OzGrav

ARC Centre of Excellence for Gravitational Wave Discovery

Annual Report 2022

CONTENTS

OzGrav's vision

To pursue exceptional research and scientific discovery.

To provide world-class research training and leadership.

To inspire young people to take up careers in science and technology.

The ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav) is funded by the Australian Government through the Australian Research Council Centres of Excellence funding scheme. OzGrav is a partnership between Swinburne University of Technology (host of OzGrav headquarters), the Australian National University, Monash University, University of Adelaide, University of Melbourne, and University of Western Australia, along with other collaborating organisations in Australia and overseas.

OzGrav acknowledges and pays respects to the Elders and Traditional Owners of the land on which our six Australian nodes stand.

SWINBURNE UNIVERSITY OF TECHNOLOGY | Australian National University | MONASH University | THE UNIVERSITY of ADELAIDE | THE UNIVERSITY OF MELBOURNE | THE UNIVERSITY OF WESTERN AUSTRALIA | CSIRO

Background image: Students discover space in Virtual Reality (VR) at the World Science Festival. Credit: World Science Festival / Brisbane Museum.
Image credits: All background images (unless stated) and artwork throughout this Report are created by Carl Knox, OzGrav-Swinburne University of Technology.

MESSAGE FROM THE DIRECTOR

Welcome to the sixth OzGrav annual report, summarising the Centre's achievements in the past year.

2022 was very productive for our Centre, with our highest number of peer-reviewed publications to-date and our members receiving many prestigious awards in recognition of research excellence. We also were pleased with the progress made on several technology translation projects that were initiated within OzGrav, which I believe reflects a growing appetite for commercialisation and entrepreneurship that we have been actively cultivating in the Centre. On a personal note, I greatly enjoyed my visits to our nodes in 2022 after the hiatus COVID induced into our normal travel schedule since 2019. It's far easier to get the vibe of a node in person than via (yet another) zoom meeting, and receive feedback on how we can improve.

Over the past year, OzGrav was excitedly preparing for the start of "O4", the fourth major GW observing run to begin in 2023, with many team members travelling to the LIGO sites and working on the upgrades. Thanks to their hard work in 2022, we envisage more than twice as many discoveries from O4 as all previous runs put together as gravitational wave astrophysics continues its exponential growth!

As you may read in this report, OzGrav has also been heavily involved in planning for the next-generation of detectors, including whether Australia could design and potentially host a high frequency gravitational wave detector in the mid-term future.

2023 is also shaping up to be a big year for the Pulsar Timing Arrays (PTAs) that are attempting to detect ultra-low frequency gravitational waves. New facilities such as the MeerKAT telescope that will be absorbed into the SKA and old workhorses like the Parkes 64m ("Murriyang") are all contributing data to the International Pulsar Timing Array, whose annual meeting will be organised by OzGrav in Port Douglas in June.

In late 2022 we had the fantastic news that the Australian Research Council had concluded its selection processes for the 2023 round of Centres of Excellence and that the ARC Centre of Excellence for Gravitational Wave Discovery was to be funded for another 7 years, with myself as the Director and Swinburne University as the host. This achievement is both a testament to the staff, students and admin staff that helped build OzGrav's national and international reputation in its first seven years and the team that put together the 2023 bid. Pleasingly, the team has been awarded 100% of the funding it requested, which will enable OzGrav to capitalise on the tremendous opportunities in relativistic astrophysics that lie ahead until 2031. A special thanks to the new OzGrav 2023 Deputy Directors Tamara Davis and David McClelland, members of the Steering Committee that placed trust in me to lead the bid, and our International and Domestic advisory committees for helping to steer us towards success.

We received this wonderful news just before our 2022 centre-wide annual retreat, which was the first in-person Centre retreat for three years. Not surprisingly, this news injected our retreat with extra enthusiasm and sharpened our focus on future planning, including the activity plans outlined in this report, as well as longer term strategic planning.

I hope you enjoy learning about our research, technology translation, and outreach activities in this report, and enjoy the striking graphics and visual design that our admin and outreach team bring to these reports each year.

Yours sincerely,
Prof Matthew Bailes
OzGrav Director
Swinburne University of Technology

MESSAGE FROM THE CHAIRS

Governance Advisory Committee (GAC)

As Chair of the OzGrav Governance Advisory Committee, I have been delighted with the progress and growth of the Centre during 2022. I also wish to congratulate the team that put together the successful bid for another $35M ARC Centre of Excellence for Gravitational Wave Discovery that will commence in 2024, immediately following the conclusion of the current OzGrav. This will provide ongoing funding through to 2031, allowing OzGrav to continue to do high impact science, attract the world's best researchers to Australia, and contribute to the planning and design of the next generation of detectors that will be able to observe out to the very edge of the Universe.

It was impressive to see OzGrav meet or exceed most of its Key Performance Indicators, especially considering the benchmarks for many of OzGrav's KPI had been set much higher than in previous years, in response to feedback via the ARC's Mid-Term Review of the Centre. Additionally, five new KPIs were introduced in 2022 to help measure the Centre's level of international engagement, research translation and innovation efforts, industry engagement, and high-impact studies led by early career researchers.

The past year saw some incredible successes in the translation of OzGrav research into industrial applications. A major highlight was the acquisition of a spin-off company founded by OzGrav early career researchers, Lyle Roberts and James Spollard, by the company Advanced Navigation in a deal worth up to $40M. Advanced Navigation aims to commercialise the researchers' IP for use in autonomous and robotic navigation across land, air, sea and space. Roberts and Spollard were the first recipients of an OzGrav Research Translation Seed grant back in 2018/19, and we have been pleased to see the growing interest in the Seed grant scheme by our early career researchers, including the exciting project described on pages 18-19 exploring the use of lasers as an environmentally-friendly weed management tool in agriculture.

2022 saw the completion of a special project in which OzGrav collaborated with Swinburne's Moondani Toombadool Centre and the Wurundjeri Woi Wurrung Cultural Heritage Aboriginal Corporation to run a competition inviting Indigenous artists to design an Acknowledgement of Country artwork with OzGrav science as inspiration. There were two winning designs: one for use in digital media and another that was brought to life by the artist, Wurundjeri Elder Uncle Colin Hunter, who burned it onto a large wooden panel and painted it in the traditional style of his Wurundjeri people. Visitors to the OzGrav headquarters are now greeted by this stunning artwork at the entrance.

Please enjoy this annual report, which outlines OzGrav's achievements in 2022 and plans for the future.

Sincerely,
Professor Ian Young AO

Scientific Advisory Committee (SAC)

As the Chair of OzGrav Scientific Advisory Committee (SAC), I am delighted with the scientific progress and international impact made by OzGrav researchers in 2022.

During a year when the LIGO and Virgo detectors were not operating due to upgrades, OzGrav's scientific output was still outstanding. The Centre produced 164 peer-reviewed publications, with 45% of those led by an OzGrav student or postdoc, and of those, 82% were in high-impact journals. Notably, OzGrav publications have been cited over 53,000 times since the Centre's commencement in 2017. OzGrav's science and discoveries are also having an impact more broadly, with OzGrav featuring in over 400 media articles, and engaging with over one hundred schools and thousands of students during 2022.

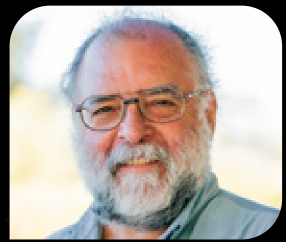
Science highlights over the past year include: the International Pulsar Timing Array's Data Release 2, consisting of precision timing data from 65 millisecond pulsars that reveal strong evidence for an ultra-low frequency signal that is consistent with those expected from a gravitational wave background (pages 6-7); development of a new laser mode sensor with unprecedented precision (pages 8-9); a study showing the potential role of dark matter particles in slowing the rotation speed of black holes (pages 10-11); and the discovery of a jet of matter travelling close to the speed of light created by a supermassive black hole tearing apart a star (pages 12-13).

As you may read in this report, OzGrav members were the recipients of numerous competitive awards in 2022. This is testament to the quality and impact of their research. Congratulations to all award winners, including the large number of students and early career researchers, reflecting the promising future for this field of research.

Of course, one of the biggest OzGrav stories in 2022 was the announcement by the Australian Research Council that a further seven years of funding would be awarded to the ARC Centre of Excellence for Gravitational Wave Discovery. This is tremendous not only for Australia but also for the international gravitational wave community that benefits enormously from the significant and unique contributions from the OzGrav collaboration.

On a personal note, I was fortunate to attend the OzGrav Retreat in November and to hear about their progress and plans directly. I was particularly pleased to see the number of students and early career researchers there. Their engagement, diversity and emerging leadership gives great hope for the future of gravitational wave science.

Sincerely,
Professor Stanley Whitcomb



CENTRE SNAPSHOT

164 PUBLICATIONS IN PEER REVIEWED JOURNALS

74 (45%) PAPERS WITH OZGRAV STUDENTS/POSTDOCS AS FIRST AUTHORS

53,160 CUMULATIVE CITATIONS

91 CONFERENCE PRESENTATIONS

412 MEDIA ARTICLES & INTERVIEWS

119 SCHOOLS

7,178 STUDENTS

298 TEACHERS

38 EVENTS, WORKSHOPS & TALKS FOR THE GENERAL PUBLIC

33,683 MEMBERS OF PUBLIC ENGAGED WITH

104.2 MIL POTENTIAL MEDIA REACH

AFFILIATES 47

POSTDOCTORAL RESEARCHERS 41

ASSOCIATE INVESTIGATORS 32

PARTNER INVESTIGATORS 18

CHIEF INVESTIGATORS 22

MEMBERS 299

PHD RESEARCHERS 74

MASTERS STUDENTS 17

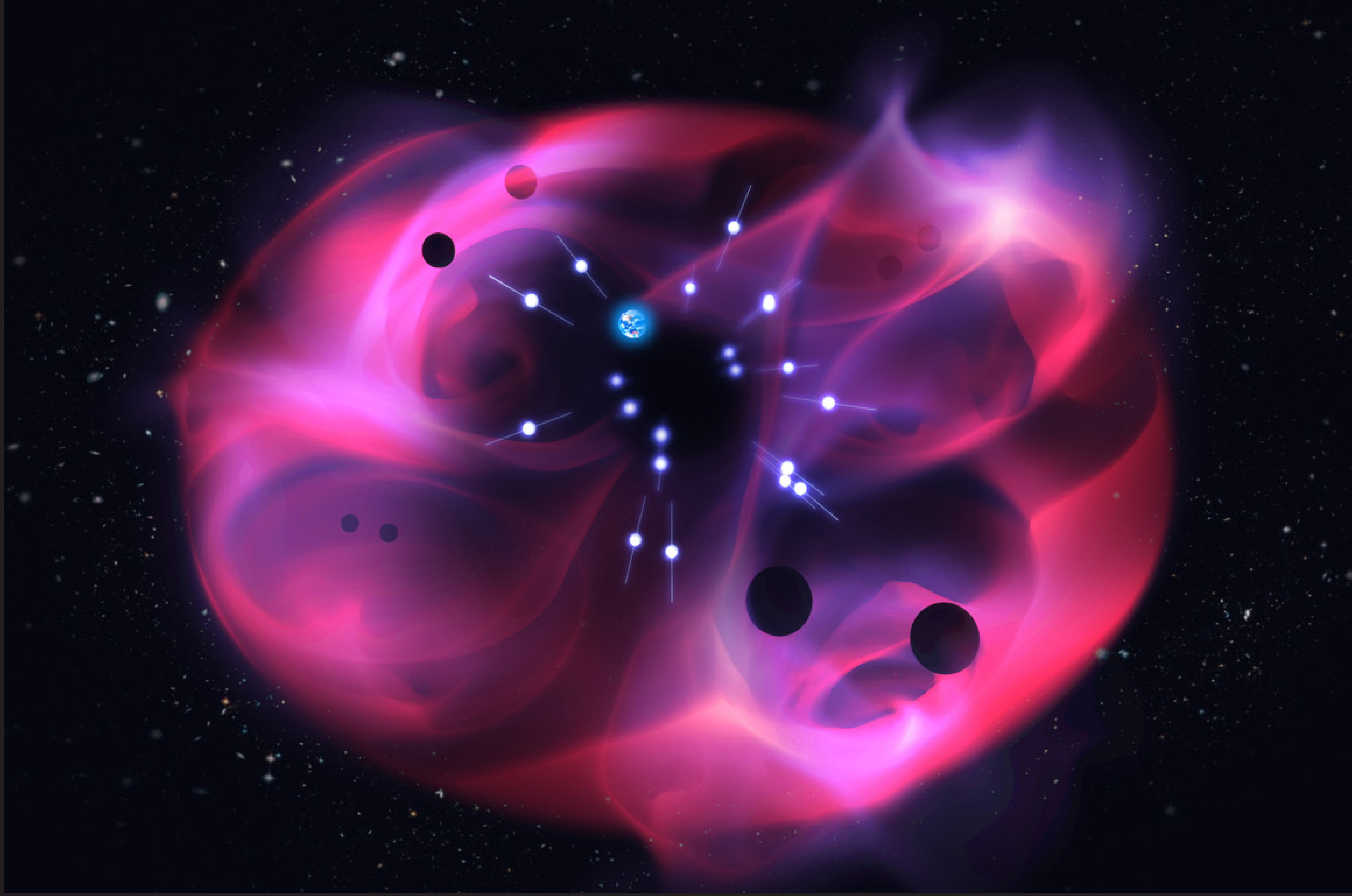
HONOURS STUDENTS 2

UNDERGRADUATE STUDENTS 4

PROFESSIONAL AND TECHNICAL STAFF 32

RESEARCH ASSISTANTS 3

SCIENCE HIGHLIGHTS



International collaboration offers new evidence of a gravitational wave background

The results of a comprehensive search for a background of ultra-low frequency gravitational waves have been announced by an international team of astronomers including scientists from the ARC Centre of Excellence for Gravitational Wave Discovery: Ryan Shannon, Daniel Reardon, Matthew Bailes, Stefan Oslowski and Boris Goncharov.

These light-year-scale ripples, a consequence of Einstein's theory of general relativity, permeate all of spacetime and could originate from mergers of the most massive black holes in the Universe or from events occurring soon after the formation of the Universe in the Big Bang. Scientists have been searching for definitive evidence of these signals for several decades.

The International Pulsar Timing Array (IPTA), joining the work of several astrophysics collaborations from around the world, recently completed its search for gravitational waves in their most recent official data release, known as Data Release 2 (DR2).

This data set consists of precision timing data from 65 millisecond pulsars – stellar remnants which spin hundreds of times per second, sweeping narrow beams of radio waves that appear as pulses due to the spinning – obtained by combining the independent data sets from the IPTA's three founding members: The European Pulsar Timing Array (EPTA), the North American Nanohertz Observatory for Gravitational Waves (NANOGrav), and the Parkes Pulsar Timing Array in Australia (PPTA).

These combined data reveal strong evidence for an ultra-low frequency signal detected by many of the pulsars in the combined data. The characteristics of this common-among-pulsars signal are in broad agreement with those expected from a gravitational wave "background".

The gravitational wave background is formed by many different overlapping gravitational-wave signals emitted from the cosmic population of supermassive binary black holes (i.e. two supermassive black holes orbiting each other and eventually merging) – similar to background noise from the many overlapping voices in a crowded hall. This result further strengthens the gradual emergence of similar signals that have been found in the individual data sets of the participating pulsar timing collaborations over the past few years.

OzGrav Associate Investigator Dr Boris Goncharov from the PPTA cautions on the possible interpretations of such common signals: "We are also looking into what else this signal could be. For example, perhaps it could result from noise that is present in individual pulsars' data that may have been improperly modeled in our analyses."

To identify the gravitational-wave background as the origin of this ultra-low frequency signal, the IPTA must also detect spatial correlations between pulsars. This means that each pair of pulsars must respond in a very particular way to gravitational waves, depending on their separation on the sky.

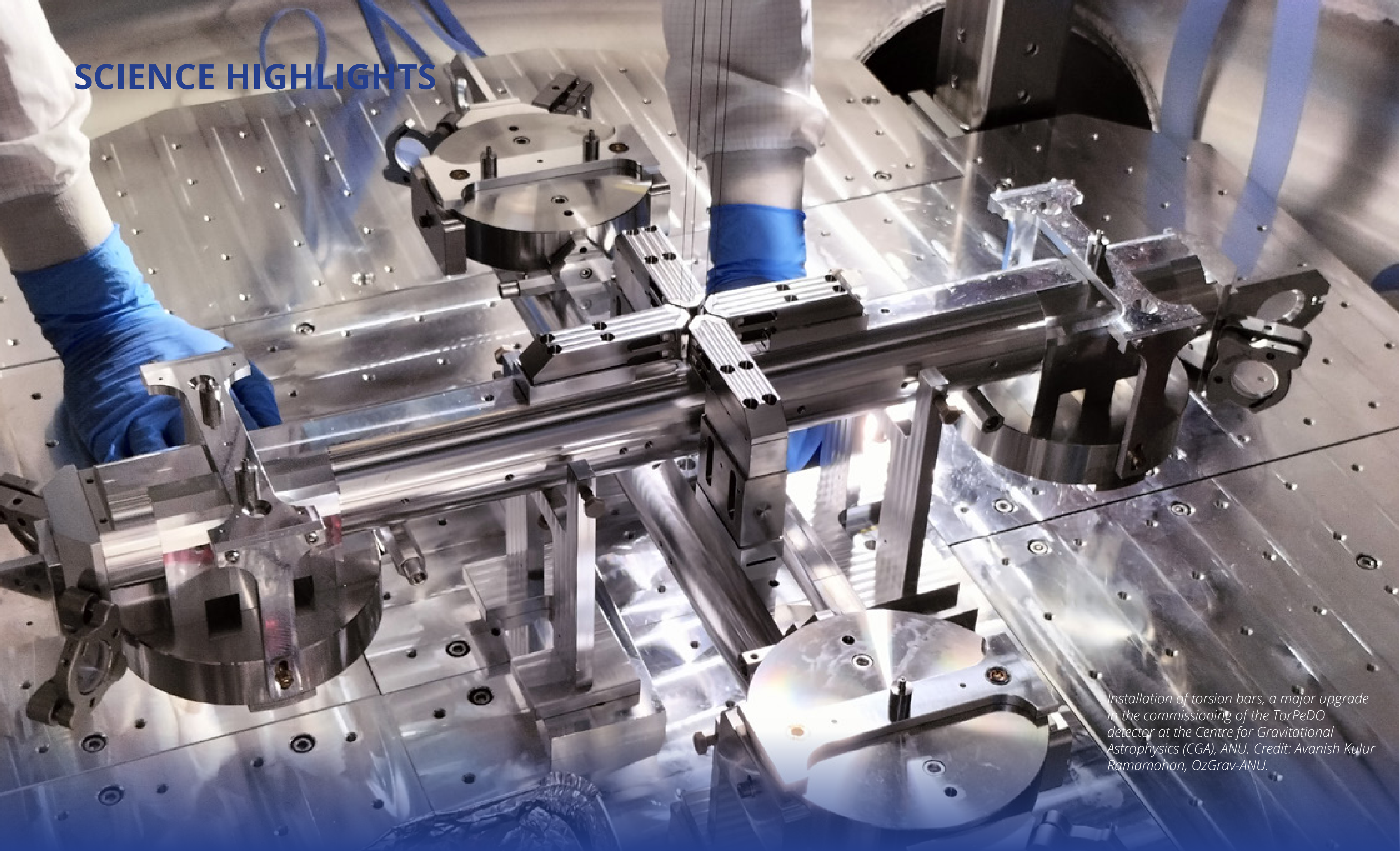
These signature correlations between pulsar pairs are the "smoking gun" for a gravitational-wave background detection. Without them, it is difficult to prove that some other process is not responsible for the signal. Intriguingly, the first indication of a gravitational wave background would be a common signal like that seen in the IPTA DR2. Whether or not this spectrally similar ultra-low frequency signal is correlated between pulsars in accordance with the theoretical predictions will be resolved with further data collection, expanded arrays of monitored pulsars, and continued searches of the resulting longer and larger data sets.

Consistent signals like the one recovered with the IPTA analysis have also been published in individual data sets more recent than those used in the IPTA DR2, from each of the three founding collaborations. The IPTA DR2 analysis demonstrates the power of the international combination giving strong evidence for a gravitational wave background compared to the marginal or absent evidence from the constituent data sets. Additionally, new data from the MeerKAT telescope and from the Indian Pulsar Timing Array (InPTA), the newest member of the IPTA, will further expand future data sets.

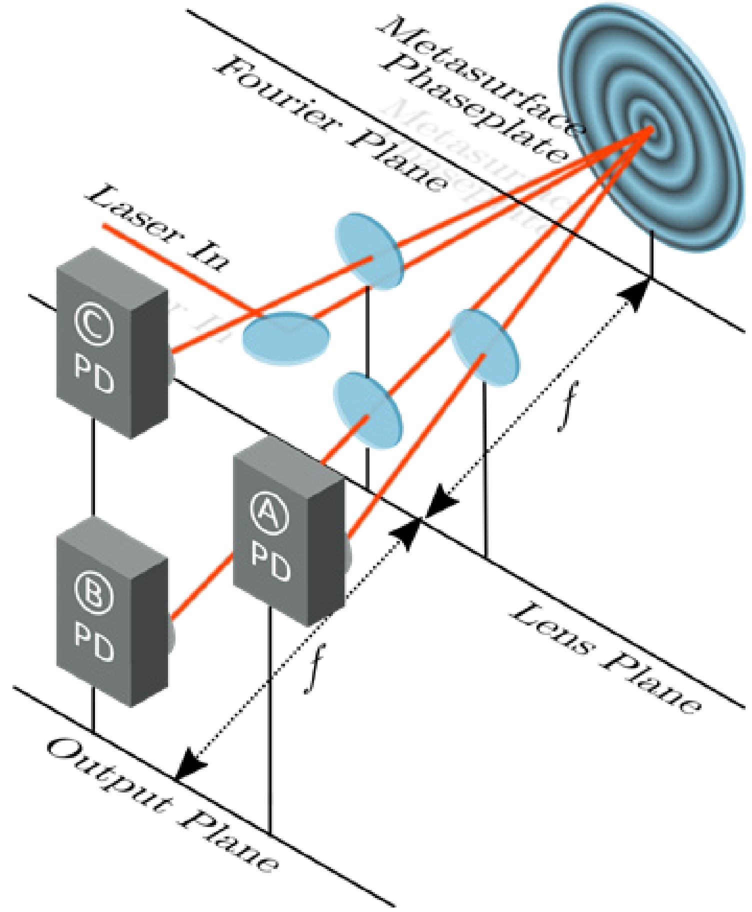
Given the latest published results from the individual groups who now all can clearly recover the common signal, the IPTA is optimistic for what can be achieved once these are combined into the IPTA Data Release 3. Work is already ongoing on this new data release, which at a minimum will include updated data sets from the four constituent PTAs of the IPTA. The analysis of the DR3 data set is expected to finish within the next few years.

This is an edited extract from the original media release on Eureka Alert.

Image: An array of pulsars around the Earth embedded in a gravitational wave background from supermassive black hole binaries. The signals from the pulsars measured with a network of global radio telescopes are affected by the gravitational waves and allow for the study of the origin of the background. Credit: Carl Knox, OzGrav-Swinburne University of Technology.



Installation of torsion bars, a major upgrade in the commissioning of the TorPeDO detector at the Centre for Gravitational Astrophysics (CGA), ANU. Credit: Avanish Kulur Ramamohan, OzGrav-ANU.



Gravitational wave scientists develop new laser mode sensor with unprecedented precision

Lasers support certain structures of light called 'eigenmodes'. An international collaboration of gravitational wave, metasurface and photonics experts have pioneered a new method to measure the amount of these eigenmodes with unprecedented sensitivity.

In gravitational wave detectors, several pairs of mirrors are used to increase the amount of laser light stored along the massive arms of the detector. However, each of these pairs has small distortions that scatters light away from the perfect shape of the laser beam. This scattering can cause excess noise in the detector, limiting sensitivity and taking the detector offline.

From the recently submitted study, Prof Freise (from Vrije Universiteit Amsterdam) says: "Gravitational wave detectors like LIGO, Virgo and KAGRA store enormous amounts of optical power – in this work, we wanted to test an idea that would let us zoom in on the laser beam and look for the small wiggles in power that can limit the detectors' sensitivity."

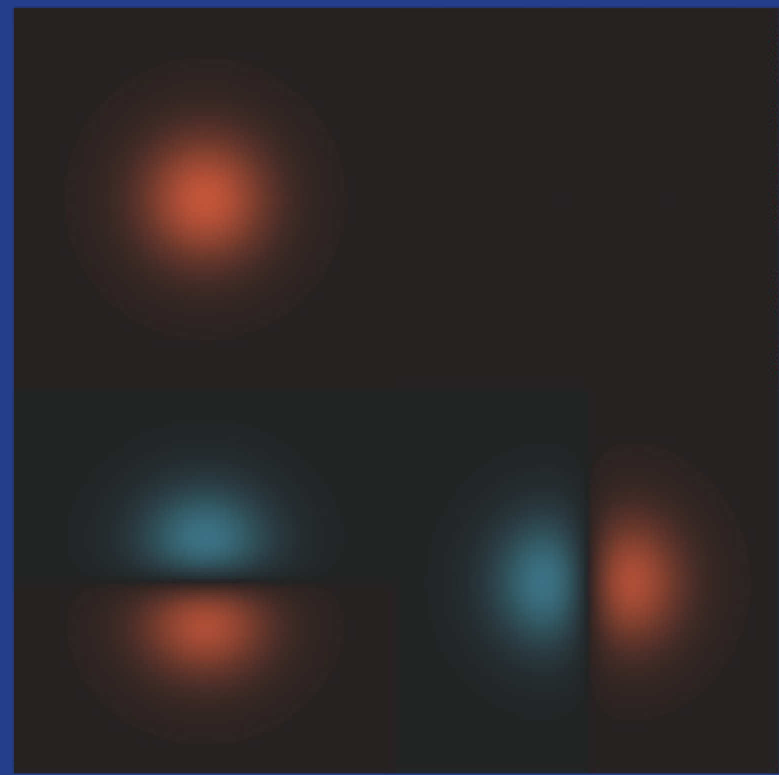
A similar problem is encountered in the telecoms industry where scientists want to use multiple eigenmodes to transport more data down optical fibres. OzGrav researcher and lead author Dr Aaron Goodwin-Jones (University of Western Australia - UWA) explains: "Telecoms scientists have developed a way to measure the eigenmodes using a simple apparatus, but it's not sensitive enough for our purposes. We had the idea to use a metasurface and reached out to collaborators who could help us fabricate one."

In the study, the proof-of-concept setup the team developed was over 1000x more sensitive than the original way developed by the telecoms scientists. The researchers will now look to translate this work into gravitational wave detectors, where the additional precision will be used to probe the interiors of neutron stars and test fundamental limits of general relativity.

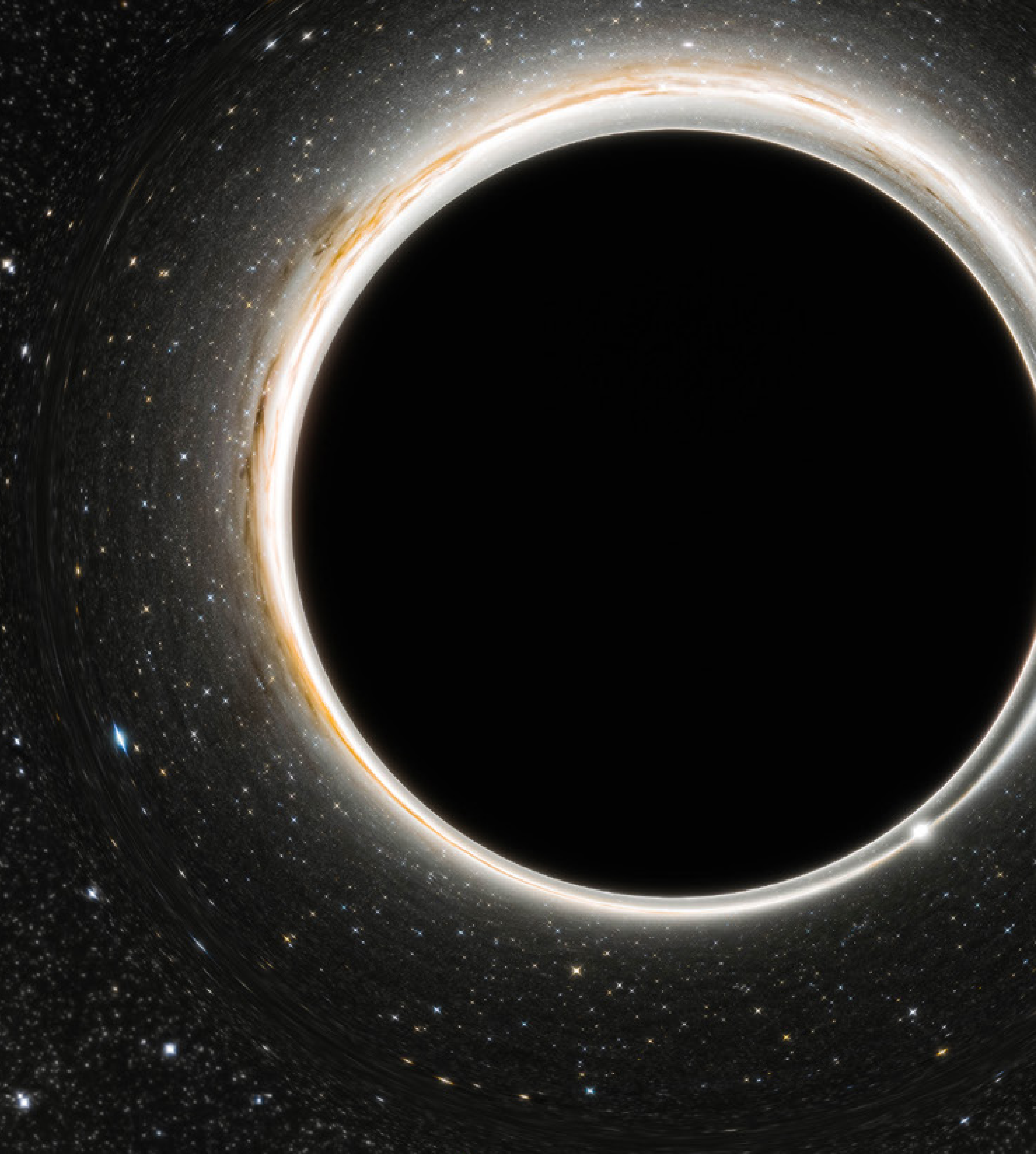
OzGrav Chief Investigator, A/Prof Zhao (UWA) says: "Solving the mode sensing problem in future gravitational wave detectors is essential, if we are to understand the insides of neutron stars."

Figure 1 (above right) A schematic of the apparatus used by the researchers, where f is the focal length of the lens. Credit: Aaron Goodwin-Jones, OzGrav-UWA

Figure 2 (right) False colour image of laser eigenmodes that were tested. The colour indicates the phase of the light. Red is 0 degrees, blue is 180 degrees. Credit: Aaron Goodwin-Jones, OzGrav-UWA



SCIENCE HIGHLIGHTS



How a dark matter embrace could slow a spinning black hole

A new study led by Dr Lilli Sun and her colleagues from the Centre for Gravitational Astrophysics have found that counting large black holes could help us find elusive dark matter particles. Large black holes are formed when smaller ones collide – in dense regions of the universe this could happen multiple times. But if the colliding black holes are spinning fast then the new black hole could be kicked out of the dense area, preventing any further mergers.

But Dr Lilli Sun and her colleagues from CGA and the ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav) realised in some scenarios dark matter clouds can form around fast spinning black holes. In the process the black holes lose their rotational energy and avoid ejection from the dense area.

“If certain ultralight particles exist, then a huge number of them could appear and get trapped in the black hole’s powerful gravity field, forming a cloud co-rotating with the black hole,” said Dr Sun, from CGA and OzGrav. The formation of the cloud could spin down a black hole very quickly, because the rotational energy of the black hole is extracted into the boson cloud.”

Since the first detection of gravitational waves in 2015 many black hole mergers have been found, some involving black holes larger than could be formed by stars collapsing at the end of their life – such behemoths must have come from smaller black holes merging into larger ones, perhaps multiple times.

However, Dr Sun and her collaborators realised that dark matter could play a significant role in the cosmic game of dodgem cars that black holes play in regions packed with stars.

But that depends on what dark matter actually is – which to date is not known. Its existence is known from large scale gravitational effects, such as the rotation of galaxies, but the nature of it has remained elusive. One theory proposes clouds of small particles, and it is this proposition that Dr Sun and her colleagues have explored, in a paper in the Astrophysical Journal.

“These hypothetical particles have been proposed as solutions to a number of astrophysics and particle physics problems,” said first author, Ethan Payne, formerly from CGA and OzGrav, now a PhD student at Caltech in the United States.

“The intricate physics of blackhole superradiance provides a bridge between novel observations of binary black-hole mergers and the possible impacts of ultralight bosons.”

If dark matter were made up of such small particles, it is possible they could interact with a black hole through a process called superradiance, that would sap the rotation of the black hole.

The superradiance effect is maximized if the Compton wavelength of the particles is comparable to the size of the black hole, which would create a resonance that would allow the energy to be efficiently coupled out of the black hole.

Such a multistep link – small particles slowing black holes, leading to more mergers and therefore on average larger black holes – is difficult to prove. It’s a conceptual proposition that might apply to populations of black holes in dense clusters, but it’s not straightforward – there are many subtleties, Dr Sun said.

This article was first published in the Research School of Physics from ANU College of Science Newsletter, and featured in physics.anu.edu.au

Background image by Carl Knox, OzGrav-Swinburne University of Technology

SCIENCE HIGHLIGHTS

Star's fatal encounter with black hole creates rare luminous flash.

Astronomers from OzGrav have played an important role in the discovery of a rare luminous jet of matter travelling close to the speed of light, created by a supermassive black hole violently tearing apart a star.

Published in Nature, the research brings astronomers one step closer to understanding the physics of supermassive black holes, which sit at the centre of galaxies billions of light years away.

Swinburne Professor Jeff Cooke, who is also a Chief Investigator for the ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav), was a key member of the research team.

"Stars that are literally torn apart by the gravitational tidal forces of black holes help us better understand what exists in the Universe," says Professor Cooke. "These observations help us explore extreme physics and energies that cannot be created on Earth." Supermassive, super rare and super far away!

When a star gets too close to a supermassive black hole, the star is violently ripped apart by tidal forces, with pieces drawn into orbit around the black hole and eventually completely consumed by it. In extremely rare instances – only about one per cent of the time – these so-called tidal disruption events (TDEs) also launch luminous jets of material moving almost at the speed of light.

The co-lead authors of the work, Dr Igor Andreoni from the University of Maryland and Assistant Professor Michael Coughlin from the University of Minnesota, along with an international team, observed one of the brightest ever TDEs. They measured it to be more than 8.5 billion light years away, or more than halfway across the observable Universe.

The event, officially named "AT2022cmc", is believed to be at the centre of a galaxy that is not yet visible because the intense light from the flash still outshines it. Future space observations may unveil the galaxy when AT2022cmc eventually fades away.

It is still a mystery why some TDEs launch jets while others do not appear to. From their observations, the researchers concluded that the black holes associated with AT2022cmc and other similarly jetted TDEs are likely spinning rapidly.

This suggests that a rapid black hole spin may be one necessary ingredient for jet launching—an idea that brings researchers closer to understanding these mysterious objects at the outer reaches of the universe.

These include the Zwicky Transient Facility in California that made the initial discovery, X-ray telescopes in space and on the International Space Station, radio/mm telescopes in Australia, the US, India and the French Alps, and optical/infrared telescopes in Chile, the Canary Islands and the US, including the W. M. Keck Observatory in Hawaii.

Postdoctoral researcher Dr Jielai Zhang, a co-author on the research, says that international collaboration was essential to this discovery.

"Although the night sky may appear tranquil, telescopes reveal that the Universe is full of mysterious, explosive and fleeting events waiting to be discovered. Through OzGrav and Swinburne international research collaborations, we are proud to be making meaningful discoveries such as this one," Dr Zhang says.

This paper, "A very luminous jet from the disruption of a star by a massive black hole" was published in Nature on November 30, 2022.

Image: A supermassive black hole rips apart a star, causing a bright optical flare to emerge. Credit: Carl Knox, OzGrav - Swinburne University of Technology

RESEARCH TRANSLATION HIGHLIGHTS

OzGrav researchers shape the future of photonic sensing with spin-off company Vai Photonics

In 2021 Australian researchers Lyle Roberts and James Spollard, from the Australian National University (ANU), co-founded Vai Photonics: a spin-off company developing patented photonic sensors for precision navigation. OzGrav played a key role in kickstarting Vai Photonics by providing seed funding towards fundamental LiDAR research, which translated to real-world, industry applications. In 2022 Advanced Navigation, one of the world's most ambitious innovators in AI robotics and navigation technology, acquired Vai Photonics in a deal worth up to $40M. Advanced Navigation aims to commercialise Roberts and Spollard's research into exciting autonomous and robotic applications across land, air, sea and space.

OzGrav researchers and Vai Photonics co-founders Lyle Roberts (left) and James Spollard. Credit: ANU

Vai Photonics co-founder James Spollard explained: "Precision navigation when GPS is unavailable or unreliable is a major challenge in the development of autonomous systems. Our emerging photonic sensing technology will enable positioning and navigation that is orders of magnitude more stable and precise than existing solutions in these environments.

"By combining laser interferometry and electro-optics with advanced signal processing algorithms and real-time software, we can measure how fast a vehicle is moving in three dimensions," said Spollard. "As a result, we can accurately measure how the vehicle is moving through the environment, and from this infer where the vehicle is located with great precision."

The technology, which has been in development for over 15 years at ANU, will solve complex autonomy challenges across aerospace, automotive, weather and space exploration, as well as railways and logistics. OzGrav Director Professor Matthew Bailes said he was thrilled to see such a positive outcome for our early career researchers that were supported by OzGrav's industry seeding scheme and workshops. "It reinforces the fact that pushing the limits of instrumentation for scientific purposes can often create opportunities for Australian innovators and industry," said Bailes.

Professor Brian Schmidt, Vice-Chancellor of the Australian National University said: "Vai Photonics is another great ANU example of how you take fundamental research – the type of thinking that pushes the boundaries of what we know – and turn it into products and technologies that power our lives.

"The work that underpins Vai Photonics' advanced autonomous navigation systems stems from the search for elusive gravitational waves – ripples in space and time caused by massive cosmic events like black holes colliding. The team have built on a decade of research and development across advanced and ultra-precise laser measurements, digital signals and quantum optics to build their innovative navigation technology. We are proud to have backed Vai Photonics through our Centre for Gravitational Astrophysics and business and commercialisation office. It's really exciting to see the team take another major step in their incredible journey," said Prof Schmidt.

Co-founder Dr Lyle Roberts looks forward to an autonomous future: "This is a huge win for the Vai Photonics team – together with Advanced Navigation we are able to bring our product to market much faster than originally planned. We now have access to leading research and development facilities along with strong distribution channels. We couldn't have asked for a better outcome and look forward to navigating the future with Advanced Navigation."

This acquisition fits into Advanced Navigation's larger growth strategy to expand its product and solutions portfolio across deep technology fields that look to solve the world's greatest challenges facing the autonomy revolution. The Vai Photonics team has been integrated into Advanced Navigation's research and development team, based out of the new Canberra research facility.

This article is based on the original article written by Laura Hayward published on www.advancednavigation.com

Co-founders Lyle Roberts and James Spollard with ANU Vice Chancellor Brian Schmidt. Credit: ANU

Scientists track space junk on path to collision with moon

The University of Western Australia's Zadko Observatory team, in collaboration with the European Space Agency, have tracked an out-of-control booster rocket before it crashes into the dark side of the Moon. The booster rocket was originally believed to be a part of a Space-X rocket weather satellite but it is now believed to be 2014-065B, the booster rocket for the Chinese Chang'e 5-T1 lunar mission. It is possible the booster rocket has been in orbit between the Earth and the Moon since 2014 and scientists predict this large piece of space junk will collide with the Moon on March 4 2022.

OzGrav Chief Investigator Associate Professor David Coward said there is a lot of junk in space. "The space around Earth is becoming increasingly busy with orbiting debris and this debris is for the first time reaching the Moon," Associate Professor Coward said.

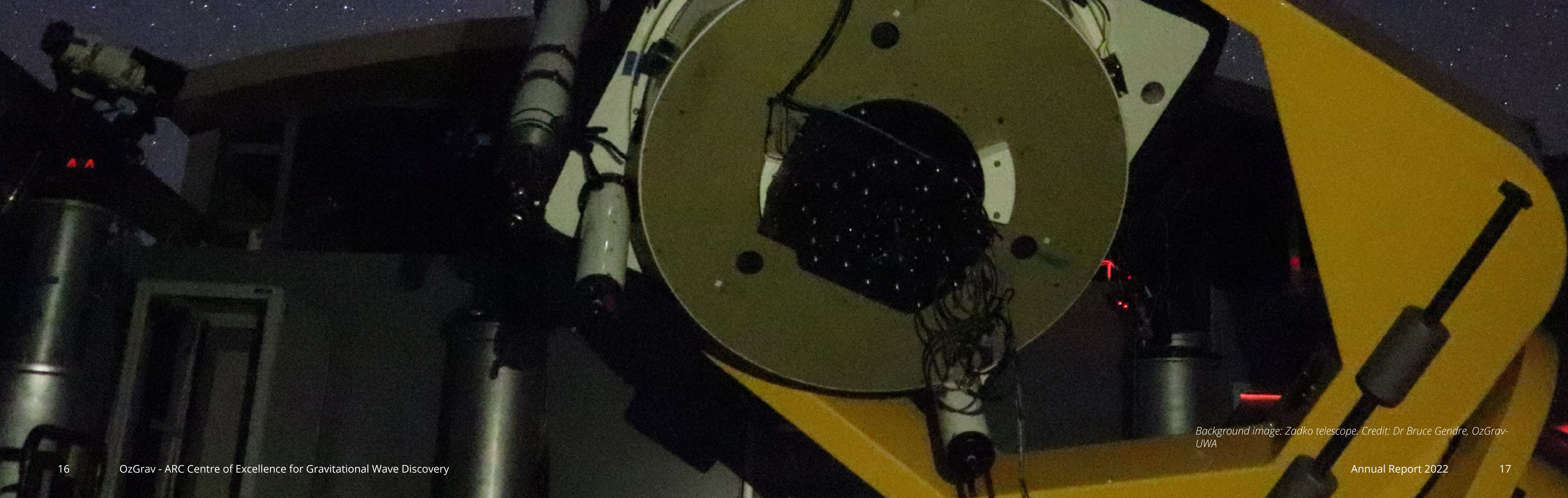
The Zadko Observatory scientists at UWA's Department of Physics are contracted by the European Space Agency to track potentially hazardous debris near Earth. European Space Agency scientist Dr Marco Micheli said tracking the space junk with the Zadko Telescope was helping scientists refine the orbit and the location of the crash. Zadko Observatory systems manager Dr Bruce Gendre said acquiring accurate positional data on an object 177,118km from Earth and travelling at over 700km per minute was not trivial. "The exact impact site is uncertain because small effects, such as the rocket tumbling, changes the orbit slightly as it approaches the Moon," Dr Gendre said.

Making things more difficult, UWA astrophysics student Eloise Moore had to battle with the Zadko telescope to regain control as its robotic system went rogue just as she was trying to take the images. "We finally got control of the telescope only minutes before the critical imaging was due to start," Ms Moore said.

At 4am on February 10, she succeeded in capturing some of the last images of the booster, which showed signs of the rockets tumbling as it hurtled through space before the expected collision. "Even though the impact will occur on the dark side of the Moon, which is not visible from Earth, future lunar probes will be able to image the impact site to study effects of space junk on the lunar surface," Ms Moore said.

As featured on UWA news.

Zadko telescope (UWA) during a visit from a French Embassy delegation. L to R: Dr Bruce Gendre (UWA); Eloise Moore (UWA); Federic Filipo (Embassy); His Excellency Mr Jean-Pierre Thebault (Ambassador of France); A/Prof David Coward (UWA); John Moore (UWA) and Wg Cdr Franck Arnaudon (French Air Force Canberra). Credit UWA



Background image: Zadko telescope. Credit: Dr Bruce Gendre, OzGrav-UWA

RESEARCH TRANSLATION HIGHLIGHTS

Pulsed Tm-fiber (Thulium) lasers for weed killing

Traditional weed control using herbicides is becoming increasingly problematic. Pestilent weeds reduce productivity in agriculture by damaging crops and reducing yield in a multi-billion-dollar farming industry. Current methods of weed control resort to the use of herbicides and toxic substances that persist in soil and are detrimental to humans and wildlife.

The use of CO_2 lasers to prevent or delay weed growth has been demonstrated as an eco-friendly and economically viable alternative. The concept has already been proven with CO_2 lasers mounted on land-based vehicles for short row crops like vegetables. In 2022 OzGrav awarded a $25,000 Seed grant to a team led by OzGrav student Zachary Holmes, to investigate extending laser weed killing capabilities to taller field crops such as grains and grasses, orchards, or vineyards, which has not yet been demonstrated. The proposed system is readily adaptable to replace other pesticides and has greater potential for mounting on a drone to improve speed and non-invasiveness.

The cost-effectiveness of laser-based weed killing depends critically on the laser parameters and SWAP (Size, Weight, and Power) performance. Laser weed killing exploits the very high water content and very low reflectance in the 1.90-1.94 μm band. This project will use a Thulium (Tm) fiber laser to determine the optimum laser parameters (wavelength, beam diameter, average power, pulse width) for weed killing.

The laser weed killing demonstration is also a pathway towards translating research into single-frequency laser diode-seeded Tm-fiber amplifier sources into a commercialisable laser weed killing unit for mounting on an autonomous vehicle. The project is in collaboration with the Weed Science Research Group in the School of Agriculture, Food & Wine at the University of Adelaide (UoA).

We will configure, test and optimise the laser system, and then install it at Waite Research Institute. Our team includes ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav) experts in fiber laser development:

- Zac Holmes, PhD student in the field of laser source design and stabilisation with first-class honours in mechanical engineering, who has designed and successfully demonstrated a seed source and Tm:fiber amplifier concept for future adaptation;
- Dr Sebastian Ng, co-chair of the OzGrav Quantum Program with extensive experience in fiber laser development, and space applications team leader at QuantX Labs, translating terrestrial laser and quantum technologies for satellite payloadsl;
- Prof Peter Veitch, Head of School of Physical Sciences and OzGrav Adelaide node leader with a proven track record of coordinating and undertaking research in laser systems for environmental, industrial, and defence applications; and
- Emeritus Prof Jesper Munch, a longstanding member of the Australian optics community with invaluable contributions to the fields of high-power lasers, nonlinear optics, and gravitational wave detection.

The team also includes University of Adelaide School of Agriculture, Food and Wine experts in weed control research:

- Dr Andrew Hennesey, Image and Data Analyst specialising in the classification of hyperspectral vegetation datasets;
- Dr Jenna Malone, a senior postdoctoral fellow in the Weed Science Research Group researching the understanding and management of herbicide resistant weeds;
- Dr Darren Plett, the Technology and Development Lead at the Plant Accelerator researching phenotyping technologies to improve agricultural crop productivity; and
- Prof Timothy Cavagnaro, an expert in management of soil ecological processes with a great degree of experience in cross-disciplinary technologies and techniques.

The team proposes to use a Tm-fiber laser source to research the optimum parameters (wavelength, beam diameter, average power, pulse width) for laser weed killing of flat-leaf weeds. Our proposed demonstration with a Tm-fiber laser source is also a pathway towards mounting onto an autonomous vehicle for field testing. The vehicle is equipped with Artificial Intelligence (AI) weed detection and locating capabilities, including a scanner to direct the pulsed laser beam(s) towards the target weed. A likely field test of the system will be laser weed killing in a vineyard through collaboration with the Australian Wine Research Institute. Further collaboration will be initiated with autonomous vehicle experts in the UoA's School of Mechanical Engineering and AI experts at the UoA and Australian Institute of Machine Learning (AIML), who are currently developing AI detection systems for other applications. The team will pursue further funding to progress this study beyond the proof-of-concept phase.

Image: Prof Peter Veitch (L) and PhD student Zac Holmes (R) at University of Adelaide testing lasers on weeds. Credit (all photos on both pages): Zac Holmes, OzGrav-University of Adelaide

EDUCATION AND OUTREACH

Wallal Eclipse Centenary Celebrations

Did you grab your special coin from the Royal Mint?

100 years ago the eyes of the world were focused on an expedition of international and Australian scientists to Wallal, 300km south of Broome in Western Australia, where conditions would be ideal for photographing a total eclipse due on 21 September 1922. The photographic images taken during this ground-breaking expedition allowed for the precise measurements of the apparent position of the stars near the eclipsed Sun, giving scientists the evidence proving Albert Einstein's revolutionary Theory of General Relativity as correct!

The UWA Wallal expedition Centenary celebration lasted two weeks throughout September 2022. The two-week celebration catered for people who have a passion for science, art, history and education. It consisted of multiple public talks, an exhibition, workshops, art sculptures, posters, videos, and the Royal Australian Mint Wallal coin launch. UWA joined the Perth Observatory, Gravity Discovery Centre and Scitech who offered their own exhibition and talks in celebration of the Wallal Expedition 100 years ago.

The Hon Robert French AC, UWA Chancellor, launched the fully illustrated book "Uncovering Einstein's New Universe" by David Blair, Ron Burman and Paul Davies, published by UWA Publications. The book describes the adventures of many people who between them changed humankind's common understanding of our universe and the nature of physical reality. Some of those people yearned to know and understand, some were adventurers, some were inventors and most shared the joy of being part of a common enterprise dedicated to our best understanding of the truth. It starts by telling the story of the Wallal Eclipse expedition, then goes on to describe the later verification of Einstein's theory of gravity, culminating in the discovery of gravitational waves.

There were free STEM talks and workshops for students in Years 3-12. More than 1000 students attended the sessions. Speakers included lecturers from UWA's School of Physics, Mathematics and Computing, Einstein First Project, Jackie Bondell - OzGrav Education Public Outreach Coordinator and ABC Catalyst presenter of "Black Hole Hunter" Professor Tamara Davis - University of Queensland.

Many thanks to our volunteers who trained, managed and contributed to the day-to-day running of the exhibition, presenting talks and workshops, and discussing our science with the general public. It was also a fantastic chance to showcase the educational work happening in the Einstein First project, and for guests to snap a black hole selfie.

We acknowledge the generosity and support of sponsors of whom the centenary celebration of the Wallal Expedition would not have been possible: Department of Jobs, Tourism, Science and Innovation; Big Questions Institute; Royal Australian Mint; and Atomic Sky.

Credit (all photos on both pages): UWA Brand, Marketing and Recruitment

EDUCATION AND OUTREACH

Acknowledgement of Country plaque project

We're delighted to share this special project was unveiled at OzGrav HQ – Swinburne University of Technology in 2022.

Despite COVID stalling progress, this project that started a few years ago culminated with the installation of an Acknowledgement of Country (AoC) and beautiful artowrk at our OzGrav offices at Swinburne University of Technology. Initially we were going to create a fairly simple AoC metal plaque, but after consulting with our Swinburne Indigenous liaison group, we decided to run this as a prize for local Indigenous artists to design the AoC artwork with OzGrav science as inspiration.

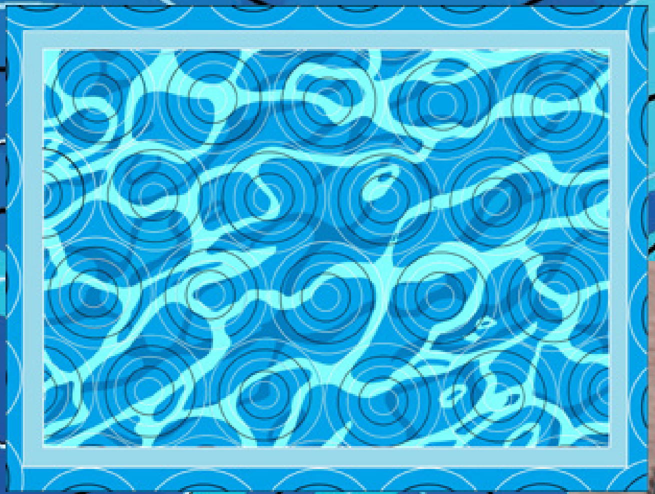
One of the winning designs was "Rippling Out" by Wurundjeri artist Judy Nicholson (who has sadly since passed away). We are using Judy's art for our electronic AoC, for use in digital presentations (also seen here as the background image).

The other design was by Wurundjeri Elder Uncle Colin Hunter, which we then commissioned Uncle Colin to bring to life as an artwork to be installed alongside the physical plaque. Uncle Colin's design is titled "Circling through space" which juxtaposes the waves generated by boomerangs with the gravitational waves generated by black holes.

Uncle Colin was very keen to create the artwork himself by burning it onto wood and painting it as per the traditional style of his Wurundjeri people. His ongoing enthusiasm for the project has been amazing.

We are deeply grateful to Uncle Colin for his engagement in this project and for the final (massive!) artwork, which is on display at the Hawthorn campus of Swinburne University of Technology.

Artwork "Circling through space" burnt and painted on a wooden backrground by Wurundjeri artist Colin Hunter.



mage: Artwork "Rippling Out" by Wurundjeri artist Judy Nicholson

Background image: "Rippling Out" by Wurundjeri artist Judy Nicholson

Light projections

Rippling gravitational waves and space-time projections at the Firelight Festival

OzGrav Graphic Artist Carl Knox created amazing space-time projections for the Firelight Festival in early July at the Docklands in Melbourne. The rippling gravitational waves were both mesmerising and educational. Great work Carl – we can't wait to see what's next. The projections were a collaboration with OzGrav and Renew Australia.

Pilot Projection Night at Wolfhound

Carl Knox has also been working on some immersive light projections, as well as some non-touch interactive apps to engage people in the fun side of black hole science.

We held a fun night at Wolfhound Café in Fitzroy with science talks and catching up with colleagues after a long break due to working from home. The projections lit up the walls of Wolfhound, while Carl embedded their presentations within the moving background animations. We had 3 short talks from early career researchers (ECRs). Shanika from Monash investigates the lives of black holes. Andrew from Swinburne shared info about pulsars and pipelines. Christine from University of Melbourne talked about gravitational wave burst detection.

Projection art by Carl Knox. Photo credits: Carl Knox, OzGrav-Swinburne University of Technology

EDUCATION AND OUTREACH

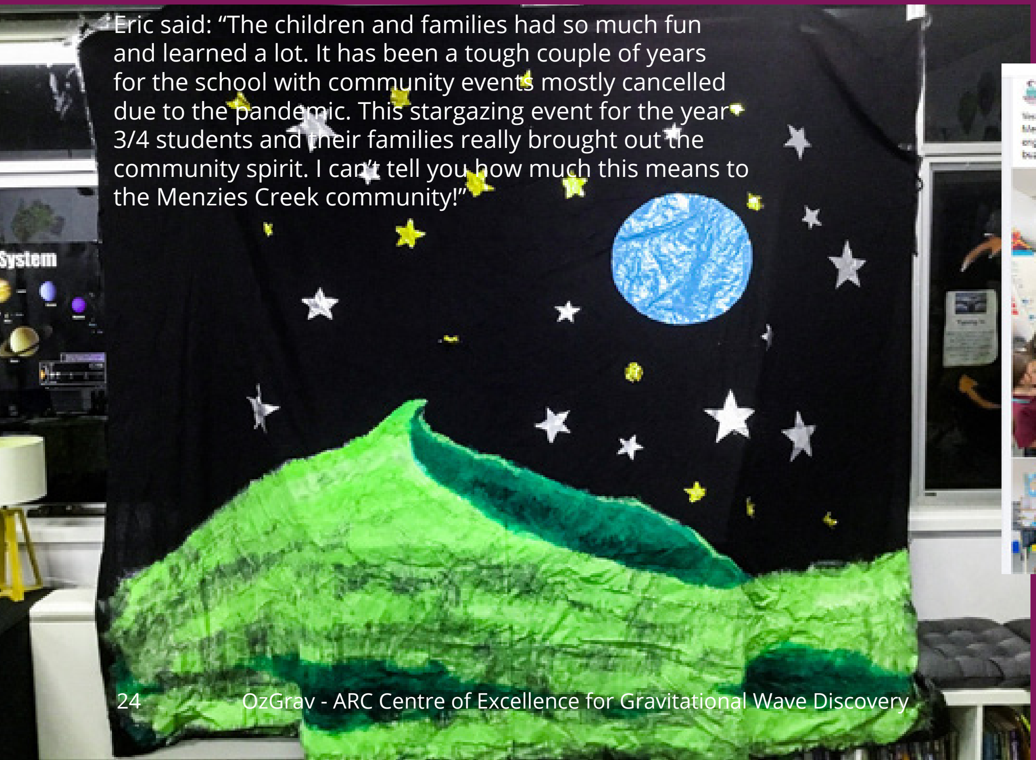
Mount Burnett Open Day

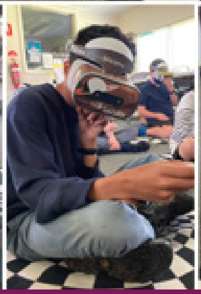
It was fantastic to get back to some in-person science outreach and join many other volunteers for the Mount Burnett Observatory Open Day on Saturday 26 March. The event celebrated 50 years of the Monash Dome, and visitors young and old were able to look through observatories and telescopes. It was a festival atmosphere with a BBQ, various science activities, and OzGrav's VR tour and games about gravity, black holes and gravitational waves. A big thank you to our volunteers!

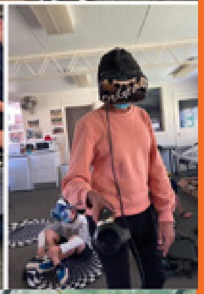
Menzies Creek Primary Stargazing

OzGrav outreach volunteers joined OzGrav Chief Investigator Eric Thrane and his children for a special stargazing night at Menzies Creek Primary School on 6 April. Several volunteers from Mount Burnett Observatory brought their telescopes out to the oval, while OzGrav hands-on science activities were noisily crowded in a classroom. The special event capped off several weeks of Year 3 and 4 learning about space, and they were excited to show their rocket designs to friends and families. Eric also gave a special talk earlier in the week, showing students a gravity experiment and describing how we detect gravitational waves.

Eric said: "The children and families had so much fun and learned a lot. It has been a tough couple of years for the school with community events mostly cancelled due to the pandemic. This stargazing event for the year 3/4 students and their families really brought out the community spirit. I can't tell you how much this means to the Menzies Creek community!"







Space Camp

OzGrav works with many partner organisations, including SciScouts for their week-long Space Camp in Canberra this year. We worked on the lives of stars, neutron stars and black holes, uncovering properties of space and time. VR is always popular, both the tethered Vive (showing Carl Knox's planet throwing game) and untethered Mirages (showing Mark Myers's Guided Tour of the solar system, neutron stars, black holes and gravitational waves). We had plenty of time for scouts to create their own space design that we made into a badge with the badge machine. Other activities during the camp included stargazing, robotics and a visit to Canberra Deep Space tracking station.


Menzies Creek Primary School

Yesterday the 3/4 students had a wonderful learning experience thanks to astrophysicist and Menzies Creek parent Eric Thrane. We learnt lots about gravity and black holes thanks to an engaging presentation and a "gravity well". The kids asked many great questions and they are still buzzing about it today, thanks Eric!

Facebook posts of student artwork and Eric Thrane's classroom visit. Credit: Menzies Creek Primary School

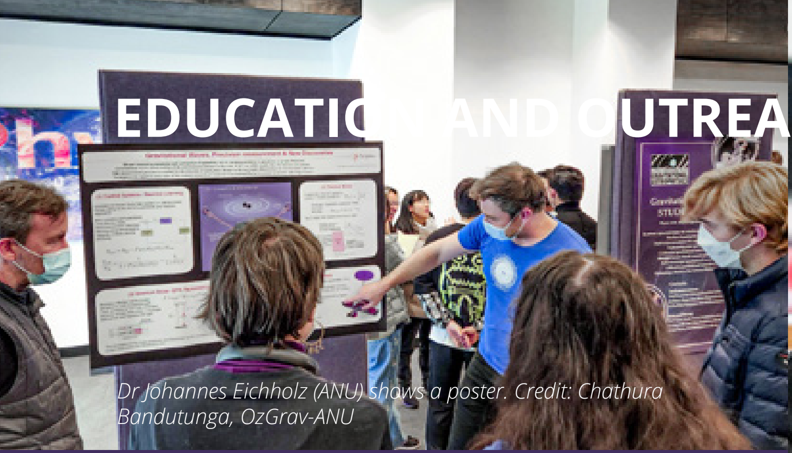
Science Alive! Adelaide

Science Alive is all kinds of awesome. It's the biggest event of its kind in Australia, with over 19,000 people in Adelaide joining in over 3 days. Friday was the Science Alive STEM Day Out, providing Year 7-12 students a window into the wide variety of STEM careers now available. Saturday and Sunday were the family days, where everyone could chat to our researchers and PhD, Masters and Undergraduate students, try virtual reality (VR), find out about LIGO (and don't get too close to the laser). We send a huge thanks to all the people who helped explain AMIGO (Adelaide Michelson Interferometer for Gravitational-wave Outreach) and took people on VR experiences across the exhausting 3 days.

Science Alive! is the largest, single, interactive, mobile science exhibition in Australia. With over 60 exhibitors including all the big names in science and technology, people could experience interactive and dynamic displays, plus spectacular science shows and performances for all ages. It builds our community's awareness of the scope and importance of science and technology in our everyday lives, inspiring future generations of science and technology professionals. There's something to spark the curiosity in all of us!

Thanks to our volunteers explaining LIGO science and showing VR demos. All photos on this page are credited to Meaghan Coles on behalf of Science Alive Adelaide.

EDUCATION AND OUTREACH



Dr Johannes Eichholz (ANU) shows a poster. Credit: Chathura Bandutunga, OzGrav-ANU

ANU Open Days

ANU Physics Market Day is an event held for students of ANU and external students to interact with ANU researchers and discover research opportunities at all levels. This year ANU node had five posters with project titles across Instrumentation as well as Data and Astrophysics themes. Student engagement was good.

ANU Open day took place on Sat 3 Sep in the Marie Raey building superfloor on the ANU campus. The open days mainly target high-school students who are pursuing higher education at undergraduate level. The ANU School of Physics has a booth at which 3 OzGrav members helped with demonstrations and answering questions. We set up the gravity well for the visitors to play with and understand the concept of space-time curvature and merger of high-density cosmic objects, which was well received. The group also set up the mini Michelson Interferometer and demonstrated the principles of laser interferometry and its applications in precision measurement.

ANU node partnered with ANU Astronomy Society for National Science Week 2022 (NSWk) and supported their event 'Glass: More than meets the eye' by supplying five Mirage headsets and training the users. The ANU Astronomy Society is a student society at ANU dedicated to running social and academic events for students passionate about astronomy and space. They further aim to connect members with opportunities in and out of the ANU to give a starting point for many young careers. This event was a stall for ANU Astronomy Society which they ran as part of the Science Society Science Mayhem in National Science Week. It was open to the general public

PhD student Disha Kapasi (ANU) demos a laser. Credit: Chathura Bandutunga, OzGrav-ANU

and ANU students to give an interactive experience to the general community, showcasing the best of our science initiatives. It was an incredibly successful stall with OzGrav VR headsets set up for students (with a particularly big interest from the undergraduate science community) to use and try out the applications.

Explore UWA Open Day

It was a warm spring day in Noongar land (Perth) for the Explore UWA Open Day on Sunday 28 August. OzGrav UWA students and staff were engaged with the public using our VR headsets for a Solar System Tour and testing the curvature of space on Einstein First's Space Time Simulator. We also gave away OzGrav stickers and

PhD student Alistair Mcleod (UWA) takes a child on a VR tour through space. Credit: Weichangfeng Guo, OzGrav-UWA

Dr Fiona Panther (UWA) describes how LIGO detects gravitational waves using a laser interferometer. Credit: Weichangfeng Guo, OzGrav-UWA

People take a black hole selfie. Credit: Weichangfeng Guo, OzGrav-UWA

the Gravity Geniuses posters. Some 300 posters were given away within the 5-hour event!

This year we added a tabletop interferometer to explain the instruments built and designed to aid in the first discovery of gravitational waves from a pair of coalescing black holes. There was even a chance to take a Black Hole Selfie. The Black Hole Selfie activity was especially enjoyed by our young visitors who repeatedly returned to the large monitor to see their image distorted. We gratefully acknowledge the use of the Pocket Black Hole app made by Laser Labs at www.laserlabs.org, on behalf of the Gravitational Wave Group at the University of Birmingham, UK.

Astrofest Perth

Did you catch the team at Astrofest in Perth in November? Astrofest is coordinated by ICRAR on behalf of Astronomy WA, the collective of astronomy communication, education and outreach organisations across Western Australia. ICRAR works closely with Scitech, Curtin University, CSIRO and the University of Western Australia in the coordination of Astrofest, and puts together a large scale science communication event in Perth. Thanks to our OzGrav researchers and students explaining the science behind gravitational waves to thousands of eager visitors.

Dr Carl Blair (UWA) talks to a crowd at Astrofest. Credit: Ruby Chan, OzGrav-UWA

ASTROFEST
AN ASTRONOMY FESTIVAL OF EPIC PROPORTIONS

PhD student Weichangfeng Guo (UWA) shows how space and time bend with heavy objects. Credit: Weichangfeng Guo, OzGrav-UWA

School sessions and Work Experience

The OzGrav Outreach team continue to take our Virtual Reality (VR) headsets and custom-built programs to schools around Australia. We are excited to partner with OzGrav early career researchers to share the research they are working on, and show students interesting visualisations explaining difficult concepts. Rowina (PhD student at Monash) gave a talk and helped run the "Mission Gravity" program in Melbourne. Maddy, Amy and Sammi have been busy at Adelaide schools, running "Mission Gravity" and showing how we use a laser interferometer to detect gravitational waves with AMIGO. We also had 6 groups of Year 10 students come through the Swinburne Astrophysics Work Experience program, discovering properties of stars, black holes and gravitational waves.

PhD Student Rowina Nathan (Monash) shares her science in a high school class. Credit: St Catherines

Undergraduate students Maddy, Amy and Sammi (Adelaide) run Mission Gravity VR workshops in a high school class. Credit: Lisa Horsley, OzGrav-Swinburne

Sunset at Astrofest in Perth. Credit: Weichangfeng Guo, OzGrav UWA

EDUCATION AND OUTREACH

Avanish Kulur Ramamohan from ANU (left) and Sammi Summerford from University of Adelaide (right) share VR tours and talk to participants at the World Science Festival in Gladstone. Credit: Lisa Horsley, OzGrav-Swinburne

Credit: World Science Festival / Brisbane Museum

Science Communication training at Regional Queensland World Science Festivals

World Science Festival events are run by the Queensland Museum in towns in regional Queensland, taking science to new audiences and encouraging hands-on participation for all ages, with both school and public event days.

The OzGrav Outreach team took these opportunities to take and train some of our early career researchers (for example PhD and undergraduate students) in science communication. It was a great way to meet lots of people and practice explaining our science to young and old participants. We were really excited to meet science communicator and author Dr Karl in Gladstone!

Virtual Reality (VR) is always popular at these events, so sometimes we had long queues waiting to take a virtual trip out to space. This gave us more time to chat to people about space study and careers, and show them some black holes games on the iPads. Download your own Pocket Black hole and more apps at www.ozgrav.org/apps.

Credit: Lisa Horsley, OzGrav-Swinburne

Credit: World Science Festival / Brisbane Museum

Credit: Lisa Horsley, OzGrav-Swinburne

Credit: World Science Festival / Brisbane Museum

Next generation STEM Leaders

Since its inception, the main goal of OzGrav's Education and Outreach programs is to "inspire the next generation of Australian scientists and engineers." In conjunction with Hume Central Secondary College in Broadmeadows, Victoria, the OzGrav outreach team piloted a new program to mentor early secondary students to serve as science ambassadors to help host science activities for local primary school students.

Education and Outreach Coordinator Jackie Bondell connected with Principal Vivienne Caravas to discuss a way to collaborate with the school to provide a unique science opportunity for her students. Principal Caravas is a tireless advocate for providing STEM enrichment for the students from Hume Central, a cohort from a diverse range of backgrounds that have been traditionally under-served in STEM opportunities.

We designed a program in which OzGrav would train two cohorts of Year 7 students across two campuses of Hume Central Secondary College to deliver OzGrav outreach activities such as the VR Guided Tour, the Gravity Well, app-based games, and the ever-popular badge machine! Led by OzGrav Outreach Officer Lisa Horsley, these training sessions not only taught the 40 Year 7 STEM Ambassadors the basics of OzGrav science but also prepared the students for confident science communication.

Over two days, the STEM Ambassadors (with oversight from Lisa and Jackie) ran activities with over 200 primary school students in Years 5-6 from five local primary government schools.

Principal Cavaras wrote, 'On behalf of everyone here at HCSC, I just wanted to thank you both once again for providing our students with such a great opportunity. Both our Year 7 ambassadors and primary school students loved the applied learning experiences. We look forward to working with you in 2023 and beyond!' OzGrav plans to continue this model of 'training the trainers' as a way to broaden the impact of its Education and Outreach programs.

National Science Quiz

As part of National Science Week 2022, OzGrav was a sponsor for the National Science Quiz. This night of science and fun was hosted on 7 August in front of a live audience of over 200 people in Fed Square in Melbourne and live streamed on YouTube for remote participation to over 400 at-home teams.

The event was hosted by Charlie Pickering from ABC-TV and featured two teams, each with two scientists and a comedian, merging scientist content with humorous banter in the quest to be crowned the National Science Quiz Champion!

Kirsten Banks (Astrophysics and Science Communication), A/Prof Bradley Moggridge (Environmental and Indigenous Water Science), A/Prof Jacqui Romero (Experimental Quantum Physics), and Prof Barbara Holland (Mathematical Biology) were joined by ABC presenters Lawrence Leung and Nate Byrne.

After a suspenseful tie-breaker question, the team of Jacqui, Lawrence and Bradley was declared the winner, and the team of Kirsten, Barbara and Nate was slimed! The National Science Quiz was led by FLEET, the ARC Centre in Future Low-Energy Electronics technologies, and sponsored by additional ARC Centres of Excellence including OzGrav, EQUS, Plant Success, Exciton Science, TMOS, as well as Matrix, Monash Engineering and the Department of Defence.

The success of the Quiz comes from building science capital with public engagement. This event shows that there are many ways to engage with science, encouraging people to feel that STEM is an important and useful part of people's lives. The NSQ material will be available as educational resources for schools. You can read more about the Quiz or play along at home at: https://www.nationalsciencequiz.com.au/

Credit: Hume Central Secondary College

AWARDS AND HONOURS

Disturnguished Professor Susan Scott
Credit; Tracey Nearmy, ANU

Congratulations to OzGrav Chief Investigator Susan Scott (ANU):

- for receiving the 2022 Monash Faculty of Science Distinguished Alumni Award;
- for being awarded the AIP Walter Boas Medal for her leadership in the development of the field of GW science, general relativity, and cosmology;
- appointed as the first Australian Editor-in-Chief of the international journal Classical and Quantum Gravity;
- and for having received the prestigious 2022 Walter Burfitt Prize from the Royal Society of NSW for scientific contributions deemed of the highest scientific merit. Amazingly well done!

Congratulations to Distinguished Professor Susan Scott for being elected as Fellow of the International Society on General Relativity and Gravitation (ISGRG) for 2022 - the first Australian to receive this honour!

Distinguished Professor Scott attended an international award ceremony in Brussels as she was the first Australian awarded the Blaise Pascal Medal for Physics by the European Academy of Sciences (EurASc). The award recognises her research in General Relativity, Cosmology and Gravitational Wave science, and also reflects well on the quality of research performed at the ANU Centre for Gravitational Astrophysics (CGA), OzGrav, and in Australian science generally. Susan hopes it will provide inspiration and encouragement, particularly to young women entering STEM fields, that anything and everything can be possible if they pursue their dreams of a career in science.

Professor Matthew Bailes (Swinburne University of Technology) attained a Fellowship of the Australian Academy of Sciences for outstanding contributions to science. Matthew Bailes is an astrophysicist who has specialised in the study of pulsars, transient radio bursts and gravitation, making major contributions to establishing Australia's high international profile in these areas. In particular, he has played a pivotal role in the development of a new branch of astrophysics, Fast Radio Bursts, guiding projects that led to Australia's dominance of the field. He established the Swinburne University Centre for Astrophysics and Supercomputing, recognised internationally as a centre for astrophysics and virtual-reality content for public outreach.

Congratulations to Professor Ilya Mandel (Monash) for being appointed to the ARC's (Australian Research Council) College of Experts.

Congratulations to Ethan Payne (Caltech/Monash/ANU) and Dr Ling (Lilli) Sun (Caltech/ANU) for the LIGO Laboratory Award for Excellence in Detector Characterization and Calibration!

A/Prof David Coward (UWA) and collaborators were awarded with the ARC Linkage Grant "Characterising satellites using un-resolved optical observations".

Dr Bruce Gendre (UWA) secured an ARC LIEF (Linkage Infrastructure, Equipment and Facilities) 2023 award for Transforming the Zadko Observatory into a Space Surveillance Hub.

Prof Dave Ottaway (Adelaide) and collaborators also secured a LIEF 2023 award for Adaptive Optics for Advanced Gravitational Wave Detectors.

Prof Dave Ottaway was appointed Fellow of Optica (Formerly Optical Society of America).

OzGrav is excited to announce that three of our OzGrav members were awarded DECRAs (Discovery Early Career Researcher Awards). Congratulations to Dr Katie Auchettl (University of Melbourne), Dr Dan Brown (University of Adelaide) and Dr Anais Möller (Swinburne University of Technology).

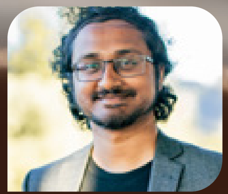
Katie Auchettl's project aims to understand the unexplored population of non-active or quiescent supermassive blackholes (SMBHs) using tidal disruption events - the multi-wavelength outburst resulting from a star being ripped apart by the tidal forces of the SMBH. Dan Brown's project will develop new optimised designs for gravitational wave detectors and an array of innovative new open-source numerical models for exploring new designs of quantum optics experiments. Anais Möller's project aims to single out the most exciting exploding stars and extreme events out of the millions detected each night at the world's largest optical telescope.

In February 2022 Swinburne University of Technology announced Victoria's largest supercomputer will be built at the Hawthorn campus. The supercomputer has the capacity to analyse and process data a million times faster than standard computers. It allows astronomers to monitor space in unprecedented detail and will also assist researchers in areas including bushfire detection, natural disaster planning and response, neuroscience, cancer detection and defence.

Lisa Horsley won the Centre for Astrophysics and Supercomputing (CAS) Director's Outreach Award from Director Prof Jean Brodie at Swinburne University of Technology. Lisa ran many outreach events, as well as science communication and team building workshops to train early career researchers at multiple Universities and ARC Centres of Excellence.

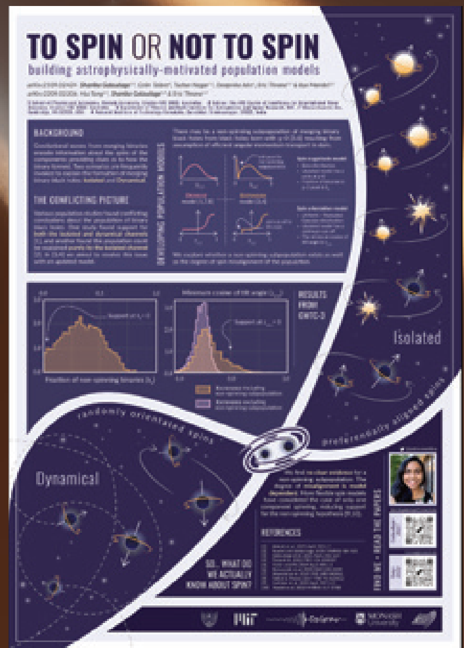
Carl Knox's video animation of a Neutron Star and Black Hole (NSBH) merger was included in a public outreach exhibition on gravitational wave astronomy in the Tech Art center in National Tsing Hua University (NTHU) in Taiwan. Carl is OzGrav's Digital Media and Marketing Officer, combining his digital skills with his background in fine arts.

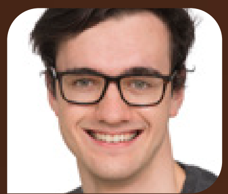
AWARDS AND HONOURS



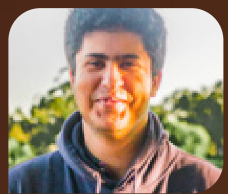
Chayan Chatterjee (UWA PhD student) was the runner-up for the JP Macquart Best Student talk Award at Australian National Institute for Theoretical Astrophysics (ANITA22). He also won the prize for the best presentation at the AMSI Summer School which is "the biggest Maths event in Australia" for honours and postgraduate students in the mathematical sciences. Chayan was also runner-up for the PSA Research Week Best Student Talk Award from the Postgraduate Student Association – UWA.

Congratulations to Shanika Galaudage (Monash University PhD student) on winning the international GWPAW meeting "People's Choice" poster prize at the conference held in Melbourne in December.

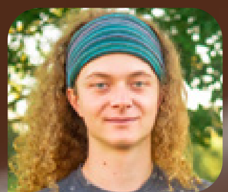




Ethan Payne (Monash Masters student then ANU Research Assistant) won the TH Laby Medal from the Australian Institute of Physics for the best Honours or Masters thesis from an Australian University.



Congratulations to OzGrav Associate Investigator Nikhil Sarin (Monash PhD student then Postdoctoral Researcher at Nordita Institute, Stockholm) who in May 2022 was awarded the Robert Street 2021 Prize for the best PhD in the School of Physics and Astronomy for his thesis on 'The observational signatures of nascent neutron stars'.



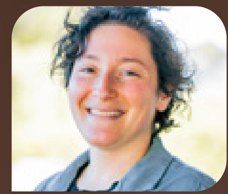
Congratulations to OzGrav PhD students Lucy Strang from the University of Melbourne and Ben Grace from the Australian National University for jointly winning the Kerr Prize for the best student talk at the 11th Australasian Conference on General Relativity and Gravitation.

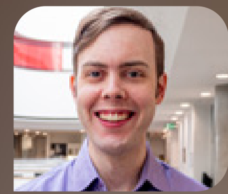
Congratulations to Yuanming Wang (PhD student at University of Sydney) who won the NSW Award for Postgraduate Excellence in Physics from the Australian Institute of Physics (AIP).

OzGrav 2022 Retreat Awards

Best Lightning talk.

Student winner: Anastasia Popkova (UWA);
Runner up: Emily Rose Rees (ANU).



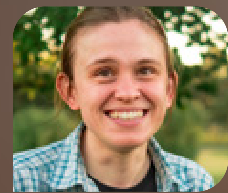


Postdoc winner: Dr Kelly Gourdji (Swinburne);
Runner up: Dr Andew Cameron (Swinburne).

Biggest contributors to Research Briefs, Media Releases and Newsletter Features

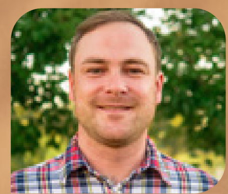
Dr Poojan Agrawal (Swinburne), Dr Evgeni Grishin (Monash), Prof Ilya Mandel (Monash), Dr Hannah Middleton (Swinburne / Uni of Melbourne) and Dr Ling (Lilli) Sun (ANU).

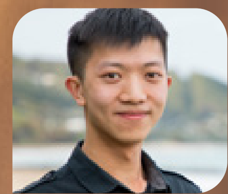
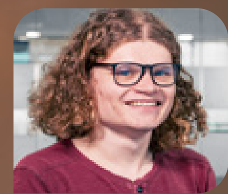
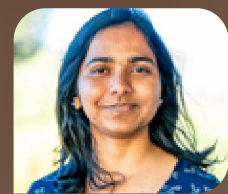
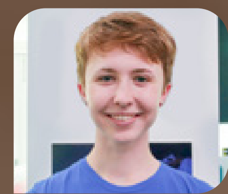


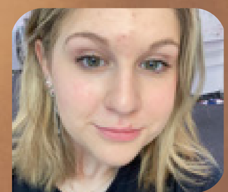


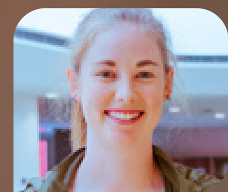

Outreach Superstars

Emily Rose Rees and Johannes Eichholz – Australian National University
Shanika Galaudage and Mike Lau – Monash University
Jacob Askew and Pratyasha Gitika - Swinburne University of Technology
Maddy Parks, Amy Pollard and Sammi Summerford – University of Adelaide
Christine Yi Shuen Lee – University of Melbourne
Kyla Adams (Einstein First), Hayden Crisp and Jack Williamson - University of Western Australia







INSTRUMENTATION THEME

OzGrav's Instrumentation Theme, led by Chief Investigator Prof David McClelland (ANU) aims to carry out core and critical path research and development on a scale and focus of relevance to existing and planned detectors.

The instrumentation theme is pursued under seven programs:

1. Commissioning - Program Chairs: Dr Dan Brown (Adelaide) and Dr Bram Slagmolen (ANU)

2. Quantum - Program Chairs: Dr Terry McRae (ANU) and Dr Sebastian Ng (Adelaide)

3. Low frequency Newtonian noise mitigation - Program Chairs: Dr Bram Slagmolen (ANU) and Prof JU Li (UWA)

4. Distortions and Instabilities - Program Chairs: Dr Carl Blair (UWA) and Prof David Ottaway (Adelaide)

5. Space Instrumentation - Program Chair: Dr Andrew Wade (ANU)

6. Pulsar Timing - Program Chair: Prof Matthew Bailes (Swinburne)

7. Future Detector Planning - Chairs: Prof Matthew Bailes (Swinburne) and Prof David McClelland (ANU)

Installation of torsion bars, a major upgrade in the commissioning of the TorPeDO detector at the Centre for Gravitational Astrophysics (CGA), ANU. Credit: Avanish Kulur Ramamohan, OzGrav-ANU.

INSTRUMENTATION THEME

Commissioning

Program chairs: Dr Daniel Brown (Adelaide) and Dr Bram Slagmolen (ANU)

Commissioning trips to LIGO resumed from mid-2022 after the COVID-19 travel issues. Observing Run 4 (O4) aims to start in mid-May 2023 and several OzGrav members have been contributing to the commissioning efforts.

Dr Daniel Brown (Adelaide), Mitchell Schiworski (Adelaide), and Nutsinee Kijbunchoo (ANU) visited LIGO Hanford Observatory from Nov-Dec. They worked on a mixture of thermal correction system optimisations and contributed to successful commissioning of the new filter cavity addition, for providing frequency independent squeezing. Dr Aaron Goodwin-Jones (UWA) also visited LIGO Livingston and LIGO Hanford in mid-2022. He worked on applying his new technique for measuring mode-mismatches in the interferometer.

Remote commissioning efforts are slowly building up. Dr Daniel Brown (Adelaide), Dr Jennifer Wright (ANU), and Nutsinee Kijbunchoo (ANU) are providing remote support for simulation, squeezing, and TCS commissioning. Numerous new postdocs and students will be starting in early 2023 to aid in this effort and work is ongoing in training and exploring how to efficiently deploy these new remote commissioning resources. Georgia Mansell and Craig Cahillane from Syracuse and LIGO Hanford Observatory also visited Adelaide and ANU in Dec 2023 for remote commissioning activities and discussions on further remote commissioning activities.

Image left: Frosty LHO X-arm at LIGO Hanford Observatory. Credit: Mitchell Schiworski, OzGrav-Adelaide.

Image above: Remote commissioning with Dr Bram Slagmolen (ANU). Credit: Georgia Mansell, LIGO Hanford Observatory.

Image right: LHO Control room at night. Credit: Mitchell Schiworski, OzGrav-Adelaide.

INSTRUMENTATION THEME

Quantum

Program Chairs: Dr Terry McRae (ANU) and Dr Sebastian Ng (Adelaide)

Quantum noise limits the sensitivity of gravitational wave interferometers by imposing fluctuations on the quadratures of the electromagnetic field. These fluctuations can be suppressed (squeezed) in the quadrature we ultimately use for measurement at the expense of the other quadrature. The quantum noise can also be modified by changing the laser power and/or wavelength or the configuration of the interferometer.

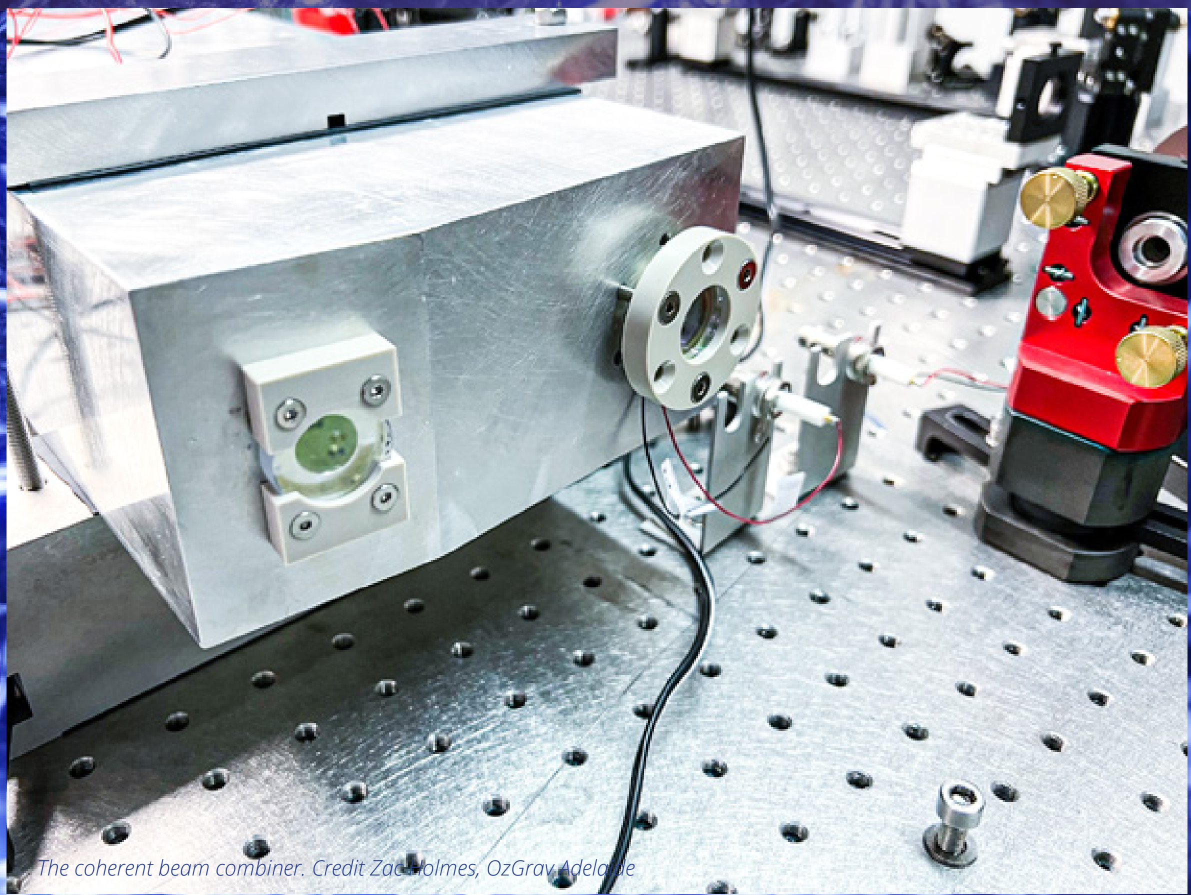
Laser development

Amplification of the extended cavity diode laser (ECDL) developed at ANU with a Thulium fibre preamplifier developed at Adelaide has been demonstrated. Preliminary tests indicate the amplified ECDL meets the power and stability requirements for squeezing at longer wavelengths envisioned for the next generation of gravitational wave detector and is ready to be integrated into the ANU long wavelength squeezer. A Multi-port coherent beam combiner is under testing in collaboration with the Albert Einstein Institute. Research translation is underway into the use of 2 micron (μm) fibre lasers for weed control. Development of 3.6-3.7 μm lasers suitable for thermal compensation for gravitational wave detectors is underway.

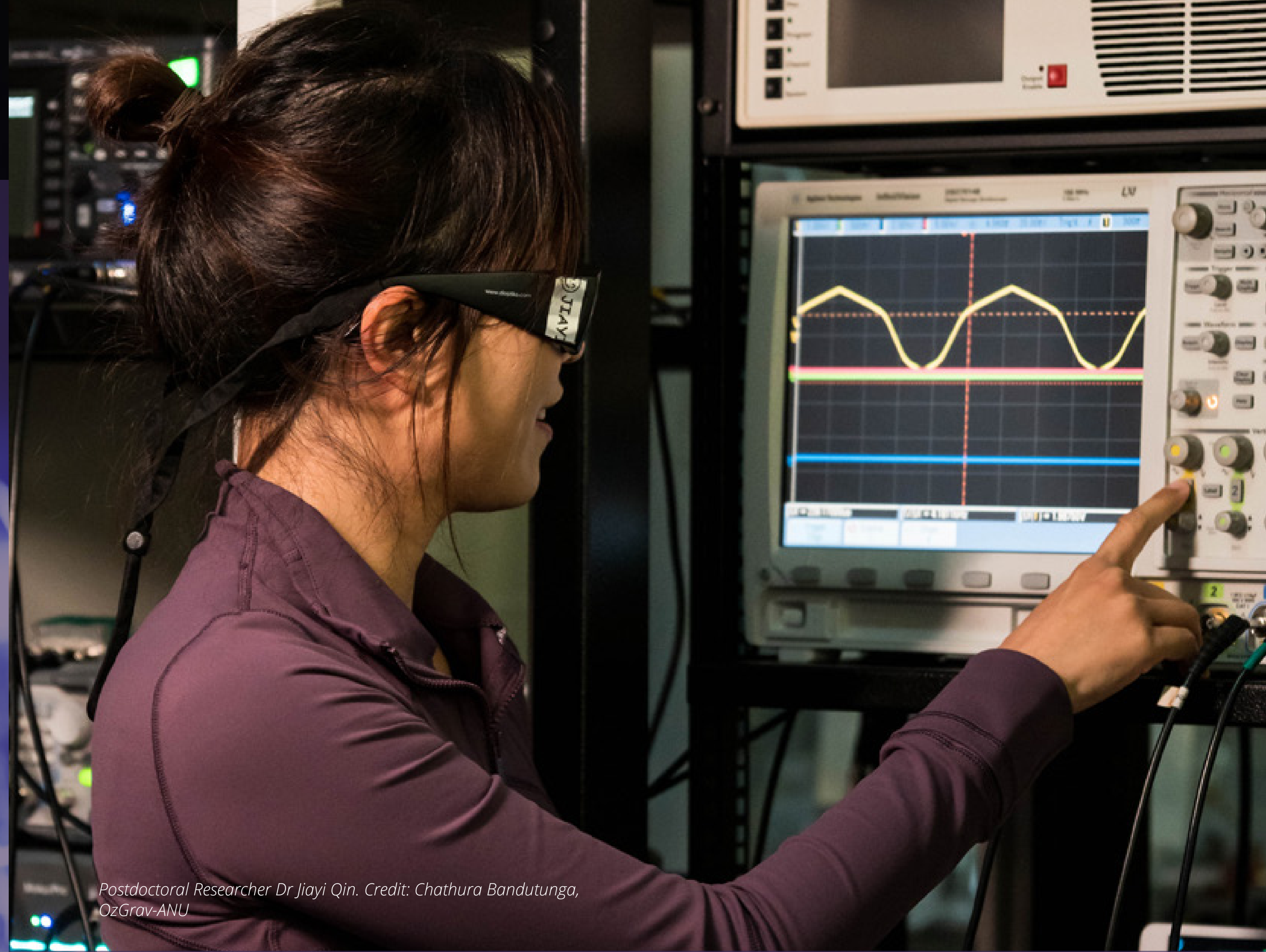
Squeezing configurations

Investigations of squeezed light and interferometer configurations at ANU are continuing. Tests are underway with dual interferometer systems to correlate the signals and anti-correlate the noise. Tests with squeezed light generated inside the interferometer where the signal is reduced but the noise is further reduced to improve the signal-to-noise ratio are ongoing. We are developing protocols for non-degenerate internal squeezing where squeezing at different frequencies can preferentially sample different parts of the interferometer to enhance the signal-to-noise ratio. We are testing an alternative procedure that does not rely on semiconductor materials science using optical parametric amplification to overcome poor photodiode quantum efficiencies.

Optomechanical techniques can introduce correlations between the position and momentum uncertainty of a mirror and the amplitude and phase uncertainty of the light that it reflects. Recent theoretical work at UWA has shown that a white light cavity, where the arm cavity resonance is broadened by optomechanically changing the phase response of the signal recycling cavity, can be intrinsically stable while improving the sensitivity bandwidth if reading the gravitational wave signal from optomechanical cavity. The high frequency sensitivity can be boosted even further in a detuned signal recycling cavity with a detuned stable white light cavity. A desktop experiment is underway with a silicon nitride membrane to demonstrate the sensitivity enhancement. Separate experiments are underway to enhance the peak sensitivity at particular frequencies with an optical parametric amplifier to enhance the optical spring effect.



The coherent beam combiner. Credit Zac Holmes, OzGrav Adelaide



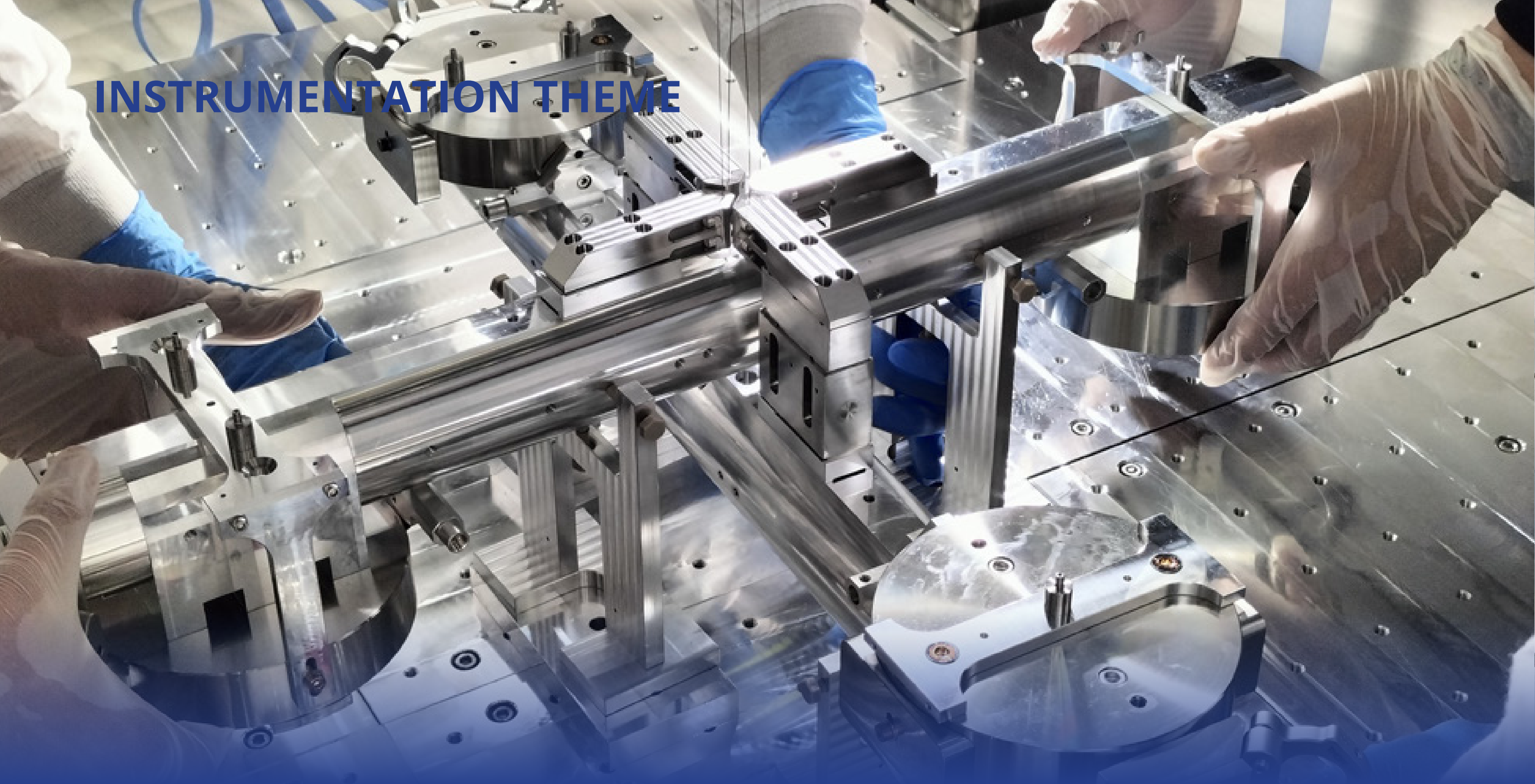
Postdoctoral Researcher Dr Jiayi Qin. Credit: Chathura Bandutunga, OzGrav-ANU

Case Study

Coherent Beam Combination to Meet Next-Gen Detector Laser Requirements

Next-generation ground-based gravitational wave detectors will continue forward as the avant-garde of high-precision metrology technologies to search deeper into the cosmos than ever before. To improve detector sensitivity, future detector concepts such as Cosmic Explorer, the Einstein Telescope, and the Neutron star Extreme Matter Observatory (NEMO) will require an ultra-stable laser source at an operating wavelength deeper into the near-infrared (1.5-2.1 μm) than current detectors (1 μm). The interferometer seed laser will further require higher power to reduce quantum noise susceptibility, which, alongside a change in wavelength, poses a significant challenge to the capabilities of a single high-power, narrow-linewidth laser source.

Coherent beam combination circumvents such single-source limitations as optical nonlinearities and thermal instabilities by coherently combining multiple lower power laser beams into a single, high-power beam. We at the Adelaide node of OzGrav have successfully demonstrated the coherent combination of three laser beams within a passive optical bow-tie resonator, in collaboration with the Albert Einstein Institute in Hannover, Germany. The resonator is the 4-port aLIGO pre-mode cleaner, retro-fitted with mirrors optimised for coupling equal light-injection in three ports. Thus far, we have achieved the coherent combination of 3 x 5 W of laser power into a single 11 W beam, while cleaning the higher-order optical mode content of each input. Coherent beam combination utilising a passive resonator as a combining optic presents a pathway forward for wavelength-independent power scaling with damage thresholds far beyond single-source limitations. The exciting potential for our novel technology includes the scalability of inputs and all the optical power we could ever need.



Installation of torsion bars, a major upgrade in the commissioning of the TorPeDO detector at the Centre for Gravitational Astrophysics (CGA), ANU. Credit: Avanish Kulur Ramamohan, OzGrav-ANU.

Low Frequency Newtonian Noise Mitigation

Program chairs: Dr Bram Slagmolen (ANU) and Prof JU Li (UWA)

Commissioning of the Isolation and Suspension Chain has been ongoing, starting with the MultiSAS inverted pendulum stage. A horizontal resonance frequency below 100 mHz was achieved. Subsequentially, an error in the suspension wire length was discovered and required shortening of the wires. This was a major undertaking, to prepare tooling and procedures for how to safely and accurately do this in a cleanroom environment. After this intervention the actual torsion beams were successfully suspended.

In addition, all four injection lasers are phase locked to a fifth reference laser. A detailed control model has been developed to help characterising their locking performances.

The digital interferometer sensing technique has undergone an upgrade to place all the fibers and folded free-space testbed inside a pressure and thermal stable environment.

For the tilt sensor ALFRA, we have gone through a major redesign. The new ALFRA-2 design has changed from a beam rotation sensor to a compact form that enable the sensor to be used in a confined space with 3DOF sensing. There are many innovative design concepts that improves the robustness, with lower frequency, higher sensitivity and higher dynamic range.

For the Gingin seismic array project, we used 12 seismometers to form a mini-array to study the wind-induced seismic noise. We developed a method for a detailed site characterisation study. This study is not only useful for the Gingin site, but will be of interest for site study for any potential GW detector sites. The large array with the 36 seismometers has been designed. Work on deploying the closer seismometers has begun. Permission to install seismometers in a far field in the Nature reserve has been requested.

Carl Blair installing the seismometers for the piezo pre-isolated table for use on 7m 2 μm suspended cavity (pictured) and 80m coupled cavity experiments. Credit Jian Liu, OzGrav-UWA.

Distortions and Instabilities

Program chairs: Dr Carl Blair (UWA) and Prof David Ottaway (Adelaide)

Several major changes occurred in the distortions and instabilities theme in the last 12 months. A LIEF grant awarded for cryogenics at University of Western Australia has resulted in a focus on the cryogenics design. A LIEF grant was awarded for a Thermal Compensation System Test Stand based at Adelaide University resulting in effort to design it. There has been slower progress (than anticipated last year) repairing the Gingin South arm vacuum envelope, with parts ordered – this has led to a shift in focus to a 7m cavity experiment. Vacuum safety mitigation in the Gingin East arm is complete, however there have been subsequent issues with the input test mass suspension system that have prevented experiments.

Complete characterisation of birefringence of silicon sample using photoacoustic technique was completed. This investigation demonstrated that a 100mm float zone silicon test masses birefringence meets Einstein Telescope requirements in the central region of the test mass. Stress induced birefringence was measured and smaller than the ET (Einstein Telescope) requirement in the 100mm test mass. Suspected impurity induced birefringence surpassed the ET requirements in a ~50mm streak on the test mass. The investigation will be followed up with theory and measurement of thermal stress induced, coating and beam splitter birefringence detailed in tis years plan.

The paper demonstrating imaging of parametric instability with a phase camera was published. This combined work between Adelaide and UWA demonstrated the phase camera was able to measure the unstable mode in the Gingin cavity. The short period between instability and saturation made the measurement difficult. With saturation being accompanied by instability in the angular controls, it is thought that the measurement will be easier in a gravitational wave detector where the time constant of instability is longer.

We demonstrated optical feedback control of parametric instability for the first time, as Vlad moved to LIGO Livingston for a detector engineering job.

Study on parametric instability mechanical mode mapping theory was investigated. The idea to use birefringence Hartman style sensor was ruled out as a tool to measure the mechanical mode.

Beam splitter thermal aberrations were investigated, and results were presented with international collaborators. These investigations show a beam splitter compensator technique can reduce optical losses but a NEMO or Voyager design could not be achieved.

A 7m 2um suspended cavity experiment is progressing, however issues with the piezo pre-isolated table have resulted in some delays. Suspended 80m silicon test mass cavity has been held up by the tube collapse. The suspension build has progressed. The end test mass suspension frame is built. Input test mass suspension

INSTRUMENTATION THEME

almost complete - control still needs to be installed. The AlGaAs coating also suffered multiple delays due to COVID travel restrictions. The optics are now in Germany being coated. The successful LIEF grant for cryogenics will bring forward the cryogenic system with heat shields and cool links being installed in the first iteration of the 74m cavity.

The new study of parametric instability in the proposed NEMO gravitational wave detector was completed. The study surprisingly shows that parametric instability severity will not be dramatically worse than in Advanced LIGO. Mitigation will however be required with parametric gains reaching ~100 in the frequency band between 20 and 80kHz. A subsequent mitigation (acoustic mode damper and thermal compensation) investigation is ongoing.

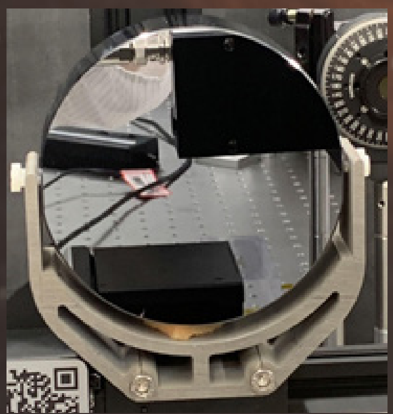
A study that detailed a way to optimise Q factor measurements of gravitational wave detector test masses was completed. The increased loss from the application of AlGaAs coatings should be measurable allowing the loss factor of the coating to be determined from before and after Q measurements.

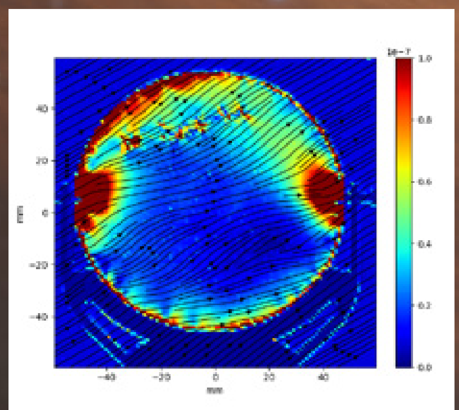
Aaron Goodwin-Jones and Ammar Al-Jodah preparing test masses for 7m 2 µm suspended cavity. Credit: Ju Li, OzGrav-UWA

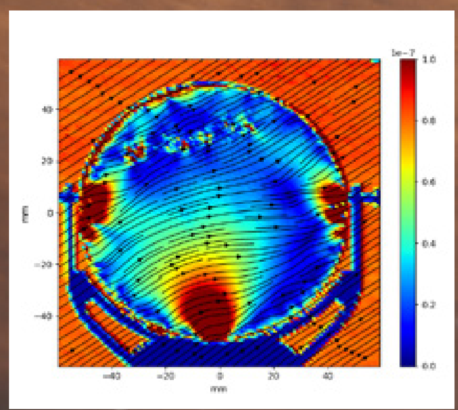
Case study

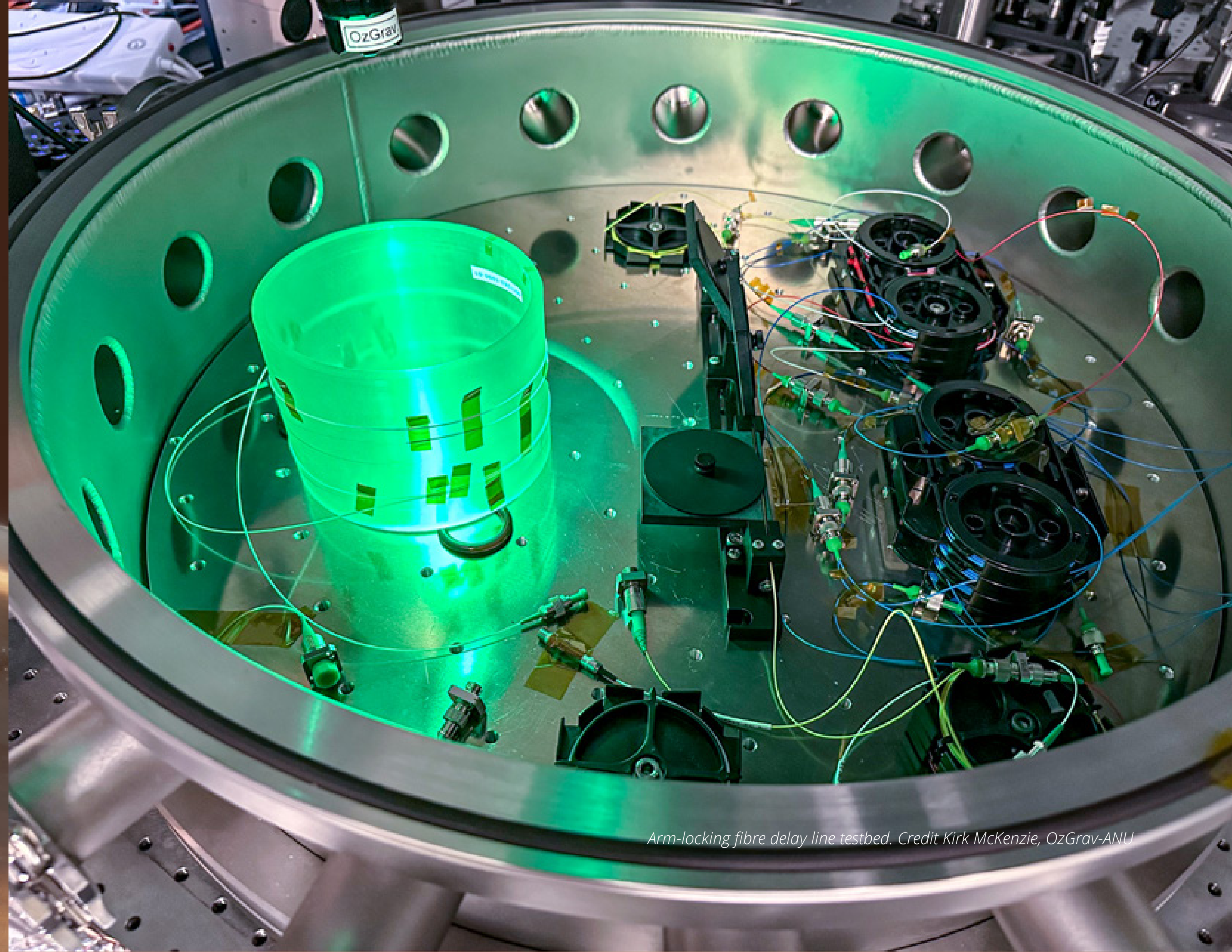
The birefringence measurement device developed at UWA produces beautiful maps. The sensitivity is exquisite, with residual birefringence and noise at the 10^{-9} level. A selection of maps of float zone silicon test masses are shown in the figures. This is the purest Silicon production method though to have the lowest birefringence. Stress induced birefringence (from gravity), impurities and residual stress from machining holes on either side are clearly visible in the scans.

Figures (left to right): silicon test mass; birefringence map supported on 4 pins on the sides; and birefringence map sitting on hard base with foam side support. Arrows indicate birefringence angle.









Arm-locking fibre delay line testbed. Credit Kirk McKenzie, OzGrav-ANU

Space Instrumentation

Program Chair: Dr Andrew Wade (ANU)

The Space Program continues on three themes 1) weak light phase tracking and recovery, 2) absolute laser frequency readout, and 3) laser frequency stabilisation for space-based interferometers.

Several milestones were completed on time in 2022. These were:

- to assemble a new high finesse cavity testbed;
- to submit absolute frequency results against atomic reference for journal publication;
- and publish results of an inter-spacecraft arm locking study.

A fourth milestone to complete weak light optical results will be completed in early 2023.

Phase tracking of ultra-weak optical powers

Instrumentation for recovering phase from optical heterodyne signals is an essential enabling technology for space-based laser interferometers. Improved robustness in the presence of noise is important for de-risking existing space-based gravitational wave detectors and earth-focused mass change missions. This work also enables new longer arm length missions probing new bands into the µHz, bridging an important gap between pulsar timing arrays and the soon to be launched LISA (Laser Interferometer Space Antenna) mHz band. The main achievement this year was the implementation of an optimised phasemeter design in an optical test bed. A pair of pre-stabilised lasers were compared with both an ultra-weak heterodyne beat signal and a stronger reference signal to compare our optimised phasemeter's performance in the presence of typical optical system noise. This work demonstrated a tracking of optical signals to below one femtowatt of optical power, a world record. Completion of this milestone is expected in the first quarter of 2023.

Absolute laser frequency readout

Knowing the absolute frequency of lasers used in inter-satellite interferometry is valuable for reducing the number of degrees of freedom in link acquisition sequences and essential for calibrating the scaling of ranging signals from phase into true displacement (strain). Work is ongoing in developing a technique and hardware for a cavity-based absolute frequency readout. This technology targets space missions with rigorous requirements on weight, power and complexity. A prototype scale factor readout unit was delivered for the generation of gigahertz waveforms and readout of cavity resonant spacing. OzGrav personnel Rees and McKenzie

INSTRUMENTATION THEME

travelled to JPL-NASA in Pasadena California to integrate this hardware into the GRACE-FO mission's optical testbed. A publication was accepted comparing cavity based absolute frequency readout against an atomic reference.

Laser stabilisation for space interferometers

A detailed study combining the Arm-Locking laser frequency stabilisation scheme with an optical cavity readout was published. This work showed arm locking to be compatible with the baseline laser stabilisation planned for the LISA mission. Using the LISA arms as an ultra-stable reference, the existing mission hardware can be used to augment the current cavity only stabilisation system. Benefits include risk reduction and possible architecture simplifications with no additional hardware and at least an order of magnitude improvement across the LISA sensitivity band. A fibre based optical test bed with 10 km delay line was commissioned with a successful blended feedback control using an optical cavity and arm delay to a laser.

High finesse cavity reference testbed

A high finesse cavity was commissioned and two-laser-one-cavity test bed was assembled for verification of laser stabilisation performance. This setup will be used as a stable light source for a range of laser ranging and thermal noise experiments in the OzGrav-ANU laboratory.

Pulsar Timing

Program Chair: Prof Matthew Bailes (Swinburne)

In 2022 our investment in pulsar processors at the MeerKAT and Molonglo telescopes started to pay dividends. The PTUSE instrument on the MeerKAT telescope led to 10 publications, including a stunning observation of the celebrated double pulsar demonstrating light bending around the companion pulsar, and the first formal data release of the MeerTime Pulsar Timing Array.

We continue to push the boundaries that the computers can handle, by implementing new modes for higher time and frequency resolution. This is enabling resolution of the scintillation bands exhibited by the double pulsar and might ultimately lead to a precise distance. This is required to remove the covariance between the pseudo acceleration the system is experiencing and its masses.

Our spin off company Fourier Space completed its first year of operations with the construction of the SKA pulsar processors as part of the global effort and we were visited by senior SKA staff.

Molonglo Observatory Synthesis Telescope (MOST) is a parabolic cylindrical antenna located near Canberra. Credit: Dr Chris Flynn, OzGrav-Swinburne University of Technology

Future Detector Planning

Chairs: Prof Matthew Bailes (Swinburne) and Prof David McClelland (ANU)

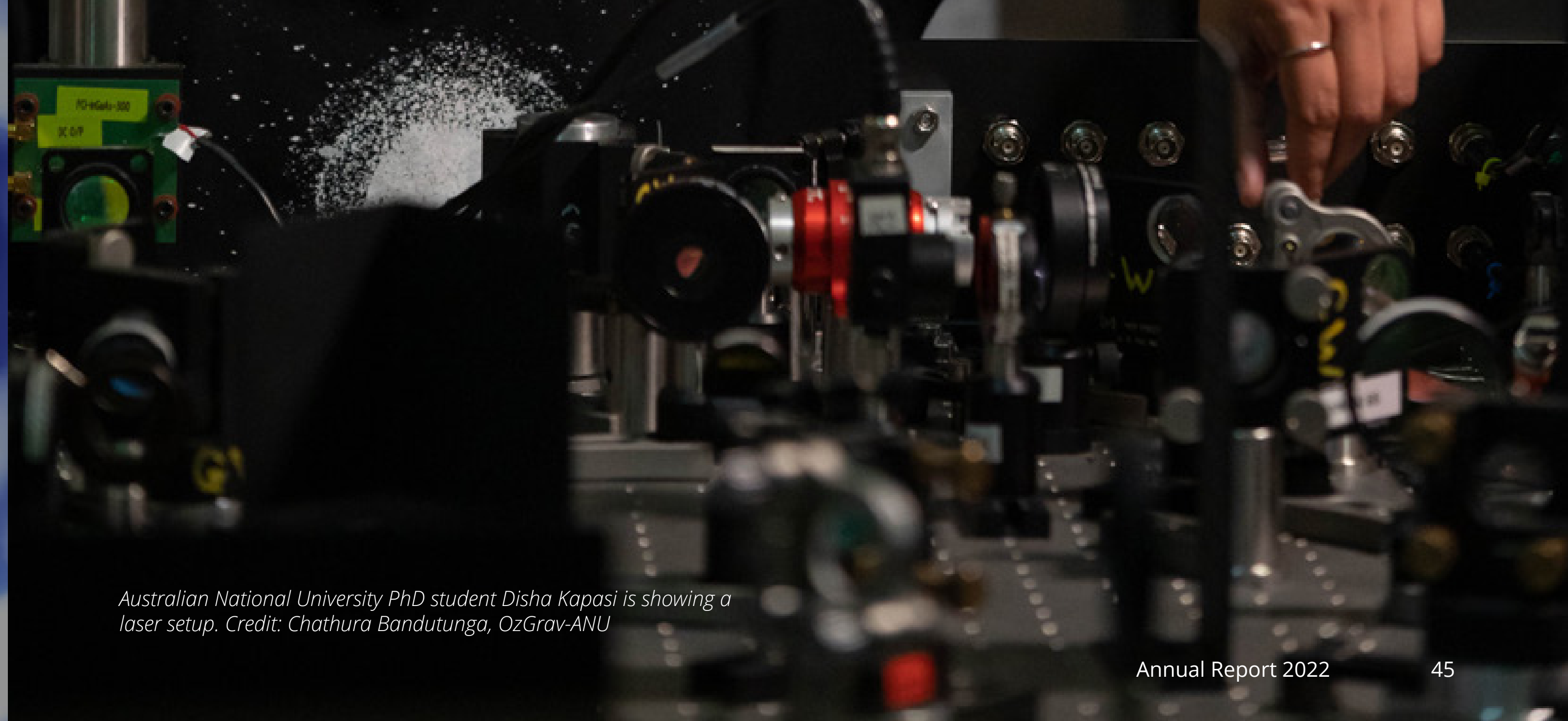
Strong progress was made in 2022. OzGrav members have taken on an increasing number of leadership roles in both the Cosmic Explorer (CE) and Einstein Telescope (ET) projects.

Particularly pleasing is OzGrav's growing relationship with ET: OzGrav Postdoctoral Researcher Dr Dan Brown (Adelaide) became the co-chair of ET's Low Frequency Optical Design group and is contributing to the ET cost-benefit analysis. He will be running an international ET Optical Design workshop in Nikhef in June. CI Dr Ling Sun (ANU) was invited to join Division 5 (Synergies with other gravitational-wave observatories) of the ET Observational Science Board. Postdoctoral Researcher Dr Aaron Goodwin-Jones (UWA) co-authored the ET Pathfinder paper, contributing to the frequency noise estimates and longitudinal locking scheme requirements. He was also a member of the Wavefront Sensing and Control working group.

We also continued to engage strongly with the CE Project. CI Dr Ling Sun (ANU) joined the Cosmic Explorer Data Analysis as a Calibration Scientist. She also contributed to CE Science Data Processing Proposal writing. She led the US Community Study on the Future of Particle Physics (Snowmass) White Paper drafting the paper on "Probing dark matter with small-scale astrophysical observations" and contributed to the white paper "Dark Matter in Extreme Astrophysical Environments." CI Dr Bram Slagmolen (ANU) was a key contributor to the Snowmass "Cosmic Frontier White Paper: Future Gravitational-Wave Detector Facilities." A team led by CIs A/Prof Paul Lasky and Prof Eric Thrane (Monash) completed a study on how third-generation observatories will be able to use NSBH observations to undertake unique experiments in nuclear physics. Postdoctoral Researcher Dr Rory Smith (Monash) led a study on how well CE will be able to measure the NS Equation of State (EOS) using realistic signals + Bayesian inference techniques. CI Dr Bram Slagmolen (ANU) is a member of the CE Vacuum System Design team and contributes to CE Site Selection/ Indigenous Engagement team. Prof David McClelland (ANU) is a member of the CE Project Science Advisory Board.

Locally, we completed a small scoping study on a low environmental impact infrastructure for an Australian detector NEMO (Neutron-star Extreme Matter Observatory). We are in the final stages of completing a preliminary study quantifying the value-add of an Australian NEMO detector to a global detector array, and made good progress on developing a "site selection" tool to identify optimum sites in Australia for a third-generation (3G) detector. Director Prof Matthew Bailes (Swinburne) and Deputy Director Prof David McClelland (ANU) continue to represent OzGrav on the Gravitational Wave International Committee (GWIC).

In the final year of OzGrav we will complete the studies described above and continue to advance international, national and regional engagement to ensure a leading role for Australia in the next exciting era as 3G detectors are designed, constructed and operated.

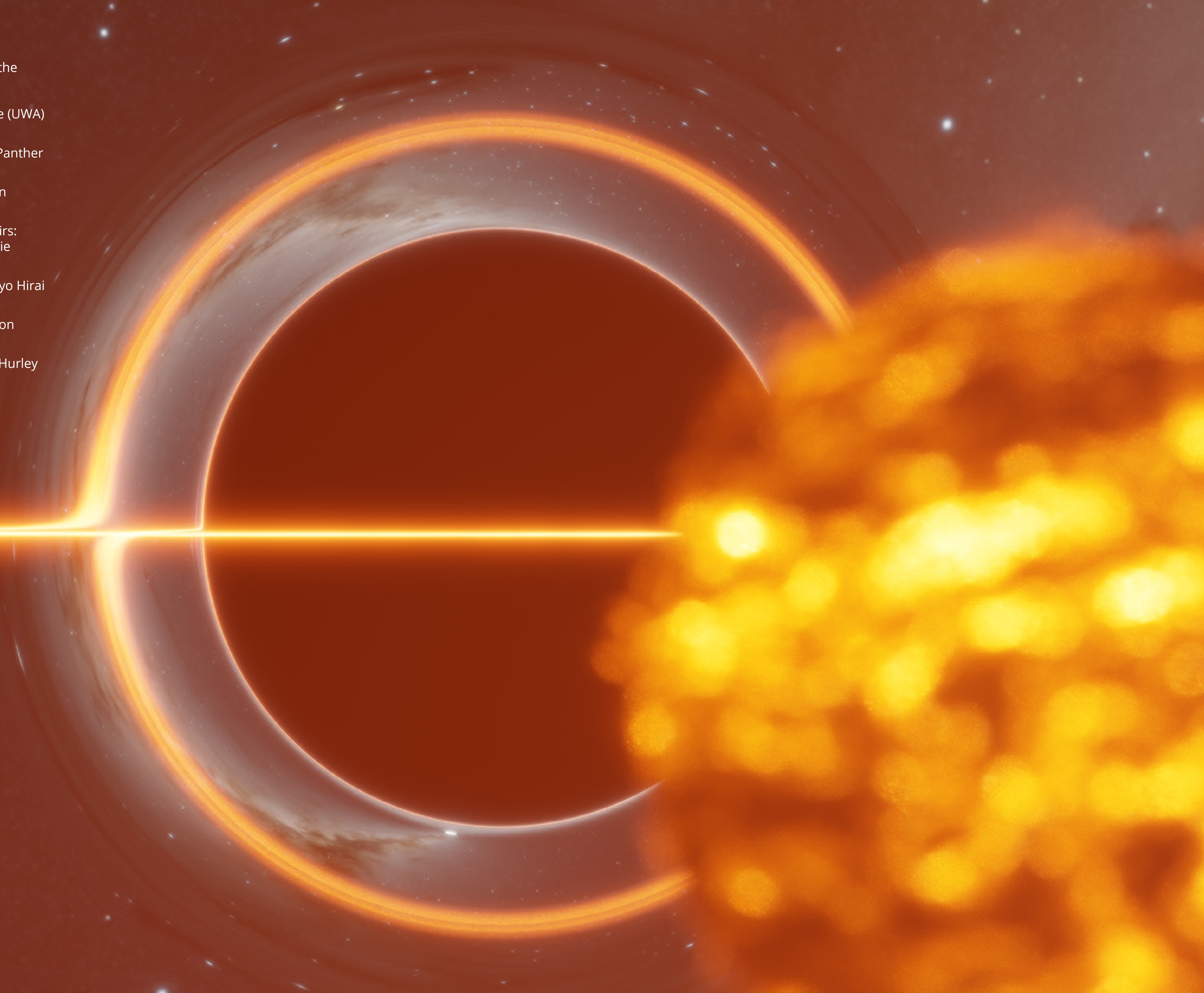


Australian National University PhD student Disha Kapasi is showing a laser setup. Credit: Chathura Bandutunga, OzGrav-ANU

DATA AND ASTROPHYSICS THEME

OzGrav's Data and Astrophysics Theme is led by Prof Matthew Bailes (Swinburne) and Prof Eric Thrane (Monash) under 6 science programs, and the underpinning OzSTAR supercomputer program:

- Inference - Program chairs: Chayan Chatterjee (UWA) and Dr Rory Smith (Monash)
- GW Data Analysis - Program chairs: Dr Fiona Panther (UWA) and Dr Jade Powell (Swinburne)
- Pulsar Detections - Program chair: A/Prof Ryan Shannon (Swinburne)
- Multi-Messenger Observations - Program chairs: Dr Katie Auchettl (Melbourne) and Dr Dougal Dobie (Swinburne)
- Relativistic Astrophysics - Program chair: Dr Ryo Hirai (Monash)
- Population Modelling - Program chair: Dr Simon Stevenson (Swinburne)
- OzSTAR supercomputer - Leader: Prof Jarrod Hurley (Swinburne)



Artist's impression of a neutron star and black hole merger. Credit: Carl Knox, OzGrav-Swinburne

DATA AND ASTROPHYSICS THEME

Inference

Program chairs: Chayan Chatterjee (UWA) and Dr Rory Smith (Monash)

In preparation for Observing Run 4 (O4) Bilby (user-friendly interfaced Bayesian Inference Library) and parallel bilby (pbilby) are undergoing review in LVK. The ADACS (Astronomy Data and Computing Services) team are working to make pbilby review ready for O4, with optimisations to keep up with the high number of expected events, and computational cost of expensive analyses.

The Gravitational Wave Data Centre (GWDC)/GWCloud teams are working on accessibility, creating a searchable repository for creation and curation of GW inference results. It enables bulk data analysis on GW events to be performed with bilby and automatically included into a database. It has a real-time online posterior-sample visualisation tool, and users can upload bilby results and share interactive plots.

In the area of new sources and physics, we are looking at quasi periodic oscillations and using Bayesian framework to characterise dynamics of QPOs in astrophysical transients. We are using Bayesian framework to infer physics in GWs from core-collapse supernova (CCSN). Work continues in eccentricity in GWs, as we move beyond quasi-circular inspiral approximation to incorporate more physics and understanding of binary formation. We are implementing new GW models, and new statistical techniques to measure eccentricity. We are using Bayesian methods to place upper limits of undetected pulsar glitches in UTMOST data. We are also working with LIGO/Virgo/KAGRA noise, introducing a new framework to understand subtle correlations in LIGO-like noise introduced by data conditioning.

“Surrogate models” are high-fidelity models in micro-milliseconds for rapid inference. We are working to reduce computational cost as we anticipate the number of detections to balloon. We continue to work with the ADACS team for user-friendly surrogate modeling codes. We are also developing fast surrogate models of binary population synthesis outputs, to enable quick prediction of likely formation channels of, e.g., LVK sources. We formed an industry partnership with Quaisr (pronounced “quasar”). We are working on fast simulations of test-mass mirror heating, which is relevant for design and characterisation of post-O5 and XG Thermal Compensation Systems.

We continue to work on machine learning (ML) for rapid sky localisation. Deep learning techniques are being developed with an aim to get sky location in milliseconds. ML is taking off in LIGO parameter estimation circles, and variational autoencoders claim full parameter estimation of LVK sources in milliseconds (minutes to days without).

Case Study

Deep learning for rapid pre- and post-merger sky localisation of gravitational wave events

The catalogue of gravitational wave (GW) detections from compact binary mergers is expected to grow exponentially in LIGO/Virgo/KAGRA’s future observation runs. Among the possible future detections, events with a neutron star component is particularly exciting for astronomers worldwide because within ~2 seconds of their merger, electromagnetic signals in various wavelengths can be observed. However, algorithms used by the LVK Collaboration for sky localisation have a wide range of latencies - from a few seconds, to hours and even days! Faster inference techniques that can predict the GW sky directions in less than a second, and can also send out pre-merger alerts are therefore necessary for rapid electromagnetic follow-up observations

To address this, our team have designed ‘CBC-SkyNet’ or Compact Binary Coalescence Sky Localisation Neural Network - the first deep learning model for both pre- and post-merger sky localisation of compact binaries. The novel feature of CBC-SkyNet is that it is trained on matched filtering outputs from GW searches, instead of the raw strain data directly. This radically reduces the dimensionality of input data needed for parameter estimation, especially for binary neutron star and neutron star-black holes binaries, enabling accurate inference at least three orders of magnitude faster speeds, compared to traditional methods.

CBC-SkyNet has also been applied for pre-merger sky localisation of binary neutron star events up to 60 seconds before merger and has shown comparable accuracy to other analyses. These results thus help envision a near future where existing bottlenecks in GW data analysis can potentially be removed using deep learning.

ANU Chief Investigator Dr Ling Sun (centre) works with PhD students Dana Jones (left) and Ben Grace. Credit: Chathura Bandutunga, OzGrav-ANU.

GW Data Analysis

Program chairs: Dr Fiona Panther (UWA) and Dr Jade Powell (Swinburne)

In the GW Data Analysis program, members of OzGrav have made a large amount of progress and achievements in the areas of compact binary coalescences (CBCs), continuous gravitational waves (CW), gravitational wave burst, and detector characterisation.

We developed a joint study between OzGrav and industry partner Eliiza to produce fake gravitational-wave transient noise.

From data from Observing Run 3 (O3) we undertook an O3 magnetar search, a GPU F-stat continuous wave search, an O3 Viterbi Sco X-1 search, and an O3 accreting millisecond pulsar search. We investigated CW from millisecond pulsar J0437-4715.

We developed new studies of ultralight boson clouds around black holes.

We investigated one ringdown NR waveform study, and another new method using collective filters to search for black hole (BH) ringdowns.

We worked on rapid localisation of CBC sources.

We developed methods for inferring neutron star properties with continuous gravitational waves. We spent time validating CW candidates, and we looked at the calibration impact on Hubble constant measurements.

Dr Jade Powell and Dr Bernhard Mueller organised a week-long conference for Supernovae in the Gravitational Wave Era, with 50 talks presented. Driven by the seminal observations of black hole and neutron star binary mergers, the field of gravitational wave science has expanded tremendously since 2015. Core-collapse supernovae are one of the next great challenges for gravitational wave astronomy. A nearby supernova will be an opportunity to combine the recently demonstrated power of concurrent observations in photons and gravitational waves with the diagnostic potential of neutrinos that already proved itself 35 years ago during the explosion of SN 1987A, tying together two of the groundbreaking successes in multi-messenger astronomy. The huge potential of a once-in-a-lifetime event in our cosmic vicinity is complemented by the swelling stream of data on more distant transients and supernova remnants. Fully exploiting these opportunities requires a comprehensive view of supernova dynamics, stellar evolution, and the capabilities of instruments and data analysis techniques. To this end, this conference seeks to bring together theorists and observers working in the field to address the current challenges in supernova modelling, phenomenology, and observations. The workshop was held at Swinburne University of Technology, Melbourne.

Case Study

Astronomers search for X-ray signposts of elusive continuous gravitational waves

In the last few years, astronomers have achieved an incredible milestone: the detection of gravitational waves, vanishingly weak ripples in the fabric of space and time emanating from some of the most cataclysmic events in the universe, including collisions between black holes and neutron stars. So far there have been over 90 gravitational-wave detections of such events, observable for only ~0.1 to 100 seconds. However, there may be other sources of gravitational waves, and astronomers are still on the hunt for continuous gravitational waves.

Continuous gravitational waves should be easier to detect since they are much longer in duration compared to signals from compact-object collisions. Neutron stars are a possible source of continuous waves. These are stellar "corpses" left over from supernova explosions of massive stars. After the initial explosion, the star collapses in on itself, crushing atoms down into a super-dense ball of subatomic particles called neutrons — hence the name neutron star. The continuous wave signal is related to how fast the neutron star is spinning, so precise measurements of the spin frequency using more conventional telescopes would greatly improve the chance of detection of these elusive waves.

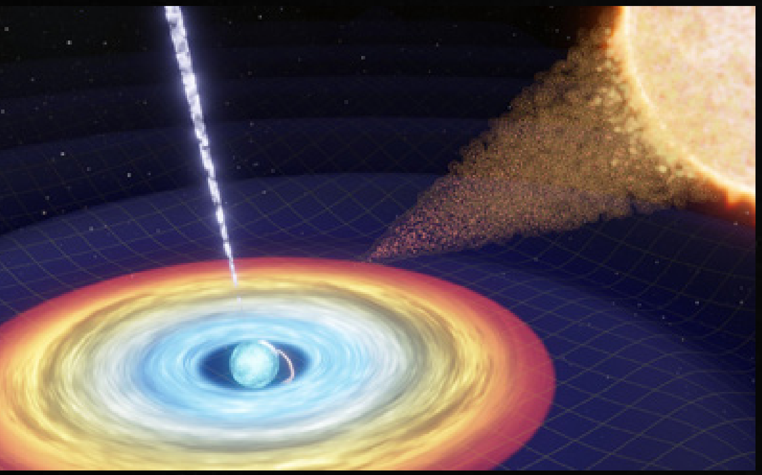
In a recent Monthly Notices of the Royal Astronomical Society study, led by OzGrav PhD student Shanika Galaudage from Monash University, scientists aimed to determine neutron stars' spin frequencies to help detect continuous gravitational waves.

Possible sources of continuous gravitational waves

Researchers hypothesised that continuous gravitational waves indirectly come from the gradual accumulation of matter onto a neutron star from a low-mass companion star–these binary systems of a neutron star and companion star are called low mass X-ray binaries (LMXBs).

If the neutron star can maintain an accumulated "mountain" of matter, (even if only a few centimeters in height.), it will produce continuous waves. The frequency of these waves relate to how fast the neutron star is spinning. The faster this matter accumulates, the bigger the "mountain," producing larger continuous waves. Systems that accumulate this matter more quickly are also brighter in X-ray light. Therefore the brightest LMXBs are the most promising targets for detecting continuous waves.

Scorpius X-1 (Sco X-1) and Cygnus X-1 (Cyg X-2) are two of the brightest LMXB systems–Sco X-1 ranks second in X-ray brightness compared to the Sun. In addition to their extreme brightness, scientists know a lot about these two LMXB systems, making them ideal sources of continuous waves to study. But their spin frequencies are still unknown.



Artist's impression of one potential source of continuous gravitational waves - Asymmetric accretion onto a spinning neutron star. Credit: Mark Myers, OzGrav-Swinburne University

"A way we can determine how fast these neutron stars are spinning is by searching for X-ray pulsations," says study lead Shanika Galaudage. "X-ray pulsations from neutron stars are like cosmic lighthouses. If we can time the pulse we would immediately be able to reveal their spin frequency and get closer to detecting the continuous gravitational-wave signal."

Sco X-1 is one of the best prospects we have for making a first detection of continuous gravitational waves, but it's a very hard data analysis problem," says OzGrav researcher and study co-author Dr Karl Wette, from the Australian National University. "Finding a spin frequency in the X-ray data would be like shining a spotlight on the gravitational wave data: 'here, this is where we should be looking.' Sco X-1 would then be a red-hot favorite to detect continuous gravitational waves."

Searching for X-ray pulsations

The team performed a search for X-ray pulsations from Sco X-1 and Cyg X-2. They processed over 1000 hours of X-ray data collected by the Rossi X-ray Timing Explorer instrument. The search used a total of ~500 hours of computational time on the OzSTAR supercomputer.

Unfortunately, the study did not find any clear evidence of pulsations from these LMXB sources. There are a number of reasons why this could be: the LMXB could have weak magnetic fields which are not powerful enough to support detectable pulsations. Or it could be that the pulsations come and go over time, which would make them hard to detect. In the case of Sco X-1, it could possibly be a black hole, which we would not expect to produce X-ray pulsations.

The study does find the best limits on how bright these X-ray pulsations could be if they did occur; these results could mean that neutron stars cannot sustain mountains of matter under its strong gravity. Future research can build on this study by employing better search techniques and more sensitive data.

Article by Shanika Galaudage (Monash University) for Phys.org

Pulsar Detections

Program chair: A/Prof Ryan Shannon (Swinburne)

Pulsar timing arrays (PTA) intend to detect low frequency gravitational waves through the precise timing of ultra-stable millisecond pulsars (MSP). Activity and excitement in the field has increased markedly as data sets from all major pulsar timing arrays are now showing evidence for a common spectral process, which may be the precursor to a gravitational wave detection. OzGrav has made key contributions in the past year and is poised to lead high impact results in the coming year.

The program has made progress across all of its key activities. The program leads efforts in pulsar timing and data analysis with the MeerKAT array in South Africa and Murriyang in NSW, Australia, as well as contributing to international efforts through the International Pulsar Timing Array.

Data sets: The MeerTime MSP data release was completed. UTMOST pulsar timing has continued. The GWDC hosted data portal was completed, which includes the pulsar encyclopedia.

Inference: Further analysis of the PPTA data showed that the data set was consistent with containing a common red noise process. Scintillation analysis was used to better constrain the orbital properties of the best millisecond pulsar J1909-3744. Searches for neutron star masses were conducted in MeerKAT MSP data.

We are working on profile domain timing methods, and investigating alternative detection statistics that can help confirm or refute any claimed GW detection. We are investigating techniques to improve timing with the wide bandwidth.

We ran the Australasian Pulsar Telecon, a fortnightly zoom meeting bringing together pulsar and FRB researchers in Australia, New Zealand, and India. We organised a number of hack weeks and busy days where OzGrav members and key partners met (in person and virtually) to learn the tools of pulsar timing inference and to use them in pulsar timing data analysis.

We have published the MeerKAT release, which has also been provided to the IPTA. The PPTA data release was finalised and will be published as part of the coordinated IPTA 3 paper plus (3P+) process by mid 2023. Work continued on characterising the properties of common red processes. Gravitational wave searches with the PPTA data set planned for 2022, will be published as part of the 3P+ paper in 2023.

Case Study

The MeerKAT Pulsar Timing Array first data release

Swinburne leads MeerTime, the pulsar timing large project on MeerKAT, and the MSP timing subproject, the MeerKAT Pulsar Timing Array. Timing commenced in earnest in 2019. We initially undertook census observations of all ~ 188 MSPs visible to MeerKAT, both to provide a homogenous sample of observations to study MSP emission, but more importantly to assess achievable timing precision. Since then we have undertaken regular, fortnightly observations of a subsample of 89 pulsars. The observations strategy optimised to find a gravitational wave background, targeting at least 1 microsec precision on all pulsars (for the best pulsars we achieve much higher precision). We published our first data release this year, comprising the first 2.5 years of data.

Pulsar timing requires the reference of pulse arrival times to the best available time standards. This requires corrections between observatory clocks (typically Hydrogen masers which provide accurate time on short time scales but slowly drift with time), time distributed through global position satellite systems, and time measured by an ensemble of atomic clocks housed at international standard laboratories such as the International Bureau of Weights and Measure. To demonstrate the sensitivity of the MeerKAT pulsar timing array, we used the pulsars to deduce the difference between the MeerKAT clock and GPS time. We are able to measure variations in the clock signal with precision of a few tens of nanoseconds with pulsars alone.

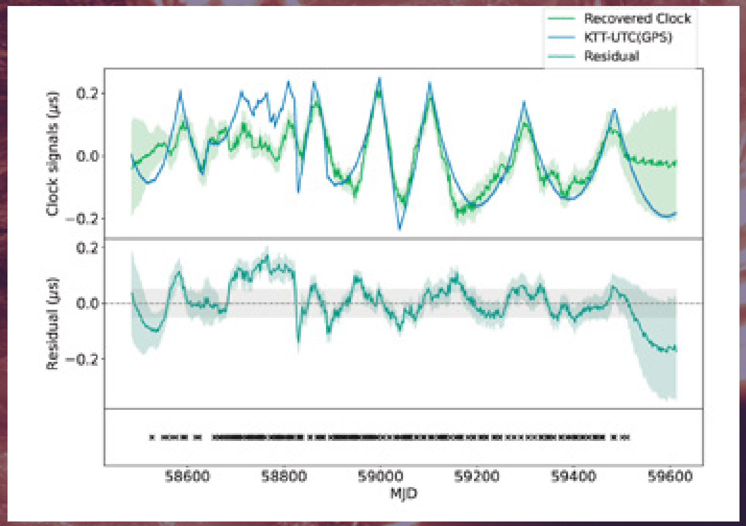


Figure: Top panel: The reconstruction of the MeerKAT clock. The blue line shows the predicted difference between the observatory clock (Karroo Terrestrial Time, KTT) and Coordinate University Time (UTC(GPS)) in blue and the clock reconstruction (green) and its uncertainty (green shading). Middle panel: The difference between the predicted clock signal and reconstruction, highlighting the discrepancy between MJD 58700 and 58800. Bottom panel: dates of the observations used in the analysis and data release. Figure reproduced from Miles et al. (2022).

DATA AND ASTROPHYSICS THEME

Multi-Messenger Observations Program chairs: Dr Katie Auchettl (Melbourne) and Dr Dougal Dobie (Swinburne)

The OzGrav multi-messenger observation program leverages observations using gravitational waves, neutrinos, cosmic rays and the entire electromagnetic spectrum to study a variety of transient astrophysical phenomena. The past year has seen a flurry of scientific results, as well as some major steps towards planning for future gravitational wave observing runs and beyond.

Follow-up of events during O3

We presented two years of ASKAP observations targeting the possible neutron star-black hole merger GW190814. While this search did not detect a counterpart to the merger, it was the most sensitive widefield search for radio transients ever conducted and did detect an unrelated transient source. OzGrav investigators were also involved in the spectroscopic assessment of optical counterparts to GW190814.

The LOFAR data reduction pipeline has been successfully migrated to OzSTAR, enabling low-frequency radio observations of gravitational wave events to be analysed by OzGrav researchers. The pipeline produces 21 deg^2 radio maps of gravitational wave events with an rms of approximately150μJy. During 2022 we used the pipeline to process LOFAR follow-up of the neutron star-black hole merger S190426c, which was detected during O3.

Preparation for O4

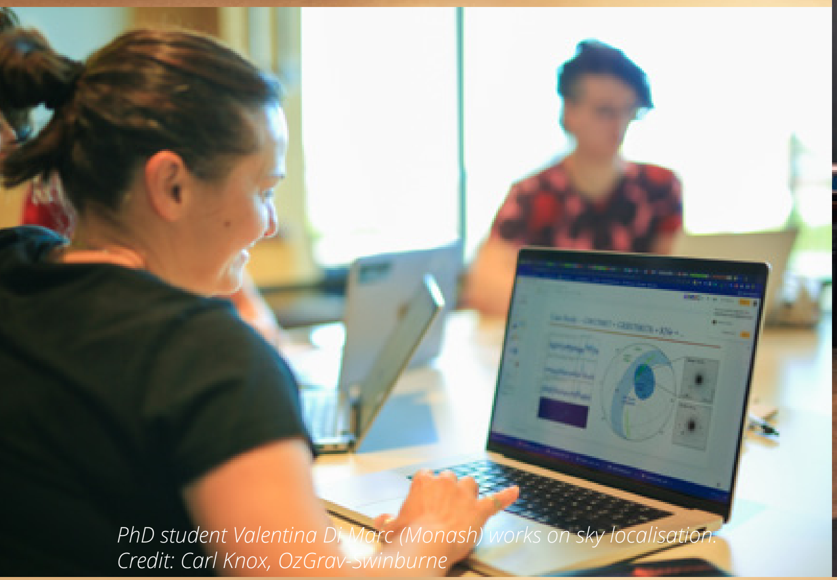
During O4 the Murchison Widefield Array (MWA) will play an important role in searching for coherent emission from binary neutron star mergers. In 2022 we worked with Astronomy Data and Computing Services (ADACS) to build a web application (TRACE-T) for parsing transient alerts and triggering automated MWA follow-up.This system was also deployed in triggering gamma-ray burst follow-up.

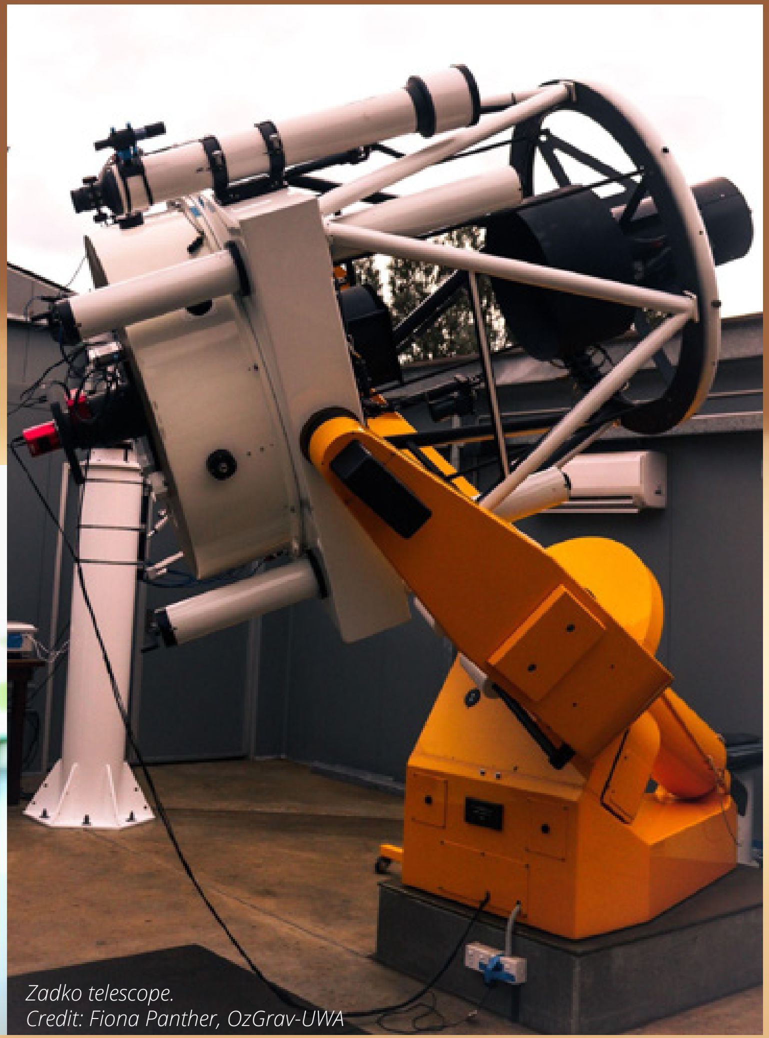
In 2022 OzGrav investigators secured substantial time allocations on the world's leading radio interferometers for gravitational wave follow-up during O4 including 780 hours on the Australia Telescope Compact Array, to search for radio counterparts, and 48 hours on the Long Baseline Array for high resolution radio imaging.

Dr Karelle Siellez joined OzGrav as an Associated Investigator and has led an upgrade to the University of Tasmania's Greenhill Observatory to enable it to follow-up and search for Gravitational Wave counterparts, kilonovae, gamma ray bursts, and micro lensing events.

The Zadko Telescope has undergone substantial upgrades during 2022 in order to ensure that it is ready for O4. In addition the Zadko team were also awarded two ARC grants in the 2022 LIEF and Linkage grant rounds to fund further upgrades to the telescope.

In late 2022 the platform and domes for the planned GOTO-South telescope were installed at the Siding Springs Observatory, marking a substantial step towards full operations and gravitational wave follow-up.


PhD student Valentina Di Marc (Monash) works on sky localisation.
Credit: Carl Knox, OzGrav-Swinburne


Zadko telescope.
Credit: Fiona Panther, OzGrav-UWA

Significant progress has been made towards fully automating the ANU 2.3m telescope, enabling rapid-response observations of gravitational wave counterparts. The first target-of-opportunity interrupt observation was carried out this year, with exposures beginning less than 200 seconds after the alert was received.

Over the course of 2022 the SkyMapper team obtained deep observations of the entire sky south of +10 degrees declination, which provide vital reference images for gravitational wave counterpart searches. In addition, they have developed an ensemble-based transient classifier that will drastically speed up classification of candidate counterparts, and fine-tuned their observing strategy in order to optimise follow-up.

At the 2022 Annual Scientific Meeting of the ASA, OzGrav members led a special session on transient astrophysics that aimed to improve collaboration between the various Australian transients groups. The productive discussions that began at this session have continued, with plans for coordinated observing campaigns and further sessions and workshops underway.

Deeper, Wider, Faster

The Deeper, Wider, Faster program (DWF) continued its simultaneous multiwavelength observation program to search for fast transients on timescales of milli-seconds to days; from Fast Radio Bursts to supernovae. DWF had one successful run during 2022, including follow-up of the short gamma-ray burst 220831A. The DWF team discovered an optical counterpart to the burst using the Dark Energy Camera and analysis of it is ongoing. The results of the September 2021 DWF run included the detection of eight highly variable radio sources, including the discovery of periodic pulses from the slowest rotating radio-loud ultracool dwarf ever detected.

Keck Wide-Field Imager

The Australian-led Keck Wide Field Imager (KWFI) is a wide field optical imager optimised for UV sensitivity designed for the 10m Keck telescopes. The planned 1 degree diameter field of view, extreme sensitivity and fast filter exchange system will make it the premier instrument for discovering optical counterparts to gravitational wave events. KWFI will be over ten times more sensitive than other wide-field optical telescopes, capable of detecting over 90% of LIGO/Virgo events missed by current telescopes.

KWFI is the top priority of the Keck Observatory and continues to make good progress. KWFI have succeeded, to date, in receiving over $800,000 from the Keck Observatory, SSC, and Swinburne funding for design and development. Major construction funding is currently being proposed via US, Australian, and private avenues.

KiloNova Transient Program

The KiloNova Transient Program (KNTraP) carried out a successful 11 night observing run with the Dark Energy Camera in Feb 2022. The aim of this program is to search for kilonovae, independent of gravitational wave detections. Many candidates are currently under analysis and three were followed-up during the run, along with a rare tidal disruption event (GCN 31647, TNS 450, 1335). During the run, the KNTraP team also detected optical emission from the relativistic jet produced by a high-redshift tidal disruption event.

Australian Square Kilometre Array Pathfinder

The Australian Square Kilometre Array Pathfinder


Siding Spring GOTO-South observatory.
Credit: Krzysztof Ulaczyk, University of Warwick

(ASKAP) has been steadily ramping up towards full science operations over the past two years. Throughout 2022 there was substantial progress towards utilising its full potential as a radio transient-finding machine, with dedicated transient search observations along with analysis of the Variables And Slow Transients Pilot Survey that was completed in late 2021. In addition to the gravitational wave follow-up and transient searches outlined above, it was also used to discover multiple pulsars, stars, and as-yet unclassified transient sources.

Case Study

The most probable host of CHIME FRB 190425A, associated with binary neutron star merger GW190425

Understanding the host galaxies of Fast Radio Bursts (FRBs), the millisecond burst of coherent radio emission, provides an opportunity to determine the origin of these rare astrophysical objects. FRBs are broadly classified as either repeating or (apparent) non-repeaters, with non-repeating FRBs potentially originating from the merger of two compact objects. Unlike supernovae and other transients, only a fraction of FRBs so far detected have been localised to individual host galaxies.

Dr Fiona Panther led the analysis of radio and optical observations of the probable host galaxy of FRB 20190425A, which has been proposed to be coincident with the LIGO/Virgo binary neutron star merger GW190425. Dr Panther identified and studied the probable host galaxy of FRB 20190425A, UGC10667, and placed constraints on the presence of an electromagnetic afterglow associated with GW190425. She finds that the characteristics of UGC10667 are consistent with a long-delay time origin for the transient, including the merger of a binary neutron star and no evidence for radio afterglow associated with the FRB or GW event within 100 kpc of its host.

Case Study

Discovery of the brightest pulsar outside the Milky Way

Over three thousand pulsars have been discovered, most of which have been found via searches for their distinct repeating signal. However, this search technique is computationally intensive and may miss more exotic pulsars that do not fit the standard paradigm.

OzGrav PhD student Yuanming Wang discovered a new pulsar, PSR J0523-7125, located in the Large Magellanic Cloud. Despite its radio luminosity making it one of the brightest ever found, it had been missed by traditional searches because of its slow, wide pulses. Instead, it was discovered by searching for circularly polarised sources in images obtained using the ASKAP radio telescope as part of the Variables And Slow Transients (VAST) survey.

The circularly polarised emission it produced combined with the large change in brightness observed across a period of several months suggested this source was extremely interesting, but there were no known pulsars, stars or other astronomical objects at its position. A pulsar search with the Parkes (Murriyang) telescope revealed no pulses, while no X-rays or infra-red light was detected from it with observations from the Neil Gehrels Swift Observatory and Gemini telescope respectively. It wasn't until OzGrav researchers obtained observations with the MeerKAT radio telescope that they were able to confirm that it is indeed a pulsar.

This discovery demonstrates the capability of ASKAP to detect new exotic pulsars, and we expect even more discoveries during 2023 as the full VAST survey gets underway.

Artist's impression of the PSR J0523-7125 in the Large Magellanic Cloud. Credit: Carl Knox, OzGrav-Swinburne University

Relativistic Astrophysics

Program chair: Dr Ryo Hirai (Monash)

In 2022 the Relativistic Astrophysics program has focused on exploring extreme matter physics and testing general relativity, with strong synergies with the multi-messenger astronomy and pulsar detections program.

We rolled out the upgraded version of the MeerPipe data processing pipeline which forms the backbone of the MeerTime project on MeerKAT, which includes key science themes such as relativistic binaries and pulsar timing arrays. The pipeline is now fully automated, is configurable for multiple project specifications, and produces near real-time diagnostic images and downloadable TOAs (Time of arrival) that can be accessed through the MeerTime data portal (pulsars.org.au). New improvements are being released all the time.

Extreme matter physics

We worked with collaborators to calculate the cooling and internal heating of neutron stars. According to their follow-up work, it may be difficult to infer the presence of hyperons just with thermal luminosities.

We discovered that the presence of axions (a good candidate for dark matter) can induce an unphysical dynamo in the cores of neutron stars that quickly generates large magnetic fields that are not observed. This allows for the significant constraints on the axion parameter space.

We discovered the possible formation of mountains on neutron stars through repeated crust cracking, based on a method using cell automatons.

We performed N-body calculations to study the effect of vortex avalanches in neutron stars with accelerating/decelerating spin. Our models show that "anti-glitches" like those found in NGC300 ULX-1 may be explained by this model.

A group of OzGrav researchers showed from an updated analysis that an age-dependent glitch law is preferred over other models.

GRB/Multimessenger astronomy

We calculated the probability of multi-messenger gamma ray burst (GRB) observations.

A large OzGrav collaboration calculated the rates of binary neutron star (BNS) and neutron star black hole (NSBH) mergers throughout the Universe, in addition to constraining other properties such as jet-launching fraction and beaming angle using rates of GRBs, BNS and NSBH mergers.

We analysed the optical transient AT2020blt, showing that the data is best explained by a low-efficiency, on-axis long GRB.

We were involved in a work with King's College London that calculated whether we can ever detect a stochastic GW background from f-modes in neutron stars induced by giant magnetar flares. The results show that it may be difficult to do so.

We explored ways to infer astrophysical parameters of core-collapse supernovae from their gravitational wave signals. We also studied the detailed dynamics of magneto-rotationally powered core-collapse supernovae.

We investigated the consequences of neutron stars colliding with their binary companions after supernovae. It may be able to explain the origin of superluminous-supernovae, pulsar planets and Thorne-Zytkow objects.

Case study

Breaking gravitational ground with a relativistic binary pulsar

In 2022 OzGrav postdoc Andrew Cameron was able to bring to fruition a 6-year long research project studying a relativistic binary pulsar, PSR J1757-1854. A 21.5-ms pulsar in a highly eccentric, 4.4-hour orbit around a companion neutron star, this system is one of the most extreme double neutron star binaries ever discovered, and as such is an ideal laboratory for testing relativistic theories of gravity. They had previously derived three such relativistic tests, each of which Einstein's theory of General Relativity had already passed with flying colours, but one additional effect they had long expected to see in this system was "geodetic precession"; the wobbling of the spin-axis of the pulsar due to the relativistic effects of spin-orbit coupling. This would be detectable as gradual changes in both the shape and polarisation of the pulsar's average emission profile over time as the pulsar tipped to point either closer to or further away from us.

Dr Cameron and a team of international researchers (including several within OzGrav) have now conclusively demonstrated the presence of geodetic precession in PSR J1757-1854 for the first time. They identified significant changes in both the pulse profile's shape and polarisation. Although these changes are not yet sufficient to determine a new test of gravity, they are consistent with General Relativity, and allow for rare constraints of the pulsar's viewing geometry under the assumption of General Relativity's correctness. They also predicted that an even rarer test of gravity (a relativistic deformation of the pulsar's elliptical orbit seen only twice before) may be detectable in PSR J1757-1854 as soon as the end of 2026, work in which OzGrav will play a vital and ongoing role.

DATA AND ASTROPHYSICS THEME

Population Modelling

Program chair: Dr Simon Stevenson (Swinburne)

With the fourth Observing Run (O4) postponed until 2023, the OzGrav Population Modelling program spent 2022 extracting the maximum amount of information possible out of the existing gravitational-wave catalogue.

We reexamined the distribution of binary black hole spins in the third gravitational wave catalogue (GWTC-3) with an updated model and found that it remains difficult to really precisely constrain the spin properties of binary black holes at present. In particular we find no strong evidence for a population of black holes with negligible spins. We argued that the presence of such a population (which is expected from theory) would help avoid the need for invoking large black hole natal kicks to explain the distribution of misalignment angles of black holes.

We borrowed a tool from finance, and we introduced the gravitational-wave world to copulas, which we used to explore possible correlations between the mass ratios and spins of binary black holes, finding that a merger is more likely to contain a highly spinning black hole if one of the black holes is significantly more massive than the other.

We explored a method of identifying which population models are a good fit to the data using the concept of the maximum population likelihood.

Separate from analysing the gravitational wave data, a large fraction of our work aims to make theoretical predictions of what should be observed based on various astrophysical scenarios. We published a thorough, modern review of the rates of compact binary coalescences expected from a variety of astrophysical formation scenarios.

The COMPAS binary population synthesis code is used to make predictions for gravitational-wave mergers (and other associated stellar/binary phenomena) arising from massive, isolated binary evolution. We published a large set of COMPAS models, exploring the impact of various uncertainties in massive binary evolution and the cosmic star formation history on predictions for gravitational-wave mergers. We also used these models to examine how frequently mass ratio reversal occurs in the formation of merging binary black holes.

We explored the formation of the first two neutron star-black hole mergers. We also studied the correlated impact of uncertainties in massive binary evolution on predictions for the rates and masses of binary black hole mergers using COMPAS.

The common envelope phase is a crucially important stage in the evolution of many close binary stars, that brings the stars close enough together that their remnants can merge due to the emission of gravitational waves within the age of the universe. However, it is also poorly understood, and a large amount of work is conducted within OzGrav in order to better understand it. We studied the response of massive stars to mass loss as a way of understanding when a star could successfully be considered to have survived common envelope evolution. We also developed a new two-stage formalism for the common envelope which accounts for the structure of massive stars and is more appropriate than the traditional 'alpha' formalism. We investigated the impact of recombination energy as a potential contributor to the energy budget for ejecting a common envelope from a massive star.

In order to make predictions for other formation channels, such as from star clusters or galactic nuclei, other tools are required. We constructed a phenomenological model for binary mergers in the disks of active galactic nuclei.

We described the population of binary black holes formed in a series of dense star cluster models performed with the NBODY code. We updated several prescriptions in the NBODY which are relevant for modelling massive binary black holes, such as metallicity dependent stellar winds, prescriptions for pair instability supernovae and black hole natal spins. We used a suite of star clusters evolved with the NBODY code to study the formation of the massive gravitational-wave event GW190521 through repeated black hole mergers.

Residual orbital eccentricity at the time of merger may be a signature of these formation channels. We analysed the population of binary black holes detected in O3b searching for signs of orbital eccentricity and identified an additional two events which may be eccentric, increasing the total number of candidates to four.

Beyond gravitational-wave mergers, the OzGrav Population Modelling Program also studies the properties of other associated populations, such as pulsars and neutron stars. We studied the implications of gravitational-wave observations on the progenitors of short gamma ray bursts.

We studied the outcomes of collisions of newly born neutron stars with their stellar companions.

We studied the implications of electron capture supernovae in wide binaries for forming wide binary pulsars that may be observable with the SKA.

We used the observed population of pulsars with well determined velocities to calibrate the physical prescription for neutron star natal kicks, significantly reducing the uncertainty in these physical models.

We looked at the differences between sets of massive star models, firstly highlighting these differences in a set of publicly available models, before systematically exploring the uncertain physics assumptions leading to these differences.

Case study

Black hole carnivals may produce the signals seen by gravitational-wave detectors

Since 2015, the LIGO-Virgo-KAGRA Collaboration have detected about 85 pairs of black holes crashing into each other. We now know that Einstein was right: gravitational waves are generated by these systems as they inspiral around each other, distorting space-time with their colossal masses as they go. We also know that these cosmic crashes happen frequently: as detector sensitivity improves, we are expecting to sense these events on a near-daily basis in the next observing run, starting in 2023. What we do not know — yet — is what causes these collisions to happen.

Black holes form when massive stars die. Typically, this death is violent, an extreme burst of energy that would either destroy or push away nearby objects. It is therefore difficult to form two black holes that are close enough together to merge within the age of the Universe. One way to get them to merge is to push them together within densely populated environments, like the centres of star clusters.

In star clusters, black holes that start out very far apart can be pushed together via two mechanisms. Firstly, there's mass segregation, which leads the most massive objects to sink towards the middle of the gravitational potential well. This means that any black holes dispersed throughout the cluster should wind up in the middle, forming an invisible "dark core". Secondly, there are dynamical interactions. If two black holes pair up in the cluster, their interactions can be influenced by the gravitational influence of nearby objects. These influences can remove orbital energy from the binary and push it closer together.

The mass segregation and dynamical interactions that can take place in star clusters can leave their fingerprints on the properties of merging binaries. One key property is the shape of the binary's orbit just before it merged. Since mergers in star clusters can happen very quickly, the orbital shapes can be quite elongated — less like the calm, sedate circle that the Earth traces around the Sun, and more like the squished ellipse that Halley's Comet races along in its visits in and out of the Solar System. When two black holes are in such an elongated orbit, their gravitational wave signal has characteristic modulations, and can be studied for clues to where the two objects met.

A team of OzGrav researchers are working together to study the orbital shapes of black hole binaries. The group have found that some of the binaries observed by the LIGO-Virgo-KAGRA collaboration are indeed likely to have elongated orbits, indicating that they may have collided in a densely populated star cluster. Their findings indicate that a large chunk of the observed binary black hole collisions — at least 35% — could have been forged in star clusters.

"I like to think of black hole binaries like dance partners", explains Dr Romero-Shaw. "When a pair of black holes evolve together in isolation, they're like a couple performing a slow waltz alone in the ballroom. It's very controlled and careful; beautiful, but nothing unexpected. Contrasting to that is the carnival-style atmosphere inside a star cluster, where you might get lots of different dances happening simultaneously; big and small dance groups, freestyle, and lots of surprises!" While the results of the study cannot tell us — yet — exactly where the observed black hole binaries are merging, they do suggest that black hole carnivals in the centres of star clusters could be an important contribution.

This paper was written by OzGrav members Isobel Romero-Shaw, Paul Lasky and Eric Thrane - "Four Eccentric Mergers Increase the Evidence that LIGO–Virgo–KAGRA's Binary Black Holes Form Dynamically".

DATA AND ASTROPHYSICS THEME

OzSTAR Supercomputer

Leader: Prof Jarrod Hurley (Swinburne)

The Swinburne OzSTAR supercomputer continued to provide vital data and computing resources for OzGrav researchers with 99% uptime across 2022. OzSTAR provides OzGrav researchers with access to approximately 6,000 compute cores, 230 Nvidia P100/V100 GPUs and a 12 PiB lustre filesystem for data storage.

OzGrav usage on OzSTAR in 2022 was spread across 31 distinct research projects and over 140 users. The combined OzGrav usage was 32% of OzSTAR averaged over 2022 which represents 17 million hours of data processing and simulations. Healthy usage was reported across the Monash, Melbourne, Swinburne, ANU and UWA nodes.

OzGrav researchers worked closely with technical support staff at Astronomy Data and Computing Services (ADACS) and the associated Gravitational Wave Data Centre (GWDC) to perform software development across the following projects:

- "Reduced order modelling for the masses", CI Rory Smith (Monash);

- "Australia's FRB archive", CI Ryan Shannon (Swinburne);

- "StarFit", CI Alex Heger (Monash);

- "Rapid and automated telescope triggering – the future of transient astronomy", CI Gemma Anderson (Curtin).

Each project was selected through a competitive time assignment process. In total about 25 developer weeks were contributed to these projects. This is in addition to advancements made to the following key projects that receive dedicated support via the GWDC: the SPIIR search pipeline; the GWCloud parameter estimation interface; the GWLab laboratory for continuous wave workflows; the MeerTime access portal for pulsar data; and the GWLandscape environment for population synthesis of gravitational wave sources.

The Swinburne CVMFS Stratum 1 server went into production in April 2022. This serves data and software packages to Australian gravitational wave researchers, benefitting jobs running through the LIGO Open Science Grid (OSG) on OzSTAR, as well as any workflows relying on a CVMFS client. It also provides numerous scientific datasets to the wider Australian research community (bandwidth approx. 400GB/month). Previously, the high latency associated with transferring this data from overseas resulted in delays for data-intensive workflows.

A major activity for 2022 was the procurement, delivery and initial installation of the new Swinburne supercomputer for which $5.2M of funding was awarded through the Victorian Higher Education State Investment Fund in late 2021. Procurement was completed during the first half of 2022 with Dell awarded the contract to provide a facility comprising 182 compute nodes with 11,648 AMD EPYC 7543 compute cores, 88 NVIDIA A100 80GB GPUs, NDR infiniband and upgraded storage hardware. Delivery ran from September to December, with the bulk of the nodes racked in the Swinburne Data Centre by the end of the year. Work also proceeded on building the operating system for the new nodes and other software configuration considerations.

OzGrav's supercomputer OzSTAR at Swinburne University of Technology. Credit: Carl Knox, OzGrav-Swinburne.

The funding announcement included a visit from a Victorian State Government delegation led by Gayle Tierney, Minister for Training and Skills. Visitors were shown through the OzSTAR supercomputer by Swinburne PhD student Grace Lawrence, Postdoctoral Researcher Adam Batten, and Supercomputer Leader Prof Jarrod Hurley. Credit: Office of Gayle Tierney.

Case Study

New Supercomputer announced

In February 2022 Swinburne University of Technology announced Victoria's largest supercomputer will be built at the Hawthorn campus, to be named by Wurundjeri Woi Wurrung Traditional Owners in acknowledgment of local Aboriginal knowledge of astrophysical phenomena. The supercomputer will cost $18.5 million, with $5.2 million invested from the Victorian State Government.

The supercomputer has the capacity to analyse and process data a million times faster than standard computers and uses information generated from space- and earth-facing satellites. It allows astronomers to monitor space in unprecedented detail and will also assist researchers in areas including bushfire detection, natural disaster planning and response, neuroscience, cancer detection and defence. The new technology builds on Swinburne University's research reputation and enhances its existing supercomputer OzSTAR, which was installed in 2017 and is one of Australia's fastest computers. It has been used for astronomy, oceanography, agriculture, medicine, molecular dynamics and quantum chemistry.

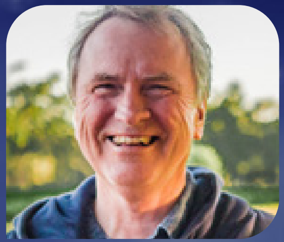
The new supercomputer will be named and used in collaboration with Wurundjeri Woi Wurrung Traditional Owners, in recognition of Aboriginal knowledge of astrophysical phenomena. The supercomputer will also have a Woi Wurrung design on its façade that reflects local Aboriginal knowledges about the spectacular Southern night sky, created through consultation with the Wurundjeri community led by Swinburne's Moondani Toombadool Centre.

Dr Sadie Heckenberg, Academic Director (Indigenous Research) and a Senior Aboriginal and Torres Strait Islander Research Fellow within Swinburne's Moondani Toombadool Centre, said the supercomputer's Woi Wurrung name and design was an important way to connect the new supercomputer with the local Wurundjeri community and Aboriginal and Torres Strait Islander knowledges.

"At Swinburne, we strive to embed Aboriginal and Torres Strait Islander knowledges into every element of what we do and work to ensure that our partnerships with Indigenous communities are co-designed and create long-lasting, beneficial outcomes. I'm excited that, through the leadership of the Moondani Toombadool Centre and close consultation with the Wurundjeri Elders and community, the new supercomputer will clearly demonstrate this ongoing commitment."

The facility will be supported by Astronomy Australia Limited (AAL), a non-profit organisation whose members are Australian universities and research organisations with a significant astronomical research capability. The new supercomputer builds on Swinburne's long history of supercomputer design, development and operation, which includes discovering many of the first Fast Radio Bursts. It will replace the OzSTAR machine, which has been in operation since 2017. OzSTAR has supported Swinburne research across a diverse range of fields and has been a de facto national facility for astrophysics computation in Australia through AAL support, helping define the nature of black holes through gravitational waves.

PEOPLE OF OZGRAV - INSTRUMENTATION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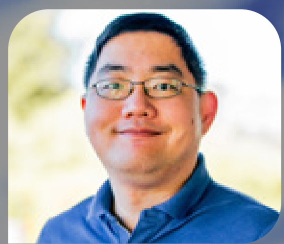
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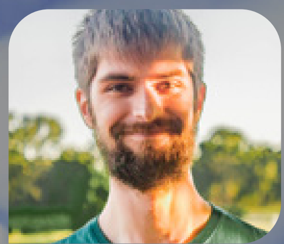
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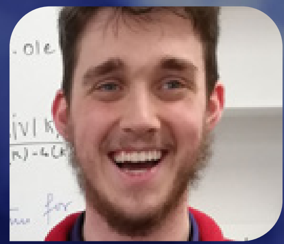
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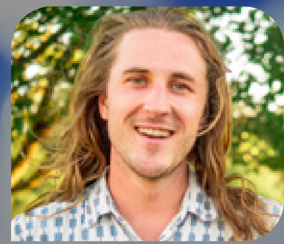
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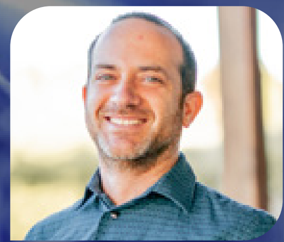
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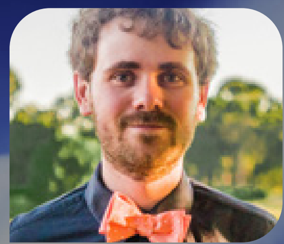
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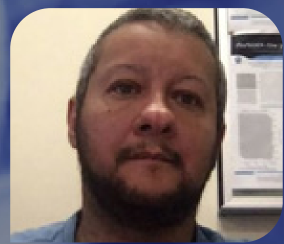
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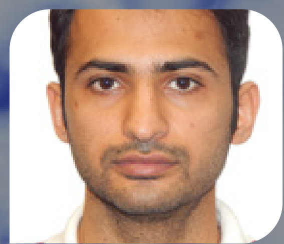
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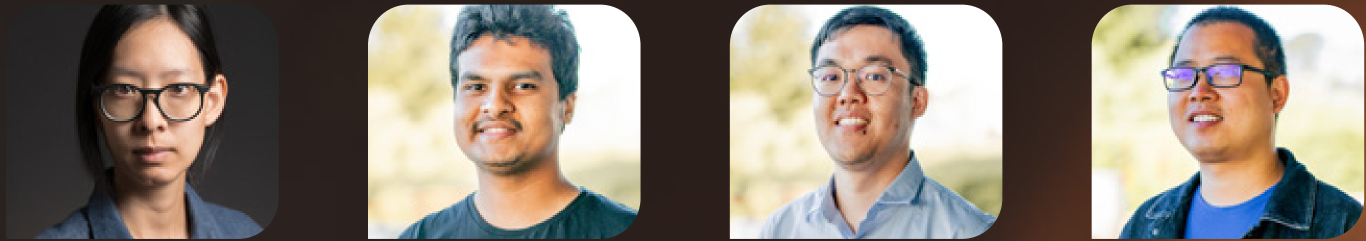
PEOPLE OF OZGRAV - INSTRUMENTATION



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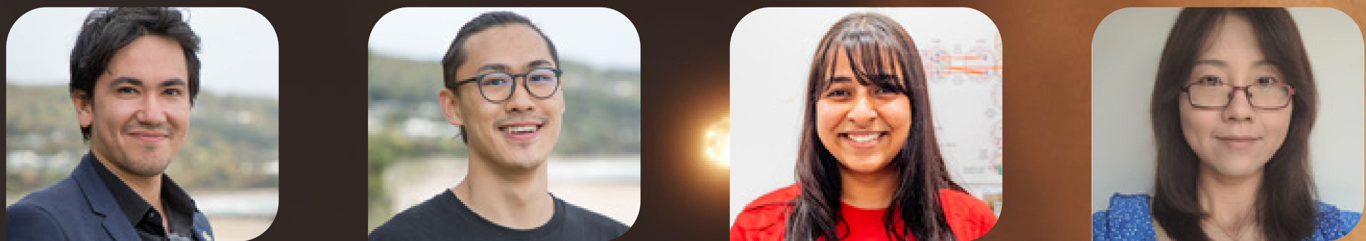

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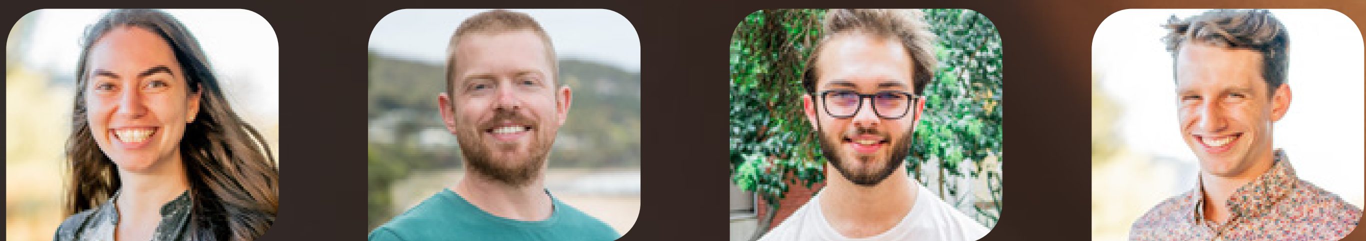

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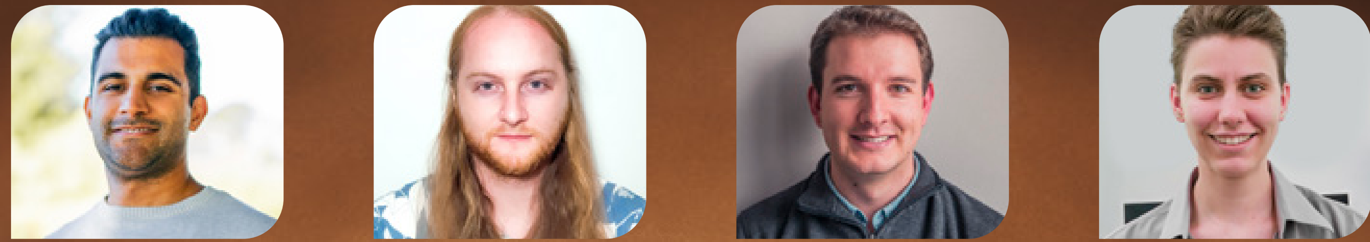

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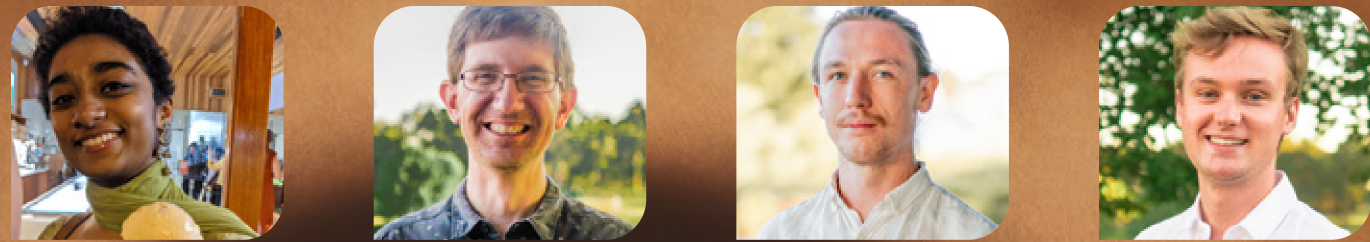

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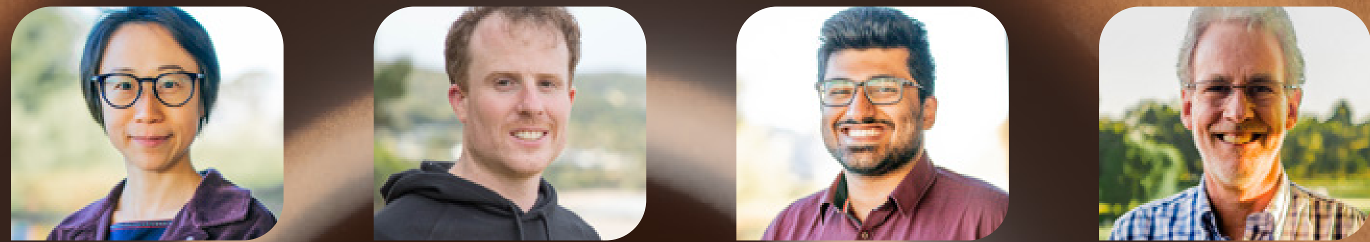

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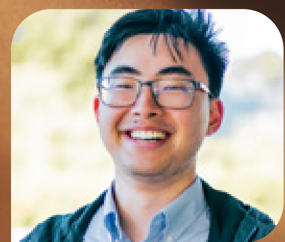

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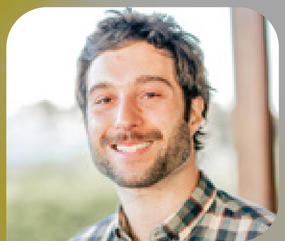
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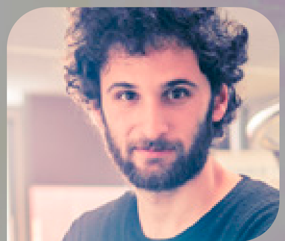
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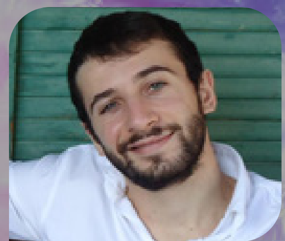
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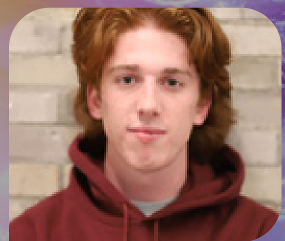
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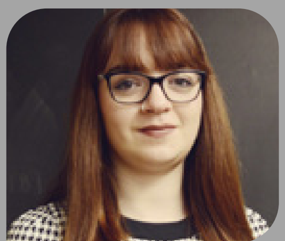
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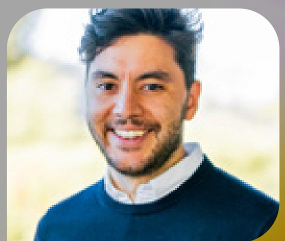
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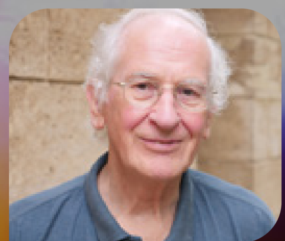
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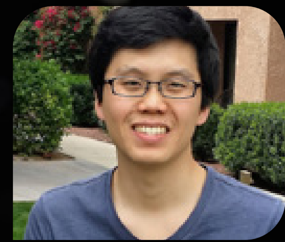
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PEOPLE OF OZGRAV - DATA AND ASTROPHYSICS

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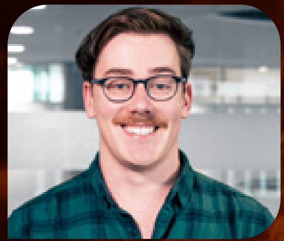

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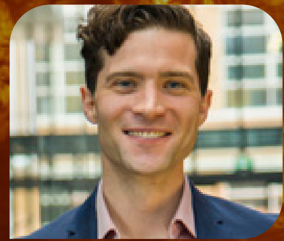

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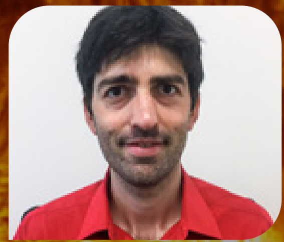

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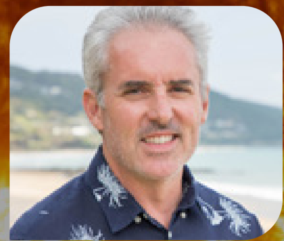

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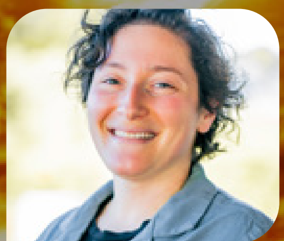

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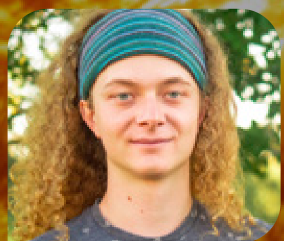

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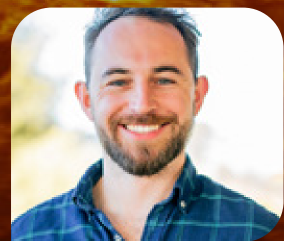

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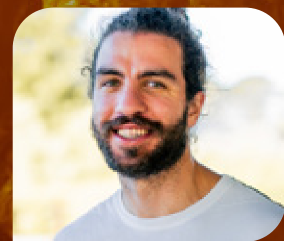

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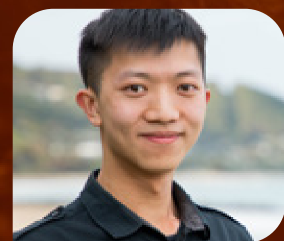

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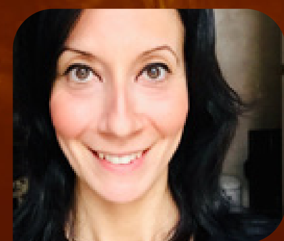

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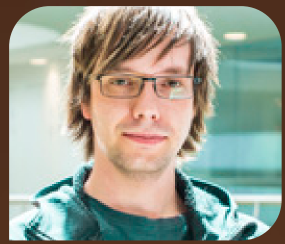

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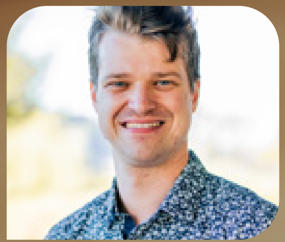

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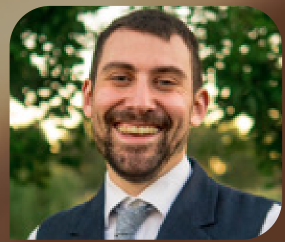
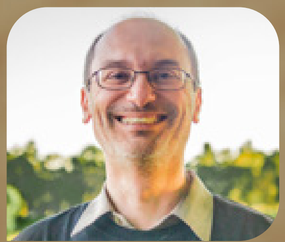
University of Western Australia
Masters Student

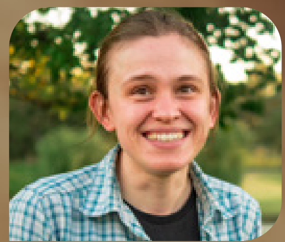


Dr Grant David Meadors
Los Alamos National Laboratory
Affiliate



Prof Andrew Melatos
University of Melbourne
Chief Investigator

Dr Patrick Meyers
Caltech
Associate Investigator



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Matthew Miles
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PhD Student

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Postdoctoral Researcher

Dr Anais Möller
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Dr Travis Yik Lun Mong
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Eloise Moore
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Masters Student

Prof Tara Murphy
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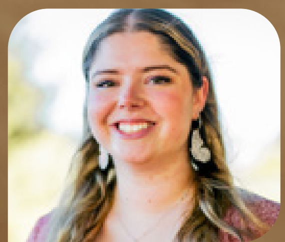

Rowina Nathan
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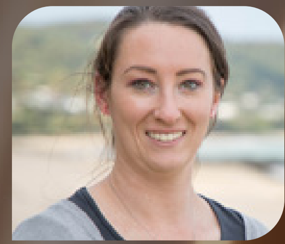

Dr Fiona Panther
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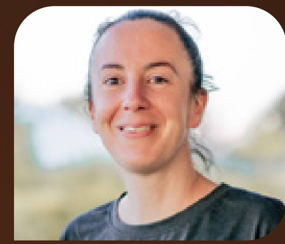

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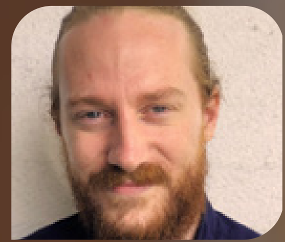

Joshua Pritchard
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Dr Liana Rauf
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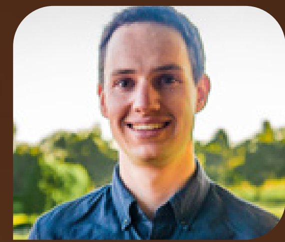

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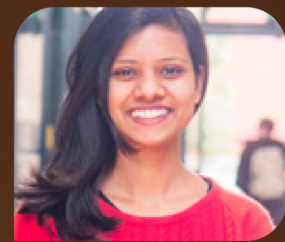

Dr Nandini Sahu
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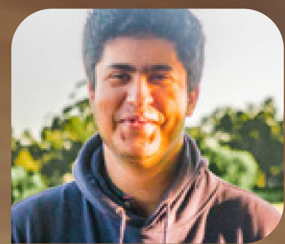

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Dr Rahul Sengar
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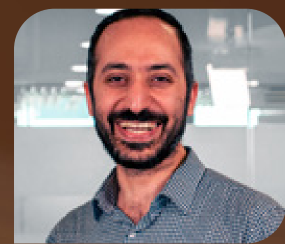
PhD Student



Mohsen Shamohammadi
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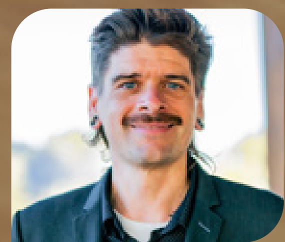

A/Prof Ryan Shannon
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Associate Investigator

Dr Karelle Siellez
University of Tasmania
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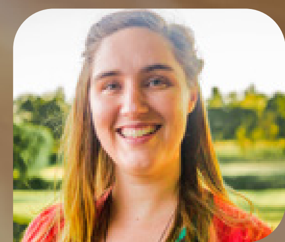

Teresa Slaven-Blair
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Dr Rory Smith
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Postdoctoral Researcher

PEOPLE OF OZGRAV - DATA AND ASTROPHYSICS


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Avi Vajpeyi
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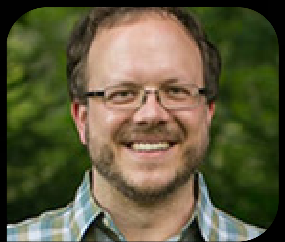
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Auckland University of Technology, NZ
Associate Investigator


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Outreach

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Professional Staff
Node administration and Outreach

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Research Assistant
Outreach

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Luke Davis
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SPIIR online coherent pipeline

Kim Dorrell
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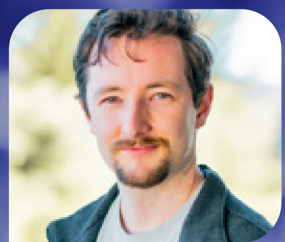
Node Adminstration

Dr Yeshe Fenner
Swinburne University of Technology
Chief Operating Officer (COO)

Ariadna Hernandez De la Cruz
Swinburne University of Technology
Node Administration and Events Officer



Deon Hickey
Australian National University
Newtonian Noise characterisation

Lisa Horsley
Swinburne University of Technology
Node Administration and Outreach

Dr Jyoti Tejinder Kaur
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Magdalena Kersting
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Professional Staff

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Dr Anastasia Popkova
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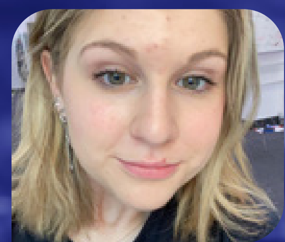
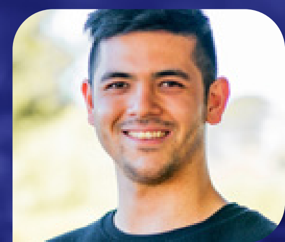
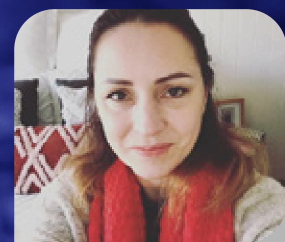


Sammi Summerford
University of Adelaide
Undergraduate
Outreach



Daniel Tang
University of Western Australia
Machine Learning



Lana Urbina
University of Western Australia
Public Relations and Marketing

Phillip Tian Wu
Australian National University
Technical Staff

Timothy Davies
University of Western Australia
Professional Staff

Ken Field
University of Western Australia
Professional Staff

Andrew Gozzard
University of Western Australia
Technical Staff

Dean Harvey
University of Western Australia
Professional Staff

Stephen Key
University of Western Australia
Professional Staff

Dr David Liptai
Swinburne University of Technology
Professional Staff

Bec Todd
Swinburne University of Technology
Gravitational Wave Data Centre Admin

OZGRAV GRANT SUCCESS

Over the past 2 years there has been an intensive effort by the Australian gravitational wave community to plan for, and develop, an application for another ARC Centre of Excellence that focusses on gravitational waves.

The proposed Director Matthew Bailes (Swinburne) and proposed Deputy Directors Tamara Davis (University of Queensland) and David McClelland (ANU) led a large community-wide process to develop the science program for the new Centre. The process included community workshops; a call for White Papers that elicited 30 Papers put forward by members of the broad astronomy and gravitational wave communities; extensive consideration and refinement of the research program; and the selection of a new set of CIs for the proposed Centre.

This effort culminated in the submission of an 875-page application to the ARC, involving 23 Chief Investigators, 12 Partner Investigators, and 22 Associate Investigators. The new Centre aims to build on the success of OzGrav, with a mission to use gravitational waves to make critical discoveries about the fundamental nature of relativistic gravity, ultra-dense matter and cosmology, and to position Australia as a leading player in the gravitational-wave megascience instruments of the 2030s and 2040s.

In November we had the fantastic news that the Australian Research Council had concluded its selection processes and that OzGrav was to be funded for another 7 years! This achievement is both a testament to the staff, students and admin staff that helped build OzGrav's national and international reputation in its first seven years and the team that put together the 2023 bid. We drew great confidence during the bid process from the number of people who contributed their ideas, and time to the text, and left no stone unturned. This will enable OzGrav to capitalise on the tremendous opportunities in relativistic astrophysics that lie ahead until 2030.

The new Centre will be pursuing six major Key Projects, and we will be joined by the University of Queensland and the University of Sydney as this field of science grows. Our female Chief Investigators count is more than double that of the original Centre.

The Centre is built around six Key Projects:

1. Optimisation: Maximise the science returns of gravitational-wave observatories in the 2020s;

2. Detection: Discover and interpret gravitational-wave sources and high-energy electromagnetic transients;

3. Gravity: Probing the nature of gravity and extreme spacetime;

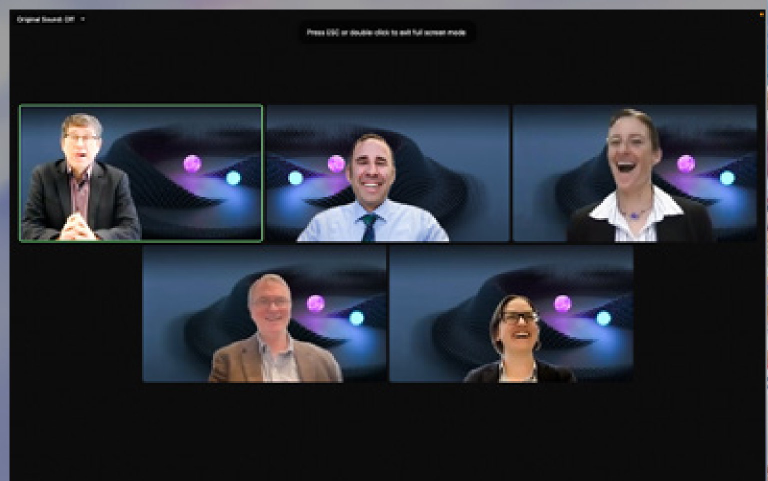
4. Extreme Matter: The physics of ultra-dense matter;

5. Cosmos: Determine fundamental properties of the Universe;

6. Future Tech: Develop key technologies for next-generation detectors.

A special thanks to the new OzGrav 2023 Deputy Directors Tamara Davis and David McClelland, members of the Steering Committee that placed trust in Matthew Bailes to lead the bid, our International and Domestic advisory committees, and Yeshe Fenner for administrative support and Carl Knox for making everything associated with the bid look a million dollars. We aim to commence the new Centre's activities in early 2024 when OzGrav version 1 is concluding.

The interview team (L to R): Prof Eric Thrane (Monash), Prof Tamara Davis (University of Queensland), Distinguished Prof David McClelland (ANU), Prof Tara Murphy (University of Sydney) and OzGrav Director Prof Matthew Bailes (Swinburne). Below: The team on Zoom videocall.



EQUITY AND DIVERSITY COMMITTEE

In 2022, OzGrav saw a number of highlights and achievements that advanced our Equity, Diversity and Inclusion goals.

A big highlight of 2022 was the installation and unveiling of a stunning artwork created by Wurundjeri Elder Uncle Colin Hunter to accompany an OzGrav Acknowledgement of Country plaque at OzGrav's headquarters. The artwork is titled "Circling through space" and it juxtaposes the waves generated by boomerangs with the gravitational waves generated by black holes.

In 2022, we made progress increasing engagement with indigenous students, largely through our UWA-based Einstein First and ASPIRE programs that have been engaging with a network of Aboriginal High Schools in regional/rural Western Australia. One of the Einstein First team spoke about their experiences engaging with indigenous students at one of our weekly Centre-wide meetings.

In 2022, we appointed two new Chief Investigators, both very talented early-to-mid-career women researchers. This increased the number of female CIs from 3 to 5 (out of 22 CIs). We also assembled a successful team of CIs for the new OzGrav CE23 Centre, which includes 7 women CIs out of 23. We hope that one of the legacies of our centre is a significant and sustained improvement in the diversity of people working in these fields.

In order to increase opportunities for underrepresented people to engage in OzGrav research, in 2022 we ran a scheme to Centrally-fund 50% of a PhD stipend if the student is from an underrepresented group or working with underrepresented supervisors. We also ran a scheme to Centrally-fund a vacation scholarship program where at least half of the students were from underrepresented groups or working with underrepresented supervisors.

In 2022, we joined with other STEM-focused ARC Centres of Excellence to run the first ever inSTEM conference: a networking and career development workshop for people from marginalised or underrepresented groups in STEM, and their allies. It was very well attended and we received overwhelmingly positive feedback from attendees, and expect to run it again in 2023.

OzGrav prepared an application for a Gold 2022 Pleiades Award from the Astronomical Society of Australia (ASA) to recognise our continued commitment to promoting equity and inclusion. The Gold Pleiades award recognises a truly outstanding sustained commitment to best practice in relation to the aims of the ASA's Inclusion, Diversity and Equity in Astronomy Chapter. Attaining a Gold Pleiades award would be an exceptional accomplishment, and we look forward to hearing in 2023 whether we have moved from our current Silver status to Gold.

Monash PhD students Isobel Romer-Shaw (above) and Shanika Galaudage (below) attend the International Women's Day event for high school students at Casey Tech School. Credit: Lisa Horsley, OzGrav-Swinburne

Monash PhD student Shanika Galaudage presents a talk at the OzGrav Winter School in Adelaide. Credit: Lisa Horsley, OzGrav-Swinburne

PROFESSIONAL DEVELOPMENT COMMITTEE

Over the past year, OzGrav continued to refine and implement our Professional Development Program and make excellent progress against most elements of the 2022 activity plan.

Each year we offer training and PD opportunities on topics of interest and benefit to our Early Career Researchers (ECRs), delivered by more senior researchers and/or appropriately credentialled external facilitators. Topics are selected based on the results of our member survey, private feedback to Executive and feedback to the PD committee members at each node. In 2022 we provided sessions on the following topics throughout the year via webinar and/or in-person at our annual 2-day ECR workshop:

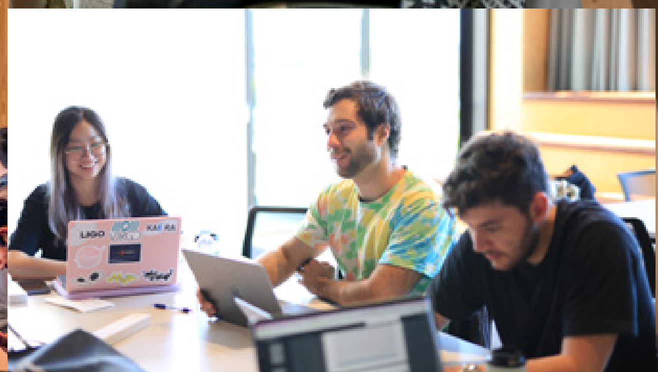
- Grant writing tips
- Scientific writing
- Bystander intervention training
- Science communication
- Project management
- Communication and Peer Coaching
- Conflict resolution
- How to be a strategic researcher
- Speed-meet-a-CI/AI
- Careers panel
- Taking charge of your PhD
- Taking charge of your postdoc career
- Building your career at home or overseas

In addition 2022 saw our first ever Winter School, which was designed and run by ECRs from our Adelaide Uni node. The Winter School provided training across a broad range of technical and scientific topics, as well as a welcome opportunity for networking. Following the impacts of COVID on travel in 2020-2021, this was the first OzGrav in-person event for many attendees. The post-event survey affirmed that it was a highly successful and productive event, which we will now run annually going forward.

In 2022 our recently launched Research and Innovation Grant scheme awarded three grants to support our students and early career researchers to pursue novel ideas in areas ranging from data analysis to space instrumentation. This scheme aims to incentivise collaboration and support ECRs to publish short-author papers.

Discussions at OzGrav Winter School in Adelaide. Credit: Lisa Horsley, OzGrav-Swinburne

Panel discussions and talks at OzGrav's ECR Workshop and Annual Retreat in Canberra. Credit: Carl Knox, OzGrav-Swinburne



RESEARCH TRANSLATION COMMITTEE

In 2022 we made excellent progress against our 2022 activity plans. On the training front, we supported two teams of OzGrav researchers to participate in the Cruxes Ascend program, which is designed to give researchers the skills and support to drive partnerships with industry, government, and community groups to create impact extending beyond gravitational wave research.

We also coordinated with our nodes to offer training on the processes involved in protecting and commercializing intellectual property. Each university has slightly different procedures so local university-run training sessions were offered.

We ran an OzGrav Commercialisation Discovery Program in 2022, led by Ilana Feain from Big Science Advisory. As part of this program, we identified eight projects with commercialisation potential. Big Science Advisory did a deep dive into the most promising projects, providing them with expert advice on the next steps to progress their idea. We expect that at least two of those projects will be supported through our Seed funding program in 2023.

In 2022 we awarded several new Research Translation Seed grants, including one grant to a student-led project exploring the use of lasers for weed management in agriculture, and another to a postdoc-led project investigating a renewable energy grid to power gravitational wave detectors sustainably.

OzGrav holds a weekly centre-wide videocon, with very high attendance. During 2022 we used this timeslot to run sessions with special guest speakers from industry including Kirk Bresniker, Chief Architect of Hewlett Packard Labs, and former OzGrav/EQUS/ANU researcher Lyle Roberts who shared his journey taking gravitational wave-related technology and applying it to the autonomous vehicle industry, including the big development of their start-up company being acquired by Advanced Navigation in a deal worth up to $40M. Lyle's talk inspired one of our students to pursue the laser weed killing idea that ended up receiving one of our Research Translation Seed grants.

Discussions at OzGrav Winter School in Adelaide. Credit: Lisa Horsley, OzGrav-Swinburne

Masters student Sophie Muusse (University of Adelaide) gives a research translation talk at OzGrav's ECR Workshop and Annual Retreat in Canberra. Credit: Carl Knox, OzGrav-Swinburne

ACTIVITY PLAN 2023

Instrumentation

Commissioning - Program Chairs: Dr Dan Brown (Adelaide) and Dr Bram Slagmolen (ANU)

Remote commissioning training for new members will be carried out across all nodes by mid-2023. Remote commissioning support will be provided by the University of Adelaide, as well as in-person commissioning trips up to May 2023, when the O4 run is anticipated to start.

Quantum - Program Chairs: Dr Terry McRae (ANU) and Dr Sebastian Ng (Adelaide)

The Quantum program will continue to focus on the development of long wavelength high power fibre lasers suitable for main laser operations, squeezed light applications, thermal compensation systems and research into silicon cryogenic test masses for future gravitational wave (GW) detectors.

Several squeezed light and interferometer configurations will continue to be developed that are designed to increase the sensitivity of future GW detectors. We would like to measure degenerate internal squeezing early in 2023 and explore non-degenerate external/internal squeezing later in the year. We should have results early this year to show if we can use an optical parametric amplifier to mitigate photodetector inefficiencies.

Research will continue on the white light cavities (WLC) to extend the GW detector bandwidth and with the use of an optical parametric amplifier to enhance the optical spring effect in the signal recycling cavity to tune the frequency of maximum sensitivity in the GW detection band.

More theoretical work will focus on understanding the sensitivity limits relevant to gravitational wave detectors as described by quantum information protocols such as Fisher information and Holevo bounds.

Low frequency Newtonian noise mitigation - Program Chairs: Dr Bram Slagmolen (ANU) and Prof JU Li (UWA)

The main goal for 2023 for the TorPeDO experiment is to commission the full Isolation and Suspension Chain. This requires us to level each of the four pendulum stages and to bring them to their operating point, using complex controls implementations. With all four lasers phase locked, they will be injected into the four linear optical cavities on the TorPeDO beams. Their control will be via a hierarchical control system with the PLL control loops.

The TorPeDO-DI development will be integrated into the TorPeDO systems once performance has reached the design target.

For the rotation sensor project, the goal is to have all the ALFRA-2 new design subsystem constructed and tested.

It is planned to have ALFRA-2 sensors mounted with the TorPeDO.

In 2023 we plan to deploy the large seismic array with the remote data acquisition completed ready for data analysis and vibration feedback/feedforward control.

Distortions and Instabilities - Program Chairs: Dr Carl Blair (UWA) and Prof David Ottaway (Adelaide)

We will work on silicon beam-splitter birefringence, to be completed mid-2023. We will complete the Gingin TSAMs build and test by June 2023. We will continue to work on thermal stress induced birefringence throughout the year.

Space Instrumentation - Program Chair: Dr Andrew Wade (ANU)

In 2023 the Space Instrumentation Program will continue work on weak light phase tracking topics, minimal hardware absolute frequency determination, and laser frequency stabilisation and readout techniques.

With the publication of our work on weak light phase-tracking with laser pre-stabilisation, our research focus will move to applications. A focus on schemes making use of lower trackable powers will include examining the application of weak light tracking to space missions with passive retro-reflectors, for example, the next generation gravity missions.

The NASA-Germany replacement to the GRACE Follow-On mass change mission will reach a critical point of technology down selection for an expected 2028 launch. For a laser instrument only mission a wavelength scaling calibration will be needed to translate phase measurements into length (strain) and accurately subtract static gravity signals in month-to-month comparisons. Cavity free-spectral-range readout has been identified as a strong candidate. Addressing technology readiness and retiring risk for the technique will be essential for seeing this technique fly in 2028. We will collaborate with NASA-JPL through test and characterization of a prototype instrument. Our 2023 focus turns to addressing mirror etalon systematic effects in a testbed upgrade, and to a study of systematic offsets induced by mirror coating dispersion and geometric effects.

Finally, work will continue in the area of laser frequency stabilisation with a focus on an experimental demonstration of arm locking in a fibre delay line optical setup. This work will experimentally demonstrate the feasibility of blending traditional optical cavity laser stabilisation with that of the stable reference offered by the delayed propagation between spacecraft in a table top experiment.

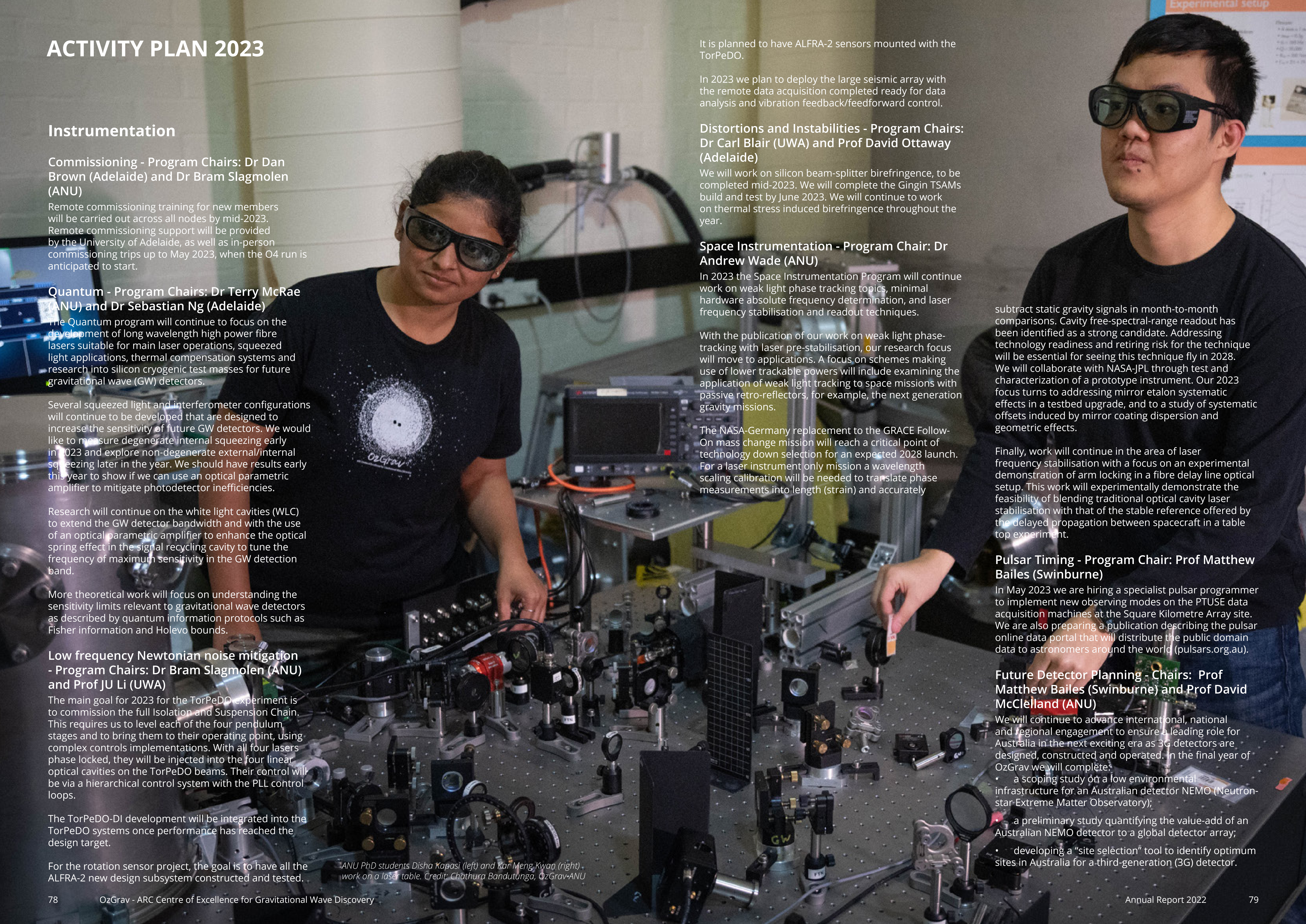
Pulsar Timing - Program Chair: Prof Matthew Bailes (Swinburne)

In May 2023 we are hiring a specialist pulsar programmer to implement new observing modes on the PTUSE data acquisition machines at the Square Kilometre Array site. We are also preparing a publication describing the pulsar online data portal that will distribute the public domain data to astronomers around the world (pulsars.org.au).

Future Detector Planning - Chairs: Prof Matthew Bailes (Swinburne) and Prof David McClelland (ANU)

We will continue to advance international, national and regional engagement to ensure a leading role for Australia in the next exciting era as 3G detectors are designed, constructed and operated. In the final year of OzGrav we will complete:

- a scoping study on a low environmental infrastructure for an Australian detector NEMO (Neutron-star Extreme Matter Observatory);
- a preliminary study quantifying the value-add of an Australian NEMO detector to a global detector array;
- developing a "site selection" tool to identify optimum sites in Australia for a third-generation (3G) detector.



ANU PhD students Disha Kapasi (left) and Kar Meng Kwan (right) work on a laser table. Credit: Chathura Bandutunga, OzGrav-ANU

ACTIVITY PLAN 2023

PhD student Zac Holmes (University of Adelaide) gives a research translation talk at OzGrav's ECR Workshop and Annual Retreat in Canberra. Credit: Carl Knox, OzGrav-Swinburne

Director Prof Matthew Bailes (Swinburne) and Deputy Director Prof David McClelland (ANU) continue to represent OzGrav on the Gravitational Wave International Committee (GWIC). OzGrav members will serve in an increasing number of leadership roles in both the Cosmic Explorer (CE) and Einstein Telescope (ET) projects. Postdoctoral Researcher Dr Dan Brown (Adelaide) will be running an international ET Optical Design workshop in Nikhef in June.

Data and Astrophysics

Inference - Program Chairs: Chayan Chatterjee (UWA) and Dr Rory Smith (Monash)

The 04 run is anticipated to start early 2023. In the first part of 2023 the Inference program team will work on essential inference projects of 04, including pbilby, ROQs and Rapid sky localisation. The UWA Machine Learning (ML) group will develop online ML infrastructure for inference for O4 and beyond.

GW Data Analysis - Program Chairs: Dr Fiona Panther (UWA) and Dr Jade Powell (Swinburne)

In 2023 there will be a strong focus on finishing preparations for O4 and detecting and analysing detection candidates once the O4 run begins in mid 2023.

In the first half of the year we will Complete the O3b FRB search. We will finish the SPIIR code review, and develop infrastructure for online machine learning (ML). We will develop new techniques for post-merger detection and parameter estimation (PE) of post-merger remnant signals + high frequency detector characterisation/noise mitigation. We will complete the O3 SN search.

Many members of the team have ongoing LIGO reviewer commitments. When the O4 run starts early- to mid-year, we will run the SPIIR pipeline to find CBC signals in low latency in O4. We will participate in the O4 TGR effort. We are collaborating with the theory group at Perimeter Institute. We plan to lead the directed search for vector bosons in O4 around CBC merger remnants.

We will also continue to work on optimisation of NEMO for post-merger detection signals based on NR waveforms and realistic BNS populations.

Pulsar Detections - Program Chair: A/Prof Ryan Shannon (Swinburne)

Pulsar Timing Data Sets: The year will see OzGrav data combination efforts pivot toward international facilities. We will produce updated MeerTime data sets and the four-year MeerTime data release. This, along with the Parkes Pulsar Timing Array (PPTA) DR3 data set will be provided to the International Pulsar Timing Array (IPTA) for an updated data set to be completed by the middle of the year. As experts in PPTA and MeerTime data sets, OzGrav members will play a leading role in ensuring the IPTA data sets are maximally sensitive.

Pulsar Inference: The new data sets will motivate sensitive next-generation gravitational wave (GW) searches. We will finalise GW searches with the PPTA DR3 data set. We will also undertake noise and GW searches with an updated MeerTime data set. This high-risk high-reward search will motivate continued PTA work with MeerKAT and highlight the role the SKA will play in IPTA efforts. We will also continue to work on pulsar timing algorithms necessary for our new wide bandwidth instruments, and GW detection algorithms that can account for misspecification in pulsar-timing data sets.

2023 IPA Science Meeting: 2023 is poised to be a breakthrough year in pulsar timing. One of the highlights will be the 2023 student workshop and science meeting. This will be the first in-person meeting since 2023, so will both allow the community to share undoubtedly exciting results, but also reconnect. The student workshop will be held at CSIRO in Sydney 13-16 June. The science meeting is scheduled to be held in Port Douglas, Queensland 19-23 June.

Multi-Messenger Observations Program Chairs: Dr Katie Auchettl (Melbourne) and Dr Dougal Dobie (Swinburne)

The fourth LVK observing run, O4, will begin in early-2023 after approximately 3 years of detector down-time resulting from planned upgrades and the COVID-19 pandemic. The primary goal of the Multi-Messenger Observations program is comprehensive follow-up observations of neutron star and neutron star-black hole mergers detected during O4, including the detection of multiple electromagnetic counterparts.

At low radio frequencies, the Murchison Widefield Array will carry out low-latency follow-up of neutron star mergers searching for FRB-like signals. LOFAR will be back online toward the end of 2023 after undergoing a year-long upgrade, enabling significant overlap with the O4 run and improvements to the low-latency triggering capability.

At gigahertz radio frequencies, the Australia Square Kilometre Array Pathfinder ASKAP) is the only radio telescope capable of observing entire gravitational wave localisation regions with a single pointing, enabling OzGrav researchers to search for counterparts independent of observations at other wavelengths. The Australia Telescope Compact Array will be used to search for and monitor radio emission from known counterparts, while the Long Baseline Array can be used to image them at extremely high resolution.

In the optical regime, the Zadko and Skymapper telescopes will search for optical counterparts, with SkyMapper also expected to have its fourth data-release in early 2023. The ANU 2.3m telescope will begin full automated operations in March 2023, enabling rapid spectroscopic follow-up of gravitational wave counterparts and their host galaxies. The GOTO-South telescope is expected to come online by mid-2023 and will provide vital widefield coverage of Southern gravitational wave events.

In addition to OzGrav-led programs, OzGrav researchers are also involved in gravitational wave follow-up programs on the world's leading telescopes spanning the entire electromagnetic spectrum. Another Deeper Wider Faster (DWF) run will start in late 2023.

Relativistic Astrophysics - Program Chair: Dr Ryo Hirai (Monash)

The relativistic astrophysics program has overlapping interests with most of the other programs within OzGrav. It is important to keep this synergy going, in order to optimise our strategies for future observations as well as making sense of new discoveries. In 2022, the astronomy community enjoyed the advent of the James Webb Space Telescope (JWST), which made exciting new measurements every day. In 2023 there are a number of new observations and surveys planned to start, including the LIGO/Virgo/KAGRA O4 operations, and first light for the Vera Rubin Observatory. In particular, the expected large number of gravitational wave detections by O4 in the JWST era may be a game changer. In 2023 the relativistic astrophysics program will focus on establishing new ways to extract information from the updated observational facilities.

In addition, the program will continue to explore extreme matter physics through theoretical investigation. For example, we will continue studies of neutron star superfluids, superconductors and glitches, with the aim of producing falsifiable theories. Recent work on modelling magnetic mountains and neutron star cooling curves will be extended to further understand their

ACTIVITY PLAN 2023

interior properties. Pulsar timing and pulsar timing array theory will also be areas where innovations are expected to be made.

By mid-2023 we will establish a method to constrain the nuclear equation of state from neutron star black hole (NSBH) mergers. By late 2023 we will understand the effect of evolving mass and spin on binary black hole merger remnants and the properties of quasi-periodic oscillations.

Population Modelling - Program Chair: Dr Simon Stevenson (Swinburne)

In readiness for the next LIGO Observing Run (O4) in early-to-mid 2023, our team will update COMPAS Population Synthesis Code, and update prescriptions in NBODY code. In the first part of the year we will also prepare Population Models for O4. We expect to be busy with O4 data from the start of O4 onwards.

OzSTAR supercomputer - Leader: Prof Jarrod Hurley (Swinburne)

A major activity for 2023 will be to finalise the installation of the "Ngarrgu Tindebeek" supercomputer which will succeed OzSTAR as the primary GW data and computing engine in Australia, noting that OzSTAR will continue to be run in parallel with the new machine. We plan to have "Ngarrgu Tindebeek" ready for test users in early March and fully deployed by the end of March 2023. A highlight will be unveiling the artwork on the new machine – by local Indigenous artist Mandi Barton – at around the same time. Activity related to the supercomputing environment will continue as a focus throughout the year, as we further upgrade the storage hardware, transition users and optimise workflows.

An important deliverable is to secure the next round of funding for the Gravitational Wave Data Centre (GWDC). Current funding will only take us through to July 2023. If further funding is not secured we will need to delay or halt progress on development projects which will limit our ability to support Australian involvement in O4 science. We will work closely with AAL to secure further funding to avoid this scenario.

We will continue to work with the GWDC and OzGrav researchers to make significant contributions to GW software development and data delivery, primarily across the key projects (SPIIR, GWCloud, GWLab, GWLandscape, MeerTime). A continued focus will be readiness and support for O4 (data streaming, live searches) and growing the user-bases of the data portals that serve the data products.

Professional Development Committee

Deliver and grow the OzGrav webinar series including topics of particular interest to Early Career Researchers. Expand our PD Program to provide more PD and mentoring opportunities to mid-career and senior researchers.

Continue to grow the pool of mentors in our mentoring program, including people from industry and other sectors, and encourage more senior OzGrav researchers to be part of the program as mentees as well as mentors. Run a mentor/mentee networking and speed-meet-a-mentor event.

Design an innovative and constructive ECR Workshop for the OzGrav Annual Retreat, in consultation with the Early Career Researcher Committee.

Support our ECRs to run a Winter School.

Continue to implement and monitor progress against the recommendations from our Mid Term Review. Continue the promotion of ECRs and MCRs into the role of Program Chairs, with the appropriate mentoring from node and theme leaders.

Raise awareness, and ensure appropriate uptake, of the grant opportunities available within the Centre, including the Research & Innovation grant and the Professional Development grant.

Equity and Diversity Committee

Continue to implement, update, and evaluate progress against, the OzGrav Equity and Diversity action plan.

Run a workplace culture review that will be undertaken by an external expert company. This review will report on strengths and weaknesses across the Centre and within nodes and research groups, and will make recommendations for changes or improvements.

Continue to monitor the level of diversity and inclusiveness in the centre, assess changes over time, and identify further areas for improvement.

Coordinate with other Centres of Excellence to share and adopt best practice in equity, diversity and inclusion.

Run webinars on a range of equity, diversity and inclusion topics.

Hold two special events in 2023: 1) recognition of IDAHOBIT Day in May, 2) celebrations of OzGrav's cultural diversity in August.

Increase engagement with our education and outreach program by people from underrepresented or disadvantaged populations, with a particular focus on engaging with schools in indigenous communities.

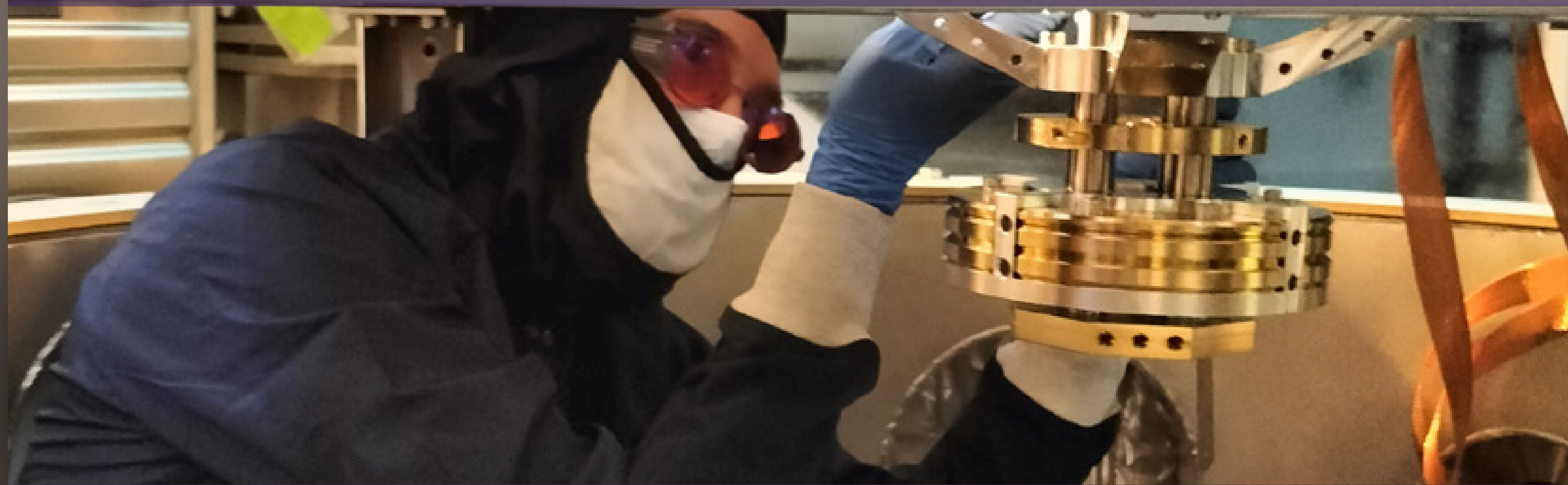
Implement recruitment, professional development, and succession planning strategies, as per the recommendations from our Mid Term Review, to increase female representation among our membership at all levels in the centre, with the aspiration of achieving gender balance.

Run vacation scholar and work experience programs that prioritise students from historically underrepresented groups in STEM.

Research Translation Committee

Our Research Translation Committee has crafted an action plan for 2023 to lift our members' interest in, and exposure to, research commercialisation, intellectual property identification and protections, and broad industry engagement. The plan incorporates a bottom-up approach to educate and empower our members to explore RT of their ideas, alongside top-down strategic approaches to identify projects and technologies with the greatest potential for translation and commercialisation. Key elements of the 2023 action plan are:

- Provide training in commercialisation and Intellectual Property that includes information about each institution's specific processes and resources.
- Continue to run a seminar series featuring researchers who have commercialised technology, started companies, or had major industry engagement. The aim is to inspire OzGrav researchers, excite them about the possibilities of research commercialization, and educate them on the various processes.
- Continue to engage with an astronomy research commercialisation expert to further drill down into these capabilities to identify those with most promise, and help map our skills and technologies to real-world industry challenges.
- Support our members to increase uptake of Research Translation Seed grants and provide relevant mentoring to grant recipients.
- Hold OzGrav-meets-industry networking and pitchfest events, including the potential for a joint hackathon initiative with other STEM-focused ARC Centres of Excellence.
- Provide pitch session training to give our members practice and confidence in selling their science and research translation ideas to a range of audiences including government and industry.
- Deliver briefings to industry, and provide industry internship opportunities.



Installation of torsion bars, a major upgrade in the commissioning of the TorPeDO detector at the Centre for Gravitational Astrophysics (CGA), ANU. Credit: Avanish Kulur Ramamohan, OzGrav-ANU.

Outreach

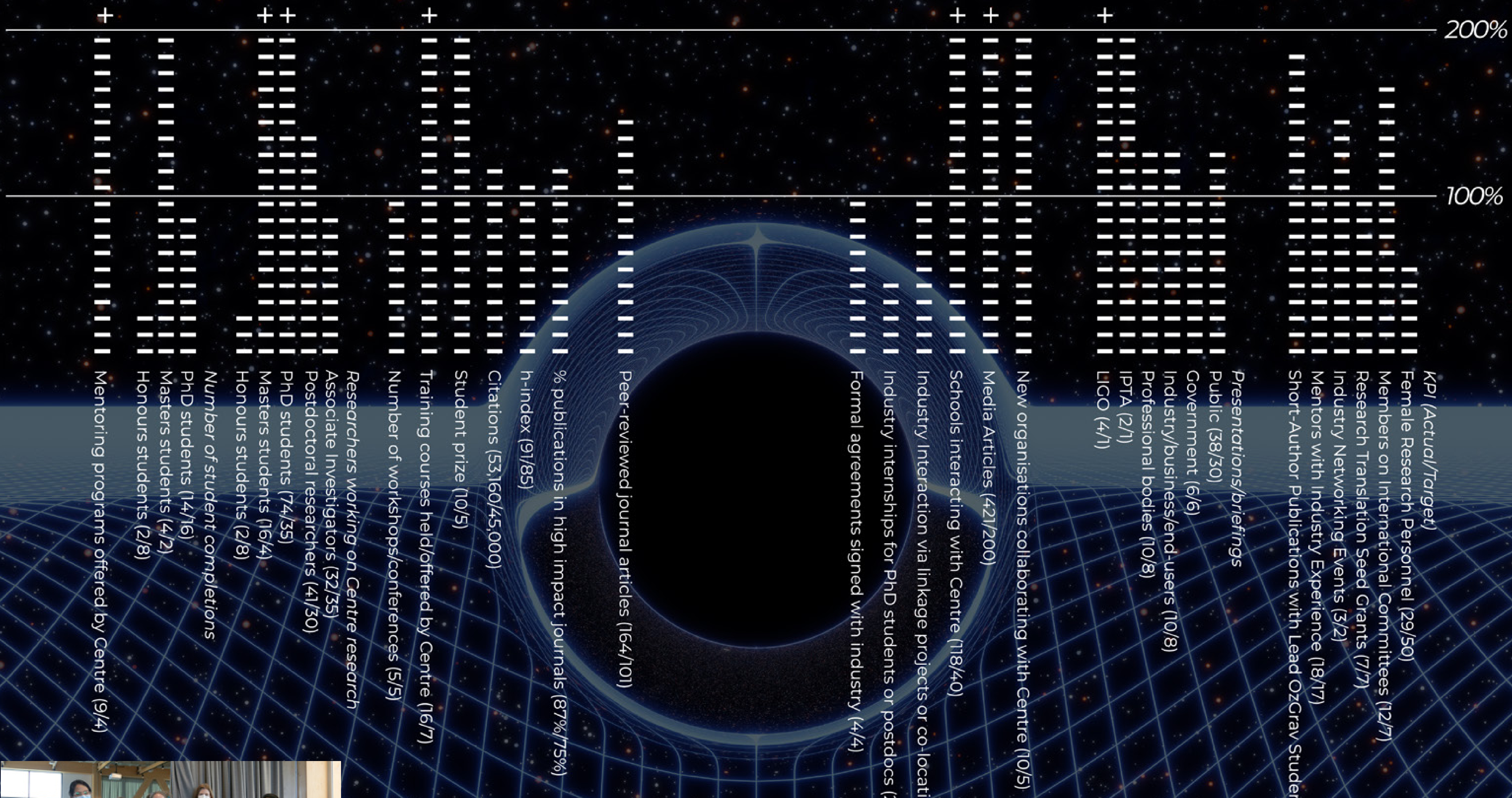
Schools Programs: We will continue to offer our existing face-to-face and virtual incursions across a geographically diverse network of students and teachers. We have expanded our schools incursions to include lessons and activities for primary schools and will continue to build with networking with primary science teaching organisations. A major goal for this year is to collaborate with our instrumentation researchers to scale up the education modules developed by the University of Adelaide team. We will ensure the material is accessible to not only teachers across the country (via teacher professional development) but also to schools across our node states. The Einstein-First team will continue to expand their curriculum across all year levels.

Public Outreach: After the successful pilot of interactive projections in 2022, we will be liaising with groups such as science centres and observatories to bring these assets to a broader audience. We will also investigate how to scale the gravitational wave projections so each node has access and ability to use them for their own local purposes. We will continue to engage with the general public across all node states by partnering with various public activities across Australia such as Pint of Science, Science Alive, and Astrofest. For National Science Week we will be a partner with other Centres of Excellence (CoEs) for the National Science Quiz.

Member Training, Media, and Science Communication: In addition to offering public communication opportunities as part of the ECR Retreat, we will continue to offer targeted communication training opportunities for members with specific goals of increasing comfort with public speaking and media interviews. To build the science communication capacity of our ECRs, we will support them to travel with members of the HQ team to large public outreach events for hands-on, real-time training. We will continue to support our members with animations, explainers, and graphics to accompany media articles related to OzGrav work. Additionally, we will continue to offer support to our researchers to share their stories via our social media channels.

Diversity and Accessibility: We will view our outreach and engagement events and programs through a lens of diversity and accessibility so that we target groups traditionally underserved in STEM. This means we will prioritise engagement with audiences in regional and rural communities, female and culturally diverse audiences, and other audiences who would otherwise not self-select into STEM opportunities. To further increase our ability to engage with all members of our community, we will focus on increasing the accessibility of our content for members of our low-vision or low-hearing communities. Where possible, new materials we develop for education and outreach will have multiple modes of engagement to ensure these audiences can interact via tactile and/or sound enhanced options.

KEY PERFORMANCE INDICATOR (KPI) DASHBOARD



Admin team (l to r) Ariadna Hernandez De La Cruz (Swinburne), Ruby Chan (UWA), Lisa Horsley (Swinburne) Dr Yeshe Fenner (Swinburne) and Dr Sareh Rajabi (ANU) at the OzGrav ECR Workshop and Annual Retreat in Canberra. Credit: Carl Knox, OzGrav-Swinburne

LINKAGES AND COLLABORATIONS

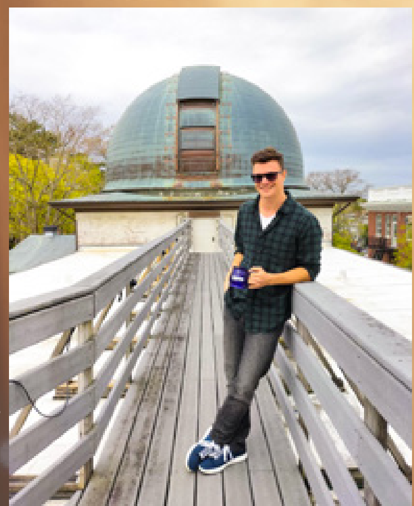
OzGrav students and researchers are involved in many collaborations, both international and Australia-wide.

International Partners and Collaborators

Airbus Ariane Rocket GeoTrack Group
AstroParticle and Cosmology Laboratory (APC)
Auckland University of Technology
California Institute of Technology (Caltech)
Centre National De La Recherche Scientifique (CNRS)
CHIME
Chinese Academy of Sciences Institute of Theoretical Physics
Cyprus University of Technology
European Space Agency (ESA)
Flawless Photonics
French Space Agency
Google
GOTO Collaboration
GrandMa collaboration
Harvard University
INFINI.TO: Planetarium of Turin
IPHT - Leibniz Institute of Photonic Technology
Kavli Institute for Theoretical Physics China
Laser Interferometer Gravitational-Wave Observatory (LIGO)
Ludwig Maximilian University of Munich (Universität München)
Massachusetts Institute of Technology (MIT)
Max Planck Institute for Gravitational Physics (Hannover) Albert Einstein Institute
Max Planck Institute for Radio Astronomy
Neils Bohr Institute
MeerTime Collaboration (Manchester, ASTRON, MPIfR, CNRS, SARAO, NRAO, CSIRO, Curtin, AUT, UBC, INAF)
Montana State University
NASA Goddard Space Flight Centre
NASA JPL
Polish Space Agency
Quaisr
Tsinghua University
University of Arizona
University of Birmingham
University of Florida
University of Glasgow
University of North Carolina - Chapel Hill
University of Otago
University of Science and Technology China (USTC)
University of Tokyo
University of Urbino
University of Warwick

National

Advanced Navigation
Aerometrex Pty Ltd
Arq group
Astronomy Australia Ltd
Australia Post
Australian Astronomical Observatory (AAO)
Casey Tech School
CEA Technologies
Centre for Eye Research Australia (CERA)
Charles Sturt University
CSIRO Australia Telescope National Facility (ATNF)
DST (Defence Science and Technology)
Eliiza Data Science
Gravity Discovery Center
International Centre for Radio Astronomy Research (ICRAR)
Liquid Instruments Pty Ltd
University of Queensland
University of Sydney
Xcalibur Multiphysics



Reinhold Willcox at the Harvard Observatory.

OzGrav hosted the international Gravitational Wave Physics and Astronomy Workshop (GWPAW) in Melbourne in December 2022 with over 50% international attendance. Credit: Ilya Mandel, OzGrav - Monash University

LIGO Scientific Collaboration (LSC) – to LVC in 2019 and LVK in 2020

LIGO (Laser Interferometer Gravitational-Wave Observatory) is the world's largest gravitational wave observatory and a cutting-edge physics experiment, comprising two enormous laser interferometers located thousands of kilometres apart in Hanford (Washington) and Livingston (Louisiana), USA. LIGO exploits the physical properties of light and of space itself to detect and understand the origins of gravitational waves. The next observing run for LIGO – Virgo – KAGRA (LVK) is planned for the end of 2022.

LIGO is funded by the NSF, and operated by Caltech and MIT, which conceived of LIGO and led the Initial and Advanced LIGO projects. Financial support for the Advanced LIGO project was led by the NSF with Germany (Max Planck Society), the U.K. (Science and Technology Facilities Council) and Australia (Australian Research Council) making significant commitments and contributions to the project. More than 1,200 scientists and some 100 institutions from around the world participate in the effort through the LIGO Scientific Collaboration, which includes the GEO Collaboration and the Australian collaboration OzGrav. Additional partners are listed at http://ligo.org/partners.php. The Virgo collaboration consists of more than 280 physicists and engineers belonging to 20 different European research groups: six from Centre National de la Recherche Scientifique (CNRS) in France; eight from the Istituto Nazionale di Fisica Nucleare (INFN) in Italy; two in the Netherlands with Nikhef; the MTA Wigner RCP in Hungary; the POLGRAW group in Poland; Spain with the University of Valencia; and the European Gravitational Observatory, EGO, the laboratory hosting the Virgo detector near Pisa in Italy, funded by CNRS, INFN, and Nikhef.

Image: LIGO Livingston, USA. Credit: Caltech / MIT / LIGO Lab

Image: LIGO Hanford, USA. Credit: Caltech / MIT / LIGO Lab

Image: Virgo detector, Italy. Credit: Virgo Collaboration

Image: KAGRA detector, Japan. Credit: ICRR, University of Tokyo

LINKAGES AND COLLABORATIONS

The LIGO Scientific Collaboration now works closely with the Virgo Collaboration, with joint papers released by the LIGO and Virgo Collaborations (LVC).

We welcomed KAGRA Japan to the observing run O3b in 2020 and beyond, and moved to the LIGO – Virgo – KAGRA collaboration (LVK). KAGRA is the laser interferometer with 3 km arm-length in Kamioka, Gifu, Japan. The host institute is the Institute of Cosmic Ray Researches (ICRR), the University of Tokyo, and the project is co-hosted by National Astronomical Observatory in Japan (NAOJ) and High Energy Accelerator Research Organization (KEK). KAGRA completed its construction in 2019, and joined the international GW network of LIGO and Virgo. It became operational on 25 February 2020, when it began data collection. KAGRA Scientific Congress is composed of over 460 members from 115 institutes in 14 countries/regions.

We are also excited by the progress of land site selection in India, and eagerly await more news from our friends at LIGO India.

LSC/LVC/LVK and other international working groups

OzGrav PhD students and postdocs make significant contributions to LSC/Virgo leadership through serving as lead analyst/author of many LSC/Virgo observational papers, as well as serving in LSC/Virgo Collaboration management roles. This provides valuable leadership training for OzGrav early career researchers.

Dan Brown - AIC Chair

Phillip Charlton - Stochastic DetChar Co-chair

Eric Howell - Co-Lead of GW-FRB search (as part of the Burst-GRB subgroup), Chair of Paper writing team (PWT) for O3b GW-FRB Search paper, PWT member for O3a GW-FRB Search paper

David McClelland - LSC Speakers Board

Hannah Middleton - LIGO Magazine editor-in-chief

Jade Powell - Burst group Co-chair

Simon Stevenson - CBC PE Review Coordinator

Eric Thrane - member of the Editorial Board and an LVK Ally

Karl Wette - Continuous Wave Working Group Co-chair

LIGO Magazine

The LIGO Magazine is a twice-yearly publication by the LIGO Scientific Collaboration and is available for free to read online at www.ligo.org/magazine. The magazine publishes stories in an accessible way to a wide audience, highlights outreach efforts taking place and gives a voice to some of the personal stories and experiences of our community. It not only provides an important function in highlighting what LIGO does to the broader public, but also to showcase the work of individuals and groups to the rest of the LIGO/Virgo/KAGRA collaborations.

Hannah Middleton (OzGrav Postdoctoral Researcher at University of Melbourne) has been the Editor-in-Chief since 2018 and prior to that was Deputy Editor-in-Chief from 2014-2018. She leads a team of editors based all around the world. Together they discuss topics for each issue, commission and edit articles and make sure everything is ready for each issue to be published at the LIGO/Virgo/KAGRA meetings. The magazine has a big reach both internally and externally. Additional OzGrav editors include Nutsinee Kijbunchoo, Deeksha Beniwal and Kendall Ackley.

FINANCE

	2022 Forecast	2022 Actuals	2023 Forecast
INCOME			
ARC Centre Grant	$ 4,884,868	$ 4,884,868	$ 5,169,455
Institutional cash contribution	$ 1,114,000	$ 1,220,365	$ 1,152,500
Other income		$ 175,939	
Total Income	$ 5,998,868	$ 6,281,172	$ 6,321,955
EXPENDITURE			
Salaries & scholarships	$ 4,987,707	$ 4,941,768	$ 6,000,686
Equipment	$ 376,498	$ 269,135	$ 435,783
Travel, Meetings, Workshops	$ 907,500	$ 914,101	$ 1,629,547
Research maintenance and consumables	$ 766,269	$ 374,776	$ 381,698
Outreach, operations and other expenditure	$ 262,588	$ 297,209	$ 686,966
Total Expenditure	$ 7,300,562	$ 6,796,989	$ 9,134,681
Carry-forward from previous year	$ 6,997,742	$ 6,997,742	$ 6,481,926
BALANCE	$ 5,696,048	$ 6,481,926	$ 3,669,199

Installation of torsion bars, a major upgrade in the commissioning of the TorPeDO detector at the Centre for Gravitational Astrophysics (CGA), ANU. Credit: Avanish Kulur Ramamohan, OzGrav-ANU.

GOVERNANCE

The OzGrav Executive Committee oversees the management, operations, and performance of the Centre across the six collaborating research nodes. Led by the Centre Director, the Centre Executive Committee comprises representation from each node. The Executive receives advice from six OzGrav committees; the Governance Advisory Committee, Scientific Advisory Committee, Research Translation Committee, Professional Development Committee, Early Career Researcher Committee, and Equity and Diversity Committee.

Day-to-day operational matters are managed by the core administrative team, led by the Chief Operating Officer, in consultation with the Centre Directorate (comprising the Centre Director, Deputy Director, and Chief Operating Officer).

The Centre's Governance Advisory Committee includes prominent representatives from Australian education, research, engineering and business sectors. This committee advises on OzGrav's strategic direction, governance and fiscal management, structure and operating principles, performance against Centre objectives, and intellectual property and commercialisation management.

The role of the OzGrav Scientific Advisory Committee is to provide the Centre with independent scientific expertise, advice, and experience from established national centres and leading international laboratories regarding the OzGrav research program.

The Research Translation Committee identifies and manages commercialisable technologies developed under the Centre, and advises on strategies and initiatives to support industry engagement and technology transfer.

The Professional Development Committee identifies and advises on career development and training opportunities to equip our members with a broad range of translatable skills. The committee is also responsible for developing and overseeing the Centre mentoring program.

The Equity and Diversity Committee oversees the development and implementation of strategies to enable positive and supporting work environments for all our members, and to promote equity and diversity. The committee has developed an equity and diversity action plan, and regularly reviews and monitors the Centre's performance against the plan.

The Centre makes excellent use of videoconferencing to facilitate communications and collaboration among our dispersed team and committees. Our weekly centre-wide videoconferences have helped galvanise the Centre. These meetings are attended by as many as 100 people each week and give members an opportunity to discuss science and share general updates.

Chief Investigators, Associate Investigators, postdoctoral researchers, students and professional staff are included by Theme earlier in this report. For a full list see our website www.ozgrav.org.au.

OzGrav Executive Committee

Prof Matthew Bailes - OzGrav Director
Swinburne University of Technology

Prof David McClelland - OzGrav Deputy Director
Australian National University

Prof David Blair - Outreach Leader
University of Western Australia

Prof Rob Evans - Research Translation Leader
Australian National University

Dr Yeshe Fenner
OzGrav Chief Operating Officer (COO)
Swinburne University of Technology

Prof Jarrod Hurley
Swinburne University of Technology

Prof Andrew Melatos
University of Melbourne

Prof Tara Murphy (observer)
University of Sydney

Prof Susan Scott - Career Development Leader
Australian National University

Prof Eric Thrane
Monash University

Prof Peter Veitch
University of Adelaide

A/Prof Chunnong Zhao
University of Western Australia

Early Career Researcher Committee

Kyla Adams
University of Western Australia

Chayan Chatterjee
University of Western Australia

Dougal Dobie
Swinburne University of Technology

Pratyasha Gitika
Swinburne University of Technology

Zac Holmes
University of Adelaide

Disha Kapasi
Australian National University

Christine Yi Shuen Lee
University of Melbourne

Credit: Carl Knox, OzGrav-Swinburne

Dr Dan Brown (University of Adelaide) gives a LIGO talk at OzGrav's Winter School in Adelaide. Credit: Lisa Horsley, OzGrav-Swinburne

Credit: Carl Knox, OzGrav-Swinburne

GOVERNANCE

Partner Investigators

Prof Rana Adhikari
California Institute of Technology - Caltech

Dr Douglas Bock
CSIRO

Dr Marica Branchesi
Urbino University

Prof Rong-Gen Cai
Kavli Institute for Theoretical Physics (China)

Dr Brad Cenko
NASA Goddard Space Flight Centre

Prof Karsten Danzmann
Max Plank (Einstein) Institute for Gravitational Physics

Prof Michèle Heurs
Liebniz University Hannover

Dr George Hobbs
CSIRO and Australia Telescope National Facility - ATNF

A/Prof Mansi Kasliwal
California Institute of Technology - Caltech

Prof Michael Kramer
Max Planck Institute for Radio Astronomy and University of Manchester

Prof Shrinivas Kulkarni
California Institute of Technology - Caltech

Prof Nergis Mavalvala
Massachusetts Institute of Technology - MIT

Dr David Reitze
LIGO and University of Florida

Prof Sheila Rowan
University of Glasgow

Dr David Shoemaker
MIT Kavli Institute for Astrophysics and Space Research

Reader Danny Steeghs
University of Warwick

Dr Stephen Taylor
California Institute of Technology - Caltech

Prof Alan Weinstein
California Institute of Technology - Caltech

Governance Advisory Committee

Prof Ian Young AO - Chair
Kernot Professor of Engineering at the University of Melbourne, Chief Executive with Conviro Pty Ltd and President, Cloud Campus Pty Ltd.

Prof Matthew Bailes
OzGrav Director, Swinburne University of Technology

Dr Gregory Clark
Visiting Fellow, Australian National University

Prof Tamara Davis
Vice-Chancellor of Research and Teaching Fellow, University of Queensland

Dr Yeshe Fenner
OzGrav COO, Swinburne University of Technology

Prof Mark Hargreaves
Pro Vice Chancellor Research Partnerships and Infrastructure, University of Melbourne

Dr Tanya Hill
Senior Curator, Melbourne Planetarium, Museum Victoria

Prof Karen Hapgood
Deputy Vice-Chancellor (Research), Swinburne University of Technology

Dr Chiara Mingarelli
Flatiron Institute's Center for Computational Astrophysics

Dr John O'Sullivan
CSIRO

Dr Sarah Pearce
Director, SKA-Low Telescope

Scientific Advisory Committee

Prof Stanley Whitcomb – Chair
LIGO, American Physical Society (APS) and Optical Society (OSA)

Dr Stuart Anderson
Research Manager - LIGO, California Institute of Technology

Prof Matthew Evans
Principal Investigator, MIT and LIGO

Prof Stefan Hild
Professor of Experimental Physics, Maastricht University

Prof Selma E de Mink
Scientific Director, Max Planck Institute for Astrophysics, Germany

Dr Jocelyn Read
Assistant Professor of Physics, California State University

Research Translation Committee

Prof Rob Evans - Chair
Research School of Electrical and Electronic Engineering
University of Melbourne

Dr Carl Blair
Postdoctoral Researcher, University of Western Australia

Dr Yeshe Fenner
OzGrav COO, Swinburne University of Technology

A/Prof Duncan Galloway
Chief Investigator, Monash University

Dr Doris Grosse
Instrument Scientist, ANU Institute for Space

Dr Aaron Goodwin-Jones
Research Associate, University of Western Australia

Dr James Murray
Director of Operations, Astronomy Australia Ltd (AAL)

Dr Sebastian Ng
Research Associate at University of Adelaide, and Laser Physicist at QuantX Labs

Dr Joe O'Leary
Postdoctoral Researcher, University of Melbourne

Dr Andrew Sutton
ANU Alumni

James Wilson
CEO, Eliiza Data Science

Equity and Diversity Committee

Prof Matthew Bailes - Chair
Swinburne University of Technology

Scarlett Abramson
University of Melbourne

Dr Katie Auchettl
University of Melbourne

Dr Andrew Cameron
Swinburne University of Technology

Dr Yeshe Fenner
Swinburne University of Technology

Dr Kelly Gourdji
Swinburne University of Technology

Dr Eric Howell
University of Western Australia

Lucy Strang
University of Melbourne

Prof Eric Thrane
Monash University

Professional Development Committee

Prof Susan Scott - Chair
Australian National University

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Prof Tamara Davis (University of Queensland) gives a talk at OzGrav's ECR Workshop and Annual Retreat in Canberra. Credit: Carl Knox, OzGrav-Swinburne

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