



Gravitational Wave Astronomy

# 28

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# LIGO MAGAZINE

04

A cornucopia of results

GW241011, GW241110 & GW250114

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10 years after LISA PATHFINDER  
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to growing bone

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## Front cover

**T**he main image shows an artistic representation of a binary black hole system like those which produced GW241011 and GW241110. An interesting feature of the GW241011 and GW241110 signals is that at least one black hole's rotation is in a peculiar direction relative to the orbital plan. These unusual spins provide clues about the formation of the systems. Find out more about Observing Run 4 in the article on pp. 6-9 and specifically about GW241011 and GW241110 on p. 9.

**Top inset:** An artistic representation of a core-collapse supernova. Article on pp. 10-13.

**Bottom inset:** What does LIGO research have to do with growing bones? Find out more on p. 19.

**Bottom-left (diagonal) inset:** Artist's impression of LISA Pathfinder, a proof-of-concept mission which paved the way for the upcoming LISA mission. We celebrate the 10 year anniversary of LISA Pathfinder on pp. 24-26.

## Image credits

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**p. 3** Antimatter comic strip by Nutsinee Kijbunchoo.

**pp. 6-9** Artistic representation of GW250114 by Maggie Chiang for Simons Foundation (p. 6). Timeseries comparing GW150914 and GW250114 by LIGO/J. Tisino (GSSI)/R. Hurt (Caltech-IPAC) (p. 7).

**pp. 10-13** Artistic illustration of a core-collapse supernova by Carl Knox/OzGrav/Swinburne (p.10). Voices of the CCSNe community by Christine Lee (pp. 8-9).

**pp. 14-15** Photo of Rai's 90th birthday party courtesy of Vivishek Sudhir (p.14). Photo of Rai working courtesy of MIT (p.14).

Rai Weiss courtesy of Nergis Mavalvala (p.15).

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**p. 18** Photo of the author by Ian Venart (photographer). Hometown photo by Reem Alfaidi.

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**pp. 20-21** Product images by Noisy Labs

**pp. 22-23** Cosmic Canvas poster by LIGO India (p. 22). "The step that was never completed" (sketch) by Anvay Ugemuge (p. 23, top).

"United by brilliance" (digital art) by Pranjal Sharma (p. 23, bottom).

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**Back cover:** Illustration by Bartosz Fornal.

**LIGO Magazine layout by Sascha Rieger (Milde Science Communication).**

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## Antimatter by Nutsinee Kijbunchoo



# Welcome to the 28th issue of the LIGO Magazine!



Hannah Middleton  
Editor-in-Chief

A handwritten signature in blue ink that reads "H Middleton".



Anna Green  
Deputy Editor-in-Chief

A handwritten signature in blue ink that reads "A Green".

**W**elcome to the twenty-eighth edition of the LIGO Magazine.

Observing Run 4 (O4) is over, but the data continues to be analysed and the bumper crop of results continues. In this edition, we hear from some of the people involved in paper writing and analysis for three very interesting gravitational-wave events in "O4: Cornucopia of results continues!". We also shine a spotlight on the hunt for gravitational waves from core-collapse supernovae with Christine Lee as our guide to this formidable challenge in "Hunting Core-Collapse Supernova: A unified effort." Did you know that the Big Bang may have produced primordial gravitational waves? In this edition's How It Works, Bartosz Fornal tells us how finding such a signal would provide break-through insights into particle physics and the structure of nature.

Meanwhile in Space, we celebrate the 10 year anniversary of the LISA Pathfinder mission, with perspectives from early career researchers who worked on the mission. We also take a look back at 30 years of technical innovation at GEO600, and shift our gaze to the future, hearing all about preparations towards the Einstein Telescope (ET) with experiences from junior members of the ETpathfinder team.

This edition we also say a sad farewell to Rainer Weiss whose passing has left a huge hole in our community. Rai's friends and colleagues share fond recollections in "Remembering Rainer Weiss".

Gravitational-wave science and technology has many applications in the real world and in this addition we check out two such spin-out ventures. We hear about the latest squeezing tech from Noisy Labs and we find out what gravitational waves have got to do with growing bones!

Are you thinking about taking on a service role in the LIGO-Virgo-KAGRA collaboration? In this edition's LAAC Corner, Daniel Willaims and Elise Sanger share their experiences of the hidden clockwork of collaboration life. In "Inspiring science through art", Debarati Chatterjee shares some of the wonderful artworks that have been created as part of the LIGO India Cosmic Canvas competition.

As always, please send comments and suggestions for future issues to [magazine@ligo.org](mailto:magazine@ligo.org).

*Hannah Middleton and Anna Green, for the Editors*

# News from the spokespeople

Observing Run 4 (O4) has ended, and the LIGO Observatories certainly lived up to their names! Besides achieving the best sensitivities yet for gravitational-wave signals, the observatories kept motoring along for over two years with just a couple of commissioning breaks. This success was due to the care with which the LIGO detectors were designed and put together, but also due to the dedicated observatory staff and LIGO Scientific Collaboration (LSC) members who managed day-by-day operations, tune-ups, monitoring and calibration to provide the best data possible. Virgo kept pace with steady data collection during the latter 2/3 of the run and helped produce a number of rather well-localized events, while KAGRA continued to push its envelope and demonstrated sensitivity gains during parts of O4.

The science has followed, and there is much to celebrate. The LIGO-Virgo-KAGRA Collaboration (LVK) released 22 papers just in the second half of 2025, including deep investigations of five exceptional events that enabled particularly strong tests of general relativity and astrophysics. Ever-better searches for new signals continue in parallel with studies enabled by the growing sample of compact binary merger events. LVK members continue to mine the data, with several analyses now nearing completion and plans for dozens more papers to be released by the end of 2026.

Still, this is experimental science and there is always a drive to do it better. The LIGO, Virgo and KAGRA detectors are currently in a different mode with many people hard at work upgrading, reconfiguring, reprogramming, ... as well as thinking creatively about how to push even further in the future. LVK colleagues are carefully re-working not only the detectors, but also the organization of how we do science, as the details of the International Gravitational Wave Observatory Network (IGWN) continue to be hammered out. The intermediate-length "IR1" run starting in September or October 2026 will be a test not only of some incremental LIGO upgrades on the path to completing A+ but also of how the LIGO, Virgo and KAGRA communities will plan and operate in more unified ways under IGWN. We recognize that change brings uncertainty and even anxiety, and we are doing our best to represent and promote your interests in this transition. We thank the many people who have been contributing time and energy to the Design Committee, the Program Committee, and the Digital Infrastructure team to help implement the IGWN vision. Changing a well-established scientific enterprise is challenging, but even under the umbrella of a truly global organization with a new name, the LIGO Observatories will continue to anchor the exploration of the universe as revealed by gravitational waves.



Stephen Fairhurst  
LSC Spokesperson



Peter Shawhan  
LSC Deputy Spokesperson



## 04: Cornucopia of results continues!

**A** decade after the first observation of gravitational-waves with GW150914, the LIGO-Virgo-KAGRA (LVK) Collaboration announced the detection of a binary black hole merger with very similar properties but about three times as loud, GW250114, observed on the 14th January 2025. After 10 years of observatory and analysis improvements, the GW250114 signal was beautifully clear, providing fascinating insights into what happens after a black hole merger.

The LVK produced two papers about GW250114: one about the discovery itself and the other using the signal to test general relativity. Here, several members of the paper writing and analysis teams share their experience of working on and publishing the GW250114 results, a race against the clock!

### GW250114 – a beautifully clear binary black hole signal



**Teagan Clarke** is a postdoc at Princeton University who works on extracting all kinds of astrophysics from LVK data. Teagan enjoys martial arts, Melbourne coffee and trying to keep houseplants alive.

I was a member of the paper writing team for the GW250114 discovery paper. It was a sprint to the finish line from the moment the paper team was established in June 2025 until the publication in September 2025. Our task was a difficult one—to analyze, write and publish a high impact study for the recent loud binary black hole merger GW250114 in time for the 10 year an-

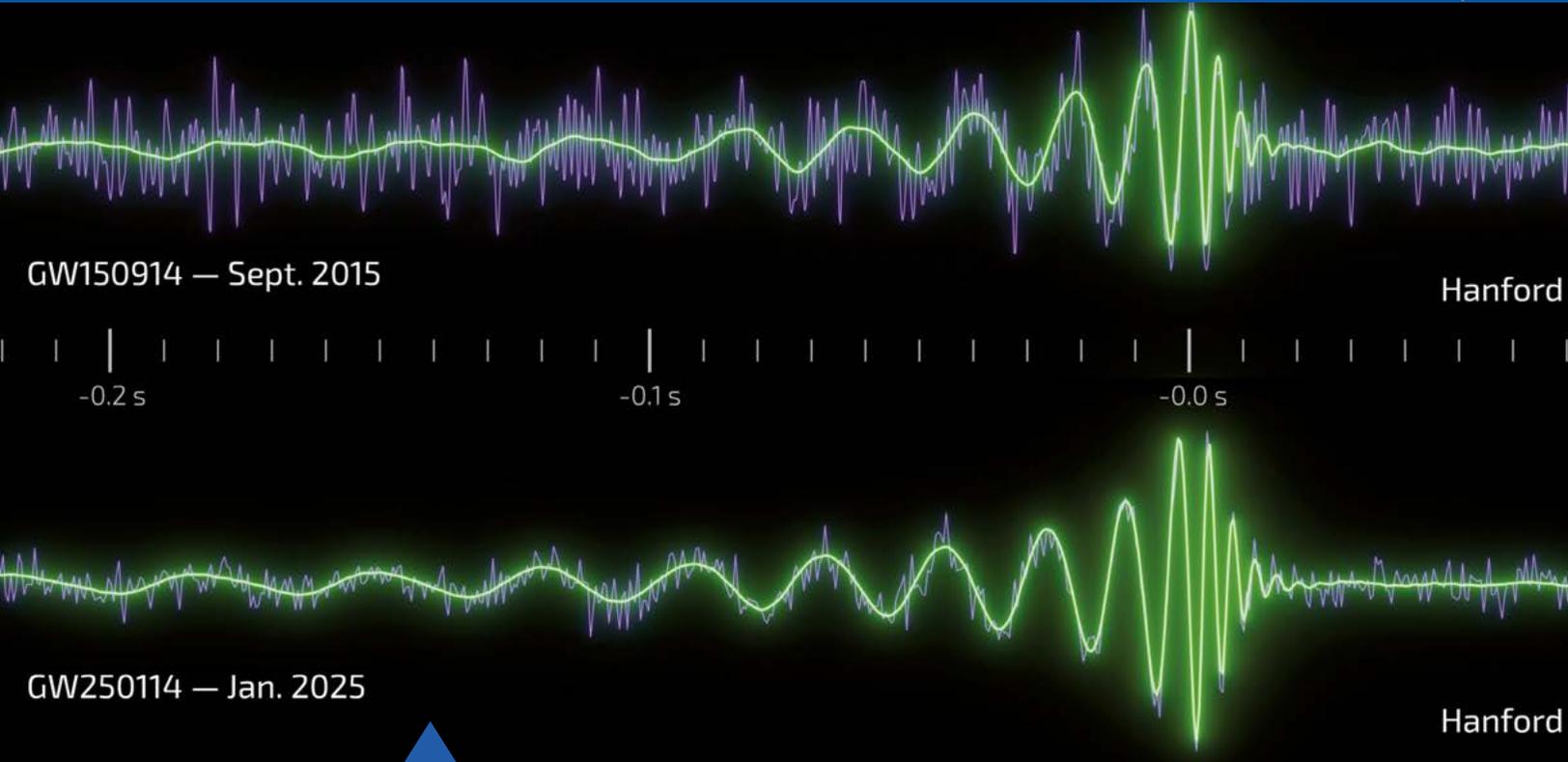
*An artistic representation of gravitational waves from GW250114, the clearest binary black hole signal yet!*

niversary of GW150914.

Luckily, it was a beautiful, amazingly clear signal encoding deep physical insights, one being Hawking's Area Law, which became the core story for this paper.

Those short months were some of the most intense of my PhD. It was a time of almost daily meetings, late nights, analysis, plots, review, deadlines... repeat. In the end, the paper was accepted for publication just a week before I submitted my thesis. I slept a lot after all that! It was totally worth it though.

I got to work with a lot of brilliant people in the collaboration during this effort - big thanks to everyone who helped me and the rest of the team make this the



Comparing two signals, observed 10 years apart. The top timeseries shows GW150914, the first gravitational-wave observation in 2015. The bottom timeseries shows GW250114, a very similar black hole binary merger observed in 2025. The purple trace shows the data from the LIGO Hanford Observatory and the remarkable reduction in noise between the two signals is thanks to fantastic improvements in noise reduction over the last decade. The green trace shows the best-fit prediction of the signal from general relativity.

is a worthy heir to GW150914 and the perfect demonstration of 10 years of amazing scientific progress. — TC



**Jacopo Tissino** is currently finishing his PhD at the Gran Sasso Science Institute in L'Aquila, Italy. In his free time, he runs on trails and does acrobatics.

needed to decide which were the most important, and focus on them quickly!

Like the preparation for a space launch, this kind of mission required a domino of earlier and earlier deadlines to allow for the journal's peer review as well as various stages of internal review: tracing them back, it meant that we needed a good draft of the paper within a month—and we were starting from an empty document and a couple of preliminary figures.

best paper it could be. I am so proud of our work and of the resulting paper. So many people worked really hard on this in many different capacities.

The rest of the discovery paper writing team: Max Isi, Katerina Chatziioannou, Jacopo Tissino, Chad Hanna and Ian Harry were a blast to work with—I learnt a lot from all of you! GW250114

The black holes giving rise to GW250114 were very similar to those of the first event, but due to the improvements in sensitivity of our detectors, the signal to noise ratio was almost three times as high. Even though it came from very "standard" black holes, without high spins or eccentricity, a signal detected with this level of clarity definitely enabled some great scientific results—we

The paper writing team had members from four different time zones: we were often literally working around the clock. I was lucky to be "in the middle", in Europe: Teagan often needed to join calls after local midnight in Australia! I remember those days as surprisingly peaceful: I'd decided that my summer would be occupied by this project, which brought a certain mental clarity.

# From GW150914 to GW250114

It was starting to get hot in Italy, so I often went for a run in the morning and then stayed until the evening in the air-conditioned office. Even though we did not all know each other (I hadn't met any of the other members before), the team became efficient very fast: communication among us was consistent, and it felt like progress was coming along nicely.

The six of us were not the only people dedicated to this effort: the paper went through several rounds of internal review, where every sentence and line of code was scrutinized, and several analyses were performed redundantly with independent means to ensure robustness. The communication and logistics needed to uphold these strict requirements, combined with the time-sensitiveness, were probably the hardest part of the project.

The paper had been through so much internal scrutiny that the review process for Physical Review Letters in August was quite fast and painless. We were able to publish it, and simultaneously release the data and code, with a few days to spare before the tenth anniversary of GW150914. — JT

*Hawking's Area Law states that the event horizon area of a black hole—a simple function of its mass and spin—cannot decrease over time. As it was such a clear signal, GW250114 provides a fantastic opportunity to confirm the Area Law by comparing the event horizon areas of the black holes before they merged and the horizon area of the resulting black hole after the merger.*



**Vasco Gennari** is a PhD student at the *Laboratoire des 2 Infinis (L2IT)* in Toulouse, France. When he's not struggling to understand black holes, you'll probably find him playing the piano, editing photos, or planning his next hike.

I was primarily involved in the analysis of the ringdown phase, both as an analyst and as part of the writing team for the tests of general relativity paper. My focus was on understanding how the newly formed black hole vibrates after the merger, and on identifying which of these vibrations are strong enough to be detected. While observations usually reveal only the main, fundamental vibration, we found that an additional one (the first overtone) was necessary to obtain results that are consistent with analyses of the full gravitational-wave signal.

Detecting two vibrational modes opens the door to directly testing the predictions of general relativity in the extreme regimes around black holes. By allowing for theory-agnostic deviations from the expected values, we showed that the clearest data available so far are fully consistent with Einstein's theory of gravity, the very question that first drew me to research a few years ago.

The entire production and publication process was extremely intense (from zero to a finished paper in just one month!) and necessarily required a full-time commitment from everyone

involved, with deadlines and meetings becoming part of our daily routine. I won't hide that the experience was both energy draining and mentally challenging, especially for a second-year PhD student as I was.

Still, it was remarkable to see how a group of people, many of whom had never worked together before, could self-organise around a shared goal: pushing our understanding forward, tackling unknown problems, and ultimately creating something that did not exist before. It is a complex process that also teaches you to appreciate the beauty of different—and sometimes diverging—viewpoints, something seemingly simple, yet the very fuel that drives research.

At the end of this roller coaster, I realise I'm left with more questions than I started with. To me, this is proof that we are on the right track. — VG



**Simona Miller** is a fifth year PhD student at Caltech working on robustly measuring the spins of binary black holes at every step of LIGO's data analysis pipeline.

*In their free time, Simona loves to rock climb, read, and organize for social justice.*

I was very excited to be highly involved with several papers on Observing Run 4 data, from using exceptional events to probe fundamental physics to constraining the properties of the astrophysical population of binary



black holes that we've observed over the last decade. I loved applying my expertise to collaboration-level research, and feeling like I was contributing to a scientific project bigger than myself.

I was one of the two main analysts behind the first-ever high-confidence observational confirmation of Hawking's Area Law with GW250114. The time-domain inference code I have dedicated a large portion of my PhD to developing was applied to measure the masses and spins, and thus areas, of GW250114's progenitor black holes from just the signal's inspiral data. The most satisfying moment of this project was seeing everything come together: after a long summer—certainly the most intense of my PhD—with around-the-clock meetings, review calls, and debugging on a tight timeline, combining my inspiral results with Nicole Khusid's ringdown results to see the final Area Law confirmation was extremely gratifying.

Personally, this work felt especially important in the face of the proposed NSF budget cuts over the summer. Not only was I producing exciting new discoveries, but those results were being used to help push back against deprioritization of science funding in the US at the federal level. I was even quoted in an article in a popular-science magazine about the groundbreaking measurement! — SM

## **GW241011 and GW241110 – the spinning twins**

**Two black hole binary mergers observed a month apart, GW241011 and GW241110 have been dubbed**

**the “spinning twins” due to the high spin black holes involved in the two mergers.**

**The GW241011 and GW241110 mergers involved one black hole which was both rapidly spinning and was significantly larger in mass than the other. These clues help us unlock the mysteries surrounding the lives of the stars from which these black holes formed. It is likely that the black holes themselves formed from earlier mergers, a process called the dynamical formation scenario. The black holes probably live in a star cluster—a dense crowd of stars and black holes in which multiple mergers are more likely to occur!**



**Mattia Emma**  
*is a final-year PhD student at Royal Holloway, University of London. In his free time, he enjoys playing basketball and beach volleyball with locals*

*while traveling.*

I had the opportunity to work as a parameter estimation expert, leading the analysis of the special events GW241110 and GW241011. These two events are remarkable—not only because they occurred at almost “twin” times, but also because they share intriguing global properties. Both provide evidence supporting dynamical formation scenarios for binary black hole systems, and their components rank among the highest-spinning black holes detected through gravitational-wave signals to date.

As this was my first experience contributing to a paper-writing team, the excitement was great. I was determined to ensure that our analyses were as precise and rigorous as possible. It was inspiring to see researchers from around the globe collaborating on a single project, overcoming time-zone differences, summer holidays, and the inevitable challenges of coordinating such a complex effort. The enthusiasm for each new result was contagious and incredibly motivating.

Because this was a special event paper, some of the analysis pipelines were not yet fully adapted for Observing Run 4b events. As a result, our team was the first to encounter and resolve several previously unseen technical issues—a challenge that proved to be an invaluable learning experience, but also caused some sleepless nights, veeeeery long email chains and git-lab issues :). Through this process though, I gained hands-on experience navigating the specific guidelines, approval processes, and workflows that are unique to LVK projects.

Equally rewarding was the chance to build new connections within the collaboration. Sharing the hard work and excitement of the analysis created a bond with colleagues, which continues to spark conversations at conferences and beyond. I am deeply grateful to all the collaborators who guided and supported me throughout this project, and I hope to pay it forward by mentoring future students in similar projects. — ME

## Hunting core-collapse supernovae:

### A unified effort

**M**assive stars, with mass more than eight times the mass of the Sun, end their lives in a Core-Collapse Supernova (CCSN). In this process, their layers plunge inward onto a dense proto-neutron-star core and rebound, generating a shock wave that drives a cataclysmic explosion. Despite their brevity, CCSNe\* leave lasting imprints, forging the elements that make up much of everything and everyone we know, and thus hold the answers to our cosmic origins.

CCSNe have been observed and interpreted in various ways for millennia. Ancient Chinese astronomers charted them as “guest stars,” and today they are among the most commonly observed astronomical transients. Yet



*Christine Lee is a postdoc at The University of Melbourne. Her work focuses on LIGO detector characterization, methods for detecting gravitational waves from core-collapse*

*supernovae, and the detection of pulsar glitches using Hidden Markov models. She is also a passionate science communicator, actively involved in outreach and promoting in-house codebases developed by the Melbourne group. Outside work, Christine enjoys travelling, tap dancing, and playing the piano and guitar.*

researchers are still endeavoring to ascertain the physics of their explosions, a quest that unites many disciplines, from theoretical physics to

*An artist illustration of a core-collapse supernova. Stars with mass more than eight times the mass of the Sun end their lives in a Core-Collapse Supernova.*

data analysis. This article highlights how the LIGO-Virgo-KAGRA collaboration, alongside the wider astronomy and astrophysics community, combines diverse expertise to advance this long-standing quest.

#### **Modelling CCSNe**

CCSNe involve a complex interplay of physical processes. Studying how these processes influence one another relies on detailed computational modelling. Neutrinos, a type of nearly massless elementary particles, are believed to drive CCSNe explosions. Therefore, understanding their production, transport, and

interactions in dense stellar environments is key to revealing the explosion mechanism. Equally important are (i) hydrodynamics, which governs the shock wave dynamics and the fluid instabilities that assist neutrinos in powering the shock wave that pushes the star apart and (ii) gravity and nuclear physics, that govern the behavior of the high-density matter in the stellar core. In addition to revealing the interior dynamics, accurate models are also crucial for predicting multimessenger signals (electromagnetic, neutrino, and gravitational wave) from these events, and guiding their detection. These signals bear the imprint of the supernova central engine.

### Multi-messenger observations

The first messenger through which CCSNe were observed is, of course, **electromagnetic radiation**. Hundreds of CCSNe have been observed electromagnetically providing insights into the explosion energetics, the synthesis of heavy elements, and ejecta dynamics. However, electromagnetic signals cannot penetrate the many layers of stellar material and thus cannot reveal the interior dynamics of the explosion. Fortunately, the era of multi-messenger astronomy is upon us; the largely unobstructed propagation of neutrinos and gravitational waves provides a new observational window into the hidden depths of CCSNe. Electromagnetic observations complement these multi-messenger signals by providing both the time window and sky location for targeted follow-up searches, particularly for **gravitational waves**.

Gravitational waves from CCSNe are

relatively weak due to smaller mass asymmetries compared to compact binary mergers, making their detection particularly challenging. Moreover, the signals are complex, unpredictable, and can easily be mimicked by transient noise, or glitches. Therefore searches must be versatile, but carefully executed to minimize the risk of false detections. As mentioned earlier, CCSNe modellers provide gravitational-wave analysts with predicted waveforms

*The mission to unravel the mysteries of CCSNe weaves together a constellation of expertise. As detecting multi-messenger signals remains a formidable challenge—limited by instrument sensitivity and the rarity of CCSNe in our galaxy—success depends on preparation, ingenuity, and a touch of cosmic luck.*

to study detection prospects. Since the early 2000s, the collection of CCSN waveform models has grown from a single family, with signals lasting only a few milliseconds, to multiple tens of families with signals lasting up to seconds, yielding improved constraints on the types of CCSNe that can be detected. Current instruments are sensitive enough to detect gravitational waves from a CCSN only if it occurs within the Milky Way. Nonetheless, significant efforts

have gone into optimizing detection techniques for current and future instruments, ensuring that strategies are in place to extract as much astrophysical information as possible, if a detectable CCSN occurs.

As the main drivers of CCSNe, **neutrinos** carry almost all the energy and signal the fate of the dying star. This was vividly illustrated by the detection of neutrinos from supernova SN 1987A, which confirmed that a core collapse had occurred and complemented electromagnetic observations. Unlike SN 1987A, not all core collapses produce visible explosions—some are obscured by dust, while others form black holes directly—but a neutrino signal can still confirm the collapse, constrain its timing and location, and provide insight into the explosion energy.

### Reflection

The mission to unravel the mysteries of CCSNe weaves together a constellation of expertise. As detecting multi-messenger signals remains a formidable challenge—limited by instrument sensitivity and the rarity of CCSNe in our galaxy—success depends on preparation, ingenuity, and a touch of cosmic luck. In that spirit, theorists and experimentalists must continue to collaborate and convey the challenges of their work, forming a feedback loop that sharpens predictions and detection strategies. This shared understanding will maximize both our chances of detection and the scientific rewards we will enjoy upon such a detection. May the universe be in our favor!

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# Voices of the CCSNe community

This article draws from conversations with members of the CCSNe community, both within and beyond the LVK collaboration. Alongside scientific perspectives, they also generously shared their personal thoughts and experiences in this area of research.

## Gravitational-wave data analysis



**Marco Cavaglià**, Missouri University of Science and Technology  
“What’s better than a supernova to learn from? And the thrill of being the first to know – that’s the coolest thing!”

**Michele Zanolin**, Embry-Riddle University

“I love CCSNe research for it’s many layers of interaction [...] each layer brings new ideas, and sometimes they activate parts of my brain I didn’t even know existed.”



**Marie Anne Bizouard**, Artemis, Université Côte d’Azur  
“Long-term developments, working with students, and transferring my knowledge to bring a new generation into the field is the best part of my work.”

**Marek Szczepańczyk**, University of Warsaw

“There is a lot of physics we can extract from CCSNe, [...] everything is so fresh and you can put a lot of your own creativity into it – I like that freedom.”



**Adrien Paquis**, IJCLab  
“We don’t know what we’re looking for yet. That’s exactly what makes it so exciting—anything could happen!”



**Yanyan Zheng**, Missouri University of Science and Technology

“The combination of complex supernova physics and the analytical challenges drew me into this field. [...] and the possibility of uncovering new physics keeps me excited.”

## CCSNe modelling

**Anthony Mezzacappa**, University of Tennessee

“What keeps me going is ultimately the same thing that ignited the flame to begin with: my love for relativity.”



**Jade Powell**, Swinburne University of Technology

“Making some of the biggest objects in the universe explode is just really cool. [...] And my favourite aspect of CCSNe is that, if you get a really close one, you could see it in your garden.”

**Marco Cusinato**, University of Valencia

“It is an area full of open questions. A future galactic supernova would provide an unprecedented opportunity to test our models and uncover new physics.”



## Electromagnetic observations



**Rosa Poggiani**, University of Pisa

“We work on our topics with our own identities and skills, and when we put it all together, we create something that is more than the sum of individual contributions.”

## Neutrino theory

**John Beacom**, Ohio State University

“I like synthesizing things – connecting theory and computation to experiments and observations, pulling things together from different fields to make it all work.”



# Inspirational physicist and indefatigable individual



## Remembering Rainer Weiss

**W**hen Rainer Weiss passed away on August 25, 2025, the worldwide physics community lost not only an inspirational and brilliant physicist but also an indefatigable individual who delighted in continually trying to understand the world – and people – around him. Simultaneously down to earth while coming up with profound insights into how some piece of physics worked, Rai always brought curiosity, passion, and a 'tinkerer's' attitude to his work.

Throughout his long career, Rai mentored many students, post-docs, and junior scientists. Beyond that he inspired countless more through his nearly 70-year career in physics. Rai was a giant in two separate fields: the cosmic microwave background produced by the Big Bang and gravitational-wave astrophysics.

Rai's leadership as the co-founder and chair of the scientific working group for the Cosmic Microwave Background Explorer (COBE) was critical to COBE's Nobel-winning spectral mapping of the residual 3 K degree background radiation from the early Universe, in the late 1980s and early 1990s. His pioneering insights in the 1970s into how to build an interferometric gravitational-wave detector ultimately resulted in LIGO and its first direct detection of gravitational-waves from merging black holes, for which he shared the Nobel Prize in 2017.

Rai never shied away from questioning himself or anyone else if he couldn't understand something. And he (in sometimes humorous and colorful language) was never shy about expressing his viewpoint. But almost everyone who

Rai celebrated his 90th birthday with friends and colleagues at MIT.

"This is the photo that comes closest to illustrating the Rai who fixed the computer. Here he is fixing a cryogenic bolometer amplifier, but the room, the epoch, and the T-shirt are all spot-on. There is even a 3 nuns tobacco tin and corn-cob pipe there!"

David Shoemaker



had substantial interactions with Rai came away from them a better person in some way. Here are a few reminiscences about Rai and the wonderful influence he had on us.

- Dave Reitze -



In 1972, upon hearing for the first time of Rai's idea to detect gravitational waves using laser interferometry, I wondered if Rai had gone crazy; the challenge looked outrageously difficult.

With Misner and Wheeler I was preparing to ship off to our publisher the manuscript of our textbook *Gravitation* (commonly known as MTW). So into the manuscript, at the last moment, I inserted a very brief description Rai's interferometry idea in a broader context, and a statement that it was likely to be "of little experimental interest".

Forty three years later, when LIGO observed its first gravitational wave, Rai and I both took great delight in a photocopy of my negative pronouncement – MTW Section 37.3, item 1 – taped to Rai's MIT office door. What a joy it was to work closely with him over several decades to confirm my stupidity!

- Kip Thorne -

Many stories come to mind which show Rai's great warmth, intelligence, imagination, and occasionally patience. I will recount here a story of our computer from the 1980s, a DEC PDP 11/20. This machine supported all the data acquisition and analysis in the lab as well as running a word processing program that I had written for my thesis. A graduate student (who shall remain unnamed) was rolling a rack with a powerline to it near the computer, pulled on the cord, exposed a conductor, and put 120V onto the frame of the computer, and with a snap and a bright blue flash it went down.

I turned to a Selectric typewriter for my thesis. Rai took out a fresh tin of Three Nuns tobacco and a new corn cob pipe, sat down crosslegged on the Building 20 floor in his grey work pants and white T-shirt, and started troubleshooting the computer. About two weeks later, he had found the 100 or so blown transistors and soldered in new ones, and the computer was back in business. I don't remember him complaining at all about it, and suspect Rai really enjoyed that break from COBE and LIGO-to-be.

- David Shoemaker -

A fond memory of Rai was that he never lost his connection to and admiration of makers. I had the pleasure to work with Rai, Boude Moore, Bill Althouse, Alex Abramovici and Steve Vass on early experimental work to devise the practices that would allow us to build one of the world's largest vacuum systems, capable of achieving a trillionth of an atmosphere in 5 miles (8km) of meter-diameter beam tube at each observatory. It was hard enough to do in experimental prototypes in the campus labs at Caltech. But when a left-over fingerprint can contaminate miles of tube or a hard-to-see blemish on a weld can cause big problems, how do you translate strange [manufacturing and controls] procedures for, and get buy-in and engage the minds and hearts of all the builders on board?

Rai knew how: You talk to them.

We paid the union boilermakers at the Big Pasco manufacturing plant to listen to Rai explain how each step of their work connected to Einstein as

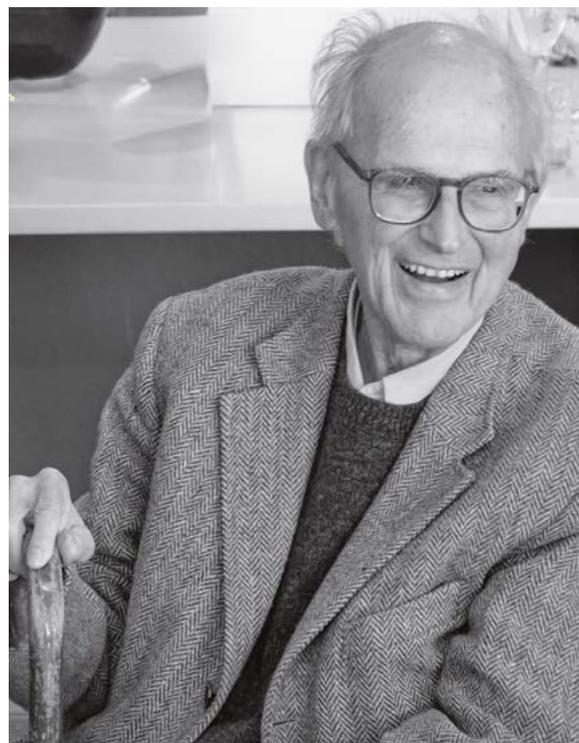
well as to the future of astronomy that their children and grandchildren would learn about in school. It worked!

- Fred Raab -

While I have always been amazed and guided by Rai's ingenuity, integrity, and humility, I was most impressed by his breadth of vision and ability to move between worlds. He could seamlessly shift from the smallest technical detail of an instrument to the global vision for a future observatory. In the last few years, as the idea for a next-generation gravitational-wave observatory grew, Rai would often be at my door, sharing ideas for how to move the project forward on all levels. These discussions ranged from quantum mechanics to global politics, and Rai's insights and efforts have set the stage for the future.

- Matt Evans -

Rai on his 90th birthday.



29. September 1932 - 25. August 2025

# The LVK meeting in the countryside of Tuscany



## Embedded in the land of science:

## Virgo in Pisa

Photo by Enrico Sacchetti

*The beginning of the north tunnel of the Virgo detector; the laser travels through the left tube, while the right tube is part of the squeezing cavity, a system that helps reduce quantum noise.*

**T**he next LIGO-Virgo-KAGRA Collaboration Meeting will be held in Pisa, a thirty minutes drive away from the European Gravitational Observatory (EGO), which hosts the Virgo detector.

The 3 km long arms of Virgo sit peacefully on the Tuscany countryside, their blueish-purple color specifically designed to match that of the horizon and make sure that the detector, one of the largest scientific experiments in Europe, doesn't impact on the landscape that makes this region famous worldwide.

*The Museo Galileo in Florence houses the only surviving instruments of Galileo Galilei.*

Actually, this area is flatter than the usual countryside of Tuscany (that's important if you need to build a gravitational-wave detector) and more crowded: there's more roads, houses, small factories, tractors working the fields. It's a region full of life, and while from a scientific point of view some of these things represent noises for the detector, Virgo is embedded in the land that hosts it and engaged in a constant

dialogue with its community, which began over 30 years ago and is of fundamental importance for the success of this experiment.

After all, Virgo's presence in this territory is far from a matter of chance. Tuscany, and the Pisa area specifically, has always been a land of science. The city's university was founded 700 years ago, making it one of the oldest in Europe, and Pisa has

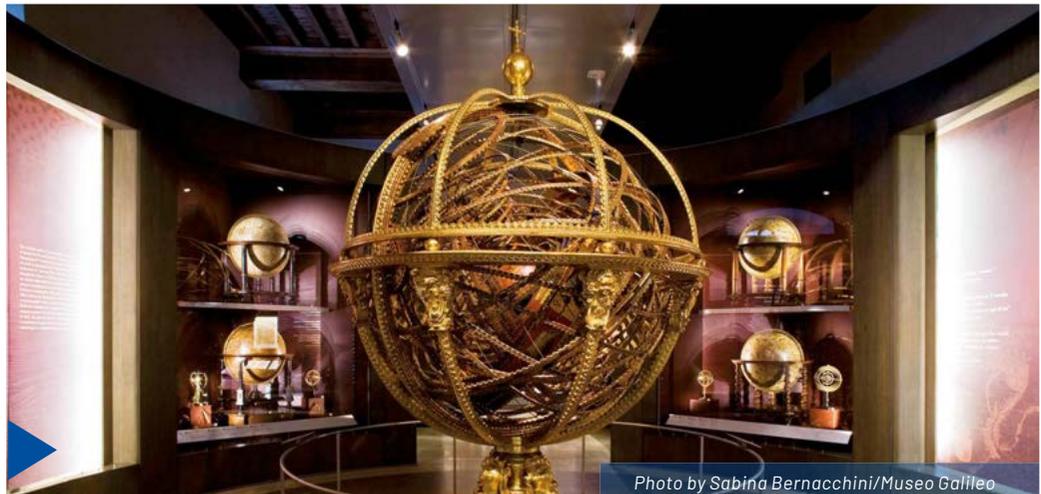


Photo by Sabina Bernacchini/Museo Galileo



Photo by Enrico Sacchetti



Photo by Luca Morgantini

been the home of many important scientists, the most famous being Galileo Galilei. Today the area continues to be a very relevant hub of scientific research in Italy, with various universities and important research institutions in the city and the area nearby, such as

the Scuola Normale Superiore, the Scuola Sant'Anna, the CNR Area of Pisa, the Navacchio Technology Hub and the Pontedera Technology Hub.

If you're joining the LIGO-Virgo-KAGRA Collaboration Meeting, in these pages you can find some sug-

***The 3 km long arms of Virgo sit peacefully on the Tuscany countryside, their blueish-purple color specifically designed to match that of the horizon and make sure that the detector doesn't impact on the landscape that makes this region famous worldwide.***

gestions among the many scientific, historical, and artistic attractions of the area. The venue for the conference itself, Pala Todisco, is located at the foot of the Monti Pisani, where you can enjoy relaxing walks and visit picturesque villages. An hour's drive away, you enter the provinces of Siena and Florence, which are equally rich in spectacular landscapes and artistic and historical sites. And if you miss the more 'stereotypical' tuscanian landscapes, endless rolling green hills with villas surrounded by cypress trees, they are only a short drive away.



*The site of Galileo's famous experiment on gravitation.*



Photo by Gervasio Ruiz



I grew up in a small town in the Saudi desert, spending much of my childhood with my grandmother. Life there was quiet, surrounded by wide open land and clear skies. At night, I loved to sit outside and look at the stars. The desert sky was full of light—the Milky Way, the moon, and countless stars that seemed so close. I did not know it then, but those nights were the beginning of my interest in the universe.

When I began university, I was drawn to physics because it offered a way to understand how the world works, from the smallest particles to the largest galaxies. Later, I moved to Glasgow to pursue my master's degree, which was my first experience studying abroad. It was both exciting and challenging—a new country, a new culture, and a new approach to research. During my master's studies, I took a course on gravitational-wave detection, and that was the moment everything changed. After completing my master's degree, I decided to continue my academic journey by beginning a PhD at the University of Glasgow.

My PhD research focuses on early warning detection of gravitational waves from compact binary coalescences using machine learning, particularly Long Short Term Memory (LSTM) neural networks. The goal is to detect gravitational-wave signals before the final merger happens. Early detection could give telescopes time to point toward the source and observe any light or other signals that follow the merger. These observations help scientists better under-



Reem Alfaidi

is a PhD student at the University of Glasgow working on early warning detection of gravitational waves from compact binary coalescences. Her research focuses on applying machine

learning techniques to detect gravitational-wave signals prior to merger, enabling rapid multi-messenger follow-up observations. Outside of her research, she enjoys running, hiking, and spending time at the gym.

stand neutron stars, black holes, and the physics behind these extreme events.

In my work, I use LSTM neural networks to analyse gravitational-wave detector strain time-series. The model learns how gravitational-wave signals evolve over time and how to distinguish them from detector noise. I train the model using simulated data, where compact binary coalescence signals are injected into noise. The results so far are promising—the model can detect some events tens of seconds before merger.

Looking ahead, my plans include training and testing the model on real detector data, moving beyond idealised simulations. I also plan to extend this work to include event localisation, combining early detection with estimates of the source position in the sky to support rapid follow-up observations.

Outside my research, I am committed to science outreach, particularly in Saudi Arabia and the Arabic-speaking

world. I write and speak about gravitational waves in Arabic, and I work on podcasts and a personal website where I explain these topics in accessible language. My goal is to make gravitational-wave science more visible and to inspire students who may not yet see themselves represented in this field.

In the future, I hope to help build a Saudi research group that can take part in the LIGO–Virgo–KAGRA collaboration. I believe Saudi Arabia has many talented students and researchers who could contribute to this growing field, and that outreach and education are important steps toward building this community.



Reem's home town.

## From gravitational waves to growing bone

**O**n October 3, 2008, I was a postdoc working with Professor Sir Jim Hough and Professor Sheila Rowan when we received an intriguing email from Professor Emeritus Adam Curtis.

Adam was an eccentric character who'd held the first Chair in Cell Biology in Europe back in the 1960s (before this they just had Chairs in Biology). He'd planned a peaceful retirement, gardening and ocean diving. But, during his final conference trip in Greece, he was bitten by a fish leading to an undiagnosable flesh-eating disease that kept him in the lab instead.

He needed help delivering tiny vibrations to cells to potentially manipulate and control cell behaviour. These vibrations were "astronomical" compared to gravitational wave signals, so we jumped at the chance to help!

It turns out that stem cells are very sensitive to mechanical signals. We - the biologists and LIGO physicists - discovered something surprising: vibrations of just 20-30 nanometers at 1 kHz (a thousand cycles a second) - which is between the musical notes B and C two octaves above middle C - coax mesenchymal stem cells (MSCs)\* to become bone-building cells. No drugs needed. No complex scaffolds. Just mechanical vibration, measured and controlled using our LIGO-honed techniques including



*Stuart Reid leads a team of researchers working on both optical coatings and stem cell research at the University of Strathclyde and is also CEO of the UK's laser damage testing and certification test house - BRL Laser Damage Ltd. He is married to Mariela (who also works in the LSC) and has four children, Noah (6), Ollie (3), Emily (1) and Tyler (due May 2026).*

laser interferometry and computational modelling.

This was the first time anyone had promoted bone formation in the lab through purely physical means in standard culture plates. We developed and patented a nanovibrational bioreactor, eventually demonstrating it could work in 3D gel constructs suitable for surgical grafts. Bone is the second most transplanted tissue after blood.

This technology is now moving toward patients. Between 2018 and 2021, we conducted trials applying nanovibrational stimulation directly to people with spinal injuries. Our recent findings showed bone formation markers appearing in their blood—hinting that this approach might help treat or even reverse osteoporosis. More work needs to be done to enhance the effect.

I hope this is an encouragement to younger researchers to explore opportunities outside their immediate field of research and an encouragement to group leaders to support their younger staff to explore opportunities.

Next year, we're planning the first-in-human study for surgical grafts, funded initially by £2.8M from the Sir Bobby Charlton Foundation (the late ex-Manchester football player) and European grants. Meanwhile, a large £11M EPSRC-MAINSTREAM grant is tackling how to scale up stem cell manufacturing for treating blood cancer and regenerating damaged tissues.

I am extremely grateful to my colleagues in LIGO and at the Institute for Gravitational Research (Jim, Sheila and many others at the University of Glasgow) for allowing me as a postdoc to develop the skills that could be applied to medical applications. I also want to shout out to Matt Dalby (biologist) and Manuel Salmieron-Sanchez (biomedical engineer), the professors who lead the big projects in Glasgow - and for keeping me a part of the work whilst keeping 50% of my time for LIGO research.



*A wearable bone conduction headphone device for possible treatment of osteoporosis.*

I hope this is an encouragement to younger researchers to explore opportunities outside their immediate field of research and an encouragement to group leaders to support their younger staff to explore opportunities.

\* MSCs are adult stem cells in our bodies that have the ability to form the connective tissues - bone, cartilage, muscle and fat.

## From tabletop experiments to commercial squeezed light sources

Interferometric measurements are a widespread tool with applications ranging from monitoring the structural integrity of buildings to observing wind conditions on airports. Interferometric measurements with conventional laser light are ultimately limited by photon shot noise. In 1981, Carlton Caves proposed to squeeze the shot noise. Since then, a lot of R&D efforts have led to reaching this limit and even beating it.

Photon shot noise also limits the sensitivity of gravitational-wave detectors. Measurements beyond this shot noise limit can be performed using squeezed states of light. The term “squeezed” refers to an electromagnetic field in which the quantum uncertainty in a specific property (the amplitude or phase quadrature) is reduced below that of the quantum ground state, while the noise in the complementary property is increased to obey Heisenberg’s uncertainty relation. Squeeze factors greater than ten are generated in non-linear crystals using cavity enhanced degenerate parametric down-conversion.<sup>1</sup> The GEO, LIGO, and Virgo gravita-



*Axel Schönbeck*

*studied physics at the Universities of Hannover and Queensland. His PhD at the University of Hamburg in 2018 was about a compact squeezed light*

*source at 1550 nm. He continued developing squeezed light sources, and co-founded Noisy Labs in 2023 to make this technology available to researchers in science and industry and to support the development of squeezed-light enhanced quantum technologies.*

tional-wave detectors were already successfully improved with squeezed light. This achievement marks an important milestone in the development of photonic quantum technologies: The first use of squeezed light in a user application.

Research shows that many more applications may benefit from the sensitivity enhancements of squeezed light in the future, solving important problems of our time. Improvements in biosensing applications, like the characterization of cancer cells, could translate to faster and improved diagnosis and shorter times

spent in the operating theater which improves both the quality of life of patients and the economy of hospitals and healthcare. Simulations that are run on photonic quantum computers that use squeezed light as a non-classical resource for entanglement may help in the search for high temperature superconductors or new battery materials.

To realize this potential, research and development are required on the user side. However, researchers working in these areas face the expensive and time consuming challenge to build their own squeezed light sources in-house, which often are large scale quantum optical set-ups covering entire optical tables. A commercially available package consisting of squeezed light sources, high quantum efficiency balanced detectors, inte-



*Noisy Labs’ balanced detectors are equipped with high quantum efficiency photo diodes and are available at 1550 nm, 1064 nm, and in the 600 to 900 nm range.*



grated control electronics, and support for the application of squeezed light would be ideal.

Noisy Labs was started to make this a reality. The company was founded by Jan Südbeck, Jascha Zander, Dieter Berz-Vöge, Roman Schnabel and Axel Schönbeck and is currently supported by two part time employees and two remote assistants. Jan, Jascha, Roman and Axel bring their expertise in quantum optics, squeezed light generation and squeezed light applications to the table, while Dieter's expertise is in business development and growing companies.

The company and its developments in compact squeezed light sources, high quantum efficiency balanced detectors and integrated locking technology is based on years of research that was initiated by Roman Schnabel and his group members at the University of Hannover and continued at the University of Hamburg as well as in the PhD theses of the founders.

Major questions that were solved in the development process include:

- How can a table-top sized squeezed-light source be transferred onto a compact breadboard?
- How can the technology be brought to other labs and how will it perform in different working environments?
- How do scientists interact with the technology and which settings and signals do they need access to in order to make the most of the source?
- How can the usability of the technology be improved?
- What is next and will be needed in the future?

Noisy Labs is continuously working on answers to these points to improve the technology and make it fit the needs of researchers and the applications they are working on. The team is happy that it was able to rely on supportive partners from the very beginning that use the technology

and provide invaluable feedback and insights by doing research and development with Noisy Labs products, thus pushing the limits of quantum technology towards real-world applications of squeezed light.

*The name "Noisy Labs" was chosen to be memorable and a little unexpected. The company offers quantum noise reduction with squeezed light. "Noisy Labs" is a reversal of the company's main objective, creating a catchy name that is easy to remember and sparks curiosity about the products.*

Noisy Labs

LIG 2026



*Noisy Labs' squeeze laser consists of a control unit (left) and an optical unit (right). It provides up to 10 dB of squeezing at 1550 nm or 1064 nm and includes locking technology to stabilize the squeezing angle and readout phase in balanced homodyne detection.*

#GWSciArt2025

# Cosmic Canvas

Inspiring Science

Cosmic Dust

through Art

*Cosmic Canvas Poster 2025*

**D**uring the pandemic back in 2021, when I was newly appointed Chair of LIGO-India Education and Public Outreach (LI-EPO), I introduced the LIGO-India blog Gravity Matters, with a section specially dedicated to art inspired by Gravitational wave science, called “GWSciArt” [1]. It featured artworks of various media such as poetry, digital and traditional artwork, astroportraits and more, mostly contributed by researchers and students working in the LIGO-Virgo-KAGRA collaboration. This created a new movement on social media inspiring many, and was also featured in the LIGO magazine special issue #18 [2].

*Debarati Chatterjee*



*is a Theoretical Astrophysicist, currently Professor at Inter-University Centre for Astronomy and Astrophysics (IUCAA) in Pune, and Chair of Education and Public Outreach for the LIGO-*

*India project. She is also a passionate Science communicator and Ambassador for Diversity, Equity and Inclusion. She finds work-life balance through diverse activities like learning languages and dances from across the globe, sketching, yoga and adventure sports.*

The goal was to now reach out to a broader audience. In 2022 the #GWSciArt theme challenge [3] was launched by LI-EPO ahead of the National Science Day (NSD) in India (28 Feb). Entries

were open to artists from all skill levels, and in any artform that expresses the themes “Gravity”, “Wave” and “Motion”. In 2024, this was given a more formal framework, when the SciArt competition “Cosmic Canvas” was announced. The competition was advertised through social media platforms and had the themes “Gravity”, “Light” and “Waves”. This time it received an overwhelming response, with several hundred entries received from science enthusiasts, including junior school students! The entries ranged from traditional paintings, sketches, digital art, astrophotography or even poetry. The screening of the entries was done by the then LI-EPO team members (me, along with Senior and Junior outreach coordinators, Saurabh Salunkhe and Jalak Mehta). The winning entries were showcased through an art exhibition at IUCAA during the NSD2024 cel-

celebrations and also featured in a virtual gallery [4].

In 2025, the focus of the “Cosmic Canvas” SciArt competition was on comic art in any medium. There were various fun topics to choose from - “Newton vs Einstein”, “Cosmic dust”, “Star wars: the Dark Side” and “Relativity theory”. During this contest, LI-EPO featured the Museum of Cartoon Art, Savitribai Phule Pune University, on its third anniversary. This museum was established in 2022 under the Department of Media and Communication Studies, with the objective of inculcating interest in cartoons and caricature. The museum exhibits works of renowned cartoonists in India and has a huge collection of vintage cartoons from the pre independence era of Indian history, editorial cartoons, illustrations, caricatures, comic strips, varied collection of books and resource material for research. Dr Priya Gohad, curator of the Museum of Cartoon Art, was invited to be jury for the comic art contest. The entries received were hilarious and numerous, and displayed a fantastic sense of humour! The winning entries for the theme “Newton vs Einstein” were highlighted across LIGO-India social media platforms.

From mid Nov-mid Dec 2021, I had organised an online astrophotography webinar series for LI-EPO, featuring some of the top astrophotographers from the country: Rakesh Rao, Dorje Angchuk, Nishant Gor and Rahul Zota. A contest was announced at the end of the series, and the entries were spectacular! The images were displayed in a virtual astrophoto gallery “Astropix” [5] on NSD2022. An astrophoto calendar was also launched in 2022 with the winning entries, and was available to

download for free. In 2024, LI-EPO also created another astrophoto calendar [6] with photos by astrophysicist and award-winning science communicator, Dr. Sumeet Kulkarni.

In 2026, the focus of the Cosmic Canvas contest is on astrophotography. This is timely, as astrotourism is growing in India, with many regions identified and recognised as dark sky locations in Ladakh (Hanle, Spiti Valley), Uttarakhand (Kumaon Hills, Mukteshwar), Gujarat (Rann of Kutch), and Rajasthan (Jaisalmer). There is a growing need to leverage minimal light pollution for stargazing, astrophotography as well as cultural immersion, astronomy education and supporting local livelihoods. To promote this activity, an Astrophotography webinar was organised by LI-EPO on 16 December 2024 by Dr. Sumeet Kulkarni, who shared many guidelines, tips and tricks to capture the night sky. The Astrophotography contest has been announced as this year’s medium for SciArt. Particular weightage will be given to astrophotos capturing celestial patterns with educational value, cultural significance (such as heritage, astro-heritage sites or mythological context) or regional relevance. The best selected images will be displayed at the LIGO-India booth on NSD2026 or featured in the virtual SciArt gallery. Hoping to see a good response and some beautiful captures!

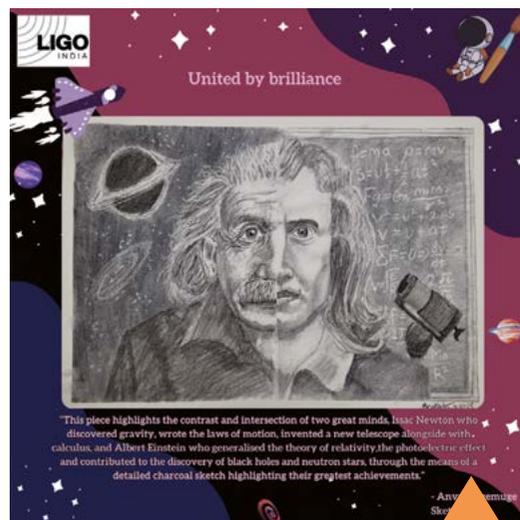
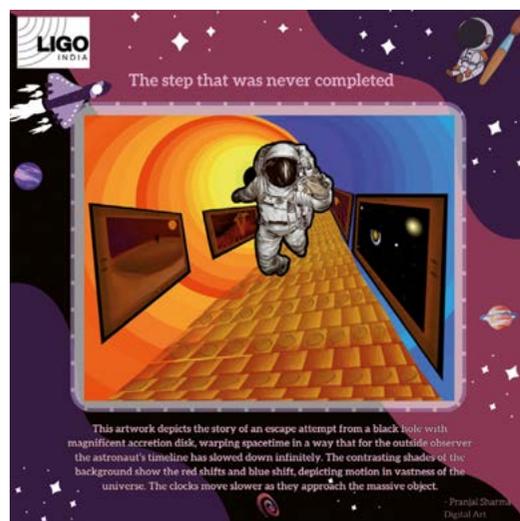
**Additional details:**

**Cosmic Canvas 25'** - 89 Entries (36 Selected: 8 Poems, 23 Hand Drawings & paintings, 5 Digital)

**Cosmic Canvas 24'** - 102 Entries (27 selected: 10 Digital, 5 Poems, 11 Hand drawings & paintings, 1 Digital Video)

**Links**

- [1] <https://www.ligo-india.in/sciart/>
- [2] <https://www.aei.mpg.de/1207077/LIGO-magazine-issue18.pdf>
- [3] [https://www.ligo-india.in/gws-ciart\\_nsd2022/](https://www.ligo-india.in/gws-ciart_nsd2022/)
- [4] <http://www.ligo-india.in/ligo-india-cosmic-canvas24>
- [5] [https://www.ligo-india.in/astropix\\_gallery/](https://www.ligo-india.in/astropix_gallery/)
- [6] <https://www.ligo-india.in/astrophotography-calendar-2024/>



*These images are representative of the quality of received entries.*

# Meanwhile ... the quietest place in space



## LISA Pathfinder: Ten year anniversary!

*The LISA Pathfinder control room at the European Space Operations Centre (ESOC) in Darmstadt, Germany. An adjacent room was a home away from home for the operations team of scientists, ESA experts and industry partners until July 2017.*

**L**ISA Pathfinder (LPF) was a proof-of-concept mission led by the European Space Agency (ESA) with contributions from NASA. Launched in December 2015, its goal was to test the technology required to achieve a gravitational-wave observatory in space and it was a resounding success! The mission concluded in July 2017 having achieved a sensitivity far beyond the mission requirements. LPF paves the way for LISA (Laser Interferometer Space Antenna), a space-based gravitational-wave observatory scheduled for launch in 2035.

### Creating the quietest place in space

Gravitational-wave detectors measure changes in distance between objects known as test masses. Different to ground-based detectors, the test masses in space are golden cubes a few centimeters each side and approximately 2kg in weight. At the heart of LISA's science goals is the need for very quiet test masses that are influenced only by gravity. This ensures that the tiny changes in distance between two test masses due to gravitational waves can be monitored. Achieving such near-perfect free fall in space is technically challenging: tiny residual accelerations are always present. Back at the end of the last century, the required levels of residual acceleration needed

for LISA were orders of magnitude below anything that had flown to the day. For this reason, a dedicated proof-of-concept mission was deemed necessary—the birth of LPF!

LPF delivered this crucial measurement, creating the quietest environment ever measured in space [1], using sophisticated sensors [2], and trialing different control modes [3]. Now teams are busy preparing for the LISA mission, a constellation of three spacecraft flying in triangle formation. LISA will unlock new types of gravitational-wave observations at lower frequencies than ground-based observatories like LIGO-Virgo-KAGRA.

Here we mark 10 years since LPF with reflections from some of the ear-

ly-career scientists who participated in the mission operations and we look forward to a gravitational-wave observatory in space in 2035!

### Analysing the LPF data in near-real time



**Roberta Giusteri** is a postdoctoral researcher at the Trieste Astronomical Observatory (Italy) where she is part of the team responsible for monitoring the instruments on board the Euclid satellite.

*Euclid is a space telescope designed to answer fundamental questions in cosmology by mapping the large-scale structures of the Universe. In her free time, she enjoys Zumba and cooking.*

Being part of the LPF collaboration was truly a privilege! I never imagined that I would be working as a PhD student on a space mission that was about to be launched. Before it became operational, the whole team was involved in designing and testing analysis procedures using simulated data and preparing for the operational phase. On LPF, as in a space laboratory, a series of experiments were conducted with the aim of characterizing and limiting the main disturbances affecting the scientific measurement. The experience at the European Space Centre (ESOC) in Darmstadt, Germany, was very exciting: every day a small team was in charge of analysing the data

*Showing the LISA Pathfinder test masses (gold cubes) within the LISA Pathfinder science module.*

from the previous day's experiments and sharing the results with the entire team spread across the globe.

I recall the constructive atmosphere that reigned in that room, where everyone had a role and could count on the support of ESA engineers. From the scientific point of view, I remember how surprised we all were by looking at the high level of precision already achieved in the early stages of operations: it was incredible that the instrument worked so well millions of kilometers away! This was also the case for the experiment I was mostly involved in: with great excitement, we could repeat and adapt it to different configurations and our predictions were confirmed in all cases.

The unique scientific opportunity I

***I remember how surprised we all were by looking at the high level of precision already achieved in the early stages of operations.***

experienced would not have been the same without the stimulating spirit of the team, formed by many young researchers supported by inspiring scientists. I believe this is certainly the



best environment for scientists who are at the beginning stage of their careers! As a matter of fact, after my PhD, I decided to keep working in this field, like many of us, and I joined the LISA group at the Albert Einstein Institute in Hannover, Germany.

### Winning the ESA Team Achievement Award in 2017



**Sarah Paczkowski** is a postdoctoral researcher at the Max Planck Institute for Gravitational Physics (Albert Einstein Institute). She works

*on mitigating tilt-to-length coupling in LISA data processing, supporting the LISA Performance & Operations as well as the LISA Distributed Data Processing Centre. Outside of physics, she enjoys, for example, hiking and swimming.*

It was a unique experience to contribute to the LPF science as a PhD student. I remember very well my first shift on the science and data analysis team at the ESOC in Darmstadt, Germany, at the beginning of the nominal operations phase. Typically, we started our shifts around nine in the morning, after the data to be analyzed was telemetered to ground and the initial processing was done by the experts.

As background: the free-falling test masses on LPF experienced a local static gravitational acceleration inside the satellite. Thanks to very careful engineering, this acceleration was much smaller than expected. As a result, we were able to lower the maximum actuation settings, which the senior scientists expected would reduce



the residual acceleration noise. On my first shift, we analyzed data from one of the early measurements using reduced actuation settings. It was exciting to see that not only nothing broke but more importantly, that the residual acceleration noise was indeed lower than in previous configurations. This was an important step toward the measurements we later published.

In the course of the mission, we could also do more detailed experiments and it was great to see that experiments you planned or prepared for were actually run and then to analyze the data!

Behind the scenes, there was a large team from the industrial partners, ESA specialists and scientists from many countries working together in an informal and friendly atmosphere—which, together with the success of the mission, had us winning the ESA Team Achievement Award in 2017!

## A welcoming, supportive, and enthusiastic environment



**Lennart Wissel** is a postdoc at the Max Planck Institute for Gravitational Physics (Albert Einstein Institute) working on LISA, with respect to on-board data processing and noise modeling. In his free time he enjoys hiking, reading and exploring the world outdoors.



My personal experience with LPF was exciting and exhilarating. Just back from a year in Birmingham, UK, where I spent part of my master's degree, I joined the LPF team at the Albert Einstein Institute in Hannover for my thesis research. What an opportunity and treat this was. I found myself thrown into a mission I had not worked on before, contrary to all the people I met during launch preparation and subsequent mission operations. However, I cannot stress enough how welcoming, supportive, and enthusiastic everyone was, helping me navigate this new environment. The scientists, engineers, industry partners, and folks at ESA were deeply committed to this project, but they carried that seriousness with curiosity and passion about this rare opportunity: measuring things no one ever had seen!

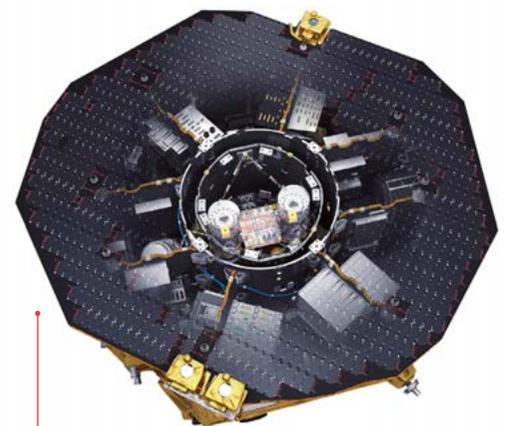
My personal contribution consisted of a broad range of tasks: from hardware monitoring to designing, simulating, and analyzing specific experiments (mainly focused on laser intensity noise coupling) during the main mission phase and its extension. After the mission concluded, I helped synthesize the full picture of the optical readout's performance—a phenomenal system thanks to the hard work of many people before my time.

My biggest takeaway for LISA is that when we connect and share our enthusiasm and curiosity, LISA will become the great success that LPF

and the entire gravitational-wave community have paved the way for. To me, the legacy of LPF is not only the data and results but also a great gift passed on through the collaboration and team spirit.

## Links to selected publications

- [1] The best residual acceleration measurements: <https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.120.061101>
- [2] The first sub-picometer laser interferometer in space: <https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.123.111101>
- [3] Different satellite control mode as one example for the many detailed experiments: <https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.126.131103>



The LISA Pathfinder science module placement at the centre of the single LPF spacecraft.





## To coldly go ...

*Pengbo (PhD student in Antwerp) adjusting one of the vertical Linear Variable Differential Transformers (LVDTs) for motion readout of the beam splitter bench.*

**Y**ou step into the black “inkwell” building at Du-boisdomein 30, pass a scale model of the Einstein Telescope (ET), and head upstairs to Maastricht University’s gravitational-wave hub. The corridor buzzes with activity: conversations about boreholes, ministerial visits, and deadlines spill out of offices. A wall of photos reveals a rapidly growing team of more than forty researchers, including staff and students. A ramp leads into the lab area, where stressed undergraduates lounge on inflatable couches, waiting out exam week.

Beyond the control room, laser goggles on, you climb to the visitor gallery overlooking the ETpathfinder clean-

room. Below you stretches a 35 × 23 m facility, dominated by an L-shaped vacuum system with six tall towers for suspension structures. The prototype is very much alive: laser noise is being chased down, optics aligned on suspended benches, vacuum-compatible cables assembled, and optical tables delicately balanced in preparation for operation.

ETpathfinder is a prototype facility designed to test key technologies for the low-frequency interferometer of the Einstein Telescope. At its heart will be two folded cryogenic interferometers with Fabry-Perot arm cavities of 9.22 m length formed by pairs of 3.29 kg silicon mirrors suspended inside cryostats. Silicon is a prime mirror and suspension material candidate for

ET, combining excellent mechanical properties at low temperatures with a vanishing thermoelastic expansion.

Funded by an international consortium and involving more than twenty research institutions from 8 countries, ETpathfinder operates independently of the ET site selection while informing critical technology choices for the observatory’s initial design and future upgrades. Subsystems can be tested here at full-system level, including their compatibility with cryogenic suspended interferometry. As the injection and beamsplitter towers are commissioned and prepared for vacuum, the cryogenic system for the mirror towers, developed by an industry consortium, is on track for installation by the end of 2026.

ETPathfinder is steadily transforming from a construction site into a proving ground for the next generation of gravitational-wave detectors and a training facility for technicians, engineers and researchers.

In this article, we gathered some junior members of the ETPathfinder team to share their experience of making it all happen.



**Mathijs Baars**

*is a mechanical engineer based at Nikhef, Amsterdam. He likes coffee, making obnoxiously loud music with friends, and his*

*three-year-old son, who has now successfully learned to make coffee for him.*

I started working on ETPathfinder in 2019 when I got my contract as a mechanical engineer at Nikhef, the Netherlands. This was my first proper job as an engineer and since then I have exclusively worked on ETPathfinder. I began only making technical drawings while learning from the senior engineers in the project, which was invaluable since they had unique experience and knowledge, but they all retired within a few years which left us with a very small and young team to work on the project. The finalization of the mechanical design and its procurement was largely done by me and one other colleague, which often struck me as a bit absurd, but extremely exciting and gratifying.

Now the work is shifting from making designs and building vacuum vessels and infrastructure systems, to actually

making the complex inner mechanics of ETPathfinder. I am taking a more organizational role by managing and joining the installation efforts of all the mechanics. With almost 2 towers out of 6 towers done, I think we should be finished with this in 2 years.



**Luise Kranzhoff**

*joined ETPathfinder in early 2022 when she started her PhD with a focus on quantum-noise reduction schemes. In her free time,*

*she likes to go gravel-biking or running in the hills surrounding Maastricht.*

From day one, I was drawn to hands-on work in the ETPathfinder cleanroom. Whenever there was something to install, assemble, or commission, I jumped in – helping to build the vacuum system and later contributing to the construction and commissioning of the first suspended optical bench. Over the course of my PhD, I watched the facility grow from an empty hall into a complex research infrastructure. Staying on now as a postdoctoral researcher, I have an even stronger focus on installation and commissioning. There is no Einstein Telescope yet, but ETPathfinder feels like the closest thing to ET that already exists.

One of my PhD projects tackled a key challenge for cryogenic interferometers: cooling suspended mirrors to temperatures as low as 18 K without introducing vibrations. Within the ET Technologies project, a local precision engineering company (JPE) developed a compact active vibration isolator designed for cryogenic ultra-high-

vacuum environments. I designed and built a dedicated test setup to validate this device for ETPathfinder, demonstrating its ability to actively suppress vibrations transmitted from the cooling system. Working at this interface between fundamental physics and industrial innovation has been one of the most exciting parts of my time at ETPathfinder, and a glimpse of what it will take to make the Einstein Telescope a reality.



**Nicole Knust**

*is a final-year PhD student from Leibniz University Hannover / Max Planck Institute for Gravitational*

*Physics. When she is not working on laser stabilization, she enjoys bouldering, board games and being outside.*

I heard about ETPathfinder for the first time while looking for a PhD position. I applied, because contributing to this prototype and thus ET through experimental work sounded amazing to me. Now I am one of ETPathfinder's many frequent visitors. I set up the 1550 nm laser source in Hannover before it was transported to ETPathfinder. Currently I am doing commissioning work during various visits.

ETPathfinder needs a laser source that is very stable in terms of frequency and power to enable investigating novel techniques for overcoming the limits of the current gravitational wave detectors. So far, one cannot simply buy such a well performing laser, so we implement an available laser into a stabilization setup to pro-

duce a “pre-stabilized laser system” (PSL). The difficult part is that many different kinds of noises can couple into our system and decrease the stability. To remove this excess noise, we first have to identify the source and then find technical solutions to suppress it. For the next year I hope to improve the performance of the laser system further and to move it from its current preliminary location to its final position.



**Elise Van den Bossche**

*is a second-year PhD student at Vrije Universiteit Brussel in Brussels. She balances academic life with reading,*

*wandering under clear skies, and making music through clarinet duets.*

I first heard about ETpathfinder during my master’s studies, at a colloquium by Stefan Hild in Leuven. I was immediately intrigued by the ambitious goals of this prototype. Until then, my experience had been purely theoretical: I had completed my bachelor’s thesis on gravitational waves and was looking for a way to continue working in this newly emerging field. I therefore contacted Professor Hild to ask whether it would be possible to do a summer internship at the facility. That internship marked my first hands-on experience with optics, laser beams and building my own electronics. Needless to say, I never went back to theory. I quickly developed a passion for constructing experimental set-ups, finding creative solutions to unexpected problems and watching the ETpathfinder grow day by day.

Following my internship, I carried out my master’s thesis at ETpathfinder, which ultimately led to the start of my PhD. Recently I have been commissioning the 1550 nm input mode cleaner (IMC). This is the final interface between the PSL and main interferometer. Due to its placement inside the vacuum system on a suspended optical table, it also provides additional suppression to low-frequency noise. Since October, we have been preparing joint measurements with the PSL and the IMC placed on the suspended beamsplitter tower bench. In the next year I hope to see the effect that our suspended mode cleaning resonator has on the noise of the laser.



**Emma Prins**

*is a first year PhD candidate at Maastricht University, working on the cryogenics of the ETpathfinder, optical simulations and*

*science communication and education. In her free time, she enjoys going on a run around Maastricht, bouldering and trying out new baking recipes.*

I started my research as a PhD candidate for ETpathfinder in June 2025, though this was not my first encounter with the project. As a bachelor student at the Maastricht Science Programme in 2021, I conducted theoretical research on general relativity in the same research group, and then worked as a research assistant at ETpathfinder for a year. By then, the cleanroom was already finished, though empty. I was very impressed to see and lend a (small) helping hand to the hoisting of the first vacuum tower

into the ETpathfinder cleanroom. After that I moved away from Maastricht for a few years to obtain my master’s in Amsterdam, though I remained intrigued about the field of gravitational waves and am very excited to be back.

Currently, my research focuses on the cryogenic system of the ETpathfinder. I will be conducting seismic and thermal characterization tests on the prototype of the complete cryogenic system, including the cooldown to 18K, in order to map the noise it contributes to the system. Later this year, the first full system will be assembled in Maastricht and I look forward to seeing all systems come together in the first mirror tower.



**Elliott Duvieusart**

*is a lab technician with ETpathfinder and the wider research group, lending a hand to every part of the project. In his*

*spare time he organises boardgame days, Dungeons&Dragons sessions with his colleagues, and writes songs about the latest lab breakdowns.*

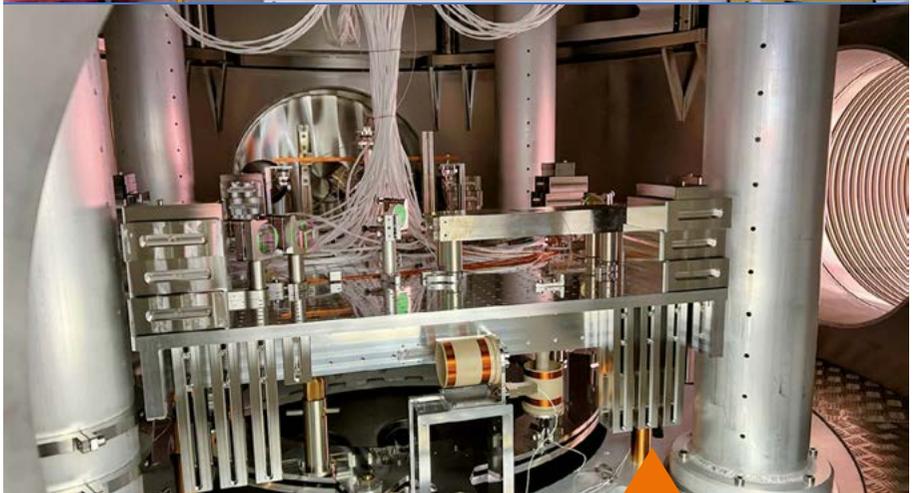
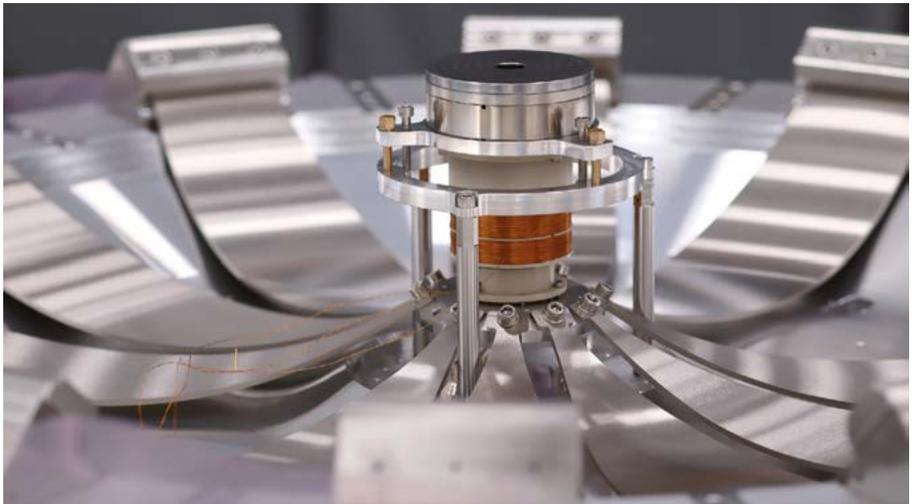
I started working as a part-time lab technician at Maastricht University in 2023. While I initially helped our group’s PhDers with electronics assembly etc., this inevitably led to tasks more directly linked to ETpathfinder. By 2024 I was permanently hired full-time – it became clear that both general lab work and ETpathfinder-related tasks required more personpower. Now I am involved with nearly every hands-on part of the project, while still supporting all



of the surrounding experiments of our group at dub30.

By design, I have no single focus. I set up optical benches, assemble electronics, maintain our cleanroom standards, oversee the electrical connections of all the devices and sensors, and will soon be responsible for the electrical works in the cleanroom. Of course this includes responding to unexpected increases in entropy in the labs (I set up a “gremlin food” box to try and lure them away from the important parts). It is the beauty of my position that I get to interact with every single project and each researcher passing through our labs. On the flip-side, it can be overwhelming to deal with so many moving parts, each sensitive to various effects and requiring attention in a different way. Luckily I can rely on an experienced colleague, and together we try to keep everything running smoothly.

In just 3 years I have already seen a great many projects (big and small) start and/or complete, friends and colleagues climbing the academic ladder, so many weeks or months of frustrating issues leading to the exhilaration of successful experiments, each contributing to building the ETpathfinder as a whole. It has been a privilege and a pleasure to work with everyone involved, and I look forward to the culmination of so many people’s work coming to fruition in the next few years.



**Top:** Geometric Anti-Spring (GAS) filter with LVDT motion readout being prepared for installation as vertical isolation stage.

**Middle:** Preparations and final checks before lifting the internal mechanics from the buildup site to its vacuum tower.

**Bottom:** Floating bench inside the beam splitter tower.

## Collaboration Service Work

**L**arge collaborations such as the LIGO-Virgo-KAGRA collaboration (LVK) need tight coordination. Without a dedicated administrative branch, scientists do much of this service work, which is essential to keep the collaboration running and to deliver high-quality science quickly. Some roles are quite visible (e.g. working group chairs), but many crucial tasks happen behind the scenes. For instance, election of a new chair is organized by the election committee, which is appointed by the spokesperson and follows the set of rules – Policies and Procedures – maintained by the Collaboration Council, and the whole process requires reliable computer infrastructure.

Likewise, every collaboration paper requires coordinated data preparation, writing and review, and the multi-thousand-member author list must be kept current. Additional committees like the Academic Advisory Council, Climate & Sustainability, and Diversity, Equity & Inclusion (DEI) also support the collaboration. Nearly all of this work is voluntary, done by members alongside their LVK science and responsibilities at their home institution. What drives people to do that



*Daniel Williams*  
is a postdoc at Glasgow University. He is the chair of our DEI Committee, and the chair of the paper writing team for the GWTC-4.0 Results paper. Previously, he managed the parameter estimation (PE) for GWTC-4.0, and helped to deliver the PE for GWTC-2, 2.1, and 3. When he's not doing that you can probably find him running up a hill.



*Elise Sanger*  
is a PhD student at the Max Planck Institute for Gravitational Physics in Potsdam, and the chair of our Climate & Sustainability Committee. She also is on the paper writing team for O4b tests of general relativity (TGR) after serving as an analyst for the O4a TGR paper. In her free time, she enjoys reading and playing games, both the physical and digital kind.

and how can one benefit from doing such work? LAAC Members Jessica Steinlechner and Mikhail Korobko interviewed two LSC scientists, Daniel Williams and Elise Sanger, who took on a variety of service work early on in their careers, about their experience.

They asked what motivated Daniel and Elise to take on these roles. 'In both cases, I think, I stumbled into the positions,' says Daniel. He worked on the team already, when the need for a new coordinating role arose, and he stepped up to take it. Elise worked in the Climate & Sustainability

Committee because she cared about the topic, but was initially reluctant to take on the role as chair, as she had just started her PhD. When the leading role was at risk of remaining vacant, she decided to step up: 'I accepted it because I believed in the committee and did not want it to die out...'. Taking such roles as an early-career researcher is not an easy decision: without deep involvement in the behind-the-scenes work, the learning curve is quite steep, as it was for both our respondents. At this stage the support of the colleagues was essential: "people have been very helpful (and understanding when I mess up!)" says Daniel.

Another challenge of service roles is that it's hard to predict the impact of the work on the career, especially since it always comes with extra time commitment that is not directly related to science. But it can make a difference in life and personal development: "My work in the collaboration made me more confident doing different types of things," says Daniel, and Elise agrees: "These positions have improved my confidence and taught me to sometimes do things that are outside my comfort zone." The positions also open the possibility to learn new skills that would come useful in the future careers. For Daniel, it was running the large group of people with different opinions: "I have definitely picked up some new diplomatic skills navigating disagreements constructively and building consensus across multiple viewpoints. It also forced me to learn much better project management skills: my life now has a lot more Gantt charts in it." For Elise, it was im-



proving her time management capabilities when she had many different tasks: "...as part of that, it has taught me to sometimes say 'No' if I already have too much on my plate." Navigating the extra time commitment is not always easy: Daniel shares that his role in the GTWC project "made me work through my summer vacation, and once I needed to deal with panicked messages while I was at a wedding. I need to learn to get better at turning my phone off!" Elise had a similar experience: "I try to not work in the evenings or weekends, but if a new GW event gets detected while you are on shift, then you will have to respond anyway."

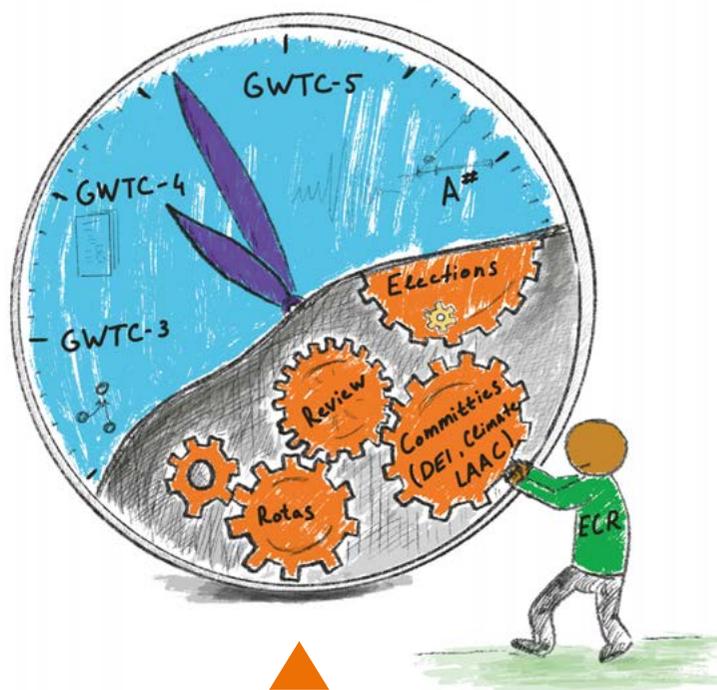
The fear that ECRs often have when stepping into such roles is having to lead a group of more senior people. However, for both Daniel and Elise that was not an issue. Elise shares: "Most senior people have been very helpful and appreciative of my work. Of course there is always some criticism as well, especially with a more controversial topic like climate change, but I always took these as learning opportunities."

Overall, both agree that the positive impact they make outweighs the negatives: "While it might not seem like it immediately improves your career chances, the skills you learn along the way are useful in all aspects of life and I believe they will positively impact your career because of that," says Elise. Daniel also advises: "But make sure you have something else in your life to allow you to escape when you need to. For me that was sport (it's good to have an outlet for excess

energy, and sometimes very mild frustration!) and painting Warhammer minis (and I'm trying to learn how to paint watercolours, which feels like an entirely different pace from LVK business!)"

To conclude the interview, Elise and Daniel were asked whether they had any words of encouragement for other ECRs considering taking on such roles. They both responded: "Do it!"

You can read the full version of the interview here:  
<https://dcc.ligo.org/T2600061/public>



***You have to make sure that you have something else in your life to allow you to escape when you need to!***

## GEO600 Gravitational-wave detector and technology pathfinder

Aerial view of GEO600 in Ruthe, near Hannover.

**G**EO600 represents more than 30 years of groundbreaking research and technological innovation, it is one of the most influential detectors in the history of the field – a facility that fundamentally shaped how gravitational-wave detectors are conceived, constructed and operated.

The German-British gravitational-wave detector is more than just technology. It is a place of collaboration and exchange, bringing together scientists from around the world; a training ground for generations of young researchers; and an environment in which boundaries were continuously pushed – by creative use of science and technology.

GEO600 is designed and operated by scientists from the Max Planck Institute for Gravitational Physics and the Institute for Gravitational Physics at Leibniz Universität Hannover, along

*Harald Lück*



*is a senior researcher at Leibniz University Hannover and the Max Planck Institute for Gravitational Physics (AEI). He played a leading role in building and commissioning GEO600, is a long term LSC member, and co-initiated the Einstein Telescope efforts in 2004, currently serving as Deputy Spokesperson of the ET Collaboration. After retiring this summer, he's looking forward to more time for cycling, travelling, and reading.*

*Michael Weinert*



*has been a GEO600 operator for nearly 20 years, keeping the detector running smoothly – from subsystem repairs and laser power upgrades to electronics improvements. As part of today's small GEO600 team, he maintains deep knowledge of its many subsystems, ensuring reliable operation and continued technical development. Outside work, Michael enjoys cycling and collecting rare century-old radios.*

with partners in the United Kingdom. It is part of the worldwide network of gravitational-wave detectors. GEO600 is funded by the Federal Ministry of Research, Technology and Space, the State of Lower Saxony, the Max Planck Society, the Science and Technology Facilities Council (STFC), and the VolkswagenStiftung.

### **A detector that shaped a field**

GEO600 played a central role in advancing gravitational-wave detection, not because of its size – in fact, quite the opposite. Its compact scale compelled researchers to invent, install, and integrate novel optical, mechanical, and control techniques, and made it an ideal proving ground for technologies considered too risky for larger facilities at the time. Many of these innovative technologies were later adopted as standard solutions in the larger observatories LIGO, Virgo, and KAGRA.

# GEO600: A detector that shaped a field

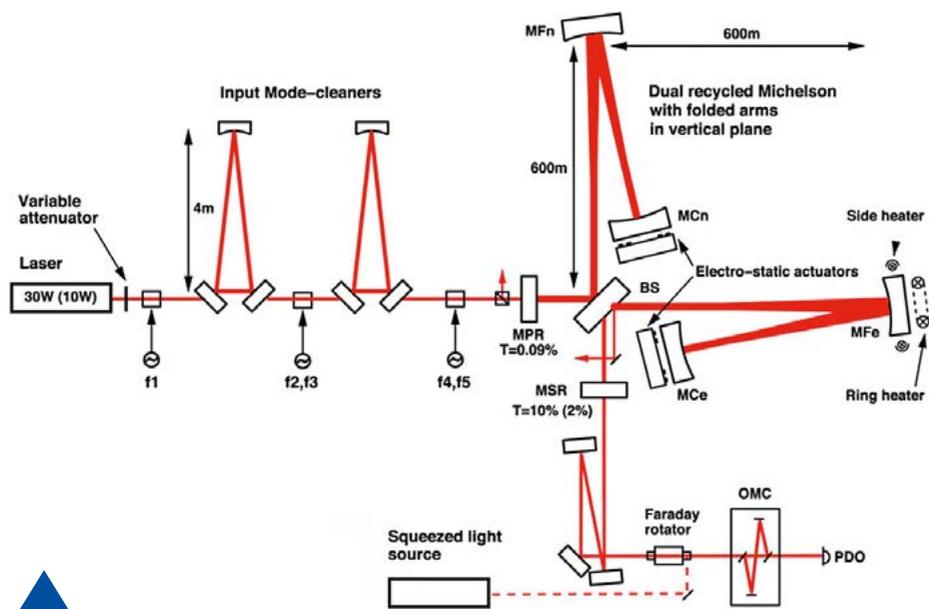
GEO600 is a British–German interferometric gravitational-wave detector with 600 m-long folded arms, giving an unfolded length of 1200 m. Construction began in 1995, after earlier plans for a 3 km detector in the Harz region proved financially impossible. GEO600 joined the first science run with LIGO in 2002, and over the following decades, it became a constant presence in the network. During periods when the larger detectors were offline for upgrades, GEO600 continued to observe as an “Astrowatch” detector, achieving a high duty cycle and providing continuous coverage for the global network.

## Unique detector aspects

Compared to LIGO, Virgo, and KAGRA, GEO600 stands out through several distinctive design features:

- Shorter arms of 600 m, compared to 3–4 km in Virgo and LIGO, with folded arms resulting in 1.2 km length.
- No arm cavities, resulting in exceptionally high circulating power at the beam splitter – unique among current detectors but similar power levels as foreseen in the high-frequency interferometers of the Einstein Telescope.
- Signal recycling (SR): Implemented early at GEO600; detuned SR operation is possible and was first demonstrated here [3].
- Innovative vacuum tube design, using 600 mm-diameter corrugated stainless-steel tubes (316LN) with a wall thickness of only 0.8 mm, achieving mechanical stability without the need for additional stiffeners or bellows [1].

*GEO600 high-frequency design sensitivity with a successively detuned signal recycling cavity. Adapted from Ref. [20] with author's permission.*

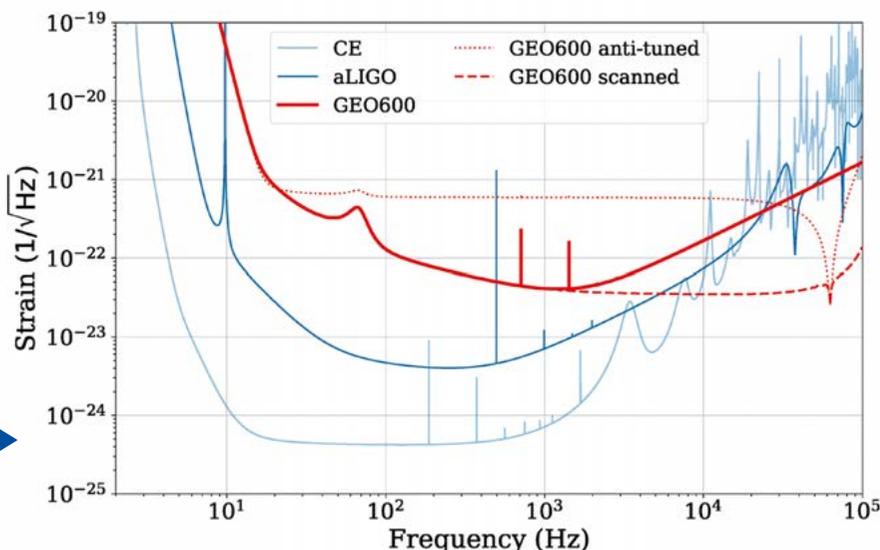


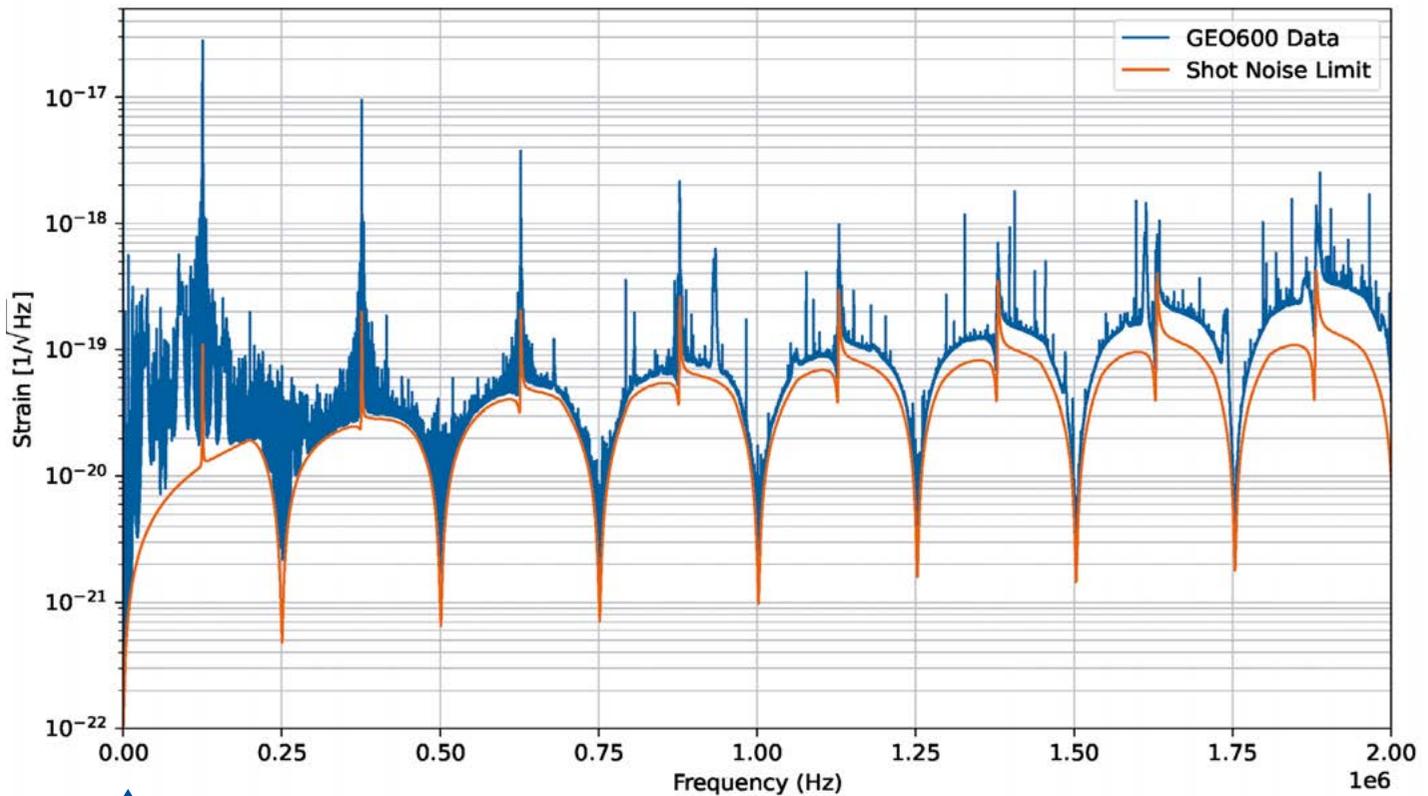
*Simplified optical layout of the GEO600 detector. GEO600 is a dual recycled Michelson interferometer with single folded arms within 600 m long beam tubes. The squeezed light source, Faraday rotator and output mode cleaner (OMC) were added in 2009/2010 as part of the GEO-HF\* program. All optics except for the laser, attenuator and squeezed light source are contained in a vacuum enclosure. The laser system was upgraded in 2024–2025 to increase output power up to  $\approx 70$  W. [18]*

## A detector that never stopped innovating

GEO600 remains a place where new ideas can be tested quickly and creatively. The detector is now in an ambitious upgrade aimed at extending its sensitivity band to very high frequencies of up to 2 MHz – far beyond the operating range of current large ground-based detectors, which are optimized for roughly 20 Hz to 10 kHz.

Enabled by its optical layout and the ability to operate with a widely detuned signal-recycling cavity, GEO600 can cover this full frequency range. A recent publication [20] discusses high-frequency upgrades, demonstrating the potential for GEO600 to open a new observational window in gravitational-wave astronomy – targeting signals that have so far remained inaccessible.





*First attempts to calibrate the GEO600 strain data up to 2MHz: simulation and measured GEO600 data, tuned to DC.*

Following a recent upgrade driven by the very-high-frequency project, GEO600 has become the first large-scale gravitational-wave detector to continuously acquire and store strain data at sampling rates of up to 4 MHz.

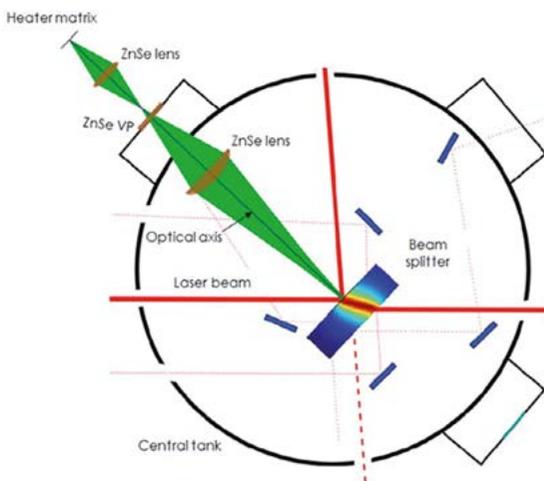
### Testing technologies for the Einstein Telescope

In parallel to the upgrade work, important groundwork for thermal compensation at the Einstein Telescope beam splitter is carried out within the GEO600 thermal compensation project. Owing to its unique design – power recycling without arm cavities – GEO600 is the only existing detector that can realistically reproduce the high-power density expected at the Einstein Telescope beam splitter, making it an essential testbed for developing and validating thermal compensation concepts under ET-like conditions.

### Innovation drives progress

Many of the technologies that enabled the first direct detections of gravitational waves were born, tested, or matured at GEO600. Its contributions live on in the current detector network and in the design concepts for future observatories such as the Einstein Telescope and Cosmic Explorer. As the field looks ahead to the next generation, GEO600 stands as a reminder that innovation, not scale alone, drives progress – and that some of the most transformative ideas emerge from smaller, more flexible experiments.

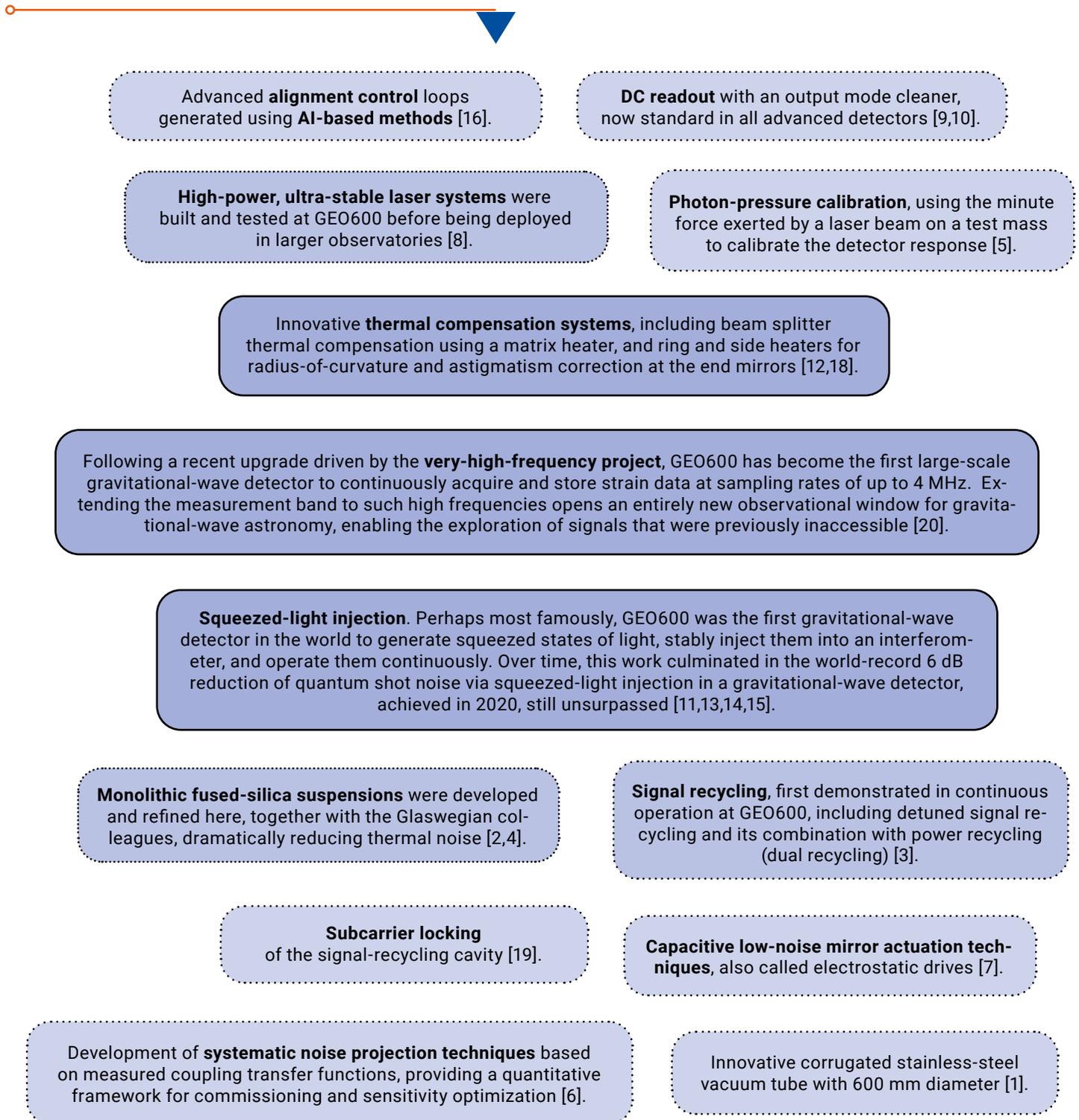
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*Beam splitter thermal compensation with Matrix heater [12,18]*

## Technological firsts and lasting contributions

Much of what is now taken for granted in advanced gravitational-wave detectors was first explored and validated at GEO600. The detector serves as a proving ground for bold, sometimes uncertain, and ultimately transformative ideas.



## A list of the most relevant papers

- [1] Lück, H. et al.; The Geo600 Team: The Vacuum System of GEO600. In: Second Edoardo Amaldi Conference on Gravitational Wave Experiments, pp. 356 – 359
- [2] Plissi, M. V.; Torrie, et al.: GEO600 triple pendulum suspension system: Seismic isolation and control. Review of scientific instruments 71(6), pp. 2539 – 2545 (2000)
- [3] Gerhard Heinzel et al.: Dual recycling for GEO600. Class. Quantum Grav. 19(2002) 1547–1553
- [4] Cagnoli G. et al.: Silica suspension and coating developments for Advanced LIGO J. Phys.: Conf. Ser. 32 386 10.1088/1742-6596/32/1/059(2006)
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- [6] J. R. Smith et al., “A hierarchical method for identifying noise contributions to the output of the GEO600 gravitational wave detector”, Classical and Quantum Gravity 23 (2006) 527–537
- [7] Hewitson, M. et al.; Charge measurement and mitigation for the main test masses of the GEO600 gravitational wave observatory. Classical and Quantum Gravity 24 (24), S. 6379 – 6391(2007)[6]
- [8] Willke, B.: Stabilized lasers for advanced gravitational wave detectors. Laser & Photonics Reviews 4 (6), S. 780 – 794 (2010)
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- [12] Wittel, H. et al.: Thermal Correction of Astigmatism in the Gravitational Wave Observatory GEO600. Classical and quantum gravity 31(6), 065008 (2014)
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- [15] Lough, J.; Schreiber, E.; et al.: First demonstration of 6 dB quantum noise reduction in a kilometer scale gravitational wave observatory. Physical Review Letters 126, 041102 (2021)
- [16] Mukund, N. et al.: Neural sensing and control in a kilometer-scale gravitational-wave observatory. Physical Review Applied 20 (6), 064041(2023)
- [17] Bergamin, F. et al.: Characterization and evasion of backscattered light in the squeezed-light enhanced gravitational wave interferometer GEO600. Optics Express 31 (23), pp. 38443 – 38456 (2023)
- [18] Nadji, S. L.; Wittel, H.; et al.: GEO600 beam splitter thermal compensation system: new design and commissioning. Classical and Quantum Gravity 42 (2), 025009 (2024)
- [19] Bergamin, F.; Development of a squeezing-compatible signal recycling cavity control at GEO600. PhD Leibniz U., Hannover (2024) 10.15488/17442
- [20] Jungkind, Christopher et al.: Prospects for High-Frequency Gravitational-Wave Detection with GEO600. General Relativity and Quantum Cosmology arXiv:2506.08315 (2025)

[www.geo600.org](http://www.geo600.org)

LIGO  
2026

## Career Updates

**Abhishek Sharma** has been awarded a PhD from the Indian Institute of Technology Gandhinagar, with a thesis titled “Advancing gravitational-wave data analysis for terrestrial and space-based observatories”. During his PhD, he developed methods to search for exotic gravitational-wave signals and worked on accelerating parameter inference for compact binary sources. He has joined IUCAA, Pune, as a postdoctoral researcher, where he will continue his work in gravitational-wave data analysis.

The LIGO team at the University of the Balearic Islands continues to grow, with recently joined members including **Cecilio García Quirós** and **Ornella Juliana Piccinni** as tenure-track faculty members and **Matthew Ball**, **Alice Bonino**, **Panagiota Kollitidou** and **Lorenzo Mirasola** as postdocs.

**Émile Lalande** from Université de Montréal has successfully defended his thesis entitled “Couches amorphes et monocristallines pour les miroirs des détecteurs d’ondes gravitationnelles”.



*Émile Lalande (right) celebrates defending his thesis with Audréanne Matte-Landry (left) and Jeanne Vanier (center).*

**Swarnim Shirke** successfully defended his PhD thesis from Inter-University Centre for Astronomy and Astrophysics (IUCAA, Pune) on 16th January 2026.

## Awards

In November 2025, **Prof. Debarati Chatterjee** from the Inter-University Centre for Astronomy and Astrophysics (Pune) was conferred with Honorary Professorship by

the Indian Centre for Space Physics, Kolkata, based on her academic career.

The Third Prize for the 2025 Buchalter Cosmology Prize was awarded to **Harsh Mehta** and **Suvodip Mukherjee** of the Tata Institute of Fundamental Research for their work on cosmology at the American Astronomical Society Meeting 2026 for their work on axion-like particles.

**Lorenzo Speri**, Research Fellow at the European Space Agency and former PhD student in the Astrophysical and Cosmological Relativity department at the Max Planck Institute for Gravitational Physics (Albert Einstein Institute) in Potsdam has been awarded the GWIC-Braccini Thesis Prize: <https://www.aei.mpg.de/1330976/new-methods-for-a-new-gravitational-wave-frontier>

**Miguel Zumalacárregui**, group leader in the Astrophysical and Cosmological Relativity department at the Max Planck Institute for Gravitational Physics (Albert Einstein Institute) in Potsdam, receives a Consolidator Grant with a budget of 2.2 million euros from the European Research Council on gravitational-wave lensing: <https://www.aei.mpg.de/1359867/erc-consolidator-grant-for-miguel-zumalac-rregui>

In December 2025, The Government of India awarded the Vigyan Yuva-Shanti Swarup Bhatnagar award to **Prof. Surhud More** from the Inter-University Centre for Astronomy and Astrophysics (Pune) for his significant contributions to advancing fundamental research in physics. (1. Measured Dark Matter and Dark Energy through galaxy clustering and lensing. 2. Discovered splashback radius, the edge of dark matter halos. 3. Advanced gravitational wave cosmology research.)

## New LSC positions

**Andrew Spencer** has been elected as chair of the Laser and Auxiliary Optics working Group.

**Jessica Steinlechner** has been elected co-chair of the Optics working group.

**Giles Hammond** has been elected Technical Advisor to the Oversight Committee.

**Mikhail Korobko** has been re-elected Chair of the Quantum Noise working group.

Within the LAAC, **Elena Capote** has been elected co-chair, **Andrew Spencer** is elected senior member, **Narenraju Nagarajan** and **Divyajyoti D.** are the new postdoc representatives and **Ann-Kristin Malz** has been elected as graduate student representative.

## Other News

Thanks to the generous support of Washington State, **LIGO Hanford** recently opened their updated exhibit hall with many brand new exhibits focused on LIGO and gravitational waves.



*Excited staff and their family members exploring the new hands-on exhibits at LIGO Hanford Observatory.*

**Prof. Debarati Chatterjee** from the Inter-University Centre for Astronomy and Astrophysics (Pune) was featured in the Nature series Changemakers in Science (21 Nov 2025)

The Simons Foundation provides eight million US dollars to fund a worldwide collaboration on black holes and strong gravity.

**The Max Planck Institute for Gravitational Physics in Potsdam** is part of the network aiming to decipher the secrets encoded in gravitational-wave data: <https://www.aei.mpg.de/1269794/simons-collaboration-on-black-holes-and-strong-gravity>

Composer **Ana Schurmann** is currently touring her event "The Symphony of the Universe: Translating Gravitational Waves into Musical Structure by Ana Schurmann" - next appearing on May 16th at the Hercílio Luz Bridge 100-Year Celebration in Florianópolis, Santa Catarina, Brazil.

**In April 2025 the spokespeople received the following email regarding an article in Issue 26. The Einstein Papers Project has asked that it be printed verbatim. Therefore, after a packed 10th Anniversary special edition, we now include the letter here in Issue 28:**

"The latest issue of LIGO Magazine contains an article by Pauline Gagnon on Albert Einstein's first wife, Mileva Marić (Issue 26, pp. 10-13). In this article Gagnon resurrects the claim, which has been made and disputed over the years, that Marić never got the credit she deserved for contributions she made to some of Einstein's most famous publications. In making her case, she relies heavily on Serbian sources (Popović, Milentijević, Krstić, Trbuhović-Gjurić). She does not cite any sources disputing her claim. In particular, she does not cite a 2019 book by David Cassidy and Allen Esterson with contributions by Ruth Lewin Sime, *Einstein's Wife, the Real Story of Mileva Einstein-Marić* (The MIT Press), favorably reviewed in the July 2019 issue of *Physics Today* by Alberto Martinez (who also devotes a chapter to the issue in his book *Science Secrets. The Truth about Darwin's Finches, Einstein's Wife, and Other Myths* [University of Pittsburgh Press, 2011]). These authors carefully considered the sources cited by Gagnon and concluded that the evidence they seem to provide for Marić having contributed substantially to Einstein's physics does not hold up under scrutiny. In fact, there is broad consensus among Einstein scholars that Marić did not make substantial contributions to Einstein's physics. Hence the title of an early article on the issue by John Stachel, founding editor of *The Collected Papers of Albert Einstein*: "Albert Einstein and Mileva Marić: A collaboration that failed to develop" (in Helena M. Pycior, Nancy G. Slack and Pnina G. Abir-Am, Eds., *Creative Couples in Science*. Rutgers University Press, 1996). We hope you will draw the attention of the readers of LIGO Magazine to these other peer-reviewed sources."

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- continued on the next page -

Pauline Gagnon offered the following response to the above letter:

“My work is mostly based on the biography written by Radmila Milentijević; which is by far the most thoroughly documented and researched biography ever written about Mileva Marić. One of the main arguments evoked in the book by Cassidy & Esterson is to dismiss any Serbian authors since they cite Mileva’s relatives or acquaintances, which they qualify as hearsay. I find this to be biased. I highly recommend you point your readers to a radio show made by Natasha Mitchell from the Australian Broadcasting Corporation (ABC) in April 2019 with interviews from Esterson, Milentijević and myself. People can then judge for themselves.”

The ABC radio show, ‘Who was Einstein’s first wife?’ can be found at:

Part 1:

<https://www.abc.net.au/listen/programs/sciencefriction/who-was-einsteins-first-wife/10998526>

Part 2:

[https://www.abc.net.au/listen/programs/sciencefriction/who\\_einsteins\\_first\\_wife\\_debate\\_heats\\_up\\_part2/11029694](https://www.abc.net.au/listen/programs/sciencefriction/who_einsteins_first_wife_debate_heats_up_part2/11029694)

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*A visitor group on the gallery in the GEO600 central building. In the front, the cleanroom with some vacuum tanks*

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**P**rimordial gravitational waves may have been produced within one-trillionth of a second after the Big Bang, leaving a long-lasting footprint – a stochastic gravitational wave background detectable today. Discovering such a signal would provide invaluable information about the early Universe and might be the key to understanding physics at high energies, inaccessible in other types of experiments.

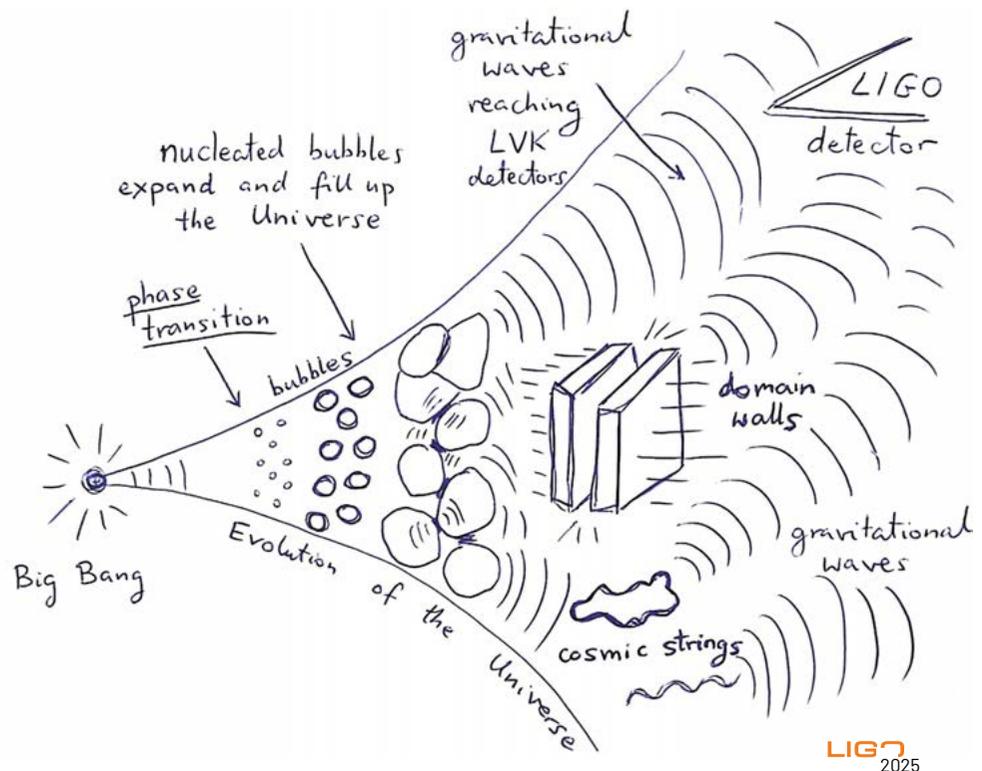
Indeed, despite the huge success of the standard model of particle physics and cosmology, our insight into fundamental physics is incomplete and many questions remain unanswered, such as the nature of dark matter, the origin of the matter-antimatter asymmetry, or the mechanism behind neutrino masses. What is exciting is that many particle physics theories offering solutions to those problems imply novel phenomena at the early stages of the Universe, leading to primordial gravitational wave signals.

Among the most spectacular processes of this type are first order phase transitions. They would occur if the Universe, while expanding and cooling down, underwent a change in its fundamental state triggered by symmetry breaking. In an analogy to water (when the temperature drops, liquid water becomes ice), a cooling Universe could undergo a phase transition to a new, less symmetric state.

This process would involve nucleating bubbles of the new state, which would then expand and fill up the entire spacetime. Gravitational waves

would be generated from sound waves, bubble collisions, and turbulence. Other phenomena resulting from symmetry breaking and leaving behind distinct gravitational wave signatures include topological defects such as cosmic strings (one-dimensional, analogous to cracks in ice) and domain walls (two-dimensional, boundaries that separate two different regions).

The LSC Stochastic Group has recently used the newest LIGO/Virgo/KAGRA data to search for a primordial gravitational wave background generated by early Universe phenomena, such as the ones discussed above. Although no signal has been found, the analysis set important constraints relevant for many particle physics models. Any future discovery of such a signal would mark a true breakthrough in particle physics, bringing us closer to understanding the fundamental structure of Nature.



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