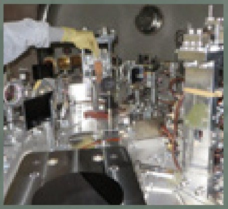
LIGO Scientific Collaboration

LIGO MAGAZINE

issue 13 9/2018

Getting Ready for New Science: Commissioning for O3



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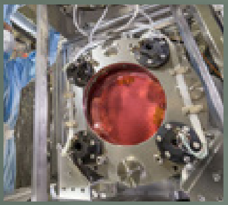

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Front cover

The main image shows Sheila Dwyer (left) and Keita Kawabe (right) aligning the squeezer beam into the interferometer during recent HAM5 in-chamber work at LIGO Hanford. Top inset: commissioning is underway at the LIGO Observatories (see 'LIGO in 2018: A Commissioning Story' on p. 6). Bottom inset: the assembly of an ultra-high-performance vibration isolation system at KAGRA (see 'KAGRA: Next Step Full Lock' on p. 11).

Image credits

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Cover: Main photo from Nutsinee Kijbunchoo. Top inset from G. Mansell/C. Austin/D. Sigg/A. Effler/N. Kijbunchoo. Bottom inset photo from National Astronomical Observatory of Japan/photographer Yutaka Iijima / caption adapted from one by Yoichi Aso (translation by: Hiroko Tsuzuki and Ramsey Lundock).

p. 3 Comic strip by Nutsinee Kijbunchoo

p. 6-9 Photos from G. Mansell/C. Austin/D. Sigg/A. Effler/N. Kijbunchoo.

p. 11-12 Lock celebration courtesy of ICRR, the University of Tokyo. KAGRA's Y-arm from KAGRA

p. 13-14 Images from Maddie Wade.

P. 15-16 Images from TJ Massinger.

p. 17-23 Glitch image from LIGO/Virgo. Time frequency plots from LIGO/Virgo/Brown/Lovelace/McIver/Macleod/Nitz. Sky localisation from LIGO/Virgo/NASA/Leo Singer (Milky Way image: Axel Mellinger). Swope image from 1M2H Team/UC Santa Cruz & Carnegie Observatories/Ryan Foley.

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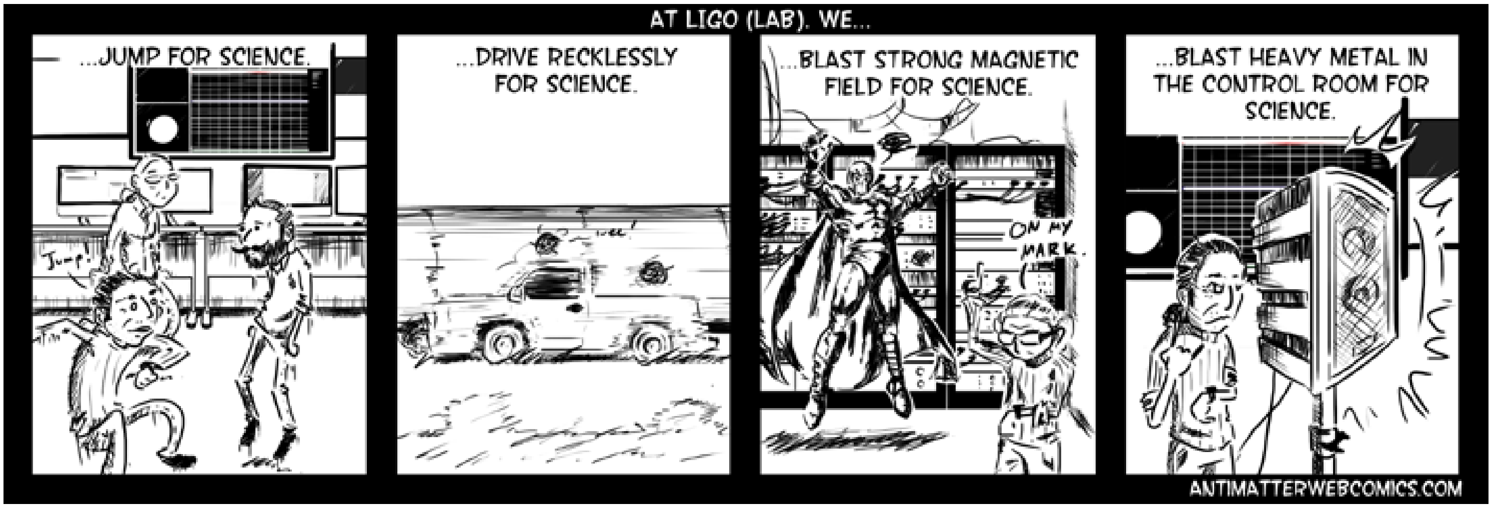


Welcome to the LIGO Magazine Issue #13!

Welcome to the thirteenth issue of the LIGO Magazine. We have now had a little more time to catch our breaths since last year's observation of the first merging binary neutron star, GW170817, on 17 August 2017. In 'Memories of GW170817', we gather recollections and stories of this exciting time from people around the world.

Preparations are well under way for Observing Run 3 and we hear about what it takes to get ready in 'A Commissioning Story'. In 'Next Step Full Lock' we hear about the exciting progress at KAGRA from Keiko Kokeyama and Yutaro Enomoto. Gravitational wave observatories are extremely sensitive and complex instruments, so in this issue we also hear about how to get from the detector to the data, with a look at the calibration process from Maddie Wade and, from TJ Massinger, we hear about characterizing the hums, buzzes and bangs in the data.

Turning to space-based instruments, we have updates from LISA as well as an interview with Jennifer Wiseman, Senior Project Scientist for the Hubble Space Telescope, on what it's like to work with the Hubble mission and the observation of electromagnetic light from the binary neutron star merger last year.

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

Jocelyn Read and Hannah Middleton, for the Editors

Jocelyn Read

HMiddleton

News from spokespeople

We have now seen one year pass since the neutron-star observation of August 2017, and in many ways that event still reverberates in the Collaboration, both in the past year's activities and in what we hope to deliver for the next observing run.

The LSC is hard at work wrapping up the analysis and the publications from Observing Run 2 (O2), with most of the targeted full Collaboration papers on the binary neutron star (BNS) behind us but with a trove of results about other events and astrophysical interpretation still underway. This effort to extract and share the observations is valuable in its own right, of course, but also is showing us how we want to proceed for the next observing run.

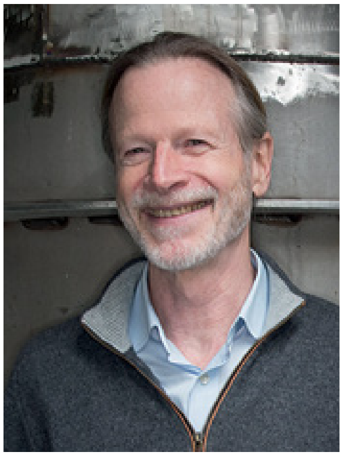
We often think back on the month of August 2017 in particular and the remarkable number of events we saw – and look forward with a mixture of joy and trepidation to 'a year of Augusts' in the O3 run, and working to see how to manage that onslaught of discoveries. We can expect not only more exciting results from the LVC analyses and publications, but also a greater community outside of the LVC both motivated and capable to 'do science' with gravitational waves alone or in synergy with electromagnetic and particle observations. We need to plan on both being timely with our own papers, but also collaborating creatively with scientists outside of the LVC. Beyond the immediate scientific reward is also the growth of the community that can voice their support for future upgrades and also future observatories to house 3rd generation instruments.

We are making good progress in ensuring that hosts of future 'EM Bright' events will be discovered shortly after coalescence to try to grab the earliest points in the evolution post-coalescence. The machinery for low latency public alerts is developing well, and is planned to be tested soon in engineering runs. The analysis pipelines for transient events are being tuned up for coherent analysis of the Virgo and the two LIGO instruments which will observe in O3.

The LIGO instruments are just wrapping up the installation of many new components. Some of these are replacements and upgrades of previous components; new test masses with coatings which are more uniform and have better specifications across wavelengths have gone in at both observatories, and one damaged mirror that may have held back Hanford's sensitivity has been swapped out. New baffling is in place. And at both observatories squeezed vacuum light sources have been installed and are in testing (with a slight sensitivity improvement even seen in a test!). The commissioning is now getting underway, with the goal of 120 Mpc for BNS in place for the instruments, and the best estimate at this time is that this can be reached very early in 2019, pacing the start of O3. And we have high hopes that KAGRA will be able to join toward the end of O3.

The next 6 months must be a focused effort to be ready – to have O1/O2 substantially behind us, to have machines at the requisite sensitivity and uptime, and to have the low-latency notices, pipelines, and post-detection code ready to go. We will be richly rewarded.

David Shoemaker and Laura Cadonati



David Shoemaker
LSC Spokesperson

Laura Cadonati
LSC Deputy Spokesperson

Laura Cadonati

LIGO in 2018

A Commissioning Story

The prototype electric field meter in the chamber.

The third observing run O3 is currently projected to begin in early 2019. LIGO's second observing run (O2) ended on August 25, 2017, and work toward the next observing run began soon after. Between science runs, scientists and engineers at the detector sites work to install new systems and to improve their performance.

What is commissioning?

For me, commissioning is the most exciting and rewarding activity that takes place at the site. Multiple teams of people around the world design and install parts in the interferometer to make it more sensitive to gravitational waves. Once these parts are installed, it is up to commissioners to get the interferometer back up and running. Commissioning takes a team of people with varied expertise working together for many long hours to achieve a common goal. The challenges are beyond difficult (literally problems that have never been thought of, much less solved), but the sense of accomplishment that accompanies solving even the smallest of challenges makes it all worthwhile.
Corey Austin (LLO)

As the commissioning leader at the Hanford Observatory I have to coordinate the integration of all subsystems in the detector. This includes everything from the laser to the seismic isolation, the optics, the sensors, the servo controls and many more. They all have to work together perfectly to make the next observation run possible. Part of the challenges are technical, but it is equally important to have an excellent and motivated team.
Daniel Sigg (LHO)

We are a diverse team of engineers, operators, commissioners all trying to coordinate a plethora of subsystems. Everything is coupled to everything else, and we all heavily rely on each other's expertise to understand exactly what is going on. There are so many different noise sources we've been working to address since the last observing run.
Georgia Mansell (LHO)

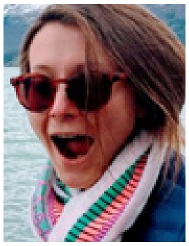
The important part of commissioning is "Does this make DARM (*Ed: differential arm motion - see Calibration article pg 13)* better?" If the answer is no you're wasting your time. That takes a long time to absorb. You think, "Oh, this thing is noisy over here, maybe I should look into it," but we have enough other problems.
Anamaria Effler (LLO)

What are the current challenges?

Most of the problems we are facing are probably more mundane than many imagine. Like a bug that crawls onto an optic on the laser table which in turn absorbs enough heat to melt a hole into the mirror. Not good! But, every now and then we have an interesting noise source that is fun to chase down.
Daniel Sigg

There are so many parts and so many electronics and cables. I know which cable goes where, what to disconnect, where to disconnect it - stuff like that which is very simple but you only learn it by spending a ridiculous amount of time on site. Then it turns out that some random piece of electronics in the middle of ten boxes connectected together is noisy. How do you efficiently troubleshoot that? Any semi knowledgeable physicist,

Georgia Mansell



is a MIT postdoctoral associate based at LIGO Hanford Observatory (LHO). When she is not commissioning she enjoys hiking, cycling, cooking, and tending to an ever-growing collection of houseplants.

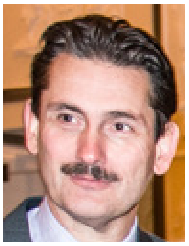
Corey Austin

is a graduate student at LSU working on stray light control at the LIGO Livingston observatory (LLO). When not working at LIGO, Corey enjoys spending time at the gym and playing disc golf.

Anamaria Effler

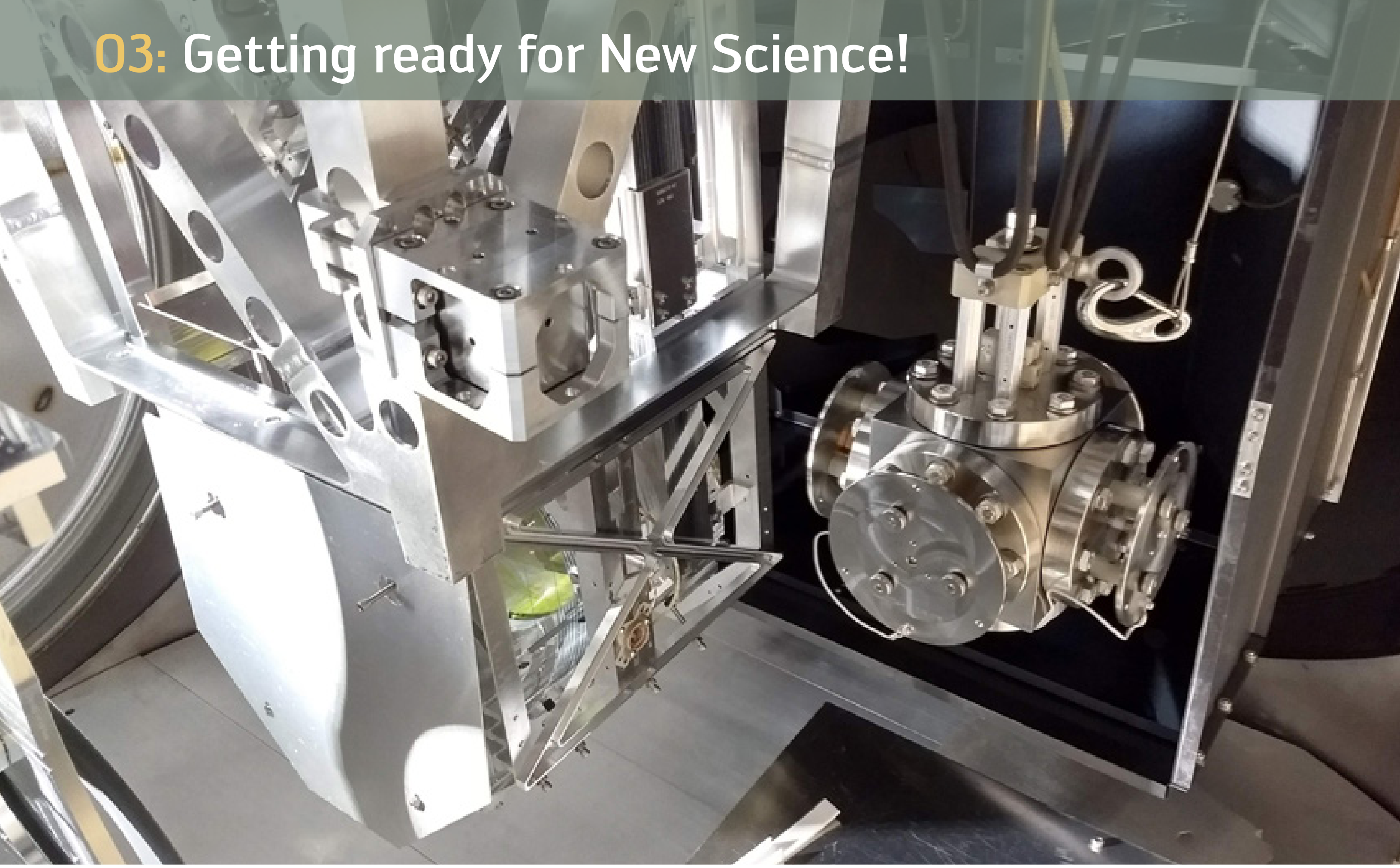
is a scientist at the LIGO Livingston Observatory. She has been with LIGO for 12 years and is originally from Romania.

Daniel Sigg



has been working at the LIGO Hanford Observatory since its inception. In his free time he likes to explore the local wineries and sample the wares.

03: Getting ready for New Science!



The electric field meter (EFM) that is installed at end-X at Hanford, shown next to the test mass.

given infinite time and all the electronics drawings and documentation, will eventually work it out. But there's just so many things, and that's where the wizardry happens. I know exactly where to go and what to do because two years ago that bit malfunctioned and I'm like "oh no not this **** again."

Anamaria Effler

Stray Light

I work on stray light control. Stray light control mitigates the effects of light that scatters from the main beam and reduces the overall noise in the interferometer. The main way that we reduce the effects of stray light is by installing baffles to limit the amount of stray light that recombines with the main beam, thus limiting the amount of noise caused by stray light.

Corey Austin

We have a problem with output arm scattering. We're going to put some baffles around there. I'm really excited about that. There are so many baffles in there I'm not sure if there are many more options. But we've made some not-very-precise measurements that suggest part of the low frequency noise is from the scattering.

Anamaria Effler

Between 10-100 Hz, the sum of our known noise sources does not add up to the measured noise. This unexplained noise is often attributed to stray light, and in order to meet our sensitivity goals for O3 and beyond, we must reduce the contribution of stray light displacement noise in this band. For most of 2017, the Stray Light Improved Control (SLiC) working group designed a set of baffles to be installed between the end of O2 and the start of O3. As these baffles were installed and commissioned, additional opportunities for improvement were identified and solutions for those opportunities are currently being designed and implemented.

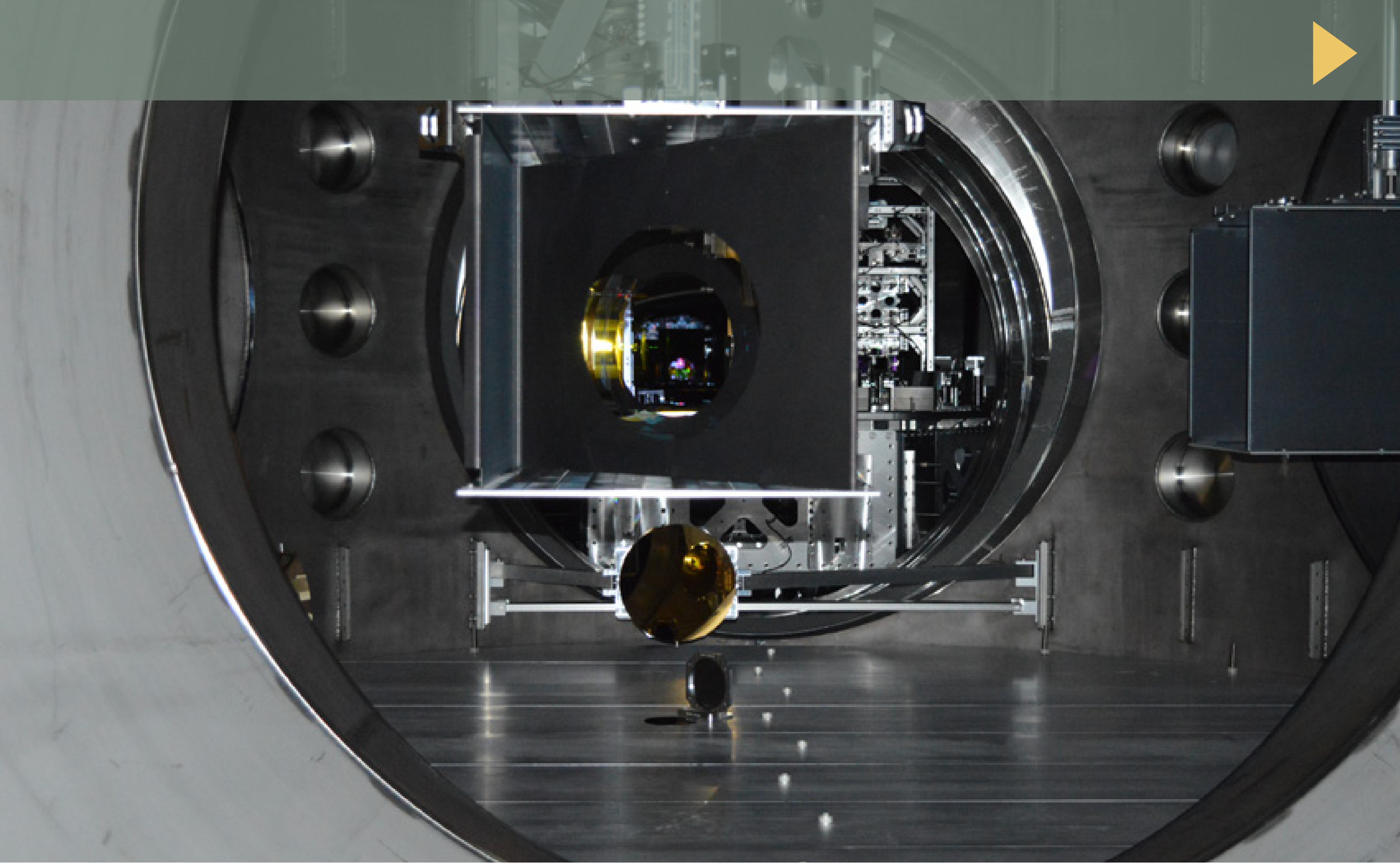
Corey Austin

Charge on test masses

I've recently started working on understanding electrical charge on the test masses, and electric fields in the vacuum chambers the test masses reside in. This is interesting and important as it may hold the key to the mystery noise seen at Hanford.

Georgia Mansell

In some sense it's as simple as: we have a lot of metal around optics, so we have a lot of field lines going every which way. If there's charge on the optics that's going to make them move, because charge lines are not stationary.



A view from the thermal compensation system through the beam splitter.

There are always stray electrical fields and it would take a complete overhaul of our grounding and electronics and building power to get rid of them. Between O1 and O2 Livingston vented, and since we were in we also discharged our test masses. Hanford did not vent and did not discharge their optics, as the way to charge without opening was not set up yet.

Unfortunately it is very difficult to measure pure electric fields. You can measure charge noise in some ways by driving mirrors at some frequency and seeing the response in the DARM noise spectrum, but then you're only testing the charge that is in the field lines of between the reaction mass and the test mass, not the charge that's on the other side of the optics. Now we have installed at both end stations the Electric Field Meter (EFM) that Rai Weiss designed, because he's been concerned about this for a long time.
Anamaria Effler

In the last couple of months I've been installing and characterising an Electric Field Meter (EFM), as part of a team of awesome scientists. It consists of four plates - two for each axis - and some clever electronics to measure the differential voltage between the plates caused by electric fields. All of this is mounted on a cube that is suspended in the chamber next to the test mass. The whole thing weighs 15 kg, and installing it in-chamber at End Test Mass X (in one of the end stations) was a fun and informative experience. The EFM is sensitive enough to see fields of the same strength as those we know have coupled into the interferometer readout, so this should be a very useful tool in the next observing run.

Even with the EFM and the electrostatic drive to help us, it's hard to measure the actual charge on the test mass to know what's going on. If we commission this interferometer and still find this mystery noise at 100 Hz, even with the new test masses, I think overcoming that will be a big challenge to reach design sensitivity.
Georgia Mansell

Other noise sources

Other interesting noises include laser jitter noise. This is modulation of the input laser light from vibrating optics. Some of it was caused by plumbing in the old high power laser and will be improved with our new 70 W amplifier. And, of course squeezed light injection! Both sites now have squeezers installed; they're being commissioned right now and will im-

prove the high frequency shot noise limited part of the spectrum, without having to turn up the laser power.
Georgia Mansell

All the cavities have to be very well mode-matched to each other, and the whole interferometer has to be mode-matched to the output mode cleaner, and the matching changes with laser power. Putting the story together involves a lot of measurements, and a lot of modeling from the Birmingham Finesse (interferometer simulation software) group. It’s cool that you can pull in people from very different backgrounds, and ask: can you spend a month following along with us and telling us what your modeling tells you, or: what can the thermal compensation system group do to measure or change the thermal state of the optics.

We had this radio frequency (RF) whistle problem at Livingston, it doesn’t quite show up at Hanford or at least not in the same way. It seems to have something to do with the reference cavity, so right now we’re working on a way to take the cavity out of the system. That’s really hacky but if it works, it works. I have disconnected every RF cable in this place and some of the noise is still there and it’s so frustrating. So now we’re taking this other approach: if we can take this part out, what happens?
Anamaria Effler

Commissioning surprises?

Probably the biggest misconception is the idea that the motivation for working on the instrument must be to find more gravitational waves. As an instrument scientist, I’m more interested in solving the technical challenges that pop up day to day. Finding more gravitational waves is the icing on the cake that keeps the funding agencies and the general public happy so that I can continue working on the technical challenges.
Corey Austin

It’s funny how the instruments are so different. Hanford and Livingston have identical components but are often facing different problems. I talk to Sheila Dwyer at Hanford and we ask each other to do the exact same test, but more often than not the result is “we don’t see it, good luck.” That part sucks a little. Both sites get this question all the time - how does the other site deal with this problem? And 75% of the time it’s “well, they magically don’t have this problem”.
Anamaria Effler

A neat feature I didn’t expect at Hanford is the wildlife, there is a lot of wildlife living very close to the site. So far this summer I’ve encountered porcupines, coyotes, a hawk and, one time, an elk.
Georgia Mansell

The future of commissioning

With all the enthusiasm that the first detections generated, the tension between trying to get more science data and attempting to improve the sensitivity will intensify. This is a good challenge to have.
Daniel Sigg

I think that it’s easy for prospective students and postdocs to say that LIGO has already achieved its goal, and they would rather work on something with a more exciting future. Of course, LIGO has only just begun exploring the universe, and for me, as a student working at the Livingston detector, I have an opportunity to make the most precise scientific instrument ever built even more sensitive. That’s pretty cool!!
Corey Austin

Next Step Full Lock

This picture was taken in Apr. 2018, to celebrate the lock of the first cryogenic Michelson interferometer at KAGRA.

What is KAGRA working toward?

Keiko Kokeyama: For KAGRA, the next observation run will be our first observation run. So far, engineering runs had been only in the simple Michelson interferometer configuration. As with the other interferometers, the locking of the full interferometer, and the noise hunting will be most challenging. We hope a lot of LIGO and Virgo experiences will help.

Yutaro Enomoto: We don't have an operating interferometer yet, so achieving the full lock of our interferometer will be the first step to improved sensitivity. Among all the work toward the full lock, I am currently on noise budgeting (or noise modeling) and servo design of the green lock system. This will hopefully help quick recovery of the interferometer after its lock loss during the next observation run.

Keiko Kokeyama: Most parts are similar to the LIGO installation and commissioning, but we are in an underground environment. Underground, there is no difference between day and night, or between the seasons, in terms of the temperature and humidity. The natural tunnel temperature is 12 degrees C, and more than 90% relative humidity. Actually, the temperature in the tunnel has been rising since the tunnel excavation finished and we started using electricity. The electric consumption heats up the space more than 10 degrees C. The most contributing power consumption are the clean booth fans. Recently, we had a nation-wide torrential rain, and the humidity of the tunnel went up 10~20 % in about a day. It seemed a large amount of water

Keiko Kokeyama

is an assistant professor in Institute for Cosmic Ray Research, University of Tokyo. She worked at the LIGO Livingston site from 2011, and moved to the KAGRA site in 2015. Brainwashed by a crazy cat lady in LIGO Livingston, she adopted a Louisiana calico cat during her LLO time. The cat now lives in the KAGRA area.

Yutaro Enomoto

is a PhD student at the University of Tokyo who works on interferometer commissioning at KAGRA and is a big fan of Star Wars. He is looking forward to detecting a new SW event as well as a GW event that happened a long time ago in a galaxy far, far away.

by Keiko Kokeyame & Yutaro Enomoto

▲

KAGRA's Y-arm under construction

had soaked into the mountain. Some water leaked out from the tunnel walls. The temperature dropped accordingly, by up to 2 degrees C.

These unusual process of the environment change is unlike any ground-based detector sites. We developed an original monitoring system, using commercial sensors with a wireless communication function, integrated in the CDS network. There are more than 30 locations to be monitored in the KAGRA tunnel. In the later phase (coming soon) with the full interferometer commissioning and noise hunting, the temperature change can cause mechanical problems on the suspensions. We have started installing some air conditioners in the corner station, but it is unsure how precisely we can control the environment.

The biggest improvement of the current detectors are the automations and intelligent controls based on the more sophisticated digital and network systems. In the next decades, with more powerful computers and faster network, even more intelligent controls will be rapidly developed.

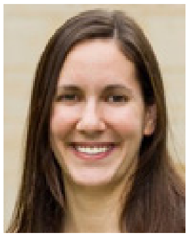
Yutaro Enomoto: Cryogenic suspension is interesting, because almost everything gets different when it is cooled down to cryogenic temperature. Maintaining stable operation against high power laser (more than 100W) injected into KAGRA interferometer will be challenging. As the power goes up, the heat extraction from test masses, to keep the masses cryogenic, will be tougher.

Keiko Kokeyama: In the long term, although it is not a technical or scientific point of view, for KAGRA, it is going to be more difficult to secure the researchers of the next generation. Japan has a serious issue of low birthrate, and decreasing numbers of next generation graduate students and young researchers. Recruitment competition between academia and industry is getting severe. We must not only keep the scientific field attractive, but also make stable academic careers which can compete with industry positions. The work environment needs to be changed to welcome more non-Japanese collaborators, and correcting the gender gap in STEM (and all other fields) is also one of the most important steps.

LIGO 2018

Calibration:
A Short Introduction

Maddie Wade



works on calibration of the LIGO interferometers and searches for compact object mergers. She also enjoys gardening, teaching, and canoeing with her family.

The LIGO interferometers are sensitive to the relative changes in the length of the two interferometer arm cavities caused by passing gravitational waves. Calibration describes how measurements with the observatory's instruments – the photodiode outputs and control systems – are converted into the strain data that we use for all astrophysical analyses. The final product of calibration is the strain, *h(t)*: the differential arm motion (DARM) that would result from freely-swinging test masses divided by the average unperturbed arm length.

Many external stimuli besides gravitational waves (GWs) also induce differential motion of the two interferometer arms, and at much larger amplitudes than the average gravitational wave. To keep the instrument stable, the difference between arm lengths must be held steady to less than a femtometer – less than the width of a proton – during operation. To accomplish this, motion that changes the arm lengths is actively compensated.

A system of electromagnetic actuators is suspended in parallel to the quadruple pendulum seismic isolation system that holds the test masses at the end of the interferometer arm cavities. Fig. 1 shows a basic diagram of the interferometer, including an inset that shows the actuation system hung in suspension parallel to the end test mass suspension system. Calibration is the process of reconstructing the external, free-swinging DARM motion from the power fluctuations at the photodiodes combined with the actions of the control system.

The calibration process involves modeling the optical components of the interferometer as well as modeling the actuation system that is actively compensating for arm motion. Fig. 2 is a diagram of the DARM control loop. The left side describes how the motion of the interferometer arms is controlled: The residual DARM motion, ΔL_{res}, is the relative motion of the arms that is left over after the actuation system applies a control motion (ΔL_{ctrl}). This residual displacement is converted into a digitized signal, representing the laser power fluctuation at the GW readout port, by the sensing function *C*. The sensing function includes components such as the optomechanical response of the Fabry-Perot cavity, the physical time delay due to the light-travel-time in the interferometer, and the responses of the readout electronics.

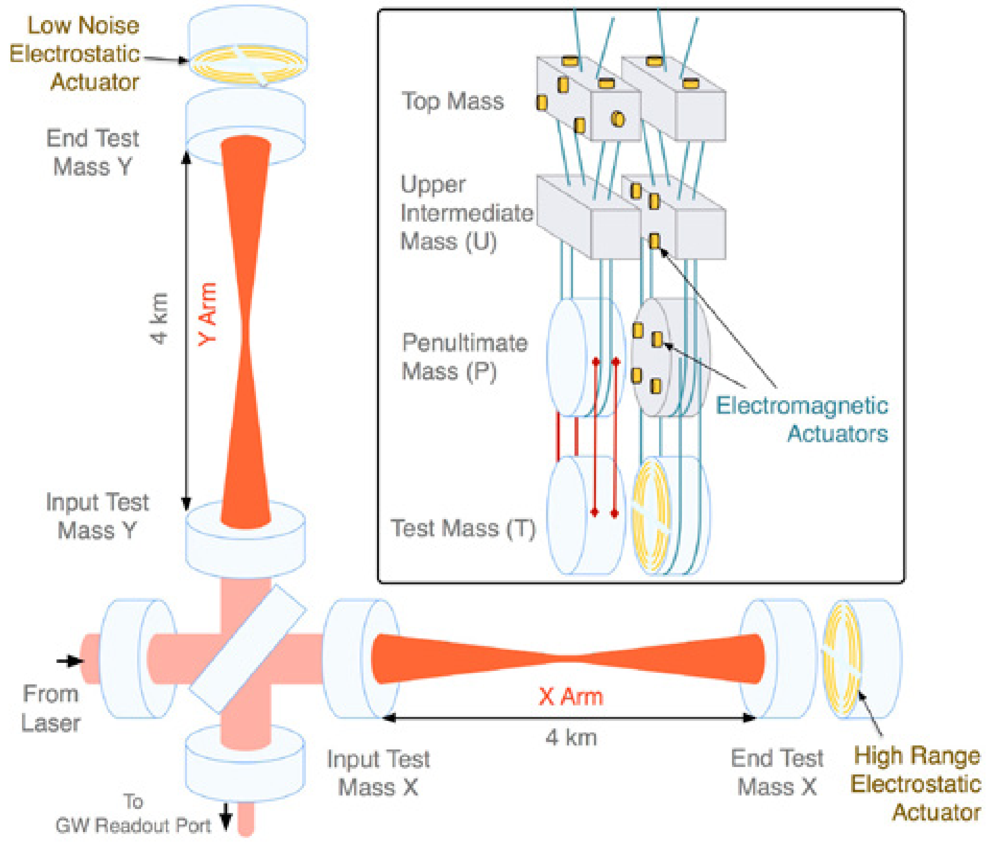


Figure 1: *A simple schematic of the LIGO interferometer. Four highly reflective test masses form the two arm cavities in the horizontal plane. A photodiode at the GW Readout Port is used to measure the interferometer response. Inset: one of the dual-chain, quadruple pendulum suspension systems is shown in the vertical plane.The inset shows the actuation system that hangs in parallel to the pendulum suspension system and actively compensates for differential arm motion.*

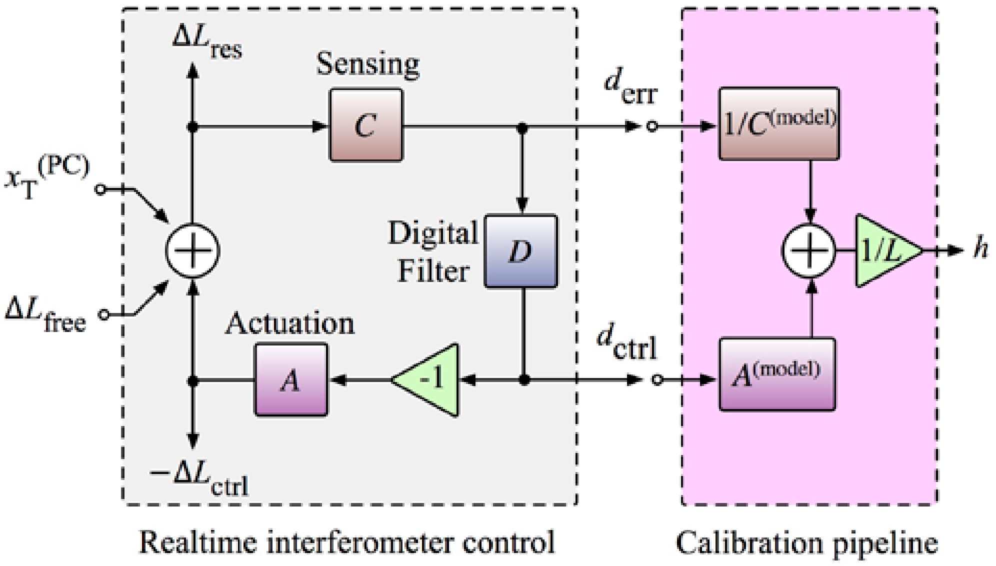


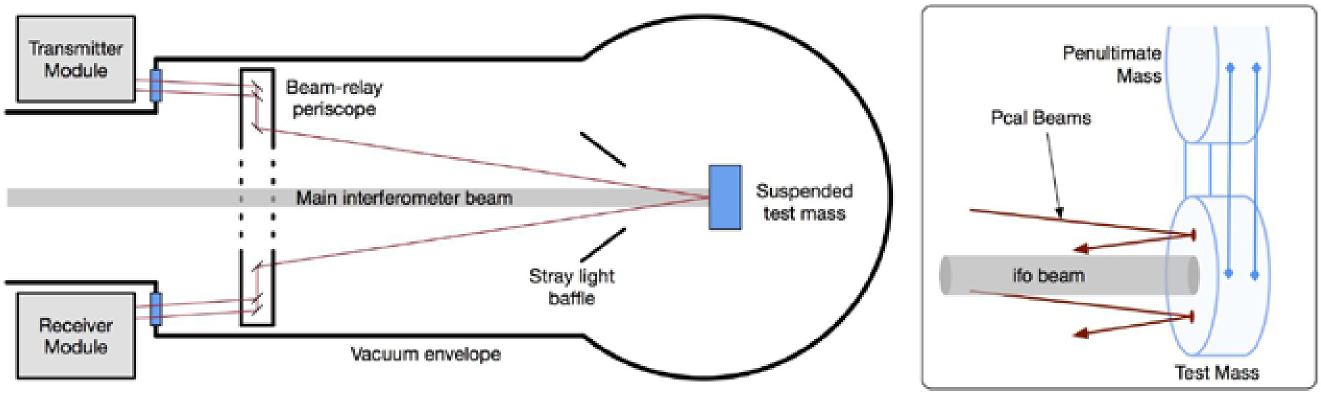
Figure 2: Diagram of the DARM feedback loop. The control loop, on the left hand side, stabilizes the relative length of the arm cavities. Calibration, on the right hand side, undoes this loop to reconstruct the astrophysical strain from the digital readouts of the instrument.

This digitized error signal is then filtered *(D)* to construct a corresponding control signal to compensate for the residual motion. That control signal is sent to the actuation system to cause physical displacement at each stage of the pendulum, which maintains the differential arm cavity length. The actuation function for each stage of the pendulum, *A*, captures the translation from digital control signal to physical displacement.

The major components that calibration needs to reconstruct the free DARM motion from the digitized error and control signals are the sensing function and the actuation function. The right-hand-side of Fig. 2 shows how a model for the inverse of the sensing function is applied to the digitized error signal, to find $\Delta Lres$, and a model for the actuation function is applied to the digitized control signal, to find $\Delta Lctrl$. The results from the models are combined and divided by the average arm length *L* to reconstruct the strain *h(t)*.

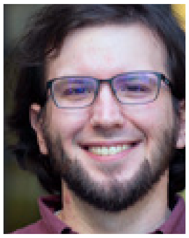
A system known as the photon calibrator (PCal) is used as an absolute calibration reference when constructing the models for the inverse sensing and the actuation. Fig. 3 shows the photon calibrator system. The photon calibrator uses a small one-watt auxiliary laser to induce motion of an end test mass with photon radiation pressure. Two PCal beams are incident on the end test mass, one above and one below the main interferometer beam, to avoid deforming the surface of the test mass in the region sensed by the interferometer beam. The power of the PCal laser is modulated to induce a known amount of differential arm motion, which is used as a reference for the calibration models.

Figure 3: The photon calibrator system.



Characterization: Of Bangs and Buzzes

TJ Massinger

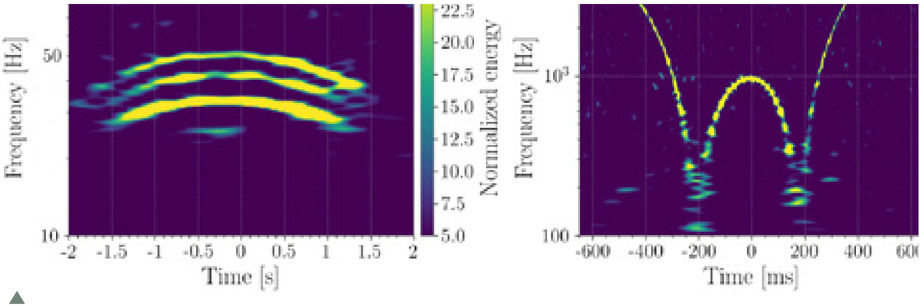


earned his PhD from Syracuse University and is now a postdoctoral scholar at the California Institute of Technology working on detector characterization. In his spare time, he enjoys playing board games, going camping, and playing with his lazy cats.

In an ideal world, LIGO data would be comprised of predictable, well-behaved Gaussian noise and the occasional transient gravitational wave signal. In the real world, LIGO data contains numerous classes of noise on timescales ranging from short millisecond bangs to features that buzz or hum for days. These instances of noise are problematic for everyone; data analysts don't want their analyses to be contaminated or biased and instrumentalists want detectors with optimal and well-understood performance. The Detector Characterization (DetChar) group is responsible for investigating noisy data with the primary goal of improving the detectors when possible and otherwise mitigating the effects of noisy data on astrophysical searches.

Things that go bump in LIGO data

The most commonly considered type of excess noise in LIGO data are noise transients, or "glitches", which come in many shapes and sizes depending on their source. A thirsty raven pecking at an iced over pipe (LHO alog 37630) may show up as a seconds-long burst of repeated glitches. Scattered light reflecting off of a surface and recombining with the main laser beam may show up as a series of sweeping arches in the time-frequency plane (see figure below). These glitches can mimic or overlap with true transient gravitational wave signals, making detecting and characterizing these sources difficult. Efforts to categorize LIGO and Virgo glitches have been spearheaded by the GravitySpy glitch classification project, which lives at the interface of DetChar and citizen science *.



Time-frequency depictions of transient noise from Advanced LIGO's second observing run. Left: Arches caused by scattered light recombining with the main laser. Right: A whistle caused by beatnotes between drifting RF oscillators.

In addition to transient noise, LIGO data often contains long duration noise that appears when calculating a noise curve from long stretches of data. Some cases of long duration noise, such as mechanical resonances, exist at fixed frequencies and appear as narrow lines in the noise curve. In rarer cases, non-stationary noise appears as "breathing" in the noise curve, resulting in a low frequency modulation of the detector sensitivity. Recent efforts have focused on correlating these slow changes in sensitivity with environmental or instrumental changes such as temperature variation.

Hunting LIGO noise sources

In addition to gravitational-wave strain data, there are roughly 200,000 auxiliary data streams, or "auxiliary channels", recorded at each LIGO Observatory. These include monitors of detector performance, environmental influences, real-time computing, and control system diagnostics. These auxiliary channels are critical for discovering and investigating sources of noise in LIGO data.

There are two primary approaches to identifying noise sources: instrumental investigations and examination of background noise events. Automated algorithms are run on a daily basis that are designed to discover correlated noise between auxiliary channels and gravitational wave strain channel. The output of these algorithms can be compared to the results of astrophysical search pipelines to assess whether or not a particular noise source is contributing to a high rate of background noise events. Alternatively, the most problematic background noise events for an astrophysical search can be tracked back and linked to a specific instrumental noise source.

Data quality during an observing run

When a noise source has been investigated and an instrumental coupling has been discovered, an algorithmic approach is used to

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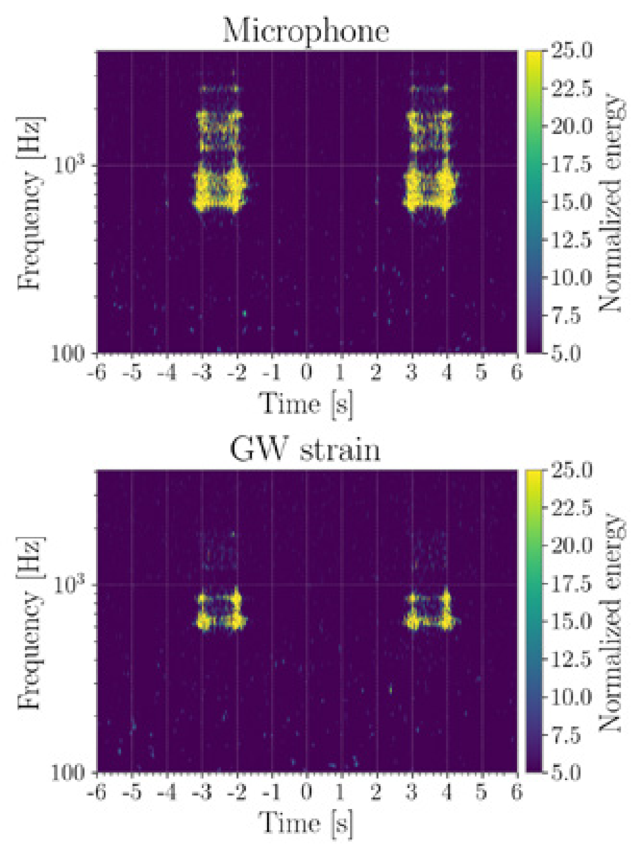
* Help LIGO and Virgo classify detector glitches! Visit gravityspy.org

mark times when such noise is predicted to occur. These times are omitted from astrophysical analyses in the form of data quality "vetoes". Alongside the general detector state information (e.g. "science mode"), a subset of data quality vetoes are provided for use in rapid searches for gravitational waves. It is important for these searches to incorporate as much data quality information as possible to enable confident surveys for electromagnetic counterparts, particularly in the era of automated, public alerts. In the case where new information becomes available that casts doubt on a potential gravitational wave signal, a retraction can be sent. For less urgent astrophysical searches that are run days to weeks after strain data is recorded, a more thorough suite of data quality vetoes is developed to remove systematic noise sources from analysis time.

Assessing whether a candidate event is real

When a candidate event is being considered for publication, the cumulative information about the state of the detectors and any noise in the data is collected to assess whether a candidate event is a genuine astrophysical signal or the result of terrestrial noise. For example, evaluating the physical environment monitors is an important check to ensure an event recorded in multiple detectors wasn't caused or influenced by global environmental events like lightning. Each result published by the LIGO-Virgo collaboration represents the DetChar group's collective effort in understanding the detectors, the character of the data, and the impacts of features in the data on astrophysical searches.



▲

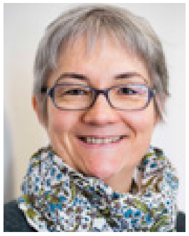
An example of coupled instrumental noise during Advanced LIGO's second observing run. A telephone ringing in the enclosure that houses the main laser acoustically coupled into the gravitational wave strain data.

Memories of GW170817: The First 24 Hours

August 2017 was a busy time for LIGO and Virgo: Virgo had joined LIGO for observations (Observing Run 2) on the 1st of August, and just a couple of weeks later a binary black hole merger GW170814 had been seen - the first observation to be made with the triple detector network. There were just a couple of weeks left before observations would be stopped for upgrades to the instruments. Here is a sampling of stories and recollections from some of people involved in the exciting events of the August 17th discovery.

Laura Nuttall

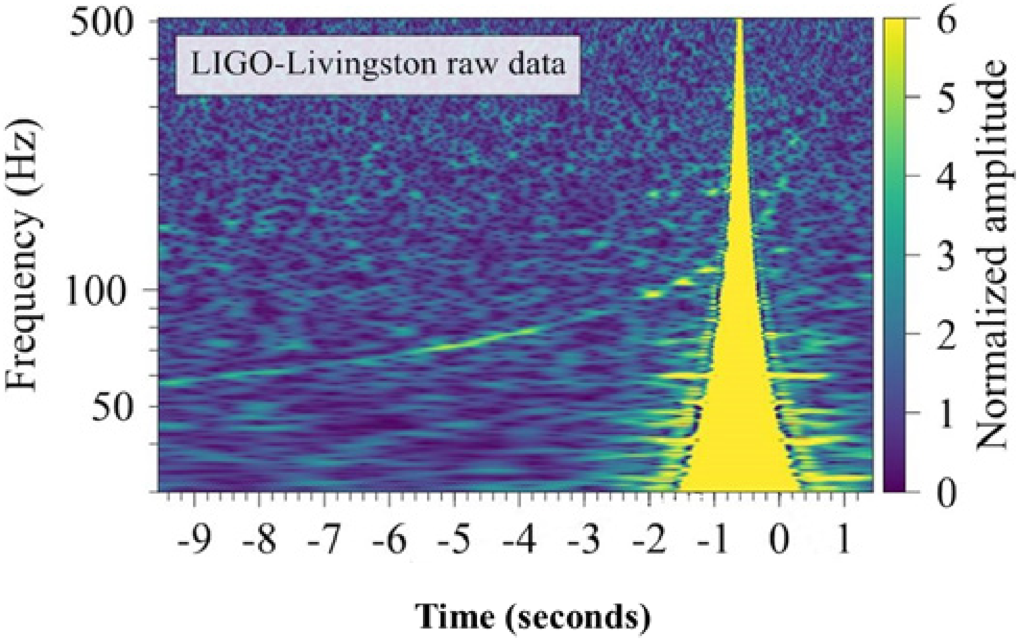
Just before GW170817, I remember writing out the names of all the signals we had seen so far on the whiteboard behind my desk (I'm including the quiet signal LVT151012). Six binary black hole signals, not bad for two observing runs. My other colleagues who I share my office with were quite certain, after the excitement at the beginning of the week with the binary black hole observation GW170814, that we were done with detections for this run with less than 2 weeks to go. But we did jokingly comment that the last time I did this exercise that GW170814 arrived a few hours later… "What are the odds that would happen again?" I smugly joked. You know the rest of the story...



Frederique Marion

The construction of Advanced Virgo was a bumpy road, run like a marathon and ended in a sprint. The prospect of joining Observing Run 2 was stimulating, but the pressure was straining, especially for colleagues working on the instrument. Joining the run was a milestone, but we hardly thought a few weeks of data taking would be enough to detect a signal. Then came GW170814... Honestly? I was ready to declare success at that point and wouldn't even have dreamed of asking for more. Especially since so late in the run, a binary neutron star looked like something we would have to wait for Observing Run 3 to hopefully detect.

A time-freqency spectrogram of raw Livingston data. The bright yellow region is the "glitch" in the LIGO-Livingston data, with the curve of a binary chirp trace visible beneath it. The glitch lasted only ¼ of a second, but had a large amplitude, and stopped automated systems from distributing the signal.

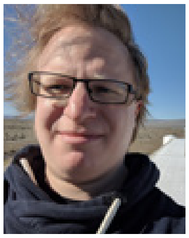


Giulia Stratta

The second observing run of the two Advanced LIGO interferometers started by the end of 2016 and lasted to the end of August 2017. For people working in the LIGO/Virgo team as me, these nine months have been characterized by an hectic activity, including weekly (and sometimes daily) teleconferences with the LIGO/Virgo Collaboration and astronomer collaborations and 24 hour duties in order to be ready to catch any event in real time and communicate it to the astronomer community. As an astronomer, I also participated in collateral activities as computations of the expected emission finalized to the optimization of telescope proposal writing, necessary to guarantee observational time for the highly competitive search of the possible electromagnetic counterpart of GW sources. By the second half of August 2017, when already 5 binary black hole coalescences have been discovered and the planned end of Observing Run 2 was approaching, everybody was nearly exhausted and starting to relax.

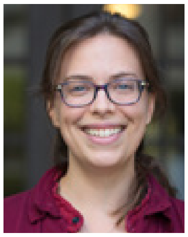
Aaron Zimmerman

During August 2017 triggers had been coming in fast and furious, with a strong detection on 14th, along with a bunch of lower significance triggers. Nothing let up until the run was over. I think I was already on autopilot before GW170817, waking up regularly in the middle of many nights to respond to triggers with Carl and Soichiro and wiki pages for parameter estimation (PE) results (for estimating the properties of the gravitational wave source).



Carl-Johan Haster

We were so completely overwhelmed by the cadence of triggers in the days leading up to GW170817. I was however "better off" timezone wise than Aaron, since I'd spent the end of the summer at the Kavli Program in Copenhagen. August 17 was in the last week of the workshop, so my days there were supposed to be filled with finishing-up-projects as well as going-away-dinners, but the PE rota work added another layer of tasks on top of that.

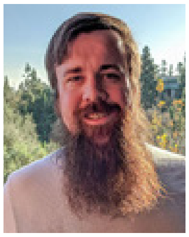


Jess McIver

In the past I've always been closer to gravitational-waves-focused experiment; gravitational wave data analysis and interferometer instrumentation. When I had the opportunity to participate in the Kavli Summer Program in Astrophysics last summer along with other LIGO colleagues, I got my first in-depth exposure to the optical astronomer side of multi-messenger astronomy. At the time I'd thought it would be limited to learning about clever ways to search for optical counterparts to gravitational wave signals, particularly from the UC Santa Cruz Swope team, but the binary neutron star signal had already nearly arrived and I was about to see the results in practice.

***2017-08-17 12:47:18 UTC** - Event G298048 is automatically uploaded to the gravitational-wave candidate event database, GraceDB. It is a loud (signal-to-noise ratio of 14) single-detector event from the Hanford instrument. G298048 was found by the gstlal search pipeline by matching to a template waveform with a total mass approximately 2.77 times the mass of the sun and a coalescence time of 12:41:04 UTC. The listed false alarm rate is 1 per 9112 years. Because of the low mass, the event is also automatically flagged as having a 100% chance of being "EM-Bright" - capable of emitting electromagnetic radiation (light) as well as gravitational waves.*

Minutes earlier, the Fermi Gamma-Ray Burst Monitor (GBM) had reported a gamma-ray burst (GRB), and a copy of the automated notice had been uploaded into the database immediately after its detection at 12:41:06 UTC. The burst had occurred two seconds after the gravitational wave chirp. LVC and Fermi scientists had been on the lookout for such a coincidence.



Cody Messick

To my knowledge, I was the first person to see the alert. It caught my attention because it's rare to see a single detector event with such a low probability of being a false alarm. I messaged Chad Hanna about it immediately, who noticed the coincident gamma ray burst from the Fermi Gamma-ray Burst Monitor (GBM). Chad asked me to send an email to the collaboration because he was shaking too much from excitement to type.

Kipp Cannon

The complication with this event was that it was a single-detector event, and maybe the first one after the collaboration agreed to enable electromagnetic alerts from single-detector events. The machinery that phoned people, and told them about the event, and triggered an "EM follow-up telecon", for example, was not ready for single-detector events. So at first it was just people who were getting GraceDB alerts directly who found out about it. When I joined the telecon

Chad was already online, and I believe Reed, but that was it. Chad had to manually click something somewhere to get the EM alert to go out, and let operators and other people know they needed to get online.

Carl-Johan Haster

On August 17 itself I'd just come back from a pleasant lunch break when I got a text alert pointing me to the original H1 trigger from gstlal, which initially didn't give me too much hope due to it being a single interferometer trigger. The incredible false alarm rate meant I looked closer however, at which point I saw that there was a Fermi coincidence. This caused me to walk over to Ben Farr's office (he was next to my office, but since my office mates were non-LSC members I couldn't speak to them…) where I spent the rest of the afternoon on TeamSpeak.

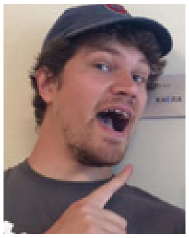
Giulia Stratta

On August the 17th (a typical holiday period in Italy), I was working at home under the porch when my mobile started to ring announcing that the automatic pipelines had revealed a possible gravitational wave event that required immediate human control. As soon as I connected via TeamSpeak with my colleagues and after a first check of the main pipeline output, we immediately noticed that the preliminary estimate of the masses at play in this new source were much smaller than all the previous detected sources. Since I am naturally skeptical, I was not very excited at the beginning. However, as the checks went on, no strong evidence for a non-astrophysical object was emerging and it was becoming clear that we were detecting, for the first time, the gravitational waves produced by a neutron star binary merger, a source from which electromagnetic radiation is expected. Indeed, a Short Gamma-Ray Burst was observed just 1.7 seconds after!

Kipp Cannon

Don't forget, Fermi was just minutes away from going dark due to it entering the South-Atlantic Anomaly (Ed: a region over the South Atlantic with a high density of charged particles trapped by the Earth's magnetic field, which interferes with satellite instrumentation). They had already turned off the Large Area Telescope (LAT) detector, and were about to turn off the GBM when the particle count pinged. The times when the GBM detectors had to turn off are a fun part of the story.

There is a problem - the LIGO-Livingston detector has a large instrumental glitch (a noisy interference in the detector data) at the same time as the observation.



Reed Essick

I'd been travelling to visit collaborators at Penn State University (PSU) that week (we detected GW170814 while I was in State College) and had just gotten back the night before. After taking a shower that morning, I saw a text from Cody Messick at PSU telling me to get online immediately, which I'm pretty sure I did while still in a towel. It was immediately clear that we had something special because of the coincident Fermi GBM trigger and the fact that we could see the inspiral track clearly in a spectrogram. The PSU folks had seen the LIGO Hanford spectrogram, but not the one from LIGO Livingston, and it's likely I was the first person to see the Livingston spectrogram with the big glitch on top of the inspiral. At that point, we rang alarm bells throughout the collaboration by hand because the automated software in place was designed to ignore single-detector triggers; the glitch in Livingston caused the search pipeline to only report the event in Hanford.

Laura Nuttall

I was on shift for vetting any candidates that day from a detector characterisation viewpoint. I happily ignored GW170817 when it initially came through, until an email drew my attention to the event being coincident with something from Fermi. I hastily started to look at the data around this signal, wondering why I had initially dismissed it. Sadly a non-Gaussian transient or glitch was present at Livingston, independent of the signal. What are the odds this would happen? Except I recognised this glitch. Its morphology was something I saw all the time. Rushing on to a telecon I tried to assure others that detector characterisation knew what this glitch was, and to send an alert. I know I didn't express or explain myself well at all, I was far too excited.

Jess McIver

The excitement of the binary neutron star signal alert and the rapid response team call where we decided whether to send out the signal was unforgettable. We were all pretty giddy to see the clear binary neutron star trace along with a gamma ray burst alert, even with the stomach-jolting glitch in LIGO-Livingston.

Cody Messick

I'll never forget sitting in the telecon after everybody noticed you could see the track in L1 behind the glitch, the excitement was palpable; this was the eureka moment that people dream about when they get into science.

From the GraceDB Record:

Aug 17, 2017 12:47:19 UTC
GstLal CBC
Log File Created [in GraceDB]

Aug 17, 2017 12:47:24 UTC
GraceDB Processor
RAVEN: External trigger candidate found: E298046 within [-1, +5] seconds

Aug 17, 2017 13:03:11 UTC
Nicola Menzione
operator signoff certified status as OK for V1: At the time of the event we are in Science Mode, nobody around site; good weather condition. Nothing unusual to report

Aug 17, 2017 13:05:52 UTC
Alan Weinstein
advocate signoff certified status as OK: There is a BNS trace in L1 as well. And a GRB.

Aug 17, 2017 13:08:14 UTC
Marc Lormand
operator signoff certified status as OK for L1

Aug 17, 2017 13:08:14 UTC
GraceDB Processor
AP: No hardware injection found near event gpstime +/- 2.0 seconds or from Virgo injections statement if V1 is involved.
Aug 17, 2017 13:17:38 UTC

Corey Gray
operator signoff certified status as OK for H1: [...] H1 is OK and has been locked for 38hrs with range of 53Mpc. We were currently under a GRB stand down time as well.

The LIGO EM followup team puts together Gamma-ray Coordinates Network (GCN) circulars to send out to collaborator observatories around the world, so that everyone knows where to point their telescopes try and find light from the merging gravitational wave source. With only one detector registering the signal, the first alerts have poor sky localization.

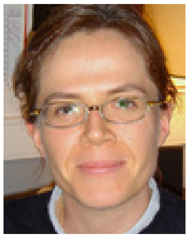
Reed Essick

During that initial telecon, I helped draft the initial GCN circular, the alert that is sent out to partner astronomers when an interesting event happens, and generally coordinated the immediate response. At one point, I even demanded that folks stop talking, I gave them 30 seconds to just read the draft, and then we sent it.

TITLE: GCN CIRCULAR
NUMBER: 21505
SUBJECT: LIGO/Virgo G298048: Fermi GBM trigger 524666471/170817529: LIGO/Virgo Identification of a possible gravitational-wave counterpart
DATE: 17/08/17 13:21:42 GMT
"The online CBC pipeline (gstlal) has made a preliminary identification of a GW candidate associated with the time of Fermi GBM trigger 524666471/170817529 …"

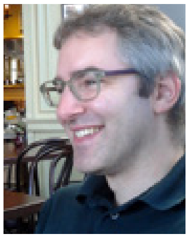
TITLE: GCN CIRCULAR
NUMBER: 21509
SUBJECT: LIGO/Virgo G298048: Identification of a binary neutron star candidate coincident with Fermi GBM trigger 524666471/170817529
DATE: 17/08/17 14:09:25 GMT
"A binary neutron star candidate was identified in data from the LIGO Hanford detector … The neutron star coalescence candidate is also clearly visible in data from the LIGO Livingston detector, although there is a coincident noise artifact in the L1 data. To be clear, the binary neutron star candidate is clearly visible in the L1 data on top of the noise artifact. … "

News spreads through the collaboration, and scientists around the world are pulled away from their daily routines.



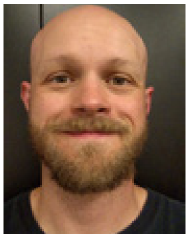
Marie Anne Bizouard

This was supposed to be an easy half leisure - half work day. Virgo had joined O2 and monitoring the triggers coming was kind of an amusement. This was also our 6 year old's birthday on that particular day. Champagne was already cooling in the fridge. I was finishing an exquisite lunch at the beach of Villefranche when I got the alert on my cell phone. Oh another BBH, I thought. 30 seconds later another SMS arrived, from Nelson, with a single word "GRB". Nelson was already back at work. Something was obviously happening and I must say the drive up the hill of the Observatoire seemed to me incredibly longer than usual.



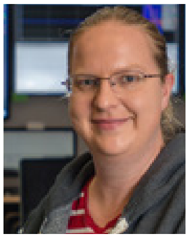
Tito Dal Canton

I received the burst of initial alerts from gstlal while I was waiting for the bus to my office. I remember being surprised by the lack of alerts from PyCBC and wondering if something really exceptional had happened, or something had gone wrong. The moment when I got to my office and saw the spectrograms and GRB was the most exciting of my current postdoc and might well be the second of my entire career.



Paul Marsh

August 17th started like a routine day at Hanford, as far as listening to the universe with a 4km laser cavity goes. My room-mate Philippe was the first to notice the unusual email from Keita at 7:40am (14:40 UTC): "A significant candidate was detected...send an email to me stating where at the site you were and what you were doing." Reporting work activities after a possible detection was normal; reporting them by email, directly to Keita, and doing so immediately, was not. That certainly got the blood pumping a little. Most people read email from most recent to least recent, though. Once we noticed Mike Landry's email titled "Possible BNS detection", breakfast was over and we were booking it for the car.



Jenne Driggers

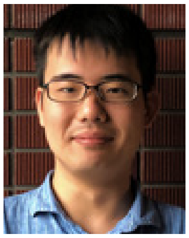
The morning of August 17th, 2017 was a great one. As is my usual, I started going through my emails before getting ready for the day. I often had email alerts from graceDB, although every one before then had been either rejected for data quality, or had been a binary black hole (like the one only 3 days before). The one this morning was special though - it was a binary neutron star candidate with excellent confidence that it was astrophysical. This changed my entire morning. I immediately jumped up and danced across the house to start my morning routine. I was out of the house and on the way to LIGO Hanford in record time. I spent the day following email threads regarding the detection, and starting to prepare noise-subtracted data around the event.

Maya Fishbach

I didn't check my email on the morning of August 17, because I was hurriedly finalizing a presentation that I was scheduled to give on a telecon. I remember that I was disappointed when, instead of attending my (very exciting) presentation on the upper mass gap in the black hole mass spectrum, most of the usual attendees were gathered on the electro-magnetic followup channel. Just an hour before, a binary neutron star, with a coincident GRB, had been detected for the first time.

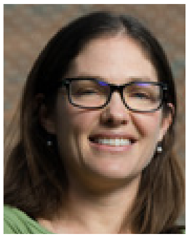
Aaron Zimmerman

In the week of GW170817 I was traveling to collaborate with Sam Gralla and Peter Zimmerman at the University of Arizona, and staying with my brother. GW170814 came in during the morning of the first day of my visit, and GW170817 on Thursday. What I remember was working in the early mornings on my brother's couch on the detections, going in to a coffee shop to work some more, and then practicing my poker face all day long as we discussed Green functions at the University of Arizona, with me regularly and rudely checking my email.



Soichiro Morisaki

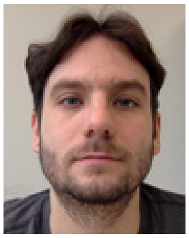
The detection was at night in my local time (JST), and I was on a train to go home at that time. Seeing the e-mails from GraceDB and LSC people, I noticed that something remarkable happened. I was so excited, and I hurried on home. On that day, everything was going really fast. I had to see emails to see what is going on at midnight.



Joey Shapiro Key

Several LSC members spent the summer of 2017 at the Kavli Summer Program in Astrophysics at the Niels Bohr Institute in Copenhagen, Denmark. The program focused on topics in astrophysics with gravitational wave detections, and this turned out to be perfectly planned. For six weeks we worked on research projects with colleagues and students. One morning in the last week of the program, I was in the small attic kitchen by our office with Jess McIver and Jeandrew Brink making coffee and discussing a student project. We heard feet running up the stairs and Ben Farr told Jess and me to come down immediately to his office, leaving Jeandrew to guess about the excitement. GW170817 is even more memorable because we were able to share the discovery in person with so many colleagues in the historic setting of the Niels Bohr Institute.

Meanwhile, the race is on to remove the glitch, combine the data from multiple detectors, and find out where in the sky the gravitational waves came from and let others know.



Ian Harry

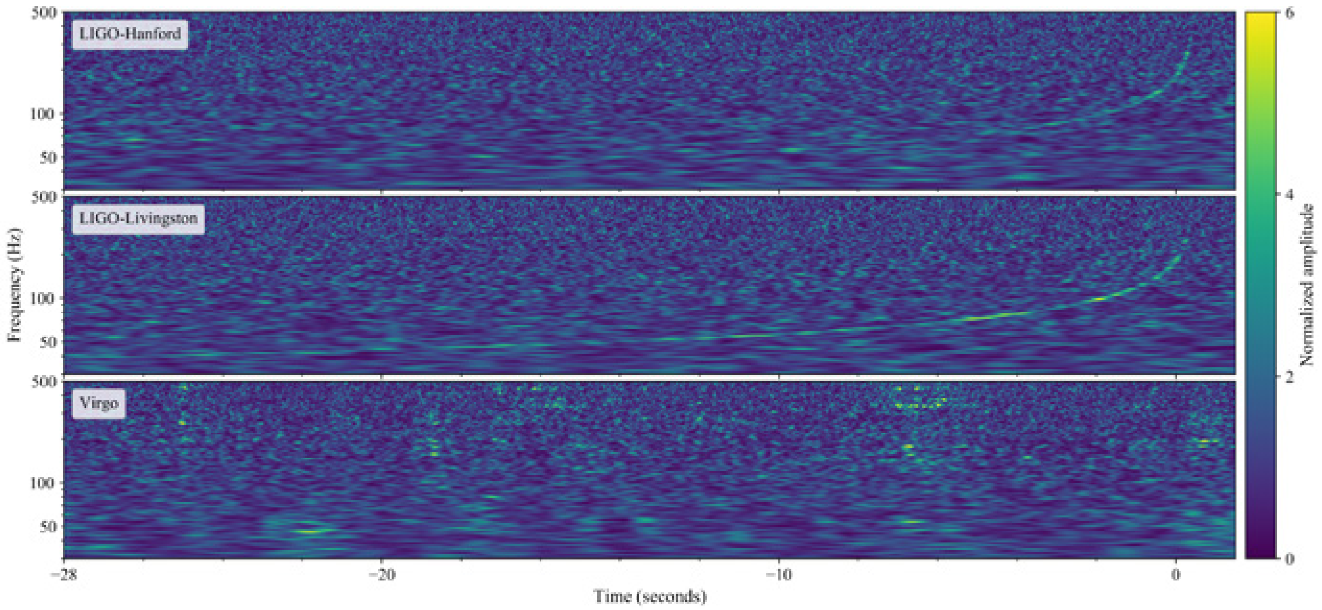
My job on the afternoon of 17 August 2017 was to manually remove the loud non-Gaussian transient from the data in the Livingston data immediately preceding the merger of the two neutron stars. While the non-Gaussian transient was present in the data it was not possible to make a 3-detector sky-map and so this work was needed to be able to point telescopes to see GW170817.

Marie Anne Bizouard

I finally reached the Observatoire and could join the EM follow up Team Speak call. The initial notice was getting prepared. I got the summary from Nelson. Of course the Fermi GBM alert was striking. But then what about Virgo? Did Virgo see the event? Unfortunately, there had been an issue with Virgo data transfer to the LIGO clusters that day. Oh gosh, that was not the right moment.

Carl-Johan Haster

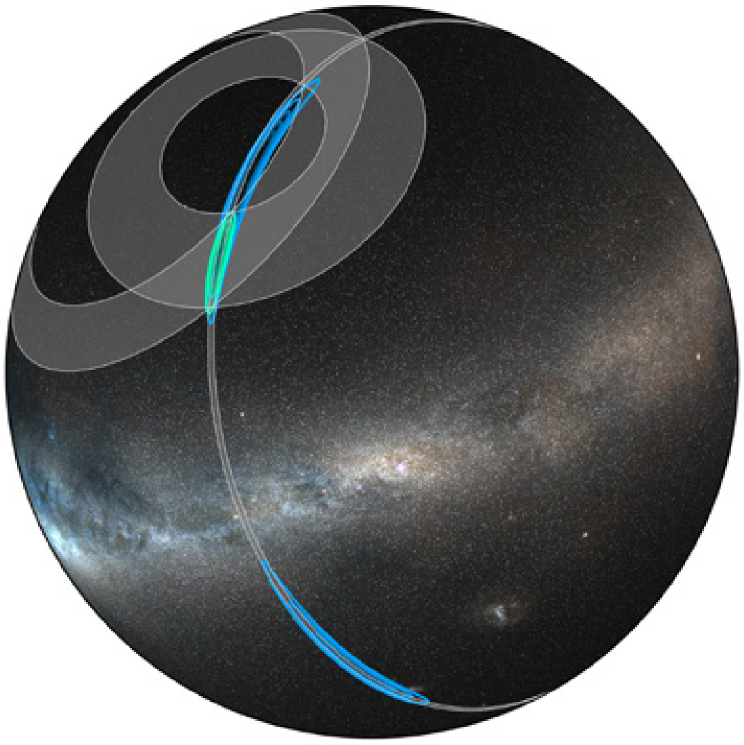
I don't have an incredibly clear gauge of what happened when, but this is most likely caused by me frantically working to manually setting up the necessary LALInference runs, manually checking for the Virgo and L1 data, finding out that the L1 data had a massive glitch, working with the PyCBC people (mostly Duncan Brown if I remember correctly) to get frames with the the glitch removed and finally starting the "correct" set of runs. And in between this I shouted excited things at Ben Farr, Jess McIver and Joey Key (who were also at the workshop) who then shouted as excited things back to me ("I can't believe this is true", "the universe is crazy" etc.)!



LIGO and Virgo data after the final glitch mitigation. The binary signal "chirps", starting at low frequencies at early times on the left side, then ramping up into a steep curve on the right side. The signal is visible by eye in the LIGO data for the last ten seconds or so, but the "gstlal" automatic search used data starting six minutes before the final coalescence to make the initial detection. Virgo data does not show a visible indication of the signal.

Aug 17, 2017 16:11:22 UTC – *Event G298107 is manually created in gravitational-wave candidate event database and data from all three detectors is linked. With the Hanford and Livingston data combined, the signal-to-noise ratio rises to more than 28, but the pycbc search doesn't pick up any signal in the Virgo data. However, Virgo data has a significant impact on the sky localization for the event.*

Alexander Harvey Nitz After we saw the initial notice of this event in just the Hanford data, and there was visibly a signal in spectrograms of the data, it was clear that producing an accurate skymap for this event would be essential. Unfortunately, the information from a single observatory can not provide an accurate skymap. It was my responsibility to search for the signal in the full network of observatories. I was a primary



Sources like GW170817 can be pinpointed much more accurately by triangulating the signal between Hanford, Livingston, and Virgo. The improvement of using three detectors instead of two can be seen here: the rapid Hanford-Livingston localization is shown in blue, and the final Hanford-Livingston-Virgo localization is in green. The grey rings show triangulation using each of the three detector pairs.

developer of the PyCBC Live analysis, which I used to quickly re-analyze the data from the LIGO-Hanford, LIGO-Livingston, and Virgo observatories. We were able to use this information to generate the 3-detector skymap used by telescopes to see GW170817 for themselves. Those couple hours may well be the most stress inducing *and* exciting moments in my career!

Marie Anne Bizouard

Finally Virgo data got analyzed. The SNR in Virgo is low. We spent the next hours trying to understand why. Not a great location for Virgo in the end, but what a great sky map ... the rest is known.

Tito Dal Canton

Before the event, I had been involved in developing PyCBC's ability to use Virgo for sky localization in Observing Run 2. I was delighted to see such a huge return from relatively straightforward work we had finished just weeks before.

TITLE: GCN CIRCULAR
NUMBER: 21513
SUBJECT: LIGO/Virgo G298048: Further analysis of a binary neutron star candidate with updated sky localization
DATE: 17/08/17 17:54:51 GMT

We performed a preliminary offline analysis using the PyCBC search (Nitz et al. arxiv:1705.01513, 2017) of the binary neutron star candidate G298048 (LSC and Virgo, GCN 21505, 21509, 21510) identified in low-latency by the gstlal online search (Messick et al. Phys. Rev. D 95, 042001, 2017).

…

An updated BAYESTAR sky map (Singer et al. 2016, ApJL 829, 15) that uses data from all three gravitational-wave observatories (H1, L1, and V1) is available for retrieval from the GraceDB page …

Carl-Johan Haster

At this point I also knew about the "deadline" from the electromagnetic partners mentioning the latest time we could give them an updated sky map for that night's follow-up. This gave me a few hours of "downtime" at which point I did go for a end-of-workshop-dinner with Ilya Mandel (and mostly other non-LSC people, so again I was in quietly and discreetly denying anything mode) followed by some drinks at a nearby brewpub. Following this I then went back to my apartment and got back on TeamSpeak to work on the skymap updates. My runs had then converged enough that the skymap was stable, so together with whoever was on the call by then (I think Will Farr might have been there, possibly Leo Singer, and I know that Reed Essick was on) I then made the skymap which was distributed in GCN Circular 21527.

After that I went to sleep since it was already well into August 18 then, and I completely expected another trigger to come our way a few hours later…

Reed Essick

Throughout the rest of the day, the first several hours of which I spent in a towel, most of my time went to comparing and sanity checking skymaps and the like. Hsin-Yu Chen, a former University of Chicago grad student and current Black Hole Initiative postdoc, was at MIT at the time. We worked together to get a preliminary skymap from more comprehensive parameter estimation released before that evening (the LALInference map released after the HLV Bayestar map). In the middle of that, Dan Holz landed at LAX after a trans-Pacific flight and his phone immediately exploded. Hsin-Yu and I skyped with him while he was still in the airport and very jet-lagged, along with several EM collaborators. Observations began that night, and you probably know the rest.

TITLE: GCN CIRCULAR
NUMBER: 21527
SUBJECT: LIGO/Virgo G298048: Updated sky map from gravitational-wave data
DATE: 17/08/17 23:54:40 GMT

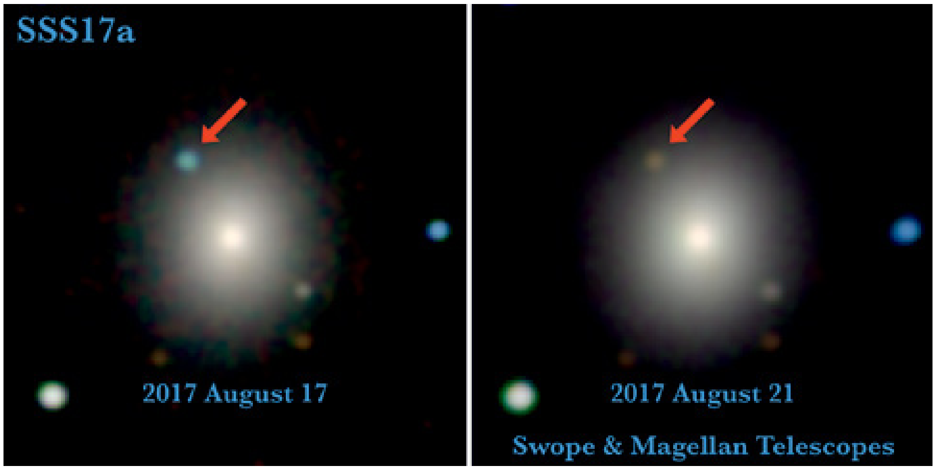
Parameter estimation has been performed using LALInference (Veitch et al., PRD 91, 042003) and a revised sky map … is available for retrieval from the GraceDB event page …

Jess McIver

I was equally blown away to get a text early the next day from Dave Coulter that read, "I think I found it." And the Swope team had indeed discovered the optical counterpart. That moment really highlighted for me that

The first optical image of GW170817's source was taken using the Swope Telescope at the Carnegie Institution's Las Campanas Observatory in Chile.

▼



GW astronomy is now a firm cornerstone of multi-messenger astronomy. To me, that's when the field I'd been working in for a decade instantaneously evolved in a monumental way.

Aaron Zimmerman
I think the moment where things sunk in for me was when the Swope image first circulated on the email lists. Looking at the first light ever imaged from a binary neutron star merger, a real tangible photograph, I knew that I was in the middle of something historic.

Throughout the rest of the day (and also the weeks and months to follow) the gravitational wave data is analysed and follow-up observations are made in multiple frequencies across the electro-magnetic spectrum.

Soichiro Morisaki
After taking a relatively short sleep, I went to the office to discuss with Kipp Cannon the next afternoon. Fortunately since that week is a vacation in Japan, few people were in the office. Therefore, we could talk about that very exciting event without having to be careful not to let non-LSC people notice the detection. At that moment, I realized that it is a historic moment and I felt happy I was a tiny part of that moment. I was very surprised at the fact that these extraordinarily important events (the Virgo detection and BNS event) happened in the same two-weeks.

Maya Fishbach
Only one year into doing GW research at the time, I certainly hadn't spent years anticipating this moment. But the excitement, expressed in the rapid accumulation of emails – hundred-message long, divergent, overlapping threads – was contagious, and I couldn't help getting sucked in. I was glued to my laptop screen late into the night (and for the next few weeks), trying to keep up with all of the new observations and interpretations.

Paul Marsh
The rest of the day, week, and month, are a little blurry. Through significant aid from Wikipedia, a multitude of informative collaboration telecons, and the world class physicists I was surrounded by, I eventually came to understand that I had unknowingly participated in the beginning of combined optical and gravitational astronomy. What this means to me isn't measurable in words and I'll forever carry LSC's spirit of discovery along with me.

Jenne Driggers
That evening, as with GW150914, a group of LHO staff and visitors gathered at my home to celebrate (we certainly weren't going to work on commissioning, which would disturb the background data acquisition for either event). This time though, we opened the champagne the night of the detection!

Reed Essick
Another fun fact: while biking to work the morning of the detection, a stinging insect of some kind flew into my face and embedded it's stinger in my jaw underneath my helmet's strap. It was a weird day.

Marie Anne Bizouard
The kids came back from the beach. The rest of the evening had been of course totally disrupted. At some point, we remembered we had a birthday to celebrate. At least a bottle of champagne to drink!

Frederique Marion
GW170817, with its chirpy spectrograms and counterparts – such a beautiful and "easy" first, once again! Virgo's impact for GW170817 is a reminder that there are multiple ways to contribute, and the whole story a reminder that bumps on the road can be a blessing, as in this case they meant extending the run till August.

Giulia Stratta
The detection of a nearly simultaneous short gamma-ray bursts and of an optical "kilonova", magnificently confirmed the theoretical expectations and the huge physical and astrophysical output that is still coming out from these observations is marking the powerful multi-messenger astronomy dawn. The possibility to assist in the first raw to such discovery has been thrilling and a unique privilege.

Maya Fishbach
There was (and still is) so much science to try to piece together from GW170817; even those of us without prior experience could contribute to this huge, messy effort. It was thrilling to take part in this discovery – to learn so much so quickly – and thrilling to realize that there is so much left to learn. This is still just the beginning of GW astronomy.

Ian Harry
This observation is, in my opinion, one of the most important observations LIGO will ever make, I was glad to play a part!

Biographies

Soichiro Morisaki is a Ph. D. student working on modified gravity and gravitational-wave data analysis at the University of Tokyo. In his spare time he enjoys cycling and playing table tennis.

Carl-Johan Haster is a Postdoctoral Associate at the MIT Kavli Institute. When not estimating parameters for the LVC he's on the lookout for the best music, finding a strong correlation with more northern (or more specifically Scandinavian) origins.

Aaron Zimmerman studies black hole ringdown and simulates binary black holes. He recently moved to the University of Texas at Austin, where he can enjoy the green chile of his native New Mexico.

Frederique Marion is the Virgo co-chair of the detection committee and a recent soccer World Cup champion by proxy.

Laura Nuttall (University of Portsmouth) spends far too much of her time thinking about noise. To try and stop this, she runs as much as possible.

Paul Marsh spent one faithful summer at LIGO Hanford as an intern, in between many months of reading DCC articles. His daily work is researching environmental and biomedical sensors for a PhD in electrical engineering.

Tito Dal Canton is a postdoc at Goddard Space Flight Center, working with PyCBC to detect compact binary mergers and with Fermi/GBM to observe associated GRBs. He loves discovering new places, food, beer, and occasionally tinkering with unnecessarily complicated electronic contraptions.

Jenne Driggers is a commissioner at the Hanford Observatory, working to make the interferometer as sensitive as possible. She also enjoys camping and backpacking with her dogs.

Kipp Cannon is a member of KAGRA and the LSC at the University of Tokyo who works on rapidly detecting the mergers of compact objects. He and his partner split their time between Tokyo and Toronto, where their cats live.

Marie Anne Bizouard is a CNRS staff scientist and a member of Virgo since 1998. Among other things, she is looking for gravitational wave unmodelled transient events. She is currently co-chairing the LVC burst group. When not at work, she likes to garden, read and listen to music.

Reed Essick is a KICP Fellow at UChicago working on a variety of topics, most of which can be traced back to fall-out from GW170817.

Ian Harry is one of the main developers of the PyCBC software package used to detect compact binary mergers. He spends most of his spare time changing nappies and chasing an overactive 1-year old.

Alexander Nitz is a researcher at the Albert Einstein Institute in Hannover, Germany who develops low-latency and deep searches for compact binary mergers. He enjoys sailing and avoiding warm weather.

Joey Shapiro Key is an Assistant Professor of Physics at the University of Washington Bothell. She enjoys riding ferries, mountain running, and eating gummy bears.

Maya Fishbach is a PhD student at the University of Chicago. In her spare time, she enjoys baking, practicing yoga, and learning language.

Jess McIver is currently a postdoc with the LIGO lab at Caltech. When not science-ing, she enjoys exploring new cities around the world, hiking, and trees.

Giulia Stratta is a gamma-ray burst and kilonova hunter at the Urbino University. She also enjoys playing piano and outdoor activities.

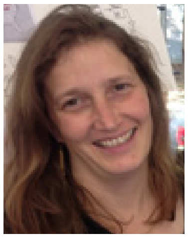
Glossary

BNS: Binary Neutron Star
BBH: Binary Black Hole
CBC: Compact Binary Coalescence
EM: Electromagnetic
LHO/H1: LIGO-Hanford observatory
GBM: Gamma-ray Burst Monitor
GCN: Gamma-ray Coordinates Network
GRB: Gamma Ray Burst
GraceDB: GW Candidate Event Database
GW: Gravitational Wave
LLO/L1: LIGO-Livingston observatory
O2: Observing Run 2
PE: Parameter Estimation
SNR: Signal to Noise Ratio
V1: Virgo observatory

The Early Years:
The Multi-Messenger Effort in LIGO

The first multimessenger astronomy discussion I remember took place during a dinner in Louisiana, and the topic was SN1987A. Soon after, Szabi Márka proposed LIGO multimessenger efforts to Barry Barish, who enthusiastically supported them. The LSC joined SNEWS, the SuperNova Early Warning System, and initiated multimessenger search related code development with vigor and enthusiasm.

Zsuzsa Márka



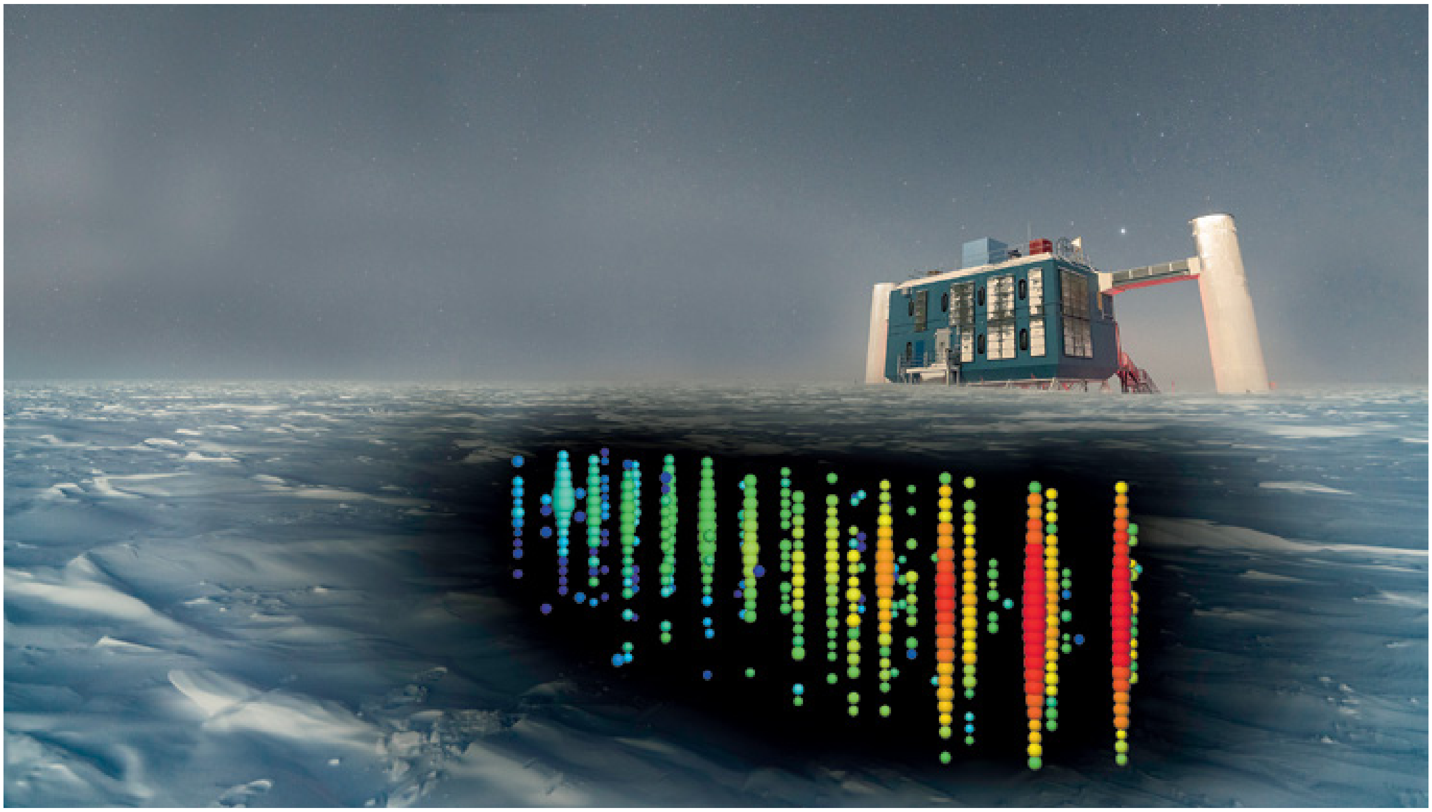
is a long time LIGO member in the Columbia Experimental Gravity group, and works on timing diagnostics and multimessenger searches. She has 4 children, who are what she is the most proud of in her life.

A joint detection from a supernova is still a long shot with current detector sensitivities, but definitely it is worth waiting for. On the other hand, gamma ray bursts (GRBs), especially the short kind, were excellent candidates. LIGO started to receive GCN circulars originally on an old Sun workstation that Szabi recovered from LIGO-Caltech IT expert Larry Wallace's 'graveyard' and installed in his office. The first published externally triggered search for gravitational waves (GWs) associated with a gamma-ray burst was performed for GRB030329, while the paper on GRB070201 was the first multimessenger observational paper of LIGO with an astrophysical impact. An especially important consequence, from the social viewpoint and for the future of multimessenger efforts, was the establishment of a grassroots effort that was organized around the External Triggers team, or 'ExtTrig,' whose many early members still constitute the backbone of LIGO's multimessenger efforts today.

The regular ExtTrig telecons (and dinners during meetings) were the places to discuss everything multimessenger related. It was a friendly and vibrant community, a fun place to be. Except for some innovative faculty, mostly postdocs and graduate students were the driving forces behind the vision. Virgo members also joined the effort. I vividly remember hearing Alessandra Corsi's voice over the phone as she talked about the hallmark Virgo-GRB analysis. Beyond GRB related searches, the ExtTrig members also developed new methods and published observational papers on pulsar glitches, magnetar flares, innovated by organizing an outside speaker series, enabled theoretical astrophysics focused discussions, and provided the first discussion forum for starting the high-energy neutrino and the electromagnetic follow-up efforts. Since the binary neutron star (BNS) discovery I have often reflected back on a key ExtTrig telecon from 2010 with Brian Metzger as an external speaker presenting on "Optical counterparts to BNS mergers from the radioactive decay of heavy elements in the ejecta".

The joint GW high-energy neutrino project idea was conceived at Columbia during a visit of Chad Finley from IceCube in November of 2006. We were so excited about our back of the envelope calculations that we quickly submitted an abstract, with Yoichi Aso joining the team, for a poster for the upcoming Gravitational Wave Data Analysis Workshop. It was clear that a correlation analysis of gravitational wave data and IceCube events was promising and should be pursued further. As of writing, the latest news from IceCube was just announced: On September 22, 2017 the IceCube Neutrino Observatory detected its first multimessenger event, a high-energy neutrino associated with a flaring blazar. I was especially pleased to see that the so far missing 'holy grail', a GW/high-energy neutrino event (maybe with an electromagnetic counterpart) was highlighted as an ultimate goal at the press conference. Only nature can tell, we must keep searching.

In February 2007 Peter Shawhan was visiting us at Columbia and we were mulling over the implication of a 2003 paper by Julien Sylvestre, "Prospects for the detection of electromagnetic counterparts to gravitational wave events." Julien was no longer with LIGO, and no significant work was done on optical follow-ups at that time. It occurred soon that we should just do it! That required somewhat of a 'guerilla action', as this was before there were formal procedures for working with external collaborators. The route was to work together with two innovative astronomers who were affiliated with our university to receive telescope time. We involved an astronomy undergraduate student who also travelled to the telescopes to point them to directions that the low latency analysis of the LIGO data indicated. The resulting paper (Jonah Kanner et al.) from that groundbreaking effort during the summer of 2007



This event display, from the high-energy neutrino detected by IceCube on Sept. 22, 2017, shows a muon, created by the interaction of a neutrino with the ice very close to IceCube, which leaves a track of light while crossing the detector. In this display, the light collected by each sensor is shown with a colored sphere. The color gradient, from red to green/blue, show the time sequence.

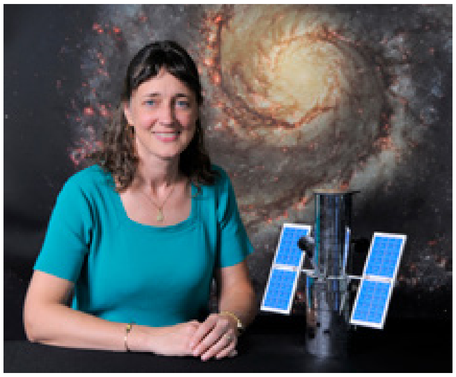
was a great ammunition for Peter, Szabi, and Erik Katsavounidis to rally up the astronomy community for the electromagnetic follow-up campaign that took place at the end of the initial LIGO-Virgo detectors era. Interestingly, the telescope that was first to observe the optical counterpart of GW170817 is the same SWOPE telescope that was used in the first electromagnetic follow-up observations during the summer of 2007.

LIGO 2018

The 1-meter Swope Telescope at the Carnegie Institution's Las Campanas Observatory in Chile was used for early LSC follow-up studies in 2007, and later to discover SSS17a, the counterpart to GW170817.

The Hubble Space Telescope, as imaged from the Space Shuttle after the final servicing mission in 2009.

The Hubble Space Telescope: Window to the Multi-Messenger Universe



Dr. Jennifer Wiseman is NASA's Senior Project Scientist for the Hubble Space Telescope (HST). Along with stargazing, she enjoys nature walks, chocolate, and communing with cats. Here, she is interviewed by Hannah Middleton about her career in astronomy, and what it's like to work with the Hubble mission...

Hannah Middleton: The Hubble Space Telescope is iconic for astronomy around the world, and modern astronomy has been heavily influenced by Hubble's discoveries. How is the Hubble telescope doing now?

Jennifer Wiseman: We just celebrated Hubble's 28th birthday! It's been operating all these years because of a series of successful astronaut servicing missions that have refreshed the telescope, keeping it at the forefront of astronomical discovery. The last Space Shuttle servicing mission was in 2009, and the astronauts (and all the people on the ground who worked so hard to prepare for the mission) did a fantastic job, so even this many years later we are now getting the best science return from Hubble in all the history of the mission. We have multiple cameras and spectrographs on board, and pan-chromatic capabilities spanning from ultraviolet through visible and into the near-infrared spectral regimes. A couple of gyroscopes have failed, but we have redundancies, so while we cannot predict with complete certainty, we believe Hubble will be returning good science well into the 2020's.

HM: Were there any tense moments during those astronaut repair missions?

JW: Yes indeed. It takes literally years to prepare for such a mission, with lots of engineering work needed to prepare the instruments, tools, and procedures astronauts will employ. All of that work can be lost in a moment if something goes wrong during the mission, and there were indeed a couple of tense times on this last servicing mission when unexpected problems (bolts that wouldn't budge, for example) strongly threatened the ability of the astronauts to repair or replace two of the science instruments. This would have been a major loss to science! So, thankfully, they were able to complete those tasks, and as a result we are enjoying the major scientific contributions of instruments including the STIS spectrograph and the newer Wide Field Camera 3 on board.

HM: Your job is the Hubble Senior Project Scientist, what does that involve?

JW: There are a lot of people involved with Hubble, so let me set the stage. Hubble is a partnership between NASA and the European Space Agency, and hundreds of people work in supporting roles for the mission. Many of the daily science operations and interfaces with the scientific community are run by the Space Telescope Science Institute (STScI), with experts overseeing Hubble's science instruments, proposal reviews, data archive, and science news. The Hubble Space Telescope Project at NASA's Goddard Space Flight Center is ultimately responsible for the mission from NASA's perspective, so engineers, financial managers, and project scientists work together at Goddard to ensure the overall health of this flagship mission. My role as the senior project scientist is to ensure that the mission as a whole is achieving the best scientific return for NASA. This involves oversight of policies and decisions regarding the scientific uses and priorities of the various instruments and classes of observing programs, careful attention to the scientific impact of technical decisions regarding observatory operation, and input on the scientific impacts of budget allocations for the mission. My favorite part of the job is to provide scientific review of all the press releases regarding Hubble science results and images. I feel like I get to enjoy the first fruits of all the most interesting science advances Hubble is making in everything from solar system exploration to the detection of the most distant galaxies ever yet seen. I also enjoy giving many talks to both public and scientific audiences on the science of Hubble, and how Hubble and other observatories complement one another in the exploration of the universe.

HM: How will Hubble be used in its remaining years, since the Space Shuttle is no longer operating, and therefore no more servicing missions are planned?

JW: We know Hubble won't last forever, so we are considering carefully how best to use the unique capabilities of this incredible asset while we still have it. HST users contribute great advice in this regard through the "Space Telescope Users Committee". One such effort is the "ultraviolet initiative", through which Hubble users are encouraged to propose observations in ultraviolet light, a capability no other general purpose observatory will have for the foreseeable near-term future. Legacy projects are also encouraged, which provide data (such as from a survey) that will likely be of use for many varied future studies by researchers using the archived data. Hubble's archive, by the way, is already providing an abundance of rich data – half of the refereed Hubble papers published are based on data pulled from the archive rather than on new observations.

HM: What about gravitational waves, and electromagnetic counterparts? Tell us about Hubble observations of the neutron star merger.

JW: Well this was incredibly exciting! As you know, as soon as NASA's Fermi Gamma-ray Space Telescope identified a short gamma-ray burst associated with the LIGO detection of gravitational waves, astronomers and observatories around the world turned their sights toward the source. Along with other observatories, Hubble picked up radiation from the kilonova associated with the merging neutron stars that were responsible for the gravitational wave event. What I like about Hubble's visible image of the kilonova is that it shows where it is in the context of the host galaxy, and shows the fading of the burst with time. Several teams are continuing to work with Hubble observations of the kilonova, including infrared spectral observations that indicate an interesting variety of isotopes were produced and dispersed in the kilonova event.

The Lagoon Nebula. This colorful image of a very turbulent star forming region was taken by the Hubble Space Telescope in celebration of Hubble's 28th anniversary. ▶

HM: How did you come to be in this role? Tell us about your career path.

JW: Working for NASA, and with a major mission like Hubble, is indeed a great and exciting privilege. I'm grateful. My career path has been quite varied – let that be an encouragement to those with a variety of interests. I grew up on a farm in the Arkansas Ozark mountains in the central part of the U.S.. I didn't know any scientists, but my love of the natural world and the night sky made science and eventually astronomy a good fit. I studied physics to keep my options open, and then went on to study astronomy in graduate school. My research centered on radio astronomy observation of star forming regions and protostars in galactic molecular clouds. After several years of postdoctoral research, I grew more interested in broad questions of science, policy, and society, and ended up pursuing some unusual opportunities. I became a U.S. Congressional Science Fellow, working in a congressional science committee, and from my experiences there I was poised to take a position in astrophysics program leadership at NASA headquarters. My first official role with Hubble was there – as the HST Program Scientist. A few years later I became Chief of the Laboratory for Exoplanets and Stellar Astrophysics at NASA's Goddard Space Flight Center. In this role I learned so much about a variety of mission concepts and missions studying everything from exoplanets and protoplanetary disks to stellar evolution. Then in 2010 I was named the Senior Project Scientist for the Hubble Space Telescope mission. I'm so grateful to work at NASA alongside engineers, scientists in diverse fields, and science communicators, with everyone very enthusiastic about space exploration.

HM: You also have a personal interest in broader societal interactions with science, right?

JW: Yes – I've always been interested in the big picture, and how science interfaces with the values of peoples' lives. One thing I do along those lines is to direct the program of Dialogue on Science, Ethics, and Religion (DoSER) for the American Association for the Advancement of Science. AAAS is a major scientific society, and this AAAS program facilitates communication between the scientific community, ethicists, and religious communities on interesting implications of scientific advancements for questions of ethics, science in service to the world, and how we see ourselves as human beings.

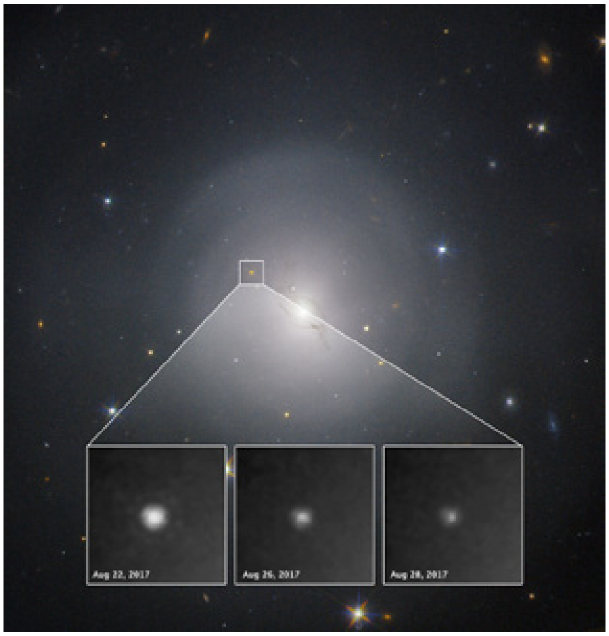
HM: I heard that you discovered a comet! How does one find a comet?

JW: This was indeed a very exciting surprise! It happened way back in 1987, when I was an undergraduate student at MIT. Legendary Professor Jim Elliot took several students out to Lowell Observatory in Arizona each winter, so one year I was able to go and to learn what astronomers really do. Thanks to the mentorship of Dr. Ted Bowell, I learned how to use a "blink comparator" to compare two images of the same sky position taken hours or days apart. Only nearby objects like asteroids will "move" relative to the background stars in such a short time span. Comparing two such telescopic images taken by astronomer Brian Skiff, I saw a fast-moving object that didn't appear to be an asteroid. Upon subsequent measurements and observations, the object was determined to be a previously unknown comet, and it was named "Comet 114P/Wiseman-Skiff" by the Minor Planet Center that keeps up with such things.

HM: What in astronomy excites you the most at the moment?

JW: Well of course gravitational waves and electromagnetic counterparts are near the top of the list. Also the very hot topic of exoplanets and related astrobiology: we may truly be able to discern the presence of biosignatures on nearby exoplanets within our lifetimes. But for me the most awesome realm of astronomy is that of what I call "time machine" astronomy – that is, being able to actually see how galaxies have changed and grown and become enriched and habitable for life over cosmic time, through direct observations of galaxies at different distances and therefore epochs in the history of the universe. I'm also encouraged by the passion I see in young people as they hear about the incredible universe we are exploring through astronomy, and as they want to be a part of this marvelous enterprise.

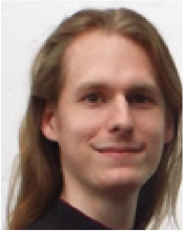
LIGO 2018



◀ *Hubble Space Telescope images of a kilonova flare associated with a neutron star merger, the source of gravitational waves detected by LIGO. The kilonova's position within galaxy NGC 4993, as well as its fading intensity over the days between the images, can be seen.*

Did LIGO's Black Holes Have Echoes?

Julian Westerweck



is a PhD student at the Max Planck Institute for Gravitational Physics (Albert Einstein Institute) in Hanover. When not investigating effects of strong gravity with gravitational waves, he dons armour with his friends or misuses classical piano lessons for Star Trek tunes.

Gravitational wave detections have given us access to a unique laboratory for strong gravitational fields: compact objects such as neutron stars and black holes. There, we can test our theories about these objects and about the fundamental physics of gravity itself. Einstein's theory of general relativity (GR) is the well-tested theory of gravity for these environments, but it is also here that deviations from it are expected.

Have we already seen the first of these deviations in LIGO's gravitational wave data?

Gravitational waves have been used to test Einstein's theory of gravity before: Their first indirect detection by Hulse and Taylor demonstrated that GR correctly predicted the energy loss of a binary system through gravitational waves. The theory has passed all tests, but few of these probe strong gravitational fields such as near black holes. So far, LIGO's direct detections are in excellent agreement with GR predictions for the waveform of a binary black hole coalescence.

The shape of the gravitational wave (the waveform) depends on its sources and thus allows us to learn about the physics involved in its creation. In the case of a binary black hole collision for example, the exact form of the wave depends on the black holes' masses and on their spins. As the detector data is dominated by noise, the waveform cannot easily be extracted directly from the data. Instead, a template of an expected waveform is compared to the data and their match is calculated, both to detect a signal in the first place and then to find the precise waveform that best fits the data. Learning about the sources requires us to go back to theory, and first find the waveforms we can search for.

To predict the waveform of a binary system of compact objects, we split its evolution in three phases. During the initial inspiral phase, both objects are well separated, orbiting each other. They are modelled as point particles using post-Newtonian corrections. As energy is emitted through gravitational waves, the radius of the orbit decreases until both objects collide. This merger phase is modelled by numerical relativity simulations. It is followed by the ringdown phase, during which the single final object settles down from its perturbed state after the merger. Perturbation theory helps model the emission in this phase. Silence follows, as the (likely) resulting spinning black hole does not emit gravitational radiation.

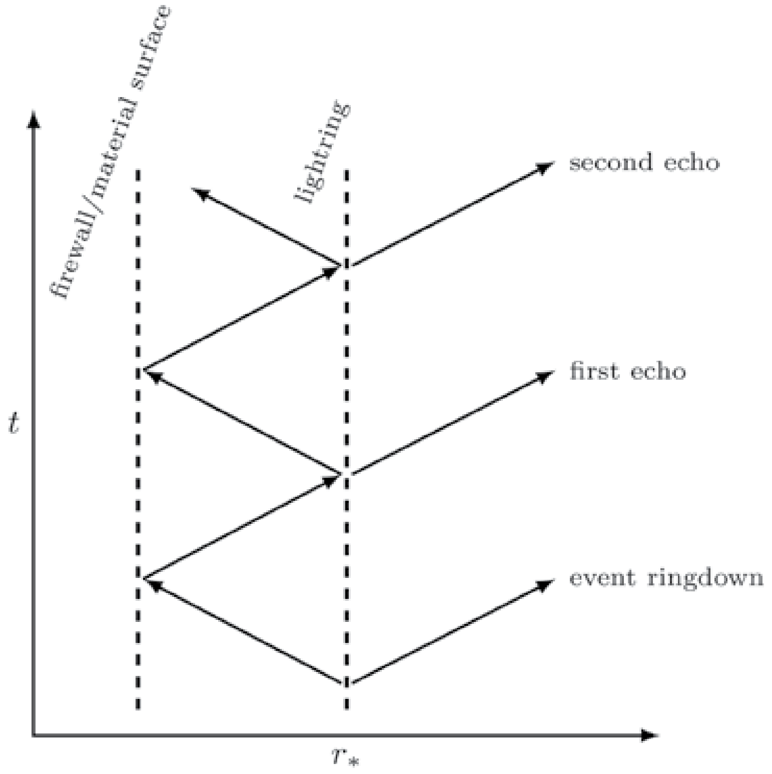


Illustration of the cavity formed by the photon sphere and the surface close to the horizon. The ingoing component of the original event's ringdown signal is not lost at the horizon, but reflected and partially transmitted outward. The radial coordinate is the tortoise-coordinate of Eddington-Finkelstein coordinates.

But what if we are not dealing with a black hole - or not only with GR? Then, a fourth phase of a signal might be possible. In the shell-like “photon sphere” region of a compact object, gravity is strong enough that light could orbit around it, neither escaping nor falling inwards. We can think of the ringdown as being emitted from this region. This emission has an outgoing component, detectable far away, and an ingoing one, to be lost behind the event horizon. However, if there was a material surface outside the horizon, the ingoing wave might be reflected outwards and also be detected.

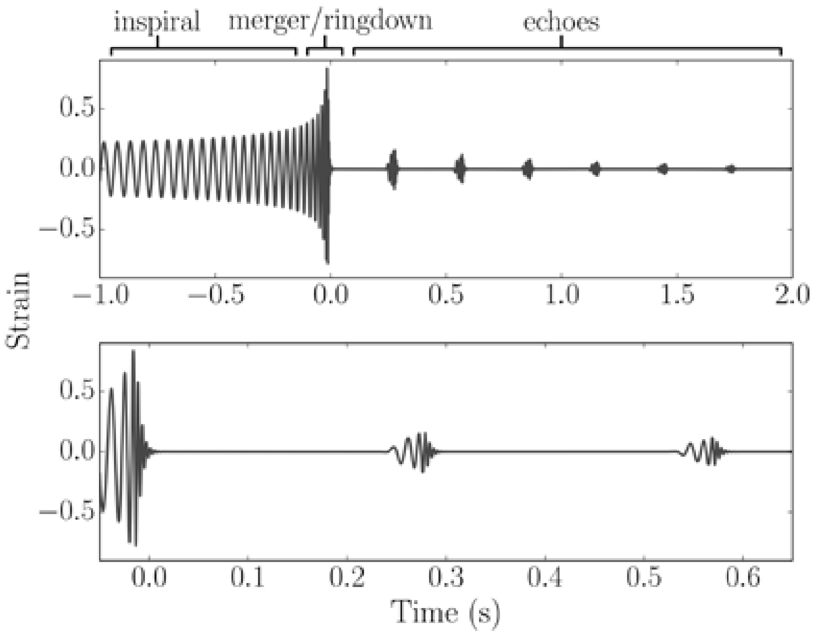
Exotic compact objects, alternatives to a black hole of similar compactness, could have a photon sphere but no horizon. Boson stars or gravastars would instead possess the required material surface. In classical GR, no material surface is expected to persist outside the horizon of a black hole. But going beyond GR and including quantum effects, it might persist, in the form of the proposed firewall surrounding the black hole. The proposal addresses conceptual problems of the interface of quantum physics and strong gravity as found at the horizon of a black hole.

In these scenarios, the signal of the first three phases could change in subtle ways. While this may be detectable in the future, the proposed objects must closely mimic the emission of a black hole to agree with LIGO’s detections. But a weak signal after the ringdown might still be hidden in the noise: the reflection of the ingoing component of the ringdown, following the original signal. It would be delayed by the travel time from the photon sphere to the surface and back out. Even though we see time slowing down so close to the horizon, this time is finite – it diverges only logarithmically when the surface approaches the horizon. A simple estimate for the black holes of the first detections places the delay at a few tenths of a second.

So we could find this signal in the data directly after the event, and more signals after that: The photon sphere is partially reflective itself and only a part of the first reflection passes through to the outside. The rest is reflected inwards again and the photon sphere and inner surface form a cavity. The result are several damped repetitions: echoes of the ringdown.

Abedi, Dykaar and Afshordi[1] say they have found such echoes in public LIGO data. They used a simple model for echo signals to build a waveform template for the search. Letting the inner surface be perfectly reflective, the echoes would be a copy of the ringdown, delayed by the travel time in the cavity. The echoes are damped by a constant factor to account for the partial transmissions. They started with the ringdown part of the full waveform from the LIGO Open Science Center (LOSC[2]). Then they built a bank of templates, each with different parameter values, e.g. for dampening and delay. The search for these templates is based closely on the LOSC’s matched filtering, and the template with parameters best matching the data is selected.

The final step is determining the significance of the results, as any result found in the noisy data could in principle be due to random chance. Here, p-values were used: We count how often we find a given result (here, loudness of the detection) for a number of trials using random noise, where no signal is present. When combining the first three gravitational wave events – such that the signals with common characteristics remain while the random noise tends to cancel out – about 1 in 100 trials is reported to have a louder response than after the event.



Echo signal as expected for GW150914 based on a simple model. The delay between echoes is on the order of tenths of a second. The form of the echoes depends on several parameters, e.g. the dampening factor chosen as 0.7 here.

The prospect of finding such a signal is fascinating, and so the results of this search have gained much attention. While many questions are open on the side of theory, the initial report also raised questions about its methodology. So we, a group of researchers at the AEI Hanover, set out to investigate the methods and results, and, reproducing them in an independent implementation[3], discovered some issues.

A simple test for the performance of a method is applying it to injections – a known simulated signal overlaid with the noise found in the detectors. We found that the method can in principle detect injected echoes, but their amplitudes need to be very high, and more so to find the correct parameters. Searching in pure noise finds amplitudes as were reported for the detection and reveals a strong bias in the parameter recovery, which we can attribute to an asymmetry in the template bank.

The reliability of the p-value estimation depends on the number of random samples. But the effective number of samples for the reported values was very small, and only part of the public data was used.

When we performed an estimate similar in nature, but correcting for these problems and adding the fourth gravitational wave event, the resulting significance for echoes was generally lower. LVT151012, the noisiest of the first events and just below the detection threshold, turns out to contribute most to the echo significance: The best combined p-value remaining without it is 1 in 6 instead of 1 in 100, a low significance. While we use p-values as a straightforward tool, they do not encode all available information but depend only on the noise model, where we used real noise samples. Further information about the experiment and physics can be incorporated through a choice of priors. This is especially important for marginal p-values (as in the case of echoes) which impacts the interpretation of the results.

After the improvements to the method, the significance for echoes is low. But we also find that the method cannot provide reliable evidence for reasonable echo signals. So finding no echoes with this method does not mean there are none – the negative result of this analysis does not yet rule out such a signal.

We are just beginning to probe the near-horizon region through gravitational wave data and the possible insights are fascinating. More sophisticated methods and models are needed, and the extraordinary claim of departure from GR requires convincing evidence. But not only a detection is a success – confident upper limits on signals let us select the most promising models.

There is currently much interest in this topic in both data analysis and theoretical physics communities. Together with several other groups, we are working to improve search methods, waveforms and theoretical models - analysing available data for echoes and preparing for the next observing run of LIGO. Exotic compact objects and the interaction of quantum effects and strong gravity are the source of intriguing mysteries and controversy – and gravitational wave observations are just beginning to shift these into the realm of observation.

[1] Abedi, J., Dykaar, H., & Afshordi, N. 2017, PRD, 96, 082004

[2] LIGO Open Science Center, losc.ligo.org

[3] Westerweck, J., Nielsen, A. B., Fischer-Birnholtz, O., et al. 2018, PRD, 97, 124037

Albrecht Rüdiger: A Life Dedicated to Science

It is with great sadness that we report the passing away of our colleague, mentor and friend Albrecht Rüdiger on the 6th of July 2018, after a rewarding life at the ripe age of 88.

▲

Albrecht Rüdiger during the viewing of the Nobel prize gala at the Grand Hotel in Stockholm.

Born on 21st of December 1929 in the contemplative German town of Bad Homburg, he studied physics in Frankfurt and joined the Max Planck Institute for Physics in Göttingen in 1957. Working in Heinz Billing's group for Numerical Calculation Machines, he and his peers created several special-purpose computer hard- and software, mainly for astrophysical calculations and bubble chamber trace detection.

Between 1969 and 1975, two separate chains of events would change Albrecht's field of work considerably: On the one hand, industrial manufacturers finally realized the future importance of computers and poured more money into their development than a single research institute could afford. On the other hand, Joseph Weber's first attempt to measure gravitational waves with a resonant bar detector could never be reproduced by anybody else, and alternative detection schemes were sought. In 1975, Heinz Billing therefore completely switched to developing a gravitational wave detector using laser interferometry as suggested by Rainer Weiss.

Albrecht contributed to many of the insights and technical innovations that first came from this new research field, which had by then moved to Garching near Munich. Perhaps the best example to mention to today's generation was the innovation of the use of a Fabry-Perot cavity in transmission as a mode cleaner to increase the laser beam quality. But the entire team, consisting of Albrecht, Roland Schilling, Walter Winkler, Karl Maischberger and Lise Schnupp worked as an incredibly well-tuned synergistic group, with Albrecht as a leader in careful and thorough pursuit of problems and their solutions.

Since the Garching prototype instrument pioneered new optical methods and produced improved sensitivity over the years, it became clear that km-scale systems were motivated. Therefore, the mid-80s saw several proposals for large interferometers in Germany, the USA and Japan, with Albrecht a key figure in suggesting a triangular system of interlocking interferometers. Not least due to his writing and editing skills, these proposals lead to corresponding grants forming the base of such detectors like GEO 600, LIGO and LISA.

Albrecht's deep love of languages, which was so instrumental in the success of published papers, stemmed from listening to baseball games on the Voice of

America in the 40s. His mastery of English was such that he taught many native speakers what bit of grammar remains in their language, and how to write well in their mother tongue. There are many in our field who marveled – and sometimes gritted their teeth – at the detailed feedback they would receive on all aspects of publications that fell under Albrecht's hands: the physics, organization, wording, grammar, and typesetting were all given a very thorough going-over. His mix of mock and genuine horror at a forgotten subjunctive or misplaced nominative case made it clear that he would not expect a repeat occurrence.

His communicating skills experienced another boost at an age that other people normally draw a pension: Since being detached from physics held no attraction for him, he transitioned toward 'retirement' in the most active sense conceivable. As the gravitational-wave group slowly moved from Garching to Hannover under the new director Karsten Danzmann, Albrecht took up the mantle of communicating our field around the world in speaking engagements and also was frequently the one who took up the digital pen to write another article on the subject. In particular he developed close ties with a number of Chinese groups, and made significant progress in both writing and speaking yet another language, hosting also a number of visitors (and was also frequently hosted in China himself). This way, he kept close to science, and happily and appropriately was able to get to Stockholm to see the field rewarded with a Nobel Prize.

Whatever challenge Albrecht tackled, he put all his heart into it to get the most out of it. This was not only apparent in his professional work, but also his private life: Whether it was becoming German Basketball Champion (sic!) in early years, learning inline skating at the age of seventy-odd (for carnival, and as reminiscence of an old black-and-white movie he cherished, in which the Messenger of the Gods featured winged roller skates), departure-skiing faster than anybody else during Aspen Conference leisure times (only downhill he was completely free of pain from his arthrosis), or lovingly attending to his wife who suffered from dementia until her passing away in the last year.

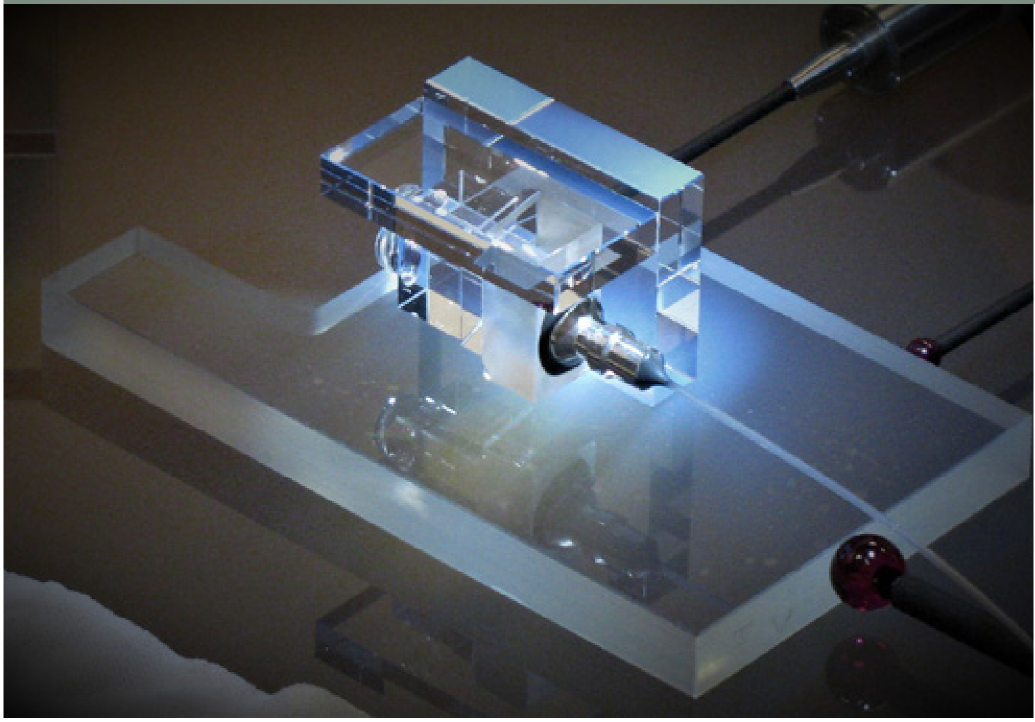
Perhaps Albrecht's most admirable feature, permeating everything he did, was his unshakeable optimism and unceasing good will, which never allowed him to be grumpy or forbidding. Even during a phone call a month before his death – when he was already in the grip of illness, and talking difficult for him, consuming lots of energy and time – he simply refused to be downhearted and insisted on being in good spirit and well taken care of.

The funeral on the 24th of July was a somber affair, despite the sun benignly casting radiant smiles out of an azure sky – as if to remind us not to dwell too long on our loss, but more on Albrecht's infectious joy, enthusiasm, warmth and caring personality those of us who knew him had the pleasure of experiencing. Perhaps the sun was right…

David Shoemaker
Andreas Weidner
Walter Winkler

LISA:
A Snapshot of Strides Forward

Following the successful Mission Definition Review in January of this year, LISA formally entered Phase A – the concept design and formulation phase – in April. Due to last two years in total, the Phase A study will produce a concept design for the overall LISA spacecraft and instrument, and continue development of the key technologies required to make LISA work. Over 400 scientists from across Europe and the US are busy developing LISA at the moment, together with significant industrial engineering teams funded by both ESA and the European member states, and by NASA.



Ultra-stable fibre collimator being developed for the LISA optical metrology system.

The design of the LISA instrument being developed is rooted in the technology developed and demonstrated on LISA Pathfinder – in particular the demonstration of sub femto-g/√Hz free-fall. However not all of the technology required for LISA was demonstrated on LISA Pathfinder and much remains to be done. In particular the significant increase in the complexity of the laser interferometry system, the need for complicated post processing in the form of time delay interferometry, and the unique data analysis challenges of LISA, mean that there is plenty to keep the international teams busy.

And with the recent establishment of the LISA Consortium, the international effort is now formally organised, with many working groups driving ahead with research on a host of LISA topics, from payload hardware issues, to data analysis strategies and underpinning science.

Ewan Fitzsimons (UK Astronomy Technology Centre, Royal Observatory, Edinburgh) and Harry Ward (University of Glasgow) at ESA's ESOC mission control centre in Darmstadt, Germany, during the LISA Pathfinder shutdown in July 2017.

In the UK, on the payload side we are working to extend the laser interferometer technologies we developed for LISA Pathfinder to make them appropriate for LISA. One focus is on development of ultra-stable fibre optic collimators, where we have recently prototyped a candidate design and have demonstrated pointing stability broadly compatible with the LISA requirements. Another activity, undertaken with colleagues at the AEI in Hannover, is to explore the possible techniques that can be used to form the virtual beamsplitter in each LISA spacecraft – the so-called "backlink" issue.

Since the UK is committed to supplying the optical benches for LISA, another major focus is on developing a constructional approach – and facility – capable of dealing with the sheer scale of the build for LISA. While LISA Pathfinder involved building one 200mm square interferometer with 22 components, LISA presents a much bigger challenge, requiring building of more than six, half metre scale, double sided interferometers, with over 40 components each, and with improved alignment accuracy compared to Pathfinder. To complete this scale of construction in an acceptable time will require a high degree of automation of component placement, alignment and hydroxide catalysis bonding with an angular accuracy of a few micro-radians. The first stages of such a semi-automated process have been prototyped with great success and further stages are now under study.

The foregoing is, of course, a snapshot of just one area of LISA development. Similar strides forward are being made in a range of payload areas, from telescope design and laser developments, to phase readout systems and charge management systems. Progress on all fronts is impressive and well on-track to allow a timely adoption of the mission and an on-schedule launch in 2034 – or earlier if budgets permit.

The impressive results from LIGO and Virgo started the era of gravitational wave and multi-messenger astronomy. It will not be too long before LISA expands the gravitational wave window, doubtless bringing a host of new discoveries. Exciting times, indeed!

LIGO 2018

Career Updates

Ka Lok (Rico) Lo has completed his undergraduate degree at CUHK, pursuing LIGO research with Tjonnie Li, and will begin graduate work at Caltech with Alan Weinstein's group at LIGO Laboratory.

Shreya Anand has completed her undergraduate degree at U Maryland, pursuing LIGO research with Leo Singer, and will begin graduate work at Caltech with Alan Weinstein's group at LIGO Laboratory.

Bence Bécsy finished his MSc in Physics at Eotvos University, Hungary, and will start a PhD in Physics in the Fall at Montana State University with the LIGO group

Kentaro Mogushi, a graduate student working at the University of Mississippi, will spend eight weeks in Fall 2018 as an exchange INFN student at the University of Pisa performing detector characterization with Massimiliano Razzano (Virgo-University of Pisa).

Jonathan Cripe successfully defended his thesis on "Measurement and reduction of quantum radiation pressure noise in the audio band" at LSU, and will start a job at NIST (National Institute of Standards and Technology) in the fall with a prestigious National Research Council fellowship.

Elvis Ferreira defended his thesis, entitled "Study of the treatment of niobium cavities for the Mario Schenberg detector and performance of the Multi-Nested Pendula for use in interferometric detectors", at the National Institute for Space Research, Sao Jose, Brazil.

Ling (Lilli) Sun completed her PhD work at U Melbourne and is joining Alan Weinstein's group at LIGO Laboratory - Caltech as a postdoctoral scholar.

Max Isi will complete his PhD work with Alan Weinstein at Caltech in the Fall, then move to the LIGO Laboratory - MIT group as a NASA Einstein Fellow.

Surabhi Sachdev will complete her PhD work with Alan Weinstein at Caltech in the Fall, then move to Penn State U as a postdoc, working under Chad Hanna.

Sina Köhlenbeck successfully defended her thesis, entitled "Towards the SQL Interferometer - Length Stabilization at the AEI 10m-Prototype" at the Max Planck Institute for Gravitational Physics in Hannover in June.

Vaishali Adya successfully defended her thesis, entitled "Ways to stop mirrors from moving unnecessarily: Design of advanced gravitational wave detectors" at the Max Planck Institute for Gravitational Physics in Hannover in April.

Nathaniel Indik successfully defended his thesis, entitled "Optimal Template Placement for Searches of Gravitational Waves from Precessing Compact Binary Coalescences" at the Max Planck Institute for Gravitational Physics in Hannover in April.

Andrew Williamson and **Max Fays** received their PhDs from Cardiff University.

Juan Calderon Bustillo will be moving from Georgia Tech to Paul Lasky's group at Monash as a postdoc.

Marie Kasprzack has started a Caltech LIGO staff engineering position.

Christopher Berry is moving from Birmingham to Northwestern for a new job as the CIERA Board of Visitors Research Professor.

Alex Urban moved in April from LIGO Laboratory - Caltech to a staff position with Gaby Gonzalez at LSU.

We hear that ...

Miriam Cabero Müller will be starting a postdoc in October with Frans Pretorius at Princeton University.

Aaron Zimmerman will be starting as an Assistant Professor at the University of Texas, Austin in the Fall

Jax R Sanders will start as an Assistant Professor at Marquette University in Milwaukee, WI.

Haris Markakis will start as a Lecturer in Numerical Relativity at the Queen Mary University of London.

Awards

Zoheyr Doctor was awarded a William Rainey Harper Dissertation Fellowship and a Nathan Sugarman Award for Excellence in Graduate Research.

Sheila Rowan, Director of the Institute for Gravitational Research, University of Glasgow, has been elected a Fellow of the Royal Society.

Vassiliki (Vicky) Kalogera, Director of the Center for Interdisciplinary Exploration and Research in Astrophysics, Northwestern University, was elected to the US National Academy of Sciences.

Bala Iyer was conferred an honorary doctorate by the Central University of Karnataka, India "in recognition of his meritorious contributions to the field of Science".

Nergis Mavalvala was awarded a 2018 Wellesley College Alumnae Achievement Awards as an Outstanding Communicator, Leader, & Innovator of Science.

Stephen McGuire, Southern University, received the 2018 Alpha Phi Alpha Fraternity, Inc. Beta Iota Lambda Chapter Trailblazer Award in recognition of "Outstanding Commitment to Public Service and Leadership within the East Baton Rouge Metropolitan Community.

The **American Physical Society elected as fellows**, nominated by the Division of Gravity,
Jolien D Creighton, University of Wisconsin–Milwaukee
Eric Keith Gustafson, Caltech
Daniel Holz, University of Chicago
Vuk Mandic, University of Minnesota
and, nominated by the Division of Computational Physics,
Gabrielle D Allen, University of Illinois at Urbana–Champaign

The **2018 European Physical Society Edison Volta Prize** has been awarded to
Alain Brillet, Observatoire de la Cote d'Azur, Nice, France
Karsten Danzmann, Max-Planck-Institut für Gravitationsphysik and Leibniz University, Hannover, Germany
Adalberto Giazotto, INFN, Pisa, Italy
Jim Hough, University of Glasgow, UK
for the development, in their respective countries, of key technologies and innovative experimental solutions, that enabled the advanced interferometric gravitational wave detectors LIGO and Virgo to detect the first gravitational wave signals from mergers of Black Holes and of Neutron Stars.

Vicky Kalogera was awarded the 2018 Dannie Heineman Prize for Astrophysics for her work studying compact objects – black holes, neutron stars and white dwarfs – in astrophysical systems.

Peter Fritschel, Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, USA received the 2018 Charles Hard Townes Award. Fritschel is recognized for advances in quantum-limited precision measurement in the Advanced LIGO detectors.

Sir James Hough, University of Glasgow Research Professor in Natural Philosophy in the School of Physics and Astronomy, received a knighthood in the Queen's Birthday honours 2018 "for services towards the detection of gravitational waves".

David McClelland has been awarded the prestigious Boas medal, by the Australian Institute of Physics, "for key contributions to one of the greatest achievements in the history of physics – the observation of gravitational waves by the Laser Interferometer Gravitational-wave Observatory (LIGO)."

Rainer Weiss was awarded the Joseph Weber Award for Astronomical Instrumentation for his invention of the interferometric gravitational-wave detector.

Christopher Berry won the IOP Astroparticle Physics Early Career Prize http://www.iop.org/activity/groups/subject/ap/prize/page_67116.html

Kipp Cannon has been awarded the Dunlap Prize for innovation in astronomical instrumentation from The Canadian Astronomical Society for the development of the gstlal detection system leading to the discovery of GW170817.

The PI of the Korean Gravitational Wave Group, **Prof. Hyung Mok Lee**, has been selected as the president of Korea Astronomy and Space Science Institute (KASI) from Jan. 2018.

Other News

Dan Moraru (LIGO Hanford IT Admin) and **Kimberly M. Burtnyk** (LIGO Laboratory Technical Writer/Editor) were married on May 20th, 2018, at Mt. Wilson Observatory in Pasadena. Their first date was watching the total lunar eclipse of October 8th, 2014, from the LIGO Hanford Observatory parking lot.

Guillermo Valdes participated in a Gravitational Waves episode of the Mexican public television show "Ciencia en Todos Lados" (Science Everywhere).

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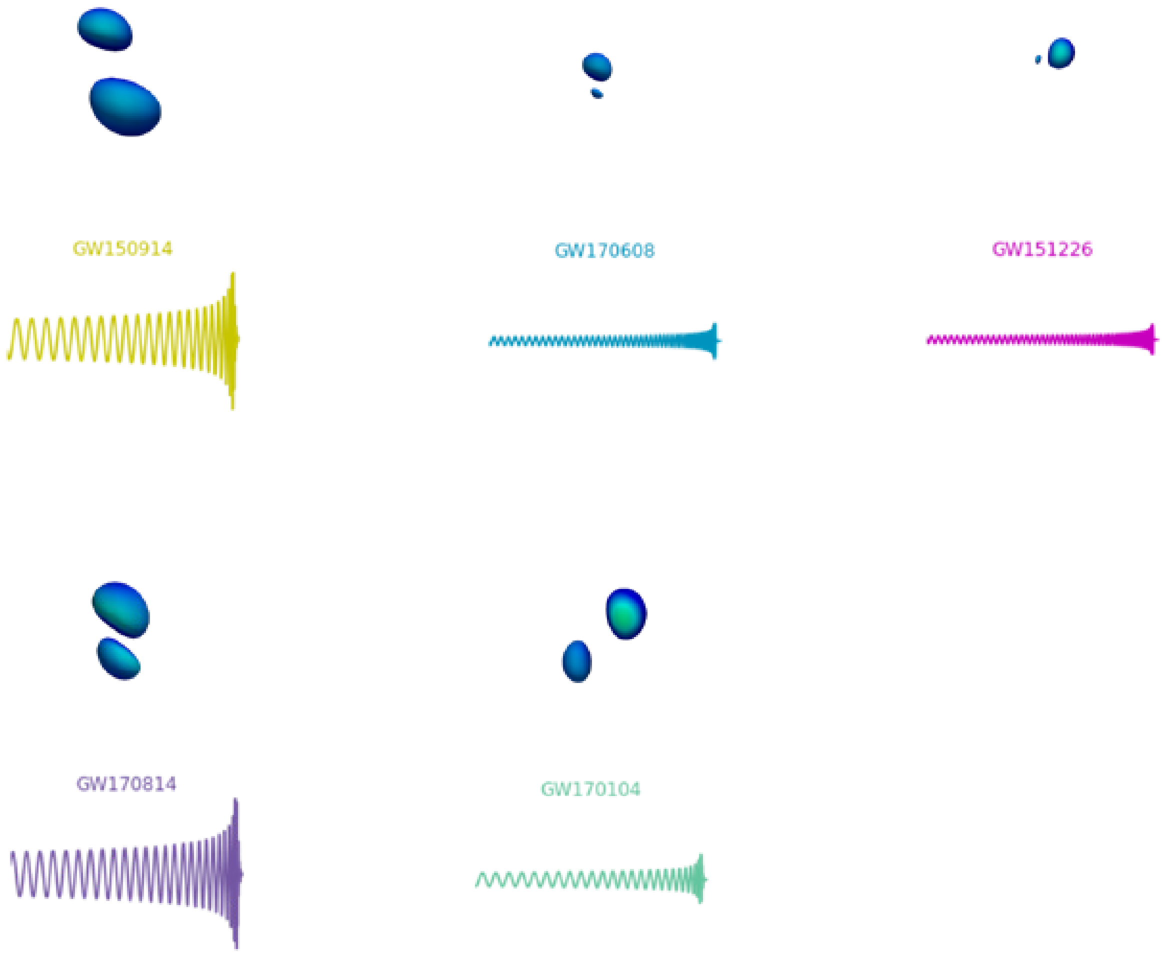
Five Merging Binary Black Holes

by Teresita Ramirez



A **visualization of five merging binary black holes observed in 2015-2017**

The images show numerical relativity calculations of two black hole horizons immediately before a merger. Below the horizons, the last 0.7 seconds of the simulated waveform is shown. The masses and spins of each numerical relativity calculation are consistent with one of the LIGO-Virgo observations.

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