



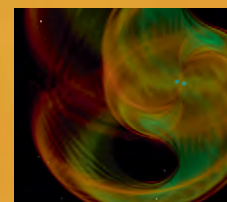
LIGO MAGAZINE issue 16 3/2020

03 update

Upgrades and tweaks:
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Mid-03 essential commissioning p.6



GW190425:
An unusual compact binary merger
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... and the LVK take on climate change and diversity in science p.15 / p.23

Front cover

Numerical-relativity simulation of the binary neutron star coalescence and merger which resulted in the gravitational wave event GW190425. The colors show the strength of the gravitational-wave signal ranging from low to high with red, yellow, green to blue.

Top inset: Unlocking one of the mirrors after cleaning at LIGO Livingston during the Observing Run 3 commissioning break.

Bottom inset: A second snapshot of the numerical-relativity simulation shown in the main image (see above).

Image credits

Photos and graphics appear courtesy of Caltech/MIT LIGO Laboratory and LIGO Scientific Collaboration unless otherwise noted.

Cover: Main image and bottom inset by T. Dietrich (Nikhef), S. Ossokine, A. Buonanno (Max Planck Institute for Gravitational Physics), W. Tichy (Florida Atlantic University) and the CoRe-collaboration. Top inset from Caltech/MIT/LIGO Lab.

p. 3 Comic strip by Nutsinee Kijbunchoo.

p. 6-11 Hanford photos by Nutsinee Kijbunchoo (p. 6-7). Livingston photos from Caltech/MIT/LIGO Lab (p. 8-9). Virgo photos from EGO/Virgo Collaboration/Francescon (p. 10) and Valerio Boschi (p. 11).

p. 12 T. Dietrich (Nikhef), S. Ossokine, A. Buonanno (Max Planck Institute for Gravitational Physics), W. Tichy (Florida Atlantic University) and the CoRe-collaboration.

p. 14 Plot and table by LIGO/Virgo.

p. 15 NASA Earth Observatory images by Joshua Stevens and Lauren Dauphin, using VIIRS data from NASA EOSDIS/LANCE and GIBS/Worldview, and the Suomi National Polar-orbiting Partnership, MODIS data from NASA EOSDIS/LANCE and GIBS/Worldview and Landsat data from the U.S. Geological Survey.

p. 16-19 Lighting photo by Guillermo Valdes (p. 16). CAD drawing by Eddie Sanchez (p. 17). Photo by Alena Ananveva (p. 17). Plot by Corey Austin (p. 18).

Plots on p. 19 by Data Quality shift operators from summary pages: <https://ldas-jobs.ligo-la.caltech.edu/~detchar/summary/day/20190526/> https://ldas-jobs.ligo-la.caltech.edu/~detchar/summary/day/20190526/sei/ground_blrms_overview/

p. 20-22 Photos by Michael Weinert, p. 22 top image by Skodock, Tobias Gersch, p. 22 middle image by Nikhil Mukund

p. 23-25 Photos by William Katzman.

p. 26-27 Images by Jessica Steinlechner.

p. 28-31 Photos by the Einstein First Project/Rahul K. Choudhary.

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Back cover: Plot by Meg Millhouse.

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Antimatter



Welcome to the LIGO Magazine Issue #16!



Welcome to the sixteenth issue of the LIGO Magazine! As observing run 3 (O3) draws to a close, we hear about the first “exceptional” O3 discovery from Rossella Gamba and Xingjiang Zhu in “GW190425: An unusual compact binary merger”. So far gravitational waves have been observed from compact binary mergers, but how do you look for gravitational waves from new or surprising types of signals? Meg Millhouse explains in this issue’s “How it works”.

Last October, the observatories were taken offline for the mid-O3 commissioning break, in “O3: Commissioning break at LIGO and Virgo”, Nutsinee Kijbunchoo, Carl Blair, and Maddalena Mantovani describe just what went on at each of the sites and why. The bangs and bumps that affect detectors can have quite the variety of origins, from thunderstorms and earthquakes to light, as we hear from “Environmental noises in gravitational-wave detectors”. Moving over to GEO600 news, we have a tale of the difficulties of vacuum repair as told by the GEO600 operators in “GEO600: Vacuum repair with pure nitrogen / There’s a hole in my bucket”.

Looking to the next generation of scientists, we hear from two schemes from around the world. At LIGO Livingston, William Katzman describes the push for diversity in science in “Exploring the LIGO/SUBR docent program” and in Australia the Einstein First team are trialing out teaching modern physics concepts to school students in “Teaching reality: at the Einstein First Project”.

In addition, we also have articles on the latest from the LISA mission progress, what to do after a PhD and what the LIGO-Virgo-KAGRA collaborations are doing to reduce our climate impact.

As always, please send comments and suggestions for future issues to magazine@ligo.org.

Hannah Middleton, for the Editors

News from the spokesperson

It is gratifying to look back over the past ten years and to think about how far we have come as a Collaboration and as a field. The initial LIGO detectors were decommissioned at the end of 2010 and the installation of Advanced LIGO began. We were looking forward to the first detection and the beginning of gravitational-wave astronomy. What an exciting decade it turned out to be. GW150914 opened a new window on black holes and GW170817 established a modern era of multimessenger astrophysics. And the detectors have transitioned to full-fledged astronomical instruments.

With ten calendar months of O3 behind us, we have more than 50 detection candidates that were announced publicly within minutes of acquiring the data. We have published results on the second binary neutron star merger GW190425, and we plan to submit more than 30 Collaboration papers over the next 12 months. This is an ambitious goal that will require a lot of work. On the other hand, the data is the most sensitive ever taken and these papers will have outsized impact as a result. Please get involved!

Over the next 5 years, detector upgrades will be interleaved between observing runs with the goal of increasing LIGO's reach for compact binary mergers by almost 3 times in distance. The research, development, and engineering needed to make this a reality is challenging. As we know from past experience, it's extremely important to pursue multiple approaches to improving the detectors including those that look past the concrete plans. So we must continue to foster a vibrant instrument science research program across the Collaboration. We should take every opportunity to bring the best people and ideas together

to address our major challenges. At the Collaboration meeting in Wisconsin, we will hear more about the near-term efforts, the ideas to reach the sensitivity limits of the current facilities, and the plans for next generation facilities.

Last November, we signed an agreement that establishes the LIGO-Virgo-KAGRA collaboration. This agreement extends our vision for an international network of gravitational-wave detectors to carry out an exciting program of observational science through this decade. The LIGO-India detector represents a unique opportunity for our Collaboration and the global network. Three LIGO detectors operating at similar sensitivity would be transformational. So we should all work hard to make it possible.

A major revision of the LSC Bylaws will be brought to a vote of the Council in March. I want to thank the Bylaws Committee for all of their work on this. I think the proposed structural changes will substantially improve the Collaboration. Please discuss this with your Council representatives so that any lingering concerns can be addressed before the vote.

The LSC is a great place to work and play. Sometimes, open scientific discussion may include passionate exchanges and interactions. The strength of our collaboration lies in our ability to embrace new insights while acknowledging the many contributions that make our scientific output excellent. Please be respectful of each other at all times. Discuss the merits of issues. Pay careful attention to the origin of ideas and give appropriate credit. Listen with the intention to understand. If you have concerns about the LSC, talk to me!



Patrick Brady
LSC Spokesperson

A handwritten signature in blue ink that reads "Patrick Brady".



Observing Run 3: Upgrades & tweaks

▲
Working inside the vacuum chamber at Hanford.

Commissioning breaks are temporary pauses in observation runs where the detectors are upgraded and repaired. Observing Run 3 (O3) started on 1 April 2019 and will last for a year.

The mid-O3 commissioning break took place from 1 October to 1 November. During this time essential works are carried out which require more time than available during normal weekly maintenance. This includes working inside the HAM (Horizontal Access Modules) chambers where the optics of the interferometer are housed in vacuum during observation time. To access HAM chambers they need to be vented so that the doors can be

opened and then slowly restored to vacuum once work is completed. Then the detectors are brought back into observation mode.

Commissioning breaks are key to improving the sensitivity of the detectors and reduce noise. The binary neutron star (BNS) range of a detector indicates how far away it could find a BNS inspiral signal measured in mega-parsecs (Mpc) - the higher the BNS range, the more sensitive it is.

But what work happened in the O3 commissioning break? Nutsinee Kijbunchoo, Carl Blair, and Maddalena Mantovani give updates from LIGO Hanford, LIGO Livingston and Virgo.

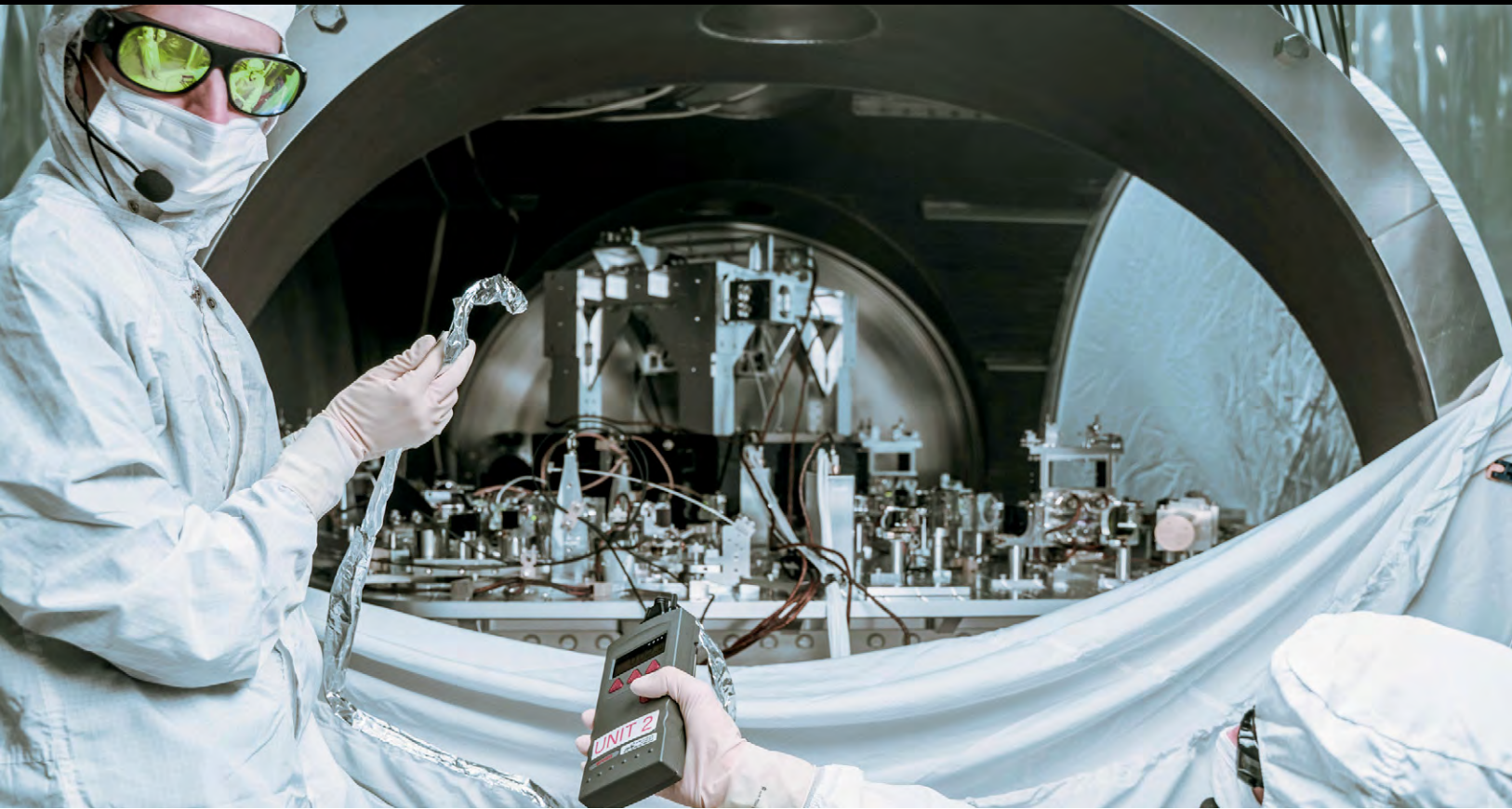
Nutsinee Kijbunchoo



is a third year PhD student working on quantum optics at the Australian National University, and has so far spent about half the time at LIGO Hanford. "I lab, drink, and draw things".

Hanford Commissioning break

The commissioning break started on October 1st, 2019 and lasted a whole one month. At Hanford squeezer maintenance was the top priority. The squeezer manipulates the quantum fluctuations in a vacuum to reduce quantum noise and improve detector sensitivity. An optical fiber that plays a crucial role in generating squeezed vacuum was degrading in transmission. This meant that less and less light was being delivered from one place to another (from the in-air table to the in-vacuum optical parametric oscillator inside HAM6), limiting the per-



▲ Working on the vacuum squeezer at Hanford.

formance of the squeezer and how much quantum noise we could reduce. Without the squeezer LIGO Hanford would have been listening to 50% less in volume than it currently is. Together with scientists and engineers from the site, MIT, and ANU, the fiber replacement was successful and eventually we were able to recover the same amount of squeezing we used to have when O3 started back in April. The fiber swap itself was done in two days. However, the recovery of the vacuum level and the interferometer itself took much longer.

There are several major tasks that took advantage of this opportunistic down time. The first being a replacement septum window: the in-vacuum windows between vacuum chambers which allow the laser beam to travel through. The window between HAM5 and HAM6 was replaced in an attempt to mitigate scattered light noise. Unfortunately, there was no large

improvement observed and the investigation is on-going.

The second task was working on the phase camera. As the laser power is increased the interferometers become increasingly affected by mismatches (differences between the shape of the laser beam and the shape of the mirrors) and highly absorbing absorbers in the coatings of the test mass mirrors. These thermal deformations can have an adverse effect on the various optical fields we use to control the interferometer. This poses problems in interferometer locking that uses multiple frequencies as locking signals (sidebands) and there were previously no tools installed in LIGO that could measure this effect in real time. The phase camera from the University of Adelaide was installed and tested at LIGO Hanford to look at what was happening inside the interferometer. This phase camera is based on a new optical demodulation

technique. The output yields images that show the amplitude and phase differences between individual sidebands (eg. 9MHz and 45 MHz). The data allowed commissioners to monitor the change in the optical fields circulating with the interferometer as the injected laser power increased. Analyzing this data can hopefully provide more insight into what knobs we can tweak for optimizing the interferometers performance in the future.

The third was the vacuum system repair. Aging pump stations (turbo and roughing pump) were swapped in order to mitigate risk (thanks to the \$2.5M “vacuum recovery” fund from NSF). H2 vertex vacuum equipment was decoupled from the rest of the corner station so it can be kept in-air and we can start removing components that are needed for A+ upgrade. (H2 was a 2 km interferometer which ran in parallel to the 4 km Hanford detector). In addition,

03: Commissioning break at LIGO & Virgo



▲
Unlocking one of the end test-masses (mirrors) after cleaning at Livingston.

Carl Blair

a residual gas analyzer was added to HAM6 for ability to monitor partial pressures in chamber. All of this (and more that couldn't be listed) was done on top of HAM6 and corner station vent support for squeezer work and septum window replacement. Thanks Team Vac!

Last but not least, is the wind fence installation. Ground sensors are attached to, well, ground. When the whole building is tilted due to strong wind, the sensors see translation instead of tilt causing the control system to respond incorrectly. The beam rotation sensor helps this, but it's better to just reduce the tilt all together. So, the wind fence was introduced. The fence is 12 feet tall, about 300 feet long, and made of 40% porosity fabric. It is designed to withstand 100 mile per hour wind conditions (I have seen 80 mph wind there. This is not a crazy number for Hanford site!). The fence was partially

installed during the break and later completed for End X.

Livingston Commissioning break

One month is a short commissioning break. It's a high risk operation, open up the instrument and make things better, or open up and make things worse. A high risk operation on a short timeframe is always going to be pretty tense.

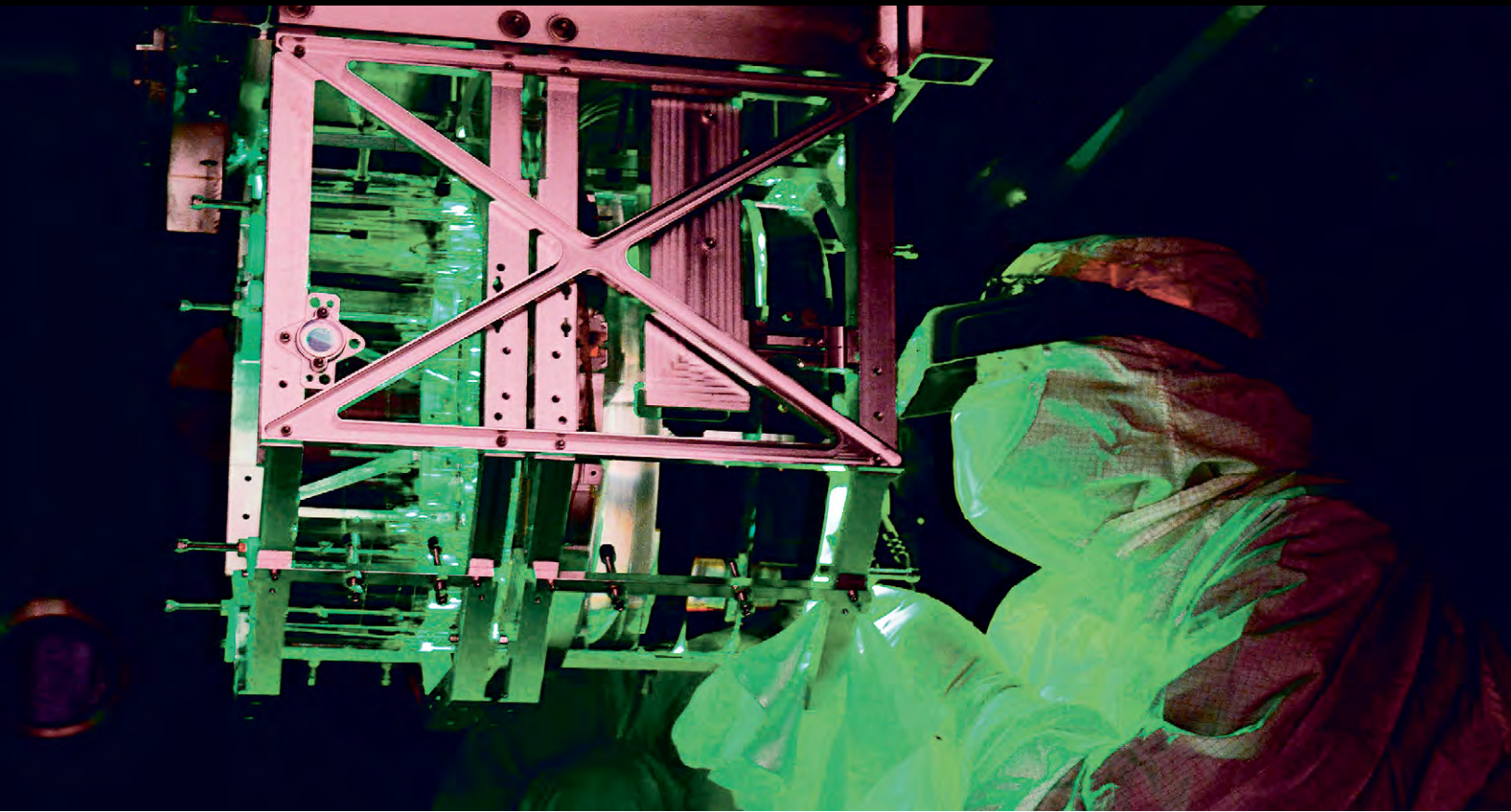
O3 at Livingston was running smoothly, a cool BNS range of 140Mpc. However every day as we arrived to work, the range would dive by 20Mpc. A phenomena known as scattered light noise was back with a vengeance. This "daytime noise" is due to the interferometer light scattering off things that are moving due to the seismic noise of people, machinery and trains. Scattered light noise is very hard to predict and we are never sure if a scatter culprit has been identified. Previous guesses



has been the commissioning postdoc at Livingston for the last two years. He was recently awarded a "Discovery Early Career Research Award", is now based at the University of Western Australia and returned to

Livingston for the commissioning break. Unfortunately, in September, he snapped his achilles tendon, so he recounts the break from the control room (and sometimes the hospital bed) perspective.

on identifying intervention locations have had confusing results. The swath of light-absorbing baffles put in between the previous Observing Run 2 and O3 definitely reduced this noise, however it is hard to be sure which ones are responsible for the improvement. The proposal was to soak up any scattered light with baffles at a few locations in the end stations, but we were all wary of putting too much hope in this solution.



▲
Inspecting a mirror surface (test mass) at Livingston.

The other major issue for O3 has been point absorbers. Point absorbers are locations in the high reflectivity coatings of the test mass mirrors that have excess optical absorption. These point absorbers thermally distort the test mass surface. As the laser power is increased, the distortions scatter light, resulting in increased noise and wasted light. So along with the normal vent cleaning procedures there was a special intervention, to locate and investigate possible cleaning strategies of point absorbers.

From the control room perspective the Livingston vent teams operated as a well-oiled machine. Crew arrived from Caltech, MIT, India. Teams were assembled and the activities adhered remarkably closely to the planned timeline. The in vacuum optical table at the X end station now looks like a stealth tank (much like most of the corner station tables). There were a few issues with team cleaning - a cleaning prod-

uct that works like a face mask for the test masses did not peel off cleanly first try. But the final peel left an optic that was visually much the same as the original. There are some nice microscope images of the point absorbers taken in situ.

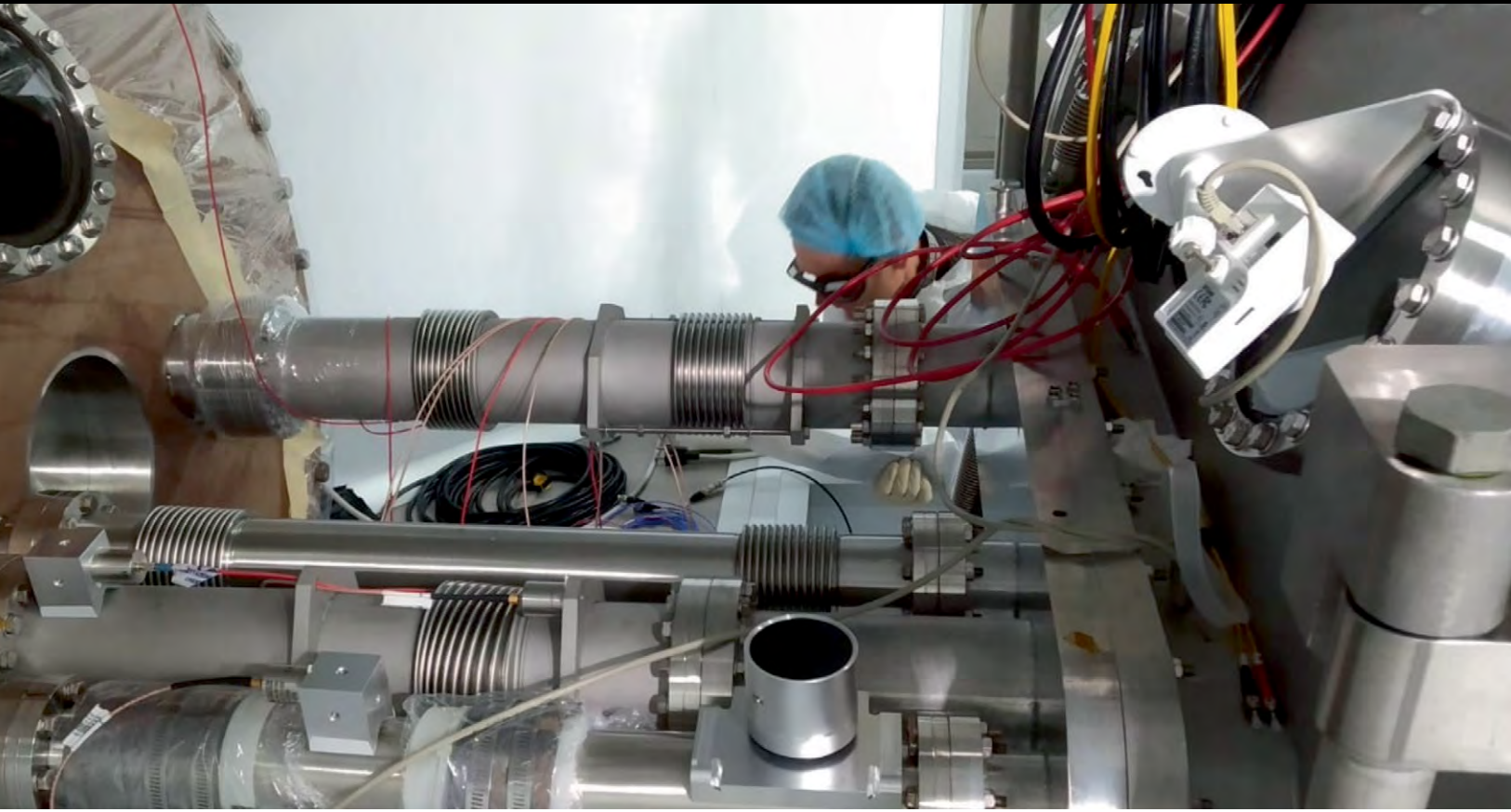
Then the short intervention was over, doors were back on and the vacuum pump down began. The pump down feels excruciatingly long. We finally got the interferometer back and were free to commission away (for about 100 hours). Commissioning being the process of getting the interferometer working its best.

Turns out we didn't need 100 hours, after an evening of recovering alignment of the laser beams, by the next evening noise was low. We were missing a whopping 20% of our light though. Some coarse beam position adjustment recovered a small portion. This was indeed disturbing information, as

it indicated the point absorber landscape had changed for the worse. However, much of the range that should have been lost due to decreased optical power was recovered with squeezer tweaking - better quantum manipulation of the light. So all in all to those watching the interferometer sensitivity in BNS range there has not been a significant change. Then we waited - the first day, there wasn't much scattered light noise, the first train didn't seem to affect BNS range much, ... the second train did! It's so hard not to start making sweeping statements based on our feelings from too little information. But slowly it became clear that daytime noise is gone (well is a lot smaller).

So all in all the the break was a success - with a mixed bag on the contributing factors. As usual, being a part of the commissioning team was great fun and an enlightening experience.

03: Commissioning break at LIGO & Virgo



▲ Investigating scattered light noise at Virgo. The pipes have been temporarily equipped with monitoring accelerometers to perform diagnostic measurements.

Virgo Commissioning break

Activities during the O3 commissioning break for the Advanced Virgo interferometer were focused on increasing the input power for the laser from 18 to 26 Watts. This increase to an intermediate power level is necessary to verify the capability of the detector to operate at higher power prior to Advanced Virgo + when the input power will be further increased to 40 Watts. An additional benefit was an improvement in shot-noise limited sensitivity at high frequency which increased the BNS range by a few Mpcs. The shot-noise is the fundamental noise limiting the sensitivity at high frequency, higher circulating laser power corresponds to a better sensitivity.

The increase of input power is a challenging step for the Advanced Virgo interfer-



commissioning.

ometer due to its marginally stable recycling cavities, compared to the stable cavities of Advanced LIGO. Marginally stable cavities have a poorer capability to filter out higher order optical modes from the laser beam. Optical modes describe how complex the amplitude profile of the laser beam is: the fundamental mode is the simplest and higher order modes are more complex. Higher order modes can

Maddalena Mantovani

Maddalena Mantovani, is a physicist working in the EGO group at the Virgo interferometer site as Interferometer Sensing and Control (ISC) coordinator deeply involved in detector

be caused by interferometer deformations, for example from optical defects or thermal aberrations due to the laser beam heating the optics. As the laser power increases, this will exacerbate the presence of higher order modes. A finely tuned thermal compensation system (TCS) is used to counteract thermal lensing due to the main laser. The TCS intentionally creates thermal lensing on a thin compensation plate close to the back face of the test mass mirrors. This acts directly on the test mass through a ring heater surrounding the mirrors.

Tuning the TCS is a long process as the mirrors can take hours or days to respond to heating. Several weeks of tuning was required after the increase of input power. This complicates the tuning process as



Scattered light noise hunting in the Advanced Virgo Laser laboratory. The Laser bench is visible on the left.

several extraneous factors may change during the thermal transient. However, the tuning was expedited due to the use of validated simulations and expertise gained during past commissioning phases. After careful tuning, the interferometer converges towards the best optical configuration, i.e. a perfectly thermally compensated interferometer.

Aside from the main task of the O3 commissioning break, the commissioning team took the opportunity to study and mitigate technical noises. Most importantly, a study was conducted to characterize the relationship between the output mode cleaner alignment and the so-called "flat noise". This technical noise is the limiting factor of Advanced Virgo sensitivity in the frequency range of tens to hundreds

of Hz. Another significant improvement has been the mitigation of the scattered light originating from the terminal detection benches. The suppression was obtained by refining both the longitudinal (along the beam axis) and the transversal control between the bench and the terminal test masses.

Additional lower impact noise sources have mitigated such as the noise at 48 Hz which was due to resonances in the optics suspension. In conclusion, the O3 commissioning break was quite profitable for Advanced Virgo. The interferometer was verified to operate successfully at higher input laser power. Further, the BNS range improved by about few Mpc due to the increase in power and the identification and suppression of technical noises.

03: First "exceptional" discovery

GW190425:

An unusual compact

binary merger event



On the 6th January 2020, the LIGO Scientific Collaboration and Virgo Collaboration announced the first “exceptional” discovery, GW190425, made during the third observing run (O3) of the LIGO and Virgo detectors. As its name suggests, the signal was detected on the 25th April 2019. It lasts around 128 seconds and the chirp-like feature indicates it was produced by a merger of two compact objects. Soon after the detection, the event raised people’s eyebrows in the collaboration because the combined mass of the two merging objects was unusually high for a neutron star merger, around 3.4 times the mass of our Sun (M_{\odot})!

Before the detection of GW190425, LIGO and Virgo had detected a handful of binary black hole mergers and one binary neutron star merger event. These black holes typically have masses from around $6 M_{\odot}$ up to $50 M_{\odot}$. Neutron stars used to be thought to have a typical mass of $1.4 M_{\odot}$, mostly thanks to the Hulse-Taylor binary pulsar that led to the 1993 Nobel Prize in Physics (see text box). Nowadays, neutron stars are found to cover a relatively large mass range, from around 1.2 to $2.1 M_{\odot}$.

Detections like GW190425 can provide insight about the matter that makes up neutron stars as well as the formation history of binary neutron stars.



provided the chance

Rossella Gamba

is a PhD student at Friedrich-Schiller University (Jena) who works on waveform modelling and extreme matter. She loves music games, and will challenge you at Guitar Hero if



with pulsars. He plays football (aka soccer) for fun.

Xingjiang Zhu

is an OzGrav Postdoctoral Fellow at Monash University in Melbourne Australia and works on studying neutron stars with gravitational waves and searching for gravitational waves

Neutron star matter

Neutron stars are objects made of extremely dense matter: the mass of a few suns is enclosed within a volume spanned by a radius of “just” 11 to 13 km. Discovering the microscopic composition of their core, in terms of particles and interactions, is one of the most challenging problems of contemporary astrophysics.

Gravitational waves offer an novel way to shed light on the issue. For neutron stars in a coalescing binary system, it is not appropriate to describe the evolution of the two stars simply as that of point-like masses orbiting around each other, as is done for black holes. Matter effects leave a detectable imprint on the gravitational wave signal emitted by the source. This imprint depends on the masses and - critically - on the equation of state of neutron star matter. The equation of state is the relation between pressure and density that exists within the star. It fundamentally encodes the microscopic properties of cold,

dense matter and can be related to the macroscopic quantities (mass, radius etc.) of the object.

The heavy nature of GW190425, coupled to its relatively low signal-to-noise ratio, means that - unfortunately! - it was very hard to measure matter imprints for this system. Though not much could be learnt about neutron star matter, a number of analyses were carried out. All in all, GW190425 was an opportunity to sharpen analysis tools, revisit and improve older methods, and engage in long, productive discussions.

Comparing GW190425 to other binary neutron stars

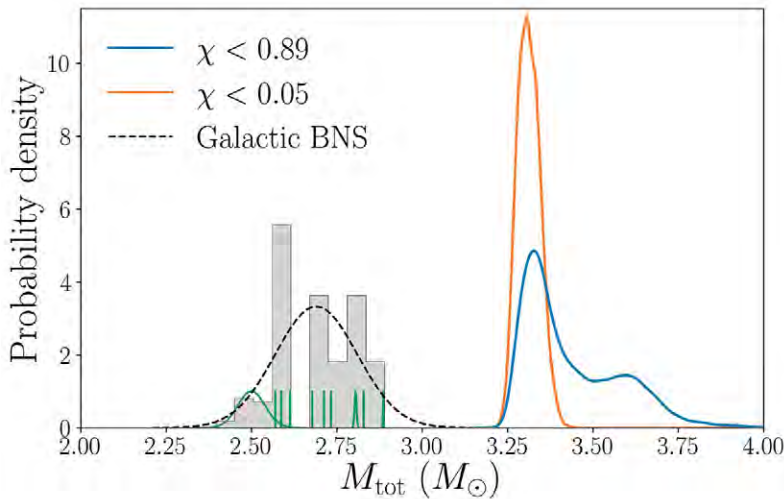
In 2017, LIGO and Virgo detected their first neutron star merger, GW170817. In the case of GW170817, the combined mass of the two stars is $2.73 M_{\odot}$, with the individual stars masses ranging from 1.2 to $1.6 M_{\odot}$. GW190425 is clearly a merger

What is a pulsar?

A pulsar is a fast-rotating neutron star, that emits beams of electromagnetic waves along its magnetic axis which is usually misaligned with the rotating axis. A pulsar’s beam sweeps across the Earth like a lighthouse in the cosmos. By timing the arrival times of the pulsar’s pulses, astronomers can precisely measure the masses of the pulsar and its companion star. For the Hulse-Taylor binary, the pulsar is found to have a mass of $1.4398 M_{\odot}$, and its companion neutron star is $1.3886 M_{\odot}$.

of something more massive. After the detection, LIGO/Virgo scientists were speculating the nature of GW190425 on Mattermost (an online communication platform)

03: First "exceptional" discovery



The distribution of possible total masses for GW190425. The x-axis shows the total mass measured in solar masses (the mass of our Sun). Two curves on the right show the probability distribution for the combined mass for different assumptions about the spins of the two objects (blue allows for higher spin and orange only lower spin). The grey histogram and black dashed line shows the combined masses of 10 Milky Way binary neutron stars for comparison.

whilst eagerly looking through preliminary analysis results. Some online conversations suggested it might be the merger of two neutron stars, one with the typical mass of $1.4 M_{\odot}$ and the other being a massive $2 M_{\odot}$ guy. Another argued it could be due to a neutron star colliding into a small black hole. Apart from gravitational wave mergers, black holes have also been found in X-ray binaries. However, there is no clear observational evidence for small black holes less than $\sim 4 M_{\odot}$. So interpreting GW190425 as containing at least one black hole component would mean a completely new population of black holes.

In the Milky Way, radio astronomers have collected a dozen pulsar-neutron star systems including the Uls-Taylor binary (see pulsar box on p.13). Their masses are more or less similar to that of GW170817, with total masses ranging from 2.5 to $2.9 M_{\odot}$, and individual masses from 1.17 to $1.65 M_{\odot}$. GW190425 represents an obvious outlier from this Galactic population. So while it is reasonable to believe it is a binary neutron star merger, one may ask how it could have been formed and if its formation differs from that of binary neutron stars in the Milky Way.

Table of properties of the binary neutron star that produced GW190425 from the discovery paper. dcc.ligo.org/public/0161/P190425/007/gw190425-discovery.pdf



Formation scenarios: dynamical or isolated?

One idea is that this system was formed as a result of dynamical interactions in dense stellar environments such as globular clusters - clusters of many stars bound together by gravity. Pulsar astronomers have found evidence for neutron stars with masses up to about $2 M_{\odot}$ in globular clusters. Frequent gravitational interactions between stars could lead to the formation of a neutron star binary. However, this scenario is somewhat disfavoured because theorists find it difficult to form and merge binary neutron stars this way. In the Milky Way, only 1 in 10 known binary neutron stars that are capable of merging are found in globular clusters.

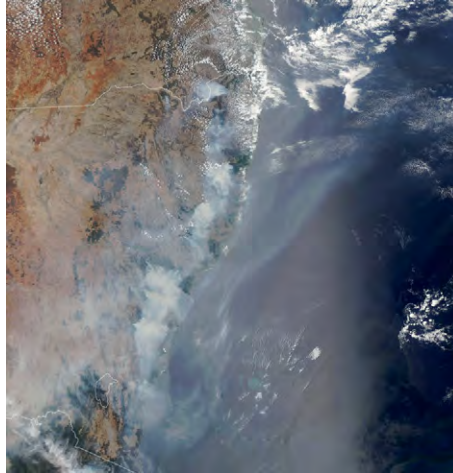
The standard way of forming binary neutron stars is to evolve an isolated binary of two massive stars. These binaries do not interact with other stars over the course of their lives. The two stars die sequentially through supernova explosions. They leave behind two remnant neutron stars orbiting each other. It is an exquisite mechanism: the binary needs to survive two explosions, and the separation between the stars needs to be just right so that

| | Low-spin prior ($\chi < 0.05$) | High-spin prior ($\chi < 0.89$) |
|--|--|--|
| Primary mass m_1 | $1.62 - 1.88 M_{\odot}$ | $1.61 - 2.52 M_{\odot}$ |
| Secondary mass m_2 | $1.45 - 1.69 M_{\odot}$ | $1.12 - 1.68 M_{\odot}$ |
| Chirp mass \mathcal{M} | $1.44^{+0.02}_{-0.02} M_{\odot}$ | $1.44^{+0.02}_{-0.02} M_{\odot}$ |
| Detector-frame chirp mass | $1.4868^{+0.0003}_{-0.0003} M_{\odot}$ | $1.4873^{+0.0008}_{-0.0006} M_{\odot}$ |
| Mass ratio m_2/m_1 | $0.8 - 1.0$ | $0.4 - 1.0$ |
| Total mass m_{tot} | $3.3^{+0.1}_{-0.1} M_{\odot}$ | $3.4^{+0.3}_{-0.1} M_{\odot}$ |
| Effective inspiral spin parameter χ_{eff} | $0.013^{+0.01}_{-0.01}$ | $0.058^{+0.11}_{-0.05}$ |
| Luminosity distance D_L | 161^{+67}_{-73} Mpc | 159^{+69}_{-71} Mpc |
| Combined dimensionless tidal deformability $\tilde{\Lambda}$ | ≤ 600 | ≤ 1100 |

A global challenge

the binary will spiral-in and merge. One idea to explain the unusually high mass of GW190425 is that binaries with similar masses are easy to miss in the Milky Way because they don't live long. A system like GW190425 might be formed with extremely tight orbits, e.g., two neutron stars orbiting around each other multiple times per hour. In comparison, the tightest Milky-Way binary neutron star has an orbital period of 2 hours. These binaries form and die (in astronomical terms, with a lifetime of less than 1 million years for example), so there isn't much chance to catch them while surveying for pulsars in the Milky Way. Gravitational wave detectors, on the other hand, are sensitive to the final merger of two stars; the chance of detecting a binary merger has more to do with how far away these detectors can see rather than how fast a binary merges (as long as it merges within the age of the Universe). It is very rare that a neutron star merger happens inside the Milky Way, something like once in a hundred thousand years. Detectors like LIGO and Virgo are sensitive to galaxies far beyond our own Galaxy, hundreds of millions of light years away. This will enable the observation of signals like GW190425 and GW170817 at least multiple times per year once the detectors reach the full sensitivity.

As LIGO-Virgo detectors keep improving their sensitivities and the new Japanese detector KAGRA joins the international network, more compact binary mergers similar to GW190425 will be discovered in the next few years. Future multimessenger observations of these events will help answer the outstanding questions on the neutron star matter and the formation history of binary neutron stars.



▲ NASA Earth Observatory image of the Australian bush fires pictured in December 2019.

Climate change is one of the most significant challenges facing the world today. We believe that all of us, as scientists, should be playing leading roles on this issue.

The LIGO, Virgo, and KAGRA (LVK) collaborations have established a Committee on Climate Change at the initial instigation of Steve Fairhurst, chaired by Daniel Holz. Our goal is to come up with suggestions that would reduce the carbon footprint of our collaborations. For example, we will investigate ways to reduce travel, and explore alternatives such as improved remote participation options. We will also evaluate our computing resources and usage, and how we operate our detectors and research labs. Of course, any direct action we take will have only a minimal impact on



Steve Fairhurst is a Professor at Cardiff University working on finding and understanding gravitational waves from binary mergers. When it's not raining in Wales, Steve tries to get outside and enjoys hiking, canoeing and trail running.



Daniel Holz is a Professor at the University of Chicago working on gravitational-wave astrophysics and cosmology. He also helps set the time of the Doomsday Clock [<https://thebulletin.org/doomsday-clock/current-time/>], which is a lot more frightening than thinking about black holes.

the global threat of climate change. Nonetheless, our actions can have a disproportionate effect: our collaboration has a prominent international profile due to our outstanding scientific breakthroughs. We are in a position to serve as role models, both personally and professionally, and our efforts to address climate issues are likely to be noticed and perhaps emulated.

In the coming months our committee will undertake the task of quantifying our impact on the climate, and identifying approaches to mitigating these impacts. Climate change is a critical global issue, and we welcome input from all members of the collaboration. We will hold Town Hall meetings to inform everyone about our activities, and to solicit ideas and suggestions (and volunteers!) for ways to address this burning issue.

We look forward to working together to confront this profound threat to civilization.

Thunderstorms, light & earthquakes in gravitational-wave detectors

Guillermo Valdés



is a postdoctoral researcher at the Louisiana State University working on detector characterisation. He was born and raised in Mexico. Guillermo loves going out to the movies and eating popcorn, practicing boxing to help him stay active and relax after work, and improving his guitar skills.

Corey Austin



is a graduate student at Louisiana State University and works on stray light control at the LIGO Livingston observatory. Outside work, he enjoys disc golf, kayaking and spending time with his

friends. In addition to this, Corey also likes to play with his beautiful dog Ninja who will be turning 13 this year.

Anne Baer



is a graduate student at the Christopher Newport University. She works on data analysis for earthquake predictions and understanding their effects on LIGO detectors, glitch shifts and noise

studies. In her spare time, Anna enjoys writing and collecting interesting rocks.



▲
Lightning strike at Baton Rouge.

The LIGO detectors need to be isolated from external non-astrophysical influences to enable them to detect minute ripples in space-time. Despite our best efforts, environmental disturbances can contaminate the readout signals and reduce the sensitivity of the detectors. Here we describe three such environmental noise sources; thunderstorms, scattering light noise & earthquakes.

Thunderstorms

There is something that I cannot forget from the first time I visited the LIGO Livingston detector in 2009: the loudest thunderclap I had heard in my life. In 2017,

I moved to Louisiana and found that thunderstorms were common in the state and that the thunderclap in 2009 was not the loudest I would hear in my life.

South Louisiana is located next to the Gulf of Mexico. It has warm and humid weather, a perfect recipe for thunderstorms. In the list of U.S. cities ranked by the average number of thunderstorm days per year (based on the 1961-1990 data), Baton Rouge is number 10 with 72.0 days, and New Orleans is number 12 with 67.2 days [1]. Livingston is located more or less between these two cities.

Besides lightning strikes close to your apartment frying your internet modem (something I learned two summers ago), they can

also excite magnetic Schumann resonances in the closed waveguide formed by Earth's surface and the ionosphere [2]. These resonances cause an increase in the amplitude of the local magnetic field as measured by magnetometers on site. However, their magnetic field amplitudes are on the order of a picotesla; too small to produce strong signals in LIGO's gravitational-wave channel [3], at least for now.

Another way we know thunderstorms introduce noise to the gravitational-wave channel is through scattering. Let me explain: Depending on the distance from, and the nature of, the lightning strike, thunders can range from a sharp, loud crack to a long, low rumble. The rumble causes the vacuum chambers to shake. When laser light scattered out of the main beam reflects from the walls of the vibrating chambers and recombines with the light resonating in the optical cavities, it can couple noise from thunderstorms into the gravitational-wave channel. Thunders are registered by the LIGO auxiliary sensors, like microphones and accelerometers, at frequencies between 10Hz and 100Hz. During a thunderstorm, the 20-200Hz frequency band is excited in the gravitational-wave channel, and the BNS range (the distance a detector can pick up a binary neutron star signal) can drop by around 20Mpc.

It might take some time for the LIGO detectors to be fully isolated from thunderstorms. Meanwhile, we can identify these meteorological phenomena using the auxiliary channels (which monitor the detector status) and flag the corresponding segments of data. We can also take advantage of this information. Like with PEM injections, where an intentional stimulus is introduced, and the responses of auxiliary sensors and

the gravitational-wave detector analyzed, we can compare the relationships between accelerometer and detector data at various locations to determine which place seems to be more correlated with the noise in the gravitational-wave channel. This process could save us some time by avoiding the installation of shakers, driving them at various frequencies, understanding the coupling of noise into the detector and repeating this process two to three times during an observation run. Of course, it is not that simple, we need to separate the thunders by location and find out a way to quantify the amplitude of the "natural injection" (spoiler alert: we are working on that). For the moment, in terms of thunderstorms, we could be glad the detector is not in Florida.

Guillermo Valdés

Scattering light noise in LIGO

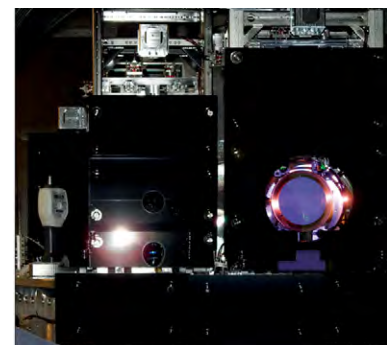
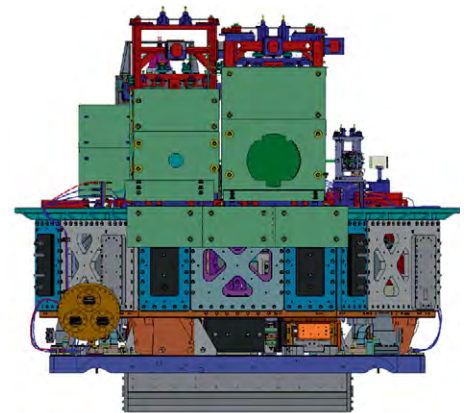
LIGO uses advanced coating methods and materials to limit the amount of light which scatters out of the main interferometer beam. However, a small amount of light does scatter. This scattered light can interact with surfaces inside the interferometer which are not seismically isolated and recombine with the main beam, thus introducing excess noise into the gravitational-wave channel. Finding and mitigating the sources of scattered light noise in the LIGO detectors is an ongoing challenge and necessary for continuing to improve the detector sensitivity.

Scattered light noise, which couples into the detector, depends on the power in the scattered beam as well as the displacement of backscattering surfaces among other

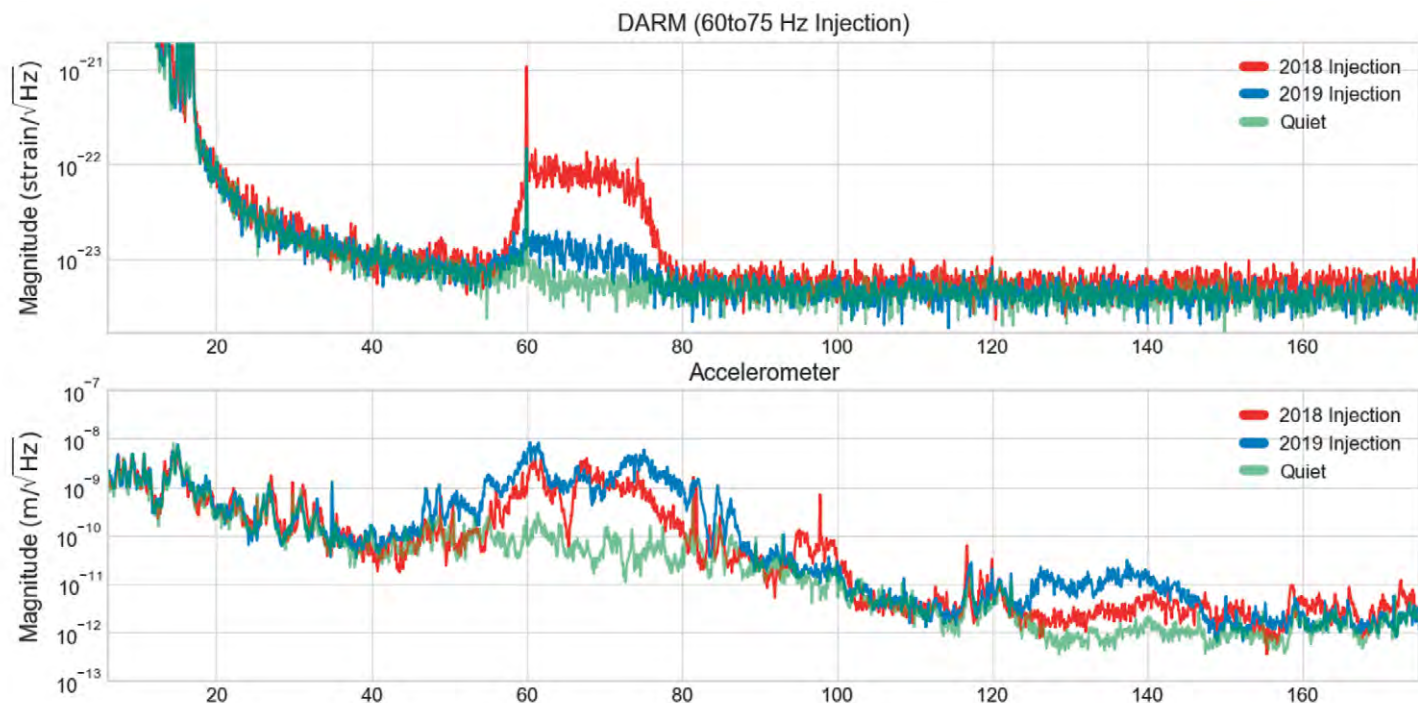
CAD drawing of baffles to be installed in the output arm of LIGO livingston (left) and baffles after installing in the interferometer (right).

things. Since scattered light can interact with any surface inside the interferometer, making accurate measurements of the aforementioned parameters would require installing far more sensors than is practical.

One method for locating noise sources in LIGO is via injections. For scattered light noise, we cannot easily change the amount of light incident on the scattering surface. However, we can increase the motion of the scattering surface. This is achieved by attaching a mechanical shaker to the outside of the vacuum envelope and driving the shakers at various frequencies. We then look at the gravitational-wave channel to see if this increased motion has resulted in increased noise. By moving the shakers to various locations throughout the interferometer, we can identify areas of high coupling and design solutions to mitigate the scattered light noise.



Environmental noises



▲
Comparing an injection made in November 2018 to one made in October 2019 (after new baffles were installed). The bottom panel shows that the witness accelerometer saw more or less the same amount of motion during the 2019 injection, but the gravitational wave channel (DARM) saw less noise during the 2019 injection.

One of the ways we can mitigate scattered light noise is via installing baffles in locations where coupling to the gravitational-wave channel is high. These baffles have specialized coatings to absorb most of the scattered light and to direct the remainder away from the main beam. After installing baffles, shaker tests are repeated to quantify any improvements to the sensitivity of the detectors

Prior to the start of the third observing run (O3), shaker tests indicated that scattered light was coupling to the gravitational-wave channel near the end test masses at LIGO Livingston. In October of 2019, we installed baffles in both end stations to cover up some potential scattered light paths. After installation, shaker tests were repeated and revealed that the noise coupling had been reduced. Even with the improvements we saw after October, we continue to see scat-

tered light noise in the gravitational-wave channel from time to time. Our investigation into the potential sources of scattered light noise is ongoing and we plan to install additional baffles once O3 is over.

Corey Austin

Earthquakes

Although the LIGO interferometers search for gravitational-wave signals from the most distant reaches of the universe, we cannot forget about the effects of our own planet on the interferometers. From phenomena such as oceans waves lapping onto a beach to tectonic plates colliding under the Earth's surface, the Earth is constantly in motion. Seismic noise, which is defined as any vibrations associated with the Earth's interior and surface, is constantly monitored by the ground-based facilities and must be mitigated for the detectors to operate.

There are several types of background seismic noise including microseism, which are primarily caused by natural phenomena such as ocean waves and small earthquakes; and anthropogenic noise, which tend to be caused by human activity and atmospheric disturbances. Medium and large earthquakes are not frequent enough to be included in these groups but are responsible for generating the most dramatic seismic noise.

Large earthquakes from anywhere around the world will be detected by seismometers on site. The signal from an earthquake is significantly louder than any astrophysical source (although at a different frequency). Even seismic waves produced during a moderate to severe earthquake on the opposite side of the planet can generate enough vibration to make the ground-based gravitational-wave observatories go offline for several hours.

Small earthquakes (magnitude of 2 or less) occur hundreds of times a day. A majority of these earthquakes tend to be hidden in the background microseism of the planet. Various active & passive seismic isolation and suspension systems that are already in place significantly reduce the amount of seismic noise coupling through to the gravitational-wave channel. More powerful earthquakes occur less frequently, with the largest earthquakes (magnitude of 7 or greater) occurring about 15 times per year.

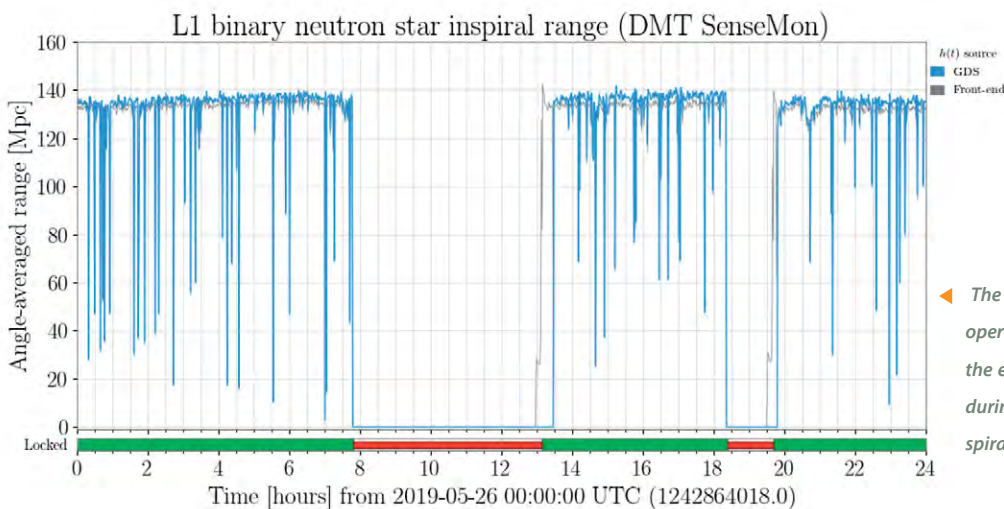
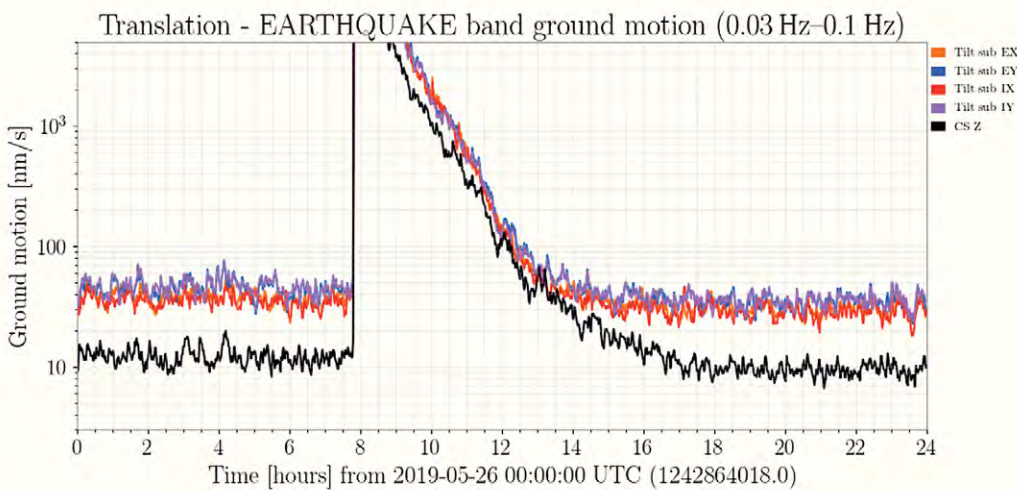
When the detector loses lock, it is no longer in a state where data can be collected,

and the search for gravitational waves must be halted. It can sometimes take several hours to get the detectors back online. Even if a large earthquake does not cause lock-loss, it can still introduce a significant amount of noise, rendering the data at the time the earthquake unreliable.

Thanks to the hard work of Jim Warner, Eyal Schwartz, and the rest of the seismic team, an earthquake mode has been integrated into the detectors to help them ride through more earthquakes. The first successful demonstration of this mode in op-

eration occurred on March 7, 2019, when it allowed the Hanford detector to operate during a 5.7 magnitude earthquake from New Zealand without losing lock. As long as the gravitational-wave detectors are on the surface of the Earth, earthquakes will be an unavoidable source of noise. However, as isolation technology and earthquake predictors become more advanced and reliable, the effects of these earthquakes will be lessened. This will allow the detectors to keep searching for gravitational waves during increasingly larger earthquakes.

Anne Baer



◀ The effect of magnitude 8.0 earthquake from Peru on the operation of LIGO livingston detector. The top image shows the excess ground motion recorded by accelerators on site during this time. The bottom plot shows the neutron star inspiral range before, during and after the earthquake.

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GEO600: Vacuum repair with pure nitrogen

There's a hole in my bucket,
dear Liza, dear Liza, There's a
hole in my bucket, dear Liza, a hole.

Then fix it dear Henry, dear Henry,
dear Henry, Then fix it dear Henry,
dear Henry, fix it.

It's a mild 15 C and last weeks storm has abated. The sun breaks through the cloud cover on this afternoon of the 22nd of October 2019 south of Hanover, Germany. *Henry* (the GEO Team) have spent many days preparing and planning for this day. However, unlike the bucket in the German song from the 1700s, this cannot be mended with only straw. In front of the GEO600 central building there are 48 steel cylinders each two meters long. Each is filled with high purity nitrogen 6.0 compressed to 200 bar. Their contents will soon flood the 200 cubic meters of vacuum in the north tube of the gravitational wave detector GEO 600, which has been switched off for the upcoming repairs. The large gate valves to separate the north tube from the rest of the vacuum system are closed. The next 24 hours are carefully planned. The team for the night shift has arrived and waits for the ok to flood GEO's north tube with nitro-

gen during the night, so that the welders from the Skodock company can finally seal the leak in the tube at daybreak the next morning.

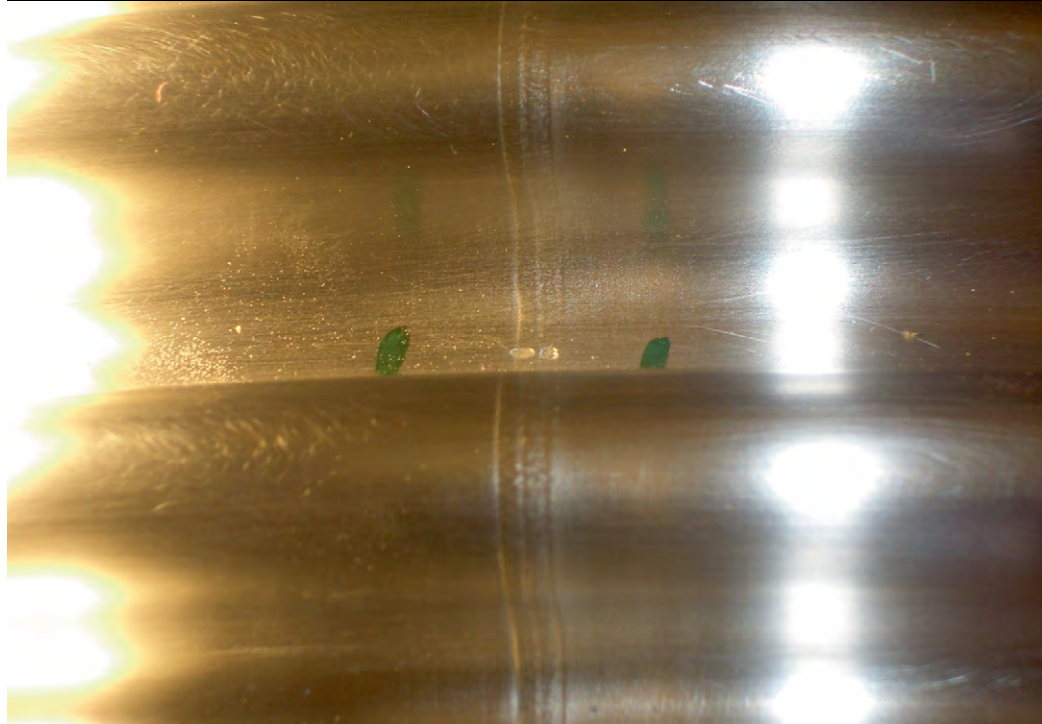
It all started on 1st August 2017 when the GEO 600 team noticed an initially mysterious pressure increase in the vacuum system. The first suspicions were a pump failure or a defective valve. However it soon became clear that systems were operating well. The vacuum system must have developed an internal or external leak.

Searching for the leak

The search for the leak began, first by evaluating pressure gauge data: The cause had to be somewhere beyond the central vacuum tank cluster towards the north tube. The search continued in the central building, using a residual gas analyser as a detector for helium sprayed around the vacuum system. No reaction. After applying more ge-

nerous amounts of helium, slowly but surely signs of the gas showed up in the analyser. Spraying helium closer to the rubber seal, where the vacuum tube passes through the wall to the tube trench outside made the signal even stronger. The leak had to be outside the central building in the tube trench!

After entering the trench outside the central building, where the corrugated vacuum tube is suspended, one could immediately see quite a pile on the tube. Probably the droppings of a marten, or some other animal that had found a cosy dry and warm place on the tube at the passage to the central building. When Marc Brinkmann started gently cleaning the excrement from the tube, a dramatic sudden pressure increase immediately showed that this was the place we were looking for. The jump in pressure was so high that the large turbo pumps had trouble coping with the suddenly increased gas load.



▲
After Skodock polished the affected area, direct on the longitudinal welding seam, on the right is the leak, and to the left is a starting corrosion.

It was only by Marc's courageous closing of the leak with his finger that prevented a further pressure increase and thus the imminent failure of the pumps, which would ultimately have led to an uncontrolled flooding of the pipe. GEO has an ultra-high vacuum level (10⁻⁹ mbar). If uncontrolled flooding had happened, the associated contamination and water vapour intake would have taken years to reach the same ultra-high vacuum level. So Marc kept the leak under control with his finger while others were kneading Tra-Bond vacuum glue, readying it for use. There was another tricky moment when the finger was replaced by Tra-Bond, but it worked out.

The leak was closed! A later estimate indicated the leak size was around 100 µm.

After a day of pumping, the vacuum pressure slowly returned to acceptable values and the detector was brought back into observation mode. In the time following, the vacuum level was keenly watched, but as time went by, confidence grew and the team believed that the Tra-Bond glue was a good solution.

Until 17th December 2018. Everyone had almost forgotten the leak when the alarms indicated a problem with the vacuum system; the problem was again the leak at the north tube. The glue had become brittle and was just loosely lying on the tube. The situation was critical, similar to the first time. Tra-Bond was not a permanent solution, but it was the only one for the moment. After quite some worries and a procedure similar to the first time, the detector was quickly back up and running again. We were very lucky that this happened during normal working hours and not at night. Had some animal detached the Tra-Bond from the tube – it would have truly been a nightmare...

With what shall I mend it, dear Liza, dear Liza?

The search for permanent solutions began. Many variants to seal the leak were discussed but in the end they all had one thing in common: to close the leak permanently, the area had to be cleaned thoroughly and this required venting the vacuum tube.

With the decision made to vent the tube, welding had to be the method of choice.

The company Skodock had manufactured and installed the GEO600 vacuum tubes in the 1990s. The tubes have a diameter of 600 mm and are made of high quality 316LN stainless steel. Due to the corrugated tube design, a thickness of only 0.8 mm (without additional stiffeners) is sufficient to withstand the air pressure; this innovative design considerably reduced the amount of stainless steel needed. Skodock had manufactured the tubes themselves and delivered them in units of 4 m lengths. On site, the two 600 m long arms were connected by lip welds.

A plan was developed to fill the tube with high purity nitrogen. This could help to avoid the overall pollution and especially contamination with water, which would have required us to bake the tube afterwards. Whether this would work with nitrogen and whether the chosen specification Nitrogen6.0 with 0.5 ppm H₂O is sufficiently pure was verified by runs in a vacuum test chamber. The results showed a promising reduction of water contamination.

The 22nd October: the night the tube is filled with nitrogen; it turns surprisingly cold. Although the connector behind the pressure reducer to the 50m long 8mm thick copper pipe, which led down to the clean room to the connector on the north tube, is constantly heated with a hot air gun, condensation and even ice formation forces the team to reduce the ventilation rate and so the filling of the tube takes longer than originally

Tobias Gersch (Skodock) and Christoph Affeldt during a test measurement at the demo tube. The nitrogen bottles can be seen in the background.



There's a **Hole** in My Bucket¹

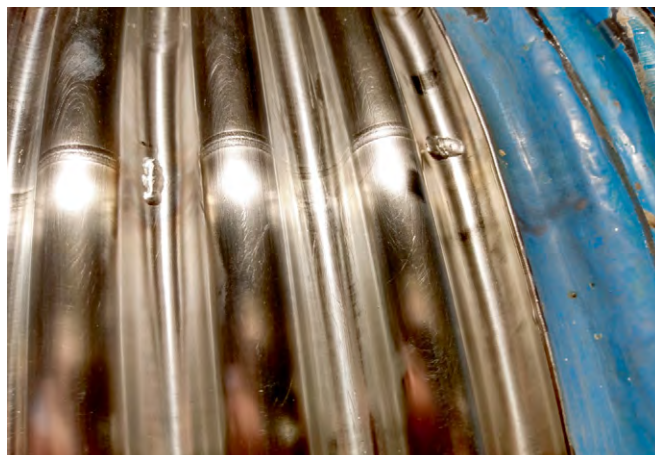
assumed. When the rest of the GEO600 team arrives in the morning together with the welding team, not all cylinders have been emptied and the pressure in the tube is only 0.8 bar. It takes until noon to get things ready for the welders (20 bottles were needed for the 200 m³ of the tube). The differential pressure gauge now reaches 2 mbar overpressure in the tube, which was the agreed overpressure for welding.

The Skodock team polishes the stainless steel at the affected area, welds the leak and adds a patch on top. The whole procedure takes less than an hour and the task for the evacuation of the north tube could be started. It needs two days of pumping out the nitrogen with a scroll pump, till the pressure level was good enough to restart the turbos. After 12 days the gate valves were opened and GEO600 was running in science mode again.

I've mended the bucket, dear Liza, dear Liza...

Nearly half of the complete GEO 600 vacuum system had been vented with nitrogen 6.0. The leak is now fixed permanently, with a downtime of less than 16 days. A great success!

¹ "There's a Hole in My Bucket" is based on a German song from the 1700's



▲
The welding seam to seal the leak.



▲
Nikhil Mukund during the night the north arm was flooded with nitrogen.



▲
The authors Volker Kringel, Marc Brinkmann, and Michael Weinert in front of the demo tube at GEO 600.

Exploring the LIGO/ SUBR Docent Program

In 2017 Rai Weiss, Kip Thorne and Barry Barish received the Nobel prize in Physics for the ingenuity and perseverance to create LIGO and “for decisive contributions to the LIGO detector and the observation of gravitational waves.”[1] Seeing them accept the award at the Nobel ceremony was surely a highlight for most of the LIGO Scientific Collaboration (LSC) membership. Yet there was something familiar about that sight: three white men receiving an award. What if that wasn’t the normal picture? What if when people thought scientists they thought of a multicultural group of scientists?

Diversity in LIGO

The LSC Diversity Committee, Humans of LIGO and other projects within the LSC are working towards that goal. Another project working towards that goal is the LIGO/SUBR Docent project – a project between LIGO, Livingston Observatory and Southern University and A&M College, Baton Rouge (SUBR), and funded by the National Science Foundation in conjunction with Baton Rouge Area Foundation (BRAAF).



▲ LIGO/SUBR docents outside the LIGO Science Education Center (SEC) at LIGO Livingston Observatory.

The LIGO/SUBR docent project involves university undergraduates from Southern University – a HBCU (historically black college/university) – and LIGO Lab staff. The project began with the establishment of LIGO Livingston’s Science Education Center (LIGO SEC) – an interactive educational center located at LIGO, Livingston Observatory.

LIGO SEC provides a combination tour, formal classroom experience and informal science center visit to school children from the surrounding area and beyond. Fourteen years ago LIGO outreach staff

started training a small group of SUBR undergraduates to do LIGO-related outreach. This was the birth of the LIGO/SUBR Docent program. SUBR staff recruits undergraduates from the science, technology, engineering and math departments (STEM) for the program. STEM majors are a natural fit – they have a better chance of understanding the science and they have shown interest in related fields. Staff don’t just recruit STEM majors though. After all, LIGO SEC targets school children, so SUBR staff actively recruits education majors. Education majors have the built in interest in communicating and educating school

children. By combining education majors with STEM majors we reasoned that we would have the best of both worlds: those with an interest in teaching would help the STEM majors engage with school children effectively while those with an interest in STEM would help explain science and engineering concepts to educators, and more importantly excite them about science, engineering and even math!

The undergraduate docents were trained to interact with school children and the public around LIGO's exhibits. In 2010 we started doing drop-in public days where we set up small lobby activities as well. Starting in 2010 the docents were then trained on how to interpret those lobby activities for the public. Later, when LIGO SEC started assisting with family math and science nights at local schools, the docents were trained to assist with those. Everything the docents do involves interpreting LIGO experiences and more importantly engaging visitors in the act of exploring science and engineering experiences. The docent training didn't start out that way though.

Across the 14 years, the docent training has undergone major shifts. We started training the undergraduates in multiple short two-hour long sessions over a one-year time period, but we found that this didn't result in the cohesiveness we desired from the docent program. So we shifted the training to a more intense three-day training experience, culminating with the docents interacting with the public on the final day of training. We conduct this training at the very beginning of the semester (during registration), which allows the staff who train the docents time to plan and execute the training – and it avoids conflicts with classes. We didn't do this alone.



(10) & Ellie (7)...often to his wife's (Anita, Ageless) chagrin.

William Katzman

is the Program Leader for LIGO's Science Education Center at LIGO Livingston Observatory. When not at LIGO he's often found experimenting with (not on) his two children: Mikey

When we shifted to the three-day training experience we brought out museum docent trainers from San Francisco's Exploratorium in order to focus our training efforts with the docents, and help us create a cohort of docents who could rely on each other for support.

Away from content towards questions & engagement

During this time, we shifted away from a content-based approach of docent training to a question and engagement approach. Originally we made the training content heavy – focusing on understanding the science of waves, and understanding the math behind some of the exhibits. Unfortunately, we found that the docents had a tough time connecting with the visitors, so we revamped the training to focus more on interacting with the visitors. We now train docents on how to engage visitors around exhibits, and encourage the visitors to ask investigable questions at exhibits. The docents are encouraged to make their own connections between their everyday lives, the exhibits and LIGO-related science. Then the docents in turn encourage the visitors to do the same – making connections across disciplines. These are training techniques used by the Exploratorium with their exhibit staff, so we've adapted these for LIGO SEC's docent program.

More recently we started giving experienced "veteran" docents additional responsibilities. Veteran docents now run many of LIGO SEC's offsite outreach events. Veteran docents help train the newer, incoming docents as an explicit part of their docent training. The veterans train the incoming docents to engage with visitors around exhibits by using questioning techniques. Veteran docents give the incoming docents some perspectives on the docent program that are different than and complimentary to the perspectives staff provide. Perhaps most importantly to us, veteran docents have been instrumental in recruiting new docents, as they share their experiences with other undergraduates.

The partnership between LIGO Lab and SUBR is important, because SUBR acts as a source of STEM and Education majors that has a racial demographic that reflects its local community. LIGO Livingston, sits in Louisiana, where 43% of the school children are black. More locally to the observatory although the Livingston area is overwhelmingly white, the majority of nearby Baton Rouge school children are black (74%). Since SUBR is a HBCU, the docents serve as natural role models who look similar to many of the students. Some of the docents even went to the same school as the students coming to visit LIGO!

When we established the docent program we established it with the idea that students from local schools would come to LIGO, see the scientists & engineers, then see the docents and they would realize the full set of steps they could follow to become STEM professionals. We were looking to inspire the school children in their future career paths. The evidence suggests that we have been relatively successful in that endeavor – past stud-



▲ LIGO/SUBR veteran docent training new docents at the tornado exhibit at the LIGO Science Education Center.

ies show that school children are more inclined to think positively about science and scientists after visiting LIGO. We didn't think much about the effect of the docent program on the docents themselves. We should have.



Currently, 152 docents have been trained. Two of the docents are currently working with LIGO, but most of the docents go into other non-LIGO related STEM and education careers. According to our evaluators, Inverness Research, [2][3], the LIGO docent program offers a unique experience that positively impacts the way docents interact at work and within their community. This experience IMPACTS the docents. In particular, a number of docents have noted that they can more easily engage the public. One docent reported that the program "enhanced my confidence when dealing with the public" [3 p. 52; 3], while another noted that the experience even helped the docent "presenting PowerPoints" [3 p. 52]. The docent program not only affects the docents' ability to communicate science, but it seems to increase their desire to communicate it to others. Most notably, the LIGO-SUBR docent program enhances docents' confidence in communicating with others and "inspires

LIGO/SUBR docents explore the Catenary Arch exhibit together at the LIGO Science Education Center. ▼

docents to give back" [3 p. 53]. Docents report that "LIGO has taught me the importance of reaching out to our youth, which are the foundation to the future of this country," and that the docent experience has "made me more interested in volunteering and giving back to the community," [3 p. 53]. We have heard from docents that they are more likely to volunteer for education and outreach opportunities at their jobs due to their docent experience. What we realized is that this is THE central effect of the docent program. This didn't come from the docent training, but from the experience of doing outreach as part of being a docent.

If former docents volunteer to share their experiences as STEM professionals with others, then they will encourage even MORE people to go into STEM careers beyond those that visit LIGO. Each docent can be a beacon that engages their new communities around STEM topics. This could slowly reformat science and engineering beyond the laboratory walls so that the typical picture of the white guy as a scientist morphs into a picture of a multicultural group of scientists.



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I finished my PhD – what now?

Jessica Steinlechner



is an assistant professor at Maastricht University in the Netherlands. Her research focuses on the development of mirror coatings for future, cryogenic gravitational-

wave detectors. She likes to develop picture stories explaining gravitational waves to children, for which her own children are always a grateful audience.

Vaishali Adya



is a postdoctoral fellow at The Australian National University in Australia. She works on squeezing and other quantum noise mitigation techniques

but occasionally does optical modelling for gravitational wave detectors. When not at work, she loves baking desserts and climbing an odd hill or small mountain.



We are all facing this question sooner or later. Some of us know exactly what we want to do, others cannot decide between too many options or think not enough options are available. We would like to help you by pointing out a few possibilities and experiences from past and current LVK members.

Academia

Staying in academia is probably the choice you know most about, as you are surrounded every day by people who chose this career. Your senior colleagues and supervisors are the most valuable help you can get for this path. You can find job offers within, and outside, the LVK here: wiki.ligo.org/LAAC/JobPostings. But do not despair if there is no job opening, often you can create one yourself by applying for a fellowship.

"In 2018, I accepted the Japan Society for the Promotion of Science (JSPS) Postdoc-

toral Fellowship and moved from Canada to Japan to work at the Research Center for the Early Universe (RESCEU). Along with working on gravitational wave data analysis, I visited KAGRA, climbed Mt. Fuji and went to a 花見 or "cherry blossom-viewing" with everyone at RESCEU!"

- Heather Fong, JSPS postdoctoral fellow, Japan

Private Sector

A job in the Private Sector is another well-known option, including a variety of choices in industry, consultancy, finance, software engineering, health care, but also permanent jobs as a scientist at a research organisation (e.g. NASA, ESA etc.). Jobs of this last category are also often included in our Job Postings. There are plenty of options to get in touch with companies at industrial fairs at your university or at conferences, but do speak to your supervisors and colleagues - they all had PhD students or colleagues who went to the private sector and can provide you with valuable contacts. You can also join our mentoring programme via LAAC.docs.ligo.org/project/mentoring.

"The difference between working in academia and industry is often exaggerated. Skills useful in academia tend to be useful in industry and the other way around."

- Laura van der Schaaf, data scientist, Ilionx, The Netherlands

Science Communication

Science Communication is an interesting option if you love to share your passion with a public audience. You can work in public relations for a university or research institution, discuss scientific breakthroughs in magazines and newspapers, or indeed per-

form any outreach activity you can think of - be creative, and be prepared to constantly reinvent your work when new opportunities and technologies arise! You can always try something independent on the side of another job to find your way into a permanent SciComm career. If this sounds like you, you are probably already involved in outreach activities at your home institution and take part in the activities of the LSC EPO group: wiki.ligo.org/EPO.

"Science communication is competitive, collaborative, and always evolving. It's given me opportunities to work with lots of people, and on different projects."

- Brynley Pearlstone, freelance science communicator, and host of SciCurious Podcast

Teaching

Becoming a high school teacher for physics (and/or math) could be an option for you if you enjoy teaching. Depending on the demand for teachers and the system in your country, you may need additional teaching qualifications - or can jump straight in. If your university offers a degree in teaching, this will be a good place to start. Your supervisor or mentor may also be able to get you in contact with previous PhD students who became teachers, or you may email us and we will help you to get in touch with people who have chosen this path: LAAC@ligo.org.

"Between obtaining my PhD and my follow-up academic career, I spent quality time as a high school teacher. This is an important role: example breeds enthusiasm, enthusiasm fosters talent. I found it an honour and pleasure to be the face of science to a whole class of potential new scientists."

- Gideon Koekoek, teacher in The Netherlands for 5 yrs.

Welcome to the LAAC Corner!

The LSC Academic Advisory Committee helps students and postdocs to learn more about LVK, find useful information and collaborate. In this article series we will discuss topics of particular interest for young researchers within our collaboration. Let us know if you have wishes for themes!

If you have any questions or comments, please visit our website: LAAC.docs.ligo.org the LAAC wiki: wiki.ligo.org/LAAC or email us: LAAC@ligo.org Have fun reading!

Kate Dooley & Jessica Steinlechner,
LAAC co-chairs



Teaching reality: At the Einstein-First Project

Children learn about tooth fairies and Santa Claus when they are small, but while they are still young they discover the truth. Lies like these are harmless. The lie that climate change is a conspiracy contrived by climate scientists is at the other extreme ... it is a really harmful lie because it gives an excuse for inaction. It also devalues science and discredit scientists. And that's a problem because science is the best method for questioning nature and discovering the truth about the physical world.

When our best understanding of the Earth was that it was flat, only a fool would sail westwards indefinitely because everyone knew they would fall off the edge. Knowing the truth, or at least our best understanding of the truth, allows us to do things that we could never do before - like circumnavigate the Earth.

But what if I suggested that because people used to think the Earth was flat, we should teach our children that the earth is flat...because it looks flat when you drive down the road, and the idea is much simpler for children to understand. Then when they get to university we can tell them, "no actually the Earth is a round ball...forget all that stuff you learnt at school." I think we can all agree that this would be ridiculous. But this is how physics is taught today, starting at primary school.



▲ *Demonstration of classroom-scale phasor-wheel which can be used to add and cancel waves using the concept of phasors.*

Albert Einstein knew why we need to teach the truth at an early age. He said, "Common sense is the collection of prejudices acquired by the age of eighteen". He un-

derstood that common sense is not sense at all. Common sense is just the ideas that we got used to when we were young.

I think of common sense as like a language...a language of reality. When we are young we easily learn to talk, but if you learn a new language as an adult, it is difficult, and though you learn to speak you never lose your accent. The language of reality is the same.

Reality has a scaffold of fundamental ideas...about space and time, light, gravity, and motion. Within this scaffold, we interpret how things happen. Today in school everyone learns a false scaffold founded on Newtonian concepts.

Newton's discoveries of a mechanistic, deterministic universe were revolutionary at the time. He thought that his idea of a force acting through empty space "so great an Absurdity that I believe no Man who has... a competent Faculty of thinking can ever fall into it" The idea of instantaneously acting gravitational forces slowly changed from absurdity to "common sense", and today it is taught in all schools. Newtonian gravity was falsified by Einstein more than a century ago, and with gravitational waves we measured its speed.

Einstein proved that time is relative and depends on height and speed, but in school time is absolute. He said that space is curved by matter, that parallel lines always

cross because space is never flat. He also proved that light comes as photons. People opposed this idea and even Millikan who successfully tested Einstein's prediction refused to believe the basic idea. He said, "Einstein's bold, not to say reckless, light-quantum hypothesis, flies in the face of the thoroughly established facts."

Today Louis de Broglie's extension of Einstein's hypothesis, that everything, whether a cricket ball, an electron or a photon of light, combines both *bulletiness*...that is the momentum you feel when you catch a heavy ball...with *waviness* like the ripples on a pond is well and truly proved. A consequence is that everything in the universe is statistical. Reality is governed by strange but precise statistical rules. Einstein himself hated this conclusion and struggled to prove the absurdity of it. He said, "God does not play dice".

Richard Feynman appreciated the weirdness of quantum reality. He said: "The rules are so strange... the rules are so screwy that you can't believe them!". But this is the truth we all have to get used to. "If you don't like it" he said, "go somewhere else... to another universe!"

Physicists and chemists have been using these rules for decades to invent transistors, computers, lasers, nuclear reactors, cameras, mobile phones, whole body MRI scanners, drugs and medicines. But kids still learn the old stuff in school - the Newtonian world view - the lies!

The Einstein-First Project

The discovery of gravitational waves provides us with the impetus to teach kids our best understanding of the universe. Six years ago in Perth we set out to find out if



leader of the Einstein-First project.

David Blair
has worked in gravitational waves since the first cryogenic detectors were developed in the 1970s. He founded the Gingin gravity research precinct, is a member of OzGrav, a passionate educator, and



Wave Discovery. In his free time, he loves watching movies, solo-travelling and also enjoys quizzing.

Rahul K. Choudhary
is a Ph.D. student at the University of Western Australia researching on teaching Einsteinian physics to school students. He is also a member of the OzGrav - ARC Centre of Excellence for Gravitational



Jyoti Kaur
is a postdoctoral fellow at the University of Western Australia. She is working on a physics education project called the Einstein-First from last seven years. In her spare time, she loves to play with her sons.

it was actually possible. We designed programs that we have tested from year 3 to year 12 (ages 7 to 18). They are fun and interactive, based on models and analogies. Each lesson is defined by an activity that illustrates an Einsteinian concept.

We converted the maths of the quantum world into the *maths of arrows*. We tested to see if kids could grasp what it means for space to be curved, and whether they could appreciate the weirdness of the quantum world. The evidence is overwhelming: the

kids enjoy it, ask for more, and wish all their science could be so engaging. They all know that the current curriculum is mostly "old stuff". Girls who normally start with a less positive attitude to science than boys, respond more strongly and come out equal with the boys. And while adults respond to the ideas, with "wow, you must be a genius to understand this science", the children just take it in their stride. They are learning a new common sense.

Following our first trials, we have been funded for a five-year program in which we are developing an integrated school curriculum called Einstein-First. It is designed for all students, not just the academically talented. Our goal is that university lecturers will never again have to say "forget all that stuff you learnt in school". We want everybody to feel comfortable in the modern world, where nearly everything is described by Einsteinian physics.

Why teach Einsteinian physics?

In the world today, a few scientists and technologists speak one language of reality, and everyone else, the consumers of Einsteinian technology, whether they be prime ministers, presidents, lawyers, primary school teachers or farmers, speak the obsolete Newtonian language of reality.

Einsteinian physics is inside our phones, solar panels, cameras and nuclear reactors. Black holes, neutron stars, quantum computers and atom bombs don't exist in Newtonian language.

Gravitational wave detection is a fabulous vehicle for teaching Einsteinian physics because it encompasses everything from the ripples in spacetime to the radiation pres-

The rules are so strange ...

sure noise of photons randomly striking the mirrors.

Without the language of Einsteinian physics all our technology may as well be magic. Understanding the physics of our world allows us to make better, more informed decisions. For example, in Einsteinian language, tiny traces of carbon dioxide in the air make a heat blanket because of the Einsteinian physics of photons interacting with carbon dioxide molecules. Similarly we can allow people to understand why high-energy photons like X-rays can damage DNA but low energy photons like those used for radios and mobile phones cannot.

Beyond understanding things around us, humans have always yearned to understand our place in the universe. And our best understanding is 100% Einsteinian. It has given us the story of the big bang creation of the universe, the formation of galaxies and stars, the making of the elements, the evolution of stars and solar systems and the future death of the sun. This most fantastic, wonderful and awe inspiring story can be shared by everyone if we all spoke the Einsteinian language of reality. All our kids deserve the opportunity to share this story.

In the Einstein-First project we emphasise that Einsteinian physics is not the end of the road, nor is it Einstein-worship! Einstein's errors and prejudices give additional insights. Major mysteries like dark matter and dark energy remain. Explaining them may lead us to another revolution. Our young people will be best able to make the next advances from the vantage point of Einsteinian physics, while using their knowledge to help solve the problems facing humanity today.

David Blair



▲ *A student calculating the probability amplitude of photons coming from two slits at different points. Using small phasor wheels on white boards, students can find the resultants at different points and calculate the probability amplitude. The square of the probability amplitude is proportional to the number of photons coming at a point per unit time.*

Experience with Year 3 students

Teaching modern concepts of space, time, light and gravity to Year 3 students (aged 7 – 8) was really challenging for the Einstein-First team. We contemplated what to present, what not to, and how much simplification was required. The first day in the classroom at Mel Maria School, Western Australia dispelled all our dilemmas. The students' curiosity about the universe, especially black holes, rendered me speechless. When I asked them, "What do you know

about Albert Einstein?" hands shot up, and several students said " $E = mc^2$ ". I was astonished. They knew his famous equation even without knowing the meaning.

The programme was started with a pre-test designed to assess students' prior knowledge about space, time, gravity and light. After that, students did a 10-minute role play on "the history of light", in which Newton, Fresnel, Einstein, and Feynman, wearing suitable wigs, coats and glasses argued about their understanding of light. They learnt how our understanding of light has changed over history. Students enjoyed it and we repeated it three times with different students. At the end of the session, they started to ask "what we were going to do tomorrow?" In fact, they wanted to know about the whole programme in one session. Every concept was taught with the help of a suitable physical activity based on lycra sheets, woks and nerf guns (for our toy photons!). All the students participated enthusiastically. The class teacher was equally engaged in this programme. An important part of the program was that the class teacher was enthusiastic, participated and reinforced the learning the next day. At the end of the programme, we gave them a post-test to evaluate both conceptual understanding and attitudes, and we recorded a question and answer review session in which some students clearly grasped the idea that light has momentum and that it can cancel itself following the "maths of arrows" $1+1=0$.

I enjoyed the program better than the high school programmes I have run, because the students were so engaged, so willing to attempt to answer questions, and so enthusiastic to perform activities in front of the class.

Jyoti Kaur

Teaching experience on quantum weirdness to Australian 14- and 15-year-old students

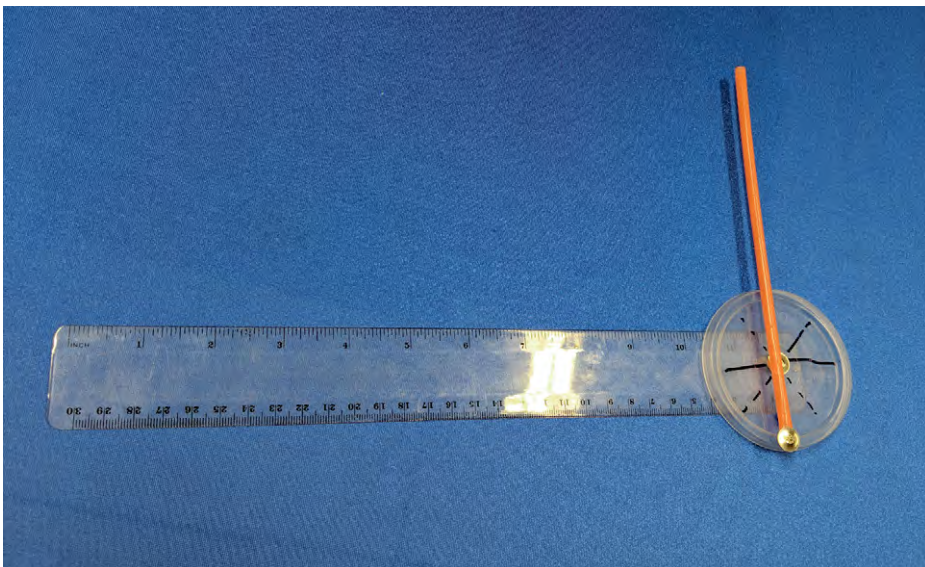
Children are ready to accept new ideas even if those ideas may sound “bizarre” to us. Very often it is assumed that young students should always be taught simple concepts (even if it is wrong!) before being exposed to critical concepts. For example, many people believe that quantum physics should not be taught early because it is too difficult and requires complex mathematical techniques, and also because it is counterintuitive.

Recently, I taught quantum weirdness to 14- and 15-year-old students in Australia. The students seemed to grasp the concepts quite easily despite them seeming counterintuitive to most adults. The key to teaching quantum weirdness was activity-based learning, and videos of single photon interference. I taught them Feynman path inte-

grals, which in Feynman’s language, is the “screwy” method you have to use to calculate the probability of photons arriving at a point. We built on their existing knowledge of vectors, and introduced them to phasor wheels that we created, for making phasor vector addition into a simple graphical task. They did not seem particularly surprised by the bizarre nature of single photons going to places where waves would go, nor to the idea of “non-locality”. They asked plenty of challenging questions like “What is a photon made of?” and “How do photons travel through space if they are not waves?”

Overall I think the students appreciated that quantum concepts were comprehensible, and how they apply both to our day-to-day lives and to sophisticated devices like gravitational wave detectors. It was a pleasure to teach them and see them intrigued by the bizarre nature of quantum world.

Rahul K. Choudhary



▲
A small phasor wheel model.

Find out more about Einstein First here:
www.einsteinianphysics.com

LIG 2020

NASA delivers first LISA prototype hardware to Europe

Rita Dolesi



is an Associate Professor working on LISA at the University of Trento in Italy. She feels extremely fortunate to have such an exciting job and a wonderful family

cheered by two lively children.

John W. Conklin



is an Associate Professor at the University of Florida and Director of the Precision Space Systems Laboratory (Twitter @precision-space). His research

focuses on technology development for future gravitational wave and Earth geodesy missions.

Construction of a new gravitational wave observatory requires worldwide collaborations to provide the remarkable resources necessary to realize large challenging detectors, whose scientific discovery potential is attracting the attention of an increasingly large community of scientists interested in studying the Universe through Gravitational Waves.

While ground-based observatory collaborations are growing, fostered by the exciting detections of Advanced LIGO and VIRGO, the LISA (Laser Interferometer Space Antenna) project is progressing toward the implementation of the first space-based observatory targeting low-frequency sources, between 20 μ Hz and 1 Hz which are inaccessible on Earth due to arm length limitations and terrestrial gravity noise.

In this frequency band, signals are expected from a very rich variety of sources, ranging from stellar mass binaries in our own galaxy to the merger of two super-massive galactic-core black holes from the recent Universe back to the Cosmic Dawn. LISA will provide precision tests of general relativity and black hole physics. It will enable multi-band correlated gravitational wave astronomy, together with ground-based observatories, and also have implications for multi-messenger astrophysics.

NASA is partnering with the European Space Agency (ESA), which leads the LISA mission, to provide several key payload technolo-



TRL4 prototype CMD, developed by the Precision Space Systems Lab at the University of Florida, delivered to the University of Trento for GRS subsystem-level testing.

gies, as well as to participate in the science data analysis and interpretation. The joint effort between Europe and the U.S. on this large-scale space observatory poses challenging issues on both the technical side, as well as the programmatic and Space Agency side. In the summer of 2019, an initial test of this international collaboration involving the first hardware delivery from the U.S. to Europe was successful.

The Technology Readiness Level 4 (TRL 4) version of the Charge Management Device (CMD), developed by the Precision Space Systems Lab at the University of Florida (UF) on behalf of NASA, was delivered to the University of Trento, Italy in July 2019 for subsystem-level testing.

LISA uses free-flying test masses as geodesic reference bodies from which to measure passing gravitational waves. Laser interferometry is used to detect the gravitational tidal deformation on these masses. The masses are housed in three separate Sun-orbiting spacecraft that form a triangular shape which is 2.5 million km on each side.

A key requirement for LISA's performance is that all forces acting on the test masses be suppressed below the femto-g level in the measurement band. In 2016 this was demonstrated by the ESA mission's precursor, LISA Pathfinder (LPF). The heart of the LPF instrument legacy for LISA is the gravitational reference sensor (GRS), which includes the test mass surrounded by a capacitive displacement sensor/force actuator, and other supporting equipment. This is the main source of the stray forces acting on it.

Electrostatic forces are one such force that arise when the test masses acquire an electric charge due to the impact of cosmic rays hitting the spacecraft. If left unchecked, this

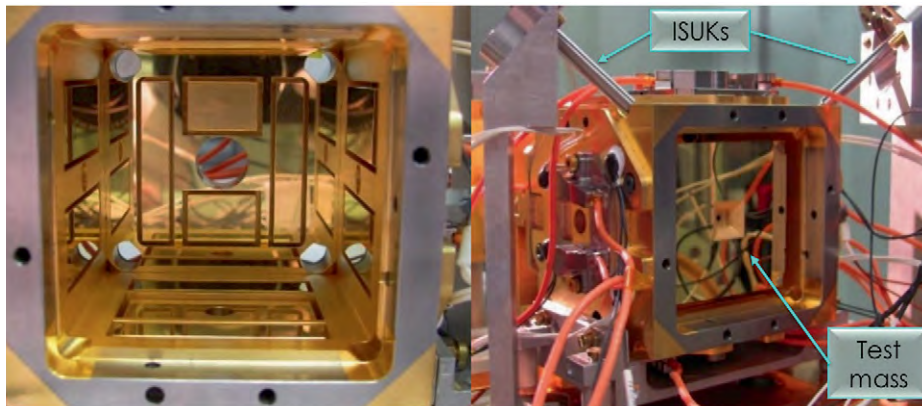
charge would build up to the point where electrostatic forces would overwhelm the gravitational wave signal. The CMD delivers ultraviolet light to the LISA GRS to produce the photoelectrons needed to discharge the test masses from accumulated cosmic ray charging. This technology was successfully demonstrated first on NASA's Gravity Probe B mission in 2004, then on LISA Pathfinder. The University of Florida team, with support from NASA, is developing an improved Charge Management Device based on UV LEDs that are smaller, lighter, less power-hungry, and more robust than the Hg-vapor lamps used on LISA Pathfinder.

Technology Readiness Level (TRL) is a categorization scheme used by both NASA and ESA to quantify the maturity of technology for flight. TRL 1 signifies a basic concept, while TRL 6 is required for space flight. The TRL 4 CMD is an integrated prototype which has the full functionality of the flight unit, but is only tested in a laboratory environment. The team at the University of Florida is currently developing the TRL 5 version of the CMD and will achieve TRL 6 status by the end of 2022 based on an independent peer review. Making full use of the LPF heritage, the University of Trento leads, on behalf of ASI (Agenzia Spaziale Italiana), the development of the overall LISA GRS. This includes the test mass itself and the surrounding electrode housing. EHTZ (Eidgenössische

Technische Hochschule Zürich) in Switzerland is responsible for the front-end electronics (FEE) of the capacitive sensor.

With the TRL 4 CMD from Florida, a prototype FEE from Switzerland, and from Italy a copy of the capacitive sensor from LISA Pathfinder, which is the baseline also for LISA, the Trento team will evaluate the performance of the GRS sub-system using their torsion pendulum apparatus. This facility is a high-sensitivity force noise instrument at mHz frequencies, developed with the support of INFN (Istituto Nazionale di Fisica Nucleare). As with LPF, the Trento torsion pendulum facility will be a vital instrument for tests that will validate the implementation of the LISA flight hardware from the design phase to the commissioning phases.

As the technology readiness for each element of the GRS increases over the next few years, the teams from Italy, Florida, and Switzerland will perform additional tests with increasingly higher fidelity technology units. In the mid-2020s, the flight program is expected to start, involving the fabrication, integration and testing of the space flight versions of these systems. This will ultimately lead to the launch of the landmark international LISA mission in the early 2030s: the first space-based gravitational wave observatory, observing new phenomena in our Universe in the millihertz frequency band and below.



Left: the capacitive sensor without one face to show its inner electrodes configuration (by OHB-Italy). Right: a LISA-like test mass inside the capacitive sensor integrated with the Inertial Sensor UV Kit (ISUK), which injects UV light. The test mass is part of the torsion pendulum inertial member.

Career Updates

Aaron Buikema recently successfully defended his thesis at MIT. His advisor was Nergis Mavalvala.

Anuradha Gupta has joined the faculty at University of Mississippi where she will soon start a new LSC group. She was formerly a postdoctoral fellow at the Institute for Gravitation and the Cosmos at Penn State and before that at the Inter-University Centre for Astronomy and Astrophysics, Pune, India.

David Keitel has moved from Portsmouth to join UIB in Palma de Mallorca as a Beatriz Galindo Distinguished Researcher.

David McManus has been awarded his PhD from the Australian National University's Centre for Gravitational Astrophysics, and is now employed as a postdoc at the University of New South Wales (Australia) working on the development of Quantum devices.

Evan Goetz began a new position as Research Associate at the University of British Columbia in October 2019. Evan will continue to lead the continuous waves working group, calibration of the LIGO instruments, and detector characterization tools and investigations.

Terra Hardwick successfully defended her thesis "High power and optomechanics in Advanced LIGO detectors" and graduated from LSU in December 2019. She has since started a new job at NASA GSFC working on LISA technology.

Thomas Abbott successfully defended his thesis on "Transients in the Advanced LIGO time-dependent calibration model", will wear the gown and graduate from LSU in May.

Awards

Anna Ijjas (AEI) and Paul Steinhardt (Princeton) received a 4-year \$1.3M award from the Simons Foundation to explore the origin and future of the universe.

Brina Martinez, an undergraduate student at the University of Texas Rio Grande Valley, was awarded for the best poster presentation, entitled "Classification of Acoustic Noise in LIGO Livingston," at the APS Conferences for Undergraduate Women in Physics (CUWiP), in January 2020.

Bruce Allen and **Bernard Schutz** will jointly receive the annual American Physical Society's 2020 Richard A. Isaacson Award in Gravitational-Wave Science. The award recognizes their "pioneering and decisive contributions to the development and successful implementation of analysis techniques required to detect and interpret gravitational-wave signals". The award ceremony will take place in April 2020 at the American Physical Society's Meeting in Washington, D.C.

Christophe Collette, an LSC PI at University of Brussels (Belgium), obtained an ERC consolidator grant for working on seismic isolation systems of future GWDs.

David McClelland was recently named a Fellow of the Australian Academy of Science.

Gabriela González was awarded a Boyd Professorship (LSU's highest and most prestigious rank) by unanimous vote of the LSU board of supervisors.

Guillermo Valdés was granted the distinction of National Researcher Level 1 by the National System of Researchers of Mexico for his research work in the characterization of LIGO detectors.

Jahed Abedi (AEI) and **Niyesh Afshordi** (University of Waterloo and Perimeter Institute for Theoretical Physics) received the 2019 Buchalter Cosmology Prize for their paper "Echoes from the Abyss: A highly spinning black hole remnant for the binary neutron star merger GW170817".

Karsten Danzmann and **Markus Otto** received the 2019 Teaching Prizes for the Faculty of Mathematics and Physics from Leibniz Universität Hannover. Karsten Danzmann was also inducted into Manager Magazine's "Hall of Fame of German Research". The award recognizes his lifelong, outstanding contributions to the advancement of research.

Kip Thorne was awarded the James Madison medal from Princeton University.

Stephen McGuire of Southern University has been appointed the James and Ruth Smith Endowed Professor of Physics Emeritus in recognition of his distinguished and meritorious contributions to research, teaching and service.

New LSC positions

Anamaria Effler has been elected as LIGO Academic Advisory Committee (LAAC) senior member (February 2020).

Anna Green has been elected as LAAC postdoctoral representative (February 2020).

Daniel Brown has been elected as chair of the Advanced Interferometer Configuration working group (February 2020).

Nicola De Lillo has been elected as LAAC graduate student representative (February 2020).

Paul Fulda has been elected as LAAC co-chair (February 2020).

Stefan Ballmer has been elected as chair of the Technical Advisor to the Oversight Committee election (January 2020).

Volker Quetschke has been re-elected as chair of the Lasers and Auxiliary Optics working group (February 2020).

Other News

Hartmut Grote has published a book on the history, technology, and first discoveries of gravitational waves. The book, titled "Gravitational Waves: a History of Discovery" is published by CRC Press and available now for order from their website.

iGrav Announcement: Last July following the Amaldia meeting in Valencia, Spain the International Gravity Outreach group, iGrav, held its inaugural meeting. iGrav brings together members of different collaborations and experiments from the broad field of gravity research. The mission of iGrav is to engage people throughout the world in exploring the exciting field of gravitation, and in particular gravitational-wave and multi-messenger astrophysics. To learn how you can be more involved please sign up for our mailing list at <https://lists.igrav.org/cgi-bin/mailman/list-info/igrav-announce> and consider joining us for our next meeting on July 25, 2020 at the University of Glasgow.

Riccardo DeSalvo gave a series of wildly popular public talks about gravitational waves as part of a celebration for the city of Matera being recognized as the European Capital of Culture for 2019.

LIGO
2020

Inspecting a point absorber on a Livingston test mass during the O3 break (the small dot in the middle of the screen).

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How it works: BayesWave unmodeled waveform reconstruction

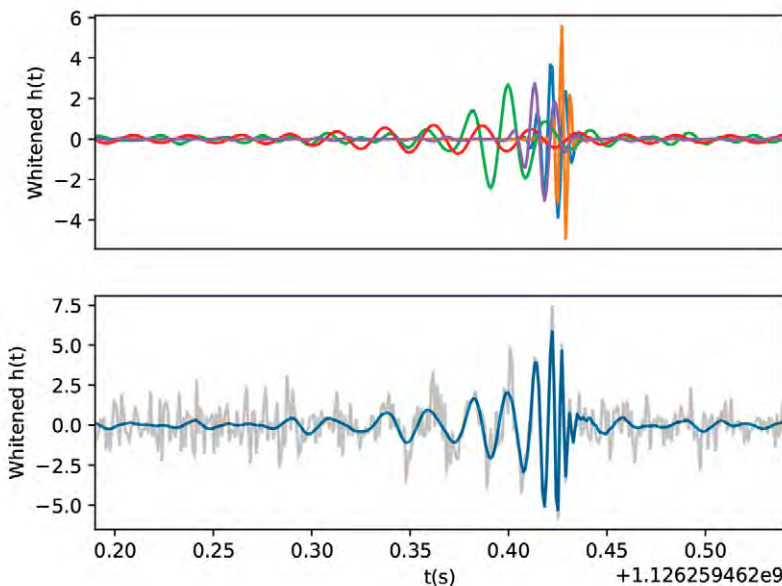
So far, all of the gravitational-wave events detected have been from compact binary coalescences — meaning two merging black holes or neutron stars. These are systems that have been studied in-depth and we have very good predictions for what the waveforms of those signals will look like (called templates). These so-called “templates” are used to help find the gravitational waves, and to infer the source properties such as the masses and spins.

But compact binary coalescences are not the only possible sources of gravitational waves! Some other events that could lead to short bursts of gravitational waves are things like cosmic string cusps, pulsar glitches, and supernovae. There is also the possibility of detecting gravitational waves from sources that we haven't even predicted yet! Some of these sources (like cosmic strings and compact binaries) have very good templates, while other sources are only

loosely modeled (such as supernovae). This means it's important to be able to find and understand a signal in our data even if we don't have templates for it.

But how do we find the underlying waveform if there's no model for the signal? One way is to use the BayesWave algorithm. BayesWave uses a basis of wavelets to reconstruct the gravitational wave signal. This way, we can find the gravitational wave signal in the data and pull out the waveform of the underlying signal without needing to rely on templates. For signals like merging black holes, we can also compare this unmodeled reconstruction to a reconstruction based on templates, to be sure our templates are accurately matching the data the way we expect it to.

As LIGO collects more and more data we might one day find a new and surprising type of signal, and we'll be ready when that happens!



◀ Reconstructing a gravitational wave signal with BayesWave. At the top is a selection of wavelets (all in different colors), and at the bottom is the resulting waveform from adding the wavelets together (in blue) overlaid on the data. The signal shown is from GW150914, the first observation of gravitational waves from a binary black hole merger in 2015. The y-axis shows gravitational wave strain $h(t)$ and the x-axis shows time in seconds $t(s)$.

