LIGO Scientific Collaboration

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LIGO MAGAZINE

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Front cover

Rainbow Swirl by Carl Knox showing an artistic representation of a neutron star - black hole merger event.
Article on pp. 6-10.

Top inset: A NASA/ESA Hubble Space Telescope image of the supernova remnant Cassiopeia (Cas A). Article on pp. 11-12.

Bottom inset: Corey Gray and Sharron Yellowfly. Sharron Yellowfly translates LIGO-Virgo-KAGRA science summaries into Blackfoot, and her son Corey Gray is an operator at LIGO Hanford. Article on pp. 18-20.

Bottom-left: The LIGO India site. Article on pp. 13-16.

Image credits

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Cover: Main image: Rainbow Swirl by Carl Knox, OzGrav / Swinburne University of Technology. Top inset: NASA, ESA, and the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration. Acknowledgement: Robert A. Fesen (Dartmouth College, USA) and James Long (ESA/Hubble). Bottom inset: Photo by Corey Gray. Bottom-left: Photo by Tarun Souradeep (IISER Pune)

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Welcome to the 19th issue of the LIGO Magazine!

Hannah Middleton
Editor-in-Chief

Anna Green
Deputy Editor-in-Chief

Welcome to the nineteenth issue of the LIGO Magazine! In this issue, we hear all about the discovery of a new kind of gravitational-wave event with not one, but two neutron star - black hole mergers observed in January 2020. Soichiro Morisaki, Rory Smith, and Leo Tsukada tell us more, and we hear perspectives from around the community.

How do you choose a location for a gravitational-wave observatory? Tarun Souradeep tells us the story of the LIGO India site selection in "LIGO India: The search for the perfect site". I'm sure we can look forward to many more updates in future LIGO Magazine issues as the LIGO India Observatory progresses.

In "Continuing continuous wave science in a pandemic", Lucy Strang is our guide to the world of long-lasting (or continuous) gravitational waves and the hunt for these signals from young supernova remnants.

A key avenue for LIGO, Virgo, and KAGRA education and outreach efforts are the Science Summaries. Translating them into multiple languages is an important part of this engagement. In "Explaining LIGO-Virgo-KAGRA results to the global public" David Keitel and Isabel Cordero-Carrión tell us all about the Science Summary effort and the amazing work of the volunteer translators from our collaborations.

In this issue's LAAC Corner, we hear from five early career researchers on how the pandemic has affected them in "Pandemic PhDs". And in our Life and Work after LIGO series we catch up with Grant David Meadors on being "Solar wind-swept to New Mexico".

In 2020, the research community was shocked by the demise of the Arecibo radio observatory. In "A giant in gravitational-wave astronomy", our editors Sumeet Kulkarni and Deeksha Beniwal take us through the history of Arecibo, its contributions to gravitational-wave science, and we feature memories of Arecibo from members of the gravitational-wave community. Heading over to space-based gravitational-wave observatories, Jess McIver updates us on the LISA community in Canada.

Finally, have you ever wondered how laser light produced by gravitational-wave observatories becomes the data that the LIGO-Virgo-KAGRA collaborations analyze? Find out in this issues' "How it works" on the back page!

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

Hannah Middleton and Anna Green, for the Editors

News from the spokesperson

When I sit down to write these updates, typically at the last possible minute, I'm always struck by how much we have accomplished in the past 6 months. We have released 11 collaboration papers since March 2021 reporting on searches for continuous waves, gravitational-wave backgrounds, unmodeled bursts, and compact binary mergers. We have extended our impact to look for lensing signatures and to place constraints on dark-photon dark matter using gravitational-wave observations. Our paper on the neutron-star black-hole mergers GW200105 and GW200115, and the release of the GWTC-2.1 catalog, were major scientific milestones.

These superb observational results are made possible by a broad-ranging research program that addresses experimental, engineering, operational, and analysis challenges with an eye on both the short and long term. Our outreach programs are also highly successful at reaching people all around the world. It is a privilege to work with such great collaborators.

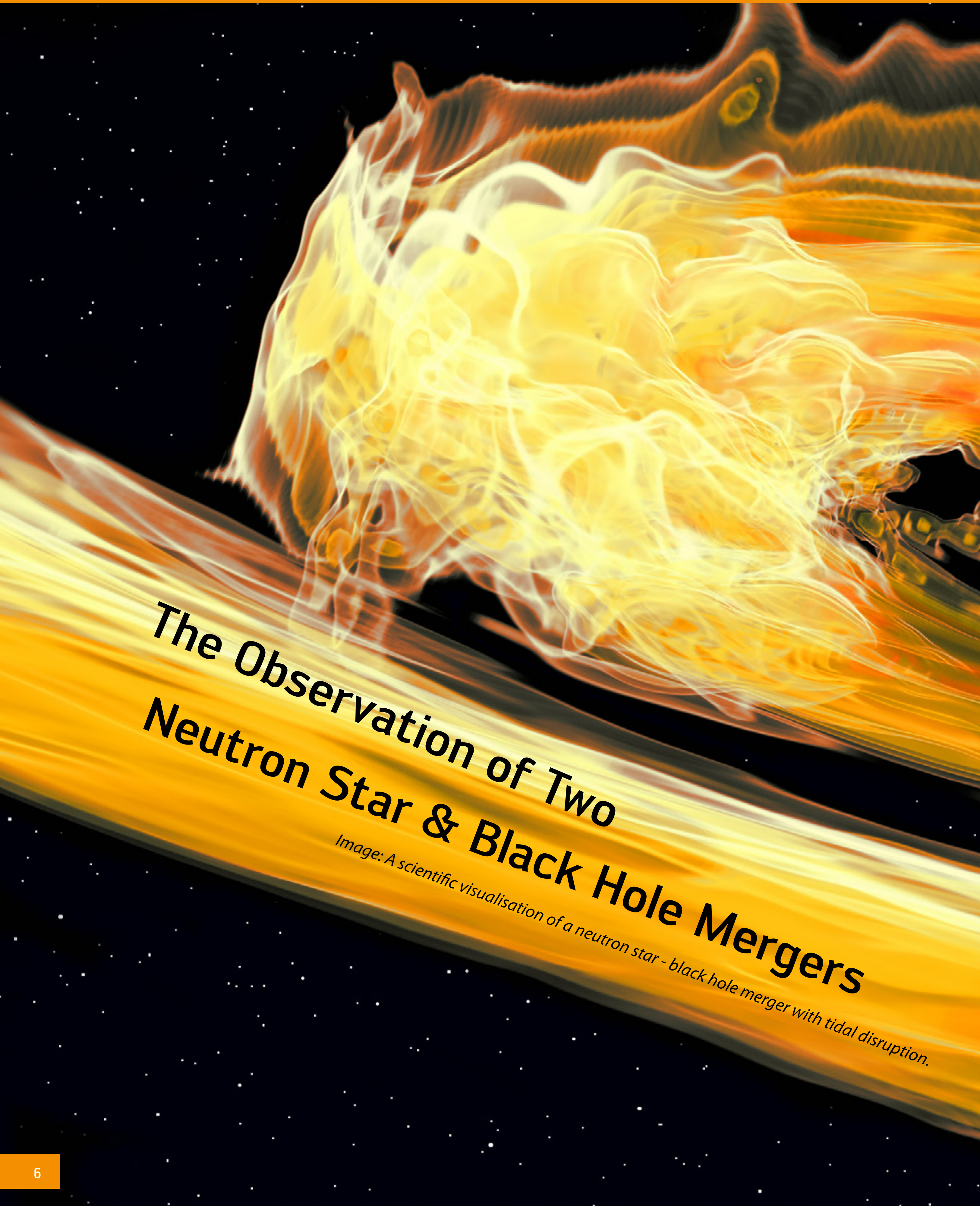
The impact of the COVID-19 pandemic continues to be felt across our whole collaboration. Many friends and colleagues in the LIGO-Virgo-KAGRA collaboration have suffered personal loss due to the pandemic. Please be kind to each other as we continue our work under this additional stress.

We have a big year ahead of us. At least 19 more papers are being written about analysis and interpretation of the Observing Run 3 (O3) data. Upgrades to the LIGO instruments and observatories are ongoing in preparation for Observing Run 4 (O4) scheduled to start in the second half of 2022. I am sure that it will bring many more exciting observational results.

In parallel, we are examining the options for post-O5 instrumental upgrades within the existing LIGO observatories. A study group, chaired by Peter Fritschel, is leading this effort. The goal is to develop an instrumental roadmap that will take us into the next decade. Please contribute your ideas to those discussions.

It has been two years since we could meet in-person at a major collaboration meeting; the last in-person meeting was in Warsaw in September 2019. As I look forward, I hope our next collaboration meeting can be held in person in Baton Rouge near LIGO Livingston. In the meantime, please contact me if you would like to discuss any aspects of our collaboration.

Patrick Brady
LSC Spokesperson



The Observation of Two Neutron Star & Black Hole Mergers

Image: A scientific visualisation of a neutron star - black hole merger with tidal disruption.

by Soichiro Morisaki, Rory Smith, and Leo Tsukada, with contributions from around the collaborations

In January 2020, a new type of gravitational-wave signal was seen for the first time by the LIGO, Virgo, and KAGRA collaborations. It was a neutron star merging with a black hole. Before this observation, we had detected binary black hole (BBH) mergers and binary neutron star (BNS) mergers, but not a confirmed neutron star - black hole (NSBH) merger. The first NSBH observation was made on 5th January 2020, and excitingly it was quickly followed by another NSBH during the following week on the 15th January 2020! The observations are named GW200105 and GW200115 for the dates they were observed (GWYYMMDD).

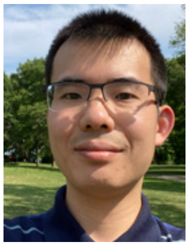
Detecting the signals

At the time of GW200105, the LIGO Hanford detector was offline and only the LIGO Livingston detector observed a signal with a signal-to-noise ratio above the threshold of detection. GW200115, on the other hand, was seen by both LIGO Hanford and LIGO Livingston. For both events, the signal-to-noise ratio recorded by the Virgo detector didn't meet the detection threshold.

When we make any detection, we estimate how confident it is. We compute the statistical significance of a detection by working out the possibility that noise could randomly produce the same signal by chance. We consider GW200115 to be an astrophysical gravitational wave signal with very high confidence: we estimate that a signal like GW200115 occurs due to random noise less than once in 100,000 years. The statistical significance of GW200105 is more challenging to estimate due to it being a single-detector observation, but it also clearly stands apart from all previously seen noise effects. A signal like GW200105 would occur due to noise less than once in every 2.8 years.

NSBH mergers can, in principle, produce light across the electromagnetic spectrum. Unfortunately, the direction of the sources in the sky could be measured only very imprecisely, to a sky localization between 2,400 and 29,000 times the size of the full Moon. Together with the large distance of around 400 Mpc (cf. 40 Mpc for GW170817) to the sources, this made observation of electromagnetic counterparts unlikely, and none has been reported so far. Future observations of NSBH mergers may produce observable light which could possibly reveal the black hole "tidally disrupting" (tearing apart) the neutron star. This could provide information about the extreme form of matter that makes up neutron stars.

Soichiro Morisaki



is a postdoctoral researcher at the University of Wisconsin-Milwaukee. In his free time, he visits breweries and enjoys some beers and cheese curds.

Leo Tsukada

is a postdoctoral researcher at the Pennsylvania State University. He likes workout and hiking as well as enjoying sci-fi movies on Netflix on weekends.

Rory Smith

is a lecturer in astrophysics at Monash University, in Melbourne Australia. In his free time, Rory likes to cook, hike around the temperate rainforests in Victoria, and explore the awesome food scene in Melbourne.

What are the properties of the NSBHs?

The heavier objects in GW200105 and GW200115 have masses approximately 8.9 times and 5.7 times the mass of our Sun, respectively. They are both consistent with other black holes observed electromagnetically and via gravitational waves.

The lighter objects have masses approximately 1.9 times and 1.5 times the mass of our Sun, for GW200105 and GW200115 respectively. These masses are consistent with known neutron stars and are well below the maximum mass a neutron star can have. They are also consistent with gravitational wave observations of binary neutron star mergers like GW170817.

Black holes can spin, and measuring the rate and orientation of the spins can help us piece together how the binaries are formed. There is a theoretical maximum spin of a black hole. We found the black hole spin for GW200105 could lie between 0 and as high as 30% of the maximum rotation rate of black holes, while for GW200115, the spin lies between 0 and 80% of the maximum rate. For GW200115, the black hole spin is likely to have a negative spin projection. This means it is spinning in the opposite sense to orbital rotation of the binary system, which is quite unusual if it is the case. We do not have strong evidence of neutron star spin because our measurements are not sensitive to it.

Why do we think we observed neutron star-black hole binaries?

Based on the masses of the heavier objects in the binaries, we're almost certain that these are black holes: there's really no other compact object they could be. The masses of the lighter objects in the binaries imply they are neutron stars, however in order to definitively claim this, measuring masses is not enough. One could alternatively argue that they are really light black holes such as "primordial black holes" that are speculated to have formed in the early Universe. We need a "smoking gun" that clearly characterizes the lighter objects as neutron stars. In principle, there are two such characteristics that could be observed.

The first is evidence of a neutron star "tidally deforming": stretching due to the gravitational strain caused by the inspiral into the black hole. This would slightly modify the observed signal. The second is observing an electromagnetic counterpart, which could be caused by a neutron star being "tidally disrupted" by the black hole: shredded apart due to extreme tidal forces before it has a chance to plunge into the black hole. Neither of these characteristics were observed. This is expected, though, given the relatively low signal to noise ratio, which makes tidal deformability difficult to measure, and the large distance to the sources makes observing any possible electromagnetic emission highly unlikely.

Without definitive evidence that we saw neutron stars, we instead check how consistent the masses are with known properties of neutron stars. The masses are consistent (see above), so GW200105 and GW200115 are suggestive that they came from the coalescence of neutron stars with black holes.

How often do neutron stars and black holes merge?

The two new discoveries allow us to directly estimate the NSBH merger rate for the first time. Currently, our ability to estimate this rate is limited by having only seen two events, as well as broad uncertainty on the population of NSBHs. We estimate that there are between 12 and 242 NSBH mergers per cubic gigaparsec per year. This measure may not be especially intuitive, however a quick back of the envelope calculation can tell us roughly how many mergers there are in a given time period. For comparison, the binary neutron star merger rate is roughly a factor of ten higher, and there is about one binary neutron star merger somewhere in the Universe every ten seconds or so. This means that, somewhere in the Universe, NSBH mergers happen every few minutes.

How did the NSBH binaries form?

The merger rate is useful to figure out how the systems may have formed. This is because theoretical models of compact-binary formation predict merger rates, so we can directly compare our measurement to theory. There are two main formation scenarios that are consistent with the measured merger rate. One of these starts with two stars already orbiting each other. The stars have masses such that when they age, they eventually explode in supernova explosions, one star leaving behind a black hole and the other leaving a neutron star. This is called “isolated binary evolution”. The other possibility is that the neutron star and black holes form from separate stars in unrelated supernova explosions, and only afterwards find each other. This is called “dynamical interaction” and can occur in dense stellar environments such as young star clusters. Both GW200105 and GW200115 could have formed through either scenario, and future observations will be required to gain a better handle on formation.

NSBH perspectives

Maya Fishbach

is an NHFP Einstein Postdoctoral Fellow at Northwestern University. She enjoys baking bread, drinking boba, and watching videos of cute animals.

My first reaction to the NSBH discoveries was “We detected every type of merger! We’re done!” But after the celebration, it can be disheartening to imagine that we will never have another “first.” Fortunately, I’m confident that this isn't our last important discovery. Even after observing dozens of BBH, a couple of BNS, and a couple of NSBH, we’ve only sampled a tiny fraction of the gravitational-wave universe. There’s just too much we still don’t understand about black holes and neutron stars, including how they’re made in the first place. In other words, our work is far from done!

Tim Dietrich

is an assistant professor at the University of Potsdam (Germany) and Max Planck Fellow at the Albert Einstein Institute in Potsdam. In his free time, he enjoys his family time, watching Marvel movies with his wife and playing football with his son.

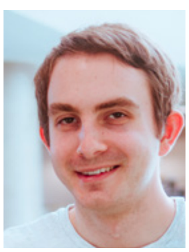
While both the first gravitational-wave detection of binary black holes and binary neutron stars have been celebrated within the entire astrophysical community, the first detection of a mixed system went relatively unnoticed. However, these observations have also been of central importance and finally complete the list of expected compact binary sources. In fact, GW200105 and GW200115 led to new scientific insights, for example a better understanding of the merger rates, and while we would have wished for an event with an electromagnetic counterpart, the 'dark nature' of GW200105 and GW200115 proved once more the importance of gravitational-wave astronomy.

Patricia Schmidt

is an assistant professor in gravitational waves at the University of Birmingham, UK, where she works on source modelling and parameter inference with her group. When not working on research, Patricia enjoys growing her own fruit and veg.

The discovery of the two (potentially even three or four if we include GW190426_152155 and GW190814) NSBH binaries presents another milestone in the still relatively young field of observational gravitational-wave astronomy. Their existence has been hypothesised for decades but promising electromagnetic candidates kept being disproved. These gravitational-wave observations provide the strongest evidence for mixed compact binaries to date. What we are lacking, however, is a measurement of tides demonstrating that the lighter companions are indeed neutron stars. Sensitivity upgrades are imminent and with the community gearing up for the third generation of gravitational-wave detectors, loud future observations will allow us to determine their nature much more affirmatively.

Simon Stevenson



is a postdoctoral researcher working on binary stellar evolution at Swinburne University of Technology, Melbourne, Australia and is a member of the Australian Research Council Centre of Excellence for Gravitational Wave Discovery (OzGrav). He is a San Francisco 49ers fan and spends much of his spare time playing video games.

Astronomers first observed neutron stars and black holes in our Galaxy in the 1960s. In the almost 60 years since, we've discovered dozens of neutron stars and black holes in binaries through observations of binary pulsars, X-ray binaries and, recently, gravitational waves.

However, until now we had never seen a neutron star and a black hole in a binary together, despite observers hunting for them relentlessly, and theorists (like me!) predicting that they should be formed from pairs of massive stars in a similar way to binary neutron stars and binary black holes. This pair of NSBH mergers (GW200105 and GW200115) therefore represent the confirmation of these theoretical predictions and the possibility of many future observations to come!

Leo Tsukada (author)

From the viewpoint of signal detection, one of the challenges for these events was the feature of single-detector observation. In these cases, the estimate of the statistical significance is relatively more uncertain compared to an observation found by two or more detectors. For GW200105, in particular, the significance estimate changed a couple of times during the re-analysis of a detection pipeline and I had a mixed feeling about the confidence. To me, that was a psychologically tough moment. I think we have got a lot of lessons to learn from these events and it will be critically important to tackle the single-detector issues in future runs where there will be many more similar events.

Soichiro Morisaki (author)

While the estimated masses of the two gravitational-wave sources are consistent with NSBH binaries, we have not detected any matter signatures of the lighter objects in gravitational-wave or electromagnetic observations. It leaves the possibility that the lighter objects are light black holes. In either case, these events are exciting: If the lighter objects are neutron stars, we detected NSBH binaries for the first time. If the lighter objects are black holes, they may be primordial black holes formed in the early Universe. Detecting the electromagnetic counterpart of NSBH merger is our next homework.

Anna Puecher

is a PhD student at Nikhef and Utrecht University, working on gravitational-waves data analysis focused on binary neutron stars and non-vanilla black holes. In non-working time, Anna loves hiking and reading.

Gravitational waves give us an insight into the most extreme events of the Universe, and allow us to test general relativity in strong-field conditions. There are different ways in which we can do this: we can look for deviations from the expected models, or measure the speed of gravitational waves; we can also look for phenomena that we know are not present in general relativity black holes, for example echoes, and much more. We are very excited that now we also have NSBH mergers as a different source of information, for these (and maybe new) ways to probe Einstein's predictions.

Rory Smith (author)

I don't think I can add much new about the scientific significance of the discoveries, so I'll just give a brief personal perspective as a member of the paper writing team. After 18 months, and what feels like a thousand telecons, a million emails, and an uncountable number of Slack and Mattermost messages, it's wonderful to see our discoveries finally presented to the world. It was a real privilege to be able to work so closely with many great people in the LVK, despite the anti-social hours of some of the telecons (Australia is a nightmare to schedule with both the US and Europe!). I look forward to all the new discoveries in Observing Run 4 and beyond!

Continuing Continuous Wave Science in a Pandemic

Lucy Strang

6am on Thursday. For a large part of 2020, that was the only marker I had that a whole week had passed. The Australian response to the COVID-19 pandemic was to close the borders and lock down any states with an outbreak. In Melbourne, this meant that for most of 2020, there were four reasons you were legally allowed to leave the house: essential work, medical emergencies, essential supplies, and one hour of exercise per day. Months and hours began to blur together as the lockdown crept on. The passage of a day was marked by my household drifting together to watch the daily press conference on the case numbers. The passage of a week was marked by the first meeting I had, the weekly meeting with the analysis team searching for continuous gravitational waves from young supernova remnants.

is a PhD candidate at the University of Melbourne with an interest in gravitational-wave astronomy, signal processing and other neutron-star physics. Outside of work, they enjoy krav maga, boxing, and creative writing. They are currently based in Naarm, Melbourne and acknowledge the Wurundjeri people as the Traditional Owners of the land.

Supernova remnants, like Cas. A (pictured p. 12), are the remains of massive stars. When a star more than eight times the mass of the sun burns through its fuel, it explodes in a supernova. The dense core of the star collapses to a neutron star, and the interaction of the explosion debris with the surrounding medium forms the intricate pattern of shocks that make supernova remnants so beautiful.

Continuous waves (CWs) are long-duration gravitational waves at a "fairly constant" frequency – in the case of this search, a rotating, elliptic neutron star. What's "fairly constant"? In this case, the gravitational waves are emitted at twice the rotation frequency of the star, so it would typically take a couple of decades to shift by one hertz. Continuous gravitational waves are much quieter than signals from compact binary coalescences.

We were a team of three, conveniently spread across three different time zones. This came with some challenges. There is no meeting time that is friendly in Australia, Europe and the U.S. – only times that are less unfriendly. My 6 AM meeting was at 10 PM in Europe. Somehow, we muddled through. Throughout the project, I learnt so much more than I expected, both scientifically and otherwise. I learnt how to collaborate across continents and language gaps and how valuable that kind of connection could be. It was difficult to appreciate it at 5:55 AM when preparing for the meeting, but in retrospect, I wouldn't trade the experience for the world.

Coordinating discussion across the team remained a challenge for the duration of the project, but fortunately, human constraints were our only challenge. A continuous gravitational-wave (CW) signal should be present as a quiet, persistent signal in the data for the entire observing run. Unlike gravitational-wave astronomers interested in transient signals, CW astronomers don't need to worry about binary coalescences not respecting a 9-5 working day. In fact, we can't use the data until the observing run is complete. Once the detector is off, the clock starts ticking as we race to complete our analyses before the data is released to the public. It's a short time frame, and one that is shrinking as we move to shorter and shorter release schedules. The data has to be calibrated and cleaned before an analysis can start, and this process takes longer every run. Every detector upgrade pushes us into new territory. As we increase the sensitivity, we find new sources of noise that were previously too quiet to detect. It's a fair price to pay for greater sensitivity, but the vital work of characterizing and controlling the noise takes time. It's an essential and often undervalued task that enables the science we do – but every tick of the clock counts.

Once the data is cleaned, the challenge becomes computing power. A CW signal should be visible in the data for the entire run, but the signal is expected to be much, much quieter than anything we've detected before. The detection of GW150914 is often compared to measuring the distance to the nearest star (Proxima Centurai, approximately 4.2 light-years away) to an accuracy around the width of a human hair. To detect continuous waves, we need to be a million times more sensitive. This would mean measuring the same distance to the accuracy around the width of a hydrogen atom.

This is (or should be) unsurprising. The energy released during a compact binary coalescence ought to be much greater than the energy available to a typical CW source (for example, a rotating neutron star). To have any hope of detection, we have to combine the data from the full observation run to try and boost the visibility of the signal enough to make a detection. So far, we haven't been lucky.

The good news is that even a non-detection can contain interesting physics. A rotating, elliptic neutron star should emit CWs described by a simple sine wave at twice the rotation frequency of the star. An elliptic neutron star is one that needs three dimensions to properly define the shape, much like a football. The more elliptic the neutron star is, the louder the gravitational waves should be. When choosing targets for a CW search, the goal is to pick targets that we expect to be very elliptic, close by, and in the most sensitive frequency band in the detector.

Neutron stars can be in binary systems or isolated. For isolated neutron stars, the ellipticity is left over from the supernova that birthed the neutron star and diffuses over time. This makes younger neutron stars more promising targets – but, as usual, there's a catch. Younger neutron stars both rotate and lose rotational energy more rapidly, so we now have to worry about the frequency decreasing slowly as the star 'spins down' (i.e. loses rotational energy). Unfortunately, accounting for a decreasing frequency is computationally expensive. To make the search tractable, we need to either know what frequencies and spin downs to search for or find new, clever ways to search the data efficiently.

The search for CWs from young supernova remnants required us to be clever. The fifteen targeted supernova remnants each had an associated compact object, but no measured rotation frequency. All we have is a lower bound on the age of the neutron star (implying an upper bound on the gravitational-wave frequency). The possible frequency range for each target spans kilohertz. Each frequency implies a range of possible spin-down rates to track how rapidly the star is spinning down. Trying to do a maximally sensitive search across the full LIGO-Virgo band isn't just impractical, it's impossible.

Fortunately, there's more than one way to run a CW search. The most sensitive searches are usually "coherent" searches. Coherent searches compare the data to a number of predefined signal models. This is the most sensitive search that can be done for a standard signal, but that sensitivity comes as a price: the computational cost skyrockets if the observation time is long or if the number of signal models required is very high, which it is for the supernova remnant search.

When a coherent search is impractical, a semi-coherent search is often the best alternative. In this scenario, we break the observation time into small blocks and analyse each block coherently before tying them together. There are many ways to tie the blocks together. By varying the way we analyse each block and how we tie them together, we can develop different analysis methods optimised to find different kinds of signals.

In the recent search for young supernova remnants, we used three different, complementary semi-coherent analyses to search for CWs. One was optimized for sensitivity; another for flexibility, allowing for unusual signals; the last was optimized for a specific physical model.

Our search for supernova remnants in Observing Run 3 didn't find a CW detection this time. But we were able to set an upper bound on how elliptical these neutron stars could be. Next time, if we're lucky, we'll be sharing a new discovery instead. If we're very lucky, we'll be able to meet in the same time zone – but until then, we can at least meet via Zoom, even if it is at 6:00 AM.

LIGO 2021

The supernova remnant Cassiopeia A (Cas A). This image was taken with the NASA/ESA Hubble Space Telescope.

LIGO India
The Search for the Perfect Site

Members of the LIGO India team with the central station marker. Left to Right: Milind Goverdhan, DCSEM ; Sendhil Raja, RRCAT; Subroto Mukherjee, IPR; Author Tarun Souradeep, currently at IISER Pune.

The story[1] of searching for a site for LIGO-India begins with a conversation I had in late 2011 with Late Professor Govind Swarup, renowned Radio astronomer and the man behind the Giant Meter-wave Radio Telescope (GMRT) and Ooty Radio Telescope (ORT) in India. Thumbing through the project proposal document that I shared with him, he quizzed "What do you think is the most challenging aspect of the project?" Before I could answer, he continued, "... you will talk about all the technical challenges, but your biggest challenge will be to identify and acquire the large swath of land. You will need to start working on it right away!"

Tarun Souradeep

currently chairs the Physics department at the Indian Institute of Science Education and Research (IISER), Pune. He has built and led a cosmology group on Cosmic Microwave background (CMB) studies. He led the sole Indian group within the international team of the Planck CMB space mission of the European Space Agency. He serves as the spokesperson for the LIGO-India mega-science project and the member secretary, LIGO-India Scientific collaboration for the construction and operation of a gravitational-wave observatory on Indian soil.

This was remarkable foresight for the challenging endeavor that was to unfold over the next eight years. LIGO-India, at that time, had no formal approval from the Government of India. It had been proposed in 2012 as a mega-science project to be jointly funded by the Department of Atomic Energy (DAE) and the Department of Science and Technology (DST) of India. Three lead institutions: Institute for Plasma Research (IPR), Raja Ramanna Centre for Advanced Technology (RRCAT), and The Inter-University Center for Astronomy and Astrophysics (IUCAA) in Pune, were identified for its execution.

The absence of a formal approval meant there were no project funds at hand. Further, it also placed huge constraints on other resources and limited our ability to formally deal with the state and district machinery. Enthusiastic support from the then Director and the Chair of the Governing Board of IUCAA helped with the former, by reserving some funds from its budget. The latter involved learning to coordinate within the limited resources and personnel available, on a very modest, but flexible, budget and with a strong element of Indian 'jugaad' (an Indian word that is now part of the Oxford English Dictionary) that makes the story more exciting.

My first visit to a candidate site was in mid-September 2011, near Challakere, a town about 200 kms from Bangalore with Bala Iyer, Albert Lazzarini and Stan Whitcomb. We wanted to check if the facility could fit and co-exist in a 11-thousand-acre span of land alongside a number of other institutions. Our early lessons? First, get an idea how far a distance of 4 kms appears on the flat ground. Second, understanding that even fairly arid and "desert-like" land in India hosts people and cultivation. And third, our first taste of state bureaucracy, albeit in this case a very positive one: from dealing with the paper-less office of the Principal Secretary, right up to presenting our findings to the Chief secretary (the topmost bureaucrat of the state administration)

[1] *A detailed site selection report is filed in the* ***LIGO DCC (T1600181)****.*

Panorama of the LIGO India site with site surveyors.

together with Directors of all the institutions to whom the land had been allocated. Although fairly promising, this reached a dead end after a short seismic survey, since coexistence with the other campuses risked significant anthropogenic noise due their planned activities.

The next year, 2012, was a total blur of many visits across the country following up many, many leads. A key milestone was the timely induction of Sharad Gaonkar, a top-notch seismologist, and then recently retired Senior Deputy Director General of the Geological survey of India. Sharad's involvement launched a more informed search, starting with poring over seismic propensity maps of a recent report of National Disaster Management more knowledgeably, creating a reasonable requirements document, establishing a protocol of following leads – first, a round of online study with Google and Bhuvan maps of the Indian Space Research Organization (ISRO), then a few exploratory site visits, discussions at district level or state levels as required and setting up a short seismic study. The experience came in all flavors, from the borders of the Thar desert to the heartland of Madhya-Pradesh, learning about fly-zones of military fighter jets from bases, sharing cups of tea (and some times a 'little' more) with village chieftains; learning from the rich, vast and varied experience of co-passengers ranging from land related bureaucracy, geological lessons, local cultivation, historical and mythological stories around various places. All this was made possible by wholehearted participation of team-members from other institutions, RRCAT, TIFR-Mumbai, IISER Kolkata, and the constant involvement at a top-level liaison from LIGO USA lead by Stan Whitcomb and later Fred Raab. Also vital were the very helpful heads, academic colleagues and other functionaries of academic institutions (ICTS, IISER Bhopal, IIT Jodhpur, Udaipur University) providing support and district/state level contacts.

Preliminary seismic studies at a shortlist of promising sites were conducted with instruments borrowed from Geophysicist, Prof. Supriyo Mitra, IISER Kolkata, set up at various instances, by his student, Sharad, Sendhil Raja and his team from RRCAT, Unnikrishnan (TIFR), Rajesh Nayak (IISER Kolkata), Sanjit Mitra (IUCAA). Managing the availability, schedule and travel was a fair task in itself, so was ensuring the safety of the equipment, and the immense time and effort devoted to picking up and carrying out the seismic data and terrain data analysis by gravitational-wave expert, Rajesh Nayak. By the end of November 2013, this extensive exercise led to a shortlist of four sites, two in the state of Madhya Pradesh and one each in Rajasthan and Maharashtra that all did well on the basic scientific requirements.

The next task was to create a prioritized list. The key issues that emerged were: (i) technical feasibility, time and cost of civil construction; (ii) challenge posed by land acquisition and expected time of completion, and (iii) long term aspects of efficient operation of the gravitational-wave observatory. Each site scored well on certain parameters, and not so well on others. We clearly needed more information to proceed further!

To even address the first point, accurate topography was required beyond that pro-

vided publicly by Google, or Bhuvan. A breakthrough here was the realization that the raw resolution of the data leading to Bhuvan maps must be considerably higher, given the specifications of the ISRO Carto-Sat satellite. A friendly phone call between the Directors of IUCAA and Space Applications Centre (SAC) of ISRO, allowed us to soon get swaths of full resolution data that allowed our team to create adequately detailed 2-D relief maps for each of the short-listed sites. It was then possible to employ the services of a top-notch engineering consultancy firm to carry out a detailed site-feasibility study focusing on the civil construction of LIGO-India observatory. To address the second point regarding the feasibility and ease of acquisition, another consultant Prof. R. Gohad (retd. College of Engineering, Pune), with expertise on land acquisition was hired at IUCAA. A thorough understanding of the applicable Land Act, its consequences for the feasibility and expected timelines for the process of acquisition were worked out. Additional information on sizes and facilities at the site, and neighboring towns and cities, was put together by some members of the team over the next year or two. A lot of rather difficult-to-find information was also made available through the efforts of Shri Pandurang Pole, a very enthusiastic official from the Indian Administrative Service.

By Fall 2014, a formal site selection committee set up by the DAE was tasked with making the final recommendation of the primary and back-up sites for LIGO India. LIGO-US also pitched in with active participation in these discussions and site visit, with the involvement of Fred Asiri, an expert who had overseen LIGO site selection in the USA. The LIGO-India site selection committee was co-chaired by the Directors of RRCAT, IUCAA, as well as involved experts of the Directorate of Construction, Services and Estate Management (DCSEM) of DAE.

By February 2016, following the scientific milestone of the GW150914 discovery, we had the momentous 'in principle' approval for LIGO-India by the Indian government. The then Secretary of the DAE immediately took charge with a keen interest to get things going, setting in place a formal project organization structure that could take final decisions on important aspects of the project. The inclusion of DCSEM as another lead institution brought into LIGO-India much needed expertise, experience and considerable manpower to finalize the site selection, acquisition, and civil construction. The final recommendation of the LIGO-India site selection committee was accepted by the project boards and their findings were recorded in an extensive report in Sept 2016. This was followed by the remarkably successful site acquisition, the feasibility of which was an important driving factor for final choice of the site.

The final LIGO-India site is in Aundha Tehsil, Hingoli district in the central Marathwada region of Maharashtra state in Western India. It is located 65 km from the city of Nanded, with the nearest airport being 220 km away in Aurangabad. Unlike the other sites which were indicated by leads, this site was essentially 'deduced' through the use of remote sensing images. Seismologist Sharad Gaonkar had a gut instinct of possible sites to the east of the Lonar crater. A systematic scan and search of the area revealed this promising site clearly standing out due to the barren soil on the Hingoli plateau. Befittingly, it was the Indian GW guru, Sanjeev Dhurandhar, who went for the first site visit along with Sharad, braving really extreme summer temperatures. The next visit was in much better weather in November 2013, and it included members from the LIGO US team.

The Hingoli plateau has a natural location advantage as an isolated region, with less interference from industrial development and the size of neighbouring settlements being small. It is largely barren with scrubby vegetation. The weather is very dry. Monsoon rains start from the month of June and end in September. For these few months, the region transforms into being pretty lush green compared to its usual barren look. The Spring brings out a lovely bright red bloom in the few small trees scattered around. Rain-fed agriculture is practiced on less than 10% of the area. The rest comprises grazing land under the state government or federal reserved forest. The region is a mix-pot of two local cultures. The Marathwada area was historically governed by the Nizam of Hyderabad and still retains quaint ties with the Nizami values and culture, while there is a healthy infusion of typical rural Maharashtra that is slowly taking over. The Aundha tehsil also hosts the ancient Aundha-Nagnath temple that, besides being an important pilgrimage site that attracts about 100,000 visitors every year, is worth a visit for its nice architecture and a taste of local culture. Nanded city hosts the second most significant sikh holy site –the Sri Huzur Sahib Gurudwara. Also close to the LIGO-India site is a geological marvel: the unique Lonar crater lake formed by meteor impact. About a 125 km drive away, it makes for an excellent day outing. We look forward to hosting curious colleagues at Aundha soon!

Beautiful stone sculptures adorn the walls of this nearly one thousand-year old temple at Aundha-Nagnath.

Spring blossoms at the LIGO India site.

Remembering
Prof. Dhiraj Bora and Dr. Srikumar Banerjee

Prof. Dhiraj Bora

It is with great sadness that we share news of the passing of Prof. Dhiraj Bora on June 19, 2021. Prof. Bora contributed towards the Technology Development and Capacity Building phase of the LIGO-India project at the Institute for Plasma Research (IPR), Gandhinagar.

Prof. Bora was an alumnus of the Physical Research Laboratory (PRL), Ahmedabad and was associated with the Plasma Physics Programme right from its inception during the early eighties, finally leading to the formation of IPR. After his work at IPR on plasma heating and current drive systems, he worked at ITER Organization (France) as the Deputy Director General and the Director of the Heating and Current Drive (H&CD) Department during 2007-2013. He subsequently returned to IPR as its Acting Director and served in this capacity till mid-2016. Prof. Bora will be remembered for his diverse contributions to IPR and the LIGO-India project.

Dr Srikumar Banerjee, Chancellor of the Homi Bhabha National Institute (HBNI), Former Chairman of the Atomic Energy Commission (AEC), and Secretary of the Department of Atomic Energy (DAE) passed away on May 23, 2021 after suffering a cardiac arrest. Dr. Banerjee had been associated with LIGO-India since its inception.

Dr. Banerjee was born in Kolkata on April 25, 1946. He was schooled at the well-known Ballygunge Government High School, passing out in 1962. Banerjee joined the Indian Institute of Technology (IIT) at Kharagpur for a degree in Metallurgical Engineering, graduating with a B. Tech. in 1967. He then joined the Bhabha Atomic Research Center (BARC) as a Scientist. He was awarded his Ph.D. in 1974 from IIT Kharagpur. Dr. Banerjee rose to become the Director of BARC in 2004. He left BARC in 2010 to become the Chairman of the AEC in 2010, a post he retained till his retirement in 2012.

Dr Srikumar Banerjee

The first formal proposal for the LIGO-India project was made to the Mega Science Consortium of the Department of Atomic Energy and the Department of Science & Technology (DAE-DST) in its meeting held in November 2012, that was co-chaired by Dr. Banerjee along with the then Secretary of DST Dr. T. Ramasami. He has also served on the LIGO Oversight Committee from 2019 and was a member of the Committee till his demise.

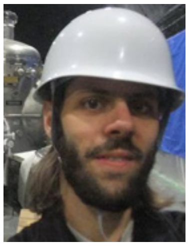
Dr. Banerjee is survived by his wife Ranjana and his son Rajarshi. The LIGO-India Team offers them sincerest condolences and mourns the passing of one of its very senior mentors and well-wishers.

Explaining LIGO-Virgo-KAGRA results to the global public

Since the announcement of the first detection of gravitational waves (GWs) shook the world in 2016, LIGO and Virgo have been successfully "making waves" in the attention of the global audience. Now also joined by our KAGRA colleagues, our "LVK" education and public outreach programmes cover the basics of our field (What is a GW? What is a black hole? How does an interferometer work?), but also the specific research we do in the here and now: What are our actual scientific journal papers about? A key medium for this are our "Science Summaries" [1]. These short texts cover the key points of each paper in a format and style accessible to a wide audience, including students at all levels and non-scientists around the world. As a global collaboration, we are also taking great efforts in translating these summaries to explain our science to more people in their own languages. For these translations, we draw on our member scientists from across the globe, and have so far published in a total of 23 different languages.

▲ *Our record holder so far: GW190521 science summary in 17 different languages.*

David Keitel



works at the University of the Balearic Islands in Palma de Mallorca, Spain on some of the "next first detections" that the LVK is going after: gravitational waves from individual spinning neutron stars and gravitationally lensed signals from compact binaries. In his free time, he likes to read or to explore the beautiful nature and coast of his host island.

Isabel Cordero-Carrión

works in the University of Valencia, Spain on applied mathematics and astrophysics, with special interest in the development of numerical methods for solving partial differential equations and performing numerical simulations of astrophysical scenarios to extract their gravitational radiation. She loves music and playing the flute in particular, dancing flamenco and playing soccer with her friends.

Summaries in the online and offline worlds

Summaries are usually between 2 and 4 print pages long, including illustrations and figures taken from the paper. They introduce the specific paper's topic, very briefly explain the methods used, and focus on the results and their impact. The reading level is somewhat higher than in newspaper science stories, more similar to dedicated science magazines for enthusiastic lay readers. We reduce mathematical notation and technical terms as much as possible, but we also try to teach the readers a few new concepts and terms in each text, using glossaries and external links to explain in more depth.

Behind the scenes, work on a summary usually starts some weeks or months before the paper becomes public. We (David and Isa) will identify someone closely involved with the paper to draft the summary and two volunteers to review it, checking that the explanations will make sense to a broad audience. This is now also integrated as a deliverable in our internal project planning and editorial team roles for each scientific paper.

For the three observing runs since 2015, we have already written around a hundred papers [2] and summaries of these. The summaries are published online at ligo.org [1] and advertised through social media. We also provide attractively formatted PDF files for download, which have traditionally proved very popular at real-life outreach events. (Special shout-out to Martin Hendry from the University of Glasgow for his tireless layouting work!) The summaries are also very useful as resources for starting research students, and science journalists like to use them to get an overview of new results, multiplying their impact.

Translations: improving our global reach

Most of global science, and science communication, is conducted in English. But to reach the broadest and most diverse audience around the globe, we need to bring our science to people in their own languages. Our first science summaries were getting translated into Spanish since 2014, but the effort has significantly picked up since 2016. By now for 22 different languages (beyond English) we have at least one summary translated and, as a record, the discovery of the exceptional event GW190521 was covered in 17 languages.

These translations are a fully volunteer-driven effort: very few LVK members are paid for outreach, so most translators are scientists and students who do this in their free time. We try to have the English summaries ready early enough to give translators time before a paper becomes public. We then send out a request to a translation volunteer email list, people self-organise to form pairs of translators and proof-readers for each target language, and often within a few days the first completed translations come in. Translators also often have a great eye for finding details that weren't 100% clear in the English version, sometimes leading to a scramble to update all versions of the summary, but ensuring a higher-quality output. For big discovery announcements, we then usually have several translations ready to go live on "release day", while for other papers the schedule may be a bit slower since volunteers have to find time among their many other commitments. So it is always worth checking back on ligo.org as additional translations will often be posted later on.

And as a take-away message for readers from other large international collaborations: you likely also have a big talent pool available for doing outreach in general and translations in specific; people just need to be motivated and organised! Writing and translating outreach texts is also a great opportunity for scientists, especially early-career researchers, to hone their writing skills. But foremost, what we realised is that when telling the global public about what we do, translations are a crucial ingredient to improve global reach and to really bring our science to the people.

Sharon Yellowfly, who translates into Blackfoot, with her son Corey Gray, an operator at LIGO Hanford.

Start of the online version of an example science summary (GW190814 discovery).

THE CURIOUS CASE OF GW190814: THE COALESCENCE OF A STELLAR-MASS BLACK HOLE AND A MYSTERY COMPACT OBJECT

Dated 23 June 2020. Read this summary in PDF format (in English) and in other languages: Blackfoot | Chinese (traditional) | Dutch | French | German | Italian | Japanese | Marathi | Polish | Spanish .

FIGURES

Artist's impression of the curious case we have discovered. Credit: Robert Hurt (Caltech)

Volunteer perspectives

To highlight the enthusiasm that goes into translating science summaries and the personal motivations, here are quotes by some of our most active volunteers:

Cristina Martí, undergraduate student at University of the Balearic Islands, translating… into Spanish:

"La traducción de resúmenes científicos brinda la oportunidad de entender la ciencia a todos, un objetivo imprescindible para conseguir una sociedad comprometida con la causa científica."

into Catalan: "La traducció de resums científics ofereix l'oportunitat d'entendre la ciència a tothom, un objectiu imprescindible per aconseguir una societat compromesa amb la tasca científica."

("The translation of science summaries provides the opportunity for everyone to understand science, an essential goal to achieve a society committed to the scientific cause.")

Nicolas Arnaud, CNRS researcher at Université Paris-Saclay and EGO, translating into French:

"Communiquer sur nos découvertes et, en particulier, les expliquer en français, ma langue maternelle, est ma façon de redonner ce que j'ai reçu. Une traduction prend du temps bien sûr mais comprendre que le public ou des lecteurs, ont découvert quelque chose de nouveau grâce à son travail n'a pas de prix."

("Communicating about our discoveries and, most importantly, explaining them in French, my mother tongue, is my way to give back. Translating can be time-consuming of course but seeing that an audience or some readers have understood something new thanks to your work is definitely worth the effort.")

Hisaaki Shinkai, professor at Osaka Institute of Technology, translating into Japanese:

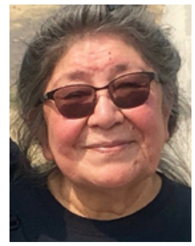
"Science Summaryは，手取り早く論文内容を理解するのに適しています．一般向けとはいうものの，内容は大学生向けでもあり，分野外の研究者にも役立つと思います．惜しむらくは，翻訳に名乗り出てくれる院生がまだいないことです．いい勉強になるんだけどなあ．私だけどんどん賢くなっちゃうよ"

("Science Summary is good for quickly understanding the contents of a paper. Although it is intended for the general public, the content is also suitable for undergrad students, and I think it is also useful for researchers outside the field. It is a pity that no graduate student has yet come forward to translate the article. It would be a good learning experience definitely. I'm getting smarter and smarter …")

Edoardo Milotti, professor at University of Trieste, translating into Italian:

"Science Summaries sono qualcosa di meno ma anche qualcosa di più degli articoli scientifici pubblicati dalla Collaborazione. Non possono comunicare i profondi aspetti tecnici degli articoli scientifici, ma spiegano la bellezza dei risultati scientifici, cercano di accendere la passione per la nostra scienza."

("The Science Summaries are both less and more than the scientific papers published by the Collaboration. They cannot communicate the deep technical aspects of the scientific papers, but they highlight the beauty of the scientific results, they aim to bring out the passion for our science.")



Sharon Yellowfly, translating into Blackfoot [3,4]:

"iss***suu***buyaabanisdaxin niixi LIGO's gii Virgo's utu?***gwi***niimaxin amustsk Abuduuxbiisii o?bigimskAAsts i_tu****doots***tsiiya sigooxgaya ***nA***buutsbiiya spuu?ts ***nu***?ganistsiitsiip ixgunadabii uutsistabiitsip gii a~ku*banyuup gii***stuun***nuun nitsi***da***biix. a***yo***?gwisxiniip myanistsiixim_daan gii ***a***gitsuubuyaabanisduutsiibya nitsi***da***bibu~a?sin, ***manii***-bu~a?siniists, ni***dumuu***?dAximst ni***stun***naan, ***nu***gusiix gii ists***gaa***biists i_tu?***duts***tsiiw iesstuumskuutsp gii its***tsii***ya. okii Albert."

("Translating LIGO's and Virgo's findings of gravitational waves from black holes colliding in space has been a life-affirming experience for me personally and a culture-affirming experience for the Blackfoot people. To learn new ideas, concepts, and abstractions and then translate them into Blackfoot, creating neologisms, connects me to my language, my people, and the science that deals with energy and matter. Thank you, Albert.")

References

[1] https://www.ligo.org/science/outreach.php

[2] https://pnp.ligo.org/ppcomm/Papers.html

[3] N. Greenfieldboyce 2019, NPR, https://www.npr.org/2019/03/31/706032203

[4] M. Fore 2021, Symmetry Magazine, https://www.symmetrymagazine.org/article/einsteins-garden-translating-physics-in-to-blackfoot

A giant in Gravitational-Wave Astronomy

The starry sky above Arecibo Observatory in Puerto Rico.

Arecibo Observatory is one of the largest single-unit radio and radar telescopes in the world. The tragic demise of this facility on 10 August 2020 came as a huge shock to the research community around the world. In this article, we briefly recap the success of Arecibo observatory and describe how it's last hurrah might have been detecting low-frequency gravitational wave hums with NANOGrav. We also hear testimonials from members of the gravitational-wave community who have benefited from visiting or working with this telescope.

Sumeet Kulkarni

is a Ph.D. student studying population properties of compact binary mergers at the University of Mississippi. He pursues astrophotography in his spare time and when the night sky permits it. Sumeet is also passionate about increasing public engagement in science, through writing popular science articles and hosting a local science cafe in Oxford, MS.

Deeksha Beniwal

is a Ph.D. student at the University of Adelaide. Her research focuses on looking for continuous gravitational wave signals from very high energy sources. Deeksha enjoys going for walks, doing cross-stitch and cooking in her spare time.

The story of the Arecibo observatory started in the era of the space race. Following the successful flight of the world's first artificial satellite (Sputnik) in 1957, the United-States Department of Defence quickly came to the realisation that the Soviet Union had advanced capability to rapidly exploit military technology [1]. In an attempt to organise competing American missile and space projects and explore technologies with potential military application, President Dwight D. Eisenhower authorised the creation of the Advanced Research Projects Agency (ARPA) in 1958.

Among other anti-ballistic missile defence projects, ARPA was exploring the idea of identifying nuclear warheads re-entering the Earth's atmosphere by their unique signature in the ionosphere. However, both the physics of re-entry and the composition of the upper layers of the ionosphere were poorly understood at the time. Around the same time, Professor William E. Gordon first conceived the idea of using incoherent scattering[1] to probe the ionosphere [2]. This idea progressed rapidly and became the basis for the design of the Arecibo Ionospheric Observatory (AIO). With funding from ARPA and oversight from the US Air Force and Cornell University, the construction of this 1000ft (305m) diameter radio observatory, located in a sinkhole near Arecibo, Puerto Rico was completed in November 1968 [2,5].

While serving its primary objective of mapping the ionosphere, this multi-purpose facility was also used by radio and radar astronomers, for example, to accurately measure the orbital period of Mercury and the Crab pulsar as well as discovering that Venus rotates retrograde about once every 245 days [3]. Since the National Science Foundation took over the funding and management oversight of AIO in 1969, the Arecibo Observatory has been at the forefront of numerous groundbreaking discoveries.

[1] *This technique involves transmitting high-power radio waves to the ionosphere where the radar waves incoherently scatter off free electrons in the ionosphere. The returned power can then be used to directly measure the electron density as well as the electron and ion temperatures and ion drift velocity.*

The receiver platform was suspended 150m above the dish. On 1st December 2020, several cables broke and the main telescope collapsed.

Among these include kick-starting the field of observational gravitational-wave physics! Arecibo observations were used in the discovery of the first-ever binary pulsar (aka the Hulse-Taylor binary) in 1974 [3]. Additionally, the orbital period of the system was measured to decay over time. This was consistent with loss of energy from the system in the form of gravitational waves, as predicted by Albert Einstein's general theory of relativity. As such, this discovery provided the first indirect detection of gravitational waves and was awarded the Nobel Prize of Physics in 1993.

Arecibo's most recent contribution to the field of gravitational-wave astrophysics has been in our search for low-frequency gravitational-wave background using pulsar timing arrays, as a part of the North American Nanohertz Observatory for Gravitational Waves (NANOGrav) collaboration.

NANOGrav and the Gravitational Wave Background

Gravitational wave chirp signals seen by ground-based detectors like aLIGO, aVirgo and Kagra have frequencies in the human audible range, and hence can be converted into audio. Being very short-duration, they sound like plucked notes of a violin.

Low frequency gravitational waves, on the other hand, sound more like the background rumble in this spacetime symphony orchestra. Such signals are expected to come from mergers of supermassive black holes. These gargantuan objects, with masses more than a million times the mass of the Sun, emit substantial gravitational-waves even when they're well separated and revolving around each other over a period of more than a year. This means that the signal frequency lies in the nanohertz (nHz) range, giving NANOGrav its name. Instead of detecting individual mergers, the low-frequency spectrum is expected to be dominated by the collective background hum of a population of supermassive black hole pairs, or binaries; think of a hundred cellos drawing different notes simultaneously, as opposed to the plucking of a few lone violin strings. This is called the stochastic gravitational-wave background.

In order to hear the gravitational-wave background, Pulsar Timing Arrays (PTAs) such as NANOGrav keep their eyes on an array of Millisecond Pulsars (MSPs) spread throughout the galaxy. MSPs are compact neutron stars: "objects with mass a little over one solar mass, squeezed into an area the size of a city downtown, and spinning as fast as a kitchen blender", as described by NANOGrav physicist Joe Simon. Being pulsars, they emit pulses of radiation with extraordinary punctuality in the millisecond timescale, which NANOGrav has kept track of using Arecibo and the Green Bank telescope. Each of the 45 pulsars acts like a probe for gravitational-wave detection, which makes NANOGrav almost a galaxy-sized detector!

Assuming the center of mass of our Solar System, or 'barycenter', is a fixed reference point in the array of 45 pulsars, the time(s) at which these pulses arrive there with respect to each other can be accurately measured. One way in which this regularity can be perturbed is by a passing gravitational wave, which displaces the barycenter like a floating duck. This leads to the pulses from the pulsars towards which we are displaced arriving sooner, and vice versa. These dis-

Damage to the telescope at the Arecibo Observatory. Taken on 8th December 2020.

placements are extremely tiny, so to make a detection we need to observe and correlate the pulse arrival times from a set of pulsars spread across all angles and over a large period of time. With enough data, we expect to see a characteristic pattern of correlation in the timing of two pulsars based on the angle they form with respect to the barycenter. This unique signature is known as known as the 'Hellings and Downs curve'.

Over many years, PTA groups around the world have published upper bounds on how strong the gravitational-wave background could be whilst still escaping our detection. In the latest results from NANOGrav, a possible signal at low frequencies has been revealed for the first time [6] and evidence is also seen by the Parkes PTA [7]. The nature of the signal is uncertain and time will tell whether this is indeed the signature of the gravitational-wave background. Future observations and combining data from the PTAs might show increasing evidence for these correlations.

While the sad demise of Arecibo is a big blow to the entire community of pulsar timing arrays, there is still recorded data from the legendary telescope that can contribute to NANOGrav's next big data release. It is only a matter of time before the right chords are struck to reveal the gravitational-wave background, and it would be a fitting tribute if Arecibo was indeed listening to it in its last moments.

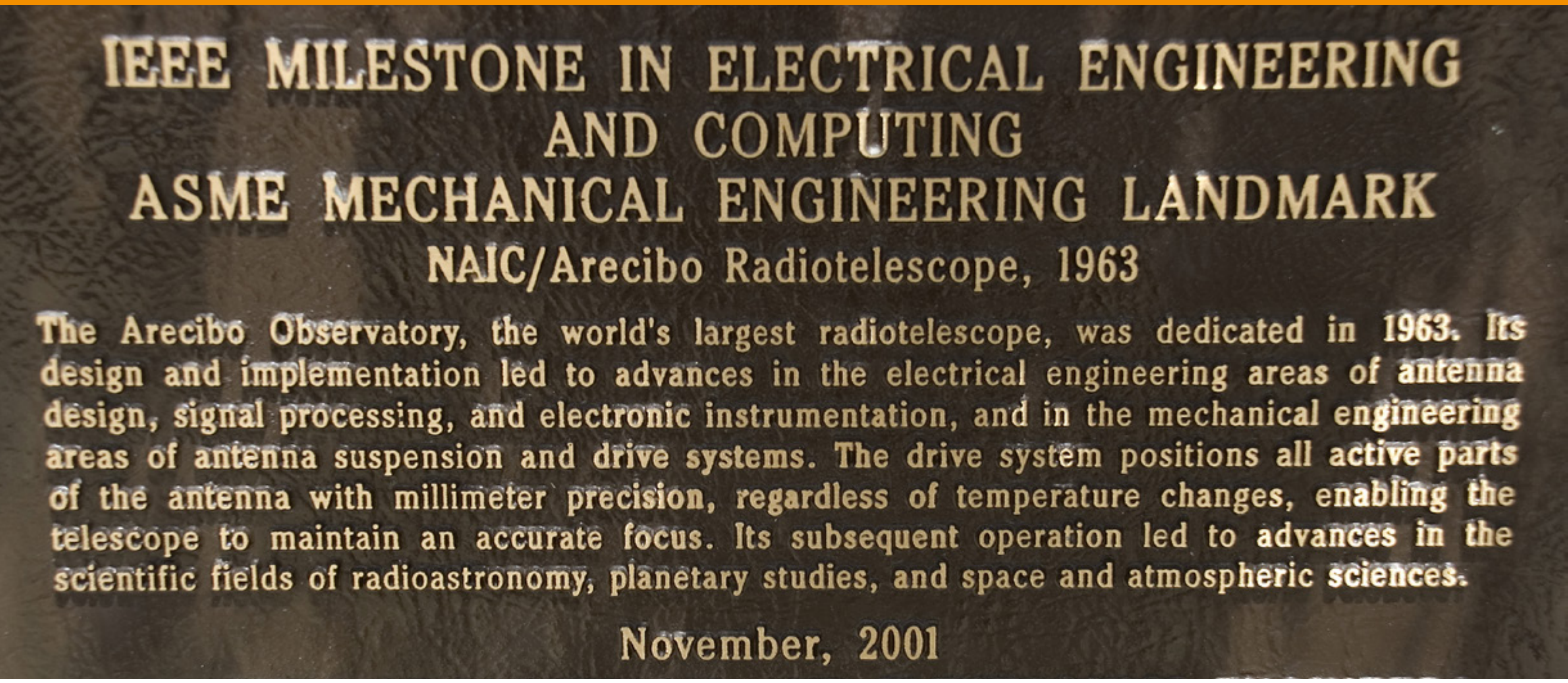
Memories of Arecibo from the gravitational-wave community

My first attempt to visit Arecibo (12 yrs ago?) was foiled when I and my friends excitedly arrived only to find it was closed for the day (a Tuesday, as I recall). Undeterred, I rented a car and drove back on my own the next day because I needed to see it. Such a magnificent facility. I still have, and use, the travel mug and grocery tote bag I purchased from their visitor center gift shop.
Kim Burtnyk, LIGO Hanford Observatory

As part of my PhD thesis I analysed PALFA pulsar survey data taken by the Arecibo telescope with Einstein@Home.. I was very lucky to discover two new pulsars – both somewhat unusual – during my studies, which helped me write a nice thesis. In 2009 I spent about ten days at the site to learn how to observe with the telescope. A truly wonderful time including a tour of the platform I'll always remember fondly.
Benjamin Knispel, Max Planck Institute for Gravitational Physics (Albert Einstein Institute) Hannover

I would like to highlight Arecibo's role in the discovery of the Hulse-Taylor pulsar (PSR1913+16) whose orbital decay provided incontrovertible evidence for the reality of gravitational waves as well as for the existence of binary neutron stars. This proved to be a precursor to the then envisioned but never before detected potential ground-based gravitational-wave detector source. Both these aspects of this discovery were used in "political" advocacy for LIGO.
Beverly K. Berger, Stanford LIGO Group

I was lucky enough to spend the summer of 2013 at the Arecibo Observatory as an REU student. I fell in love with both the telescope and pulsar astronomy; it was the beginning of a journey that eventually led me



IEEE sign at Arecibo observatory

to continuing pulsar timing array work as a postdoctoral fellow. Long nights of observing yielded exciting scientific results, which convinced me that graduate school, and an eventual career in astronomy, was something I could actually pursue. I'm heartbroken for all the staff, scientists, and students in Puerto Rico enduring the loss of the telescope, and have hope that the observatory will be re-imagined and rebuilt.
Thankful Cromartie (NANOGrav), Einstein Postdoctoral Fellow, Cornell.

In 1992, I was an undergraduate student at Penn State. I'd had no research experience and was not even sure I wanted to major in astronomy/physics or something else entirely when I approached Prof. Alex Wolszczan to see if he had any research projects. He did, and I was lucky enough to get to go to Arecibo that summer. I was completely awestruck by not only the telescope itself, but by the welcoming and enthusiastic community of scientists, engineers, and staff at the telescope, and I decided then and there that I was going to be a pulsar astronomer! I'm so grateful for the role that Arecibo has played in my scientific life and for its remarkable contributions to pulsar astronomy since that time, in particular for its vital importance to the NANOGrav project over the past 16 years.
Maura McLaughlin (NANOGrav), Eberly Distinguished Professor, West Virginia University.

I first went to Arecibo in 1972 as a first year grad student, only a few years after pulsars were discovered. My advisors and I were doing a project that required maintenance on a feed antenna, so it had to be lowered from a boom hanging off one of the carriage houses on the azimuth arm. To do that some cables had to be disconnected and I was elected to do that. As I was putting on a safety belt, my main advisor was saying, “better that you go, Jim, since I'm wearing sandals.” So there I was hanging 500 feet above the dish. Little did I know what would happen 48 years later.
Jim Cordes (NANOGrav), George Feldstein Professor, Cornell

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by Grant David Meadors

Solar Wind-swept to New Mexico

Grant David Meadors hiking up the hills of Cerro Grande on the slopes of Valles Caldera.

As Jupiter & Saturn converged in my telescope eyepiece last year, long nights heralded a brighter future: I had finally become a staff scientist in the Space Data Science group, high on the mesas of Los Alamos National Laboratory. Now I hope to help new discoveries emerge.

My journey started with summer internships at LIGO Hanford Observatory in 2005 and Caltech in 2007, through my PhD at the University of Michigan, and postdocs at AEI Hannover and OzGrav in Monash University. Characterizing instruments and analyzing continuous waves around the globe gave me pride. Too many colleagues to name helped me to coalesce into the astrophysicist who I am.

Astronomy always enchanted me, as physics revealed the stars. Wonder at the cosmos turned into self-reflection. Months measuring mirrors in the desert spurred the courage to trust in my own truth: to come out as a gay man. In the year of the Big Dog, I met another scientist who inspired me with his own clarity. He & I were divided by mountains and oceans for most of the decade we've known each other. After first detection, my sense of duty changed. We married. I returned from adventure overseas.

When I left to study the solar wind here in February 2019, I said (for now) farewell not only to tumbleweeds & telecons, but to a community. I felt both sacrifice and relief – to stop competing with my old friends.

A NASA-funded space-weather project at the Lab offered a bridge to a two-body solution. Models of the Sun's corona could use statistical particle filtering for solar wind predictions at satellites. I synthesized skills from my LIGO noise-subtraction filtering and Bayesian inference work and showcased the results at the American Geophysical Union. It was, at 2019's close, the largest conference I'd ever attended – and the last.

As the pandemic swept this piny plateau, I peeked out betwixt junipers every evening to finish the Messier galaxy catalog. Indoors, my Space Weather manuscript got published; I reviewed similar papers and even pitched in an integral for a COVID publication. We hiked down the Rio Grande and up Valles Caldera.

Being in my third postdoc, options seemed dim. Trying to simulate plasmas made me miss the relative simplicity of gravity. I applied to the Space Data Science group, keen perhaps to bring LISA to Los Alamos. Once I joined, I began experimenting with neural nets. Possibilities are beginning to appear again, and so do responsibilities.

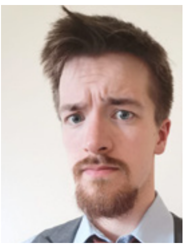
This planetary calamity has asked patience of us all. Other crises demand action. As a past LVC Ally, I now belong to local initiatives in justice, equity, diversity, and inclusion, while acknowledging the danger of assimilating into the dominant culture on this land that once belonged to the Tewa pueblo peoples. Wisely or not, researchers are respected. Our debt persists to future generations: a cooler, calmer Earth, a kinder, humbler humanity.

Understanding the universe is only the beginning. We all leap into the unknown with every theory and experiment. Life transcends LIGO.

Pandemic PhDs: How the Pandemic has Affected Us

We have now been living with the COVID-19 pandemic for well over a year, and know that it has significantly affected everyone's lives in and out of work. We spoke to five of our early career researchers to hear the negative – and positive – effects of the pandemic for them both in the shorter and longer term.

Graeme Ian McGhee



is a 2nd year PhD candidate at the University of Glasgow working in mirror coating development. Graeme began his research in 2018 as part of his undergraduate studies. He also has an avid fondness of honey and camomile tea.

Huy Tuong Cao

is currently a postdoc at the University of Adelaide, working on Active Wavefront Control upgrades for O4. When not working in the lab, he enjoys being outdoors hiking and running.

Leigh Smith

is a 1st year PhD student at the University of Glasgow working on black hole encounter burst events. She started her candidature in October 2020 during the COVID-19 pandemic.

Q: How have you found your PhD so far?

It has been a weird but rewarding experience so far. It's been 11 months since I started and I've not actually been on campus yet! Working from home took a while to adapt to, though my experience with my Master's project really helped as a solid foundation to build upon. I'm enjoying my work and have gotten well into the swing of things now. Essentially the pandemic allowed me to have an extended reading period and firm up my knowledge.

Q: What impact has the pandemic had on your wellbeing?

Adjusting to the lockdown was quite the challenge. I'm sure many of us can relate to the experience of inhabiting exclusively the same few rooms for most of the day while the world stands still, and I did get lost in my own head at times. Initially, it was hard to push through and get work done. However, things have become much better as the year has gone on, and I feel I have now adapted to this new way of working and socialising.

Q: Did lockdown have any positive impact on your progress?

Ultimately, I feel lockdown gave me a bit more control of my time management, and forced me to take that responsibility fully on myself. I was also able to dedicate a bit more time to taking college training courses than usual. Networking over Zoom has been good in certain respects as well. I've got to "attend" significantly more conferences than I otherwise would in normal times.

Q: Did you develop any strategies for getting through lockdown?

Setting myself a routine, trying to stick to the 9am-5pm, getting into the working mindset – and knowing when to switch off – really helped me. I've also been doing a lot of plant keeping, playing my Switch, and we recently got a new addition to our house, a dog, all of which has kept me happy and entertained!

Q: Have you felt supported by the collaboration and/or your institution in the pandemic?

My supervisor has been very supportive. The Glasgow data analysis group Zoom meetings have been great in integrating me into the research group, and keeping me up to date with what everyone else is working on.

Q: In the context of work is there anything you think won't ever go "back to normal"?

I think online conference integration/attendance will probably become a lot more prevalent than before.

Dr. Aaron Jones

received his PhD from the University of Birmingham in 2020 for his work on understanding impacts and mitigation of wavefront distortion in high precision interferometry. He now works as a Postdoctoral Research Associate at The University of Western Australia.

Q: How were your post-PhD plans affected by the pandemic?

I got an offer to work at the University of Western Australia (UWA), but Covid-19 brought about lots of uncertainty, and the process of getting an exemption and visa to come and work in Australia was very difficult. My fiance and I had to set hard deadlines for ourselves regarding when we would have to give up pursuing my position at UWA. We pushed this deadline back twice. The last few months before moving to Australia, we were staying with our family and it was progressively getting harder. Luckily, we got both of our exemptions and visas just days before our hard deadline, but then had to rebook flights four times. The third time, the flight was canceled on the day. We decided to give it one final try. Had it not succeeded, we would have given up and started looking for jobs back in the UK. That last attempt finally brought us to Australia, though at a much more expensive ticket price.

I'm very grateful for the support that I got during that time. UWA kindly helped with moving costs, then provided me with a top-up due to the lengthy visa and exemption complications. The research group at UWA also allowed me to start my job remotely, part-time, a week after my viva. Thanks to my colleagues at Birmingham, I also found another part-time research job there.

Q: How was your experience working remotely?

The first few months were very hard. I never really solved the problem of time difference. Initially, I was trying to follow Australia time. I would wake up at 9 am Perth time (about 2 am in the UK), but then I wouldn't go to sleep. I then tried to work with UK time. But that was not suitable for any of the telecons. I ended up using an online time tracking tool to ensure that I work an appropriate amount of hours and get sufficient rest in between.

I also found that virtual conferences are just not the same. I was excited to present and get feedback on my work at conferences before, but in a virtual conference there is a lack of networking and general chit chat, which I think is very important. In a traditional conference, where you are physically away, there is also less expectation that you continue with local tasks, attend group meetings, etc. That is however not the case for virtual conferences, and it is not only your supervisor's expectation but also your own.

Q: Do you have any tips for early career researchers in a similar situation to you?

If your plan gets delayed, make the most out of that time! The delay allowed me to finish various projects that were 80% completed, so I was able to get more publications out right at the start of my postdoctoral career.

Maya Kinley-Hanlon

is a third-year Ph.D. student at the University of Glasgow where she works on coating development. Maya began her research with Prof. Gregory Harry in 2014, joining LIGO in 2017.

Q: Which special circumstances did you experience due to lockdown?

In March of 2020, when the pandemic was just starting to go global, I became increasingly aware of how far away I was from my family and how hard it would be to reach them. Together with my advisor, we got the paperwork in motion for me to work with my undergraduate advisor from the American University in case a stay in the U.S. occurred. On the evening of March 12th, Trump shut the borders to the U.S and my advisor messaged me that if I wanted to go home, it was time to book a flight. I packed one carry-on bag and flew home. I expected to be in America for a couple of months, but have now been here for just under a year and a half.

Q: Do you think that lockdown delayed your thesis progress?

There was some delay, but I did a lot of computer modelling, paper writing and started my thesis draft. When labs in Glasgow re-opened, I was able to remotely take data, and at times we have even been able to take more data than usual because of the time difference. The most positive impact I have seen through lockdown has been the strength of the LIGO collaboration. The relationships between labs allowed me to do what is best for my degree's progress and my mental health.

Q: How did lockdown affect your (mental) wellbeing?

Calling the past year challenging feels like an understatement. The pandemic, the fight for equality, the protests against injustice, the election and violent presidential transition made it hard to focus on my research. There were days when my research paled in importance compared to the needs and wellbeing of those around me. But through everything, it also helped keep me grounded. I am very thankful for my advisors throughout this year. I have felt supported in my desire to be home and close to loved ones. Being able to work in the labs at American University has been a huge resource to stay productive.

Q: Did you feel more or less pressured to produce results etc?

Generally speaking, the greatest pressure I feel is the pressure I put on myself. This has stayed relatively the same throughout this year and has kept me largely on track with my PhD.

Q: How did lockdown affect your work in an international collaboration?

I have missed in-person conferences more than anything else regarding the LIGO Collaboration specifically. The magic of conferences, in my experience, is being able to connect with people informally and I do not feel as though online conferences have filled that gap.

Dr. Craig Cahillane

is currently a post-doc working at LIGO Hanford Observatory (LHO). He received his PhD from California Institute of Technology in January 2021 for his work in calibration and controlling gravitational wave detectors.

Q: What was your experience during lockdown?

The first lock-down at Caltech started in mid-March last year. At the time, I was on the paper writing team for the Observing Run 3 detector sensitivity paper. I was lucky that the team was already remote, preparing plots and writing for the paper. Not having an office or the usual access to co-workers made it hard to get anything done. A few months into the pandemic, we completed the paper, and I realised that I had to give up the interferometer modelling I was doing and buckle down to apply for jobs and write my thesis.

I was living with my partner, Georgia, and housemates Gautam and Magnus at Caltech in the first few months of the pandemic. Then in August 2020, Georgia had to move to work at Hanford. So we all packed our belongings into a rental car and headed north to Richland, camping along the California coast to avoid contact with many people.

Q: How was the job application process during the pandemic?

Applying for a job during the pandemic was definitely not easy. COVID led to a lot of my job application talks being cancelled, including ones at the Albert Einstein Institute (Germany) and in Japan. I ended up giving remote talks to LHO and the Australian National University (ANU). The Zoom talks for job applications over the last year really made the whole process very formal. It was much more difficult to learn about a research group working culture through Zoom meetings.

Q: What was thesis writing like?

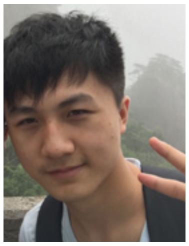
My advisor, Alan Weinstein, came up to me back in November 1st last year and told me "Craig, I'm looking at your thesis and I don't see a lot there". The only section I had written for my thesis at this point was some math required for analysing data in the Observing Run detector paper. After that, I sat down and wrote continuously for two and a half months. There were days that I collapsed after 4 hours. Luckily Georgia forced me to go for a walk to keep me sane. I developed a routine, including an hour of doing something active everyday, either walking or some indoor bodyweight workout, which was very helpful.

The day that I finished defending my thesis, Georgia and I drove to a waterfall near our place. It was an unforgettable moment – the experience of being out in nature without the looming thesis in my mind. There is that relief, but it also got me thinking about the next chapter of my life. My PhD thesis had been my proxy. As soon as that was finished, all that was left was one's personal drive, and the quest to answer what I would want to accomplish. It was a large paradigm shift that I'm still thinking over.

Q: Do you feel like you have sufficient support and supervision over the last year?

I was very lucky to have Georgia supporting me, and the commissioners and scientists at Hanford were supportive and provided lots of guidance throughout my PhD. The hardest part was worrying about my family. My mom was an essential worker. Lots of her co-workers got COVID so I was really worried about her contracting the virus. She only took a few weeks off last winter. My dad was in the most vulnerable age group so we were worried about him as well. Luckily, they all got vaccinated now so we were able to visit them in the middle of summer this year.

Liu Tao



did his undergraduate study at the University of Science and Technology of China in Anhui Province, China before starting his PhD Candidature at the University of Florida, investigating the use of novel beam shapes to reduce coating thermal noise in future gravitational-wave detectors.

Q: How was your lockdown in the US and what led you to the decision to fly back to China?

I was completing the first year of my PhD when the pandemic hit and we went into lockdown. I stayed with two flatmates, but living abroad alone still brought some worries. Despite that it was a good memory. However, at this point I had been away abroad for more than a year and I missed my friends and family in China. Travelling was getting harder, and I decided to head back to China, hoping for restrictions not to last too long. Upon arrival, I had to quarantine for a month. One good thing was the selection of food: I actually looked forward to ordering meals online and trying different things each day. It was long, but in the end I got to see my family again, so that was all good.

Q: What is working remotely from China like? Does this affect your PhD progress at all?

In a way, the work routine was similar to the lockdown in the US, but staying with my family and not having to worry about the everyday things like food meant I could be really focused on my work. I had to switch to performing simulations and calculations. I certainly have got a lot of support from my advisor and colleagues: we have weekly meetings on Zoom. This time was really productive: we have recently published a paper based entirely on the work we collaborated on remotely, and another paper is now in its final stages. I'm pleased that these works were able to progress during this difficult time. It is still difficult to say how it would affect my PhD progress in the long term as I've just started my second year. Hopefully, everything should be alright.

Q: What is your plan going ahead?

I will be flying back to Florida next week (at time of interview) as the restrictions are easing. Of course I will be missing my family, friends and the food here, but I'm also excited to get into the lab and get started on my experiments.

Q: Do you have any tips for anyone who has to work remotely in this ongoing lockdown?

I think the most important thing is to stay connected – engaging with others, whether they are your friends, family or your colleagues or supervisors. Those connections really helped me through the last year.

The Virgo filter cavity

On the path to frequency dependent squeezing for Observing Run 4

Installation of the input mirror suspension, composed by two pendulum stages sitting on a pre-isolator constituted by an inverted pendulum.

Forty years after it was first proposed, the so-called squeezing technique, developed to reduce the impact of quantum vacuum fluctuations in gravitational wave detectors, is now routinely used during observation. Indeed, the squeezing was one of the most notable successes of Observing Run 3, bringing a remarkable reduction of the shot noise and an increase of the detection rate. But for the next observing runs we want to do more.

In order to reduce the quantum noise also in the low frequency region, dominated by the quantum radiation pressure, the squeezed vacuum will be first reflected by a Fabry-Perot cavity, the "filter cavity". This technique, usually known as “frequency dependent squeezing” will rotate the squeezing ellipse differently for different frequencies before it enters the interferometer, allowing to reduce quantum noise in the whole bandwidth. It has been experimentally demonstrated in several prototypes, first in the MHz and kHz region and recently in the hundred Hz region as needed for our detectors. At Virgo, substantial progress has been made in order to make the filter cavity ready for Observing Run 4.

The installation ended in April 2021. It required the building of several pieces of infrastructure and preparing several new optical and mechanical components: a 285 m long vacuum pipe along the North arm, new clean rooms, two vacuum chambers hosting the input and the end cavity suspensions and two vacuum chambers hosting the auxiliary optical benches needed to inject the squeezed vacuum into the filter cavity, collect the reflected beams and send them toward the interferometer.

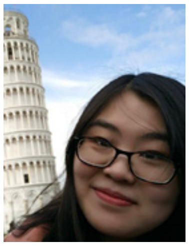
Since the cavity finesse has to be very high (about 11000), the longitudinal control is initially acquired and kept using a green auxiliary beam (experiencing a much lower finesse), and then moved to an infrared beam co-aligned with the squeezed vacuum.

The cavity mirror suspensions, composed of two pendulum stages sitting on a pre-

Eleonora Capocasa

is a researcher at APC lab in Paris. She has also spent a few years in Japan as part of the KAGRA collaboration. Besides fighting against quantum noise, she likes playing water polo and soaking in Japanese onsen.

Yuefan Guo



is a fourth year PhD student at Nikhef, Amsterdam, currently working on the commissioning of Virgo frequency dependent squeezing. When she is not working, she enjoys baking, playing board games and weekend trips around Italy.

Marco Vardaro

is a postdoc at the University of Amsterdam, currently working on commissioning at the Virgo site. In his free time he enjoys outdoor activities: mountaineering, hiking, climbing and mountain biking.

isolator constituted by an inverted pendulum, were commissioned along with their local controls in spring 2021. At the end of May 2021, we observed the first green light transmitted by the cavity. On June 22nd, we achieved the first lock of the cavity with the green beam, acting on the end mirror. Then, the stability of the cavity was improved and now the cavity can keep the lock for more than a day. Finally we were able to align the bright infrared beam (which is superposed with the squeezed vacuum) into the cavity.

The next steps will be to take measurements of the optical losses, as we want to be sure that they are low enough not to degrade these fragile squeezed states, and to improve the cavity control system. Then we should be able to measure frequency dependent squeezing: one of the important milestones of the Advanced Virgo + project.

After forty years of squeezing developments, we are very excited to continue playing with quantum mechanics and to produce frequency dependent squeezing to push further the detectors' sensitivity for the next LIGO-Virgo-KAGRA observing runs.

LIGO 2021

When Albinoni meets Virgo

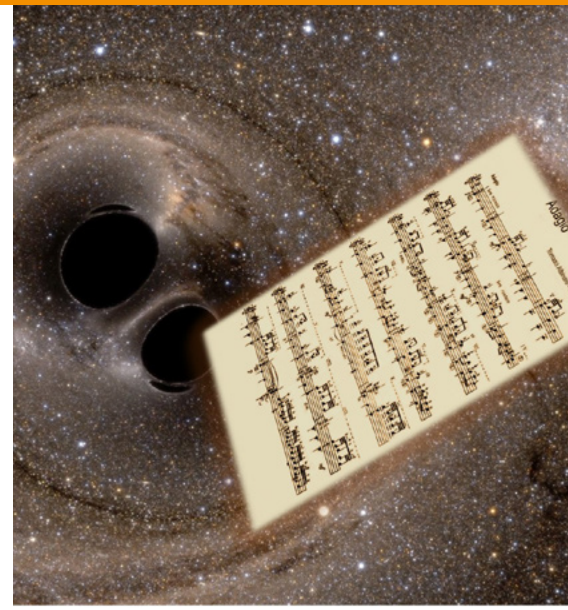
Didier Verkindt

is a CNRS physicist at Laboratoire d'Annecy de Physique des Particules (LAPP). He has been working on the Virgo experiment since 1991, currently mainly on detector characterization, monitoring, calibration, and noise subtraction. He loves astronomy and playing the piano.

If you scratch a little at the layers of history, you sometimes come across surprises in science.

This story is of a musician, Remo Giazotto, who is not well known, but came to compose a musical work known worldwide! The musician was the father of Adalberto Giazotto[1], an Italian physicist and one of the founders of the Advanced Virgo gravitational wave observatory, which is now listening to the beautiful music composed by binary neutron stars and binary black holes alongside the two Advanced LIGO detectors.

The story begins with Tomaso Albinoni, born in Venice in 1671. He had great interest in music from an early age. His father allowed him to learn the violin. However, as the eldest son, he had to take on some responsibilities in the family business at the age of twenty. At the age of 38, when his father passed away, Tomaso finally devoted himself fully to music. He was a talented violinist and prolific composer, writing over 80 operas appreciated in Venice, Munich and Dresden. After his death, many of his scores were preserved in the Dresden library.



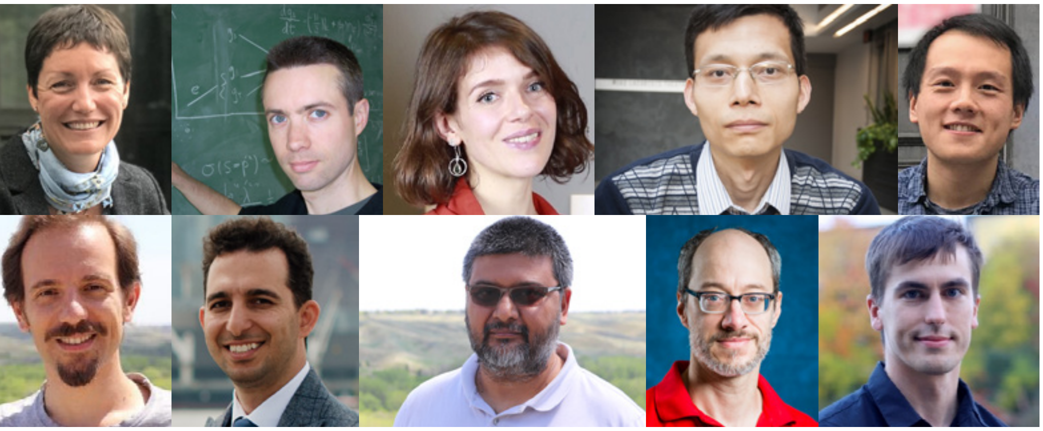
In the 1930s, Remo Giazotto, a young composer and musicologist, became fascinated by the life and oeuvre of Tomaso Albinoni, whose work had fallen into oblivion. Through his research Remo tried to collect as much information on and as many musical scores as he could find by Albinoni. During the Second World War, intensive bombing ravaged the city of Dresden, especially the library where the archived manuscripts of Albinoni were stored. In 1945, our perseverant musicologist went to search for manuscripts in the ruins of the library of Dresden. He found only ashes, but returned saying that he had found the start (a few first measures at most) of an Adagio written by Tomaso Albinoni. He stated that he had completed this score by writing the missing notes himself.

The full score was published in 1958 (by Ricordi). It acquired great success, to the delight of Remo Giazotto, who had finally managed to make the name of Albinoni known around the world. We know today that this composer and musicologist had in fact found nothing in the library of Dresden. He had composed entirely this famous Adagio, which, even today, is often attributed to Tomaso Albinoni.

LIGO 2021

[1] ***Adalberto Giazotto*** *was born in 1940 in Genoa. After a physics degree from Sapienza University in Roma, he started working in particle physics in the group of Eduardo Amaldi. In the 1980's, he worked with his Pisa group on the anti-seismic superattenuators with the aim of opening low frequency window for gravitational wave detectors and finally proposed in 1989, with Alain Brillet's group, the construction of the Virgo interferometer for detecting gravitational waves.*

The 2021 LISA Canada workshop



Members of the 2021 LISA Canada Workshop organising committee. From left to right: Daryl Haggard (McGill University), David Morrissey (TRIUMF), Djuna Croon (Durham University and formerly the UBC-TRIUMF LISA Consortium PI), Huan Yang (University of Guelph & Perimeter Institute), John Ruan (Bishop's University), Pasquale Bosso (University of Lethbridge), Saeed Rastgoo (York University), Saurya Das (University of Lethbridge), Scott Oser (University of British Columbia), Will East (Perimeter Institute for Theoretical Physics) and Jess McIver (see below).

Jess McIver

is Assistant Professor at the University of British Columbia. Jess has worked in the field of gravitational waves since she started an undergraduate research project on LIGO detector characterization at Syracuse University in 2007. Jess moved to Vancouver, Canada from the U.S. in 2019, and enjoys the oceans, mountains, and trees of the Pacific Northwest.

The LISA space mission will unlock a unique band of gravitational-wave observations, allowing new insight into stellar remnants at vast distances, novel probes of fundamental physics and cosmology, and tests of general relativity with unprecedented precision. The 2021 LISA Canada workshop (https://meetings.triumf.ca/event/220/), held virtually April 27-29, 2021, helped to fuel the growing excitement of researchers in Canada and around the world for LISA and gravitational waves.

LISA science had already caught the attention of a diverse group of Canadian researchers prior to this year. In late 2020, about eight months into the pandemic, a team of LISA group PIs in Canada realized we had a quorum of Canadians involved to the LISA Consortium: twelve PIs in total (nearly double the number of Canadian faculty who are members of the LIGO Scientific Collaboration). Up to this point, although there was a strong Canadian presence in the LISA Consortium, the coordination of efforts between LISA PIs in Canada was infrequent. This team of twelve PIs organized the 2021 LISA Canada workshop in part to create connections between these groups and establish a robust new communication network across Canada for LISA research.

In planning for the workshop, we realized we had the opportunity to broaden our goals to explore how Canada could play a significant role in enabling LISA to fly in the mid-2030s. We planned to use the workshop to gauge the interest of Canadian physicists and astronomers in LISA science. As Canada has an active commercial space industry with expertise relevant to LISA, we also sought to investigate the interest of industrial companies in contributing to the LISA mission.

To achieve these goals, we decided a key element of the program would be to provide a comprehensive introductory overview of LISA accessible to researchers of all career stages, as well as attendees from industry. To that end, we invited current leaders of the LISA mission and the LISA Consortium to give an overview of the LISA mission, its scientific potential, and the current activities of LISA working groups. Public recordings of a subset of these talks are available on YouTube[1].

The approach of giving researchers new to LISA a path to entry attracted broad interest in the workshop from around the world: 300 total participants from 33 countries registered, spanning six continents (maxing out our Zoom capacity). Over 150 participants

[1] **A list of publicly available 2021 LISA Canada workshop talks is on p.35!**

joined live on Zoom for the introductory overview talks. We also sought to make the workshop accessible to as many as possible in different time zones, likely suffering from Zoom fatigue during the height of the pandemic. We scheduled the program for three consecutive days of talks and discussions, lasting no more than three hours each day. This structure (in topic and time) may serve as a useful model for future virtual scientific workshops as well as engaging scientists from different fields around the world in an exciting emerging topic.

By the numbers: an emerging LISA research community in Canada

At the time of the LISA Canada 2021 workshop, 25 Canadian researchers, including 12 at the faculty-level across nine Canadian institutions, were active members of the LISA Consortium.

A total of 108 Canadian researchers registered for the LISA Canada 2021 workshop, from 30 different Canadian institutions. In a post-workshop survey, 100% of Canadian respondents who were not already members of the LISA Consortium indicated they would like to join.

Canadian researchers who participated in the LISA Canada 2021 workshop currently work in wide array of disciplines, including gravitational-wave astronomy with ground-based detectors such as LIGO and Virgo; cosmology; extreme stellar environments and stellar history; galaxy formation; modeling sources of gravitational radiation; tests of general relativity and theoretical explorations of extreme spacetime; particle physics and tests of dark matter; and experimental subatomic physics, among others. Workshop organizers noticed similar trends in current discipline for registrants from other countries, demonstrating that the LISA mission has the potential to leverage interdisciplinary expertise across Canada and around the world on a large scale.

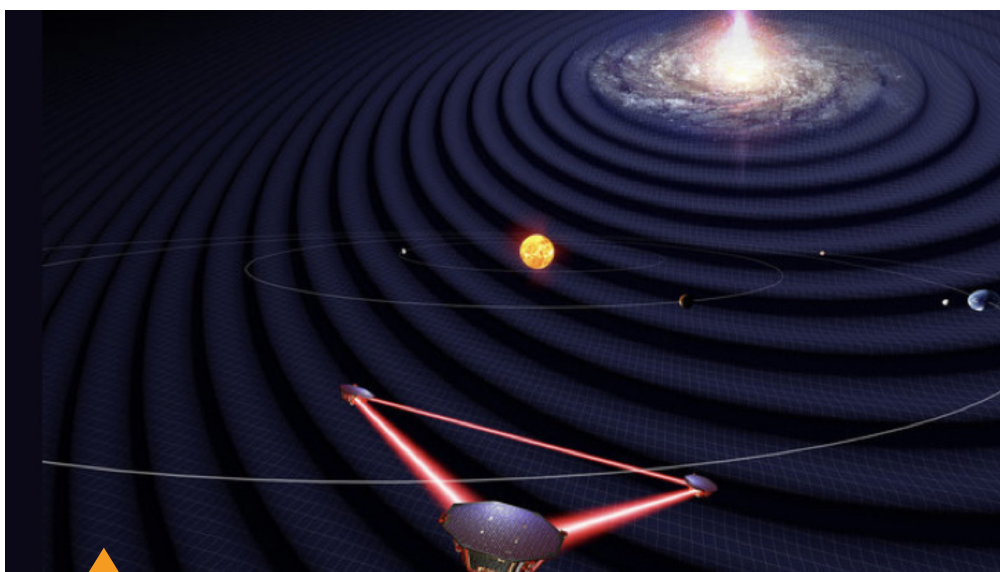
Forging new connections between LISA and Canadian potential

Participants from the European Space Agency (ESA) and the LISA Consortium also discussed opportunities for Canada to contribute hardware to the LISA mission during the workshop. A key outcome from the closeout discussion was the establishment of a line of communication between the workshop organizers, ESA, and the Canadian Space Agency (CSA) to identify potential overlap between the LISA mission needs and Canadian industrial expertise. Workshop attendees also identified computing infrastructure (hardware and software) as a potential contribution to the LISA mission where Canada has considerable experience and expertise.

Looking ahead: the future of LISA research in Canada

In post-workshop survey results, Canadian researchers expressed interest in future semi-annual LISA Canada meetings as well as collaboration on proposals to fund LISA-related research. Canadian respondents also identified guidance from the LISA Consortium and funding for student and postdoctoral trainees as the resources most needed to effectively contribute to LISA science. We hope that the 2021 LISA Canada workshop sparked interest and enthusiasm that will establish a critical mass for LISA research in Canada in the long term.

To learn more, you can read our executive summary of the 2021 LISA Canada workshop and its outcomes on the workshop website: https://meetings.triumf.ca/event/220/



"LISA will be able to detect the reverberations of cataclysmic events in the early universe, not unlike the echo from a booming Hayley Wickenheiser slapshot." - David Morrissey, Research Scientist, TRIUMF

We hear that ...

Career Updates

Sharan Banagiri has finished his Ph.D at the University of Minnesota and is now working as a postdoc at CIERA at Northwestern University.

Craig Cahillane earned his PhD in Physics from Caltech (thesis: LIGO-P1800022), and is now a Postdoctoral Scholar in Physics at Caltech, stationed at LIGO Hanford Observatory.

Tim Dietrich has been appointed Max Planck Fellow at the Max Planck Institute for Gravitational Physics (Albert Einstein Institute) https://www.aei.mpg.de/666244/tim-dietrich-appointed-max-planck-fellow?c=26160

Grant David Meadors is now a staff scientist in the Space Data Science group at Los Alamos National Laboratory.

Kentaro Mogushi has graduated from Missouri S&T with a thesis on detector characterization, entitled "Improving the data quality in gravitational-wave detectors by mitigating transient noise artifacts." He has now moved back to Japan to start a job in a pharmaceutical company.

The Australian National University has promoted Professor **Susan Scott** and Professor **David McClelland** to its highest academic level of Distinguished Professor.

Sidd Soni has graduated from Louisiana State University with his PhD focused on detector characterization. He will be a postdoc at MIT next.

Colm Talbot, Postdoctoral Scholar at Caltech LIGO Lab, will be moving to MIT as a Kavli Postdoctoral Fellow in September.

John Zweizig, Staff Scientist at LIGO Laboratory Caltech (for the past ~25 years) will retire in October 2021, at which point he will continue to contribute to LIGO as a part-time consultant.

Awards

Christopher Berry recently received the General Relativity and Gravitation Young Scientist Prize from the International Union of Pure and Applied Physics (IUPAP), awarded by the International Society on General Relativity and Gravitation.

Sylvia Biscoveanu has been awarded the 2021 Barrett Prize for astrophysics at MIT.

Alessandra Buonanno has been elected member of the US National Academy of Sciences and elected member of the Leopoldina https://www.aei.mpg.de/691072/alessandra-buonanno-elected-member-of-the-us-national-academy-of-sciences?c=26160 https://www.aei.mpg.de/687527/Prof_-Buonanno-elected-member-of-the-Leopoldina?c=26160

Tim Dietrich has been awarded the Heinz Maier-Leibnitz Prize https://www.aei.mpg.de/660938/heinz-maier-leibnitz-prize-for-tim-dietrich?c=26160.

Colm Talbot was recently awarded the 2021 Charlene Heisler Prize of the The Astronomical Society of Australia, for the most outstanding PhD thesis in astronomy or a closely related field, accepted by an Australian university. https://asa.astronomy.org.au/prizes_and-grants/prizes-awards/charlene-heisler-prize/

Marina Trad Nery (AEI Hannover) won the 2020 GWIC-Braccini Thesis Prize for her PhD thesis “Laser Power Stabilization via Radiation Pressure”

Professor Bernard Schutz has been elected as Fellow of the Royal Society. https://www.aei.mpg.de/697530/bernard-schutz-elected-fellow-of-the-royal-society?c=26160

New LSC positions

Stefan Ballmer has been elected as the Elected Member of the LSC Management Team.

Patrick Brady has been re-elected as Spokesperson of the LSC.

Marco Cavaglia has been re-elected as co-chair of the LSC-Virgo Burst Working Group.

Vuk Mandic has been re-elected as co-chair of the LSC-Virgo Stochastic Working Group.

Jessica Steinlechner has been elected as chair of the Optics Working Group.

Other News

The oral history of **Stephen C. McGuire**, Southern University Endowed Professor of Physics Emeritus, has been featured in the AIP History Newsletter Volume 53 (2021), Number 1. P. 19. https://www.aip.org/history-programs/history-newsletter

The five year anniversary of the LISA Pathfinder mission was celebrated with a series of short video clips, which can be viewed at https://www.lisamission.org/news/latest-news/lisa-pathfinder-space-saga

Publicly available 2021 LISA Canada workshop talks (from p.32)

Workshop Introduction
(Jess McIver):
https://youtu.be/P_dUYB-EgT8

LISA Science Overview
(Kelly Holley-Bockelmann):
https://www.youtube.com/watch?v=VrIi-6Tpx3Y

LISA Detector Overview
(William Weber): https://www.youtube.com/watch?v=fb0vpAwde6g

LISA Astrophysics Working Group
(Shane Larson): https://www.youtube.com/watch?v=DVaPbXUmC2Q

LISA Data Challenge Working Group
(Nikolaos Karnesis): https://www.youtube.com/watch?v=BaBkQ8snODs

LISA Parallel Session A
(Observations/Instrumentation):
https://www.youtube.com/watch?v=PlrbfloGF44

LISA Parallel Session B
(Theory): https://www.youtube.com/watch?v=TPsowHIayhk

LISA Consortium Overview
(Nelson Christensen): https://www.youtube.com/watch?v=90gQ_3mUfLI

LISA Canada Workshop Discussion Summary and Closeout:
https://youtu.be/i-zsUtCKch4

"Keita Kawabe checks the beam centering and optic angle on the VOPO platform - the heart of the squeezer - at LIGO Hanford. We've made some modifications to the platform to accommodate paths to and from the new 300m filter cavity. This particular optic he's holding the card in front of is on the path between the squeezer and filter cavity, so it's crucial there is minimal loss." - Georgia Mansell.

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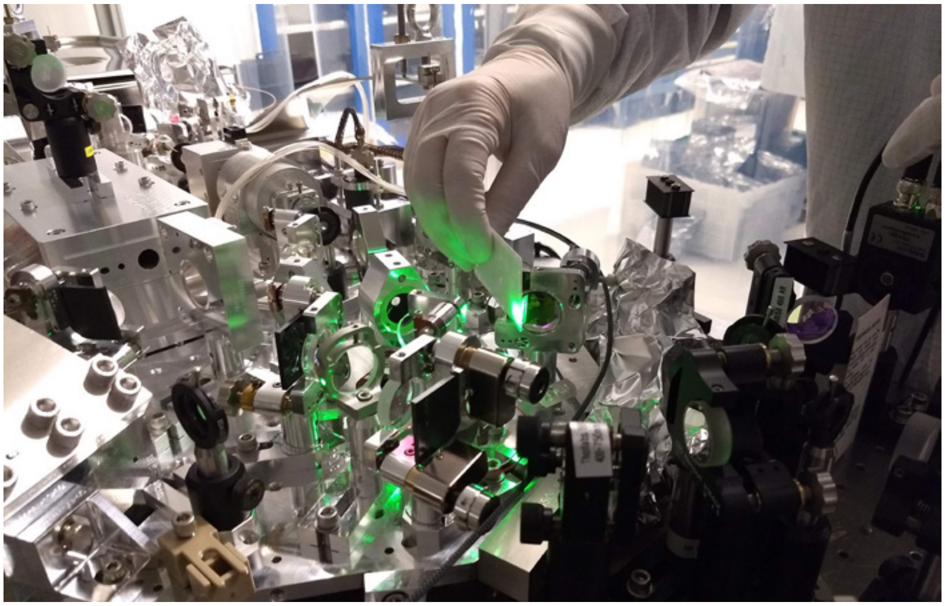
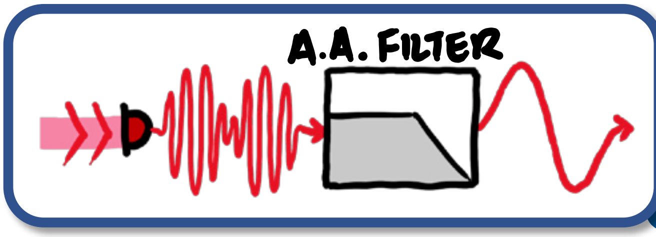


How it works: LIGO Controls and Data System (CDS)

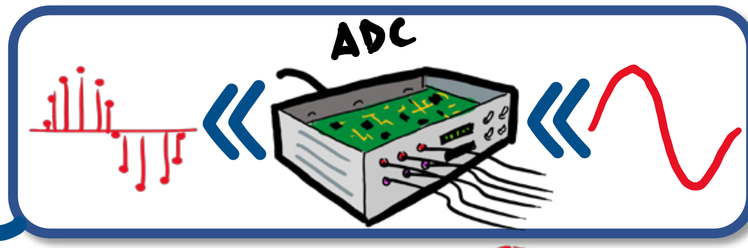
LIGO uses laser light to search for gravitational waves, but how does the laser light get turned into data that gets analyzed? Let's follow the signal path from the detection photodiode to find out…

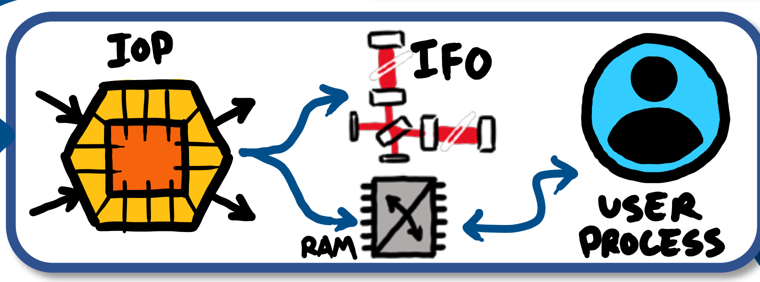
1. Laser light hits the photodiode, creating an analog electrical signal that passes out of the main lab area to the CDS electronics room.



2. The signal passes through an anti-aliasing (A.A.) filter which removes frequencies too high for the analog-to-digital converters (ADC).

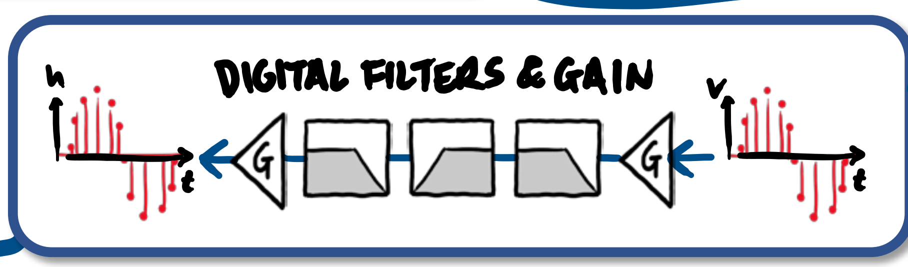
3. The signal is digitized by an ADC in the CDS input-output (IO) chassis. The digital signal is sent over PCIe bus to the computer.

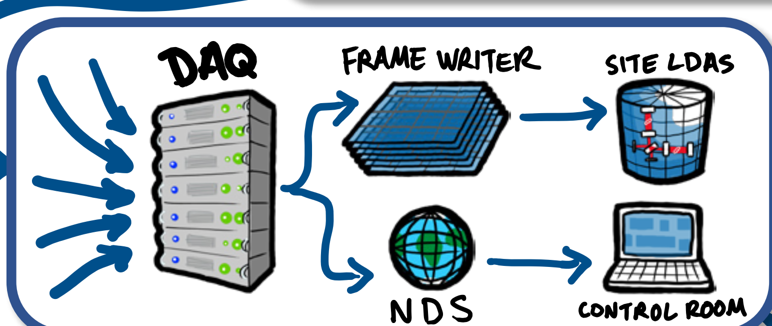




4. The signal is read by the Input/Output Processor (IOP) at 64kHz, where it can be routed to instrument actuators and written to shared memory. The User Process reads/writes a down-sampled signal at 16kHz from/to the IOP.

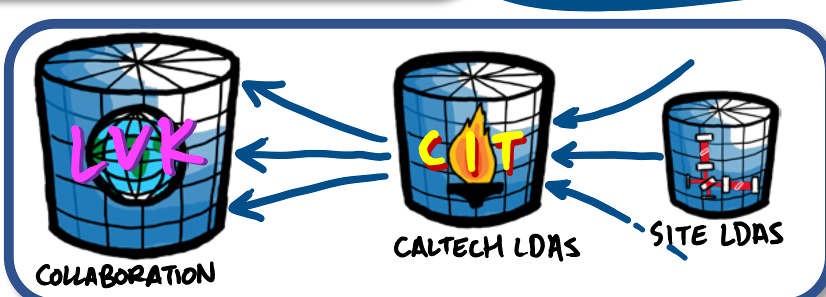
5. In the User Process the digital signal is amplified and filtered to produce the calibrated gravitational wave signal.





6. The calibrated signal is sent to the Data Acquisition System (DAQ), where it is combined with all the other CDS signals. The signals are sent to the control room by the Network Data Server (NDS) and written as frames by the frame writer.

7. The frame files are sent to the site's LIGO Data Analysis System (LDAS), which in turn sends to the Caltech LDAS and then on to the LIGO-Virgo-Kagra collaboration members for analysis.



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by Dave Barker, illustrations by Paul Fulda