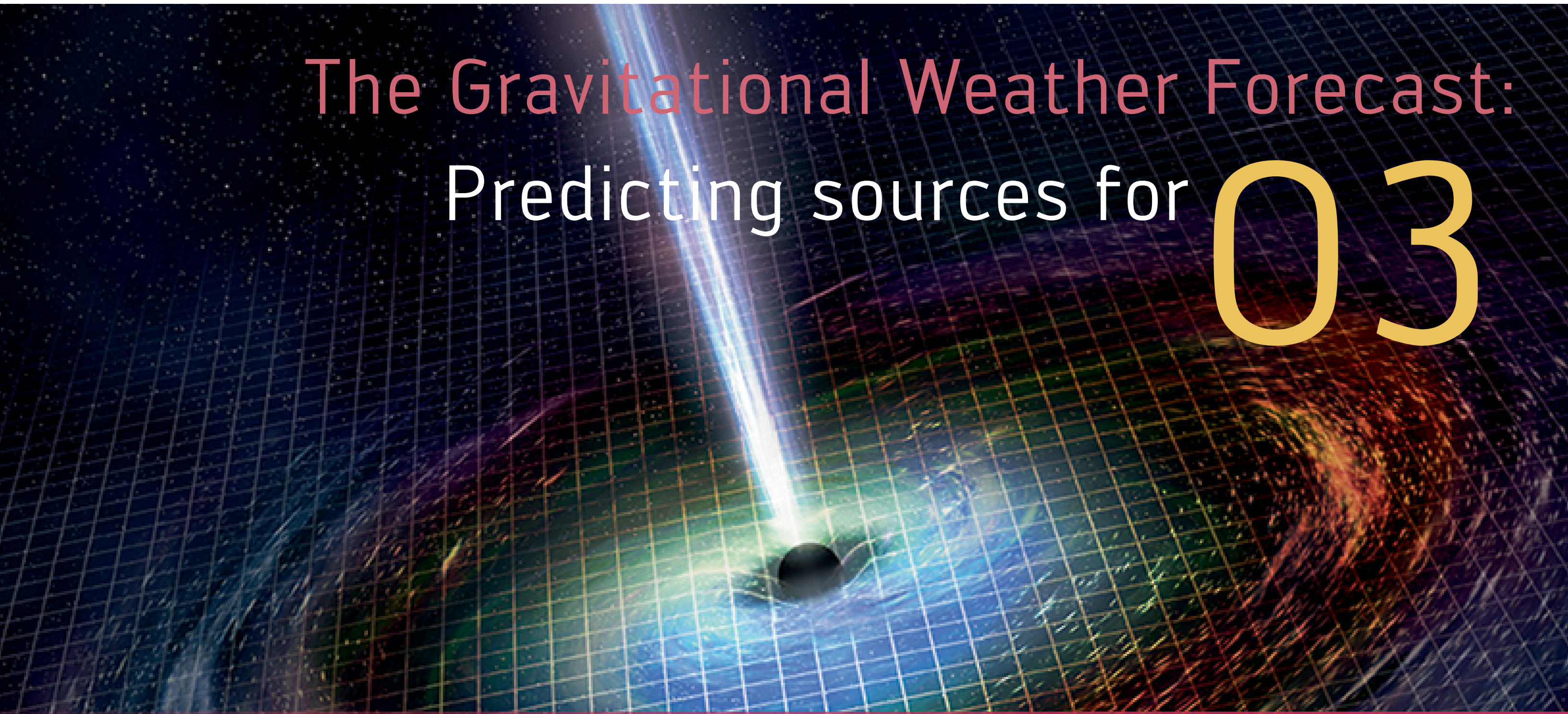
LIGO
Scientific
Collaboration

issue 14 3/2019

LIGO MAGAZINE

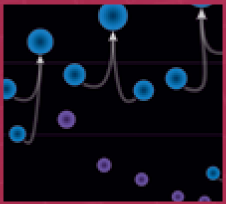


The Gravitational Weather Forecast:

Predicting sources for O3

Upgrades to Hanford, Livingston and Virgo sites

Getting ready for O3 p.12



The LVC's first Gravitational Wave Transient Catalog

Inventorizing the dark side p.15

... and an interview with Sir James Hough on the early days p.19

Front cover

A new study using Chandra data of GW170817 indicates that the event that produced gravitational waves likely created the lowest mass black hole known. The artist's illustration shows the black hole that resulted from the merger, along with a disk of infalling matter and a jet of high-energy particles. (Credit: NASA/CXC/M.Weiss)

The top inset shows the view from below the 'north input test mass' of Virgo. The bottom inset shows a schematic of binary mergers observed by LIGO and Virgo so far.

Image credits

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

Cover: Main illustration from NASA/CXC/M.Weiss. Top inset from M. Perciballi / The Virgo collaboration. Bottom inset from LIGO-Virgo / Frank Elavsky / Northwestern University

p. 3 Comic strip by Nutsinee Kijbunchoo

p. 6-9 Colliding neutron stars illustration by NASA/CXC/M.Weiss. Gravitational wave sources by Chris Messenger. Sensitivity curves from LIGO/Virgo/KAGRA

p. 12-14 Livingston photo by Matthew Heintze. Hanford photo by Nutsinee Kijbunchoo, Virgo photo by M. Perciballi / The Virgo Collaboration.

p. 15-18 Time frequency plots and waveforms by S. Ghonge, K. Janu / Georgia Tech. Masses in the Stellar Graveyard by LIGO-Virgo / Frank Elavsky / Northwestern University. Waveforms from numerical relativity by Teresita Ramirez/Geoffrey Lovelace/SXS Collaboration/LIGO-Virgo Collaboration

p. 19 Photo of J. Hough from University of Glasgow.

p. 20 Bar detector observation from Institute for Gravitational Research, University of Glasgow.

p. 20-23 Party photos by Peter Murray from University of Glasgow

p. 24 Pulsar observation from G. Hobbs / Parkes.

p. 25 Parkes at night by CSIRO, Wayne England. Pulse@Parkes students by G. Hobbs / R. Hollow / Parkes

p. 26 Photo by Charlotte Bond.

p. 27-28 Photos and plots from Jim Lough / GEO 600

p. 29 Still image from https://svs.gsfc.nasa.gov/13043 by NASA's Goddard Space Flight Center

p. 31 Photo by Russian Quantum Center

p. 33 Photo by Gianfranco Chiocci

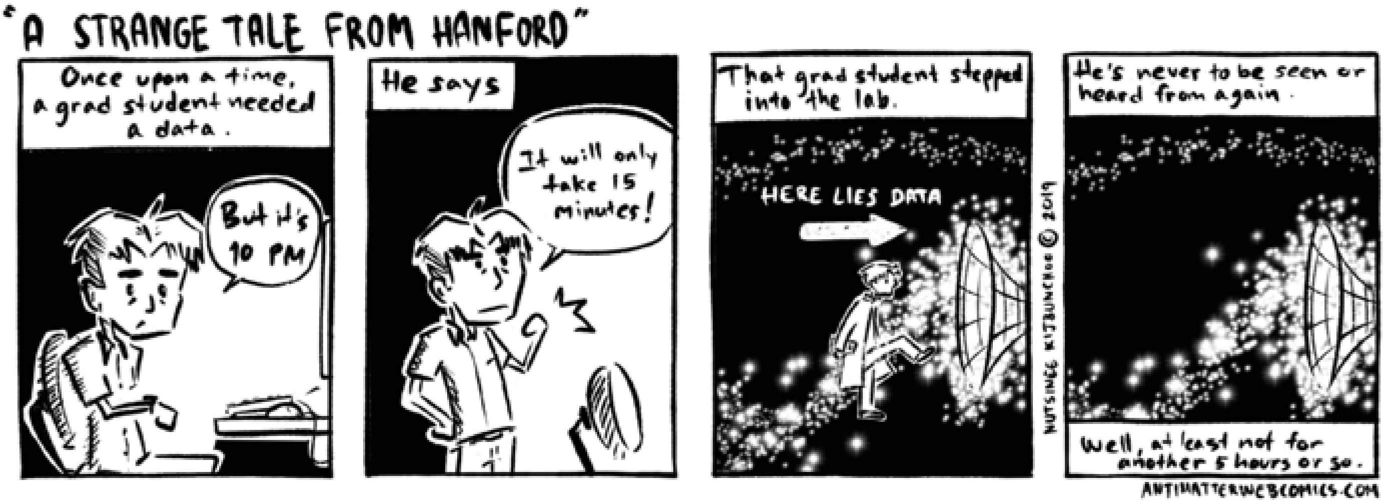
p. 34 Artworks by Kathryn Williamson (top) and Michele Banks (bottom).

p. 35 Artworks by Sarah Guerry & Kathryn Williamson (top) and Susan Kleinberg (bottom).

Back cover: Illustration by Nutsinee Kijbunchoo

Contents

Antimatter



Welcome to the LIGO Magazine Issue #14!

H Middleton.

Welcome to the fourteenth issue of the LIGO Magazine! With preparations well underway for observing run 3, we hear some thoughts of what gravitational wave sources we might be looking forward to seeing next in 'The Gravitational Wave Forecast'. At the observatory sites work continues towards getting the instruments ready. We hear all about this in "Upgrades of Hanford, Livingston and Virgo" and also a new record set at GEO600 with squeezing.

New results have been announced from the first two observing runs as we hear from Patricia Schmidt on the creation of the "First Gravitational Wave Transient Catalog" along with perspectives of how the open data has been used so far. On the backcover, we hear from Patrick Clearwater on the search for the illusive continuous gravitational wave. We are also very pleased to have "An interview with Sir James Hough", in which Sean Leavey chats to Jim about the early days of the search for gravitational waves.

Looking to other gravitational wave frequencies, we hear about exciting upgrades to the Parkes radio telescope and the search for nanoHertz gravitational waves as well as the multi-messenger astronomy that we can look forward to from the LISA space mission. Further afield, we hear from Charlotte Bond about work outside of LIGO in "Building instruments for Keck".

Our Editor in Chief, Jocelyn Read has recently stepped down, so this will be my first issue as Editor in Chief. I'd like to say a huge thank you to Jocelyn for her leadership of the magazine over the last few years and I look forward to continuing this work in the future.

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

Hannah Middleton, for the Editors

News from spokespeople

The last six months have been incredibly productive and have brought us much closer to readiness for the O3 Observing run.

On the Astrophysics front, we have brought effectively all the searches from previous runs to conclusion and publication. While many papers have crossed the transom, certainly the O1-O2 Catalog and the accompanying papers were a sign of maturity of the field, the Collaboration, and a signal that we are solidly into the domain of gravitational-wave astrophysics; the fact that we can make statements about the populations of stellar-mass black holes is, well, stellar. Another notable accomplishment is the wrap-up of the LIGO Scientific Collaboration (LSC) and Virgo Collaboration continuous wave (CW) searches; nearly all CW flagship searches have been submitted for publication. Completing these studies and drafting the papers under difficult circumstances was a tour de force of organization and discipline. Well done!

In parallel, the low-latency alert infrastructure has made great strides and is also ready for O3 to begin. This means a lot for the Collaboration's ability to keep up with the anticipated event rate in O3, and of course to maximize the Multi-Messenger Astrophysics that can come from our triggers. It is also a sign of evolution of the Collaboration relationship to the greater scientific community: We are working toward more openness and a desire to share the scientific fruit of our observations with a wider audience, and that will be good for our field in the long run.

The many other parts of the Machine that need to handle the O3 event rate have also progressed, with computing infrastructure and efficiency, data quality, calibration, multi-instrument pipelines, and more and updated parameter estimation packages all significantly advanced in their ability to work with less intervention and greater speed.

The detectors are closing in on their sensitivity goals after a long and arduous process of installation, debugging, and commissioning. As we write, Livingston has well exceeded the 120 Mpc BNS goal, and getting a significant boost from the use of squeezed light. Hanford is catching up, and Virgo is also about at its goal of 60 Mpc. Stability, noise stationarity, and ease of locking all are the focus, and the ER14 Engineering Run is providing a window to tweak as we approach the start of O3.

In parallel there continues robust activity on the activities needed to make better detectors possible. Many technologies are being explored to both improve what can fit in the current LIGO Observatories, and to enable a big step forward with new, longer, infrastructures. The A+ Upgrade Project is running at full speed thanks to a dedicated team and funding from the NSF and the UK STFC. The GWIC 3G (third generation) Subcommittee, including many LSC members, has mapped out the science and technologies that can take us into the 2030's and beyond.

Of even greater importance, a new wave of young people and several new groups have joined and are learning our discipline and giving the field its future. That's a vital aspect of our mission and one of which we can all be proud.

The past two years have been filled with excitement and rewards, and we are honored to have been able to serve the LSC, and we thank you all for helping us help the Collaboration along. We look forward to a continued growth of the field of gravitational wave astrophysics, to an ever maturing collaboration and to the full deployment of LIGO's potential. Let's together look forward to what's next!

David Shoemaker
LSC Spokesperson

DH Shoemaker

Laura Cadonati
LSC Deputy Spokesperson

Laura Cadonati

The gravitational wave 'forecast' for Observing Run 3

The third observing run O3 is currently projected to begin in spring 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.

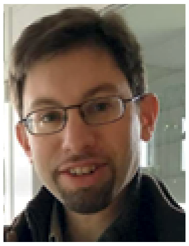
What will we see in O3?

Tom: 'Predictions are hard to make, especially about the future.'

Who actually said that? Not Einstein, not Mark Twain .. some people think Niels Bohr, but he apparently took it from a little-known Danish humorist. In any case it's equally true today when we're trying to tell you what the LIGO-Virgo network is going to detect in the next observing run, O3 — which will start in Spring 2019 and extend for about 12 months. But this article is not all that likely to stand the test of time. We can give our best guesses, but the fact that we just don't know what is really out there — no previous observations have searched as deep into the Universe for gravitational waves (GW) as O3 will — means they are unlikely to be accurate. (Though we'll happily take credit for any that are actually on the money ..)

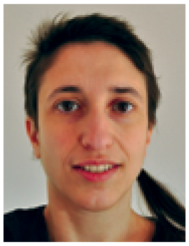
Chris: I'll get us started! Low hanging fruit first, I suppose: how about them binary black holes? They're definitely going to dominate our detection sample in O3 — probably something like 10-50ish. Ultimately, the number at the end of the day will be affected by several factors: how

Thomas Dent

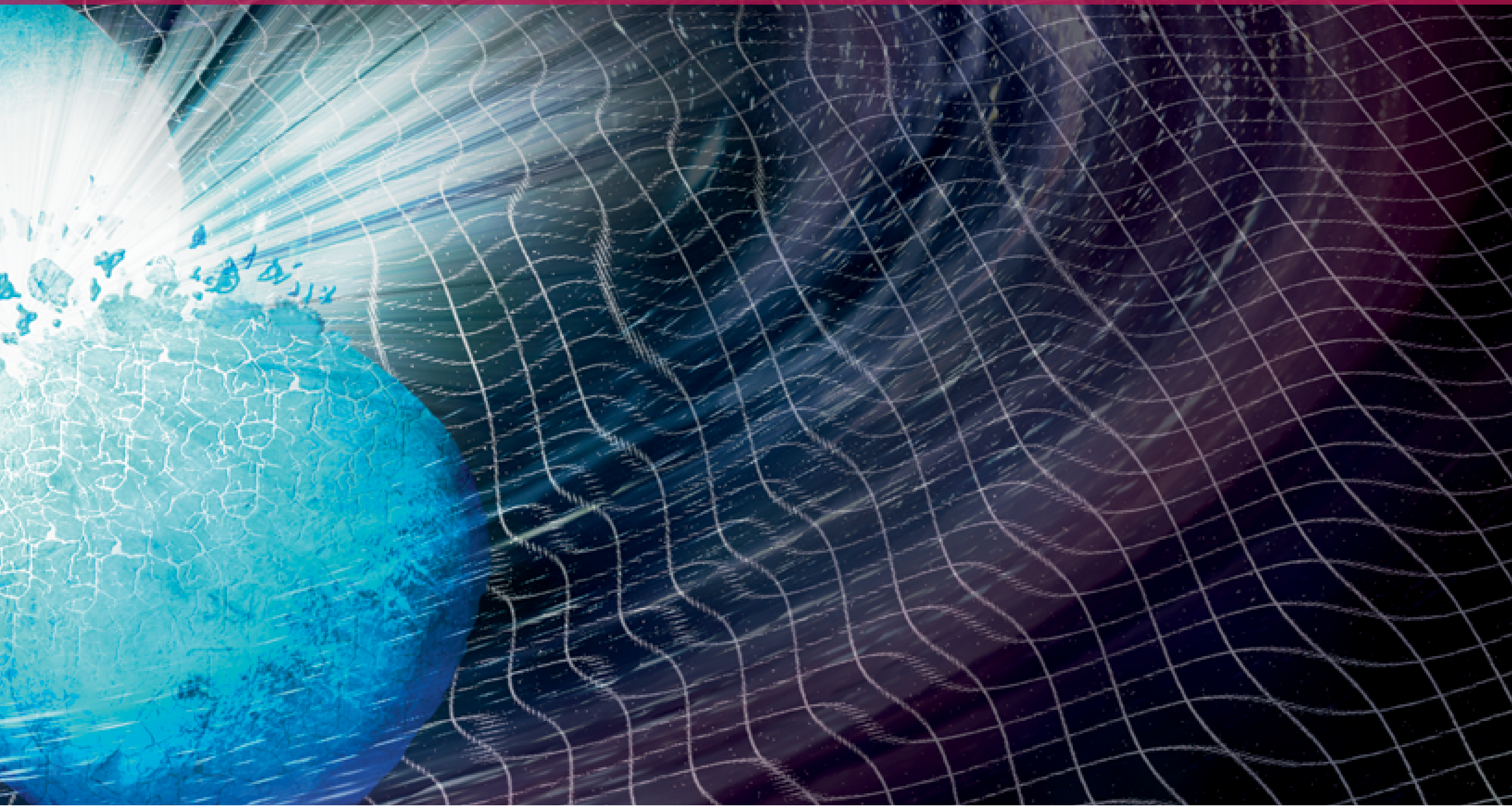


is a group leader in the Galician Institute for High Energy Physics (IGFAE) in Santiago de Compostela, Spain. When not worrying about false alarm rates in gravitational wave searches, he enjoys cycling up and down steep hills and trying to work out whether Italian or Spanish food is better afterwards.

Michela Mapelli



is professor at the University of Padova and head of the DEMOBLACK ERC team. She lives with the obsession of understanding the formation channels of binary compact objects. Above all, she is a cat addicted person.



A new study using Chandra data of GW170817 indicates that the event that produced gravitational waves likely created the lowest mass black hole known. The illustration shows a key part of the process that created this new black hole, as the two neutron stars spin around each other while merging.

Chris Pankow

is a postdoctoral fellow at Northwestern University in the Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA). Science interests include all the compact object astrophysics as well as statistical modelling. Less sciency interests include card and board games, playing the guitar poorly, and dreaming of that one fateful day when he can dust off the drums again.

Karelle Siellez

is a postdoctoral researcher at University of California Santa Cruz. She is a wave hunter: Gravitational Waves using Gamma-Ray Bursts, ocean waves while surfing, she even tries to create some by painting black holes or playing guitar.

long can we keep the interferometers locked (in observing mode), and can we reach beyond the sensitivity anticipated for the beginning of the run?

Michela: It is reasonable to expect that O3 will at least double our binary black hole (BBH) sample. Twelve months from now we might have 40-50 BBHs to play with. And maybe one, two more binary neutron stars.

Tom: Yes, merging black hole binaries are the one source where we've had a pretty solid rate of detections with Advanced LIGO-Virgo — 1 per 15 days of observing time (on average!). With O3's better sensitivity that detection rate is going to go up. The uncertainty in the number of future detections comes both from statistical fluctuations in counting the number of detectable mergers — 10 so far with an 'error bar' of about 30% — and from the unknown factor by which the detectors will be more sensitive in O3 than O1 and O2.

Michela: The number of BBHs after O3 might approach the threshold for distinguishing the main formation channels: evolution in binary systems versus dynamically triggered BBHs. Of course, I do not expect that after O3 we will be able to tell how many BBHs form by dynamics and how many of them come from binary evolution, but I do hope that masses and spins will start drawing the general picture we are looking for.

Chris: I agree completely with Michela, but I may be biased because I lead the rates and populations group for LIGO. Perhaps the most important open question for black hole mergers is: what's the distribution of the actual properties of the sources? This is something that we're only beginning to scratch the surface on — just recently we published our catalog of detections and performed the first population predictions for binary black holes with ten binaries! Of course, ten events may seem like a lot now, but it's insufficient to pin down more than a few major points. For instance, we can predict that there will be few black holes detected above 50 solar masses. If they existed in the local universe, then we should have seen them, else, some other process conspires to make their merger rate low. Ultimately, when we include all the information at hand — along with some simple models of the black hole mass and spin distributions — it turns out that the intrinsic event rate is very close to one of our earlier estimates.

Karelle: I think we will be surprised in O3, especially regarding the BNS (binary neutron star) expectations! The low luminous afterglow through a short gamma ray burst (GRB) discovered in coincidence with the BNS (GW170817) opened new questions regarding our understanding of the short GRB population. What if more low luminous afterglows were emitted and not detected by Gamma-ray satellites? What if we developed a new method to detect these hidden signals in the data to check if there was a gravitational wave in coincidence with them? And what if we used the low subthreshold GW candidates or single detector events to check in the electromagnetic (EM) detector if there was actually something that might have been missed. This is the bet we took with the (Fermi GBM) Gamma-Ray Burst Monitor team: we have created incredible tools to track down even the fainter GW events that would have an EM counterpart, and the fainter GRB that could float in the data leading us to a BNS or an NSBH: we are ready for them!

Chris: So, another question about binary neutron stars (or the ever elusive neutron-star black-hole binary) is whether we'll have another event like GW170817, our first binary neutron star. Sadly, I think the answer is no. We got pretty lucky with how close GW170817 was to the Solar System, and I suspect most of the future binary neutron star detections will be two or more times further away: that makes detection, localization, and identification of potentially fainter electromagnetic emission more challenging. Then again, we've been continually surprised in the past…

There are intriguing open questions on pretty much all aspects of the population of binary neutron stars. Again, the most important role is played by the masses of the binary's component neutron stars — previous models had predicted a tight distribution with a narrow width, centered near 1.35 solar masses. In contrast to the black hole case, the uncertainty on the neutron star intrinsic merger rate is much higher, so while the mass distribution shifts the rate up or down, the uncertainty on the rate is what drives the range of possible detections. The good news is that predictions made by using observations of pulsar binaries in our own Galaxy agree reasonably well with our measurements.

Tom: But O3 might not just be about black holes and neutron stars, might it ..

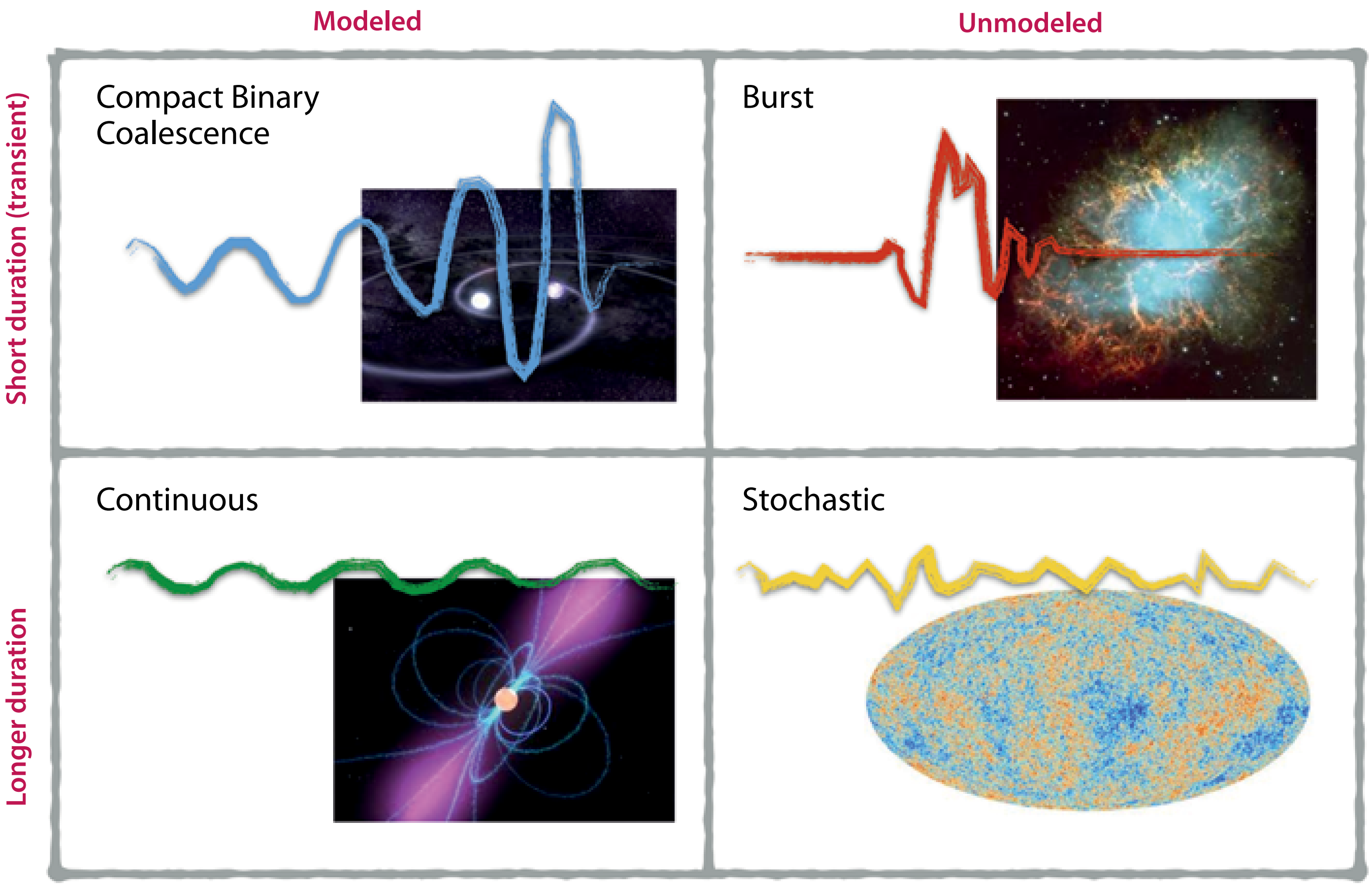
Karelle: Definitely not! In fact there are many different types of expected sources for LIGO-Virgo. We usually describe these sources and their gravitational-wave signals as either long or short duration ("transient") and modeled or unmodeled (see figure).

Tom: The question is "Do we think we have a good enough theory of what is happening inside the astrophysical system, so that we can predict the gravitational-wave signal it will emit?" The binary signals we detected so far required (in total) decades of effort to predict accurately, this pales in complexity next to the signal from a core-collapse supernova. Even throwing some of the biggest supercomputers we have at the problem, theorists are still not quite sure why these big, burnt-out old stars explode as they do — gravitational wave might help us figure that out...

Chris: Galactic supernovas are always a prime target, and we should be able to "hear" a reasonably large fraction of the Milky Way, should one go off.

Tom: That's if the predictions for how much energy they give off in the form of gravitational waves hold up .

Chris: Also true. There is a bevy of modelling for all the different features we think supernovae might expose — some of those features produce gravitational waves, some don't. Another uncertainty is that the average supernova rate in the Galaxy is pitifully low — an estimated 1 per 30 to 50 years, based on observing the electromagnetic (light) emissions from other supernovae in far-away gal-



Gravitational wave signals can be classified into short duration, such as binary mergers and burst events (e.g. supernova) and long duration, such as continuous waves from rotating neutron stars and the stochastic background of gravitational waves. They can also be classified in terms of "modeled" and "unmodeled" based on how well our astrophysical theories can predict the signal.

axies. With one year of observation time, that's only a 0.02–0.03 chance of it even happening. The payoff would be incredible though, if astronomers found the electromagnetic signal — if it wasn't hidden behind our dusty galactic plane — it could be even bigger than GW170817!

Tom: And don't forget neutrinos — a supernova gives off way more of them than any other type of radiation, including light. If one goes off anywhere near our galaxy, neutrino detectors might be the first to know.

We haven't really mentioned long-lived gravitational-wave sources yet: continuous waves, for instance. These originate from rapidly-spinning neutron stars that can give off gravitational radiation for millions of years. Unlike the binary neutron star, GW170817, these neutron stars are not colliding and merging with each other; they're just sitting around in space and rotating steadily. Because of the ridiculous high density of neutron stars — they have more mass than the Sun compressed into just a few tens of kilometers — they have been considered a likely detectable source. The one catch is that if a neutron star is perfectly round (symmetric about its rotation axis) it just doesn't emit any gravitational waves. To detect them, we need the neutron stars to have mountains.. but no-one knows how high these mountains are. Recently it was argued the smallest they might be is 1 billionth of the neutron star radius.. if that was scaled up to the size of the Earth it would be about as high as a pea. If neutron stars are really that round their gravitational waves would be out of reach of our detectors for many years to come.

Why is it important to make predictions on what we expect to observe?

Michela: Predictions are essential to get ready for what we are going to observe and to optimize our analysis tools. Let's take the first BBH, GW150914: if nobody would have predicted the existence of black holes with mass larger than 30 solar masses, we might have missed the clue to analyze and interpret these terrific data.

Tom: Not to mention if people hadn't made predictions back in the 80's and 90's that binary neutron star mergers would be detected by instruments like LIGO — and, note that some of those calculations turned out to be pretty accurate — would the detectors have gotten built in the first place?

Chris: There's also a practical aspect to it. We have to prepare and budget our resources to deal with what we know is coming. Each event spurs a team of people and a pool of resources (e.g. computing and detector characterization efforts) to understand that event as precisely as we are able. Our preparations would be different based on a handful versus a deluge of transients. This also propagates to the preparations and potential science that others outside our community are gearing up for. My personal tools are usually modelling of the rates with our data and Monte Carlo simulations of compact binary populations. More detailed modelling and model selection is important as well and I contribute to those projects frequently.

Michela: After O2, the black hole mass distribution looks like a puzzle whose pieces are slowly finding their place. The results of O2 are fairly consistent with a dearth of black holes above around 45 solar masses. Theoretical predictions suggest we will hardly observe black holes with mass between about 60 and 120 solar masses, because these fall in the "pair-instability desert": evolved stars with Helium core mass ranging from around 30 to 130 solar masses efficiently produce electron-positron pairs at their center; this drives pair instability, leading to enhanced mass loss, or even to the complete disruption of the star. As a result, there is a 'mass gap' where no coalescing black holes are expected to be seen, unless we invoke some exotic dynamical channel. O3 data are crucial to shed light on this possible upper mass gap.

Karelle: To get the most science out of GW detections, we need to coordinate with other observers — mainly 'electromagnetic' astronomers — sometimes exchanging information on timescales of minutes or seconds. We do this because we think there are possible sources which could emit gamma, X-ray, optical, radio, neutrinos, cosmic rays etc. as well as GW — in fact we are pretty sure that some common sources already exist. So these astronomer partners need to be prepared ahead of time to react to alerts of possible GW events, even a rough prediction for how many real alerts we might get is much better than no information at all.

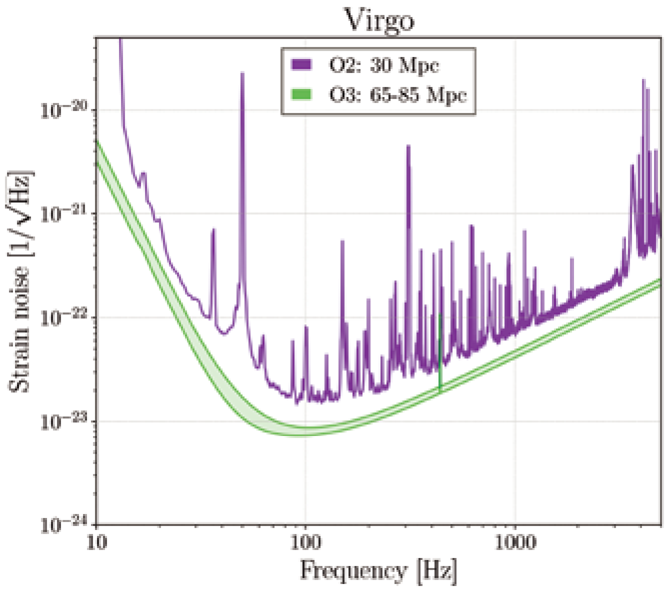
What observation are you most hoping O3 will bring?

Michela: Intermediate-mass black holes! Intermediate-mass black holes (with masses of around 100 times the mass of our sun or greater) are possibly the missing link between stellar-mass black holes and super-massive black holes. And they are a genuine nightmare for astrophysicists. Evidence for intermediate-mass black holes has been claimed many times in the last decade and, in most cases, was duly disproved. Only few strong candidates exist, based on electromagnetic data (mostly X-rays and radio).

The coalescence of two intermediate-mass black holes would be a Rosetta stone of star cluster dynamics, a nice clue to massive black hole assembly, and strong hint for the existence of very massive (>150 Msun) metal-poor stars. Last but not least, I did my Master thesis on intermediate-mass black holes (about 15 years ago), and I am still waiting for one of them to be spotted…

Chris: The universe has been continually surprising us: as we reach further into the universe, we may find that the merger rate increases with binaries at farther

Evolution of the global gravitational wave network sensitivity: The y axis shows the level of the noise in the detector (the lower the line, the better the sensitivity) against the gravitational wave frequency. Past Virgo sensitivity for O2 is shown in purple. The target sensitivity range of Virgo for O3 is the shaded band.



distances, or a whole new population of binaries will be revealed. Intermediate mass binaries are definitely a possibility. Like Michela, my PhD thesis was on this very possibility. Interestingly enough, one of the scenarios for AT2018cow (a recent very peculiar transient that has many astronomers excited) could be the shredding of a white dwarf by an IMBH.

Michela: A neutron-star black-hole binary is the missing coalescence event. Most theoretical predictions suggest that the probability of observing them is very low (their predicted merger rate is a factor of around 2–10 lower than BBH's), but gravitational waves have well prepared us for surprises..

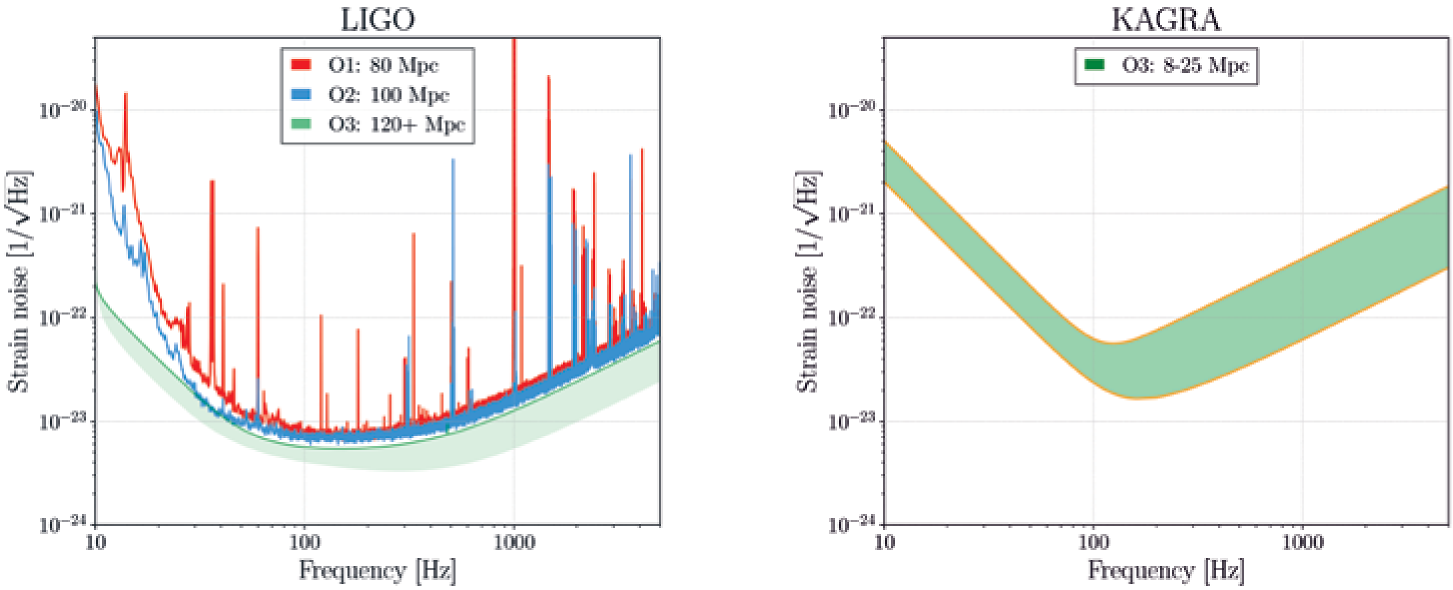
Chris: Of course, other sources are harder to predict when your current knowledge of the intrinsic rates include zero, e.g., they may not emit GW at all.

Karelle: I agree with Michela, and as Chris mentioned, rates are hard to predict based on theoretical model that could be modified by the unknown of the Universe. And there is a debate on the ratio of neutron-star black-hole binaries compared to BNS, as we should also consider globular cluster and dynamical encounters of these events. So I really hope we will get this one. It will help us understand models, rates, EM emission and at least confirm the existence of this type of sources!

Chris: I'll take the long bet: it's really only a matter of time before a continuous wave (deformed neutron star) source is uncovered. So far only upper limits, but in this case we're really limited by our ability to search the data, not necessarily by their rarity.

Karelle: Quite likely there is a correlation between the discoveries so far in the first two observing runs and the ones that will come… so we will probably stay in the compact binary case. It's interesting to show that we just opened a window, and there is so much left to do!

Similarly to the Virgo sensitivity, these plots show the gravitational wave sensitivity for LIGO and KAGRA. Past sensitivities for observing runs 1 and 2 (O1 and O2) are shown in red and blue for LIGO. The target sensitivity ranges for observing run O3 are shown by the shaded bands for both LIGO and KAGRA.



Upgrades of Hanford, Livingston and Virgo

Inspecting the fibres just welded to the new end test mass at Livingston.

Shortly after the end of the second observing run (O2) in August 2017, preparations for the third observing run (O3) were underway. We hear from the Hanford, Livingston and Virgo sites about the work taking place at the detectors to get ready for O3 in the Spring of 2019.

Livingston

The second observing run O2 ended August 2017 and the third observing run O3 is scheduled to begin in April of this year. The time in between has been spent upgrading the interferometers with the goal to increase the binary neutron star (BNS) inspiral range to ~120Mpc (a measure of gravitational wave detector sensitivity based on the distance to which the detector can observe a binary neutron star merger). At Livingston, this goal has been reached and surpassed, with the detector now seeing out to 130Mpc.

Most of the upgrades between O2 and O3 are aimed at improving the shot noise limited sensitivity (>100Hz) of the interferometer. There are two obvious ways of doing this. The first is to increase the optical power inside the interferometer. The second is to quantum mechanically squeeze the phase noise of the light at the dark port. Both approaches have been implemented for O3.

Adam Mullavey

is the Detector Controls Engineer at the LIGO Livingston Observatory. He was born and raised in Australia, but has lived in Louisiana for the last 7 years. Outside of work he enjoys swimming, playing board games, trivia nights and watching Australian Rules Football.

Right after O2 ended a new high power amplifier was installed that would nominally increase the output of the laser from 35W to 70W. With this extra power available, we've increased the input power into the interferometer from 25W to 40W.

The end test masses (ETMs) have also been replaced with less lossy versions. This swap-out happened in the middle of last year. The previous ETMs had a spiral pattern in the coatings that resulted in higher scattering losses. With the new test masses we have a by Adam Mullavey, Daniel Sigg & Joris van Heijningen

Installing the squeezer at Hanford.

higher build-up of circulating power in the arms of the interferometer. With the extra input power and the new end test masses there is approximately 225kW circulating in each arm, which is about a factor of 2 increase compared to O2.

To squeeze the phase noise, a device called an optical parametric oscillator (OPO) was installed inside the vacuum enclosure. The OPO is a non-linear crystal that converts green photons into entangled infra-red photons. This squeezed vacuum field is injected into the dark port of the vacuum. Recently we achieved our goal of 3dB improvement in the shot noise limited sensitivity.

Some other notable upgrades include the swap out of the signal recycling mirror and the installation of various new baffles in an effort to reduce scattering noise.

Hanford

After the second observation run the detector engineering and commissioning teams at the LIGO Hanford Observatory had a fair amount of in-vacuum work to complete. The first item was to replace the input test mass in the X-arm which had a point absorber that increased the sensitivity to input beam jitter. This was successfully completed and the new test mass is performing much better. We have a new laser amplifier that potentially allows us to double the input laser power. We added a new RF modulation sideband that helps with aligning the signal recycling cavity. We added an active wavefront control system which allows for better mode matching between the interferometer and the output mode cleaner.

The second major task was to swap both end test masses with the final mirrors. The old mirrors showed a spiral scattering pattern that was due to the way the high reflective coating was laid down. The new mirrors lead to much lower losses in the arm cavities and a corresponding higher power recycling gain. One benefit of the new test masses is that they are equipped with acoustic mode dampers to reduce the occurrence of parametric instabilities. With current arm cavity powers that are significantly higher than during the last run, we have seen no sign of them! One set back was that the broken in-vacuum wire connection for the electro-static drive of the Y end test mass. For the upcoming run we will be using the X end test mass only for actuation.

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.

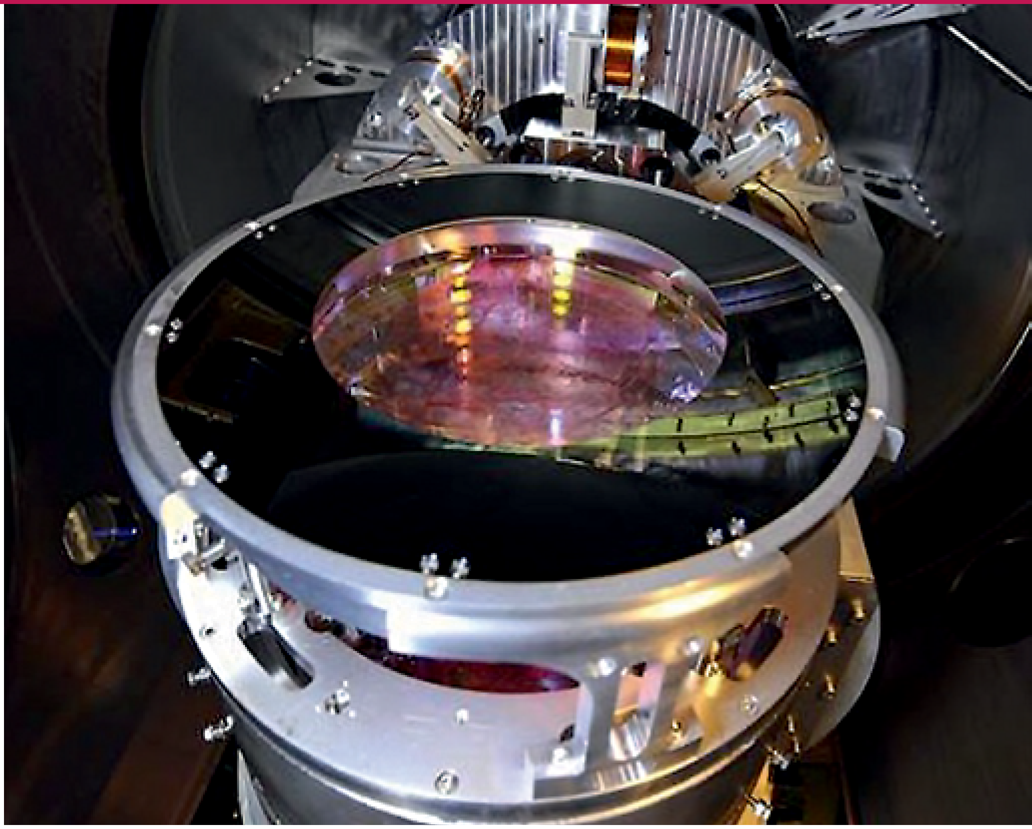
The third major task was the installation of the squeezed light source. An optical parametric oscillator was installed in the output chamber at the anti-symmetric port. Together with two tables worth of optical components outside the vacuum and two steering mirrors, this allows for squeezed light injection into the interferometer through an open port of the output Faraday isolator. This work is ongoing with the squeezed light source assembled and waiting for interferometer time. With time running short, we are hard at work preparing for the next observation run starting in spring.

Virgo

Advanced Virgo (AdVirgo) joined the two Advanced LIGO (aLIGO) detectors on August 1, 2017, in the last month of O2, i.e. the second observation run. After a heroic effort by the commissioning team, AdVirgo listened for incoming gravitational waves with a BNS range around 30 Mpc and displayed a duty cycle of 85% (the percentage of time a detector is in observation mode). Despite having roughly half the sensitivity of the aLIGO detectors, AdVirgo was able to contribute significantly. In particular, the localisation area, i.e. the sky area the source of the gravitational wave would be, could be reduced dramatically. This proved vital in pinpointing the host galaxy for GW170817, the infamous binary neutron star merger. It allowed astronomers to detect a kilonova, a kind of radioactive oven where elements heavier than iron, such as gold, platinum and uranium are produced. This finding helps explain the abundance of these elements in the Universe.

After this spectacular August, AdVirgo and aLIGO shut down for about one-and-a-half years to upgrade and prepare for O3. For AdVirgo, this meant the following. Glass mirror suspensions broke down several times prior to O2 and the decision was made to run with steel suspensions. After finally finding the culprit -dust particles from the vacuum pumps hitting the fibres causing them to shatter- the suspensions team could install the monolithic suspensions for the main mirrors which greatly improved the low frequency sensitivity. Additionally, a new 100 W laser was installed by the Artemis (Côte d'Azur, France) group, which could ultimately provide 50 W interferometer input power; while 200+ W laser development continues, this will be enough for the coming years. More optical power in the interferometer improves the high frequency sensitivity by lowering the effect of shot noise. This can be further improved by using squeezing techniques. The Albert Einstein Institute (AEI, Hannover, Germany) has installed a GEO600-like squeezer at the dark port of the interferometer. Finally, AdVirgo will be the first testbed for subtraction techniques to battle Newtonian Noise, i.e. gravitational coupling of changing mass distributions around the mirrors caused by e.g. passing seismic waves. A vast seismometer array to measure and subtract the effects of this noise will be installed.

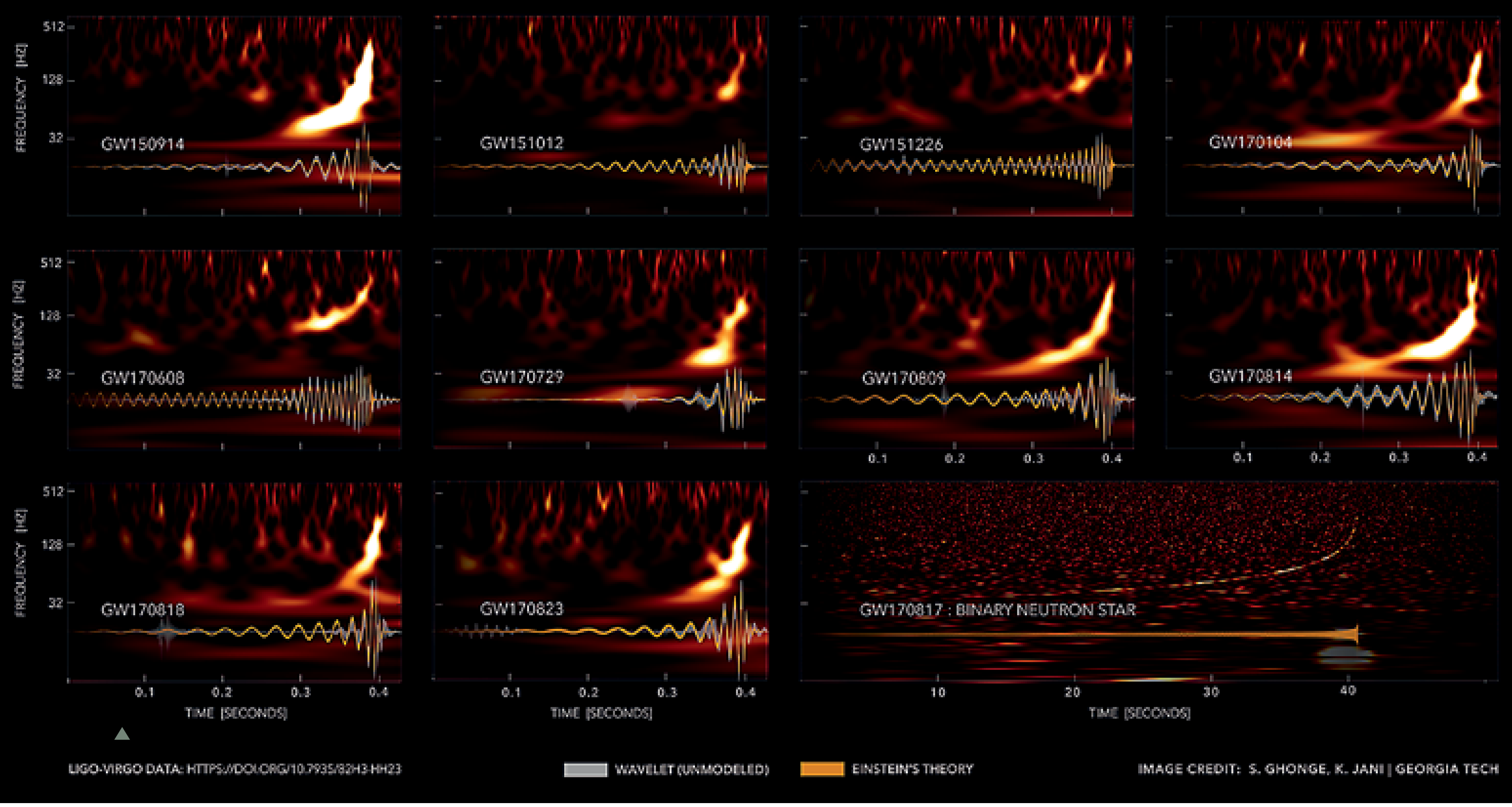
AdVirgo is now routinely reaching a BNS range of 55 Mpc and is pushing to increase sensitivity further. The team is looking forward to O3 and more spectacular science!



▲ *View from below the Virgo 'north input test mass', which is one of the four main mirrors of an interferometric gravitational wave detector, The mirror has a pink color because of the 'first contact', a protective layer which is removed as the last step of the suspension process. Above the mirror several coil-magnet pairs can be seen which are used to keep the mirror where it needs to be.*

Joris van Heijningen

is an instrumentation postdoc at the University of Western Australia after working on vibration isolation systems in Advanced Virgo during his PhD. He plays the saxophone and sings in rock 'n' roll and jazz bands making all sorts of beautiful, high energy noise!



LIGO-VIRGO DATA: HTTPS://DOI.ORG/10.7935/82H3-HH23

IMAGE CREDIT: S. GHONGE, K. JANI | GEORGIA TECH

Figure above: *Gravitational wave observations of ten binary black holes and one binary neutron star. The time-frequency plots are shown for each along with the gravitational waveform overlayed.*

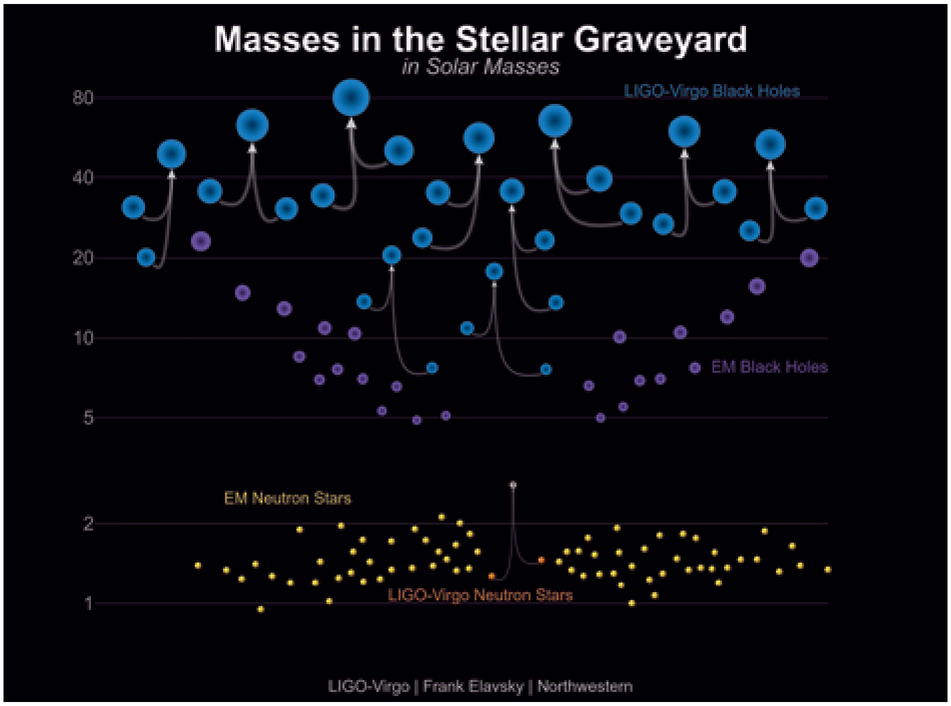
The LVC's First Gravitational Wave Transient Catalog

Patricia Schmidt

is a lecturer at the University of Birmingham working on different aspects of gravitational wave science, focussing on the modelling of colliding black holes. When not thinking about how we can improve our understanding of compact objects, Patricia likes to travel and explore the oceans of the world.

Gravitational wave astronomy is moving from the observations of a few individual events to observing the astrophysical population. With the release of the first gravitational wave catalog in 2018 we hear an insider perspective from Patricia Schmidt on this transition as well as from people outside of the LIGO/Virgo community who have made use of the publically available observation data.

Back in 2016, when the collaboration first discussed moving towards publishing results in the form of an astronomical catalogue rather than individual events, opinions were naturally divided. After all, gravitational-wave astronomy was a newly born field and we had only just finished our first observing run of the advanced detector era. Given the novelty and importance of these observations, shouldn't every gravitational-wave event have its own dedicated publication? Many of our colleagues would argue yes, but as the second observing run unfolded, it became clear rather quickly that with increasing event rates, stand-alone publications would become increasingly time consuming. And comprehensive catalogues accompanied by data releases hosted on the Gravitational Wave Open Science Center would be the way forward. Any particularly outstanding event, for example if



The masses of black holes and neutron stars observed. The black holes observed by LIGO and Virgo (shown in blue) have masses that are larger than those seen before with X-ray studies alone (purple). Neutron stars with known masses are also shown (yellow) along with the masses of the binary neutron star merger observed by LIGO/Virgo (orange).

there was clear indication for misaligned spins or a highly unequal mass ratio, would still be highlighted and thoroughly examined in a detailed publication similar to other fields. However, bulk releases of results are the standard practice across most established areas of astronomy and particle physics, and with eleven merger events gravitational wave astronomy has now entered that era too. Additionally, catalog releases have the advantage of providing the scientific community with a concise compendium representing our current state of knowledge, allowing them to perform their own analyses on the most complete data set (a selection of perspectives from open data users are included throughout this article).

The first gravitational wave transient catalog (GWTC-1) was released on December 1st, 2018, and does not only revisit previously announced GW detections, but also presents four new binary black hole mergers for the first time. These new events are of similarly high mass as GW150914 and GW170401, with GW170729 being the heaviest black hole binary observed to date. With almost a dozen observations including some with rather similar properties, statistics has already become a key aspect of gravitational wave astronomy, allowing us to start looking at the underlying populations. But our catalog does not only contain all gravitational wave events we have identified to date but also a list of marginal triggers – events recorded by the detectors with a certain false alarm probability (the probability that an observation is not a gravitational wave signal) but whose origin cannot be determined conclusively – some of them could be subthreshold gravitational waves, while others are most likely caused by instrumental noise. Nonetheless, these are very interesting triggers in particular for our partner scientists who can now search their archival data for any coincidences, for example with short gamma ray bursts. GWTC-1 was released in late 2018 – a natural question to ask is why it took more than a year after the second observing run finished? The simple answer is that we took our time to perform the most rigorous analysis of our data in order to provide the best possible results. This required many different working groups interacting closely, sharing knowledge and analysis tools, as well as code and results reviews. GWTC-1 is a major milestone not just for the LVC but for all of astronomy, marking a new era and it needed to be done with due diligence.

Lynn Cominsky
(Sonoma State University)

I have been investigating ways to use open data in activities that are accessible to undergraduate students. In general, they do not know very much about gravitational waves or their data analysis and do not have sophisticated computer programming skills. The existing python tutorials and analysis methods are too advanced for them to easily understand, so I have been trying to find the best way to provide additional scaffolding to allow less experienced users to get involved in gravitational wave science. The catalog is a great resource to show students the exciting released results without having to wade through the complicated discussions that are ongoing in the analysis groups. It also allows electromagnetic observers to gain insight into the complexity of the data and to get a feeling for the analyses that are being used with the LVC. I find the list of confident and marginal detections is very useful for public talks. However the newer catalog pages do not have audio files or other outreach-oriented displays (e.g. sky location maps), so not all the information is available that is really needed for use in the classroom or to engage the public. The website also has many acronyms and undefined terms which make it less accessible than it could be.

In the beginning, the prospect of building GWTC-1 was a daunting task: defining our goals, coordinating analyses across many different working groups, and trying to satisfy a diverse target community — not easy goals to achieve. Especially, as throughout this almost two-year long process, the content was a moving target, which posed a challenge for everyone involved. Would we discover new gravitational wave events? Would they be special enough to have their own publication or would the catalog have the privilege of announcing them?

Luckily, after our searches were complete, nature had surprised us with four more binary black hole detections. At least our content was now more or less well defined. But naturally one then has to decide on how much detail of each analysis, each event to include in a catalog release. What information in the catalog paper and the online database would be the most useful for scientists from other disciplines, hobby astronomers and teachers? With the aim of reaching a broad audience, and evidently not satisfying everyone 100%, we settled on a variety of data products as well as plots and figures and a detailed description of each event, in particular the new ones. Of course, there is always more content, more science that could have been added to GWTC-1 but focusing on the main aspect — data, searches, properties and derived rates – our catalog leaves room for scientists to do additional exciting science that is not covered in this compendium.

Let me end by saying that whilst it was certainly not an easy task — presenting for the first time details of 40% of all the binary black

Eric Myers
(State University of New York
at New Paltz)

Pioneer Academics[*] programs give interested and accomplished high school students the opportunity to work on creative research projects with college professors in a wide variety of fields. For the LIGO program students get to perform a research project of their own design using real data from a cutting-edge physics experiment, and the sample code helps lower the initial barrier for working with the data. This program would not be possible without the public release of data by LIGO/Virgo, and it would be much more difficult without the sample code.

Whilst the most important data, the strain time series – aka h(t) – are released, other interesting projects would also be possible if the related data was released (such as the seismometer data from the Physical and Environmental Monitor (PEM) sensors).

[*] *https://pioneeracademics.com*

Davide Gerosa
(Caltech & University of Birmingham)

Astronomers should not need to reanalyze the data from scratch to compare their models against LIGO detections. I welcome the release of somewhat high-level data products, like event posterior distributions (although more variables could be released). I also appreciate the current effort to make data products as usable as possible (for instance, the recent release of both posterior and prior samples allows researchers to access the likelihood, which is crucial in population studies).

I believe open data are instrumental to make a scientific experiment successful, and LIGO/Virgo is no exception. The astronomy community learned a tremendous lesson from the recent Gaia data release, with dozens of groups around the world using their results to complete a large variety of astrophysical studies. LIGO's O3 and O4 data will be awaited with the same impatience.

Robert Hilborn
(American Association of
Physics Teachers)

I and a colleague (Anatoly Svidzinsky, Texas A&M University) are using gravitational wave data from the GW170817 (binary neutron star) event to study the polarization nature of gravitational waves. Without the availability of the open data catalog, our work would not have been possible. Having the raw strain data available in an easily accessible form along with detailed information about the data set, the time of the event peak, data quality indicators, and so on has been extremely helpful.

The merging black holes observed by LIGO and Virgo so far. The size of the black hole horizons and the gravitational waveforms shown correspond to numerical relativity calculations consistent with each merging binary black hole in the gravitational wave catalog.

hole detections observed to date while simultaneously presenting updated results for all previously announced detections is major undertaking — it has been a fantastic outcome but most importantly, it has been absolute privilege to work with so many talented junior as well as established scientists. Together, we have delivered a beautiful reference work in a tremendous team effort and I hope we will look back at this achievement with our heads held up high and a great sense of pride. Let the next observing run begin!

To download data from the gravitational wave transient catalog visit:
www.gw-openscience.org/catalog/

Lior Burko
(Georgia Gwinnett College)

My first use of the open data was right after the announcement of GW150914. I immediately thought of writing up a pedagogical paper, accessible to undergrads and in particular students of the introductory courses. I constructed a computational project / lab for students, for which the students download the waveform, and then extract some properties of the signal's source. This lab exercise has been very popular with students, many of whom are excited to be able to do new science, not just the science of a hundred or more years ago.

Open data is a necessary condition for me to do any work related to LIGO results. Not being a member of the LSC, that is the only way I can work with the actual data. In addition to the pedagogical computational lab, I was also able to use the LIGO waveforms in order to show how the gravitational wave emission from extreme and nearly-extreme black holes would be different. The Open Data catalog is an invaluable resource! So far I have used only the waveforms. It was useful to have both the Hanford and the Livingston waveforms, and even more so for me, the corresponding numerical relativity generated waveform. While these were easy enough to find online, I did have some questions about the data. The LIGO team was extremely helpful in answering the questions, and they made the data more accessible.

An interview with Sir James Hough

On 31st January, James Hough received a knighthood from Prince William for "services towards the detection of gravitational waves". James, or Jim to those who know him, emeritus holder of the Kelvin Chair of Natural Philosophy at the Institute for Gravitational Research (IGR) in Glasgow, has spent the past four decades working in the field.

The knighthood followed a string of awards for Jim in the past few years, with one of the most significant being his Gold Medal in astronomy – the highest honour the Royal Astronomical Society can award – also for his work over the years culminating in the first detection.

We made an extensive interview with Jim in 2015 intended for the September LIGO Magazine that year; however, a certain gravitational wave event completely changed the plans for that issue. Together with Jim we have updated the interview for 2019 and added a few photos a few photos from the celebrations in Glasgow that followed his knighthood.

Jim is interviewed by Sean Leavey, a postdoc in the 10m prototype group at the AEI in Hannover having previously earned his PhD in the IGR in Glasgow. Sean enjoys hill walking and mountain biking, automating things, and letting the magic smoke out of transistors.

▲ *Jim Hough is a graduate of the University of Glasgow where he became Professor of Experimental Physics in 1986. He was director of the University's Institute for Gravitational Research from 2000 to 2009 and is now Associate Director. Jim has wide interests from photography of steam trains and steam ships to the highly frustrating pastime of repairing vacuum tube radios. He owns two aging sports cars, a Porsche and a TVR, which he never seems to have time to drive, and is a butler to two oriental cats. His son is a radar engineer with Leonardo in Edinburgh, his daughter an administrator with the Scottish Government and he has a four year old grandson well schooled already in trains, ships and black holes. The above photograph shows Jim in 2016 having received his honorary DSc degree from the University of Glasgow.*

SL: What made you choose the field of gravitational wave detection as a research topic all those years ago?

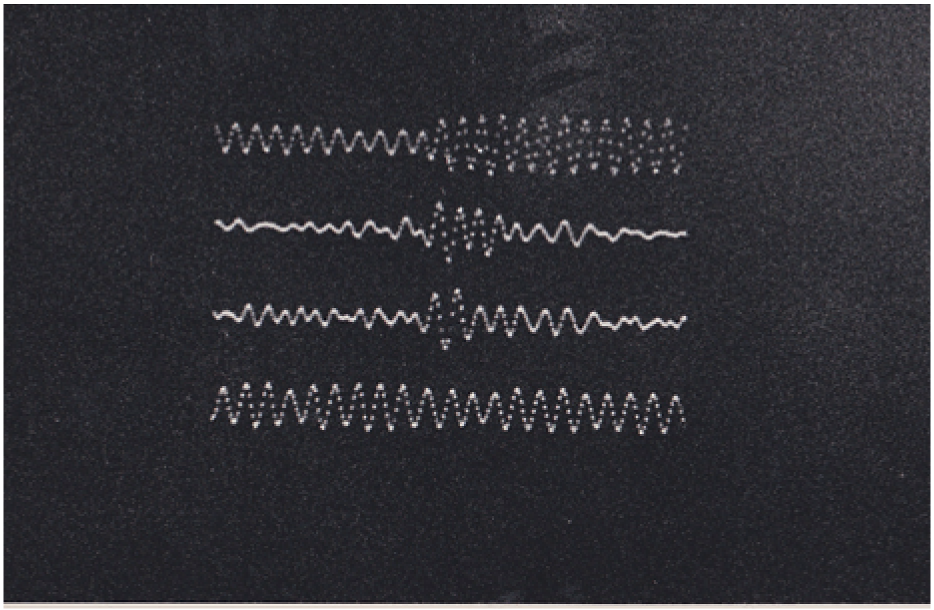
JH: Well, I had just finished my PhD – this would be about 1971 – and you know pulsars had just been discovered a few years before by Jocelyn Bell Burnell – a Glasgow graduate – in 1967. So pulsars were very big. I had done my PhD in nuclear physics but I didn't find it particularly exciting at the time. And Ron Drever was here, and he thought we would detect x-rays from pulsars by looking at phase fluctuations in low frequency radio waves. So we set up an experiment to do just that: to look at the phase of radio waves from a transmitter in Germany, and looking for phase fluctuations at the same kind of frequency as a known pulsar – I think it was CP1133. And just before that, around 1969 or 1970, Joseph Weber had set up his gravitational wave detectors and was beginning to report having seen events. It became very interesting, this field of gravitational waves, because this was something new, a little bit like the new pulsars from a few years before. So at that point Ron Drever thought it would be a good idea to see if we could build some gravitational wave detectors.

SL: These were bar detectors, right?

JH: Yes. So as a postdoc and young lecturer I worked with him to build them. We built two bar detectors, one of which is still in the entrance hall of the Kelvin Building, where the IGR is based.

SL: How long did they take to build?

JH: Not very long. You could build one in a month or less, because they were so simple. But they were very fun to play with! And then we ran these detectors in coincidence to see if we could see anything.



▲ *Photograph of the recorded coincident event from the Glasgow bar detectors in 1972 (from the Institute of Gravitational Research, Glasgow). This result was published in Nature, vol. 246, pp. 340-344 (1973).*

SL: So that was the start of your involvement in instrumentation for detection of gravitational waves.

JH: Yes, and after a while, in 1972, we thought we saw one signal that looked significant to us, which we ended up publishing in Nature.

SL: This was the one – I heard a story – that happened during a visit from your funding agency at the time!

JH: Yes, it was during the lunch break of a funding visit – and we never understood what happened – it was amazing, that suddenly there was this signal, and we never saw anything like it after for years, and there had been nothing like it before.

SL: And what did you say it was in your Nature publication?

JH: Well we didn't claim it was a gravitational wave signal, we claimed that we had seen this event and partly we were interested to see if anyone with any other kind of astronomical instrument had seen something at the same time. But all the other gravitational wave detectors were off the air for one reason or another. And there were several other detectors at that time: there was one in Germany, in Munich; there were two in Italy, in Frascati; there were the US ones: Tyson's one at Bell Labs, one in Rochester at that point, and of course the original Weber ones – two of them – but unfortunately they were all off during the time we saw the signal.

SL: Do you think, if one of those had been online and they had seen it, that you would have claimed a detection?

JH: Yes – it would have been. If it was a signal, it would have been something very close like a supernova, somewhere close to us in the galaxy, but perhaps hidden by dust clouds or something like that. It's not impossible, because you do expect a supernova maybe once every 30-100 years, and there hasn't been one observed in our galaxy since the 1600s, so you could say we were due to see one.

SL: Out of curiosity, how did you coordinate timing between detectors before GPS, in order to be able to claim a corroborated detection?

JH: We were using radio signal timing. I'm trying to remember exactly how we did it. There were radio timing transmitters – the things which modern radio watches pick up. At that point there was an MSF transmitter in Rugby in England and of course the timing is much better than is needed for a watch – if you have a proper setup it can determine the timing to within a millisecond.

SL: And that was enough for the experiments at the time?

JH: Yes it was enough for the detectors to be able to time when the signal came in. And then I think that would have been accurate enough to claim something if someone else had seen a similar signal around the same time.

SL: Was it difficult to convince funding agencies in the 70s and 80s to spend money on gravitational wave detection efforts?

JH: It's a very interesting story. At that point funding was very different. Mostly your funding came locally from your university. I think this was our first attempt to get external funding from the then Science Research Council in the UK. I think, during the event on our bar detectors, that was the first visit from a panel of people from the funding council to see what we could do. But of course we didn't know about the signal while the visitors were there – we only knew afterwards because we were busy doing things with the visitors, so it was after all the people had gone we found it on the photographic films when we scanned them. Amazing! But that was enough to keep me in the field – it gave me the feeling that we just needed a bit of sensitivity improvement, so we worked in trying to improve the bar detectors. There were two ways to go: either to reduce the temperature, to reduce the thermal noise in the detector; or to separate out the masses. As we were not liquid helium people here, we thought the best thing to do was to separate out the masses and use laser light.

SL: And by that point, it was already proposed that interferometers could be a possible way of detecting them?

JH: Yes, already at that time Bob Forward in Malibu had a small interferometer running and was listening – actually with earphones – for chirps. The whole start of using interferometry is a little bit murky, as to who actually suggested it – Weber claimed that he actually suggested it to Forward, and around 1972 Rai Weiss had been looking into it – possibly independently – and he published that beautiful noise analysis. (Historically, it seems that the idea was first published by Gertsenshtein and Pustovoit in Soviet Physics JETP, 1962). Our German colleagues in Munich in the 1970s also thought this was a good way forward and set up an experiment.

SL: Was that in Garching, where the 30 meter prototype was later built?

JH: No, I think it started off at the Max Planck Institute for Physics in Munich, then it moved to Astrophysics in Garching, then it moved to Quantum Optics in Garching, but it started in Munich at Heinz Billing's group. Our friends Albrecht Rüdiger, Roland Schilling, Lise Schnupp and Walter Winkler were all part of that group. So that's how it started, and then developed – we had a prototype here in Glasgow that we were building up, like the Garching one, and it began to get really good displacement sensitivity. Around about that stage – the mid to late 1970s – people knew we were making quite good instruments so they persuaded Ron Drever to move part time to Caltech. He spent half time at Caltech and the other half in Glasgow.

SL: And that was the beginning of LIGO.

JH: That was the beginning of LIGO: it was Ron, Kip Thorne and Rai Weiss. We had started with a 1 meter interferometer here that grew to be the 10 m interferometer – it's now gone, of course, replaced by a much better one in the JIF lab in Glasgow, but it used to be in the switch room where we still run fibre experiments. Meanwhile, Ron built the 40 meter prototype at Caltech which was based on the 10 meter here at the time with pretty much identical stuff apart from the longer arms. So we had the two interferometers and developed them somewhat in competition to see who could get the best displacement sensitivity - and that's how LIGO really started.

SL: So was LIGO around before GEO?

JH: Well what happened there was that – I've got a slide with all the dates that I should really dig out – around about the same time as LIGO was being proposed, we in the UK also thought it was a good way forward, independently, so I think around 1986 we proposed to build a big interferometer.

SL: I read somewhere that the early plans for GEO got cancelled due to the fall of the Berlin Wall!

JH: Oh yes, but we need to recount some history. In the UK we proposed a large detector around 1986 to be built either in Tentsmuir Forest or Buchlyvie, both in Scotland. Yes, GEO could have been built in Scotland! There was also an idea from the German end to build something large there. In the UK we had planning permission from both Scottish sites to build it – it was great fun getting the planning permission – but, when it came to get funding for it, both the funding agencies – ours, and the German one, said: look, why don't you people get together? So we came up with a joint proposal. But here in the UK, a new chief executive came in to the Science Research Council and found a black hole in the finances and decided that this gravitational wave stuff was all nonsense. In the meantime, the Berlin Wall came down in Germany, which of course dramatically affected their end.

I'll never forget that phone call from our research council saying they were shutting us down. That the new chairman thinks that this is not worthwhile. Then we were told to stay absolutely quiet, not make a fuss, just to stay totally silent and not say anything to anyone, and a little bit of money would keep coming to us to run our group in Glasgow.

Then, things changed: a new research council – PPARC – was formed in the UK with a new enthusiastic chief executive; similarly, things improved in Germany – what happened there was that the Garching group leader had left and they had to find a new one, and that's when Karsten Danzmann came home from Stanford – first to Garching. The Max Planck Society is good, because they always have enough money to keep things going. Then, in Northern Germany, in Hannover, a well known laser physicist called Herbert Welling was very keen to get something going in the north, because at that time there was a feeling that, with the Wall coming down, an awful lot of money was being invested in the eastern part. So he persuaded the Volkswagen Foundation that it would be a good thing to fund the a detector there.

SL: So Volkswagen helped to fund GEO…

JH: Yes – in fact, it was only until recently that the Volkswagen Foundation had been giving money to GEO. And together with the Max Planck Society that's how we managed to get started in Hannover. And by that time things were better in the UK, and the funding people thought this would be quite good, and gave us some money to help with building and running GEO.

Jim's knighthood celebrations began with an an afternoon of talks on the past, present and future of gravitational wave detection. Among those giving talks were Jocelyn Bell Burnell and Rai Weiss.

SL: That is fantastic.

JH: Now, we didn't have enough money to build a big detector, only 600 m, and that's how we came to have the silica suspensions and the signal recycling.

SL: The challenge of having a smaller budget must have meant you had to think outside the box to push the state of the art.

JH: That's right, and then it became clear that these were things to eventually upgrade LIGO with. But in GEO these improvements didn't quite give us the sensitivity that it should have, and that might still be important today – the mystery noise.

SL: I think there has been suspicion that this mystery noise might be scattering.

JH: Narrow angle scattering, yes, perhaps around the beam splitter. It's much more important for GEO because of the lack of arm cavities. So we might find there's some interesting physics going on. I don't know – this will take a little bit of investigation – I have a deep-seated feeling that we are going to find that there's something interesting, but we'll need to wait and see.

SL: Working in a new field that, for very long, had no signal, must have been challenging. Did you ever think of giving up and moving to a different topic?

JH: I never really thought of giving up. We had two big scares where we thought the group would get shut down, but I never thought of leaving. What keeps you going in these long experiments is the spin-off technologies. Particularly from when I started. My real expertise was lasers.

SL: Pound-Drever-Hall-Hough? You were the fourth author on that paper!

JH: Yes, I was involved in that quite a bit (the backwards beamsplitter is my fault). It was great fun, stabilising lasers. If you ask me what my favourite type of experiment was, I would say laser stabilisation. The most fun I ever got was taming lasers. Some lasers were very untamable!

SL: Was that when you were using the cooling pipes that you can still see on the ceilings of corridors here in the Kelvin building?

JH: Yes. We were using so much water to cool the lasers that for a short time we heated the building with it, until the water leaks became too bad! It needed a huge, huge amount of cooling water. And in 1983 I spent six months with John Hall, the Nobel Prize winner, in JILA, working for him, and also for Pete Bender, working on what is now LISA. That was all great fun!

SL: When you think back, apart from the discoveries, what do you think was your most significant moment during your research in gravitational wave science?

JH: Maybe it was when our first silica suspension in GEO was hung, just before 2000, and didn't fall down. We realised that we could make an interferometer with fused silica. I think for me that probably is the most significant.

SL: And was that suddenly a vast improvement in noise performance over steel wires?

JH: Oh yes. When you look now at Advanced LIGO and Advanced Virgo it is a very large factor improvement in thermal noise over the initial generation around about 20 Hz or so, because it is now silica.

▲

In the evening, dinner was provided at the Glasgow Science Centre where attendees could interact with the various exhibits with a drink in hand

Sir James is made an honorary Louisianan by Joe Giaime of LIGO Livingston.

▼

SL: And those had been made by your group?

JH: Well, the fibres had been made here, but the bonding to the masses was actually done over in Stanford. We took the masses there to do the silicate bonding and welding because of their experience with hydroxide catalysis bonding for Gravity Probe B. Despite the idea of using silica fibres – a number of people, such as our Russian colleagues at Moscow State University, had that idea too – nobody quite knew how to joint the silica fibres to the test masses. The Russian colleagues, what they wanted to do was to form little pegs inside holes in the test masses and weld the fibres to those, but that was difficult to do. The bonding of the masses for Advanced LIGO was done at MIT, Caltech and the sites.

SL: Would the peg idea also have lowered the fibre and test mass Q-factors?

JH: Well, not just that but you can also wreck the whole test mass, which is very expensive, if you're not careful. We were initially going to use optical contacting, because at that time we were quite friendly with people in Ferranti (now Leonardo, where my son works) – an engineering company in Edinburgh – who make laser gyroscopes and did very good optical contacting. But then colleagues in Stanford pointed out this silicate bonding technique that had been developed for Gravity Probe B and suggested that we try it. Sheila Rowan, our current director at the IGR, was at that time in Stanford, so we had very strong association with the group there and they were particularly helpful in letting us try out the technique. The silica suspensions in GEO were really a collaborative effort between Russian colleagues, Stanford colleagues and ourselves. And of course to this day we still have very strong collaboration with Stanford.

SL: What are you looking forward to, now that we are in the era of gravitational wave astronomy?

JH: I suppose I'm looking forward to seeing Advanced LIGO get down to its final design sensitivity, where I would guess we are going to be seeing maybe almost an event a day! That's when it will get really exciting! Of course, one a day is a vast amount of data, which is a new challenge. But hopefully we will also see neutron star black hole binaries as well as more binary neutron stars and binary black holes.

SL: There is a small chance that Advanced LIGO could see, at full design sensitivity, the black hole binary stochastic background.

JH: That would be fantastic. I would be slightly surprised, but you never know.

SL: If LIGO doesn't see it then the Einstein Telescope and Cosmic Explorer might.

JH: That's right, and that's the next step. We are coordinating to make the advanced detectors more sensitive and to build super-detectors in Europe and the US. I would really like to be able to see far enough out into the universe to be able to check that the expansion is still accelerating, and check that there really has to be something like dark energy, and that it's not some artifact from relying on supernova brightness to give you the distance scale.

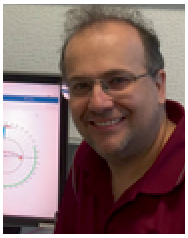
SL: Those are things that the third generation of detectors could start to probe?

JH: Yes, that's right. That's when I really think one starts to do cosmology. You see we've always wanted to feel that we are doing real astronomy. We are now doing so, with the first detections, but there's so much more to come.

Jim is serenaded by David McClelland with the pipes in the time-honoured Scottish fashion. ▶

A new era
for the Parkes radio telescope

George Hobbs



is a research astronomer at CSIRO, Astronomy and Space Science. Apart from pulsars and big telescopes, George likes travelling to out-of-the-way places. In 2018, he went out of Back O' Bourke, Xanadu and the tip of South-West Wales.

The CSIRO Parkes radio telescope began observing the Southern sky in 1961. Almost 60 years later, it is still a world-class telescope operating at the forefront of astronomical research.

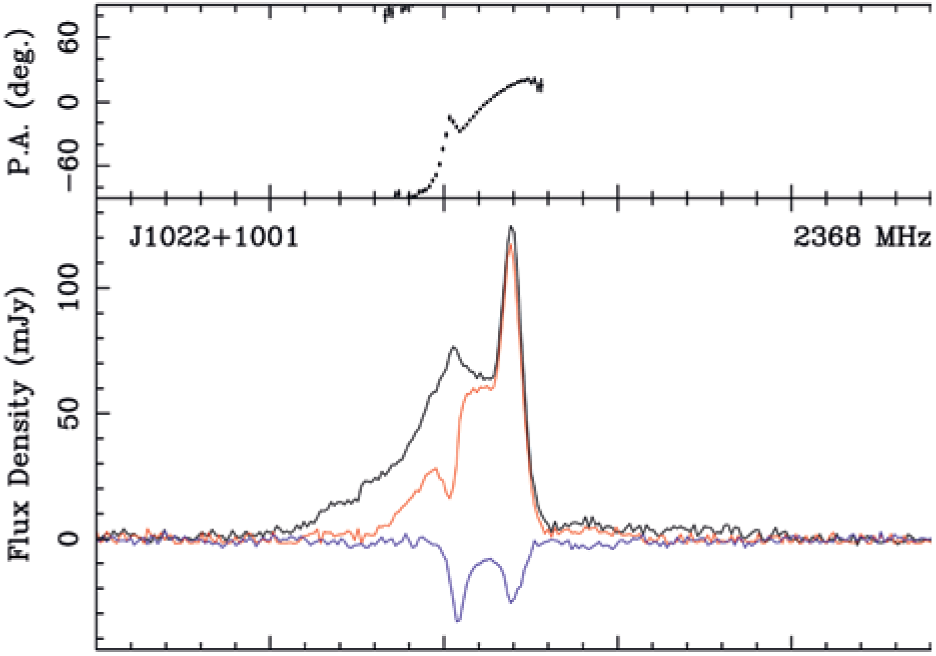
The Parkes telescope has discovered more than half of all known pulsars. Pulsars are rapidly rotating neutron stars that emit beams of radio radiation and are detected as pulses of radiation as the star rotates. There are two primary reasons for why the Parkes telescope has been so successful in discovering pulsars: (1) it is sited in the Southern hemisphere and can carry out sensitive surveys of the plane of our Galaxy (where most pulsars reside) and (2) the telescope observing system continues to be upgraded with the most up-to-date receiver and computing technology.

During 2018 we have been busy installing and commissioning a new receiver system at the observatory. This new receiver was developed by CSIRO and a consortium of Australian universities led by Swinburne University of Technology, with funding from the Australian Research Council, Germany's Max Planck Institute for Radioastronomy and the Chinese Academy of Sciences. A receiver determines which radio frequencies the telescope can "hear". In the past we have had relatively small observing bandwidths and to study a pulsar in detail have had to switch between receiver systems. The new receiver covers a massive frequency range (from 700 MHz to 4000 MHz).

The new receiver has reinvigorated the astronomical community's interest in the Parkes telescope, with observing proposal numbers up and new science capabilities possible. One of the primary goals for the receiver is to support the International Pulsar Timing Array project in the hunt for the elusive, ultra-low-frequency (nanoHertz) gravitational wave signals. Such gravitational waves will occur as supermassive binary black holes in the centre of massive galaxies coalesce. The search for these gravitational waves is based on making high precision measurements of the arrival times of pulses from a range of stable pulsars. The new receiver enables us to make more precise measurements and, as we do not need to switch between receivers, allows us to use the telescope more efficiently and observe more pulsars than we previously could.

The new observing system comes with a new set of challenges. The primary challenge is the massive data rate and volume. This has required us to upgrade our computing sys-

Observation of PSR J1022+1001, a millisecond pulsar observed as part of the Parkes Pulsar Timing Array project using the ultra-wide-bandwidth receiver. The black line in the bottom panel shows the pulse shape, the red line indicates the linearly polarised component (with angle as given in the top panel) and the blue line represents the circularly polarised emission.



The Parkes radio telescope is now 10,000 times more sensitive than when it was originally built in 1961.

tems and software, develop new algorithms and to consider cloud-based processing methods. If you would like to get your hands on some data then note that all of the pulsar observations obtained with the Parkes telescope are archived and are publicly available from https://data.csiro.au after an embargo period of 18 months.

The telescope is operated as a National Facility by CSIRO Astronomy and Space Science (CASS). More information on the Parkes telescope is available from http://www.parkes.atnf.csiro.au. In the near future we plan to continue upgrading the receiver systems at the observatory. The receiver that has been used to discover so many new pulsars will soon be replaced by a “phased-array-feed” (PAF) that will enable us to observe even more of the sky at a given time. We are also planning a second ultra-wide-bandwidth receiver that will provide us with the capability to observe between 700 MHz and 25 GHz.

With the upgrades to the Parkes and Molonglo telescopes, the development of MeerKAT in South Africa and the future Square Kilometre Array telescope, the future is bright for pulsar astronomy (and, hopefully, ultra-low-frequency gravitational wave detection and study) in the Southern Hemisphere.

For more information on the ultra-wide-band receiver get touch with George Hobbs (George.hobbs@csiro.au) and for information about the Parkes observatory, Jimi Green (james.green@csiro.au).

High school students observing as part of the PULSE@Parkes outreach project in which they observe pulsars for use in gravitational wave detection experiments.

by Charlotte Bond

Building Instruments for Keck

Working on the summit of Mauna Kea. I'm standing on the Subaru telescope with the two Keck telescopes (left) and others in the background.

After completing my PhD in 2014 I found myself contemplating my next career move. After 8 years of study at the University of Birmingham my main goal was to spend time living and working outside the UK, but I was also keen to expand my academic horizons and try research outside the field of gravitational waves.

A chance to do this came in the form of a postdoc working on adaptive optics at Laboratoire d'Astrophysique de Marseille in France, where I started in 2015. Here I worked on new concepts for wavefront sensing for large, ground-based telescopes and, although applied to a different regime, my PhD research on the impact of beam and mirror distortions on the performance of optical systems (namely laser interferometers) provided a good basis for my new field of study. The change of field was daunting at first: going from an area I had studied for 4 years and starting over in a new field was sometimes frustrating. Initial discussions were filled with mysterious new acronyms. However, I relished the challenge and was soon granted my own lab to carry out my research, allowing me to develop my experimental skills within this new field.

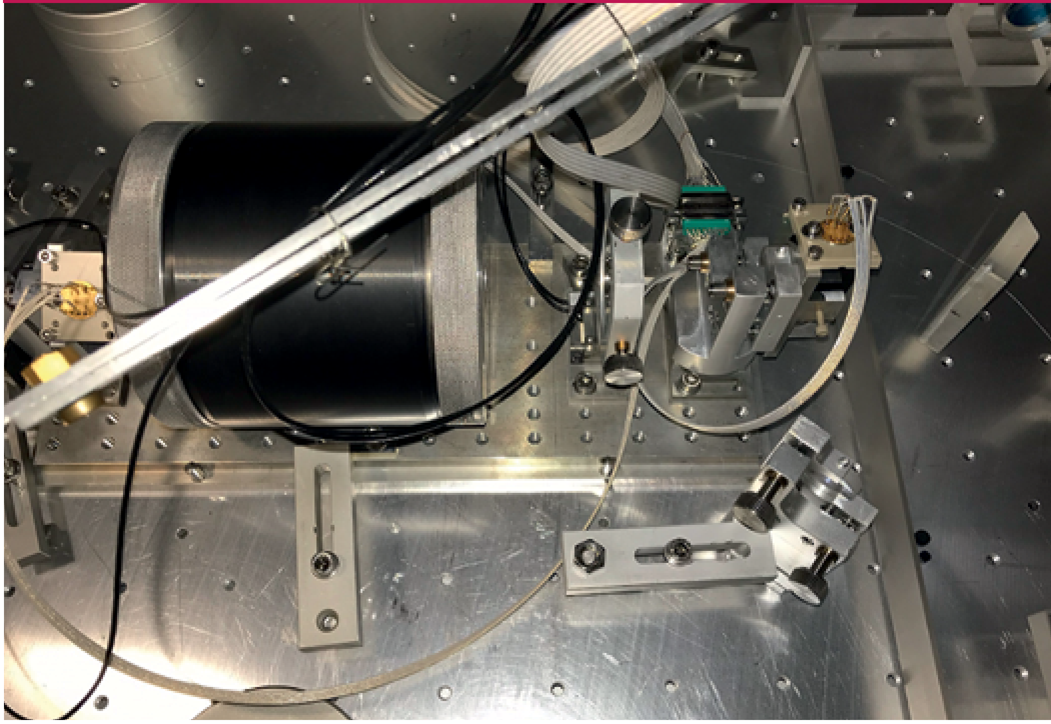
One of the major perks of working in adaptive optics is the chance to live and work in Hawaii, as one of the premier locations in the world for ground based astronomical observations, and in 2017, I moved there to work at the Institute for Astronomy. I was tasked with leading the implementation of a new wavefront sensor on the Keck telescope: an infrared Pyramid wavefront sensor, part of the Keck Planet Imager and Characterizer (KPIC). This new system aims to provide high resolution images for the study of faint red objects, such as exoplanets around M-dwarf stars. After an eventful start to my life in Hawaii (last year saw a false missile alert, volcanic eruptions, earthquakes and a hurricane) I settled in and the project quickly began ramping up. The demands of an active observatory can be very different to work in a university, similar I imagine, to the demands of industry. We were on a tight schedule and had to make sure we fit our work around the many ongoing projects and observations. Nevertheless, in September 2018 we installed the KPIC instrument on the Keck II telescope. After testing with an internal light source we saw our first star light in November, successfully operating the system on sky. We are now currently in the process of commissioning the instrument, with our first science demonstrations scheduled for later this year.

Working directly at an observatory has been a very rewarding experience, and I've been especially privileged to have been able to drive a project from the design, through the installation and commissioning phases, all the way to the first observations. And for anyone not quite sure of their next career step: don't be afraid to take chances on new experiences. You never know where they can lead.

A new squeezing record at GEO600

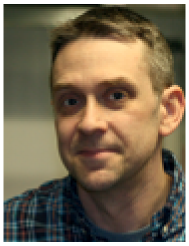
The GEO 600 gravitational wave detector located in Ruthe, Germany as part of the Albert Einstein Institute located about 20km to the north of Hannover, has achieved a new record in squeezing, with our best observed noise reduction factor at 5kHz of 5.9 dB. This is nearly a factor of two reduction in noise at high frequencies, or about a factor of 7.7 in observable volume for sources of gravitational radiation at such frequencies.

The gravitational wave detectors we all love today are limited at high frequency by shot noise of the light on our photodiode. In other words, counting statistics of the individual photons hitting the sensor. This is a limit imposed on us by quantum mechanics. We can reduce this noise in our calibrated data by increasing the power into the detector. This becomes harder and harder to do largely due to thermal effects. Eventually, we want to see what we can do to manipulate the limitations at the quantum mechanical level. The uncertainty comes naturally in two orthogonal parameters. Squeezing is a reduction of the quantum mechanical uncertainty in one parameter (the measurement one) at the expense of increased uncertainty in the other.



Our new faraday assembly in the detection tank.

Jim Lough



is the lead scientist for the GEO 600 gravitational wave detector located in Germany, focusing on squeezing and other technology development for advanced detectors. He enjoys hanging out with his kids as well as getting grandparents to travel over the ocean so he can go hiking in the Alps with his wife.

Squeezed light is very delicate and is particularly sensitive to optical loss. The recent jump in squeezing level was due primarily to a focus on the reduction of optical loss. First, we completed an upgrade to the in-vacuum faraday isolator that incorporates photodiodes for in-situ monitoring of rejected light from polarizing optics. This allows for careful optimization in a lab then fine-tuning and monitoring after installation. After integrating the new Faraday isolator assembly, we found indications that one component of the squeezer, the Optical Parametric Amplifier (OPA)*, was damaged, so we replaced this shortly after. Then we were ready to optimize everything.

Part of this optimization was to clean all in-air optics and redo the path from scratch, placing optics carefully one-by-one, as well as introducing a couple new optics to ensure the polarization is linear and in the right orientation where it needs to be.

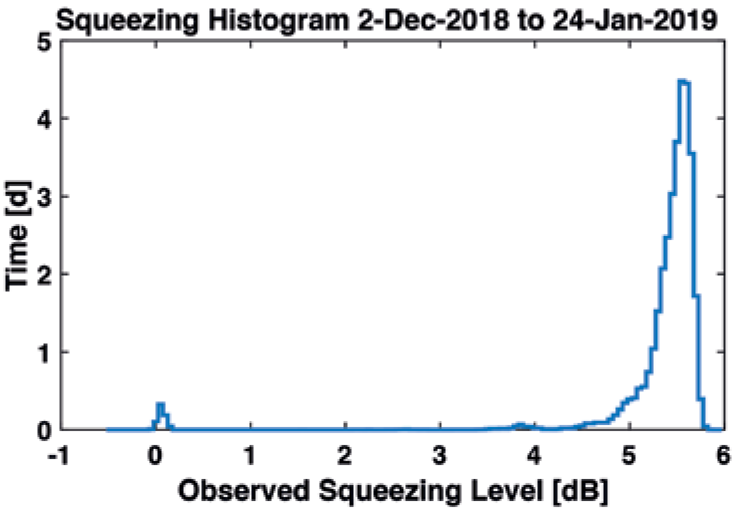
Another limiting factor for the observed squeezing level is the amount of technical noise. One source of technical noise can come from so-called backscattered light. Light from the interferometer that travels along an unintended path and couples back into the interferometer will typically pick up technical noises that can limit our sensitivity. In the application of squeezing, we don't want light to travel from the interferometer to the squeezed light source. Light that couples into the squeezer gets re-injected into the interferometer with any technical noises that it picks up along the way. To reduce this backscattered light, we employ Faraday isolators. These allow light to travel only in one direction and block light in the other direction. Real Faraday isolators don't block 100% of the light. Typically,

---

* This is the component which generates the squeezed vacuum from frequency doubled light.

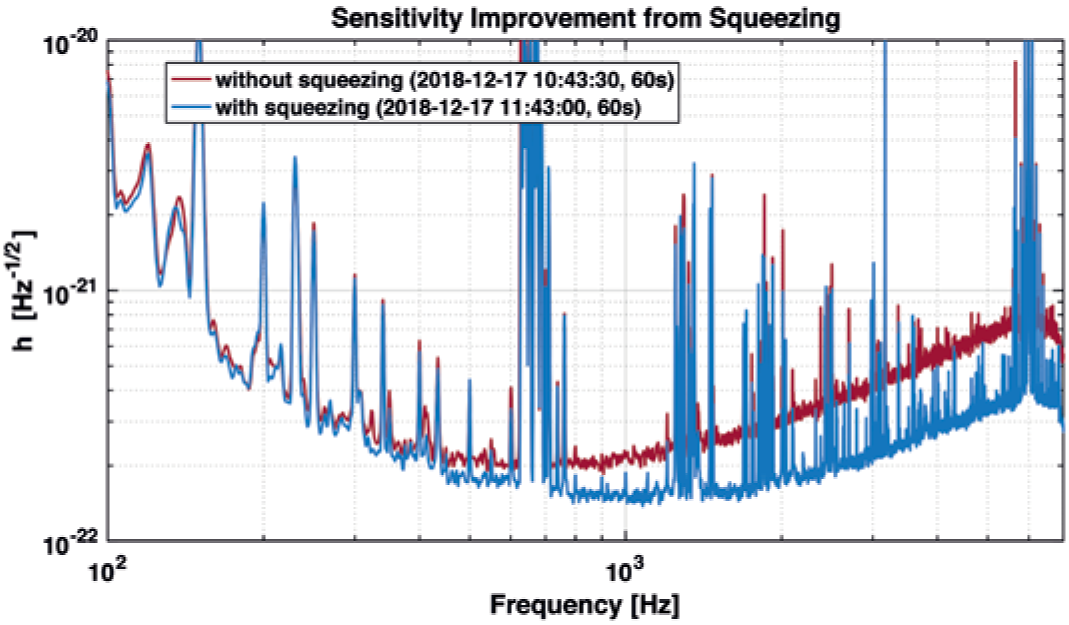
with the isolator tuned well, the amount of light leaking through can be less than about 0.01% of the incoming power. Even this small amount of light can disturb the detector's sensitivity, so we use multiple isolators. We have also recently employed a feedback system which controls the path length of this light at low frequencies, reducing its impact, which is particularly important when environmental factors cause the isolators to drift away from optimum over time.

GEO has been running continuously with applied squeezing for nearly 10 years using a squeezed light source developed at our home base in Hannover. During this time, we have been working to study and improve the integration into large scale gravitational wave detectors. The recently refreshed squeezed light source along with improvements to optical loss and backscatter light control give us this new record in applied squeezing and bring us very close to our intermediate goal of 6dB observed squeezing as we push on towards 10dB which is the level assumed in many plans for 3rd generation detectors.



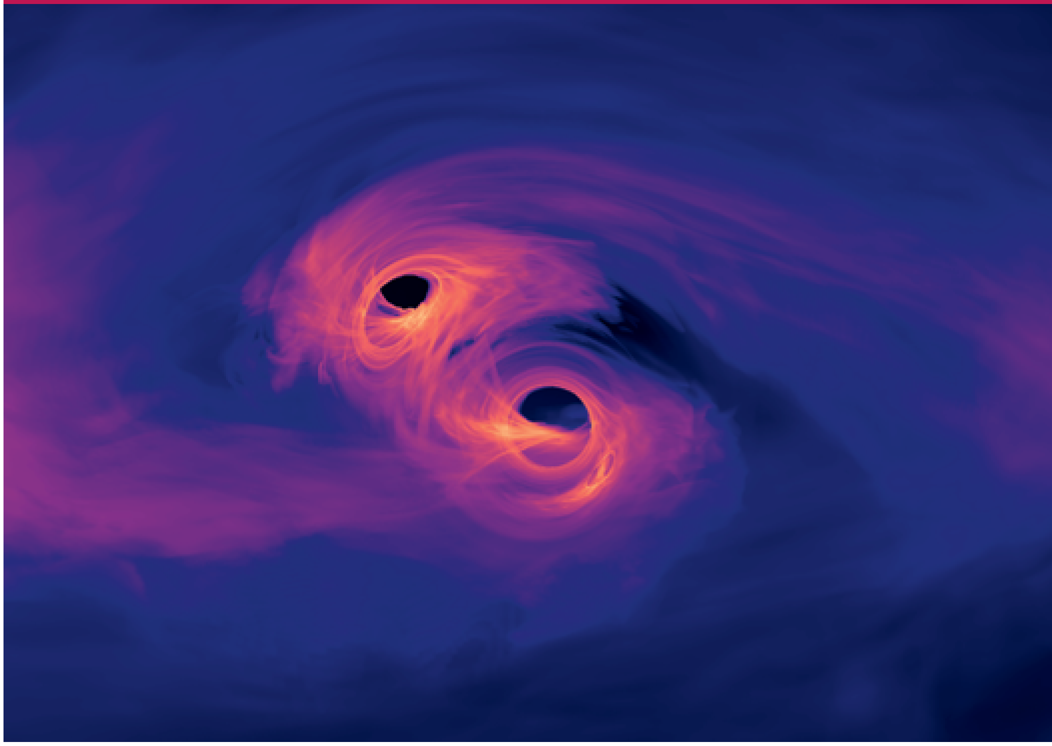
This histogram shows the squeezing level since just before achieving a nominal squeezing level of 5.7 dB on the 4th of December. The peak of the distribution is slightly lower at 5.6 dB over long term with minimal intervention. The bump around 0 dB is due to an error in the squeezing system that wasn't automatically detected. Squeezing was applied 91% of the total science time during this period.

GEO600 sensitivity at high frequency improves by nearly a factor of two with the application of squeezing!



Multi-messenger observations with LISA

On August 17th 2017, the gravitational wave from two colliding neutron stars was spectacularly accompanied by a multicolour flash of light, initiating the long-promised era of multi-messenger astrophysics. The disruption and coalescence of the two dense stars caused a plethora of luminous phenomena, including a relativistic jet emerging from gas swirling around the rapidly rotating remnant, and a wind polluted with neutrons and protons clumping up to form the heaviest elements in the universe. No flashes of light have yet been detected to unambiguously accompany the stellar black hole coalescences, emerging in the LIGO and Virgo data stream. Indeed, the naive expectation is that these events are gas-starved and thus dark. However, improvements in the joint sky localization by LIGO and Virgo may beat the odds and reveal a more complex picture of these mergers.



▲

Simulation of inspiralling massive black holes only 40 orbits from merging. Gas in these systems glows predominantly in ultraviolet and X-ray light. The full simulation can be viewed at svs.gsfc.nasa.gov/13043

Let us now scale up in cosmic dimensions and imagine two colliding massive black holes each of them as massive as millions of suns. Contrary to their stellar cousins, their natural surroundings can be effortlessly conducive to flashes of light. Indeed, the accompanying galaxy mergers often trigger major gas inflows into the nuclear region where the two massive black holes pair and form a binary. It is therefore expected that these binaries evolve and merge in an extremely dense environment, rich of cold gas, stars and compact objects. Another propitious case, where a black hole binary inspiral and merger can have an electromagnetic imprint involves an actively accreting supermassive black hole, whose disc succeeds in capturing a stellar mass black hole from a surrounding stellar nuclear cluster after many "grinding down" passages through the gas. These cosmic events are out of reach for ground-based interferometers while falling right into LISA's lap.

LISA

LISA, the Laser Interferometer Space Antenna, with foreseen launch around 2034, promises another revolution in Astronomy by opening a new window on the Gravitational Universe. LISA will explore the 0.1 to 100 mHz frequency interval, anticipated to be the richest in variety of sources, from compact object binaries at all mass scales, to whispers from the primordial universe. Signals from black hole mergers with masses between hundred thousands and ten millions of solar masses can be detected throughout the universe. LISA's science case is indeed outstanding per se, but the additional science from concurrent electromagnetic observations with ground and space based telescopes promises to be equally groundbreaking.

LISA's localisation of the sources

Like its ground-based counterparts, LISA is an all sky monitor sensitive to sources at most points on the sky. To build localization information, LISA exploits the long duration of the gravitational wave signals which characterize most of the prospected sources. In fact the late inspiral of massive binary black holes is observable for several months, and during this time LISA's orbit around the Sun introduces frequency and amplitude modulations in the signals that can be used to infer the source position within a few square degrees of uncertainty days/hours prior to final merger. For the closest, loudest events, at distances less than a few gigaparsecs, prospects are even more promising, with anticipated localization within a few arc minutes at merger. This enables sending alerts to the worldwide astronomical community.

Specific multimessenger phenomena linked to LISA black holes

Detecting the joint gravitational wave and electromagnetic emission during coalescence events will have far reaching consequences for our knowledge of both massive black holes and accretion physics. During the inspiral phase, radiation from a distorted circumbinary gas disc enshrouding the binary and from individual discs fed by streams around the black holes may give rise to multi-frequency emission from the optical, to UV and X-rays. If the sites of the emission show a high level of asymmetry, light may trace the black hole orbital motion, thus being modulated with a frequency commensurate with that of the gravitational chirp. This is the "smoking gun" to identify the host galaxy among the many candidates in the crowded sky. After the merger, targeted and repeated multi-frequency observations within the LISA sky localization error box might let us witness the re-birth of an Active Nucleus, or/and of an incident jet. Late (weeks to years) follow-up observations might reveal emission from gas bound to the recoiling black hole moving at high speed through the stars of the host galaxy. Moreover, an intermediate or stellar mass black hole spiralling-in towards a massive black hole through an active disc will inevitably disturb the gas resulting in distortions or radial shifts of X-ray emission lines. Remarkably, a variation of the previous scenario involving an extreme mass ratio inspiral (EMRI) can give rise to a multi-messanger and multi-band event. Solar mass black hole mergers—detectable by LIGO and Virgo—may indeed be enhanced in active galactic nuclei discs and once a binary merges, its remnant would become an EMRI source for LISA.

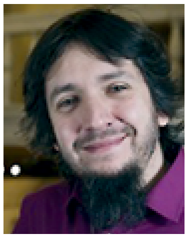
Monica Colpi

is Full Professor at the University of Milano Bicocca. Her research covers themes related to the astrophysics of gravitational wave sources, from neutron stars to black holes of all mass scales, with particular interests on dynamics and radiative processes. She is a member of the LISA Consortium Board, of the LISA Science Study Team, and member of the Virgo Collaboration.

Elena Maria Rossi

Associate Professor at Leiden Observatory, works on gas and stellar dynamics around compact objects of all masses. Although her work is mainly theoretical, it also exploits observational facilities and data across the electromagnetic and gravitational wave spectrum. She is Deputy Team Leader of the whole LISA science Group.

Alberto Sesana



is Associate Professor at the University of Milano Bicocca. His research focuses on the astrophysics of gravitational wave sources, with particular interest on massive black hole binaries, exploring their dynamics and detectability within the realm of the multi-band and multi-messenger astronomy. He is Core member of the LISA science group, and a member of the PTA Collaboration for more than a decade.

What science can we learn from multi-messenger observations?

LISA will shed light on how, when and where the massive black holes, powering quasars and lurking at the centre of the bright galaxies today, form, grow and assemble in concordance with the assembly of cosmic structures. Their origin is still a mystery that LISA will unravel. Numerous signals of coalescing massive black hole binaries are expected, occurring across the epoch of cosmic reionization and during the culmination of the star formation rate in the Universe. LISA will enable measurements of black hole spins and masses in the interval between tens of thousands and tens of millions solar masses, among the loudest sources of gravitational waves in the Universe. LISA will be also sensitive to the long-lasting signal of an EMRI, shedding light on the elusive geometry of space-time around an astrophysical black hole. The addition of electromagnetic counterparts to these signals will enable us to directly connect massive black hole coalescences with the physical conditions of the galactic host, to explore in a unique way accretion physics in the violently changing geometry of a merger and to study, for the first time, accretion onto black holes of known mass and spin. Witnessing (or not) the creation of jets before and/or after a massive black hole merger will allow us to unveil the mystery of the ubiquitous jet production. Finally, joint electromagnetic and gravitational wave observations of massive black hole binaries will provide a new class of standard candles, that can be used to probe the geometry of the expanding universe throughout the cosmic history.

As fascinating as it already appears, this is in fact just a selection of multi-messenger LISA's science cases that must be extended to also include currently unforeseen possibilities. It is indeed frontier science, bringing with it the exciting possibility that the currently unknown will be heard loud and seen bright from somewhere across the Universe.

Remembering Michael Gorodetsky

With great sadness we must say farewell to our dear colleague and friend, professor of Moscow State University Michael Gorodetsky. Michael joined our scientific group at the MSU in the beginning of the 1990s. His influential work spanned a wide range of advanced topics in physics ranging from fundamental quantum limits to optomechanics and novel laser systems. In particular he, together with V.B.Braginsky and V.S.Ilchenko, initiated the development of optical whispering-gallery mode dielectric resonators with ultra-high Q factors, which have now become an invaluable tool in quantum and nonlinear optics.

For almost two decades, since the end of the 1990s, Michael has been a committed member of the LIGO scientific collaboration. He studied non-trivial noise sources in the test masses — in particular, he and his colleagues developed models for thermoelastic and thermorefractive noises in highly reflective multilayered coatings of LIGO mirrors. He also actively participated in the development of new detector topologies and proposed several quantum non-demolition detection schemes that allow for the sensitivity to go below standard quantum limit. In 2016, he shared the Special Breakthrough Prize in Fundamental Physics with other colleagues in the collaboration for his contribution to the detection of gravitational waves.

Starting from 2014, Michael combined his work at MSU with the leading of research group at the Russian Quantum Center. There, he focused his research on the non-trivial nonlinear effects in the whispering-gallery mode dielectric resonators. His prediction and experimental observation of the coherent soliton frequency comb generation possibility in microresonators became a milestone in modern photonics. In addition to his outstanding research efforts, he has also taken up the position of the Scientific Director of the Russian Quantum Center in 2016.

The last year was very successful for Michael. He has published several influential papers in the leading scientific journals. He was full of scientific plans and till his very last day was completely confident that he will return to work soon. We will miss him greatly.

By the current and former LSC MSU group members: Igor Bilenko, Stefan Danilishi, Farit Khalili, Valery Mitrofanov, Leonid Prokhorov, Sergey Strigin, Kirill Tokmakov, Sergey Vyatchanin

We hear that ...

Career Updates

Marco Cavaglia has moved to the Missouri University of Science and Technology where he is leading the newly-formed astrophysics group, after 15 years at the University of Mississippi. Missouri S&T joined the LSC in November 2018.

Grant David Meadors, previously a postdoc at Monash University as part of the ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav), moved to Los Alamos National Laboratory in February to take up a Postdoc Research Associate position. His research will start with a NASA-funded space weather project: adaptive tuning of coronal magnetic flux forecasts using sequential Monte Carlo.

Ian Harry and Laura Nuttall are now Senior Lecturers at the University of Portsmouth (joining Andy Lundgren). Ian moved from the AEI-Potsdam and Laura Nuttall moved from Cardiff.

Katerina Chatziioannou will start as Assistant Professor of Physics in Fall 2020, after completing her postdoctoral position at the Flatiron Institute. Katerina works on LIGO gravitational wave data analysis, and plans to start an effort at Caltech preparing for the LISA space mission.

Madeline Wade and Leslie Wade are professors at Kenyon College, a small undergraduate-only college in Ohio with a small collection of 4-8 students working on LIGO research at any one time. One student, **Kyle Rose**, just got a Deep Learning Software Internship with iRobot (the company that makes those Roomba vacuum cleaners). His qualifications come from his work on applying machine learning to LIGO glitch identification. His professors are very proud of Kyle's achievements and the work he has done for LIGO.

Maya Kinley-Hanlon has graduated with a BS from American University and is now a graduate student doing LIGO coating work at Glasgow University.

Ross Kennedy graduated with his Ph.D. from The University of Sheffield and Ed Daw was promoted to professor at the same institution.

Thomas Dent left Albert Einstein Institute (Hannover) in October 2018 to start a new GW group in IGFAE (Galician Institute of High Energy Physics) at the University of Santiago de Compostela.

Awards

Alicia Sintes has been awarded with "Premi Bartomeu Oliver 2018" of the prizes 31 de Desembre from the Obra Cultural Balear for her "contribution to the research from the UIB that has opened a window to the cosmos" (December 2018). Alicia also took part in the "Selección Española de Ciencia 2018" from QUO and CSIC for her involvement in the gravitational waves (November 2018) and has been awarded with "Premio Sincronizados" from Agencia SINC for her involvement in science communication and outreach activities (November 2018). She was named "Filla Predilecta de Sant Lluís" (July 2018). http://grg.uib.es/news/fillapredilecta.php http://menorcaaldia.com/2018/12/01/alicia-sintes-ya-es-hija-predilecta-de-sant-lluis/ and has also been awarded with the Rotary Ramón Llull award from The Rotary Club (2018).

Bernard Schutz, professor at Cardiff University, has been awarded the Eddington Medal from the Royal Astronomical Society for his "theoretical discovery that gravitational waves can be used to measure the cosmic expansion rate". https://ras.ac.uk/sites/default/files/2019-01/awards/Eddington%20Medal%20-%20Bernard%20Schutz.pdf

K G Arun (Chennai Mathematical Institute) was awarded by the Swarnajayanti Fellowship by the Department of Science and Technology, Govt of India.

P. Ajith received N. R. Sen Young Researcher Award of IAGRG (Indian Association for General Relativity and Gravitation) 2019 for his pioneering contributions to research on gravitational waves.

New LSC positions

Bala Iyer and Stefan Ballmer have been elected as 'at-large' members of the LSC Executive Committee (February 2019).

Evan Goetz has been re-elected as Continuous Waves co-chair (February 2019)

Jolien Creighton has been re-elected as Compact Binary Coalescence co-chair (February 2019).

Karl Wette has been elected as Continuous Wave co-chair (September 2018).

Marco Cavaglia has been elected as LAAC Senior Member (September 2018).

Vaishali Badrish Adya has been elected as LAAC Postdoc Representative (September 2018).

Other News

The LIGO International Physics and Astronomy program for educators

will be held this July at LIGO Hanford for the second year. The program has been well received by teachers with the organizers receiving 74 applications from 23 countries. The best 24 applicants will be selected to participate in the 1 week program which will cover topics from LIGO and General Relativity to Nucleosynthesis and Dark Matter. All with the intent of helping teachers bring these topics into their classrooms.

From the KAGRA and Einstein Telescope collaborations

The KAGRA Gravitational Wave Observatory and the nascent Einstein Telescope (ET) collaboration, represented by the KAGRA Nobel laureate Takaaki Kajita and the ET steering board chairmen Michele Punturo and Harald Lück, respectively, signed a letter of intent to collaborate on the development of 3rd generation detectors. The agreement was signed at the 1st Kagra-Virgo-3G Detectors Workshop held in the beautiful Sala dei Notari in Perugia, Italy on Saturday February 16, 2019.

The KAGRA experiment builds a bridge between the second generation of Gravitational Wave detectors like Advanced Virgo and Advanced LIGO and the third generation of Gravitational Wave observatories like the Einstein Telescope and Cosmic Explorer.

KAGRA will participate in the next scientific data collection of the global network of advanced detectors and is a pioneer in the development of the Einstein Telescope with its innovative technological solutions. The first KAGRA-Virgo-3G Detector Workshop illustrated the potential for synergies between the KAGRA, Virgo and 3G observatories and consolidated the long-standing tradition of collaboration between the respective scientific communities.

At the first KAGRA-Virgo-3G Detectors Workshop in Perugia, representatives of KAGRA Gravitational Wave Observatory and the Einstein Telescope collaboration sign an agreement to collaborate on the development of the common technologies.

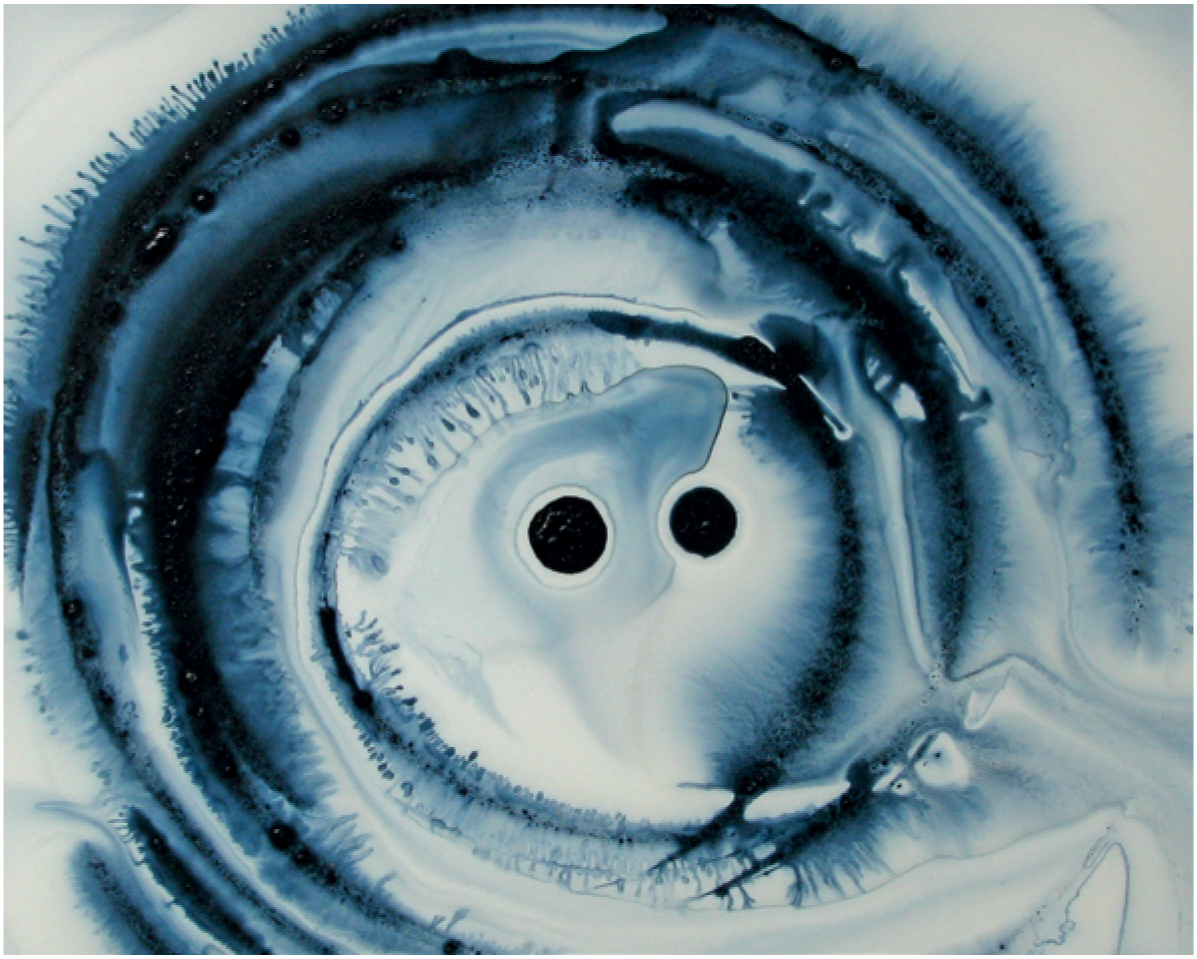
Kathryn Williamson is a Teaching Assistant Professor of astronomy at West Virginia University, where she manages the WVU Planetarium and plans astronomy outreach events to engage students and the public. In her spare time she enjoys getting out into nature, playing piano, and painting.

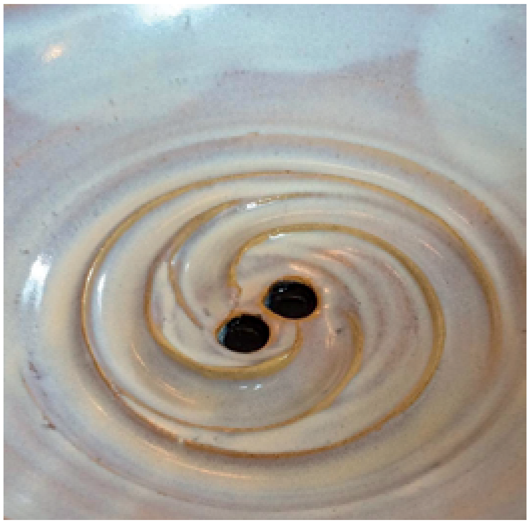
◄ **Spacetime**

Michele Banks is an artist inspired by science. You can find lots more of her work here https://www.etsy.com/shop/artologica and here https://www.artologica.net/ and follow her on Twitter and Instagram @artologica

Gravitational Waves 2, Ink on Yupo, 2016

▼





▲

Inspiral Bowls

Sarah Guerry & Kathryn Williamson created these inspiral bowls, inspired through conversations with astronomers in West Virginia University's Center for Gravitational Waves and Cosmology. The black holes were created by pressing into the clay and melting black marbles. The rippling of the clay mimics gravitational waves emerging from the orbiting black holes as they lose energy and spiral inward.

BALAFRE by Susan Kleinberg. A rift, a scar, a slash, a way through... A digital video with sound, BALAFRE derives from work over three years with the scientific team of the Louvre, using their high-powered microscope, referencing meteoric material that composes the crown of an ancient demonic statue (Afghanistan, 3,000 BC) from the museum's collection. The audio is from the hour of the September 14, 2015 detection, the unwhitened audio, and the raw wave, unmodulated, coming to us almost imperceptibly across 1.3 billion years. Edited into the audio track also is the sound of GW151226, again barely perceptible, along with slowed-down versions of both waves. For more information and the video link - www.susankleinberg.com

BALAFRE ►

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

The authors gratefully acknowledge the support of the United States National Science Foundation (NSF) for the construction and operation of the LIGO Laboratory and Advanced LIGO as well as the Science and Technology Facilities Council (STFC) of the United Kingdom, the Max-Planck-Society (MPS), and the State of Niedersachsen/Germany for support of the construction of Advanced LIGO and construction and operation of the GEO600 detector. Additional support for Advanced LIGO was provided by the Australian Research Council. The authors also gratefully acknowledge the support of LSC related research by these agencies as well as by the Council of Scientific and Industrial Research of India, Department of Science and Technology, India, Science & Engineering Research Board (SERB), India, Ministry of Human Resource Development, India, the Istituto Nazionale di Fisica Nucleare of Italy, the Spanish Ministerio de Economía y Competitividad, the Conselleria d'Economia i Competitivitat and Conselleria d'Educació, Cultura i Universitats of the Govern de les Illes Balears, the European Union, the Royal Society, the Scottish Funding Council, the Scottish Universities Physics Alliance, the Hungarian Scientific Research Fund (OTKA), the National Research Foundation of Korea, Industry Canada and the Province of Ontario through the Ministry of Economic Development and Innovation, the Natural Science and Engineering Research Council Canada, Canadian Institute for Advanced Research, the Brazilian Ministry of Science, Technology, and Innovation, Fundação de Amparo à Pesquisa do Estado de Sao Pãulo (FAPESP), Russian Foundation for Basic Research, the Leverhulme Trust, the Research Corporation, Ministry of Science and Technology (MOST), Taiwan and the Kavli Foundation.

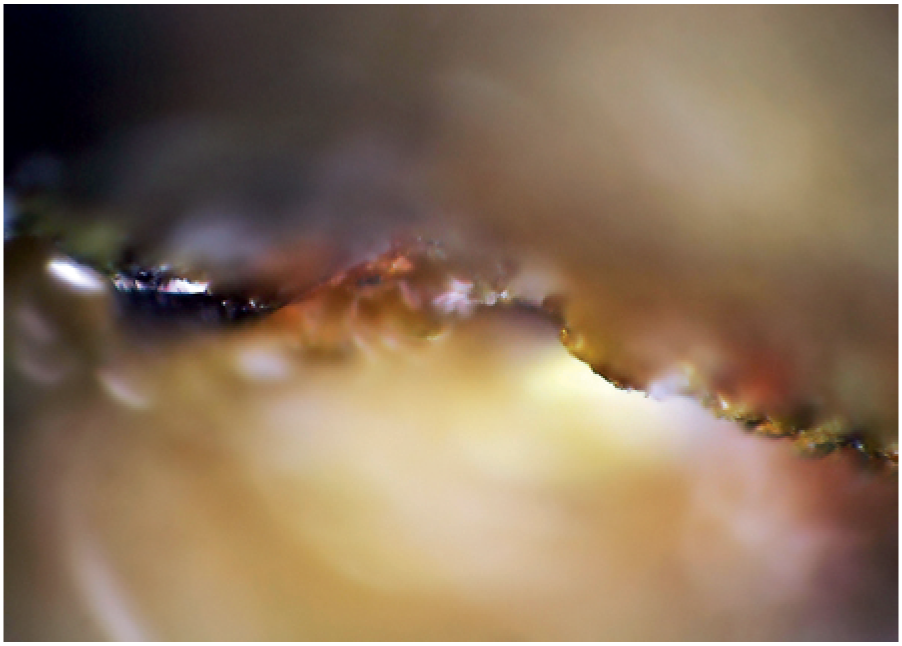
Online ISSN: 2169-4443
World Wide Web URL: http://www.ligo.org/magazine
Publisher: LIGO Scientific Collaboration, Pasadena, CA, USA
LIGO DCC: LIGO-P1900089
Contact: magazine@ligo.org

Editor-in-Chief: Hannah Middleton

Editors: Kendall Ackley, Laura Cadonati, Alex DeMaio, Andreas Freise, Tobin Fricke, Paul Fulda, Gabriela González, Amber Strunk Henry, Dale Ingram, Nutsinee Kijbunchoo, Mike Landry, Sean Leavey, Susanne Milde, Christopher Moore, Jocelyn Read, Brian O'Reilly, Sascha Rieger, Brett Shapiro

Design & production: Milde Marketing | Science Communication + formgeber
Printed by GS Druck und Medien GmbH Potsdam

The LIGO Magazine is printed on certified sustainable paper.



How it works: Continuous waves searches

by Patrick Clearwater

A key as-yet-undiscovered target for LIGO searches are continuous gravitational waves, from sources such as rapidly-rotating neutron stars. Because continuous waves should be present all the time, most approaches to searching for continuous waves are based on combining all of the LIGO data to fish out evidence for continuous wave signals. One big challenge when doing this is something called spin wandering: the spin frequency of the source is not *quite* constant, but has a small random variation.

LIGO's gravitational wave discoveries have so far been of transient events: signals that last, at most, tens of seconds. Continuous waves have so far been elusive, but are a promising candidate because they are persistent: that is, they should be present in the LIGO data at all time. This means there's no need to be lucky and observe at exactly the right time, but it also means that sophisticated data processing algorithms need to be employed to have a hope of detecting these fantastically weak signals.

Why the interest in neutron stars?

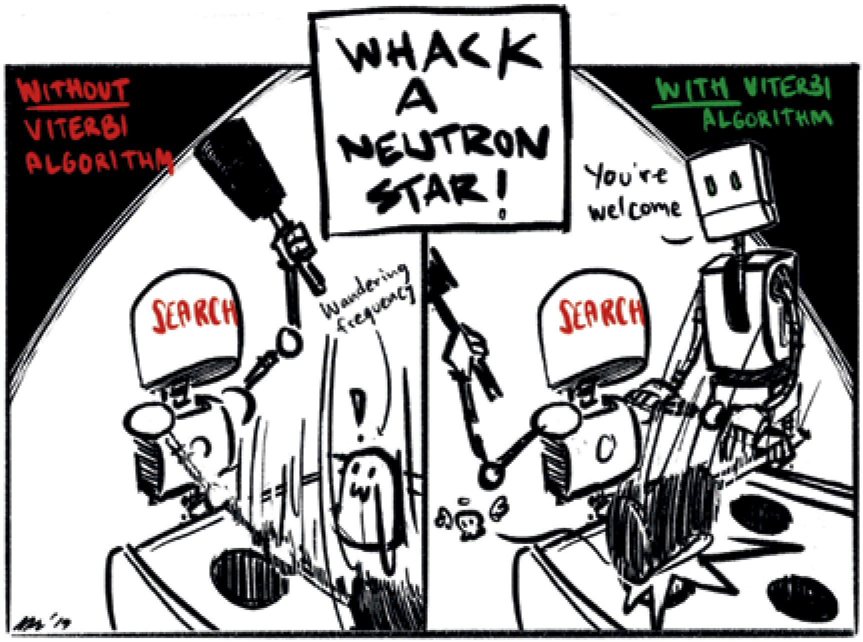
Neutron stars are a key target for most continuous gravitational wave searches because they are high density and spin fast (typically, on the order of tens to hundreds of times per second). For there to be gravitational wave emission, there needs to be something that makes the neutron star non-symmetric: for example, matter falling on to a certain part of the neutron star. Discovering continuous waves from a neutron star would also help us learn about the neutron stars themselves, for example, answering questions about how large volumes of matter behave at very high densities (the "equation of state").

And what about spin wandering?

One of the many challenges for finding continuous waves from neutron stars is that the spin frequency of the neutron star (and thus the frequency of the gravitational wave) changes very slightly, typically about a one part in a million change over the course of a week. This may not sound like much, but it's enough to throw off searches that assume the frequency stays exactly constant. What's worse is that we have no way of predicting how the frequency will change: it's effectively random from the perspective of a search.

There are many approaches to dealing with this. One way is to analyse LIGO's data by assuming a signal exists, and then finding most likely frequency path in LIGO's data. This could be done by checking every possible frequency path, but there are way too many to check them all. One algorithm, borrowed from signal processing and called the Viterbi algorithm, cleverly searches only a subset of paths by starting with just a small portion of the full observation, finding the best frequency path in that, and building from there – while guaranteeing it still finds the best overall path.

LIGO 2019



DCC number P1900089 https://dcc.ligo.org/P1900089