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LIGO MAGAZINE

Building A GW Catalog

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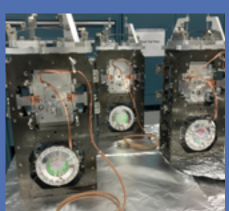
Of magic mirrors, losses and small creatures

Double suspensions for active mirrors in O4 p.14



The LIGO Exploration Center

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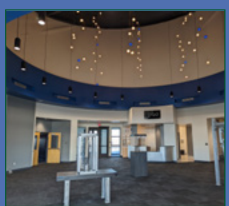

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Front cover

Time–frequency representations of gravitational-wave observations so far. For many of the events, the characteristic chirping shape of the signal can be seen by eye as the signal sweeps up in frequency over time. The image is from a poster created by Sudarshan Ghonge and Karan Jani.
To download different versions of the poster, visit: https://dcc.ligo.org/LIGO-G2102338/public. Article on pp. 6-13.

Top inset: Upgrades underway at the LIGO detectors. Three suspension systems containing new active mirrors arrive at MIT. After their curvature has been measured at CIT, they are suspended at the sites. In the photo, the three P-SAMS Double Suspensions are complete at LIGO Hanford Observatory. Article on pp. 14-15.
Bottom inset: At the new LIGO Exploration Center at LIGO Hanford a prototype of LIGO's quad suspension systems, as well as one of the 2017 Nobel Prize medals, greets visitors in the lobby of the LIGO Exploration Center. Article on pp. 16-17.
Bottom left inset: Artist's impressionof a LISA Spacecraft. Article on pp. 26-27.

Image credits

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

Cover: Main image: from a GWTC-3 poster by LIGO/Virgo/KAGRA/S. Ghonge/K. Jani. Top inset: Piezo-SAMS photo by Rahul Kumar. Bottom inset: LExC photo by Amber Strunk. Bottom-left (diagonal): Artistic impression of a LISA Spacecraft courtesy of AEI/MM/exozet.

p. 3 Antimatter comic strip by Nutsinee Kijbunchoo.
pp. 6-13 GWTC-3 poster by Carl Knox/OzGrav/Swinburne University of Technology (p. 6). Scattered light plot made by Siddharth Soni (p. 7). Martin Hendry's author picture created by his A345 Cosmology class (p. 11). GWTC-3 team sticker created by Laurence Datrier using a still from a numerical relativity simulation of GW190521, N. Fischer, H. Pfeiffer, A. Buonanno (Max Planck Institute for Gravitational Physics), Simulating eXtreme Spacetimes (SXS) Collaboration (p. 12). GWTC-3 Twirl Orrery still by Zoheyr Doctor, see also: dcc.ligo.org/LIGO-G2102282/public (p. 13).
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Welcome to the 20th issue of the LIGO Magazine!

Hannah Middleton
Editor-in-Chief

Anna Green
Deputy Editor-in-Chief

Welcome to the twentieth issue of the LIGO Magazine! In this issue, we first hear from some of the many people behind the third Gravitational Wave Transient Catalog (GWTC-3), which was recently released by the LIGO, Virgo, and KAGRA collaborations. Various members of the GWTC-3 teams describe the extensive work and rich community that evolved in the process of building the catalog.

Preparations for the fourth observing run are ongoing at the observatory sites. Maire Kasprzack tells us about the suspensions for 'magic' new optics at the LIGO Livingston Observatory, and Haoyu Wang explains why cryogenically cooling KAGRA will help with sensitivity in this issue's "How it works". Over at the LIGO Hanford Observatory, the brand-new LIGO Exploration Center will soon be engaging visitors with gravitational-wave science as we hear from Amber Strunk and Cassidy Eassa. Moving online, Jonah Kanner explains how the GW Quickview app has been helping people easily visualize gravitational-wave data, and if you enjoy board games, check out Vincent Boudart and Grégory Baltus' article on developing GWcatcher!

The lack of diversity in our collaborations and academia more generally is a long-standing problem. In "There but for fortune…", Steve Penn discusses how class discrimination is too often overlooked and encourages our collaborations to include class diversity in equality initiatives and discussions.

If you are thinking about doing a postdoc, this issue's LAAC Corner, from Jessica Steinlechner and Anna Green, provides suggestions on things to consider while navigating this sometimes confusing career stage.

Exciting times are ahead for gravitational-wave science! Turning to the future, we feature updates from around the community in "A bright future for GW science". Martin Gehler tells us of LISA's milestone achievement in "Meanwhile in Space". Finally, Karan Jani explains how the Moon could be a good location for a future gravitational-wave observatory!

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

We reached a major milestone last November with the public release of version 3 of the Gravitational-Wave Transient Catalog (GWTC-3) and the strain data from the second half of the third LIGO-Virgo-KAGRA observing run (O3). To date, we have published or released 39 papers reporting observational results arising from O3. That is about one Collaboration paper per month since the beginning of O3.

The scientific impact of the data and our papers continues to be exceptional. For example, according to the SAO/NASA Astrophysics Data System, our GWTC-2 paper has received more than 750 citations since its release in October 2020. In addition to our LSC papers, there were 1000 other papers submitted by small teams to the LSC Publications and Presentations System (https://pnp.ligo.org/publications) since the beginning of O3.

As we devote more attention to the next observing runs, O4 and O5, infrastructure and operations activities other than observational papers become more important. Through a continuous program of research, development, and engineering, the LIGO detectors are made more sensitive over time. Detector improvements should increase the detection rate of compact binary mergers to about one per day during O4 and several per dayin O5. The post-O5 study group is leading the development of a roadmap of LIGO detector improvements that will push the sensitivity towards the facility limits in the early 2030s. With every substantial improvement in sensitivity, we can extract more science from the compact binary signals we detect and have the possibility of detecting new sources of gravitational waves.

In parallel with detector improvements, our operations working groups are improving the systems and services that allow us to deliver qualified data, to analyze that data as part of the international gravitational-wave observatory network (IGWN), and to interpret the detections we make. Between now and the end of the year, we will refocus attention onto O4 operations activities. Every LSC Group contributes a minimum amount of effort to infrastructure and operations activities; I encourage everybody to contribute more than that minimum as these activities are essential to the near-term success of LIGO.

To a large extent, early career researchers power our success through their hard work, dedication and creativity. It is important that the LSC gives these members sufficient credit. Over the next 6 months, we will begin to publicly list LSC (LVK) roles and the names of those who fill them, we will continue to run webinars at which multiple LVK members present our latest science, and the Academic Advisory Committee will introduce an LSC Awards program for early career researchers. The Speakers and Awards Committee has implemented more robust procedures to distribute speaking invitations and to encourage meeting organizers to look beyond the usual names to give key presentations on behalf of the LSC. We are also exploring other approaches to recognizing high-impact contributions to LSC infrastructure and operations that are made with little fanfare and without which we would be less successful.

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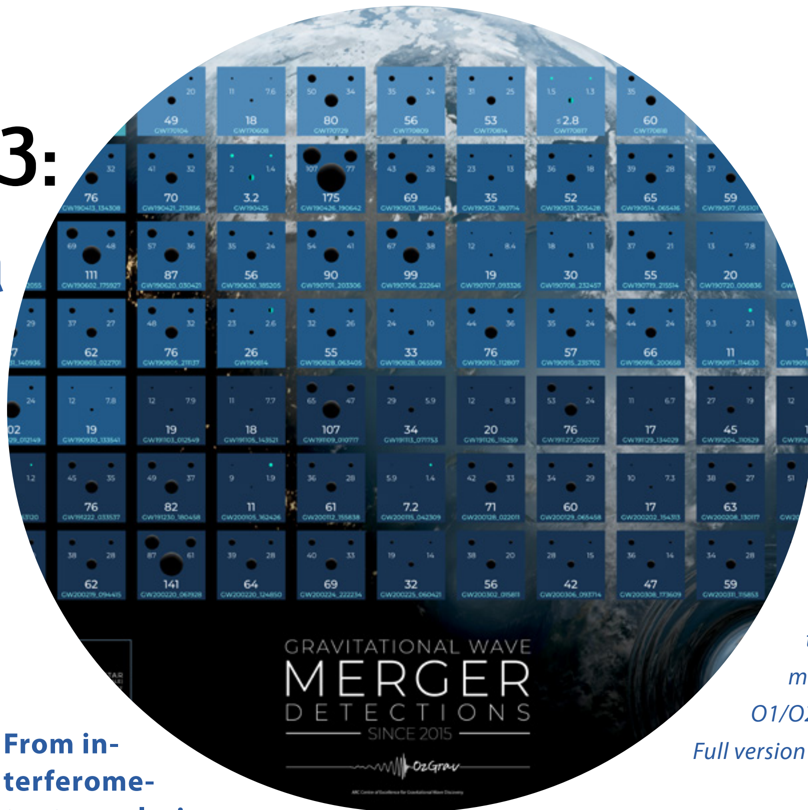
Patrick Brady
LSC Spokesperson

GWTC-3: Building a gravitational wave catalog



A poster of gravitational wave mergers from O1/O2/O3a/O3b. Full version on p. 18-19

GWTC-3 is the third Gravitational Wave Transient Catalog from the LIGO, Virgo, and KAGRA (LVK) collaborations. GWTC-3 includes observations of gravitational waves (GWs) from compact binary coalescences – mergers between black holes and neutron stars. Catalogs are cumulative, each new catalog building on the results of the previous one. GWTC-3 assembles GW observations from the first three observing runs and contains an impressive 90 GW events!

Building a catalog is a complicated task with many steps: from identifying GW signals in detector data to using them to learn about our Universe. GWTC-3 is the work of many, many people. In this article we hear from several members of the GWTC-3 teams who have worked on the different ingredients that go into building a GW catalog, and their experience of being part of these projects.

From interferometer to analysis: calibrating the data

Interferometer data must be *calibrated* – the process where we calculate the relative change in length along the interferometer arms (the strain) from the interferometer's electronic readout. The biggest challenge in calibrating the interferometer signal during Observing Run 3 (O3) was achieving a high level of accuracy and quantifying this accuracy precisely. The LIGO and Virgo calibration teams embraced this challenge and were able to produce the best calibrated strain data to date! I had the honor of co-chairing the calibration group throughout O3 and working as a member of the GWTC-3 editorial team. Both of these tasks were enjoyable and challenging. The amount of detail-oriented, precise work that goes into each of the thousands of tasks required to put together the final product which is GWTC-3 and the open data release is truly astounding. I most enjoyed seeing members of the collaborations work together and lean into each other's strengths in order to put forward the best product possible.

Gravitational wave transient catalogs so far are:

- **GWTC-1: 11 events from the first and second observing runs (O1 and O2)**
- **GWTC-2: adds 39 events from O3a (the first part of the third observing run)**
- **GWTC-2.1: revisits the GWTC-2 analysis, adding 8 events and removing 3 (due to reclassification)**
- **GWTC-3: adds 35 more events from O3b (the second part of the third observing run).**

Maddie Wade

is an associate professor of physics at Kenyon College in Gambier, Ohio, U.S. and has been a member of the LIGO Scientific Collaboration for about 12 years. In addition to physics, Maddie loves spending time going on hikes with her husband, kids, and dogs.

Jess McIver
is an assistant professor of physics and astronomy at the University of British Columbia in Vancouver, Canada. You may find her exploring the mountains, waterways, and forests of the Pacific Northwest.

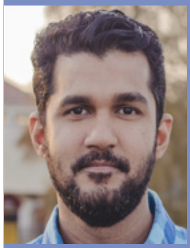
Bumps in the machine: getting rid of the glitches

LIGO and Virgo detector data contains many *glitches*; short-duration bursts of noise that can mask or mimic true GW signals. An important task for any GW search is to characterize how these glitches are affecting the statistical significance of event candidates. A great team of detector characterizers analyzed the data surrounding every GWTC-3 candidate event for signs that it was caused by noise. For example, two *marginal* candidates reported in the catalog were found to be caused by the light scattering phenomenon Sidd Soni describes below. True GW signals can coincide with glitches making it tricky for us to accurately recover their true properties. This is unfortunately pretty common – eight candidates in the GWTC-3 catalog required some form of glitch subtraction! Coordinating these efforts is a huge challenge. Every time the list of candidates is updated, we need to validate the surrounding data, then identify and subtract any nearby glitches – a process which can take weeks, if not months! Hundreds of people, many with very different expertise, came together to produce these results.

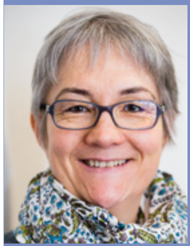
The most frequent source of glitches

Scattered light was the most frequent source of glitches during O3 at both LIGO detectors. Scattered light is laser light that is reflected from the detector mirrors at random angles, bounces off some other moving component of the detector and back into the main laser beam, causing unwanted noise. Fast Scattering is a type of scattered light that appears as short duration arches in the time–frequency spectrogram (see the picture). Its rate has been found to be highly correlated with an increase in ground motion near the detectors due to human activities, construction work, logging, etc. We hope to identify the source of fast scatter and mitigate it before the start of Observing Run 4 (O4).

You can find out more about glitches and help us to understand their origins by visiting the citizen science project Gravity Spy at www.gravityspy.org.



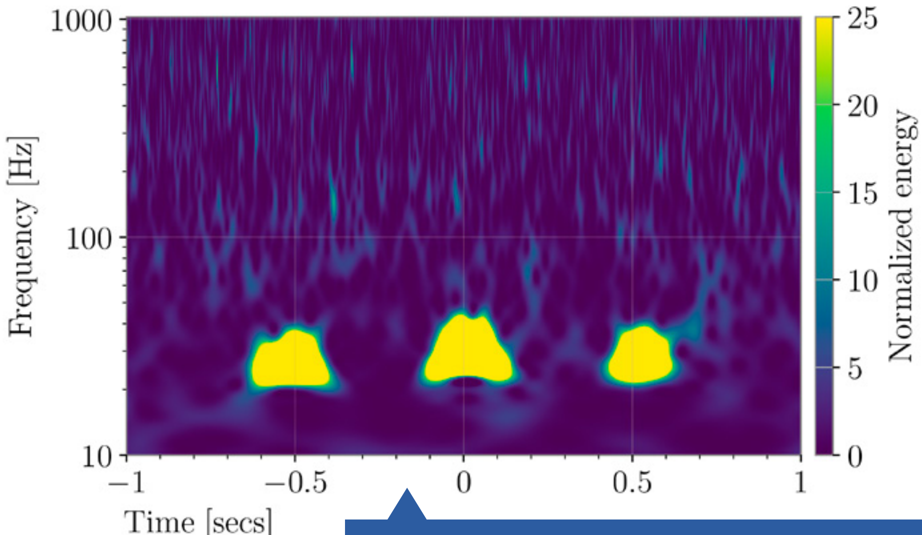
Siddharth Soni
is a Postdoctoral Associate at MIT Kavli Institute working with the Detector Characterization group at LIGO. He enjoys hiking, going on road trips and visiting national parks.



Frédérique Marion
is a senior scientist at LAPP in Annecy, France. She recently enjoyed reading The Pillars of the Earth (by Ken Follett), after hearing from the team that the book was (more or less) about building a catalog.

Hunting for gravitational wave signals

Search analysis identifies potential signals from compact binary coalescences, then estimates their significance and their probability of being of astrophysical origin. This led to the set of significant candidate events presented in GWTC-3. Several search pipelines were used to analyze O3 in both online (as the data is taken) and offline (at the end of the observing run) configurations. Work done for the catalog included assessing differences in the results from the online and offline searches, as well as across the different search pipelines and estimating how sensitive our searches are using simulations.



Scattered light: *A time–frequency representation of fast scattering in LIGO. Scattered light was one of the main causes of glitches at LIGO during Observing Run 3.*

The science in the catalog is great, but what made the experience so enjoyable was the paper writing team itself – a bunch of incredibly dedicated people – and the leadership of its chair (Christopher Berry), who has a unique and perfect mix of composure, authority and humor.

Gareth Cabourn Davies

is a Research Fellow in the Institute of Cosmology and Gravitation at the University of Portsmouth, UK. Gareth likes Piña Coladas, getting caught in the rain and making outdated pop culture references.

Different approaches to search for signals

Using different approaches to search for signals means that we can be confident about detecting as many signals as possible. The offline searches give us a great chance to find things we wouldn't have been able to see in low latency (online). The longer computational time and the additional data quality information mean that we can dig deeper into the data and uncover so much more.

Being part of the catalog team has given many of us an opportunity to work with people we would not have worked with outside the catalog. There has been a nice mixture of expertise in the team, and learning about all the different areas that go into making the catalog has been really interesting. And meeting loads of nice people was of course great as well!

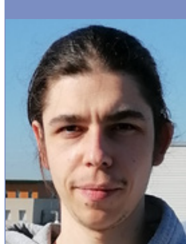
Becca Ewing

is a fourth year graduate student at Penn State University. In free time outside of work Becca enjoys baking and collecting records.

Keeping track with the e-catalog

Having started work on the catalog as a relatively new graduate student, it was sometimes intimidating and often challenging. I took on the responsibility of the "event juggling" in the e-catalog. In O3, we started to have so many candidates that keeping track of all of them and their individual properties presented a unique challenge. There were definitely late nights and early mornings spent poring over event lists and tables making sure we had everything in place. But, ultimately this was a great problem to have as it meant we were collecting tons of interesting results. After a year and a half of working alongside the excellent paper writing team, I've learned so much and gotten the chance to work closely with people all over the world who I never might've met otherwise.

Dimitri Estevez



is a postdoctoral researcher at the University of Strasbourg, France, sharing his work between data analysis of compact binary coalescence signals and calibration of the Virgo detector. In his spare time, he enjoys playing drums and guitar.

What was that signal? It's all about the probability!

Having identified a list of candidate GW signals, we investigate how likely it is that each of them is a real astrophysical observation. A signal's "probability of astrophysical origin" estimates how likely a trigger in the data is to be an astrophysical signal or not. It relies on assumptions about how often we expect a signal like this to happen. Each search analysis uses different assumptions to compute the probability of astrophysical origin.

When I was asked to write about this topic in GWTC-3, I was already in charge of developing this computation for one of the pipelines and I was very excited. However, I also had some doubts about my ability to bring reliable expertise on it since it was quite new for me, as I came from a more instrumental background. Anyway, I got into it right away and I knew I would have support at any time if required.

It was quite challenging to gather and describe all the different computation methods used but it has been a rewarding experience to discuss this work with many people I might not have met otherwise. I am now looking forward to the next observing run O4, which should bring more information to help us to better assess the probability of astrophysical origin of our candidate events!

Parameter estimation: A closer inspection of the properties of the GW signals

Being based in Australia while putting together GWTC-3 in the midst of the pandemic was an interesting experience. The paper-writing process took more than a year, spanning several of Melbourne's strict lockdowns. Working on GWTC-3, often during very late nights that turned into early mornings, provided some excitement in my otherwise monotonous routine. I was part of the group that focussed on obtaining and presenting the parameter estimation results — learning about the properties (such as the compact object masses) of the GW events. There were definitely some stressful moments for us! The threshold for accepting an event into GWTC-3 shifted and changed multiple times which meant that there were repeated games of spot-the-difference between new and old event lists, with any newbies having to be quickly incorporated into the analysis pipeline. We ended up with a diverse set of events, including such exciting pairs as black hole–neutron star binaries! All of our new binaries add a few more pieces to the puzzle of understanding how these systems form and what they tell us about the wider Universe.

Isobel Romero-Shaw

has just completed her PhD at Monash University in Melbourne, Australia. When she's not analysing GW data, she likes to read, go exploring, or do creative things.

Asimov: A new framework for faster analyses processes

Plenty of us can remember the amount of time and effort which went into producing the analyses of the events from O1 and O2, so as the events started pouring in during O3 it became clear that getting everything done in both a timely and consistent manner was going to be a big challenge.

We started pioneering automation of the production parameter estimation, the process we use to get results for the catalogue papers, when GWTC-2 was being written. However the demands of the GWTC-3 analysis were considerably greater: for the first time we were using new codes (Bilby and RIFT), and new waveforms for the analysis. This substantially complicated the process of setting analysis up. We were also running analyses on all of the GWTC-2 events in parallel with the new codes in order to produce GWTC-2.1.

To handle all of this we developed asimov which is a new framework for building automated "bot" processes, and then monitoring them on the LIGO data grid. This allowed us to set up new analyses much faster than we could before, giving us extra flexibility to test a variety of settings on tough-to-analyse events, and the ability to monitor the state of hundreds of parallel analyses on the supercomputer clusters.

We learnt a lot during the O3 analyses, and we've now got just under a year to go away and complete further developments for O4!

Daniel Williams

is a postdoc at the IGR in the University of Glasgow, who works on developing statistical methods for GW analysis. If he's not working on code for GWs or some other side-project you'll probably find him playing Dungeons and Dragons, or running up a hill somewhere in the Scottish Highlands.

Rosa Poggiani

is an associate professor at the University of Pisa, Italy. During free time Rosa enjoys reading, movies, food and photography.

Searching for light – electromagnetic telescopes follow up GW candidates

Combining GW observations with electromagnetic and particle observations builds up a multi-messenger picture of astronomical objects. While the LIGO/Virgo detectors are almost omnidirectional, electromagnetic observatories need a pointing direction. During O3, when a GW candidate was identified by the low latency searches, public *GCN* alerts[1] were issued with the event time and sky position. These alerts were released within about 30 minutes of detection to enable quick follow-up from electromagnetic and particle observatories. About one hundred observatories, both ground and space based, were involved in followup, covering gamma and X-rays, visible, infrared and radio domains, and neutrinos over broad energy ranges. This time, there was no confirmed counterpart in any observation over the whole electromagnetic spectrum and on the neutrino side.

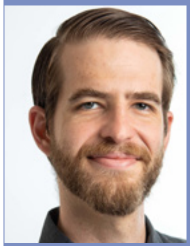
Results are reviewed internally before release

More than anything else I have done with the collaborations, organizing the review for GTWC-3 drove home the complexity of the analysis done by the LVK in making and analyzing GW detections. Every quantitative statement and every number in the

[1] *Public LIGO/Virgo alerts are distributed using NASA's Gamma-ray Coordinates Network (GCN).*

catalog paper arrives at the end of a long chain of events, starting from the instrumental data and ranging through searches, a dizzying number of followup analyses, scripting, contact with a writer's brain, finally ending in macros and text. The task of the reviewers is to check each statement from the beginning to end of that chain, making sure the codes are correct, the results are sane, that data was shepherded faithfully from one step to the next, one directory to another, one format to the next, until the final checks of the paper text. At my last count, around 100 people participated directly just on the reviews going into GWTC-3, not to mention the companion papers on astrophysical populations, testing general relativity, and cosmology. It wouldn't have been possible without the hard work that went into organizing the previous catalogs, the ongoing review of our code libraries, and the willingness of so many people to take time and do an often boring job, too often at short notice. I'll take the opportunity of this article to thank everyone again for all their help. It was a true team effort.

Aaron Zimmerman



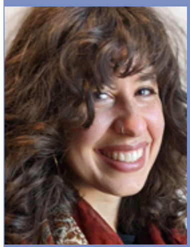
is an Assistant Professor at the University of Texas at Austin, and currently co-chair of the Parameter Estimation working group. He is forever trapped between loving rainy days and the desert.

Understanding GW signals as a group – the population of merging compact binaries

Every individual event in the catalog is truly stunning and interesting in its own right. For me, the magic happens when we put all of the events together and understand what they tell us as a group. This kind of *population analysis* can tell us which events are flukes, which events are expected, and even how the majority of events are formed. I think that one of the most exciting population analysis discoveries was that black holes collided more often in the past than they do now and I was grateful to be one of the first people to learn that fact about our Universe.

Scientific advances weren't the only part of the project. Probably the most notable part for me was the experience of working with such a large group of people. There were a bunch of organizational tasks that aren't as rewarding as doing the science itself. The population analysis team sits at the end of a very long pipeline — we often get changing inputs as people earlier in the pipeline work hard to figure out their processes and it is necessary to have a team with an array of different expertise working together closely. In the end this was integral to my sanity during the pandemic since Zoom calls with the team were often the only connection I had to the scientific world.

Amanda Farah



is a PhD student at the University of Chicago. In her free time she enjoys caring for her ever-growing family of plants and attempting to run outdoors in the Chicago winter.

On the O3b publication team: Why do it again after O3a?

The field of GW astronomy is growing rapidly, and it's amazing to be a part of it through the LIGO collaboration. I was on the writing team for the O3b publication about what we can uncover about the formation and evolution of black hole and neutron star pairs by studying their population.

This wasn't my first experience on a writing team, I was also on the team for the O3a version of this paper. Why do it again? Because I wanted to get to know more people in the collaboration. When working on these collaboration papers, you learn a lot of new research skills very quickly, really by necessity. While this was stressful at times, the experience was rewarding, and of course, we had our fellow team members for support.

Being based in Australia, one of my main challenges was keeping up with team conversations in real-time since most telecons happened at around 2 am! Sadly, this meant I missed some of the fun science chats, but overall this experience allowed me to connect with some amazing researchers. Here's hoping I get to meet the people I have worked with on these papers face-to-face in the near future!

Shanika Galaudage

is in her final PhD year at Monash University in Melbourne, Australia. Outside of studying the cataclysmic collisions of black holes and neutron stars, she enjoys playing chess, making desserts and papercrafting.

Putting general relativity to the test

More than asking if Einstein is right, we ask if Einstein is wrong. The testing general relativity (GR) paper from GWTC-3 looked to see how the new events impact our understanding of GR as the theory of gravity. So far, we are consistent with GR. My role was managerial, think shepherd or maybe sheep dog, and it was fascinating to work with the analysts doing the hard work of testing GR with the data. I learned that our colleagues are tough, Arun would work beyond any reasonable expectations to get the paper out, Marta Colleoni could be called upon to the rescue, and that the whole editorial team (Jenne, Haris, Krishnendu, Marta and Arun) were committed to do their best for the science. As I look to the future tests of GR, as the detectors get more sensitive, I see that we must work hard to drive down all our errors including those that arise building the waveform templates.

Deirdre Shoemaker

is a physics professor and directs the Centre of Gravitational Physics at the University of Texas at Austin. She spends free time with her husband and their two dogs, usually hiking or sometimes drinking a beer in a beer garden.

A shiny new bound on the graviton's mass

The paper on tests of GR comes out of the heroic efforts of many analysts: each of them was a key piece for this huge choral work. We bumped into a few puzzles and struggles along the way, but despite all challenges we managed to push further previous constraints, and even obtained a shiny new bound on the graviton's mass! I especially appreciated the sense of cohesion inside the editorial team and the time taken by experts in the field to share their knowledge. Despite a 13+ hours difference between our timezones, spanning from California to India, we managed to keep up the team spirit! All of our new binaries add a few more pieces to the puzzle of understanding how these systems form and what they tell us about the wider Universe.

Marta Colleoni

is a postdoctoral researcher at the University of the Balearic Islands. When offline, she likes writing, swimming in the beautiful Majorcan sea and playing padel (not too well!).

Embedding dark sirens as a viable alternative to traditional cosmological probes

Ever since I began my PhD, in the late 1980s, I've been interested in measuring the Hubble constant and understanding why we get such different values using different methods — what we nowadays refer to as the "Hubble Tension".

Making our first siren Hubble constant measurement with GW170817 (the first observation of a binary neutron star merger) was already very exciting, but with GWTC-3 we had the opportunity to really embed dark sirens (i.e. sources without an electromagnetic counterpart) as a viable alternative to traditional cosmological probes, properly understanding some of their systematics.

This felt like a big leap forward for gravitational-wave cosmology, even if there's still a way to go before we can look to sirens to resolve the Hubble Tension. All of our new binaries add a few more pieces to the puzzle of understanding how these systems form and what they tell us about the wider Universe.

Martin Hendry

is Professor of Gravitational Astrophysics and Cosmology at the University of Glasgow. He's a big Star Wars fan, so when he's not studying what happened "a long time ago in a galaxy far, far away" he likes catching up on the latest adventures of the Mandalorian.

Simone Mastrogiovanni

is a postdoctoral researcher at the Nice Observatory in France. When he is not studying gravitational-wave sources, he likes hiking, baking pies and making sangria for his friends.

Finding out about formation channels of binary black holes

When O3 started, we were all very excited. We knew that O3 was going to bring us many new GW events and we were hoping to have a source associated with an electromagnetic counterpart. GW sources with electromagnetic counterparts are very special for cosmology, you "easily" use them to study cosmology.

Unfortunately, O3 gave us only sources without a counterpart and that's why we had a Plan B: the use of galaxy catalogs. But the Universe never stops to give us lectures, in the middle of O3 we realized that even our Plan B was not working! We kept getting very weird measurements of the cosmological parameters.

We suddenly realized that we were forgetting a key component in our analysis, our ignorance of the formation channels of the many binary black holes that we were observing. Everybody worked very hard to develop methods to take this component into account and in the end we managed to keep cosmology at the same pace as the GW transient catalog!

Kent Blackburn

has been a senior scientist with LIGO Laboratory (Caltech) for the past 27 years having worked on multiple aspects of data from design, collection to analysis and currently focusing on open data. Kent enjoys fly fishing in the high sierras, building high performance road bicycles, riding as often as possible (over 15000 km last year), and deep space astrophotography.

Sharing the news: Releasing the paper

The GW catalog paper writing process illustrated the enormous complexity in the levels of data products necessary to identify candidates for the catalog, starting from the instrumental strain data, intermediate search products, parameter estimation samples to final astrophysical numbers and figures. Working through all these levels and sorting out how to track and version control the data products, while planning for public presentation was challenging in the beginning and highly rewarding in the end. As a side note, working with the catalog teams gave me the chance to work closely with many colleagues, both old and new, that don't normally fall within my horizon of activities. Everyone was extremely dedicated to the monumental tasks at hand and made the challenges a real team effort.

Hannah Middleton

recently started a postdoc at the University of Birmingham, having moved from OzGrav in Melbourne. She enjoys getting out for walks in the countryside, photography, knitting, and editing for the LIGO Magazine!

Sharing the news: Releasing the data online

GWTC-3's data release had to be made public at the same time as the paper – and no earlier! To get ready for this long-anticipated moment of releasing the data into the wild, we uploaded some of the data into draft webpages (using Zenodo). All the time, we were very careful not to accidentally press the "Publish" button too soon – a potentially career-ending mouse click! Finally a time and day to release the paper was settled on, and we got ready to push that data release button too. On the day, Isobel and I jumped on Zoom together to press Publish for our webpages. At the same time, the paper came out, the GWOSC pages of Kent's went online, and we were excited to see news of GWTC-3 appearing in the media – including Carl Knox's beautiful graphic. It was great to see everyone's hard work shared with the world.

Laurence Datrier

is a PhD student at the University of Glasgow, working on multi-messenger astronomy with kilonovae and cosmology with GWs. Currently writing her thesis, the rumour is that she once had hobbies.

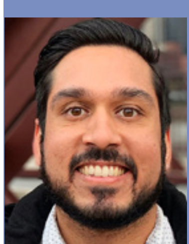
The art of gravitational waves

I've been making some LIGO and GW-themed stickers for a while, so of course when this happy little binary black hole was pointed out to me I thought it'd make a great sticker! I was approached by Christopher Berry a few weeks later about turning it into a mission patch for the GWTC-3 team, who were at the time doing some truly heroic work to get it all finished. Well-deserving of their own mission patch! A few printing mishaps later, 30 stickers were on their way to Christopher who would then distribute them as a morale booster. It's a small thing, but I hope this made the team smile!

A mesmerizing visualization

The Twirl Orrery software came into being when we were writing the GWTC-2 paper. I was trying to procrastinate on my paper writing tasks, so I decided to make some art instead! I wanted to create a mesmerizing visualization that captured the properties of black holes and neutron stars we had detected, so I got to coding and a week later had the first version of Twirl. To my pleasant surprise, folks online really enjoyed watching each cartoon binary orbiting endlessly, so I revamped it last fall to include the GWTC-3 events. It makes a great screensaver! Now I have the difficult task of figuring out how to make a new Twirl Orrery in O4 when we'll have more binaries than I can easily fit in one panel…

Check out the GWTC-3 Orrery of O3b events here: www.ligo.caltech.edu/video/ligo20211107v1 (or dcc.ligo.org/LIGO-G2102282/public).

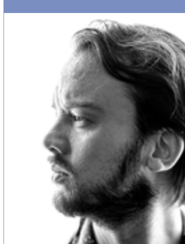


Zoheyr Doctor works on quantifying the distributions of black hole masses and spins seen in LVK data and uncovering how black holes are formed in nature. He is co-chair of LVK Rates and Populations subgroup.

Creating the poster

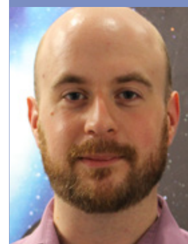
The key to making a good graphic is to start early. Hannah Middleton came to me months before the graphic was needed, before the data set was even finalised, and this allowed us to try many different iterations before settling on the final design. This was the first time I'd incorporated real data into an artwork so I wasn't even sure if we were going to be able to make it work. I feel quite proud to have had the privilege to create a piece that shows off the amazing data that many of you brilliant and hard-working scientists and researchers have spent years putting together. Bring on the O4 run!

Check out the poster on pages 18-19!



Carl Knox is a visual technologist and multidisciplinary artist, reveling in the art of astonishment and seeking to blow people away through cutting-edge visual technologies. Carl has studied both in Melbourne and in Los Angeles, and holds a full time position at OzGrav, working with researchers and academics in visualising GWs and the extreme physics of warped space-time.

Data for all observations as well as our analyses are available online. Head over to the Gravitational Wave Open Science Center (GWOSC) to find our more and download the data: www.gw-openscience.org



Christopher Berry is currently a Lecturer at the Institute for Gravitational Research, University of Glasgow, and was formerly the CIERA Board of Visitors Research Professor at Northwestern University. He is fond of bad puns, countryside strolls and naps. Find him on Twitter @cplberry or visit cplberry.com

Chairing the catalog

Catalogue papers are special. They're much bigger than usual papers. Working on them, you really get to know the signals and all the people working on them. Normally, you might analyse a few signals in detail, but with a catalogue you get to know them all: the beautiful loud ones like GW200129 with interesting properties, the awkward quiet ones that we're not quite sure about (I have a soft spot for underdogs, and GW191219 is one of my favourites), and the ones in the middle that aren't particularly remarkable, but you come to love because they never cause any trouble in the analysis. Similarly, where you'd normally only work with a small group on a paper, with a catalogue, you have to work with everyone. It is remarkable how many people work together to produce these results! It is a big responsibility to make sure that all this work comes together on time. I am proud of how the catalogue paper team has done! Analysing the O3b data is an ambitious task, and somehow we managed it during a global pandemic. We've never all met in person, but I hope that at a future meeting, we'll be able to celebrate the publication of GWTC-3 together.

▲ *Six out of the seven O4 Double Suspensions are ready in the LIGO Livingston Observatory Optics Lab for the insertion of the bottom stage. At that step of the assembly procedure, they are all identical.*

Double Suspensions for A+ Active Mirrors in O4

Marie Kasprzack

is an optical engineer at Caltech who works on detector improvements for A+ upgrades to Advanced LIGO. She devotes her spare time to experimenting all kinds of crafts and perfecting butter croissant recipes.

"A compelling scientific explanation must always be a good story", my supervisor used to repeat to me. I decided to take his advice literally, so I am going to tell you a story that involves magic mirrors, evil losses and small creatures. Because what makes better stories than fairy tales?

Once upon a time, more precisely in 2018, LIGO decided to bring a new type of technology to the detectors: active optics. Think of a magical mirror that would reflect a corrected version of yourself in real time. Initially developed for astronomy to redress pictures of stars blurred by atmospheric turbulence, adaptive mirrors are able to adapt their shape to the shape of the incoming light wavefront. In LIGO, the fundamental mode of these mirrors, i.e. their curvature, will be dynamically controlled to match the shapes of the incoming laser beams, improving the coupling of light from one cavity to another in critical optical systems. The O4 (Observing Run 4) squeezer[1] and the gravitational wave signal coupling into the output detectors are particularly sensitive to laser mode-matching. Reducing the losses will directly improve the detector performance for the O4 operation. Pretty wondrous right?

[1] *The squeezer improves the sensitivity of gravitational wave detectors by manipulating quantum noise.*

by Marie Kasprzack

The active mirrors need to be suspended in-vacuum with two stages of isolation, active damping and tip-tilt steering capabilities. All of this on a small footprint in order to fit in the crowded optical platforms. Suspending active optics that require electrical connections, without compromising the suspension isolation is a challenge in itself. So new little creatures started to make their way into LIGO chambers last year, extending the large LIGO family of suspensions. Seven little suspensions for each interferometer, packed with cutting-edge innovation. The compactness of the design is quite remarkable when seeing the double suspensions all aligned in the lab, ready for the final steps of the assembly (see picture). They all look alike except for the bottom stage that host four different types of active or controlled mirrors. At once similar and diverse, just as the Seven Dwarfs, I like to think of them as having distinct personalities. Let me introduce them to you.

At core they are a concentrate of the mature LIGO technology: two stages of suspension for passive seismic isolation, blades for vertical damping, magnetic passive damping, Optical Sensors and Electro-Magnetic actuators to actively control the mirror position, .… Novelty begins with the monolithic structures, coated to limit scattered light. Yet, the major innovation lies in the two types of active mirrors developed for LIGO, called SAMS[2]. In both types, a 2" mirror is captured into a heated aluminum flexure during initial assembly. When the flexure cools down, the contraction induces stress in the mirror, modifying its curvature.

The first model controls the mirror stress with a piezoelectric stack. The flexure mechanism converts axial displacement of the stack into a moment on the barrel of the mirror. Steady and reliable, it is called a Piezo-SAMS. Personally, I renamed it Doc. Three units of this model will be installed in the same large vacuum chamber as the squeezed light source, where it will lead the mode matching improvement to the newly installed 300m filter cavity, as well as between the filter cavity and the core interferometer.

In the second model, called Thermal-SAMS, resistors delivering heat change the temperature of the flexure, relaxing or increasing the stress on the mirror, thus modifying its curvature. This model is the result of an international effort: designed and made at Adelaide, Australia, in collaboration with the LIGO-Lab, tested at CIT, assembled at the sites. It has more range than a Piezo-SAMS but it reminds me of Sleepy, because it is slower to react. However, its strategic position at the gravitational wave signal output makes it a crucial observer.

To support the in-vacuum alignment, two suspensions with voice coil actuators will dither the laser beam at a frequency of 2 kHz before the 300m filter cavity. Used for intermittent and fast actuation, I call them Sneezy. Most of our colleagues will refer to them as Dither suspensions.

The last type is the simplest, used as a relay between the interferometer and the squeezer. I would compare it to Dopey. While it doesn't perform any special task, it is an essential part of the system.

These seven Double Suspensions are all in the late stage of assembly and installation at both Observatories and should be ready on time for operation in O4. Like in the infamous tale, our mirrors won't lie. Will they be powerful enough to combat the mode-matching losses? Will the O4 laser beam be the fairest one of all? It's not quite the end of the story yet ...

References:

[1] Snow White
[2] LIGO internal documents: T1800480, E1800314, E1900010

Stuart Aston positioning the first Piezo-SAMS Double suspension in the LIGO Livingston Observatory vacuum chamber where the squeezer light is being installed.

[2] *SAMS: Suspended Active Matching Stage*

The New LIGO Exploration Center

Defunct components of the LIGO detector provide a unique element to the exterior of the new LIGO Exploration Center at LIGO Hanford Observatory (Washington state, U.S.).

The LIGO Hanford Observatory (LHO) recently completed construction of the LIGO Exploration Center (LExC). Since its beginnings in the 1990's, LIGO Laboratory has pursued a high-impact STEM education mission alongside its scientific goals. As an Education and Public Outreach (EPO) team our mission is to inspire a sense of wonder, to engage curiosity, and to encourage and diversify the future STEM workforce; for over two decades the EPO team at LHO has worked to fulfill this mission by both inviting thousands of visitors to our site and sending our educators out into local classrooms. The historic detection of gravitational waves in 2015 resulted in skyrocketing visitor interest, which intensified the need for a dedicated outreach center. The recent completion of LExC at LHO will begin a new era in our outreach programs allowing us to amplify our ability to connect with students, families, and teachers in the local community.

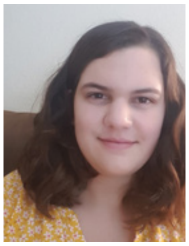
> **"The LIGO Hanford Observatory education program began in the 1990's, describing the new science of gravitational-wave astronomy to teachers at a LIGO construction trailer and expanding in quality and quantity over decades. LExC is an investment by the State of Washington to provide teachers and learners across Eastern Washington with outstanding science education experiences in the future." - Dr. Fred Raab, Associate Director of Operations, LIGO Laboratory**

It is human nature to be curious and to ask questions about the universe in which we live, and at its core that is what LIGO does. LExC will help to inspire that same sense of curiosity in visitors by focusing on inquiry-based learning in a free-choice environment. When asked about his hopes for LExC, Dr. Michael Landry, LHO Observatory Head, said, "When I think of what made me want to study physics, it boils down to three or four moments that rocked my world view. My hope is the LExC provides these experiences for students to inspire them to explore, to challenge them to seek deeper understanding of the world around them. And, no matter what career they choose, they interpret that world deliberatively."

Amber Strunk

is the Education and Outreach Lead at LIGO Hanford Observatory. When she is not spreading the exciting physics of gravitational waves she is spending time with her two sons and plotting her next DIY project.

Cassidy Eassa



is a science educator at the LIGO Hanford Observatory. She currently spends nearly all of her free time with her puppy, but when she's allowed a reprieve she enjoys playing D&D with her friends and being pretentious about horror movies.

by Amber Strunk & Cassidy Eassa

A prototype of LIGO's quad suspension systems, as well as one of the 2017 Nobel Prize medals, greets visitors in the lobby of the LIGO Exploration Center.

The completion of LExC is the culmination of years of hard work and advocacy. In 2009 Dr. Fred Raab, then-Observatory Head of LHO, submitted the first of several proposals in an attempt to secure funding for the Center. While initial attempts at funding were unsuccessful, a turning point for LExC occurred in 2015 when then-state representative Larry Haler approached Dr. Raab about the possibility of funding being obtained from the State of Washington. The advocacy of numerous local organisations and individuals took this idea and turned it into reality. Through two grants in 2017 and 2019, Washington State generously provided $8.1 million for the planning and construction of the Center.

Local companies Terence L. Thornhill Architect Inc. and DGR Grant Construction were selected as LExC's design-build team. In October 2020, after years of planning, construction began. Despite the many hurdles posed by the pandemic, the design-build team kept the construction of the Center on track with only minimal delays, reaching substantial completion in November 2021.

The design of LExC was inspired by the detection of GW150914. With this historic event in mind, architect Terence Thornhill designed the building with two circular components merging in the lobby as one, ensuring gravitational-wave science is at the center of the building itself. Additionally, inclusivity and accessibility were important considerations in the design process to ensure an equal opportunity for all potential LIGO visitors to engage and learn. With these principles in mind, a lactation room and gender neutral bathrooms were included along with considerations for the physical accessibility of the building and furniture for visitors and staff.

As visitors enter LExC they are welcomed into a circular lobby lit with several multicolored chandeliers, suggestive of a field of stars. Gazing around the lobby they encounter objects representing significant points in LIGO's history, including a prototype of LIGO's quad suspension system, a suspended glass fiber, and a replica of Rainer Weiss's 2017 Nobel Prize medal featured directly in the center of the space. Beyond the medal is a panoramic window showing the untouched shrub steppe in which LHO is located, part of the traditional homeland of many local Indigenous communities. Dominating the horizon is Lalíik, commonly referred to as Rattlesnake Mountain, which is held sacred by these local tribes.

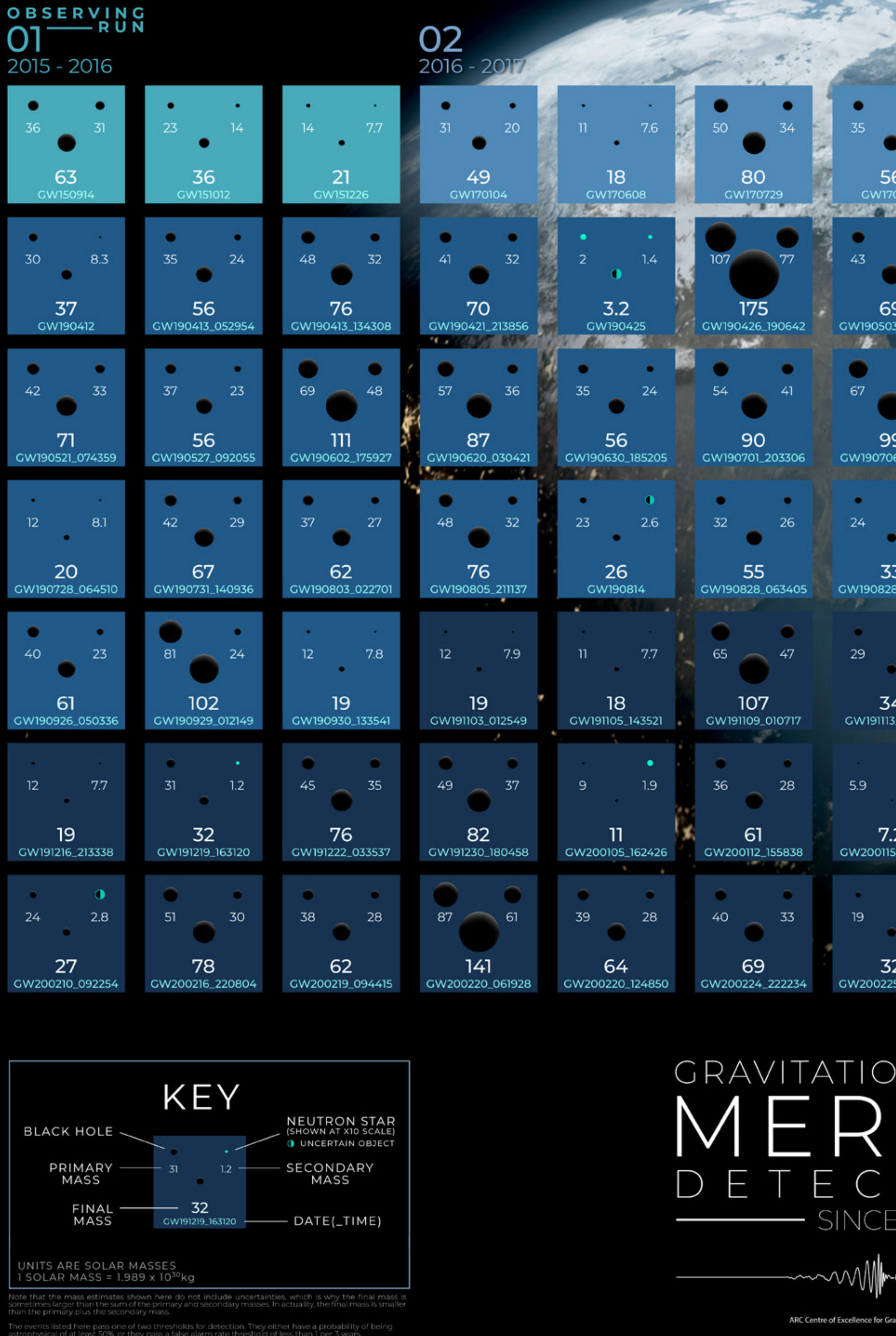
To the left of the entrance, LExC's 5,000 sq. ft. exhibit hall welcomes visitors to explore and play. This exhibit hall will be home to exciting interactive and hardware exhibits focused on the science and engineering of gravitational wave detectors. Here visitors will explore everything from fundamental physics concepts and the exciting new field of multi-messenger astronomy to the people and collaborations that make it all possible.

In addition to the exhibit hall, another focal point of the building is the activity room, which can be split into two rooms with a retractable wall. Particular attention was paid to making this space welcoming and exciting for both students and teachers to learn and participate in LIGO educator-led activities. In this space students will get hands-on experience through engineering lessons while teachers will participate in professional development opportunities that prepare them for bringing gravitational wave astronomy into their classrooms.

We are excited to begin sharing this new space with visitors. We plan to begin hosting small student groups in the spring of 2022 and a tentative plan for a grand opening has been set for late spring. We look forward to sharing this space with all of you!

LIGO 2022

Gravitational wave merger detections since 2015



from O1, O2, O3a and O3b

Poster by Carl Knox

There but for fortune[1]...

Steve Penn

is a professor at Hobart & William Smith Colleges and an adjunct research professor at Syracuse University. He is the Chair of the LSC Council. Steve grew up in rural Maryland and earned his BS and PhD from MIT. He was once invited to dinner with Nelson Mandela as a thank you for leading the apartheid divestment campaign at MIT.

Swiss Bread

We would shop on Monday evenings in the aisle where the old food was placed on sale before it was discarded. I was the calculator, working out the unit prices in my head so that we bought only the very cheapest. Most of our food we raised or hunted, but a few staples, like our bread, we bought — even though at times we would open the week-old loaves and find them spotted with mold.

"I hate buying moldy bread," I raged one morning. "I hate it. I hate squash sandwiches. I hate eating squirrel. I hate it all." I wanted to throw it all away … everything, absolutely everything … everything in our life felt broken. My mother knew the demon that haunted me. In poverty, the worst demon was despair — the slow and relentless asphyxiation of hope as you sink further into the quagmire of poverty. We had lost our first farm. We were on the verge of losing the second. With no money left, we would soon have to split up our family and squeeze in with relatives. We were trapped.

In our society, the poor, like litter on the street, are discarded, ignored, and often simply unseen. In general, society treats the poor as undeserving of equal rights and privileges because they contribute nothing to the economy. "If they worked harder they would not be in poverty. If they are unhappy with their condition, they have only themselves to blame." And, by and large, the poor do blame themselves, because a lie told many times is often believed. Many among the poor lose all self worth and come to accept a life of destitution. Other's cling to the Horatio Alger fairy tale that working hard will lift them out of poverty. And when it does not, they seek escape in alcohol or drugs or suicide or the insane hamster-wheel of get-rich-quick schemes. Members of my family traveled all these roads; they all eventually lead to despair.

Anger was better. Angry people are alive. And it is strangely rational to not accept the insanity of poverty. My mother, who raised four children on minimum wage, could navigate our anger. "It is not so bad," she declared as she cut away the moldy spots. "Look, it's Swiss Bread!" And we ate it.

Poverty is Violence

Like me, about 1 in 8 children in the US are raised in poverty. That number is remarkably stable because there is a feedback loop to maintain it. The Federal Reserve sets the interest rate to a targeted unemployment rate [2,3]. (The poverty level tracks the unemployment rate.) This policy is in place to maintain an economic environment that is favorable to business. It is argued that as the interest rate is lowered, the unemployment rate will drop, making workers in demand. These workers, thus empowered, would then demand higher wages, better working conditions, and more rights — a clear threat to the profit margins of American business. Therefore, unemployment is justified as a guard against inflation even though the correlation is weak [4]. Nevertheless, by maintaining a stable level of unemployment, the Federal Reserve ensures that business profits are not threatened by the demands of the working class for a living wage, adequate health care, or equal educational opportunities.

Oddly, society has largely accepted this seemingly static level of unemployment as either the natural order or as the required sacrifice to maintain a stable economy. Somehow, in the most affluent country in history, we require the poor to exist and to suffer. Society's indifference only reinforces the narrative that the poor deserve their poverty because they are literally worth less. The cost of society's indifference is measured in lives spent in destitution or drudgery, having never enjoyed the opportunities that the privileged classes take for granted.

Poverty is violence. Not the thrilling, fast-paced violence that we see in action movies. It is the slow, ratcheting of stress as the choices that society allows the poor grow ever more inhumane. It is the stress borne by the workers in our fields and factories who labor long hours until their backs ache and their hands are heavily calloused but who earn very little to support their families. It is the impossible choice given poor parents who cannot afford both food and healthcare for their children. It is the reality faced by most of the poor and working class who see only a future of drudgery and broken dreams. It is these relentless pressures which fuel the alcoholism, abuse, and violence that are ever-present in the lives of poor children.

The Ivory Tower

The university is often idealized as an intellectual meritocracy unsullied by the prejudices that exist in general society. In reality, we in academia recognize that discrimination remains in our institutions. In general, there is support for diversity, equity, and inclusion (DEI) based on gender and race. Reading through the job postings in our field shows the almost universal inclusion of statements encouraging candidates who are women, people of color, LGBTQ, veterans, etc. However, what is in general not understood or acknowledged is the level of class discrimination. By any measure of representation, discrimination against the poor and working class far exceed that of any other demographic.

> "Race, gender and L.G.B.T. status get more attention now, but … (t)he largest group of all that falls through the cracks is probably made up of those from poor, chaotic or working-class backgrounds. **Children from the top 1 percent are 77 times more likely to attend an Ivy college than kids from the bottom 20 percent.**"
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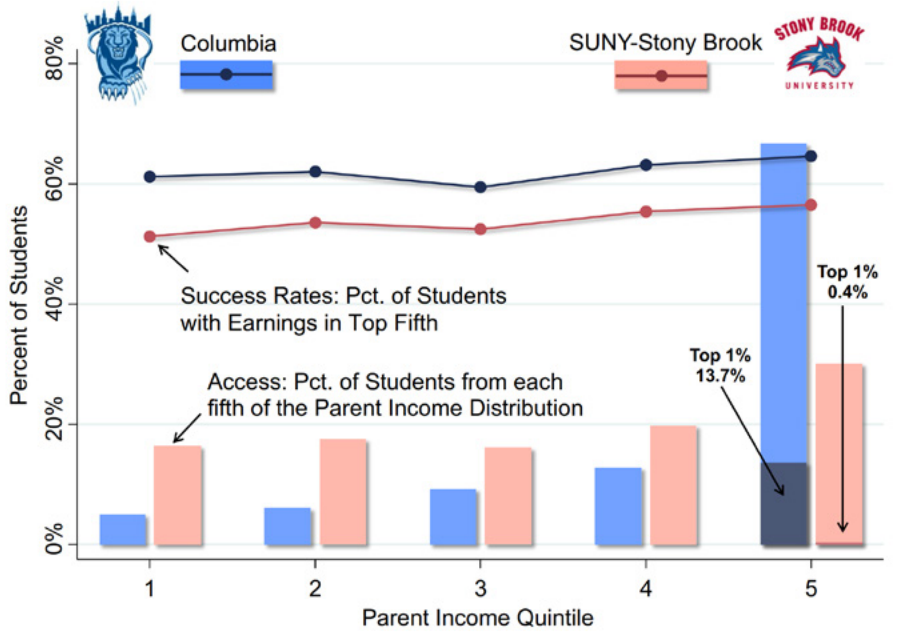
> Nicholas Kristof, NY Times, May 25, 2019 [emphasis mine]



Across the board, student populations draw more from the top 20% of highest-income parents than from all other income quintiles. At Ivy league schools such as Columbia, the percentage of students from just the top-1% families can exceed than the entire lower 50%. Bars: estimates of the fraction of parents in each quintile of the income distribution. Lines: estimates of the fraction of students from each of those quintiles who reach the top quintile as adults. Reproduced from [5].

Kristof is referencing a study [5] which shows that the 77 x favorable bias for the very rich is the product of a 6 x underrepresentation of the poor and a 13 x overrepresentation of the uber-wealthy. This underrepresentation of students from poor and working class families (i.e. the level of class discrimination) varies by institution. A database and accompanying article [6] in the *NY Times* provides the class representation for US institutions of higher education. The most disturbing observation is that "At 38 colleges in America, including five in the Ivy League – Dartmouth, Princeton, Yale, Penn and Brown – more students came from the top 1 percent of the income scale than from the entire bottom 60 percent." Can you imagine that disparity being tolerated for other demographics in the US?

This class inequity is often attributed to there being less college-capable students who are poor. While there are deep flaws in our educational system and a class bias in the quality of education, the problem is more extensive. In a study [7] on the low representation of college students from poor families, Caroline M. Hoxby & Christopher Avery found that "the vast majority of very high-achieving students who are low-income do not apply to any selective college or university." No single reason explains this low application rate, but socioeconomic forces, such as the need to provide income and the perceived lack of preparedness, are strong contributors in the decision to skip college. Wealth inequality is driving two other disturbing trends. According to a University of Michigan study, in the past 40 years the rate of college completion has fallen by 50% for poor students [8]. In addition, Prof Sean F. Reardon of Stanford University has found that "the gap in standardized test scores between affluent and low-income students has grown by about 40 percent since the 1960s, and is now double the testing gap between blacks and whites." [9]

A major force in perpetuating the class divide in higher education is the class divide in primary education. In the article "Private Schools are Indefensible" [10], Caitlyn Flanagan notes "Less than 2 percent of the nation's students attend so-called independent schools. But 24 percent of Yale's class of 2024 attended an independent school. At Princeton, that figure is 25 percent. At Brown and Dartmouth, it is higher still: 29 percent." The competition among these schools is even tracked and ranked (polarislist.com). The combination of well-funded private schools, whose annual tuitions rival that of private colleges, and underfunded public schools, sharply tilt educational and future economic opportunities toward the rich. Flanagan concludes "We have become a country with vanishingly few paths out of poverty, or even out of the working class. We've allowed the majority of our public schools to founder, while expensive private schools play an outsize role in determining who gets to claim a coveted spot in the winners' circle. Many schools for the richest American kids have gates and security guards; the message is you are precious to us. Many schools for the poorest kids have metal detectors and police officers; the message is you are a threat to us."

New Ways of Seeing

In our field, thinking and working on multidimensional problems is commonplace. At the risk of stating the obvious, let me be clear that discrimination and injustice are multidimensional problems. By noting the proliferation of class prejudice, I am not saying that we should focus on class to the exclusion of other forms of discrimination. Rather we should expand our analysis and our actions to include class. It is a good sign that anyone in our community advocating for racial equality, but not for gender equality, would be seen as illogical and out of touch. Now, imagine how it sounds to hear someone promoting diversity who does not include an analysis of class.

Colleagues have said to me that, at first glance, it can be hard to know people's class origin. I understand the sentiment (even if I do not fully agree). Unlike in other equality movements, there is no one celebrating poverty. No campaigns that promote "Poor Pride". No anthems stating "I'm poor and I'm proud." People don't want to be poor, and they usually deflect attention away from any sign of their poverty. The poor make their situation invisible because they do not want its identity.

Class origin may not be as visually obvious as gender or race, but in the gravitational-wave community we are renowned for our ability to see events that were invisible to other observers. We can meet this challenge. We just need to develop a new way of seeing. An important start is to understand what we expect to see.

"You worked hard and rose out of poverty. Maybe we should encourage the lower class students to work harder?" If hard work brought people out of poverty, there would be no poverty in the US. It is my observation that the poor work harder than any other class, and, ironically, from my limited vantage point, the rich appear to work least. I had an opportunity for a good education only through a rare scholarship for poor children in Maryland. I certainly seized this opportunity, but social change is not made through rare opportunities. All of the children from my poor rural community deserved the same chance. They did not choose to be born poor. Why must they be punished for it? Even condemned to it. Economic mobility in the US is very low. Unfortunately, the American Dream is not the American reality.

Research collaborations, like the LSC, have limited ability to enact social change, but when we take action to address discrimination based on gender, race, LBGTQ-identity, etc., we should also fight class discrimination. To be clear, in determining class, it is class origin that is the determiner. Like a material whose properties are determined by its thermal history, the crucible of poverty shapes the children raised within it and sets them on a trajectory far different from the children of the wealthy or bourgeois classes. DEI efforts are an attempt to correct some of that discrepancy. Those diversity efforts which include a focus on recruiting and supporting underrepresented social groups, should include class origin as a primary diversity criteria.

That change would be a small but significant step. It is worthwhile to consider and discuss the changes required for our society to eliminate class discrimination and poverty entirely. But those topics are beyond the scope of this article.

And there but for fortune…

Growing up, there was a boy who lived a few farms away. We played together because he was the only kid my age within walking distance. Like me, he was poor, and his family was filled with strife. Like me he was angry much of the time, and we were often in trouble. Then, one year, our paths quickly diverged. Our family lost our farm and our home, but I received a scholarship. I was sent away to school. He was left behind – with no way out. I never saw him again, but I did hear that he inevitably found an outlet for his anger … and has spent his adult years in prison for arson. "And there but for fortune may go you or I".

References

[1] "There but for fortune" is a song written by Phil Ochs in 1963.

[2] N. Gregory Mankiw, "Alan Greenspan's Tradeoff", Fortune, December 8, 1997 (scholar.harvard.edu/mankiw/content/alan-greenspans-tradeoff)

[3] A. S. Blinder and R. Reis, "Understanding the Greenspan Standard", presented at the Federal Reserve Bank of Kansas City symposium, The Greenspan Era: Lessons for the Future, Jackson Hole, Wyoming, August 25-27, 2005. (www.princeton.edu/~blinder/papers/05sept12GreenspanWP.pdf)

[4] K. Cashman, "FedWatch: Low Interest Rates in the Late 1990s Led to 4.2 Million More Workers Employed" (cepr.net/fedwatch-low-interest-rates-in-the-late-1990s-led-to-4-2-million-more-workers-employed/)

[5] Chetty et al., "Mobility Report Cards: The Role of Colleges in Intergenerational Mobility" (www.equality-of-opportunity.org/papers/coll_mrc_paper.pdf) see also [6]

[6] "The Upshot: Some Colleges Have More Students From the Top 1 Percent Than the Bottom 60. Find Yours." NYTimes Jan 18 2017 (https://www.nytimes.com/interactive/2017/01/18/upshot/some-colleges-have-more-students-from-the-top-1-percent-than-the-bottom-60.html)

[7] C. M. Hoxby & C. Avery, "The Missing "One-Offs": The Hidden Supply of High-Achieving, Low Income Students", 2012 (www.nber.org/papers/w18586)

[8] S. Tavernise, "Education Gap Grows Between Rich and Poor, Studies Say" NYTimes, Feb 9 2012

[9] S. Reardon, "The Economic Achievement Gap in the US, 1960-2020: Reconciling Recent Empirical Findings" (https://cepa.stanford.edu/sites/default/files/wp21-09-v112021.pdf)

[10] C. Flanagan, The Atlantic, "Private Schools are Indefensible" April 2021 (www.theatlantic.com/magazine/archive/2021/04/private-schools-are-indefensible/618078/)

Astro2020 and GW Science

Tuck Stebbins retired from NASA after 15 years as the LISA Project scientist, and a career in precision measurements that spanned lunar laser ranging, solar oblateness, helioseismology, LIGO seismic isolation, and LISA. He currently resides in the Methow Valley of the North Cascades.

On November 4th, the National Research Council (NRC) released the 7th decadal survey of astronomy and astrophysics, colloquially referred to as Astro2020. These surveys establish the programmatic direction for astronomy and astrophysics at NASA, NSF and DoE for the next decade.

Traditionally, the decadal survey takes stock of the field, solicits community input, and then recommends a science program, larger projects/activities, small and mid-sized programs, and actions bearing on workforce and infrastructure. In addition to committee and panel meetings, Astro2020 collected 867 white papers, held multiple town halls and public meetings, heard agency briefings on current budgets, and received technical readiness, risk and cost evaluations of larger projects.

The principal product of the decadal is the 616-page report, Pathways to Discovery in Astronomy and Astrophysics for the 2020s. Astro2020 identified three broad science themes – Worlds and Suns in Context, New Messengers and New Physics, and Cosmic Ecosystems – and anticipates that gravitational-wave (GW) astrophysics will contribute to the latter two.

Astro2020 concluded that "Gravitational wave detection is an essential capability for advancing the frontiers of astronomy and astrophysics" (§7.6) and strongly endorsed both upgrades to LIGO and investing in the next large facility.

GW observations are recognized as the premier source of multi-messenger events. In the category New Medium and Large Initiatives: Space, Astro2020's "highest-priority sustaining activity is a space-based time-domain and multi-messenger program of small and medium-scale missions." (§7.5.3.1)

LISA received strong support for full U.S. participation in the ESA-led mission and for science activities in the U.S, in response to an explicit query from NASA. The decadal recommends that NASA works with ESA to ensure that LISA "achieves the full scientific capability envisioned by [Astro2010]," and that NASA should "establish funding for LISA science at a level that ensures U.S. scientists can fully participate in LISA analysis, interpretation, and theory." (§7.7.3). This came at a crucial time in NASA's planning for its part of the science ground segment. However, the decadal makes no mention of a next-generation space-based GW detector for which technology development would optimally begin in the 2020s.

While pulsar timing arrays are generally at a funding level below that considered by the survey, Astro2020 did recommend that the NSF should proceed with "a program to support science design, development, cost studies, and antenna prototyping" for the Next Generation Very Large Array (ngVLA), followed by construction if possible (§7.6.1.4) later in the decade. NANOGrav would be a likely user when ngVLA starts operation c. 2034.

What impact will these recommendations have? Congress generally expects the agencies to follow decadal recommendations insofar as budgets permit. Agency program managers commonly present their programs in terms of their response to the survey, and near the middle of the decade, the NRC conducts a statutory mid-term review of agency progress against the recommendations. Astro2020 therefore provides strong endorsement that can be carried into grant evaluations, planning and budgeting processes.

In summary, Astro2020 saluted the accomplishments of GW observations, recognized the promise of GW astrophysics, and recommended the critical actions.

For a free PDF of the report visit: www.nap.edu/catalog/26141/pathways-to-discovery-in-astronomy-and-astrophysics-for-the-2020s

Easy web apps for gravitational wave data

Jonah Kanner is a senior scientist with LIGO Laboratory, Caltech, and the director of the Gravitational Wave Open Science Center. He usually gets around by bike and is currently advocating for safe bicycle routes[1] in Pasadena, CA.

What does LIGO data look like? For lots of file types, you can point-and-click to get an idea of what's inside. Typically, a double click lets you see an image, text files are quickly read in text editors, and even astronomy images can be viewed with easy point-and-click tools. But for LIGO data, it's almost impossible to take a peek at the data, without first conjuring up a few lines of python or some other programming language.

This is a big problem for many visitors to the Gravitational Wave Open Science Center (GWOSC) web site. Students, artists, amateur scientists, and other members of the public are interested in LIGO research, but may not know anything about programming.

I'd been looking for a tool that would let people "see" the data, without needing to write any code, and so, Leo Singer got my attention when he mentioned a new package for making web apps in python called streamlit. I dove in and before too long, I had a draft app called "GW Quickview"[2], that would visualize LIGO data with a simple point-and-click interface. The app allows users to quickly create a "Q-scan" (a time-frequency representation of the data) and a filtered time-series of any stretch of public LIGO data, so that they can see how these data look – hopefully, as easily as opening an image file!

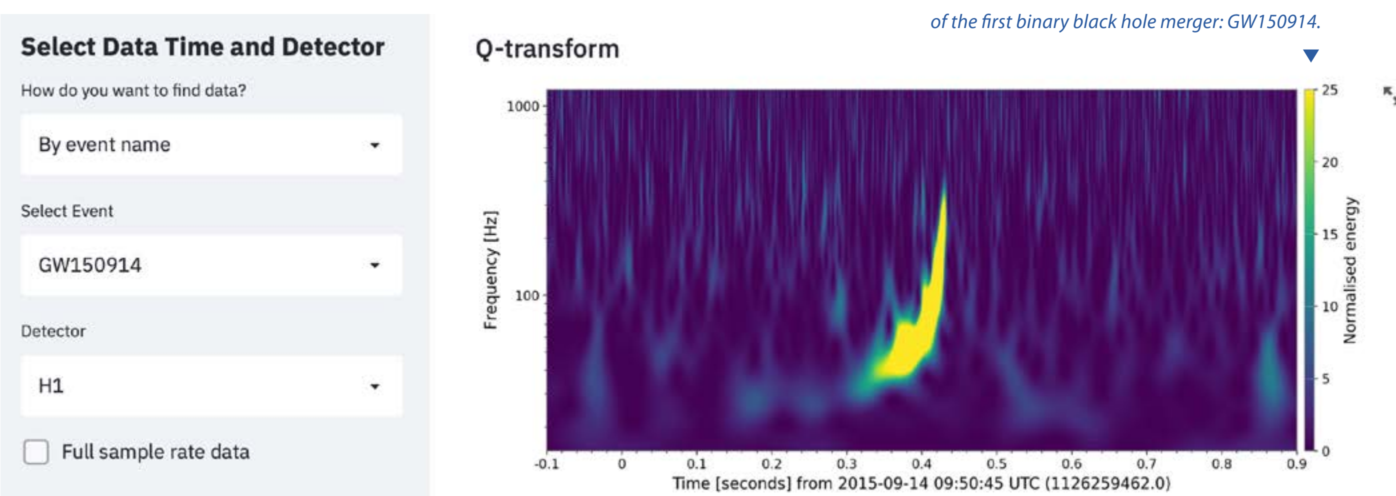
I needed some help debugging the app, and posted in the streamlit community forum. The streamlit team liked the idea, and not only helped me debug the app, but also gave me an opportunity to write a short blog post about the experience[3]. Jamie Rollins and Leo Singer worked on the post with me, highlighting both this app and a few others.

Since then, I've been delighted that the streamlit team has continued to feature GW Quickview on their homepage[4]. As best I can tell, this exposure has introduced LIGO science to a number of people outside our field. The app currently gets around 10,000 views per month, and I suspect a large fraction of these visits are from data scientists who are only casually interested in LIGO science. In addition, I think the app provides a few important features for people who ARE deeply interested in LIGO science. For example, the app allows data to be filtered via the point-and-click interface, and then downloaded into a CSV file. For amateur scientists and younger students who don't want to use python for their projects, this feature is essential. In addition, even mature scientists who have access to other tools for plotting data, may sometimes want to see a spectrogram or whitened time series without going through the steps of writing computer code.

But my favorite feature of streamlit is that it allows app creation with only python, meaning the learning curve is relatively easy for many members of the LIGO/Virgo/KAGRA community. This means that streamlit can be an easy tool for creating new apps, and gives our scientists a kind-of super power to create easy-to-use data visualizations of all kinds.

You can try GW Quickview at: https://share.streamlit.io/jkanner/streamlit-dataview/app.py

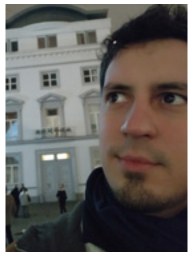
A time-frequency representation created with GW Quickview of the LIGO Hanford (H1) observation of the first binary black hole merger: GW150914.



1 www.pasadenacsc.org/roseway-network, 2 https://share.streamlit.io/jkanner/streamlit-dataview/app.py, 3 https://blog.streamlit.io/gravitational-wave-apps-help-students-learn-about-black-holes/, 4 https://streamlit.io/

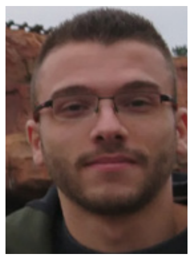
A gravitational wave board game

Grégory Baltus



is a Ph.D. student at the University of Liège working on a machine learning technique for the early detection of binary neutron stars. In addition, Gregory is interested in a lot of different things, like philosophy, martial art, and board games.

Vincent Boudart



is a PhD student at the University of Liège, working on the detection of long duration transient gravitational waves. During spare time, Vincent practices a lot of sports such as football and running and enjoys making pastries for friends and family.

Making physics available to the general public is a challenge for scientists all over the world. Journals and social media now play a key role in spreading scientific advancement in a way that is accessible to everyone. However, the physics behind state-of-the-art technologies is sometimes more easily understood when people put their hands on it. That is why we decided to develop a unique way to learn more about Gravitational Wave (GW) detectors: a board game.

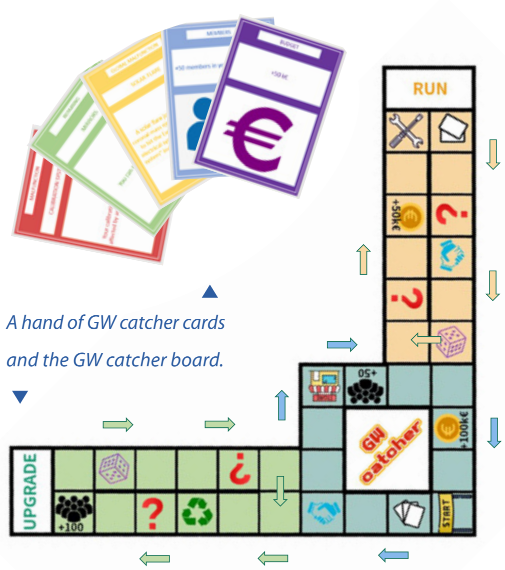
The original idea came when I (Vincent) offered to host high-school students during Carnival vacation at the University of Liège, in Belgium. Grabbing the attention of a dozen teenagers while explaining what I study to them is quite challenging. The best way to learn while sitting together is certainly to play a game. However, to be valuable in terms of learning, the game should contain many aspects of the real GW detectors. A few discussions and lots of printing later, GW catcher was born.

In GW catcher, each player incarnates a collaboration with its own detector similar to the LIGO and Virgo interferometers. As the leader of your collaboration, you can move freely around the L-shaped board to carry out upgrades of your instruments or to enter a "run period" and search for GWs. To simulate the effect of instrument upgrades, we use dice from role play games. We reduce the number of instruments to four categories whose upgrades affect the dice in different ways. The concept of duty cycle is also included, illustrating that real interferometers are not gathering data 100% of the time. The ultimate goal of the game is to be the first player to reach 100 detections.

At the first stage of its development, GW catcher did not include any interaction between the players. When a player was lucky with the dice roll, it was hard to beat them. We therefore introduced some new mechanics through the "Malfunctions & Repairs" cards. These cards can be played to slow down the other players by damaging one of their instruments, but they can also bring you funding or new members, unlocking some benefits throughout the game. If your opponent is luckier than you at rolling dice, you can still catch them up and take the win.

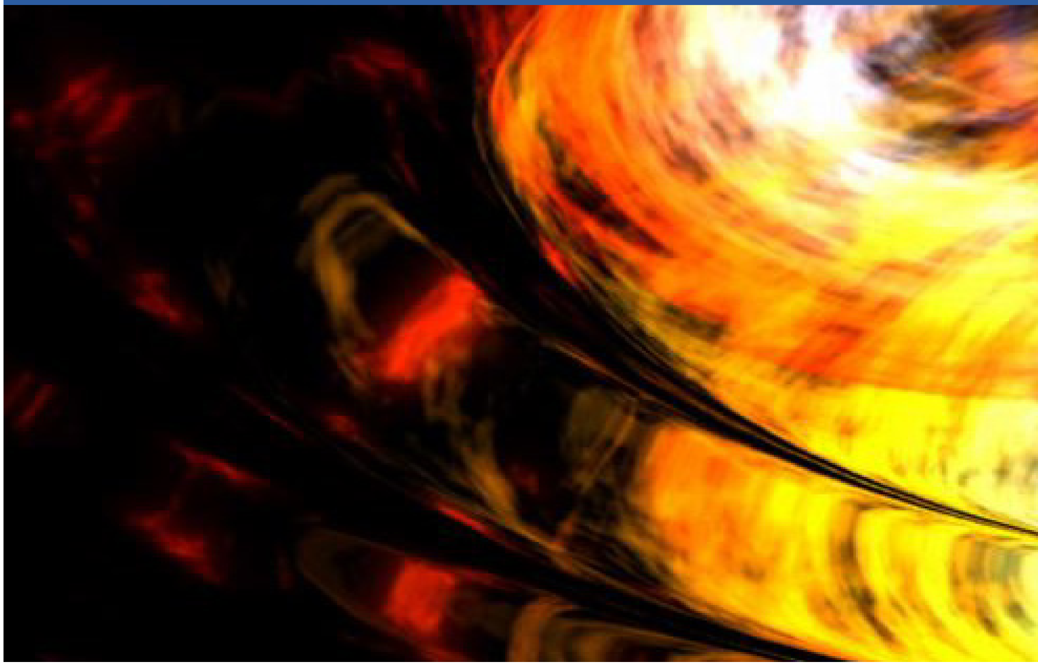
The board is full of special areas where plenty of events happen. Some areas award you some money or members while some others allow you to draw multiple cards or exchange them with other teams. Among the particular zones, chance cards (marked with a red "?"), give you either an advantage or a handicap for the next turns as in the famous "Monopoly". These cards aim at simulating events occurring in the real life of a scientist such as delays in instrument upgrades, colleagues who are retiring, meetings dedicated to young researchers, etc.

It was the first time developing a board game for both of us. The main challenge comes from the adaptation of real aspects of GW detectors into funny game mechanics. Our experience in playing board games and discussions with GW colleagues brings a lot of interesting ideas, especially the dice rolling. Although it is already playable, the game is still in development with the hope of creating our own game box in the next months. We are also aiming to design educational versions with guidelines on how to introduce GW science with our game. If you are either a board game enthusiast or a passionate GW scientist, this game is certainly a must-have for you. Stay tuned!



A hand of GW catcher cards and the GW catcher board.

The LISA Mission Moves Into The Next Phase



Artist's impression of the merging of two supermassive black holes as galaxies collide.

Martin Gehler

In December 2021, LISA passed a major milestone in its development and transitioned out of Phase A studies into Phase B1, laying the groundwork for implementation. After a long history from first sketches around the 1980's, to first mission concepts, then to mission studies at NASA and ESA around the turn of the century, LISA has now been selected as one of ESA's large class missions in the Cosmic Vision Programme, following in the footsteps of JUICE, a mission to explore the icy moons of Jupiter, and Athena, the next generation X-Ray telescope.

With LISA's selection in 2017, ESA took responsibility for the overall mission implementation, including the development of the space segment, the procurement of launch services, as well as the ground segment.

For such an ambitious mission, international partners are crucial to secure success. NASA will contribute key instrument hardware – telescopes, lasers, charge management devices – together with contributions to the science ground segment. In Europe, ESA member states are developing payload instrument units – a description of which can be found in Issue 17 of the LIGO magazine – and leading the development of the data processing centres and toolchains. The LISA Consortium offers its members access to multiple scientific groups involved in the development of the mission, as well as to the groups developing the instruments.

ESA's Mission Development Process

For large class missions, ESA follows a standard development logic. This is based on well-known project phases used in both the US and Europe. The logic is presented in Figure 1. A mission begins with the Study Phase, split into Phases 0, A, and B1. ESA's key decision point is the Mission Adoption at the end of Phase B1, at which the funding required for implementation is secured.

The Mission Formulation Review (MFR)

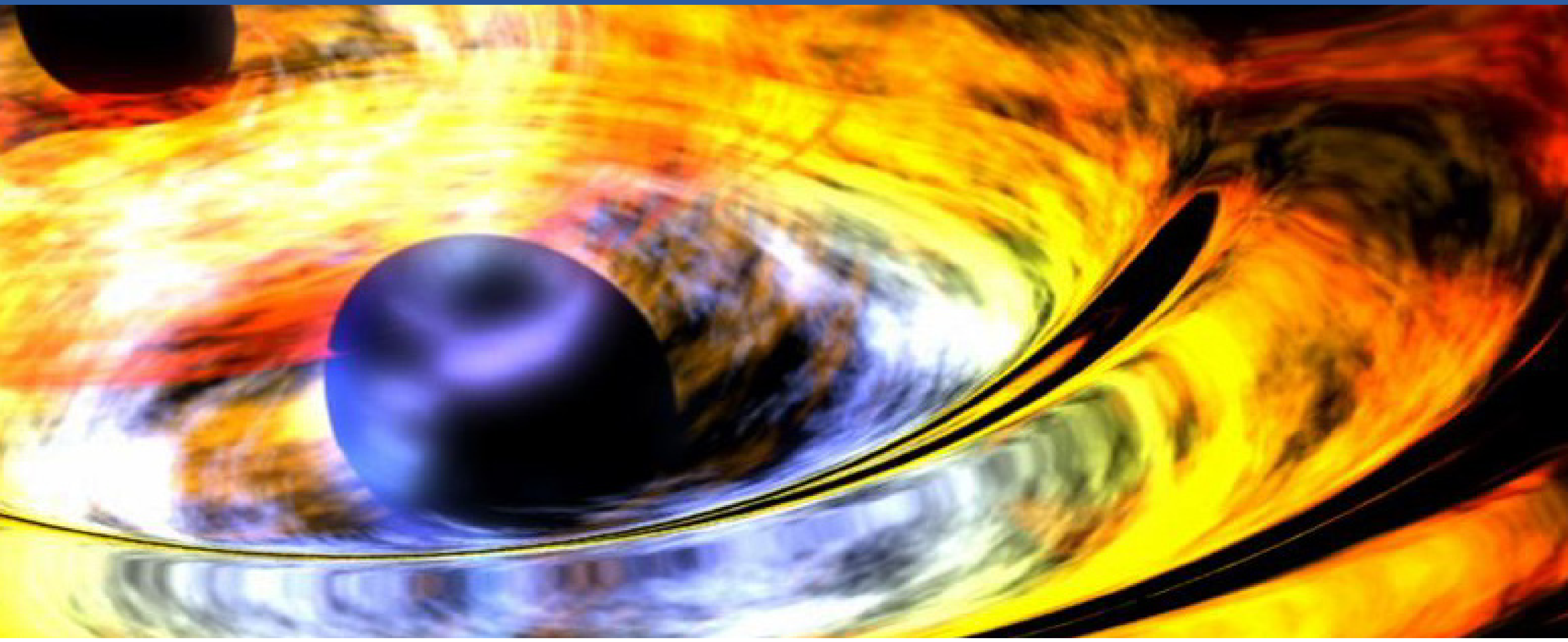
The Mission Formulation Review marks the end of the feasibility assessment – Phase A – and looks at the mission baseline design, the correct identification and flow of requirements, the status of technology developments, as well as at cost, schedule, and risk.

is the Study Manager for the LISA Mission at the European Space Agency since the start of preparatory work in 2015. When not working on LISA, Martin can be found tinkering with his home network or exploring the world with his family. He dearly misses mountains in the Netherlands.

All partners and contractors submitted exhaustive sets of documentation which were reviewed by panels of experts consisting of ESA's subject matter experts, participants from NASA, and members of the study team itself. The panels' findings were then presented to a Board of senior ESA personnel. As no issues affecting mission feasibility were identified, the Board confirmed that LISA has reached sufficient maturity and gave the green light to proceed into the next Phase.

Into Phase B

by Martin Gehler



The MFR also confirmed the new share of responsibilities between the partners, placing the development, integration, and test of the Moving Optical Sub-Assemblies (MOSAs) under ESA's scope, thus giving us the mandate to proceed at full speed with the developments. The MOSA combines the telescope, optical bench, and gravitational reference sensor into an integrated assembly.

What's in store for Phase B1

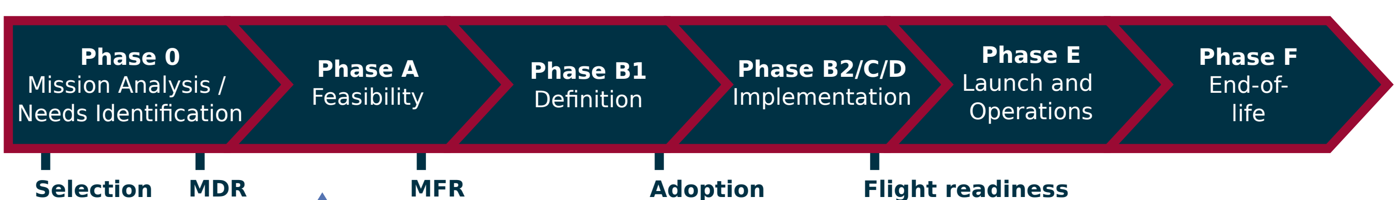
Building upon the foundations laid in Phase A, we are now focused on consolidating the requirements baselines for the mission. This means that all mission partners and contractors will agree to a set of key interfaces and performance requirements, which will then be used as a basis for contracts in the implementation stage. Simultaneously, smaller issues identified in the MFR will be addressed, and all remaining technological developments should reach an appropriate Technology Readiness Level, what we call TRL5/6, to minimize the inherent risks associated with new elements.

Phase B1 is also the time to cast the relationships between ESA and its mission partners into stone by setting up the necessary international agreements. For these, subjects such as hardware provisions, responsibilities for the scientific exploitation of the mission and data rights/proprietary periods will be finally decided.

After the successful completion of Phase B1 and passing the Mission Adoption Review (MAR), the mission, together with its legal framework will be presented to ESA's advisory bodies for adoption.

Launching LISA

Transitioning into Phase B1 finally lifts the mission out of concept studies and marks a major milestone for the involved scientists and engineers. With an implementation duration of around 10 years, LISA is expected to fly in the mid-2030s and, following a year-long cruise to its final, low-disturbance destination, can start to fulfil its mission to observe gravitational waves from space and enable new scientific discoveries. We can't wait!



Timeline for the LISA Mission. LISA is now transitioning from Phase A to Phase B1. During Phase A and B1, industrial competitive studies, activities on instrument development, as well as necessary technology developments are run. MDR is Mission Definition Review and MFR is Mission Formulation Review.

Postdoc Jobs and How To Find Them

Jessica Steinlechner

is an assistant professor at Maastricht University in the Netherlands. Her research focuses on the development of mirror coatings. She likes drawing, reading and coffee.

Anna Green

is a postdoc at the University of Florida, focused on simulations of LIGO interferometer behaviors and testing new input & output optics hardware. When not hunched over her laptop, she enjoys playing her flute and switching to a different crafts hobby every few months.

Are you considering a position as a postdoctoral researcher, or "postdoc", for your next career step? Postdoc jobs can take many different forms, and career paths in academia can generally be quite tricky to navigate, particularly considering the various systems within the many countries of our international community. While we can't hope to cover every aspect, below we've compiled a selection of topics you might want to explore. There may be major (and unexpected!) differences to what you've seen in your current institution/country.

Postdoc positions are frequently advertised via wiki.ligo.org/LAAC/JobPostings. Some useful information about applying for your own funding is collated at dcc.ligo.org/LIGO-G2101624.

When should you start looking?

Early! Funding of research positions is complex, and the majority of research groups will not have unfilled postdoc positions waiting for applicants. However, they may be waiting for the outcome of applications, existing positions may become free, and there is also the option of applying for your own funding, e.g. via fellowships, for which you have to find a host institution first and which usually have annual application deadlines.

So time scales can be long, and to avoid unfunded time periods it is recommended that you start looking for your next job in good time. Use LVK meetings or other conferences to expand your network – and evaluate the situation at your current institution: there may be the option for a few more months of funding and/or short-term projects to bridge the time until your next position starts.

Longer-term planning

Your priorities for your postdoc will depend on your long-term career plans. Are you thinking of becoming a professor? Teaching? Industry? In addition to your core research, consider what other skills will be beneficial in the long-run. For example, a position in another country is often encouraged as a way to expand your network and understand other academic systems better; it is also particularly useful for building your language skills e.g. if English is not your primary language. If you did not apply for funding to generate your position, consider outreach and travel funding applications to build your grant-writing skills.

Teaching commitments & expectations

The amount of teaching a postdoc is expected to do can vary significantly between countries, contracts and grant conditions. If you are planning a career path that will eventually include lecturing or class teaching, make sure your career steps now provide opportunities to build and demonstrate your teaching skills – if not through formal teaching then through running outreach, tutorials, or training activities for your peers. Some countries also have teaching-only faculty positions which you can apply for immediately after your PhD. Most of these do not include funding (or time) for research activities, although, of course, there are exceptions.

Supervision opportunities

Does your long-term career goal involve acting as a supervisor or mentor? If so, consider how you can build relevant experience now. If your position is part of the host institution's project grant, you may be expected to support the supervision of PhD and undergraduate students working on that project. Different groups may have an overabundance of, or zero, students, which will impact how much time you have for your own research as well as supervisory opportunities. If your work is very independent, you may need to consider how else you can build supervisory experience, for example by hosting a summer student or becoming an LSC mentor[1].

Split-host & Split-grant positions

While it comes with additional (organisational) challenges, positions split between institutions are not uncommon. This could mean two neighboring institutions sharing a grant, or two groups doing similar research (e.g. within the LSC) who may even be located in different countries that you alternate between for shorter or longer time periods. Even within one institution you may be part-funded by multiple grants. If you will be working with multiple groups, institutions, or PIs, you may want to discuss their expectations of how your time/priorities are split. If you are interested in contributing to a wide range of different projects, ask your host institution about it.

Changing field

Perhaps you want to change field entirely by moving out of (or into) gravitational-wave research for your postdoc, or change sub-field, for example from instrumentation to data analysis. This can be challenging: research groups will usually expect their postdocs to already have the skills and knowledge to do the job they advertised! Therefore if you are planning to shift focus, start finding ways to develop - and demonstrate - these skills now. This might mean talking to your current supervisor to find a research project closer to your interests, or making time for training courses or extra curricular projects. But keep your eyes open: sometimes groups will actively search for a postdoc that can bring in different, new expertise. They may be looking for you!

Non-university positions

You might also consider positions outside of universities. In the US, examples include DOE national laboratories (nationallabs.org/our-labs/where-we-are/) postdoctoral programs (e.g. Los Alamos, Oak Ridge), or the NASA postdoctoral program (npp.orau.org). As well as providing a vibrant research environment for a postdoc stint, working at one of these institutions can be a great stepping stone towards a long-term civil servant scientist position (although such positions are limited to national citizens). If you like the idea of doing publicly funded research as a career but aren't so keen on teaching, a position like that might be for you.

Ask around

Finally, we recommend that you talk to your supervisor or senior colleagues, as well as any peers who have recently graduated. They may have useful advice and are usually well connected within our community. Of course their referral cannot create jobs – but it can have immense value.

1 laac.docs.ligo.org/project/mentoring

A bright future for GW science

There is a lot to look forward to in the field of gravitational-wave science. Current-generation ground-based detectors have opened a new window on the Universe with observations of black hole and neutron star binary mergers, but future observations of new sources and the development of next-generation facilities will see us learning more than ever about our Universe with gravitational waves. In this article we hear the latest updates from next-generation facilities, pathfinder studies, and a signal that could be the first hints of the detection of ultra-low frequency gravitational-waves from the international pulsar timing array community. Gravitational-wave science truly has a bright future ahead!

The Einstein Telescope reaches a new phase

In June 2021 the European Strategy Forum on Research Infrastructures (ESFRI) decided to include the Einstein Telescope (ET), Europe's proposal for a next-generation ground-based gravitational-wave observatory, in the 2021 upgrade of its roadmap. The Italian government submitted the proposal for the ESFRI-roadmap in September 2020, supported by the Netherlands, Belgium, Poland and Spain.

Preparing the proposal has been a two-year-long effort involving several research institutions and universities, now forming the Einstein Telescope Consortium. The ESFRI Roadmap identifies the most promising European scientific structures on the basis of an in-depth evaluation and selection procedure. ESFRI does not provide funding for the Einstein Telescope. However, inclusion on the Roadmap is a major step towards the realisation of large European projects and brings the Einstein Telescope into a new phase, unlocking other opportunities for national and European funding.

In January 2022 the growing ET Consortium submitted a funding proposal for the preparatory phase of the experiment. This will support the legal framework, governance schemes and financial regulations under which the ET observatory will be constructed and operated. This proposal was submitted with support from Italy, the Netherlands, Belgium, Poland, Spain, Germany, France, Hungary, Austria, Switzerland and the UK.

Read more about ET at www.et-gw.eu.

Andreas Freise
Nikhef / Vrije Universiteit Amsterdam

ETpathfinder officially opens

ETpathfinder aims to serve as a testbed to develop new technologies and interferometry concepts for future gravitational-wave detectors, in particular the Einstein Telescope, and to test the interplay of relevant subsystems of a full interferometer at attometer sensitivities. On 8 November 2021 the facility was opened in Maastricht in a festive ceremony by the Minister of Education, Culture and Science of the Netherlands Ingrid van Engelshoven. Speakers at the opening included amongst others the minister herself, Nikhef director Stan Bentvelsen, Nick van Remortel (Antwerp), INFN (the Italian National Institute for Nuclear Physics) president Antonio Zoccoli, chair of the ETpathfinder Scientific and Technical Advisory Committee David Shoemaker (MIT) and the ETpathfinder project leader Stefan Hild (Maastricht & Nikhef).

In the initial phase ETpathfinder's research program focuses on exploring the matrix of cryogenic mirror temperatures (120K, 15K) and laser wavelength (1550nm, 2090nm). ETpathfinder started off in 2019 as an Interreg funded project with 14.5 million Euro of equipment investment and as collaboration of 15 universities and research institutions from the Netherlands, Belgium and Germany. By now it has grown to more than 20 partners and also includes contributions from France, the United Kingdom and Spain.

For more about ETpathfinder visit www.et-pathfinder.eu and read the Design Report at apps.et-gw.eu/tds/?content=3&r=17177

Stefan Hild, University of Maastricht & Nikhef

The Minister of Education, Culture and Science Ingrid van Engelshoven officially opens ETpathfinder with the push of a button inside the cleanroom.

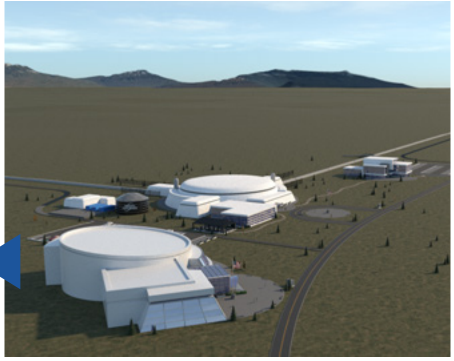
Cosmic Explorer takes shape: Updates from the US 3G detector

Summer 2021 saw the release of the NSF-funded Cosmic Explorer (CE) Horizon Study, which presented the key science goals and capabilities of the next-generation US-based observatory. The study fleshed out the detector concept, revealing that two L-shaped detector with equal arm lengths of 40km and 20km could meet all of the key science goals encapsulated within the themes "Black Holes and Neutron Stars throughout Cosmic Time", "Dynamics of Dense Matter" and "Extreme Gravity and Fundamental Physics".

CE received a strong endorsement both from the Astro2020 Decadal Survey and at the NSF DAWN VI meeting, and is now transitioning to the project phase. The immediate goal is to acquire funding for the conceptual design phase as defined in NSF's Research Infrastructure Guide. At the same time, the window is wide-open for R&D contributions from the entire gravitational-wave research community. The NSF is expected to support this technology development effort through the traditional gravitational-wave research funding avenues.

The CE Consortium has also recently been established, with the intent of providing an open and efficient way for members of the international physics and astronomy communities to contribute to the conceptualization of CE, its design, and its future use. You can read more and join the consortium at: cosmicexplorer.org.

Varun Srivastava & Stefan Ballmer, Syracuse University



Artist's concept of the corner station of one of the envisioned Cosmic Explorer observatory facilities.

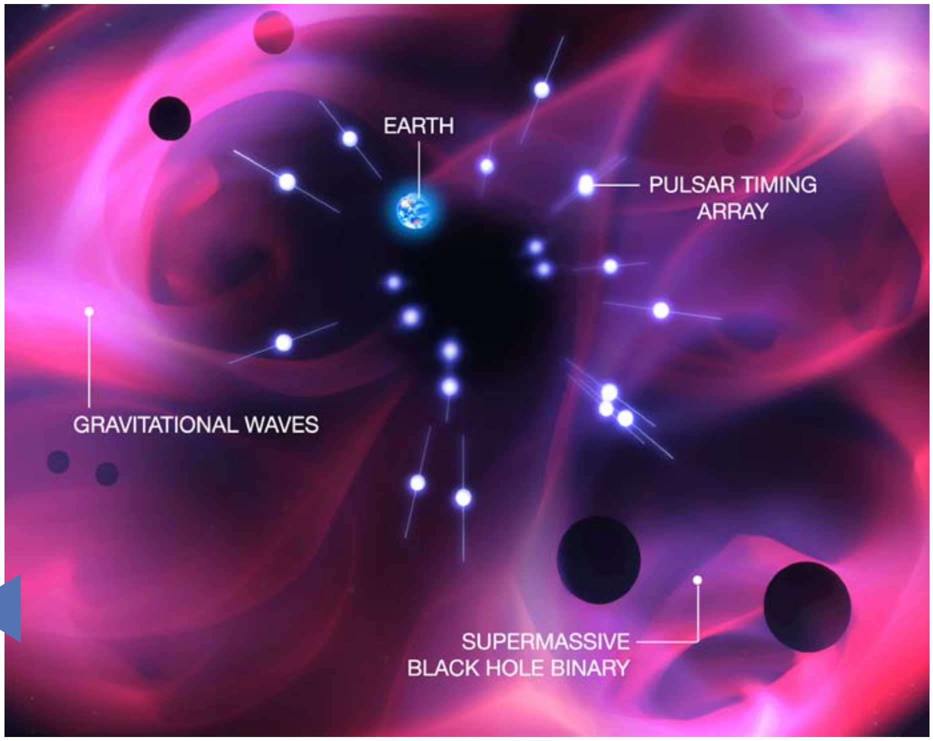
Hunting for ultra-low frequency gravitational waves with pulsar timing arrays

An international team of astronomers has announced the results of a comprehensive search for a background of ultralow-frequency gravitational waves using a world-wide network of radio telescopes in the International Pulsar Timing Array (IPTA) data release 2 (DR2). This data set consists of precision timing data from 65 millisecond pulsars combined from independent data sets from the European Pulsar Timing Array (EPTA), the North American Nanohertz Observatory for Gravitational Waves (NANOGrav), and the Parkes Pulsar Timing Array in Australia (PPTA). This search includes an extensive comparison between individual data sets from the large regional scientific collaborations and the combined data set. The gravitational-wave search of the IPTA DR2 has revealed strong evidence for an ultralow-frequency signal detected by many of the pulsars in the combined data. The characteristics of this common-among-pulsars signal are in broad agreement with those expected from a gravitational wave "background". However, the necessary characteristic spatial correlations for a gravitational-wave origin have not been detected. We hope that a new IPTA combination of the recent individual data sets will enable us to identify the origin of this signal in the near future.

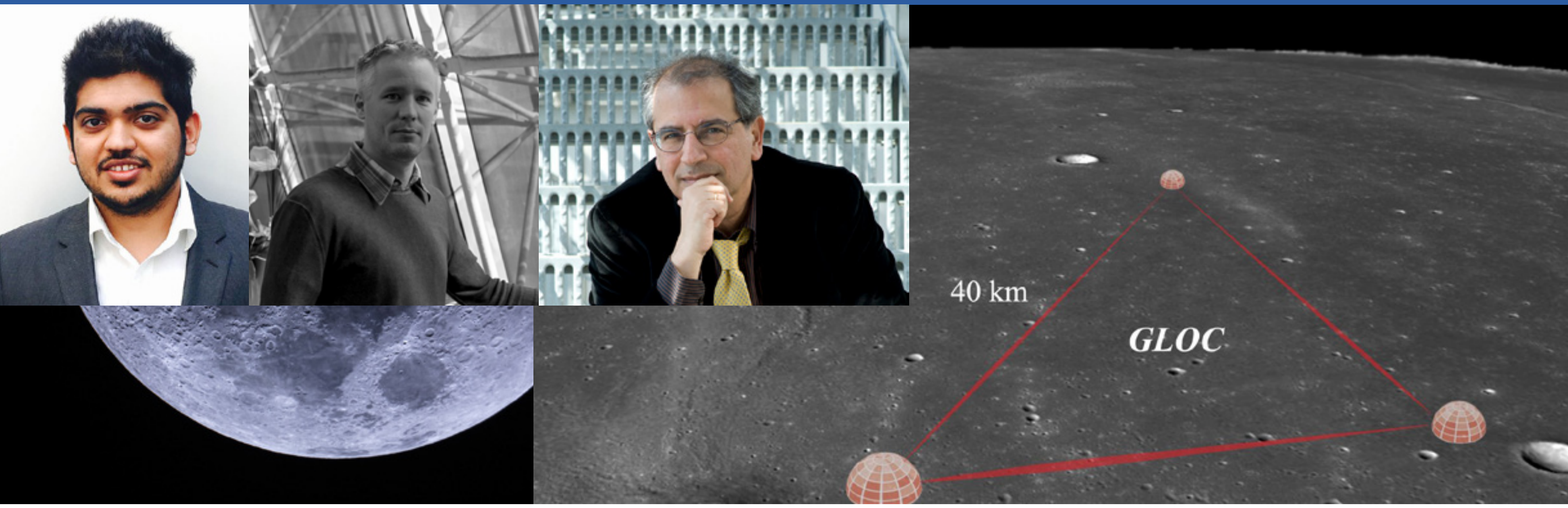
For more about the IPTA and DR2 see ipta4gw.org and arxiv.org/abs/2201.03980.

Siyuan Chen, Kavli Institute for Astronomy and Astrophysics at Peking University.

LIGO 2022



Artist's impression of a pulsar timing array.



▲ *Concept design for GLOC, the Gravitational-Wave Lunar Observatory for Cosmology.*

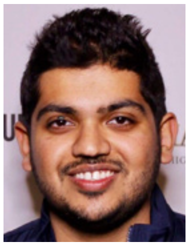
1st International Workshop for Gravitational Wave Detection on the Moon

A detector on the lunar soil has the potential to access gravitational waves near deci-Hertz frequencies, a regime that is challenging for both terrestrial and space missions. In this frequency band, we get a rare cosmic peek into the origins of intermediate-mass black holes, progenitors of Type1a Supernovae, and physics beyond the Standard Model. The First International Workshop for Gravitational-Wave Detection on the Moon[1] held in October 2021 commenced an exciting new chapter of gravitational-wave science.

During the last human mission to the Moon in 1972, the Apollo 17 crew carried with them a 12.7 kg instrument called the Lunar Surface Gravimeter (LSG). The principal investigator of this device was none other than Joseph Weber, the founding father of experimental detection of gravitational waves. LSG was humanity's very first attempt to detect gravitational waves outside the terrestrial terrain. A design flaw greatly limited the scientific scope of the LSG. Nevertheless, the idea of building a "Lunar LIGO" found its mention in Kip Thorne's classic text "Black Holes and Time Warps".

▲ ***Above:*** *Organizing co-chairs of the First International Workshop for Gravitational-Wave Detection on the Moon. From left to right: Karan Jani (Vanderbilt University), Jan Harms (Gran Sasso Science Institute), Stavros Katsanevas (European Gravitational Observatory).*

Karan Jani



is a research assistant professor in astrophysics at Vanderbilt University. He has been working in gravitational waves since 2008, bridging black holes across the gravitational-wave spectrum: from LISA space mission to LIGO-Virgo and, more recently, deci-Hertz detectors.

The first academic conference to discuss lunar-based gravitational-wave astronomy was held on October 14-15 2021 at the European Gravitational Observatory headquarters – the site of the Virgo detector in Italy. It was chaired by Stavros Katsanevas (European Gravitational Observatory), Jan Harms (Gran Sasso Science Institute), and Karan Jani (Vanderbilt University). This inaugural workshop convened more than 350 leading experts from the fields of gravitational-wave science, planetary science, lunar exploration space agencies, and private industries.

After a welcome speech by a representative of the Italian Ministry of Foreign Affairs, two days of exciting presentations followed with invited speakers including the co-chair of National Academies' Astro2020 Decadal Survey,

[1] www.ego-gw.it/blog/2021/10/22/gw_detection_moon_2021/

ESA, NASA, Gravitational-Wave International Committee, LISA leadership and private industries. Discussions were focused on properties of the Moon and opportunities for gravitational-wave observation, key technologies, and coordination with funding agencies. All participants agreed that lunar gravitational-wave detection is a realistic pursuit.

Why the Moon?

The Moon offers a natural environment for constructing a large-scale gravitational-wave interferometer. The atmospheric pressure on the surface of the Moon is comparable to the currently implemented ultra-high vacuum (10^{-10} torr) at each of the LIGO facilities. The seismometers left by the Apollo missions suggest that at low-frequencies (<0.5 Hz), the seismic noise on the Moon is expected to be about a hundred times lower than on Earth. Seismic noise is a fundamental limitation for the low-frequency sensitivity of gravitational-wave detectors on Earth (for example, LIGO, has very low sensitivity below 10 Hz due to seismic noise). The frequency range of 0.1-1 Hertz is very challenging to pursue with space missions like LISA, as they are fundamentally limited by the laser shot noise.

It is this “deci-Hertz band” that we get a rare peek into white dwarf mergers, a possible progenitor of Type Ia Supernovae. The frequency spectrum also opens the prospect of multi-band observations for LIGO-Virgo sources, providing their precise sky-location days in advance. The intermediate-mass black hole population could be surveyed across the observable Universe with a lunar detector, thus solving the fundamental mystery surrounding the growth of supermassive galactic black holes.

An additional advantage is that the Moon is not corrupted by any unpredictable noise from human activities. In the event of a serious hardware failure, parts of the detector can be replaced and repaired by astronauts. The benefit of performing on-request maintenance is not available for space-based gravitational-wave detectors, making the Moon a better long-term investment. In addition, future space missions like LISA are limited in their lifetime (typically a few years), after which the gravitational perturbation from solar system objects will disrupt their geometry. In contrast, a lunar-based detector might operate and be steadily improved for decades. Unlike a similar setup on Earth, a lunar-based detector is only weakly affected by environmental factors. This would ensure the continuous operation of the detector.

An emerging lunar gravitational-wave community

With the rejuvenation of the NASA Artemis Program[2] in the last few years, it is evident that humanity is on the verge of returning to the Moon, and this time for a permanent settlement. The Artemis Accord has led to new international cooperation for the Moon not witnessed since the development of the International Space Station. The NASA Commercial Payload Services Program has initiated contracts to private companies for building lunar landers. Furthermore, ESA has given a commitment to the development of the European Large Logistics Lander, and China’s Chang’e missions open new opportunities also for ambitious lunar science missions.

Building on these exciting developments, three teams independently proposed lunar gravitational-wave detector concepts: The Gravitational-Wave Lunar Observatory for Cosmology (GLOC), the Lunar Gravitational-Wave Antenna (LGWA), and the Lunar Seismic and Gravitational Antenna (LSGA). GLOC is a laser-interferometric concept and therefore lies close to the design of LIGO-Virgo detectors. LGWA and LSGA exploit the Moon itself as their gravitational detector, studying its response to incoming gravitational waves similar to Weber’s bar detector. LGWA foresees the use of seismometers to monitor surface vibrations caused by gravitational waves, while LSGA foresees the use of optical fibers and laser strainmeters.

Turning vision into action

Within the US, community white papers on lunar gravitational-wave astronomy have been submitted to the NASA Artemis, Snowmass 2021 (the particle physics decadal) and the Biological and Physical Sciences Decadal Survey. These white papers have been endorsed by over 100 astronomers and physicists. In Europe, similar enthusiast support was found for submissions to an ESA call for ideas for missions on the Moon. The International Space Science Institute in Bern will also be organizing a forum on this topic with various space agencies.

All things considered, our beloved satellite responsible for creating tides on Earth holds plenty of promise to help us detect gravitational waves from the Universe.

2 www.nasa.gov/specials/artemis/

Career Updates

Greg Ashton has become a lecturer and started a new group at Royal Holloway, University of London, focused on relativistic astrophysics of neutron stars and black holes.

Dripta Bhattachajee got her PhD at Missouri S&T in November 2021 with her thesis "Reduced Calibration Uncertainties for the Global Network of Gravitational-Wave Observatories and the Impact on Sky Localization of Burst-Like Sources." She has now moved to Kenyon College for her first postdoc to work (still on calibration!) with Maddie Wade and as an LSC Fellow stationed at Hanford.

Alessandra Buonanno has been elected member of the Berlin-Brandenburg Academy of Sciences and Humanities.
https://www.aei.mpg.de/709900/alessandra-buonanno-elected-member-of-the-berlin-brandenburg-academy-of-sciences-and-humanities

Prof. Sukanta Bose (Senior Professor and Project Coordinator of LIGO-India at IUCAA) was elected Fellow of the prestigious Indian Academy of Sciences (IASc), Bengaluru, in January. IASc was founded in 1934 by Sir C V Raman to promote progress and uphold the cause of science.

Sudarshan Ghonge graduated from his PhD program, and has now moved to an industry job working on cloud-based physics simulations.

Frances Hellman at UC Berkeley is the APS President for 2022, having been elected to the presidential line in 2019.
https://aps.org/publications/apsnews/202201/hellman.cfm

Martin Hendry was recently appointed Clerk of Senate and Vice Principal of Glasgow University. He will take up his new position on August 1st 2022.

Georgia Mansell and **Craig Cahillane** have accepted tenure track positions at Syracuse University, and are due to start at the beginning of O4. Their groups will work on instrumentation for Cosmic Explorer, while maintaining close ties to aLIGO commissioning.

Hannah Middleton has started a postdoc at the University of Birmingham's Institute for Gravitational Wave Astronomy (UK) having moved from OzGrav in Australia.

Arnaud Pelé, detector engineer at LLO, is moving to California to start a senior mechanical engineering position at CIT in March 2022.

Susan Scott, from the CGA at ANU, has been appointed the new Editor in Chief of the Institute of Physics journal Classical and Quantum Gravity.

Prof. Tarun Souradeep, Spokesperson for LIGO-India, has become director of the Raman Research Institute (RRI) in Bengaluru as of 20 January 2022. He was previously a professor and chair of the physics department at the Indian Institute of Science Education and Research (IISER), Pune, and is a Fellow of the National Academy of Sciences, Indian Academy of Sciences, International Society on General Relativity and Gravitation among others.

Marcella Wijngaarden recently completed her PhD at the University of Southampton. Her thesis has two parts, one on neutron star envelopes and cooling and the other part on code development for analyses that combine both the inspiral and post-merger gravitational wave data.

Several members of LIGO Lab community have retired recently, including: **Jeff Bartlett** (Operations Specialist, LHO), **Rolf Bork** (Lead Research Engineer, CIT), **Dennis Coyne** (LIGO Lab Chief Engineer, CIT), **Eric Gustafson** (Instrument Science Group Leader, CIT), **Kathy Holt** (Senior Educator, LHO), **Ken Mason** (Research Engineer, MIT), **Greg Mendell** (Senior Scientist, LHO), **Hugh Radkins** (Detector Engineer, LHO), **Norna Robertson** (Lead Scientist, CIT), **Kyle Ryan** (Lead Scientist, LHO), and **John Zweizig** (Senior Scientist, CIT).

Awards

Alessandra Buonanno has been awarded the Balzan Prize 2021 in the field of "Gravitation: physical and astrophysical aspects", as well as the Dirac Medal.
https://www.aei.mpg.de/785060/balzan-prize-2021-for-alessandra-buonanno
https://www.aei.mpg.de/761682/alessandra-buonanno-earns-dirac-medal

Peter Fritschel at MIT has won the APS Richard A. Isaacson Award in Gravitational Wave Science (2021) for 30 years of scientific leadership of the aLIGO detectors. https://aps.org/programs/honors/prizes/isaacson.cfm

Ben Grace from the CGA at the Australian National University and Lucy Strang from the University of Melbourne, both members of OzGrav, were jointly awarded the Kerr Prize for the best student talk at the 11th Australasian Conference on General Relativity and Gravitation held in Hobart 2-4 February.

Anna Green was awarded a Veni grant by the NWO (Dutch Research Council) for her proposal "Smoothing the Optical Bumps in the Road for Future Gravitational-Wave Detectors". She will be based at Nikhef for this 3-year postdoctoral project. https://www.nwo.nl/en/news/89-researchers-awarded-nwo-veni-grant-worth-280000-euros

Simon Stevenson was awarded (following an appeal) an Australian Research Council (ARC) Discovery Early Career Research Award (DECRA) for his project entitled "Discovering the origin of gravitational waves". This postdoc fellowship, worth about $500,000 AUD, means Simon will remain at Swinburne for the next 3 years. (See https://www.arc.gov.au/news-publications/media/media-releases/additional-funded-research-projects-following-arc-appeals-process)

Christine Ye has been selected as a top 40 scholar for the Regeneron Science Talent Search competition. She worked with Maya Fishbach on her project "Inferring the Neutron Star Maximum Mass and Lower Mass Gap in Neutron Star–Black Hole Systems With Spin". www.societyforscience.org/regeneron-sts/2022-scholars

Haocun Yu at MIT has won the APS Carl E Anderson Division of Laser Science Dissertation Award (2021) for her work in producing frequency independent squeezing. https://aps.org/programs/honors/prizes/laser.cfm

New LSC positions

Sylvia Biscoveanu has been elected as LAAC Student Representative.

Daniel Brown has been re-elected as chair of the Advanced Interferometer Configurations working group.

Anna Green has been elected as LAAC Postdoc Representative.

Lee McCuller has been elected as chair of the Quantum Noise working group.

Volker Quetschke has been re-elected as chair of the Lassers and Auxiliary Optics working group.

Surabhi Sachdev has been elected as co-chair of the Compact Binary Coalescence working group.

Bram Slagmolen has been elected as Technical Advisor to the Oversight Committee.

Other News

Disha Kapasi, a PhD student at ANU, participated in the 10th anniversary edition of the Global Young Scientists Summit (GYSS). Out of ~800 participants, Disha was one of just 19 selected to highlight their research, with her talk "Probing Deeper into the Gravitational Universe using Near Infrared Lasers", and was also shortlisted for an informal chat with Prof. Takaaki Kajita (Nobel Prize Physics, 2015). https://www.nrf.gov.sg/gyss

Explore the Frontier of Physics and hop from Black Holes to the Quantum Scale in this virtual exhibition: exhibition.sagex.org. Many videos and interactive elements introduce the wonderful and strange world of Scattering Amplitudes, from basic concepts to cutting-edge ideas.

Featuring in the next issue:

LIGO-India: Prototyping the vacuum chambers

LIGO-India is currently in the pre-project, prototyping phase. Here we see two types of vacuum chamber: the Basic Symmetric Chamber and the Horizontal Access Module, fabricated and assembled in the workshop in India. They are major elements of the LIGO vacuum system housing the detector optics. ▶
– Vijay Bedakihale and S. Suni

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

The authors gratefully acknowledge the support of the United States National Science Foundation (NSF) for the construction and operation of the LIGO Laboratory and Advanced LIGO as well as the Science and Technology Facilities Council (STFC) of the United Kingdom, the Max-Planck-Society (MPS), and the State of Niedersachsen/Germany for support of the construction of Advanced LIGO and construction and operation of the GEO600 detector. Additional support for Advanced LIGO was provided by the Australian Research Council. The authors gratefully acknowledge the Italian Istituto Nazionale di Fisica Nucleare (INFN), the French Centre National de la Recherche Scientifique (CNRS) and the Netherlands Organization for Scientific Research, for the construction and operation of the Virgo detector and the creation and support of the EGO consortium. The authors also gratefully acknowledge research support from these agencies as well as by the Council of Scientific and Industrial Research of India, the Department of Science and Technology, India, the Science & Engineering Research Board (SERB), India, the Ministry of Human Resource Development, India, the Spanish Agencia Estatal de Investigación, the Vicepresidència i Conselleria d'Innovació, Recerca i Turisme and the Conselleria d'Educació i Universitat del Govern de les Illes Balears, the Conselleria d'Innovació, Universitats, Ciència i Societat Digital de la Generalitat Valenciana and the CERCA Programme Generalitat de Catalunya, Spain, the National Science Centre of Poland and the Foundation for Polish Science (FNP), the Swiss National Science Foundation (SNSF), the Russian Foundation for Basic Research, the Russian Science Foundation, the European Commission, the European Regional Development Funds (ERDF), the Royal Society, the Scottish Funding Council, the Scottish Universities Physics Alliance, the Hungarian Scientific Research Fund (OTKA), the French Lyon Institute of Origins (LIO), the Belgian Fonds de la Recherche Scientifique (FRS-FNRS), Actions de Recherche Concertes (ARC) and Fonds Wetenschappelijk Onderzoek Vlaanderen (FWO), Belgium, the Paris Île-de-France Region, the National Research, Development and Innovation Office Hungary (NKFIH), the National Research Foundation of Korea, the Natural Science and Engineering Research Council Canada, Canadian Foundation for Innovation (CFI), the Brazilian Ministry of Science, Technology, and Innovations, the International Center for Theoretical Physics South American Institute for Fundamental Research (ICTP-SAIFR), the Research Grants Council of Hong Kong, the National Natural Science Foundation of China (NSFC), the Leverhulme Trust, the Research Corporation, the Ministry of Science and Technology (MOST), Taiwan, the United States Department of Energy, and the Kavli Foundation. The authors gratefully acknowledge the support of the NSF, STFC, INFN and CNRS for provision of computational resources.

Online ISSN: 2169-4443
World Wide Web URL: https://www.ligo.org/magazine
Publisher: LIGO Scientific Collaboration, Pasadena, CA, USA
LIGO DCC: LIGO-P2200085
Contact: magazine@ligo.org

Editor-in-Chief: Hannah Middleton • **Deputy Editor-in-Chief:** Anna Green

Editors: Kendall Ackley, Deeksha Beniwal, Laura Cadonati, Andreas Freise, Tobin Fricke, Paul Fulda, Gabriela González, Amber Strunk Henry, Nutsinee Kijbunchoo, Sumeet Kulkarni, Mike Landry, Sean Leavey, Susanne Milde, Brian O'Reilly, Sascha Rieger

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

Supported by the Max Planck Institute for Gravitational Physics (Albert Einstein Institute/AEI), and the California Institute for Technology (Caltech)

The LIGO Magazine is printed on certified sustainable paper.

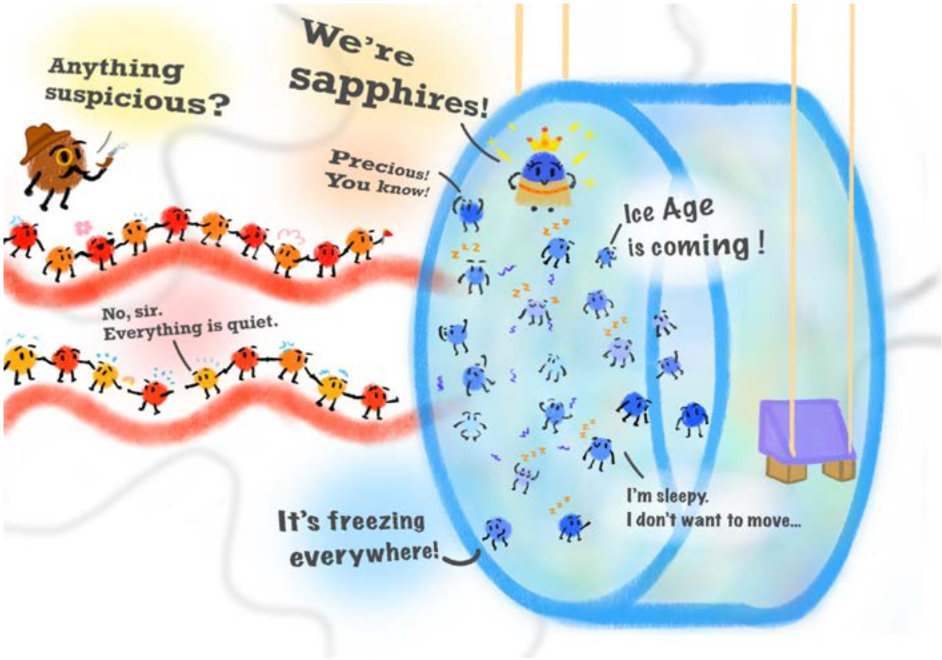
KAGRA is a newly-built 3km-long gravitational-wave detector located in Japan. It is now in the final commissioning phase and preparing to join LIGO and Virgo's 4th observation run (O4) by the end of this year.

KAGRA is a unique detector with two main features: underground construction and cryogenic operation. Being underground reduces the influence of the Earth's seismic motion on the detector. Operating at cryogenic temperatures reduces thermal vibration on the surfaces of its high-quality mirrors. These mirrors are core components of the detector, acting as test masses to sense extremely small gravitational-wave signals. The thermal noise in the mirrors' highly reflective coatings limits the detector's performance around 100Hz, which is in the most sensitive frequency band of ground-based detectors.

KAGRA has a specially designed cryogenic system to cool down its mirrors to around 20 Kelvin (about -253 Celsius or -424 Fahrenheit). At this temperature, the test mass molecules are almost completely stationary, and their Brownian motion (the random motion of molecules) is greatly reduced. This means that the laser photons interacting with the mirror surface won't be limited to seeing distance changes from molecules' movements, and instead be able to see perturbations in space caused by gravitational waves.

However, extracting so much heat from a test mass mirror that is 15 cm thick, 22 cm in diameter, and weighing 23 kg is not easy. KAGRA uses sapphire as the material for the mirrors due to its high thermal conductivity as well as good optical performance. Most importantly, the cryostat must work constantly and very quietly so that it does not introduce additional vibrations to the test mass. So far, the cryogenic operation has been achieved and tested. KAGRA is edging closer towards taking its special role in the gravitational-wave network.

The laser "inspector" sees no movement from a cryogenic-cooled mirror!



LIGO 2022

 by Haoyu Wang, illustration by Ming Zhang