LIGO Scientific Collaboration

LIGO MAGAZINE

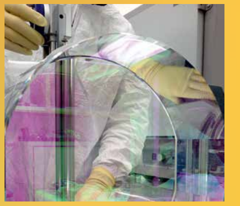
online issue 4 3/2014

The Future

LIGO and Virgo in 2020

Installing the Advanced LIGO detector at LIGO Livingston:

A brief history p. 6



Advanced LIGO Coating Research

Technology p. 10

... and 4 pages of LIGO Outreach.

Title image

The Transmission Monitoring Suspension (TMS) hangs behind the End Test Mass. The lower section directly behind the Test Mass consists of a telescope, which carries the transmitted light to an optics table suspended on the upper level. The TMS suspension can be seen clearly in the accompanying photo in the "Installation of the Advanced LIGO Detector at LIGO Livingston" article in this issue (pp. 6-7). In particular one can see the larger telescope mirrors at the bottom level and some components on the optic table above. The purple and green colors come from the coatings on the optics.
Photo by Michael Fyffe, LIGO Livingston

Image credits Photos appear courtesy of LIGO Laboratory/LIGO Scientific Collaboration unless otherwise noted.
pp. 6-7 Top image, credit: Michael Fyffe, LIGO Livingston
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Upcoming Events (compiled by the editors)

The LSC-VIRGO March Meeting
17 – 21 March 2014,
Observatoire de la Côte d'Azur,
Nice, France
http://lvc2014-nice.sciencesconf.org/

Stellar tango at the Rockies
23 – 28 March 2014,
Lake Louise, Alberta, Canada
http://astro.physics.ualberta.ca/rockies14/

The Structure and Signals of Neutron Stars, from Birth to Death
24 – 28 March 2014, Florence, Italy
http://indico.cern.ch/conferenceDisplay.py?ovw=True&confId=264202

APS April Meeting 2014
5 – 8 April 2014, Savannah, GA
http://www.aps.org/meetings/april/index.cfm

3rd Session of the Sant Cugat Forum on Astrophysics, Gravitational Waves Astrophysics
22 – 25 April 2014, Sant Cugat, Spain
http://www.ice.csic.es/research/forum/2014.html

10th International LISA Symposium (LISA Symposium X)
18 – 23 May 2014, Gainesville, Florida
http://www.phys.ufl.edu/lisasymposiumx/

The Gravitational-Wave Advanced Detector Workshop 2014
25 – 30 May 2014, Takayama, Japan

Aspen Workshop: Ultra-compact Binaries as Laboratories for Fundamental Physics
8 – 29 June 2014, Aspen Center for Physics, Aspen, Colorado

Gravitational-wave Astrophysics at the 40th COSPAR Scientific Assembly
2 –10 August 2014, Moscow, Russia
https://www.cospar-assembly.org/

The LSC-VIRGO September Meeting
25 – 29 August 2014,
Stanford University, Stanford, California

11th Edoardo Amaldi Conference on Gravitational Waves
21 – 26 June 2015, Gwangju, Korea

A public web page with a calendar and list of upcoming conferences and meetings that may be of interest to members of the LSC is now available on ligo.org: https://wiki.ligo.org/LSC/UpcomingConferencesAndMeetings

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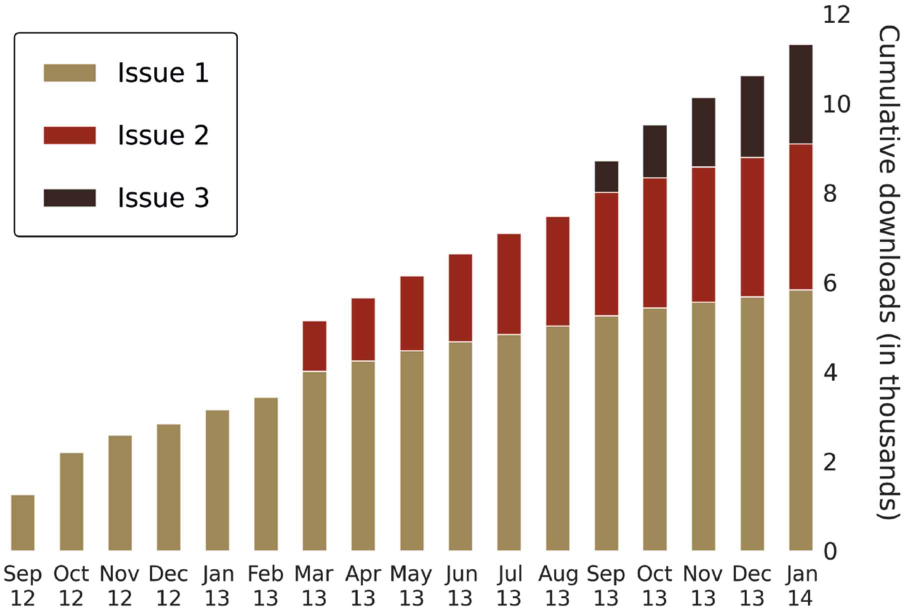
LIGO Magazine Download Statistics

The LIGO Magazine has become an important way for the LSC to communicate its activities and share information, both within the collaboration and outside of it. As of January 2014, the 3 published issues of the magazine have been downloaded from the ligo.org server a total of 5800, 3300 and 2200 times respectively. We as editors are very pleased with the strong interest in the LIGO Magazine and look forward to expanding the impact of our stories from around LIGO to an increasing number of interested readers!



Download statistics for the LIGO Magazine from September 2012 until January 2014. Image credit: Lucia Santamaria with data from the ligo.org server

Welcome to the fourth issue of the LIGO Magazine!

With the advanced detectors moving closer to operation, 2014 is set to be an exciting year for the gravitational wave community. We think this would be a good moment to feature bits of the past, the present, and the future of LIGO in the magazine. This issue's story "Looking to the future: LIGO and Virgo in 2020" focuses on possible observations that await us in the era of an advanced detector network, we also retrace the development of the mirror coatings in "History of Advanced LIGO coating research", and our correspondent from the LIGO Livingston site provides an inside view of the "Installation of the Advanced LIGO detector at LIGO Livingston", currently nearing completion. We also take a look at some of the many diverse and colorful outreach activities related to gravitational waves in the larger collaboration. It is very exciting to see, and be part of, this rapidly advancing and evolving field and we thank all the contributors who invested their time and effort to report to us in the form of articles, photographs, and news items!

The LIGO Magazine has now been downloaded more than 10,000 times from the main LIGO webpage, a sign that it is becoming an important way to share information within and outside the collaboration. We have started to prepare our next issue for September of this year. If you have any ideas, suggestions, or stories, please get in touch and drop us an email at **magazine@ligo.org.**

Andreas Freise
for the Editors

Andreas Freise

LIGO Scientific Collaboration News

I hope you have enjoyed a happy holiday season with family and friends – we are now highly engaged again in the 2014 activities in the LSC and elsewhere.

The Election and Membership Committee has been very busy over the past few months. Barry Barish and Peter Saulson were elected to the LSC Executive Committee, replacing Nergis Mavalvala and Laura Cadonati, who is continuing as member of the Executive Committee due to her new role of LSC Data Analysis Coordinator. Roman Schnabel and Matt Evans were elected chairs of the Quantum Noise and Advanced Interferometer Configuration working groups, respectively, replacing Yanbei Chen and Rana Adhikari. Ik Siong Heng was elected co-chair of the burst group, replacing Laura Cadonati. Jocelyn Read is the new co-chair of the LSC Academic Advisory Committee, replacing Alberto Vecchio. The 2013 elections for LAAC positions also saw Beverly Berger elected new Senior Member, replacing Laura Cadonati, and Matthew Pitkin and Maggie Tse elected Postdoc and Graduate Student Representatives, respectively, replacing Jocelyn Read and Laura Nuttall. As we write, nominations are sought for candidates in the elections of Optics, Suspension and Isolations, Stochastic, Con-

Gaby (Gabriela) González
LSC spokesperson

GGonzález

tinuous Waves, and Compact Binary Coalescence working group co-chairs. Many other groups and committees saw new appointments in the last months of 2013. David McClelland was appointed chair of the Instrument Science working groups, replacing Rana Adhikari, Laura Cadonati and Steve Fairhurst were appointed co-chairs of the Data Analysis Council and the Publications and Presentations Committee, replacing Maria Alessandra Papa and Ray Frey, respectively, who stepped down after many years of service. We thank all new and past chairs, as well as all election candidates, for their important service to the collaboration!

By the time you read this, we will likely have signed many agreements with astronomy collaborators to prepare for the first observing run in 2015 with Advanced LIGO detectors, ready to follow up interesting gravitational wave candidates in the electromagnetic spectrum. The future is close, and we have a lot of work to do to be ready ourselves for the smooth and fast searches of the detectors' data. We will also have signed the most important agreement we have, with our Virgo colleagues. We are all together entering the new era of advanced detectors!

The Diversity Committee is now a joint LSC-Virgo Committee with Pia Astone serving as Virgo co-chair. Following the recommendation of the Diversity Committee, the LSC Council approved in September new "Best Practices" for the Collaboration (LIGO-M1300501). We invite everyone to read and follow these best practices to help maintain a welcoming environment for all LSC members. If you have at heart diversity issues (and we know many of you do!), please join the Diversity Committee by subscribing to the **lsc-diversity@ligo.org** mailing list.

We are discussing many important issues in the collaboration, like how to best (and fairly) give academic and visible credit to all contributing LSC members, especially those looking for career opportunities. Your opinions are very important – please let us know what you think, answering surveys and talking or writing to us.

Thanks again to all for your important contributions – that is what makes our science exciting and our collaboration strong. Keep up the good work!

Gaby and Marco.

Before each major installation effort at LIGO Livingston the entire installation team meets to go over the installation procedure and safety protocols. This meeting was held before the Beam Splitter cartridge install, which was our first cartridge installation at LLO.

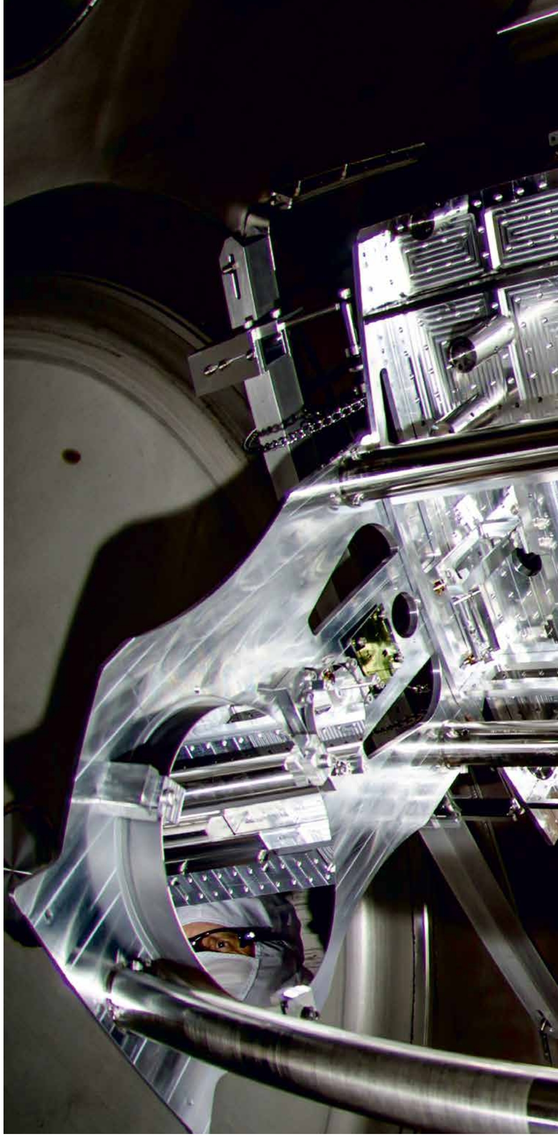
▼

Installation of the Advanced LIGO detector at LIGO Livingston

For the past three and a half years, the assembly and installation of the Advanced LIGO (aLIGO) detectors has been in progress at both LIGO Observatories. The process began in October 2010, and now, in March 2014, the first installation is near completion at the Livingston Observatory.

Brian O'Reilly

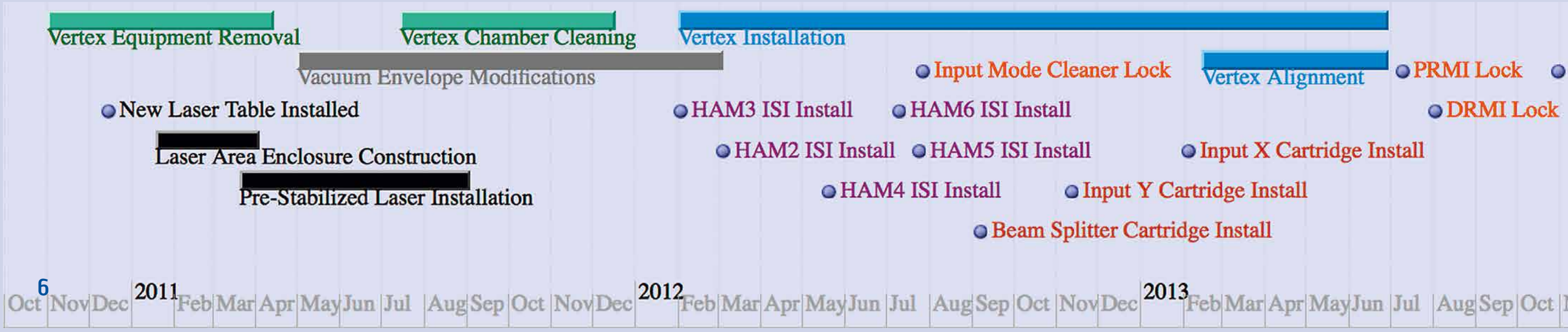
Brian O'Reilly is a Senior Staff Scientist at the Livingston Observatory, where he oversees Advanced LIGO activities including installation. Young children, a dog, and the occasional hurricane account for that aspect of existence previously known as "spare time".

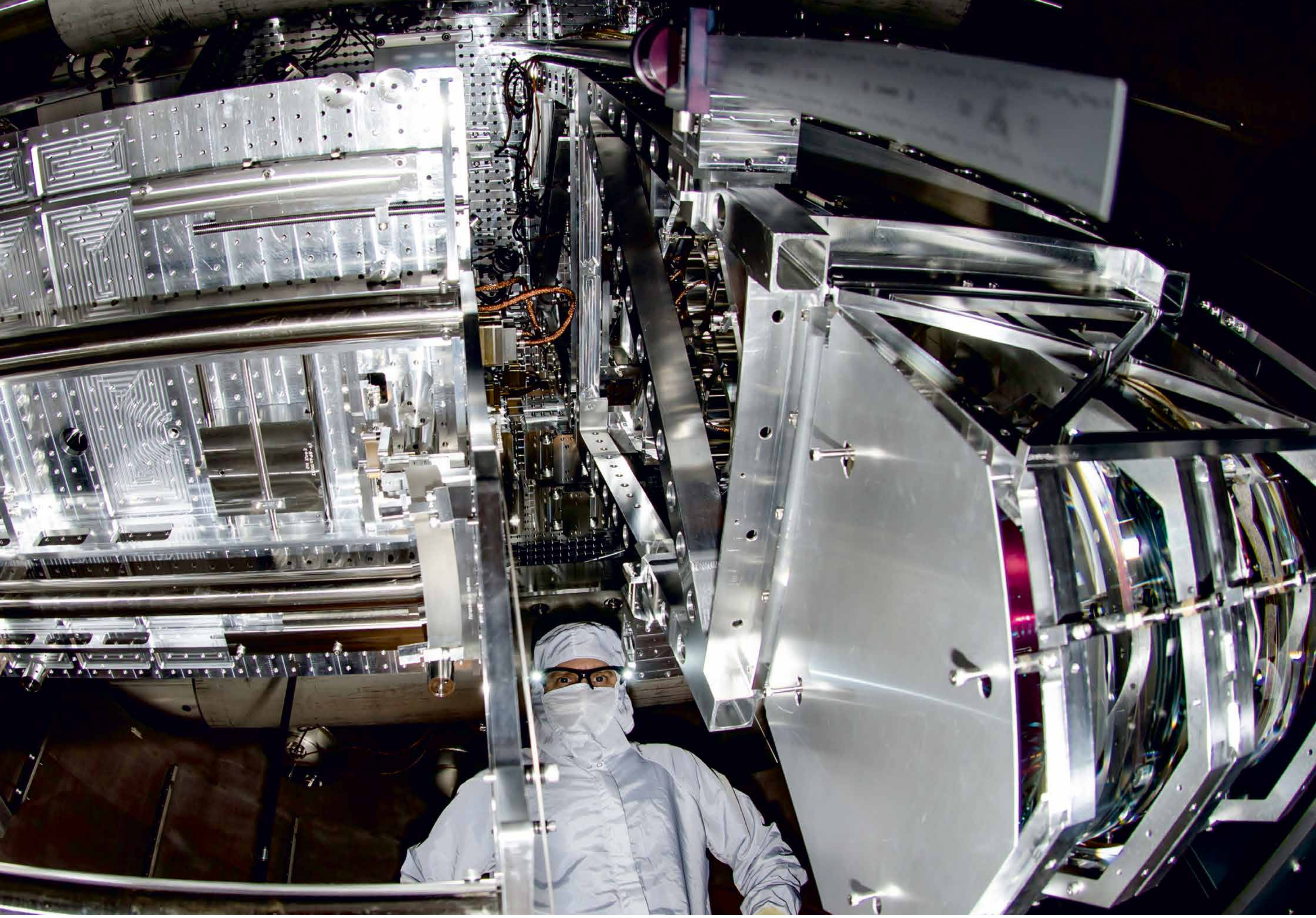


▲ *A fisheye view of the installed ETMX cartridge, Gary Traylor (center) taking a final look before closing out the chamber. His reflection to the left is from one of the TMS mirrors which carries light from the cavity up to the TMS telescope and also doubles as part of the injection path for the green laser light used to lock the arm cavity.*

The process began with the removal of the initial LIGO (iLIGO) components. We started in the vertex region of the interferometer. This is the area which contains the input and output components, the Beam Splitter and the two test masses that form the input side of the detector arms. By late November of 2010, all of the input and output chambers had been emptied. By mid-February of 2011, the Beam Splitter and Input Test Mass chambers were similarly empty, and we began the process of removing the input and output tubes and reconfiguring the vacuum envelope. This involved relocating two of the input chambers: one on the input arm and one on the output arm. (See also the two articles in Issue 1 of the LIGO Magazine which cover this phase of activity: "Under construction: Advanced LIGO" by Mike Landry and Brian O'Reilly and "Vacuum System Modifications in Advanced LIGO" by Dale Ingram.)

We then embarked on a lengthy process of cleaning each vacuum chamber to remove an oxide layer that was formed during the initial construction of the vacuum envelope. We realized during iLIGO that this oxide layer was not fixed and was contributing to particulate contamination of the in-chamber environment. Removal involved using rotary steel brushes to scrub the interiors of all the chambers. Vacuum hoses attached to the tools removed the dislodged particulate. To avoid hydrocarbon contamination of the interior, we had to use minimal lubrication, and it took several months to get a workable set of tools in place. Chamber cleaning began in earnest in mid-July of 2011, and all chambers, with the exception of those at the end of each arm, were cleaned by years' end. Cleaning of the end chambers was



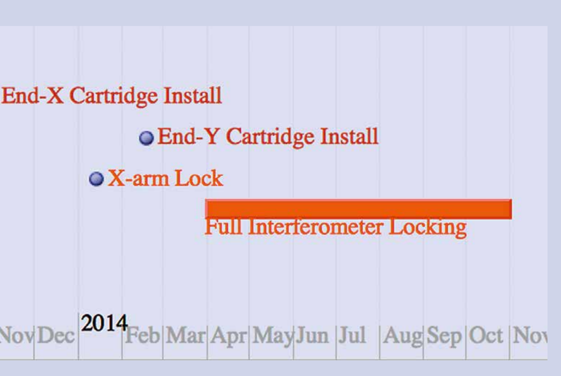


deferred due to manpower availability and other vacuum work.

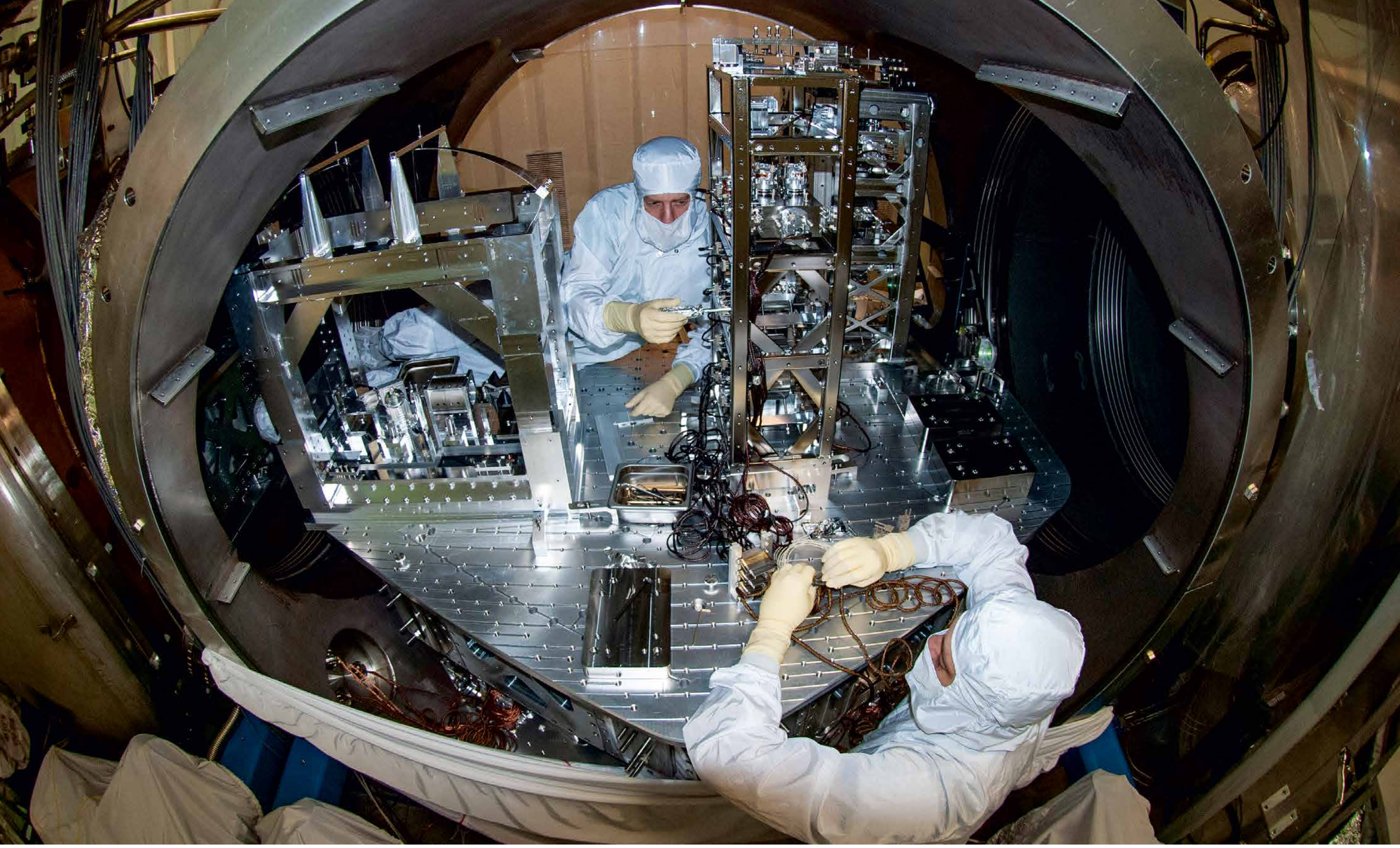
The first installations in the input and output chambers were of the Internal Seismic Isolation (ISI) Platforms. For the Beam Splitter and Test Mass chambers (BSC), both at the input and end, we performed a "cartridge" installation. The "cartridge" is our term for the combination of the seismic isolation platform, the suspension for the optic and any other ballast mass or in-vacuum components that hang from the isolation table. This cartridge was then inserted as a unit through the top of the BSC chambers. The input and output chambers were populated by first installing the ISI platform, and then mounting the optics on the table surface. These "HAM" (Horizontal Access Module) chambers contain the input mode cleaner (IMC), power recycling (PRC) and signal recycling cavities (SRC), along with in-vacuum input and output electronics and optics.

The attached timeline is an indication of the pace of progress of the installation in each chamber. As the project continued the time between platform installations slowed due to the work required for insertion and testing of optical components. Additionally, the later chambers were all cartridge installations with increasing complexity. The beam splitter is a wire-hung triple suspension and is comparatively simple compared to the glass-fiber suspended input test mass in a quadruple suspension, complete with a reaction chain. The end test mass is similar to the input test mass, but with the addition of a suspended transmission monitoring telescope, which doubles as an injection path for a green laser beam used to lock the arm cavities.

The installation of ISI platforms in the vertex took one year, and it took another full year to install the two end station cartridges. This is in large part due to concentrating on populating the vertex chambers and preparing for dual recycled Michelson Interferometer (DRMI) commissioning. The first IMC lock occurred on July 28th, 2012, just a couple of days after we completed installation work in the HAM2 and HAM3 chambers. The power recycled Michelson Interferometer (PRMI) was first locked on July 10th, 2013, again quite quickly after closing the vertex chambers. Stable locking of the DRMI was achieved on August



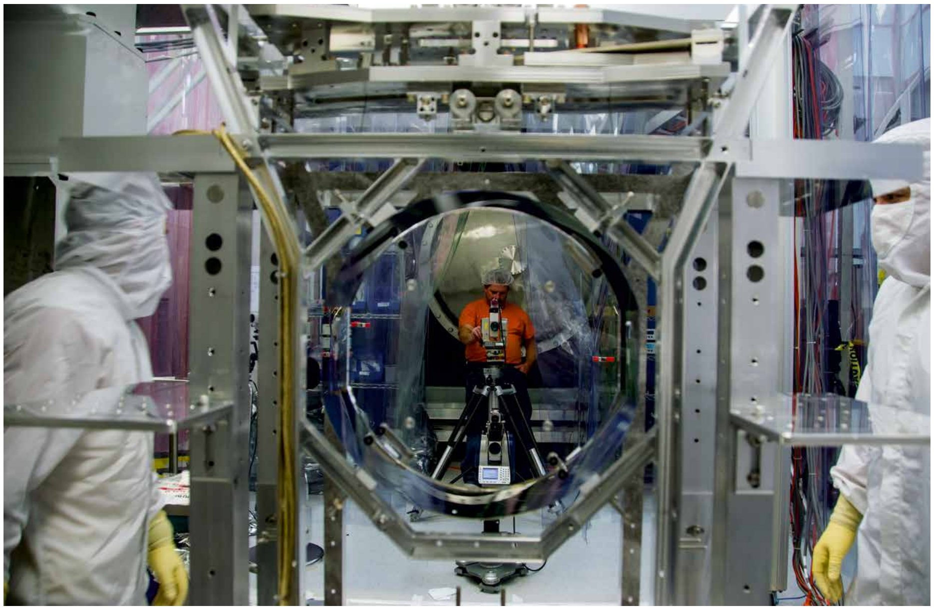
Notable events in the Advanced LIGO installation at LIGO Livingston.



Matthew Heintze (Front) and Danny Sellers (Back) installing suspension cables in HAM5. The Output Faraday Isolator, suspended by wire from two blade springs, is visible on the left. In the foreground on the right is the Signal Recycling Mirror (SRM), and in the background is the SR3 suspension.

3rd; the rapid progress was due in part to careful installation and alignment. Aligning the vertex optics began in early February of 2013 and continued for four months ending early in June. We have made several incursions into the vertex since this first lock to fix or add stray light control baffles, clean optical components and to mitigate problems found during commissioning. Differential heating of the suspension wires on one of the Power Recycling optics, due to stray light, was causing the optic to pitch and affecting the cavity alignment. The solution was to install oxidized sheet metal baffles on the suspension cage in order to shadow the wires in question.

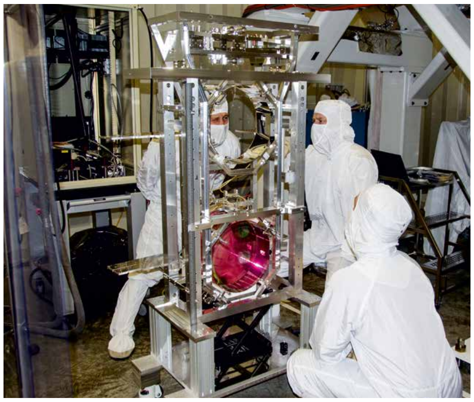
The installation of the cartridge at the X end was followed by two months of intense in-chamber work; testing the installed cartridge; finishing the installation of stray light control baffles; Installing photon calibrator telescopes, which will use radiation pressure induced motion of the test mass to calibrate the instrument; and alignment. This work was finished by the end of December 2013, and we had our first lock of the X-arm cavity in early 2014.



Joe Hanson (center) setting up to monitor the alignment of the ETMY Test Mass optic during fiber welding. The pitch, yaw, roll and height of the test mass are all tracked during the process of welding glass fibers between the penultimate mass and the test mass. Careful alignment on the test stand saves considerable time and effort post-installation.

Members of the installation team after successful installation of the ITMX cartridge. Back Row Left to Right: Adrien LeRoux, Matthew Heintze, Jeremy Birch, Harry Overmier, Bryan Smith. Front Row Left to Right: Hannah Rodriguez, Gary Traylor, Celine Ramet.

Keeping the vacuum interior, and especially the optics, free of contamination is a major ongoing effort. Here Danny Sellers photographs the ITMX optic using lighting provided by Matthew Heintze.



From Left to Right: Gary Traylor, Danny Sellers and Travis Sadecki inspect the ETMX penultimate optic after fiber welding. The welding process involves using a CO2 laser to bond the glass fibers to "ears" on the Test Mass barrel. These welds are then annealed using the same laser. Any imperfections in the weld must be corrected before suspending the 40 kg test mass.

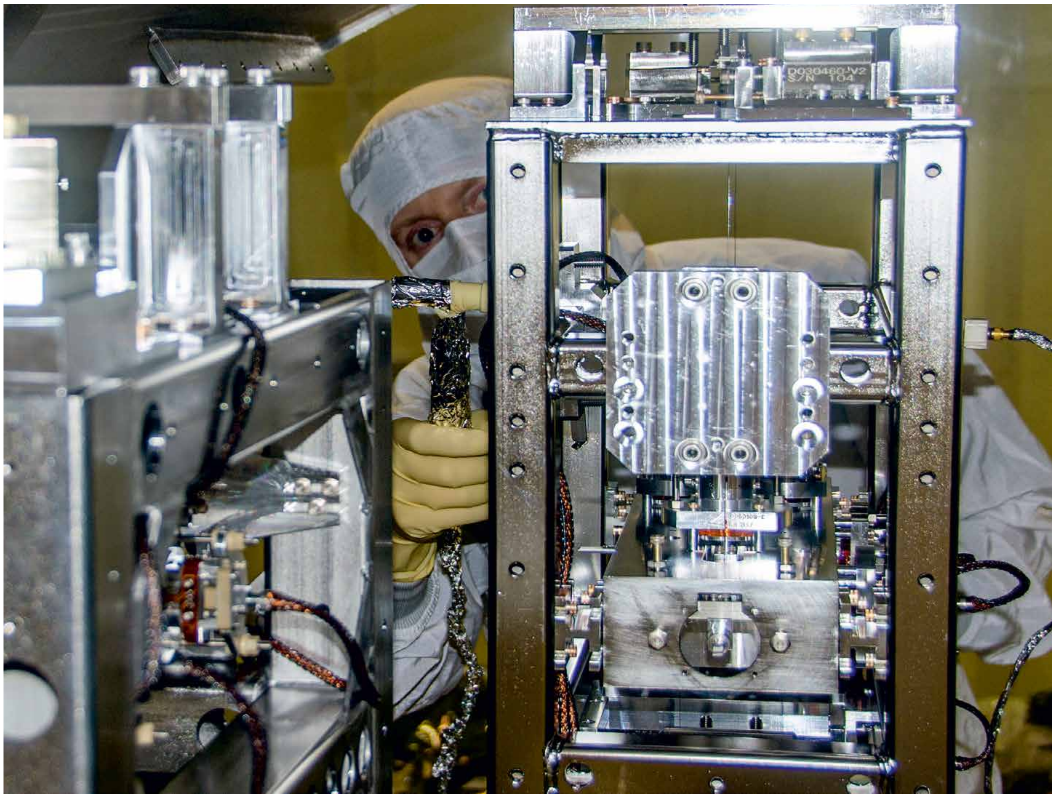
The Y-end cartridge install in late February of 2014 has been followed by an identical period of in-chamber work. The balance of the month of February and all of March was spent on closing out this chamber. We expect to begin locking the Y-arm cavity in early April 2014, with full interferometer locking to follow soon after.

A summary such as this glosses over many of the details that go into such a complex endeavor. Some of these efforts will continue during the aLIGO era. A good example is contamination control, which concentrates on ensuring the cleanliness of the in-vacuum environment. This has grown into a complex and systematic venture in its own right, complete with specialized tooling and training. We are already seeing significant improvement in the level of particulate in the chambers.

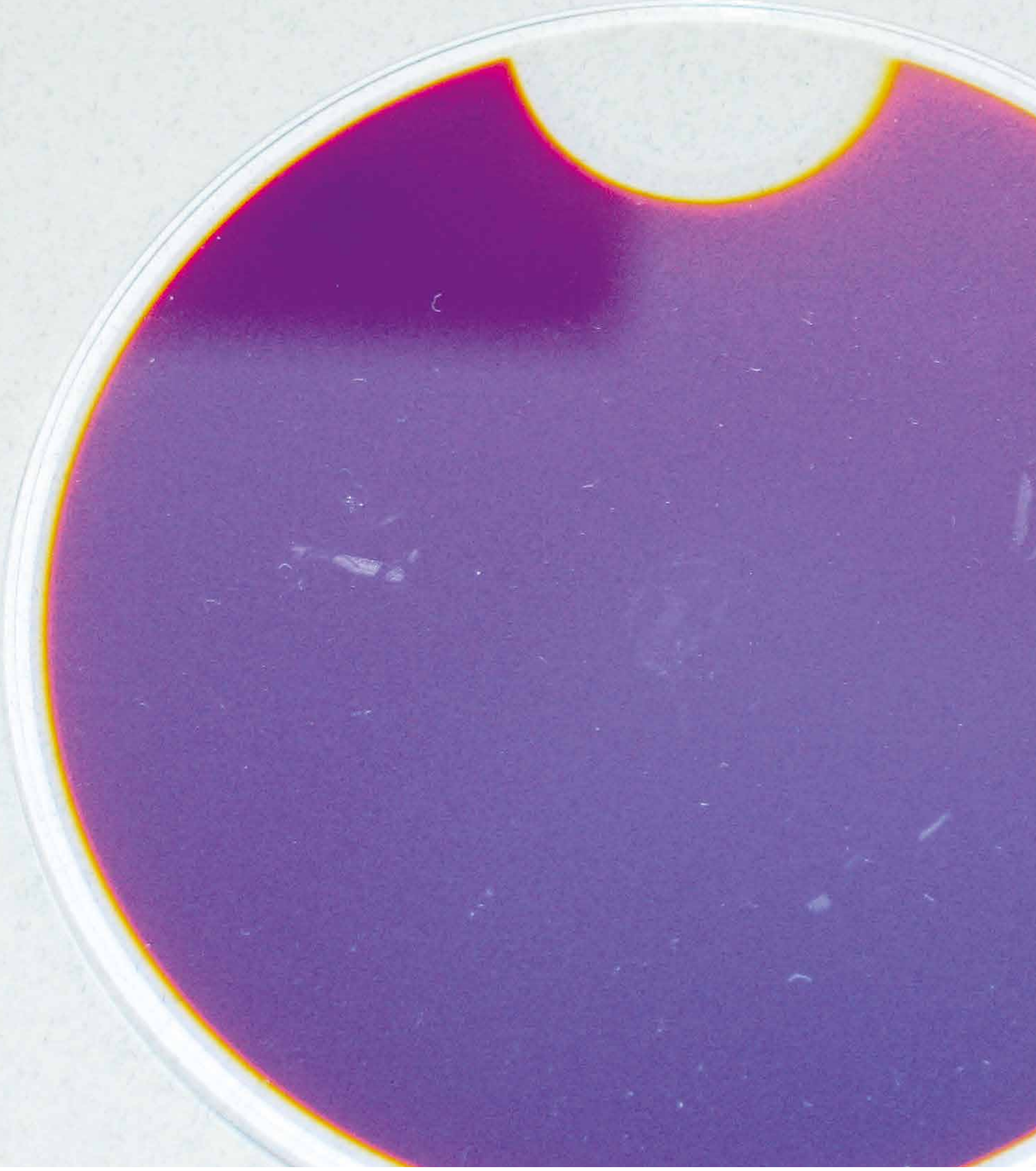
The installation of the advanced LIGO detector at Livingston is now essentially complete, and the commissioning efforts, which were already in progress, will now assume center stage. The goal is to achieve full interferometer operation before years' end. It has been a busy and productive period in LIGO's history, and sets the stage for an exciting period of scientific investigation and discovery.

Acknowledgements: The author wishes to thank the many people who worked diligently to make the installation process a success. Our excellent local staff has benefitted greatly from the many expert visitors who travelled to the site from all over the world to work with us on this great endeavor.

Stuart Aston using a Brüel & Kjær hammer and a tri-axial accelerometer to excite and measure structural resonances of the Signal Recycling Mirror in the HAM5 chamber. The Brüel & Kjær hammer provides a calibrated impulse to the structure and allows us to verify that the first structural mode of the suspension is consistent with model predictions and meets requirements.



History of Advanced LIGO Coating Research

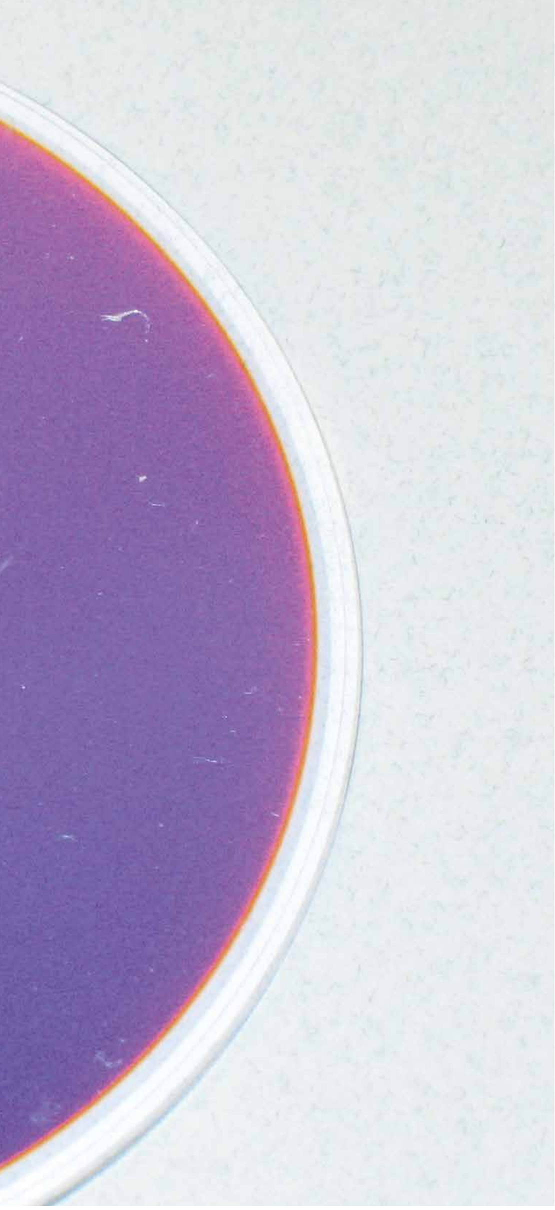


Gregg Harry

Gregg Harry, an Assistant Professor at American University, researches thermal noise issues. He enjoys raising a six-year old daughter and playing the board game Diplomacy.

The Advanced LIGO coating story starts with a 1998 paper written by Yuri Levin, then with Kip Thorne's group at Caltech. Levin described a way to use the fluctuation-dissipation theorem (FDT) to directly calculate the thermal noise arising from an interferometer mirror. Thermal noise represents the thermally-driven collective motion of atoms, in this case atoms in the mirror. A gravitational wave interferometer cannot discriminate between thermal noise and mirror displacements, meaning that the noise is indistinguishable from gravitational waves. According to the FDT, the source of fluctuations (i.e. atomic motion) also causes energy dissipation. The amount of mechanical loss determines the extent of atomic motion - low mechanical loss means low thermal noise. Before Levin's paper, researchers used the mechanical loss of the entire mirror to calculate the mirror's thermal noise. Sometimes referred to as the "Q" method, this technique produced a value for the mechanical loss through the measurement of quality factor (Q) of a mirror vibration normal mode. High Q systems display low thermal noise and lose energy very slowly.

Levin wrote that the thermal noise contribution from a mirror depends on the extent to which the interferometer beam interacts with the mirror material. Consequently the mirror surface coating, although very thin, must strongly contribute to the optic's overall thermal noise profile. LIGO found this result very disturb-



Silica disk test sample coated with experimental coating for consideration for use in Advanced LIGO. This sample has its quality factor, Q, measured both with the coating in place and without. The difference in Q, along with computer modeling of how the sample bends, allows the mechanical loss of the coating to be calculated. This, in turn, allows for the coating thermal noise in Advanced LIGO to be predicted. The half-moon region without coating serves as the weld spot for a thin silica fiber. This fiber supports the disk during measurement without contributing significantly to the Q. If the coating is too close to the fiber, it would degrade under the heat used to weld the fiber to the disk.

ing. Although the substrate mechanical loss was reasonably well understood and low, the coating loss remained a mystery. High coating losses might mean that the thermal noise contribution from 7 microns of coating might overwhelm the contribution from 10 cm of substrate.

The revelation that test mass thermal noise critically depends on optical coatings sparked significant interest within the LIGO instrumentalist community. Levin's paper provided a formula to calculate thermal noise using the coating parameters, the most important of which is the mechanical loss angle. But neither the LIGO community nor the wider field of optics research knew the mechanical loss of the thin film silica and tantala coatings used by Initial LIGO. As in many research areas, LIGO needed to blaze a new trail. No previous optical measurement had been limited by coating thermal noise; no need had existed for the calculation.

I joined Peter Saulson's Syracuse group just after the publication of Levin's paper. Andri Gretarsson, Steve Penn and I sought to measure the loss angle of coating materials. Glasgow, Stanford, the LIGO Lab and others collaborated with the Syracuse group on the study of coating thermal noise.

We coated thin silica substrates to determine losses, meaning that our results would differ significantly from those in the much thicker LIGO mirrors. We measured the Q for thin samples. By calculating the fraction of energy in the coating we could determine the coating's mechanical loss. At Syracuse we developed a technique for Q measurements in which we welded glass fibers to the coated samples. I quickly learned that LIGO coatings crystallize and fall apart when heated with a flame. The optics community knew this well, but not a typical postdoc just arriving from the field of resonant mass gravitational wave detection. We soon obtained successful Q measurements by making samples with no coating near the weld point. Uncoated fused silica substrates would ring for many minutes in vacuum. Once coated, the samples rang for less than 30 seconds - a much lower Q, thus high mechanical loss and high thermal noise. The Syracuse measurements agreed with similar results from Stanford's Sheila Rowan, now the head of the Glasgow group, and in Glasgow by David Crooks and Peter Sneddon with guidance by then Glasgow head Jim Hough. David and Peter have since left the LSC.

Simultaneous with these early measurements, members of our coating collaboration applied Levin's theorem to obtain a formula for LIGO test mass coating thermal noise due to mechanical loss. Many individuals contributed; the resulting Gretarsson-Nakagawa formula is named for Andri Gretarsson and Norio Nakagawa who played leading roles in its development. This formula and the Q measurements from Syracuse, Stanford, and Glasgow gave us the means to calculate thermal noise in LIGO test masses.

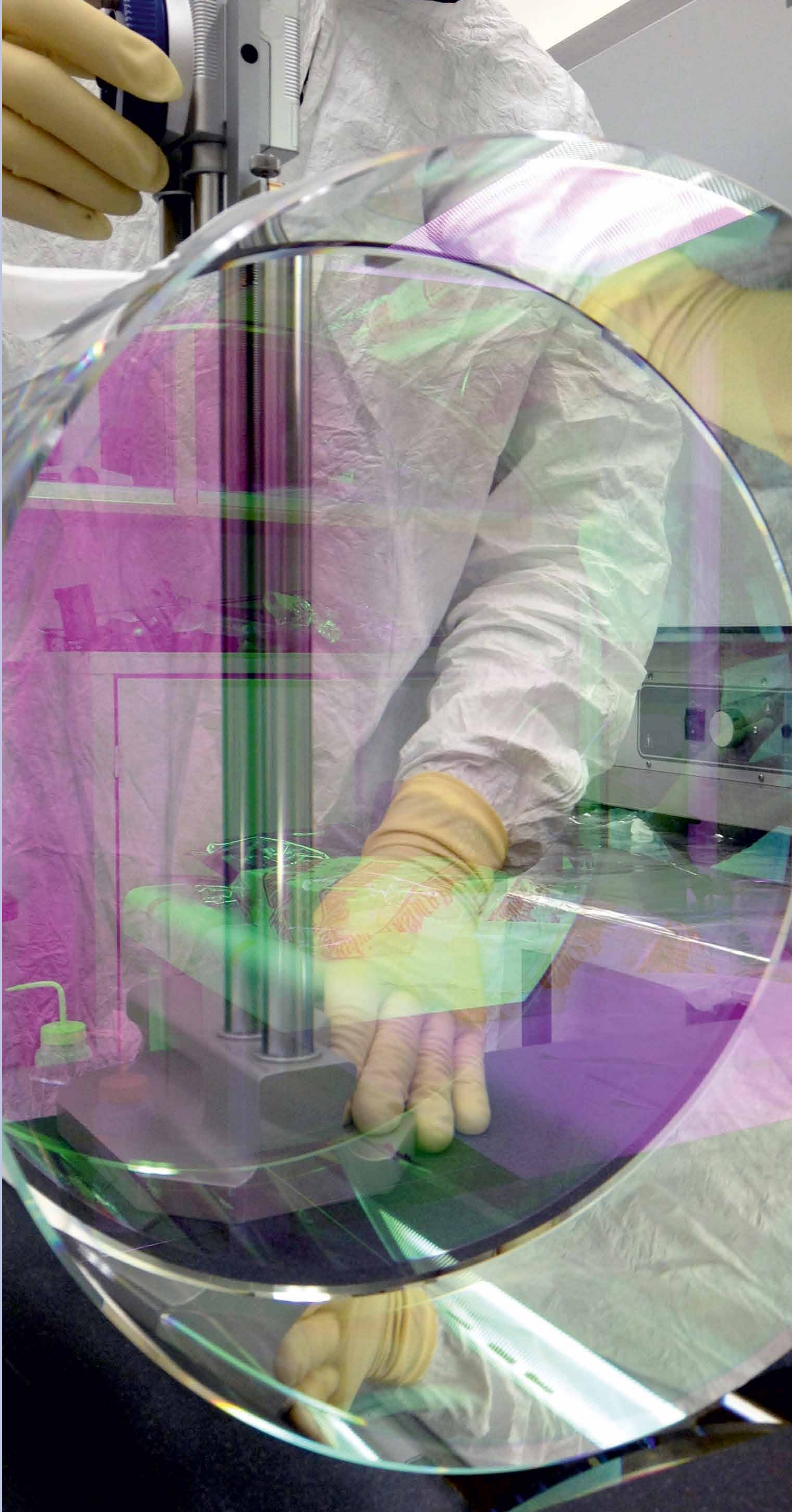
The good news: Coating thermal noise most likely wouldn't limit the performance of Initial LIGO. The bad news: A detector with tenfold better sensitivity definitely would face a coating thermal noise challenge. This result arose just as early ideas for Advanced LIGO were coming together. We knew at this time that coating thermal noise would place a substantial hurdle in the path to a more sensitive detector.

As a first step in improving the coating thermal noise we needed to understand the cause of poor mechanical loss. The collaborators developed a research program to test three primary hypotheses: 1) Mechanical loss was intrinsic to the coating materials (internal friction). 2) Dissipation occurred between the coating's alternating layers of silica and tantala. 3) Dissipation occurred at the interface between the

Coating thermal noise was originally just a problem for gravitational wave detectors, but in the last few years some other experiments have become sensitive enough that they are limited by it as well. I first became aware of this through Nergis Mavalvala when we were both at MIT. Her work spans the two fields of gravitational wave detection and quantum optomechanics. She introduced me to Markus Aspelmeyer, a quantum experimentalist who was having problems with coating thermal noise in his experiment. We talked about having a meeting of everyone with an interest in coating thermal noise, and the result was the 2008 Workshop on Optical Coatings in Precision Measurements held at Caltech following an LSC meeting. We had representatives not only from the gravitational wave and quantum optomechanics field, but also the disciplines of frequency stabilization and cavity quantum electrodynamics as well as coating vendors.

The Workshop went well, but this collaboration was taken to the next level by a discussion at the 12th Marcel Grossmann Meeting in Paris. There was a representative from Cambridge University Press at MG12, and he and I discussed turning the coating workshop into a book. Editing a book turned out to be a big job. I was helped by co-editors Tim Bodiya and Riccardo DeSalvo as well as over twenty five authors, including representatives of all the fields at the Workshop. There are technical chapters on different aspects of coating thermal noise, primarily written by LIGO authors, and also chapters on each application that is limited by coating thermal noise. Finally in 2012 the book was published.

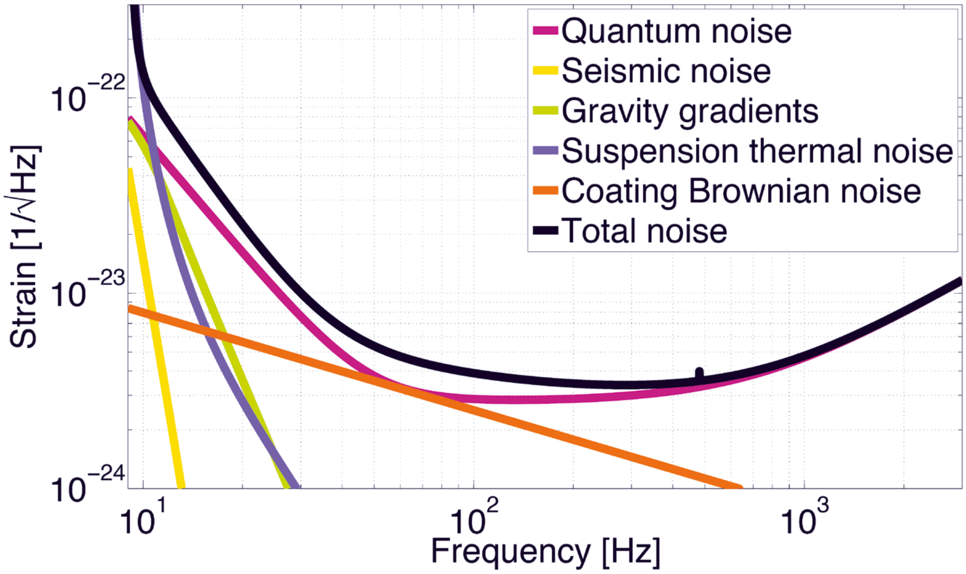
One very tangible result that came out of the book was a collaboration between LIGO and Garrett Cole, then a postdoc working with Markus. Garrett is an expert in aluminum gallium arsenide (AlGaAs) coatings and is working with a number of us on developing AlGaAs for future gravitational wave detectors. AlGaAs has had great success in quantum optomechanics and frequency stabilization experiments bringing down thermal noise. All the optical, mechanical, and thermal needs of a coating for gravitational wave detectors, however, make it not straightforward to translate that success to LIGO. Even so, AlGaAs is one of the better options for future LIGO coatings, and it came to us through this collaboration with other precision measurement fields. - GH



coating and the silica substrate. The data clearly pointed to internal friction as the culprit and internal friction in the tantala in particular. Our direction became clear: Find coating materials with lower intrinsic internal friction from which to build the Advanced LIGO coating.

Our choices for possible materials were quite limited because the Advanced LIGO coating must meet a number of performance specifications in addition to thermal noise, such as low optical loss (both absorption and scatter), high uniformity, matched performance of paired optics in an interferometer, and thermal stability. Low optical absorption, important to minimize the amount of laser power that converts to heat, represents a stringent requirement. Proper performance of the Advanced LIGO thermal compensation system dictates that Advanced LIGO coatings typically can display no more than 0.5 parts per million (ppm) absorption, a performance level significantly beyond the capabilities of coating vendors when we started the Advanced LIGO coating research program. Results from laser gyroscope development pointed to silica, tantala and titania as very low absorption coatings. The cross-pollination from ring laser gyros to LIGO occurred through LIGO Lab engineer Helena Armandula, who had worked on coating development before coming to Caltech. Marty Fejer's group at Stanford, through measurements produced by Ashot Markosyan, provided an understanding of the details of absorption in LIGO coatings.

◀ *Jeff Lewis carefully measures the diameter of an End Test Mass at Caltech. The precise diameter must be known in order to calculate the position where the fused silica ears will be placed. The ears are bonded to the side of the optic and serve as the point of contact between the optic and the fused silica suspension fibers.*



Advanced LIGO noise curve showing coating thermal noise (in red) limiting sensitivity

The notion of pairing titania-doped tantala with thin film silica for the Advanced LIGO coating originated with the larger-than-life head of the coating facility Laboratoire Material Advancee (LMA), Jean-Marie Mackowski. His idea was inspired. The addition of titania to tantala not only improves mechanical loss but also slightly improves the absorption and even increases the index of refraction, which permits thinner coatings for a given value of reflectivity. Q measurements identified the best concentration of titania in tantala. The Advanced LIGO coating materials fell into place.

An effort to directly measure coating thermal noise occurred in parallel with the Q measurement program. Direct measurements would provide a large challenge — an interferometer as sensitive as Initial LIGO did not see coating thermal noise. Eric Black at Caltech's Thermal Noise Interferometer led this work along with Kenji Numata at the University of Tokyo as part of his thesis research. Direct observation of coating thermal noise in both locations produced additional confidence in both the Gretarsson-Nakagawa equation and the mechanical loss numbers from Q measurements.

Concerns existed that thermally-driven fluctuations in coating index of refraction and layer thickness, collectively called thermo-optic noise, might act as an important noise source in Advanced LIGO. This is a different phenomenon than so-called Brownian thermal noise which arises from mechanical loss. Theoretical work led by Matt Evans of MIT showed that the two parts of thermo-optic noise can partially cancel each other because both parts are driven by the same thermal fluctuations. We expect that Advanced LIGO won't incur a performance limit from thermo-optic noise; this circumstance might change for future detectors. Andri Gretarsson, now at Embry-Riddle Aeronautical University, and Greg Ogin at Whitman College continue to explore thermo-optic noise.

Titania doping yielded modest improvements in thermal noise. The level of interferometer sensitivity necessary to detect an "average" binary neutron star inspiral at 200 Mpc (the Advanced LIGO design goal)

▲

Photo of the largest Ion Beam Sputtering (IBS) coating machine at LMA in which the Advanced LIGO test masses are coated. Thanks to the large coating chamber, two mirrors can be coated at the same time to ensure similar characteristics for both mirrors. The coating machine (as well as the metrology instruments) reside in a class 1 clean room.

would require more progress. Significant improvement comes from increasing the size of the laser spot on the input and end test masses. Larger spots provide better averaging of the thermal noise at each point on the mirror and a better overall noise value, but larger spots create more challenges in the polishing process. Test mass polish also determines the minimum achievable scatter. LIGO initiated a research project on polishing, led by LIGO Lab's Garilynn Billingsley, who also has overseen Advanced LIGO test mass development, procurement, and installation in her role as Advanced LIGO Core Optics leader.

Optimization of each coating layer thickness generated some small further thermal noise improvement. Even with titania doping, tantala layers contribute more thermal noise than silica layers. Innocenzo Pinto of the University of Sannio and his collaborators developed a coating layer recipe to minimize thermal noise without compromising test mass reflectivity. Innocenzo's improvement arrived just as LIGO's Interferometer Sensing and Control group decided to use green light for long arm lock acquisition. The coatings must provide specific reflectivities at the green wavelength along with the infrared wavelength of the main interferometer laser. Fortunately the Pinto thermal noise optimization for the coating design worked well for the green beam. No agonizing trade-offs were needed.

Finally a complete design for the Advanced LIGO test mass high reflective coatings was born. My story doesn't cover details concerning the anti-reflection coatings, the beam splitter coating, the recycling mirrors or the auxiliary optics –only the test masses, which now could undergo fabrication. LMA, the developer of the titania doping technique, became the vendor. Very few coating facilities can coat two 40 kg silica mirrors at the same time, much less at the specifications required by Advanced LIGO. CSIRO in Australia - the Commonwealth Scientific and Industrial Research Organization – received a contract to coat the beam splitters, recycling mirrors, and other Advanced LIGO optics.

LMA and CSIRO, world-class coating facilities, have faced challenges in optimizing their processes for their Advanced LIGO contracts. LMA installed a planetary gearing system to reach the coating uniformity requirements. CSIRO needed to fine-tune its annealing process to deal with the surprisingly high anti-reflection absorption. Bill Kells and Hiro Yamamoto at Caltech have extensively studied uniformity concerns to ensure that the final optics meet LIGO's requirements. Livingston and Hanford have received the L1 and H1 test masses; several of these now reside in the vacuum with the remainder in the installation queue. The vendors continue to deliver backups and third interferometer optics.

Significant coatings progress notwithstanding, we project that coating thermal noise will limit Advanced LIGO sensitivity between about 40 Hz and 200 Hz. Improved coatings represent a possible enhancement to Advanced LIGO.

Research into improved coating materials and techniques continues on a number of fronts. Valuable work led by Riccardo Bassiri to understand the molecular causes of mechanical loss is underway at Stanford, Glasgow, Southern University and other LSC institutions. This research expands on previous work led by Southern's Steve McGuire and utilizes the Stanford Synchrotron Lightsource. These experiments complement computer modeling work on the sources of mechanical loss by Hai Ping Cheng at Florida and Rachel Vincent-Finley at Southern, with collaborators at Glasgow and elsewhere.

Annealing an amorphous coating can reduce its mechanical loss, but most coatings break down or crystallize at high temperature. Steve Penn at Hobart and William Smith Colleges seeks to develop lower loss coatings that survive these high temperature anneals.

Very thin coating layers may provide lower mechanical loss and could achieve the same optical performance as normal coatings with lower thermal noise, a concept under study by Innocenzo Pinto, Riccardo DeSalvo, and Shiuh Chao.

Temperature reduction provides a straightforward way to reduce thermal noise and is under examination at Glasgow by Iain Martin and others. Temperature also drives mechanical loss and other coating parameters, potentially limiting the gains available from cryogenics.

Crystalline materials show promise with respect to mechanical loss, although their optical properties do not, thus far, rival silica/tantala. Angie Lin at Stanford focuses on aluminum gallium phosphide while aluminum gallium arsenide has drawn the attention of Steve Penn and I and others in the LSC in collaboration with Garrett Cole from quantum optomechanics.

All-reflective interferometry, including grating reflectors, may allow for greater absorption tolerance.

Shaping the arm cavity beams can improve averaging in a way that mimics the effect of larger spot sizes. Kip Thorne first addressed this issue on the theoretical side, with many contributing since then. Experimentally, Riccardo DeSalvo at Caltech first explored different beam shapes and Andreas Freise's Birmingham group has followed suit. Dave Ottaway at Adelaide and Stefan Ballmer at Syracuse have offered a recent idea for a folded cavity design that can reduce coating thermal noise. Vladimir Braginsky has even proposed designs for nearly coating-free mirrors. Many promising techniques are emerging for the making of reflective surfaces that will enhance gravitational wave astronomy.

Can you solve our unique LIGO sudoku puzzle?

LIGOku grid

	G		h	L				
	h				M			+
×	M	+				h	G	
M								
	L	×		+		c	M	
								G
	f	M				L	η	h
h			η				c	
				h	G		+	

Standard Sudoku rules apply!

Each row, column and 3 x 3 box should contain exactly one of the nine symbols commonly used in gravitational wave physics: c: The speed of light; h: The gravitational-wave strain; f: The frequency of the gravitational wave; η: The Minkowski metric; G: The gravitational constant; +: The "plus" polarization; ×: The "cross" polarization; L: The length of one LIGO arm; M: The chirp mass. – by Martin Hendry

Looking to the Future: LIGO and Virgo in 2020

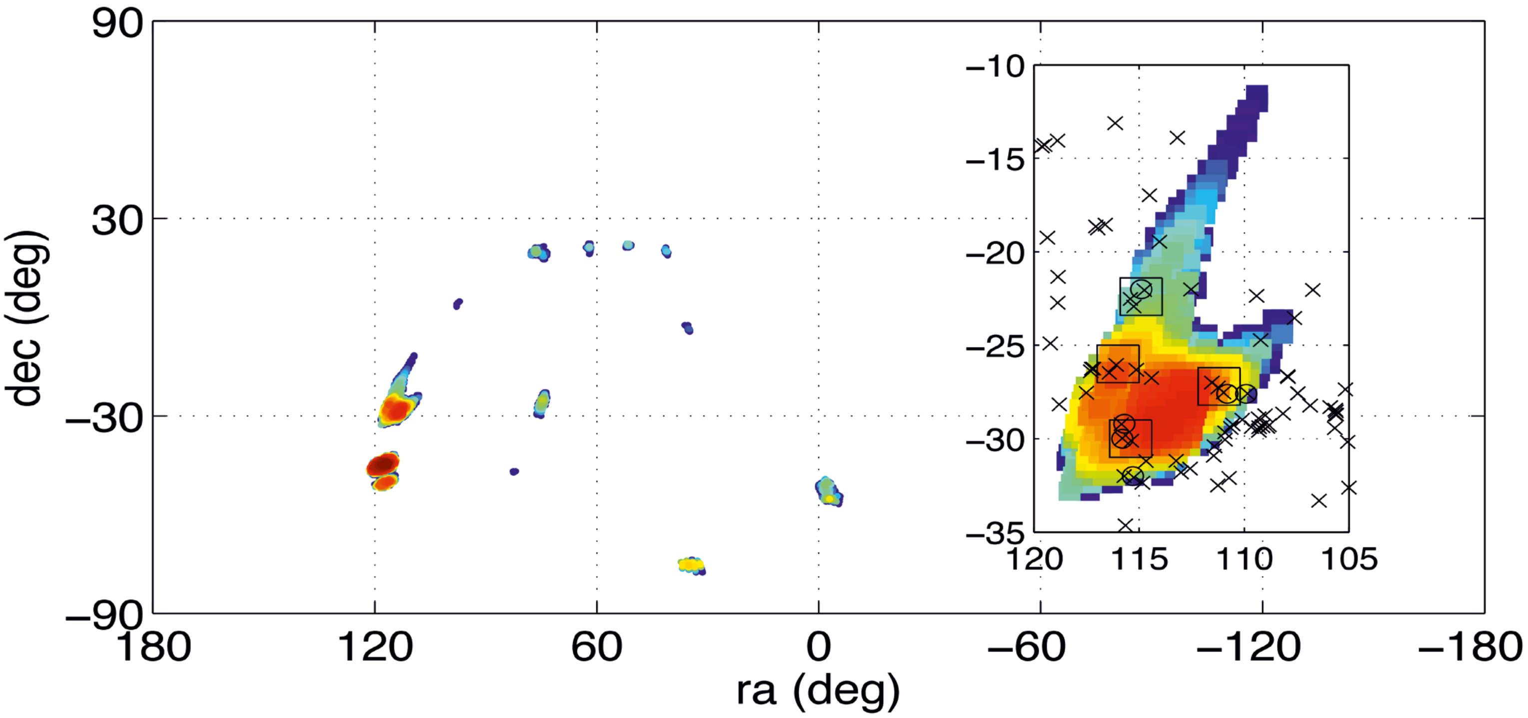
Patrick Sutton

Patrick Sutton is a Reader at Cardiff University. His research focuses on the detection of gravitational-wave bursts associated with supernovae, gamma-ray bursts, and other astrophysical transients. His personal research focuses on single malt whiskies from Islay and rums from the Caribbean and Latin America.

At each successive LIGO-Virgo meeting there is a palpable excitement about the progress of the second generation gravitational-wave interferometers. But this excitement is not confined to our Collaborations; there is also growing enthusiasm among the wider astronomy community for the science that can be done with Advanced LIGO and Advanced Virgo. And with little surprise - the history of astronomy shows that the opening of each new waveband has revealed new insights into the Universe. In the case of gravitational waves, we have known for a long time that their combination with electromagnetic observations will be greater than the sum of the parts. A classic example is Bernard Schutz's seminal 1986 paper in which he showed that gravitational waves from binary neutron star mergers are standard candles which, if combined with redshift observations, could be used to determine the Hubble constant without need for the famously tricky cosmological distance ladder. Indeed, LIGO and Virgo have a long history of looking for gravitational waves associated with violent phenomena seen by electromagnetic observatories, such as gamma-ray bursts. Short-duration gamma-ray bursts are particularly exciting because they are thought to be produced by neutron-star mergers, Schutz's standard candle, which are arguably the most common detectable source for LIGO and Virgo.

More recently, a lot of thought has been devoted to the converse: can we find electromagnetic transients associated with candidate gravitational-wave events? The first effort was made in the last joint science run of LIGO and Virgo (2009-10). Rapid "online" analyses of the data searched for general gravitational-wave bursts as well as the distinctive chirp signal characteristic of binary mergers. Candidate events were found, vetted, and reported to a network of partner telescopes for followup with about an hour latency. The best-known example was the "Big Dog" event, a simulated merger signal secretly added to the data as a test of our detection systems. The Big Dog was spotted by an online processor and followed up by a range of optical telescopes, as well as the Swift satellite. While the Big Dog was a great success for online analyses, it also highlighted the challenges of finding electromagnetic counterparts to gravitational-wave signals. In particular, sky positions determined by gravitational-wave observations are very poor by the standards of electromagnetic astronomy, with uncertainties measured in degrees rather than arcseconds! This has prompted many papers exploring strategies for solving this needle-in-a-haystack problem, and studying the science to be gleaned from electromagnetic counterparts.

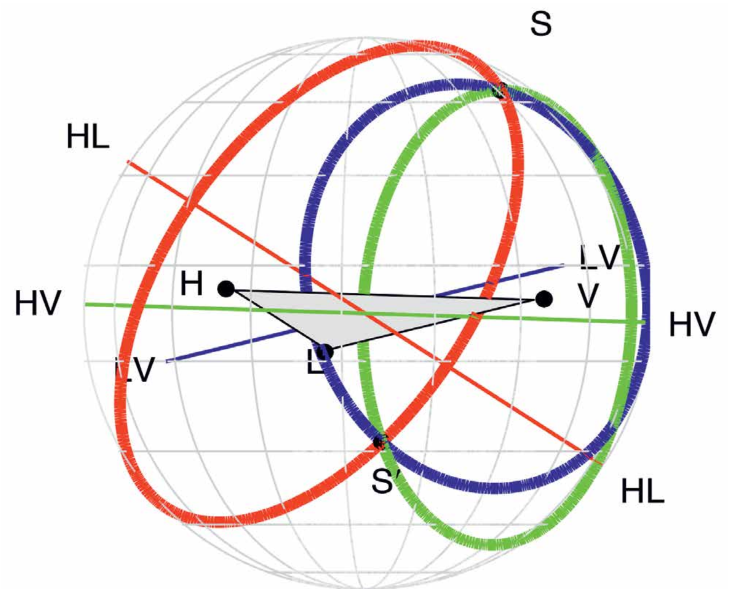
With this in mind, LIGO and Virgo have recently released the document "Prospects for Localization of Gravitational Wave Transients by the Advanced LIGO and Advanced Virgo Observatories" (http://uk.arxiv.org/abs/1304.0670, submitted to Living Reviews in Relativity). Known in the collaborations as the "observing scenarios" paper, its goal is to facilitate planning for multi-messenger astronomy with gravitational waves. The paper lays out the current best estimates for the



Sky position uncertainty map of the "Big Dog" event as estimated by the LIGO/Virgo online processor. This information was sent to telescope partners for follow-up observations. The axes are right ascension (ra) and declination (dec). The color represents the relative probability that the signal came from that sky direction; the total area covered is approximately 160 square degrees. The inset shows the region focused on for follow-ups: crosses mark the location of known galaxies within 50 Mpc, while squares and circles indicate regions imaged by partner telescopes.

plausible evolution of Advanced LIGO and Advanced Virgo from first switch-on until early in the next decade. This evolution is envisioned as periods of commissioning alternating with observing runs of increasing duration and sensitive range. The first science data is expected to be from a 3 month run of the LIGO detectors in 2015, with neutron star merger sensitivity ranges between 40 Mpc and 80 Mpc. Virgo will join LIGO for a joint 6 month run in 2016-17. LIGO is expected to reach its final design range of 200 Mpc around 2019, with Virgo reaching its design range of 130 Mpc around 2021.

These sensitivity projections can be used to predict the likely number of neutron star merger detections, and how well LIGO and Virgo will be able to determine the sky position to direct electromagnetic followup observations. The rate of binary neutron star mergers in the universe



Source localization by triangulation for the LIGO-Virgo network. H, L, and V represent the LIGO-Hanford, LIGO-Livingston, and Virgo detectors. The signal arrival time delay between each pair of detectors restrict the possible source location to a ring on the sky, concentric about the baseline between the two sites. For three detectors, these rings may intersect in two locations. One is centred on the true source direction, S, while the other (S') is its mirror image with respect to the geometrical plane passing through the three sites. For four or more detectors there is a unique intersection region of all of the rings.

is not known with any real certainty. The best guess is around one such event per Milky-Way equivalent galaxy per 10,000 years, but the true rate could be ten times higher or a hundred times lower! The good news is that even under the most pessimistic predictions, the design range of 200 Mpc should give at least one merger detection per year. Even better, if the more optimistic predictions hold true, then we could have the first detections during the very first observing run in 2015, and hundreds of detections per year by the end of the decade.

Detecting a gravitational wave is only the first challenge. Observing an electromagnetic counterpart could reveal the host galaxy, environment, redshift, and electromagnetic spectrum, and may be key to identifying the nature of the event. This is where determining the direction to the source becomes critical. LIGO and Virgo rely on the age-old procedure of triangulation: by measuring the time delays between when the gravitational wave reaches each of the detectors, we can estimate the approximate direction to the source (see image p.17 bottom). But there is a catch: it is vital to have detectors at three or more geographically separated sites. Two detectors alone, as in the 2015 run, can only restrict the gravitational-wave source to a ring on the sky. The strength of the signal in each detector provides a little more information, but in practice it's very hard to determine the source direction without a third instrument. The necessity of detectors spread over a large geographic area highlights the importance of expanding the gravitational-wave detector network beyond the USA and Italy, and explains the excitement about the construction of KAGRA in Japan and the hoped-for construction of a LIGO detector in India. Calculations show that with LIGO-India added to our network (c.2022), not only would our detection rates increase, but the long baselines between India, Europe and the US would dramatically improve our ability to locate sources on the sky. With a LIGO-Virgo-India network, half the detected neutron-star mergers would be localised to under 20 square degrees, and many to under 5 square degrees – within the field of view of existing or planned telescopes. These benefits are not restricted to mergers: studies of the localization of generic gravitational-wave transient signals show similar performance. The advanced detector era will be an exciting time - so stay tuned!

LIGO$_{2014}$

Observing Schedule: the Next Decade

Observing Schedule: the Next Decade. The LIGO and Virgo collaborations expect periods of commissioning alternating with observing as the detectors become increasingly sensitive. This is a plausible observing schedule:

late 2015:

- 3-month observing run with the two LIGO detectors only
- neutron star merger sensitive range between 40 Mpc and 80 Mpc
- at this range we're unlikely to detect any mergers within 3 months

2016-17:

- 6-month observing run with LIGO and Virgo
- ranges between 80 Mpc and 120 Mpc (LIGO) and 20 Mpc to 60 Mpc (Virgo)
- at this range we have a good chance to see our first signals

2017-18:

- 9-month observing run with LIGO and Virgo
- ranges between 120 Mpc and 170 Mpc (LIGO) and 60 Mpc to 85 Mpc (Virgo)
- very likely to see several signals

2019-2022:

- regular observing with LIGO and Virgo ranges reaching design targets of 200 Mpc (LIGO) and 130 Mpc (Virgo)
- expect several to many binary merger signals per year

2022+

- LIGO-India joins the network with 200 Mpc range, further increasing number of detections.

Starting right: Building an LSC clean lab from the ground up

David Kelly

David Kelley is a graduate student in the SU Gravity group. He spends his time on optics, suspensions, food and beer. He is entering the fourth year of his PhD program.

Antonio Perreca

Antonio Perreca is a postdoc in the SU Gravity group. He has been in the group for three years. He likes optics, wine, and the sunny beaches of Napoli.

In the fall of 2010, Stefan Ballmer arrived at Syracuse University with the goal of building an angular optical trap; a table-top demonstration of angular control that could be used to eliminate angular sensing noise in future interferometric gravitational wave detectors, increasing sensitivity. The experiment would use radiation pressure from two pairs of beams, controlling the position and angular degrees of freedom of a half-gram mirror, to keep the mirror "trapped" at a fixed length and orientation relative to a larger, more massive mirror.

Stefan's team has grown and now includes a full-time research associate and three graduate students. Now, in 2014 as we approach our first lock, we take a moment away from the frenzy to look back at the challenges of setting up a functional, clean LSC research lab.

One of the first tasks in setting up our lab was to build a digital infrastructure. We have three different tools that we use to maintain lab organization: an aLog, a wiki, and an SVN repository. Our aLog is a digital logbook that we use to record changes, pictures, and results from our experiment. It is an exact copy of the one deployed at the Hanford and Livingston sites. We have found it very useful to keep several people working on different aspects of the same experiment coordinated and updated. The lab wiki runs on the DokuWiki framework. We use it to keep records of purchases and inventory, to document experimental systems, and to record common lab procedures. The SVN is where we keep all of our code, documents related to our experiment, and the data that we take in lab.

Our experiment has two optical tables that are pneumatically floated and rigidly connected with metal tubes. One of the tables is devoted primarily to preparing a frequency and intensity stabilized light source with mode cleaning. The trap cavity, which is formed by the trapped small mirror and the larger mirror, has a high finesse (around 8,000), which means that it is very sensitive to frequency noise from the laser. Frequency stabilization and intensity stabilization of the input laser are required to prevent the optical "spring constants" of the two beam pairs from fluctuating. The second table holds the vacuum bell jar which contains our trap cavity.

A vital concern when building and maintaining the LIGO interferometers is to ensure the highest possible cleanliness of everything that enters the vacuum. Many of the reasons for keeping this level of cleanliness, ranging from deposits on optical surfaces to mechanical agitation of suspended optics, may also apply to smaller R & D projects like ours. So with the assumption that we need to pass some 'clean' threshold to avoid problems, the first question should be: How clean is 'clean'? We have two methods for measuring dirtiness. Outside of the vacuum system, we count the number of particles in a volume of air. The number of particles per cubic meter can be translated into a 'class' of cleanroom. Inside the vacuum chamber, we measure the partial pressure of contaminant gases with a Residual Gas Analyzer (RGA). As we plan to open the vacuum system regularly, we need to make sure that both inside and outside of the vacuum system is clean, so that the vacuum chamber does not get contaminated when we open it.

What is a good target for overall lab cleanliness? Our goal was to meet the LIGO standard of a Class 100 clean room (see US Federal Standard 209E). We obtained a particle counter and set out to see where we were starting from. We worry about all particles larger than 0.3 micrometers, which is the limit set by the particle counter we use. Our first measurement in lab came to about 3×10^7 particles/meter^3. You would perhaps expect this level of particles on a street in a city. After this minor shock, we installed HEPA filters on the air vents coming into lab. That got us down to about 2x10^5/meter^{-3} and this dropped slowly over time as we regularly cleaned the lab. At that point, we were below class 10,000. At this level we need to walk about in cleanroom attire and walk on sticky mats when we enter the room. Seeking further improvements, we bought cleanroom enclosures for both of our optical tables. These enclosures use HEPA filters and fans to create a positive pressure of very clean air inside the enclosure to actively keep dust out. Inside the enclosures we pass the limits of our particle counter, but we are well below 1x10^3 particles/meter^3, at least a class 10 cleanroom. This passes the specification at the LIGO sites, so we're set there.

What is a good target for a vacuum system to be clean? Guidelines from initial LIGO give requirements for a number of different gasses, but LIGO has to deal with gas particles pushing around the optics. For our surface areas and operating pressure, this effect should be negligible. The more serious concern is hydrocarbons depositing onto optical surfaces, causing unwanted absorption and heating. Compunds like water and nitrogen, while they raise the pressure, are less of an issue because they will disappear over time without affecting the optics. Fragments of hyrdrocarbons mostly show up in the RGA as lines at 41 and 43 AMU (atomic mass units) and multiples of those numbers. For our experiment we arbitrarily set a standard that partial pressure of 41 and 43 AMU lines should be below 1x10^{-8} torr.

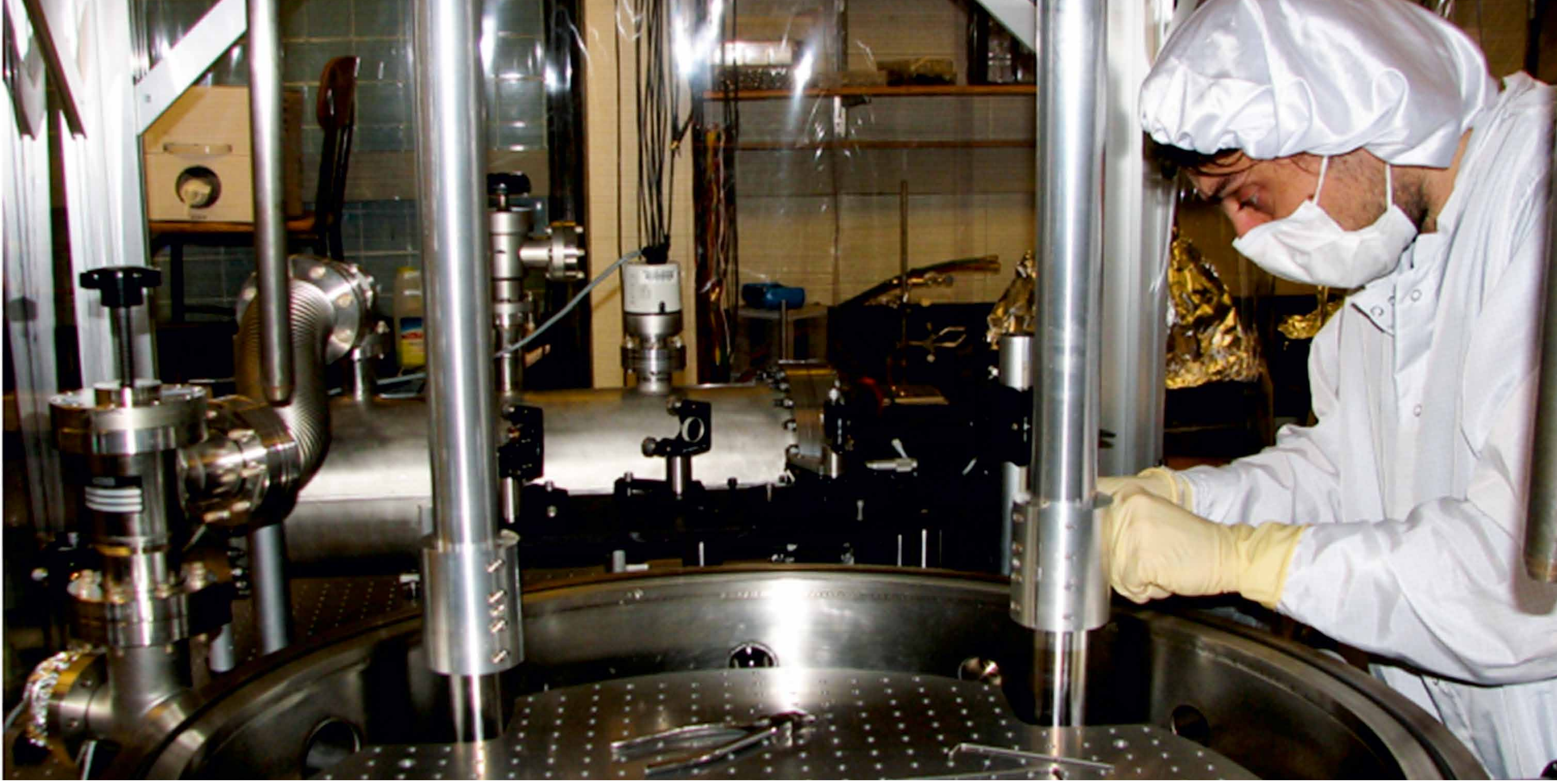
The observatories use a testing method that involves putting substances in a vacuum system with a high power optical cavity, then checking for degradation of the cavity over time. These experiments take months to complete. The results were used to create specifications for cleaning procedures and material choices in an official LIGO cleaning document. We try to follow these guidelines as closely as possible.

Once we had everything cleaned up, we started putting things into our vacuum system; suspensions, cables, etc. To the best of our knowledge everything was vacuum safe and cleaned to the proper specification. Initially we were happy with the levels of cleanliness we saw. At some point, however, we saw a sharp rise in the 41 and 43 AMU hyrdocarbon lines. After this 'contamination event', we tried to figure out exactly what happened. After some research and investigation, it seems most likely that this was a 'backstream' of oil from a bearing in the turbopump. This can happen if there is a significant pressure difference across a 'wet' turbopump when it turns on. The pressure difference can pull air (contaminated with bearing oil) backwards through the turbopump into the vacuum chamber. We learned two important lessons from this episode. First, 'Wet' turbopumps that use oil bearings are potentially very dangerous to use in a clean lab; 'dry' pumps that use magnetic bearings are much safer. Second, procedures must be put in place that elimi-

When we bought our second cleanroom enclosure, we had an interesting design problem: the bell jar that houses the optical trap is opened vertically. This was a problem for us! Cleanroom enclosures usually have hard tops with fans in the center and this would make it impossible to open the bell jar. After a number of options were considered, we decided to go with a large opening in the middle of the enclosure, moving the fans to the sides, that would allow the entire bell jar to be raised out of and lowered into the enclosure normally. However, this left us with a significant gap between the enclosure and the bell jar. We needed a way to raise and lower the bell jar without exposing the inside to 'dirty' air. We got as far as making a design for a flexible cover that would connect the bell jar to the enclosure, but we were lost when it came to attaching the pieces together.

Enter David's mom. She came up to Syracuse with her sewing machine and a few meters of velcro strip. Over one weekend we assembled a removable dust cover out of polyurethane-coated nylon fabric. With a little counseling from the local machine shop, we came up with a way to wedge plastic strips into the enclosure frame to hold the cover in place.

David and his Mom next to the newly created bell jar dust cover.

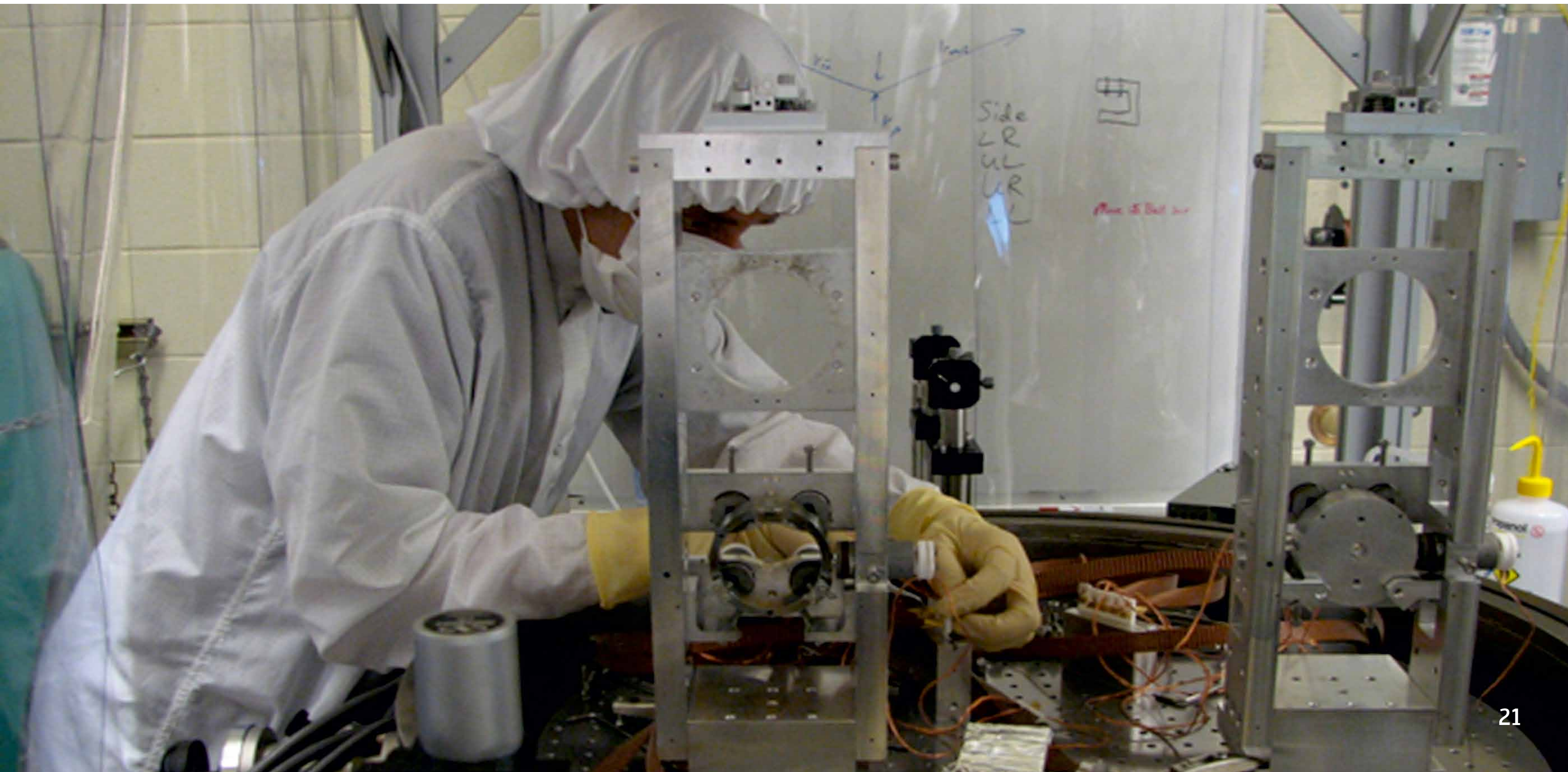


Antonio working in the cleanroom enclosure.

nate the possibility of catastrophic failure during operation; several layers of redundancy are preferred.

After we found the contamination and decided it could be avoided in the future, we started taking steps to remove the contamination from our bell jar. We turned to vacuum baking to decrease the pressure (especially the partial pressure due to heavy hydrocarbons). While baking the system, we found that we drastically decreased the total pressure, but did not impact the hydrocarbon content significantly. Further investigation showed that there was oil in the system; we realized that we had evaporated the hydrocarbons, but they had simply condensed in the pipe connecting the system to the pump, which was not heated during the baking. After another round of cleaning and several months under vacuum, we finally have a clean system (the 41 and 43 amu partial pressures are below 10-8 torr) . We are pushing forward, aligning our trap cavity and setting up systems to test the optical trap. We hope that some of the lessons we have learned will be useful for other groups starting their own labs.

Graduate student Jim Lough working on the suspensions for the optical trap cavity mirrors.



On the life and death of simulation codes

Jerome Degallaix

Jerome Degallaix is a staff scientist at the Laboratoire des Matériaux Avancés (L.M.A.). When Jerome is not simulating simulation results, he tries to master the art of breaking eggs with one hand.

In 2013, during a commissioning and simulation workshop at LIGO Livingston Jerome was inspired to reflect on the life and death of simulation tools. An overview of the workshop has already been presented in the previous issue of the LIGO magazine by Holger Wittel and this article is an extract from the full report of the workshop available on the LIGO DCC (T1300497) and Virgo TDS (VIR-0238A-13).

People who are using optical simulations should be aware that many simulation packages developed in the gravitational wave collaborations have a relatively short lifetime compared to commercial software such as Zemax, ANSYS or Matlab. As we will see, this is intrinsic to the development model practiced within the gravitational wave community where one code is usually developed by only one person.

The family tree of the FFT codes

As an example, we can have a look at the genealogy of the main FFT codes as shown in the figure next page. Similar situations also happens to modal expansion codes, mode matching tools or to a lesser extent also to ray-tracing programs. Several things can be noted from this example. First, there is not one unique code (to rule them all), but rather a large number of packages that co-exist simultaneously. Second, some codes appear while other disappear indicating a constant renewal of the simulation tools.

Accompanying the renewal, the programming languages used to develop the simulations are also evolving, following trends in programming (Fortran 77, Fortran 90 then Fortran 95, C or Matlab more recently). For the record, in the early 90s all the FFT codes in the different collaborations have a common origin: the first code from LAL which was possible thanks to the vision of Jean-Yves Vinet.

So, as we have just seen, the simulation landscape is not static, yet it evolves on the time scale of a decade. So why are we not just working with only one code since the beginning? To answer this question, we could have a closer look at the situation.

Common points between codes

The different optical simulation packages share some similar features: behind one code, there is mainly one developer. This developer is not working full time on the code, but treats it rather as a side job (or as a hobby). Typically the code was not supposed to be public from the start, but just an internal and convenient tool to speed up the understanding of a complex system. It is typically started during a PhD or a post-doc. Looking at the core of the code itself, the program is rather simple and straightforward (few thousands of line at best). To simulate a certain configuration, scripts are usually used, therefore eliminating the need for fancy graphical interfaces. The developer of the code is also the main user of the code (with exceptions, such as, for example, Finesse or Optickle). Keeping in mind those few points, the current situation of the simulation landscape can be explained.

Live and let die

The main cause of slow death for a code is the departure of the main programmer. It is a direct consequence of the lack of permanent positions in the field. Codes are developed during a PhD or post-doc while the developer does not have a permanent position. The developer may change jobs or change domains and without any further support, the code becomes quickly outdated and forgotten. In some rare case, the package is replaced by a more powerful and versatile tool.

Born to be wild

On the other side, a spontaneous generation of code happens in a permanent manner. Since the code lengths are relatively small, it is easier to start a new code from scratch than to try to modify an existing one. Moreover, it is an occasion to understand how the simulation works internally and new codes typically also bring some innovative improvement.

New codes are also generated to try a new technology from a new propagation technique or to test a new computing technology (GPU, new language). Then, natural selection will strike and only the improvements which can make a difference will survive. Codes can also be generated only to solve a particular problem. If well advertised, they can easily keep the supremacy in a niche market.

Special cases

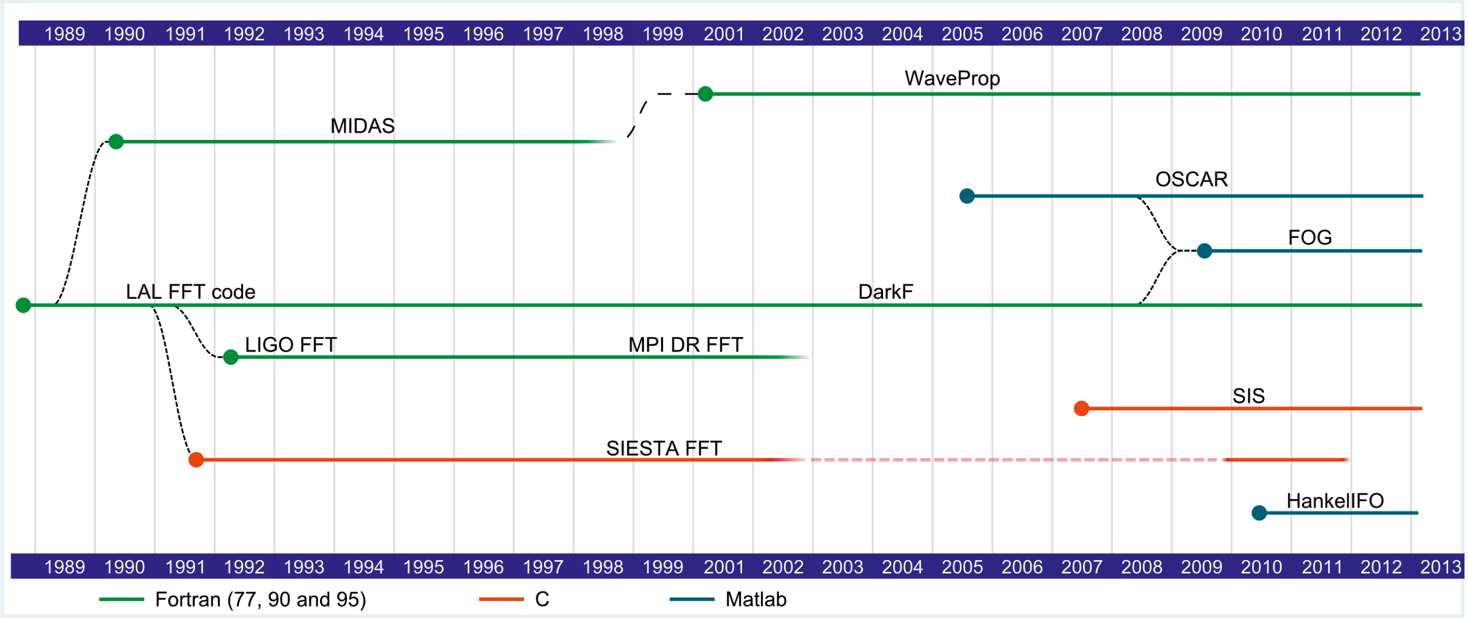
Two codes with special fates are Finesse and Optickle. Both simulation tools are widely used with a large number of users in several collaborations. These are rather rare situations and they give you a good idea of what happens when a developer has access to a pool of students

Concluding remarks

One can wonder if this is a bad thing that optical simulation codes are so diversified and the long term support is uncertain. From the outsider, it may look a waste of time to reinvent the wheel each time, however it ensures the inner mechanics of the code and its limits are well understood by the developers when starting from scratch. Moreover the presence of different codes allows the cross checking between tools and hence the validation of the results and increase the confidence in the simulations.

From the user perspective, the following question can arise: “if I stay in the GW field for several decades, does that mean that I will have to always use new tools?”. The answer is no, you will keep using the same old tools simply because you are comfortable with them and in any case, if you stay long enough in the field, you will likely have no time to do simulations yourself and your students will take care of it with contemporary tools

LIGO 2014



Timeline of 20 years of the FFT codes used in the gravitational wave community.

This is not an exhaustive list of all the simulation tools based on FFT but the main ones are there.

Checking in with LIGO Public Outreach

A young scientist generates a fundamental sound and its harmonics with a "Whirly Tube"

Do your neighbors know anything about gravitational waves? What about your distant relatives, your children's friends, or the non-science majors at your university? LIGO continues its quest to make the answer a "yes" for all by bringing an ever-expanding array of public outreach activities and programs to venues and outlets that span the spectrum from local to international. Groups across the LSC are joining with the LIGO Laboratory to invite all sectors of the public to experience the science, technology and people that are making gravitational wave astronomy real. Space limitations prevent an even modestly comprehensive presentation of all that's going on in LIGO's education and outreach effort. Instead, we offer a small sample: several recent projects, products and activities that reflect the diversity and creativity of the LIGO personnel and bring gravitational-wave science to an inquisitive public in interesting and engaging ways.

Heritage University Family and Community Science Festival

Dale Ingram, LIGO Hanford

A large percentage of our outreach work at LIGO Hanford (LHO) grows out of community partnerships. Heritage University's *Family and Community Science Festival* on November 13, 2013, was a typical example. Undergraduate students in the Heritage Science Club (HSC) created the four-hour festival to reach out to nearby communities through hands-on science. Their motivation meshed with LIGO's interest in creating enjoyable opportunities for families based on science that relates to gravitational-wave astronomy. From the two parties' shared outreach interests, a community event was born.

Roughly 300 school-aged children and family members sampled the festival in a large room on the Heritage campus. Throughout the afternoon participants visited HSC stations that involved chemistry, biology, forensics and other science. LHO offered nearly 20 station-based activities that ranged from simple sound-generating "whirly tubes" to an audio input/PC oscilloscope setup and a Michelson interferometer. HSC members helped staff the LIGO stations.

Heritage University is located on the Reservation of the Yakama Nation and serves students from the Reservation and beyond, including the large Hispanic/Latino population in south central Washington. The seeds of the November 13 collaboration were planted months earlier when the LSC's Gaby Gonzalez and Marco Cavaglia broke away from a several-day meeting at LHO to join me and LHO's Corey Gray for an evening presentation and reception on the Heritage campus. Gaby's public talk drew an audience that barely numbered in double digits, but one participant was HSC member Jessica Martin. Later Jessica contacted LHO to propose the joint November 13 activity. The willingness of Gaby and Marco to participate in something small led to the development of something much bigger: a pattern that we've often witnessed in our outreach work at LHO.

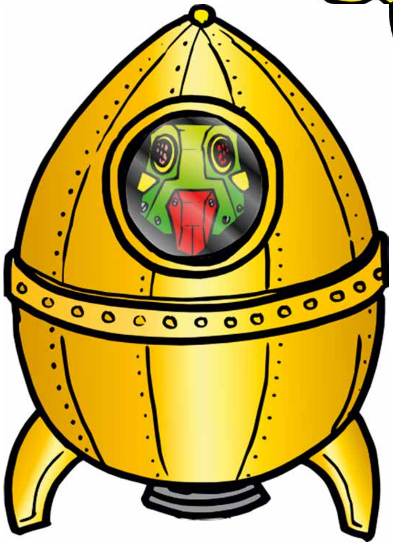
Dale Ingram coordinates education and outreach at LIGO Hanford Observatory where he enjoys interacting with visitors of all ages and backgrounds over matters of gravitational waves.

Space-Time Quest

Paul Fulda, University of Florida

The game *Space-Time Quest* was developed at the University of Birmingham to educate young audiences about key aspects of gravitational-wave detector design. It takes the form of a "manager sim" style game in which the player must use a limited budget to build the most sensitive gravitational-wave detector possible. Eye-catching, cartoon style graphics and fun animations grab the attention of younger players. We've used the game at several science outreach events and in Birmingham-area schools with good results. Young users grasp the game more effectively when we walk them through the process of building and running a detector before leaving them to tinker on their own.

SPACE-TIME QUEST



Space-Time Quest requires a bit more patience from younger users than an arcade-style game like Black Hole Pong. The online highscore hall of fame reveals many players — 7000 entries and counting. Become a player and try to top TOMA's current highscore of 54.825 megaparsecs! You can download Space Time Quest for free at http://www.gwoptics.org/stq.

Paul Fulda now works on auxiliary optics development and detector commissioning simulations at the University of Florida as a postdoc. He plays several loud musical instruments and enjoys acrylic painting and the type of football that's less popular in Gainesville.

This is the Space-Time Quest control room where the interferometer locking happens and science mode is initiated. The design takes after the LIGO control rooms with some extra colors and artistic liberties added. Like all the images in Space-Time Quest, this illustration began with pen on paper followed by scanning, conversion to a vector graphic and coloration using Inkscape.

Astronomy's New Messengers was created in 2009 and has visited numerous U.S. locations. Send inquiries about the exhibit to Marco Cavaglia at cavaglia@phy.olemiss.edu.

Black Hole Bash

Laura Nuttall, University of Wisconsin-Milwaukee

What was the *Black Hole Bash*? Two days of hands-on exhibits, outdoor cooking, live music, planetarium shows, stargazing and public talks at the University of Wisconsin-Milwaukee (UWM) in November 2013. Bash organizers invited the public to tour the interactive traveling exhibit *Astronomy's New Messengers: Listening to the Universe with Gravitational Waves,* whilst enthusiastic graduate students and postdocs assisted with interpretation. Visitors strolled through some of the key ideas of gravitational waves, played with a small interferometer, manipulated a space-time fabric model, and occasionally beat "experts" at finding a gravitational-wave signal hidden within noise. Kids proved especially good at this! The UWM planetarium hosted shows about the nature of black holes. Academics explained specific black hole ideas during public talks while live music played in the background. We stayed late each evening to chat with interested guests, many of whom hadn't encountered physics since high school. The bash offered a great opportunity to spread the excitement of our field, and I think we managed to pass it on!

Laura Nuttall is a postdoc at UWM working on detector characterisation and the Intermediate Palomar Transient Factory. Having lived in Milwaukee for the last 6 months she is missing netball, gravy and the tropical UK climate. Does winter ever end in the midwest?

An Outreach Film: The Invisible Colours of the Universe

Pablo Rosado, MPI/AEI

My idea for *The Invisible Colours of the Universe* arose in May 2013 when I learned about the Fast Forward Science contest, which offered a prize of 6000 Euros for an outstanding European five-minute science film. I thought that our science — galaxy collisions, supernovae, black holes — could make for a very cool movie. My friend Juan Jesús Eslava (alias Guaje), a professional animator, agreed to participate. He's not a physicist, so we needed to talk at length about the astrophysical processes. When I saw Guaje's first animation of a galaxy collision, I said "We will make something cool!"

I was preparing my PhD thesis while working on the film's script. Nine days before the contest deadline of August 31, my friend Gabriel Incertis and I recorded the voices of my colleagues Natalia Korsakova, Benjamin Knispel, Rutger van Haasteren, and Thomas Adams (the main narrator). By August 28, only a few "little" tasks remained at Gabriel's studio: editing, cutting, special effects and music. I knew that my musical score should help communicate the beauty of the physics that we do.

After midnight on deadline day, completely exhausted, Gabriel and I watched the finished video. That was a great feeling! On YouTube, ours became the most popular of the 90 contest videos. Two weeks after delivering my PhD thesis, I learned that we had won the contest! Gabriel, Guaje and I received the award at the Forum Wissenschaftskommunikation (Forum of Scientific Communication) in Karlsruhe.

The contest gave us a great opportunity to share our research with a global audience in an artistic and entertaining manner. The film's reach was multiplied by the media attention received. I like to think that our video has helped promote science in this critical moment in which countries like Spain are investing less and less money in public education, research and development. Since the film's release, more than 10,000 people have heard that "Gravitational waves will unveil the invisible colours of the universe!"

Pablo recently earned his PhD from MPI/AEI, focusing on stochastic background modeling. He enjoys writing and playing music regularly and displays excellent skills in film! Photo by Ismail Tuzhaev.

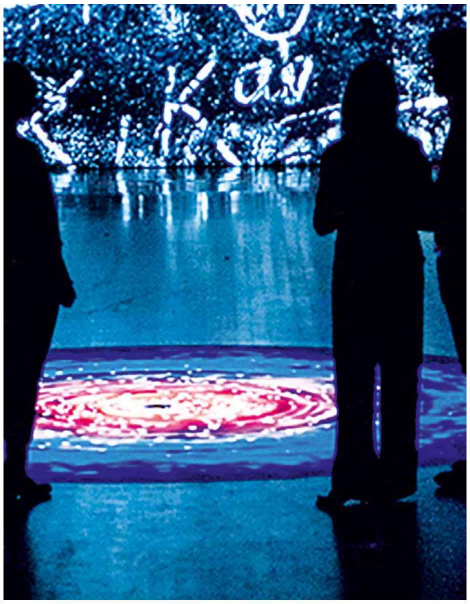
Celebrating Einstein

Joey Shapiro Key, University of Texas at Brownsville

The initital *Celebrating Einstein* occurred at Montana State University in Bozeman, MT, during April 2013. The event included an immersive art installation, an original film with accompanying score for a live symphony, a danced lecture on gravitational waves, a lecture series, and school activities. Project leaders Nico Yunes and I experienced both challenges and joy in bringing together scientists and artists to share a vision that would inspire and inform the public. Scientists sometimes struggle to communicate our passion for exploration with those who do not share our language; our artist colleagues brought innovative and evocative forms of expression to this marriage of science and art.

The celebration offered the multimedia theatre performance *A Shout Across Time* to the public at no charge. Would anyone attend, and would they enjoy the show? Our year-long investment of preparation had reached the big moment. I stood in the rear of the theatre as the curtain opened on the live symphony orchestra, and I watched the audience react as a large screen dropped in front of the musicians and conductor. At the end of the film the screen raised to reveal the performers — the audience gave them a standing ovation!

The Head of the Physics Department, a condensed matter physicist, approached us after the performance to say that he had gained a great appreciation for gravitational-wave astronomy and that the performance had brought him to tears. We queried audience members with questions before and after the show. I remember very well the young girl who didn't know about gravitational waves beforehand and afterwards exclaimed "They are waves in space!"



The immersive art installation Black (W)hole.

Joey Shapiro Key is the Director of Education and Outreach for the Center for Gravitational Wave Astronomy at UTB. She is trained in gravitational-wave data analysis and is learning the challenges, joys, and secrets of education and outreach.

Reaching Students and the Public through Outreach to Undergraduates

William Katzman, LIGO Livingston Science Education Center

LIGO's Science Education Center (SEC) continues to partner with Southern University of Baton Rouge (SUBR) and the Baton Rouge Area Foundation on an NSF-supported program for SUBR students who major in education and in STEM disciplines (science, technology, engineering and mathematics). The program enlists these students as docents for the Livingston LIGO SEC. Students train with LIGO-SEC staff to better understand LIGO-related science and the exhibits in the LIGO-SEC exhibit hall. The students also learn techniques of engagement to utilize on school children and the general public.

Guests at LIGO Livingston's Science Education Center aren't just greeted by current scientists, engineers and teachers. They are also greeted by SUBR students — future scientists, engineers and teachers — who, in many instances, share the ethnic and cultural backgrounds of our visitors. The docent program creates young STEM role models for K-12 students, helping them envision the steps they need to take in order to work at a research facility like LIGO.

What do the docents receive from this arrangement? Our early findings indicate the following:
1) 84% of the docents indicated that they acquired knowledge and skills they could not have gained elsewhere.
2) An increased self-confidence. A docent writes, "The program reinforces positive traits that help me with everyday things."
3) 96% of the docents indicated the program taught them how to effectively communicate about STEM concepts and skills. One docent wrote: "This program helped me to break certain concepts down and explain them on a more basic level."

A SUBR docent demonstrates the Colored Shadows exhibit in the SEC's exhibit hall

Everybody wins. This collaboration delivers positive outcomes to all of the partners and to our customers – the students and general public visitors who encounter SUBR docents when visiting the SEC.

William Katzman leads the active and energetic LLO SEC Outreach team (primarily he leads them on wild goose chases).

There's always room for more public outreach! Contact LSC Education and Public Outreach working group chair Szabi Marka at Columbia University (sm2375@columbia.edu) for more information on ways in which your LSC group can join the outreach effort.

Reaching out to Klingons!

Erin MacDonald

Erin MacDonald is a postdoc at Cardiff University focusing on gravitational waves from gamma-ray bursts. In her spare time she trains as a voice actor and is known for her many geeky tattoos.

Outreach is a vital, but sometimes overlooked, part of being a scientist. Erin Macdonald, a postdoctoral researcher at Cardiff University was invited to a popular science fiction and fantasy convention, DragonCon, held in Atlanta, Georgia over Labor Day weekend 2013, as an Attending Professional. Through this medium it is possible to reach thousands of taxpaying citizens who are ready to rally for a cause in which they believe. Presenting our case to this wide audience can get them on the side of scientific research which is vital for future research funding and public support.

Main lobby of the Marriott at DragonCon 2013. Photo by sciencensorcery : http://www.flickr.com/people/xstarsprinklesx/

DragonCon, where to begin? A beautiful, massive festival for every type of self-identified nerd or geek out there. In 2013 there was 57,000 people over Labor Day weekend. Five "host hotels" take part and dedicate any available conference room or ballroom to a topic (a "track") for the full four days. These topics can range from Star Wars, to fantasy fiction writing, to costuming, to science... you get the idea. There are workshops and advice for budding professionals as well as chances to meet stars from science fiction and fantasy. You also see the most amazing costumes that you will ever see.

So what was I doing here? My college friends and I reunited at DragonCon in 2011 and became instant fans. When I registered for DragonCon 2013, I was asked to attend as an "Attending Professional", due to my experience as a researcher. This meant I would sit on relevant panels, give talks and have a "VIP" badge. I, of course, said yes, instantly picturing myself partying it up with Kate Mulgrew and Patrick Stewart in some red-carpeted cocktail reception. This did NOT happen, but it became the most fun I have ever had in science outreach.

Day 1

I fly to Atlanta from London on Thursday evening, and my college friends pick me up at the airport having already checked in and dropped off copious amounts of costumes and equipment. This is where the fun kicks in. The hotel arrivals area is full with hundreds of people unloading massive crates of costumes, food, booze, etc. The camaraderie has already begun, total strangers high-fiving each other, helping with their stuff, sharing stories and everyone anticipating the insanity ahead.

Day 2

The first day of DragonCon, Friday, I am on a panel for women with PhDs in science to discuss gender-gap and experiences. The room was completely full and we have great discussions about how to engage girls in science and engineering, at what age and what gender-gap obstacles still exist.

Many questions are asked about personal experiences and how to handle difficult situations. The audience is extremely interested in our own backgrounds and how we developed an interest in science, if our experiences could shed light on how to inspire future children to pursue science. It became one of the most successful gender-oriented events I have attended.

After, I get the fantastic opportunity to meet some of the wonderfully talented cast of Futurama. They spent about 15 minutes with me and giving me advice on voice acting, a personal hobby. That evening we go to "An Evening At Bree", and you've not seen weird until you've seen Spiderman dancing with Gandalf!

Day 3

Saturday is the busiest day of the convention and I have to finish my talk for the evening. I avoid the crowds and spend the day in my room with "DragonCon TV" on where they stream big celebrity panels. Once I finish my talk, I wander down to see George Takei give an excellent panel on his life and experiences. As you do.

My talk on gamma-ray bursts (GRBs) is at 8:30pm. Personal experience in public talks made me think that a lecture on Saturday evening would be poorly attended. Surprisingly, the room is filled with hobbits, klingons and loads of varied, interesting people! I discuss the history and science of GRBs and the audience asks loads of questions! People are most interested in how GRBs might affect humanity and our local universe, so that's an opportunity to discuss population estimates and how beaming plays a factor, i.e. if a GRB happened in our galaxy during our lifetime, it is likely not to affect Earth because it points away. This leads into discussions about the Ordovician-Silurian mass extinction and the hypothesis that it was caused by a GRB in the Milky Way. There are a lot of questions about popular science articles on GRBs, so it is important when giving these talks to be aware of not just the technical advancements, but how these are presented in the media, as there may be misconceptions. After all of the discussion about mass extinction and probability of humanity being wiped out, everyone is up for a pint, so we clear out at 10pm. Being in a host hotel has the disadvantage that you quickly lose track of time in the evening because the general party sounds never die down all night, and soon it's 4:30am!

Day 4

I have Sunday off from talks, so I am able to enjoy the convention a bit more. We do some geek shopping at the massive vendors area. Later, I queue up to join the world record attempt for most people dressed in Star Trek costumes in one room. We get to nearly 1000 people, but fall short of the record. I then cement my nerd cred by wandering downtown Atlanta in a Star Trek uniform at 11pm!

Day 5

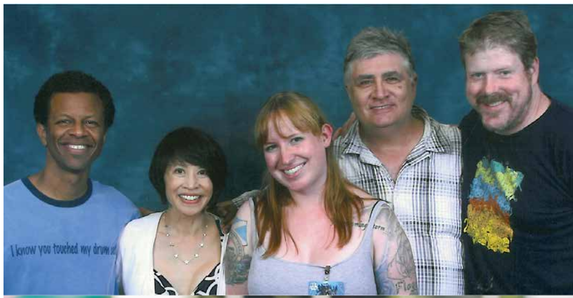
We all wake up on the last day of the convention, exhausted after many sleepless nights and excitement. My talk is in the afternoon and is surprisingly well-attended, though I suspect some just want to sit in a dark room for an hour!

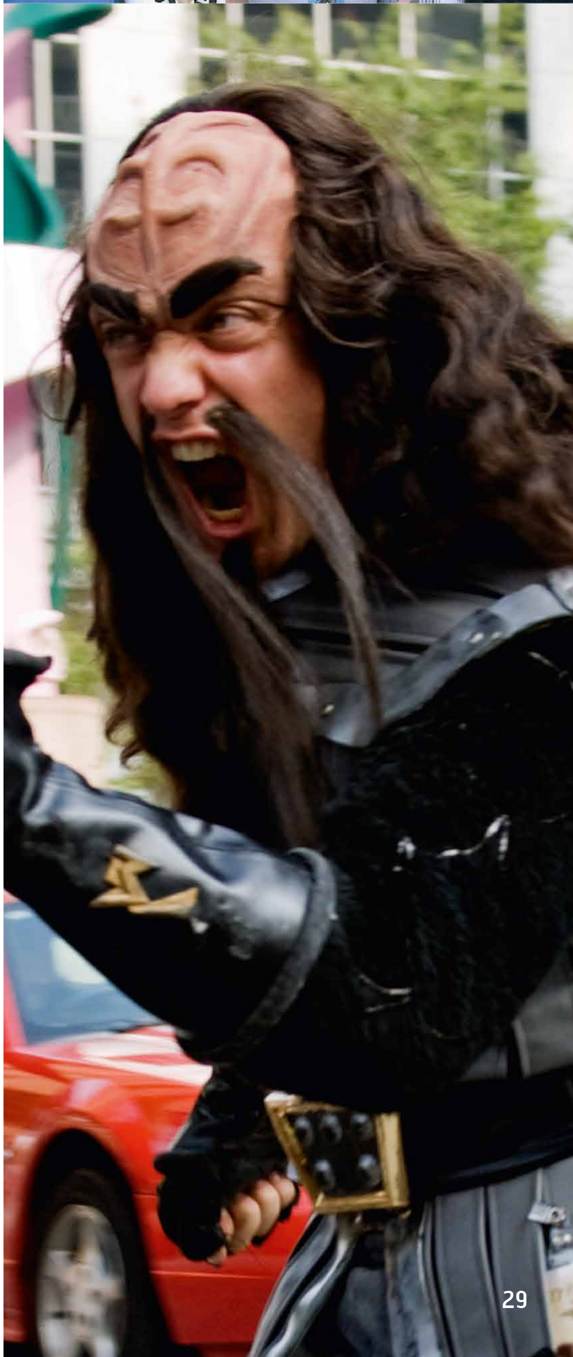
There is lots of great mind-bending questions, appropriate for the generally exhausted and laid-back atmosphere of the room. People have a lot of interest in the technology of the LIGO detectors as well as how general relativity works and implications of the discovery of gravitational waves. This is an important point as obviously the public is much more skeptical of something that has not been detected yet, but once we discuss the multi-messenger astronomy that can be done and how much physics we can learn, the audience becomes excited about the prospect of gravitational waves.

After my talk, I head to the airport, along with many other exhausted attendees and reflect on a weekend well-spent: I met some great actors, caught up with friends and was able to engage the public on science in a fun, and certainly unique, atmosphere!

LIGO 2014

Meeting the cast of Futurama (L to R): Phil LaMarr, Lauren Tom, Erin Macdonald, Maurice LaMarche, John DiMaggio. Photo by Erin Macdonald and Froggys Photos 2013





Now that is a how a Klingon should look!

Photo by Bart: http://www.flickr.com/people/cayusa/

GWPAW 2013
Impressions from India

Matt Pitkin

Matthew Pitkin is a post-doc in the Institute for Gravitational Research at the University of Glasgow. He spends most of his time searching gravitational wave data for signals from pulsars. In the past he's tried his hand at drumming (badly), but the arrival of his son last year curtailed any further rock-and-roll dreams.

IUCAA

Gravitational Wave Physics and Astronomy Workshop(GWPAW)
Dt. 17 to 20 Dec.2013

The 3rd Gravitational Wave Physics & Astronomy Workshop (GWPAW) took place in Pune, India in December 2013, which seemed like a perfect opportunity for an adventure in a new country! GWPAW replaced the Gravitational Wave Data Analysis Workshop (GWDAW) which ran for 14 years. GWPAW is aimed at bringing together scientists with different research focuses, but all related to gravitational waves. While it would have been a great opportunity for me to see India, sadly, I was unable to bookend my trip with any site-seeing, so my experience of India outside of the confines of IUCAA mainly came from my taxi ride from Mumbai to Pune.

The taxi ride itself was a fantastic insight into travel in India - the first half of the approximately three and a half hour ride (it's about a 170km journey) was just in leaving Mumbai, where the roads are about as chaotic as they come. However, once you leave Mumbai, the freeway between Mumbai and Pune is one of the best roads in India, and offers great views as you climb up into the rocky hills.

In Pune I stayed at the Seasons Apartment Hotel, which as the name suggests offered large apartments with a lounge and kitchenette (and free bottled water, which is a must for travellers there). Not feeling very adventurous on my arrival I opted for dinner at the hotel, and it was definitely worthwhile as the open air rooftop bar/restaurant offered beautiful views of the city. The hotel was just about walking distance of IUCAA, where the meeting was held, but the organisers had put on a taxi service to and from the hotel every day for which I was thankful once I saw the complicated roads! IUCAA is situated on the Pune University campus, but is self-contained for guests, students and postdocs to stay. During the meeting we didn't have to go far between talks in the Chandrasekhar auditorium, coffee breaks (which consisted of really strong black tea) and meals.

As well as our taxi service the organisers provided breakfast, lunch and dinner within IUCAA under a large marquee. The food was great, for me especially as I am a huge fan of curry! Some of the dishes were definitely on the spicy side, but I suspect they were toned down from their usual heat levels. We also had freshly made roti cooked in a tandoor oven by the side of the marquee.

On the first evening we had entertainment put on in the form of a Kathak Dance Recital in the meeting auditorium. The singing and musical accompaniment was mesmerising.

And what about the science? The meeting was weighted towards compact binary coalescences (CBC) and electromagnetic follow-up, but that's not surprising given that these are the most likely sources of the first advanced detector observations.

Photos on both pages by Matt Pitkin

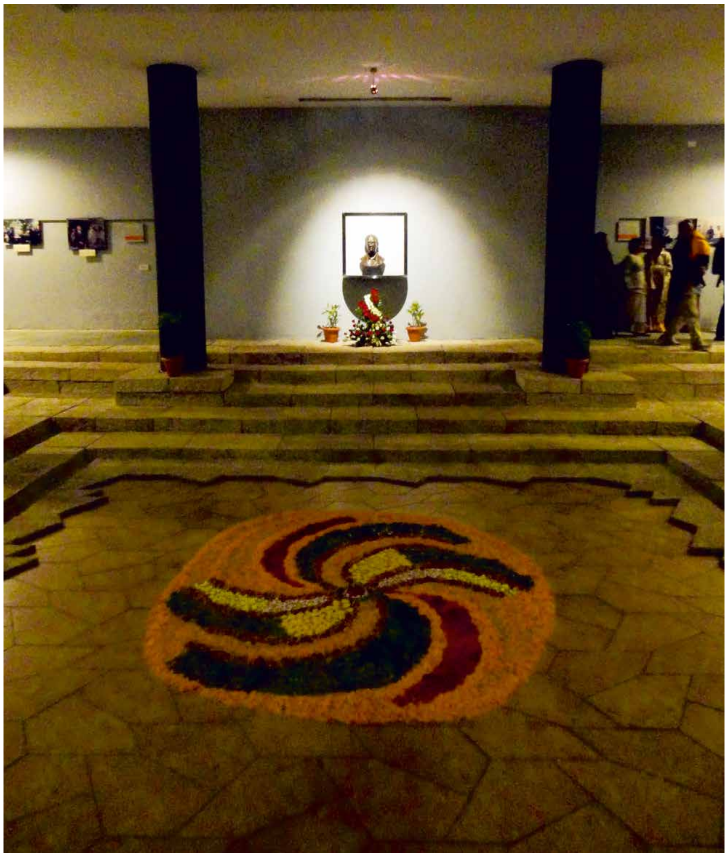
In fact it was good to have a GWPAW where many of talks were about things that could be done in the near future, rather than having to look ahead decades, further cementing the idea that gravitational wave detections are on the horizon! A couple of standout talks were Parameswaran Ajith's overview of the status and prospects for modelling CBC waveforms and Jocelyn Read's talk on the potential for measuring neutron star equations of state with advanced detectors. Most sessions had lively discussions following the talks, with one particular participant always ready to provide some vigorous questioning.

The breaks and poster sessions in the grounds of the auditorium (which amongst other things contained a giant sundial and a set of swings connected as a coupled harmonic oscillator) were always buzzing with conversation, which for me yielded a potential future collaboration with an IUCAA postdoc. There were many interesting posters, but I particularly liked a couple: one was Chris Messenger's describing a method to extract redshift information from neutron star mergers by observing modes of a potentially short-lived post-merger hyper-massive neutron star; and another was Shaon Ghosh's on electromagnetic follow-up of CBC signals. During the meeting my own poster was upgraded to a talk (due to passport related issues for one of the invited speakers causing him to miss the meeting), so I had to quickly put together my own slides.

The meeting turned out to be incredibly productive and fascinating, as well as welcoming and well-organised. It was a great chance for many Indian students and postdocs to attend the meeting and share their work, and for people from the LVC to interact with them. This was particularly useful because the distance means many collaborators in the USA and Europe got to discuss topics in person, and allowed us to develop these relationships in the run-up to LIGO India. There was a great deal of enthusiasm from the IUCAA director Ajit Kembhavi to keep up the efforts with the suggestion that IUCAA and other Indian institutions host summer school-type events in the future. The next GWPAW to look forward to will be in Osaka, Japan in June 2015, closely followed by Amaldi in South Korea.

It's a shame I didn't get to experience more of the country, but I did I get to discover a taste for the Indian Coca-Cola equivalent, "Thums-Up", while discussing exciting science halfway around the world.

LIGO 2014



Lobby of the Chandrasekhar Auditorium at IUCAA. The design on the floor is made from petals.

We Hear That ...

Recent Graduations

Berit Behnke defended her PhD thesis, “A directed search for continuous gravitational waves from unknown isolated neutron stars at the Galactic center” at AEI-Hannover.

Oliver Gerberding defended his PhD thesis, “Phase readout for satellite interferometry,” at AEI-Hannover on February 7th.

Emelie Harstad defended her PhD thesis, titled “A Targeted LIGO-Virgo Search for Gravitational Waves Associated with Gamma-Ray Bursts Using Low-Threshold Swift GRB Triggers,” at the University of Oregon.

Shivaraj Kandhasamy completed his PhD at the University of Minnesota and started a postdoc position at the University of Mississippi.

Dmitry Simakov defended his PhD thesis, titled “Dynamical Tuning of a Signal-Recycled Gravitational Wave Detector,” at AEI-Hannover on January 27th.

Mengyao Wang defended her PhD thesis, titled “Quantum noise reduction for gravitational wave detectors: developing realistic interferometer schemes” at the University of Birmingham in October 2013.

Career updates

Stuart Aston is now Detector Opto-Mechanical Engineer at the LIGO Livingston Observatory.

Bernard F. Schutz will retire as director of the Albert Einstein Institute in Potsdam/Golm, Germany after 19 years.

Alessandra Buonanno, professor of physics at the University of Maryland, will assume the directorship of the Astrophysical and Cosmological Relativity division of the Albert Einstein Institute in Potsdam/Golm.

Alex Ivanov, CDS engineer with the LIGO project for 16 years, has left LIGO. He now works for idtvision.com on FPGA-based slow motion camera designs.

Haixing Miao has been awarded a Marie Curie International Incoming Fellowship to work at the University of Birmingham on “Exploring quantum aspects of gravitational wave detectors” from March 2014.

Adam Mullavey, previously a post-doc at LSU, has taken the position of Detector Controls Engineer at the LIGO Livingston Observatory.

News/Elections

David Blair, Neil Cornish, Ben Owen and Daniel Shaddock were elected as fellows of the APS.

Marc Favata from Montclair State University was elected as a KITP Scholar for 2014-2016.

Richard Middlemiss, PhD student at the University of Glasgow, will be representing Scotland at the UK final of Famelab (famelab.org/uk) with a three minute presentation on gravitational waves. The UK final, which is free to attend, will be held at the Bloomsbury theatre in London on the 23rd April.

Fan Zhang, a postdoctoral associate with the Kavli Institute for Astrophysics and Space Research at MIT, was elected as a Senior Member of IEEE, “denoting a personal and professional commitment to the advancement of technology.”

LSC Elections

Burst Working Group: **Laura Cadonati** resigned from her post as Burst Group co-chair at the end of the summer, having been appointed chair of the LIGO Data Analysis Council. In November, 2013, **Siong Heng** was elected as the new Burst Group co-chair for a 2-year term.

Quantum Noise Group: Election held in Oct, Nov 2013. **Roman Schnabel** was elected as Quantum Noise Group chair for a 2-year term, replacing Yanbei Chen and David McClelland.

Advanced Interferometer Configurations: Election held in Oct, Nov 2013. **Matthew Evans** was elected chair of the Advanced Interferometer Configurations group for a 2-year term, replacing Rana Adhikari.

Lasers and Auxiliary Systems Group: The group voted to have the next chair appointed, and in December Gaby Gonzalez appointed **Volker Questchke** as chair for a 2-year term, replacing Guido Mueller.

Executive Committee. This one was complicated, but the basic result is that **Barry Barish** and **Peter Saulson** have been elected to full terms in the Executive Committee and the (originally 1-year) terms of **B. S. Sathyaprakash** and **Norna Robertson** will be extended to March 2015.

There were also elections for the LIGO Academic Advisory Council (LAAC) in fall/winter 2013. The new committee members are: Co-chair: **Jocelyn Read**, Senior Member: **Beverly Berger**, Postdoc Representative: **Mathew Pitkin**, Graduate Student Representative: **Maggie Tse**.

Elections for co-chairs of the following working groups are in progress as of mid-January 2014: Compact Binary Coalescence Group, Continuous Waves Working Group, Optics Working Group, Stochastic Working Group Suspensions and Isolations Working Group. None of these current elections have closed; we are hoping to be done by the LVC meeting.

LSC elections results provided by David Tanner.

Send us an update!
Have you changed jobs, won an award, or do you have another update you'd like to share in the next issue's "We Hear That" feature? Email us at **magazine@ligo.org**.

Recent papers

This issue of the "Recent LIGO papers" article is a bumper issue, reflecting the hard work and dedication of many scientists within the LIGO and Virgo collaborations! The collaborations have published six new papers since the last edition of LIGO Magazine which are reported here. Three further papers hit the press after this article was written and these will be reported in the September issue of the magazine. You can read about these papers, and many other LIGO and Virgo publications, by going to http://www.ligo.org/science/outreach.php.

Three of the papers were focused on the goal of detecting gravitational radiation emitted from rapidly-rotating neutron stars with the initial LIGO and Virgo observatories. Neutron stars are the collapsed cores of massive stars that ran out of fuel and went supernova. To generate gravitational waves a rotating neutron star must have some distortion that is not along its rotation axis. While the term "mountain" is used to describe these distortions, in reality they would not be expected to be any larger than about 10cm (4 inches) in height. This may not seem like much but consider that gravity on the surface of a neutron star is more than 100 billion times stronger than on the surface of the Earth, climbing Everest is a stroll in the park compared to climbing a neutron-star mountain!

The first of our recent neutron-star papers, *"Gravitational waves from known pulsars: results from the initial detector era" (http://arxiv.org/abs/1309.4027)*, presents the results of a search for gravitational waves emitted by known pulsars in our galaxy. Pulsars are highly magnetized, rapidly-rotating neutron stars that emit strongly beamed electromagnetic radiation along the direction of the magnetic poles. As the star, and the magnetic poles, rotate, the emitted radiation sweeps around the sky. When this beam hits the Earth we see a strong pulse emanating from the star. Pulsars are often described as cosmic lighthouses! By focusing their search on a set of known pulsars, the scientists behind this work were able to achieve much higher sensitivities than the broader searches described below. While no gravitational-wave signals were observed, this work was able to place limits on the amount of gravitational-wave radiation emitted by each of the known pulsars. This directly allows limits to be placed on the maximum size of mountains on each pulsar.

Our first search is only sensitive to the targeted pulsars, and would not detect gravitational emission from other, unknown, neutron stars in our galaxy. This is because not all neutron stars are pulsars, and not all pulsars will be visible from the Earth. It is believed that we have only discovered a small fraction of the neutron stars that are in our galaxy. Our second neutron star paper, *"A directed search for continuous Gravitational Waves from the Galactic Center"* (http://arxiv.org/abs/1309.6221), presents the results of a search for gravitational-wave emission from potential neutron stars at the center of our galaxy. As a large number of massive stars have been observed near the center of our galaxy, it is believed that there will also be a large population of neutron stars. This search benefits from targeting a specific region on the sky, but has to search for any potential neutron star in that region, which increases the complexity of a search. No gravitational-wave signals were observed but the work was able to place limits on the maximum deformation that neutron stars at the galactic center would have. Our third neutron star paper, "Application of a Hough search for continuous gravitational waves on data from the 5th LIGO science run" (http://arxiv.org/abs/1311.2409), presents a search for neutron stars from any location on the sky. As this work searches a much broader region than the previous two works it loses some sensitivity, but the previous works have no sensitivity to any region not being targeted. Like our other neutron-star papers, this work also observed no gravitational-wave signals but was also able to place interesting limits on gravitational-wave emission from neutron stars in our galaxy.

While neutron-star searches have certainly been a focus in LIGO and Virgo publications over the past few months, gravitational-wave observatories are sensitive to a variety of astrophysical sources. This is reflected in our next papers. Gamma-ray bursts (GRBs) are of particular interest to gravitational-wave astronomers. These are short-duration bursts of high-energy gamma-ray emission, which are associated with cataclysmic events in distant galaxies. They are commonly separated into two types, short and long GRBs, which are believed to correspond to different formation mechanisms. The favored progenitor for a short GRB is the merger of two compact objects: neutron stars and/or black holes. Long GRBs are thought be formed from the explosion of a massive star. The recent LIGO and Virgo paper, "Search for long-lived gravitational wave transients coincident with long gamma-ray bursts" (*http://arxiv.org/abs/1309.6160*), presents a search for gravitational-wave signals in coincidence with long gamma-ray bursts, looking for gravitational-wave signals lasting tens to hundreds of seconds. No gravitational-wave signals were observed by this search, however it is possible to place lower limits on the distance to the progenitor GRBs and to demonstrate that such searches are ready for when Advanced LIGO and Advanced Virgo become operational.

Another potential source of gravitational wave emission was the focus of the next paper, "Constraints on cosmic (super) strings from the LIGO-Virgo gravitational-wave detectors" *(http://arxiv.org/abs/1310.2384)* Cosmic strings are one-dimensional line-like objects, similar to vortex lines in liquid helium, that could be left over after the early Universe went through a phase transition. There is currently no observational evidence of the existence of cosmic strings and gravitational-wave astronomy offers the most promising avenue for detecting these objects. Gravitational-wave emission is the main mechanism for cosmic strings to dissipate energy, when a string in a cosmic string network crosses itself, a loop separates from the string. This loop will then oscillate, radiate gravitationally and eventually evaporate; strong gravitational-wave emission would occur at the pinch-off points of the loop: the cusps, which move with velocity close to the speed of light. This work detected no evidence of a cosmic-string signal, however this non-detection allowed scientists to place constraints on the properties of cosmic strings that are more stringent than any previous work.

Our final paper for this issue, "*First Searches for Optical Counterparts to Gravitational-wave Candidate Events" (http://arxiv.org/abs/1310.2314)*, describes the first time that LIGO and Virgo have worked with electromagnetic telescopes to perform prompt electromagnetic follow-up of gravitational-wave triggers. A number of gravitational-wave sources, for example gamma-ray bursts, also emit in the electromagnetic spectrum.

LIGO 2014

LIGO Crossword #2: Three Letter Acronyms

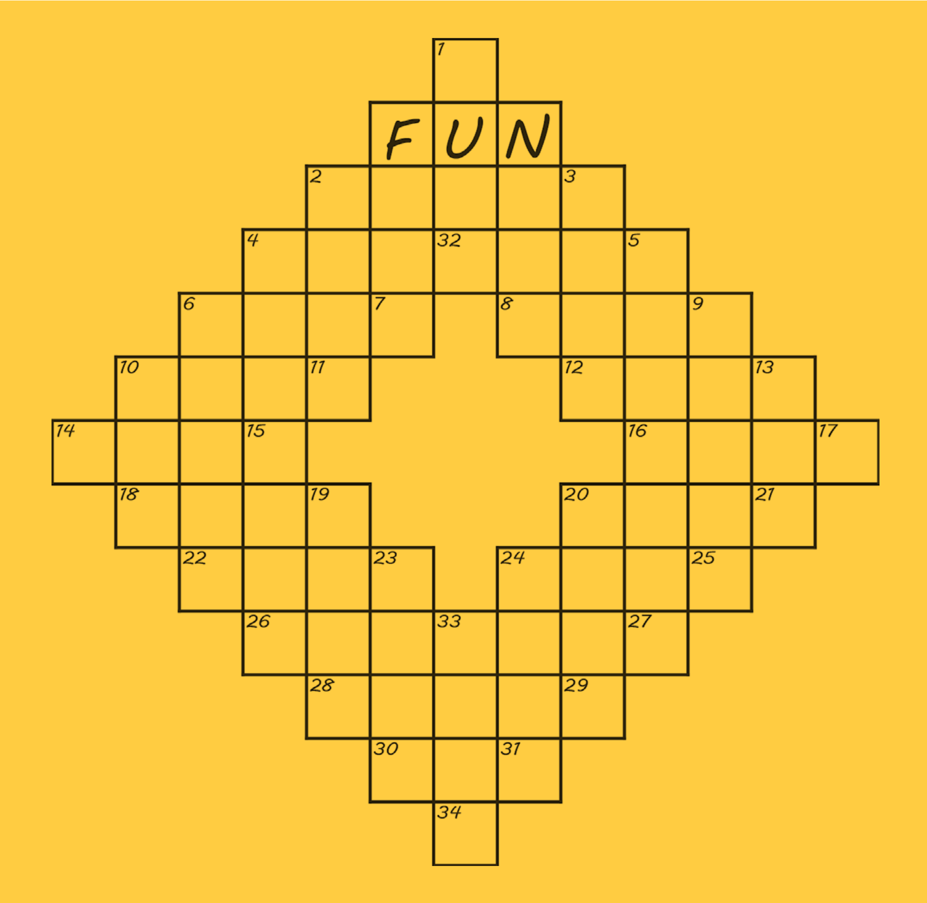
Crossword Clues

Modeled after the world's first crossword puzzle. Enjoy.

2-3. Hansel and Gretel did this to the Witch?
4-5. LIGO needs these/Vampires don't.
6-7. Paper or Plastic.
10-11. Considered harmful by Edsger Dijkstra
14-15. Southwestern beam profile
18-19. Like mean or median.
22-23. In a tree or a network.
26-27. Around and around.
28-29. Sector capital of the Chommell sector.
30-31. Never said at GEO.
8-9. A state of Mind, most would not say they are fruits
12-13. Probably can't buy interferometer parts here.
16-17. The part of a distribution with the signal.
20-21. Every GW interferometer needs this.
24-25. Meanings, like a melody or being a snob.
10-18. Often a building or close to a finger

6-22. Second part of the name.
4-26. The person with the muleta.
2-11. An acronym.
19-28. A famous garden.
F-7. Keep animals warm
23-30. First name of a LIGO student fellow.
1-32. With Brown, semiconductor pioneers.
33-34. Orbit minus r; for dying stars, transmitted with gw's
N-8. Tracer gas used in aLIGO seismic pods.
24-31. Member of the Lily family.
3-12. Add head to get a resonance type.
20-29. Recorder.
5-27. Natural height of a person.
9-25. What the detectors are built on.
13-21. Has short legs.

By Hans-Peter Bischof



The LIGO Magazine

LIGO is funded by the National Science Foundation and operated by the California Institute of Technology and Massachusetts Institute of Technology. This material is based upon work supported, in part, by the National Science Foundation. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

We gratefully acknowledge the support of the United States National Science Foundation for the construction and operation of the LIGO Laboratory, the Science and Technology Facilities Council of the United Kingdom, the Max-Planck-Society, and the State of Niedersachsen/Germany for support of the construction and operation of the GEO600 detector. We also gratefully acknowledge the support of the research by these agencies and by the Australian Research Council, the International Science Linkages program of the Commonwealth of Australia, the Council of Scientific and Industrial Research of India, the Istituto Nazionale di Fisica Nucleare of Italy, the Spanish Ministerio de Economía y Competitividad, the Conselleria d'Economía Hisenda i Innovació of the Govern de les Illes Balears, the Royal Society, the Scottish Funding Council, the Scottish Universities Physics Alliance, the National Aeronautics and Space Administration, OTKA of Hungary, the National Research Foundation of Korea, Industry Canada and the Province of Ontario through the Ministry of Economic Development and Innovation, the National Science and Engineering Research Council Canada, the Carnegie Trust, the Leverhulme Trust, the David and Lucile Packard Foundation, the Research Corporation, and the Alfred P. Sloan Foundation.

Online ISSN: 2169-4443
World Wide Web URL: http://www.ligo.org/magazine
Publisher: LIGO Scientific Collaboration, Pasadena, CA, USA
LIGO DCC: LIGO-P1400002
Contact: magazine@ligo.org

Editor-in-Chief: Andreas Freise
Deputy Editor-in-Chief: Tobin Fricke | Editors: Hans-Peter Bischof, Dale Ingram, Marco Cavaglià, Ian Harry, Gabriela González, Mike Landry, Erin Macdonald, Brian O'Reilly, David Ottaway, Jocelyn Read, Lucía Santamaría, Ruslan Vaulin

Design & production: Milde Marketing Science Communication + formgeber with the assistance of Matthew Abernathy

How to make a LIGO mirror coating:

Light reflects off any boundary between different materials. To get the very high reflectivity needed in an Advanced LIGO mirror, many thin layers of regular silica glass and a specialty glass, titanium-doped tantalum oxide, are stacked together to create many boundaries. The thickness of each of these layers is chosen carefully so that all of the reflected light beams from different layers combine together while the light rays that transmit through the layers cancel each other out. This allows for reflection of as much as 99.99995% of the light. This only works for a particular color of light, however, so the Advanced LIGO coatings only give this reflectivity for the Advanced LIGO laser light.

Another concern is how much light is absorbed in the coating and turned into heat. Losing light is never good, as the light is what carries the gravitational wave signal, but a bigger problem with absorption in the coating is the heat. This heat causes the mirror to expand and bend so that the reflected beam no longer has the right shape to combine with the beam from the other arm of the LIGO detector. Coating absorption is reduced by depositing the coatings using the ion beam deposition method. To do this, targets of silicon (for the silica glass) and titanium mixed into tantalum (for the specialty glass) are placed near the uncoated mirror in a chamber mostly empty of air but with some residual oxygen. Argon atoms are shot by a gun to hit the targets at high speed. The collision of the argon with the targets knocks off individual atoms of silicon, titanium, or tantalum. These then hit the mirror with high speed, combine with the oxygen, and densely pack to form the glass layers. By moving the argon beam back and forth between the silicon and the titanium/tantalum targets, alternating layers of silica glass and specialty glass can be formed. In the Advanced LIGO End Test Masses, over 30 layers are created this way.

Gregg Harry

Drawing of ion beam coating process by Hannah Fair.