

## INTRODUCTION

Research in physics at Stanford is driven by many of the 21<sup>st</sup>-century questions about the physical world that will extend our view of the universe on all scales.\*

- How did the Universe form, how has it evolved and what are its constituents?
- What are the mechanisms that control the formation and evolution of astrophysical objects such as stars, galaxies, black holes, neutron stars and supernovae?
- What is the fundamental nature of dark matter and dark energy?
- How do particles acquire mass?
- Can quantum mechanics and gravity be unified?
- Are there new spatial dimensions?
- What does the quantum world look like at the level of a single atom or molecule?
- How does a simple quantum system interact with its environment?
- How can quantum mechanics be used to test basic physical principles or build practical sensors?
- How do systems change at temperatures close to absolute zero?
- How do complex systems give rise to novel properties not intrinsic to the individual components?
- How is the function of biomolecules related to their atomic structure?

These are some of the questions addressed by the faculty, students and scientific staff in the Physics Department at Stanford University in collaboration with colleagues in many other departments, including the Particle Physics and Astrophysics and Photon Science Departments at the Stanford Linear Accelerator Center, the Applied Physics and Biological Sciences Departments, and departments in the School of Engineering. These are some of the questions addressed by the faculty, students and scientific staff in the Physics Department at Stanford University. They work in collaboration with colleagues in many other departments, including the Particle Physics and Astrophysics and Photon Science Departments at the Stanford Linear Accelerator Center, the Applied Physics and Biological Sciences Departments, and departments in the School of Engineering. In these pages, you will discover the intellectual questions that inspire and motivate physicists at Stanford. You will learn about the environment in which this research thrives. And along the way, you will be introduced to some of the individuals and achievements that mark the history of the Department. If you would like to learn more about the Physics Department at Stanford, please consult our website at <http://www.stanford.edu/dept/physics> or phone (650) 723-4344.

### **The Physics Department in the 20<sup>th</sup> Century**

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\* The color of the bullet for each question matches the color of the corresponding research area shown in the schematic overview of physics at Stanford on the opposite page.

Stanford University opened in 1891, with the Department of Physics among the very first departments at the new University. By the early 1900s, research on X-rays had begun, first under the direction of David Webster, and later under Paul Kirkpatrick. When Swiss physicist Felix Bloch arrived in 1934, physics research at Stanford truly became a key area of research at Stanford. Bloch was only 28 years old when he joined the Stanford faculty, but he had already made extraordinary contributions to physics: the theory of electron transport in metallic crystals, the Bethe-Bloch equation of the stopping power of fast particles in matter, the theory of ferromagnetism, including the invention of spin waves and domain (Bloch) walls. Soon after he arrived at Stanford, Bloch, together with Berkeley physicist Robert Oppenheimer, organized a joint seminar on theoretical physics that met alternately at Stanford and Berkeley. By the mid-1930s, Stanford was recognized as an important center for physics.

In 1938, Bloch, in collaboration with Luis Alvarez, made the first experimental measurement of the magnetic moment of the neutron, marking the beginning of the work for which he is perhaps best known. By the end of World War II, Bloch, with William Hansen and Martin Packard, succeeded in observing nuclear magnetic resonance (NMR) by the method of nuclear induction. For these discoveries, Bloch shared the 1952 Nobel Prize in Physics with Harvard's Edward Purcell. It was Stanford's first Nobel Prize in any field. NMR has since become a crucial spectroscopic technique in chemistry and biology; magnetic resonance imaging (MRI), an imaging technique based upon it, is considered the greatest advance in medical imaging since the discovery of X-rays in 1895.

In the late 1930s, the Varian brothers, Russell and Sigurd, working in collaboration with Professor Hansen, invented the klystron, a high-power microwave source and amplifier. The klystron was rapidly developed during World War II for use in radar, navigation, and blind-landing devices for aircraft. Hansen, however, was interested in using the klystron for the acceleration of particles. By 1947, he had built the first linear electron accelerator, which accelerated electrons to 6 MeV. Just four years later, Edward Ginzton and Marvin Chodorow completed a 1-GeV electron accelerator that allowed Robert Hofstadter to study the charge and magnetic structure of nuclei and nucleons, work that earned him the 1961 Nobel Prize in Physics.

### **Stanford Linear Accelerator Center**

By 1967, the Stanford Linear Accelerator Center (SLAC), a national facility with a new two-mile accelerator, was completed and running. The founding Director, Wolfgang K.H. Panofsky, also played a key role in shaping the government's science and nuclear policies and went on to win the National Medal of Science in 1969 and the U.S. Department of Energy's Enrico Fermi Award in 1979. In 1976, Stanford's Burton Richter shared the Nobel Prize for the discovery of the charm quark. In 1988, Mel Schwartz, a long-time member of the department, shared the Nobel Prize for his discovery of the muon neutrino (work done at Brookhaven). In 1990, Richard Taylor shared the Nobel Prize for his SLAC-based studies of deep inelastic scattering that indicated the existence of quarks. In

1995, Martin Perl (another member of the SLAC faculty) won the Nobel Prize for his discovery of a new elementary particle known as the tau lepton.

In the past several years, SLAC's mission has changed significantly and now includes both particle astrophysics and cosmology (through the Kavli Institute for Particle Astrophysics and Cosmology, which is joint with the Physics Department), and photon science.

### **Quantum Mechanics and Leonard Schiff**

Leonard Schiff's 1949 book on Quantum Mechanics inspired several generations of physicists who learned this subject. Schiff became department chair in 1948. He and Bloch formed a departmental appointments committee that brought many outstanding new faculty to Stanford, including a nuclear-physics program under Stanley Hanna and Walter Meyerhof and a low-temperature program under Bill Fairbank and Bill Little.

### **Optics and Laser Spectroscopy**

Art Schawlow joined the Stanford faculty shortly after he invented the laser in 1958, in collaboration with Charles Townes at Bell Laboratories. Ted Hänsch and Schawlow pioneered the development of Doppler-free high-precision spectroscopy and other powerful laser techniques that have made possible new and fundamental studies of atomic and molecular systems. In 1981 Schawlow shared the Nobel Prize for the discovery of these new techniques in laser spectroscopy. Steve Chu, who won the Nobel Prize in 1997, took these optical techniques to yet another level with "optical molasses" (the cooling of particles in a light field to microkelvin temperatures), the laser trapping of atoms, and the development of optical tweezers for biological experiments. Subsequently, Hänsch shared the 2005 Nobel Prize, largely for work initiated at Stanford.

### **Condensed Matter Physics**

Condensed matter physics at Stanford is led by a groundbreaking group of faculty. Robert Laughlin shared the 1998 Nobel Prize for his explanation of the quantum and fractional quantum Hall effects. Doug Osheroff, the 1996 co-recipient of the Nobel Prize in Physics for his discovery of superfluidity in  $^3\text{He}$ , is a leading experimentalist in the area of quantum solids and fluids and other properties of matter of temperatures very close to absolute zero.

## **RESEARCH INTERESTS**

The faculty in the Physics Department tackle many of the leading edge questions in physics. The focus of each faculty member's research is summarized here, grouped according to research area.

### **ASTROPHYSICS, PARTICLE ASTROPHYSICS AND COSMOLOGY**

**Tom Abel – Associate Professor**

### ***What were the first objects that formed in the Universe?***

Professor Abel's group explores the first billion years of cosmic history using *ab initio* supercomputer calculations. He has shown from first principles that the very first luminous objects are very massive stars and has developed novel numerical algorithms using adaptive-mesh-refinement simulations that capture over 14 orders of magnitude in length and time scales. He currently continues his work on the first stars and first galaxies and their role in chemical enrichment and cosmological reionization. His group studies any of the first objects to form in the universe: first stars, first supernovae, first HII regions, first magnetic fields, first heavy elements, first galaxies, and so on.

Tom Abel also heads the KIPAC computational physics department [http://www-group.slac.stanford.edu/kipac/comp\\_physics.htm](http://www-group.slac.stanford.edu/kipac/comp_physics.htm), which provides super-computing resources and algorithmic advice to members of KIPAC.

### ***Other interests include:***

- Galaxy formation
- Cosmic genesis of magnetic fields
- Super-massive black holes
- Present day star formation
- Relativistic hydrodynamics
- Astrophysical plasmas

### **Steven Allen - Assistant Professor**

#### ***What is the physics of galaxy clusters? What can we learn about the Universe from galaxy clusters?***

Professor Allen's research examines the physics of galaxy clusters using the best available X-ray and other multi-wavelength data. He uses the observed properties of clusters to probe the nature of dark matter, the weakly interacting yet dominant matter component of the Universe, and dark energy, the driving force behind cosmic acceleration.

Intrigued by why the largest galaxies are not as bright as theory predicts, Allen's team showed that supermassive black holes are likely responsible for the suppression of star formation, pumping out huge amounts of energy from the hearts of galaxies in the form of relativistic jets, fueled by the hot, surrounding gas. Research continues on the 'duty-cycle' of black hole heating, the accretion process, jet formation and black hole growth.

Allen has been involved in the construction and utilization of some of the most powerful X-ray cluster catalogs ever made, including the ROSAT Brightest Cluster Sample, the Extended Brightest Cluster Sample and the Massive Cluster Survey. His research group

is currently carrying out detailed multi-wavelength follow-up of the sources in these catalogs, including deep gravitational lensing studies, optical imaging and spectroscopy, and infrared and radio observations.

### **Roger Blandford – Luke Blossom Professor in the School of Humanities & Sciences**

#### *How is Einstein's theory of relativity relevant to astrophysics and cosmology?*

Professor Blandford works primarily as a theorist studying explosions and particles that move with speeds close to that of light and the strange properties of relativistic objects like black holes and neutron stars. He is also very interested in the structure and evolution of the Universe at large and astronomical approaches to understanding the properties of dark energy and dark matter empirically.

#### *Current Areas of Focus:*

- Gravitational lenses
- Cosmic jets
- Supernova remnants
- Measuring the Universe

### **Blas Cabrera – Professor**

#### *What is the identity of dark matter in our Universe?*

Professor Cabrera's group sends detectors deep underground in the Soudan Mine in northern Minnesota to search for evidence of weakly interacting massive particles, or WIMPs. If WIMPs are the dark matter, they forced the formation of structure in our Universe and they are responsible for the formation of galaxies, of solar systems and of life. Working on an international project called the Cryogenic Dark Matter Search (CDMS II), Professor Cabrera and colleagues from 12 other institutions seek to determine whether WIMPs make up the unidentified portion of the Universe referred to as dark matter. Their search is the major effort in the United States, and is the most sensitive experiment of its kind in the world.

#### **Other interests include:**

- Superconducting Quantum Interference Devices (SQUIDS)
- Laser-operated superconducting switches
- The Cooper pair mass in a superconductor
- The absolute nature of the Bohm-Aharonov effect
- The pinning force experienced by a single trapped vortex in a superconductor

## **Sarah Church - Associate Professor**

### ***What happened after the Big Bang?***

Professor Church's group builds instrumentation to observe small fluctuations in the faint glow from the Universe called the Cosmic Microwave Background (CMB). By studying the CMB, it is possible to test current understanding of the laws of physics in the extreme conditions that occurred in the first few moments after the Big Bang. The group uses telescopes at some of the best sites in the world for millimeter-wavelength astronomy, including the South Pole, the Chilean Andes, and Mauna Kea in Hawaii.

### ***Areas of focus:***

- Sunyaev-Zeldovich effect
- CMB anisotropies
- Bolometric techniques

## **Stefan Funk – Assistant Professor**

### ***How are particles accelerated to ultra-relativistic energies in astrophysical sources? What are the highest photon energies emitted by astrophysical particle accelerators?***

Professor Funk's research focuses on high-energy astrophysics to investigate how particles are accelerated in violent astrophysical sources such as Supernova remnants or Pulsar Wind nebulae. By studying the universe using high-energy photons from X-ray to gamma-rays spanning more than 11 decades in energies, it is possible to test current understanding of the acceleration of charged particles such as protons or electrons in the most energetic objects in our Universe. Stefan Funk's research utilizes data from satellite missions such as the GLAST-LAT instrument as well as from ground-based Cherenkov telescopes, such as the H.E.S.S. telescope system in southern Africa.

### ***Areas of focus:***

- Study of gamma-ray emission from Supernova remnants and Pulsar wind nebulae
- Understanding particle acceleration in astrophysical objects
- Investigation of the origin of cosmic rays
- Identification strategies of gamma-ray sources through multi-frequency observations at radio or X-rays frequencies
- Design and planning of a future international gamma-ray instrument

## **Steven Kahn - Cassius Lamb Kirk Professor in the Natural Sciences**

### ***How did the structure of the Universe evolve with cosmic time?***

Professor Kahn is the Deputy Director of the Large Synoptic Survey Telescope (LSST), a large-aperture wide-field telescope that is under development to survey half the sky every

few nights. LSST will detect over three billion galaxies, providing detailed measurements of their redshifts, shapes, and properties. Through a technique called *weak gravitational lensing*, these data can be used to map out the structure of dark matter in the Universe, and how that structure has evolved with cosmic time. The results will provide very sensitive constraints on the nature of dark matter and dark energy. LSST will also provide crucial data on the structure of the outer regions of the Milky Way, make a census of moving objects in the solar system, and discover transient phenomena in the Universe on a wide range of timescales.

***Other interests include:***

- X-ray spectroscopic observations of cosmic sources
- Atomic physics measurements of highly charged ions relevant to astrophysical plasmas
- Development of space and ground-based instrumentation

**Chao-Lin Kuo, Assistant Professor**

***How did the Universe begin?***

Professor Kuo's group seeks to answer this profound question by studying the most ancient light, the Cosmic Microwave Background (CMB) radiation, emitted when the Universe was in its infancy.

Professor Kuo is involved in both the cosmological interpretation and instrumentation/technology development. The group frequently adopts advanced experimental techniques, such as cryogenics, superconductivity, and micromachining, to maximize detector sensitivity to the faint CMB signal.

***Ongoing projects:***

- BICEP/SPUD: a South-Pole based multi-telescope observatory that will carry out deep surveys of the CMB polarization.
- SPIDER: a NASA long-duration balloon flight that will produce polarized CMB maps over large sky area with wide frequency coverage.

**Peter F. Michelson — Professor**

***What are the mechanisms that generate high-energy particles and radiation in the Universe? How and when do massive black holes form? What is the nature of dark matter?***

Professor Michelson is the lead investigator of an international team that has designed and constructed the next generation of space-based high-energy gamma-ray telescope.

GLAST will be launched into space in early 2008 and will carry out the most sensitive survey of the cosmos ever done in the energy band from 20 MeV to more than 300 GeV.

Professor Michelson and his research group have been studying the nature of the mysterious high-energy gamma-ray sources discovered by EGRET. These studies require observing sources across the electromagnetic spectrum with other ground and space-based observatories. Sources include neutron stars and stellar-mass black holes in our galaxy, supermassive black holes in active galaxies, and diffuse radiation, a component of which may be generated by the decays of dark matter particles. During the next several years, major progress in understanding is expected to come with GLAST data.

### **Vahe Petrosian – Professor**

*How do things evolve in the Universe? How are particles accelerated in the Universe?*

Professor Petrosian's research covers many topics in the broad area of theoretical astrophysics and cosmology, with a strong focus on high energy astrophysical processes.

Cosmological studies deal with global properties of the universe and the focus of the research here is the Universe at high redshifts, the evolution of galaxies and quasars or active galactic nuclei, arcs in clusters of galaxies, and gravitational lensing.

High energy astrophysics research involves interpretation of nonthermal astronomical sources where particles are accelerated at high energies and emit various kinds of radiation. These processes occur on many scales and in all sorts of objects: in the magnetosphere of planets, in the interplanetary space, during solar and stellar flares, in the accretion disks and jets around stellar size and supermassive black holes at centers of galaxies, in gamma-ray bursts, in supernovae, and in the intra-cluster medium of clusters of galaxies. Plasma physics processes common in all these sources for acceleration of particles and their radiative signature is the main focus of the research here.

### **Roger W. Romani - Professor**

*What are the physical conditions around compact objects? How do they accelerate particles to the highest energies seen?*

Professor Romani is interested in the physics of the most extreme objects in the observable Universe - neutron stars and black holes - where density, gravitational field and, often, magnetic field reach their maximum measured values. His group makes observations of such objects, using premiere telescopes on the ground and in space, and constructs theoretical models to interpret the remarkable behaviors seen. One particular interest is studying how black holes and neutron stars accelerate particles to energies much higher than those yet produced on Earth and how they generate relativistic outflows in the form of winds and jets.

***Other interests include:***

- Populations of gamma-ray sources
- The origin and evolution of radio pulsars
- Supernovae and their products
- Instrumentation for fast optical variability
- Pulsar timing and gravity wave searches

**Risa Wechsler - Assistant Professor**

***How did structure form in the Universe? How do galaxies form and how can they be used to understand the nature of dark matter and dark energy?***

Professor Wechsler uses theoretical models and massive numerical simulations to understand how quantum fluctuations in the early Universe develop into the galaxies and structures of galaxies that we see today. Most of this work is conducted in the context of the Cold Dark Matter model for structure formation, which predicts that galaxies and galaxy clusters were built up from smaller galaxies that collided and merged. Professor Wechsler's work has recently concentrated on understanding the connection between this cold dark matter, which is thought to comprise about 85% of the mass in the Universe, and the visible light that can be detected by telescopes.

Professor Wechsler also works with observers to help interpret the results of large galaxy surveys. She has recently worked with the Sloan Digital Sky Survey to create the largest existing sample of galaxy groups and clusters, which is being used to study galaxy evolution and constrain cosmological parameters. She is also a member of the Dark Energy Survey and the Large Synoptic Survey Telescope project, two upcoming galaxy surveys that will together map billions of galaxies over the entire sky. Her theoretical work with these surveys will be crucial for interpreting the observations and using them to test the current cosmological paradigm.

**EXPERIMENTAL ATOMIC, MOLECULAR AND OPTICAL PHYSICS**

**Phil Bucksbaum – Professor**

***How can we study atomic and molecular processes at the shortest relevant time scales? What can we learn about atomic motion and molecular bonds with these tools?***

Professor Bucksbaum studies time-dependent quantum processes in atoms and molecules, from the passage of electrons across atoms in a few hundred attoseconds (billionths of a billionth of a second), to the bending and breaking of molecular bonds during collisions or chemical reactions in a few picoseconds (millionths of a millionth of a second). These observations are made using novel laser sources, some of which are unique to Stanford. The world's first X-ray free electron laser at the Stanford Linear Accelerator Center

(SLAC), which will begin to operate in 2009, will allow us to view atomic motion on the atomic time scale for the first time.

**Steven Chu — Professor (on leave)**

*What does the quantum world look like on the level of a single atom or molecule? What can this teach us about Nature, from the fundamental particles through the subtleties of many-body physics to the vast complexities of biophysics?*

Professor Chu utilizes the interactions of light and matter as versatile tools to cool and trap single atoms and molecules, and to manipulate them with extraordinary precision. His research interests range from precision measurements at the basis of fundamental laws of physics, to polymers and biophysics.

**Atomic physics:** Current research includes experiments with Bose-Einstein condensed atoms in rotating optical microtraps and the development of large-area atom interferometry based on high-order Bragg diffraction for tests of fundamental properties of the Standard Model of particle physics.

**Polymer physics:** The group explores polymer dynamics by imaging individual molecules of DNA to study polymer solutions, polymer brushes, and vesicles.

**Biophysics:** The current research involves the development and use of atomic force microscopy, optical tweezers and single-molecule fluorescence techniques to study protein dynamics, protein-protein interactions, and signal transport at the single molecular level.

**Mark Kasevich - Professor**

*How can we control and exploit the quantum properties of atoms and photons?*

Professor Kasevich's current research interests are centered on the development of quantum sensors of rotation and acceleration based on cold atoms (quantum metrology), the application of these sensors to tests of General Relativity, the investigation of many-body quantum effects in Bose-condensed vapors (including quantum simulation), and the investigation of ultra-fast laser-induced phenomena.

**EXPERIMENTAL PARTICLE PHYSICS**

**Patricia Burchat - Gabilan Professor of Physics**

*What is the Universe made of? What are the laws of physics that govern the fundamental constituents of the Universe?*

Professor Burchat has been a key player in a number of accelerator-based particle physics experiments that probe these fundamental questions. She has recently worked with the BABAR experiment, which studies differences in the time evolution of matter and

antimatter, as well as the production and decay of particles such as heavy quarks and leptons.

Using astronomical observations of gravitational lensing (the bending of light by matter), Professor Burchat investigates the distribution of dark matter in the Universe and the nature of dark energy. She is analyzing images from the Subaru telescope in Hawaii to measure the masses of clusters of galaxies.

Professor Burchat is also a member of the Large Synoptic Survey Telescope (LSST) project, a ground-based telescope that will map the entire sky every few nights over the course of a decade. The LSST will provide a wealth of information about the content and evolution of the Universe.

### **Giorgio Gratta - Professor**

#### ***What are the properties of neutrinos and what is their role in the Universe?***

Professor Gratta's research includes experimental studies of neutrino properties with the KamLAND and the EXO (Enriched Xenon Observatory) experiments. KamLAND is an ultra-long baseline neutrino oscillation experiment that uses nuclear reactors as neutrino sources. In their first paper (December, 2002) KamLAND reported the first observation of neutrino oscillations from an experiment using artificially produced neutrinos. Neutrino oscillations occur because neutrino masses are non-zero. KamLAND is now performing precision measurements of neutrino oscillation parameters and, in 2005, produced the first measurement of global uranium and thorium content of the Earth, using the neutrinos that they emit.

While neutrino oscillations have demonstrated that neutrino masses are non-zero, the phenomenon of "neutrino-less double-beta decay" will likely establish the scale for neutrino masses over the next several years. The EXO project, led by the Stanford group, is commissioning a first double-beta decay experiment in a deep underground site in New Mexico while, at the same time, developing the tools for a much larger and more sensitive future detector. EXO detectors study the decays of the isotope 136 of xenon and, in the larger version, will identify the individual barium atoms resulting from the decay of the xenon atoms. Techniques borrowed from particle and nuclear physics, AMO and surface science are being brought together in these detectors.

In a separate effort, the group is also investigating the possibility that neutrinos are a component of the mysterious ultra-high-energy cosmic rays that some groups claim to have detected.

### **Stanley Wojcicki – Professor**

#### ***What is the nature of neutrinos?***

Professor Wojcicki's research program focuses on understanding the properties of

neutrinos. Neutrinos are fundamental constituents of nature, and until recently, were believed to have zero mass. Recent experiments, first in Japan, provided evidence that neutrinos do have mass, albeit very tiny masses - much lower than that of other fundamental particles, such as the electron.

The main focus of Professor Wojcicki's current program is the MINOS (Main Injector Neutrino Oscillation Search) experiment. Neutrinos are produced at the Fermi National Accelerator Laboratory near Chicago, and detected in a former iron mine in Soudan, MN, after traveling some 735 km through the earth. As neutrinos travel, they change (oscillate) from one type to another. Studies of these oscillations provide information about neutrino properties.

Longer range, Professor Wojcicki's focus will be the NOvA experiment, which will also study neutrino oscillations from Fermilab to Minnesota, but will use a new detector in a different location. The goal is to eventually look for matter-antimatter asymmetries in neutrino interactions; some theories predict that this may hold the clue to the predominance of matter in our Universe.

***Areas of interest:***

- Precise measurement of oscillation parameters in dominant modes
- Search for subdominant oscillation modes
- Comparison of neutrino and anti-neutrino interactions

**THEORETICAL PARTICLE PHYSICS**

**Savas Dimopoulos -- Professor**

***What is the origin of mass? Are there other universes with different physical laws?***

Professor Dimopoulos has been searching for answers to some of the deepest mysteries of Nature. Why is gravity so weak? Do elementary particles have substructure? What is the origin of mass? Are there new dimensions? Can we produce black holes in the lab? Are there other universes with different physical laws?

Elementary particle physics is entering a spectacular new era in which experiments at the Large Hadron Collider at CERN will soon shed light on such questions and lead to a new deeper theory of particle physics, replacing the Standard Model proposed forty years ago. The two leading candidates for new theories are the Supersymmetric Standard Model and theories with Large Extra Dimensions, both proposed by Professor Dimopoulos and collaborators.

Professor Dimopoulos is collaborating on a number of experiments that use the dramatic advances in atom interferometry to do fundamental physics. These include testing Einstein's theory of general relativity to fifteen-decimal precision, atom neutrality to thirty decimals, and looking for modifications of quantum mechanics. He is also

designing an atom-interferometric gravity-wave detector that will allow us to look at the Universe with gravity waves instead of light, marking the dawn of gravity wave astronomy and cosmology.

### **Shamit Kachru - Professor**

*What are the microscopic underpinnings of our laws of nature? Can they be understood as arising from geometry and topology alone?*

Professor Kachru studies string theory, a theoretical framework that unifies gravity and quantum mechanics. String theories have extra dimensions of space-time, and the laws of physics we see in four dimensions depend on the geometry and topology of these extra dimensions. Professor Kachru and his collaborators focus on techniques to find geometries that can produce the late-time cosmic acceleration and early-Universe cosmic inflation that are indicated by current experiments. His group also develops methods to perform exact computations relevant for particle-physics model building, using techniques from algebraic geometry. He is interested in finding intrinsically "stringy" phenomena or concrete string models that can help to explain the mysteries of the current Standard Model of particle physics.

#### *Areas of focus:*

- Stringy modifications of geometry and topology
- String dualities and exact results
- Models of dynamical supersymmetry breaking
- Inflation and string cosmology

### **Renata Kallosh – Professor**

*What is the mathematical structure of string theory and its relation to cosmology?*

Professor Kallosh works on the general structure of string theory, supergravity and supersymmetry. She studies cosmological consequences of these theories and their implications for the theory of black holes. Her main interests are related to the models of vacuum stabilization and inflation in string theory. She develops string theory models explaining the origin of the Universe and its current acceleration. With her collaborators, she is analyzing possible consequences of the expected new data from the Large Hadron Collider (LHC) and the results of the future cosmological observations. These results may affect the relationship between superstring theory and supergravity, and the real world. Professor Kallosh works, in particular, on future tests of string theory by CMB data and on the relation between the gravitino mass and the amplitude of the gravitational waves produced during inflation.

#### *Areas of focus:*

- String theory and inflation

- String theory and dark energy
- Stabilization of moduli in string theory
- Black hole attractors
- Finiteness issue of N=8 supergravity

**Andrei Linde — Professor**

***What is the origin and the global structure of the Universe?***

For a long time, scientists believed that our Universe was born in the Big Bang, as an expanding ball of fire. This scenario dramatically changed during the last 25 years. Now we think that initially the Universe was rapidly inflating, being in an unstable energetic vacuum-like state. It became hot only later, when this vacuum-like state decayed. Quantum fluctuations produced during inflation are responsible for galaxy formation. In some places, these quantum fluctuations are so large that they can produce new rapidly expanding parts of the Universe. This process makes the Universe immortal and transforms it into a multiverse, a huge fractal consisting of many exponentially large parts with different laws of low-energy physics operating in each of them.

Professor Linde is one of the authors of inflationary theory and of the theory of an eternal inflationary multiverse. He continues his work in this direction, with a special emphasis on the cosmological implications of string theory.

**Stephen Shenker — Richard Herschel Weiland Professor in the School of Humanities & Sciences**

***How can ideas from nonperturbative approaches to quantum gravity be applied to cosmology and the interiors of black holes?***

Professor Shenker's research focuses on string theory and M theory, with an emphasis on nonperturbative aspects, including matrix formulations.

**Eva Silverstein - Professor**

***What are the basic degrees of freedom underlying gravitational and particle physics? Why is spacetime curvature so small relative to the other scales in nature?***

Professor Silverstein develops mechanisms for breaking supersymmetry and for stabilizing the extra dimensions of string theory to model the immense hierarchies between the cosmological horizon, electroweak, and Planck scales in nature. In addition, Professor Silverstein uses the ultraviolet completion of gravity afforded by string theory to attack questions of quantum gravity, such as singularity resolution and the physics of black hole and cosmological horizons.

***Ongoing research includes:***

- Models of de Sitter expansion in string theory

- A novel field-theoretic mechanism for inflation which is observationally falsifiable on the basis of its non-linear effects in the cosmic microwave background
- Mechanisms by which the extra degrees of freedom in string theory -- specifically, strings stretched around topologically nontrivial circles in generic spatial geometries -- induce transitions between spaces of different topology and dimensionality
- A simple mechanism for supersymmetry breaking that stabilizes the weak hierarchy with relatively few additional degrees of freedom

**Leonard Susskind — Felix Bloch Professor of Physics**

*What does quantum gravity tell us about black holes, information and the Universe?*

Professor Susskind's current research interests include particle physics, quantum field theory, quantum gravity, black holes, string theory and cosmology.

**CONDENSED MATTER PHYSICS**

**David Goldhaber-Gordon — Assistant Professor**

*How do electrons organize themselves on the nanoscale?*

We know that electrons are charged particles, and hence repel each other; yet in common metals like copper billions of electrons have plenty of room to maneuver and seem to move independently, taking no notice of each other. Professor Goldhaber-Gordon studies how electrons behave when they are instead confined to tiny structures, such as wires only tens of atoms wide. When constrained in this way, electrons cannot easily avoid each other, and interactions strongly affect their organization and flow. The Goldhaber-Gordon group uses advanced fabrication techniques to confine electrons to semiconductor nanostructures, to extend our understanding of quantum mechanics of interacting particles, and to provide the basic science that will shape possible designs for future transistors. The Goldhaber-Gordon group makes measurements using cryogenics, precision electrical measurements, and novel scanning probe techniques that allow direct spatial mapping of electron organization and flow. For some of their measurements of exotic quantum states, they cool electrons to twelve thousandths of a degree above absolute zero, the world record for electrons in semiconductor nanostructures.

*Other interests include:*

- How does a simple quantum system interact with its environment? Why isn't quantum mechanics manifest in everyday life?
- Building model systems in semiconductor nanostructures: engineering "designer Hamiltonians" for comparison with exotic theoretical models.
- Electrons in carbon nanomaterials – nanotubes and graphene – where they behave in some ways like light rather than electrons.

- Measuring and manipulating electron spins.
- Quantum coherence and entanglement of wavefunctions.

### **Hari Manoharan - Assistant Professor**

***What new science and technologies lurk at the smallest scales of condensed matter?  
How does physics change in lower dimensions?***

Throughout history, humans have sought to expand their mastery of the material world. The ability to manipulate matter has been continuously refined, extending to constructions of colossal size and extreme complexity. Progress in the diametric direction of diminishing scale has proved increasingly vital to society. Well-known contemporary examples include the microelectronic and biotechnology industries. The efforts within these fields rely predominantly on new tools that extend control and measurements to progressively smaller length scales.

Instead of this "top-down" approach, what if one proceeds from the bottom and works up? For the first time, we are poised to explore critical science starting from the basic building blocks of matter. Professor Manoharan seeks to apply the "bottom-up" approach of atomic and molecular manipulation to a variety of outstanding problems in science and technology. The primary experimental apparatus for these investigations are custom-built scanning probe microscopes capable of both studying and controlling matter at or below the nanometer length scale.

#### ***Research interests:***

- Scanning tunneling microscopy and spectroscopy
- Nano-assembly using atomic and molecular manipulation
- Single quanta physics
- Spin-charge manipulation
- Local probes of electrons in reduced dimensions
- Collective excitations in complex materials and superconductors
- Exploring nanoscale paradigms in computation
- Atomic and molecular electronics
- Carbon-based nanotechnology

### **Kathryn Moler - Associate Professor**

***How does quantum decoherence occur? What is the correct theoretical description of strongly correlated electron materials?***

The goal of Professor Moler's research is to answer these two questions about the fundamental behavior of electrons in materials. In the next five years, her focus will be:

- to create a toolbox of sensitive, quantitative, high-resolution local magnetic sensors, enabling routine and noninvasive characterization of small magnetic

- fields in novel quantum materials, and to share the designs for these tools with other scientists;
- to conduct a systematic survey of the energetics and dynamics of individual quanta of magnetic flux in various superconductors, to elucidate the mechanism of superconductivity;
  - to conduct a systematic survey of persistent currents in mesoscopic normal metals and superconductors, to understand the mechanisms of quantum decoherence in electronic systems, and
  - to educate a group of creative and highly skilled graduate and undergraduate students.

**Douglas Osheroff — J. G. Jackson and C. J. Wood Professor of Physics**

*What is the order near absolute zero?*

Professor Osheroff studies the nature of order that exists in systems close to absolute zero temperature. This includes ordering in both liquid and solid  $^3\text{He}$ , where three unconventional BCS (superfluid) states and two nuclear spin antiferromagnetic states are known to exist. Issues such as how impurities can affect the BCS states and what sort of magnetic defects might occur in the ordered solid phases are typical of studies undertaken. In addition, Professor Osheroff's group also studies some of the most highly disordered systems at ultra-low temperatures – glasses -- many properties of which are dominated by active two-level tunneling defects, even within 1 mK of absolute zero.

*Typical studies undertaken:*

- New superfluid states stabilized by impurities
- How the phase transition between the two superfluid phases is nucleated in the bulk and on surfaces
- Spin-wave heat flow in the U2D2 nuclear anti-ferromagnetic phase of solid  $^3\text{He}$
- Spin dynamics of the U2D2 nuclear antiferromagnet
- Magnetic domain wall motion and solid-liquid boundary motion in the U2D2 solid-superfluid system
- Interactions between thermally active tunneling systems in glasses, and their response to swept electric fields and magnetic fields

**Zhi-Xun Shen - Paul Pigott Professor in the Physical Sciences**

*What is the nature of quantum matter? How does complexity give rise to unusual and extreme properties?*

Professor Shen conducts fundamental and applied research on quantum matter. His primary interest is the physics of “many,” where interactions among multiple constituencies give rise to novel properties not intrinsic to the individual components. He sends electromagnetic waves to probe matter, including X-ray, ultra-violet, laser, and

microwave radiation. Insights are gained through precision analysis of ejected particles, either photons or electrons.

***Other interests include:***

- High temperature superconductors
- Strongly correlated and magnetic materials
- Nano-structured Carbon
- X-ray techniques and novel light sources
- Modern photoelectron spectroscopy – energy, momentum, spin and time resolution
- Laser and microwave spectroscopy and imaging
- Application of novel materials

**THEORETICAL CONDENSED MATTER PHYSICS**

**Sebastian Doniach - Professor**

***How is the function of biomolecules in living systems related to their atomic structure?***

Professor Doniach's research group uses scattering of synchrotron X-rays from electron storage rings at SLAC and at the Argonne National Laboratory to study changes in conformation of molecules as their solvent environments are changed. The research also involves computer simulations of the dynamics and energetics of the resulting changes.

Recent advances in the biology of DNA have shown that a very large part of the genome in eukaryotes codes for small RNA molecules that appear to be central to the way the genes (coding for proteins) are put together. Doniach's group is currently studying structural changes that occur when some small functional RNAs turn on and off gene expression (riboswitches) without needing to involve protein transcription factors. Understanding RNA control mechanisms is central to our ability to intervene in biological functions such as generation of biofuels by bacteria or of intervention when cells start to go cancerous.

The Doniach group's bio-simulation work involves new ways to represent changes in molecular structure, in which the entire trajectory for a change of conformation is represented in a large number of CPUs where each time slice of the trajectory is managed by one of the CPUs. In this way, a representation of changes involving thousands of degrees of freedom may be obtained at atomic resolution. This method has recently been applied to look at protein misfolding. Another project involves using a highly simplified normal mode representation to represent large scale conformational changes in molecular motor molecules and DNA polymerase. The group is also working on ways to improve the methods of computing the statistical mechanics of counter-ion shielding of the very large Coulomb forces engendered by the phosphate backbones of DNA and RNA. Software has been developed that modifies the solving of the Poisson Boltzmann equation to include the effects of finite ion size. Further modifications are being worked on to include effects of ion-ion correlations.

***Other interests include:***

- Membrane proteins
- Protein aggregation in diseases such as Parkinson's and Alzheimer's
- Topics in the dynamics of many-particle systems including condensed matter systems

**Aharon Kapitulnik - Professor**

***What happens to an electron-system when interactions dominate? What is the role of disorder in such systems?***

Professor Kapitulnik studies materials with novel electronic states at low temperatures. The research concentrates on the occurrence and properties of superconductivity, charge-density, or magnetic states in such systems. The group uses a variety of measurements and novel probes such as scanning tunneling microscopy and spectroscopy and high-resolution magneto-optics.

***Is the  $1/R^2$  law of gravitational force true at all length scales?***

A variety of recent theories of physics beyond the Standard Model would, if true, lead to deviations from Newtonian gravity on experimentally accessible length scales. To detect or constrain such deviations, we have constructed two experiments, both with cantilever-based probes, to directly measure the force between two masses separated by tens of microns. Our apparatus include novel solutions to experimental challenges culminating in detection capability of forces at the range of attonewton ( $10^{-18}$ ) strength.

***Other interests include:***

- Physics of disordered systems
- Superconductivity
- Thin films and physics of low-dimensional systems
- Vortex physics

**Steven Kivelson – Professor**

***How do the interactions between the vastly many electrons in solids produce the emergent phenomena we recognize as the macroscopic behavior of the materials we encounter in everyday life, and in the exotic materials and devices we engineer in the laboratory?***

The central source of intellectual vitality and practical importance of condensed matter physics is the richness and diversity of behaviors exhibited by strongly interacting systems with many degrees of freedom, ranging from the collective behavior of neurons in the brain to the collective condensation of Cooper pairs that produces the macroscopic

quantum phenomena associated with superconducting order. The main thrust of the research carried out by Professor Kivelson is the search for theoretical characterization of qualitatively new behaviors of interacting electrons (*i.e.*, new states of matter) as well as new regimes of parameters in which familiar states of matter behave in new and different ways. In particular, he seeks to explore, qualitatively, the relation between the microscopic interactions between electrons and the effective parameters that control the macroscopic behavior of solids.

**Robert B. Laughlin - Anne T. and Robert M. Bass Professor in the School of Humanities and Sciences**

***Where does physical law come from?***

As our experimental understanding of nature has matured, we have come to realize just how artificial the distinction is between fundamental physical law - something that "just is" - and other kinds of physical law that "emerge" through self-organization. Everyday examples of the latter include material rigidity, magnetism and superfluidity, but there are countless others. Things become more troubling, however, when we realize that the vacuum of space-time also has symptoms of being emergent. "Fundamental" quantities such as the electron charge defocus and change value as you examine the vacuum at smaller and smaller length scales. Unification of forces becomes mathematically indistinguishable from "quantum phase transitions" of the vacuum. Heats of formation and other collective effects in the vacuum become implicated in inflationary theories of the Universe. We are increasingly realizing that finding law -- a quantitative relationship among measured quantities that is always true -- is not the same thing as finding fundamental truth. Indeed, when you measure only at "low" energies, you simply cannot tell the difference between a law that emerges and a law that "just is".

Professor Laughlin is a theorist with interests ranging from hard-core engineering to cosmology. He is an expert in semiconductors (Nobel Prize 1998) and has also worked on plasma and nuclear physics issues related to fusion and nuclear-pumped X-ray lasers. His technical work at the moment focuses on "correlated-electron" phenomenology - working backward from experimental properties of materials to infer the presence (or not) of new kinds of quantum self-organization. He recently proposed that all Mott insulators - including the notorious doped ones that exhibit high-temperature superconductivity - are plagued by a new kind of subsidiary order called "orbital antiferromagnetism" that is difficult to detect directly. He is also the author of *A Different Universe*, a lay-accessible book explaining emergent law.

**Shoucheng Zhang – Professor**

***Can states of matter take other forms besides the three familiar ones, namely gas, liquid and solid?***

Indeed, laws of quantum mechanics predict many other interesting states of matter; for example, states displaying superconductivity and the quantum Hall effect. Professor

Zhang's group investigates the quantum physics of many interacting electrons. Recently, his group predicted a new electronic state that displays the quantum spin Hall effect without any external magnetic fields. This effect has been subsequently observed experimentally. Beyond the fundamental importance of new states of matter, electronic circuits operating on these new principles could also offer alternatives to the current semiconductor chips, and extend the reach of Moore's law.

*Other interests include:*

- High temperature superconductivity
- Quantum spintronics
- Quantum Spin Hall effect
- Magnetism

### **EXPERIMENTAL CONDENSED MATTER PHYSICS AND GRAVITATIONAL PHYSICS**

**John Lipa — Professor (Research)**

*Does the renormalization group theory fully represent the behavior of second order phase transitions, or is a deeper theory needed? And what is the nature of the supersolid state of matter recently reported at very low temperatures?*

Experiments on the ground and in space are used to study the superfluid transition of liquid helium, allowing vastly improved tests of the renormalization group theory. Both static and dynamic properties are investigated by Professor Lipa's group. The apparent supersolid behavior is currently being explored using torsion oscillator techniques and plans are being made for a search for a fountain pressure effect, analogous to that in superfluid helium-4, but much smaller in magnitude.

*What are the laws that govern the interplay of time and space?*

In special relativity, Einstein derived the Lorentz transformations by assuming the constancy of the speed of light. But experimentalists must ask the question: are there small but non-zero violations of the Lorentz transformations that can be detected? In the case of hypothetical Lorentz-violating extensions to the Standard Model, it has been argued that effects might be seen at the 1 part in  $10^{17}$  level. Superconducting cavities are being developed for use in high stability microwave oscillators for frequency comparison experiments that would be performed as a function of orientation and velocity relative to the cosmic microwave background.

### **SOLAR PHYSICS**

**Philip H. Scherrer — Professor (Research)**

*What is the structure and dynamics of the interior of the sun, and how do they affect solar activity?*

Professor Scherrer does research on the nature and evolution of solar activity and its effects on terrestrial systems. His group's primary emphasis is on the structure and dynamics of the solar interior using techniques of helioseismology. The primary observations from space have been with the Michelson Doppler Imager instrument on the Solar and Heliospheric Observatory mission (since 1995). His group is developing a Helioseismic and Magnetic Imager instrument for the Solar Dynamics Observatory, with an expected launch in 2008. His group also studies solar magnetic fields from space and from the ground using the Wilcox Solar Observatory at Stanford, which has been operating since 1975.

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**EMERITUS FACULTY:**

**Alexander Fetter — Professor (Emeritus)**

Theoretical Condensed Matter Physics

What happens to a dilute gas at ultra-low temperature (1 microK or colder)? Quantum mechanics plays an essential role in answering this question. For bosons (one of two types of particles or atoms), the gas can form a single coherent state (the condensate) with a macroscopic wave function analogous to the coherent laser state for photons (light).

Questions of current interest to Professor Fetter include collective modes of the condensate, creation and stability of vortices and vortex lattices, the limit of rapid rotations, and persistent currents in multiply connected geometries.

**Stanley S. Hanna — Professor (Emeritus)**

Experimental Nuclear Physics

Professor Hanna's interests include nuclear structure, giant resonances, polarization of nuclear radiations, lifetimes of nuclear states, resonance absorption and fluorescence, analogue states, nuclear moments, heavy ion reactions, weak interactions, electron scattering, intermediate energy physics, hyperfine interactions, positron polarization, and Mossbauer effect.

**William A. Little — Professor (Emeritus)**

Experimental Condensed Matter Physics

Professor Little's research focuses on the theoretical and experimental study of the basic science of superconductivity of organic, metal-organic, and high temperature ceramic superconductors, with a particular focus on understanding the mechanism responsible for the pairing interaction in each of these systems, using innovative optical and electrical techniques. This work usually involves the preparation, characterization and experimental study of such materials over a wide range of temperatures. The work in the group is characterized by an involvement of each student in both theoretical and experimental

work. Other research involves the study of neural networks using methods of statistical mechanics, and the study of novel cryogenic cooling techniques.

**David M. Ritson — Professor (Emeritus)**

Experimental Particle Physics, Experimental Accelerator Physics

Professor Ritson's interests are in experimental particle physics, accelerator physics, and climate change research.

**H. Alan Schwettman — Professor (Emeritus)**

Experimental Accelerator Physics and Laser Physics

Professor Schwettman's research activity is focused on the development of optical techniques that exploit the unique capabilities of the Free Electron Laser (FEL) in materials and biomedical research. At the Stanford FEL Center the large investment in optical and electronic instrumentation makes it possible to support a broad and sophisticated scientific program that offers very special opportunities for graduate student research. Examples of optical capabilities include picosecond pump-probe and photon echo experiments for studies of liquids, glasses, proteins, and semiconductors, cavity ringdown experiments for spectroscopy of very thin films and dilute gases, and infrared near-field microscopy for imaging single living cells.

**Todd Smith — Professor (Research, Emeritus)**

Experimental Accelerator Physics and Laser Physics

Professor Smith's accelerator physics interests lie mainly in the areas of the production, diagnosis and utilization of high brightness electron beams. Such beams (high density in 6-D phase space) are critical to progress in high-energy physics colliding beam experiments and in the development of X-ray Free-Electron Lasers. Presently, the ability to measure electron beam parameters (position, size, angular spread, pulse length, energy spread, etc.) with sufficient precision is limiting progress; some of the work involves studying new ways of making these measurements. The experimental program is carried out on the Superconducting Linear Accelerator in the W.W. Hansen Experimental Physics Laboratory on the main campus at Stanford. The Superconducting Accelerator was used in the invention of the Free-Electron Laser (FEL), and is now an integral part of the Stanford Free-Electron Laser Center. At the Center, his group not only studies the physics of FELs, but makes the infra-red and far infra-red (from 4 microns to 100 microns) optical beams produced by our FELs available to researchers in all fields. They have an elaborate complex of rooms and equipment utilized by physicists, chemists, materials scientists, and biologists for sophisticated optical experiments that make use of the FEL's unique properties (wavelength, pulse structure, and power).

**John Turneure — Professor (Research, Emeritus)**

Experimental Gravitational Physics and Precision Measurement

Professor Turneure's research interests are in the areas of experimental general relativity and precision measurements. His group worked on the development of a satellite-based test of general relativity. This is done by measuring the geodetic and frame-dragging precessions of gyroscopes in earth polar orbit with an accuracy of better than 0.5 milli-arcsec/year. The gyroscopes operate at 2.5 kelvin and are read out using a superconducting quantum interference device magnetometer, which detects the London moment of the spinning superconducting gyroscope. The gyroscope spin direction is measured with respect to a guide star using a star tracking telescope, also operated at 2.5 kelvin.

**Robert V. Wagoner — Professor (Emeritus)**

Theoretical Astrophysics

Professor Wagoner studies oscillations of accretion disks surrounding black holes and neutron stars, and other signatures of strong gravitational fields. Other interests include theories of gravitation, physics of the early Universe, gravitational lensing, cosmological distance indicators, and sources of gravitational waves.

**J. Dirk Walecka— Professor (Emeritus)**

Theoretical Particle Physics

Professor Walecka has made fundamental contributions to our understanding of the nucleus as a relativistic quantum many-body system, and provides theoretical guidance on exploiting electromagnetic and weak-interaction probes of the nucleus. After leaving Stanford in 1987, he became the Scientific Director of CEBAF, the Continuous Electron Beam Accelerator Facility (now the Thomas Jefferson National Accelerator Facility). Professor Walecka has authored a number of textbooks, including three that he co-authored with Professor Alexander Fetter: "Quantum Theory of Many-Particle Systems," "Theoretical Mechanics of Particles and Continua," and "Nonlinear Mechanics: A Supplement to Theoretical Mechanics of Particles and Continua."

**Mason Yearian — Professor (Emeritus)**

Experimental Particle Astrophysics

Professor Yearian's past research includes developing detectors for X-ray and gamma-ray astronomy, and work on the GRO/EGRET experiments. He also developed a computer-based curriculum for teaching introductory physics courses in high schools and universities.

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**UNDERGRADUATE PROGRAM**

How did Einstein derive  $E = mc^2$ , and how did Heisenberg come up with the Uncertainty Principle? Why are lasers capable of creating the coldest temperatures in the Universe, right here on earth? What's the difference between dark matter and dark energy, and what's the evidence for each? The study of physics will lead to answers to these and many other intriguing questions.

Aside from gaining a deeper understanding of these interesting concepts, what can one do with a degree in physics after college? The study of physics provides a broad knowledge of the basic principles underlying all of the sciences, and teaches one how to critically analyze and solve problems in almost any situation. For many students, an undergraduate degree in physics prepares them for graduate study and then a research and/or academic career in universities, government research labs or private industry. A physics background can also lead to entry into almost any technical field. Physics graduates may enter fields such as biology, chemistry, geophysics, statistics/applied math and any branch of engineering, as well as medicine, law and education.

The Physics Department helps facilitate the entry of undergraduates into research groups. Most physics majors work in a group for at least part of their undergraduate career. Students work directly with faculty in Physics, as well as in Applied Physics, Electrical Engineering, Mechanical Engineering, Biological Sciences/Biophysics/Medicine, Materials Science, and at SLAC (Stanford Linear Accelerator Center). Our department's Summer Research Program gives every physics major the opportunity for at least one summer of funded laboratory research on campus.

The Stanford Society of Physics Students (SPS) provides opportunities for social and academic interactions among students, and between students and faculty. The SPS sponsors faculty noon-time seminars presented at the undergraduate level. Past activities have included faculty/student social gatherings, including movie nights, laser tag, Ultimate Frisbee matches, trips to the beach, to the Great American Amusement park, and to the Lick Observatory. The SPS also sponsors panel discussions with Stanford physics alumni who have gone on to pursue a broad range of careers.

## **THE PhD PROGRAM**

Physics students at Stanford come from all around the world with many different backgrounds. There are multiple organizations on campus for international students and students of various ethnic and cultural interests. Almost half of graduate students live on campus and the active graduate student council organizes weekly cultural and social events. There are many opportunities for intellectual and social interaction - in the Physics Department, the entire Stanford community, and in the surrounding Bay Area.

Graduate students in the Physics Department at Stanford have the opportunity to conduct forefront research in areas ranging from particle physics, astrophysics and cosmology, to atomic and condensed matter physics, quantum information science, photon science and biophysics. Students work with faculty in many departments, including Physics, Applied Physics, Chemistry, and departments in the Schools of Engineering and Medicine, as well

as the Particle Physics and Astrophysics and Photon Science Departments at SLAC.

All graduate students in the Physics Department receive financial support through teaching assistantships or research assistantships, or both. To help incoming graduate students find a research group that best matches their interests, the department offers a unique research "rotation" program. Students in their first year have the opportunity to work with a different research group each quarter in order to explore various sub-disciplines of physics. Toward the end of the first year or the beginning of the second year, graduate students select a research group for their thesis work. For a more detailed picture of the many research topics pursued at Stanford, please visit the Physics Department website.

The first year of graduate study is normally devoted to formal courses, teaching and exploring research opportunities. The curriculum includes advanced particle, continuum, and statistical mechanics, classical electrodynamics, quantum mechanics, a seminar on teaching Physics, and a first year seminar on current research activities at Stanford. The department also offers advanced courses in the areas of Condensed Matter, Quantum Optics and Atomic Physics, Astrophysics and Gravitation, Nuclear and Particle Physics, and Biophysics.

Prospective graduate students should apply to the Ph.D. program in mid-December (see the Physics Department web site for the official deadline date) to be considered for admission the following autumn quarter. Applications are reviewed in January and February of each year, and admission decisions are made in early March. All applicants will be notified of their admission status by mid-March.

For information on applying for graduate studies at Stanford contact:

Graduate Admissions Office  
Office of the Registrar  
Stanford University  
Stanford, CA 94305  
Telephone: (650) 723-4291  
Or see their website: <http://gradadmissions.stanford.edu/>