Carnegie Mellon University
INTERACTIONS
DEPARTMENT OF PHYSICS 2017

Scott Dodelson Appointed Head of Department of Physics

By Jocelyn Duffy

Renowned physicist Scott Dodelson has been named the head of the Department of Physics in Carnegie Mellon University's Mellon College of Science.

Dodelson conducts research at the interface between particle physics and cosmology, examining the phenomena of dark energy, dark matter, inflation and cosmological neutrinos.

He is the co-chair of the Science Committee for the Dark Energy Survey (DES), an international collaboration that aims to map hundreds of millions of galaxies, detect thousands of supernovae and find patterns of cosmic structure in an attempt to reveal the nature of dark energy. On Aug. 3, the DES released results that measured the structure of the universe to the highest level of precision yet.

Dodelson also works with the South Pole Telescope and the Large Synoptic Survey Telescope (LSST). The South Pole Telescope studies the Cosmic Microwave Background to gain a better understanding of inflation, dark energy and neutrinos. The LSST, which is currently being built in Chile, will survey the sky for a decade, creating an enormous data set that will help scientists determine the properties of dark energy and dark matter and the composition and history of our solar system.

Dodelson was attracted to CMU in part by the Physics Department's varied areas of strength and the leadership role the department's McWilliams Center for Cosmology and its faculty play in a number of large, international cosmological surveys, including LSST and the Sloan Digital Sky Survey.

"Within the McWilliams Center, I found kindred spirits in the faculty who are leading scientific projects aimed at understanding the universe, but I was equally attracted to the department's strong groups in biological physics, condensed matter and nuclear and particle physics," said Dodelson. "I'm excited to learn about these diverse fields and connect with other departments throughout the university."

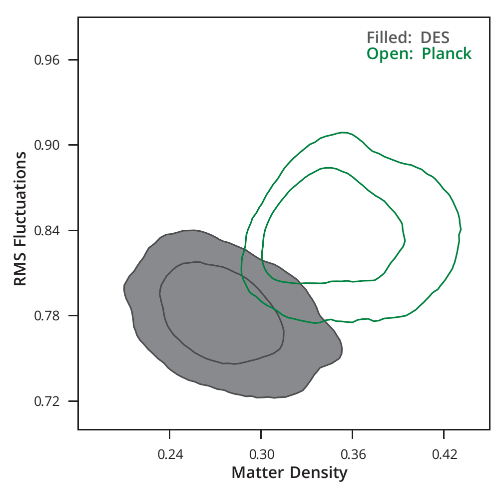
Under Dodelson's leadership, the Physics Department will partner with other departments within the Mellon College of Science through a new theory center and continue to collaborate with colleagues in Statistics, Computer Science and Engineering. Dodelson also hopes to increase the department's partnerships with other universities and research initiatives worldwide and bring physics to the community through outreach programs.

"I was drawn by the university's enthusiasm for foundational research," Dodelson said. "The Physics Department will strive to bring this excitement to students, alumni and the broader community."

Dodelson comes to Carnegie Mellon from the Fermi National Accelerator Laboratory (Fermilab), where he was a distinguished scientist, and the University of Chicago where he was a professor in the Department of Astronomy and Astrophysics and Kavli Institute for Cosmological Physics. While at Fermilab, Dodelson served as head of the Theoretical Astrophysics Group and co-founder and interim director of the Center for Particle Astrophysics.

Dodelson earned a joint B.A./B.S. degree in applied physics and a Ph.D. in theoretical physics from Columbia University. He completed a post-doctoral fellowship at Harvard University.

Dodelson assumed the position of department head from Stephen Garoff who has served as head since 2013.



Constraints on two cosmological parameters (the density of matter and amplitude of fluctuations) from the first year of data from the Dark Energy Survey (DES-Y1) and from the Planck satellite. Planck probes the universe when it was only 400,000 years old, while DES probes the universe billions of years later. Remarkably, the two very different experiments produce similar constraints, although there is a hint of tension. Dodelson serves as co-chair of the DES Science Committee and coordinated the analysis.

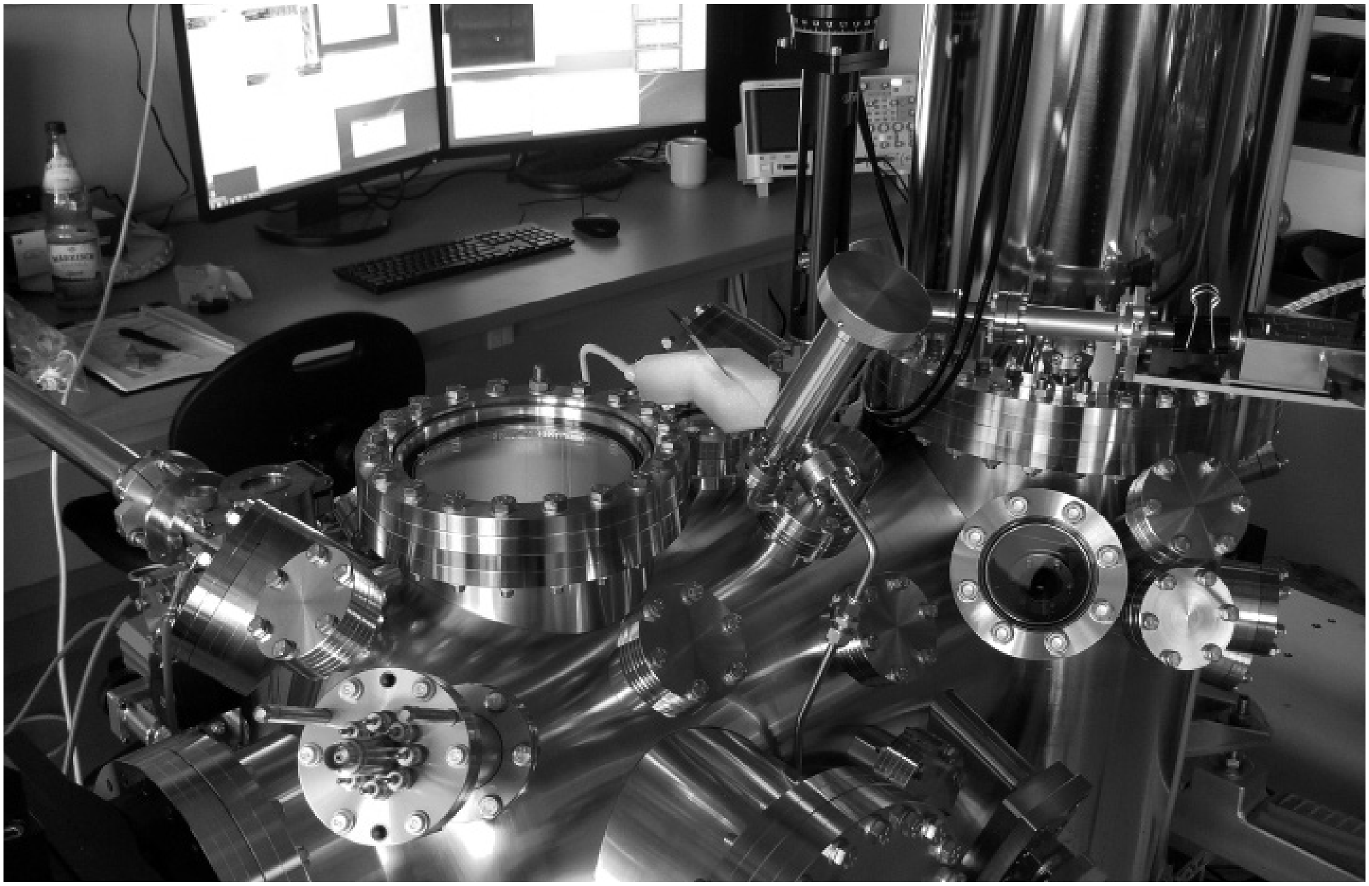


Figure 1

Randall Feenstra

Quantum Electronics
by Randall Feenstra

The Condensed Matter group within the Physics Department has, over the past decade, built up considerable expertise in the area of quantum electronics. This article discusses what is encompassed by this field of research and what's happening in the department to further this activity.

The area of quantum electronics concerns the electronic and magnetic properties of materials, which we view in terms of the various degrees of freedom of the electrons. The familiar properties of the electrons are, of course, charge and spin. The latter refers to the fact that all electrons carry a magnetic dipole moment – they are tiny magnets – with the "spin" being a way of characterizing the strength and direction of those magnetic dipoles. Magnetic moments from electrons also arise from their motion, often referred to as "orbits" for the case of motion around individual atoms, with the associated orbital angular momentum then providing a measure of these additional magnetic moments. Spin-orbit coupling is familiar to all physics students, at least for the case of isolated atoms. In solids the trajectories of the electrons are much more complex than in atoms, and the spin-orbit interaction plays a correspondingly less obvious role. It is critical, however, in many of the modern, novel phenomena associated with quantum transport in solids.

The Physics Department now has a group of five faculty members active in this area of quantum electronics. My own expertise is in the area of semiconductor materials and devices, and that of Sara Majetich is in magnetic phenomena and nanostructures. These areas of semiconductors and magnetic materials, historically somewhat separate, nicely come together in the new classes of materials and phenomena that form the core of quantum electronics. Di Xiao, a theorist hired in 2012, is an expert (and co-inventor) of the area of "valleytronics" as well as other emergent type of electronic phenomena in solids (often utilizing Berry phase). Benjamin Hunt, an experimentalist hired in 2015, is an expert in the study of atomically thin two-dimensional (2-D) materials, which he studies using electronic transport of low (milliKelvin) temperatures and high magnetic fields. Michael Widom, a theorist who has been active in many research areas including quasicrystalline materials and aspects of biological physics, is now also working in the quantum electronics area. Additionally, a search is presently underway for a further experimentalist in this area, with expertise in optical phenomena.

Experimentally, many of the existing facilities in the Condensed Matter group are now devoted to research in this Quantum Electronic area, including a facility we constructed several years ago (funded by the deans of MCS and Engineering) for preparing atomically thin 2-D materials. Additionally, in 2016 we successfully obtained a Major Research Instrumentation grant from the National Science Foundation to purchase a low-temperature scanning tunneling microscope. This instrument, pictured in Figure 1 (at the factory in Germany where it was being commissioned during July of this year), allows atomic-scale imaging and electronic studies of surfaces of materials. The low temperature (liquid helium, 4.2 Kelvin) operation of the instrument permits the study of phenomena that occur only at those temperatures, e.g., superconductivity and charge density waves. It also provides the instrument with an extraordinary degree of stability, so that sensitive and time-consuming measurements as a function of spatial location and of energy can be made of the quantum states in materials. At the time of writing, this instrument is being air shipped to Pittsburgh. A laboratory has been prepared on the first floor of Wean Hall (low vibration space) for housing the instrument. This laboratory will include a helium liquefier, relocated from another part of the department, along with other instruments that also require liquid helium for their usage. This core facility has been dubbed the "Quantum Electronics Lab," and it is hoped that further expansions in space and equipment will produce a truly unique, world-class facility in this exciting research field.

This reference to electron trajectories brings us to an additional degree of freedom of electrons, namely, the wave vector and wave function associated with the particular quantum state that they move in. For the case of semiconductors materials, these states are often located near the minimum (or "valley") of a band of states, so understanding the "valley physics," including coupling to spin, is an active research area. Finally, the concept of Berry phase plays an important role in understanding the electronic states in solids. Performing a closed line integral over a set of states (e.g., around a valley) can yield a nonzero Berry phase in certain cases, which signifies important topological properties of the states.

To provide an example of the types of phenomena that we (and other groups worldwide) study, let us consider two different ways that electrons might circulate around the edges of a piece of material. Picture a square of material, with micrometer size on each side and being very thin in the third dimension such that only a single quantum state for the electrons exists in that dimension, i.e., a 2-D electron system. It has been known for decades that such materials could be made of depositing a thin layer of a semiconductor such as gallium arsenide between thicker layers of a material with larger band gap, such as aluminum gallium arsenide. Electrons were thus constrained to reside in the "quantum well" formed in the gallium arsenide. If one then applies a large magnetic field perpendicular to this thin quantum well, the electrons will move in circular, cyclotron orbits. However, some electrons near the edges of the material move in a "skipping" type of orbit, pictured in Figure 2(a). These particular electrons then give rise to measureable conductivity that is quantized in units of $2e^2/h$, the quantum of conductance (e is the magnitude of the electron charge, and h is Planck's constant). This discovery led to a Nobel Prize for the integer Quantum Hall effect in 1985, with a further prize for the fractional Quantum Hall effect in 1998.

Now, moving to a much more recent discovery, motion of electrons along edges of a material has been found to occur even in the absence of any magnetic field, in a new class of materials known as "topological insulators" (Nobel Prize, 2016). In this case it is the fundamental symmetries of the quantum states in the material, often characterized according to their topology as given by the Berry phase and other related measures, that turns out to produce states that exist only at the edge, Figure 2(b). These states are not the same as the well-known edge states associated with e.g., broken bonds at the edge of a material (such states are "topologically trivial"), but rather, they involve an inversion in symmetry between two bands in the solid — the valence and conduction bands — which occurs due to spin-orbit interaction. This same inversion in symmetry does not exist in the vacuum, outside of the material, and hence the special edges states necessarily form between the inner part of the material and the vacuum that is outside. Developing and understanding new materials and nanostructures that may host such states is a research topic of current interest for our quantum electronics group.

Of course, one goal of the "quantum electronic" phenomena that we study is for applications. Instructive examples can be derived from Figure 2. For the integer Quantum Hall effect, Figure 2(a), the necessity for very high fields and low temperatures clearly limits its application (although it is used for a number of instruments throughout the world devoted to precise definition of "standards," i.e., for the values of e and h). However, most significantly, the very same type of gallium arsenide quantum wells used there, formed with unprecedented levels of purity and control, were utilized in "high-electron-mobility modulation-doped field effect transistors" as developed in the 1980s. These devices form a core technology for wireless communications, e.g., as used in all of our cell phones. Surely, one could not hope for a more useful and important application than this! For the newer type of topological electronic states illustrated in Figure 2(b), their application, if any, is still far off. Indeed, for many physicists, the fascination with the novel phenomena themselves often outweighs considerations as to their applicability. Nevertheless, many researchers worldwide are actively considering implementing such states in various types of devices, intended for future use in electronic circuits and systems.

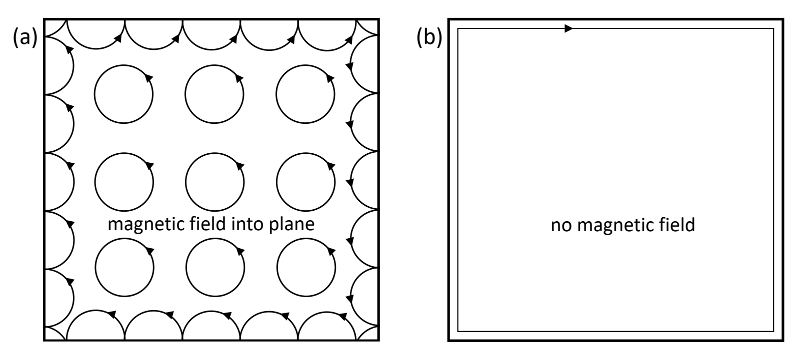


Figure 2: Schematic view of electron trajectories in (a) quantum well with applied magnetic field, and (b) topological insulator with no applied field.

From the Department Head

Scott Dodelson

To the CMU Physics Community:

Let me introduce myself by walking through an incomplete list of thank-you's.

I am so grateful to be writing to you as the new head of the Physics Department. The opportunity to sit in an office adorned with the notebook of Lincoln Wolfenstein is extraordinary. Thank you to Gregg Franklin who headed the search committee, to the MCS Dean Rebecca Doerge and to Farnam Jahanian for offering me the chance to come to this storied department and university.

Former Department Head Steve Garoff worked tirelessly over the years to provide guidance and vision to the department. Steve now gets the chance to return fulltime to research, but he remains an ever-ready source of wisdom...with e-mails starting at 4:30 a.m.! Thank you, Steve.

The undergraduate physics majors at CMU are delightful. On my first day here, they set up a telescope on campus for all to view the eclipse and the line was 100 people deep. Students can be found late at night in the hallways and classrooms working on problems, asking questions, organizing events and doing research. In my first week, I met a first-year student who was wandering the halls at 9 p.m. looking for someone to sign a piece of paper that would allow her to take a course on general relativity. Thanks to all of our students for being so enthusiastic and eager to learn.

Chuck Gitzen mans the stockroom and is in by 7:30 a.m. to set up the coffee and hot water and to spread good cheer. It's been a privilege to meet weekly with Chuck and other members of the staff as they teach me the ins and outs of everything from the registration process to when and where the donuts will be served. Thank you to Chuck, Amanda Bodnar, Patrick Carr, Heather Corcoran, Hilary Homer and Al Brunk for keeping the department running smoothly.

As you know, members of the faculty here study quanta, life and space. Thank you, Di Xiao, for pointing me to a great book to refresh my memory — after spending 30 years focused on cosmology — about quantum mechanics. The quantum electronics group here has been so generous with their time explaining their exciting plans to learn about quantum mechanics in the unexplored territory of ultra-low temperatures and high magnetic fields. Members of the sub-atomic group here are builders for experiments at JLab and CERN. Thank you for explaining to me the importance of maintaining a culture of building things. Thank you to Markus Deserno for welcoming me to his famous Plots & Scotch series of informal talks. There is no better way to learn about biophysics. It is a privilege to sit with Markus and colleagues as we try to flesh out where the big questions are in biophysics and how we are going to tackle them. The cosmology group here is second to none. Thank you to Fred Gilman for his vision in building this group.

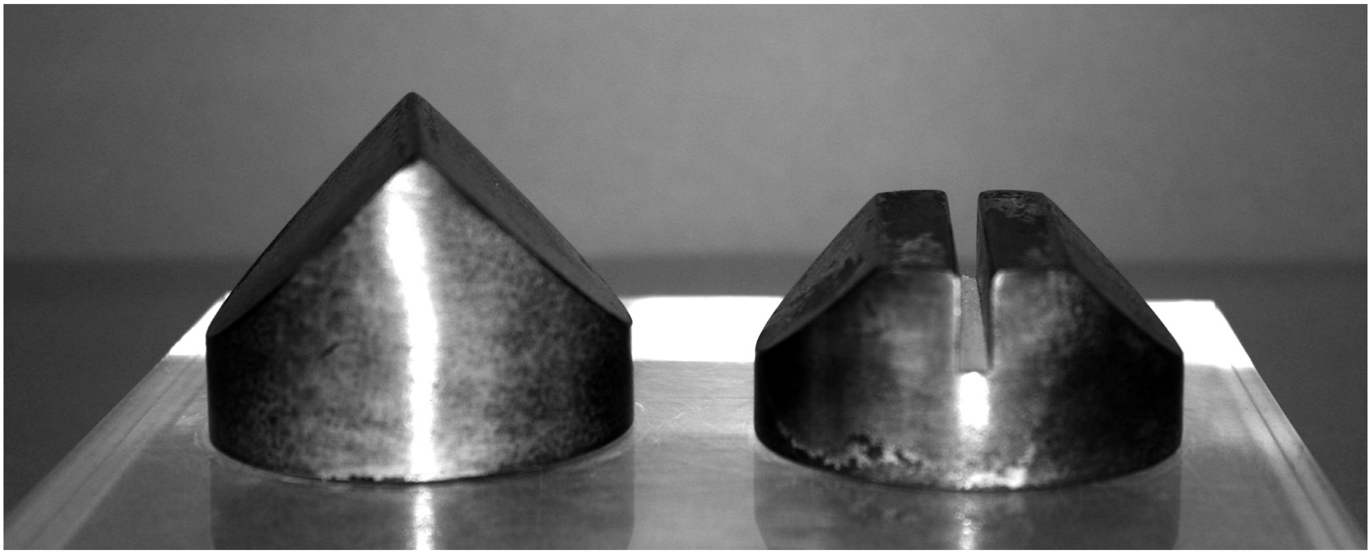
A big thank you goes to the heart and soul of the department, the graduate students. They work full time taking courses, teaching and carrying out research at the frontier of science. Yet, they have found time to start contributing as well to departmental committees. Thank you, Dacen Waters, for setting up the department's Facebook page [www.facebook.com/cmuphysics] and for the frequent posts that give our whole community a sense of the goings on in and around the department. Other graduate students are serving on the outreach, blue sky ideas (thank you Rupert Croft for chairing this one), graduate admissions and communications committees.

Physicists think, often about big ideas, and here at CMU we leverage the tools of computing and engineering to help us in our research. Postdocs in the department are often the leaders in unifying this triad of thinking, building and analyzing data. Thank you to Francois Lanusse, Danielle Leonard and other postdocs who run the biweekly meetings that bring together cosmologists with the machine learning and statistics groups. This is but one example of the interdisciplinary research that gives CMU its edge.

Finally, to those of you who spent time here in the past, the department has been blessed by your generosity. Your gifts have enabled us to support undergraduates and graduate research, to send students to conferences, to build a world-leading cosmology program in a single decade and to keep the department at the leading edge even when faced with declining funding opportunities. This one comes on behalf of all of my colleagues: thank you so much for your support. Please contact me [sdodelso@andrew.cmu.edu] if you are in town and want to talk about your experience here, quantum mechanics, cosmology, the future of physics or anything else. I would love to meet you.

Best wishes for a happy, healthy new year,

Scott



A Chapter of Carnegie Mellon Physics Department History:

Otto Stern at Carnegie Tech

Adapted from an address to the APS Division of Nuclear Physics meeting in Pittsburgh on October 27, 2017, by Professor Reinhard Schumacher (v.2, 11-8-2017)

Nuclear Magnetic Resonance (NMR) research has been a topic at Carnegie Mellon University for decades. The foundations of this technology were laid by its discovery by Isidor Rabi and others in about 1937, and further developed by Norman Ramsey and others after the end of World War II. But even before understanding NMR, it was necessary to realize that nuclei in general, and protons in particular, have both spin and a magnetic moment. The first measurements of atomic and proton magnetic moments were carried out by Otto Stern in Frankfurt and Hamburg. The famous Stern-Gerlach experiment was completed at Frankfurt in 1922 using an atomic beam of spin-one-half silver atoms. Silver atoms were sent through a non-uniform magnetic field, and were deflected before they struck a detector screen. For particles that have a magnetic moment arising in conjunction with their angular momentum, the magnetic field gradient deflects them from a straight path. The discrete points of accumulation on the detector screen, rather than the classically expected continuous distribution, was the result of the quantum nature of spin. Historically, this experiment was decisive in convincing physicists of the reality of angular momentum spatial quantization in atomic-scale systems. Rabi used a further development of Stern's molecular beam techniques to identify the magnetic resonance effect.

Now, in 1933, the grave political situation in Germany prompted the president of Carnegie Institute of Technology, Dr. Thomas Baker, to go head-hunting in Europe and to invite a number of scientists, including Otto Stern and his assistant Immanuel Estermann, to come to Carnegie Tech in Pittsburgh. The two of them joined the Physics faculty and proceeded to re-establish their molecular beam laboratory to continue their work. They brought with them all the custom-made parts of their equipment, and the university paid for large items that could be ordered commercially, such as magnets.

We have in the department a few mementos from that laboratory. The most significant one is a pair of pole-tips for a magnet used with the molecular beam work of Stern and Estermann. If you were to see this artifact, you will instantly recognize the shapes from any number of textbook diagrams you have seen of the Stern-Gerlach apparatus. One is shaped like a wedge and the other is shaped with a channel or groove. Together they produce the magnetic field gradient necessary to deflect the neutral atomic beams with non-zero magnetic moment. At first glance the pieces look like they may be the original ones used in the famous experiment, but the actual dimensions do not quite match what was reported in the original Stern-Gerlach publication. We proudly display this artifact in the Physics Instrument Museum we have on the Carnegie Mellon campus.

Otto Stern was awarded the Physics Nobel Prize in 1943, while in Pittsburgh, but he remained at Carnegie Tech not much longer. Unfortunately, starting in 1934 with an illness of President Baker, the university's strong support for his laboratory was not sustained, and the lab could never recreate the momentum of the laboratory in Hamburg. Firstly, Stern was older, and the style and professorial perquisites in doing physics at an American university were very

"Otto Stern" continued on page 6

Magnet pole tips used by Stern and Estermann in their molecular beam experiments at Carnegie Tech, *c.* 1935.

"Otto Stern" continued

different from those at a German university. Also, the physical space the lab occupied in Doherty Hall was not ideal. For example, their sensitive equipment would sometimes mysteriously go haywire. Eventually, after much consternation, Stern and Estermann found that the transmissions of a student radio club housed in the same building were the cause.

Otto Stern retired to Berkeley, California by about 1945. The molecular beam laboratory at Carnegie Tech continued for some time under the leadership of Estermann who, for example, studied the thermal velocity distribution in molecular beams. But he left to join the Office of Naval Research in 1951.

The historical and intellectual events touched upon here, starting with recognition of the nature of nuclear spin, to finding and understanding the magnetic resonance effect, to NMR-based condensed matter research, to NMR-based imaging, all have had their exponents at Carnegie Tech, or what has been known since 1967 as Carnegie Mellon University. Today, fMRI technology is producing exciting results in many fields. At the APS/DNP meeting in October 2017, recent discoveries using fMRI technology were presented about where and how the human brain encodes concepts related to physics. Psychology Professor Marcel Just showed how the human brain, which evolved initially to deal with survival by "hunting and gathering," nevertheless encodes abstract Physics concepts in a consistent way in all trained physicists.

SERGEY KOPOSOV

Give Yourself to the Dark Side

Sergey Koposov

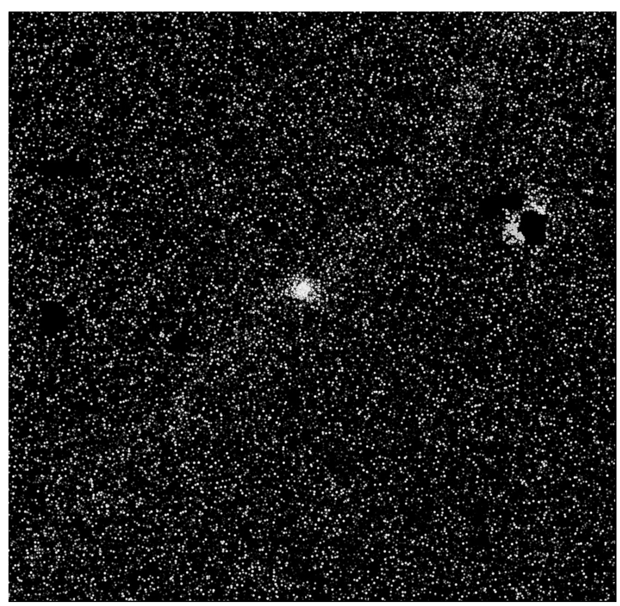
Since the middle of the 20th century, we have seen hints that the universe consists of not only ordinary (baryon) matter, but also of the so called dark matter that seems to manifest itself only through gravitational interactions.

In the last 20 years, the observations of cosmic microwave background have demonstrated unambiguously that the dark matter is indeed a major constituent of the universe that contributes about 16 percent of its energy density and is roughly 6 times more abundant than normal matter. Despite these precise measurements, we still don't know much about the properties of dark matter and what particle is responsible for it. What we do know, however, is that all the galaxies such as Milky Way and others form deep inside dark matter concentrations (halos) and that every galaxy should be surrounded by a large number of dark matter halos (clumps), some of which are completely devoid of any stars.

I, together with my research group in the McWilliams Center, am interested in understanding, detecting and measuring properties of dark matter surrounding us. One way of doing that requires looking for faint tiny dwarf galaxies that orbit around the Milky Way. These systems sometimes have barely few hundred stars and in the same time have more than 1,000 times the mass in dark matter than in stars! Dwarf galaxies allow us to trace the dark matter distribution and can be used to put strong constraints on some theoretical models of dark matter.

In the past I have used the data from large surveys of the sky such as Sloan Digital Sky Survey, Dark Energy Survey and others to find small stellar over-densities from these tiny galaxies, measure how many of them orbit the Milky Way as well as measure how much dark matter they have.

Another way of looking at dark matter around us is to use the stellar streams — streams of stars produced when a star cluster or a small galaxy is being disrupted by a tidal field of the Milky Way. The image below shows an example of such stream from a star cluster called Palomar 5 that I recently studied. These streams can tell us about the smooth dark matter distribution in the Milky Way because tidal streams approximately trace the orbits in the gravitational potential of the galaxy. Therefore when we measure velocities and 3-D positions of stars in those streams, we can constrain how dark matter is distributed around us. Finally, the streams can also tell us about very small dark matter clumps devoid of stars, as those clumps can perturb the motion of stars in the streams by creating small holes or gaps in them. So far these gaps have not yet been discovered, but the search for them is very active, as these gaps can potentially confirm or rule out the current standard cosmological model.



Astrophysics now is experiencing a very exciting period, with so much data coming from many large surveys of the sky. I am particularly very excited about one dataset that surely will revolutionize our understanding of the Milky Way and its surroundings: In April 2018 the data from the space mission called Gaia will be released and will provide positions and motions for more than a billion stars in the galaxy and will widely open many research directions including better understanding dark matter.

DIANA PARNO

Unmasking the Neutrino

Diana Parno

The neutrino is a fundamental, weakly interacting particle that still holds many secrets. For example, from neutrino flavor oscillation (the first beyond-the-Standard-Model particle interactions ever observed), we know that there are three distinct neutrino mass states, each a quantum superposition of neutrino flavor states. We've been able to measure the splittings between these mass states, but we don't know the absolute mass scale. How heavy is the lightest neutrino? Are there additional, sterile neutrino flavors that don't interact via the weak nuclear force, but that mix with the active flavors? Do other surprises await us? In my research, I use the tools of experimental nuclear physics to investigate these questions.

Neutrino Mass

The neutrino mass scale has a profound impact on both particle theory and cosmology. The incredible lightness of neutrinos (the electron is at least 250,000 times heavier than the heaviest neutrino mass state), combined with the experimental evidence that neutrinos are left-handed, means that it is difficult to generate neutrino mass via the Higgs mechanism. An extension to the Standard Model is needed.

At the same time, neutrino mass is one of the few cosmological observables that can also be studied in the laboratory. Individual neutrinos are light, but the collective mass of the neutrinos created in the early universe had a significant effect on the way that structures formed, leaving a signature in cosmological data.

The best laboratory limits, with the least model dependence, have come from precision measurements of tritium beta decay. Tritium (hydrogen-3) decays into a ^{3}He nucleus, an electron, and an electron antineutrino. The mass difference between the tritium nucleus and its ^{3}He and electron children is almost all converted into the kinetic energy of the products — but the neutrino mass represents energy that the beta electron cannot carry away.

The KATRIN experiment in Karlsruhe, Germany, will measure the high-energy tail of the tritium beta spectrum to detect the signature of that neutrino mass, with a sensitivity down to 0.2 eV/c^2 (at 90% confidence). Along the way, we will also search for sterile neutrinos and other beyond-the-Standard-Model phenomena. We are currently commissioning our apparatus to make sure that we understand it completely before we begin taking tritium data in summer 2018. It is a technically and scientifically challenging task: KATRIN's precision must be 100 times better than its predecessor experiments.

With my group and other KATRIN colleagues, I am working to understand our experimental backgrounds, characterize the apparatus via an injected ^{83m}Kr calibration source, assure the quality of the data that we acquire, and maintain the main KATRIN detector system. I am also studying the molecular physics of KATRIN's tritium source — which carries the largest single systematic uncertainty in the experiment –through a dedicated experiment, TRIMS, in Seattle. TRIMS is a time-of-flight mass spectrometer that will measure the probability that the ^{3}HeT^{+} molecule remains bound following the decay of its T_2 parent, addressing a major discrepancy between modern theoretical predictions and experimental measurements from the 1950s. In previous work with colleagues, I found that uncertainty about these molecular final states will have an even larger effect on KATRIN than previously thought, making this measurement all the more important.

Neutrino Interactions

Neutrinos are famously difficult to detect. One of the highest-probability neutrino interactions with matter, coherent elastic neutrino-nucleus scattering (CEvNS), went undetected for more than 40 years after it was first predicted — even though it is critically important in both supernova dynamics and next-generation WIMP dark-matter detection. The experimental challenge is that one must detect a tiny recoil imparted to the nucleus, like the recoil of a bowling ball that has been hit by a ping-pong ball.

This past summer, the COHERENT collaboration published the first-ever measurement of CEvNS in a cesium iodide detector at Oak Ridge National Laboratory in Tennessee. With this milestone reached, we can now test the Standard Model by measuring the probability of this interaction in different types of detectors, with different target nuclei (including argon, sodium iodide and germanium). I am working on the simulation that predicts the neutrino flux through these COHERENT detectors, which will become more important as our measurements grow more precise.

The neutrino has already surprised us many times, teaching us about the Standard Model on the way. I am looking forward to learning more from this fascinating particle.

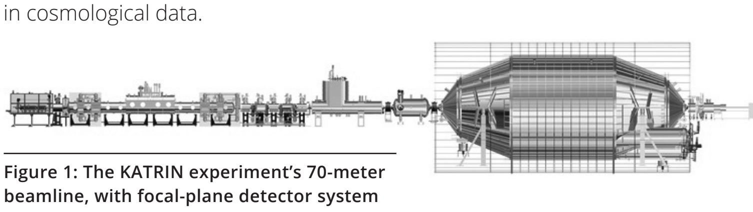


Figure 1: The KATRIN experiment's 70-meter beamline, with focal-plane detector system at the far right.

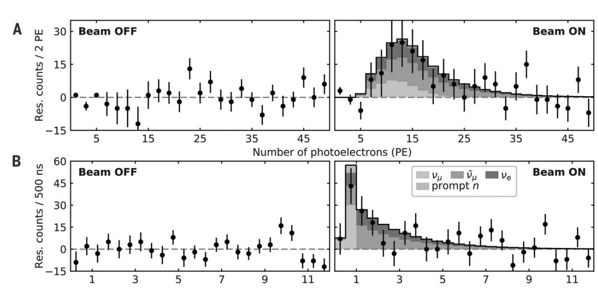


Figure 2: [Image credit: Akimov et al., Science). Observation of CEvNS. Each data point is a residual difference between CsI signals in a 12-us window after a beam trigger, and a 12-us window before, as a function of their (top) energy and (bottom) arrival time. Errors are statistical.

Undergraduate Research

Vineetha Bheemarasetty

Junior; double major in materials science engineering and applied physics

For the past three semesters I have been involved in a research project with professor Randall Feenstra of the Physics Department at Carnegie Mellon University. The topic of my research is on the emergence of moiré patterns in tunneling field effect transistors (TFETs) consisting of the two-dimensional heterostructure system MoS_2 – WSe_2. As a double major in Materials Science Engineering and Applied Physics, I was drawn to Professor Feenstra's area of research and pursued the opportunity. At the start of my sophomore year I was selected to receive funding from the Semiconductor Research Corporation through the SRC-URO program. My project is also supported by NSF, DARPA and STARnet programs.

As part of this ongoing research experience, I explore novel ways of studying the moiré pattern phenomenon in TFET devices. This phenomenon takes away substantially from the current flow and makes such tunneling semiconductor devices less efficient. My work focuses on these limitations in the current flow and the impact moiré patterns have on the efficacy in different types of electronic applications. In addition to Professor Feenstra, I work with Yifan Nie, a Ph.D. student at the University of Texas in Dallas, who performs numerous DFT calculations and sends me resultant data for analysis. I have developed a MATLAB code to quantitatively model the corrugation plot that results due to the in plane strains and interlayer interaction energies within such 2-D systems that takes this raw data as input.

Throughout this endeavor, I have gained a deeper insight into the research process and how to present my results to fellow colleagues, professionals in the field, as well as to the scientific community at large. I expect to publish my findings in a formal paper later this year.

Derek Hamersly

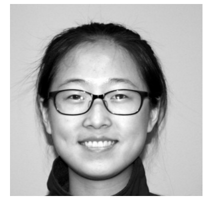
Junior; double degree in piano performance and physics

During the summer of 2017, I assisted Professor Brian Quinn in his medium-energy research on campus. I was very fortunate to be funded by the Michael McQuade Research Scholarship. Professor Quinn works with a research team at Jefferson Lab focused mainly on learning more about the structure of the neutron, such as its electric and magnetic form factors. Before the electron accelerator is turned on, they need to run calibrations to make sure all the equipment is working properly. Preparing for these calibrations was the focus of my work.

In the experiment, photoelectrons will travel through a large array of iron shielding before reaching the detectors, and it will be important to be able to accurately quantify the number of photoelectrons that reach these detectors. My co-worker, Thomas Wong, and I used LEDs to simulate photoelectrons, and we mounted 400 micron diameter optical fibers in small holes near these LEDs to carry the emitted light to the detectors. We spent most of our time testing various techniques of inserting these fibers into these holes, striving to optimize light transmission from the LEDs to the detectors.

Work was frustrating: the optical fibers were very easily damaged, the LED pulser circuits often malfunctioned (usually because of shorts), and we had to work in near-darkness to make sure not to damage the extremely light-sensitive detectors (photomultiplier tubes). But there were fun parts too, like when I tried to do statistical analysis to determine whether the LEDs were off-center by fitting measurements to a theoretical model I derived.

There is still more work that must be done to further refine calibration techniques. The many experimental skills I learned over this summer — the most noteworthy being various methods of statistical analysis, a deeper understanding of the scientific method, and better technical communication skills — will surely benefit me in future research situations.



Irene Li

Junior; double major in materials science engineering and applied physics

In 2017 summer, I did research in computational biophysics on campus. My research adviser was Professor Michael Widom and my research was funded half from Prof. Widom's DOE grant and half from the Michael McQuade Research Scholarship.

My research was focused on the secondary structure of RNA — a molecule with long chains of nucleotides. The list of base-pairings decides the secondary structure of RNA, which plays an important role in RNA's biological functions and behaviors. My work involved adding a new feature to a software package called ViennaRNA. Developed by the University of Vienna's Theoretical Biochemistry Group, ViennaRNA is one of several software packages aimed at predicting the secondary structure of RNA.

My goal was to modify one specific program *Kinfold*, which simulates the folding dynamics of an RNA molecule, but it didn't allow the forming of pseudoknots (interleaving base-pairings in RNA). My task was to enable the existence of pseudoknots in the dynamic folding process. To do that, I had to modify the data structure of RNA sequence. In *Kinfold*, RNA sequence was represented as a ring-list tree data structure, which greatly facilitates the addition and deletion of base-pairings in the folding process. I modified the data structure by constructing two ring-list trees, each of which contains a subset of the base pairings and there are no pseudoknots within the tree itself. Then I built connections between the two trees so that they can share information with each other and work consistently.

From my summer experience, I became better at extracting information from research papers and I also acquired a deeper understanding of data structure. Now *Kinfold* is capable of predicting the folding dynamics with pseudoknots. But there still exist problems with the energy functions and thus the output of *Kinfold* is not very accurate. The problems need to be resolved later.

Commencement 2017

DOCTOR OF PHILOSOPHY IN PHYSICS

Shadab Alam (August 2016)
Thesis: Mysteries of Universe Imprinted on Redshifts
Advisor: Shirley Ho

Sergio De La Barrera (August 2016)
Thesis: Layered Two-Dimensional Heterostructures and Their Tunneling Characteristics
Advisor: Randall Feenstra

Krista Freeman (August 2017)
Thesis: Viral DNA Retention and Ejection Controlled by Capsid Stability
Advisor: Alex Evilevitch

Arun Kannawadi Jayaraman (December 2016)
Thesis: Systematic effects in realistic image simulations for future Weak Lensing surveys
Advisor: Rachel Mandelbaum

Paul LaPlante (December 2016)
Thesis: Large-Scale Simulations of Hydrogen and Helium Reionization
Advisor: Hy Trac

Zachary A. McDargh (August 2017)
Thesis: Geometry, Mechanics and Biology: Applications for Membranes and Filaments
Advisor: Markus Deserno

Samuel Oberdick (December 2016)
Thesis: Patterned Magnetic Structures via Directed Assembly of Nanoparticles and E-Beam Lithography
Advisor: Sara Majetich

Melih Ozbek
Thesis: Large scale 3D Mapping of the Intergalactic Medium with the Lyman-Alpha Forest Using Hydrodynamic Simulations and SDSS-III BOSS DR12
Advisor: Rupert Croft

Stephan K. Piotrowski (August 2016)
Thesis: Characterization of Magnetersistive Nanostructures Using Conductive Atomic Force Microscopy
Advisor: Sara Majetich

Nikhil Sivadas (August 2016)
Thesis: First Principles and Wannier Functions Based Study of Two-Dimensional Electronic Systems
Advisor: Di Xiao

Nora Swisher (August 2016)
Thesis: Data Analysis of Rayleigh-Taylor Unstable Flows
Advisor: Snezhana Abarzhi

Venkatasatya (Ananth) Tenneti (December 2016)
Thesis: Cosmological Simulation Studies of the Intrinsic Alignment of Galaxies
Advisors: Tiziana DiMatteo, Rachel Mandelbaum

Varun Pradeep Vaidya (August 2016)
Thesis: Exploring New Physics via Higgs Cascade
Advisor: Ira Rothstein

Xin Wang
Thesis: Elasticity of Lipid Membrane Leaflets: Determining Pivotal Plane and Tilt Modulus in Computer Simulations
Advisor: Markus Deserno

MASTER OF SCIENCE IN PHYSICS

Ruairi Brett
Amirali Hossein
Gregory Houchins
Hung-Jin Huang
Christopher Kervick
Hao Li
Chien-Hao Lin
He Liu
Dennis J. Michalak
Alexander G. Moskowitz
Bradley David Parks
Yufeng Shen

UNDERGRADUATE HONORS

Kathryn E. Andenoro
College Honors

Robert Buarque de Macedo
University Honors
College Honors
Phi Kappa Phi

Joshua D. Fuhrman
University Honors

Yiwen Huang
University Honors

Hyunho Jeon
University Honors
College Honors
Phi Kappa Phi

David Last
University Honors
College Honors
Phi Beta Kappa
Phi Kappa Phi

Stephanie L. O'Neil
University Honors
College Honors
Phi Beta Kappa
Phi Kappa Phi

Christian B. Pederson
University Honors

Zun Yi Brent Tan
University Honors
College Honors
Phi Beta Kappa
Phi Kappa Phi

Jianwei Zhang
University Honors

UNDERGRADUATE DEGREES

Bachelor of Arts in Physics (August 2017)

Stefan A. Cuevas

Ji Yun Kwon

Bachelor of Arts in Physics, Minor in Computer Science

Siddhant Madhuk

Suresh R. Manian

Bachelor of Science in Physics

Robert A. Buarque de Macedo
Lu Feng
Nicholas W. Goman
Yiwen Huang
Patrick E. Nichols
Isabella Mary Pagano
Christian B. Pederson
Adrian Relic (December 2016)
Alexander P. Roman
Adam K. Williams

Bachelor of Science in Physics/Applied Physics Track

John C. Pyun

Jianwei Zhang

Bachelor of Science in Physics/Astrophysics Track

Savas J. Kalafatides

Max E. McHugh

Zun Yi Brent Tan

Bachelor of Science in Physics/Biological Physics Track

Kathryn E. andenoro

Bachelor of Science in Physics/Computational Physics Track (December 2017)

Xuekai Du

Bachelor of Science in Physics/Computational Physics Track, Minor in Computer Science

William R. Howard Matchen

Bachelor of Science and Arts in Physics and Music Composition

David Last

Bachelor of Science in Physics and Mathematics

Hyunho Jeon

Bachelor of Science in Electrical and Computer Engineering, Additional Major in Physics (December 2016)

Peter Pearson

Bachelor of Science Mechanical Engineering, Additional Major in Physics

Joshua D. Fuhrman

Bachelor of Science in Computer Science and Physics

Evan L. Numbers

Bachelor of Science in Physics/Astrophysics Track, Bachelor of Arts in Creative Writing

Stephanie L. O'Neil

Bachelor of Science in Physics/Applied Physics Track, Bachelor of Fine Arts in Drama

Chris S. Norville

MINORS IN PHYSICS

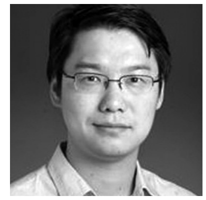
Preetam Amancharla
Andrew D. Benson
Nathaniel M. Biggs
Andrew N. Butko
Andrew C. Dewey
Yau-Yu Lee
Cheul Young Park

Departmental News

PROMOTIONS

Frank Heinrich
promoted to Associate Research Professor

Shirley Ho
promoted to Associate Professor with Indefinite Tenure



Di Xiao
promoted to Associate Professor with Indefinite Tenure

FACULTY RECOGNITIONS

David Anderson
Julius Ashkin Teaching Award

Ben Hunt
DOE Early Career Award

Manfred Paulini
elected Fellow of the American Physical Society

Fred Gilman
re-elected Chair of the AURA Management Council for the Large Synoptic Survey Telescope

Leonard Kisslinger
Carnegie Science Award

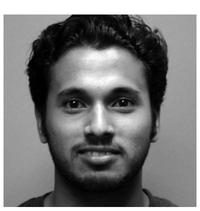
Reinhard Schumacher
Chair, Local Oprganizing Committee, 2017 American Physical Society, Division of Nuclear Physics Annual Meeting, Pittsburgh

Kunal Ghosh
Teaching Innovation Award (as part of the MCS First Year Seminar Committee)

Sara Majetich
elected Fellow of the IEEE Magnetics Society; Co-Chair, 2018 Intermag Conference, Singapore

Di Xiao
Cottrell Scholar

GRADUATE HONORS AND AWARDS



Aklant Bhowmick
Peoples Presidential Fellow

Krista Freeman
Cleveland State Alumni Award; Chair, Executive Committee, APS Forum on Graduate Student Affairs

Michelle Ntampaka
McWilliams Presidential Fellow

Sergio de la Barrera
McQuade Fellow

Alex Moskowitz
Pake Presidential Fellow

Siddharth Satpathy
MCS Hugh D. Young Graduate Student Teaching Award

RETIREMENTS

Robert Swendsen

UNDERGRADUATE HONORS AND AWARDS

Stephanie O'Neil
Andrew Carnegie Society Scholar; Fugassi and Monteverde Award; Richard E. Cutkosky Award

Riley Xu
Honorable Mention, Goldwater Scholarship; Andrew Carnegie Society Scholar

SPECIAL EVENTS

2017 Buhl Lecture — William Bialek, John Archibald Wheeler/Battelle Professor in Physics at Princeton University, "The Physics of Life: How Much Can We Calculate?", Mellon Institute Auditorium, March 13, 2017

2017 APS DNP Annual Meeting — hosted by the Physics Department, Pittsburgh, October 25 – 28, 2017 (Reinhard Schumacher, Chair, Local Organizing Committee)

2017 Bennett-McWilliams Lecture — Dan Akerib, Professor of Particle Physics and Astrophysics, Stanford University, "Do WIMPS rule? The Search for Cosmic Dark Matter" Rashid Auditorium, October 26, 2017

ALUMNI NOTES

Congratulations to **Lawrence R. Sulak** (B.S. in physics from CMU, 1966). Now at Boston University, Sulak received the 2018 W.K.H. Panofsky Prize in Experimental Particle Physics "for novel contributions to detection techniques, including pioneering developments for massive water Cherenkov detectors that led to major advances in nucleon decay and neutrino oscillation physics."

Congratulations to **Eric Dahl** (B.S. in physics from CMU, 2002). Now at Northwestern University/Fermilab, Dahl received the 2018 Henry Primakoff Award for Early-Career Particle Physics "for fundamental contributions to the development of new techniques for the direct detection of dark matter, including the bubble chamber and xenon time projection chamber."

STUDENT TESTIMONIES ON GIVING

ISABELLE GOLDSTEIN

I am a senior in the undergraduate physics program. Some of the most valuable experiences I've had as a student would not have been possible without the help of the department. Starting from freshman year, I've found opportunities to work with professors and grants that allowed me to stay over the summer and do so. With the professor's guidance, I also applied to and attended two cosmology conferences, which expanded my knowledge of the field and understanding of current research. This gave me the chance to attend conference lectures, present my own work and begin building connections. The department's invaluable infrastructure for undergraduates encouraged my growth as a researcher and my confidence in representing Carnegie Mellon to the larger field of astrophysics and cosmology.

JOANNE HSUEH

As a physics undergraduate, I am fortunate enough to be supported by my department at CMU. It has allowed me to explore my options and experience new things. Thanks to the Physics Department, Astronomy Club has been able to go to Green Bank Observatory almost every year since 2012. Seeing a dark sky full of stars never fails to amaze me or my fellow club members. In addition, the department's support has helped the Women in Science club find our bearings and allowed us to hold different events, such as talks about the Nobel Prize Winners, which are open to the whole community.

OLIVIA ZHIYAO LI

The Physics Department informed me about the Conference for Undergraduate Women in Physics at Princeton and funded my trip. It was an amazing experience. I got the chance to attend workshops on REU programs, graduate school and career development, which gave me a big and yet detailed picture of a future in science. I also listened to inspiring presentations that exposed me to current topics in physics and raised my awareness about diversity and gender issues in science. After the conference, I joined the CMU Women in Science Club to help promote equality in science and support females and minorities.

I felt a sense of belonging when I hung out with other attendants from our shared passion in physics. It was a great opportunity to bond with people whom I'll probably encounter in my future career path.

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Physics

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INTERACTIONS

Interactions is published yearly by the Department of Physics at Carnegie Mellon University for its students, alumni and friends to inform them about the department and serve as a channel of communication for our community. Readers with comments or questions are urged to send them to Interactions, Department of Physics, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, PA 15213-3890. Fax to 412-681-0648 or phone 412-268-2740. The Department of Physics is headed by Scott Dodelson. The web address is cmu.edu/physics.

Produced by the Marketing & Communications Department and the Physics Department, November 2017. 18-186