American Physical Society New England Section Newsletter

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Co-editors

- **Edward Deveney**
- **Peter K. LeMaire**

Inside this issue:

Spring 2016 Meeting of the APS-NES, April 1-2, 2016
Wheaton College, Norton MA

Theme: Fluid Dynamics of Very Large and Very Small Systems

The plenary talks will examine fluid dynamics on a wide range of scales. On a large scale, the Earth's oceans control heat transfer from the tropics, CO_2 and O_2 levels in the atmosphere, and climate change; they also support vast ecosystems, with swimmers ranging in size from a few microns (zooplankton) to several meters (whales). Fluids beyond the earth, such as the ocean on the Jovian moon of Europa, are beginning to inform our understanding of the history of the Solar System. On the small scale, nano and micro fluidics now allow us to manipulate fluid flow at the cellular level. At all scales, fluid motion is controlled by a common set of factors (viscous forces, pressure gradients, turbulent transfer of heat and momentum), but these processes vary over many orders of magnitude. Fluid motions present interesting challenges for direct observation and extreme challenges for computational modeling. The physical behaviors encountered and the scientific puzzles to be addressed vary dramatically with the size of the system under consideration. In this meeting, we will consider a variety of extreme cases.

There will also be sections for contributed papers on diverse topics on Saturday, and a poster session on Friday evening.

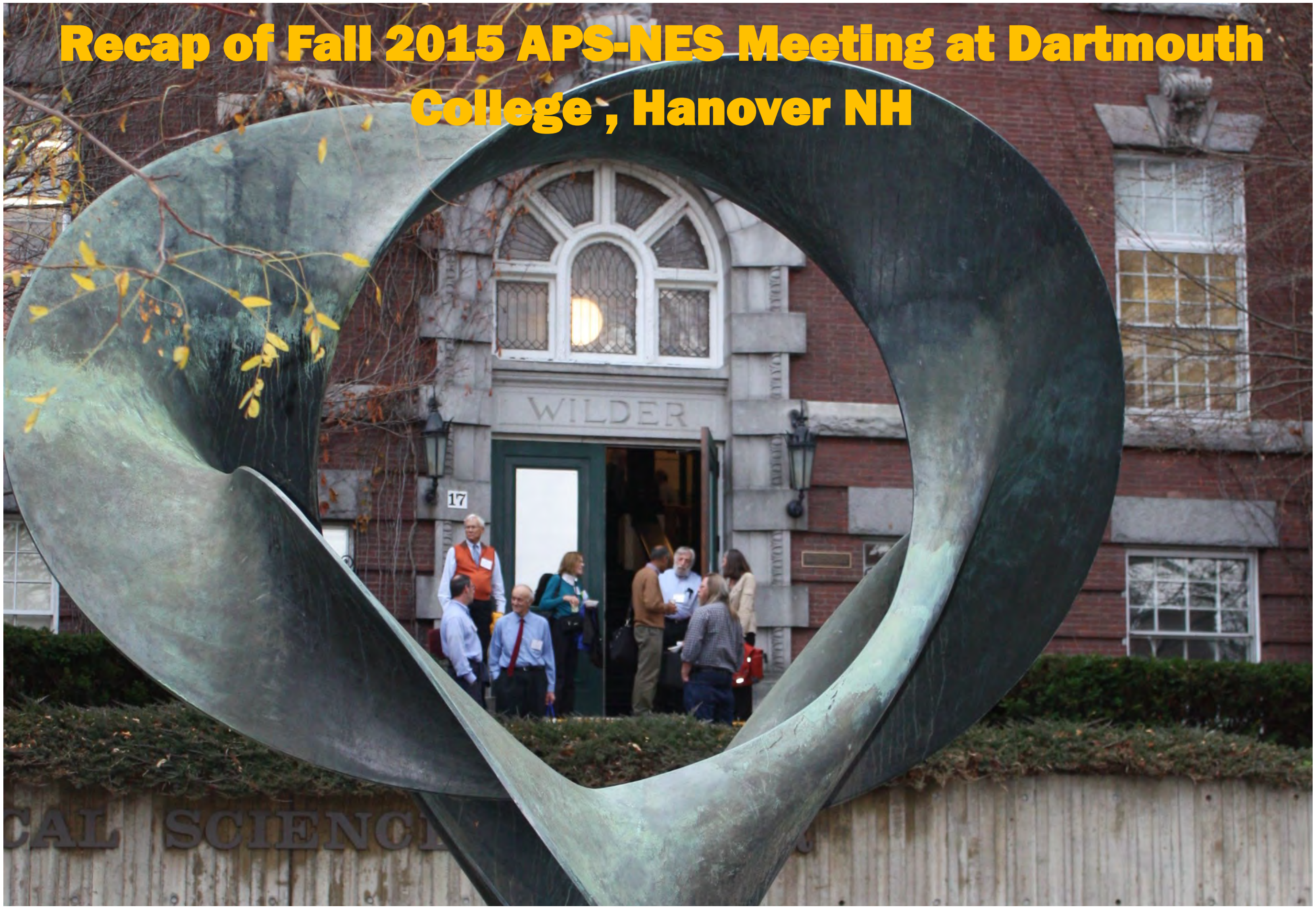
Invited Speakers

James Bird (Boston University), Claudia Cenedese (Woods Hole Oceanographic Institute), Jason Goodman (Wheaton College), Geoff Collins (Wheaton College), Blair Perot (University of Massachusetts, Amherst)

Keynote speaker: Nicole Sharp (Science Communicator, Aerospace Engineer)

Meeting website
http://apsne2016.webspace.wheatoncollege.edu/

Recap of Fall 2015 APS-NES Meeting at Dartmouth College , Hanover NH



The theme of the meeting was "Inner Space Meets Outer Space", covering topics in high energy physics, cosmology, exoplanetary astronomy among a host of very interesting diverse experimental and theoretical physics topics.

Friday November 6

The meeting got to a great start at Dartmouth Hall, with Opening welcome remarks and introductions made by Dartmouth College Physics Department Chair Professor James W. LaBelle and Professor Marcelo Gleiser, Chair for the Conference. The first invited talk was presented by Professor Sylvester J. Gates Jr. (Maryland/Dartmouth) who captivated the audience with his talk titled "From Field Theory to Riemann Surface and Calabi-Yau Structures Without String Theory". The second invited talk of the meeting was given by Professor Dimitar Sasselov (CfA, Harvard) titled "Exo-planetary Theory: New Insights from the Kepler Mission and from the Lab". After the two invited talks, the participants took a short walk to Wilder Lobby for a short coffee break where attendees interacted and discussed the two talks. This was followed by two more invited talks held in Wilder Hall – first by Professor Kevin Black (Boston University) whose talk was titled "LHC Results, Status, and Review", followed by Professor David Kaiser (MIT) presenting his talk titled "Nonperturbative Dynamics of Reheating after Inflation". The Keynote Speaker was Nobel Prize winning Physicist Frank Wilczek (MIT) and he did not disappoint. His talk titled "Intersections of Art and Science" kept the audience engaged and was followed by a very informative question and answer period.

The day ended with a poster session at Alumni Hall, and a sumptuous banquet.

Saturday November 7

The Saturday part of the meeting started with a breakfast spread at Wilder Hall Lobby. This was followed by three contributed sessions. Session I: Frontiers in Cosmology, Astrophysics & Particles was chaired by Professor Marcelo Gleiser. Session II: Frontiers in Condensed Matter & Quantum Information was chaired by Chandrasekhar Ramanathan. Session III: Frontiers in Education, History & Environmental Physics was chaired by Deborah Mason-McCaffrey

The morning and the meeting were capped off with two more exciting invited talks by Professor Lorenza Viola (Dartmouth) whose talk was titled "Perspectives on (and from) Quantum Information Science: What's Next?", and Professor Robert Caldwell (Dartmouth) giving his talk on "Dark Energy 2015".

After the closing remarks by our very gracious Dartmouth host, another very successful and educational APS-NES meeting came to a close.

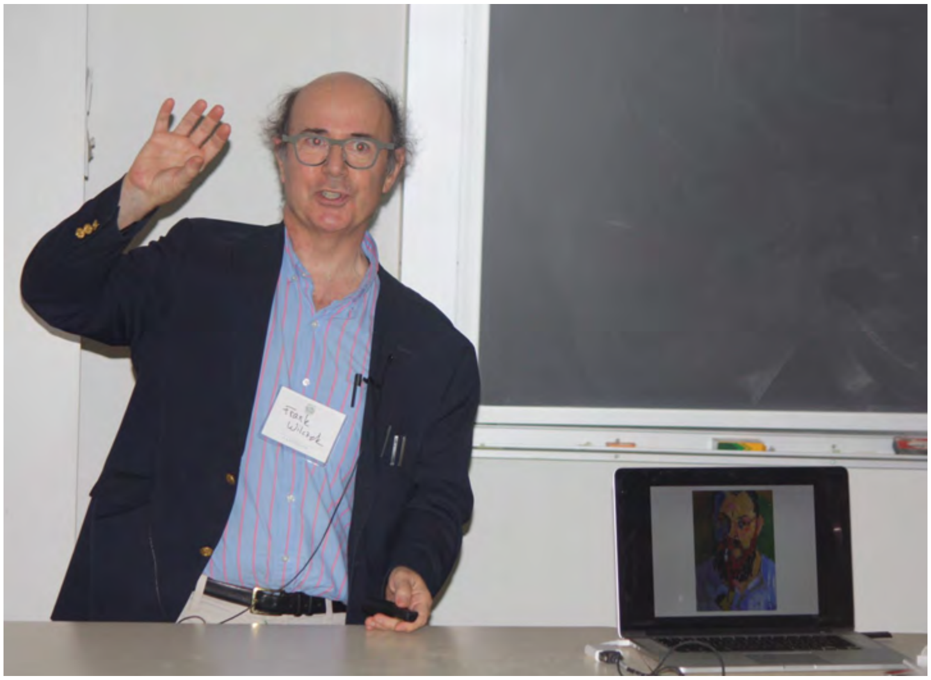
Recap of Fall 2015 Meeting…

Professor James W. LaBelle Department of Physics Chair at Dartmouth (above left) and Professor Marcelo Gleiser (above right), Chair for the Conference, welcoming and giving opening remarks at the meeting

Professor Sylvester J. Gates Jr. (Maryland/Dartmouth) giving his talk titled "From Field Theory to Riemann Surface and Calabi-Yau Structures Without String Theory".

Professor Dimitar Sasselov (CfA, Harvard) giving his invited talk titled "Exo-planetary Theory: New Insights from the Kepler Mission and from the Lab".

Recap of Fall 2015 Meeting…

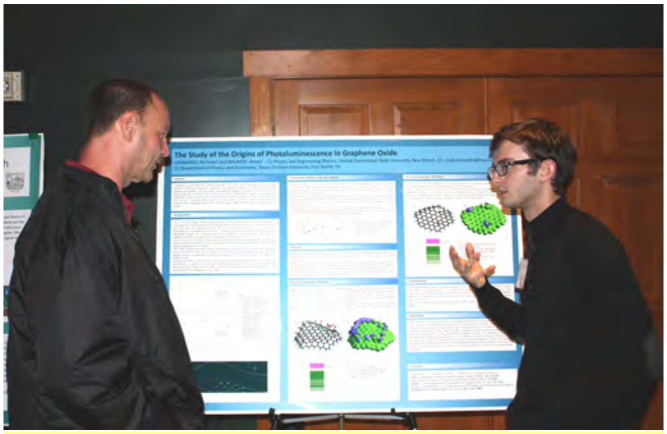


The Keynote Speaker, Nobel Prize winning Physicist Frank Wilczek (MIT) giving his talk titled "Intersections of Art and Science"

Professor Kevin Black (Boston University) giving his talk titled "LHC Results, Status, and Review",

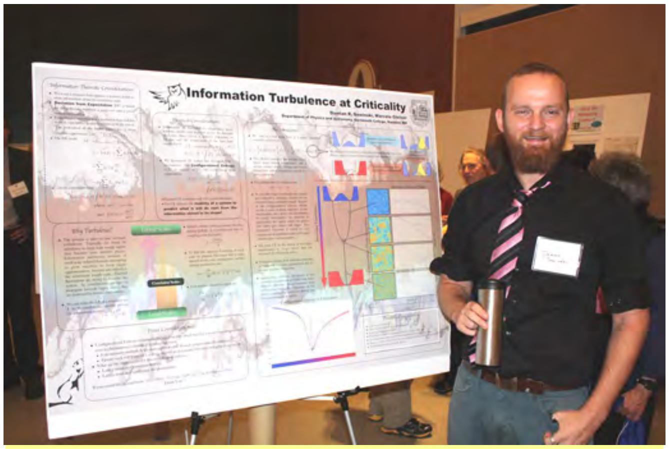
Professor David Kaiser (MIT) presenting his talk titled "Nonperturbative Dynamics of Reheating after Inflation".

Recap of Fall 2015 Meeting… Poster Session

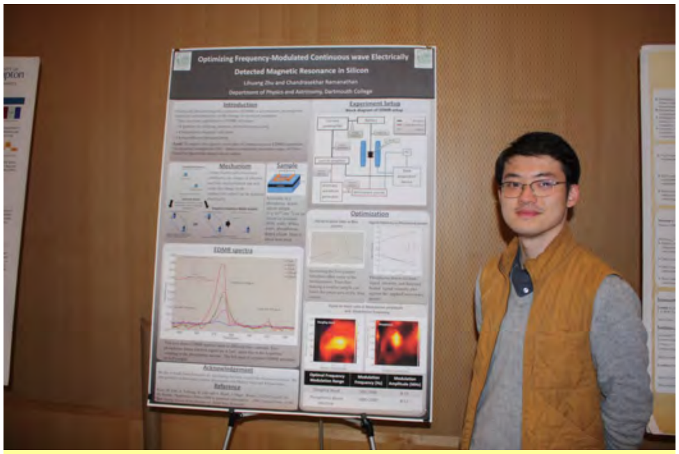


Nick Lombardo of CCSU (right) explains his poster presentation *"The Study of the Origins of Photoluminescence in Graphene Oxides"* to APS-NES co-editor Ed Deveney (left)

Abhijeet Alase (left) of Dartmouth discussing his presentation *"Generalized Entanglement as a Unifying Framework for Fermionic Entanglement"*



Damian Sowinski of Dartmouth at his poster *"Information Turbulence at Criticality"*



Lihuang Zhu of Dartmouth at his poster *"Optimizing Frequency-Modulated Continuous Wave Electrically Detected Magnetic Resonance in Silicon"*

Salini Karuvade (left) of Dartmouth explains her poster *"Dissipative quasi-local stabilization of generic Pure States"*

Spasen Chaykov (right) of Wentworth Institute of Technology discussing his poster *"Modeling Neutron Star Stability"*

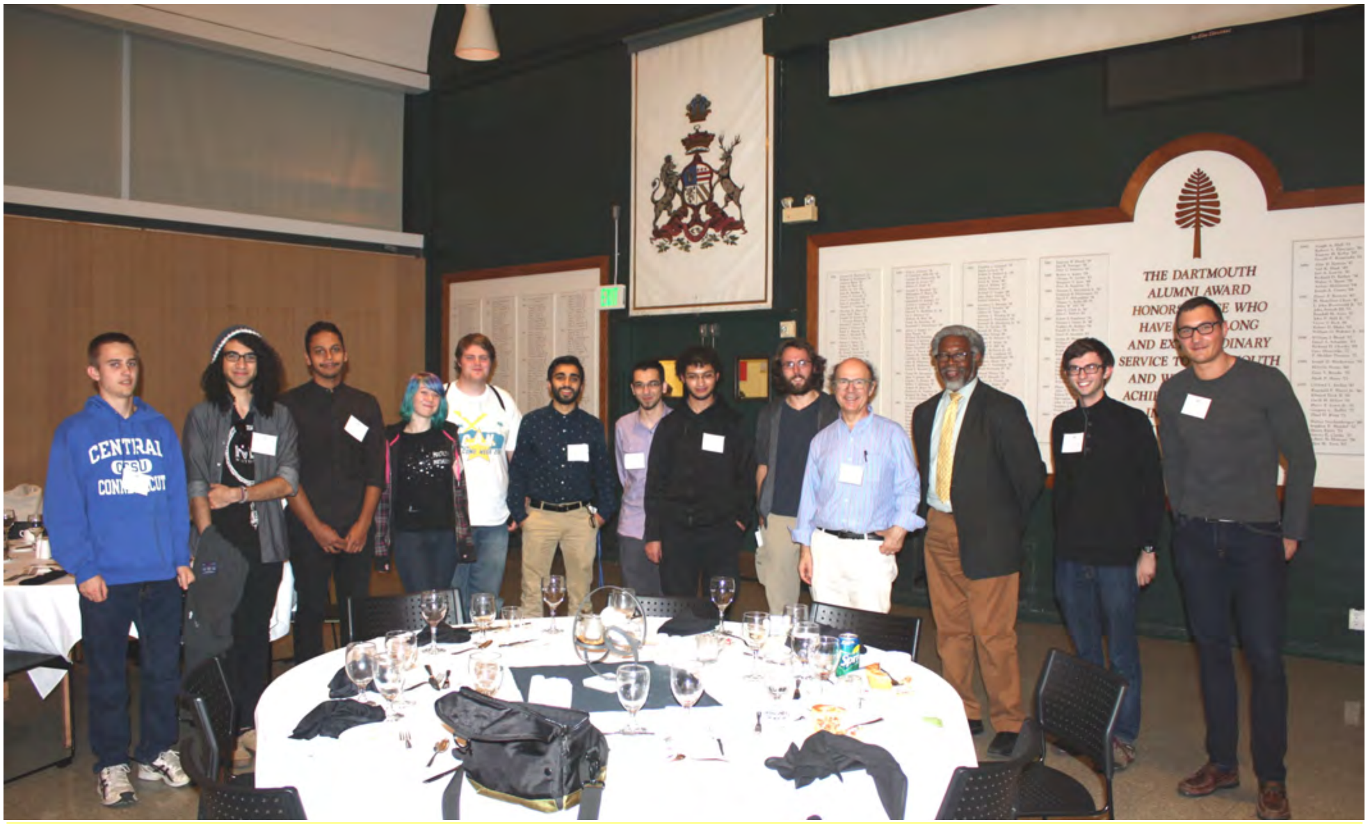
Recap of Fall 2015 Meeting…Banquet

Sylvester J. Gates Jr. and James LaBelle at the banquet

Marcelo Gleiser (left) and Frank Wilczek at the banquet

Meeting attendees at the Banquet

Recap of Fall 2015 Meeting…Banquet



Undergraduate Students from Central Connecticut State University pose for a keepsake with Professor Sylvester J. Gates Jr. (third from right) and Keynote Speaker and Nobel Prize winning Physicist Frank Wilczek (fourth from right)

APS-NES Past Chair, Partha Chowdhury (right) and APS-NES Executive Committee member Ted Ducas share a laugh at the Banquet

Recap of Winter 2016 CUWiP at Wesleyan University

Wesleyan Hosts 2016 CUWiP

by Christina Othon, Julia Zachary, and Nisha Grewal

On January 15-17th, Wesleyan University hosted more than 200 women students and professional physicists at the 2016 Conference for Undergraduate Women in Physics. Wesleyan was one of nine CUWiP sites hosted simultaneously across the country, with in total over 1200 students attending. The CUWiP events continue to grow in popularity and are helping to attract and retain new talent to the discipline. Networking and career development are the primary emphases of the conferences, and the energy and excitement of the participants attending the conference speak to the need for more opportunities to connect these young scientists to a vibrant scientific community.

Our conference opened with a fantastic talk by Dr. Aki Roberge of the NASA Goddard Space Flight Center, who spoke about her research on planet-forming disks around nearby young stars. Students were especially fascinated by Dr. Roberge's plan to use star shades to block light from bright stars in order to observe exoplanets. Following her talk, the students were welcomed with a bang, literally, when Professor Christina Othon and physics curator Vacek Miglus (Wesleyan University) began their ice-breaker demo show by launching a ping-pong ball through two empty soda cans using only atmospheric pressure. The students then mingled throughout the building, embarking on a scavenger-hunt/physics quiz that led them to rooms where interesting physical phenomena were on display. Along the way, they enjoyed liquid-nitrogen ice cream, and met physics and astronomy faculty and graduate students from Wesleyan.

Professor Ximena Cid (Assistant Professor of Physics at California State University Dominguez Hills) opened the morning's events on Saturday. She spoke at length about her experiences in the sciences and the microagressions she faced as a woman, Chicana, and Native American. Her talk emphasized the importance of retaining one's cultural heritage and creating an effective work-life balance.

The group then divided into various skill building workshops aimed at empowering students to achieve their career aspirations. The workshops included a Negotiations workshop (led by Professor Karen Daniels, North Carolina State University), Crafting a CV vs. Crafting a Resume (led by Persephone Hall and Professor Christina Othon, Wesleyan University), Applying for Graduate School (led by Professor Meredith Hughes, Wesleyan University), and Effective Science Communication (led by Angela Hight-Walker, NIST). We received rave reviews for these workshops and thank the women who contributed to them.

Over lunch, we hosted a panel discussion highlighting jobs outside of academia. Our panelists included Wesleyan Alumni: Clara Moskowitz, Nasim Khoshkhou, and Alison Leonard, as well as Maggie Wittlin of Columbia Law School and Jennifer Colangelo of Pfizer. Clara Moskowitz is Scientific American's senior editor covering space and physics. Alison Leonard is the Director of Printer Software at MakerBot Industries, a 3D printing company. Nasim Khoshkhou is a Managing Director at Argus Information and Advisory Services. Maggie Wittlin is an Associate in Law at Columbia Law School, where her research focuses on evidence and decision-making. Jennifer Colangelo is an associate research director at Pfizer Inc. studying toxicity. The panelists' careers exemplify how an undergraduate physics degree can prepare one for opportunities in many different fields outside of academia and academic research.

The panel discussion was followed by Career and Graduate School Fairs. These afforded the students the opportunity to explore job opportunities at companies

Recap of Winter 2016 CUWiP at Wesleyan University

such as Argus Information and Advisory Services, Pfizer, MakerBot Industries, Scientific American, and Green Skies solar power company. The students were excited to learn about the diversity of career opportunities available to them. The students also visited with recruiters from many of the region's graduate programs. Representatives from Bridgewater State University, Harvard University, North Carolina State University, the State University of New York, the University of Connecticut, the University of Massachusetts, the University of Rhode Island, Wesleyan, and Yale University all participated in the graduate school fair.

If you or your company would be interested in advertising opportunities to this talent pool, we would strongly encourage you to contact the CUWiP National Organizing Committee. Nationwide events are held every year, and the organizing committees for next year's CUWiP would welcome your participation.

Each year, the National Organizing Committee hosts a keynote address that is broadcast live to each of the nine host sites. This gives students an opportunity to wirelessly connect and witness the breadth of the physics community nationwide. This year, we were honored to have Ginger Kerrick, a NASA Flight Director, present the keynote address. Ginger gave an inspirational talk that highlighted her own perseverance and the importance of having mentors support young leaders. Ginger's tenacity, warmth, and humor radiated throughout the telecast, and many students were surprised and impressed by her strength and candor. She has reached the pinnacle of leadership within the NASA flight planning community, and her story resonated strongly.

Following the keynote address, the students had the opportunity to present their own research. We had over 40 posters and 16 student talks ranging in topics from high energy and condensed matter physics to biophysics, astronomy, and atomic and optical physics. Awards were given for the best posters and speakers. This year, the honorees named were: Betsy Hernandez from CUNY Hunter College, Kalina Slakova from the University of Pennsylvania, Emma Thomas from UMass Amherst, and Emma Regan from Wellesley College.

During our evening dinner banquet, we enjoyed a meaningful discussion on the importance of diversity, inclusion, and intersectionality. This discussion was led by some stunning community leaders who represented diversity in ethnicity, sexuality, gender identity, and physical ability. The panelists included Professor Candice Etson - Wesleyan University; Jessica Mink - Harvard-Smithsonian Center for Astrophysics; Professor Kerstin Nordstrom - Mount Holyoke College; and graduate student Jesse Shanahan - Wesleyan University.

Sunday morning opened with our Graduate Panel discussions. This panel is always one of the most popular of the CUWiP events, and this year was no exception. The students clearly identified with these young scientists and were eager to seek their advice on making decisions ranging from choosing a graduate program to finding a research advisor. Our panelists in-

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Announcement of CUWiP & Diversity Workshop Harvard Univ. January 2017

The Harvard University Physics Department is extremely pleased to host the northeastern site of the 12th Annual Conference for Undergraduate Women in Physics, to take place on January 13-15, 2017.

In keeping with the goals of the conference series, we aim to provide a supportive atmosphere for all young physicists to connect with their peers and with established women in the field. We hope that the event inspires attendees to pursue careers in physics and to embrace a positive, invigorated vision for the future of women in science.

Our conference will feature research talks by leading faculty and industry physicists chosen to represent a broad range of fields and life experiences. The attendees will be able to sharpen their own presentation skills by sharing their research experiences with their peers through talks and a poster session, demonstrating the remarkable research that is possible even as an undergraduate. A panel discussion will explore both academic and non-academic career opportunities and will be followed by a career fair with participants hailing from the rich academic and industrial environment of the Boston area and surrounding communities. Parallel breakout sessions will offer the participants a choice of topics to explore in small groups: from building community in the department, to creating a work-life balance, to combating sexual harassment and discrimination, among others. And taking full advantage of our location at a research university, we will open our labs for tours.

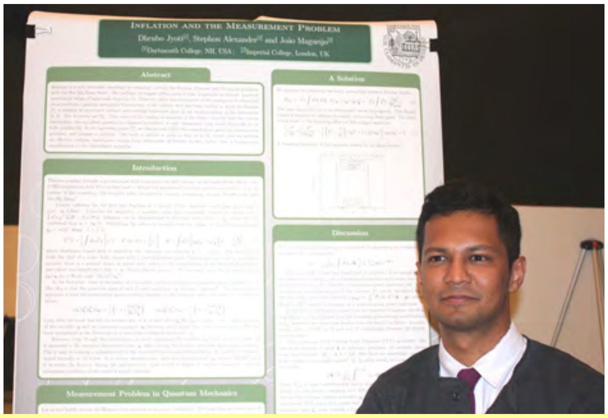
Above all, undergraduate women majoring in or considering majoring in physics will be given opportunities to connect with peers and with graduate students, professors, and professionals in a casual setting. The first night of the conference will break the ice with an interactive maker event, designed to promote creativity, communication, and teamwork. The second night will finish with a liquid nitrogen ice cream social. Throughout, we will encourage all our speakers, panelists, and session leaders to join the participants at a meal (or two!).

Unique to the Harvard site is a pilot project to further bolster those who are minorities within the minority in a more intimate setting, prior to the main conference. On January 12-13, we will invite up to 50 women who are members of racial and ethnic minorities, are LGBTQN, have physical and learning disabilities, are from low income backgrounds, are first generation college students, and/or are members of other underrepresented or underserved communities. This one-day program will include panels and workshops covering how, even as a minority within a minority, it is possible to succeed in an undergraduate physics program and in a career based on that degree. It will also provide many opportunities for participants to discuss their experiences and ask questions of mentors with diverse backgrounds.

We will be sending out "Save the Date" cards to those colleges and universities within our sector this spring and will follow up in the fall. In the mean time, please visit our website at https://sites.google.com/site/harvardcuwip/ for more information, or contact Susannah Dickerson at dickerson@fas.harvard.edu.

Authors:
Susannah Dickerson and Anna Klales
(Conference Coordinators for 2017 CUWiP at Harvard University)

Inflation and the Quantum Measurement Problem



Dhrubo Jyoti of Dartmouth at his poster presentation : Inflation and the Quantum Measurement Problem

Introduction -- Inflation is a very successful paradigm, solving Horizon, Flatness and Monopole problems. But perhaps its most interesting aspect is that, it traces the origin of structure in the Universe to quantum zero-point fluctuations [1,2]. We believe that the Universe had a quantum mechanical beginning, but how exactly did the classical universe we are familiar with emerge? For a review, see [3].

We propose a solution to this cosmological quantum measurement problem. Our approach is an effective wavefunction collapse mechanism arising from a novel interaction between Fourier modes, inspired by a weakly-interacting Bose gas, to be contrasted with fundamental modifications to the Schrodinger equation [4,5]. An alternative approach is Bohmian mechanics, which interprets the wavefunction as an actual field and avoids the notion of an observer collapsing the wavefunction [6].

The CMB has an average temperature of 2.7 K, but has small variations of order one part in 10^5. These are signatures of slight variations in the gravitational field in the primordial Universe, $\zeta(\mathbf{x})$, which eventually lead to the formation of large scale structures (LSS) such as galaxies. They are analyzed as follows

$$a_{lm} = \frac{1}{(2\pi)^{3/2}} \int d\Omega_{\mathbf{e}}\, d\mathbf{k}\, \frac{1}{5}\, \zeta_{\mathbf{k}}\, Y^*_{lm}(\mathbf{e})\, e^{-i\mathbf{k}.\mathbf{e}} \qquad (1)$$

where we defined the Fourier modes $\zeta_{\mathbf{k}}$. For a given l, the a_{lm}'s fit a normal distribution with mean zero and standard deviation $\sqrt{C_l}$. The a_{lm}'s are essentially a weighted sum over $\zeta_{\mathbf{k}}$'s. But if the latter are independently-distributed random variables, then the Central Limit Theorem (CLT) states that the probability distribution for each a_{lm} will approach a normal distribution in the limit of large number of $\zeta_{\mathbf{k}}$'s. Interestingly, this means that each $\zeta_{\mathbf{k}}$ need not be normally distributed as it is in the standard description, originating from the ground-state Gaussian wavefunction of the harmonic oscillator. In other words, classical gaussianity of a_{lm}'s does *not* imply quantum gaussianity of $\zeta_{\mathbf{k}}$'s; it is not an if-and-only-if relationship. CLT essentially washes out the underlying distribution and generically yields a Gaussian Random Field. This is in accord with observations since non-Gaussianity appears to be small [7]. We use this flexibility in our solution to the cosmological measurement problem.

Measurement Problem In Quantum Mechanics – Consider the quantum state of a particle,

$$|\psi\rangle = \mathbb{I}|\psi\rangle = \int dx\, |x\rangle\langle x|\psi\rangle = \int dx\, c_x |x\rangle\,,$$

For example, the particle could be prepared in the laboratory to be in a Gaussian state, $c_x = e^{-x^2/2}/\pi^{1/4}$. The particle is in a superposition of all position eigenstates $\{|x\rangle\}$. If a measurement of the particle's location is made (*e.g.* by shining a laser), then in the standard Copenhagen interpretation the state is said to *collapse*,

$$\boxed{|\psi\rangle = \int dx\, c_x |x\rangle \overset{?}{\rightarrow} |x^{col}\rangle\,,}$$

where x^{col} is the outcome of the measurement. This is said to happen instantaneously, and so is distinct from smooth, unitary time-evolution. Collapse of the wavefunction is taken as a postulate -- quantum mechanics does not explain how it happens, *i.e.* it's dynamics.

Cosmological Measurement Problem – A similar statement can be made for the inflation field,

$$\boxed{|\Psi\rangle = \int \mathcal{D}[\zeta]\ c[\zeta]\ |[\zeta]\rangle \quad \overset{?}{\rightarrow} \quad |[\zeta]^{col}\rangle\,,}$$

The coefficients $c[\zeta]$ are easy to calculate. Please see our paper on arXiv for details.

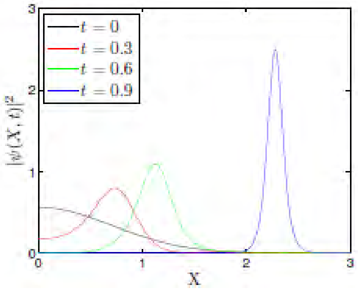
A Solution – We propose the following two-body interaction Hamiltonian H_{int} between Fourier modes,

$$\mathbb{H}_{int} = \frac{1}{2\pi} \sum_{\mathbf{k}} \sum_{\mathbf{q}:\ |\mathbf{q}-\mathbf{k}|<\Delta} \gamma(k,\eta)\ \ \delta(R_{\mathbf{k}} - R_{\mathbf{q}})\,,$$

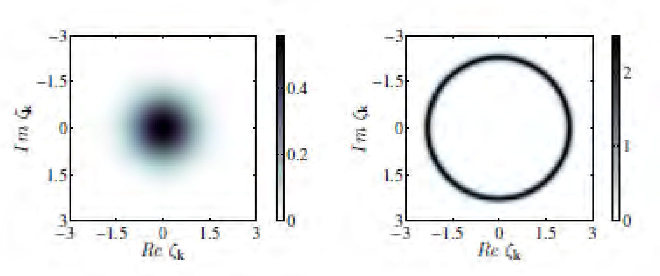
This interaction Hamiltonian leads to the following effective non-linear Schrodinger equation,

$$i\frac{\partial}{\partial T}\psi(X,T) = -\frac{1}{2}\frac{\partial^2\psi}{\partial X^2} + \frac{1}{2}X^2\psi + \Gamma X|\psi|^2\psi\,,$$

This PDE can be solved numerically as shown in the figures below:



Inflation and the Quantum Measurement ...



Conclusion – - As shown in the figures above, we reduced the dimensionality of the wavefunction manifold from two (amplitude and phase) to one (just phase). This remaining stochasticity is less disturbing than that of that implicit in the traditional description.

The cosmological measurement problem is a rich and compelling arena for both foundational issues of quantum mechanics as well as a deep understanding of early universe cosmology, and may potentially teach us about aspects of quantum gravity.

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(arXiv:1602.01216)

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Do you have interesting physics related articles, new programs, research report, physics talking points etc. that you will like to share with the New England physics community?

Send them to the co-editors:
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Small Waves Making Big Waves & Capturing Public Imagination in 2016

Gravitational Waves: A 100 Year Success Story

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Introduction:

Over the course of the few years, the world of Physics has been alive with news of groundbreaking discoveries. Many of these recent advances have been crucial to the confirmation of results that are at the cornerstone of modern physics. These triumphs are a culmination of the efforts of theorists and experimentalists alike. The spoils of recent physics, has in many cases been a testament to the patience and persistence of science. For example, in 2013, after being postulated over fifty years ago by Peter Higgs and company [1], the Higgs Boson was detected at the Large Hadron Collider (LHC) [2]. In 2008, Gravity Probe B returned to Earth with results to further verify the geodetic curvature effect of Einstein, as well as provide a first measurement of the mind blowing gravitational frame dragging effect [3]. Both of these ideas were postulated nearly 100 years ago, and the first idea for using a space-craft to measure the curvature and frame dragging effect originated over 60 years ago by the great Leonard Schiff. Today, physicists find ourselves' once again celebrating victory, with the first detection of Gravitational Waves at the Laser Interferometer Gravitational-Wave Observatory, LIGO. This was yet another discovery, a hundred years in the making. In this article, we will review briefly the history of Gravitational Waves, the methods used at LIGO for detection and take a glimpse to the future of gravitational wave physics.

Gravitational Waves

In order to appreciate the magnitude of the recent discovery, we should highlight the basics of gravitational waves. When Einstein revolutionized our understanding of gravity in 1915 with General Relativity (GR), he also forced us to expand our comprehension of the geometry of space and time itself. GR was the first metric theory of gravity, a complete description of gravitational phenomena resulting from the presence of mass, occupying a region of space-time, which in turn causes the surrounding geometry to become non-Euclidian. This is easily visualized by a small marble resting on a rubber sheet causing the fabric to curve. In the years that followed, this curvature effect was proven due to the deflection of star light experiment. Since light follows the geodesics of the system in which it propagates, the straight lines around a large object such as the sun would be curved according to GR. Hence, light should be deflected from its original path. When this was confirmed, the Einstein description was celebrated as the correct and complete interpretation. This was a huge deviation from the Newtonian description of gravity since his famous equation,

$$F_g = \frac{GM_1M_2}{r^2}$$

should not couple to massless light. Moreover, one of the motivating factors of Einstein's special relativity was the preservation of causality. Since it was a known shortcoming of Newton's theory that gravity required an instantaneous force, this is immediately at odds with causality. As it turns out, Einstein had the answer to this conundrum as well, namely that a geometric theory of gravity admits wave like solutions which travel at the speed of light. These theorized waves, would become known as the elusive gravitational waves, and for Einstein, the similarities between electromagnetism and gravity have come full circle.

Although the idea of gravity communicating via a wave is a simple analogous effect to electrodynamics communicating via waves, the physical implications are quite different. In order to quantify the physicality of such objects, let us turn to some basic GR. As a metric theory of gravity, GR relates the gravitational field to a set of space-time dependent (x^α) co-efficient functions $g_{\mu\nu}(x^\alpha)$, called the metric tensor. This set of 16 quantities (as the indices are dummies that can range from 0 to 3) fully describe the point by point geometry of a given system in a four dimensional space-time. Since the metric tensor coefficients are functions, they also hold the information for if and how the geometry of space time changes in a system. Thus, according to Einstein, knowing the metric tensor of the system completely describes the geometry and thus describes what Newton previously called gravity. So let us assume that we have a gravitational source in space time. This source will produce a metric to describe the gravity. As we do in the Maxwell equations, let us then look at the far field effect of the gravity, namely the metric tensor far from the source. In this regime, the metric tensor can take the form

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

Gravitational Waves..

Where $\eta_{\mu\nu}$ is the background metric and $h_{\mu\nu}$ is the weak perturbation to the geometry due to the source. The Einstein equations for the metric tensor are given by

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R^{\alpha}_{\alpha} = \frac{8\pi G}{c^2} T_{\mu\nu}$$

Where $R_{\mu\nu}$ is the Ricci tensor (a quantity which contains linear combinations of first and second order derivatives of the metric tensor), and $T_{\mu\nu}$ is the Energy Momentum tensor of the system. Upon using the expanded version of the metric tensor in the far field, the left hand side of Einstein's equations simplify to:

$$R_{\mu\nu} \approx \frac{1}{2} \left(\partial_\lambda \partial^\lambda h_{\mu\nu} - \frac{\partial^2}{\partial x^\lambda \partial x^\mu} h^\lambda_\nu - \frac{\partial^2}{\partial x^\lambda \partial x^\nu} h^\lambda_\mu + \frac{\partial^2}{\partial x^\mu \partial x^\nu} h^\lambda_\lambda \right)$$

We can make this simpler as well by eliminating the Ricci scalar from the system by writing, $V_{\mu\nu} = T_{\mu\nu} - \frac{1}{2} \eta_{\mu\nu} T^\lambda_\lambda$. In GR, we maintain energy and momentum conservation in the covariant form such that the covariant derivative of the energy momentum tensor must vanish. Similarly, if we are working in the weak field, then we get a similar relation for the derivatives of h (to first order), $\partial_\mu h^\mu_\nu = \frac{1}{2} \partial_\nu h^\mu_\mu$. Using these in the original formula for the Einstein equations in the far field, we obtain:

$$\partial_\lambda \partial^\lambda h_{\mu\nu} = -\frac{16\pi G}{c^2} V_{\mu\nu},$$

which if we then work in the source free zone, $V_{\mu\nu} = 0$, the Einstein equations simplify to $\partial_\lambda \partial^\lambda h_{\mu\nu} = 0$. Upon remembering the Einstein summation convention, we realize that we staring at the wave equation for $h_{\mu\nu}$, viz.

$$\partial_\lambda \partial^\lambda h_{\mu\nu} = \left(\frac{1}{c^2} \frac{\partial^2}{\partial t^2} - \nabla^2 \right) h_{\mu\nu} = 0$$

For further elaboration on these derivations, see for example Weinberg [4]. This overlap with electromagnetic theory is not only remarkable, but also gives us a definitive value of the speed of the gravitational radiation. Further, it allows us to postulate on the divergence of the correlation with electro-magnetics, in that the metric tensor itself $h_{\mu\nu}$ is the quantity which behaves like a wave. Coupling this with our earlier statement that the metric tensor describes the actual space-time structure of the system, then we are stating that under the right circumstances, wave-like disturbances in the space-time fabric are allowed in GR, and can propagate far from the source. These are the true manifestations of gravitational waves, and it was one of these disturbances in space-time that was recently discovered at LIGO.

Although the above derivation is correct, we have made the oversimplification that we set the source $V_{\mu\nu} = 0$. In order to make predictions about gravitational waves and relating them to their source in the far field, we would need to go back and set the weak Einstein equations above, to a non-zero energy momentum tensor and carry out the calculations. In this framework, the metric tensor coefficients $h_{\mu\nu}$ are related to the amplitudes of the gravitational waves $\overline{h}$, and follow wavelike solutions to the wave equation shown above (except now are non-homogeneous). These types of waves however, are only produced in the quadrupole moment of the source and hence are extremely weak amplitude waves (in contrast with electromagnetic waves which possess a dipole moment). We can get a rough estimate for the amplitudes $\overline{h}$, by assuming we are looking at a binary system, which orbits in a circular fashion (which is in-spiraling) at a distance R from center to center, with period T. The quadrupole moment is given by $P \approx 2MR^2$, where M is the total mass of the system. Since we can relate this back to the Schwarzschild radius r_s, then the approximation for the perturbation amplitude becomes $\overline{h} = \frac{r_s}{r} \frac{v^2}{c^2}$. This can be further simplified by using the virial theorem for the system, which allows the final simplification that $\overline{h} \approx \frac{r_s^2}{Rr}$. The beauty of this simplification is that we can get a good estimate for the amplitudes from simple algebra. For example, if we assume that the objects in the binary motion are of the order of solar masses, and the event is occurring in a spatial distance from earth (r) on the order of kilo-parsecs (kpc), then $\overline{h} \approx 5 * 10^{-18} m$. We will see below that this number is of significant importance to both LIGO and the signal detected a few weeks ago.

It should be noted however that long before LIGO was operational, there was indirect evidence of gravitational waves. In 1993, the Nobel Prize in Physics was awarded to Russell Hulse for the indirect detection of gravitational waves by observing a pulsar binary system [5]. The observations showed a decaying orbit of the pulsar which can be measured due to Doppler shift. Using the equations described above, one can calculate the energy carried away by the gravitational radiation, and thus predict the orbital decay. This number was measured within .2 percent of the prediction from GR. Now more than 30 years later, the direct detection of such radiation has been captured.

Gravitational Waves...

LIGO

The Large Interferometer Gravitational Wave Observatory (LIGO) was first hypothesized in the 1960's with the advent of interferometry. The idea of using laser interferometry to attempt to measure gravitational waves was studied by GR master Kip Thorne and then revisited in the 1980's when the first 40-meter prototype was built at Caltech. Fast forward to the modern day, and LIGO is one of the most ambitious and long going collaborations between powerhouse universities (MIT and Caltech to name a few), and remains the single largest collaboration ever funded by NSF. Since its inception in the early 80's, LIGO has under-went many updates and renovations which culminated in the announcement on February 11, 2016 that the first detection of a gravitational wave was found in the LIGO array.

Being a member of the physics community, one cannot escape the irony of the detection method used. The laser interferometer array used in the LIGO facilities is an experiment very similar to the famous Michaelson-Morely (MM) experiment, the failed experiment that originally paved the way for the success of special relativity over 100 years ago. The main difference now, is that we understand that there is no ether, but instead, we are searching for wiggles in the space time continuum. Figure 1 shows a simple illustration of this.

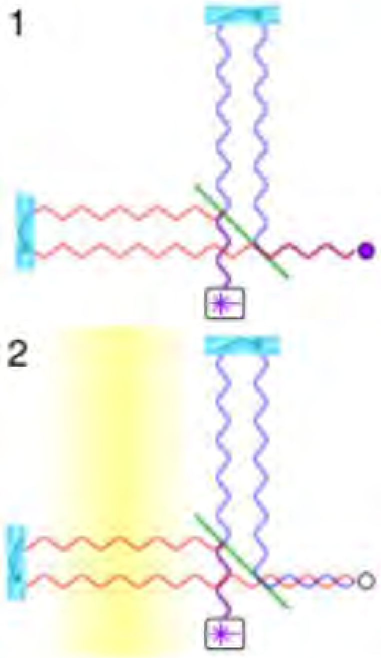

FIG. 1: A Cartoon picture of the LIGO apparatus. In the top drawing, the two beams are not interacting with a gravitational wave. In the Lower, the presence of the gravitational wave (yellow) causes a small shift in space-time and thus and interference pattern after recombining.

The beams of coherent collimated and sent into a beam splitter across two different paths. The light bounces off mirrors down the 4000m arms over 250 times and recombine for no interference pattern (the original MM result). Thus, the effective interferometer arm is essentially 1120km. This number is of extreme importance since for a wave of frequency on the order of 10-100Hz, the corresponding wavelength traveling at the speed of light is about 1000km. The null interference pattern is achieved by keeping the beams completely out of phase so that no gravity waves, implies a null result. However, if a gravitational wave were to traverse through the continuous beam, the small deviation in space time would cause an extremely small deviation in one of the paths, resulting in an interference pattern after recombination. It should be noted that the signals sought in LIGO are extremely small (spatial distortions of about 10^{-18}m, see above) and the systematic noise in the system is overwhelming [6]. Many false positives of the LIGO apparatus were due to factors such as minuscule seismic activity and simple nearby automobile traffic.

Gravitational Waves...

Since GR predicts gravitational waves, one can then directly correlate the amplitude of such waves directly back to information about the source. As an experimental apparatus, we know the sensitivity of LIGO, and therefore can figure out what types of exotic objects can put out gravitational waves strong enough to be picked up by the interferometer. This is how the group at LIGO is sure that the gravitational wave detected was the in-spiral of two black holes. The signal, dubbed *GW150914* was short but sweet. The GR prediction calls for this type of merger to radiate much of the mass away and have a wavelength that changes as the merge evolves. Over the .2 seconds, the wave began at 35 Hz, maximizing at 150 Hz. This same signal was then seen 10m/s later at the seconds LIGO site, for a combined signal to noise ratio of 24, with 90 percent certainty [7]. Figure 2 shows the actual signal measured from the two detectors.

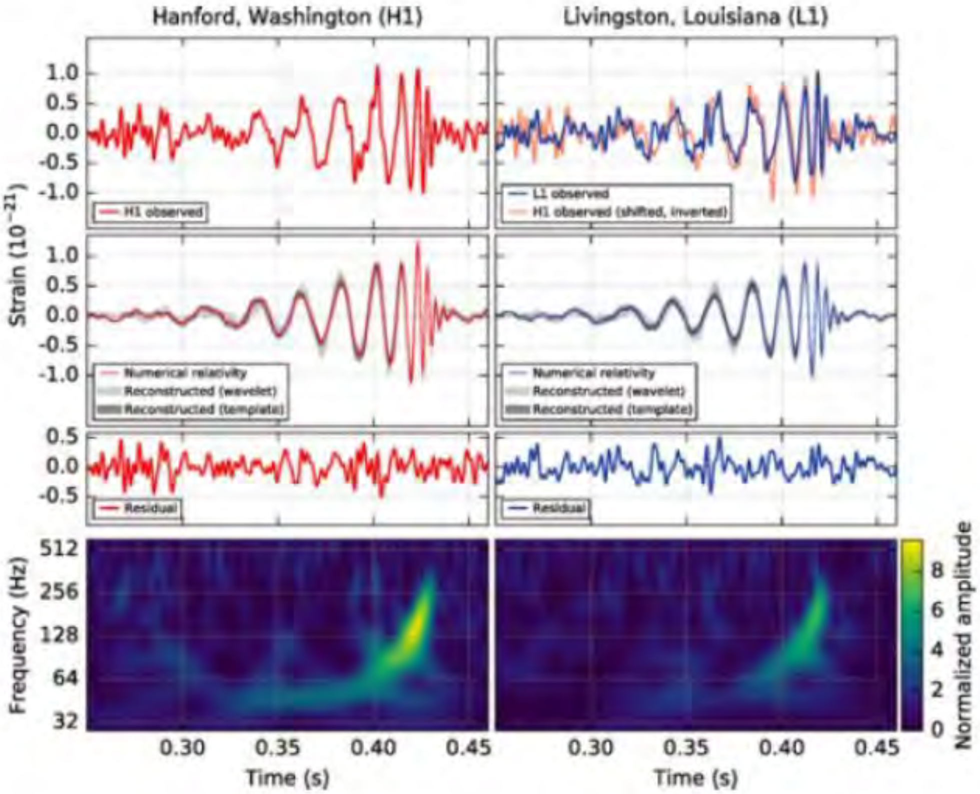

FIG. 2: The measured signal over measured at LIGO site (left) and LIGO Livingston sight (right).

The frequencies measured and change in frequencies can then be used to find the masses involved via:

$$M = \frac{(m_1 m_2)^{\frac{3}{5}}}{(m_1 + m_2)^{\frac{1}{5}}} = \frac{c^3}{G}\left(\frac{5}{96}\pi^{-\frac{8}{3}}\nu^{-\frac{11}{3}}\frac{d\nu}{dt}\right)^{\frac{3}{5}}.$$

With this equation, we can estimate the sum of the masses as being on the order of 70 solar masses. Since we relate the maximum frequency to be half the orbital frequency of the masses in-spiraling to be 75 Hz, one can compute the Schwarzchild bound to be

$$\frac{2GM}{c^2} \approx 250km.$$

Further analysis concludes the specifics of the two masses were about 25 and 39 solar masses plus or minus 4 solar masses. With the inferred masses and observed frequencies, this immediately implies the two objects had to be black

Gravitational Waves...

holes and not compact Neutron stars. Perhaps as icing on the cake, analysis can also be performed in the fall off of the signal. As can be seen in Figure 2, the fall off was measured, and is consistent with a damped waveform similar to those found in a Kerr solution for a single rotating black hole, signifying that a merger and completion was observed [8].

Future of LIGO

With this recent observation, the future of LIGO is promising. The signal was found in the arrays only a few short months after the recent upgrades to Advanced LIGO [6]. This timely event shows the importance of persistence and commitment to pure scientific research. Although LIGO may have had some funding issues in the past, it is more than likely that with the current excitement, that LIGO has not seen its first and last signal. Recently, only a short time after the signal, LIGO India was announced as a future site for gravitational wave detection. The India collaboration has been in discussion for many years, but the recent discovery has helped closed the deal [9]. Other sites including Australia have also been discussed but not confirmed [10]. Perhaps one of the outcomes of this signal, would be a re-affirmed commitment to LISA, the Laser Interferometer Space Array. The bounds on LISA as compared to LIGO can be seen in Figure 3, and would basically remove much of the noise and false positives found here on earth. It would be the hope that this may prove to be a similar advancement to gravitational wave observations as the Hubble Space telescope was to luminous observations.

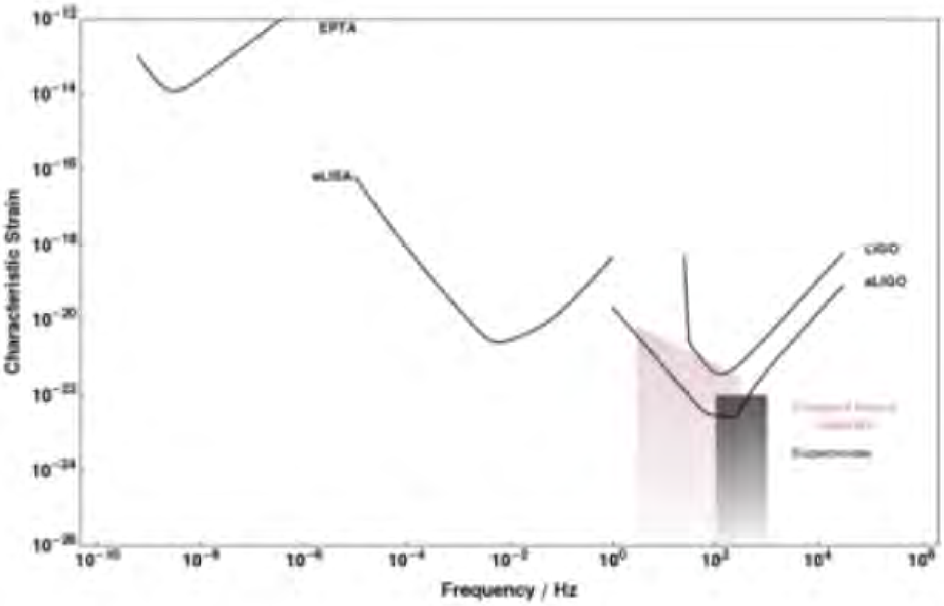

FIG. 3: The parameter space as measured by LIGO, advanced LIGO (aLIGO), LISA and other gravitational wave detectors.

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Recap of Winter 2016 CUWiP ...*continued*

cluded Mei Zheng - Princeton University, Genevieve Brett - MIT, Estella Barbosa De Souza - Yale University, and Amy Steele - University of Maryland.

The students then broke into smaller groups for discussion on work-life balance, becoming a role model in physics, career opportunities in physics, finding a summer research opportunity, and we also hosted an international student forum.

Our lunch hour discussion focused on careers in academia. The women participating discussed careers in high school education, community colleges, and four-year institutions. Our panelists included Kerstin Nordstrom - Mount Holyoke University, Renee Lathrop - Dutchess Community College, Kayla Lewis - Valley Technical High School, Renee Sher - Postdoctoral Researcher at Stanford University, and Upali Aparajita - United States Military Academy at West Point.

Our last speaker was Wesleyan Alumna Dr. Sherry-Ann Brown, M.D. Ph.D., a resident physician and cardiology fellow at the Mayo Clinic. Sherry-Ann delivered an impassioned speech on her career in physics and medicine. She wove her research and poetry together seamlessly, culminating with a reading of her poem "Just one more step". This was a fitting end to a conference whose goal was to inspire young women to persevere and become leaders within the scientific community. The event closed with many hugs, pictures, and promises to keep in contact. We enjoyed hosting all of the young women, and encourage everyone to become involved in these wonderful events.

-Photographs courtesy of Wesleyan University

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For more information on Women in Physics, including speaker lists, workshops and meetings etc., please visit

www.aps.org/programs/women/

Advanced Labs in the Spot Light:

The Barbara Wolff-Reichert Grant

Barbara Wolff-Reichert

The Grant

For the next five years (2016-2021), the Barbara Wolff-Reichert Grant will provide up to $7,500, contingent upon a 50:50 departmental match, toward the purchase of a TeachSpin instrument successfully mastered by a participant in an ALPhA Immersion.

This grant honors the special relationship I have with TeachSpIn, the advanced physics lab, ALPhA, and the dedicated men and women who teach advanced labs. I have been part of TeachSpin since it was started in our basement with the sole intention of creating a pulsed NMR designed for teaching that would make this exciting field accessible to every future experimental physicist. I have had my own horizons expanded by every new apparatus added to TeachSpin's offerings.

Because I believe an advanced lab should be a place where future physicists can explore a variety of areas of physics, I think the Immersion program, which empowers instructors willing to teach experiments outside their area of expertise, is one of the most important programs that ALPhA has created. Advanced labs, however, are notoriously underfunded. This grant is my personal acknowledgement of the contributions to experimental physics education made by the many wonderful instructors I have been privileged to know.

How do you apply for BWR grant?

You don't directly apply for this grant, but rather apply through the regular process
for an Immersion support grant from the J.F. Reichert Foundation. Use exactly the
same procedure and the same forms as the other grant applications for Immersion
support.

The steps are:

1) Fill out all the applications for the Foundation Immersion support.
2) Get your school's official commitment to fund 60 of the equipment cost.
3) If you have completed an Immersion on a TeachSpin apparatus, you will automatically be placed in the pool of applicants for the BWR Grant.
4) If your application is awarded the BWR Grant, your school will need only
fund 50 of the apparatus cost. (Subject to the limit of $7500 per grant)
5) If your application does not receive the BWR Grant, it will still be considered, along with the other applications, for funding from the Foundation's other resources.

Advanced Labs in the Spot Light:

ALPhA Mining Actualization (AMA)

A New Grant Program of the Jonathan F. Reichert Foundation

The acronym **AMA** will be taking on new meaning for the physics community. At its January meeting, the Jonathan F. Reichert Foundation Board initiated its newest program, **ALPhA Mining Actualization**. With an initial funding of $5,000, **AMA** will significantly impact the Miners' search for new experiments to expand the breadth and depth of advanced laboratory experiments. The goal of this program is quite simple – it is to promote the **actual development** of the new experiments suggested by the explorations of the ALPhA Miners. The Foundation will use some of its resources to underwrite the construction, testing and dissemination of advanced lab experiments *that are closely related to current research in physics*. We also believe that the development of such experiments by undergraduate students, under the supervision of faculty, would not only fit into independent study courses, but would also make excellent senior or undergraduate research projects. The rules for obtaining a grant are both simple and somewhat unusual. There are no forms to fill out and no deadlines to meet. However, the funds will be dispersed on a first-come, first-serve basis. Once the $5,000 has been allocated, no other funding will be available for that calendar year.

The rules:

1. Applicants must demonstrate that the ideas for the project came from the Miners' reports.
2. The maximum grant will be $2,000 per school.
3. The school must certify in an official document that it will provide matching funds equal to that of the grant.
4. The funds cannot be used to pay faculty or staff salary or travel expenses.
5. The program must involve **undergraduate students in the design, building, and testing of the apparatus.**
6. The applicant agrees to supply the Foundation with a comprehensive report of the effort at the end of the grant.
7. The awarding of these grants is at the sole discretion of the Jonathan F. Reichert Foundation.
8. Only faculty and senior staff of physics departments may apply.

We leave the format and content of the application up to the individual.

You may submit applications by email to:
Jonathan@JFReichertFoundation.org
Or by snail mail to: Jonathan F. Reichert Foundation, 45 Penhurst Park, Buffalo, NY 14222-1013

Grants Awarded for Advanced Laboratory Apparatus

Twelve schools received funding from the Jonathan F Reichert Foundation to facilitate the purchase of apparatus used by their faculty at an Advanced Laboratory Immersion offered in 2015 by the Advanced Laboratory Physics Association (ALPhA). These grants covered 40% of the cost of the apparatus with the schools shouldering 60% of the expense. For a list of recipients, the amount of each award, and other details of this new program see:

jfreichertfoundation.org