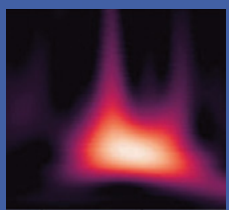
10 years of Gravitational Wave Astronomy

27
September | 2025

LIGO MAGAZINE

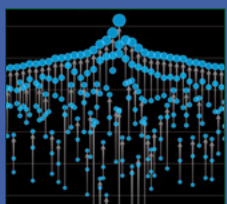
GW150914 to GW231123

A signal that changed the world p.6



GW231123: the most massive black hole merger yet!

Probing the pair-instability mass gap and beyond p.24



GWTC-4.0 Catalogue Paper

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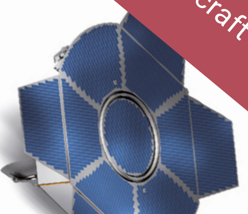

GW Observatories of the Future

LISA Spacecraft revealed! p.34

Plus Climate Change Conversations: Fossil-free supercomputing p.40

Front cover

Two gravitational wave signals. The upper signal is GW150914, the first gravitational-wave detected 10 years ago on the 14th September 2015. The lower signal is GW231123, the most recent special event announcement at the time of this edition's publication. Two traces are shown for each signal, representing the data from the LIGO Hanford and LIGO Livingston detectors.

Top inset: The time-frequency representation of GW231123, the most massive black hole merger yet. Article on pp. 24-26.
Bottom inset: Masses in the Stellar Graveyard plot showing the collected results of GWTC-4.0. Article on pp. 20-23.
Bottom-left (diagonal) inset: The LISA spacecraft design from OHB. Article on pp. 34-37.
Top-right corner: Wishing a happy 10th birthday to GW150914!

Image credits

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Cover: Main image: GW150914 and GW231123 image by LIGO-Virgo-KAGRA/Sascha Rieger. Top inset: GW231123 plot from LIGO-Virgo-KAGRA.
Bottom inset: Masses in the stellar graveyard plot by LIGO-Virgo-KAGRA/Aaron Geller/Northwestern. **Bottom-left (diagonal):** LISA image from OHB.
Top-right corner: GW150914 birthday cake artwork by Storm Colloms.
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pp. 20-23 Petri dish plot by Derek Davis/Rhiannon Udall/Caltech/LIGO-Virgo-KAGRA. Masses in the stellar graveyard plot for GWTC-4.0 by LIGO-Virgo-KAGRA/Aaron Geller/Northwestern. Earlier version of the masses in the stellar graveyard plot by LIGO-Virgo/Frank Elaysky/Northwestern University.
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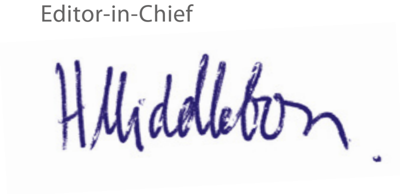
Hannah Middleton
Editor-in-Chief



Anna Green
Deputy Editor-in-Chief

Welcome to the twenty-seventh edition of the LIGO Magazine! Ten years ago, on the 14th September 2015, a gravitational-wave signal from a binary black hole merger a billion light years away wobbled the LIGO Hanford and LIGO Livingston detectors and a new field of observational astrophysics was realised.

To celebrate a decade of gravitational-wave discovery, we invited you all to share your memories. In "10 years of gravitational-wave astronomy", we look back at those times, the excitement of the discovery, the double and triple checking of results, and the celebrations when we shared GW150914 with the world. This anniversary year, our community is also saddened by the loss of Rai Weiss, who passed away at the age of 92. He will be sorely missed.

We thank you all for contributing to this special edition. We will continue to collect reflections as part of the GW150914 celebrations at https://gw-150914memorybox.docs.ligo.org. All are welcome to share your recollections and photos.

As well as looking back, we dive into new results from LIGO-Virgo-KAGRA, including the latest installment of the gravitational-wave transient catalogue, GWTC-4.0 and the heaviest black hole binary merger yet, GW231123. Throughout this edition, members of the analysis and paper writing team share their experiences of working on the results. As always, we also feature the interests of our community, from an early careers workshop to fossil-free supercomputing and the latest from the LISA Mission – we hope you enjoy.

The last decade has seen many changes in our field and the next will see many more. Throughout the years, the LIGO Magazine has captured small snapshots of our community's perspectives and experiences. Thank you to everyone who has shared stories, and also to our wonderful Editorial Team whose hard work and enthusiasm make the LIGO Magazine what it is. We look forward to hearing many more of your stories in the years to come!

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 spokespeople

We both joined the LIGO Scientific Collaboration (LSC) as postdocs over 20 years ago and are delighted to be taking a turn as your spokesperson and deputy. While it is harder now to know everyone in the collaboration personally, the joy of getting to work with excellent colleagues, both familiar and new, makes it all worthwhile.

This month we are celebrating the ten-year anniversary of LIGO's groundbreaking first detection of gravitational waves from merging black holes—a milestone that marked the dawn of gravitational wave astronomy. What a remarkable decade it has been!

This moment offers a great opportunity to reflect on the remarkable scientific achievements of the LSC over the past thirty years, and especially the transformative progress made in the last ten. Most recently, we released the data and gravitational-wave transient catalog from the first eight months of Observing Run 4 (O4). This update more than doubles the number of confident gravitational wave detections and includes several exceptional events—among them, the most massive binary black hole merger ever observed and the loudest signal recorded to date. These discoveries are deepening our understanding of black hole populations across the Universe.

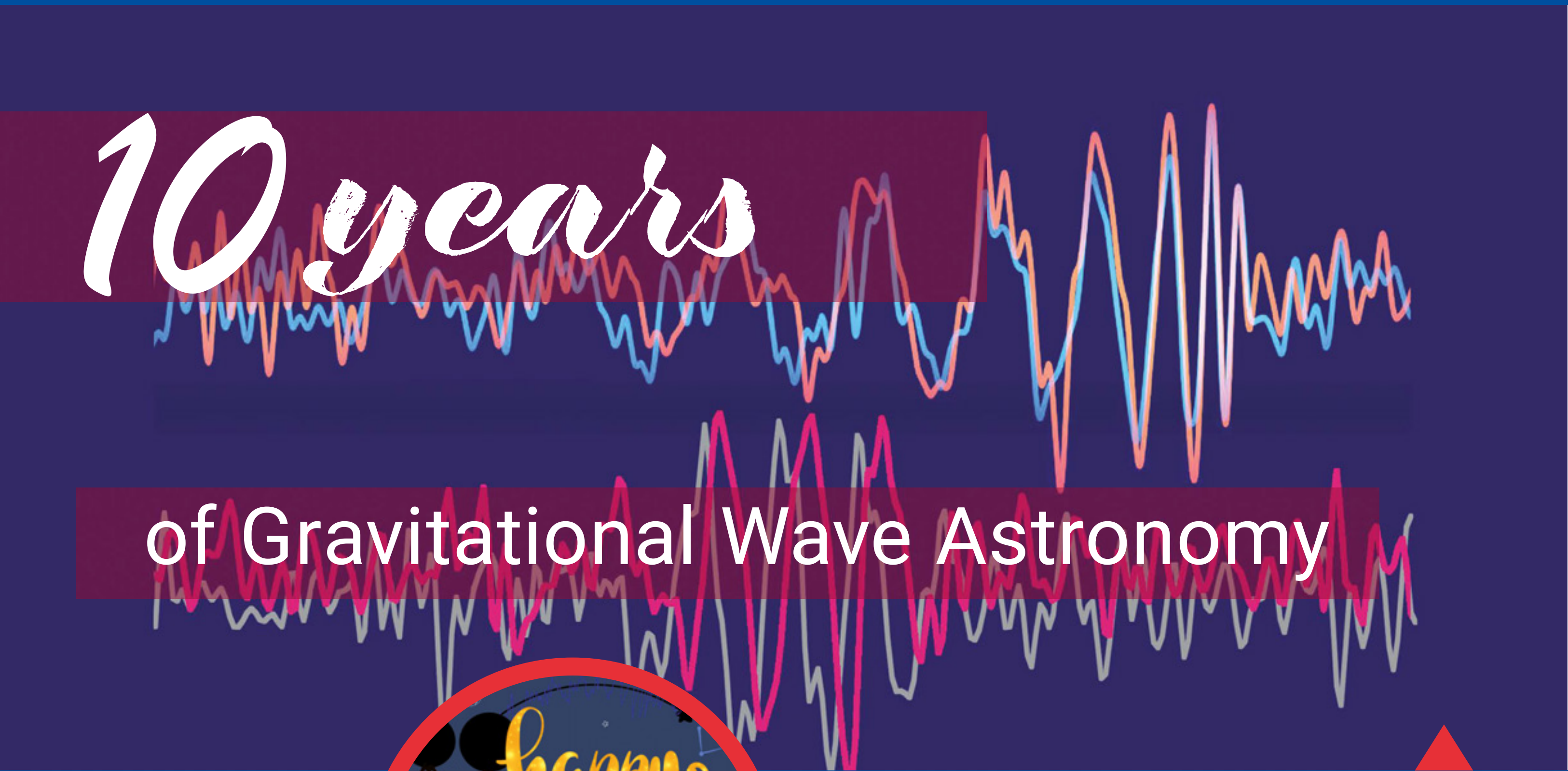
In parallel, we've advanced our searches for unmodeled transients, continuous gravitational wave sources, and both astrophysical and cosmological gravitational wave backgrounds. Our scientific scope continues to expand: we're now placing constraints on various forms of dark matter, including those that might interact directly with our detectors or generate gravitational wave signals through interactions with black holes and other objects in the Universe.

These achievements are a testament to the dedication and ingenuity of you and your colleagues in the LSC, Virgo and KAGRA. The collaboration's scientific achievements are enabled by pioneering research on interferometric and quantum technologies and by dedicated teams operating the observatories through our longest science run. We continue to issue near real-time gravitational wave alerts, enabling rapid follow-up by the broader astronomy comunity. As we sustain operations through the remainder of O4, we also look ahead to completing the analysis of the full O4 data set and planning how to operate even better as a global collaboration in the future.

The legacy of GW150914 is a perfect moment to showcase the wide-ranging contributions of current and former collaboration members. Beyond advancing gravitational wave science, our research has influenced fields from fundamental quantum theory to medical technologies. Many alumni now lead in diverse industries, demonstrating the broad impact of our work. In a time of tightening research budgets worldwide, this anniversary is a chance to remind the public and policymakers of the profound scientific and societal value of our collaboration.

Stephen Fairhurst
LSC Spokesperson

Peter Shawhan
LSC Deputy Spokesperson



10 years of Gravitational Wave Astronomy

Celebrating a decade of gravitational-wave astronomy from GW150914 (top) to GW231123 (bottom). Find out more about GW231123 on pp. 24-26.

This year we celebrate a decade of gravitational-wave discovery with the 10 year anniversary of GW150914, discovered on the 14th September 2015. That gravitational-wave signal lasted just a fraction of a second in our LIGO Hanford and LIGO Livingston data and originated from a pair of black holes merging about a billion light years away.

Now we are in the fourth observing run of LIGO-Virgo-KAGRA. The last decade has seen many more gravitational-wave discoveries, from the spectacular binary neutron star merger in 2017 (GW170817) to the heaviest binary black hole merger yet in 2023 (GW231123). Over 200 gravitational-wave candidates have been discovered, enabling analysis of the population, cosmology, tests of general relativity, and more.

Here we celebrate GW150914's 10th birthday with reflections and perspectives from around our community.

The detection!

Before the detection of GW150914, the collaboration was busy preparing for the first observing run, O1.

David Shoemaker, MIT

Andy Lundgren and I were chairing DetChar* in the fall of 2015, and in particular had been working with the teams trying to get the blind injection system running. There were technical problems that had prevented any quasi-simultaneous injections to be made, but attempts were underway on the days before the 14th September. The first question was of course if it had been an injection – we were pretty sure no

* Detector Characterisation Working Group

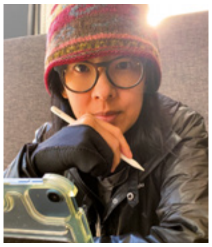
Gaby González and Fulvio Ricci cutting the GW150914 celebration cake at the LIGO-Virgo Collaboration (LVC) meeting in Pasadena (March 2016).

one was able to do it, but a check was first on the list. It was not.

At the time, Rai Weiss was vacationing in Maine as was his wont and I had the pleasure of being the first to let him know – in an email – that we likely had a signal. Peter Saulson was with him in Maine at that time and I know they both then started digging into the signal and their doubts.

Andy Lundgren, ICREA and IFAE (Barcelona)
We had been working on diagnosing the problems with the hardware injections for a few weeks at that point. That alog was posted on Sunday, September 13. We had just confirmed that we were unable to do a realistic injection of a binary neutron star, because the drive electronics could not push hard enough on the mirrors at high frequencies. The entry says "The likely path forward, in the short term, is to push the masses up into the NSBH [neutron star - black hole binary] range, like to make one object 10 solar masses." A higher mass system naturally ends at a lower frequency. I think that might have been Duncan Brown's suggestion when he called my office after seeing an earlier draft of the entry.

The next day, mid-morning in Hannover, late night at the sites, there was a beautiful signal in both detectors, and it was definitely a high-mass signal. I thought Duncan had arranged it as a sneaky test that we had finally found a way to make the blind injections work. Duncan later told me that he thought I had done the same.

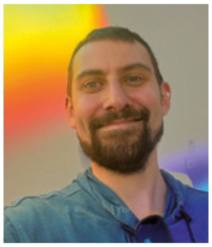


Nutsinee Kijbunchoo, University of Adelaide
I was the OWL shift operator that day, so I was the only one in the Hanford control room when GW150914 came in. Things were quiet. At some point, there were a couple of voices on the control room TeamSpeak channel, which I assumed was the Livingston operator talking to their commissioner. We were still in an Engineering Run at the time, so that kind of thing happened often, and I'd usually just ignore it.

The night was uneventful, except for an earthquake that knocked the detector out early in the morning. I took a nap on the couch before driving home—right next to where the morning meeting happens. Nobody mentioned a thing about the detection that had just happened a few hours earlier.
I didn't find out about it until after I'd gone to bed to rest up for the next OWL shift. A friend in Louisiana texted me asking if I was walking around with a slide whistle. It took me a while to get a hint. Then I was like, "Oh sh*t." At some point that week, Mike Landry asked me if I got a call that night. I was thinking he meant a proper phone call, so I said no—maybe I stepped out for a coffee when it happened? Turns out the "call" was the murmur I'd heard on TeamSpeak... which I had gracefully ignored.

Jenne Driggers,
LIGO Hanford Observatory

I was a postdoc at the LIGO Hanford Observatory in September 2015. I had just started that summer and was really hoping that we'd detect gravitational waves while I was there! On the morning of September 14th, 2015, I didn't know anything special was happening until I walked into the Control Room. The room was buzzing with activity - even more than the usual bustle of commissioning activity in the ramp-up to O1. Throughout the day I worked with others to try and rule out any possibility that it was an instrumental artifact. Since we weren't working on the detector that evening (to let it accumulate background data) and we had an unexpected night off from commissioning, a group gathered at my house for pizza and drinks. We reprised the gathering at my house after GW170817. With all the advances we've made in the last 10 years and all the GWs we've detected we no longer gather for dinner at my house for every event, but I still get excited every time I get a call from GraceDB!



Grant David Meadors
14 September 2015: O1, the first Advanced LIGO observing run: for long years, the letters gleamed like glyphs from the future — this week, it starts. My work here at AEI Hannover is calm compared to the buzz palpable in the online logbooks and in the voices down the hall.

15 September 2015: "Dear Group", begins our director's email: we LIGO members are having a special meeting. Thirty or more scientists crowd into a room. Our director enters, locking the door. "This is not a blind injection".

B. S. Sathyaprakash, Penn State and Cardiff University
On the Black Hole Trail: A Promise Fulfilled
On the morning of 14 September 2015, I was on a regular planning call with Jim Hough and Sheila Rowan to discuss our upcoming consolidated grant proposal to the UK's STFC—a recurring effort every few years to secure funding for gravitational wave research at institutions like Glasgow and Cardiff. Midway through the call, I received an urgent message from Andy Lundgren, then a staff scientist at the AEI. I excused myself to take the call.

Jenne Driggers in the Hanford Control Room.

Andy informed me that there had been a significant trigger around 9:50 UTC and, knowing I co-chaired the LIGO-Virgo Blind Injection Committee, asked if a blind injection might be responsible. Our committee had established a clear policy: no blind injections during the engineering run. Although O1 was initially scheduled to start on 15 September, a delay meant the run had not yet officially begun and we were still in ER8. I told Andy that no injection should have taken place, but I would verify.

Instead of feeling exhilaration, I spent the rest of the day concerned that someone might have misunderstood the injection policy—or assumed the run had already started. The gravity of what had occurred only dawned on me weeks later, when we began to accept that this was no blind injection—it was real. We were standing at the threshold of a new era of gravitational-wave physics and astronomy.

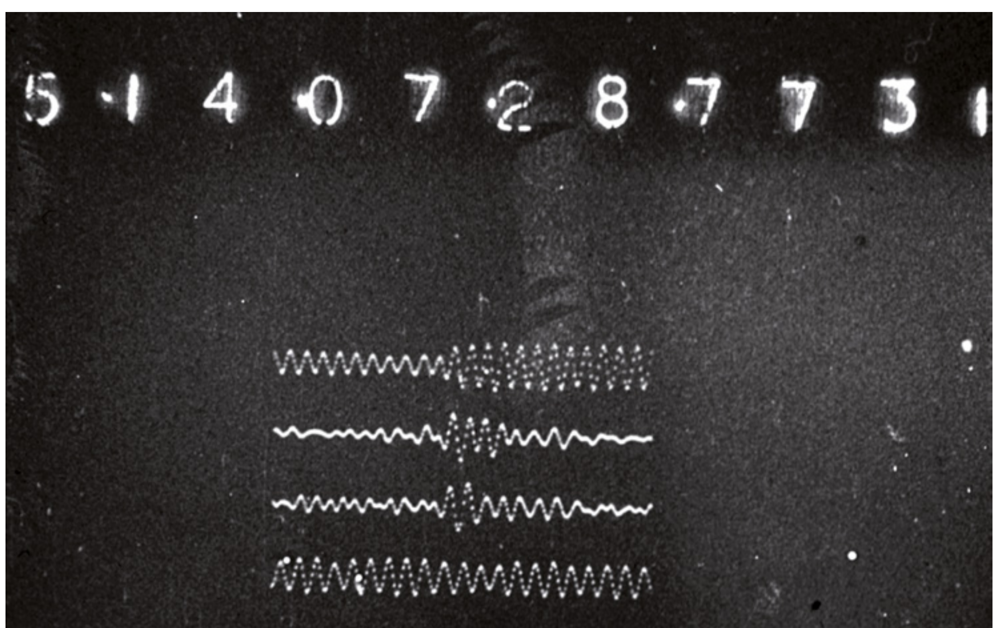
That moment triggered a memory from four decades earlier. In 1977, I had been toying with the idea of a career in classical music when I stumbled upon a popular lecture on black holes by C.V. Vishveshwara, who later became a mentor and a friend. That talk changed everything. Years later, in an article I wrote for his 60th birthday, I thanked him and wrote, "I hope one day I will be able to come and tell you that we have discovered the quasi-normal modes" he had predicted. When I looked back at that promise a few years later, it felt premature bordering on foolish. But on 11 February 2016, I had the privilege of witnessing it come true in the most extraordinary way—a moment made even more special knowing he had recently published On the Black Hole Trail, a reflection on his pioneering journey through black hole physics.

Jim Hough, University of Glasgow

On 14 September 2015 in Glasgow Sheila Rowan and I were on the phone to Sathya discussing a gamma ray burst when he suddenly told us that he had just heard from the AEI about the observation of a really exciting coincidence – the discovery event. It took me back more than 40 years when we had a very unusual coincident event between our two bar detectors in Glasgow which looked exactly what we then expected for a gravitational wave event. The probability was less than 1 in 100 years and indeed we never saw another event like it in more than 3 years of running. There were no other observations of any unusual event from any other area of astrophysics at the same time and so we could make no claim. But it gave me enormous confidence that we all would eventually be successful in our hunt. It took much longer than we expected but we were indeed successful in 2015.

Susan Scott, ANU

On the evening of Monday 14 September 2015 I was at home in Canberra, Australia. Around 9.30 pm I received a text message saying that Australia had a new Prime Minister. I was focussed on that when an email came in saying something like "there has been a very interesting event in the LIGO detectors in the last hour". I forgot about the new Prime Minister and was glued to my computer as the story unfolded. It was so exciting that I didn't sleep a wink that night, just like when I was a kid going to bed on Christmas Eve!

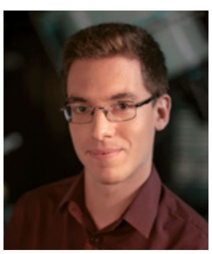


Data from two Glasgow Aluminium bar detectors 5 September 1972. Top and bottom traces are the raw Brownian motion of the two bars and the middle traces are the filtered outputs looking for changes in amplitude or phase.

Tom Dent, University of Santiago de Compostela

It was a normal Hannover Monday until Collin (Capano) put his head around my door looking more startled than usual. Come down to Marco Drago's office - a whole wing of the institute gathered round a monitor showing an undeniable binary black hole merger signal.

Was it real or fake? Badri Krishnan proposed to get pizza delivered and work on it through lunch, but we soon realized it might take weeks to get answers. And the real reward, a first detection announcement, was months later .. though we never did get that pizza.



Gergely Dálya, L2IT, Toulouse

I started my Master's and joined LIGO as an undergrad just two weeks before GW150914. I can't imagine a more thrilling introduction to gravitational waves or large collaborations than diving head-first into such a discovery. The excitement has stayed with me ever since. The hardest part? Not telling my friends what an extraordinary field I had just entered until the official announcement…

Daniel Holz, University of Chicago

It still feels like just yesterday. I remember being woken up by an alert at around 5am Chicago time. I decided it was obviously an injection and not a real event, since it was just too perfect, and went back to sleep. Later, as excitement started to mount, Hsin-Yu Chen and I had the thrill of making the first ever *observational* estimate of the rate of binary black hole mergers. It is incredible how far we've come since that first amazing day. And this is still just the beginning!

Serena Vinciguerra, then University of Birmingham, now RIVM

I remember that at first there was a lot of skepticism, "are these hardware injections?", "we just switched the detectors on… it can't be real!" were some initial thoughts you could hear here and there … and instead what a surprise it was to then reveal they were true!

I remember the excitement around the hallways and the secretive office meetings from that moment on for a few months! Everyone was super busy, it was amazing to be part of such a milestone in the history of astronomy!

For me one of most memorable moments was when the announcement was made after what felt like infinite analyses, discussions and checks! What an emotion to hear from David Reitze pronouncing "we did it!". The excitement and the electric atmosphere in the colloquium room in Birmingham, where we and our astronomer colleagues were watching the event live, was indescribable! And the party that followed was simply amazing as everything it later unlocked! 😊

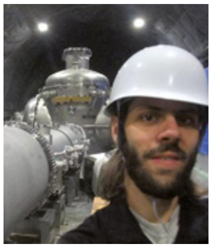
Kent Blackburn, LIGO Laboratory / Caltech

LIGO's first detection of GW150914 happened 30 years after I started by graduate research on binary system of black holes at the University of Florida, 20 years after I began my position as a scientist on LIGO at Caltech, switching coasts after a post at NASA's Goddard Space Flight Center under their HEASARC[1]. Twenty years ago the 40 meter interferometer on the Caltech campus was the place to search for gravitational-waves. I

Kent Blackburn and Rolf Bork at the 40 meter lab (Caltech) circa 1995.

[1] *https://heasarc.gsfc.nasa.gov*

have fond memories of long nights and weekends (and runs to Carl's Jr when we would remember to eat) at the 40 meter, where I was tweaking the data acquisition system to collect some data for student research. The detection of GW150914 after so many decades of personal and professional commitment paused my heart a few beats, allowing a few moments to ponder the trials and tribulations and the rewards of a lifetime hoping to add to Einstein's legacy. With some luck and continued commitment, we can all hope the Universe will provide many more reasons to reflect on the significance of GW150914.



David Keitel, University of the Balearic Islands

In September 2015, I was transitioning between jobs in Hannover and Mallorca, but while travelling I had caught an infection and came down with a high fever. So when all the excitement started, for the first few days I thought it must be just a fever dream!

Derek Davis, University of Rhode Island

I joined the collaboration two days before GW150914, so this is also the tenth anniversary of my research in gravitational waves starting! I recall discussing with my new research advisor days before the event, where he explained that he thought now was the perfect time to start working in the field because the first discovery was just around the corner. I didn't have to wait long to find out this was exactly correct. Ever since then, it's been a fantastic ride as I grew as a scientist alongside the entire field of gravitational-wave astronomy.

Sam Cooper, formerly Birmingham

GW150914 happened on the first day of my PhD, almost to the hour. I remember being confused about all the secrecy within the group as It took a few days for me to join the LSC. Once I joined it became very apparent the magnitude of what had been discovered. It was a privilege to be one for the first to hear about a truly amazing discovery.

Nobuyuki Kanda, NITEP, Osaka Metropolitan University

Three months before the first detection, at GWPAW2015 Osaka, we chatted "this may be the last data analysis workshop without real event data". The 30 solar mass binary black hole detection was predicted, and many people did not consider it so serious at that time... However, these became a reality! Nature suddenly shows us surprising things. So, let's enjoy the observational era and look forward to new wonders brought by gravitational waves!

Ilya Mandel, Monash

"...The system will remain bound, and it will be possible to obtain systems of the type pulsar + pulsar or collapsar + collapsar... Such a possibility should be considered as having low probability, at least for most systems." I had the pleasure of translating this comment from Tutukov & Yungel'son (1973) from Russian as the LVC was writing the GW150914 astrophysics companion paper. The astrophysical uncertainties they identified persist, and set my research agenda for the past ten years. :)

Pia Astone, INFN, Rome

Ten years after the historic discovery of GW150914, which I had the honour to contribute to as part of the LIGO/Virgo collaboration and as a member of the discovery paper writing team, I look back with pride on the years we have dedicated to achieving the extraordinary results we see today. Looking ahead, I foresee a decade of richer detections, deeper cosmological insights, and perhaps the long-awaited observation of continuous waves, all driven by the same passion that marked our first discovery.

Joris van Heijningen, VU Amsterdam / Nikhef

Between September 2015 and February 2016 I spent a few months at KAGRA during my PhD. My Japanese colleagues were not part of the LIGO-Virgo collaboration so I could not discuss anything about GW150914 with them, which was very frustrating. I remember reading many versions of the detection paper on a phone in a corner of the car from Toyama to the KAGRA site. Later I understood that some of the Japanese data folk had found it themselves, but I took my task of confidentiality seriously.

Aurore Simonnet EdEon STEM Learning, Sonoma State University
I was honored to be asked to create illustrations for the first LIGO observation and discovery. Of course, I was instructed to keep it all quiet until the big announcement. So in order to be able to share files without giving away a hint about the discovery, I invented my own "Secret file name: Project Closepeen" - as in clothespins but spelt completely differently to make it even harder to figure out and decipher! Where did that name choice come from you may ask? I am not sure; it just came to me...let's put it in the artists' wild imagination bag :-) Anyway, this became an amusing 'spy game' for me, and made me smile each time I worked on it!

The announcement: "We did it!"

After months of checking, double checking and triple checking, on 11th February 2016 it was time to share GW150914 with the world.

David Reitze, LIGO Laboratory, CalTech
"I have the distinct pleasure of informing you that LIGO's vision has finally been realized. We're here to report on humanity's first detection of gravitational waves arriving at earth from the distant universe."

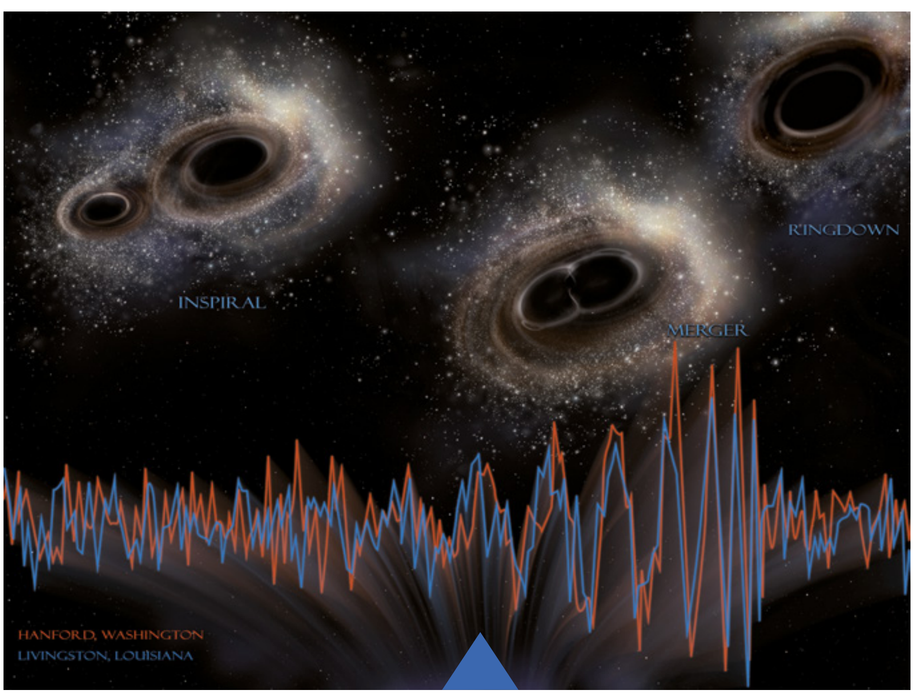
If the press conference announcing the first detection had been on February 8, this is how I would have opened. An accurate description for sure, but a little stilted and heavy, no? Well, that's what I kept thinking, too. At the in-person rehearsal held at the NSF on February 10 the day before the press conference, I stumbled and bumbled through the remarks I'd prepared. But I really wasn't feeling it. One of the press officers later asked me "What are you really trying to say?" I thought about it for a second and said "We detected gravitational waves. We did it. That's the message". She said "Well, that's a good way to start!".

Seems hard to believe that ten years have passed, but we did it!

Nicolas Arnaud, CNRS/IN2P3
Five months. Quite a long time looking 10 years backward, but also such a short period while living it. Five months that have changed everything, from the cautious (and possibly incredulous) e-mail statement "cWB has put on GraceDB a very interesting event in the last hour" to the relief speech "We did it"! There are not many events in someone's life that set such clear boundaries that time is then measured before and after them. But GW150914 was definitely one of them.

Margaret Johnston
I was a bright-eyed first year university student when news of the first gravitational wave detection was released. It seemed too amazing and impressive to be real! I am so grateful and proud to contribute to this field.

Graeme Eddolls, Glasgow, Syracuse, Goddard
I will never forget the day I sat down, with my industry colleagues gathered round, to watch the announcement of the detection. I barely knew at the time how much my alma mater, the University of



Artist's impression of GW150914 by Aurore Simonet.

Glasgow, was involved in the detection and when I saw that announcement I knew I had to be involved. Ever since, I've been able to work with some of the most talented, dedicated, knowledgeable and kind people, towards this common goal. And ever since, I try my best to appreciate how lucky I am to do so.

Catalina Miritescu, IFAE Barcelona
I was a sophomore at Caltech, majoring in Astrophysics. I just finished pulling an all-nighter working on a problem set and was heading towards the kitchen to grab a snack before bed, when passing through the common room in Ricketts I saw the live announcement of the first gravitational waves detection. Wild to think that, fast forward almost ten years, I'm now in the final year of my PhD... studying gravitational waves!

Hiroyuki Nakano
Ryukoku University
On the eve of GW150914, Japan was abuzz with binary mergers of 30-30 solar-mass black holes. The mass band important for the verification of general relativity by Kanda's analysis (arXiv:1112.3092) and that of binary black holes of Population III origin by Kinugawa et al. (arXiv:1402.6672) were showing just them. I still remember LIGO Laboratory Director, David Reitze's "We did it!" and acknowledgement to the taxpayers at the press conference. Happy 10th anniversary, GW150914!

Karl Wette,
then AEI, now ANU
The day of the announcement was exciting! I had to leave dinner early to go back to the office to do an interview with a New Zealand radio station, only to be told that they'd already found someone called R. Kerr who "did something similar to us back in the 70s" ... upstaged! Still, made it back for the post-dinner drinks.

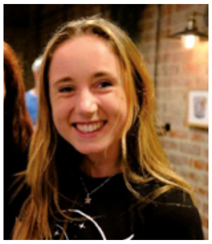
Oliver Gerberding, University of Hamburg
I had just returned to AEI and the research field of GWD in summer 2015, working mostly on LISA and other space missions, when the rumor started to spread slowly through the institute. It was a crazy time since we were all already anxiously awaiting the LISA Pathfinder launch and it was just amazing how many good news the whole field collected in the following months. I joined the LVK about 5 years later and I am still impressed by the excellent environment and science. Congratulations to all!

Purnima Narayan, University of Mississippi
While I was finishing my bachelor's and unsure of my next steps, the first gravitational wave detection made headlines. Coincidentally, around the same time, I had to present a poster on India's contribution to this detection for an outreach event. Curious, I started reading and it was love at first read! Since then, I've been working on gravitational-wave data analysis, using this new cosmic messenger to test gravity and explore new physics. Writing this is a reminder that all it takes is a moment – the right idea at the right time to find your path.

Alexandra Mitchell,
Stanford University
Despite being a student with very little idea about gravitational waves at the time of the first detection, the buzz around the announcement was impossible to miss. Since then, that moment has profoundly shaped my career and sparked my passion for the field. It is a privilege to celebrate this anniversary, whilst looking ahead to the exciting discoveries still to come.

Hisaaki Shinkai, Osaka Inst. Tech.
The first news for KAGRA people came via the youtube broadcasting on February 11, 2016. The next day, one newspaper asked me how I felt since I wrote a book on gravitational waves for general audiences in late 2015. I answered that I was excited because the story was what we had expected, especially that I was surprised by the waveform, and the impact of the news since all those analyses had been developed by researchers in many years. I explained that our science direction was right. The editor of the newspaper tried to summarize in one phrase; "I was surprised since it was what I expected." My wife (not a physics person at all) got upset when she found this comment and said, "I am confused why you are surprised

on what you have expected". I wrote another essay on this.



Isobel Romero-Shaw, University of Cambridge, University of Bristol, Cardiff University

In February 2016, I was an undergraduate student in Physics at the University of Birmingham, working on an essay project where we could choose to write about "any physics topic". Because I'd not heard of them before, and they sounded interesting, I chose gravitational waves. At the time, the general public - including me - had no idea whether LIGO had detected anything, so I wrote this whole essay about future gravitational-wave detection prospects.

Something like three days before the essay deadline, I printed my work out and carried it with me into the University, intending to submit it that day. Before I submitted it, though, I went to watch an announcement that was being made to the whole School of Physics and Astronomy. I remember that the room that had been booked for the announcement was totally full of people. The atmosphere was buzzing with anticipation.
Then the announcement was made: gravitational waves had been detected for the first time! It was very exciting - but of course, I had to go home and rewrite my essay. I think that experience of working on a topic that was actively making advances in real time sparked my determination to work in this field.

Betsy Weaver working at HAM7 LHO ~20ish years ago, days before the birth of Theo.

Betsy Weaver

Ok, maybe a tad longer than 10 years ago, but... While this year is a celebration of the decade of gravitational-wave detections, it is monumental to me in more ways than one. This year I also "celebrate" the graduation of my second and last child from high school and officially enter the empty-nester segment of life. This decade flew by fast - those detections came fast and furious, and the LIGO teams paralleled the detectors, growing into complex and amazing systems. The decade before flew by fast for me also, helping to launch iLIGO into aLIGO and also bring 2 wonderful children into the world. So many good memories of my 25 years at LIGO (and the countless and continuing hours spent inside the detector in a bunny suit. Of varying sizes.)

Storm Colloms, University of Glasgow

I was a highschooler at the time of the first detection, and I remember attending a public outreach event by Martin Hendry organised through Cafe Scientifique about gravitational waves and GW150914. I don't think I had grasped the decades of work that had gone into this discovery at the time, but after starting my undergraduate degree and witnessing other massive feats of science like the direct image of Messier 87* with the Event Horizon Telescope, I had developed an excitement for black hole astrophysics. The initial gravitational wave outreach event helped me recognise the science projects advertised for the LIGO SURF program at Caltech which I did in summer 2021, and now I have come full circle back to Glasgow for my PhD.

Panagiota Kolitsidou, University of Birmingham

The first detection took place while I was still an undergraduate student at Aristotle University of Thessaloniki, before I joined LIGO. There was a lot of excitement in the astronomy department about the upcoming announcement and my then-supervisor, Nikos Stergioulas, organised a special event at the Observatory, setting up a TV in one of the lecture rooms so we could all watch it live. Many of us attended, and there was cheering and a real sense of celebration!

In Greece, we were not always as closely involved with large international collaborations, and just watching the announcement and witnessing this historic moment firsthand gave me, for the first time, a sense of belonging to the global scientific community. That moment stayed with me and made me even more determined to work on gravitational waves.

Gabriela Conde Saavedra, Instituto Nacional de Pesquisas Espaciais (INPE)

I became interested in gravitational waves thanks to Gabriela González's talks. I was working as a lecturer at a university in my city, La Paz, Bolivia, when I first heard about the GW150914 discovery. Gabriela's enthusiasm and passion caught my attention, and I started searching for more information. I learned that gravitational radiation is produced in extreme events and involves fascinating objects like black holes and neutron stars.

At that time, I held a master's degree in astronomy, but I had put my PhD plans on hold because I wasn't sure I wanted to keep working on galaxies. After finishing my master's, I returned to my country and started teaching at the university. I had stepped away from astrophysics, but the interest never truly left me and when the first gravitational wave announcements started becoming more popular, that spark reignited. I began to seriously consider the possibility of doing a PhD in gravitational waves. It felt like a huge challenge, not only because I had no background in general relativity, but also because of my age.

Then, one opportunity came after another, until I found out that there were research groups in Brazil working on gravitational waves, and they didn't have age restrictions for PhD students. That was such good news! The timing was perfect. I participated in the selection process at the Instituto Nacional de Pesquisas Espaciais and was awarded a scholarship in 2021.

So, ten years after the first detection, I'm in the final phase of my PhD. I don't consider myself an expert in gravitational waves, not at all! I may have lots of questions, but absolutely no regrets. My life has been deeply enriched by this experience. Most importantly, I've met incredible, lifelong friends.

Some people may have high expectations, like being famous, winning a Nobel Prize or saving the world (though we really do need to save our planet). But there are also people who just want to understand the universe a little better. That might seem impractical, or even useless to some, and that's okay. All in all, the best side of humanity is expressed through arts and science.

Hartmut Grote, Cardiff University

In the summer of 2015, I had left work at the GEO600 site to work for a year at LIGO, not exactly knowing what to do after that. The detections of 2015 and beyond opened up new possibilities for many of us. So it happened that starting 2018, I changed path from a staff scientist at a Max Planck institute in Germany to become a faculty member at Cardiff University. In Cardiff, Katherine Dooley and I began setting up a new lab for experimental gravitational-

Kip Thorne at the opening of the Cardiff lab in 2019.

wave and fundamental physics. Keiko Kokeyama joined us in 2021.

We now have three labs and a thriving research program, which surely would not have happened without the detections. And BTW: Let's not forget we would all not be here without the existence of gravitational waves, as recently pointed out by Bernard Schutz and others: Heavy elements, many of them from binary neutron star inspirals, decay on planet Earth and keep the engine of plate tectonics and thus evolution humming.

Happy anniversary GW150914, and thank you for existing!

Henry, Wai Yin Wong, CUHK

The progress in gravitational-wave astronomy over the past decade has been truly remarkable. I believe we will see a significant expansion in multi-messenger astronomy over the next decade, driven by the increased combined use of gravitational-wave detectors and other astronomical observatories. Joint observations will enable access to many more exciting scientific avenues, definitely excited about it!

Barry Barish, CalTech

The success of LIGO, from our first observation to our recently discovered event having a final black hole 220 times the mass of our sun, has resulted directly from the technical and scientific skills and contributions of the LIGO Lab and LSC. Personally, it is both humbling and exciting to be part of our great adventure.

Kip Thorne, CalTech

LIGO's announcement of GW150914 ten years ago marked the birth of gravitational wave astronomy, which I expect will revolutionize our understanding of the universe over the coming decades and centuries. I thank the younger generations of LIGO and Virgo scientists and engineers, from the bottom of my heart, for the outstanding way that you are converting our dreams into reality and are carrying us into this wonderful future.

Rai Weiss, MIT

I wish that Science was considered more favorably by the present administration. I hear of one story after the

Barry Barish, Rai Weiss and Kip Thorne after their Nobel Prize lectures at the Aula Magna (Great Auditorium) in Stockholm University.

other; long running research important for all of us, not just the United States, has been halted. Some projects have lost skilled scientists and technicians that it will take many years to retrain. It could even happen to LIGO. Unbelievable as it might be after starting a new field of gravitational wave astronomy. Not a sensible decadal consequence but a possible outcome.

Fulvio Ricci, Sapienza Università di Roma & INFN Roma

The first detection of gravitational waves was more than just confirmation that Einstein was right — it marked the opening of a new window to explore the dark side of the universe.

Ten years later, we have no doubt: the LIGO-Virgo-KAGRA network is detecting a multitude of gravitational wave signals emitted by binary black holes. These previously invisible populations of black hole binaries are now being probed, allowing us to infer their mass, spin, and redshift distributions from gravitational wave observations.

The future of the LIGO-Virgo-KAGRA collaboration is bright. Many more groundbreaking discoveries are expected, just as we saw with the landmark event GW170817.

Divyajyoti Cardiff University

Due to COVID-19, a lot of career counselling sessions were cancelled in schools in India. In 2021, while things were still returning to normalcy, I got the opportunity to conduct an online session for school students in Chennai. It was a wonderful experience as a PhD student to explain difficult concepts to them in ways that they could understand. It also helped me look at the big picture, 6 years after the first detection, and think about where the field of GW is going in the coming decade.

Jess McIver, UBC

Over the last ten years it has been amazing to see many references to gravitational waves in popular media and science textbooks. We are still benefiting from an extremely successful education campaign powered by media designed by the LIGO and Virgo public outreach teams that communicated our science so well for GW150914. With each subsequent detection gravitational waves have continued to spark the public's interest. I hope that our community can channel these previous messaging successes to make a strong case for the discovery potential of future gravitational-wave observations.

Giovanni Losurdo, Scuola Normale Superiore & INFN Pisa

For over twenty years, we faced the enormous challenge of designing, building, and understanding instruments that did not yet exist, machines capable of listening to the faintest whispers of the cosmos.
And then, it happened.

The window opened. And what we glimpse through it is astonishing. A global community of researchers joined forces to push the boundaries of knowledge a bit further. And today, we can look a black hole in the eye.

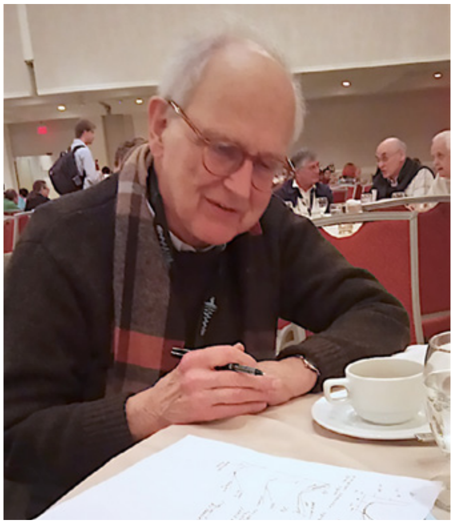
It has been, and still is, "an act of beauty, a peak of human ingenuity".

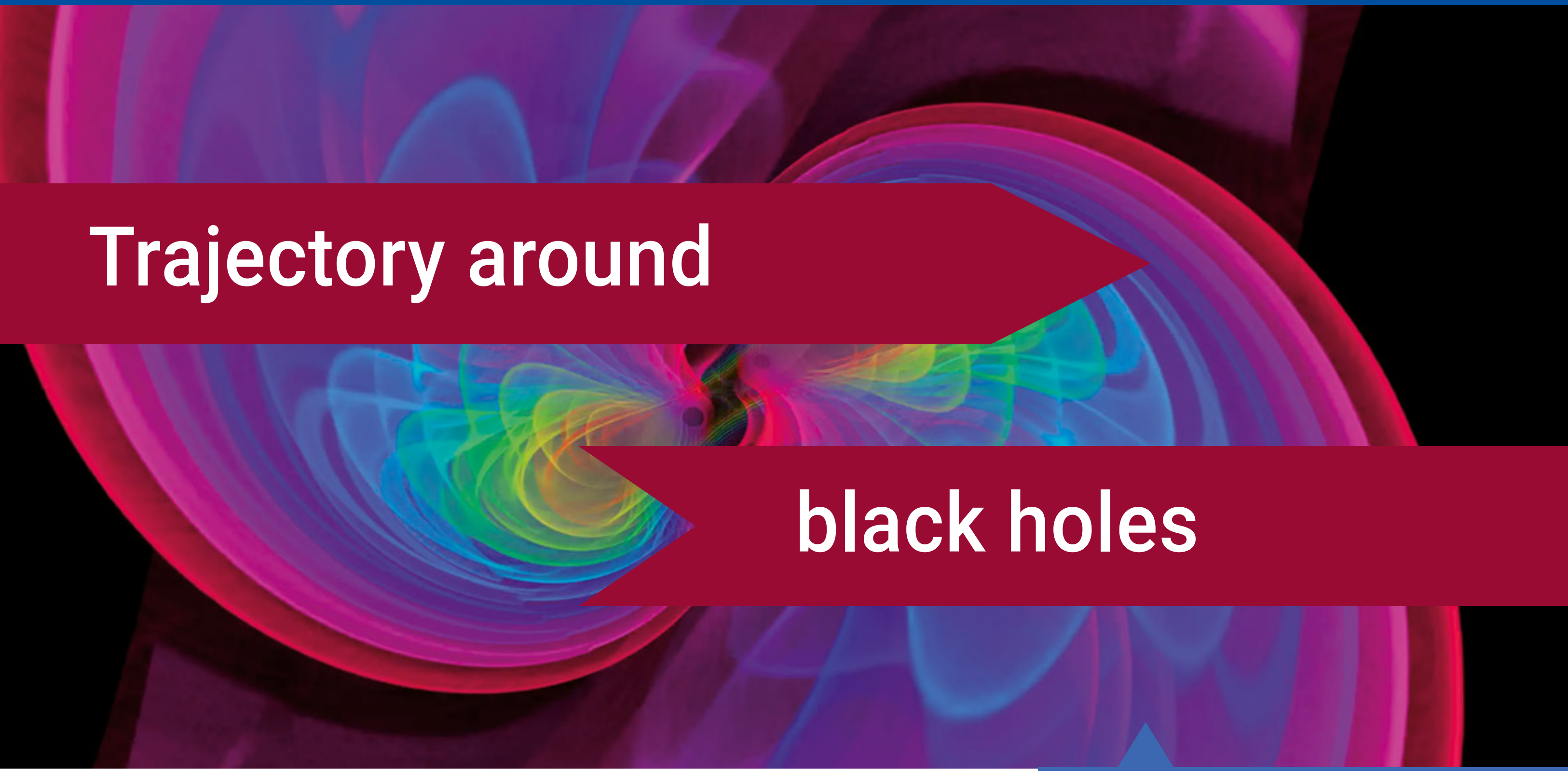
Dedicated to Rai Weiss

who passed on 25th August 2025.

It is no exaggeration to say that we work in this wonderful field of gravitational-wave science today because Rai not only had the brilliant insight in 1972 to lay out a design for gravitational-wave interferometric detector that would eventually become LIGO, but also because he had the passion and dedication to bring LIGO to fruition. As a scientist and as a mentor, Rai touched many of us in many ways and had a profound influence on everyone around him. He leaves behind a wonderful legacy but also a deep void today.

- David Reitze, for the LVK -

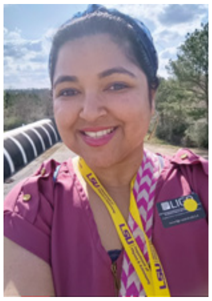




Trajectory around black holes

Numerical-relativity simulation of GW150914 - the first binary black-hole merger observed by the Advanced LIGO detector on September 14, 2015. The two inspiralling black holes merged to form a new black hole. Shown are the black hole horizons, the strong gravitational field surrounding the black holes, and the gravitational waves produced.

Debnandini Mukherjee



is a research fellow at the University of Birmingham. She works in the area of gravitational wave data analysis with the LVK collaboration, with a focus on searches for intermediate mass black hole binaries. She also works with the LISA consortium, on developing searches for massive black holes. Outside of her research, she enjoys writing, poetry and belly dancing. Horror, supernatural and detective are her favourite genres.

When David Reitze declared LIGO had found gravitational waves, in the wake of GW150914, I was in the early years of my PhD at the University of Wisconsin Milwaukee. Everyone in our group was sitting together watching the press release and also hosting one locally at our department. This came at the end of several weeks of secrecy over our results, hushed voices in the corridors about a Nobel worthy discovery, being discreet when discussing our research, the hush hush, the confidentiality to prevent scooping, I was taking it all in, partially overwhelmed, partially super excited. My friends from other groups would probe..but I told them nothing! I felt like the keeper of great secrets.. an incognito witch among muggles! It felt like being in an espionage movie, facing the press, having photos taken! I never thought that a PhD would be so exciting!

Actually my introduction to black holes did not begin with GW150914 or even during university courses. It started many years earlier, when I was in 6th grade. It was a long train ride from my then home town Asansol, to Kolkata, where my parents were originally from. Every year we made the annual “pilgrimage” to Kolkata to celebrate our fall holidays with our relatives. It was a four hour train ride taking us from the industrial districts towards the massive urban megacity close to the vast Gangetic delta. We used to subscribe to a children’s magazine in Bengali, by the name of Anandamela from the famous and revered Kolkata based Ananda Publishers. The magazine contained a fairly diverse collection of articles on science, humanities, education, comic strips, science fiction, detective novels, anything that the teens and young adults of Bengal were growing up on those days. So it contained a large part of my childhood. The issue I was reading on that specific fall day of the train ride, had two main articles. One on black holes, telling us how they suck everything in and one on Y2K, telling us how that would wipe everything out. The cover had a picture of a large black spot with a ring around it and a picture of a CRT computer monitor that seemed to be crashing. I read both articles. Both seemed to be shady hoaxes to me. My uncle, who loved all conspiracy theories, kept going on about them the entire summer.

I grew up in a small industrial town in the state of West Bengal in the eastern part of India. My parents settled there because of my fathers job as a mining engineer. I was born in and grew up around coal mining towns. In India, in my generation, the usual career expectations were engineering, medical doctor or lawyer. People expected me to be an engineer. My inspiration was my school physics teacher. Having a PhD, especially as a woman, was a very big deal in my small town, so she was deeply respected. So when most students in my cohort joined coachings to train for the engineering and medical college entrance exams, I resisted. My school called my parents and tried to convince them how not doing engineering or medicine would ruin my career. But I was stubborn and was fighting the bandwagon. After school, I started college as a physics major at the University of Delhi. After a bachelor's and a masters, I eventually moved to the University of Wisconsin Milwaukee for a PhD.

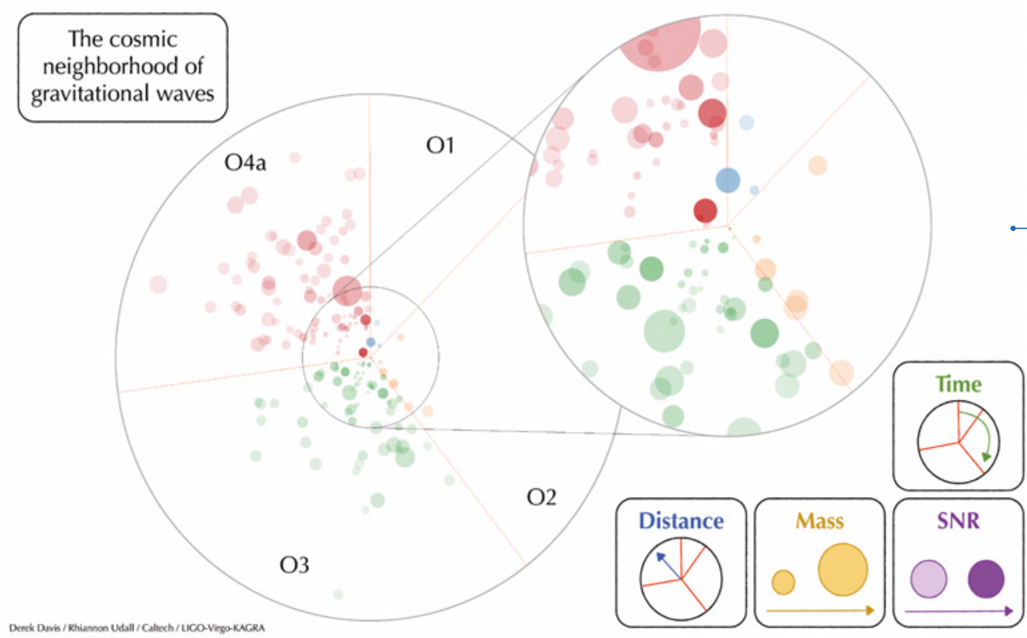
My initial intention during my masters was to go into theoretical physics. I trained in rigorous calculations of QFT, QED, QCD and Particle Physics I had almost decided to join CERN. That's when I heard my friends who were taking GR, talk about the LIGO experiment. Again it sounded very ambitious, almost overly hopeful.

Weeks of secrecy over our results, hushed voices in the corridors about a Nobel worthy discovery, secrecy to prevent scooping. I was taking it all in, partially overwhelmed, partially super excited.

But I read about it more and it grew on me. It either felt like a genius experiment or something headed towards an expensive failure. Soon we had a postdoc at our department at the University of Delhi, who told us about data analysis, parameter estimation etc.. and I was curious. I applied for a PhD to departments that had a gravitational wave group.

I started working on searches for intermediate mass black holes (IMBHs). When I took my preliminary hearing during my PhD, proposing to look for IMBHs, I heard very learned opinions like black holes with masses more than a hundred solar masses cannot exist at all. Even if they do, LIGO would never find them. I heard, got scared about my future prospects, kept at it. LIGO saw no such IMBHs in the initial two runs. But things changed in the 3rd observation run and we detected GW190521 with an IMBH remnant. The 4th observing run has brought us another clear IMBH event GW231123. I hope those who thought these massive black holes don't exist or can't be detected like being proved wrong! We are living through an exciting time of many discoveries and advancements in the field, but also through a time of great chaos in the world. In the meantime life has shown me a lot, from black coal to black holes. I hope it continues.

Visiting LIGO Livingston.



The graphic shows mass, signal-to-noise ratio (SNR), and luminosity distance of gravitational-wave events. Also known as the "petri dish plot".

GWTC-4.0 Catalog Paper

An important moment for LIGO-Virgo-KAGRA

The fourth gravitational-wave catalog (GWTC-4.0) presents the mergers of black holes and neutron stars seen by the LIGO, Virgo and KAGRA (LVK) gravitational-wave detectors. It specifically introduces the new gravitational-wave signals observed between May 2023 and January 2024. The detectors operate in long chunks of time, called 'observing runs', between which they are taken offline, upgraded, and improved. So this catalog's timespan represents black hole and neutron star mergers seen in the first part of the fourth LVK observing run. If I had to describe it in one sentence, I would say this paper is a 'one-stop shop for all the details about brand new gravitational waves from merging black holes and neutron stars'. It describes how we found the signals, how we vetted them, and how we analysed them to infer information about the black holes and neutron stars they came from.

Lucy M Thomas (she/her)

is a postdoctoral researcher at the LIGO Laboratory, California Institute of Technology, working on gravitational waveform modelling and parameter estimation of compact binaries. She loves to sing, paint and is on a lifelong quest to bake the perfect cookie recipe.

This catalog's publication is an incredibly important moment for the LVK collaboration and for me personally. It is the culmination of more than two years of work from many hundreds of people who, at every stage of identifying and investigating the gravitational waves, have worked together in sync to make this amazing achievement happen. For me, the most rewarding aspect was to see all the results collated for the first time, and the process of deciding what we wanted to tell the world about them in our catalog paper. Being a part of all this data coming to life as figures and words on a page has been incredibly inspiring.

For Lucy, the most exciting events are the ones we didn't realise were interesting until we started this process of combing through the vast amounts of data to build the catalog paper. Combing through and unpicking the puzzles that these merging black holes and neutron stars have provided is something she will never tire of. She recommends checking out GW231028_153006, a merger of two heavy black holes that are highly spinning, and are probably themselves the product of previous black hole mergers!

Collaborating with all these hundreds of people is sometimes as tricky as it sounds! Scheduling around time zones, full calendars, and attending meetings and presentations at 7 am – it can sometimes feel as though you're one tiny cog in a machine that never sleeps. But it's also a huge privilege, and having so many people available to help you at any time of day, all of whom are experts in their field, is wonderful. The fact that everybody's really friendly is an added bonus! At each stage of pulling together this catalog, we were constantly exchanging messages within teams assigned to work on different aspects of the project, and regularly presenting our findings to larger audiences within the collaboration for feedback. This helped to ensure that, at every stage, we were truly writing a paper by and for the hundreds of people in the LVK collaboration. In a world where rifts and division are becoming the norm, I've never been more proud of the way we've joined forces as individual researchers, institutions, countries, and labs to create some spectacular science.

- Lucy Thomas -

Combing through and unpicking the puzzles that these merging black holes and neutron stars have provided is something I will never tire of.

Overcoming obstacles

Pulling together a paper like the GWTC-4.0 catalog is a mammoth effort for the collaboration, with datasets and analyses being contributed from groups all across the world. Coordinating all of these, and making sure that everything is ready and in the right place for further analyses, might not be the most exciting job we do as a collaboration, but it's one we do really well, and it's what allows us to put together such a large and complex publication.

We solve some of these problems by automating repetitive tasks which might introduce errors into the process, but lots of steps still demand the expertise of human scientists, and hundreds of people have been involved in various stages of analysing, reviewing, and verifying software and data, from calibration, to event validation and detector characterisation, to the searches which find out triggers, and of course, working out the properties of the black holes and neutron stars we're observing by performing parameter estimation.

Daniel Williams is a Research Fellow in the IGR at the University of Glasgow. He enjoys finding ways to make the complicated analyses required by gravitational-wave science easier to run, and easier to reproduce. When he's not doing science you can often find him running up mountains, talking about mountains, or writing about mountains (he wrote this bio while he was sitting at the bottom of a mountain).

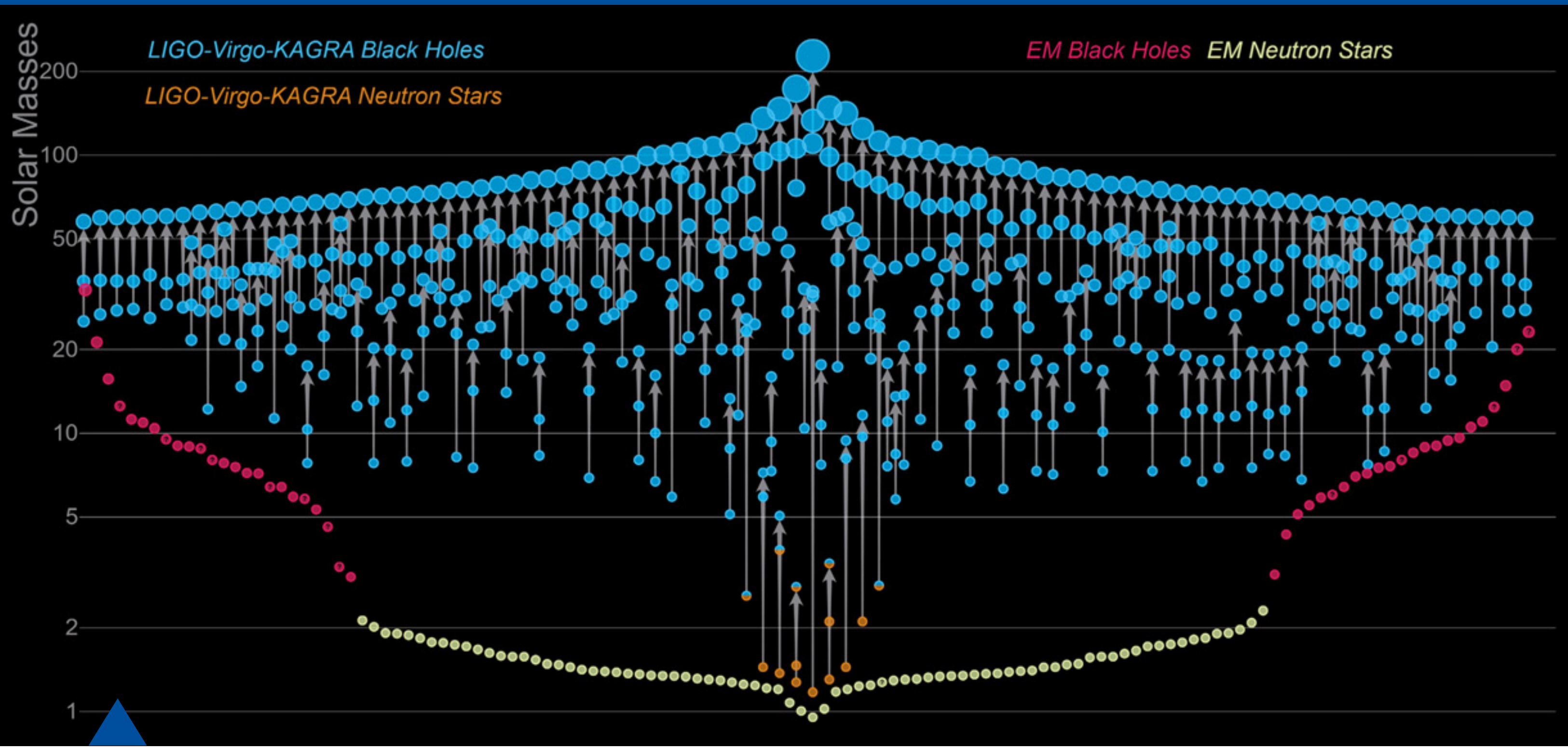
One of the biggest challenges we ran into when preparing the results for this paper was the discovery of a couple of bugs in the code we use to perform the detailed analysis. These were bad enough that we had to re-do all of the analysis. Unfortunately, we spotted one bug about a month after spotting the first, and we had to re-do everything twice! Fortunately, we spent a lot of time between the end of the third observing run and the start of the fourth observing run making powerful tools to allow us to do this quickly, and we were able to fix things without too much delay, while making sure we're releasing the most accurate results we can.

Daniel really struggles to choose a favourite event as he has spent so much time with them all in the last year that it feels a bit like choosing a favourite child! However, if he has to choose he'll go with GW231224_024321, because we detected it on Christmas Eve: who doesn't want a black hole merger for Christmas?

GWTC-4.0 contains almost as many events as we've observed in the previous three observing runs combined. Imagine trying to distil all of the highlights of the first three runs into one paper!

Despite all of this automation, and having such a large team pulling together to deliver everything we need, the paper itself has been

A one-stop shop for new gravitational waves



Masses of announced gravitational-wave detections and black holes and neutron stars previously constrained through electromagnetic observations.

an exciting challenge. GWTC-4.0 contains almost as many events as we've observed in the previous three observing runs combined. Imagine trying to distil all of the highlights of the first three runs into one paper! That's pretty much what our task has been this time, while the Universe continues to throw us fascinating new events like GW231123_135430 and GW230814_230901, which are all competing for the limelight.

- Daniel Williams -

What we found

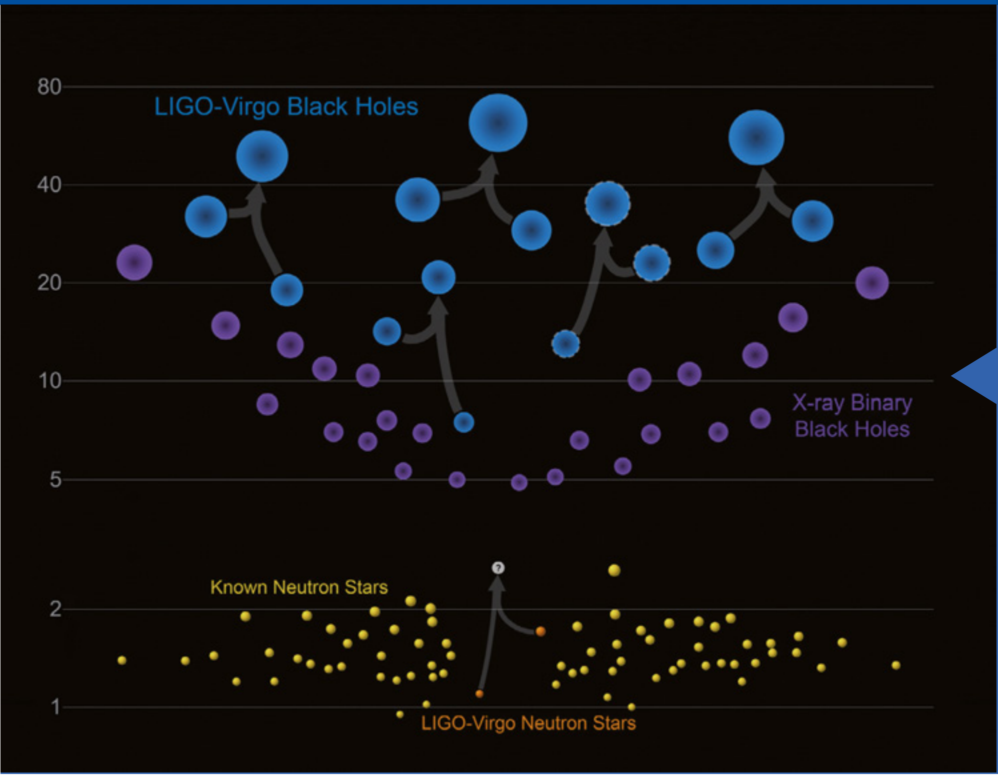
In GWTC-4.0, which collected results until the end of the first part of the fourth observing run, we made 128 new probable observations consistent with gravitational-wave signals from merging binary black holes and neutron star-black hole binaries. This more than doubles the size of the existing catalog presented in GWTC-3. While most of the new candidates have source properties similar to previous catalogs, there are a few surprises.

For the first time, we've spotted the mergers of several extremely massive pairs of black holes. One such event, GW231123_135430, is particularly noteworthy – it's about 240 times heavier than our sun, making it likely the most massive one we've ever seen. Another pair, GW231028_153006, is also very heavy at around 150 times the mass of our

Michael Pürrer

is a computational scientist and adjunct physics faculty at the University of Rhode Island. He works on applying deep learning techniques to gravitational wave modeling and data analysis. During his leisure time, he likes running, cycling and most of all playing electric guitar and getting lost in the music.

Although Michael doesn't have a clear favorite event in GWTC-4.0, he is excited about very loud mergers, such as GW230814_230901. But this particular event had fairly common properties – the two black holes were about the same mass and they were not spinning fast. He believes it would have been more exciting if the black hole masses had been more unequal and with more spin, so that the system wobbles like a spinning top which leaves imprints in the emitted signals.



The Masses in the Stellar Graveyard plot has gone through many iterations as the number of gravitational-wave observations has grown over the years. This version is from 2017.

Black holes and neutron stars are shown according to their mass (in solar masses) on the vertical axis. The horizontal arrangement of black holes and neutron stars is aesthetic. In blue are the binary black hole mergers detected via gravitational-wave observations. In orange is the gravitational-wave observation of binary neutron star merger, GW170817. Electromagnetic observations of neutron stars and black holes are shown in yellow and purple, respectively.

For an interactive version of the latest Masses in the Stellar Graveyard plot, go to: https://media.ligo.northwestern.edu/gallery/mass-plot

sun. Moreover, the two black holes, which produced GW231028_153006, were spinning very quickly, at about half their maximum possible speed, with much of its spin aligned with its orbit around its partner black hole. This is a unique feature that sets it apart from other black hole binaries we've observed.

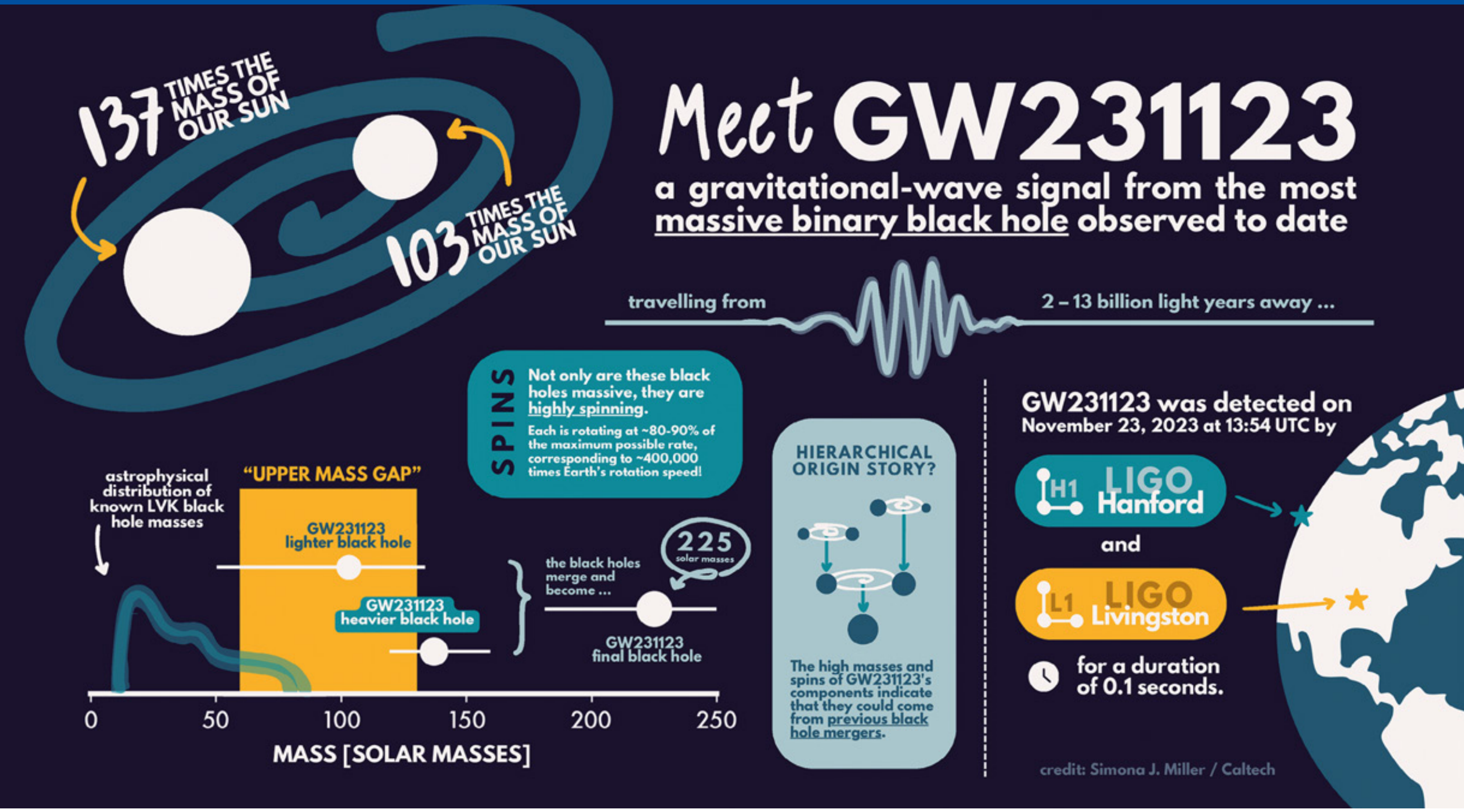
We made 128 new probable observations consistent with gravitational-wave signals from merging binary black holes and neutron star-black hole binaries.

GWTC-4.0 also includes the loudest event detected up to the end of the first part of the fourth observing run, GW230814_230901, for which the useful signal was about 42 times stronger than the background noise, resulting in a very clear signal with very little background noise. This is significantly louder than the previous record holder, GW170817. For very strong signals, even tiny differences in how we model black hole mergers can stand out. Because no single model is perfectly accurate, we used four different models to cross-check and ensure our results are as reliable as possible. In fact, for several new events (including GW231123_135430), we observe noticeable differences in the results depending on which waveform model is used.

While almost all new observations came from black hole binaries, we also detected two likely candidates from the merger of a neutron star and a black hole, GW230518_125908 and GW230529_181500. The black hole in GW230518_125908 is estimated to be almost six times more massive than the neutron star. GW230529_181500 is interesting because its black hole lies in a suspected "gap" in black hole masses between about 3 and 5 times the mass of the sun, where we expect to find very few or no black holes.

During the next observing runs, I think what many of us are really hoping for is to discover another system where two neutron stars, or a neutron star and a black hole, merge while also producing light or other signals we can see with telescopes. This would give us extra clues about what's happening in the universe. Equally exciting would be finding a clear eccentric binary – two black holes orbiting each other in an oval-shaped path – because it would reveal something unique about how the system formed. An eccentric orbit would hint at a more dramatic origin, such as the objects coming together through a collision in a crowded star cluster.

- Michael Pürrer -



GW231123: The most massive black hole merger yet!

LIGO-Virgo-KAGRA have observed the most massive black hole merger yet! This gravitational-wave signal, called GW231123, was observed on the 23rd November 2023 by the LIGO Hanford and LIGO Livingston observatories during the fourth observing run (O4). The previous record holder for the most massive black hole merger was GW190521 (detected in Observing Run 3).

The two black holes that merged were around 137 and 103 times the mass of the Sun. The resulting black hole left after the merger is around 225 times the mass of the Sun. This places these black holes firmly in the category known as intermediate mass black hole.

Here, we chat to Debnandini Mukherjee and Tanmaya Mishra about GW231123's interesting features, how it might have formed, and their experiences of working on the discovery paper.

What makes GW231123 interesting?

Debnandini: The unique aspect of GW231123 is that it is the merger of the heaviest black holes we have observed so far with high confidence. This event is also particularly interesting as the two merging black holes were spinning rapidly – at the maximum amount allowed by physics.

Tanmaya: The detection of the colossal binary black hole merger GW231123 marks a new chapter for the

LIGO-Virgo-KAGRA detectors. This extraordinary event not only allows us to probe the pair-instability mass gap, but also enables us to explore what lies beyond it, all with a single powerful gravitational-wave signal!

You mentioned the mass gap, which is a predicted range of masses which we do not expect black holes to have. Can you explain what causes that gap in the masses?

Debnandini: This mass gap is due to two specific types of supernova explosions. One is the pulsational pair-instability supernova in which a lot of the star's mass is thrown off before it collapses to a black hole below about 60 solar mass. The other is the pair-instability supernova which destabilizes heavy stars and tears them apart leaving no black hole. The combined effect is expected to not allow the creation of black holes in the mass range of about 60 to 130 solar masses. Above this range, the massive progenitor star directly collapses to a black hole.

Tanmaya: According to stellar evolution models, black holes in the mass range 60 to 130 solar masses should not form due to these two supernova processes. Both the merging black holes in GW231123 lie within this mass gap (or the heavier black hole may even lie beyond it).

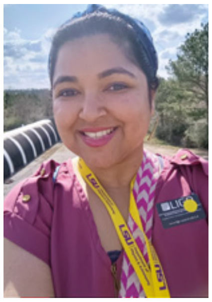
So, what's the story behind the mass of the black holes of GW231123?

Tanmaya: GW231123 challenges traditional stellar evolution theories and is a clear outlier in the binary black hole population observed by LIGO-Virgo-KAGRA. It possibly originates from hierarchical merger scenarios under dense astrophysical environments – this means that the merging black holes were themselves formed by previous mergers of black holes.

Debnandini: The high mass and high spins of these black holes provide crucial information regarding their formation mechanism and formation environment. These clues point to the possibility that the merging black holes formed through subsequent mergers of massive black holes. We have seen the formation of black holes as heavy as the two black holes of GW231123 from gravitational-wave observations made by LIGO-Virgo-KAGRA before. From our observation of GW231123, we can tell that the merging black holes were probably also formed from parent black holes with large spins.

GW231123 not only allows us to probe the pair-instability mass gap, but also enables us to explore what lies beyond it, all with a single powerful gravitational-wave signal!

Debnandini Mukherjee



is a research fellow at the University of Birmingham. She works in the area of gravitational wave data analysis with the LVK collaboration, with a focus on searches for intermediate mass black hole binaries. She also works with the LISA consortium, on developing searches for massive black holes. Outside of her research, she enjoys writing, poetry and belly dancing. Horror, supernatural and detective are her favourite genres.

Tanmaya Mishra

recently completed his PhD at the University of Florida and is joining the University of Portsmouth as a postdoctoral researcher. His research focuses on gravitational-wave data analysis techniques aimed at understanding intermediate-mass black holes. Outside of physics, he enjoys playing guitar, experimenting with new cuisines, and exploring local coffee shops.

There are other mysteries to GW231123, what about testing general relativity?

Tanmaya: The signal exhibits only four or five discernible cycles in the observable band, dominated mostly by the merger and ringdown* phases. This makes GW231123 an ideal case for testing general relativity through black hole spectroscopy. Ringdown studies with minimal assumptions show strong agreement between theoretical predictions and observed data. However, due to the complex morphology of the GW231123 signal, subtle features in the data remain unexplained, hastening the development of improved waveform models and advanced analysis tools.

* *The ringdown is the part of a gravitational-wave signal after the merger has happened. The gravitational-waves fade away as the newly armed black hole settles down, similar to the sound of a bell fading to silence.*

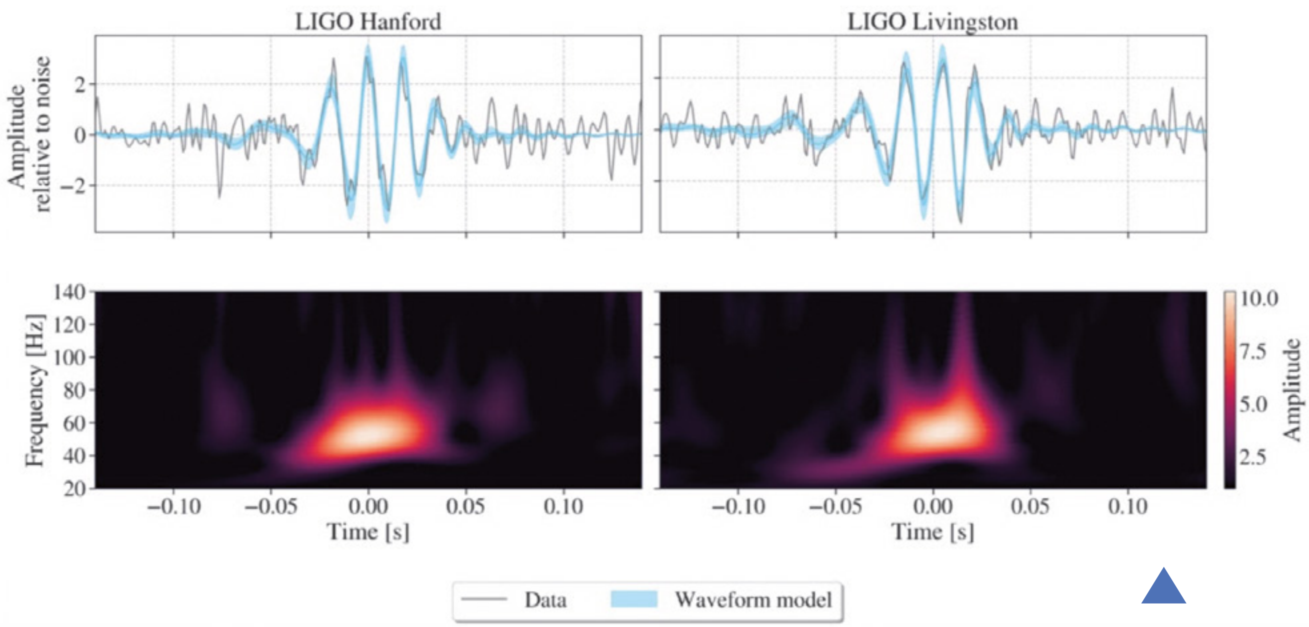
What were you working on in the science investigations for GW231123?
Debnandini: I worked with the search algorithm GstLAL and led the search for intermediate mass black holes and the analysis required for this paper. When searching for signals in gravitational-wave data, we typically use multiple search algorithms. GW231123 was observed most confidently using an algorithm with specialist modifications that are sensitive to heavy mass black hole binaries. Before the paper writing itself, I was also part of the science case study team which was charged with establishing if the trigger was actually a gravitational wave event, distinct from noise artifacts. After that, I became a part of the paper writing team that followed.

Tanmaya: I also first contributed as part of the science case study team, where we investigated the event's astrophysical origin, and I later joined the paper writing team. My primary focus was on establishing GW231123 as a confident detection through significance studies using the cWB search algorithm. Significance studies are used to work out how likely it is that this signal is real as opposed to being caused by random noise fluctuations in the detector data. I also worked on detection comparison studies across all LVK search algorithms.

What was your experience of working in the GW231123 paper writing team?
Debnandini: Typically such special detection papers have to be completed within a specific short time and have to be released before the full catalogue including the more vanilla gravitational wave detections. We are constrained by deadlines set by the collaboration policy for the public release of the data. Complex events like GW231123 are difficult to analyze and so it takes time. We are also constrained by the waveforms available to us which were not showing sufficient agreement because of their limitations in simulating a system like GW231123. Hence we had a busy few months full of analysis, presenting our results on collaboration wide calls and having our work reviewed by other members of the collaboration to ensure accuracy.

Tanmaya: Working on the discovery of the GW231123 event was an incredible experience, marked with a sense of urgency and awe. The experience was both thrilling and humbling, as we worked through multiple calls, navigating waveform inconsistencies, varying detection significances, and exploring alternative formation scenarios and black hole interpretations. Overall, it deepened my appreciation for the vast unknowns involved in detecting gravitational-wave signals from intermediate-mass black holes.

Debnandini: I was collaborating with colleagues in multiple time zones, often requiring me to work well beyond my usual working hours making it somewhat stressful, but that is also quite typical in our line of work. The truth is that each exciting achievement in science has a back story of hard work and stress.



The GW231123 signal in LIGO Hanford (left) and LIGO Livingston (right). The top plots show the signal amplitude over time in grey and the estimated model of the signal in blue. The bottom panels show the time-frequency plots of the signal where brighter colors represent a higher amplitude.

See also the GW231123 item on public reception in the Other News section of "We hear that ... " on p.53

Statement of Support for Gravitational Wave Detectors

Since its inception almost 30 years ago, the Gravitational Wave International Committee has been overseeing the development of the exciting new field of gravitational wave physics.

Gravitational Waves were predicted a century ago by Einstein, and for many decades thought to be undetectable. But with persistent work by thousands of physicists and engineers, gravitational waves were brought within reach. In 1974 the Hulse-Taylor pulsar discovery with NSF-funded Arecibo Observatory demonstrated their existence, resulting in the 1993 Nobel prize for Physics, and spurring the development of the LIGO detectors for gravitational wave discovery.

It was with great joy therefore in 2015 that we witnessed the first direct observation of gravitational waves from the collision of two black holes by the NSF Advanced LIGO detectors in Louisiana and Washington State with the world's largest quantum sensor, opening a new window on Einstein's Universe.

In 2017, the Advanced LIGO detectors in collaboration with the European VIRGO detector witnessed the collision of two neutron stars that coincided with a gamma-ray burst, one of the most significant astrophysical events in history.

Later that year the leaders of the NSF LIGO project received the Nobel Prize for Physics, and individuals and collaborations globally also were given a host of other international awards.

Since 2015 LIGO has detected over 300 sources of gravitational waves, including the merger of the two most massive black holes to date, creating a treasure trove for scientific discovery.

Now, in July 2025, the international community has gathered in Glasgow at GWIC's biannual Amaldi meeting to hear about the latest developments in gravitational wave physics. This includes evidence for gravitational waves from supermassive black holes seen by the NSF-supported NANOGrav collaboration and other Pulsar Timing Arrays around the world, and the LISA space mission, a collaboration between ESA and NASA that will launch in 2035 set to further revolutionise our understanding of the universe.

The promise for transformational scientific discovery in this nascent field is strong, but progress is threatened by proposed cuts to the NSF and NASA budgets.

The committee strongly supports the efforts to preserve the critical financial support which enables progress in science and technology, develops the careers of a generation of scientists and engineers, and maintains the US's central and crucial ongoing role in this new domain of science.

- Professor Matthew Bailes (GWIC chair) - with the unanimous support of the Gravitational Wave International Committee.

The evolution of Gravitation

FUTUR

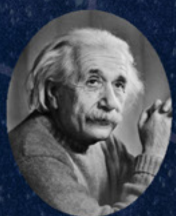
GW astronomy is entering an exciting and
India underway, next-generation ground-bas
and the Einstein Telescope in developmen
Interferometer Space Antenna (LISA) on t
observatories is rapidly expanding. These
boost detector sensitivity, enabling us to
Progress in GW astronomy, together with
observations, can help answer long-standing
violent births of heavy elements to th

1910s

START

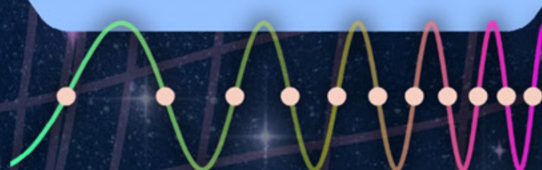
In 1905, Henri Poincaré proposed the existence of GWs propagating at the speed of light, analogous to electromagnetic waves. A decade later, Albert Einstein predicted the existence of GWs as a direct consequence of his theory of general relativity.

$E = mc^2$



1950s

Andrzej Trautman, Ivor Robinson, Felix Pirani, Hermann Bondi, and Richard Feynman developed frameworks showing that GWs are not artifacts of the coordinate system, but instead carry energy and produce measurable physical effects, such as the relative motion of particles.



1978

Russell Hulse and Joseph Taylor discovered a binary pulsar exhibiting orbital decay due to energy loss through GW emission. This observation confirmed the predictions of general relativity and provided the first indirect evidence for the existence of GWs.

Initial dete

The search for GWs began
detectors before adva
interferometry, which then le
LIGO in the 1980s. The initi
Hanford and Livingston, USA
in 1999. Independently, the
developed by a European
inaugurated in 2003. The
began joint observati

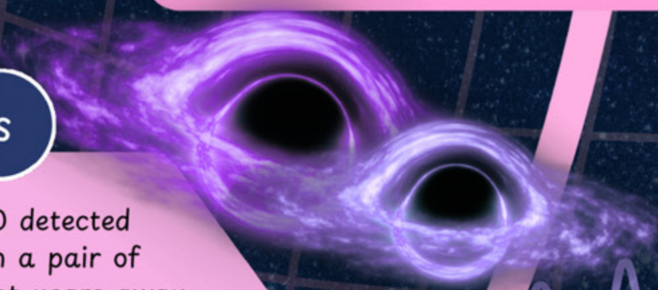
nal-Wave (GW) science

RE

transformative era. With LIGO-
ed detectors like Cosmic Explorer
t, and the space-based Laser
he horizon, the network of GW
advancements will significantly
probe deeper into the cosmos.
electromagnetic and neutrino
astrophysical questions, from the
he nature of dark matter.

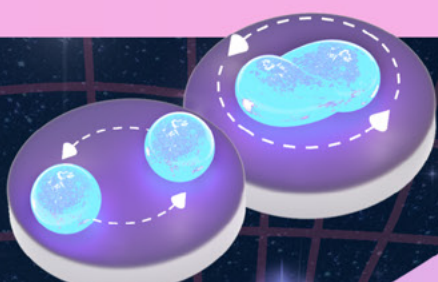
10 years of GWs

GWs have enabled the study of obscured astrophysical sources and interiors previously inaccessible to electromagnetic observations. So far, the LIGO-Virgo-KAGRA collaboration has detected over 300 GW events, confirming key predictions of general relativity, revealing intermediate-mass black holes, and offering new insights into black hole formation and populations.



First detections

On September 14 2015, LIGO detected GW150914, a GW signal from a pair of merging black holes 1.3 billion light-years away, marking the first direct observation of GW. Two years later, the joint LIGO-Virgo network detected GW170817, the first GW signal from a pair of merging neutron stars, accompanied by multiple electromagnetic counterparts.



ectors

with resonant-bar
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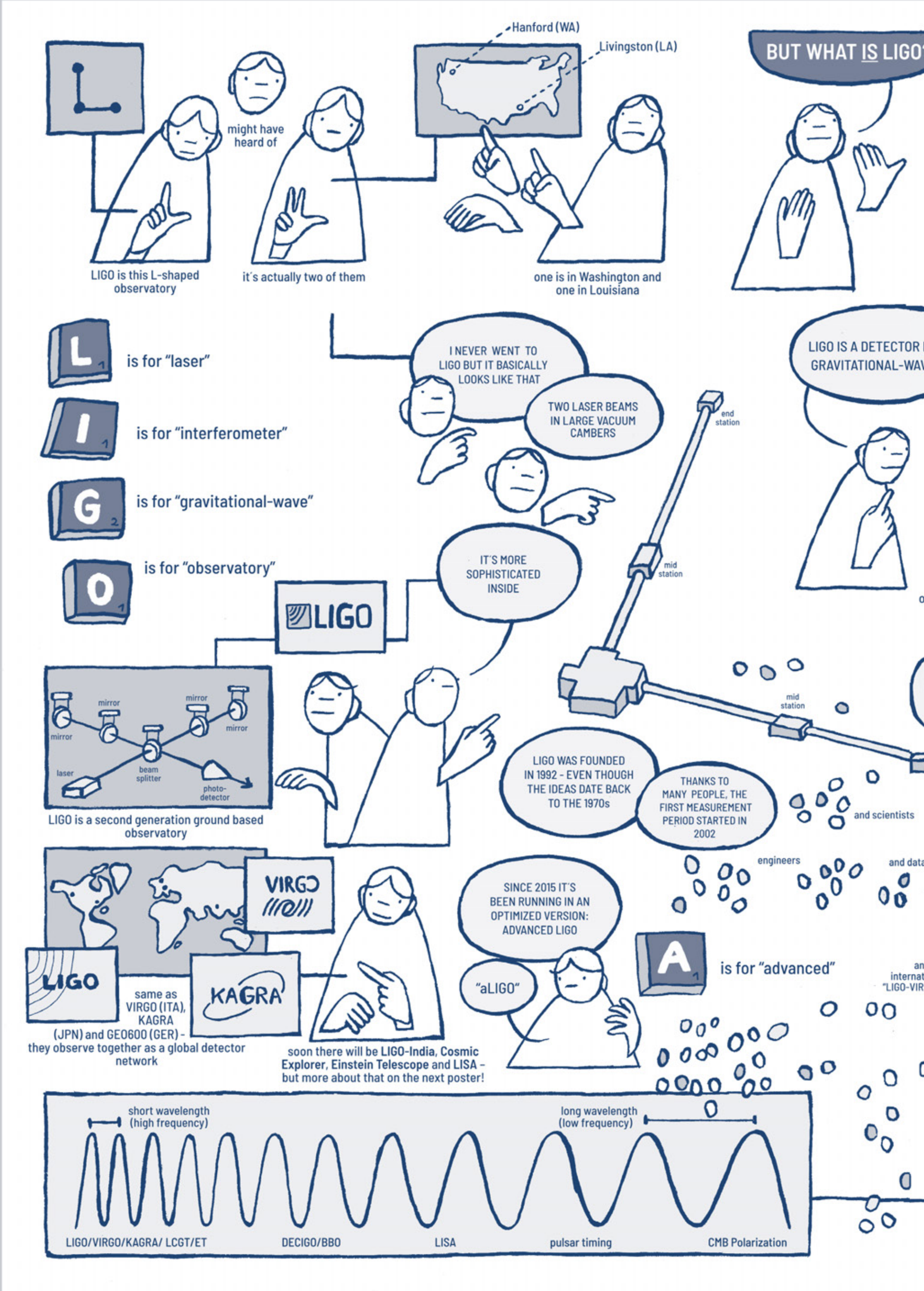
ed to the founding of
al LIGO detectors in
A, were inaugurated
Virgo project was
collaboration and
two observatories
ons in 2007.

Advanced detectors

In the 2010s, LIGO and Virgo underwent major upgrades. With increased laser power and noise isolation, sensitivities of Advanced LIGO and Virgo were enhanced tenfold, enabling detection of GWs from more distant sources. In parallel, the cryogenic KAGRA detector was being commissioned in Japan.

credit: Yi Shuen Christine Lee / Carl Knox / OzGrav

View the poster at https://dcc.ligo.org/G2501957/public

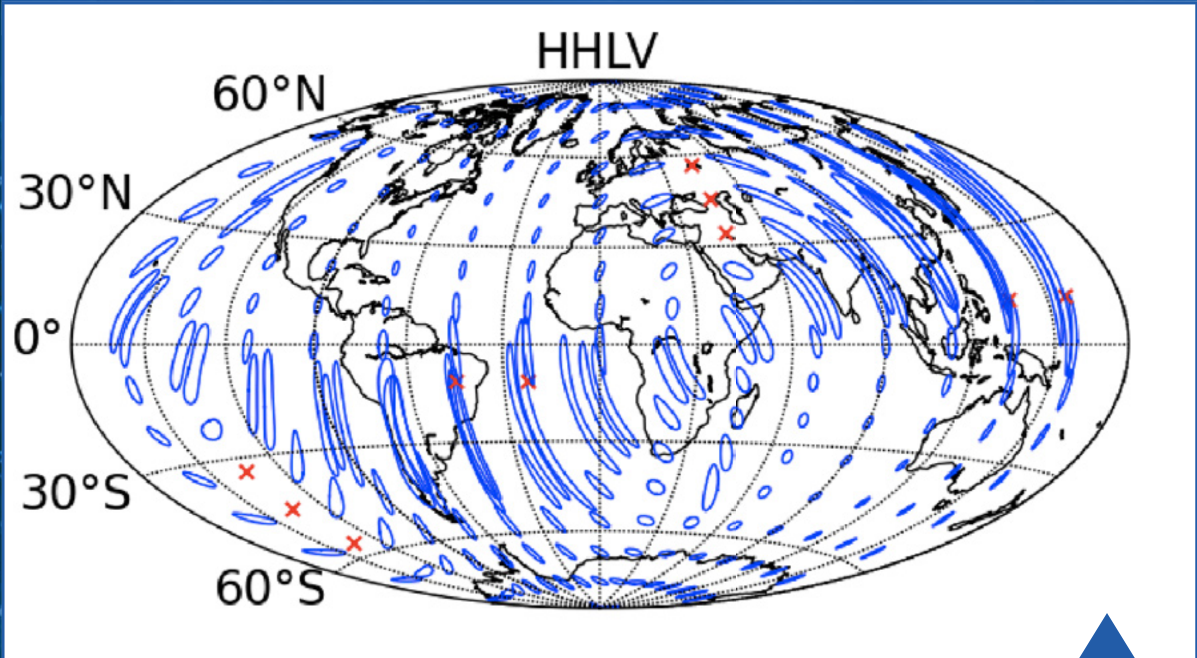


Hanford (WA)
Livingston (LA)
BUT WHAT IS LIGO
might have heard of
LIGO is this L-shaped observatory
it´s actually two of them
one is in Washington and one in Louisiana
LIGO IS A DETECTOR
L is for "laser"
I is for "interferometer"
G is for "gravitational-wave"
O is for "observatory"
I NEVER WENT TO LIGO BUT IT BASICALLY LOOKS LIKE THAT
TWO LASER BEAMS IN LARGE VACUUM CAMBERS
end station
mid station
IT´S MORE SOPHISTICATED INSIDE
LIGO
mirror
mirror
mirror
mirror
laser
beam splitter
photo-detector
LIGO is a second generation ground based observatory
mid station
LIGO WAS FOUNDED IN 1992 - EVEN THOUGH THE IDEAS DATE BACK TO THE 1970s
THANKS TO MANY PEOPLE, THE FIRST MEASUREMENT PERIOD STARTED IN 2002
and scientists
engineers
VIRGO
LIGO
same as VIRGO (ITA), KAGRA (JPN) and GEO600 (GER) - they observe together as a global detector network
KAGRA
SINCE 2015 IT´S BEEN RUNNING IN AN OPTIMIZED VERSION: ADVANCED LIGO
"aLIGO"
A is for "advanced"
soon there will be LIGO-India, Cosmic Explorer, Einstein Telescope and LISA - but more about that on the next poster!
short wavelength (high frequency)
long wavelength (low frequency)
LIGO/VIRGO/KAGRA/ LCGT/ET
DECIGO/BBO
LISA
pulsar timing
CMB Polarization

View the poster at https://dcc.ligo.org/G2501956/public

LIGO India

The LIGO-India Project is for the construction of a 4 km arm length Advanced interferometric Gravitational Wave Detector in India under an international collaboration with Laser Interferometer Gravitational-wave Observatory (LIGO) Laboratory, USA. The four lead institutes, Raja Ramanna Center for Advanced Technology (RRCAT, Indore), the Institute for Plasma Research (IPR, Ahmedabad), Directorate of COnstruction Services and Estate Management (DC-SEM, Mumbai) and the Inter-University Centre for Astronomy and Astrophysics (IUCAA, Pune), will work with the LIGO Laboratory, USA in realizing LIGO-India as one node of the international gravitational wave detector network in India.



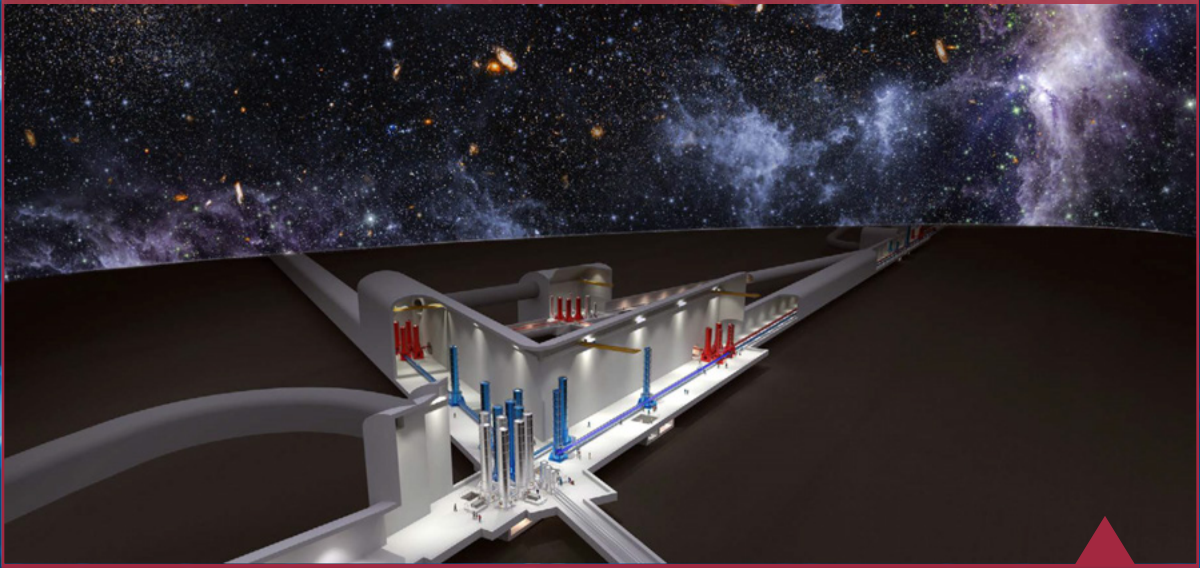
The main motivation for constructing a third LIGO interferometer in India is to build a larger global network of gravitational wave detectors. The advanced sensitivity of this detector and its geographic location in India will result in improved estimation of the location of the gravitational wave sources in the sky, enhancing the existing global network of detectors, i.e. the advanced LIGO (US), advanced Virgo (Europe) and KAGRA (Japan). The accurate localisation of the sources is crucial for performing follow-up observations with conventional telescopes (optical, radio, X-ray, etc.).

Learn more about LIGO India at https://www.ligo-india.in/

Cosmic Explorer CE (3rd Gen)

Cosmic Explorer is a next-generation observatory concept that will greatly deepen and clarify humanity's gravitational-wave view of the cosmos. It is the planned U.S. contribution to the global next-generation ground-based gravitational-wave observatory network. The design concept for Cosmic Explorer features two facilities, one 40 km on a side and one 20 km on a side, each housing a single L-shaped detector. Find out more at: https://cosmicexplorer.org/

Einstein Telescope ET (3rd Gen)



The Einstein Telescope is poised to revolutionise our comprehension of the Universe and the fundamentals of gravity, while pushing the boundaries of technology. The instrument is designed as a third-generation underground facility. The ambitious European project is driven by an international collaboration, uniting scientists and resources from around the globe to achieve pioneering discoveries. Read more at https://einsteintelescope.eu/

Left: *Shaking hands after signing the agreement to build LISA. On the left is European Space Agency (ESA) Director of Science, Carole Mundell. On the right is OHB System AG CEO, Chiara Pedersoli.*

Right: *Oliver Jennrich & Nora Lützgendorf celebrating LISA Adoption!*

LISA construction starts: Industrial prime contractor selected!

In June 2025, at Le Bourget airshow, the formal signature of the contract between ESA and the LISA prime contractor OHB System AG took place. The selection of OHB as industrial prime contractor was the culmination of almost a year of intense activity following the ESA adoption of LISA in January 2024 (see LIGO Magazine issue 24 pp. 14-15). OHB will now work with the LISA Team to finalise the spacecraft design and begin construction of LISA.

Here, LISA project scientists Oliver and Nora share their experiences of the selection process.

What happened before LISA's adoption?

The typical path of a mission starts much earlier than adoption. Most ESA science missions start out as a scientific proposal in response to a call for missions. The proposal includes the science the mission would address and a high-level description of how this science would be achieved. As an L mission ('L' for 'large' and 'leadership'), LISA had no direct competitors for its launch slot, but underwent a rigorous study phase nevertheless.

The process starts in ESA's Concurrent Design Facility where critical technologies, the proposed spacecraft architecture, the orbits, and a first cut at the performance budget were assessed. This phase ('Phase 0') is where ESA's project scientists first get officially involved. We are assigned as an interface between ESA's engineers and the wider scientific

Oliver Jennrich *is one of the Project Scientists for LISA at ESA and works on LISA since 1993. In his spare time he tries to combine his love for cycling and photography.*

Nora Lützgendorf *is the ESA Lead Project Scientist for LISA, a role she's held since 2020 after starting as Study Scientist, with a background in intermediate-mass black holes and eight years working on JWST's NIRSpec instrument. Outside of work, she enjoys graphic design and riding horses – a long time hobby, though she's still waiting for her own horse to magically appear.*

community, helping to define a mission that can deliver the proposed science and support scientists to formulate science requirements that can be achieved in orbit.

In the following Phase A, ESA contracted two European teams, Airbus Germany and a consortium of OHB and Thales Alenia Aerospace, the two so-called 'primes', to competitively study the mission. Each comes up with a mission concept, detailing the required technology development, the spacecraft and payload design, and a mission operations concept.

In general Phase A is fully competitive, usually leading to mission designs unique to each industrial contractor, and lasting 2-3 years. We were heavily involved in this phase to make sure that the proposed mission design could fulfil the science of the mission. In addition, we had the responsibility to formally define the science requirements together with the Science Study Team recruited from the LISA community.

Phase A, the "mission formulation", is followed by a more rapid Phase B1, the (early) design phase. Often taking less than one year, it has one primary goal: formalizing the design to a point where a robust cost-estimate for the mission can be established. Together with the Science Study Team, we prepared the so-called 'Red Book', formally the 'Mission Definition Report', which is the basis for the formal adoption by ESA's Scientific Programme Committee. The Red Book lays out the science of the mission as it can be conducted with the current mission design, addresses the mission operations and science operations concept, and also describes the spacecraft and payload architecture.

The challenge here is to convey as much information as possible without breaking the strict confidentiality

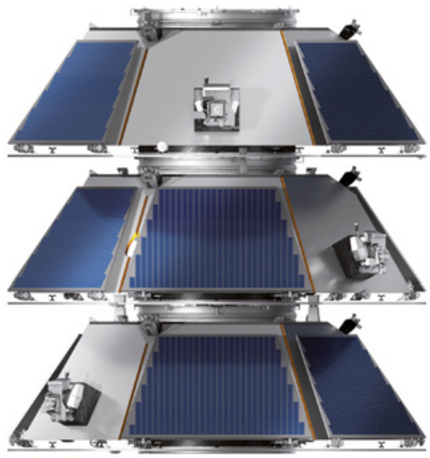
One of the surprising parts of the proposals was that they had their specific "personality". They both displayed a very characteristic "company spirit" that everybody noticed.

of the industrial studies – many details cannot be shared at this point in time.

What happened after adoption?

Once adoption was secured, we prepared for the selection of the industrial 'prime contractor'. While most elements of each payload module are provided by the member states, NASA, and ESA, the LISA prime contractor is responsible for building the three spacecraft themself, composed of the platform and the payload module.

The first step is to come up with a detailed statement of work describing what the prime contractor will have to do. All the relevant documentation had to be brought up-to-date. We had to make sure that the science requirements were correctly "flowed down" to the documents that actually matter, including the requirement documents provided to the prime contractors. Things like the sensitivity curve required for the science of LISA were broken down into easier to

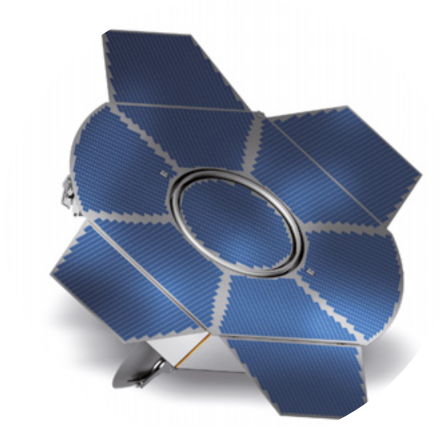


The 3 LISA spacecraft from OHB.

control chunks, such as the required thermal stability on the spacecraft, the residual jitter of the spacecraft, the required laser power, and the accuracy needed by the phase meter. As usual, some margin was added so that the resulting requirements are often more stringent than the science requirements, but also more robust – slight underperformances will not jeopardize the science of the mission.

This process is under the control of the LISA Project Team. This Team, led by the Project Manager, works with the industrial prime contractor and the instrument providers, but also the science ground segment development and the mission operations development to ensure that the mission is implemented as planned.

Inside the Project Team, the mission Performance and Operations team is responsible for formulating the performance requirements, tracking the results of subsystem tests, and modeling the overall performance of the mission. Our role as Project Scientists is to advise the Project team on all scientific aspects of the mission, assisted by the LISA Science Team. If there are questions about the scientific impact of a performance issue of one of the subsystems, the Project Scientists get involved to assess the severity of the situation. For LISA, the performance of the instrument is key and even small oversights might lead to larger problems later.


LISA has petal-shaped solar panels.

In practice, for us this required regular meetings with the Performance Team in the LISA Project Team to discuss about apportionment of error budgets to subsystems and also to discuss the approach to science operations and data analysis with the teams at ESAC (European Space Astronomy Centre, Madrid) and the ground segment teams: the Distributed Data Processing Centre (DDPC) and the NASA Science Ground Segment (NSGS). While the latter are not part of the industrial prime contract, their performance is critically linked to the overall performance of LISA, so it is absolutely necessary to make sure that mission operations and science operations are working hand-in-hand.

Once the documentation was prepared, ESA issued the "Invitation to Tender" (ITT), inviting all interested industrial primes to submit a proposal. This happened 31 March, a mere two months after the adoption. Proposal submissions were requested at the beginning of August.

ESA mandates a balanced 'geo-return' – the member states expect the amount of money flowing back to "their" industry to be commensurable with the fraction of the ESA science budget they contribute. This constrains the possible bidding consortia. For LISA, the competition was restricted to one consortium led by Airbus Defence and Space GmbH and a consortium led by OHB with Thales Alenia Space.

Both proposals arrived at the beginning of August 2024 and over summer and autumn the LISA Project evaluated the proposals. Many of the relevant criteria were out of our direct experience, and while it is interesting to look into the proposed management structure and the frequency of certain meetings or the quality assurance procedures, one of the key issues when working in a large project is to leave it to the relevant experts, whenever possible. For us, that meant to support the evaluation of the technical part of the proposals.

While the two primes were constrained by the fact that ESA prescribed large parts of the payload architecture, the spacecraft architecture differed significantly. As LISA has very tight performance requirements where e.g. the gravitational field of the satellite not only matters but is also determined by the spacecraft architecture, the actual assessment of the proposals required a lot of discussions with the performance team but also structural and thermal experts.

A particularly challenging issue arose from the strict confidentiality. Some of you might have met one of us during this phase and might have been surprised that we were not able to even talk about what the spacecraft would look like. During the competitive phase no information was to be given out so as to not jeopardize the process. This is almost entirely orthogonal to the scientific culture where we are used to discussing problems or different approaches openly with our colleagues.

Looking back, one of the surprising parts of the proposals was that they both had their specific "personality". In a mission like LISA, where the first serious efforts of ESA hark back to the early 2000s with the first industrial studies, the industrial teams and their preferences and strengths are well known. So, some variation in the focus of the proposals was expected, but it was more than different levels of details for one technical solution versus the other, the proposals displayed a very characteristic "company spirit" that everybody involved in the process noticed.

The other thing that stood out was the sheer amount of documentation submitted in the proposals. This shows the determination of the industrial teams, and would have been a daunting task were any individual tasked with carefully assessing every single page. Instead, the review of the proposals took a very layered approach, with different panels addressing different parts of the proposals, organised over many meetings, and finally reporting to a review board that took a decision to recommend one of the proposals to be accepted. This review board included senior ESA management and also us as Project Scientists as observers. This was more than a passive role – while observers have no formal voting power, our inputs were requested and heard.

Knowing that one's view has an influence upon who might win a contract worth almost a billion Euro can be frightening. Questions like "Is this a fair assessment or is it just me?" or "Is that really a problem or do I just not understand what is proposed?" come up more than once. At the end, the many discussions with colleagues lead to a coherent picture of the strengths and weaknesses of the respective proposals.

Choosing the prime

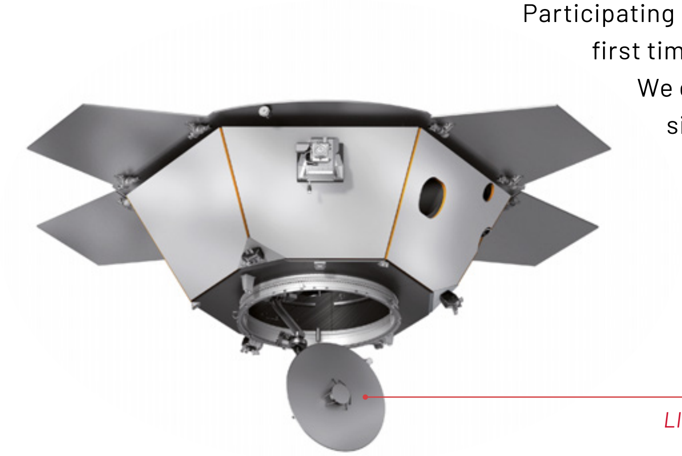
The review board met in October 2024. And while both proposals were of high quality, the decision was very clear. The board recommended accepting the OHB/Thales Alenia Space proposal and engaging in negotiations and the so-called "co-engineering" phase. This recommendation went to the Industrial Policy Committee (IPC), who agreed with the recommendation and authorized the LISA Project to actually start with negotiations and "co-engineering".

Very often, a detailed list of negotiation points is drawn up by the review board, but it stands as testimony to the quality of the recommended proposal that the project manager was authorized to negotiate the relevant points under his own responsibility.

A new experience

The two of us (Nora and Oliver) have different, quite complementary backgrounds. Oliver worked for many years in designing the mission and has a strong background in instrument building for gravitational-wave detectors; Nora has a much deeper astronomy and astrophysics background as well as operational experience from her time in JWST.

This played out well during the preparation of the documentation. Participating in this process for the first time was fascinating. We gained valuable insights from reviewing those massive proposals to observing detailed evaluations in board meetings and panels.

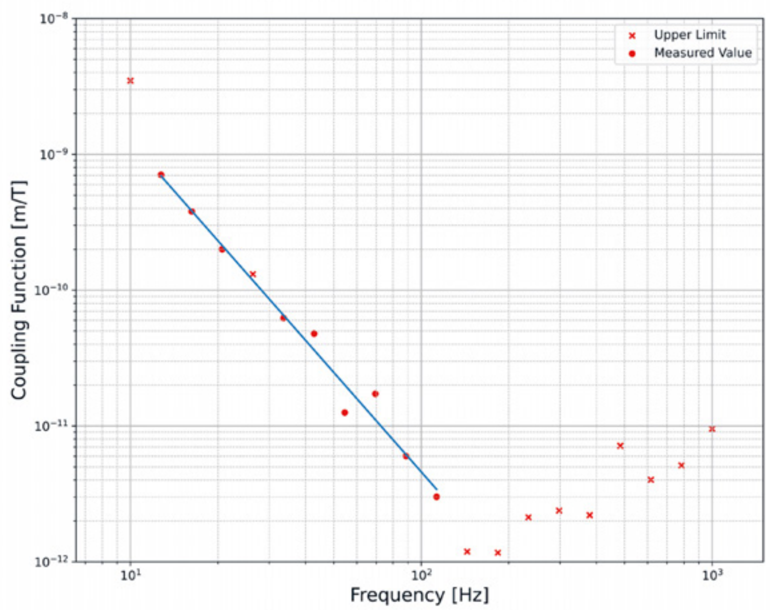


LISA calling Earth.

The "co-engineering"-phase is meant to iron out and clarify points that were left open in the proposal or were not worked out in sufficient detail. Here, performance and science are not affected, so the involvement of the project scientist is limited to some "background work", such as engaging with the prospective industrial team on performance.

It was also interesting to see how quickly information about the IPC decision leaked to the public, even before our internal communications, but that's another story...

From Noise Hunting to Olympiads



The frequency dependence of the magnetic coupling function— the core result of the students' analysis.

Catalina Miritescu is a final year PhD student at IFAE in Barcelona, Spain, working on stochastic background searches. In her free time, she enjoys hiking in the mountains or exploring the sea — snorkeling or diving — or painting, usually inspired by the nature she's surrounded by.

When I started my PhD in October 2022, I understood the physics behind gravitational waves: the theoretical description of general relativity, how the waves propagate and their polarizations, and the basic idea behind the working of an interferometer. However, I was not aware of an essential element and the biggest challenge of them all: NOISE. And not just the existence of noise, but the many types of different noise sources that can make observing the gravitational waves signals feel like a Sisyphean task.

I became acquainted with them (well, most of them) when I joined European Gravitational Observatory's (EGO) environmental noise team in spring 2023 for a 6-week research stay. The project focused on understanding and characterizing Virgo Interferometer's response to a particular type of noise: magnetic fields. Those who patiently illuminated my uninformed mind were Irene Fiori, Maria Concetta Tringali, and Federico Paoletti. They taught me about all the equipment needed to create and measure magnetic fields, such as the large coils mounted on the walls, the small portable coils, the big single-axis magnetometers, and the small tri-axial ones. They explained the concept of noise injections and the different types that are customarily used for these studies: line injections – when the voltage sent to the coil creating the magnetic field is a sinusoidal with a set frequency and amplitude; colored noise injections – the voltage covers a large range of frequencies simultaneously; sweep injections – the voltage applied corresponds to sequential frequencies from a set interval.

I learned about the advantages and disadvantages of using each type: how a line injection can send more power at a targeted frequency, increasing the probability to see a response from the detector, but how injecting only lines can miss some interesting features hidden between two distinct frequencies that might instead be picked up by a sweep injection, for example. They showed me what a coupling function is and explained the idea behind an upper limit when such a value cannot be directly measured. We worked together (with help from other members of the ENV Noise team) to develop the injections scripts that would monitor the variations of the magnetic coupling functions throughout the O4 run, which are now active and produce weekly results and intuitive data files, thanks in particular to Maria's efforts.

The stay was highly informative. It allowed me to explore in depth a subject I had not previously encountered—one

I likely would not have discovered on my own without this opportunity. I was lucky, and recognizing my fortune, I felt motivated to share my newly acquired knowledge with others. What follows is the story of how I set out to achieve that.

Astronomy is a subject which is rarely part of the middle school or high school curriculum across the globe. Romania is no different in that regard – there are no mandatory classes offered in public schools, no widely available optional courses for interested pupils to attend (by the time this article is published, this statement will fortunately be outdated since two new optional Astronomy courses will be added to the national curriculum in September 2025), no Astronomy textbooks available – unless we count the last textbooks published 50 years ago, which, believe it or not, some students still use to this day. Yet, the number of participants to the National Astronomy and Astrophysics Olympiad has been gradually increasing since its inception in 2007, with 147 participants in 2023, 182 in 2024, and 221 in 2025. The contest is well known throughout the country and usually students with an aptitude for physics and a curiosity for astronomy are eager to participate. I myself competed all 4 years of high school, and I believe the Olympiad was a big part of my decision to pursue an academic career in this field.

While access to resources is not straightforward, access to novel methods or ideas – such as gravitational waves detectors – in an easy-to-understand way is an even more challenging issue. I decided to create an Olympiad problem based on my research stay at the Virgo detector, thus bringing outreach into exam settings. This problem was part of the data analysis exam at the National Olympiad on Astronomy and Astrophysics in 2023.

In this exercise, students were introduced to the process of environmental noise characterization that takes place prior to an observing run. Specifically, they were informed about the importance of identifying and understanding magnetic field disturbances in and around the detector buildings. Students were given 20 magnetic line injections spanning frequencies from 10 Hz to 1000 Hz in logarithmic intervals, with corresponding values recorded by the Hrec channel and the magnetometer witness sensor channels during the injection. They were required to: (1) identify which data points meet the criteria for a valid coupling function (CF) calculation and which only allow for an upper limit estimation; (2) compute and tabulate those values; (3) plot them on logarithmic graph paper; and (4) fit a power-law function through the measured CF values using the least squares method to determine the power dependency of the coupling. The full text of the problem and the complete solution can be found at [1].

70 participants attempted this problem. Of these participants, approximately 25% achieved a score of 50% or higher. This distribution suggests that while the problem was appropriately challenging, a significant portion of students were able to engage meaningfully with the material and demonstrate a solid understanding of the key concepts involved.

While the problem successfully achieved its immediate goal of identifying students with the data analysis skills required to excel in the international Olympiad, it also served a broader educational purpose. It introduced students to a novel and relevant scientific topic, offering them a glimpse into the kind of real-world research conducted in gravitational wave astronomy. Beyond its initial use, the exercise has since become part of the training material for students preparing for the national Olympiad year after year.

As a final note, this activity was also presented as a poster at the 6th Shaw-IAU Workshop on Astronomy for Education, organized by the IAU Office of Astronomy for Education (proceedings are available at [2]) and as talks at the joint 24th International Conference on General Relativity and Gravitation & 16th Edoardo Amaldi Conference on Gravitational Waves and at the 2025 European Physical Society Conference on High Energy Physics. Inspired by the positive responses, I plan to create more problems based on other fascinating topics I've encountered (and will undoubtedly stumble upon) during my PhD journey. I also aim to increase the accessibility of these resources by providing translations in English and making them widely available—schedule permitting, of course, as I prepare to tackle the final and most demanding stage of my PhD: the last six months. Stay tuned!

[1] https://bit.ly/41jt0YS [2] https://owncloud.gwdg.de/index.php/s/yEmweDqg3sbwXfp

A Path to Fossil-free Supercomputing

LUMI data center, Finland.

The most energy-intensive part of LIGO-Virgo-KAGRA's work is computing. We perform signal searches, parameter estimation, numerical relativity simulations, and many other computations to enable gravitational-wave astronomy. In many computing locations, the electricity used is still substantially powered by fossil fuels, which are responsible for driving the climate change we all witness. To cut the carbon footprint of computing, one can switch their electricity for renewable energy sources.

How hard is it? In this interview, Ivan Markin talks to Pekka Manninen from LUMI, which runs a supercomputer in Finland completely on renewable electricity, to find out.

Pekka Manninen

is the Director of Science and Technology at CSC - the Finnish Supercomputing Center, where he specialises in High-performance Computing. He is also Adjunct Professor of Physical Chemistry, Department of Chemistry at the University of Helsinki.

Ivan: It is a pleasure to have you here for an interview with LIGO Magazine. Can you say a couple of words about LUMI and highlight some of the workloads that are running on it?

Pekka: LUMI is one of the fastest supercomputers in the world, and, until very recently, the fastest in Europe. Designing LUMI over five years ago, we envisioned building a Swiss army knife that goes through pretty much anything that scientists have to tackle. We have a very large spectrum of scientific disciplines using LUMI with thousands of users and tens of different disciplines: climate research, astrophysics, particle and plasma physics, biophysics, and quantum chromodynamics. New uses like digital humanities and digital social sciences, and training large language models.

Ivan: One of LUMI's main features is its use of 100% renewable energy, heat recycling, and brownfield construction. Can you tell me more about these choices?

Pekka: LUMI is located in Kajaani, Northern Finland, and was built on a former paper mill site that went out of operation 18 years ago. We, CSC, the Finnish Supercomputing Center, went there in 2012, as it is considerably cheaper to build a building within an existing building. One can save a lot of embedded carbon and thus reduce the environmental impact.

Kajaani was backed up with three of its own hydro power plants because the
paper machines used to consume 200 megawatts, and putting a 10 megawatt supercomputer there was not a big deal. The power was there, and we've been running everything on 100% hydro from the very beginning.

Supercomputers need electricity to cool water; we don't need to do that. It's cool enough throughout the year that we can do free cooling by opening up the windows and letting the heat out. The city cools LUMI for us — we push the heat to the heating system, and the water comes back cooled down. Selling the heat gives us money and also reduces carbon emissions.

Ivan: What motivated you to use renewable energy exclusively?

Pekka: Supercomputers are really power- and carbon-intensive, depending on the electricity they run on. Globally, the emissions from data centers surpass those of aviation. Using a supercomputer powered by, say, the German electricity mix, which emits 350 gCO_2e/kWh, is by far the biggest carbon footprint an individual can have. It doesn't matter if the researcher avoids flying, driving a car, or changes diet — nothing of that matters as long as you use a supercomputer on such a grid.

For us, it was clear from the very beginning that the only responsible way of running such an infrastructure is to use 100% fossil-free electricity — no question about it. It was a very natural choice: as the energy mix is almost carbon-free for the entire country, it's quite easy to buy green energy from the grid. Here in the Kajaani region, there's also an abundance of hydro and wind power.

We operated the supercomputers here in the Helsinki region until around 2010, and then we began buying certified clean energy for social responsibility reasons. Our last three supercomputer generations had carbon-neutral operations.

When it became obvious that we wouldn't be able to bring the additional power to our campus that we needed, we started to look for alternatives. We chose a site that offered hydroelectric energy.

Ivan: Did governmental policies help or hinder the choice of renewable electricity?

Pekka: One policy that made our operations very cheap was Finland's electricity tax exemption for some data centers, which has also attracted many data centers to Finland. The tax exemption also required us to reuse the waste heat. Otherwise, there were no big hurdles along the way — it was more about placing the electricity contract.

Ivan: How did you select the energy provider to guarantee renewable energy requirements?

Pekka: In Finland, one can buy certified power. Of course, electrons are electrons, but there is some control. The providers and consumers plan ahead of the investment, and speed up construction of power plants depending on what contracts people are asking for. One pays some premium for it, but the energy company commits to building a certain amount of the power source. You can ask for 100% hydro power, and you get the contract. It is about the future of the grid and the guarantee that there's always an energy production of a certain kind available.

We ran a competition for this long-term net energy and put the requirement that we want 100% hydro, period. We did not even consider any other.

Ivan: Is there an intermittency of the energy supply that affects you?

Pekka: Hydro power is very stable, unlike solar and wind, where you have more supply and demand oscillations. For hydro power, it's the gravity — the rivers keep flowing, with barely any oscillation. We haven't seen any instabilities on the grid feed. The price has been very stable and low. We also enjoy the cheapest electricity in the entirety of Europe.

For us, most of our energy is at a flat price. The electric price may have climbed quite high in Finland because there's no wind, and the houses that are electrically heated will consume a lot of energy. We pay a little bit of a premium for this price stability, but at least we stay within our power budget.

Ivan: What advice would you give to HPC systems that are considering a similar move?

Pekka: The main advice is that large HPC installations really need to be deployed where one can run them with green and cheap energy. They don't need to be on your campus, and to be even in the same country, you don't need to touch those systems. All our sysadmins work remotely, and all users are across Europe and the world. Thanks to the Internet, we don't need to sit on top of the system. Sure, it's nice to go there and receive a guest, or take a photo next to the system, but for the operational expenses and the social responsibility, I don't think that's worth it.

Ivan: What advice would you give to the existing HPC systems using electricity with a sizable percentage of fossil fuel energy?

Pekka: Go talk to the energy companies and try to find what the alternatives are for the grid. That's the only thing you can do for the carbon footprint. Anything you do with the code, tinkering with clock speeds, job placement, or energy scheduling might make no difference. What you can really do is to adjust the electricity contract. Nobody would know there's a difference in the contract: not the user, not the system administrator. Together with the energy company, go seeking options on how you can reduce the CO_2 mix of the electricity. Even if it costs a bit more, having a 2 MW cluster may be enough for the electricity company to invest in more solar panels, for example. You saying "I want a cleaner mix for my system" may already be enough of an incentive to change or build new infrastructure or transport energy somewhere else.

Ivan: Thank you for sharing your experience and the story of LUMI,and for setting a high sustainability bar by providing it with carbon-free supercomputer power.

LUMI data center and Renforsin Ranta business park in Kajaani, Finland, in midnight sun.

What is GWSolidarity?

Our current world is a scary place: science funding, universities, and even critical thinking itself are under attack; these same forces threaten immigrants, LGBTQ people, public health, and more. Everyone has a pressing obligation to do something about this. Scientists are in a unique position to act against the injustices that are affecting us all, as scientific advancement is a major avenue through which countries exert their power to the world.

We, as members of GWSolidarity, encourage individual LIGO-Virgo-KAGRA (LVK) members to post on social media, contact their political representatives, and attend protests. However, these actions do not take advantage of our critical roles as scientists nor of our strength in numbers, and therefore they have limited impact. We therefore believe that solidarity — meaning unity, care, and mutual support — is the key to success against powerful forces of injustice.

To help facilitate this collaborative work between gravitational wave researchers towards justice, we have formed the Gravitational Wave Solidarity Committee, or "GWSolidarity." We are made up of researchers within the LVK Collaboration who believe that making our community and world more just and equitable is an integral task to our work as scientists. Formed in September of 2024, GWSolidarity has steadily grown to over 60 members in under a year. Our actions are guided by our core values, as shown in the graphic.

If you are interested in getting involved with GWSolidarity or have questions about our group, we encourage you to sign up for our listserv at bit.ly/GWSolListserv, follow us on social media (@gwsolidarity on instagram and bluesky), and email us at gwsolidarity@gmail.com to join one of our meetings. Additionally, start a conversation with someone wearing a GWSolidarity pin at an upcoming conference!

- GWSolidarity Group-

GWSolidarity's core values

GWECS Early Career Workshop in Glasgow

Glasgow rolled out a very warm welcome for the ECRs.

Tired from two full days, but still patient and eager: ECR workshop attendees at the end of day 2!

In the March 2025 issue (ligo.org/magazine issue 26, pp. 26-27) we wrote about how the beating heart of the evolving field of gravitational waves (GWs) is made up of early career researchers (ECRs), spanning from PhD students to junior faculty. While many scientific fields rely heavily on ECRs, GW research is uniquely defined by this alignment—a young field powered by young scientists. Success here requires more than technical skill; it depends on strong collaborative networks in a discipline where few challenges can be solved alone. To help ECRs navigate this dynamic landscape, the GR24/Amaldi16 (iop.eventsair.com/gr24-amaldi16) organisers, Gravitational Waves Early Career Scientists (GWECS, gwecs.org) and the Institute of Physics (IOP, iop.org) hosted a dedicated Early Career Workshop in Glasgow. The aim was twofold: to provide scientific grounding for the large conference and to foster community through face-to-face connection.

The workshop kicked off on the beautiful, "Hogwarts-like" campus of Glasgow University. As co-organisers Christopher Berry, Rachel Gray and GWECS coordinators crested University Hill with a sunny Glasgow sky behind them, a growing crowd of GW researchers began to gather—exchanging tentative introductions, sticking on name badges, and filling the air with a low, excited hum. The day began with a "bingo" session that had people trying to find others matching specific conditions: who were perhaps attending their very first conference, or had been a part of the LIGO-VIRGO collaboration when the first detection was made. This networking session "...made it easier to talk and connect with others during the rest of the days," as one participant put it.

The first scientific session was welcomed by a rather full room as Scott Hughes painted a picture of black hole spacetimes—equal parts physics and imagination. Katy Clough followed, offering a sharp, clear introduction to solving Einstein's equations. The goal of the scientific talks was to help ECRs prepare for the main conference on the upcoming week, giving neces-

Fantastic idea, loved having an intro to topics outside my usual area, and the chance to meet others before the large conference started. The catering was also really good.

sary background to be able to follow in-depth plenary and parallel sessions. Separate Q&A time was set aside for every pair of lectures, and even the very first such session was full.

After lunch, the focus shifted. "Soft skill sessions - a welcome surprise", as one participant shared. Jen Gupta energized the audience with insights into science communication and public engagement. While the stories about school children becoming motivated and thriving when provided with space and guidance were inspiring, Jen's anecdote about the power of tactile learning—and the importance of experiencing the world beyond just hearing and seeing—was especially moving. In the next session, Mikhail Korobko gave practical advice on how to navigate massive academic conferences (such as the 850+ attendee GR24/Amaldi16), and Christopher Berry demystified the often-opaque world of academic writing.

The late afternoon turned to more fundamental and technical matters: Bianca Dittrich introduced quantum theories of gravity—ambitious and abstract—and John Veitch grounded everyone back in the data trenches with an intro to GW data analysis. Despite the intense first day, the Q&A session ran full, before the Local Organising Committee were forced to move on to final announcements as University staff sought to gently indicate business hours were over.

Golam Shaifullah

is a postdoctoral researcher at the University of Milano-Bicocca, using pulsars to detect nanohertz gravitational waves and for non-GW experiments. He believes a strong community is necessary for early career researchers to drive transformative science. In his spare time he loves to read, hike and learn weird and fun facts.

Elisa Maggio

is a Marie Curie Fellow at the Max Planck Institute for Gravitational Physics in Potsdam, working on tests of general relativity. She is an advocate for early-career scientists and a coordinator of GWECS. In her free time, she likes visiting museums and flea markets.

Beside the science talks that were very useful, I really liked hearing about people's history, the motivation behind their choices and what they think now about it. This is something that is not common to hear every day!

I really liked how the workshop gave a clear idea of what it's like to build a career in this field. It felt like a helpful guide to the future, especially for someone just starting out. I also enjoyed the informal networking session at the beginning. It made it easier to talk and connect with others during the rest of the days.

The next day included more scientific sessions, where Antonio Carrillo and Andy Taylor broadened the scope with talks on electromagnetic counterparts and cosmological surveys.

The diversity and informality of sessions was great!

Daniela Doneva opened minds with alternative theories of gravity, Elisa Maggio followed with how we test GR observationally, and Jonathan Gair brought it full circle with an overview of GW experiments themselves.

The highlights of the day were two panels on different career paths. On the "careers in academia" panel, Simone Mastrogiovanni, Anna Green, Christiana Pantelidou, and Adam Pound spoke candidly about navigating academia, and strategies that led them to their current success. For many in the audience, this was one of the most valuable hours of the entire workshop with one attendee remarking, "I really liked how the workshop gave a clear idea of what it's like to build a career in this field. It felt like a helpful guide to the future, especially for someone just starting out."

Soft skill sessions - a welcome surprise.

The second panel of the day looked at careers beyond academia. Erin MacDonald, Becky Douglas, Sebastian Khan, Peter Wakeford and Jen Toher took us through their experiences of leaving academia to pursue very different career paths. "I really liked hearing about people's history, the motivation behind their choices and what they think now about it," said another participant.

Often large conferences become challenging experiences for ECRs, and such dedicated workshops can allow them to prepare. For many, the workshop offered not only a deeper understanding of the field's technical landscape but also a sense of belonging to a global and collaborative research effort. As one participant put it: "I loved having an intro to topics outside my usual area, and the chance to meet others before the large conference started." We believe such practice could be adopted for future meetings for the benefit of the ECRs and the general community.

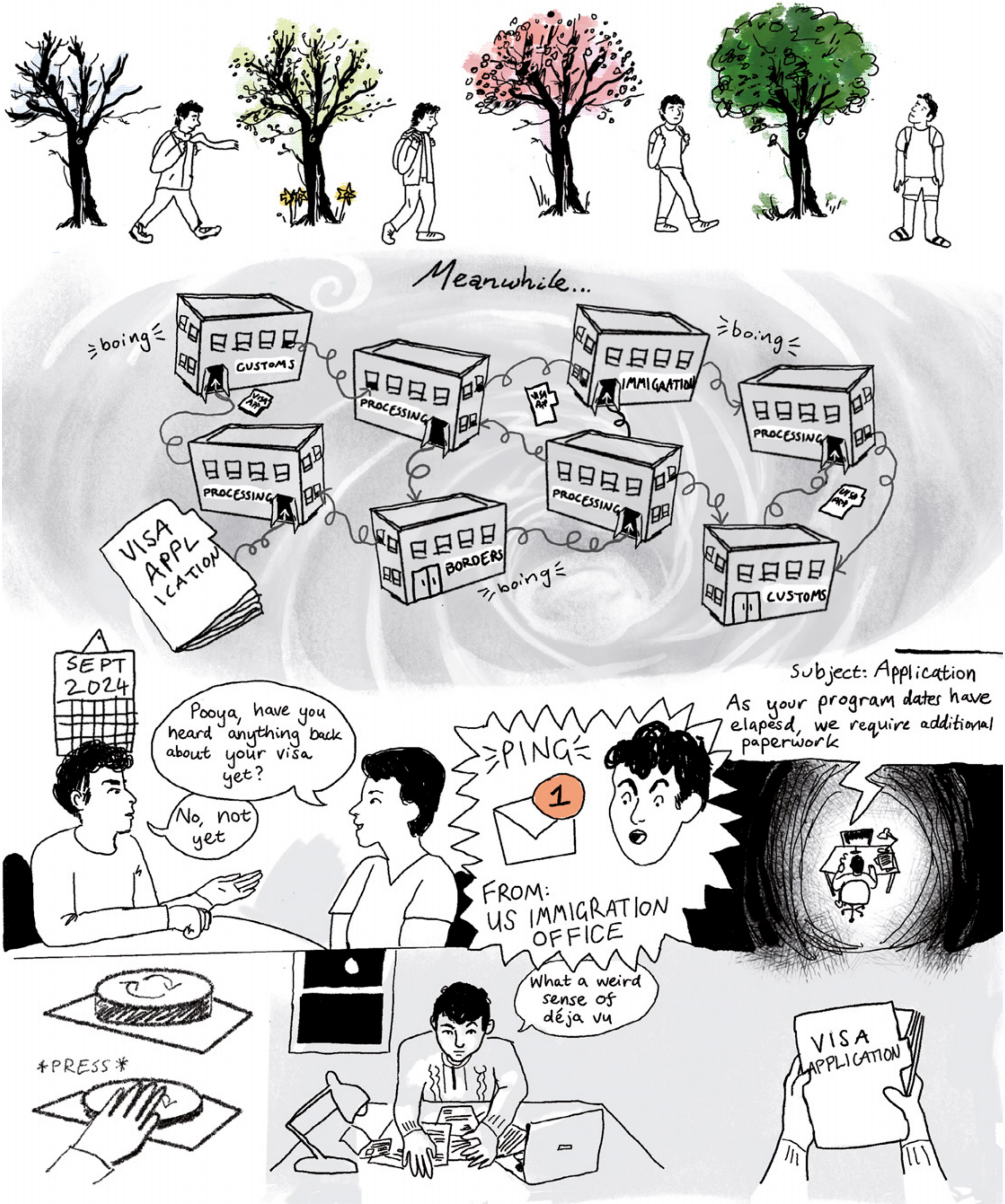
"I'm the line between the pre- and post-detection eras- the final proof of my thesis was due on January 30, 2016, so I couldn't put any information about GW150914 in my thesis. I'd always planned on getting a thesis tattoo and had settled on a set of axes to be filled in when the first detection was made - being able to put the first signal from the detector I worked on is much cooler!" – Jax Sanders

"When I arrived at LIGO in Washington, I was at a loss for words when Rick Savage opened the door, I was so excited to be there. Showing my tattoo was the only way I could 'break the ice'- and Rick looked shocked and asked "why do you have our data tattooed on your arm?"" – Rhonda Roberts

Aiden Brooks' GW150914 tattoo.

Continued on page 47.


I am Pooya Saffarieh, a PhD candidate based at Nikhef in Amsterdam, working on control aspects of suspension systems aimed for the Einstein Telescope. I enjoy exploring the boundary of art and science through different mediums: analog photography, and more recently art/science outreach installations. This is my experience applying for a visa to visit Caltech as part of my PhD.
Short visit to Caltech for research collaboration, exciting!
OCT 2023
PING
Caltech: Invitation Letter
https://usa.gov/imm
USA CUSTOMS AND BORDER PROTECTION
I just need to figure out the visa
PROCESS FOR IRANIAN CITIZENS
Official invitation
Visa Fee
Previous travel history (5 years)
Social media handles
Parent's details
AT THE US CONSULATE IN AMSTERDAM
brrr it's cold out...
VISA APPLICATION
I've made it through security, it's so crowded
Why do I have to answer in front of everyone?
I need your travel history for the past 15 years
VISA PROCESS
Applicant
Iranian
Other
send to admin processing
MORE DOCUMENTS NEEDED
A few days later...
Okay, that's everything for round two
VISA APPLICATION
I hope this works out
drawn by Storm Colloms


Meanwhile...
boing
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boing
CUSTOMS
SEPT 2024
Pooya, have you heard anything back about your visa yet?
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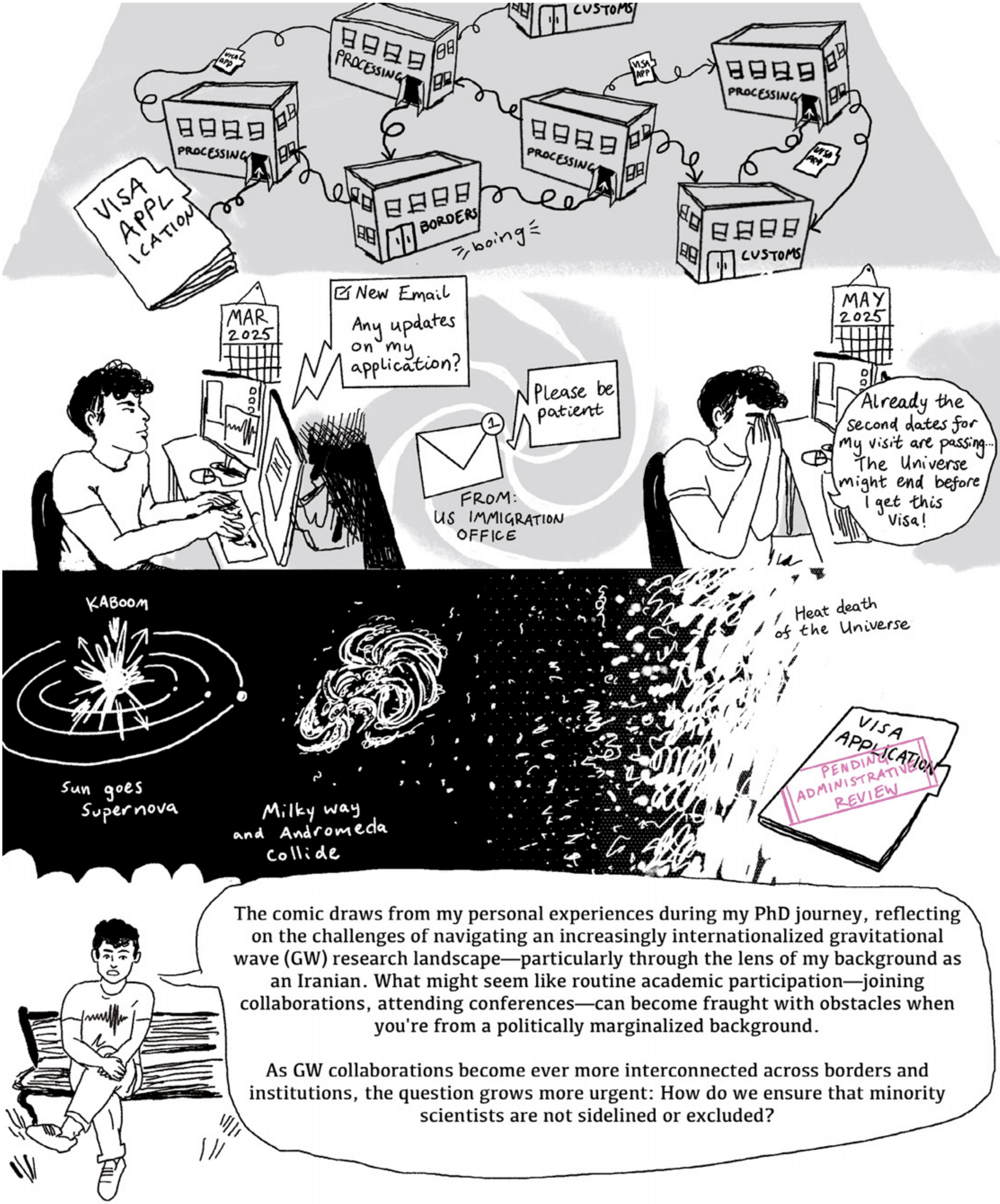
As your program dates have elapesd, we require additional paperwork
PRESS
What a weird sense of déja vu
VISA APPLICATION



Drawn by Storm Colloms

Exit Through the Gift Shop

Nutsinee Kijbunchoo

An ex-LSC. Currently an Electro-Optics Consultant at DEWC Services. In her spare time she enjoys wine tasting, drawing comics, and prototyping homemade cat toys.

I had been contemplating leaving academia for a while. I first joined LIGO in 2014, working with Gabriela González as a part-time undergrad research student at LSU. I'll never forget my first LVC meeting at Stanford. I then became an operator at LIGO Hanford for 2.5 years, did my PhD at ANU—though I spent half my time back at Hanford—and now I'm a postdoc at the University of Adelaide. There's nothing wrong with LIGO or the LSC. I simply didn't want it to be the only world I knew. When I didn't get a scientist position at the site, and the University of Adelaide didn't win a grant that would continue to pay my salary, I took it as a sign from above that it was a good time to leave.

This was all before the NSF funding cuts made it to the news.

At first, I thought applying for industry jobs in the quantum field wouldn't be that difficult. I mean, c'mon—I installed and commissioned a squeezer that's part of a billion-dollar instrument. Surely somebody would want me. To my surprise, quantum companies in Australia are looking for folks with atomic/molecular/optical (AMO) physics backgrounds. My squeezed light knowledge was useless—or at least that's how I felt.

To be honest, I didn't know exactly what I wanted to do either. I just wanted to do fun things in a fast-paced environment for a change. I applied to a wide range of jobs—from optical engineer to game designer—mostly in Australia and a few in the US. Getting interviews wasn't a problem. The problem was, I was never anyone's first choice. I never built a laser, even though I have all the knowledge to do so. I've never done AMO physics, but after reading a paper, I was certain I could pick it up. I have the right background, but no industry experience. Perhaps I didn't sell myself right? Or was it just my rotten luck? Once, my CV went through with Meta and I was supposed to be scheduled for an interview. Then all of a sudden, that position ceased to exist. Perhaps that was a divine power trying to tell me I shouldn't go to the US right now—lol.

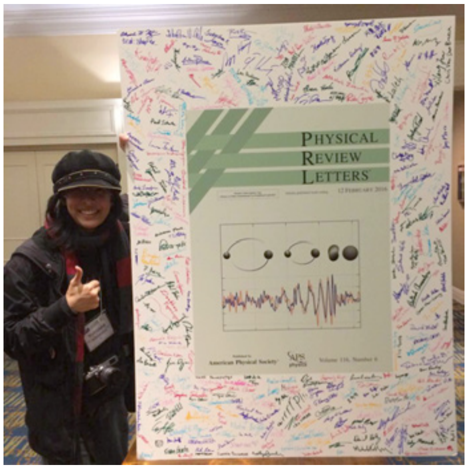
After about three months, out of the blue, a recruiter from a defense contractor reached out to me on LinkedIn. We chatted for a bit before scheduling the first phone call, and later, an in-person interview. Turns out, Adelaide is the hub for Australian defense science. The recruiter told me they were looking for someone with quantum knowledge. They couldn't tell me what I'd be working on. I did tell them my interests. I guess our interests aligned, since I was offered a job. This was possible only because I'd recently become an Australian citizen. Big shoutout to Peter and Dave and the University of Adelaide for sponsoring my permanent residency. Having a PR opened so many doors and opportunities. I'm forever grateful.

It's funny that my first job offer came from a company I didn't apply to. None of the advice I could've given anyone about applying for jobs would be worth anything. I simply liked the people I talked to, and the company looked like it was going to be a good workplace. They didn't hate me after

I asked for too much salary, but rather tried to make up the difference the best they could. So, I accepted the offer without even knowing what I'd be working on. I guess you could call it a leap of faith? The unknown excites me. I didn't even know my job title until I signed the dotted line. That probably was a bit silly. I'll find out very soon whether I made the right decision or not. I want to get this article out before I leave the Adelaide group so it doesn't get stuck behind defense red tape.

I was once told that industry is uncertain and you could get fired anytime. Well, I'm seeing the same thing happening in academia right now. People around me are leaving left and right, both in Australia and the US. Only those sitting at the top of the academia pyramid get to enjoy the luxury of job security.

Finally, I'd like to take this space to thank everyone who's been part of my journey over the past 10 years. It's been fun!



Career Updates

Alex Amato and **Anna Green** have started permanent positions as Assistant Professors in the Gravitational Waves and Fundamental Physics group at Maastricht University, and **Marco Vardo** has transitioned to a permanent position in Nikhef as Technical Coordinator of ETpathfinder, also located in Maastricht.

Matthew Ball successfully defended his PhD at the University of Oregon in May and will be taking up a postdoc position at the University of the Balearic Islands.

Sylvia Biscoveanu is starting a faculty position at Princeton University.

Luis Diego Bonavena moved from his postdoc position at University of Florida to a postdoc position at DTU FYSIK in Denmark.

Tom Callister is starting a faculty position at Williams College.

Elenna Capote has started a position as a Gravitational Wave Experimental Physicist at the LIGO Hanford Observatory.

Shreevathsa Chalathadka Subrahmanya received his PhD (dr. rer. nat.) degree from the University of Hamburg in April 2025. He is continuing as a postdoctoral researcher with Oliver Gerberding at the same institution.

Koustav Chandra, a postdoctoral fellow at Penn State, is starting a new postdoctoral position at the Max-Planck Institute for Gravitational Physics, the Albert Einstein Institute, Potsdam, Germany.

As of August 17, 2025, **Lynn Cominsky** has entered Sonoma State University's Early Retirement Program, and the SSU group will no longer be able to contribute to the LSC. It has been a great experience and she will miss everyone! Watch US Congressman Mike Thompson's video address at Lynn's leaving party here: https://officeofmikethompson.box.com/s/krv7ui91sw24e4axj88th5z5162eejmb

Derek Davis will begin a faculty position as an Assistant Professor of Astrophysics at University of Rhode Island with support from the Simons Foundation Scientific Software Research Faculty Award.

Amanda Farah received her PhD from the University of Chicago this Summer, and will start a postdoc with Maya Fishbach at CITA this Fall.

Rossella Gamba, an N3AS postdoctoral fellow at Penn State, will be moving to UC Berkeley for the remainder of the fellowship.

Jacob Golomb has graduated with his PhD from the California Institute of Technology and is now on the technical staff at Asari AI.

Ish Gupta completed his PhD from Penn State and is moving to Northwestern where he will take up an N3AS fellowship followed by a CIERA fellowship.

Sophie Hourihane has graduated with her PhD from the California Institute of Technology and has started a position working with the UAW labor union.

Max Isi is starting a faculty position at Columbia University.

Praveen Kumar successfully defended their PhD on July 31st, 2025, at the University of Santiago de Compostela (Spain), on the topic "Searches for Binary Black Hole Merger Signals in LIGO-Virgo Data", under the supervision of Thomas Dent.

Isaac Legred has graduated with his PhD from the California Institute of Technology and has started a postdoc at the University of Illinois Urbana-Champaign.

Ryan Magee has completed his staff appointment at Caltech LIGO Lab and has moved to industry.

Purnima Narayan graduated with a Ph.D. in Physics from the University of Mississippi in July 2025. Her dissertation, titled "New Physics or Missing Physics? Understanding Biases in Gravitational Wave Tests of GR," explores how unmodeled astrophysical effects can mimic or mask potential deviations from general relativity in gravitational wave observations.

Career Updates contd.

Lalit Pathak joined IUCAA Pune as a post-doctoral fellow.

Ethan Payne has graduated with his PhD from the California Institute of Technology and has started an analyst position in finance.

Surojit Saha has been awarded his PhD from the Institute of Astronomy, National Tsing Hua University, Taiwan. His thesis explores applications of machine learning algorithms to astrophysical transients and gravitational waves from core-collapse supernovae, alongside having keen interest in noise mitigation in GW detectors.

Francisco Salces Carcoba is starting a faculty position at the University of New Mexico.

Brian Seymour has graduated with his PhD from the California Institute of Technology and has started a postdoc at the Niels Bohr Institute

Sushant Sharma Chaudhary successfully defended his PhD thesis "The real-time detection infrastructure of LIGO, Virgo, and KAGRA: data products, current performance, and future developments" in April 2025 and moved to the University of Minnesota as a postdoc to continue his work in the LVK.

Rhiannon Udall has graduated with her PhD from the California Institute of Technology and has started a postdoc at the University of British Columbia.

Awards

Karsten Danzmann, director at the Max Planck Institute for Gravitational Physics in Hannover, received an honorary doctorate from RWTH Aachen University for his groundbreaking contributions to gravitational-wave research. https://www.aei.mpg.de/1230517/karsten-danzmann-erhaelt-ehrendoktorwuerde-der-rwth-aachen-university

Jose Maria Ezquiaga was awarded the 2025 IUPAP General Relativity and Gravitation Early Career Prize (https://iupap.org/who-we-are/internal-organization/affiliated-commissions/ac2-international-commission-on-general-relativity-and-gravitation/ac2-news/), given by the International Society on General Relativity and Gravitation. http://www.isgrg.org/IUPAPprize.php

Anuradha Gupta received the 2025 Simons Emmy Noether Fellowship. She will visit Perimeter Institute, Canada, for 3 months in Fall 2025 to focus on her research. https://perimeterinstitute.ca/news/meet-2025-emmy-noether-fellows. She has also received the NSF's CAREER award, "Preparation Towards the Detection of a General Relativity Violation with Gravitational-Wave Observations" at the University of Mississippi. https://www.nsf.gov/awardsearch/showAward?AWD_ID=2440327&HistoricalAwards=false

Mikhail Korobko has received the 2024 Rudolf Kaiser Prize, awarded to early career scientists for outstanding achievements in the field of experimental physics. https://www.physik.uni-hamburg.de/en/iqp/ag-schnabel/scientific-news/2025/rudolf-kaiser-preis.html

Purnima Narayan was named the 2025 Doctoral Class Marshal at the University of Mississippi - an honor bestowed on two graduating students each year in recognition of their academic excellence, research contributions, and sustained leadership and service. (https://olemiss.meritpages.com/stories/Purnima-Narayan-Named-Class-Marshal-for-Graduate-School-at-University-of-Mississippi/159591630?) As Class Marshal, she led her cohort at the doctoral hooding ceremony and delivered the student address: https://www.instagram.com/reel/DL3KIF2pWJk/

Saketh Muddu, PhD student at the Max Planck Institute for Gravitational Physics in Potsdam, has received the Charles W. Misner Award - The University of Maryland's Physics Department student prize. https://www.aei.mpg.de/1253205/charles-w1

Fred Raab received the APS 2025 Isaacson prize for his outstanding contributions in gravitational-wave physics, astrophysics, enabling technologies, and education and public outreach. https://www.aps.org/funding-recognition/award/isaacson

Isobel Romero-Shaw has been awarded an Ernest Rutherford Fellowship, to be hosted at Cardiff University. https://www.ukri.org/news/stfc-announces-latest-ernest-rutherford-fellows-2024/

Bernard Schutz, founding director of the Max Planck Institute for Gravitational Physics in Potsdam and emeritus professor at the University of Cardiff, is awarded the Rumford Medal by the Royal Society for his contributions to relativistic astrophysics, the detection of gravitational radiation, and education. He will receive the medal on 1st December 2025, during a ceremony at the Royal Society in London.

Masaru Shibata, director at the Max Planck Institute for Gravitational Physics in Potsdam, was awarded Japan's Medal of Honor ("Shiju-houshou") for his outstanding scientific achievements in astrophysics by the Emperor of Japan. https://www.aei.mpg.de/1245666/masaru-shibata-is-awarded-japan-s-medal-of-honor

Miguel Zumalacarregui, a group leader at the Planck Institute for Gravitational Physics in Potsdam, has received funds from the Max Planck Society's Annual Donation Project for the search for gravitational waves deflected by gravity. https://www.aei.mpg.de/1227766/with-einstein-on-crooked-paths

New LSC positions

Carl Blair was elected as chair of the Advanced Interferometer Working Group. Stephen Fairhurst is the new Spokesperson, and Peter Shawhan the new Deputy Spokesperson.

Stephen Fairhurst is the new Spokesperson, and **Peter Shawhan** the new Deputy Spokesperson.

Carl Haster was elected as co-chair of the CBC Working Group.

David Keitel was re-elected as co-chair of the Continuous Waves Working Group.

Vuk Mandic was re-elected as co-chair of the Stochastic Working Group.

Jess McIver was elected as member of the LSC Management Team.

Meg Millhouse was elected as co-chair of the Burst Working Group.

Other News

David Reitze has been appointed as the Vice Chair of the US National Academy of Sciences Board on Physics and Astronomy for a three year term.

The GW231123 Exceptional Event received a lot of public attention, including articles and news coverage in significant international media outlets, and in prominent science and specialty publications. Here's a selection of highlights: The Guardian, CBC News, Der Spiegel, CBS News, ABC News Australia (Video Interview), ABC Radio National Breakfast, Nikkei, Times of India, CNN, Wall Street Journal, The Independent, National Geographic, USA Today / Science News, Nature News, Scientific American, Sky & Telescope, New Scientist, Smithsonian Magazine, Discover Magazine, Ars Technica, Popular Mechanics, APS, Astronomy.com, Nature India.

Les Guthman has been filming with the LVK since August 2015. Now his ten-year archive of films, interviews, talks and live events will be available to researchers and historians in the Les Guthman LIGO Video Archive at Caltech.

→ **Submit your GW Limericks**:
A decade since the gravitational wave,
A discovery about which we rave,
Why not write a rhyme,
To celebrate this time,
Submit your limerick, be brave!

https://hannahm8.github.io/gwlimericks/

LIGO 2025

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The LIGO Magazine is printed on certified sustainable paper.

Rhonda Roberts and Corey Gray compare their GW150914 tattoos!

Why are there two LIGO observatories?

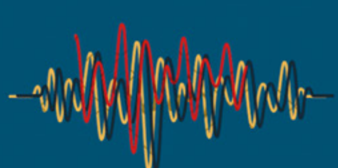
Source Localization

*With two detectors, LIGO can begin to narrow down the area in the sky where a wave originated. Adding more detectors (**like Virgo and KAGRA**) greatly improves localization.*

Gravitational Wave travel time

Gravitational waves travel at light speed, so any signal detected at both sites with a time difference of over 10 milliseconds can be ruled out as a real wave. This time-based filtering helps validate detections.

Noise Discrimination



Each detector is sensitive to local ground vibrations. By comparing data from distant locations, LIGO can filter out local noise and isolate real gravitational wave signals.

DCC number P2500538. https://dcc.ligo.org/P2500538

by Mayara Pacheco