argon condenser for DarkSide-20k and the testing setup maximally simulating the operation condition of the real cryogenics system. Right: Picture of the stand-alone liquid argon system that can be used for various tests.

## THEORETICAL ELEMENTARY PARTICLES

### Eric D'Hoker

Eric D'Hoker is the recipient of one of the 2017 Simons Fellowship Awards, which permits him to devote one year free of teaching and administration to his collaborations with D.H. Phong at Columbia University, Michael Green at Cambridge University, and Boris Pioline at University of Paris, on subjects ranging from superstring perturbation theory to the application of quantum field theory and string theory to modular forms and number theory.

One of the principal results over the past year has been the elucidation of the relation between string induced low energy effective interactions to supergravity and the modular structure of superstring amplitudes. Another direction of substantial progress over the past year has been the construction and exploration of the holographic duals to five-dimensional superconformal quantum field theories, in collaboration with Michael Gutperle and Christoph Uhlemann.

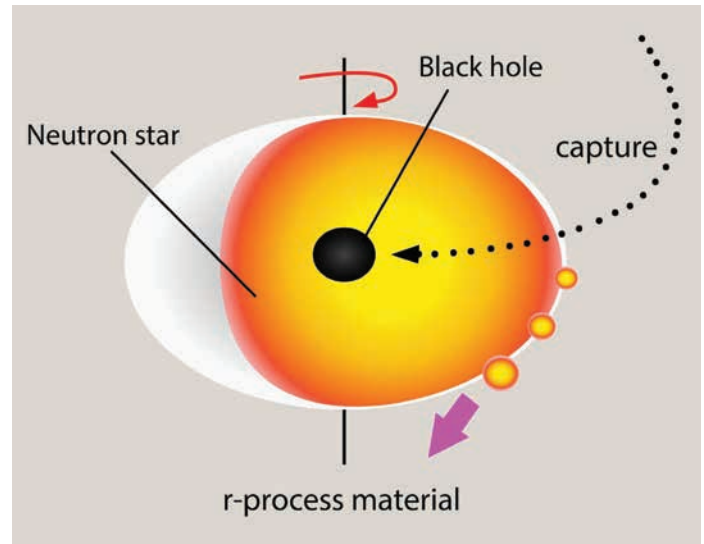
# THEORY OF ELEMENTARY PARTICLES, ASTROPARTICLE PHYSICS, AND PHENOMENOLOGY

Alexander Kusenko

**Black holes from the Big Bang.** Could black holes be produced in the early universe, at the time of the Big Bang? Can there be enough of them to explain the mysterious dark matter? If supersymmetry is realized in nature, the answer to both questions may be yes, according to a recent paper published in *Physical Review Letters* by Professor Kusenko and a UCLA graduate student Eric Cotner. Supersymmetry is an elegant theory that relates particles with different spins, bridging the gap between the particles of matter and the particles that describe physical forces. The theory predicts that known particles should have supersymmetric partners, the search for which is under way using a number of experiments. In the early universe, the fields associated with these superpartners are expected to take very large values, filling space with a “condensate” of particles. This condensate fragments into lumps, much like water spilled on the table breaks up into droplets. The droplets of supersymmetric condensate can merge and form the first black holes before the universe is even a second old. Primordial black holes formed in this process can have masses in a wide range, and they can explain all or part of dark matter, solving one of the most Professoround mysteries of nature.

**Neutron star disruptions by primordial black holes** offer solutions to long-standing astrophysical puzzles, according to a recent paper by Professor Kusenko and a UCLA postdoc Dr. Volodymyr Takhistov, in collaboration with a UCSD astrophysicist Professor George Fuller.

As Carl Sagan wrote, “The nitrogen in our DNA, the calcium in our teeth, the iron in our blood, the carbon in our apple pies were made in the interiors of collapsing stars. We are made of starstuff.” However, a different kind of furnace was needed to forge gold, platinum, uranium, and most other elements heavier than iron. These elements must have formed in an environment rich with neutrons. Small black holes produced in the Big Bang can invade a neutron star and eat it from the



inside. In the last milliseconds of the neutron star's demise, the amount of ejected neutron-rich material is sufficient to explain the observed abundances of heavy elements. Since these events happen rarely, one can understand why only one in ten dwarf galaxies is enriched with heavy elements. The systematic destruction of neutron stars by primordial black holes is consistent with the paucity of neutron stars in the galactic center and in dwarf galaxies, where the density of black holes should be very high. The ejection of nuclear matter can produce a distinctive display of infrared light (sometimes termed a “kilonova”), radio emission that may explain the mysterious Fast Radio Bursts from unknown sources deep in the cosmos, and the positrons detected in the galactic center by X-ray observations. Each of these represent long-standing mysteries. It is indeed surprising that the solutions of these seemingly unrelated phenomena may be connected with the violent end of neutron stars at the hands of tiny black holes.

The paper was published in *Physical Review Letters* and featured as Editor's Suggestion accompanied by a Viewpoint Article.

Christian Fronsdal

Professor Fronsdal has written the tenth and last chapter of his monograph.

## Adiabatic Thermodynamics Of Fluids

The book is now going into the final phase of preparation. In its present, imperfect form it can read or downloaded from Fronsdal's Departmental web page. Comments will be sincerely welcome.

The monograph, the first of 2 volumes intended volumes, presents an introduction to thermodynamics, formulated as an action principle, with numerous applications to mixtures, sound propagation and atmospheres. The last chapter introduces an action principle for hydrodynamics that allows for general, rotational motion.



## PLASMA DIAGNOSTICS GROUP

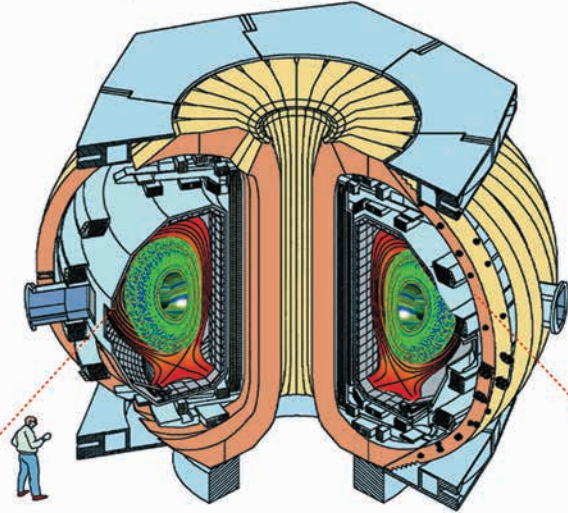
**Tony Peebles, Terry Rhodes, Neal Crocker, Lothar Schmitz, Guiding Wang, Lei Zeng, Shige Kubota, Troy Carter**

The members of the UCLA Plasma Diagnostic Group (PDG) are experts in advanced microwave and millimeter wave plasma diagnostics, plasma turbulence and transport, and global plasma instabilities. A main focus of the group is the training and education of graduate students and postdoctoral researchers in these methods and the science of fusion energy research. A second main focus is the development of advanced plasma diagnostics and performance of the science necessary to better understand fusion relevant plasmas.

The group is involved in cutting edge fusion research at multiple fusion research facilities both in the US and around the world (see example in Figure 1). PDG advances the state-of-the-art in microwave and millimeter wave plasma diagnostics – including scattering, interferometry, polarimetry, reflectometry and radiometry – developing and implementing these diagnostics in fusion research experiments across the world and exploiting them to collaborate in the investigation of plasma turbulence and transport, and global plasma instabilities in fusion research plasmas. UCLA has participated in plasma research on the Mega-Ampere Spherical Tokamak in the Abingdon, United Kingdom, the Experimental Advanced Superconducting Tokamak in Hefei, China, the Madison Symmetric Torus in Madison, WI, the Alcator C-Mod Tokamak in Cambridge, MA, the DIII-D Tokamak in San Diego, CA and the National Spherical Torus Experiment–Upgrade, at Princeton University, Princeton NJ.

Examples of state-of-the-art turbulence diagnostics developed by the group include cross-polarization scattering (CPS, to measure internal, local magnetic turbulence), Doppler backscattering (DBS, to measure local density turbulence and flow), and correlation electron cyclotron emission (CECE, to measure local electron temperature turbulence). The colorful image shown in Figure 2 illustrates the multiple instabilities (both coherent and turbulent) that can simultaneously occur in a fusion plasma. In this example, The Plasma Diagnostic Group uses advanced diagnostics to better understand the science of these types of instabilities, the possible interactions, their effect on the plasma performance, and comparisons to state of the art

**Cutaway Drawing of DIII-D Tokamak**



**Photo of interior of DIII-D Tokamak**

**Photo of Edge Protective Tiles Being Heated by the Plasma**

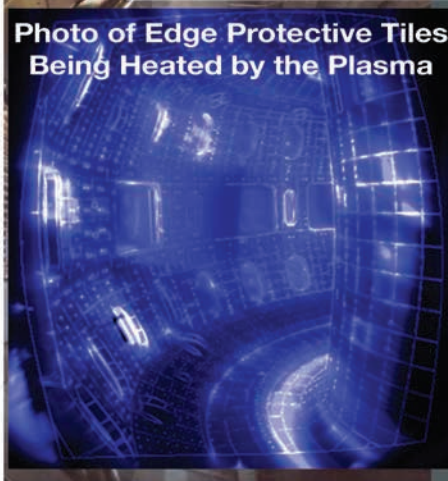


Figure 1. Drawing and photos of exterior and interior of DIII-D tokamak at the National Fusion Facility, San Diego, CA. Scientist in yellow clean suit is examining a plasma diagnostic during a vacuum vessel vent. Images courtesy General Atomics.

numerical predictions.

In general, a key mission of the US fusion energy research program is the development of fully non-inductive steady-state plasma operation at high plasma pressure. This is strongly motivated by the anticipated improvements in fusion reactor economy and reliability gained through steady-state operation and, very importantly, the increase in fusion gain with plasma pressure (or normalized pressure  $\beta$ ). A vital focus of this effort is developing a predictive understanding of stability, transport,



and the requirements for heating and current drive systems. Recent theoretical research has indicated that coupling of electrostatic and magnetic fluctuations can favorably reduce thermal transport in the core of high pressure tokamak plasmas. Recent theory has also indicated that the role of magnetic turbulence can be significant in standard tokamaks. UCLA turbulence diagnostic systems (CPS for, DBS for and flow, and CECE for ) cover three key turbulence fields needed to advance the understanding of advanced tokamak scenarios and to validate simulations putting the group at the forefront of this research.

The unique science and technological opportunities offered by this research are ideal for the Professional development and education of graduate students. Current and past UCLA graduate students have been very successful as evidenced by their invited talks and publications. Previous successful UCLA graduate students include Professor Anne White/MIT, Dr. Jon Hillesheim/JET and Dr. Laszlo Bardoczi/ORNL-GA. Other more recent examples of ongoing research are given below.

UCLA graduate student Dr. Laszlo Bardoczi (graduated in early 2017) published two journal articles in 2016, one in *Physics of Plasmas* and another in *Physical Review Letters* with a further two first author journal articles in 2017 on the work he performed at DIII-D. As an indication of the quality and impact of Dr. Bardoczi's research he was also awarded an Invited Talk at last year's APS-DPP (2016) meeting in San Jose, CA. Leading up to this Invited Talk Dr. Bardoczi led a 2015 DIII-D experiment directed at the interaction of turbulence, transport, and neo-classical tearing modes.

UCLA graduate student Ms. Shawn Tang lead an experiment on the DIII-D National Fusion Facility (General Atomics, San Diego, CA, see Figure 1) to systematically investigate the dependence of high frequency Alfvén eigenmode stability on plasma parameters (e.g. electron density and magnetic field strength) as well as dependence on externally injected fast neutral particles. (Alfvén eigenmodes are global coherent oscillations with wavelength comparable to the plasma size.) The experiment produced intriguing results, including insight into the processes driving and damping the Alfvén eigenmodes. As an indication of the significance of the work Ms. Tang gave a talk on the results at the 15th International Atomic Energy Agency Technical Meeting on Energetic Particles in Magnetic Confinement Systems in Princeton, NJ, September 5–8, 2017.

UCLA undergraduate student Mr. Jimmy (Zhi) Deng has been working with the group on analyzing microwave scattering measurements in NSTX tokamak for evidence of mode conversion of high frequency Alfvén eigenmodes to kinetic Alfvén waves, which are highly dissipative short wavelength oscillations. Based upon this work Mr. Deng was awarded a Student Travel Grant by the American Physical

Society, Division of Plasma Physics, to present the results of his research at the upcoming 59th Annual Meeting of the Division in Milwaukee, WI, October 23–27, 2017.

Overall, the science and technology that the Plasma Diagnostic Group is involved in is rich and stimulating with multiple significant research opportunities.

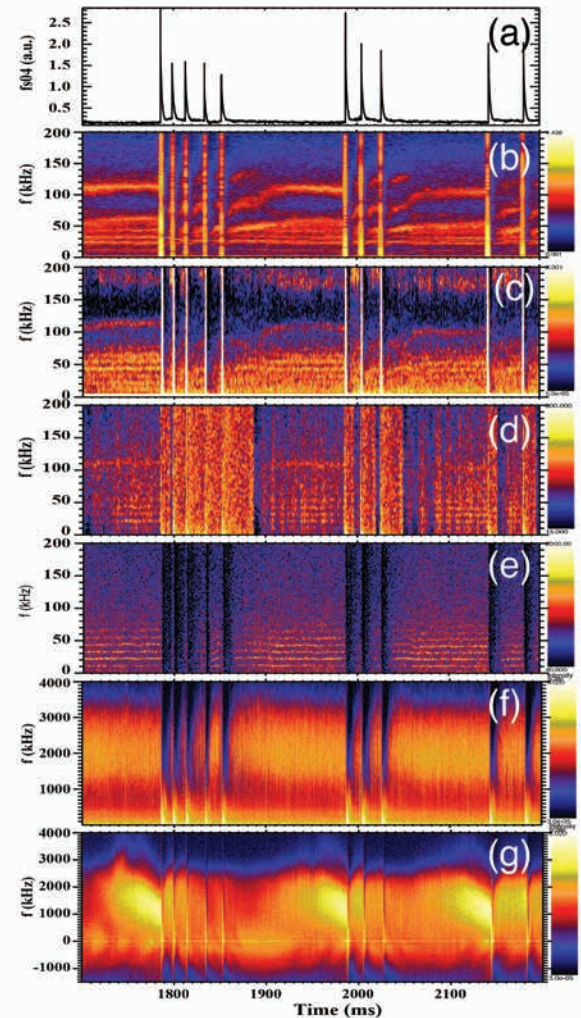


Figure 2. Frequency–time spectrogram illustrating multiple instabilities and turbulence simultaneously present. (a) Balmer-Ed $\alpha$  plasma emission, (b) magnetic probe, (c,d,e) velocity fluctuations (DBS) from three different positions, and (f,g) density fluctuation amplitude (DBS) from two different positions.

# THEORETICAL PLASMA PHYSICS

George Morales

## Avalanches in magnetized plasmas

A coordinated experimental, theoretical and modeling project involving Dr. Bart Van Compernelle, graduate student Matt Poulos, undergraduate students Suying Jin and Nikolas Ramadan, led by Professor George Morales, is exploring the unusual features of avalanches in density and temperature that can occur in a magnetized plasma. The experiments are performed in the Basic Plasma Science Facility (BaPSF) at UCLA and the project is jointly supported by DOE and NSF. The work has been the subject of several invited talks including recent presentations at the International Conference on Plasma Physics (ICPP) in Taiwan, and the Latin American Workshop in Plasma Physics (LAWPP) in Mexico City. Avalanches are sudden events, initially localized but that cause major global changes in a system. Their origin is a large gradient in a key parameter such as the plasma pressure. They are triggered when a threshold condition is exceeded, and can be repetitive if an external agent restores the gradient value. Avalanches are most commonly associated with heavy snow or hillside slides, but occur also in the solar corona and fusion devices. The team has developed a unique heating configuration that can study such phenomena, under controlled and repeatable conditions, in the laboratory, as shown in Figure 1. Theoretical models have been developed that can explain the major observations, but many new challenges remain to be understood, in particular the role of ambient plasma flows in triggering the avalanche.

An extensive literature exists in which the approach to thermal equilibrium is described in terms of reversible dynamics, i.e., using deterministic thermostats. The paradigm system is known as the Nosé-Hoover (NH) model: a free particle couples to a heat bath through a friction force whose sign and strength adjust to keep the time-average of the energy equal to the thermal energy. Professor Morales has recently

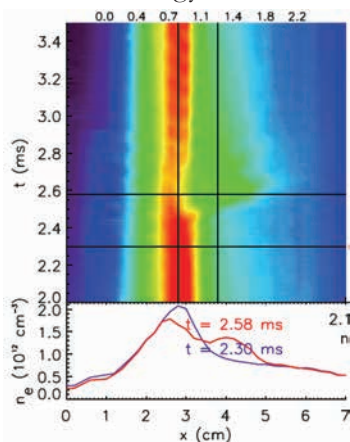


Figure 1. Top is color contour of spatio-temporal evolution of plasma density showing one avalanche event. Bottom shows modification of Professorile by avalanches.

## Thermostats with chaotic fluctuations

investigated the properties of a thermostat in which the usual frictional force is supplemented with a new Langevine-type of force that depends on the self-consistent friction coefficient. This addition results in a chaotic environment in which a stationary particle self-heats and undergoes Brownian motion, with the velocity distribution approximating a Maxwellian. The application of a constant external force results in a mobility whose value corresponds to the famous Einstein relation, as illustrated in Figure 2.

This new thermostat provides a more realistic approximation to the behavior of a free particle interacting with a heat bath, but yet adhering to the philosophy of deterministic dynamics. This methodology opens the possibility for future studies of

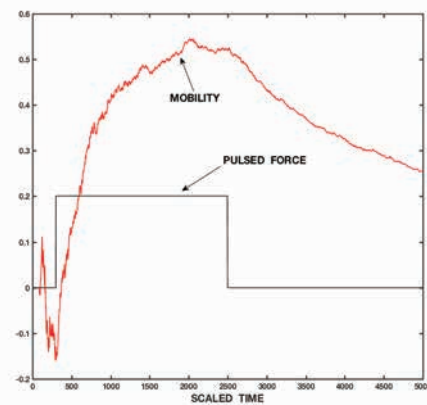


Figure 2. Application of an external force to a free particle in contact with the new thermostat results in a steady mobility whose value satisfies the Einstein relation.

systems that are driven out of thermal equilibrium by other external processes, such as by the application of powerful electromagnetic waves.

A related issue has been investigated by undergraduate student Yueqi Zhao in a Physics 199 project, supervised by Professor Morales. He has chartered the nonlinear dynamics of a particle in contact with a pure NH thermostat and that is simultaneously driven by a sinusoidal force. A variety of unexpected features that depend on the amplitude and frequency of the external driver have been identified, and that will form the basis of a future publication.

# SPACE PLASMA SIMULATION GROUP (SPSG)

**Jean Berchem, Nicole Echterling, Mostafa El-Alaoui,  
Haoming Liang, 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 group's overall approach is to use various types of numerical plasma simulation codes including global magnetohydrodynamic (MHD), large-scale kinetic (LSK) and implicit particle-in-cell (PIC) simulations, in close coordination with observations made by NASA spacecraft at Earth and at other planets. Spacecraft measurements are used both to initialize and validate the simulations. For example, measurements from solar wind monitors far away sunward of Earth are used as input to global simulations of the solar wind-magnetosphere-ionosphere system, while observations from other spacecraft closer to Earth are used to validate their results. The analysis of the simulation results is not only valuable to put single point satellite measurements in a global magnetospheric context, but it also allows the determination of the physical mechanisms responsible for the phenomena observed by the spacecraft.

One of the major endeavors of the group has been to understand how magnetic energy is transported and converted into kinetic energy of the plasma through magnetic reconnection processes occurring in different regions of Earth's magnetosphere, primarily at the dayside magnetopause and in the magnetotail. Since magnetic reconnection is a fundamental process of energy conversion in the Universe, such an investigation is of prime importance. However, because reconnection in Earth's magnetosphere involves processes occurring across vastly different scales, it is a very challenging problem. Synergistic efforts involving different numerical simulation techniques are needed to integrate together wave-particle interactions and large-scale magnetospheric stresses into a single modeling framework. We achieved such a model by embedding meso-scale implicit PIC simulations into global MHD/LSK simulations. This novel technique allows us to carry out simulations that use realistic physical parameters from fluid scales down to electron scales while being computationally feasible. Figure 1 shows an example of the type of regional iPIC3D/MHD simulations of the solar wind/bow shock region that we have been using to support the analysis of the magnetosheath-magnetopause observations from the NASA Magnetospheric Multiscale mission. This simulation was carried out to study the effects of the shock/magnetosheath plasma instabilities on dayside reconnection

for southward interplanetary magnetic field (IMF). We also have used this approach to gain a synthetic understanding of reconnection processes, in particular the localization and properties of the reconnection diffusion regions at the magnetopause and in the magnetotail, the electron and ion dynamics in reconnection regions, and the effects of heavy ions on the reconnection rate. We also have investigated the importance of MHD turbulence for large and meso-scale structures undergoing macroscopic changes through magnetic reconnection. One example is the investigation of the consequences of the evolution of the flow channels and dipolarization fronts that were created by reconnection processes during a substorm on March 14, 2008. This substorm was related to large amplitude oscillations (Alfvén waves) in the interplanetary magnetic field upstream of the Earth. Figure 2 shows two representative streamers observed by the THEMIS All Sky Imager (ASI) during the auroral onset of the substorm. The left panel corresponds to the first

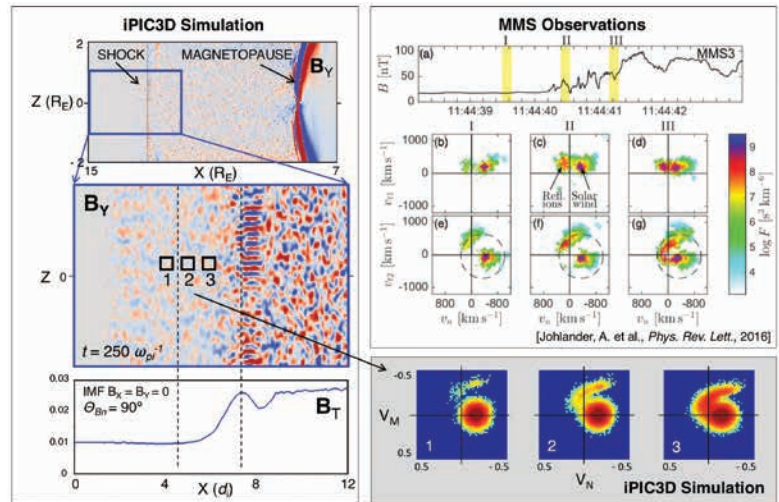


Figure 1. Results of a regional iPIC3D/MHD simulation of the bow shock-magnetosheath-magnetopause region for southward IMF from Berchem et al. [2016]. Phase space from the simulation displayed in the right bottom panel show that the details of the specular reflections of solar wind ions at the perpendicular bow shock predicted by the simulation are consistent with those observed by MMS.

auroral streamer of this substorm. The streamer was confined in latitude because the oval was still thin, before poleward expansion. The THEMIS spacecraft footprints were located near the streamer and THEMIS detected multiple fast flows starting at this time. The azimuthal extent of the streamer was  $\sim 50$  km. The equatorward propagation speed was about a few km/s, which maps to  $\sim 500$  km/s earthward flows in the magnetotail. The middle panel shows two streamers after a full poleward expansion. The oval extends much wider than in the



left snapshot. At this time, the taller streamer partially overlapped with the SuperDARN radar located at Rankin Inlet (right panel). The radar detected  $\sim 500$  m/s equatorward flow with an azimuthal extent of  $\sim 200$  km. This maps to  $\sim 6 R_E$  ( $R_E$  is the Earth radius, 6371 km) of earthward flow channel in the plasma sheet near the last closed field line. A global MHD simulation was run for the event on March 14, 2008, with results shown in Figure 3. It captured dipolarizations and other key features observed by the THEMIS A, D, and E spacecraft located on the dusk side of the mid magnetotail region, in particular, flow vortices-like around 9 to 10  $R_E$ . Early in the substorm the reconnection line was located between 50  $R_E$  and 60  $R_E$  in the magnetotail. However,

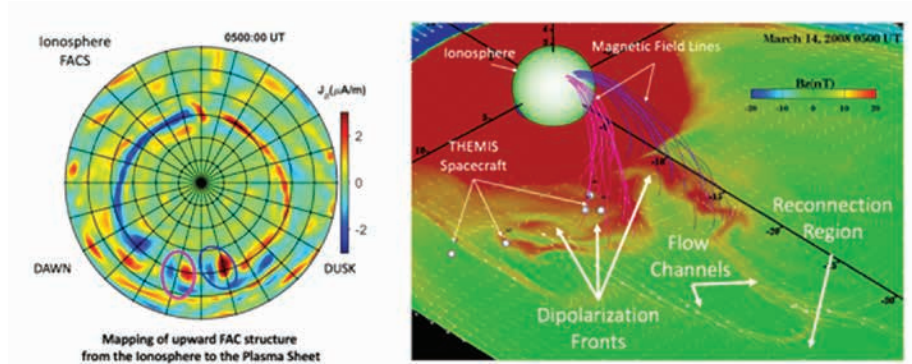


Figure 3. Results of a global MHD simulation of the March 14, 2008 substorm.

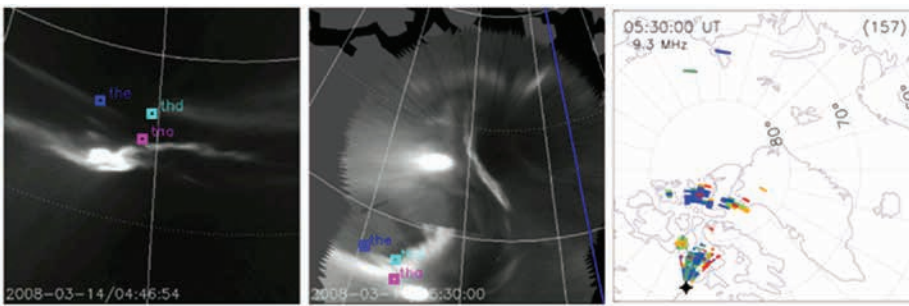


Figure 2. (Left, Center Panels). THEMIS All Sky Imager (ASI) data during an auroral onset on March 14, 2008. White solid lines indicate magnetic latitude (every  $10^\circ$ ) and longitude (every  $15^\circ$ ). The blue line is the magnetic midnight meridian. (Right Panel). Location of the Rankin Inlet SuperDARN radar.

the simulation results for the magnetotail displayed in Figure 3 (right panel) shows that the reconnection line moved around 30  $R_E$  during the intensification of the substorm at 05.00 UT. Narrow flow channels ( $\sim 2$  to 4  $R_E$  width) emerged from the reconnection region, marked by dipolarization fronts at their leading edges. Coordinated analysis of the ionospheric part of the simulation is shown in the left panel of Figure 3. It indicates that the enhancements of the structured currents along magnetic field lines (blue and red lines), or field-aligned currents (FACs) observed at the ionosphere during the intensification were associated with the buildup of the dipolarization fronts in the near-Earth region. Since FACs are associated with electron precipitation, the simulation results suggest that the streamers observed by the ASI cameras result from the evolution of the fast flow channels and dipolarization fronts as they are convected from the reconnection region to the near-Earth plasma sheet.

The group has also continued its work applying global kinetic magnetospheric simulations to the planet Mercury to provide

theoretical support for the MESSENGER spacecraft mission, which began orbiting Mercury in March 2011 and crashed into the planet in April 2015. The recent focus of the research has been on understanding the consequences of charged particle precipitation onto the surface of Mercury. Mercury is unique among magnetized planets in the solar system in the sense that it has essentially no atmosphere or ionosphere. Thus, when charged particles from space precipitate, they directly impact the surface and can modify the regolith. Over time this precipitation can result in space weathering of the surface at certain locations on Mercury. A particularly interesting example of space weathering due to charged particle precipitation occurs at the northern polar region of Mercury.

The results in Figure 4 show the precipitating electron flux and energy from the global LSK simulations on the right panel, which have been used to determine possible geochemical reactions that can occur at high northern polar latitudes near  $85^\circ$  where long-lived water ice deposits have been discovered residing in permanently

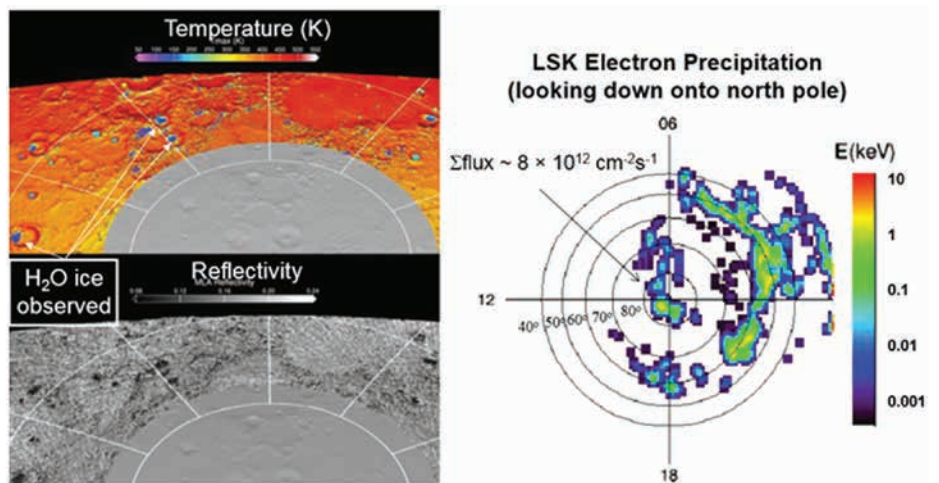


Figure 4. The left panels show the temperature (upper left) and reflectivity (lower left) of the northern polar regions of the planet Mercury, and the right panel shows the location and color-coded energy of precipitating electrons on a polar latitudinal map looking down onto the north pole of Mercury.

shadowed crater cold traps (upper left panel in Figure 4). The deposition of magnetospheric charged particles such as electrons and  $O^+$ ,  $S^+$ ,  $H_2S^+$ ,  $O_2^+$ ,  $H_2O^+$ ,  $C^+$ ,  $Na^+$ , and  $H^+$  into the water ice can produce a variety of new C-H-O-N-S-containing compounds. The end products include carbon-rich, polymeric, tar-like, refractory dark materials whose characteristics are similar to dark compounds observed by MESSENGER spacecraft instruments in the polar craters that cover the water ice deposits (lower left panel in Figure 4). The impact of many energy sources, primarily the magnetospheric cusp precipitating particles, but also galactic cosmic rays (GCR), solar energetic particles (SEP), and UV photons onto the polar ices, combined with gardening, over-turn, sputtering and other physical processes in Mercury's surface materials can create cm-thick layers of dark refractory organics like those observed by MESSENGER.

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## CONDENSED MATTER THEORY

### Elihu Abrahams

Elihu Abrahams is a condensed matter theorist, whose 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 zero temperature. It is found in many "heavy-fermion" metals and is at the forefront of research in condensed-matter physics. 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. Although quantum phase transitions between distinct ground states occur at absolute zero, their effects on electronic properties are 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 transport and thermodynamic properties in metals tuned, by e.g. pressure, magnetic field or composition, to be close to a quantum critical point. Among his most recent contributions in this area is "Strong-coupling theory of heavy-fermion criticality", *Phys. Rev. B* 90, 045105 (2014) and "Critical quasiparticle theory applied to heavy-fermion metals near an antiferromagnetic quantum phase transition", *Proc. Natl. Aca. Sci.* 109, 3238 (2012), in which remarkable agreement has been shown between this "critical quasiparticle theory" and experiment. Very recently,

a review of this work, in collaboration with theorists from the Karlsruhe Institute of Technology, has appeared as *Rep. Prog. Phys.* 80, 044501(2017). Current work in this area concerns the possible superconducting transition of the critical quasiparticles of the theory.

Another, related research activity has been on the recently-discovered iron-based superconductors, in which quantum criticality has been associated, 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 approach forms the framework for an understanding of the superconductivity in these materials, as described in a major review article by Abrahams and coworkers, "High-temperature superconductivity in iron pnictides and chalcogenides", *Nature Reviews Materials*, 1, 16017 (2016).

*A list of several of Abrahams' important recent publications may be found at [http://www.pa.ucla.edu/sites/default/files/abrahams\\_recent\\_pubs.pdf](http://www.pa.ucla.edu/sites/default/files/abrahams_recent_pubs.pdf)*

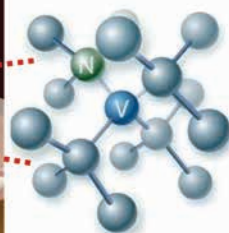
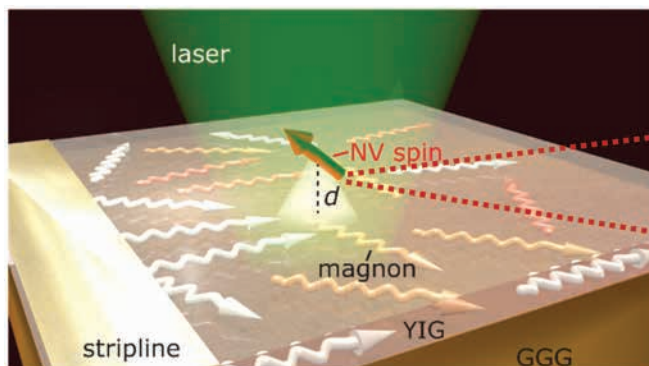


## Yaroslav Tserkovnyak

The group of Professor Yaroslav Tserkovnyak studies collective quantum transport and dynamics in systems with little dissipation, particularly electrical insulators. Recent focus has been on superfluid-like phenomena in solid-state materials, thermally-pumped instabilities and dynamic phase transitions in magnetic structures, and (real-space) hydrodynamics of emergent topological invariants. The projects cover a diverse range of current topics in condensed matter physics, with many being either in close collaboration with experimental groups – both at UCLA and elsewhere – or proposing novel measurable phenomena and functionalities. The group members co-authored more than 20 articles over the past year in *Physical Review Letters*, *Physical Review B*, *Reviews of Modern Physics*, *Science*, and *Nature Physics/Materials/Communications*.

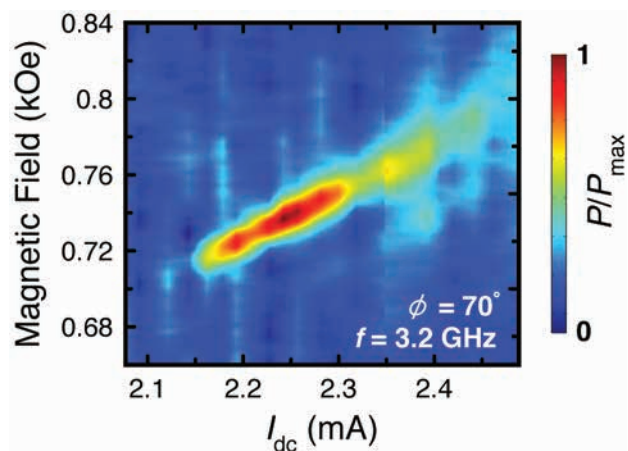
There are currently four postdocs—Se Kwon Kim, Hector Ochoa, Pramey Upadhyaya, and Ricardo Zarzuela and one Ph.D. student—Daniel Hill—working in the group, who drive not only most of the actual work but also generate original ideas behind it. Below, we highlight some of our recent work, with a focus on the collaborative efforts with experimental colleagues that connect with our theoretical predictions.

The article titled Control and local measurement of the spin chemical potential in a magnetic insulator (published in *Science*, 2017) reports a new way to peek into the internal structure of nonequilibrium fluctuations in a magnetic insulator, using a single quantum impurity (called nitrogen-vacancy center) delivered by a diamond nanorod. This groundbreaking experimental technique promises to impact the way we study transport of spin through electrical insulators. Measurements reported in this paper were analyzed using our recently developed framework of Two-fluid theory for spin superfluidity in magnetic insulators (*Phys. Rev. Lett.*, 2016). Related ideas were also used to propose Magnetic domain wall floating on a spin superfluid (*Phys. Rev. Lett.*, 2017), which we suggest to use as a building block for transistor-like functionality and long-distance low-dissipation communication in circuits that could be based entirely on insulators, and driven either electrically or thermally.



Another experimental highlight was reported in the paper Spin caloritronic nano-oscillator (*Nature Comm.*, 2017), which confirmed our prediction of a heat-current induced Bose-Einstein condensation of magnons, at room temperature. This is an exciting starting point for exploring and exploiting coherent dynamics in solid-state structures driven by (incoherent) thermoelectric means. Our related recent works in this vein include Spin superfluid Josephson quantum devices (*Phys. Rev. B, Editors' Suggestion*, 2017) and Magnetic domain walls as hosts of spin superfluids and generators of skyrmions (*Phys. Rev. Lett.*, 2017).

In addition to the original research, Professor Tserkovnyak



contributed to several review articles, including Interface-induced phenomena in magnetism and Antiferromagnetic spintronics (both in *Rev. Mod. Phys.*, 2017), which summarize the current state of the art in these burgeoning fields for graduate students and other junior investigators. Professor Tserkovnyak organized five international conferences and workshops (three in Europe, one in Brazil, and one in French Polynesia), and, together with his group members, delivered almost 20 invited talks on a range of topics of their research, in the last year. In 2017, Professor Tserkovnyak received the Humboldt Research Award from the Alexander von Humboldt-Foundation in Germany, in recognition of his “entire achievements to date.”





# EXPERIMENTAL PLASMA AND BEAM PHYSICS

Pietro Musumeci

## The Pegasus Laboratory

The Pegasus laboratory under the direction of Professor Musumeci continues to be at the forefront of accelerator and beam physics research. The group is participating in two prestigious National Science Foundation Science and Technology Centers. STROBE focused on imaging science and led by Colorado University and CBB on accelerator physics led by Cornell University. These Centers bring long term (5-10 years) funding and more importantly a long list of collaborators with diverse expertise, but sharing common scientific goals. Together with a five-year award from the Gordon and Betty Moore Foundation for developing “accelerators on a chip”, these awards ensure financial stability to the quickly growing research group. At the most recent poll, the group consists of 3 postdocs, 7 graduate students (of which 3 are female, an impressive percentage compared to the average in the department and in accelerator science in general) and a continuously increasing number of undergraduates. Former postdoc Jared Maxson was just hired as assistant Professor at Cornell University. Graduate student Nick Sudar won the student prize at the Advanced Accelerator Conference in 2016.

A couple of recent examples serve to illustrate the internationally recognized status of the group in the field of accelerator and beam physics. In 2016 Professor Musumeci was elected APS Fellow in the Division of Beam Physics in 2016 for pioneering work in the physics of high brightness beams, including ultrafast relativistic electron diffraction, and high gradient inverse free electron laser acceleration”. Last year Professor Musumeci was also tasked by the Department of Energy Basic Energy Science to co-chair a Future Electron Sources workshop. This workshop which was held at SLAC in September 2016 had the goal to trace the path forward in electron sources for all future Basic Energy Science facilities in the country. The 100+ pages long report (published on DOE website earlier in 2017) discusses and prioritizes research directions for this important sub-field of the physics of particle accelerators.

A major experimental result obtained at the UCLA Pegasus photoinjector facility in the past 12 months is the demonstration of electron bunches shorter than 10 trillionths of a second. Such short flashes of electrons can be used in electron diffraction or microscopy to capture atomic motion in a single frame and enable fundamental discoveries in ultrafast science. These bunches have been obtained using a radiofrequency compression technique which can impart a larger energy to the tail of the bunch and decelerates the front of the bunch so that simply propagating of the electron

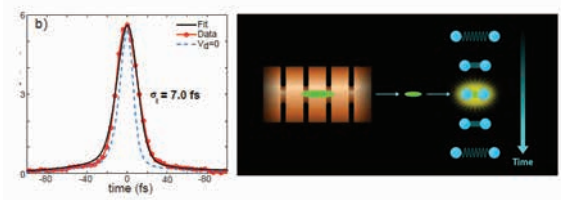


Figure 1. Compression of electron pulses to below 10 fs in duration. In the UCLA Pegasus laboratory, a relatively long electron pulse (green) produced by an electron source (not shown) enters a specially designed linear accelerator (copper; left), whose electromagnetic fields act to compress the pulse several meters downstream from the accelerator. Here, the pulse can be made so short (below 10 fs) that it would “outrun” all atomic motion in molecules (blue) and materials. In an electron diffraction or microscopy experiment with pulses like this, atoms are effectively frozen in place during an exposure (yellow).

beam will result in a strong compression. One important aspect of these measurement is the solution of how to measure such short bunches which is based on a clever use of a radiofrequency streak-camera.

Important results have been obtained also in THz-driven acceleration where graduate student Emma Curry established a world-record obtaining 150 keV modulation using a short pulse of merely 1 uJ of THz energy. THz acceleration is an exciting novel direction in advanced accelerators with significant potential to improve the performances of particle accelerators due to the very high fields achievable and to the particular time-scales associated with these waves. The results at Pegasus have been obtained using a novel zero-slippage IFEL accelerator which has the important benefit of matching both phase and group velocity of the waves and the particles and therefore enabling long distance acceleration.

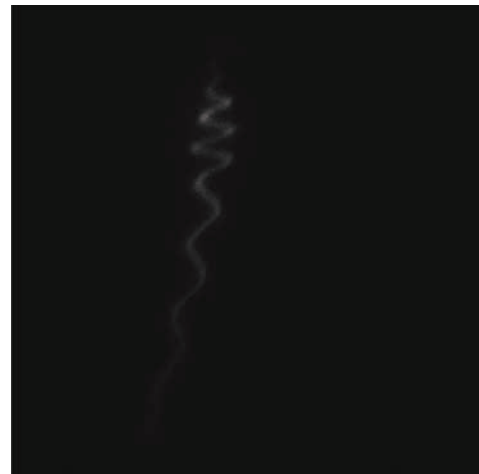


Figure 2. Longitudinal phase space of a 6 MeV beam at Pegasus after interaction in a short 30 cm undulator with THz wave.

# ACOUSTICS AND LOW TEMPERATURE PHYSICS

## Gary Williams

Professor Gary Williams gave the departmental colloquium in December 2016 to commemorate the award of the 2016 Nobel Prize to Professors David Thouless and J. Michael Kosterlitz, for their theory of the role of topological vortex excitations in two-dimensional superfluids. Research at UCLA turned out to be instrumental in their receiving the award, since experiments carried out in the 1960's by the late UCLA Professor Isadore ("Izzy") Rudnick played a crucial role in confirming the correctness of their theory. Professor Williams reviewed the history of this interplay between theory and experiment, and then went on to note how more recent research at UCLA has further developed and extended the topological ideas at the heart of the Kosterlitz-Thouless theory.

Rudnick pioneered the study of extremely thin films of superfluid helium-4 adsorbed on glass substrates (as thin as two atomic layers) in the late 1960's. He and his graduate student James Fraser looked at the propagation of thickness waves in the two-dimensional superfluid films, a mode known as third sound. They noticed something very curious, that as the temperature was increased the superfluidity in the films suddenly disappeared while the third sound velocity remained at a finite value. This was quite different from the bulk three-dimensional superfluid transition, where it was well known that the superfluidity slowly decreases and goes smoothly to zero at the critical temperature. With no theoretical guidance, Fraser and Rudnick published their result in 1969 simply noting the finite third sound velocity at the phase transition point.

Kosterlitz and Thouless published a first paper on their theory 1971, in which they predicted that the superfluidity of a two-dimensional superfluid should suddenly jump from a finite value to zero at the critical temperature. This was just what Rudnick had seen, but unfortunately the theory was published in an obscure British journal. Rudnick was unaware of their paper (he was on sabbatical in Israel), and they had not seen his paper on the experimental results. Many physicists were critical of the Kosterlitz-Thouless theory, because it postulated that the superfluid transition was the result of thermally-generated quantized vortices in the superfluid helium, an extremely novel claim at the time.

It was not until 1977 that Kosterlitz and David Nelson at Harvard published a paper in Physical Review Letters showing that the magnitude of the sudden jump to

zero of the superfluid density at the critical temperature should be a universal value determined by Planck's constant, Boltzmann's constant, and the helium atom mass, and independent of any details of the helium film except the thickness. Rudnick immediately set about analyzing his old data, and quickly showed that his measurements agreed with the universal value to within 10%. Other later measurements then began to support the theory as well, and theorists finally came to accept it as a fundamentally important advance, leading to the Nobel prize. Rudnick's "curious" results had profound consequences.

**UCLA**  
 Department of Physics & Astronomy  
**COLLOQUIUM**  
 Thursday, December 1, 2016  
 PAB, 1-434 at 4:00 p.m.

**GARY WILLIAMS**  
 University of California, Los Angeles

### Perspective on the 2016 Nobel Prize: research at UCLA on the Kosterlitz-Thouless transition in superfluid helium

This talk will be more of a historical survey of research at UCLA on the two-dimensional Kosterlitz-Thouless (KT) superfluid phase transition. The seminal 1969 third-sound measurements of the late Professor Isadore ("Izzy") Rudnick showed that the superfluid transition in very thin helium films was unusual, occurring while the 2D superfluid density was still finite. The explanation of these results began with the first KT papers in 1972-73, which introduced vortex-antivortex pairs as the topological elementary excitations causing the transition. After a brief review of the KT theory, further experimental and theoretical work in this area at UCLA will be discussed, including experiments on films in porous materials and carbon nanotubes, and an extension of the basic KT ideas to the superfluid transition in three dimensions and (more recently) to four dimensions.

David J. Thouless

J. Michael Kosterlitz

## DR. JOSHUA SAMANI



We are proud to announce the arrival of a new teaching faculty member, Josh Samani. Dr. Samani received a B.A. in physics and B.S. in mathematics from University of California, Berkeley in 2008. He completed his Ph.D. in 2014 at UCLA on aspects of the AdS/CFT correspondence applied to boundary CFTs, warped AdS spacetimes, and asymptotically Lifshitz black holes.

Dr. Samani joined our faculty this summer to pursue a program of curricular and instructional innovation rooted in research-based principles of teaching and learning. His efforts will focus on optimizing physics courses to improve student attitudes about and competency in the physicist's approach to solving hard problems, integrating computational instruction into the physics curriculum, and spearheading initiatives to increase the performance and retention of underrepresented populations in physics.

## PROFESSOR NATHAN WHITEHORN



We are proud to announce the arrival of a new Experimental Elementary Particles physics Professor, Nathan Whitehorn. Professor Whitehorn received a B.A. in Physics from the University of Chicago in 2007. He completed his Ph.D. in 2012 at the University of Wisconsin-Madison on TeV neutrino emission from Gamma-Ray Bursts with the IceCube experiment, continuing there to work on the discovery of a diffuse neutrino background at PeV energies. He was a postdoc at the University of California, Berkeley in observational cosmology and a member of the South Pole Telescope, POLARBEAR, and Simons Observatory collaborations.

Professor Whitehorn joined our faculty this summer and is pursuing a program in experimental high-energy particle astrophysics and cosmology, using the largest possible particle accelerator to understand the universe at its smallest and most energetic. His group plans to focus on using neutrinos to understand the origin of the highest energy cosmic rays using IceCube and gravitational measurements of neutrino mass and number using the recently deployed 3rd-generation South Pole Telescope, as well as the design of successor instruments.



## FACULTY 2017

### Professors

Elihu Abrahams (Adjunct)  
 Katsushi Arisaka  
 Zvi Bern  
 Dolores Bozovic - Vice Chair of Resources  
 Stuart Brown  
 Robijn Bruinsma  
 Troy Carter  
 Sudip Chakravarty  
 Ferdinand V. Coroniti - Associate Dean of Physical Sciences  
 Robert Cousins  
 Eric D'Hoker  
 Sergio Ferrara  
 Christian Fronsdal  
 Steven Furlanetto  
 Walter Gekelman  
 Graciela Gelmini  
 Andrea Ghez  
 George Grüner  
 Michael Gutperle  
 Brad Hansen  
 Jay Hauser  
 Kàroly Holczer  
 Huan Huang  
 Eric Hudson  
 Frank Jenko  
 David Jewitt  
 Hong-Wen Jiang  
 Per Kraus  
 Alexander Kusenko  
 James Larkin - Vice Chair of Astronomy and Astrophysics  
 Alexander Levine  
 Matthew Malkan  
 Jean-Luc Margot  
 Thomas Mason  
 Ian McLean - Vice Chair of Academic Affairs  
 Mayank Mehta  
 Jianwei Miao  
 George J. Morales  
 Warren Mori  
 Mark Morris  
 Pietro Musumeci  
 William Newman  
 Christoph Niemann  
 Rene Ong  
 Seth J. Putterman  
 James Rosenzweig  
 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)  
 Kang L. Wang  
 Gary A. Williams  
 Giovanni Zocchi

### Associate Professors

Michael Fitzgerald  
 B. Chris Regan  
 Rahul Roy  
 Hilke Schlichting

### Assistant Professors

Michail Bachtis  
 Wesley Campbell  
 Ching Kit Chan (Adjunct)  
 Paul Hamilton  
 Zhongbo Kang  
 Smadar Naoz  
 Martin Simon (Adjunct)  
 Ni Ni  
 Shenshen Wang  
 Nathan Whitehorn

### Professors Emeriti

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

## RESEARCHERS, LECTURERS & PROJECT SCIENTISTS, 2017

### Researchers

Jean Berchem  
 David Brower  
 Neal Crocker  
 Weixing Ding  
 Mostafa El Alaoui  
 Samim Erhan  
 Terry Rhodes  
 R. Michael Rich  
 Robert Richard  
 Lothar Schmitz  
 Frank Tsung  
 Stephen Vincena

### Associate Researchers

Gerard Andonian  
 Tuan Do  
 Mikhail Ignatenko  
 Shreekrishna Tripathi  
 Bart Van Compernelle  
 Gang Wang

### Assistant Researchers

Brian Naranjo  
 Shoko Sakai  
 Yusuke Sakai  
 Derek Schaeffer  
 Christian Schneider  
 Tham Tran  
 Chao-Wei Tsai  
 Gunther Witzel

### Project Scientists

Mani L. Bhaumik  
 Patrick Pribyl  
 Guiding Wang  
 Lei Zeng

### Associate Project Scientists

Carmen Constantin  
 Atsushi Fukasawa  
 Jeffrey Zweerink

### Assistant Project Scientists

Jie Chen  
 Warren Essey  
 Gregory Martinez

### Lecturer PSOE

Joshua Samani

## ASTRONOMY LIVE! THE UCLA PLANETARIUM

On November 6th, 2017 we hosted the seventh annual Exploring Your Universe 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, the Center for Environmental Implications of Nanotechnology. Approximately 7,000 visitors come from all over the Los Angeles area.

On August 21, 2017, Astronomy Live! joined volunteers from the UCLA Department of Earth, Planetary and Space Sciences in hosting a special solar eclipse viewing in the Court of Sciences. Solar telescopes and other demonstrations were set up for the thousands of visitors that came to campus to witness the historic event.

In 2017, the UCLA Planetarium and Astronomy Live! hosted the fourth annual Summer Observing Workshop for high school students. Eight juniors and seniors from Los Angeles area high schools were chosen based on their applications. Over the course of 8 weeks, students learned the basics of observational astronomy. They also had the chance to remotely observe using the Nickel 1-meter telescope at Lick Observatory, a research-grade telescope at an active astronomical observatory. Each student completed an independent data analysis project on a particular astronomical object using analysis guides and custom software developed by UCLA graduate students. The program culminated in a final presentation from each student showing the results of their research. We plan to continue holding this workshop in future years.

In addition, the UCLA Planetarium has had another very successful year. The graduate student-led planetarium hosted 4512 attendees over the 2016-2017 school year. Shows were given to 26 educational groups from the Los Angeles area. It played a major role in Exploring Your Universe 2017 and our High School Summer Program.





# AMERICAN PHYSICAL SOCIETY (APS) CONFERENCE FOR UNDERGRADUATE WOMEN IN PHYSICS AT UCLA



Over 250 students attend the 2017 Conference for Undergraduate Women in Physics at UCLA.

The UCLA Physics & Astronomy Department is pleased to have hosted the 2017 Western Regional APS Conference for Undergraduate Women in Physics (CUWiP). CUWiP is a multi-site, three-day annual conference held at universities throughout the US and Canada. Designed to provide students the experience of attending a professional level conference, CUWiP brings undergraduate physics majors together to learn about careers in physics, meet their peers, and network with leading scientists.

CUWiP@UCLA was held from January 13-15, 2017 at the newly built UCLA Luskin Conference Center. Over 250 students attended from California, Arizona, Alaska, and Hawaii—making UCLA the largest 2017 CUWiP

## *"Our Differences are Valuable."*

conference site. The mission statement for CUWiP@UCLA was "Our Differences are Valuable." Our conference featured plenary talks, interactive workshop sessions, a student poster session, and career fair.



Professor Nadya Mason University Illinois, Urbana Champaign.



Students eagerly engage plenary speaker Professor Nadya Mason at CUWiP 2017. APS CEO Dr. Kate Kirby, left.

The goal of APS CUWiP is to help undergraduate women continue in physics by providing them with the opportunity to experience a professional conference, information about graduate school and professions in physics, and access to other women in physics of all ages with whom they can share





Physics Graduate Student Elizabeth Mills introduces the Overcoming Obstacles in Physics. Panel: Dean Robin Garrell (UCLA) Dr. Elizabeth Merrit (Los Alamos National Lab) Dr. Farisa Morales (JPL) and Professor Smadar Naoz (UCLA)

experiences, advice, and ideas.

A typical program will include research talks by faculty, panel discussions about graduate school and careers in physics, presentations and discussions about women in physics, laboratory tours, student research talks, a student poster session, and several meals during which presenters and students interact with each other.

Conferences for Undergraduate Women in Physics (CUWiP) are three-day regional conferences for undergraduate physics majors. The first CUWiP was held in 2006 at the University of Southern California. In 2011, APS was invited by CUWiP leaders to become the institutional home of CUWiP. APS provides organizational support, institutional memory, and a home for external financial support necessary to operate and continually improve CUWiP events.

CUWiP@UCLA was organized by UCLA Physics & Astronomy Department graduate students, undergraduate students, faculty and staff. There was no cost to participants to attend. The conference was generously sponsored by:

UCLA Division of Physical Sciences

- NASA Jet Propulsion Laboratory
- UCLA Department of Physics & Astronomy
- UCLA Division of Graduate Education
- UCLA Waldo W. Neikirk Term Chair
- UCLA Office of Equity, Diversity & Inclusion
- UCLA Division of Undergraduate Education
- General Atomics
- Northrop Grumman
- The Aerospace Corporation

APS CUWiP conferences are also supported in part by the National Science Foundation (PHY-1346627) and by the Department of Energy Office of Science (DE-SC0011076)



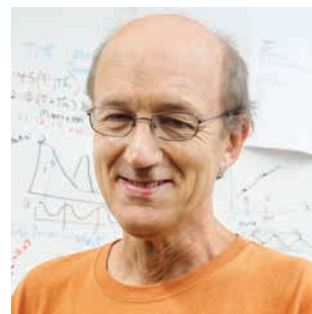
The UCLA Physics & Astronomy Department would like to thank the CUWiP@UCLA Organizing Committee led by Physics graduate students Alexandra Latshaw and Elizabeth Mills, and Faculty Advisor Professor Stuart Brown. To learn more about the conference, visit our site: <https://conferences.pa.ucla.edu/cuwip-ucla/>

## Team led by UCLA astrophysicist observes primitive comet 1.5 billion miles from the sun

A team of astronomers led by UCLA Professor David Jewitt has identified a “special comet” 1.5 billion miles from the sun. No other comet heading toward our sun has ever been seen at such a great distance. Jewitt said the discovery will enable scientists to monitor the developing activity of a comet over an extraordinary range of distances.

The comet will make its closest approach to the sun in 2022, when it will pass just beyond Mars’ orbit.

Read Article in UCLA News at <http://newsroom.ucla.edu/releases/team-led-by-ucla-astrophysicist-observes-primitive-comet-1-5-billion-miles-from-the-sun>



David Jewitt

## Physicist wins 2017 Feynman Theory Prize

Giovanni Zocchi, Professor of physics at UCLA, was awarded the 2017 Foresight Institute’s Feynman Prize–Theory at the Feynman Prize dinner at the Atomic Precision for Healthspan and Longevity workshop Sept. 16 in Palo Alto, California.

The award, in honor of physicist Richard Feynman, celebrates a researcher whose work has most advanced the achievement of Feynman’s goal for nanotechnology: molecular manufacturing, defined as the ability to construct atomically precise products in which individual atoms are positioned according to a design. Separate prizes are awarded for theoretical research and experimental work; Zocchi is honored for his theoretical research.

Zocchi received the theory prize for inventing a method called “nano-rheology,” a method to measure enzyme deformations smaller than an atom. His laboratory’s approach is informed by diverse areas of condensed matter physics, including materials science, nonlinear dynamics, nanoscience and polymer physics.

Zocchi credits the UCLA students in his laboratory for the research for which he was awarded the prize. Read Article in UCLA News at: <http://newsroom.ucla.edu/dept/faculty/physicist-wins-2017-feynman-theory-prize>

Read more about Zocchi's research on his website: <http://zocchi.physics.ucla.edu/index.html>



Giovanni Zocchi

## Dr. Andrea Ghez, UCLA, at The Montgomery Summit 2017

Dr. Andrea Ghez, Professor at UCLA Department of Physics and Astronomy speaks with Jacki Karsh at The Montgomery Summit 2017 about how technology, astrophysics and black holes collide and understanding the universe.

Watch video:

<https://www.youtube.com/watch?v=CLDS6H9BxLg>

Visit UCLA Physics & Astronomy website for up-to-date News from the department: <http://www.pa.ucla.edu>

## 37 questions with black holes expert Andrea Ghez

Andrea Ghez is an astronomy professor at UCLA and a pre-eminent expert on the role of black holes in the evolution of galaxies. Ghez was the first researcher to confirm the existence of a supermassive black hole at the center of the Milky Way. She is also an authority on star formation.

Ghez is a member of the UCLA Galactic Center Group, which has the mission of transforming our understanding of black holes and their role in the universe with high resolution observations of the Milky Way.

In a video by the UCLA College, she answers questions about her work and offers a peek inside the Keck remote observing room at UCLA, where Ghez and her team keep an eye on the center of our galaxy. Watch the video: <http://newsroom.ucla.edu/stories/37-questions-with-andrea-ghez>



## Astronomers find that the sun's core rotates four times faster than its surface

The sun's core rotates nearly four times faster than the sun's surface, according to new findings by an international team of astronomers. Scientists had assumed the core was rotating like a merry-go-round at about the same speed as the surface.

"The most likely explanation is that this core rotation is left over from the period when the sun formed, some 4.6 billion years ago," said Roger Ulrich, a UCLA professor emeritus of astronomy, who has studied the sun's interior for more than 40 years and co-author of the study that was published today in the journal *Astronomy and Astrophysics*. "It's a surprise, and exciting to think we might have uncovered a relic of what the sun was like when it first formed."

Ulrich worked with the GOLF science team, analyzing and interpreting the data for 15 years. Ulrich received funding from NASA for his research. The GOLF instrument was funded primarily by the European Space Agency. Read More: <http://newsroom.ucla.edu/releases/astronomers-report-new-measurements-of-the-suns-core-which-has-a-temperature-of-29-million-degrees-fahrenheit>



Roger Ulrich

## UCLA physicist elected to National Academy of Sciences



Claudio Pellegrini, a distinguished Professor emeritus of physics at UCLA, as well as an adjunct Professor in photon science at the SLAC (Stanford Linear Accelerator Center) National Accelerator Laboratory, was elected today to the National Academy of Sciences in recognition of his "distinguished and continuing achievements in original research." The academy announced the election of 84 new members and 21 foreign associates.

Membership in the academy is one of the highest honors that a U.S. scientist can receive. Its members have included Albert Einstein, Robert Oppenheimer, Thomas Edison, Orville Wright and Alexander Graham Bell.

"Election to the National Academy of Sciences is certainly a great honor, and I am deeply grateful to UCLA," Pellegrini said. "The time there was the best in my life. I am deeply grateful for the support I received over many years from UCLA, my colleagues, students and postdocs."



Claudio Pellegrini



## KEYNOTE SPEAKER

### 2017 PHYSICS & ASTRONOMY GRADUATION CEREMONY, BARAK BUSSEL

Friends and family and friends gathered at Ackerman Union Grand Ballroom on June 18, 2017 to celebrate the graduation ceremony in honor of the students from the UCLA Department of Physics and Astronomy. Excitement filled the air as the Chair Jean Turner presided over the celebration, which included lively student addresses and a relevant keynote address given by a highly successful and respected alumnus to the Department, Mr. Barak Bussel. Mr. Bussel spoke of the mental discipline that physics taught him and which allowed him to solve problems in a variety of domains including the economic and technological domains where he has excelled. His message to graduates was to always keep your eyes open for new opportunities as he has done; opportunities are out there in abundance if you can discern them and seize them because your physics background has prepared you for success. The speech was very well received by everyone and was followed by the presentation of the class of 2017, announcements of honors and awards, and finally a reception where all enjoyed a light buffet, animated conversation, photo opportunities and emotional good-byes.



## RESEARCH EXPERIENCE FOR UNDERGRADUATES (REU) 2017

The Department hosted its 15th annual Research Experience for Undergraduates program (REU) during Summer 2017. The program is a 10-week immersion in research for physics and astronomy students coming from all over the country, including California. In 2017, 14 students were selected from about 400 applications and were matched with a faculty mentor according to the students' stated interests, and a 10-week research project was designed and carried out in close collaboration with the faculty mentors and their groups. To date, the UCLA Physics & Astronomy program, started in 2003, has hosted 203 students. As of the last statistics, the percentage of REU students who have gone on to pursue a higher degree is 85%. Furthermore, about 72% of our REU participants have received Ph.D.s in physics or a closely related subject (mostly physics and astrophysics, but a few in engineering and math); 13% obtained a Masters degree in physics or engineering. About 10% do not pursue graduate degrees in physics or a closely related subject, but do end up employed in a STEM field (mostly as engineers). Also of interest, 40% of those who received a Ph.D. were women and 16% were underrepresented minorities. At the MS level, 60% were women and 40% were underrepresented minorities. While our program cannot claim all the credit for these statistics, it is clear that the REU program has had a positive influence on the participant's choice of direction and has been successful in fulfilling its primary objective, which is to entice bright young minds to persist in STEM fields, and particularly in Physics or Astronomy.



2017 REU students

**UCLA** College

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Physical Sciences

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Physics & Astronomy

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