LSC
LIGO Scientific Collaboration

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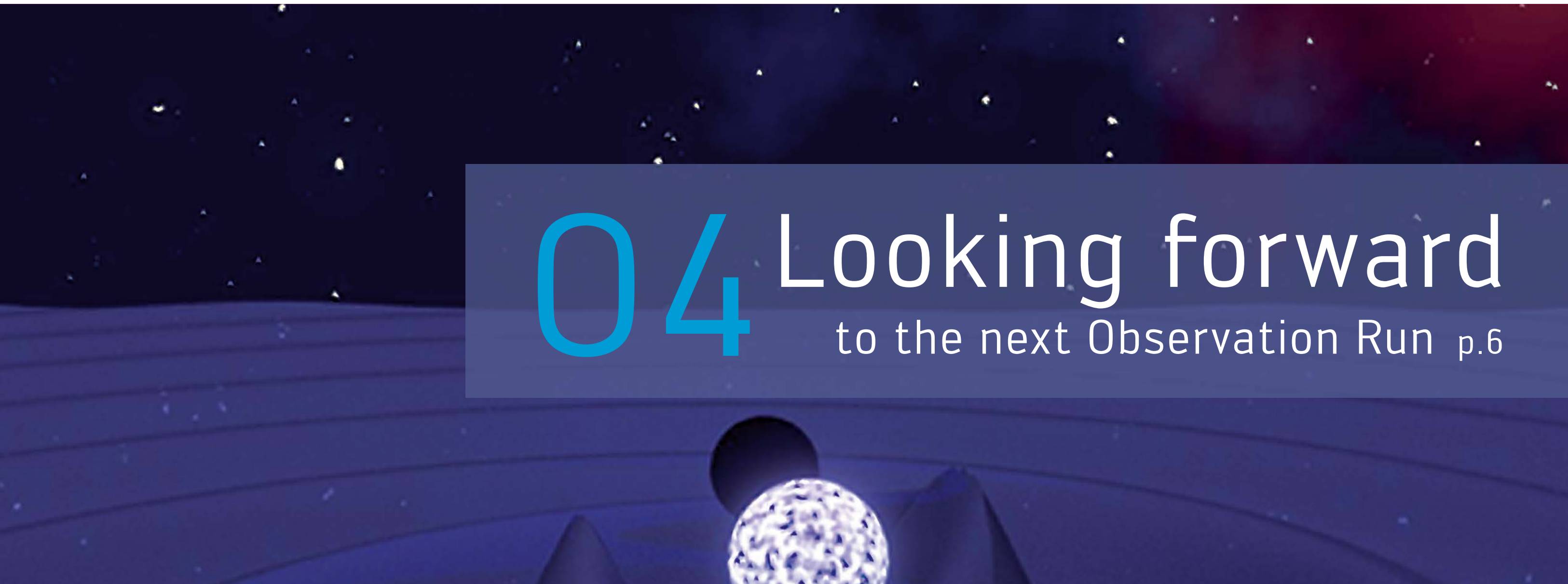

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Front cover

An artistic representation of a black hole and neutron star orbiting each other and producing gravitational waves. So far, gravitational waves have been observed from the mergers of black holes and neutron stars. We are looking forward to more observations of mergers and hoping for new types of signals in Observing Run 4. Article on pp. 6-10.

Top inset: Masayuki Nakano and Torrey Cullen celebrate after achieving more than 100 W of stabilized laser power transmitted by the pre-stabilized laser system's pre-mode-cleaner at LIGO-Livingston. Article on pp. 11-16.
Bottom inset: A solar energy system. The photo is part of the Solar Energy Generating Systems in northern San Bernardino County, California. In this issue we hear an update from the LIGO-Virgo-KAGRA Climate Committee on gravitational waves, our carbon footprint, and reducing our impact. Article on pp. 24-25.
Bottom left (diagonal) inset: An artistic representation of satellite constellations in the 2030's including LISA and the satellite pairs NGGM and MCM/GRACE-I measuring Earth's gravity field. Article on pp. 32-33.

Image credits

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Cover: Main image: Mark Myers/OzGrav/Swinburne-University. Top inset: Masayuki Nakano. Bottom inset: USA.Gov - BLM - BUREAU OF LAND MANAGEMENT, Public domain, via Wikimedia Commons (https://commons.wikimedia.org/wiki/File:Solar_Plant_kl.jpg). Bottom-left (diagonal): Max-Planck-Institute for Gravitational Physics (Malte Misfeldt), NASA / Blue Marble for textures, NASA VTAD for satellite models, LISA constellation: Milde Marketing Science Communication / Exozet Effects

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pp. 6-10 Artistic representation of a black hole and neutron star binary by Mark Myers/OzGrav/Swinburne University (p. 6). Artistic representation of a binary by Soheb Mandhai/@TheAstroPhoenix (p. 7). Artistic representation of a continuous wave source by Mark Myers/OzGrav/Swinburne University (p. 8). Hubble image of the Crab Nebula from NASA, ESA, J. Hester and A. Loll (Arizona State University) (p. 9). Artistic impression of lensed gravitational waves by Riccardo Buscicchio (p. 10).
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Hannah Middleton
Editor-in-Chief

HMiddleton

Anna Green
Deputy Editor-in-Chief

Welcome to the twenty-second edition of the LIGO Magazine!

The fourth observing run (O4) is fast approaching. A huge effort from teams across the collaborations goes into preparing for and making O4 a reality. We expect many more gravitational-wave signals from mergers of black holes and neutron stars, but O4 might also bring new types of signals. In this issue we catch up with several members of the analysis teams about their preparations and hopes for O4. At the LIGO, Virgo, and KAGRA sites, the commissioning teams are striving to achieve the best sensitivity yet. In this issue we hear just a few of the stories from the countless commissioning activities.

In recent years, virtual reality has become much more commonplace as a science outreach tool, but just how does VR perform in classroom engagement? Maddy Parks reports in “Virtual reality for astrophysics outreach”. Meanwhile, the LIGO India education and public outreach team have been returning to in-person engagement and bringing gravitational-wave science to children in remote schools near to the detector site. Debarati Chatterjee tells the behind the scenes stories from Star Fest.

In “Gravitational waves and carbon footprints”, we catch up with the LIGO-Virgo-KAGRA Climate Committee’s work to estimate the carbon footprint of our collaboration’s activities and discuss the actions we can take to reduce our impact. Meanwhile in space, the GRACE Follow-On mission has been monitoring the Earth’s gravity field for the last five years – revealing large-scale mass variations due to melting poles and glaciers. Vitali Müller updates us on both this mission and what’s coming next.

In this issue's “Work After LIGO”, we hear from Sam Cooper on “(Re) Finding my love of science”, while in the LAAC Corner, Paul Fulda shines a spotlight on the collaboration’s elected roles and explores perspectives from around our community. We also share fond memories of Stavros Katsanevas, who was one of the most active members of our community in our climate change discussions as well as countless other topics, including science, art, and building bridges between communities, he will be missed.

And gravitational-wave detectors are big... very big! Just how do people get around at the sites? Find out more in “How do you travel the LIGO arms?”

A big thank you to all of our growing team for your work on this issue! 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

It is the end of February 2023 and I'm currently on my way home from the National Science Foundation (NSF) review of LIGO Lab and the LIGO Scientific Collaboration (LSC). Three days of intense scrutiny during which LSC members from LIGO Lab and other LSC Groups presented material to a panel of 17 reviewers who listened carefully, asked probing questions, and set homework each night of the three day review. This was the culmination of 10 months of preparation by the LIGO Lab during which they wrote a 160 page proposal making the case for continued operations of LIGO and laying out the work plan to continue improving the sensitivity of the LIGO detectors. The full spectrum of activities that we pursue as a collaboration were on show, from instrumental research and design through to our efforts to make the field more diverse, inclusive and equitable. The review went well. As I listened to the panel chair present his closeout summary, I felt very proud of the team, those present and every other LSC member who contributes to the success of LIGO. Thank you all.

As I write this, there are just 90 days until the start of Observing Run 4, the next observing run that promises an increased rate of compact binary detections and another chance to detect gravitational waves from spinning neutron stars, the stochastic background, or other transient events. I'm very excited about this. The commissioning teams at LIGO, Virgo, and KAGRA are eking out every last bit of performance that they can from the improved detectors. The operations groups are beginning to integrate the infrastructure needed to support low-latency and offline analysis. The observational science groups are reviewing and adjusting analysis and paper plans. And the communications division is gearing up to share our discoveries with the world. With the abrupt end to Observing Run 3 due to the pandemic and almost two years of reduced interactions, many of us may have forgotten the amount of work needed to support 24/7 observing, data preparation and analysis. The operations division is recruiting and training LSC members to help with all of this. Please get involved!

I am looking forward to seeing everyone at the LIGO-Virgo-KAGRA Meeting at Northwestern in March. Please say hello, tell me about your work, or tell me how you think the Collaboration could be improved.

.

Patrick Brady
LSC Spokesperson

Patrick B

Looking forward to Observing Run 4

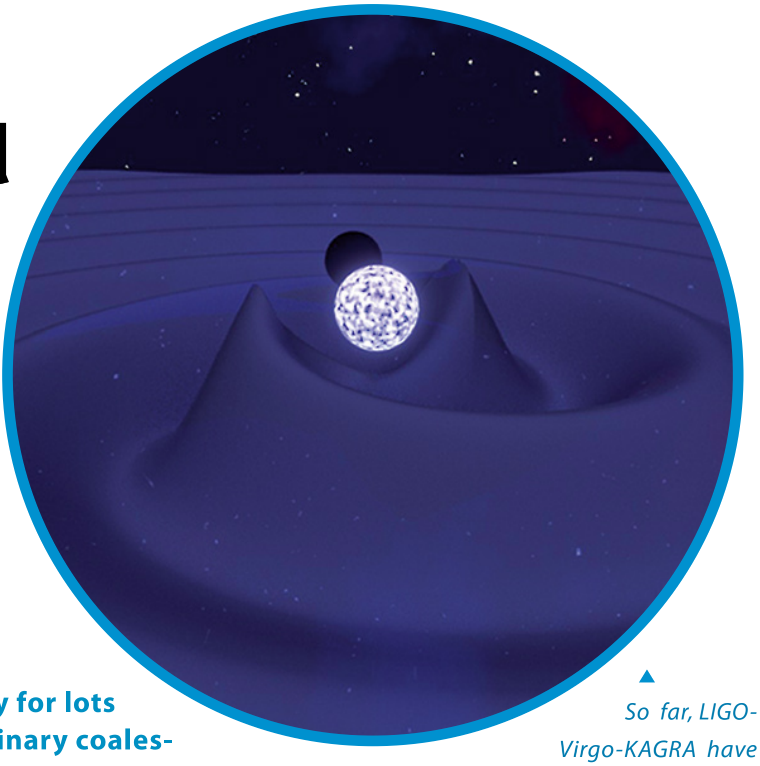
The LIGO-Virgo-KAGRA Collaboration (LVK) has been working toward a fourth observing run (O4), since the last one ended in March 2020. During the last three observing runs (O1, O2, and O3), the collaboration detected gravitational waves from almost 100 compact binary coalescences – the collisions of neutron star pairs, black hole pairs, or a neutron star and a black hole. The next observing run is planned to start this summer, and will continue for eighteen months afterwards with implementations of wide ranging improvements to both detectors and analyses.

Preparing for an observing run is a long and arduous task that takes the involvement of the entire collaboration to be successful, but promises the possibility of exciting new scientific frontiers. In this article, we hear from a variety of scientists about the unique challenges and possible discoveries that the upcoming fourth observing run may hold.

Getting ready for lots of compact binary coalescences – an organisational challenge

Managing all of the analyses from the last run, O3, was a real challenge for the team who took it on! We pioneered lots of new techniques to improve the consistency of our analyses, how they were set up, and ways to automate as much of this as we could.

We learnt a lot from this process (especially when things didn't work as well as we'd hoped!) and we've spent the last year making improvements to the software and the processes we'll use for O4, to make things run even more smoothly. That said, O4 is pretty intimidating; we're expecting to see a lot more gravitational wave events, but as we get closer I'm getting more confident that everyone's hard work will pay off, both on the organisational side, and the many improvements the hard-working analysis teams have been making. (Also, I'm hopeful we won't have another pandemic overlapping with the main analysis timeline this time about!)



▲ *So far, LIGO-Virgo-KAGRA have observed short-duration (transient) gravitational waves from the mergers of black holes and neutron stars. The image shows an artistic representation of a black hole and neutron star orbiting each other, producing gravitational waves.*

Daniel Williams

is a postdoc at the Institute for Gravitational Research in the University of Glasgow. He works on developing statistical methods for gravitational-wave analysis. When he's not coding you'll probably find him playing Dungeons and Dragons, or running up a hill somewhere in the Scottish Highlands.

Early warning – a new analysis in O4

Our search analysis looks for transient gravitational wave signals from merging black holes and neutron stars. All search pipelines try to identify gravitational waves in

Ryan Magee

is a postdoc at LIGO Lab Caltech who works on multi-messenger astrophysics and exploring how new computing paradigms can advance the field. When he's not coding, Ryan is probably out running or exploring new local eateries.

real time as data is collected by the detectors, but in O4 early warning pipelines will also try to predict upcoming transients. Early warning searches will try to detect binary neutron stars up to one minute before merger. If detected, the gravitational wave signal can be used to identify where in the sky the merger occurred. Since binary neutron stars emit both gravitational waves and electromagnetic radiation, they are prime multi-messenger candidates – events where we detect both gravitational waves and electromagnetic light from the same object. Unfortunately, the intensity of light emitted by these systems fades rapidly, so it is important to look for light as soon as there is evidence of a merger. With any luck, early warning detection will give us the advanced notice we need to observe additional multi-messenger events.

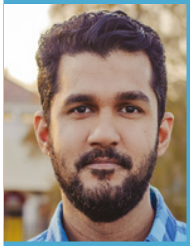
Post-merger: what is left after a compact binary coalescence?

In 2017, the observation of gravitational waves from a binary neutron star merger (GW170817) was associated with electromagnetic observations of a flash of gamma rays called a gamma ray burst (GRB170817a). After this multi-messenger detection, one major question left open is: what is the nature of the compact merger remains which act as a central engine to gamma ray bursts? Moreover, in the context of cosmological gamma ray bursts, it has been suggested that afterglows (observed in X-ray) indicate the presence of a long-lived highly magnetized neutron star called a magnetar. These newly born magnetars have also been proposed as potential gravitational wave sources. Within LVK, several post-merger search algorithms have been developed. We target, but are not limited to, finding long-lived gravitational waves from magnetars formed in binary neutron star mergers associated with gamma ray bursts. Going forward with the O4 run, we not only expect an increase in the detection rate but it will also pose a major challenge for post-merger analysis, demanding more computation. Our current major ongoing effort is to make these post-merger searches more efficient in time for the onset of O4.

Tanazza Khanam

is a fourth year graduate student at Texas Tech University. She works on post-merger gravitational wave events but her interest ranges from multi-messenger astrophysics to exploring Big data problems. She enjoys crafting, playing tennis and travelling.

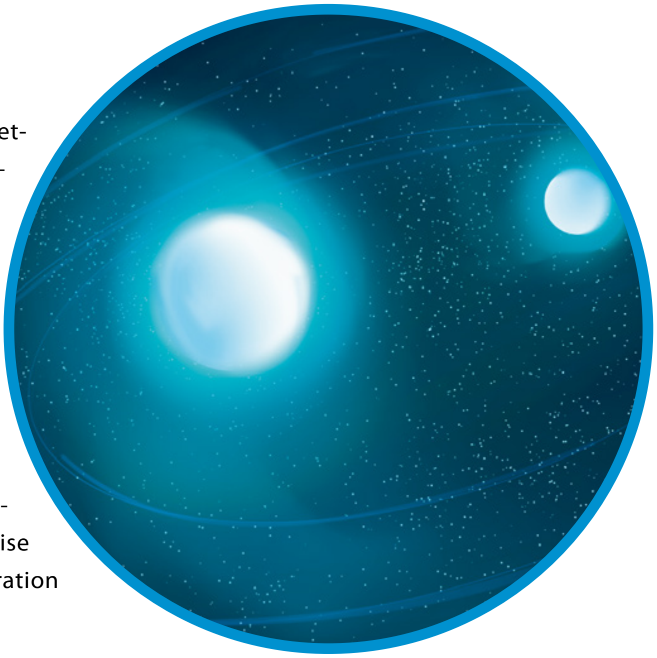
Sidd Soni



is a Postdoctoral Associate at LIGO Lab, MIT, working on the interface between Detector Characterization and instrumentation. He uses machine learning to identify new transients in gravitational-wave data and studies the impact that the environment has on data quality. During his free time, Sidd enjoys going on road trips, visiting national parks and reading classic literature.

Checking the quality of the data

Detector Characterization (Detchar) group members are responsible for monitoring the detector data quality, analyzing the impact of changes in the environment or instrument subsystems on the detector, and maintaining summary pages to share this information. A considerable amount of time is invested in examining and characterizing noise transients, which are short-duration bursts of power in the data. Since the end of O3, the detectors have undergone several upgrades to increase the sensitivity of the instrument to gravitational wave signals. The major upgrades are the addition of frequency-dependent squeezing and an increase in the circulating arm power. Enhanced sensitivity in the fourth observing run will result in an increased rate of both the gravitational wave signals as well as the noise transients.



During O4 we look forward to many more compact binary coalescences, like this artistic depiction.

In O4, the two main challenges of the Detchar group are the validation of a huge number of anticipated gravitational wave candidates and the characterization of noise transients. Event validation is the process of analyzing the data quality surrounding the gravitational wave signals to increase our confidence in their astrophysical origin. The characterization of noise transients includes noise source identification, noise modeling, and noise mitigation techniques. All of these would be at the forefront of Detchar as we step into O4.

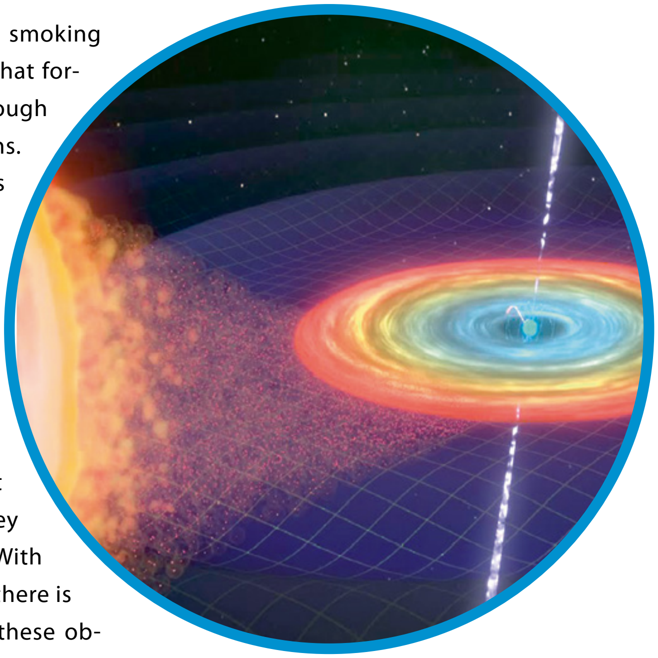
Divya Singh

is a graduate student at Penn State whose research interests range from neutron stars to dark matter detection through gravitational-wave searches for binary mergers, particularly of sub-solar mass compact objects. Divya enjoys dabbling in anything artistic like painting and crafts.

Subsolar mass compact objects

We have now detected about 100 binary mergers of supersolar compact objects, or objects with masses greater than that of the Sun. The gravitational wave signals detected include binary neutron star mergers and neutron star-black hole mergers, which provide insight into the physics of neutron stars and black holes that form through known astrophysical channels. However, gravitational wave signals could also provide a unique avenue to study exotic formation channels through the detection of mergers of subsolar mass compact object mergers, or mergers of objects with masses smaller than our Sun.

This class of objects would be a smoking gun for primordial black holes that formed in the early Universe through the collapse of overdense regions. It is possible that these objects are formed in the implosion of small neutron stars with dark matter cores, or possibly in even more exotic scenarios. Previously, subsolar mass searches have produced no confident detections, allowing us to more accurately predict with each search how often they merge – if they do exist at all. With more sensitive detectors in O4, there is an increased chance to detect these objects or at the very least further constrain models that predict their existence. If we were to make a significant subsolar mass detection, we could potentially detect the ever elusive dark sector!



▲ O4 might bring the first detection of continuous gravitational waves, which are long-lasting gravitational waves from spinning deformed neutron stars. The image shows an artistic representation of such a neutron star (right), which is feeding on material from its companion star (left).

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 as well as gravitationally lensed signals from compact binaries. In his free time, he likes to read or to explore the beautiful nature and coasts of his host island.

Continuous-waves: a new type of signal from O4

All gravitational wave signals detected so far are transients, a type of signal lasting seconds or less, from compact binaries. However, the LIGO-Virgo-KAGRA Collaboration also searches for gravitational wave signals from sources that steadily emit them over a whole observing run, or longer. We call these signals continuous waves, a name borrowed from radio communications. The ingredients for a continuous wave source are the same as for transients – something compact and massive with a rapidly varying quadrupole. The prime astrophysical candidates for this source class are spinning deformed neutron stars, and detecting them as continuous wave emitters would add a completely novel probe to the study of these cosmic laboratories of nuclear matter under extreme conditions. In addition, we also search for other possible astrophysical sources, like dark matter candidates and other exotic physics.

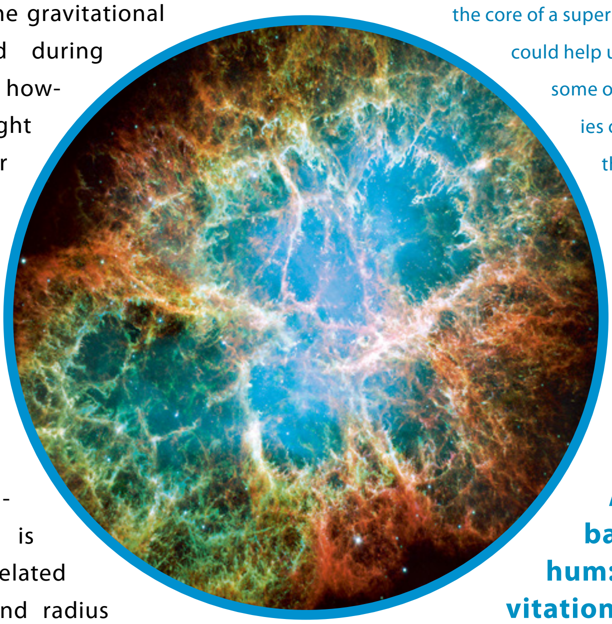
The challenge? Continuous waves are several orders of magnitude weaker than any signals detected so far, and it takes huge amounts of computing to search for them. So we are still working towards that next detection, and hope that O4 will deliver!

Gravitational waves from the core of a supernova

Core-collapse supernovae, the explosion of massive stars, have been observed electromagnetically for thousands of years. The mechanism driving the explosion is still unknown, as the light observed comes from the outer regions of the exploding star. The gravitational waves emitted during the explosion, however, come right from the inner core, which may allow us to directly probe the mechanism driving the explosion. The frequency of the gravitational waves is also directly related to the mass and radius of the neutron star forming at the center of the explosion. Although the rates for core-collapse supernovae are currently thought to be pretty low for O4, the strength of supernova gravitational wave emission is still not well understood, so we might get really lucky with a loud signal. I would be super excited for a core-collapse supernova detection during O4, but if we're not that lucky, then I'm personally hoping to find the start of a population of totally unknown burst sources.

Jade Powell

is an Australian Research Council (ARC) DECRA fellow at Swinburne University of Technology, and a chief investigator of the ARC OzGrav Centre of Excellence. She likes Guinea Pigs and travelling to new places.



This Hubble image shows the Crab Nebula, the remnants of a supernova explosion observed in the year 1054. Observing gravitational waves from the core of a supernova explosion could help us unravel some of the mysteries of what drives them.

An elusive background hum: the gravitational wave background

The gravitational wave background is a superposition of a large number of weak, independent, and unresolved gravitational wave sources. Some of these sources are compact binary coalescences with overlapping signals from core-collapse supernovae, cosmic strings, and cosmological phase transitions, among others. Studying the gravitational wave background can tell us about the population of compact binary coalescences as well as helping us shed light on some aspects of the very early Universe. Given the random nature of a gravitational wave background, distinguishing between a distant signal and local detector noise is difficult. For that reason, we search by comparing (cross-correlating) data between pairs of interferometers assuming that the noise is different between them. Even though the current detector sensitivities, and those in the next observing run, do not allow a detection of the gravitational wave background, we can still discard regions in parameter space of the models describing the signal (no detection means the signal must be weaker than the sensitivity of the detector).

Alba Romero-Rodríguez

has recently joined the Vrije Universiteit Brussels (VUB) as a postdoctoral Fellow. She works in the group of Alexandre Sevrin and Alberto Mariotti on topics related to the gravitational wave background. Apart from her love for Physics, she also enjoys long distance running (which she has been doing since she was six years old), reading novels of any genre and learning about history.

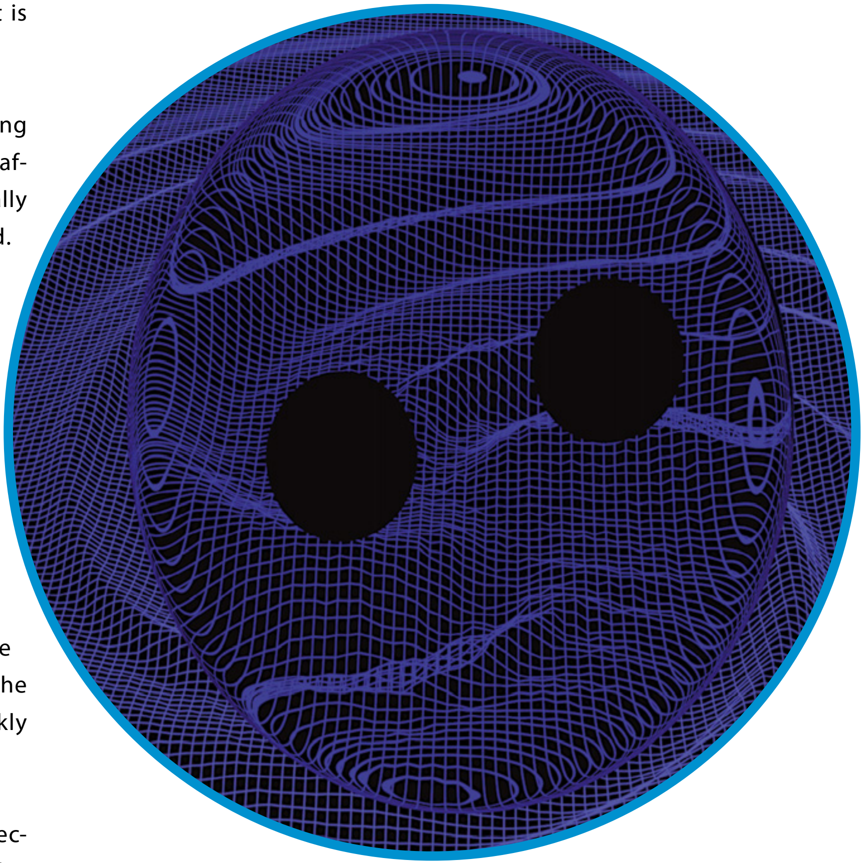
We do not expect a detection of a gravitational wave background before design sensitivities are achieved in LIGO and Virgo. However, once a detection is claimed, new challenges will arise, such as removing the astrophysical foreground (compact binary coalescences) to allow us to decipher the cosmological background and help us dig deeper into the very early Universe.

A repeating signal – looking for lensed gravitational waves

One of the new phenomena that we could observe during O4 would be gravitational lensing of a gravitational wave signal. This happens when the signal passes by anything heavy, from individual stars to galaxy clusters, before it is detected here on Earth.

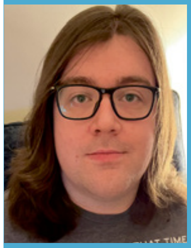
Part of our work is focused on learning more about the heavy object which affected the travelling signal, specifically how that object's mass is distributed. Gravitational lensing allows us to study not just normal matter, but also dark matter. If we can learn more about that object through the detection of a lensed signal, we could learn more about what kinds of dark matter are out there. Dark matter is not the only thing that we can learn about through lensed signals, larger lenses, like galaxies, cause a gravitational-wave signal to repeat multiple times, and the time delay between the repeats could tell us about how quickly the Universe is expanding.

I am very hopeful that the first detection of lensing will happen during O4. The search is not without its challenges, it's very computationally intensive and we're expecting a lot of events in O4, so there's a lot of work to be done to make sure everything goes well. I look forward to the challenge!



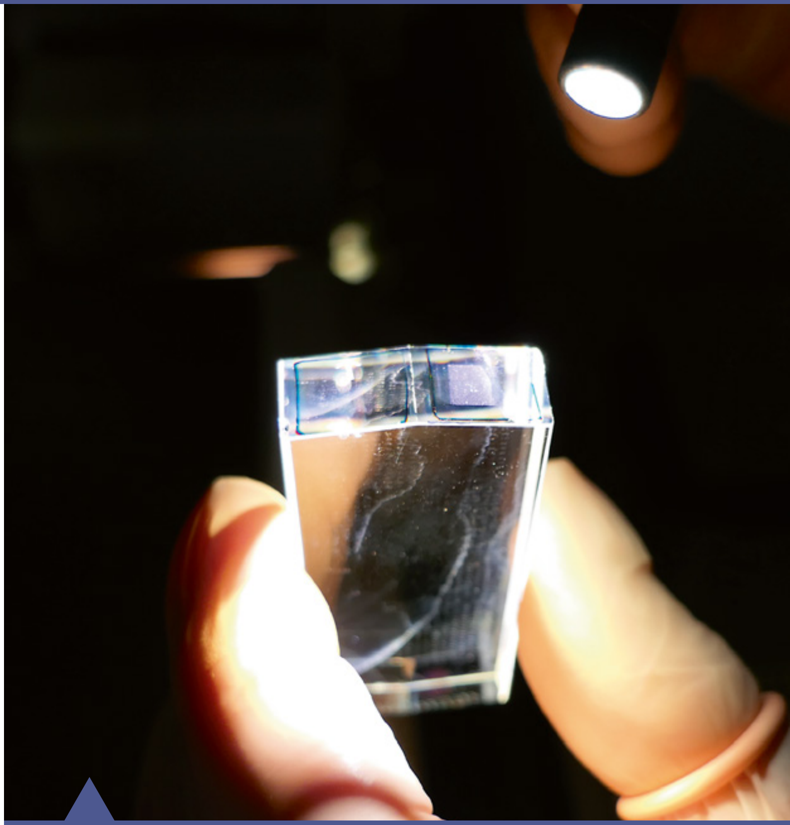
Artistic impression of lensed gravitational waves. Gravitational lensing of light emitted by distant objects in the Universe has been observed for decades – a massive object between the source of the light and the observer bends the light, creating multiple images of the same source in the sky. Gravitational wave lensing can also occur in the same way – if a gravitational wave signal passes a massive object, the signal can be repeated. A detection of gravitational-wave lensing could help us unlock some of the mysteries of these massive objects that cause lensing.

Mick Wright



is a third year PhD student at the University of Glasgow studying gravitational wave lensing. When not working, Mick can often be found battling it out on the 64 squares of a chess board or perpetually tinkering with computers (arch btw).

Bringing the detectors online - Commissioning 04



Output Mode Cleaner cavity illuminated by a white lamp.
The blue zone corresponds to the polluted surface.

Commissioners at LIGO, Virgo and KAGRA, and the wider instrument science community, have been working intensively to bring our detectors online with a higher sensitivity than ever before for Observing Run 4 (O4). In our last issue we heard a run-down of the major upgrades underway – this time we've gathered three stories that give an insight into the planning, innovation, and detective work that goes into making each part of our detectors function to the high standards we demand.

Valérie Martinez

is assistant professor at ILM working on the structural origin of mechanical loss. In her spare time, she listens to music and she likes running and cycling.

Solving the mystery of Virgo's contaminated OMC

Gravitational wave signals are so weak that an extreme sensitivity is required, so all parts of the detectors need to be close to perfection. In this article we hear about one key element of this performance: tthe Output Mode Cleaner (OMC) cavity. This is located at the output of the interferometer and its role is to filter out both the sideband fields that are used to control the detector, and distortions to the shape of the main laser beam that get introduced by small imperfections in the optical system, so that only the light containing the gravitational-wave signal is allowed to pass. A new OMC with lower losses, developed for Advanced Virgo+, was installed at the end of 2020. This was done to improve the measurable gravitational-wave signal strength. However, between January and September 2022, the laser power transmitted by the OMC decreased by 80%! We found that this performance reduction is due to a surface contamination that looks blue in color when illuminated with white light. The oblong shape of the polluted surface also suspiciously matches the oblong aperture of the OMC's aluminum cover. It is crucial to know the source of this contamination in order to prevent it from happening again.

04 - going for higher sensitivity!

How to identify the contaminant?

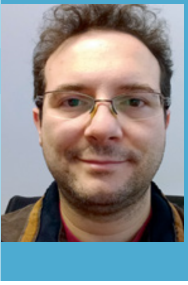
The cavity was removed from Virgo in November 2022 and the contaminated surface has been studied by Raman spectroscopy. This is a non-destructive technique, needed since we aim to reuse the OMC. Raman spectroscopy is based on inelastic light scattering and a Raman spectrum is composed of specific spectroscopic signatures of the compound. In the Raman frequency range, we have access to optical phonon modes which give us structural information at molecular scale. Our spectrometer is coupled to a microscope, enabling us to see surface defects and measure their spectra. The OMC cavity surface has various defects such as bubbles, black spots and a long but thin filament. The filament's spectrum appears to correspond to « first contact », a polymer used to protect coated surfaces while travelling. The surface contamination which results in the blue color was also analyzed by Raman spectroscopy, and the cause turns out to be... a black clamp, used to hold optics. The spectrum of the polluted surface is composed of broad bands, attributed to amorphous coatings, and of thin peaks, whose frequency corresponds to the clamp material. This clamp is located around 12cm in front of the OMC, and in June 2021, it was melted by the laser during a maintenance operation. We can then assume that the laser caused the plastic clamp to sublimate, and this gas phase was deposited on the cavity leading to optical performance reduction.

Christophe Michel

is a Research Engineer at IP2I-LMA working on coatings for gravitational-wave detectors. He likes to cook the vegetables he grew in his garden.

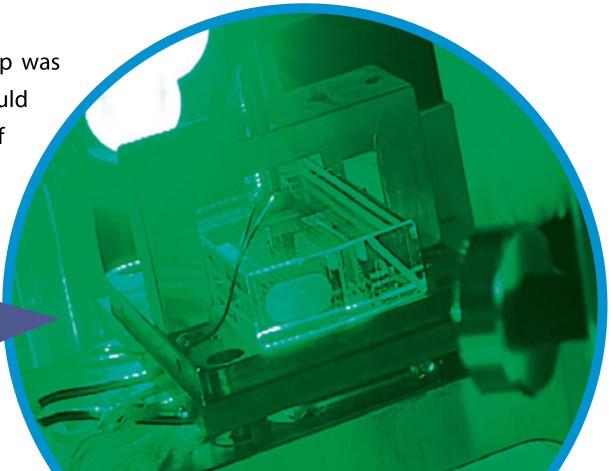
Raman spectroscopy is the ideal technique to characterize samples we don't want to damage. The polluted surface of the OMC cavity has been analyzed and it seems reasonable to assume that the guilty party this time is a clamp used to maintain optical components. Meanwhile Virgo commissioning is progressing with a spare OMC, installed in November 2022. About 10% optical loss was measured for this cavity, which does not quite fulfill the O4 target of 2%. Therefore, another OMC replacement is to be scheduled once a low loss cavity is available again. Although we can reasonably assume that this will be the case after the in-depth cleaning of the contaminated OMC, the polishing of new OMC substrates has been ordered for more safety.

Romain Gouaty

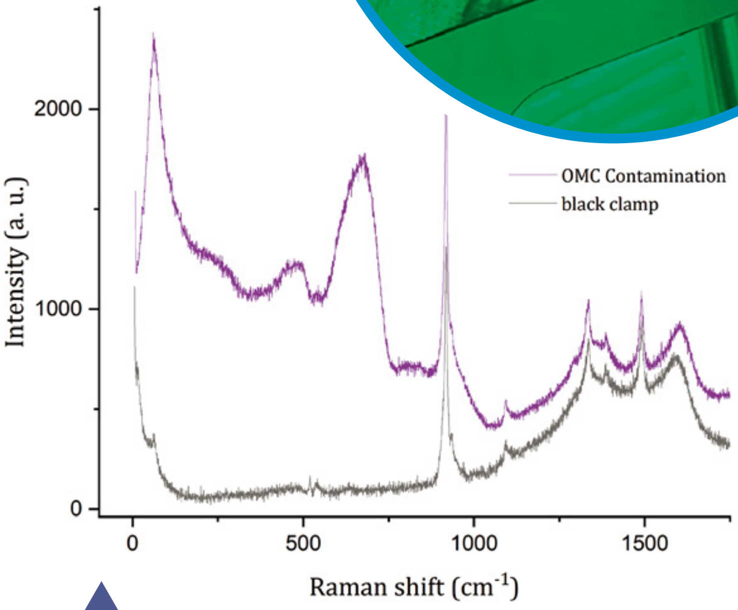


is a researcher at LAPP working on the output optics and photodiodes for the Virgo detector. During his spare time he likes playing chess.

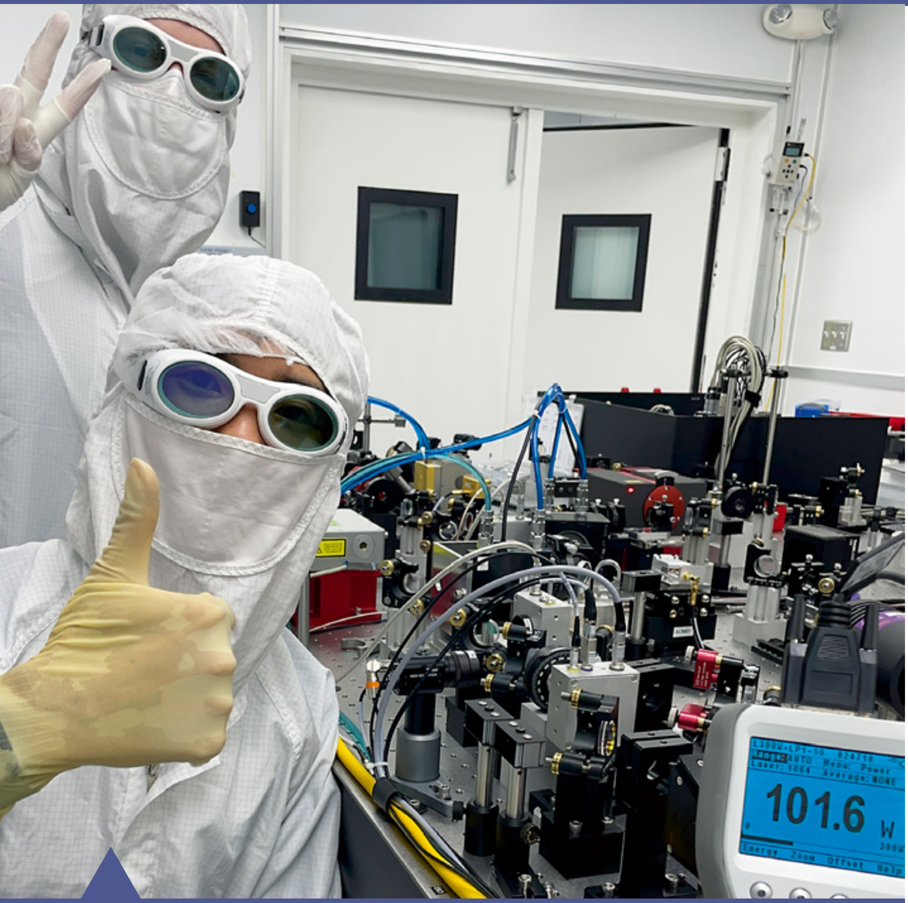
The melted part of the black clamp was cut out so that the laser beam should not be able to hit it again in case of misalignment. This incident teaches us to be extremely careful with respect to the risk of burning optics surrounding components, especially during maintenance and alignment activities.



Output Mode Cleaner cavity on its suspended bench, illuminated with a green lamp.



Raman spectra of the OMC cavity's polluted surface and a black clamp located near the cavity. The broad bands correspond to spectroscopic signatures of amorphous coatings deposited on the surface cavity, while the thin peaks are assigned to the black clamp.


Masayuki Nakano and Torrey Cullen celebrate after achieving more than 100 W of stabilized laser power transmitted by the pre-stabilized laser system's pre-mode-cleaner at LIGO-Livingston.


Nina Bode has just submitted her PhD thesis at the AEI Hannover, working on high-power laser systems for gravitational-wave detectors. In her free time she likes horse riding, playing roundnet and baking.

Powering up: How the neoVAN laser amplifier found its way into Advanced LIGO

The Advanced LIGO (aLIGO) detectors need high-power and low-noise laser sources to be sensitive enough to measure the tiny gravitational-wave signals. As no lasers with sufficiently low noise and enough laser power are commercially available, custom-made systems with laser amplification stages have to be used in gravitational-wave detectors. These laser systems, together with additional components to clean up the shape of the laser beam and stabilize its power and frequency, are referred to as "pre-stabilized laser" (PSL) systems.

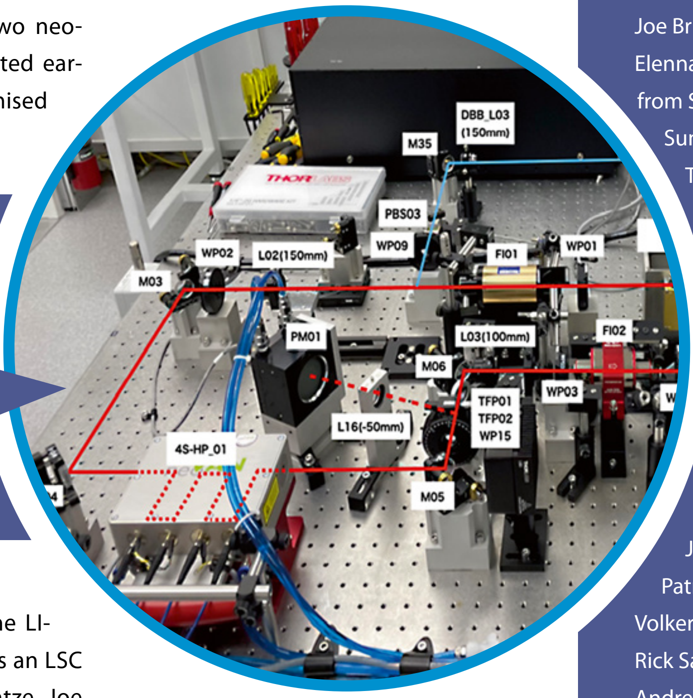
Due to some unfortunate circumstances, the laser amplification system designed and fabricated for aLIGO was damaged at the LIGO-Livingston site even before Observing Run 1 (O1) started in 2015, and could not be repaired between O1 and the second observing run (O2). Therefore, only 35 W of laser power, much less than the aLIGO goal of 200 W, was available for the first two observing runs. Other options for generating higher laser power were needed for the third observing run (O3) run and beyond to the fourth observing run (O4), starting later this year.

Innovating and testing

As one option to generate higher laser power, we tested the neoVAN-4S amplifier at the Albert Einstein Institute (AEI) Hannover, Germany. This compact amplifier is an improved version of the ones that were used in the 35 W system and was developed by the company neoLASE in Hannover. This company had been involved in the development and implementation of the original aLIGO laser system, together with Benno Willke's group at the AEI and the Laser Zentrum in Hannover. We tested this amplifier in the AEI Hannover's aLIGO reference laser system, which contains a copy of the aLIGO pre-stabilization components and thereby serves as an ideal testbed for new gravitational-wave detector laser systems. The new amplifier, in combination with the 35 W system, delivered an output power of 70 W, and we showed that it works reliably in the aLIGO laser system environment. Hence, in between O2 and O3, neoVAN-4S amplifiers were installed at both LIGO sites. They performed well without major issues for all of O3.

But as 70 W is still quite far from the originally planned 200 W, the journey didn't stop there. Shortly after our tests with the 70 W amplifier, neoLASE introduced the neoVAN-4S-HP laser amplifier, an updated version of the neoVAN-4S with a longer pump diode wavelength (improved quantum efficiency), which we first tested in Hannover for the Virgo project. It could deliver 100 W, which motivated the Virgo team to install this amplifier in their laser system for O3. During O3, a team of experts from LIGO searched for ways to increase their laser power further. As the updated amplifier worked so well in our aLIGO reference system, we tested installing a second one downstream of the first at the AEI, and achieved 195 W of output power using our 35 W source at the AEI.

The success of this experiment paved the way for the development of the aLIGO O4 laser system. Sundae Chen and Jason Oberling at the LIGO-Hanford Observatory (LHO), in consultation with the AEI Hannover team, led an effort to design a new layout for the O4 PSL system. The new layout starts with a 2 W laser source, followed by two neoVAN-4S-HP amplifiers in series. Tested earlier in Hannover, this system promised about 140 W of output power.



A section of the pre-stabilized laser system table at LIGO-Livingston showing one of the two neoVAN 4S-HP amplifiers in the foreground. Beam paths are labeled in red (vertically polarized) and blue (horizontally polarized).

Implementing for O4

In the fall of 2019, I traveled to the LIGO-Livingston Observatory (LLO) as an LSC Fellow and worked with Matt Heintze, Joe Briggs, and others to install and optimize the first prototype of the O4 laser system in LLO's Test and Training laboratory. Maik Frede, a co-founder of neoLASE, also joined the project. Maik worked during his Ph.D. research on lasers for gravitational-wave detectors in a collaborative effort of the AEI and the Laser Zentrum in Hannover. After the successful demonstration of the prototype, plans quickly proceeded for installation at both observatories in the interval between the O3 and O4 observing runs.

Installation plans were delayed somewhat due to the Covid-19 pandemic, but as soon as some level of work at the observatories was allowed to resume, the laser upgrade at LHO began in May 2021. The O4 PSL system was fully functional by January 2022, delivering 138 W of stabilized laser output power to the Input Optics system.

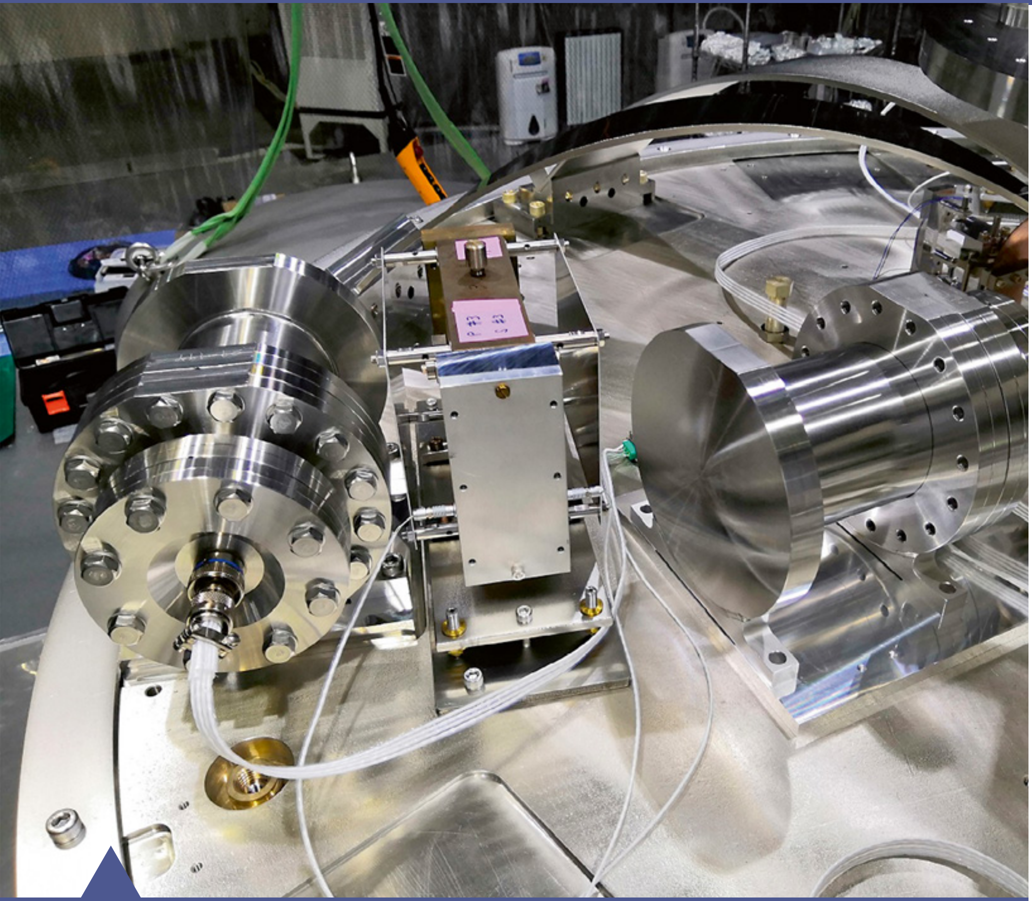
Meanwhile at LLO, the laser upgrade was deferred to coincide with replacement of the main end mirrors. Leveraging the experience from the upgrade at LHO, it started in August 2022 and was completed in November.

Commissioning time was limited due to other interferometer activities, but the system is delivering more than 100 W of stabilized laser output power to the LLO Input Optics system.

With a few minor control electronics issues still to be sorted out, both PSL systems have been operating continuously and very reliably since being commissioned. The relatively simple, compact 4S-HP amplifier systems from neoLASE are thus paving the way toward increased circulating power, and thus increased sensitivity, for the LIGO interferometers during the upcoming O4 observing run.

You can read more about LIGO's amplification system in Bode et al, Galaxies 2020, 8, 84.
[https://doi.org/10.3390/galaxies8040084]

With thanks to all involved:
Nina Bode (AEI Hannover)
Joe Briggs (LLO LSC Fellow from Glasgow)
Elenna Capote (LHO LSC Fellow from Syracuse)
Sundae Chen (LHO LSC Fellow from UWA)
Torrey Cullen (LSU)
Jenne Driggers (LHO)
Maik Frede (co-founder of neoLASE)
Mike Fyffe (LLO)
Matt Heintze (LLO)
Peter King (LHO)
Michael Laxen (LLO)
Fabian Meylahn (AEI Hannover)
Adam Mullavey (LLO)
Masayuki Nakano (LLO)
Jason Oberling (LHO)
Patrick Oppermann (AEI Hannover)
Volker Quetschke (UTRGV)
Rick Savage (LHO)
Andrew Spencer (former LLO LSC Fellow from Glasgow)
Varun Srivastava (LHO LSC Fellow from Syracuse)
Benno Willke's group at AEI Hannover



A new accelerometer is installed at the top of one of KAGRA's main mirror suspension systems to reduce the effect of ground motion. The control filter is implemented now.

Keeping KAGRA cool and calm

KAGRA's first international observation run, "O3GK", took place at the end of Observing run 3 in April 2020 jointly with the GEO600 detector. After the run we determined the noise budget with O3GK sensitivity and planned the KAGRA upgrade schedule. We found that KAGRA's sensitivity below 100 Hz was limited by noise from the suspension control system, which is used to keep the mirrors in the detector stable.

Takaaki Yokozawa

is a project assistant professor at ICRR, University of Tokyo. He is mainly contributing to KAGRA commissioning and environmental noise evaluation. He likes to enjoy the hot springs (onsen)!

To reduce noise, controlling the main mirrors in KAGRA's arms is the most important factor. First, we refurbished the suspensions. At the same time, we developed new accelerometers that are used in sensor correction to reduce the effect of seismic motion. We also designed and installed new sensors (optical levers) that can measure tilt in the suspension stages above the main mirrors in the arms. For the suspension control noises dominant below 100 Hz in O3GK, we implemented new suspension control filters that use a combination of the existing sensors and the new optical levers.

We have confirmed that the control noise has been reduced by two orders of magnitude. We used much more time to measure parameters and do "health checks" for the suspensions - KAGRA's term for measuring mechanical transfer functions and spectra - before closing the vacuum chambers to continue the interferometer commissioning without large suspension troubles.

KAGRA is a cryogenically cooled detector. Since O3GK, we have also tested a new cooling procedure on the Y-arm input mirror suspension. This is now done in three stages. First the duct shield is cooled (~250 K in the mirror) to condense and trap water from the environment. After about two weeks, the radiation shield is cooled (~80 K) to extract the oxygen and nitrogen. After another three weeks or so, finally the mirror and suspension is cooled to ~20 K to reduce the thermal noise. Before O3GK, we sometimes found frosting on the surface of the sapphire mirror. This drastically increased the optical loss in the arms, in one case meaning that light exited the cavity after roughly 7 times fewer bounces than intended, so much less power could build up. We confirmed that the frosting issue does not happen with the new procedure.

We are planning to join the Observing run 4 (O4) run from the beginning for a period of a month. After that, we will re-start commissioning, including cooling down the remaining three mirrors that form KAGRA's arm cavities. We will then optimize the suspension controls, test higher laser power operation, work on noise hunting and so on to achieve better sensitivity before rejoining for the next stage of our O4 run with more than 10 Mpc binary neutron star coalescence detection range. Commissioning is ongoing step by step for the KAGRA detector. We hope to detect our first gravitational wave in O4.

04 - going for higher sensitivity!

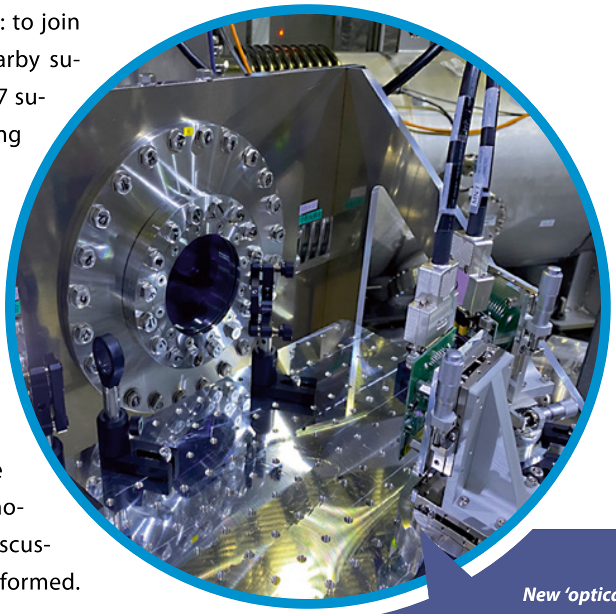
In addition to commissioning KAGRA, the Physical Environmental Monitor (PEM) team found that micro-seismic motion caused by ocean waves was the dominant source of ground vibration in a frequency range of about 0.1-0.3 Hz. Although KAGRA is underground, we could not ignore this effect - during O3GK, there were periods when we could not even lock the interferometer due to the large micro-seismic motion.

Ocean wave height data is provided by the Nationwide Ocean Wave information network for Ports and HArbourS (NOWPHAS) [1]. We selected thirteen observational locations (bays) in total, seven locations facing the Sea of Japan and six facing the Pacific Ocean. By performing a correlation analysis, the wave height trend near the KAGRA site was found to follow three major locations: one on the Sea of Japan, and two on the Pacific Ocean. Using this data, we extract the independent characteristics of the ocean wave heights (using a principal component analysis). By comparing this data to KAGRA seismometer data, we could establish an algorithm to forecast the micro-seismic motion at the KAGRA site using the wave height data in each bay, and forecasted wave height data from Otenki.com [2]. Now, we provide this data every day (e.g. the data below, from January 23rd 2023). This forecast will support the schedule of commission works.

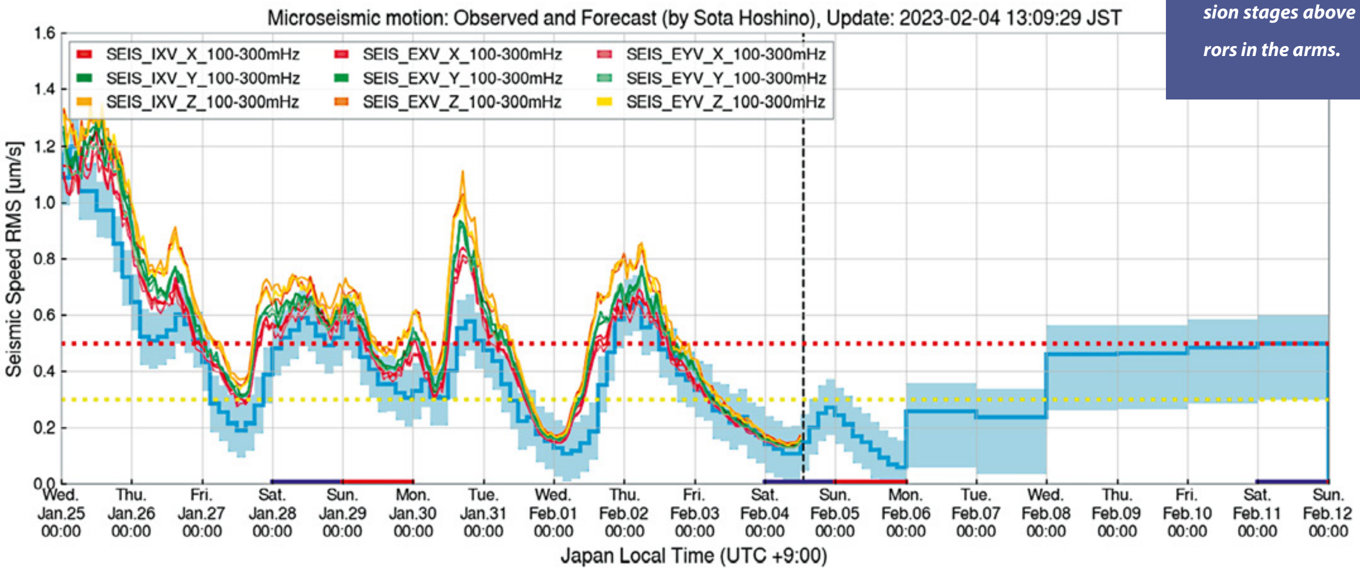
Finally, I would like to write about my most important motivation as a scientist: to join the large festival for detecting nearby supernova explosion signals. The 1987 supernova (SN1987) was detected using multiple electromagnetic signals in addition to neutrino signals. This observation accelerated our understanding of the explosion mechanism of supernovae. We also expect gravitational waves to be produced by supernovae explosions. When information from gravitational wave signals are added in for the next nearby supernova, even more detail and exciting discussions and investigations can be performed. I will be very glad if I can join the new multi-messenger festival in the near future with KAGRA data.

[1] https://www.mlit.go.jp/kowan/nowphas/index_eng.html
[2] https://m.otenki.com/wavwid_huha_week_preflist.htm (in Japanese)

LIGO 2023



New 'optical lever' sensors have been installed on the suspension stages above the main mirrors in the arms.



The observed and forecasted micro-seismic motion at KAGRA. Each color shows the observed micro-seismic motion measured by seismometers in the x- (red), y- (green) and z-axis (yellow) near the input mirror in the X-arm (IXV) and end mirrors in both the X- and Y-arms (EXV and EYV). The seismometer signals were processed to filter for signals in the 0.1- 0.3 Hz range. The blue band shows the forecasted micro-seismic motion using wave height data from Otenki.com.

Remembering Stavros

Stavros Katsanevas, director of the European Gravitational Observatory and one of the fathers of the so-called Astroparticle Physics in Europe, recently passed away. The human and scientific personality of Stavros was so rich and multifaceted, that it would probably be impossible to draw a truly exhaustive portrait of him. Therefore, we have collected several short memories from Stavros' friends and colleagues that represent, in a way, the farewell of a large global community connected to him. Goodbye Stavros.

Barry Barish, Physics Nobel Prize

The first time I met Stavros was in about 2010 at the Virgo site. I was chairing a review of Advanced Virgo and Stavros was representing CNRS, the French funding agency. He and I had probably "passed in the halls" many times before, since his background was in particle physics, like mine, and he had then moved into particle astrophysics, like me. However, it was a meeting on Advanced Virgo in Cascina, that we met and instantly developed what became a long friendship that grew until his death. Stavros had an amazing passion for science, passion for the arts, passion for people and, most of all, passion for life. We bonded first over physics, then over art, and most of all, just as two people who became very close friends. I miss a very special colleague and person.

▲ *Stavros in Berlin 2022*

Athena Coustenis, planetologist at CNRS and ESA

Like me, Stavros was born in Athens, and like me he lived and worked in many different places, in Europe and the US, before settling for some time in France, where I finally met him and his wife Aggeliki in 2008. Stavros was among the most delightful and knowledgeable people I have met. It was a pleasure to accompany him in some of his professional but also cultural activities, like the Pisa Book Festival, where I had the chance to be with him for the last time in October 2021 and see how respected and appreciated he was by his colleagues and in particular the young people. I will terribly miss him as a colleague and a friend.

Antoine Kouchner, Director of APC - U. Paris Cité & CNRS

The passing of Stavros is a shock for a whole, large and borderless community. Stavros was a man of openness, bridges and connections to many fields: physics, geophysics, arts, philosophy...

Everywhere Stavros has left a significant imprint, conveying an endless enthusiasm. Director of the AstroParticle and Cosmology laboratory in Paris, Stavros trusted me to team up with Sotiris Loucatos in the direction team. What an inspiring and friendly team! He died in action, full of projects, probably like he would have wanted. He was actually preparing his return to the APC laboratory. It is such a great sadness not to be able to welcome him back. But his vision will remain. Merci pour tout!

Fernando Ferroni, Physicist, former president of INFN

I met Stavros for the first time at the 1978 CERN School of Physics in Austerlitz, near Utrecht. Following the famous theorem 'mia faza mia raza' we became great friends while learning a lot of Physics. Then Stavros started to move around the world, Fermilab, Athens, CERN, Lyon, Paris, Pisa....and the real connections where the few memorable times when I spent vacations at his family house in the wonderful island of Sifnos, his visits to Rome or mine to Athens where our mothers prepared great dinners for us. He was one of the few people invited to my wedding where he recited an appropriate part of the Iliad! Dear Stavros, a long adventure together in life and physics lands.

continued on p. 34 ▶

An outreach gala for LIGO-India

Star Fest: Behind the scenes

Books in Marathi about Gravitational Wave Science and the LIGO-India project were distributed by the invitees to teachers from selected schools from five clusters in the Hingoli (Aundha) region.

This was my first ever visit to the LIGO-India site since joining IUCAA (Inter-University Centre for Astronomy and Astrophysics) in India as faculty in February of 2020. Soon after becoming a member of the LIGO Scientific Collaboration in January 2021, I was selected to chair the Education and Public Outreach (EPO) programme. Despite introducing innovative science communication ideas throughout the pandemic, science popularization was mostly restricted to the online platform. When the pandemic started to subside in mid 2022, we decided to organize a major comeback in the LIGO-India region near Hingoli with a gala event, a “Star Fest”. The idea was to host a two-day programme for teachers and educators selected from schools and colleges near the LIGO-India site, in order to create awareness about this upcoming mega-science project. Following an in-depth survey conducted by LIGO-India EPO (LIEPO) volunteer Atharva Pathak (Pune Knowledge Cluster) in the region, we selected New Model Degree college as the venue and 5th – 6th August as dates for the event.

Instead of taking a long car ride (lasting more than 10 hours), we decided to take an overnight train to Parbhani, a town 75 km away. We drove 1.5 hours the next morning to reach the LIGO-India guest house. The journey through the lush green landscape was fascinating, typical at this time of the year following the “monsoon” rain showers that magically transform the dry arid terrain left behind from a scorching summer. We received a warm welcome at the guest house with a sumptuous lunch. However, we had no time to lose, and we soon set out to prepare for the event. The team dispersed in groups, some to prepare the venue while some went to make arrangements for the food. I left with Atharva to visit the important government offices of the local Zilla Parishad (District council) to invite the delegates to the event. We spent hours waiting to interact with the senior government officials (District Collector, Chief Education Officer, Deputy Education Of-

Debarati Chatterjee

is Associate Professor at the Inter-University Centre for Astronomy and Astrophysics in Pune, India and Chair of LI-EPO. Her many hobbies include solo travel, high altitude trekking, rock climbing, dancing, sketching and learning languages.

ficer and others). We elaborated details about the LIGO-India project, and by evening we managed to get all of them excited about the project and convinced them to come for the inaugural event the following day.

The first day of Star Fest began early on August 5th, with the team dressing up in traditional attire and arriving at the venue. Volunteers had beautifully decorated the venue with colorful motifs (rangoli) of LIGO-India and floral patterns, while the LIEPO team had made all the arrangements with posters, banners, projector and demonstration exhibits. IUCAA SciPoP (Scientific Public Outreach Programme) in-charge Samir Dhurde arrived soon from Pune, and we eagerly awaited the delegates we invited. Upon their arrival, the inaugural programme commenced with a welcome address, followed by my talk presenting details about LIGO-India including the science case, site selection, technological challenges etc. The delegates were felicitated, followed by a book distribution (the pop-up book “Listening to the Universe” that was developed in collaboration with the University of Glasgow through the Newton-Bhabha fund). Following a tree planting ceremony, lunch and in-depth discussions about upcoming outreach plans in the region, the dignitaries left. The afternoon at Star Fest was spent with introductory talks about astronomy, gravitational-wave science and interactive demonstration sessions for the invited teachers. Books were distributed among them as take-home goodies.

The second day (6th Aug) of Star Fest continued with a science exhibition, telescope-making workshop and lectures on skywatching, astronomy and gravitational-wave science. This programme was mainly conducted by Samir Dhurde, Atharva Pathak, Tushar Purohit, Rupesh Labade, Maharudra Mate and Mayuri Patwardhan. The rest of us decided to use the opportunity to reach out to other schools and colleges in the district. Along with Shivani Pethe-Kane, Rameshwar Bankar and Ankit Bhandari, I headed out to Toshniwal College of Arts, Science and Commerce in Sengaon. Here I explained concepts about gravitational-wave science and astrophysics, and also gave in-depth guidance to students about various career opportunities, particularly motivating girls to take up careers in science and technology.

Following a quick stop for lunch, we moved to the next event at a Zilla Parishad school in Bhosi cluster in Aundha Naganath, where school children were eagerly awaiting our arrival. The kids from this remote school were mostly children of daily wage labourers with very modest resources. In the absence of proper facilities, we had to improvise to explain introductory concepts about astronomy and gravitational-wave science. We were moved by their curiosity and enthusiasm – both students and teachers posed numerous questions to the team and were eager to participate! Teary-eyed and deeply touched by the experience, we set off to return to Hingoli.

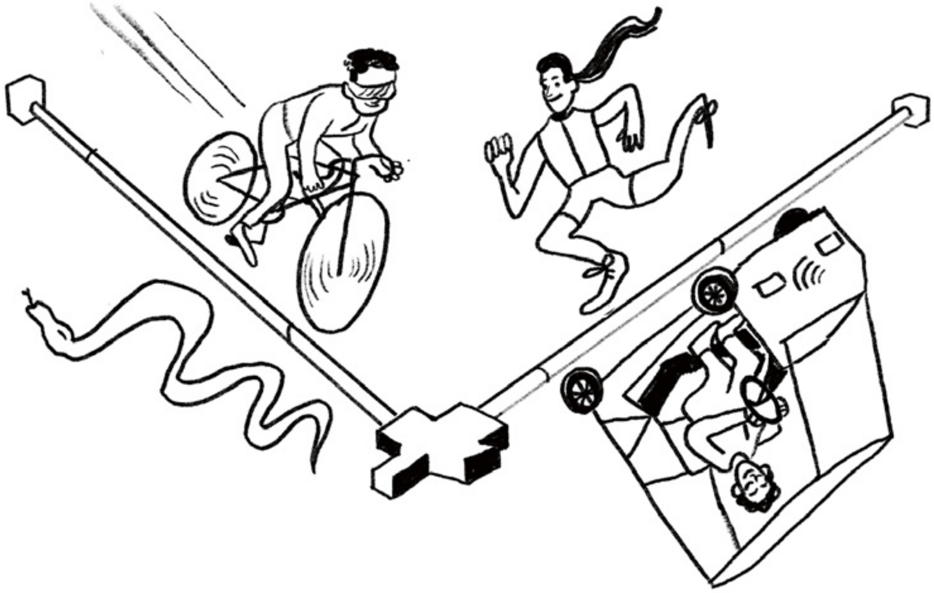
On the way, we had a chance to visit the Aundha Naganath temple in Aundha (the tourist attraction of the place which gives its name to the detector) and also the LIGO-India site. Actually seeing the cornerstone, the weather station and the site buildings for the first time gave me goosebumps! We spent a memorable evening taking many pictures of the beautiful flora and fauna and enjoying the mesmerizing sunset. The next morning, after a short touristy stopover at the Gurudwara in Nanded city (89 km from Hingoli), we caught our train back to Pune, bringing the epic adventure to an end.

The “Star Fest” not only was the beginning of a new chapter in LIEPO activities, it was also a life changing experience for me personally, giving me a new opportunity to engage in rural outreach, in addition to the LIEPO activities I had been conducting at national and international level. The enchanting countryside, warm hospitality of the local people, the enthusiasm of the students and the bonding with the rest of the team made this an unforgettable adventure. As I eagerly look forward to organizing many more events in the vicinity of the LIGO-India site in the future, this science fest made me realize how LIGO-India is touching lives in the remotest corners of the country – that is truly one of the most motivating and fulfilling rewards in gravitational-wave science outreach.

LIGO 2023

After the Star Fest, a visit to a school in Bhosi cluster in Aundha Naganath (Hingoli) was organised.

How do you travel the LIGO Arms?



The interferometers used for gravitational-wave detections are big instruments. But it can be impressive to realize how long the arms are, once you are there (and you cannot see the end...). One may wonder how to go from here to there: the answer is apparently trivial, since cars are usually the best option. But there are many other ways to travel along the arms (and enjoy the experience), as these three stories will tell you...

Chiara Di Fronzo

is a postdoc researcher in gravitational wave instrumentation in Belgium, and in 2019 she was an enthusiast wanderer of science-life at LIGO Hanford! When not science-doing, she sits on her yoga mat.

When I arrived at the LIGO Hanford site, in 2019, I was expecting the long arms. But the actual size was definitely unexpected. Afterall, it is one thing looking at pictures of those giant detectors, and another being there and getting a feel for the distances. Right after, I started to wonder how people go from one side to another of each arm. Traveling by car is the obvious solution, but there are other options: I personally experienced the little, electric yellow car, which is for shorter distances. Definitely a funny experience, considering that it really looks like driving a toy-car!

Carl Blair

is an experimental physicist developing techniques to make better gravitational wave detectors at University of Western Australia. Carl enjoys anything that slides on water (frozen or otherwise) or rolls on two wheels and loves playing with gravitational wave detectors and playing cello.

Working at LIGO Livingston came with many perks. My favourite was being able to go fishing at work. After a day in the lab, or in the control room not seeing the light of day, chilling by the ponds – marvelling at the abundance of life – watching snakes eat frogs – deer skit past, turkeys babble and chiggers eat my ankles was a great way to unwind (except the chiggers). I quickly learnt why gumboots are essential to the fisherman in Louisiana. I got the hang of rubber lures, though never caught as many as Jeremy, tried to glean some tips and tricks from the likes of Danny, Gary and Joe. I learnt fish cooking lessons from LIGO fellows – particularly Haoyu Wang who taught me the importance of removing the gills in any whole fish meal.

One lucky fish I caught in 2017 just didn't look like dinner. I'd found a large tank that I installed in my bedroom and Jimi became my pet. What a fascinating pet. Large-mouth bass are brutal predators. The first time I fed him worms he just about took my hand off. I gathered he was hungry – that began a mission of finding food for Jim. I tried the dry stuff recommended online. He would eat it grudgingly. Anything that moved though was gone in a flash and a splash. It was like magic. He grew rapidly though, after 6 months he could hardly turn around in the tank and I decided it was time for him to return to the special no fishing pond by the lunch area. I swear I saw Jim for years after coming to get food scraps by the side of the pond. He was recognisable by a crook in his fin I think he acquired always swimming the same way around my tank. See if you can spot him!

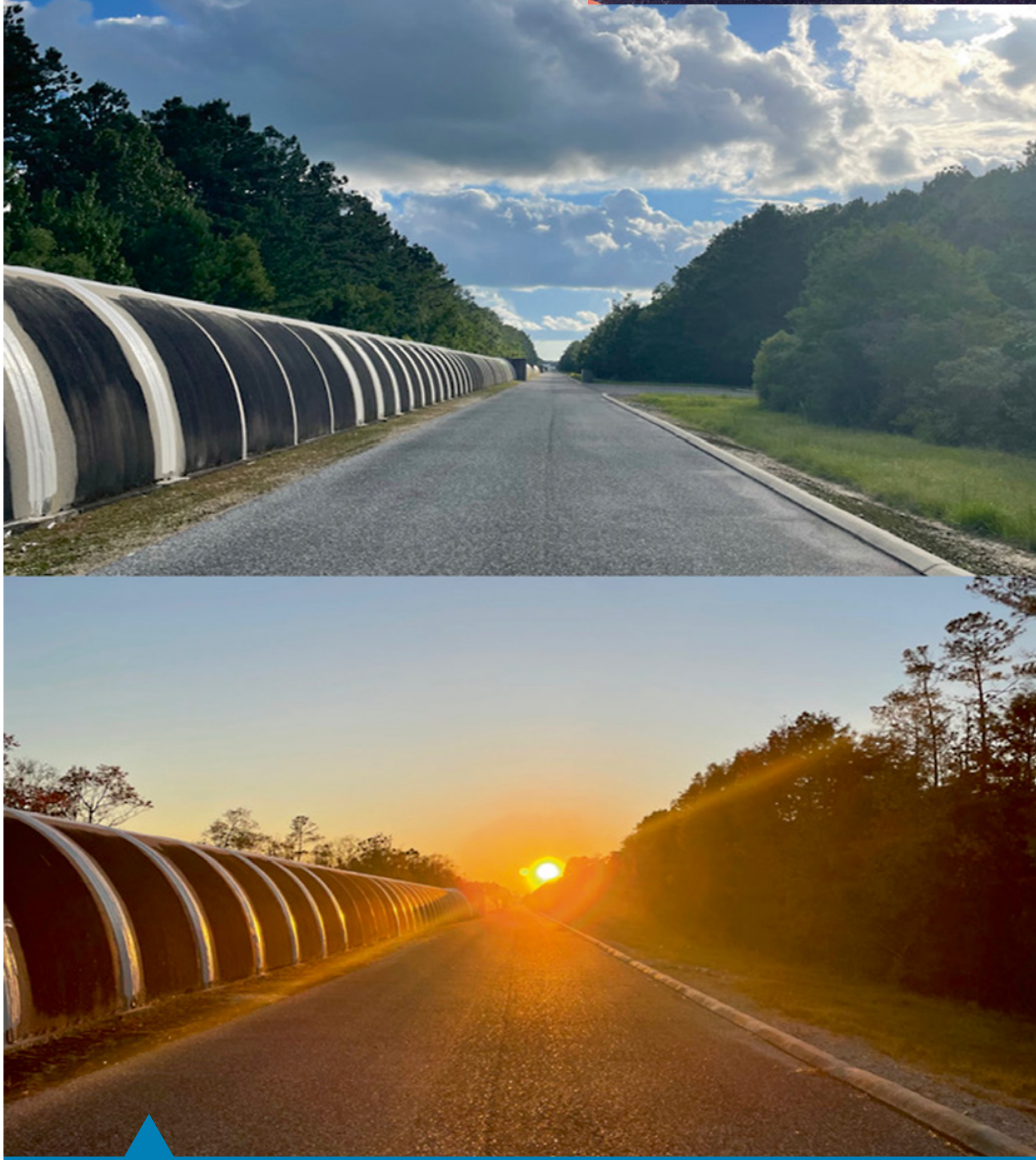
Masayuki Nakano

ran the LIGO Livingston arms more than 250 times in 1.5 years. He also loves beer after running!

The very straight long arms of LIGO are the ideal place not only for photons to feel the gravitational wave but also for the human being to feel our great life, by 'running'.

Actually, the arms are the best places for running. Straight and flat, with little traffic and only occasional other runners, running in this great place provides us with an amazing running experience like no other! Furthermore, especially on the arms in east Louisiana, we have chances to encounter lots of wildlife such as herons, bobcats, deers, raccoons, opossums, snakes, turtles, and so on.

The LIGO arm running is great fun as well as super effective in keeping your health and in developing the physical strength needed for hard research. You can't miss this great experience, and try it when you visit the LIGO site!



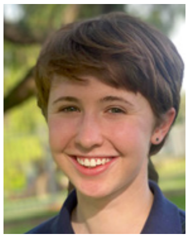
Top: Chiara riding an electrical yellow car at LIGO Hanford!

Below: Stunning views of LIGO Livingston arms during running times.

Virtual Reality for Astrophysics Outreach

Virtual reality allows fascinating, even unique, insights into scientific research

Maddy Parks



is a postgraduate student at the University of Adelaide, and found her calling for education through OzGrav's outreach program. She loves to paint in her free time, and she's slowly learning how to use her 'teacher voice'.

Over the past decade, Virtual Reality has skyrocketed into the realm of mainstream consumer electronics. A typical headset is compact and portable, provides mesmerising visuals, and will last for years of regular use – all for just a few hundred dollars. For these reasons, many educators are adopting Virtual Reality (VR) as a tool for science outreach. So, does VR strike the rare balance between novelty and relevance, and open the door for truly impactful learning?

Mission Gravity

During my time at OzGrav's University of Adelaide node, I've had the privilege of delivering a range of VR outreach programs. Mission Gravity: Life of Stars was developed by Mark Myers and Jackie Bondell, and uses VR to teach stellar evolution to students aged 12-15. Within the program, users are situated at the helm of a spaceship. They can pick up virtual tools to measure and record the temperature, size, composition and age of a nearby star as it evolves. Students work in groups of three to four, and collaboratively fill out a 'data log' of their measurements.

A reasonable concern regarding VR's role in outreach is that its game-like design may take precedence over learning. After all, headsets are often marketed as a platform for gaming and entertainment; why wouldn't students treat it as such?

The Project

I wanted to investigate whether our use of VR was engaging students in the way it was intended to, or if it was simply distracting them. To do this, I ran several Mission Gravity sessions at a local high school and measured student response to the program.

As this was a pilot study I wanted to obtain a set of baseline results; something that could be used in any future research or evaluation of the program. Additionally, limited time and resources meant that I could only investigate one demographic in depth. I opted for a group of students aged 13-14 as this was right in the middle of the recommended age bracket for the program.

Collecting Data

As most scientists know, field work is often quite far removed from lab work. I quickly found that this contrast is even more jarring when your 'field' is a classroom full of teenagers. I think I was more nervous than they were!

Whilst undertaking research of this nature was completely new to me, my wonderful supervisors Dr Daniel Brown and Dr Edward Palmer helped me to devise a mixed methods approach. Blending qualitative and quantitative methods, I took observation notes of in-session behaviour, analysed student worksheets, and distributed an exit survey at each session's conclusion. Combining these gave me a better measure of the students' response as a whole.

Worksheets

No matter how fun or interactive an outreach program is, it is only worth valuable classroom time if it's clear that the students have learned something! Worksheets are a simple, straightforward way of prompting students to show their understanding of the content.

Collecting each group's data log at the end of the session allowed me to check for evidence of learning objectives. Particular learning 'markers' I looked out for were the successful completion of the entire data log, or the correct classification of a group's assigned star (e.g. 'neutron star', 'supernova', etc).

Observation Notes

During Mission Gravity sessions, we often have to divide our attention around the classroom to ensure each group remains on track. This requires a good understanding of how students look and act when they're focused on the activity, versus when they are not. In my research, I wanted to translate this into a quantitative measurement.

My observation notes involved scoring groups based on their apparent level of engagement with the activity. Every five minutes, I would score each group from zero to three; a three indicated that every student in the group was in discussion or active participation in the tasks, whereas a zero was assigned if none of the students appeared to be on-task. This gave an idea of the students' engagement as the session played out in real-time.

Exit Survey

The extent of our interaction with students usually ends when the session does, but this study gave us the unique opportunity to hear from them after the program had finished.

The exit survey featured a mixture of Likert scale, multiple choice, and open ended questions about students' experience in the activity. This self-reported data helped us to determine the strengths and weaknesses of various aspects of the program.

Findings

Overall, Mission Gravity was generally received well by the Year 9 classes. After sifting through the data I came back with a few interesting findings.

Many students seemed to respond positively to being in control of what they saw and experienced during the session. A significant number of respondents cited making the star 'explode' at the end of its life as a highlight of their VR use.

Students also interacted with the VR interface as intended. The survey found that on average, each student measured nearly three of the four observable star properties during the session.

Interestingly these were not evenly distributed; the star's temperature was reportedly measured by 85% of students while the chemical composition was only attempted by 56%. This could be a case of students finding some concepts more challenging than others; distributing a pre-activity lesson pack may be useful in refreshing particular concepts prior to their session.

Another notable trend was that after around 45 minutes in VR, the average engagement score tanked and students began to disengage. This happens to align with the typical 50-minute lesson blocks that our students were accustomed to, so it's unclear whether this was an expected behaviour or indicative of something more.

In future it could be useful to determine whether any groups finished the task early, as this may have contributed to the collective loss of focus. The worksheets and survey were in agreement that roughly three quarters of the cohort completed their data log, but no additional information was collected.

Final Thoughts

Ultimately, it's important that we continue to characterise the growing role of VR in our educational practices in years to come. As times change, we'll continue to assess, improve and maintain these programs so that they are as engaging and impactful as they are intended to be.

Working with OzGrav on this project has taught me so much, and it has massively improved my confidence as both a researcher and an educator. It has inspired me to continue on this path, and in just a few weeks I will begin my training as a pre-service teacher.

Above all, it has been a profound reminder that the students are the reason we do this work; the responsibility falls upon all of us to help usher in the future leaders and innovators of this field.

Gravitational waves and carbon footprints

The three predominant sources of carbon emission associated with LIGO-Virgo-KAGRA are power at the sites, computing, and travel to collaboration meetings.

The LIGO-Virgo-KAGRA (LVK) Committee on Climate Change explores issues within our community in light of climate change and sustainability. One area of focus is minimizing the collaboration's carbon footprint. We are also exploring scientific exchange between the gravitational-wave and climate research communities, as well as ways to build awareness of the topic of climate change, both within and outside of our collaborations. As scientists we have an important role to inform and engage the public and policy-makers about this critical topic.

Daniel Holz

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

The main activity of the Climate Committee thus far has been to provide a rough estimate of the carbon footprint of the collaboration. There are three predominant sources of emission that can be directly associated with the LVK: power at the sites, computing, and travel to LVK meetings. We discuss each in turn.

The power usage is approximately 2 GWh (GigaWatt-hours) for KAGRA, 3 GWh for Virgo, 5 GWh for LIGO-Livingston, and 7 GWh for LIGO-Hanford (the difference between the LIGO sites is primarily due to weather). Calculating the carbon footprint of these depends on the source of the electricity at the sites. For example, Hanford emits relatively little carbon, since it is almost entirely powered without the burning of fossil fuels: ~80% hydroelectric, ~10% nuclear, and ~5% wind. Livingston, on the other hand, is almost entirely sourced through natural gas and coal. This roughly matches the overall mix of power sources available in the local regions (e.g., see [1] and [2]). Taking these various considerations into account, we estimate the overall carbon footprint due to power at the sites to be ~4,000 tons CO2 per year.

Estimating the carbon footprint due to computer usage is difficult, since LVK computing is distributed across individual institutional clusters as well as national computing centers. As a rough estimate, we find that the LVK uses on the order of 700 million CPU core hours per year. Making assumptions for the efficiencies of the cores, costs of associated cooling and other overheads, and the relevant energy mix powering these cores, we find an overall footprint of ~5,000 tons CO2 per year.

Travel can be a significant source of CO2 emission, and the LVK has historically held two full-collaboration international meetings per year. Looking over attendance breakdowns for some of the recent meetings, as well as some of the smaller face-to-face workshops, we estimate that the footprint of these meetings just from the air travel involved is ~1,000 tons CO2 per year.

Combining these estimates, we find a total LVK footprint of ~10,000 tons CO2 per year. If we divide this by ~2,000 LVK members, we find a very rough estimate of 5 tons of CO2 per year per LVK member of emission due to LVK activities. For calibration, the average yearly per person emission of various countries is (in tons; from [3]): US and Australia 15; Japan 9; Germany and China 8; France, UK, and Italy 5; India, Egypt, and Brazil 2. Thus for most LVK members the emissions associated with their LVK activities will be a significant component of their overall carbon footprint.

In this discussion we have neither considered the carbon footprint of building the detectors in the first place nor the operating footprint (due to goods and services) apart from electricity. These are expected to be a potentially significant source of CO2 emission, in particular the extensive use of cement and concrete (see e.g. [4]) along with earthworks. The carbon footprint associated with the construction of next generation gravitational-wave detectors such as Cosmic Explorer and the Einstein Telescope is being examined by the relevant design teams, and is likely to be quite significant; effort will be made to minimize the impact.

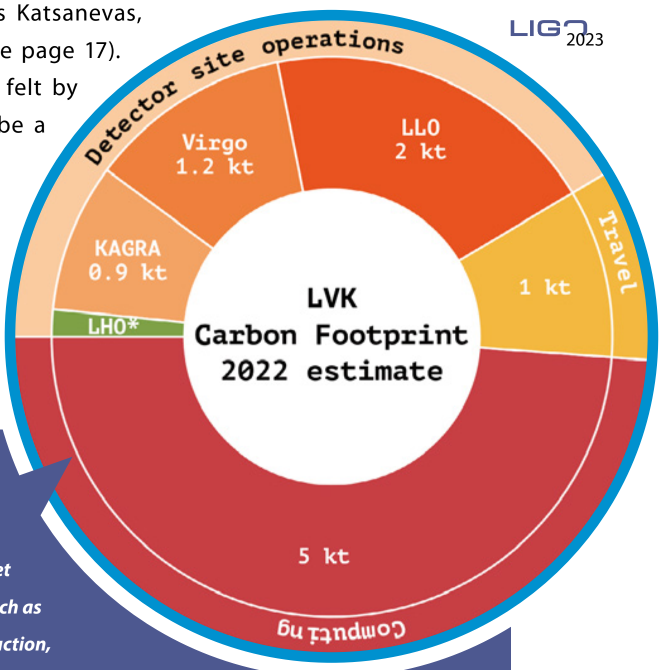
Based on these findings, we are developing recommendations to help reduce the overall LVK footprint. Low hanging fruit might include increased attention to algorithmic efficiency in our computational analysis, reducing the number of parallel pipelines pursuing the same science, working to reduce the number of passes over the data, transitioning Livingston away from fossil fuels to the extent possible, and reducing the number of international LVK collaboration meetings while improving hybrid capabilities.

It is important to note that one of the most active members of the gravitational-wave community on the topic of climate change was Stavros Katsanevas, EGO Director at Cascina (see page 17). His untimely loss is deeply felt by the community; there will be a memorial conference in his honor in Paris on June 1, 2023 [5].

The Climate Committee meets every two months, and everyone within the LVK is welcome and encouraged to participate! Please sign up for our mailing list [6]. Climate change is an existential challenge, and we look forward to working together to increase awareness and engender action.

References

[1] ourworldindata.org/grapher/sub-energy-fossil-renewables-nuclear
[2] www.nei.org/resources/statistics/state-electricity-generation-fuel-shares
[3] ourworldindata.org/grapher/co-emissions-per-capita
[4] www.nature.com/articles/d41586-021-02612-5
[5] indico.in2p3.fr/event/29126/
[6] LVK members can sign up to the Climate Committee's mailing list at: sympa.ligo.org/wws/info/climate_change



Estimated carbon emissions from LIGO-Virgo-KAGRA in 2022. The estimate does not yet include other site emissions such as those produced during construction, or from goods and services during operation.

**LIGO-Hanford (LHO)'s footprint is significantly smaller than LIGO-Livingston (LLO) as it is almost entirely powered without the burning of fossil fuels.*

The Gingin arm collapse of 2021

Carl Blair

is an experimental physicist developing techniques to make better gravitational wave detectors at University of Western Australia, and Research Director at the HOPTF. Carl enjoys anything that slides on water (frozen or otherwise) or rolls on two wheels and loves playing with gravitational wave detectors and playing cello.

After/before photos of the south arm beam tube at the HOPFT near Perth, Australia.

There is an 80m prototype interferometer in the beautiful Gingin bushland 80km north of Perth, Western Australia known as the AIGO High Optical Power Test Facility (HOPTF). This test facility has been the home of many significant contributions to the quest for gravitational wave detection. These include the first observations of strong thermal lensing, demonstrations of thermal compensation and observation with Hartmann sensors, and the first observation of parametric instability (PI) in a suspended optical cavity and subsequent development of PI mitigation strategies.

HOPTF's two 74m long 304 stainless steel spiral welded vacuum tubes initially arrived in 11.5m sections that were butt welded together within the main laboratory and then rolled out on roller supports to each end station in the year 2000. The 400mm diameter tubes have a wall thickness of 3mm giving the entire 74m length a safety factor of 1.7 - with no stiffening rings. A vacuum of 10^{-6} mbar has been maintained throughout the life of the system. This is the story of what we understand led to the collapse of the South arm vacuum tube.

The initial report to the University of Western Australia, which manages the facility, read "Over the weekend the South arm tube collapsed. A loud noise was heard by a Gravity Discovery Center (GDC) employee between 1 and 1:30pm Saturday the 11th who was working on the bush walk. There is no clear indication of a single cause of collapse. The design safety factor was 1.7."

Initial investigations revealed fresh walking tracks from one adult and one child that passed the paved path alongside the tube. They also revealed a "quite energetic" kangaroo track passing under the tube. The most important observations were that there was significant rubbing and variation in pressure between the nylon rollers of the support structure, which presumably occurred as the structure settled over the last 21 years. Lastly, the wheels which support the tube had in fact been mounted at 120 degrees (rather than the 90 degrees proposed at the time of construction) resulting in more lateral stress on the tube. This last point turned out to be critical.

The forces involved in the collapse were immense: the 20mm thick flanges at either end of the tube had been deformed by about 10mm. The self-supporting cylindrical tube now lay limp on the support structure as shown in the before and after pictures. Surprisingly the internal vacuum remained unaffected, with the Viton O-Ring flange seals at either end maintaining pressure. Both 500mm long thin wall expansion bellows at either end were critical in preventing further damage towards the main vacuum vessel including the ISO-400 gate valves.

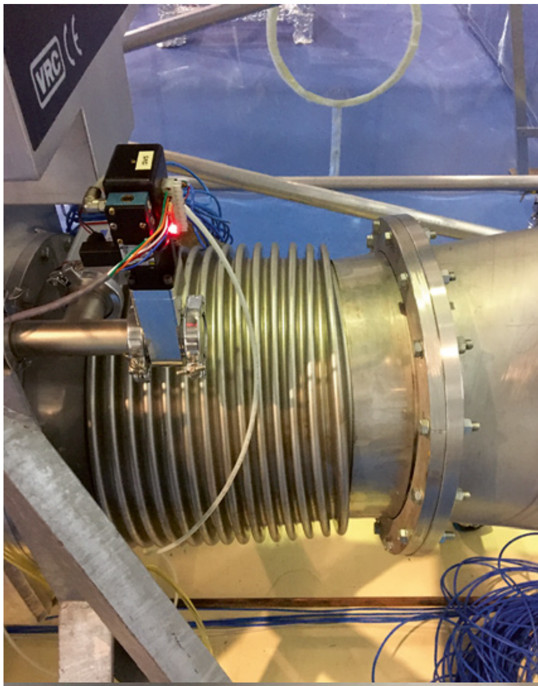
Further investigations showed that there was a seismic event recorded at 2:49pm on Saturday, but nothing in the 1:00-1:30pm interval reported by the GDC employee. The CCTV system was not functioning at the time of collapse and there was no audio recording system operating at the time.

We modeled the various collapse mechanisms including kangaroo impact, human impact, human induced impact (from stones etc., there was no sign of vehicle movement). We also modeled the settling of the support structures and thermal stress on the tube (note: the tube is exposed to the elements and regularly gets a 60°C gradient 30-90°C bottom to top of the tube in summer). No single mechanism could result in collapse.

The East arm tube (which remained intact) was vented immediately after the collapse and it is the investigations of this tube that revealed the mechanism that we believe can explain the sudden collapse after 21 years of incident free operation. Measurements revealed that the tube was on average 1cm taller than it was wide. Simulations show that this is close to the deformity required to reach the critical point of collapse. We estimate that as the tube would cool at night, it would settle a little lower into the roller supports. Then as it heated the next day, thermal expansion resulted in a lateral stress due to the roller supports being at 120 degrees. This repeated process over 21 years resulted in the observed ellipticity. If the rollers had been 90 degrees the thermal stress would have just resulted in a radial expansion with no lateral stress. If the rollers had also been rotated to a radial orientation there may have been less friction trapping the tube within the 120 degree support.

Standards in Australia (AS 1210) now require vacuum enclosures to have a minimum safety factor of 4 for environments where humans may be present (this was introduced in 2010). The East Arm vacuum tube was brought up to standard by clamping stiffening rings along the enclosure every 1.5 meters. The tube is now cylindrical again. The safety factor is now 8. The replacement South arm tube can no longer be constructed with the welding technique used previously as the lab is now full of experiments. The new tube will be supplied in 8m sections with 4mm wall thickness, using standard CF flanges and copper seals. It will have a safety factor of 5.5.

The moral of the story is that it's always better to allow an ample safety factor. The kangaroos are probably not the problem. And that we should count ourselves lucky that no one was hurt. A section of the collapsed tube will be erected as a display of the power of air pressure in the co-located Gravity Discovery Center.



*Flange seals at either end of the collapsed tube held, preventing further damage - **Top**.*

*Photo from the flange of the spiral weld of the deformed tube - **Middle**.*

*New "Stiffening rings" added to the East arm tube (which did not collapse) - **Bottom**.*

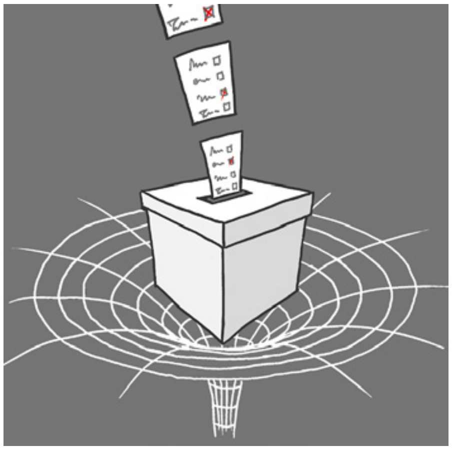
LSC elections in focus:
Running on empty?

Paul Fulda

is an Assistant Professor at University of Florida, where he works on instrument science for ground- and space-based laser interferometry. Outside of work he enjoys hiking with his family, playing soccer and attempting to grow vegetables and bonsai trees.

"I'd like to acknowledge that we have a serious problem within the observational science groups with regards to standing for election."

The sentiment above, shared by a former working group chair, is not unique among collaboration members. The problem hasn't escaped the attention of the LIGO Scientific Collaboration (LSC) Council, who have recently discussed ways to increase participation in LSC elections. While some of the reasons for rejecting a nomination might seem easy to guess, in this article we aim to dig a little deeper and get some personal perspectives from those in the know.



If you're reading this, there's a pretty good chance that you're a member of the LSC. However, the chances are much lower that you have run for one of the elected positions within the collaboration. In fact, it seems to be getting harder to find collaboration members who are willing to accept nominations. This prompted us at LAAC to reach out to a range of colleagues about their experience with LSC elections and leadership roles, to give you the lowdown on what's involved, dispel any myths about running, and share their ideas about how to improve the elections system in the future - resulting in this collection of thoughts and experiences.

Elected roles in the LSC

The LSC has many elected roles including spokesperson, working group chairs, committee members and special positions. The purpose of holding these elections is to ensure that all collaboration members can have their say in the running of the collaboration. Of course, having a say requires having a choice, and with a dearth of candidates willing to run for certain positions, the choice can be severely restricted.

To run or not to run? Deciding whether to accept a nomination

Receiving a nomination means that someone in the collaboration considered you capable of serving in that role[1]. You now have two choices: to accept or reject the nomination. While rejecting is as easy as clicking a button, to accept you must write a statement to tell the voters what you will bring to the role. And of course, if you win the election you now have a new job to learn and perform for 2 years or so! One of our respondents encapsulated the nominee's primary dilemma neatly: **"When I was first nominated for a working group chair role, I saw it as an opportunity to gain some leadership experience, which is not always easy to come by as a postdoc. Having been elected and served in such a role, I now realize the significant time commitment that's required."** In fact, the necessary time commitment and the associated opportunity cost of not doing more research and publishing were the most cited reasons for turning down a nomination: **"It would ... detract significantly from more essential activities for progressing my career, like leading and writing short-author papers"** said one respondent who declined a nomination for a working group chairship, but later accepted a different nomination and won the election. Another respondent had this to say: **"Currently, my leadership efforts within the LVK [LIGO-Virgo-KAGRA collaborations] seem to affect my applications only neutrally (or even slightly negatively, given the opportunity cost)."**

But the time investment wasn't the only factor influencing the decision to run or not: **"Oftentimes imposter syndrome strikes hard – especially with the idea that people could vote to confirm it! But, to this I would counter that simply being nominated should demonstrate you are suitable."** Concern about having the authority and backing to carry out the role effectively was expressed by more than one respondent: **"If I were**

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[1] *If you self-nominated, then that person was you and presumably you need no further encouragement to accept!*

nominated today, I would want to know that I had the ability to make binding decisions with the backing of LSC leadership to be able to carry out those decisions." and **"Chairs need to be given a clear policy to work from. They need visible support: too often I have requested help and been met with silence."**

The potential for positive career impact and the ability to direct the collaboration's efforts overcame these concerns for many of our respondents. According to one former working group chair: **"There are real benefits: leading collaboration science, invitations to present work, a hand in guiding the scientific direction"**, and in the words of another long-time LSC member: **"...my career has definitely benefited from having elected LSC offices."** For others, it was more a matter of feeling the obligation to contribute their service: **"There didn't actually seem to be a lot of other candidates willing to stand recently (...and in the end it turned out there were zero others...) and I felt that, after many years in a group, it'd almost be my duty to take on such a role eventually."**

When is the right time to take on an elected role?

In principle any LSC member can stand for any elected position. But potential nominees and also voters may have expectations about what level of experience is required for certain roles. Job stability can also be a factor in whether nominees could be confident about serving out the term. With regards to earlier career members accepting nominations, one respondent said: **"...we often focus on encouraging junior members to stand. I support that, but if chairs are to be junior, they need support: often they will be relying on letters of reference from the very people they are upsetting by making collaboration decisions."**

Another, who turned down a nomination, gave this as part of the reason: **"I was a fourth-year PhD student at the time. I didn't feel I had the authority to chair the most prolific observational science working group in the collaboration. While I am generally an assertive person, I didn't think I would be able to convincingly lead the group, which has many outspoken, senior, male members with much more storied histories of gravitational-wave data analysis experience than me."**

In the end of course it's up to the nominee and the electorate to determine when you're ready, but there was a clear expression that encouragement without the necessary support is not a popular strategy. With regards to senior members standing for election one respondent said quite bluntly: **"The elephant in the room is the complete lack of senior academics willing to stand for chair positions. They have a myriad of excuses, but cutting through it the truth is these are successful career-minded academics who believe it will be harmful to their career prospects."** The obvious question then is why should junior academics come to a different conclusion?

Ways that the election process might be improved

Some of our respondents had interesting ideas on how to improve the election process itself. Regarding nominations, one commented: **"You usually don't know who nominated you or why, so you only have the vaguest idea of whether you might be able to fulfill their expectations."** - the LSC Council recently had similar thoughts, and have now approved plans to move to an Open Nomination procedure starting with the Fall '23 election cycle.

Another thorny issue is whether or not to release the vote tallies. According to one person: **"The only thing odd about the current process is that, in my opinion, a basic principle of democracy is not respected, which is to release the vote tally so the voters and candidates have confidence in the process and are able to ask questions if the results seem odd."** On the other hand, others have expressed concern that the publication of vote tallies might further dissuade people from accepting nominations. The same respondent suggests a partial remedy for this: **"The candidates could be informed of the vote tally and asked if they are willing that their result is announced to the voters."**

Another long-time LSC member made an interesting suggestion to improve continuity in some positions: **"I like the way APS [American Physical Society] President and many other offices in professional societies work. There is a President line, a new person is elected to President-elect, then the next cycle they become President, then the next cycle they become President Emeritus. So built into the system is both a time to learn and be mentored, and a time to mentor the next person. But there is also a time to actually lead. And this is all official, and enough time is given to do all of these roles well. I think the LSC should consider this system for some of its offices, including WG [Working Group] chairs, Spokesperson, and LAAC chair."** As a LAAC Co-chair myself I'm happy to say something similar has recently come about organically and democratically in our committee, with twice-elected former Co-chair Jessica Steinlechner recently being elected senior representative, and former student representative Mikhail Korobko recently being elected Co-chair (both in multi-candidate elections).

Wrapping up

Many of our respondents expressed some concerns about the nomination and election system, but significantly more concern around the elected roles themselves and the (lack of) support provided by LSC management: **“I think the factors that influence why people decline nominations are real and tangible. This is not an “image” problem that can be fixed by explaining how great it is to be a chair. We need real change to the incentives structures to encourage people to chair and to support them whilst they do it.”** These are just some of the issues that the LSC has to address in order to make the collaboration a more inclusive and welcoming one for all members.

Of course, like many journalists we’ve focused on the negatives here, and we shouldn’t ignore the tendency for people to preferentially respond to surveys when they have a complaint to raise. To bring a little balance let’s also consider the things that our respondents did think work well:

“20 years ago, a nomination was a recognition of your stature and capability to carry out an important collaboration role. I think that is still true today.”

“The system works well, and I appreciate the opportunity to send a statement, and that voters can order the candidates rather than selecting only one, since voting for only one person is in fact to vote against the others.”

“I do have full confidence in the current Election Committee.”

“Thanks for the opportunity to express ourselves on the process."

So while there seems to be room for introspection and work to do within the collaboration on the elections issue, if you’ll allow for an extended analogy: perhaps we’re not exactly running on empty, but it might be time for an oil change and some new brake pads.

Let's not forget that the collaboration is what we make it, so please consider running or nominating in elections and be the change you want to see, even if that change is in the elections themselves! If you have more thoughts or suggestions about LSC elections that you would like to share, please get in touch with the LAAC at laac@ligo.org.

LIGO 2023

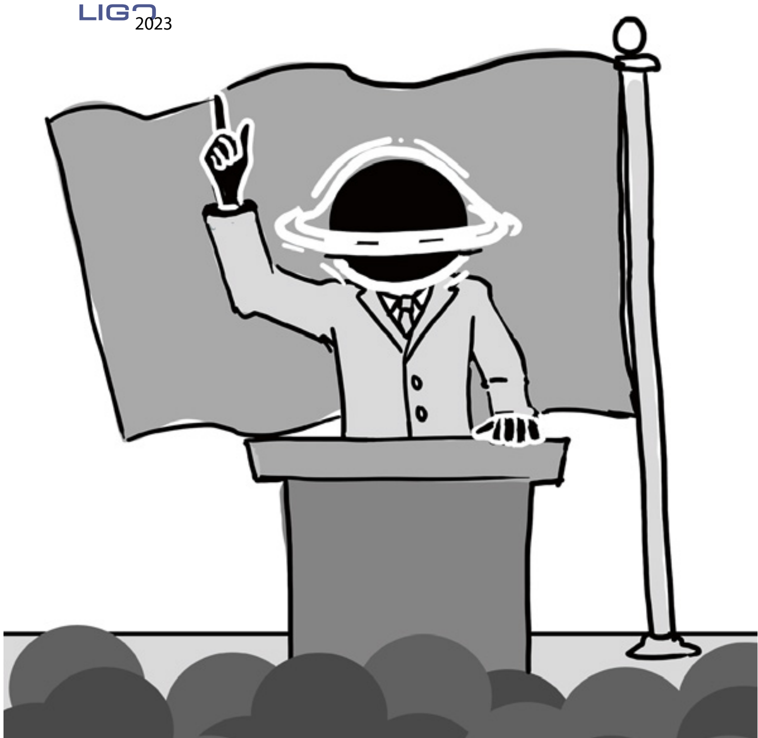
Welcome to the LAAC Corner!

The LSC Academic Advisory Committee helps students and postdocs to learn more about the LVK, find useful information, and collaborate.

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

Have fun reading!

Paul Fulda and Mikhail Korobko
LAAC co-chairs



(Re)finding my love of science

by Sam Cooper

"Do you want to see a planet?” Aged six, that was my introduction to astrophysics at a local observatory. Growing up I was a shy kid, I’d never wanted to bother anyone or to be a pain. After much convincing I stepped up to the telescope and saw Jupiter, I was amazed it looked exactly like photos in a book I was reading at the time. The shyness had completely faded at this point, when asked if I wanted to see another planet, I leapt at the chance now the telescope was pointed at Saturn. After that I was hooked, the images are as clear in my mind now as they were back then, I knew what I wanted to do as a job.

▲

Sam Cooper is a Project Manager working at Green Lemon Company – a low code software company based in Brighton UK. When he is not working Sam enjoys cooking and watching motorsports.

Fast forward a few years as a postdoc at the University of Birmingham, it was my dream job, I worked with a great group of people, had a nice mixture of different projects, and then the pandemic hit. Remote working became mandatory overnight, lab work became non-existent, and I hadn’t seen my family in about 6 months (not as long as some people, but too long for me). I knew I couldn’t bring myself to work abroad, this and some other factors took the fun out of research for me, it became harder to motivate myself day to day. *We published a new paper*. “Eh”, *JWST launched*, “who cares?”. I knew then that something was wrong with me and I needed to do something different, I’d fulfilled my childhood dream and now needed something else to do. But what? I’d convinced myself the only thing I could do was Physics, after all I’d been studying/researching it for the past 12 years.

During the pandemic, as an avid motorsports fan I took up Sim-Racing and met some people online, we got talking and they needed a project manager. I’d done some during my postdoc and enjoyed it.

The next few months were somewhat of a blur, I had a small nervous breakdown and had to do something[1]. After a couple of interviews I was offered a job at a low-code software company (with the person I’d raced with online). I completed some extra courses in project management, learning about server management and professional software development. I moved back near where I grew up, bought a house back home (one of the perks of remote working) and settled into the new job.

It's a little different to what I was used to, instead of designing and testing hardware I’m talking with developers, clients and designing bespoke software. Reading Reading specifications, understanding business cases, solving problems and thinking on my feet. There’s sadly not as much science involved, but we’re encouraged to take courses and learn new skills which is another great perk. As is spending lunchtimes walking in the countryside. Since it's a very different job, I get to look at science with fresh eyes again and when the first pictures were released from JWST, that same feeling I felt as a 6 year old kid, it was back.

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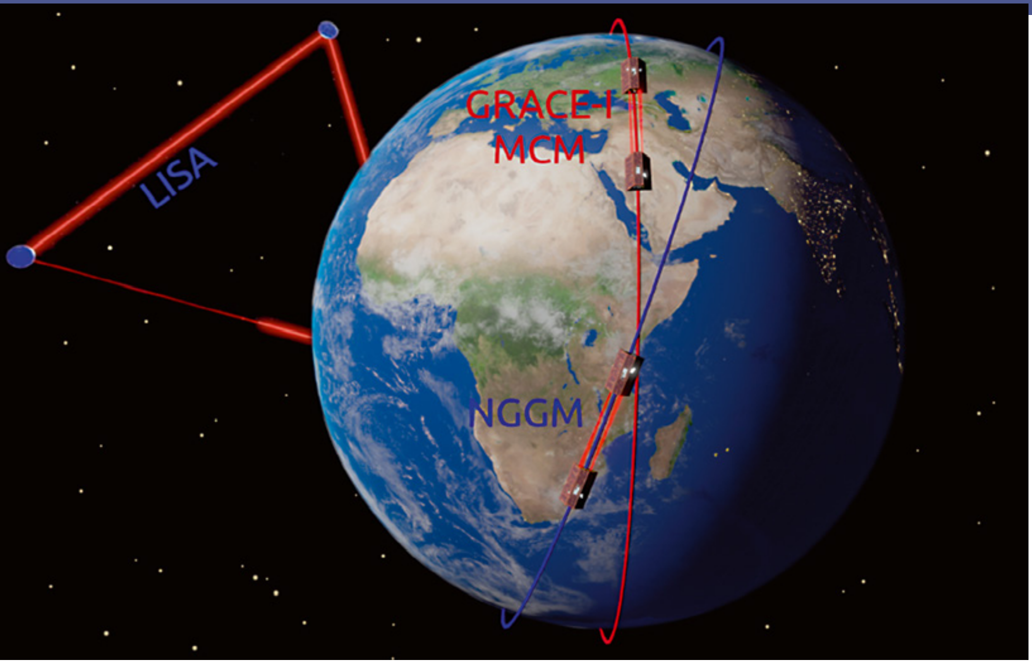
[1] *If you find yourself in a similar situation, remember support is available from your institution, as well as from family, friends, colleagues, and national organisations (e.g. mind.org.uk).*



The future is becoming MAGIC

▲ *Artistic view of satellite constellations in the 2030s: The gravitational-wave observatory LISA in the background and the satellite pairs NGGM and MCM/GRACE-I measuring Earth's gravity field.*

The GRACE Follow-On (GRACE-FO) twin satellite pair is approaching its fifth anniversary in space, and continues to provide monthly snapshots of the Earth's gravity field. These global gravity field maps reveal large-scale mass variations due to melting ice from the poles and glaciers and changes in terrestrial water storage. They can be used to infer groundwater depletion or to improve our understanding of the global mean sea level rise, where the measurement of the direct rise in level is consistent with the sum of individual measurements between 2002-2016, but inconsistent thereafter and is still being debated. The GRACE-FO datasets have high societal relevance as they provide information on freshwater resources, which are becoming increasingly important due to global warming.

Vitali Müller

works at the Max-Planck-Institute for Gravitational Physics (Albert-Einstein-Institut) in Hannover, Germany, and has so far dedicated his entire scientific career to laser interferometry for gravity satellite missions. In his free time, he enjoys geocaching, sushi and playing with his four year old son.

The principle of this mission was pioneered by the Gravity Recovery and Climate Experiment (GRACE, 2002-2017). It is based on the fact that the separation of the satellites is affected by the mass distribution of the part of the Earth over which the spacecraft flies. The distance changes are precisely tracked by a ranging instrument, while accelerometers measure non-gravitational forces acting on the satellites in order to subtract them during data processing. The original GRACE and GRACE-FO (2018-present) missions primarily use microwave-based ranging, which can resolve micrometer changes in the satellite separation. However, on board GRACE-FO there is an additional Laser Ranging Interferometer (LRI), the first inter-satellite laser interferometer, capable of resolving minute changes in the 200 km distance between the satellites down to the size of single atoms on short time-scales (200 picometer/√Hz at 1 Hz). In September 2022, the LRI team installed a flight software update that eliminates disturbances in the LRI data caused by thruster firings, greatly simplifying post-processing on ground and solving the only noteworthy issue in the LRI.

There have been a few hiccups in the mission. On the second satellite of GRACE-FO, one of the Instrument Processing Units, the processor for GPS and microwave ranging, failed, requiring a switch over to a redundant unit. The accelerometer also shows degraded performance, which can be mitigated to a large extent with some data processing tweaks. This slightly affects the gravity field maps, but the end products are still within the requirements and useful for researchers in many fields.

Now, with the surge in solar activity in the current 11-year cycle and the resulting increased atmospheric drag at ~490 km altitude, the propellant will be depleted more quickly. It is hoped that the mission will operate at least until 2028, when a new pair of satellites with an evolved LRI acting as the main ranging instrument will arrive in space.

Like GRACE and GRACE-FO, this new mission is based on a US-German collaboration. The developments were started in parallel on both sides of the Atlantic, which is why this mission is currently called "Mass Change Mission" (MCM) by NASA/US and "GRACE-I" on the German side. These satellites will use polar orbits like GRACE-FO and sample the poles at least 15 times per day, whereas the ground-track sampling at the equator is rather sparse for a single day, so that several weeks or a month of data have to be accumulated to recover a gravity field map with sufficient global accuracy and spatial resolution.

In addition to the US-German mission, the Next Generation Gravity Mission (NGGM) is being pursued by the European Space Agency (ESA) and is planned for launch around 2031. NGGM will again use laser ranging between two satellites, increasing its sensitivity to gravity compared to GRACE-FO and MCM/GRACE-I. The NGGM pair is likely to be placed in inclined orbits, increasing the sampling in the sparsely sampled low-latitude regions. Such a configuration of a polar and an inclined pair, originally called the Bender-constellation or MAGIC (Mass-change And Geosciences International Constellation), will significantly improve the monthly gravity field maps and the associated tracking of mass transport in the Earth system due to the enhanced spatial and temporal sampling of the ground-tracks and the additional east-west component of observations added by the inclined pair.

Although the ranging precision has improved by three to four orders of magnitude from the microwave to the laser-based system, the monthly maps do not show noticeable improvements due to the so-called aliasing errors caused by short-term mass variations, e.g. due to weather effects or uncertainties in ocean tide models, which distort the monthly estimates. This was expected on the basis of simulations carried out before the launch of GRACE-FO.

The low noise of the LRI data will only be fully exploited in the future when multiple pairs are available. Nevertheless, the LRI has already allowed the detection of deficiencies in some static gravity field models at small spatial scales and has been used to recover shorter sub-monthly gravity signals, e.g., from a flood event in Australia or the monsoon season in Bangladesh.

The development of the LRI for GRACE-FO, as well as for the future missions, originated from groups involved in the development of the Laser Interferometer Space Antenna (LISA). LISA will be a space-based gravitational-wave observatory made up of three satellites connected by lasers. The ranging technology for gravimetric missions and LISA have many similarities. The first demonstration of inter-satellite laser interferometry with GRACE-FO was therefore a milestone for LISA, providing many lessons learned. It is also a prime example of how fundamental research in gravitational-wave detection can benefit society by addressing issues such as climate change and improved Earth observation.

I wrote my bachelor, master and doctoral theses on topics closely related to GRACE-FO and its LRI. Therefore, I was thrilled to watch the satellite launch on 18 May 2018 in the control room at GSOC/Germany, hoping that all the efforts would not be in vain - they weren't. Everything went well, we had one surprise with some disturbances in the LRI that we were able to fix. I could have stopped there and started other projects, but I wanted to stay in a field related to climate research. So my team and I dug deeper into the LRI data and tried to understand all the little technical details. Over the past two years, activities for a new generation of missions using LRIs have been ramping up. A month before Christmas, both the German parliament and ESA approved funding for two new missions, so things are really getting serious. I am looking forward to being part of a team with colleagues in the USA, Australia and Europe to realize the next instruments.

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Ground testing of the LRI on the GRACE-FO satellites at IABG, Ottobrunn, Germany.

contd. from p.17

Stavros

Marica Branchesi, Astronomer, Virgo Collaboration, GSSI

I will never forget his strength, his enthusiasm, his vision. He was trying in every way to break down walls and build bridges, to create collaborations, to promote new ideas, a profound supporter of multi-messenger astronomy on which we often found ourselves discussing and dreaming together for the future, he thought about the world and its future by dedicating himself to sustainability and climate change. Those colleagues you cannot forget because you feel a human affinity that goes beyond the work. We will continue to do research following the path you taught us.

Tomas Saraceno, Artist

Stavros was a brilliant scientist and a true friend – it is truly one of the great privileges of my life to have known him. I will always remember his generosity of spirit, from which so many beautiful ideas and projects were born, like the Arachnophilia community event How to hear the universe in a spider/web: A live concert for/by invertebrate rights, to which Stavros contributed his amazing research on gravitational waves and spoke eloquently on the entangled relationships of both spider/webs and cosmic/webs. At Palais de Tokyo, as part of my exhibition ON AIR, Stavros and I live-streamed sonified gravitational waves and reflected on the lifeworlds of spiders/webs. It was a grand experiment made possible by Stavros' superb intellectual mentorship, that I will greatly miss.

We hear that ...

Career Updates

Richard Abbott is retiring from the LIGO Lab at Caltech on February 10th. We are all so sad to see him go. He will be missed by many!

Christian Darsow-Fromm from Universität Hamburg has defended his PhD thesis "Squeezed Light at 2128 nm for future Gravitational-Wave Detectors". Christian is now a postdoc at the same university, working on LISA phasemeter development.

Chiara Di Fronzo completed her PhD studies at the University of Birmingham in July 2022 and is now a postdoctoral researcher at Precision Mechatronics Laboratory in Liège (Belgium). She currently works within the E-TEST prototype collaboration for testing seismic control of next generation gravitational-wave detectors.

Graeme Eddolls passed his PhD viva on November 10th as part of the Institute for Gravitational Research, University of Glasgow. During his thesis, entitled "Design, build and characterisation of a prototype single crystalline silicon cryogenic suspension for 3rd generation gravitational wave detectors," Graeme built what he believes to be the world's first cryogenic silicon suspensions. Since graduation, Graeme moved to Moncton, NB, Canada to attend Moncton Flight College to pursue his pilot's license, but he is keen to keep his foot in the door with the collaboration as he may return to academia in the near future!

Tega Edo, who was a postdoc in the gravitational wave group at Sheffield for many years before going to Caltech for a further postdoc with Rana Adhikari, is leaving LIGO and starting a job as an Imaging and Embedded Systems Engineer at a space startup called OrbAstro. There he will work on a range of products including Synthetic Aperture Radar imaging systems.

Sudarshan Karki left the LSC in December to move into a new career path at a healthcare foundation in Portland, OR after many years in the LSC as a graduate student at the University of Oregon and then as a postdoc at the Missouri University of Science and Technology. We wish him all the best for the future!

Janis Wöhler from the AEI Hannover has defended his PhD thesis "Direct measurement of coating thermal noise at the AEI 10m Prototype". Janis will start a postdoc position at the University of Maastricht in April.

Awards

Alessandra Buonanno received the 2022 Tomalla Prize for her "outstanding work on gravitational-wave physics, especially for the effective one-body approach to describe the gravitational waves emitted by binary black holes or neutron stars, but also for other important contributions relevant for the detection of gravitational waves." https://www.aei.mpg.de/790105/alessandra-buonanno-receives-the-2022-tomalla-prize

Tim Dietrich received an ERC Starting Grant for his research project "SMArt" ("From Subatomic to Cosmic Scales: Simulating, Modelling, and Analyzing Binary Neutron Star Mergers") https://www.aei.mpg.de/979515/tim-dietrich-receives-erc-starting-grant-for-exploring-binary-neutron-stars

Prayush Kumar (ICTS-TIFR, Bangalore) was awarded the NASI Young Scientist Platinum Jubilee Award for 2022 by the National Academy of Science, India.

Susan Scott (Distinguished Professor at the Centre for Gravitational Astrophysics, ANU) has been awarded the international Blaise Pascal Medal in Physics for 2022 by the European Academy of Sciences and the Distinguished Alumni Award by the Faculty of Science of Monash University for 2022. https://www.anu.edu.au/news/all-news/susan-scott-first-aussie-to-win-prestigious-pascal-medal

Vijay Varma received the Postdoc award of the State of Brandenburg for his work on the analysis of GW200129 and the black hole remnant kick it created. https://www.aei.mpg.de/976665/postdoc-award-of-the-state-of-brandenburg-for-vijay-varma

New LSC positions

Amanda Christine Baylor was elected as LAAC Grad Student Representative.

Gerhard Heinzel was elected as Technical Advisor to the LIGO Oversight Committee.

Mikhail Korobko has been elected LAAC Co-Chair.

Francois Schiettekatte was elected as Co-Chair of the Optics Working Group.

Jessica Steinlechner was elected LAAC Senior Member.

Other News

Chris Messenger and wife Frances had a beautiful baby boy named **Dylan** in October 2022.

The Education and Communication Division is looking for new members to assist in communicating LSC results to the public. If you are a LIGO member interested in finding out how you can support these important efforts, contact Division Chair **Amber Strunk** (astrunk@caltech.edu).

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Stavros Katsanevas, 1953 - 2022

Why do gravitational-wave detectors need laser light?

Gravitational-wave detectors, or interferometers, use lasers to measure changes to distance, but how? And why is laser light the best light for us to use? Light is a very useful tape measure because it always travels at the same speed in a vacuum. If you can record the time taken for some light to leave your emitter and return after reflection from an object, then distance equals speed times time. Easy. But imagine trying to do that with an ordinary lightbulb.

A lightbulb is an example of an *incoherent* light source. The photons from it are not all the same as they have random phase, polarization, and amplitude, may have a range of frequencies, and are emitted in all directions! When trying to measure the returning light, how would you know if it's the same light you sent in the first place?

One solution is to use laser light. "Laser" stands for "light amplification by stimulated emission of radiation". Lasers produce what's called *coherent* light. This means that the photons they produce all have the same phase, amplitude, frequency and direction. They are ideal light sources for our gravitational-wave detectors.

The light from a typical laser on its own is not quite enough for a gravitational-wave detector – since the signals we measure are so small, we need the light to be as high quality as possible, and we need more power! So, in a gravitational-wave detector the laser light undergoes several stages of amplification, filtering, and stabilizing before it reaches the main interferometer. Find out more about the current work improving LIGO's laser amplification system on p.13.

We now utilize the coherent nature of the laser light to measure gravitational-wave signals. We look for the tiny phase shifts of the returning light caused by the stretching and squashing of the spacetime between mirrors in an interferometer when a gravitational wave passes through. This is the power, no pun intended, of the laser.

A trick of the light? Gravitational-wave detectors need high quality laser light to achieve their extreme sensitivity targets.

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by William Griffiths