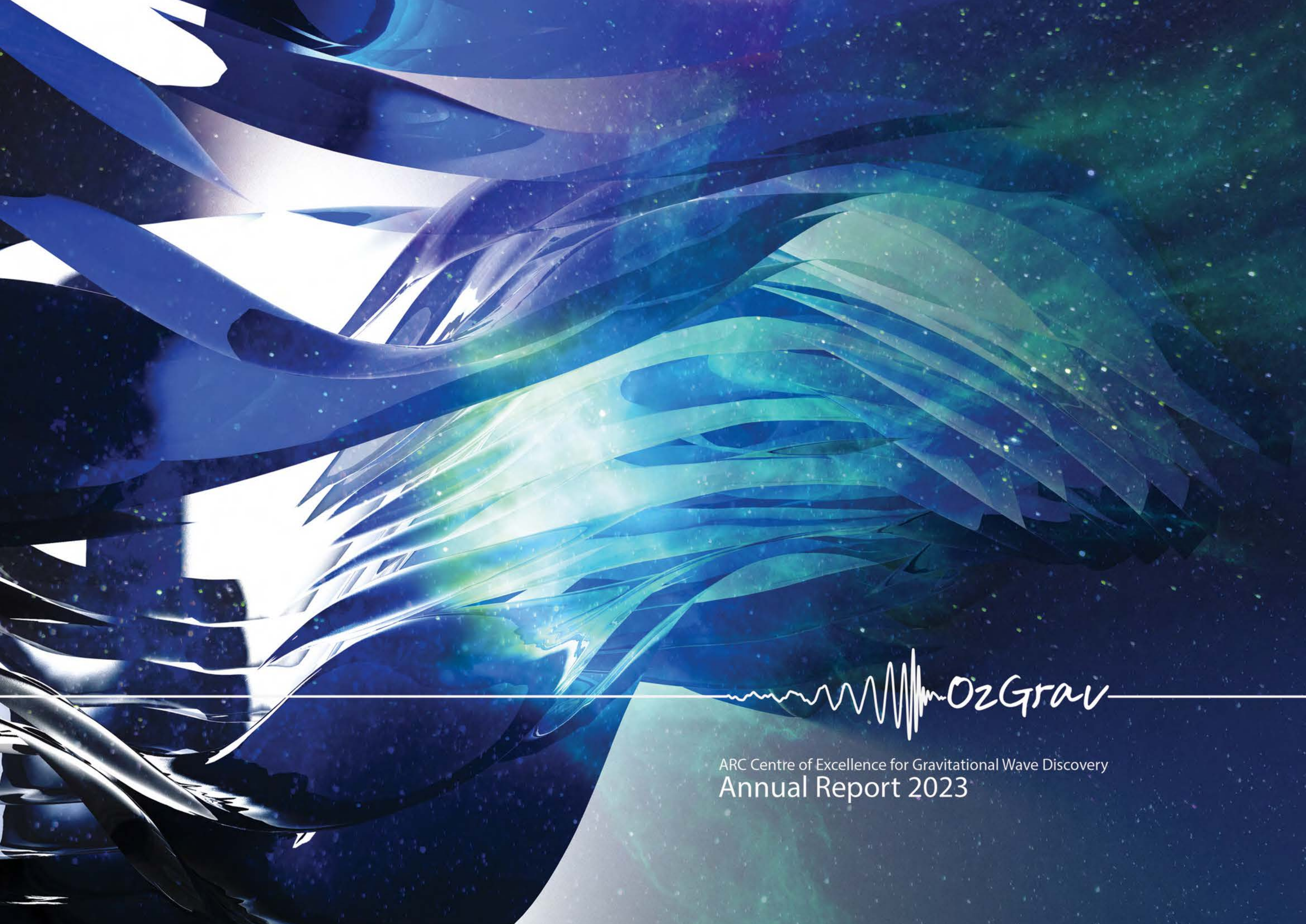

OzGrav

ARC Centre of Excellence for Gravitational Wave Discovery

Annual Report 2023

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.

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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

The last seven years have been an amazing journey of scientific discovery. When OzGrav was first conceived, the first gravitational wave to be detected was still on its way to Earth, and mainly due to hard work but also a little luck it boomed into the LIGO detector in September 2015 and was announced to the world just prior to the interviews for the 2017 Centres of Excellence. The stroke of good fortune undoubtedly influenced the selection committee, but we'd assembled a great team ready to capitalise on the fertile ground that lay before us, and were awarded a 2017 Australian Research Council Centre of Excellence to pursue the discovery of gravitational waves.

2017 was a heady year, with a flurry of discoveries in August including the only gravitational wave event to possess an optical counterpart, GW170817. Two neutron stars had annihilated each other in a dramatic coalescence and sent a burst of gamma-rays that arrived within 2 seconds of the completion of the merger. These early discoveries soon led to the awarding of the Nobel Prize in physics to LIGO's early leaders, and motivated our teams to further push technology to increase our detection rates.

Today well over 100 gravitational wave discoveries have been made, and OzGrav has been contributing all the way from mirror stabilisation, mirror fault detection, quantum squeezing, detection pipelines, analysis and theory. LIGO's latest run (O4) is shaping up to be the most successful yet.

It's been an honour to have led the OzGrav team over the past seven years and become embedded in this nascent community. Many of our staff and students have gone onto prestigious positions both overseas and in Australia, and OzGrav now has over 30 members. Our work has been cited over 68,000 times, and OzGrav has produced almost 900 refereed publications.

The spirit that permeates through OzGrav is most easily recognised at the annual retreats, with the 2023 edition held in the city of Adelaide last November. The conference dinner was very special for me, having just returned from the Shaw Prize ceremony in Hong Kong and watching the genuine warmth expressed by our members as the first ever OzGrav awards were handed out to many of our talented scientists and support staff.

I wanted to finally express my gratitude to all of the members of OzGrav for their hard work over the past 7 years, especially to our Chief Operating Officer Dr Yeshe Fenner and her admin team both at Swinburne and the nodes.

It came as no surprise to me when the ARC announced that there will be a second OzGrav, both because of the foundation laid down by this centre of excellence, but also the work done by the Chief Investigators on the bid for the next CoE which begins in April 2024. I'm honoured to be able to lead the next scientific adventure and look forward to the next 7 years of discovery.

Yours sincerely,

Prof Matthew Bailes
OzGrav Director
Swinburne University of Technology

MESSAGE FROM THE CHAIRS

Governance Advisory Committee (GAC)

Congratulations to the ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav) on a very impressive array of accomplishments in 2023. Since the Centre began in 2017, there has been continued growth in its membership, publication outputs, and the impact of its science on students and the public. OzGrav's success can partly be measured by its Key Performance Indicators on pages 82-83, and I am pleased to note that the Centre was able to meet or exceed almost all targets, despite having set ambitious stretched goals.

OzGrav has been instrumental in seeding projects that leverage its technologies and expertise to address real-world problems. As you may read in this report, some of the most recent successful research translation efforts have focused on sustainability, with one student-led project investigating the use of lasers for weed control, and another postdoc-led project developing a renewable energy microgrid to power an Australian gravitational wave test lab. Additionally, OzGrav's collaboration with industry and other Centres of Excellence in organizing a hackathon to solve pressing societal and environmental challenges is commendable.

It is heartening to see that equity, diversity and inclusion initiatives have been a significant focus throughout the year and at the retreat. While there is some way to go before achieving the desired gender balance in the Centre, it is pleasing to see steady year-on-year improvements, with the fraction of the Centre who were women or gender diverse reaching 32% in 2023.
In 2023, the Centre has held another successful Winter School, following the positive reception of the inaugural event in 2022. Well done to those Early Career Researchers who designed the program for the Winter School and also for the annual ECR Workshop, which are both vital components of the OzGrav career development program. It is also wonderful that the ECRs are getting involved in the wide array of outreach events that are showcased in this report, as it is important that school children learn from inspiring role models in whose footsteps they may choose to follow.

In the seventh and final year of operations, it was fitting that OzGrav launched its inaugural Achievement Awards to recognise the contributions of its members over the lifetime of the Centre in areas ranging from scientific accomplishments to, equity and diversity, research translation, outreach, mentoring and collaboration. Congratulations to those award winners, and to those who received competitive external awards for their exceptional work.

With OzGrav about to commence its second iteration with another seven years of funding from the ARC, we look forward to a bright future for the gravitational wave community.

Sincerely,
Professor Ian Young AO

Scientific Advisory Committee (SAC)

The scientific progress and international impact made by OzGrav researchers in 2023 has been outstanding. With the LIGO-Virgo-KAGRA detectors coming back online in 2023 following upgrades, the observations flowed fast and provided a wealth of data for the Centre to investigate. OzGrav made very significant contributions to these upgrades and the commissioning of the detectors. As described on pages 42-43, five OzGrav researchers spent significant time at the LIGO observatories and in remote control rooms in Australia preparing the detectors for the 4th observing run.

The Centre's scholarly output was substantial, with 184 peer-reviewed publications, of which 40% were led by an OzGrav student or postdoc and in high-impact journals. The impact of the Centre's research is reflected by OzGrav publications having been cited almost 70,000 times since the Centre's commencement in 2017.

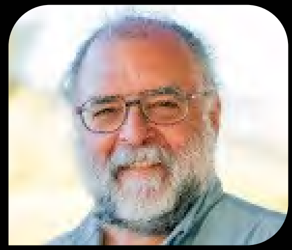
OzGrav also made waves in the media landscape, with its scientists and research being the subject of over 2700 articles across various platforms. One of the biggest news stories of the year was the announcement that the pulsar timing community had found its strongest evidence yet for low-frequency gravitational waves emitted by supermassive black holes at the center of galaxies.

It was also pleasing to see the progress made on planning for a future detector in Australia, as described on page 51. Australia has many advantages that make it an ideal site for a next-generation detector to join the international network, including seismic stability, geographically isolated locations, and a strong track record building and operating landmark astronomy infrastructure.

During OzGrav's first seven years, the Australian gravitational wave sector has seen impressive growth in both scale and prominence. The Centre's scientific contributions are commendable, and its role in nurturing a new generation of researchers is making its mark globally. With a new seven-year grant, OzGrav will generate more discoveries, lay the foundations for an Australian gravitational wave observatory, and position Australia for a world-wide leadership role in gravitational wave science and instrumentation.

Finally, I would like to congratulate OzGrav Director Matthew Bailes as co-winner of the prestigious Shaw Prize for Astronomy for discovering Fast Radio Bursts. Well deserved!

Sincerely,
Prof Stanley Whitcomb



CENTRE SNAPSHOT

184 PUBLICATIONS IN PEER REVIEWED JOURNALS

72 (39%) PAPERS WITH OZGRAV STUDENTS/POSTDOCS AS FIRST AUTHORS

68,174 CUMULATIVE CITATIONS

80 CONFERENCE PRESENTATIONS

2770 MEDIA ARTICLES & INTERVIEWS

246 SCHOOLS

8851 STUDENTS

741 TEACHERS

44 EVENTS, WORKSHOPS & TALKS FOR THE GENERAL PUBLIC

24,092 MEMBERS OF PUBLIC ENGAGED WITH

6.8 BILLION POTENTIAL MEDIA REACH

AFFILIATES 62

POSTDOCTORAL RESEARCHERS 39

ASSOCIATE INVESTIGATORS 33

PARTNER INVESTIGATORS 18

CHIEF INVESTIGATORS 22

MEMBERS 301

PHD RESEARCHERS 62

MASTERS STUDENTS 20

HONOURS STUDENTS 8

UNDERGRADUATE STUDENTS 9

PROFESSIONAL AND TECHNICAL STAFF 28

Australian astronomers find possible 'fingerprints' of gravitational waves

Astronomers using data collected by CSIRO's Parkes radio telescope, Murriyang, have found their strongest evidence yet for low-frequency gravitational waves.

For nearly 20 years the Parkes Pulsar Timing Array collaboration has monitored a set of rapidly spinning stars that pulse like a lighthouse, called pulsars.

They are looking for nanosecond pulse delays caused by gravitational waves to provide further evidence for Einstein's general theory of relativity and build on our understanding of the Universe.

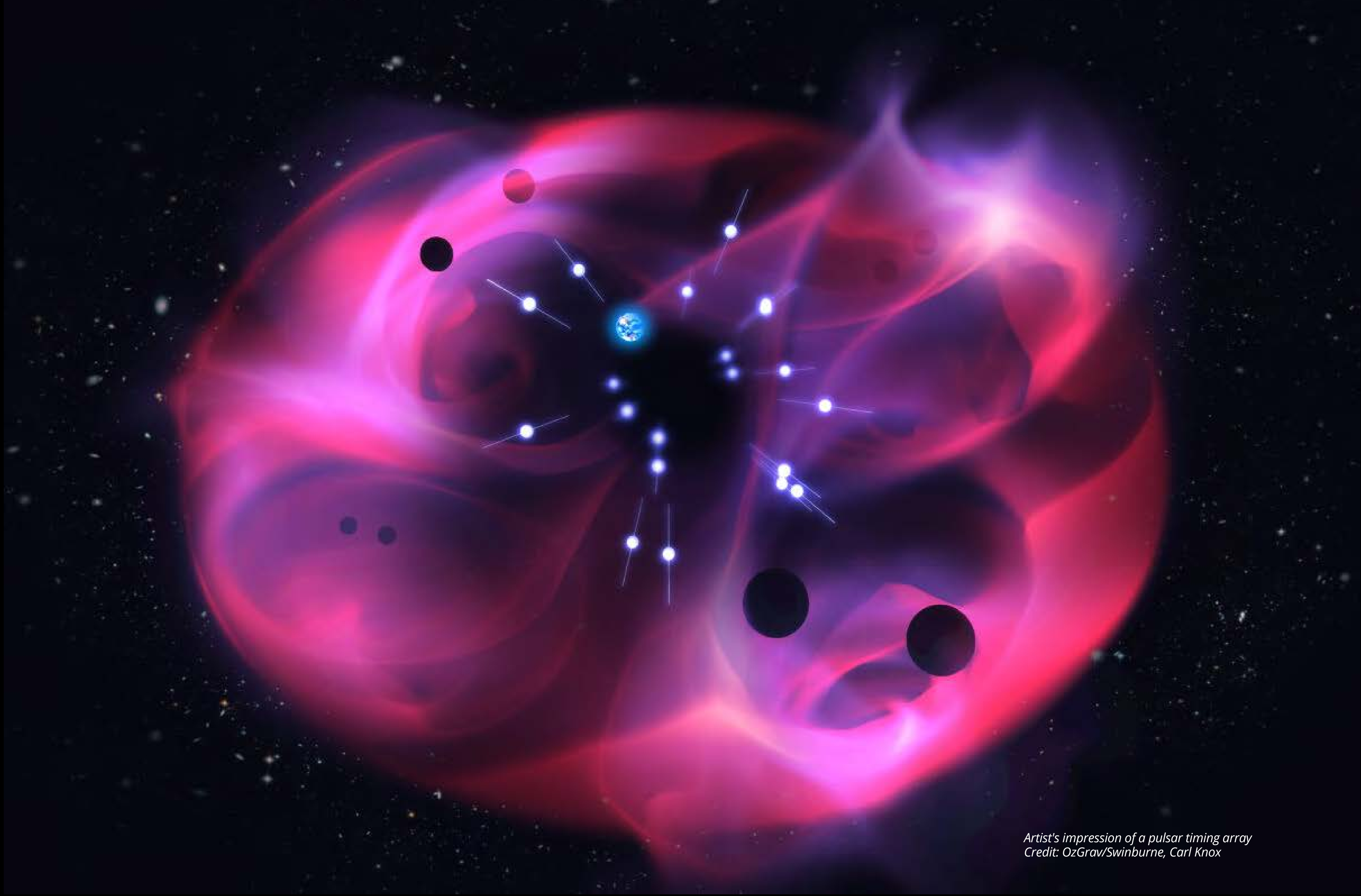
By compiling and analysing this large data set, the team has taken another step towards detecting gravitational waves through the study of pulsars.

Their latest results were published in *The Astrophysical Journal Letters and Publications of the Astronomical Society of Australia.*

In 1916 Albert Einstein proposed space-time as a four-dimensional fabric, and that events such as exploding stars and merging black holes create ripples – or gravitational waves – in this fabric.

Almost a century later, in 2015, researchers from the LIGO and Virgo collaborations made the first direct observation of gravitational waves caused by the collision of two stellar-mass black holes.

In contrast to these gravitational waves, which oscillate multiple times per second, the Parkes Pulsar Timing Array collaboration is searching for gravitational waves emitted by binary supermassive black holes at the centres of galaxies. These gravitational waves oscillate over timescales of many years.



Artist's impression of a pulsar timing array
Credit: OzGrav/Swinburne, Carl Knox

OzGrav and Swinburne University of Technology researcher Dr Daniel Reardon, who led the searches, said that as these gravitational waves pass through our galaxy and wash over the Earth, they will change the apparent rotation frequency of fast-spinning pulsars.

"We can detect gravitational waves by searching for pulses that arrive earlier or later than we expect. Previous studies have shown an intriguing signal in pulsar timing array observations, but its origin was unknown," Dr Reardon said.

"Our latest research has found a similar signal among the set of pulsars we've been studying, and we now see a hint of the fingerprint that identifies this signal as gravitational waves.

"Unlike stellar-mass bursts of gravitational waves, supermassive black holes take years or decades to complete their orbits, and so their signature takes a decade or more to emerge," he said.

Astronomers around the globe have been busy chasing this gravitational-wave signal by studying pulsars. Other collaborations in China (CPTA),Europe (EPTA), India (InPTA) and North America(NANOGrav) see a similar signal in their data; their results are also published today in several journal papers.

CSIRO astronomer Dr Andrew Zic, who co-led the analysis, said that while it is exciting all the major collaborations are seeing hints of the waves the true test will come in the near future, when all of the data is combinedinto a global dataset.

"This signal could still be caused by things like variations in a pulsar's rotation over a long period of time, or may simply be a statistical fluke," Dr Zic said.

Our Parkes radio telescope, Murriyang, has an advanced receiver and an excellent view of the best pulsars in the southern sky, which are essential for this work.

"The next step is to combine pulsar data sets collected by telescopes in both the northern and southern hemispheres to improve the sensitivity of our observations," he said.

Through the InternationalPulsar Timing Array consortium, theindividual groups around the globe – including the Parkes Pulsar Timing Array collaboration in Australia – are working together to combine their data to better characterise the signal and confirm its origin.

The next stage of our research will combine the full power of the global array, and rule out any anomalies." said Dr Zic.

Using pulsars to confirm the detection of low-frequency gravitational waves will expand this emerging area of science, to be explored further by new instruments including the SKA telescopes currently being built in Australia and South Africa.

This is an edited extract from the original media release.

The Parkes Pulsar Timing Array project is a combined effort from astronomers across several institutions in which pulsars are observed using CSIRO's Parkes Radio Telescope, Murriyang.

CSIRO's Parkes radio telescope, Murriyang, is part of the Australia Telescope National Facility, which is funded by the Australian Government for operation as a National Facility managed by CSIRO – Australia's national science agency. We acknowledge the Wiradjuri People as the Traditional Owners of the Parkes Observatory site.

SCIENCE HIGHLIGHTS

Scientists get closer to solving one of the greatest mysteries in astronomy: fast radio bursts

A new collaborative study involving Australian researchers from the ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav) promises new insights on the origin of a class of radio pulses called Fast Radio Bursts (FRBs). These bursts, so bright that astronomers can see them from billions of light years away, have been studied for over a decade. However, the origin of FRBs remains one of the greatest mysteries in astronomy today.

Australia has played a key role in the discovery and study of FRBs. Now, in this landmark study, researchers are approaching the problem in a new way, looking for the presence of ripples in the curvature of space and time (called gravitational waves) that could be associated with the radio emissions.

This recent international study has focused on the FRB models that could also produce emissions in gravitational waves. Associating a gravitational wave signal with an FRB could provide startling new evidence on the forces driving FRBs.

Scientists who conducted the study were provided with data from 800 fast radio bursts from a Canadian telescope called CHIME. OzGrav Associate Investigator Eric Howell (from the University of Western Australia) initiated the search with scientists from the LIGO (USA) and Virgo (Italy) collaborations.

There are many scientific models that predict FRBs - over 50 have been published. Some models suggest a cataclysmic origin for FRBs; this means that the bursts could result from explosive astronomical events such as supernovae that signal the death of a massive star, or from violent collisions of dead stars such as black-holes or neutron stars.

Other models suggest that FRBs could be the occasional outbursts from a more stable source, such as a neutron star – these are termed stable or persistent as they could repeat over time. A small proportion of FRBs have been observed to repeat but scientists still don't know if this applies to all of them. Currently, FRBs are labeled as 'repeaters' or 'non-repeaters'.

FRB models that could also produce gravitational waves include well-predicted signals such as colliding pairs of neutron stars and black-hole neutron stars.

"We know we can detect these types of gravitational wave signals to fairly well known distances" says Howell. "If we have an idea of the maximum FRB distance and it's within our gravitational wave range, we should be able to make a detection or rule out a particular source."

The search also looked for generic bursts of gravitational waves that could occur from less understood sources; these could be chaotic pulses or 'bursts' of gravitational wave energy.

These emissions could be the outbursts of neutron stars or from some other exotic phenomena.

OzGrav PhD student Teresa Slaven-Blair (UWA), who played a role in the analysis for the resulting paper, says that "by searching for gravitational waves around the time and sky position of each FRB, we can improve the sensitivity of the search and go deeper".

"This study is a vital stepping stone in understanding fast radio bursts (FRBs) - we are not able to rule out any gravitational wave association yet, but future observation runs at higher sensitivity may be able to capture more FRBs," says Howell.

This study is another example of how gravitational wave astronomy is playing an increasingly important role in our understanding of the cosmos. Making use of distortions in space and time to probe exotic phenomena, such as fast radio bursts, is real next generation astronomy.

This paper, "Search for Gravitational Waves Associated with Fast Radio Bursts Detected by CHIME/FRB during the LIGO–Virgo Observing Run O3a," was published in the Astrophysics Journal on September 28, 2023. It featured as an article, "A search for links between two of the universe's most spectacular phenomena has come up empty – for now," in The Conversation.

Background image by Carl Knox, OzGrav-Swinburne

"Never witnessed before" – Astronomers baffled by repeat explosions 100 billion times the energy of the Sun

Astronomers are baffled by a mysterious and extremely bright event in the distant Universe, nicknamed the "Tasmanian Devil", which has been observed to explode repeatedly and emit more energy than hundreds of billions of stars like our Sun.

The report, published in Nature, describes a Luminous Fast Blue Optical Transient (LFBOT) monitored in a new way and shown to have unusual behaviour. LFBOTs are rare, extremely powerful events – more powerful than a supernova – that evolve on timescales of just a few days, fading away rapidly. However, this LFBOT continued to explode with supernova-like energies many times, well after its initial burst and fade.

"An event like this has never been witnessed before," said co-author of the paper Professor Jeff Cooke from Swinburne University of Technology and the ARC Centre of Excellence in Gravitational Wave Discovery (OzGrav). He led observations using the W. M. Keck Observatory in Hawaii as part of this work.

When LFBOTs explode, "they emit more energy than an entire galaxy of hundreds of billions of stars like the Sun. The mechanism behind this massive amount of energy is currently unknown," Professor Cooke said.

But in this case, after the initial burst and fade, the extreme explosions just kept happening, occurring very fast – over minutes, rather than weeks to months, as is the case for supernovae."

"Amazingly, instead of fading steadily as one would expect, the source briefly brightened again, and again, and again," Cornell University Assistant Professor Anna Ho, lead author on the paper said.

"LFBOTs are already a kind of weird, exotic event, so this was even weirder," Assistant Professor Ho said. Data from the multiple observatories, including one with a high-speed camera, detected at least 14 irregular and highly-energetic bursts over a 120-day period. "However, these bursts are likely only a fraction of the total number", Assistant Professor Ho said.

The LFBOT event, which occurred on 7 September 2022, is puzzling according to Professor Cooke. "It pushes the limits of physics because of its extreme energy production, but also because of the short duration bursts. Light travels at a finite speed. As such, how fast a source can burst and fade away limits the size of a source, meaning that all this energy is being generated from a relatively small source."

The current theory is that a black hole or neutron star formed by the initial explosion is accreting an immense amount of matter and causing the subsequent intense bursts.

The W.M. Keck Observatory observations were part of a larger program of 15 observatories around the world used to monitor this LFBOT, with the Keck visual wavelength observations coordinated to occur simultaneously with X-ray observations taken by the NASA Chandra Space Telescope.

"These are important to help understand the nature of this source, how these massive stars transition during their death process, and to help find more events to understand how common they are in the Universe," Professor Cooke said.

Swinburne recently joined the W. M. Keck Observatory as a scientific partner, doubling the number of observing nights for researchers and providing Swinburne with a vote in setting science and technology priorities for the Observatory. This is the first Keck partnership of its kind with an institution outside the United States.

This paper, "Mysterious 'Tasmanian devil' space explosion baffles astronomers," was published in Nature on November 15, 2023.

Background image: This is an artist's concept of one of brightest explosions ever seen in space. Called a Luminous Fast Blue Optical Transient (LFBOT)
***Artwork:** NASA, ESA, NSF's NOIRLab, Mark Garlick , Mahdi Zamani*

SCIENTIST ANALYSE BRIGHTEST GAMMA-RAY BURST EVER DETECTED

In October 2022, a dying star released a giant gamma-ray burst, directed right towards Earth.

The burst – now called GRB 221009A – is the brightest in thousands of years, and has allowed astronomers a once in 10,000 year chance to study this astronomical phenomenon.

“The exceptional brightness of this gamma-ray burst meant astronomers were able to study it in unprecedented detail in real-time as the light arrived from that distant galaxy,” says University of Sydney astrophysicist James Leung.

“This gave us a golden opportunity to test intricate physical models that describe what happens before, during and after the death of a star.”

Two new sets of papers – one by NASA and another from an international team, analysed the gamma-ray burst in great detail, finding that the burst was 70 times brighter than any seen before.

GRB 221009A’s signal was traveling for about 1.9 billion years before we could see it from Earth. This makes it among the closest-known ‘long’ gamma-ray bursts. Long in this case meaning lasting longer than two seconds, while GRB 221009A lasted a whopping 10 hours.

Astronomers think these bursts are a type of black hole ‘cry’ which form when a huge star collapses. As it quickly ingests the surrounding matter, the black hole blasts out jets in opposite directions containing particles accelerated to near the speed of light.

Images captured over 12 days by the X-ray Telescope aboard NASA’s Neil Gehrels Swift Observatory were combined to make this movie, shown here in arbitrary colors. Credit: NASA/Swift/A. Beardmore (University of Leicester)

Oxford and Sydney University researchers – looked at the ‘reverse shock’ after the initial blast. This is the implosion that occurs at the same time as the explosion. They could map this reverse shock in ‘unprecedented detail’ for variables such as time, length, size, and energy.

“Our observations provide unmatched insights into the reverse shock model for gamma-ray burst emission, showing it is very difficult for existing models to replicate the slow evolution of the energy peaks that we observed,” said Leung.

Images captured over 12 days by the X-ray Telescope aboard NASA’s Neil Gehrels Swift Observatory were combined, shown here in arbitrary colours.
Credit: NASA/Swift/A. Beardmore (University of Leicester)

“This means we have to refine and develop new theoretical models to understand these most extreme explosions in the Universe.”

The NASA research looked at a number of other parts of the burst, but one in particular highlights an interesting question – where is the supernova?

After an explosion like this, researchers expect to see a supernova which brightens over the first couple of weeks.

However, this hasn’t yet happened.

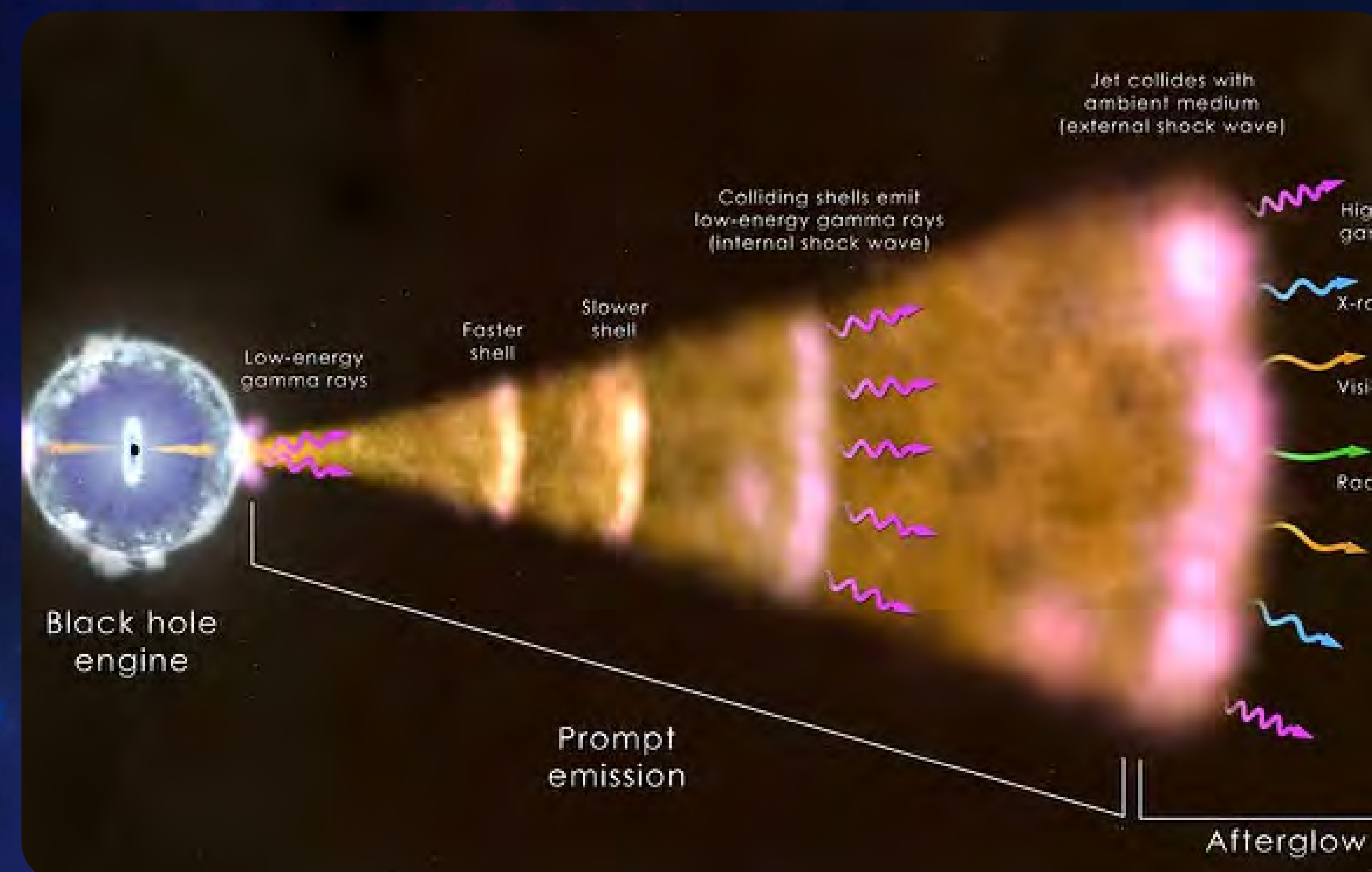
“We cannot say conclusively that there is a supernova, which is surprising given the burst’s brightness,” said Andrew Levan, a professor of astrophysics at Radboud University in Nijmegen, Netherlands. “If it’s there, it’s very faint. We plan to keep looking, but it’s possible the entire star collapsed straight into the black hole instead of exploding.”

This could be because of where the gamma-ray burst happened, as thick dust clouds are in the area and could obscure the view of any light from a supernova.
The team is planning to take more Webb and Hubble observations in infrared over the next few months to check.

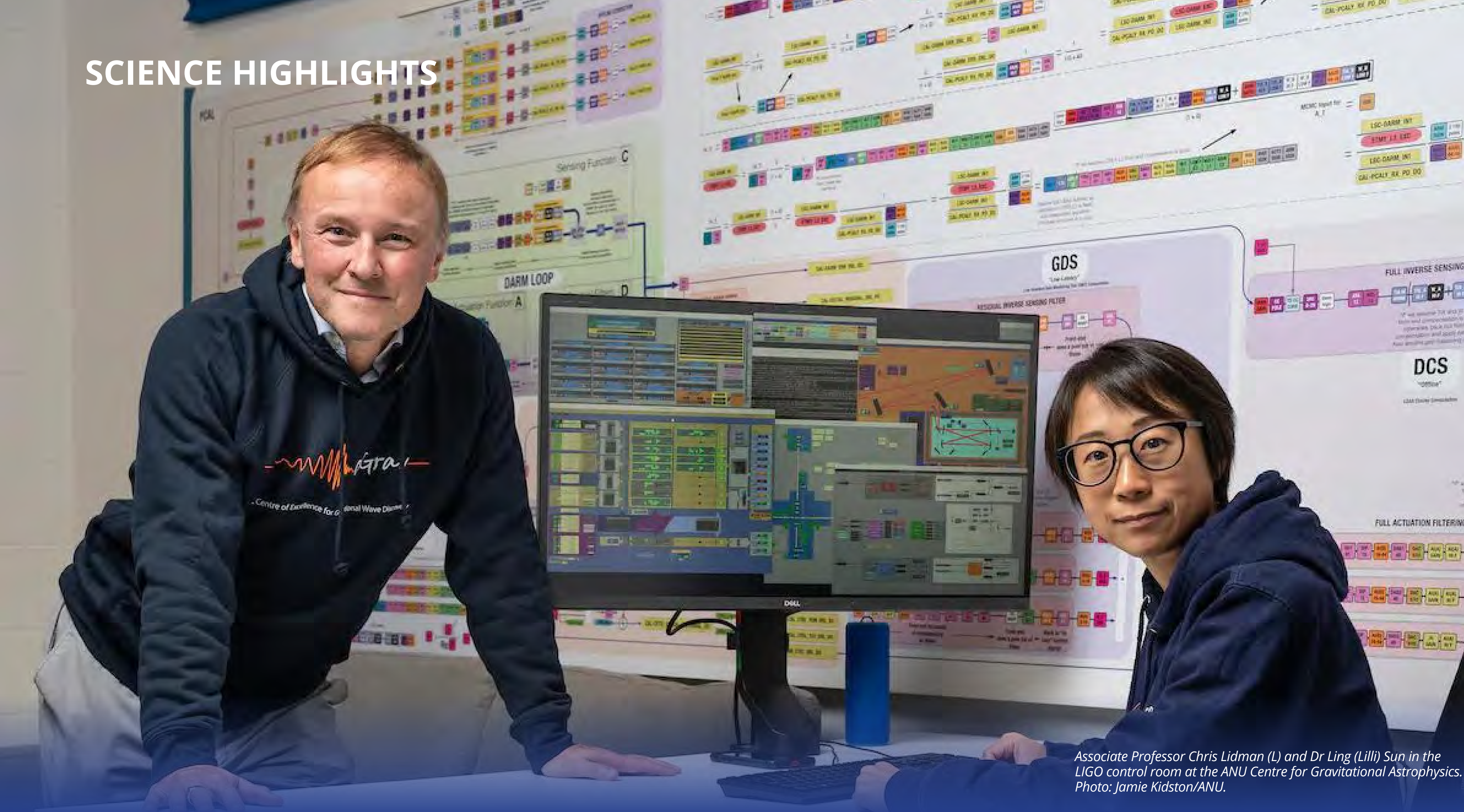
With such a rare and well captured gamma-ray burst, there’s likely to be much more science we can learn about over the next few years.

The international research is available on preprint server arXiv and has been submitted for publication in Nature Astronomy. The NASA research is part of a focus issue in the The Astrophysical Journal Letters.

Originally published by Cosmos as Scientists analyse brightest gamma ray burst ever detected.



The core of a massive star (left) has collapsed, forming a black hole that sends a jet of particles moving through the collapsing star and out into space at nearly the speed of light. Radiation across the spectrum arises from hot ionised gas (plasma) in the vicinity of the newborn black hole, collisions among shells of fast-moving gas within the jet (internal shock waves), and from the leading edge of the jet as it sweeps up and interacts with its surroundings (external shock). Credit: NASA’s Goddard Space Flight Center



Associate Professor Chris Lidman (L) and Dr Ling (Lilli) Sun in the LIGO control room at the ANU Centre for Gravitational Astrophysics. Photo: Jamie Kidston/ANU.

New OzGrav remote control facilities to boost the hunt for gravitational waves

A new facility at The Australian National University (ANU) will help scientists detect some of the most extreme events in the universe and put Australia "front and centre" of the exciting field of gravitational wave science.

Gravitational waves are ripples in space and time, but they are weak and extremely hard to detect. It needs the cataclysmic collapse of a massive star or the merger of two extremely compact objects such as black holes or neutron stars for the waves to be detected on Earth.

When detected, these waves allow scientists to study some of the most hidden secrets of our universe, such as the moment the cores of massive stars collapse and the permanent distortion of space-time.

The new facility will act as a remote control room for Laser Interferometer Gravitational wave Observatory (LIGO) in the United States (US) – one of the leading gravitational wave observatories on the planet — and play a major role in the latest global observing run, commencing today.

The LIGO remote control room is based at the Centre for Gravitational Astrophysics (CGA), the ANU node of the Australian Research Council Centre of Excellence for Gravitational Wave Discovery (OzGrav).

Dr Bram Slagmolen from CGA said the new facility gives our scientists the ability to directly engage with the operation of the US-based gravitational wave detectors.

"This facility provides real-time information on the performance of the detectors, as well as notifications on detected events," he said. "Researchers from ANU will be front and centre in LIGO's latest observing run, helping monitor the detector, respond to any potential finds and troubleshoot any problems."

Dr Lilli Sun from CGA said: "The detectors are extremely sensitive and have to be precisely calibrated before we can correctly extract the gravitational wave signals and decode the astrophysical information.

"The ANU LIGO remote control room creates a virtual environment for us to 'sit at the detector,' monitoring and understanding the response of the detectors in real-time, which is essential to accurate and precise calibration."

The latest global observing run will also be boosted by the rejuvenated 2.3-metre telescope, based at Siding Spring Observatory, which will join the ANU SkyMapper telescope in the global follow-up campaign.

The newly automated 2.3-metre telescope can now respond to gravitational wave detections in minutes rather than hours, greatly helping our understanding of these extraordinary events. Associate Professor Chris Lidman, Director of Siding Spring Observatory, said: "Hunting gravitational waves and their optical counterparts is like finding a tiny object on the tip of the needle in a massive haystack. These new capabilities will make that task a little easier."

Dr Slagmolen said that ANU scientists have contributed to tuning the two LIGO detectors to be ready for the latest observing run. This includes efforts towards control of the quantum state of light and calibrating the detectors to high precision.

"The LIGO detectors are at their highest sensitivity yet, and we are all excited to hear what the universe has to say," he said.

Dr Sun said: "Australian universities and scientists have played a fundamental role in the hunt for gravitational waves for many years. The work we are doing here at ANU will provide a more powerful detection mode for gravitational waves than has existed ever before."

Associate Professor Lidman said: "As the national university, we are proud to play a role in making sure the world benefits from our nation's incredible talent and know-how and to also make sure Australia remains a leader in these global efforts."

Similar remote control facilities are being rolled out at five other OzGrav nodes

Dr Bram Slagmolen in the LIGO remote control room. Photo: Jamie Kidston/ANU.

RESEARCH TRANSLATION PROGRAM

Microgrid Renewable Energy Project to Revolutionize Power Stability and Research Innovation at Gingin Gravity Precinct

In a significant leap forward for renewable energy and scientific research, the University of Western Australia (UWA) Node of OzGrav has embarked on an ambitious project to develop a Renewable Energy Microgrid at the Gingin Gravity Precinct, a regional site of strategic importance in Western Australia. This project, which received crucial support from an OzGrav Research Translation Seed grant in its early stages, is spearheaded by the talented OzGrav postdoctoral researcher Dr. Aaron Goodwin-Jones.

The Gingin Gravity Precinct encompasses three distinct and internationally significant facilities: the High Optical Power research Facility (HOPF), the Zadko Observatory, and the Gravity Discovery Centre (GDC). The HOPF is pivotal to the Nobel Prize-winning field of Gravitational Wave Detection, representing one of only two sites globally capable of demonstrating gravitational wave technology at scale, away from the seismic pollution caused by urban areas. The Zadko Observatory plays a critical role in Space Situational Awareness (SSA) for Australia's NATO and Five Eyes security partners, requiring a location free from light pollution. The GDC, a not-for-profit social enterprise, is recognized by Tourism WA as a site deserving special focus, contributing significantly to tourism and education.

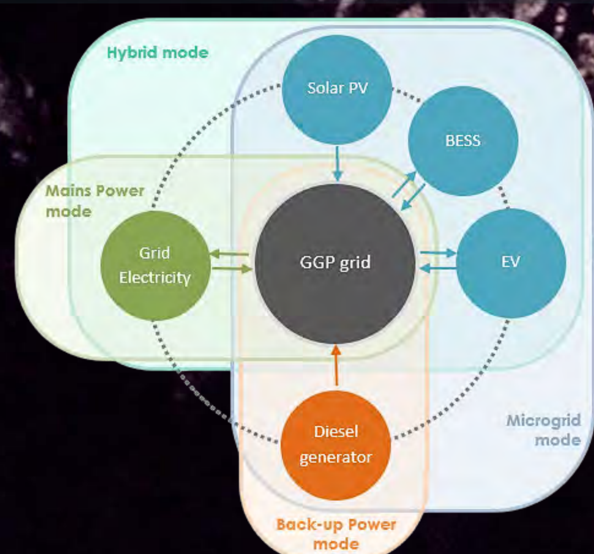
The Gingin Gravity Precinct has suffered from frequent power blackouts due to its location at the end of a long, dedicated power connection. These power interruptions not only undermine the commercial and not-for-profit functions of the site but also severely limit its research capabilities, posing a barrier to further development due to the existing grid's capacity limitations.

The Gingin Microgrid project aims to provide a secure and sustainable power solution, facilitating the precinct's growth and enhancing its contribution to scientific research and community engagement. This initiative will establish Australia's first collaborative hub focused on the strategically important field of grid-connected power electronics, addressing the technical challenge of reliable current control. By utilizing parallel and series configurations of power electronic modules, the project seeks to create grids and microgrids that are reliable, resilient, and fully integrated with advanced technologies such as battery storage systems, solar panels, electric vehicle chargers, and hydrogen electrolysers and fuel cells.

This hub will merge academic and industry expertise to translate groundbreaking research into commercial outcomes, bolstering sovereign capabilities in the design, manufacture, and control of grid-connected power electronics. The long-term benefits include enhanced power stability for critical research facilities, support for renewable energy innovations, and the promotion of sustainable practices within the scientific community and beyond.

In partnership with Magellan Power, a Western Australian leader in renewable microgrid technology, and with technical oversight provided by engineering consultancy firm GHD, the project will showcase novel inverter and battery technology developed at UWA. This collaboration will not only secure the precinct's energy needs but also provide invaluable real-life data to advance research in power and clean energy.

The Gingin microgrid will consist of a 100 kW solar array, 125 kVA Solar Inverter, 100 kVA battery inverter and 130 kWH of Battery Energy Storage System (BESS). This infrastructure will support the precinct's goal of becoming an agile research environment, contributing to UWA's energy-neutral objectives and the broader scientific and environmental communities. The team is seeking further funding from the infrastructure development from the ARENA Regional Australia Microgrid Pilot Program (RAMPP) to advance this project.



Background image credit: Aaron Goodwin-Jones, OzGrav/UWA

2023 Activities and Progress

- A major new initiative that we kicked off in 2023 was a science-meets-industry hackathon, called Better Futures Innovation Challenge, in partnership with four other STEM-focused Centres of Excellence. This deep-tech research hackathon is an exciting opportunity for our researchers to unleash their creativity, grow their networks, interact with industry mentors and partners, and tackle some exciting, industry-backed research challenges. e.g: developing an AI tool for scientific researchers; designing a game that uses or demonstrates a genuine quantum effect; building a quantum experiment on a shoestring budget. The challenges are designed to be relevant to programmers, experimentalists, theorists, observers, and data analysts. During 2023 we made significant progress including: establishing the Hackathon governance structure, securing funding, lining up our industry partners and challenges, launching our website and communications campaign, opening up registrations, and locking in the dates in 2024 to run the two-day in-person hackathon.

- We were very pleased with developments in 2023 regarding three Research Translation Seed Grants. Firstly, the renewable microgrid project concluded the Seed grant stage and is making leaps and bounds ahead, as described in previous pages. The laser weed killing project led by Zac Holmes from University of Adelaide also concluded its Seed grant stage, with promising results that the team will explore further. In addition, we awarded a new Research Seed grant to Rory Smith from Monash and collaborator Olga Panagiotopoulou for a "Rapid and optimal jaw-fracture implant design" project.

- We organised and were involved in several industry-research networking events, including an industry engagement workshop coordinated by Astronomy Australia Ltd, a session on industry careers at our retreat delivered by collaborator Gareth Kennedy from Deloitte, and an industry careers panel discussion at our annual ECR workshop.

- We were delighted with the large number of new collaborations and/or grants with industry that commenced in 2023, including: a Linkage Project grant with Quaisr and OzGrav CI Ilya Mandel (Monash), Magellan Power's involvement in the renewable microgrid project led by Aaron Goodwin-Jones, a new CRC-P with Advanced Navigation, as well as a UWA-led Linkage Project with company CGG AVIATION.

Future Plans:

- For the remainder of the CE17 OzGrav (which ends on 31 March 2024), a key focus will be seeing the science-meets-industry hackathon through to a successful conclusion. This will involve putting our participants in teams with complementary skillsets and matching them up with suitable industry challenges and running the two-day event in March 2024.

- We will also promote industry engagement by publishing technology transfer case studies on our website, social media and traditional media, and updating our industry success stories brochure.

- Looking further ahead to the new CE23 OzGrav 2.0 that begins on 1 April 2024, members of our community will develop the Research Translation strategic plan for OzGrav 2.0, building on the acheivements of OzGrav 1.0 while growing our ambitions for technology commercialisation and spin-offs.

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

BETTER FUTURES
INNOVATION CHALLENGE

EQUITY, DIVERSITY AND INCLUSION PROGRAM

Advancing Equity, Diversity and Inclusion

In 2023, OzGrav transformed our Equity, Diversity, and Inclusion (EDI) training strategy. We integrated intersectionality and psychological safety workshops, recognising that true inclusivity requires addressing structural and interpersonal aspects. This innovative approach equips leaders and team members with the knowledge and tools to foster a workplace culture that values diversity and promotes psychological safety, enabling every individual to participate fully.

Training sessions began with workshops for leaders, recognising their pivotal role in implementing and sustaining change. Research has shown that training leaders first significantly increases the likelihood of successful implementation.

Intersectionality training provides participants with a comprehensive understanding of how systems of discrimination and power intersect to shape privilege and marginalisation. Participants gain insights into their privileges and the structural dynamics influencing workplace interactions through engaging activities. This heightened awareness fosters empathy and collectively identifies areas for improvement within the Centre.

Feedback from our members underscores the effectiveness of our approach. Many found the workshops to be not only productive and meaningful but also empowering. Facilitated by individuals with lived experiences, the sessions offer practical solutions tailored to our workplace context. Attendees appreciated tools like the 'Wheel of Privilege' posters, which sparked illuminating discussions and reflections.

Psychological safety workshops focus on creating an environment conducive to open expression without judgment or reprisal. Participants learn the critical role of psychological safety in nurturing a healthy, inclusive workplace culture. Through tailored sessions for leaders and the wider team, attendees acquire skills to enhance psychological safety, fostering open communication, collaboration, and innovation.

The impact of our efforts is evident in the positive feedback received from leaders and team members alike. Attendees found the training relevant to the academic context, encouraging self-reflection and promoting a more considerate and aware environment. There is a collective appetite to deepen our understanding and application of these principles with more practical examples, indicative of our commitment to continuous improvement and inclusivity at OzGrav.

Image: Intersectionality Wheel of Priviledge Poster at University of Western Australia.

A major event in the 2023 calendar was the AIP Inclusion Breakfast, sponsored by OzGrav, at the ANU Research School of Physics. This gathering was hosted by OzGrav PhD students Emily Rose Rees and Disha Kapasi, who not only facilitated the event but also showcased OzGrav's notable EDI initiatives and achievements. The breakfast served as a forum for discussion, exchange of ideas, and networking among participants, significantly advancing our EDI objectives.

Members of OzGrav@ANU participated in the Bloody Long Walk 2023, a gruelling yet rewarding 35km challenge to raise funds and awareness for the cure of Mito disease. This reflects our dedication to contributing positively to society and supporting crucial health causes.

In recognition of RUOK Day 2023, a key date dedicated to promoting mental health awareness and suicide prevention, OzGrav@ANU hosted a morning tea. This event served as a reminder of the importance of checking in on one another, fostering a culture of care, support, and open dialogue within our community. It underscored our commitment to ensuring a supportive and mentally healthy workplace and academic environment.

EQUITY, DIVERSITY AND INCLUSION PROGRAM

HomeWard Bound Voyage

In November 2023, after several years of delays due to COVID-19, OzGrav alumni Debatri Chattopadhyay and Isobel Romero-Shaw finally travelled to Antarctica as part of the global leadership initiative Homeward Bound.

Homeward Bound is a transformative leadership program for women and non-binary people in STEM. Debatri and Isobel were initially inspired to apply for the program by OzGrav Chief Investigator Susan Scott, who spoke about her own Homeward Bound experience at the OzGrav annual retreat in Swan Valley, WA, in 2018. Another OzGrav member and Homeward Bound alumni, Lilli Sun, further encouraged them.

The impact of climate change is confronting in Antarctica. For Debatri and Isobel's trip, the entire planned itinerary had to be adjusted due to unexpected weather conditions: as well as storms and unusual wind patterns, the temperature was higher than it should have been, leading to high quantities of icebergs (broken off of long-lived glaciers due to the high temperatures) drifting into the ship's planned route. Additionally, their intended visit to South Georgia on the way to Antarctica was cancelled due to an avian influenza outbreak on the islands. The group collectively agreed that this was the right decision to avoid transferring the virus to wildlife in Antarctica.

Despite the journey being laden with unforeseen changes and challenges, it served as an exceptional opportunity to hone emergent leadership skills. Debatri and Isobel, among a group of over 100 participants, embarked on a voyage that not only facilitated networking but also provided moments for contemplation on leadership strategies and collaborative brainstorming to address social injustice and environmental issues. The vast, uninhabited wilderness became their backdrop, where they marvelled at the playful antics of whales, seals, and albatrosses in the seas, sands, and skies. Amongst the breathtaking scenery, they encountered thousands of penguins representing six different species. Additionally, Debatri and Isobel had the privilege of interacting with humans who call Antarctica home for extended periods, exploring the unique "penguin post office" at Port Lockroy and visiting the Palmer research station.

2023 Members Survey

As we embark on the transition from OzGrav 1.0 to OzGrav 2.0 in 2024, it is crucial to recognize the strides we've made and the areas where we can continue to grow. In 2023, we took proactive steps to support our members through this transition by conducting our annual Member Survey, facilitated by WISE Workplace. This survey, designed to gauge perceptions of psychological safety within the Centre, was conducted with the utmost impartiality and anonymity to encourage candid feedback from all members.

Aligned with our commitment to Equity, Diversity, and Inclusion (EDI), the survey was strategically crafted to address key cultural impact areas identified by WISE Workplace, including Inclusivity, Alignment, Trust, Wellness, and Creativity. Through this process, we aimed to achieve several objectives: advancing our EDI Action Plan, pinpointing areas for improvement, shaping training initiatives and providing a platform for meaningful contributions to our growth.

We aimed for a 75% Node response rate to ensure we had representative data. The overwhelming response to the survey—86.98%—exceeded our expectations, demonstrating a remarkable level of engagement from our members.

We were blown away by the membership engagement for this survey. Nodes met the criteria for eligibility for their Thank You Lunch funded by OzGrav HQ. Some photos of lunch can be seen on page 39 under Events & Community Highlights.

The survey revealed both areas of strength and areas for improvement within OzGrav. In terms of strengths, the survey analysis found that:

- OzGrav fosters a high level of trust among its members, contributing to a collaborative and supportive environment.
- OzGrav Managers and Executive Leaders are seen to uphold honesty and integrity, earning the trust and respect of the team.
- Managers are perceived as caring and supportive, with a significant portion of members feeling their concerns are valued and addressed.
- Members exhibit high levels of motivation, positively impacting productivity, creativity, and relationships within the workplace.
- OzGrav encourages creativity and innovation. Most OzGrav members feel confident in sharing new ideas and perceiving active promotion of innovation within the Centre.

There are areas where we can further enhance our practices, this includes:

- Increasing and expanding the methods in which OzGrav shows recognition and value of member contributions.
- Furthering transparency and fairness in allocating leadership roles and recruitment.
- Continuing the transformative strategy to increase equity and inclusion.
- Furthering to improve the clarity of expectations.
- Enhancing thorough and timely communication and conflict resolution.

These insights have been instrumental in shaping our plans for OzGrav 2.0, guiding us as we strive to build an even more inclusive, transparent, and supportive community. Together, we are poised to embrace the future with optimism and determination, leveraging our collective strengths to propel OzGrav to new heights of success, as outlined below under Future Plans.

2023 Activities and Progress:

- This year, we created the OzGrav Equity Award to recognise members who work tirelessly to create an equitable environment.
- OzGrav was honoured to be awarded a Silver Pleiades Award by the Astronomical Society of Australia, in recognition of our continued commitment to promoting equity and inclusion. The Silver Pleiades recognises organisations with a sustained record of monitoring and improving the working environment. It also recognises leadership in promoting positive actions as examples of best practice to other organisations in the astronomy community.
- OzGrav was pleased to join nine other STEM-focused Centres of Excellence to run inSTEM, a networking and career development conference for people from marginalised or underrepresented groups in STEM, and their allies. It offers attendees a safe space to meet, make connections and build relationships with other researchers and research scholars. This year's conference had a strong focus on disability, including neurodiversity, chronic illness and mental ill-health.
- In May 2023 we organised a special IDAHOBIT awareness session, run by Queers in Science, covering themes including: Trans and Queers' modern issues; Queers in STEM; and how to be an active ally for LGBTQIA+ people.
- We are progressing towards gender balance. Up by 2% in 2022, to 32% of our members are women, non-binary, or gender diverse.
- OzGrav supported over 40 talented students to participate in a vacation scholarship program designed to increase equity, diversity and inclusion in the Centre. The program requires at least half of the scholarships to support students or Chief Investigators from underserved and marginalised groups. The students gain invaluable experience working with our researchers on various real-world projects and lay a solid foundation for student recruitment, with many students pursuing higher degrees with OzGrav.
- OzGrav awarded five carer grants, totaling $6,500, last year to enable primary carers to attend professional events.

Future plans:

OzGrav's future plans are developed and informed by the areas identified from the Intersectionality and Psychological Safety Workshops, Members Survey, and other engagement activities. An overview of OzGrav's plans includes:

- Implement multiple EDI training initiatives ranging from building on the 2023 intersectionality and psychological safety training to the EDI education program with short videos available for all members.
- Host more local social gatherings, lunchtime learnings, and journal clubs to foster a sense of belonging among members.
- Develop and implement comprehensive EDI policies and processes, including a Concerns and Grievance Framework.
- Further Psychological Safety by implementing 360 assessments for Team Leaders and incorporating psychological safety discussions into meetings. Create resources to further enhance psychological safety.
- Develop an Inclusive Recruitment Checklist to support and guide our recruitment efforts and reinforce our commitment to equity and inclusion.
- Establish transparent decision-making processes, create a new Centre wiki as a central information hub, streamline the induction process, and develop an OzGrav Starter Pack for new members.
- Embed EDI principles into daily operations by co-designing OzGrav 2.0 values and developing guides for member roles and expectations.

PROFESSIONAL DEVELOPMENT PROGRAM

OzGrav 2023 Winter School:

The 2023 OzGrav Early Career Researcher (ECR) Winter School, hosted at the University of Western Australia from July 19 to 21, was a resounding success. The event brought together students and postdocs from OzGrav to engage deeply with the instrumentation, data science, and astrophysics of gravitational wave science. The three-day workshop was filled with science talks, hands-on workshops, and invaluable networking opportunities. Many thanks to UWA's Damon Beveridge for leading the organisation of this event!

The first day featured rotating tours of the Einstein First and Instrumentation Labs, providing a unique behind-the-scenes look at the cutting-edge facilities and equipment. The COMPAS & Population Synthesis Workshop highlighted innovative approaches in stellar evolution and binary systems, while talks from a range of researchers introduced exciting topics on gravitational waves, binary black hole mergers, and updates on the Zadko Telescope, respectively. The day concluded with a social activity and informal networking at Kings Park Lightscape.

The second day continued with a series of talks on diverse topics such as compact binary coalescence, mid-infrared fibre lasers for LIGO's thermal compensation system, and invisible gamma-ray pulsars. These presentations showcased the breadth of research within the gravitational wave community and stimulated rich discussions among attendees. The final day included a Python Best Practices Workshop, offering attendees tools and techniques to enhance their research productivity. A workshop on gravitational wave instrumentation provided an in-depth understanding of the detection and analysis of gravitational waves, marking a fitting conclusion to the academic program.

The Winter School not only enhanced the participants' knowledge and skills in gravitational wave science but also fostered a supportive network of early career researchers, laying a strong foundation for future collaborations and discoveries in the field.

Discussions at OzGrav Winter School in Perth. Credit: Ruby Chan, OzGrav-UWA

2023 Early Career Researcher workshop:

The OzGrav 2023 ECR workshop for OzGrav students and postdocs unfolded over two days, with a focus on personal and professional development to complement the scientific training that the Centre provides to members via the Winter School and other events throughout the year. The program was designed and organised by our amazing Early Career Researcher Committee! The program included an Archaeoastronomy session, which offered fascinating insights into the intersection of archaeology and astronomy. Attendees participated in a workshop on "Shameless Self-Promotion," providing valuable strategies for effective communication and visibility in the scientific community.

The event included a Careers Panel featuring industry representatives from Aurizn, Lockheed Martin AU, and Fleet Space, offering perspectives on career paths outside academia. The program also included an Advanced Writing Skills Workshop that equipped participants with tools for clear and impactful scientific writing. A panel on working and studying internationally broadened the attendees' outlook on global opportunities and challenges in research and education. The Outreach Communications Workshop emphasized the importance of engaging with the public and disseminating scientific knowledge effectively. The OzGrav Talents Expo was a big highlight of the event, showcasing the creativity and unique talents of the OzGrav community. Overall, this workshop helped foster a sense of belonging, while equipping our ECRs with new skills and perspectives.

Photo above, below and top right - OzGrav's ECR Workshop and Annual Retreat in Adelaide. Credit: Carl Knox, OzGrav-Swinburne

2023 Activities and Progress:

- In 2023 we were delighted to launch the new Australian Research Council (ARC) Centres of Excellence (CoE) mentoring program, a joint initiative between twelve ARC CoEs. The program is a unique opportunity to start a mentoring relationship with other researchers from the CoE community, both inside and outside of OzGrav, as well as industry professionals. By the end of 2023 there were over 350 people enrolled in the program across all 12 CoEs. The program is run on the Mentorloop platform, which facilitates matching of mentors and mentees based on criteria including skills and goals, and also enables self-matching, to ensure meaningful and productive relationships.
- Nine of our students received competitive external awards in 2023 (in addition to our inaugural OzGrav Achievement Awards). This is a testament to the exceptional talent, dedication, and hard work of our students.
- Our students and postdoctoral researchers were the lead author on 72 high-impact peer-reviewed papers in 2023 (out of a total of 184 Centre publications) – an outstanding achievement that reflects our pro-active commitment to giving leadership opportunities to our ECRs to build Australian capacity in our discipline and related industries.
- We provided training and professional development sessions on over 16 topics during 2023, including during the ECR workshop, Winter School and other workshops and webinars throughout the year.

Future plans:

- OzGrav 1.0 will end on 31 March 2024, but the next iteration of OzGrav that starts on 1 April 2024 will build on the progress and momentum from OzGrav 1.0. We expect that during 2024, OzGrav will continue to offer a broad suite of training and PD opportunities that will be developed by, and in consultation with, our Early Career Researcher Committee.
- We intend to continue to grow the pool of mentors in our joint CoE mentoring program, and encourage all OzGrav members to sign up as a mentee, mentor or both.
- We will support our ECRs to plan an innovative and constructive ECR Workshop and Winter School, or equivalent.
- We will continue to promote students and postdoctoral researchers to take leadership roles on publications, Centre Programs and committees, and on international working groups.
- We will raise awareness, and ensure appropriate uptake, of the grant opportunities available within the Centre, including the Research & Innovation grant and the Professional Development grant.

EDUCATION AND OUTREACH

Monash Maker Faire
Credit: Lisa Horsley OzGrav-Swin

Monash Maker Faire

After a lockdown break, the Monash Maker Faire was back in person for 10,000 people at Monash University's Clayton campus. The Maker Faire brought together 300 artisans, developers, hackers, inventors and tinkerers of all descriptions converging to share their passions with attendees of all ages.

OzGrav shared Virtual Reality (VR) guided tour of the solar system and beyond, AMIGO interferometer, stickers, posters and games. For more info click here.
Article written by Lisa Horsley.

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.

The 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).

For this event 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 run during the camp included stargazing, robotics and a visit to Canberra Deep Space tracking station.
Article written by Lisa Horsley.

Monash Maker Faire
Credit: Lisa Horsley OzGrav-Swin

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 CAS Work Experience program (Centre for Supercomputing and Astrophysics) across the year, discovering properties of stars, black holes and gravitational waves.

Space Camp. Credit: Lisa Horsley OzGrav-Swin

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

Welcome Week

OzGrav and the Swinburne Physics and Outer-space Club (SPOC) joined forces during Orientation and Welcome Back Week activities as we welcomed new and returning students to Swinburne campus for Semester 1, 2023.

It was a wonderful two weeks with an incredible vibe around campus and we appreciate all the astronomy students and researchers from OzGrav and CAS (Swinburne Centre for Astronomy and Astrophysics) being a part of it all.

Over the course of Orientation and Welcome Back Week we had:

- 9000+ unique students engaged
- 6,000 + club memberships
- 450,000+ impressions on our related social media content

It was an epic way to start the year. We're excited to see what the semester holds.
Article written by Kirstyn Paul, Events & Experience Officer, Swinburne Student Life

Photo credit: Swinburne Student Life

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

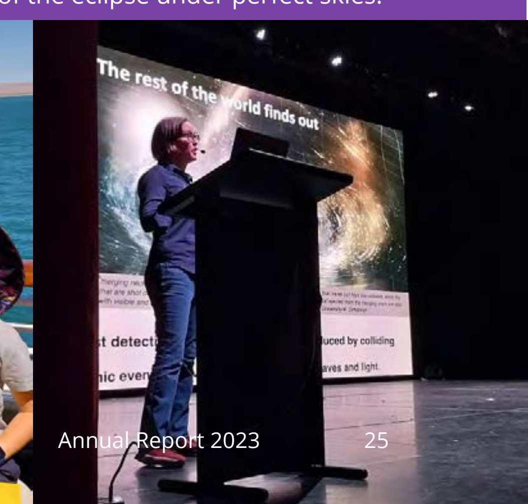
Schools Engagement

2023 was another banner year for OzGrav Schools Outreach with over 200 schools engaged! Students ranging from primary school to secondary Physics had the opportunity to learn from OzGrav ECRs and Outreach specialists. Some special highlights included supporting the launch of a new Astrophysics elective at Brentwood Secondary College in Victoria and an expansion of our programs into New South Wales with a series of incursions at the Wenona School. The schools programs would not be possible without the support of the OzGrav ECRs, sharing their enthusiasm with the next generation of scientists!

Ningaloo Eclipse Cruise

On the 20th of April 2023, a total solar eclipse crossed over the Exmouth Peninsula in Western Australia. Thousands of people travelled from across Australia and internationally to witness this event. The Astronomical Society of Australia (ASA) partnered with P&O Cruises to provide the astronomy education program for part of a cruise to observe the eclipse. OzGrav Associate Investigator Professor Tara Murphy from the University of Sydney was an invited speaker on the cruise, delivering a talk titled: '100 years of testing Einstein: from solar eclipses to gravitational waves'. Her talks were a major success, with over 600 people at each lecture!

The full education program for the cruise was developed and managed by OzGrav Affiliate Dr Rebecca Allen and Education and Outreach Coordinator Jackie Bondell, both in conjunction with their roles in the ASA. The program brought together ten astronomy academics, amateur astronomers, and education specialists to lead events such as lectures, pub quizzes, astrophotography workshops, and Q&A panels. This was in addition to the 'big event', the viewing of the eclipse under perfect skies!



EDUCATION AND OUTREACH

National Science Week Activities by OzGrav

Once again, OzGrav HQ was actively involved in multiple National Science Week events, engaging audiences of all ages with a variety of programs and partnerships. These are the activities we engaged in:

- **National Science Quiz Sponsorship**

OzGrav sponsored the National Science Quiz, a live and online event hosted in Melbourne by Charlie Pickering. This year, the quiz introduced a new feature, allowing schools to field teams and participate. Dr. Rebecca Allen, an OzGrav Affiliate, served as a panellist and, as a runner-up, she and her teammates were slimed at the end of the event! The NSQ website will continue to promote educational materials, including a careers page and a highlight video showcasing the work of sponsoring centres.

- **SciVR at Burley Brewing Event**

In collaboration with the Centre for Astrophysics and Supercomputing (CAS), the SciVR at Burley Brewing live event came together with a SciVR app-guided talk and a gravitational waves pub quiz! Audience members received a small VR headset to use with the SciVR app on their phones. Additionally, CAS student volunteers served as trivia captains for the audience, and the teams battled diligently to reach the top of the pub quiz podium. This event was fuelled by the Red Giant IPA, brewed and canned by Burnley Brewing, especially for this occasion.

- **#STEMLikeAPatsGirl at St. Patrick's Girls College**

OzGrav was invited to participate in the #STEMLikeAPatsGirl event hosted by St. Patrick's Girls College in Townsville, Queensland. At this annual National Science Week event, girls from schools around Far North Queensland come together for a day of STEM workshops and talks. OzGrav delivered two workshops as part of this event, sharing the wonder of neutron stars, black holes, and gravitational waves with over 50 girls from years 6 - 10. The OzGrav VR programs are always a highlight, as are the gravity well activities.

- **Powerhouse Museum Collaboration**

Powerhouse Museum invited OzGrav to be part of the Sydney Science Festival. OzGrav students Ashna Gulati from the University of Sydney and Liana Rauf from the University of Queensland helped lead VR activities with families visiting the event at Powerhouse's Castle Hill location, in Western Sydney. This was a very successful event, not only because it engaged a large and diverse audience but also because it fostered a growing collaboration between OzGrav and Powerhouse Museum.

Photo credits: Jackie Bondell, OzGrav/Swinburne

Science Alive! Adelaide

Science Alive is all kinds of awesome and is the biggest event of its kind in Australia, with over 20,000 people in Adelaide attending in 2023. It was a great opportunity for OzGravvers to learn from each other across Data/Astrophysics and Instrumentation groups, and everyone had a go at explaining AMIGO and showing VR to our interested attendees across the 3 days of the festival.

This year OzGrav's booth was included in the "Space Zone" hosted by the Australian Space Agency. We shared our research with 4208 students from 84 schools on the STEM Careers Day, and chatted to lots of teachers about our Australian research and links with international partners. General public days saw another 16,000 people attend, with lots of very keen young people, parents and grandparents asking all sorts of questions about black holes and gravitational waves.

EDUCATION AND OUTREACH

ANU & UWA Launch a Revolution in Australian Science Education

Two national teaching programs aiming to revolutionise science education in Australian schools have been launched by ANU and UWA, to generate the next generation of Aussie Einsteins, quantum gurus, and our future science and technology workforce.

The national launch of the Quantum Girls and Einstein-First programs is being led by two Prime Minister's Prize for Science winners and OzGrav members, Distinguished Professor Susan Scott from ANU Research School of Physics/Centre for Gravitational Astrophysics and Emeritus Professor David Blair from The University of Western Australia (UWA).

The two programs will bring primary and high school science education into the 21st century and help reverse Australia's critical skills shortage in science, technology, engineering and maths (STEM), especially among young girls.

In Einstein-First, kids are introduced to a STEM education curriculum through interactive group activities, including concepts such as black holes, quantum computers and climate science. In Australia, we face a big problem of not enough school-leavers choosing to pursue a career in STEM fields, and this is especially true for girls. The Einstein-First and Quantum Girls programs are designed to ignite the interest and passion in science among primary and secondary school children.

The Quantum Girls program expands on Einstein-First and will aim to train 200 female teachers, who will then teach quantum science and quantum computing to girls aged 11 to 15.

Prof David Blair, researcher at UWA and OzGrav's Chief Investigator, began testing Einstein-First in Western Australian schools more than a decade ago. He was frustrated that school curriculums relied upon 19th century physics and that modern concepts such as relativity often weren't taught until university. Blair says the success of the program has led to it being offered to schools across the country, having already been replicated by teachers at schools in the US and parts of Europe. "The theories of Albert Einstein, who revolutionised science in the early 1900s, aren't too hard for school kids," Blair says. "Our kids are curious and excited by science. "This is why we must modernise the curriculum ... and teach everyone the language of modern physics, the language of Einstein, starting in primary school."

Additionally, UWA has received federal funding for a new course named Einsteinian Physics for Schoolteachers, which will upskill teachers as part of the Einstein-First program. Scott hopes the programs will help reverse Australia's critical skills shortage in STEM, especially among women.

All photo credit: Jesse Grunch.
ANU and UWA launch a revolution in science education, June 12, 2023. Click here. Cassidy, Caitlin. Nerf guns, marbles and Einstein: Schools taking Quantum Leap to halt Australia's STEM crisis, June 13, 2023. Click here

Background image: Midjourney

The most recent Australian government data shows girls' confidence in STEM subjects is generally lower than boys, and falls as they get older. At the same time, women make up only 36% of enrolments in university STEM courses and just 16% of vocational STEM courses. And at a managerial level, only 8% of CEOs in STEM-qualified industries are women. "At the moment our school system is failing us in what we need for the future. We can't afford to let that happen," Scott says. "We do have a STEM crisis and our future depends on the STEM workforce. "Climate science, renewable energy - we will need a lot of people in science and engineering to solve these problems [that are] so important for this generation."
Learn more about Einstein-First and Quantum Girls at www.einsteinianphysics.com.

OzGrav's Innovative Artworks Illuminate Gravitational Wave Science at Bendigo Science Centre

This year, in collaboration with OzGrav, the Bendigo Science Centre has introduced two pioneering interactive artworks designed to share the wonders of gravitational wave science. These installations, crafted with cutting-edge body and hand-tracking technology, invite visitors to engage directly with the fabric of the cosmos. By leveraging upcycled materials from the centre, these pieces underscore our dedication to sustainability while pushing the envelope of educational technology.

Situated in the heritage Railway Goods Building, the Bendigo Science Centre has been a cornerstone of discovery in our community since its inception in 1995, drawing over 30,000 visitors annually. The partnership with OzGrav for these installations marks a significant step forward in our journey to inspire a new generation of scientists, engineers, and environmentally conscious citizens.

Photo credit: Carl Knox, OzGrav/Swinburne

Chinchilla – famous for melons

More World Science Festival fun was had by Kyla (UWA), Dana (ANU) and Lisa (Swinburne) in Chinchilla. 1400 participants tried out OzGrav's virtual reality (VR) guided tour of neutron stars and black holes, with 600 students participating on the schools day, and 800 people visiting on the general public day. It was a great way to try lots of different science in one place, with technology showcases, live animals, marine science, robots and explosive science shows with Dr Rob (SCOPE). We'll have to visit another time for the watermelon festival.

EDUCATION AND OUTREACH

Spooktacular Space

Is space scary enough to keep you up at night? Pulverizing black holes, spontaneous transients, and mysterious dark matter... oh my! At the recent Spooktacular Space Public Lecture event, led by OzGrav and co-organised by the ARC Centre of Excellence for Dark Matter Particle Physics and the Centre of Astrophysics and Supercomputing at Swinburne University, attendees were treated to a thrilling exploration of the cosmos, delving into the eerie and enigmatic phenomena that populate our universe.

The event kicked off with an engaging introduction by Science Barbie MC and OzGrav Associate Investigator, Sara Webb, who shared her insights into the spine-chilling aspects of space that keep her awake at night. From the haunting mysteries of black holes to the fleeting and mysterious transients observed in the cosmos, Sara set the stage for an evening of cosmic wonder and exploration.

Three captivating talks followed, each delving deeper into the spooky space theme. Our Dragon superstar, Yuanming Wang, equipped with her insights into the cosmos and the ASKAP telescope, illuminated the audience with her exploration of transients. From rapidly changing radio signals to the unveiling of the most luminous pulsar in the Large Magellanic Cloud, Yuanming's talk left the audience captivated and eager for more.

Men in Black Agent M, also known as Matthew Bailes, took the audience on a mesmerising journey through the world of pulsars, shedding light on these celestial objects' bizarre and fascinating properties.

But the excitement didn't end there! Throughout the event, attendees young and old were encouraged to ask questions, sparking lively discussions and fostering a sense of curiosity and wonder about the mysteries of the universe.

One of the highlights of the evening was the eagerly anticipated costume contest, which saw attendees donning an array of creative and imaginative outfits. From E.T. and Elliot to a special appearance by the fabric of spacetime itself.

As the evening drew to a close, attendees were invited to a reception where they could unwind and engage in further exploration of the cosmos. VR guided tours, presented by OzGrav PhD Outreach superstars, provided an immersive and educational experience, allowing attendees to journey through the cosmos from the comfort of the Sky Lounge.

Overall, the Spooktacular Space Public Lecture event was a resounding success. It served as a reminder of the awe-inspiring beauty and mystery of the universe, leaving attendees inspired and eager to continue their cosmic exploration.

Photo credits: Carl Knox, OzGrav/Swinburne

Future Plans

Moving into the next phase of OzGrav, the Outreach and Education program will continue to support our existing programs while developing new activities to continue to reach audiences traditionally underserved in access to STEM initiatives. For example, OzGrav is co-designing with the Gravity Discovery Centre a new school incursion that incorporates curriculum-aligned space concepts with traditional Indigenous storylines.

There will be more opportunities for our ECRs to not only engage with a variety of audiences but new chances for bespoke training to become the inaugural cohort of OzGrav Outreach Ambassadors. In a quest to find a permanent space for OzGrav digital outreach materials, the OzGrav HQ team is liaising with Swinburne University to establish a Digital Experience Room.

Awards and Honours

Matthew Bailes wins prestigious Shaw Prize

Matthew Bailes, Director of the ARC Centre of Excellence for Gravitational Wave Discovery, alongside Duncan Lorimer, Professor and Interim Chair of Physics and Astronomy at West Virginia University, USA and Maura McLaughlin, Distinguished Professor and Director of the Center for Gravitational Waves and Cosmology at West Virginia University, has been awarded the prestigious Shaw Prize in Astronomy, known as the 'Nobel of the East', for the discovery of 'fast radio bursts', which are intense bursts of energy from beyond the Milky Way. The Shaw Prize recognises exceptional accomplishments in scientific disciplines.

Matthew Bailes's innovative research has expanded our understanding of the cosmos and gained international recognition. His research centres around pulsars, highly magnetized rotating neutron stars that emit beams of electromagnetic radiation.

Through his studies, Bailes has made noteworthy discoveries, including detecting the fastest spinning known pulsar and the first-millisecond pulsar in a binary system. His work has advanced our understanding of these celestial objects and deepened our knowledge of gravity and fundamental laws of physics.

This esteemed recognition highlights Matthew's dedication and expertise in the field of astronomy. His contributions not only enhance scientific knowledge but also inspire future astronomers. This recognition emphasises the significant role of Australian scientists in astronomy, cementing the country's position as a leading hub for cutting-edge research. As we celebrate this achievement, we eagerly anticipate Matthew's ongoing discoveries and the valuable insights they will provide into the mysteries of the universe.

AWARDS AND HONOURS

2023 OZGRAV ACHIEVEMENT AWARDS

A highlight of the 2023 OzGrav Retreat was the presentation of the inaugural OzGrav Achievement Awards, recognising our members' outstanding contributions and achievements.

Below are the winners, runners-up, and highly commended individuals. Congratulations to all the recipients!

Advancing Equity Award
Winner: Sareh Rajabi

Cross-Nodal Collaboration Award
Winner: Bram Slagmolen

Runners up: Bram Slagmolen, Ju Li, Zhang Ya, Aaron Jones, Sheon Chua, Carl Blair, Jennie Wright, Avanish Kulur Ramamohan

Highly Commended: Ryan Shannon, Valentina di Marco, Andrew Zic

Mentor Award
Winner: Karl Wette

Runner up: Dan Brown
Runner up: Andrew Melatos

Highly Commended: Bram Slagmolen
Highly Commended: Magdelena Kersting

Research Translation Pioneer Award
Winner: Zac Holmes, Peter Veitch, and Sebastian Ng

Rising Star Award - Postdoc
Winner: Johannes Eichholz

Runner up: Ryosuke Hirai

Highly Commended: Zhang Ya

Rising Star Award - Student
Winner: Isobel Romero Shaw

Runner up: Natasha Van Bemmel

Highly Commended: Pratyasha Gitika
Highly Commended: Julian Carlin

Scientific Achievement in the Astro Theme
Winner: Ryosuke Hirai

Scientific Achievement in the Data Theme
Winner: Colm Talbot

Runner up: Dana Jones

Scientific Achievement in the Instrumentation Theme
Winner: Sheon Chua, Nutsinee Kijbunchoo, David McClelland, Kirk McKenzie, Terry McRae, Bram Slagmolen, Andrew Wade

Runner up: Thomas Roocke

Service Award
Winner: Ruby Chan

Runner up: Yeshe Fenner

Superstars of Outreach Award
Winner: Kyla Adams

Runner up: Jennifer Wright

Highly Commended: Rowina Nathan
Highly Commended: Sara Webb

Lightning Talks

Instrumentation
Winner: Oscar Zhu

Runner Up: Koh Baker

Data
Winner: Jacob Askew

Runner Up: Tom Kimpson

Astro
Winner: Kyla Adams

Runner Up: Jennifer Shi

Credit (all photos on both pages): Carl Knox, OzGrav/Swinburne

AWARDS AND HONOURS

Distunguished Professor Susan Scott
Credit: Tracey Nearmy, ANU

OzGrav Chief Investigator Distinguished Professor Susan Scott was honored with the prestigious Thomas Ranken Lyle Medal for her critical role in the analysis and detection of gravitational waves, and advancing our understanding of the global structure of space-time. She was also appointed as a Vice Chancellor's Professorial Fellow (Science) at Aston University UK and received the ANU Chancellor's Peter Baume Award, ANU's most prestigious award recognising eminent achievement and merit of the highest order. Additionally, she was conferred an honorary doctorate by The University of Adelaide and delivered the commencement address at the UoA graduation ceremony on September 21, 2023.

Pleiades Award being accepted EDI Committee members Robert Song and Andrew Cameron:

OzGrav was awarded a Pleiades Silver level award, a positive testament to our commitment to promoting and achieving equity and inclusion.

OzGrav PhD student Isobel Romero-Shaw won the Robert Street Doctoral Prize in Physics for the best PhD in Physics and Astronomy at Monash University

The audio visual musical Continuum which is Part II of the "Binary Coalescence Project" by Aiv Puglielli was selected as a finalist at the Quantum Shorts Film Festival! Congratulations to Linqing Wen and Carl Knox who contributed to the project


Lilli Sun and Shivani Bhandari were awarded DECRA Fellowships from the ARC

OzGrav PhD student Natasha van Bemmel received prizes the ASA Annual Scientific Meetingfor Best student poster (3rd), Best student sparkler (2nd) and people's choice award, and OzGrav students Matt Miles, Jacob Askew and Rowina Nathan got Honorable mentions for student talks.



OzGrav Chief Investigator Dr Bram Slagmolen (ANU) was elected Fellow of American Physical Society 2023 'for the development of technologies for gravitational wave detectors, for contributions to the design, construction, and commissioning of Advanced LIGO, and for leadership in the Australian gravitational wave community'


OzGrav Chief Investigator Ilya Mandel was recognised among the world's most influential scientists, ranking in the top 1% for citations in their fields over the past decade according to Clarivate and Web of Science

OzGrav Honours student Spencer Collaviti at ANU, was awarded the University Medal for 2023 for his Honours thesis on "Gravitational-Wave Signatures of Superradiant Self-Interacting Scalar Ultralight Bosons", supervised by Lilli Sun


Former OzGrav Honours student Yuhan (Hank) Hua received an ANU University Medal for their Honours thesis.

OzGrav Chief Investigator David Coward (UWA), named as a Finalist in the Australian Space Awards 2023

OzGrav student Chayan Chatterjee received a Graduate Research School Travel Award, OzGrav Student Travel Award, International Space Center Travel Award, and Postgraduate Student Association Travel Award worth a total of $7750 for international travel

OzGrav Associate Investigator Anais Moller was awarded 2nd place in the Women in AI Australia Pacific awards for Space



Neil Lu, Susan M. Scott, Karl Wette from ANU received the Fifth Award in the International Awards for Essays on Gravitation, from the Gravity Research Foundation, for their essay: What are neutron stars made of? Gravitational waves may reveal the answer.

OzGrav postdoc Ryosuke Hirai won the best presentation prize at the Monash ECN symposium, along with $2000 in prize money

EVENTS AND COMMUNITY HIGHLIGHTS

Green thumbs unite!

Explore the community garden at ANU, lovingly nurtured by our OzGrav team. It's a fantastic opportunity to connect with nature, fellow enthusiasts, and contribute to sustainability efforts right here on campus.

ANU Physics Market Day

OzGrav postdocs Jennie Wright and Johannes Eichholz (along with other OzGrav members) presented research opportunities to undergrad students.

Survey Thank you Lunch

OzGrav HQ provided a special lunch for its members as a thank-you for the Centre exceeding its target response rate of 75% in the member survey. Check out a few pictures from Swinburne and UWA

UWA Open Day

Thank you to the wonderful volunteers who supported the three exhibit areas in OzGrav and Einstein First. It was wonderful to be back in the physics building and to share the atrium floor space with our peers in the research areas of medical physics, field theory, and quantum gravity, quantum information and computation, dark matter, engineered quantum systems (EQUS), and radio astronomy (ICRAR).

Well done to Alistair who created a machine-learning app to engage the public in identifying a noise signal versus a bns signal.

UWA Node Visit

OzGrav HQ paid a visit to our node at UWA, fostering collaboration and strengthening connections within our network!

INSTRUMENTATION THEME

OzGrav's Instrumentation Theme, led by 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:

- Commissioning - Program Chairs: Dr Dan Brown (Adelaide) and Dr Bram Slagmolen (ANU)
- Quantum - Program Chairs: Dr Terry McRae (ANU) and Prof Peter Veitch (Adelaide)
- Low frequency Newtonian noise mitigation - Program Chairs: Dr Bram Slagmolen (ANU) and Prof Ju Li (UWA)
- Instabilities and Distortions - Program Chairs: Dr Carl Blair (UWA) and Prof David Ottaway (Adelaide)
- Space Instrumentation - Program Chair: Dr Andrew Wade (ANU)
- Pulsar Timing - Program Chair: Prof Matthew Bailes (Swinburne)
- Future Detector Planning - Chairs: Prof Matthew Bailes (Swinburne) and Prof David McClelland (ANU)

Vacuum tank of the Gingin 7m cavity showing SPI hardware installed. Credit: B. J. J. Slagmolen

INSTRUMENTATION THEME

Commissioning

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

2023 Progress and Achievements

Commissioning both in person and remote has picked up over 2023. Jennie Wright, Mitchell Schiworski, Carl Blair, Nutsinee Kijbunchoo, and Daniel Brown took part in pre-O4 commissioning, and many will return for the O4 break happening in Q1 of 2024.

Case studies

Stories from the frontline of commissioning: Dana Jones (ANU, LIGO Research Fellow)

I've been a research fellow at LIGO's Hanford Observatory site since mid-November 2023, where I've been working with the calibration team on improving the sensing function model. The sensing function is an important component used in the reconstruction of a gravitational wave signal based on the detector's physical response to said signal. It relates a change in differential arm length to the amount of light detected by a photodiode at the antisymmetric beamsplitter port. The photodiode signal is then digitized and processed by various electronics.

To reconstruct the gravitational-wave signals that cause differential length changes in the detector's Fabry Pérot arms, we need a highly accurate model of the sensing function that is both time and frequency dependent. To achieve this, we start with an analytic model with a certain number of free parameters. We then empirically measure the sensing function at different times and use these measurements to fit the modeled sensing function. My primary goal so far has been to investigate potential improvements in this fitting process, especially at frequencies below about 10 Hz where the systematic error is largest due to model inadequacies. However, I've worked on many other odd jobs since arriving, such as looking at how heating an optic in the output mode cleaner path affects the calibration, and studying the impact of seismic activity on the detector's duty factor over time. Through these projects, I have gained invaluable knowledge on the intricacies of the detector and on how we take a change in differential arm length and produce detailed estimates of the signal waveform and source parameters, all of which has greatly enriched my experience in gravitational wave science.

Nutsinee Kijbunchoo (UoA)

The aLIGO quantum squeezer system deploys entangled photons to combat quantum noise inside the LIGO interferometer, improving sensitivity of the detector at nearly all the relevant frequencies. The quantum squeezer has been the key to the detector range improvement since the beginning of O3, gaining 15% range improvement when it was first switched on back in 2019. The squeezer further improved the detector performance upon the integration of a 300-m long filter cavity during the "A+" upgrade.

There is an upgrade plan in place for the squeezer during the upcoming commissioning break to mitigate intensity noise following the result of our investigation done earlier last year. As I happened to be in town for Christmas I thought I'd "squeeze" in a bit of prep work before the commissioning break begins mid-January. An initial LIGO pre-mode cleaner, a three-mirror cavity, arrived from MIT just in time for the holidays to be assembled. A pre-mode cleaner selects modes of the squeezer laser and prevents noise above a certain frequency from going through. Initial LIGO photodiodes that we will use to control the pre-mode cleaner were also tested. Because the pre-mode cleaner filters the noise we need to compare with the interferometer sample, we had to move the squeezer laser locking upstream. The new Fiber Beat Note boxes were designed to be used with the modified laser locking path. I assembled and tested four brand new Fiber Beat Note boxes for both LIGO Hanford and LIGO Livingston. The Hanford unit has been installed and successfully tested. The pre-mode cleaner installation will commence the next time I visit LIGO Hanford in February.

Future plans

The O4 break represents another opportunity for OzGrav to continue its valuable support to the LIGO sites. Some members will be visiting the sites in person whilst others will be taking part remotely and via simulation workshops held at Caltech in early Feb 2024. Preparations should start being made for the post-O4 period before the detector installations begin for the O5 run. This offers researchers time to perform measurements to better understand the interferometer before installing new hardware.

Image: Dana Jones, Keita, and Rahul at LIGO Hanford during the O4 break

Quantum

Program Chairs: Dr Terry McRae (ANU) and Dr Peter Veitch(Adelaide)

2023 Progress and Achievements

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. Changing the laser power and/or wavelength or the configuration of the interferometer can modify the quantum noise.

Photon shot noise, due to the uncertainty in the arrival time of photons, scales inversely with optical power. Coherently combining multiple lower power laser beams into a single, high-power beam circumvents some single-source limitations such as optical nonlinearities and thermal instabilities. These results have now been published (https://doi.org/10.1364/OL.500684).

Three 2 micrometer (2um) wavelength Thulium fiber amplifiers developed at Uni of Adelaide were delivered to ANU where they will facilitate thermal noise measurements of new optical coatings and provide a stable low noise source for squeezed light at 2um.

The development of single frequency thulium lasers, with wavelengths between 1900-2050 nm, and holmium fiber lasers (wavelengths > 2050 nm) progressed in 2023, and we began the assembly of a 100 W thulium fiber amplifier in collaboration with DSTG.

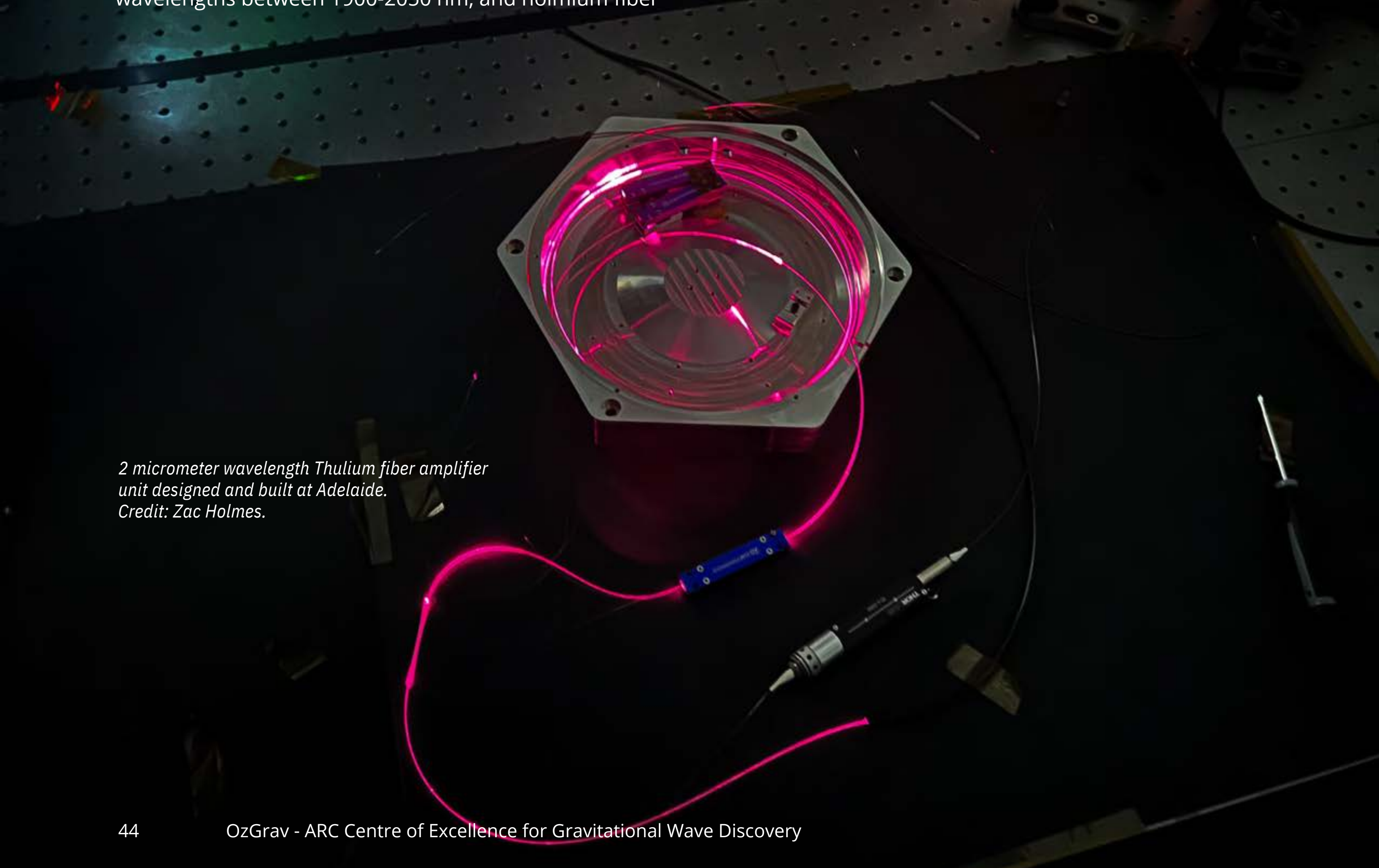
We developed fiber lasers in the wavelength range of 3.6-3.7 um, which have possible applications for the LIGO thermal compensation system.

We developed a plan to mitigate laser intensity noise that is degrading the squeezing at LIGO Hanford (LHO). We also tested a separate diagnostic to monitor the condition of the squeezing in the LHO interferometer.

Poor quantum efficiency of current photodetector technology at the 2 um wavelength significantly degrades the measured squeezing. A proposal to use phase sensitive amplification to circumvent this issue has been modelled (https://arxiv.org/abs/2401.04937) and the experimental demonstration of the model has commenced.

Results demonstrating balanced heterodyne readout that circumvent the 3 dB heterodyne signal-to-noise penalty on a dual Michelson sensor were documented for publication (https://arxiv.org/abs/2401.04940). Further signal-to-noise improvement of an injected audio-band signal was shown by applying a high-frequency two-mode squeezed state. This technique is applicable for quantum-limited metrology, and is well suited to enhance the sensitivity of gravitational wave detectors.

We studied the precision limits of detuned interferometers and other cavity–based quantum sensors.



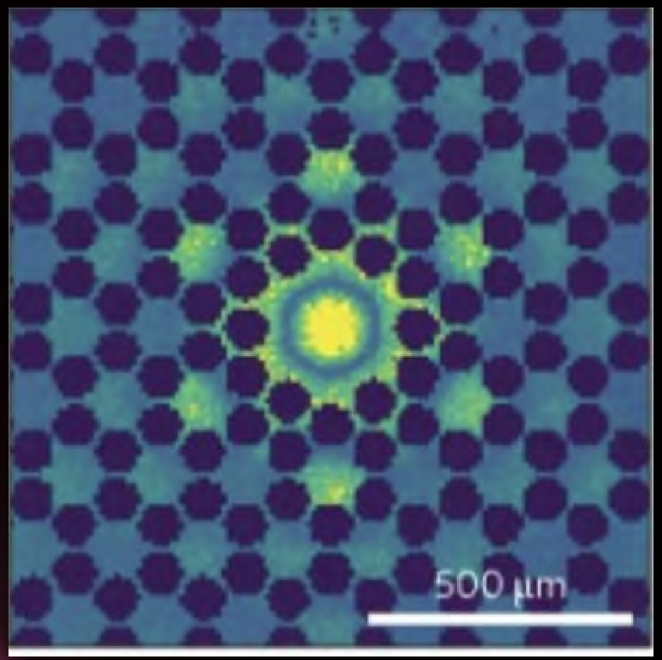
2 micrometer wavelength Thulium fiber amplifier unit designed and built at Adelaide. Credit: Zac Holmes.

The result is that a fundamental precision limit, the waveform-estimation Holevo Cramer-Rao Bound, has been established. This scheme could facilitate kilohertz gravitational-wave astronomy and has broader applications to detuned cavity–based quantum metrology. An experimental realisation has been proposed and this scheme is under review at PRL (https://arxiv.org/abs/2308.06253).

Recent modelling at UWA showed that the LIGO arm cavity resonance can be broadened by using optical radiation pressure to optomechanically change the phase response of the signal recycling cavity. The cavity can be intrinsically stable while improving the sensitivity bandwidth if reading the gravitational wave signal from the optomechanical cavity (white light effect). Experiments at UWA demonstrated precise measurements of optomechanical coupling to photonic crystal silicon nitride membrane "mirrors", allowing control of membrane instability in a mechanical mode.

Separate experiments were undertaken to enhance the peak sensitivity at particular frequencies with an optical parametric amplifier and observed an enhanced optical spring effect (Zhang et. al. Appl. Phys. Lett. 122, 261106 (2023)).

Two dimensions photonic crystal membrane reflector used to enhance optomechanical interactions at UWA. Credit: Chunnong Zhao



Future plans

Significant mid-infrared fiber laser development is planned for 2024. This includes advanced fiber joining (splicing) techniques, writing fiber Bragg gratings, and fiber-optic coupler development and a simplified optical pumping scheme. Further development using beam shaping techniques with spatial light modulators to improve output patterns and reduce speckle may allow the laser system to have thermal control applications in gravitational wave (GW) observatories by compensating power distribution across mirror surfaces distorted by the energy from the GW signal lasers. Higher power demonstrations of the coherent beam combining project are also planned for 2024.

The table top demonstration to simulate LIGO as a coupled cavity system with squeezing produced inside the signal recycling cavity has been simplified. This year should see squeezed light measured in the simplified configuration and in the original configuration with published results.

The experiment to amplify squeezed states above detector noise should produce preliminary results in 2024 after extensive modelling was completed in 2023. Ideally we would like to push the squeezing at 2 um further into the audio-band frequency range.

As part of the GQuEST project to test models of quantum gravity with an ultra-sensitive table top interferometer, we will explore new quantum states. The Fisher information framework will be used to see if these exotic states have a higher signal to noise ratio than standard Gaussian or Fock states for single photon detection.

The optical spring effect enhanced by an optical parametric amplifier has produced unexpected nonlinearities; these effects will be investigated in 2024. Separately, work will continue to improve the optomechanical cavity stability with the photonic crystal membrane.

INSTRUMENTATION THEME

OzGrav supported visiting students assembling the seismic isolation structures in March. Left: Meysem Chandoul, Right: Bastien Lassalle. Students were visiting from Léonard de Vinci Graduate School of Engineering in Paris. Credit: A. W. Goodwin-Jones/UWA/OzGrav

OzGrav international visitor Dr Di Fronzo works alongside UWA scientists commissioning seismic isolation. June. Credit: A. W. Goodwin-Jones/UWA/OzGrav

Low Frequency

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

2023 Progress and Achievements

The low frequency program investigates and develops technologies that can be used to eliminate or mitigate low frequency noise sources that limit the detector sensitivities of next generation detectors. It is a joint effort between OzGrav members at UWA and ANU.

Scientists at UWA have been working on technologies for isolation from ground seismic noise including the Advanced Low Frequency Rotational Accelerometer (ALFRA1) beam balance and the Gingin seismic isolation platform. At ANU work has continued on the TORsion PEndulum Dual Oscillator (TorPeDO), a technology to mitigate newtonian noise, ie. the local gravitational field fluctuation near the detector.

The ALFRA beam balance is a tilt sensor that can be used to sense the tilt of the ground due to seismic noise. The ALFRA1 beam balance was radically redesigned as ALFRA2 making it compact (36x36x36cm) and robust enough to be portable and easily disassembled / reassembled for repair or modular upgrade. Following full analysis, the rotation sensor module was optimised for sensitivity and simplicity, manufactured and is being characterised. Previously unincorporated shadow sensor and remote centre-of-mass tuning modules were tested. After several approaches aimed at allowing the instrument to be reoriented while remaining functional, as well as protecting the thin flexures from damage due to accidental jolts, the flexure support structure was finalised and has been partially manufactured.

At the Gingin laboratory, researchers tested lasers and new low-frequency control schemes for 3rd generation gravitational wave detectors. These detectors use 2um lasers, Silicon Optics and Cryogenics. 2um lasers and sensing technology is relatively new and the 7m cavity will give us the opportunity to demonstrate the narrowest linewidth 2um cavity to date while getting familiar with 2um technology. We installed the laser, suspensions and optics and we began the process of trying to maintain the optical cavity on resonance.

The Gingin seismic isolation platform is used to prevent seismic noise from the environment disrupting the Gingin 7m cavity. The system has 4 vertical piezo actuators, one in each leg of the table and 4 horizontal actuators placed between the table frame and the optical breadboard, each piezo has 40um range. The table then has two seismometers on it, one for feedback control and the other as a witness. We have demonstrated 40dB suppression of seismic noise between 0.5Hz and 3Hz.

At ANU, the TorPeDO suspension chain now has all four stages free-hanging. Most mechanical commissioning was completed in 2023 and work started on the control system design and commissioning. All work on the laser frequency stabilisation for the main TorPeDO lasers is complete and a sensitivity below target was achieved. Setup of a test readout cavity for the TorPeDO bars is underway. While still in development for other applications, digital interferometry was determined not to be suited to use as a Torpedo suspension sensor and it was decided to utilise a sensor based on deep frequency modulation instead.

In gravitational wave detectors, active seismic isolation is used to reduce the optical platform motion. However, inter-platform motion presents a significant noise challenge to the low frequency sensitivity of these instruments. Suspension platform interferometry (SPI) provides a potential solution via the measurement of the relative displacement and tilt between platforms, that then allows for motion stabilization using the platform actuators. The ANU-developed SPI sensor uses Digital Interferometry to multiplex and isolate the individual sensing channels by their optical time-of-flight. It showed promising table-top results. This then progressed to be a newly started collaboration experiment to test the SPI sensor at the UWA Gingin High Optical Power Facility, where commissioning work is ongoing.

Gingin SPI activities, showing the installation of the SPI hardware between the UWA and ANU nodes. Credits - Left: B. J. J. Slagmolen/ANU/OzGrav, Right: A. W. Goodwin-Jones/UWA/OzGrav

Case studies

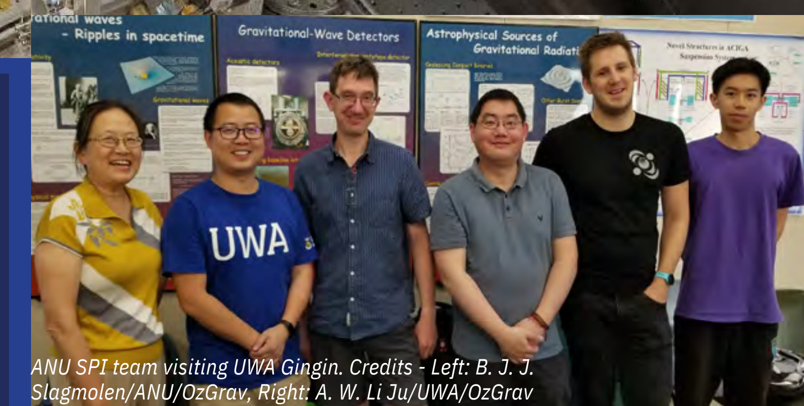
Gingin Next Generation Prototype (7m, 2 μm Suspended Cavity)

At the beginning of 2023, piezo seismic pre-isolation was installed into the vacuum system and optical breadboards were laid on top. Seismometers were installed and integrated with a LIGO-style Control and Data System (CDS) and up to 40 dB of seismic suppression was achieved. This demonstrates the viability of piezo pre-actuation and builds upon earlier work in this domain.

2 μm fused silica optics were suspended from LIGO-style suspensions and controlled using the CDS. The 2 μm laser was re-commissioned and is producing brief laser resonances in the 7m optical cavity formed between the two optics (cavity flashes). Work is ongoing to extend the length of the cavity resonances and demonstrate the noise performance of the laser.

Suspension-Platform-Interferometry at Gingin

In 2023, a new collaboration experiment between the OzGrav ANU and UWA nodes was started. During two visits of ANU researchers to Gingin, the delivery of an ANU-developed multi-channel suspension-platform-interferometry (SPI) sensor prototype with the UWA Gingin High Optical Power Facility was achieved. This new system will directly measure relative motion between the Gingin seismic isolation platforms that house a test optical cavity for longer-wavelength technology development for next-generation GW detectors. This will reduce the fluctuations in the cavity control error signal, thus improving its performance.



ANU SPI team visiting UWA Gingin. Credits - Left: B. J. J. Slagmolen/ANU/OzGrav, Right: A. W. Li Ju/UWA/OzGrav

Future plans

The 7m 2um cavity is the first in a series of planned experiments at Gingin to demonstrate the technologies of proposed future detectors like Einstein Telescope in Europe and Voyager in the United States.

The machine learning project aims to use neural networks to better simulate the behaviour of the optical breadboard (OBB) when exposed to seismic noise. Current modelling techniques of complex systems such as the OBB are time intensive. Due to the frequency of modifications made to the OBB, a more efficient method of analysing the OBB would be beneficial to decrease the time required to model the system and implement the appropriate control strategies.

Furthermore, due to the complexity of neural networks the machine learning model can better simulate complex features of the OBB including non-linearities and cross coupling. This provides a better understanding of how seismic noise influences the OBB. These factors allow for different control strategies to be explored in the hopes of having better control of the table from seismic noise and in turn the low frequency range.

INSTRUMENTATION THEME

Distortions and Instabilities

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

2023 Progress and Achievements

The Distortions and Instabilities Program develops methods to control for wavefront distortions, parametric instabilities, thermal effects, and other sources of distortion and instability.

While the process for coating production is improved at the Laboratoire des Matériaux Avancés (LMA), and there are less point absorbers in newly installed optics, thermal distortions still limit sensitivity. Parametric Instability also returned with the doubling of optical power, resulting in several lock losses and limiting the stable parameter space for the interferometer, making commissioning harder.

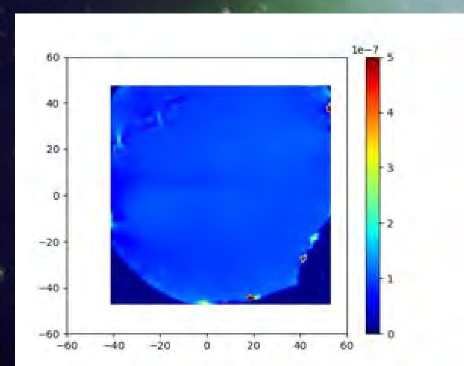
The Distortions and Instabilities Group continued to investigate issues that impact gravitational wave detectors, find solutions, and investigate potential solutions in future detector designs. Vladamir Bossilkov, a UWA graduate, has taken up a position as a Detector Engineer at LIGO Livingston, and will be involved in instrument upgrades including faster signal acquisition and better automation, that will make parametric instability easier to control.

Deliverables completed in 2023 include the publication of the LG10 mode sensing paper, tank design for the thermal compensation system (TCS) test stand, and the optical layout of the TCS test stand. The mode sensing paper led to further work with a table top demonstration that is complete but not yet published, while the TCS test stand is the beginning of a larger project with new milestones this year. An exciting new project not anticipated last year is the design of parametric instability mitigation in the A# detector design.

Projects that are still in process include: The Silicon beamsplitter investigation where the development of the theory is complete but technical difficulties have resulted in the measurements not yet being complete. The Gingin Thermal Suspended Active Mode-matching actuators were built and ready for testing. Thermal stress induced birefringence experiments will happen after the beamsplitter experiments are complete. Parts have been acquired and tested for the first matrix heater and a simulation has been run but it has not been assembled and tested as a matrix heater yet. The independent optical mode control is dependent on the east arm cavity.

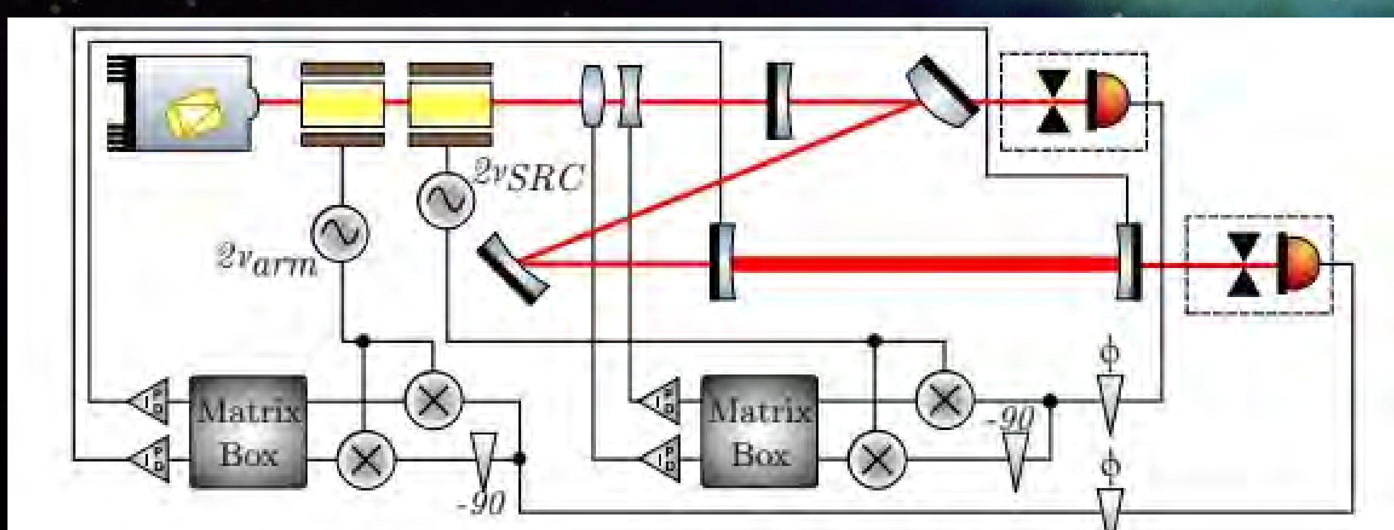
Silicon Beamsplitter Birefringence:

Exciting work in 2023 produced promising preliminary results showing about 10^-7 unitless birefringence (see figure) in a standard beam splitter configuration. The birefringence is dependent on the rotation of the optics and this is the minimum observed so far. While this figure is low, we still have to confirm if it meets the requirements of future detectors such as NEMO, Einstein Telescope and Voyager.



LG10 mode sensing:

The paper "Single and coupled cavity mode sensing schemes using a diagnostic field" describes and simulates this mode sensing scheme. The sensing scheme is simple and performs very well in simulations. In 2023, the simulated results were confirmed with a single cavity tabletop demonstration.



Gingin Thermal Suspended Active Mode-matching actuators:

The Gingin High Optical Power Test Facility (HOPF) South arm coupled cavity experiment requires coupled cavity mode matching actuation. We decided to use Thermal Suspended Active Mode-matching (TSAM) actuators developed by University of Adelaide and installed in LIGO. Using these actuators allowed rapid construction that benefits us and more real world experience that will benefit LIGO. There are two sizes: a 50mm and a 75mm mirror actuator. These were assembled and we undertook preliminary testing as can be seen in the figure below.

Case studies

Parametric Instability in A#

The A# LIGO upgrade is the proposed upgrade after the 5th observation run due to complete in 4 to 5 years time. The A# proposal will increase the test mass to 100kg, improve coating, and increase optical power. Simulations of parametric instability in the detector reveal many instabilities. As the aspect ratio of the test mass is not yet fixed, we investigated the severity of parametric instability as a function of the test mass aspect ratio. We found that there is an advantage to choosing a fairly radical test mass aspect ratio with 250mm diameter, with minor variation in severity in the less radical range of aspect ratios. We also designed acoustic mode dampers that mitigate most of the instabilities with just 3 dampers (rather than 4 used in LIGO). We began investigating solutions to the problem that the lowest frequencies of instabilities can not be damped without introducing excess thermal noise that contaminates detector sensitivity.

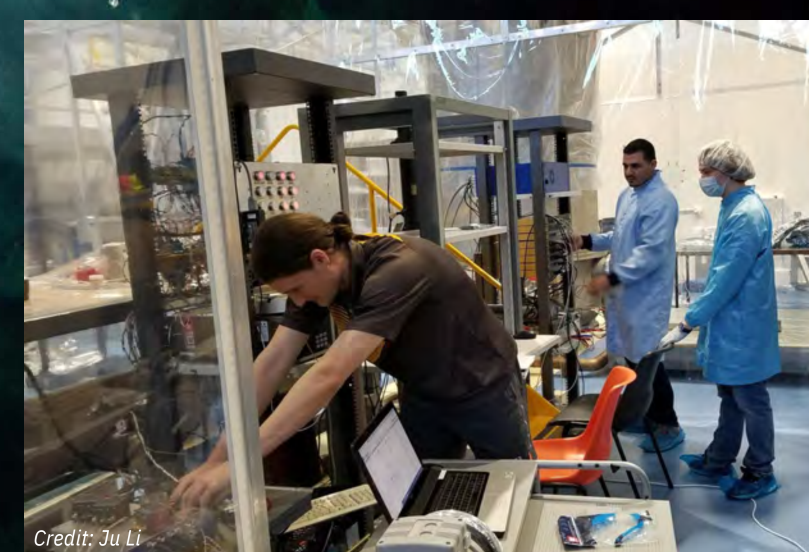
Future plans

All current and future gravitational wave detectors plan to use higher optical power than current detectors. Current detector optical power is limited by optical distortions and instabilities in the test mass optics that have 100's kW optical power incident on them. To achieve planned optical power, some combination of new coating materials, new optic materials, careful design, distortion mitigation strategies, and instability mitigation strategies will be required.

Design work is ongoing for future detectors. OzGrav is involved in this design work with key tasks such as the design of mitigation strategies for parametric instability and the simulation of these detectors with Finesse.

New optic and coating materials are being investigated within OzGrav to address many of the technological challenges associated with these new materials. The High Optical Power Test Facility (HOPF) has one arm dedicated to Silicon optics. Additionally, world class coating facilities are being developed within the collaboration.

OzGrav continues to work on instability mitigation strategies. Optical feedback was demonstrated and provides a promising means to simplify active control of instabilities and we plan to demonstrate a LIGO ready method in 2024. We also continue to work on novel passive damping approaches.



Credit: Ju Li

Aaron Goodwin-Jones' TSAMs construction picture. Credit: Aaron Goodwin-Jones

INSTRUMENTATION THEME

Space

Program chair: Dr Andrew Wade (ANU)

2023 Progress and Achievements

In 2023, the OzGrav Space program continued the themes of low light optical phase recovery and tracking, absolute laser frequency readout and laser frequency stabilization topics for space-based gravity and gravitational wave detectors. Four milestones were set out for 2023, of which three were completed and one partially completed, as described below.

Phase tracking of ultra-weak optical powers: Results from an experiment and analysis on low light tracking for space-based interferometer missions were published in Physical Review Letters [Sambridge et al. Phys. Rev. Lett. 131, 193804 (2023)]. Recovery of optical phase from links between satellites is an essential technology for space-based gravitational wave detectors, such as the planned Laser Interferometer Space Antenna (LISA) mission. Large diffraction losses mean that few photons are recovered. Robust phase tracking and a detailed understanding of noise induced cycle slips is important for de-risking planned space-based gravitational wave detectors. With the publication of this work, laser phase tracking is now proven into the sub-femtowatt regime. This is a world best performance to date. Demonstration of this low light tracking enables new space missions probing GW sources in the μHz band, potentially bridging an important gap between the planned LISA mission's milli-Hz band and the nano-Hz pulsar time array efforts. This demonstration also enables new mission architectures and configurations for climate monitoring mass change missions. This is a major achievement for the OzGrav space science technology effort.

Absolute frequency readout testbed upgrade: Upcoming mass change missions will fly with laser ranging instruments. The lasers will require long term absolute frequency tracking to calibrate ranging and static gravity subtraction for month-to-month mapping of water transport about the earth. Optical cavity free-spectral-range readout has been selected in the baseline designs to estimate laser frequency. Activity in 2023 to complete this milestone has seen the implementation of an improved Iodine frequency reference and upgrades to the flight-like optical cavity. These testbed upgrades will enable testing of engineering and flight hardware for future missions.

Fiber delay line implementation of cavity-arm length locking scheme with submission of results for publication: Work was undertaken to implement a blended feedback control system using a fiber optic delay line and optical cavity for laser stabilization. This work experimentally demonstrated the feasibility of 'arm-locking' schemes in future GW space missions (LISA) where traditional optical cavity laser stabilisation is augmented with the stability offered by the delayed propagation between spacecraft. A publication is in preparation and is expected to be submitted in early 2024.

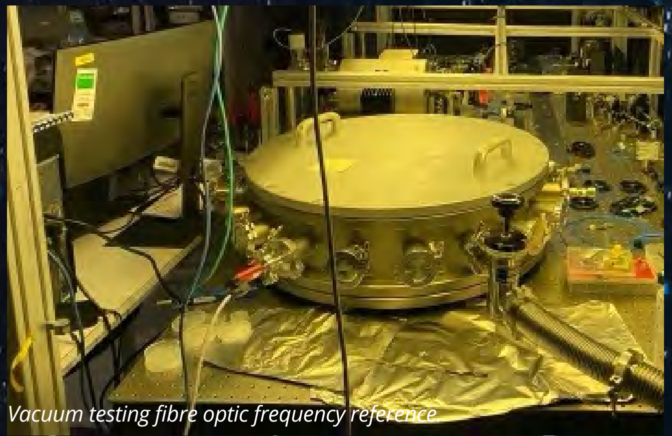
Study of absolute frequency offsets induced by mirror coating dispersion: A study of offsets induced by cavity mirror coating dispersion and geometric effects was initiated. This addresses systematic offsets in the absolute frequency of cavity resonant modes induced by bragg reflector coatings. This will inform calibration of free spectral range (FSR)-based estimates of absolute frequency used for wavelength calibration in future space missions. This is expected to result in publications in late 2024.

Future plans

Space offers a unique environment in which to make high precision measurements for gravitational wave detection. As the field of gravitational wave astronomy matures, missions like the LISA will be increasingly important as the field looks towards the milli-Hertz band. This band is expected to be rich in sources of massive black holes, extreme mass ratio inspirals and compact binaries. Technologies and techniques that offer a pathway to de-risk already launched or committed missions through minimal hardware configuration changes are an opportunity for OzGrav and Australia to actively contribute to this important and growing field. Improved approaches to laser stabilization and optical link phase recovery also offer opportunities to contribute to the baseline designs of future missions. Lower light phase tracking and laser stability offer opportunities for new architectures and mission designs with less stringent requirements and lower risk.

Next steps in this field should leverage OzGrav expertise in low light tracking for future mission architectures for Mass Change Missions beyond the Gravity Recovery and Climate Experiment (GRACE-C) and future space-based gravitational wave detectors. Work in novel laser stabilization techniques, such as delay line arm-locking and Higher-Order-Mode enhances cavity thermal noise mitigation, are also an area of active research with significant potential benefit to the field of space-based laser interferometry.

Following the launch of GRACE-C, future mass change missions will require robust and lightweight laser stabilisation and ranging systems. Fibre based references and atomic frequency references and an area where OzGrav and Australian research has experience and advantage and offer opportunities for improved size, weight, and power improvements for missions of the future.



Vacuum testing fibre optic frequency reference

Pulsar Timing

Program Chair: Prof Matthew Bailes (Swinburne)

2023 Progress and Achievements

2023 was the most productive for pulsar timing yet, with the MeerKAT radio telescope operating flawlessly and collecting data for the Globular Cluster, Relativistic Binaries, Pulsar Timing Array and Thousand Pulsar Array themes. Pulsar Timing User Supplied Equipment (PTUSE) has now completed 39,999 observations of pulsars over more than 4 years of operation. In March 2023 the first data release went public for the Pulsar Timing Array in a paper by Miles et al. (2023, MNRAS, 519,3976). This release included data from 78 millisecond pulsars, each of which had at least 30 observations. 2023 also saw the first observations with the S-band receivers.

Future Detector Planning

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

2023 Progress and Achievements

In 2023, the OzGrav community unanimously endorsed the vision to establish a third-generation gravitational wave observatory in Australia on a 20 year timeline. Recognizing that this vision is outside the scope and timeline of the Centre of Excellence, the community endorsed the establishment of an Executive Committee for the "Australian Gravitational-Wave Observatory Project Office" (AGWOPO) tasked with driving forward the science and business case for an Australian Observatory. The Executive Committee was selected to represent the broad interests of Australian institutes involved in gravitational-wave astronomy, providing requisite skills and expertise in instrumentation, data analysis, and astrophysics. The inaugural committee is: Yeshe Fenner, Li Ju, Paul Lasky (chair), David McClelland and David Ottaway. Given the 20+ year timeline, AGWOPO will operate outside of, but closely, with OzGrav and its successors in pursuing this vision.

While the AGWOPO Executive Committee and OzGrav members are experts in the science, it was recognised that a Project Manager is needed to prepare a preliminary roadmap to seed the business, strategy, and investment case. This will include industry engagement that will allow local and national businesses to bid for, and build, key infrastructure components, and the identification of international partners and investment opportunities for this billion-dollar-scale project. Funding for this position, supported by a Project Scientist, is being sought.

Future plans

Research on developing new detector technologies will continue within OzGrav and its successors in collaboration with the international Cosmic Explorer and Einstein Telescope communities. The high regard for the Australian community was recognised with the awarding of the prestigious 2024 Gravitational Wave Advanced Detector Workshop to Australia, planned for Hamilton Island in May 2024. In addition, OzGrav Director Bailes has been elected Chair of the Gravitational Wave International Committee (GWIC) to serve a two-year term.

DATA AND ASTROPHYSICS THEME

OzGrav's Data and Astrophysics Theme is led by Prof Matthew Bailes (Swinburne) and Prof Eric Thrane (Monash) and encompasses six science programs plus the underpinning supercomputing program:

- Inference - Program chair: Chayan Chatterjee (UWA)
- GW Data Analysis - Program chair: Dr Fiona Panther (UWA)
- Pulsar Detections - Program chair: 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)
- Supercomputing - Leader: Prof Jarrod Hurley (Swinburne)

Credit: Carl Knox, OzGrav-Swinburne

Inference

Program chairs: Chayan Chatterjee (UWA)

2023 Progress and Achievements

The OzGrav Inference program is committed to the development and improvement of Bayesian inference and parameter estimation (PE) tools. These tools are vital for extracting impactful science from gravitational wave (GW) and multi-messenger observations within the Data/Astrophysics theme. In the past year, the focus has been on reviewing and maintaining existing parameter estimation pipelines and developing innovative inference techniques for the LIGO-Virgo fourth observation run (O4). Several OzGrav members have been actively involved in core LIGO activities during O4, including conducting parameter estimation shifts immediately following GW candidate detections. Below is a summary of progress under various projects within this Program:

O4 Activities:

Bilby and parallel Bilby (pBilby) have been reviewed and are now operational with O4 data. Simon Stevenson is serving as the LVK PE review coordinator and is also reviewing pBilby and the reduced order quadrature (ROQ) method for rapid binary neutron star (BNS) parameter estimation. OzGrav members Simon Stevenson, Teagan Clarke, Hui Tong, Rowina Nathan, Shun Yin Cheung, and Christian Adamcewicz have completed shifts in the O4a PE Rota.

Analysis of Interesting GW Sources:

James Paynter and Eric Thrane investigated the properties of supermassive black hole (SMBH) candidate progenitors. The study, concluding with observations of high recoil velocity and spin misalignment, suggests a merged origin in hot gas [Paynter and Thrane; ApJL]. Avi Vajpeyi led a paper on the deep follow-up study of GW event GW151226, analyzing two competing mass ratio-effective spin (q–χeff) posterior peaks. The study concludes that neither hypothesis can be conclusively ruled out [Vajpeyi, Smith, Thrane; ApJ].

Beyond Compact Binary Coalescences (CBCs):

Continuous GWs:

Neil Lu and colleagues Karl Wette, Susan M Scott, and Andrew Melatos developed a method to infer a neutron star's characteristics from continuous GW detections using Fisher matrix and Monte Carlo simulations [Lu, Wette, Scott, Melatos; MNRAS]. Dana Jones led a paper on a novel Hidden Markov Model for detecting continuous GWs from ultralight boson clouds, currently used in O4 Continuous Wave (CW) searches. The study also assesses horizon distances and detectable boson masses for current and future detectors [Jones, Sun, Siemonsen, East, Scott, Wette; PRD].

Modelling Signals and Background:

Teagan Clarke and collaborators developed a phenomenological waveform model for disrupting neutron star-black hole (NSBH) systems, exploring neutron star tidal disruption measurement prospects [Clarke, Chastain, Lasky, Thrane; ApJL]. Rowina Nathan and team introduced the 'dynamic pulse fitting' method for pulsar timing, enhancing the sensitivity to a GW background and finding more null pulses compared to traditional timing [Nathan, Miles, Ashton, Lasky, Thrane, Reardon, Shannon, Cameron; MNRAS]. Valentina Di Marco led a study on Pulsar Timing Array (PTA) experiments' ability to estimate noise backgrounds and novel techniques for GW background detection [Di Marco, Zic, Miles, Reardon, Thrane, Shannon; ApJ]. Rory Smith and Simon Stevenson co-authored a paper introducing a refined ROQ method for parameter estimation, reducing binary neutron star (BNS) sky location search area by about 30% [Morisaki, Smith, Tsukada, Sachdev, Stevenson, Talbot, Zimmerman; submitted].

Machine Learning:

Chayan Chatterjee led a study on a deep learning model for GW sky localization, applicable to all compact binary coalescence sources [Chatterjee, Kovalam, Wen, Beveridge, Diakogiannis, Vinsen; ApJ]. In a follow-up, Chatterjee and Wen adapted the model for pre-merger source localization of BNS sources, showing comparable results to BAYESTAR [Chatterjee and Wen; ApJ]. Damon Beveridge, Linqing Wen, and Andreas Wicenec developed deep learning techniques for binary black hole (BBH) signal detection from noisy data, showing sensitivity comparable to matched filtering methods [Beveridge, Wen, Wicenec; submitted].

Other highlights during 2023 included: running a workshop on GW parameter estimation using machine learning at the OzGrav Winter School 2023; and an OzGrav Research Translation Seed Grant being awarded to Dr. Rory Smith for optimizing surgical implants for jaw fractures, collaborating with anatomist Dr. Olga Pangiotopoulou (Uni Melbourne and Monash).

Case Studies

Robust Detection of Nanohertz GWs:

Several pulsar timing arrays have reported preliminary evidence for a nanohertz gravitational-wave background. However, confident detection is challenging due to systematic errors in pulsar noise models. Quasi-resampling methods, such as sky scrambles and phase shifts, are used to assess the Hellings & Downs correlation significance in data, indicating detection. Di Marco et al. (2023) showed that current quasi-resampling methods might be limited to about 100 independent realizations. They developed a "super scramble" method, increasing independent realizations to about 1000. Statistically dependent scrambles produced well-behaved p-values for hypothesis testing, paving the way for further investigations into the reliability of these methods. This paper was featured in the AAS Journal Author Series: https://www.youtube.com/watch?v=oBnNW5blSU

GW Detection and Parameter Estimation

Pipeline:

The University of Western Australia researchers Chayan Chatterjee, Damon Beveridge, Alistair McLeod and Linqing Wen are developing an end-to-end pipeline centered around deep learning-based detection and sky localization models. This pipeline, the first to use template-based matched filtering outputs for training and inference, is designed for rapid GW discovery and parameter estimation in current and future detector eras. Preliminary results demonstrate that for both binary black hole (BBH) (Beveridge et al., 2023; submitted) and binary neutron star (BNS) signals (McLeod et al.; in preparation) this technique can radically improve the sensitivity of deep learning models for GW detection, which is particularly important for signals with potential electromagnetic counterparts such as BNS and neutron star-black hole (NSBH) binaries. Deep learning models for rapid pre-merger (Chatterjee and Wen 2023; ApJ) and post-merger sky localization (Chatterjee et al. 2023; ApJ) of compact binaries have also been developed, which demonstrate comparable accuracy to standard techniques.

In early 2023, with the support of OzGrav Travel grants, researchers from UWA presented their work at the Accelerating Physics with Machine Learning meeting at Massachusetts Institute of Technology. This meeting resulted in a white paper discussing how physicists are using machine learning in their workflows to accelerate data processing and replace existing domain-specific algorithms (ArXiv:2306.08106). Damon Beveridge, Chayan Chatterjee, Sunil Choudhary, Weichangfeng Guo, Alistair McLeod and Linqing Wen are listed as co-authors in the paper.

Participation at the meeting also led to new collaborations with researchers from various institutes in Taiwan including National Cheng-Kung University and the KAGRA Machine Learning Asian Network for developing machine learning models for real-time data analysis of GWs.

Future plans

In 2024, the Inference program will continue its involvement in core LIGO-Virgo-KAGRA (LVK) activities related to O4. This includes participating in the O4b PE Rota, analyzing GW candidates, and contributing to paper writing.

Collaborations within OzGrav and with external researchers will continue through 2024, with some evolving into the research program of the new OzGrav2 that commences on 1 Apr 2024. Key projects include:

- Digital twin for LIGO's thermal compensation system (Rory Smith and Dan Brown): Designing reduced-order Finesse models for real-time IFO state measurement, with plans to demonstrate at LIGO Livingston and/or Hanford.
- Steady-state point absorber detection algorithm with computer vision and tree-based models (led by Simon Goode) [completed in 2023].
- Developing surrogate models for COMPAS likelihood (Avi Vajpeyi, Jeff Riley, Ilya Mandel, Chayan Chatterjee).
- Machine learning for actuation modeling to minimize low-frequency noise in IFO (Ethan Elliot, Aaron Jones, Carl Blair, Chayan Chatterjee, Shreejit Jadav).
- Machine learning for GW sky localization (Chayan Chatterjee, SPIIR group, researchers from National Cheng-Kung University, Taiwan, and KAGRA Machine Learning Asian Network).
- Developing metrics for high-dimensional distribution comparison (Rory Smith and Ilya Mandel): Focusing on prior distributions and observed strain data.
- Bayesian inference for BBH ringdown tones measurement (Teagan Clarke and Eric Thrane)
- Exploring NSBH as a fast radio burst source (Teagan Clarke and Eric Thrane).
- Development of a search pipeline for generic ML searches on LIGO data (Shreejit Jadav and Jade Powell).
- Microsecond TOV equation solver using neural networks and tree-based models (Spencer Magnall and Simon Goode).
- Investigating cosmic variance in an isotropic GW background (Rowina Nathan, Eric Thrane, Valentina Di Marco, Atharva Kulkarni, Matt Myers, Ryan Shannon).
- Pulsar timing model misspecification (led by Valentina Di Marco).
- Transdimensional Bilby development and science (Hui Tong, Nir Guttman) .
- Fast population inference (Christian Adamcewiz and Hui Tong).
- Model testing for exceptional events inference (led by Lachlan Passenger).
- GW memory inference (led by Shun Cheung).
- Search for vector boson clouds in O4 and place constraints in the absence of detection (Dana Jones and Lilli Sun).

DATA AND ASTROPHYSICS THEME

GW Data Analysis

Program chair: Dr Fiona Panther (UWA)

2023 Progress and Achievements

After a long break, the Fourth LIGO-Virgo-KAGRA observing run began in late May 2023, with the Hanford and Livingston detectors online and gathering data through to mid-January 2024. Despite much of the Open Public Alert system now being automated, the rapid influx of events saw a number of OzGrav members taking part in various levels of the Rapid Response Teams. Rota members included S. Chua, J. Wright, J. Powell, S. Stevenson, D. Beveridge, A. Mcleod, W. Guo, F. Panther and B. Gendre. To date, 60 events have been detected, the majority of which have been tentatively classified as binary black hole (BBH) mergers. The Summed Parallel Infinite Impulse Response (SPIIR) team has been particularly hard at work detecting these events with their low-latency pipeline, with a number of upgrades planned for the second half of O4 to improve the sensitivity of the search.

While new data flows in, many members have continued analyzing the abundance of data from O3. A large number of projects targeting the detection of continuous gravitational wave emission have now come to fruition: Andreas Vargas published work using O3 data to target the low mass X-ray binary Sco X-1, with an improved orbital ephemeris and a new study on how temporal spin wandering of a rotationally-powered pulsar affects the accuracy with which a secular, braking, power-law torque can be measured. Tom Kimpson developed a new method based on adaptive noise cancellation for the subtraction of instrumental lines in gravitational wave data to assist continuous gravitational wave searches. In addition, a series of papers from the University of Melbourne's Andrew Melatos introduced a self-consistent signal processing framework for parameter estimation in the context of X-ray pulsars. This method was then applied to real observational data for the X-ray transient SXP 18.3 by Joe O'Leary. In a second paper, they extended the analysis to 24 X-ray transients in the Small Magellanic Cloud (SMC). In addition, Karle Wette published an invited review offering a retrospective of continuous GW searches.

At UWA, OzGrav members Damon Beveridge, Alistair McLeod and Chayan Chatterjee have made significant in-roads in advancing the use of machine learning to detect gravitational waves. This extends the use of machine learning beyond more typical applications in parameter estimation and event verification, with Damon Beveridge's neural network achieving sensitivities comparable to conventional matched filtering.

Looking far ahead to the future, James Gardner, Lilli Sun and Bram Slagmolen studied how an Australian-based Southern Hemisphere 2.5-3rd generation detector could improve the localization accuracy of gravitational wave detections and boost our chances of multi-messenger detections.

2023 saw the graduation of a number of valued OzGrav members from their PhD and Masters studies: at UWA, Manoj Kovalam and Chayan Chatterjee were awarded their PhD degrees, and Siqi Zhong, Carlo Mungoli and Scott Hardie received their Masters degrees. At the University of Melbourne, Julian Carlin and Andreas Vargas received their PhD degrees, and at the Australian National University, Hank Hua achieved his BSc(Hons) degree, as well as a University Medal and an Honorable Mention for the 2023 Astronomical Society of Australia's Bok Prize.

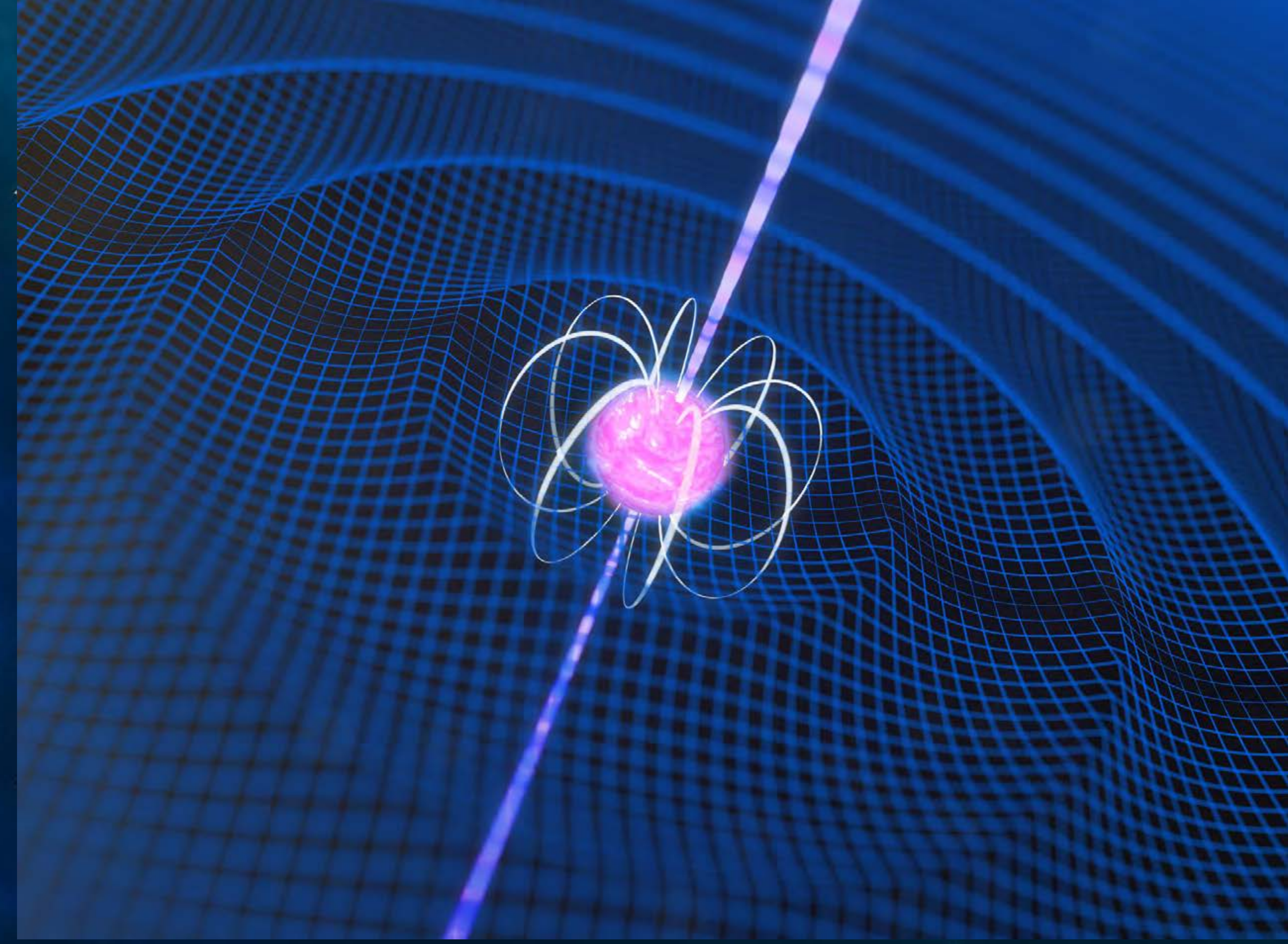
Case studies

Continuous Waves and Continuous Improvements in Gravitational Wave Detection

At the Australian National University (ANU) Node, groundbreaking research into gravitational waves has been advancing through the work of dedicated students under the mentorship of Dr. Karl Wette and Prof. Susan Scott. PhD student Ben Grace made a significant breakthrough in 2023 by developing a novel algorithm for detecting gravitational waves emitted after the collision of two neutron stars. His innovative approach aimed to capture the elusive, high-frequency signals from a potential surviving newborn neutron star, and was published in Physical Review D.

Meanwhile, Honours students Neil Lu and Yuhan (Hank) Hua further advanced the field. Neil's project broke new ground by integrating electromagnetic radiation data to infer neutron star properties from continuous gravitational wave signals, earning recognition with a notable award from the Gravity Research Foundation. Hank extended Neil's work, developing a comprehensive framework for simulating neutron star signals and enhancing parameter estimation techniques using Bayesian inference, culminating in an ANU University Medal and another key publication.

Together, these students' contributions, supported by ANU and an OzGrav Research and Innovation Grant, have extended our understanding of gravitational waves and neutron star dynamics. Their collective efforts demonstrate the power of innovative research methodologies and interdisciplinary collaboration in uncovering the cosmos' secrets.



Artist's impression of a neutron star radiating both continuous gravitational waves and electromagnetic radiation.
Credit: Carl Knox, OzGrav-Swinburne

Future plans

With gravitational wave detectors offline until early March 2024 for a commissioning break, many will be looking forward to the beginning of the second half of O4, when the European Virgo detector will observe in concert with the Livingston and Hanford detectors.

The three-detector network will greatly improve the localization accuracy of gravitational wave detections, offering exciting opportunities to combine gravitational wave data with multi-messenger observations. The improved localization accuracy will enable more precise dark siren measurements of the Hubble Constant, with the era of gravitational wave cosmology being ushered in by the second iteration of OzGrav. In addition, sensitivity upgrades to the detector network will be leveraged to not only detect more binary coalescence events, but to improve analyses led by OzGrav members to test General Relativity and search for dark matter.

In the medium term, there are exciting prospects for the introduction of machine learning into gravitational wave searches. This can yield a significant improvement in the latency of detection, important for searching for multi-messenger counterparts. And with more data than ever, the eyes of many will be turning to searches for continuous gravitational waves.

A detection would prove yet another watershed moment for gravitational wave astronomy, and be an important payoff for the hard work of our OzGrav colleagues who have been refining search techniques over many years.

Looking even further ahead, we must start to think how we would analyze data from our future observatories. Although highly speculative, the discovery potential of these new facilities can only be realized if we are fully prepared for the influx of data that will require the development of novel techniques to disentangle overlapping signals and uncover the currently unknown unknowns that can be revealed by 2.5 and 3rd generation detectors. Australia has made substantial contributions in the analysis of gravitational wave data to date. With a growing base of scientists with the specialized knowledge to develop new analysis techniques and state-of-the-art facilities like Ngarrgu Tindebeek, OzGrav can become a true tour-de-force in gravitational wave data analysis in years to come.

DATA AND ASTROPHYSICS THEME

Pulsar Detections

Program chair: Dr Ryan Shannon (Swinburne)

2023 Progress and Achievements

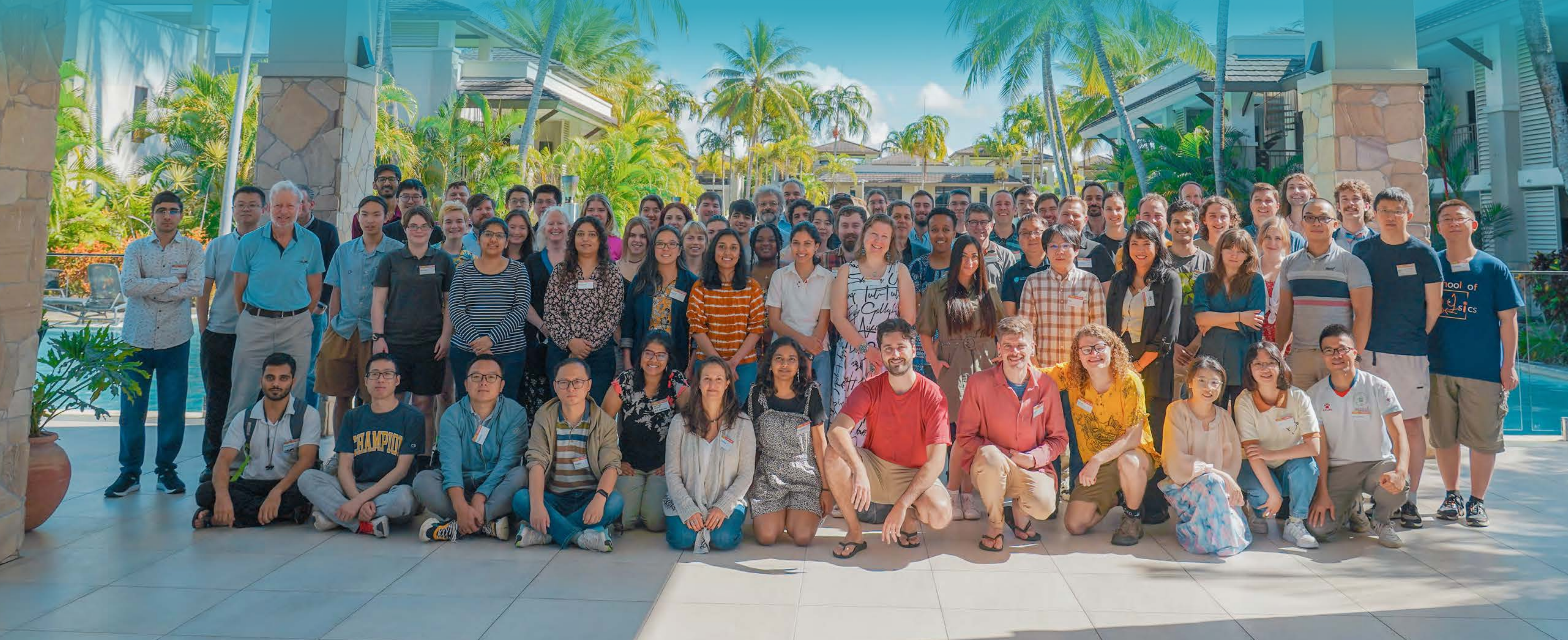
This was a pivotal year in pulsar timing array (PTA) experiments. The major long standing PTA experiments in Australia, Europe, India, and North America announced the results of their latest gravitational wave searches. Searches with the Parkes Pulsar Timing Array (PPTA) were led by Daniel Reardon (Swinburne) and Andrew Zic (CSIRO). The searches showed the strongest evidence to date for evidence of nanohertz-frequency gravitational waves -the detection of which is one the key goals of OzGrav. Further details of these searches are described under Science Highlights.

2023 saw the publication of the first data release from the MeerKAT Pulsar Timing Array, and work continued on producing a second data release from the project. With increased sensitivity to gravitational waves, the second data release is expected to have sensitivity equivalent to that of the current pulsar timing array experiments.

OzGrav co-organised the 2023 International Pulsar Timing Array science meeting and student workshop. The student workshop was held in Sydney at the headquarters of CSIRO Space & Astronomy and was attended by over 50 people in person and 50 online. The Science meeting was held in Port Douglas Queensland. This was the first meeting held in person since 2019. The meeting occurred the week before PTA GW searches were publicly announced and was a great opportunity to share the results of the searches.

Future plans

Pulsar timing array research will soon transition from discovery to study of the gravitational-wave Universe. The MeerKAT Pulsar Timing Array promises to be a vital instrument for pulsar timing array searches. OzGrav researchers are finalsing gravitational wave searches with a 4.5 year MeerKAT data set. Preliminary results from the searches are very exciting, and careful checking is underway. With larger and more sensitive data sets, it will be necessary to develop more sophisticated data analysis tools.



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

2023 Progress and Achievements

Although there have not been many gravitational wave events suitable for follow-up observations, the multi-messenger observations program has made significant progress on facility readiness and ancillary science.

Optical:
The Southern node of the Gravitational-wave Optical Transient Observatory (GOTO) network was deployed in March-April 2023, and commenced operations shortly afterwards. The instrument consists of two mounts each housing eight 40-cm optical telescope assemblies, with a combined field-of-view of approx. 80 deg^2. The GOTO team reported their first detection of a gamma-ray burst afterglow in September 2023.

OzGrav researchers are also working on automating the 2.3m WiFeS pipeline. The new version of the pipeline is now available in GitHub and is functioning well; the next step is to integrate with the online archive to provide the necessary calibrated data to the users. The LIEF-funded Zadko telescope refurbishment was also carried out, with the telescope resuming multi-messenger alert follow-up from October 2023.

The SkyMapper team has successfully transitioned the Alert Science Data Pipeline to Python 3, enabling automated real-time responses to a new General Coordinates Network (GCN) Kafka Broker. As planned in 2023, the fourth catalogues and images from the SkyMapper Southern Survey were released, improving the deep coverage of the southern sky, particularly enhancing capabilities for gravitational wave counterpart searches.

Karelle Siellez is leading multi-messenger transient follow-up using the Harlington H50 (50cm diameter) and H127 (50inch diameter) optical telescopes at the Greenhill Observatory of the University of Tasmania. Their team has followed up 8 transients so far.

PhD student Jim Freeburn and the Deeper Wider Faster team continued their follow-up of the short gamma-ray burst GRB220831A, discovering tentative evidence for the presence of a kilonova. PhD student Natasha Van Bemmel has continued her search for kilonovae.

Radio:

Dougal Dobie led programs on the Australia Telescope Compact Array and the Australian Square Kilometre Array Pathfinder (ASKAP) for follow-up of mergers during O4, triggering on three candidate optical counterparts to S230518h.

Gemma Anderson is leading a search for prompt radio signals from neutron star mergers with the Murchison Widefield Array (MWA) and Transient RApid-response using Coordinated Event Triggering (TRACE-T) using an optimised observing strategy developed by PhD student Jun Tian.

Kelly Gourdji has developed a novel approach for modelling high resolution radio imaging of compact binary merger afterglows, which can provide tight constraints on the merger viewing geometry, break model degeneracies and in turn, improve standard-siren measurements of the Hubble Constant.

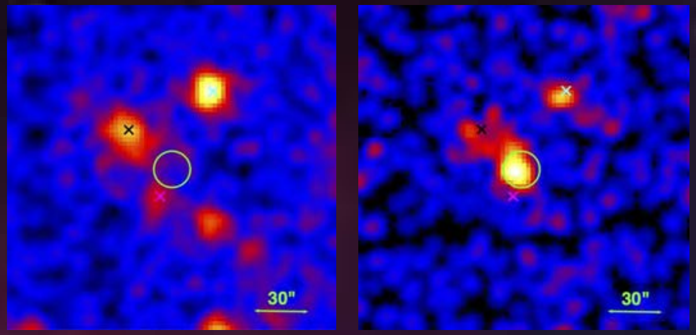
Yuanming Wang led the development of the VASTER pipeline, which has enabled the discovery of a variety of second-minute timescale transients such as pulsars and flare stars.

The ASKAP Variables And Slow Transients Survey (VAST) also completed its first year of observing, resulting in the discoveries of a bright polarised burst from near the Galactic centre (D. Dobie), a highly scattered pulsar (Z. Wang), a new redback pulsar (A. Zic, Z. Wang), a new population of radio stars (J. Pritchard), a variety of orphan afterglow candidates (J. Leung).

Zadko Telescope. Credit: Fiona Panther, UWA

X-ray:

Sonja Panjkov and Katie Auchettl led a study on the progenitor properties and post explosion X-ray evolution of the closest supernova in a decade, SN2023ixf (https://arxiv.org/abs/2308.13101). They were able to place constraints on the mass-loss rate and pre-explosion variability of the progenitor prior to explosion.



X-ray images of SN2023ixf taken with the Neil Gehrels Swift Observatory (left) prior to supernova explosion and (right) post-supernova explosion (Figure adapted from: https://arxiv.org/abs/2308.13101).

Case studies

Minutes-duration optical flares with supernova luminosities

A team involving OzGrav Chief Investigator Jeff Cooke discovered a Luminous Fast Blue Optical Transient (LFBOT), nick-named the 'Tasmanian Devil', which they described in a publication in the prestigious journal Nature. LFBOTs are rare and only a handful are known. They burst with extreme luminosity (over 100 billion Suns - i.e., brighter than supernovae) and evolve quickly, in about a week or so, as opposed to supernovae that take 1-2 months to about a year. The team monitored this LFBOT with 15 telescopes over nearly all wavelength ranges and our group performed Keck observations using Swinburne's Keck access and coordinated the time with NASA Chandra X-ray telescope. Our researchers discovered that this one exploded again, which was very unexpected, as it was assumed that the initial explosion should obliterate the source. Remarkably, it was found to explode with similar luminosity 14 times and likely exploded many more times, as we only were able to observe it when we had access to the telescopes. Moreover, the subsequent explosions were faster than anything witnessed before - some as fast as just 10 minutes. Nothing like this had ever been seen and the physics behind them is currently unknown.

Bringing back to life old giants

Robotic telescopes and observatories play a unique role in helping to understand the sources of gravitational waves, as they can react almost instantaneously to capture electromagnetic signals produced during a GW event before they fade away. The Zadko Observatory has been playing this role for many years, and was in need of an upgrade. After defining a refurbishment plan in 2021, and securing funds in 2022, 2023 was the year of transformation for the observatory! After a year spent retro-fitting its instrumentation and control systems; installing new IT systems; and upgrading its robotic systems; the Zadko Telescope went back online, making its first new observations in December.

As well as its scientific contributions, Zadko is an important facility for key industry partners. The Zadko Observatory continues to engage with international space agencies and hosts several fully autonomous instruments for space surveillance and space traffic management. These agencies include French based Ariane Group, Japanese Space Agency (JAXA), US Defence Department contractor Slingshot and Polish Space Agency (POLSA). The French Space Agency CNES also utilizes the Zadko Telescope for Near Earth Asteroid follow up. In conjunction with UNSW the Zadko Telescope has also joined the International Asteroid Warning Network (IAWN) to monitor, track and categorize Near Earth Asteroid's as part of a global space defence project coordinated by NASA.

An artist's concept of a Luminous Fast Blue Optical Transient. Credit: NASA, ESA, NSF's NOIRLab, Mark Garlick , Mahdi Zamani

DATA AND ASTROPHYSICS THEME

A new Australian telescope for transient discovery

2023 saw the deployment of a new Australian telescope designed for detecting the optical counterparts of gravitational wave sources, Gravitational-wave Optical Transient Observatory (GOTO)-South. This instrument, located at Siding Spring Observatory, NSW, is part of an international network led by Warwick University (UK), with a second site at La Palma, Canary Islands. The GOTO instruments promptly and autonomously respond to various astronomical triggers, including from LIGO/Virgo and gamma-ray satellites. Since deployment, the combined network has been operating smoothly and successfully detecting new astronomical objects, and eagerly awaiting the first binary neutron-star or neutron star-black hole LIGO detection.

Future plans

OzGrav has built world-class facilities and developed follow-up capabilities over the past seven years that has elevated Australia as a leader in the field of gravitational wave follow-up, and transient astrophysics more broadly. More specifically, OzGrav members are key players in the GOTO collaboration, with the GOTO-South Telescope which is located in Siding Springs now online and detecting not only potential gravitational wave counterparts, but also a wide variety of transients. It is clear that GOTO will continue to be an important survey for discovering, and following up a wide range of transients, especially as we move into the era of the Vera Rubin Obsrevatory. The automation of the ANU 2.3m WiFeS telescope has led to a significant increase in papers, and spectroscopic follow-up/discoveries in which WiFeS has played a key part. Zadko will continue to play a key part in multi-messenger alert follow-up.

The dynamic radio sky is ripe for exploration and OzGrav members are well-placed to lead the major discoveries over the coming years. The OzGrav radio follow-up program will provide calorimetry for a variety of mergers, while the high resolution imaging techniques developed within OzGrav will enable the direct measurement of merger inclination angles. The ASKAP Variables And Slow Transients Survey (VAST) survey is carrying out the first comprehensive widefield search for image-domain radio transients and will detect orphan afterglows, provide serendipitous coverage of multi-messenger transients and ultimately probe a completely unexplored parameter space.

Background Image: GOTO Telescope. Credit: http://goto-observatory.org

DATA AND ASTROPHYSICS THEME

Relativistic Astrophysics

Program chair: Dr Ryo Hirai (Monash)

2023 Progress and Achievements

2023 was yet another successful year of breakthroughs and achievements in the Relativistic Astrophysics program within OzGrav. Although the first half of the O4 run did not discover any neutron star-related merger events, significant theoretical progress was made in the meantime.

Testing GR and extreme matter physics:
The quest to understand the physics of neutron stars continues to be one of the main focus points of the program. Several studies were carried out to investigate the complicated physics of neutron star interiors. The University of Melbourne group showed how the superfluid vortices are even more complicated than previously thought (Thong, Melatos, Drummond 2023) and how the pulsar glitch rates can help constrain the forces acting on such vortices (Melatos, Millhouse 2023). The Monash group led a demonstration of how the gravitational waves from the inspiral phase of NS-BH mergers could be used to constrain nuclear physics, but unfortunately not much more information can be gained than binary neutron star mergers.

Great progress was made to improve pulsar timing techniques that are crucial for constraining properties of neutron stars. It was shown that the anomalous pulsar braking indices are the result of timing noise and a criterion for when this happens was derived (Vargas, Melatos 2023). A new technique applicable to X-ray pulsar timing data was developed which can measure the star's magnetic moment and accretion efficiency independently (Melatos, O'Neill, Meyers, O'Leary 2023).

Perhaps a notable achievement this year was the development of an in-house numerical relativity code. In the work led by Spencer Magnall, they combined the smoothed particle hydrodynamics code Phantom with the numerical relativity code Einstein Toolkit to perform Lagrangian hydrodynamic simulations (Magnall et al. 2023). They so far apply this to cosmological applications but there are many exciting opportunities lying ahead with this new tool.

Gamma Ray Bursts (GRBs) and multi-messenger astronomy:

Gamma Ray Burst (GRB) 211211A was a local (350Mpc) event that is most likely from a binary neutron star (BNS) merger. A study led by the Monash group shows this could have been observed with proposed O5 sensitivity (Sarin, Lasky, Nathan 2023). Future detections of similar events will be useful in constraining the merger rate, beaming fraction and jet-launching fraction of GRBs.

As an alternative way to detect binary black hole mergers, high-energy neutrinos may be useful (Zhu 2023). In this new model proposed by OzGrav researcher Jin-Ping Zhu, if the merger occurs in an active galactic nuclear disc, the accretion onto the new-born black hole could form a jet that creates high-energy neutrinos at the head and this could be observable with neutrino detectors like IceCube.

Core-collapse supernova:

Numerical investigations of the core-collapse of massive stars provide us more insight into the physics of supernova explosions. This year, Jade Powell (Swinburne) and collaborators explored the impact of magnetic fields on the explosion of the higher mass stars and how it may influence the remnant properties and gravitational wave emission (Powell et al. 2023a). They also showed that it is possible to distinguish between different explosion mechanisms from the gravitational wave signatures (Powell et al. 2023b).

Case studies

Apparent dispersion pulsar braking index measurements caused by timing noise

The long-term evolution of a pulsar's braking torque, examined by measuring braking indices through timing experiments, provides insights into the physics of these objects' magnetosphere and interior. In special cases, theoretical predictions propose braking torques proportional to a power of the spin frequency, with the exponent aligning with the braking index in the absence of stochastic fluctuations. Examples of power-law braking include electromagnetic radiation (braking index equal or close to three) or gravitational-wave radiation from a mass quadrupole (braking index of five). While some pulsars show braking indices consistent with electromagnetic origins, others exhibit "anomalous" braking indices, which greatly exceed the standard electromagnetic value, suggesting an alternative mechanism is at play.

Vargas & Melatos (2023) explore a plausible explanation for this experimental results, where the deterministic, power-law braking torque is maked by a stochastic process which dominates the second time derivative of the spin frequency over typical observational time-scales and produces temporal wandering of the spin frequency — an instance of timing noise. The paper shows through analytical calculations, Monte Carlo simulations involving synthetic data, and modern Bayesian timing techniques, that the variance of measured braking indices scales with the square of the timing noise amplitude. The results include an analytically derived inequality, confirmed through Monte Carlo simulations, which delineates the required timing noise amplitude for anomalous braking indices. Said Inequality may prove helpful in analyzing and interpreting real data in the future.

Possible extensions of this work include the use of real data, pulsar population studies, and similar studies using synthetic data generated using different braking torque models.

Future plans

As the relativistic astrophysics program is closely related to all the other programs in OzGrav, it greatly benefits from the developments in all fields. The O4 run by the LIGO/Virgo/KAGRA collaboration so far has provided great insight into the populations and properties of massive black holes. We expect even more knowledge to be gained in the second half of the run, planned to resume in 2024, as well as the O5 run and future gravitational wave detectors (Cosmic Explorer, Einstein Telescope, NEMO).

First light of the Vera Rubin Observatory is anticipated to happen in 2024. The Vera Rubin Observatory will be a complete game changer in terms of time-domain astronomy, discovering millions of transients every day. We should all prepare in advance for the huge influx of data, both by developing analysis tools as well as making theoretical predictions of what kind of transients to anticipate.

In parallel with the observational advances, we will need to continue pure theoretical investigations of extreme matter physics and general relativity. For example, continuous waves from neutron star mountains are yet to be discovered. Preparing detection tools as well as modelling attempts of such mountains and their waveforms will be one of the key steps going forward. The mechanism of neutron star kicks is still poorly understood and will benefit from observational and theoretical constraints. The new Lagrangian numerical relativity code should have many applications such as binary neutron star mergers and core-collapse supernovae. The list of key areas in the field goes on and we hope to make significant contributions from OzGrav in the years to come.

Population Modelling

Program chair: Dr Simon Stevenson (Swinburne)

2023 Progress and Achievements

Former OzGrav member Isobel Romero-Shaw led a paper examining the formation of high-mass X-ray binaries using the binary population synthesis code Compact Object Mergers: Population Astrophysics and Statistics (COMPAS), finding that systems like Cygnus X-1 can only be reproduced with reduced stellar winds and an updated treatment of binary mass transfer.

Poojan Agrawal and the team behind the next-generation population synthesis code, METISSE, expanded the software to model the evolution of interacting binaries, and used it to examine the formation of neutron star and black hole binaries.

Riley and Mandel (2023) developed a surrogate model for COMPAS using neural networks. They used this to perform population inference on parameters governing the cosmic star formation history using gravitational-wave observations.

Liana Rauf and collaborators combined COMPAS with the semi-analytic galaxy formation model SHARK and studied the host galaxies of binary black hole mergers.

Interested in checking out COMPAS? Try out the new web portal www.gwlandscape.org.au, where you can run COMPAS interactively in the browser, and download data behind the papers.

Studying the population of binary black hole mergers, Monash student Christian Ademcewicz and collaborators found evidence for a compelling correlation between the binary mass ratio and the effective spin, which may have important implications for the formation channels of merging binary black holes.

Payne and Thrane (2023) developed the maximum population likelihood, a statistic useful for diagnosing how well a population model fits a set of observations.

Monash postdoc Evgeni Grishin and collaborators studied the influence of thermal torques on the formation of migration traps (where binary black holes may form) in active galactic nuclei (AGN), finding that they preferentially exist in low-luminosity AGN.

OzGrav members published a trio of papers discussing the natal kicks of neutron stars. O'Doherty et al. studied the potential kicks of a large sample of binary pulsars. Shamohammadi et al. (2023) used pulsar timing data from MeerKAT to study the velocities of a sample of millisecond pulsars. Kapil et al. (2023) calibrated the physical supernova models of Mandel & Mueller 2022 using a sample of young pulsars with velocities well measured with very long baseline interferometry.

OzGrav postdoc Ryo Hirai continued his studies of supernova companion interactions, demonstrating that observations of a companion post-supernova can potentially constrain the pre-supernova binary properties and shed insights into common envelope evolution.

Recent OzGrav graduate Reinhold Willcox (Monash) studied the impact of the stability of mass transfer on the evolution of binary stars.

OzGrav postdoc Jin-Ping Zhu has been studying magnetar-driven supernovae along with his collaborators, including looking at the formation of fast-spinning neutron stars in close binaries and magnetar-driven stripped-envelope supernovae. Jin-Ping has also studied the formation of lower mass-gap black hole-neutron star binary mergers through super-Eddington accretion.

The LIGO/Virgo/KAGRA GWTC-3 catalogue paper was finally published in 2023, as was the companion paper describing the population properties. Both papers were published in Physical Review X. The ongoing fourth LIGO/Virgo/KAGRA observing run (O4) will double/triple the known gravitational-wave population and open up exciting new opportunities to learn about the population and its origins.

Future plans

The upcoming fourth gravitational-wave transient catalogue (GWTC-4) will vastly expand the size of the known gravitational-wave population. This larger population will allow us to more precisely resolve features in the mass and spin spectra, more tightly constrain the merger rates of binaries containing neutron stars, and will create new opportunities to search for correlations between binary parameters such as mass and spin. With these new insights, astrophysical models will be updated, refined and combined to explain the global population.

DATA AND ASTROPHYSICS THEME

Supercomputing

Leader: Prof. Jarrod Hurley (Swinburne)

2023 Progress and Achievements

A major achievement for 2023 was finalising the installation of the Ngarrgu Tindebeek supercomputer to bring it online alongside OzSTAR as an expanded OzSTAR supercomputing environment. We gradually introduced OzGrav test users onto Ngarrgu Tindebeek throughout March 2023 and achieved full deployment shortly afterwards. Ngarrgu Tindebeek comprises 182 compute nodes with 11,648 AMD EPYC 7543 compute cores and 88 NVIDIA A100 80GB GPUs. This is in addition to the 4,212 Intel Skylake compute cores and 230 Nvidia P100/V100 GPUs available on OzSTAR. Both supercomputers are networked to the same lustre filesystem for data storage. Related work included upgrading the operating system on all compute nodes to present an enhanced overarching OSTAR supercomputing environment to all OzGrav users. A large part of this work was building the software applications stack: synchronising the software module trees across various architectures and building modules on the compute nodes to work with the new operating system. This represented a significant change in the supported software architecture.

The Swinburne OzSTAR supercomputing environment continued to provide vital data and computing resources for OzGrav researchers throughout the year with an impressive 99% uptime. OzGrav usage in 2023 was spread across 44 distinct research projects and over 160 users. The combined OzGrav usage was 29% of the available resources averaged over 2023 which represents 26 million hours of data processing and simulations. Healthy usage was reported across the Monash, Melbourne, Swinburne, ANU and UWA nodes.

Work continued on the Open Science Grid (OSG) deployment at Swinburne which sits between the High Performance Computing (HPC) and OpenStack cloud environments at Swinburne, accepting jobs submitted by LIGO users through the OSG head-node. We continued to work with LIGO OSG staff on testing different job types and coordinating OSG resource sharing on the nodes. Regular system updates were performed. We also experimented with different virtual machine (VM) sizes to improve the stability of the deployment and performed a network migration for the OSG nodes.

Computational support was also provided for gravitational wave researchers through the HPC helpdesk ticketing system on OzSTAR. In particular, users were assisted with migration of workflows to the new operating system on OzSTAR. This included extensive help for creating containerised workflows.

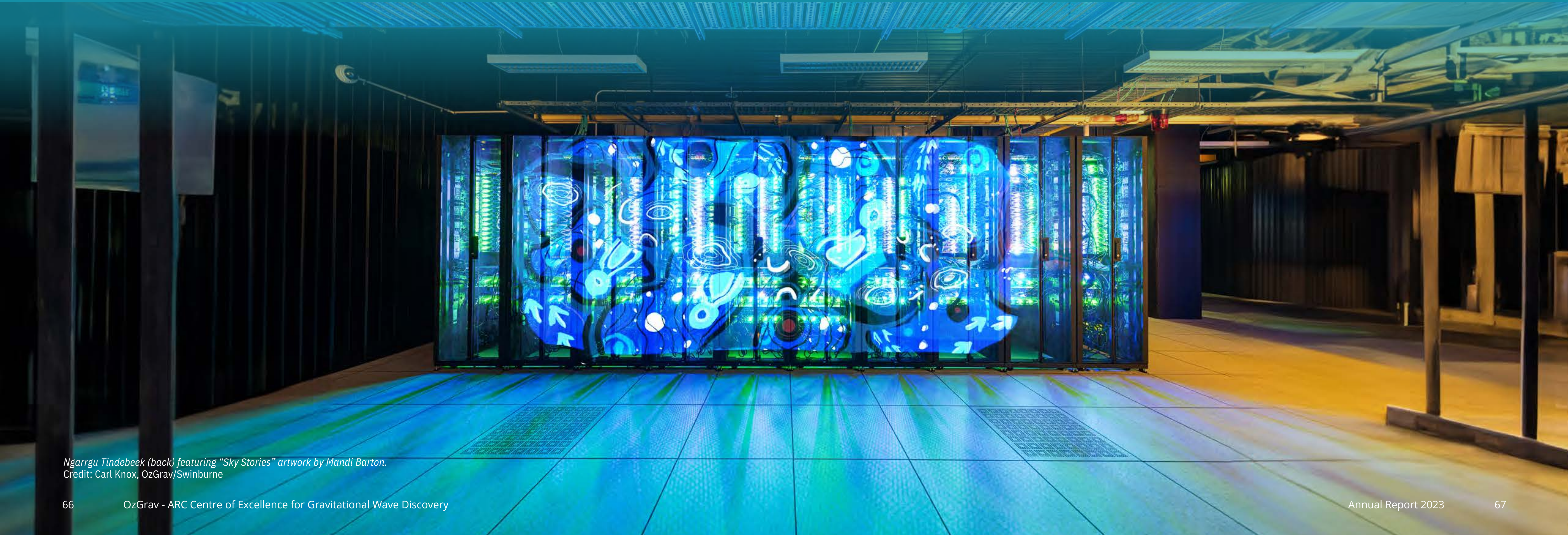
The Swinburne CernVM File System (CVMFS) server continued to be heavily relied upon by the Australian research community. This serves data and software packages to Australian gravitational wave researchers (bandwidth approx. 400 GB/month), which benefits OSG jobs running on OzSTAR, as well as any workflows relying on a CVMFS client. O4 was served to Australian LIGO researchers via this server. Additionally, this data is also mirrored on OzSTAR's parallel file system to provide high speed access to researchers on the supercomputer. Regular maintenance and updates were performed for the server.

Crucially, further funding was secured to continue operating the Gravitational Wave Data Centre (GWDC) through to mid-2026. OzGrav researchers worked closely with GWDC technical staff to perform software development across various key projects: 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. SPIIR received support for code development (e.g. the online monitoring system) and the LVK review process. Highlights for GWCloud included changes to allow unauthenticated users to be able to access the system and implementation of an advanced job search capability. GWLab saw work to complete the integration of the three system modules and an extensive round of "expert walkthrough" user testing. GWLandscape also experienced changes arising from a user testing campaign and a range of software development activities, e.g. creation of a publications module and API. Activities for MeerTime included implementing support for data from the Molonglo telescope and adding the ability for authenticated users to find and directly download data for specific pulsar observations.

Future plans

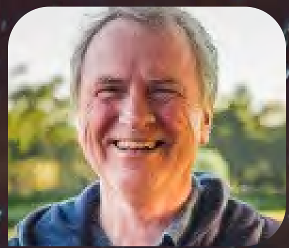
For the supercomputing environment the focus in 2024 will be on commissioning new hardware to upgrade the storage component of the facility. This will remove dependencies on older disk enclosures, metadata servers and network routers, as well as expand the capacity to approximately 16 petabytes. Preparatory work is complete and we will be aiming to bring the new hardware online with minimal disruption to users. There will also be ongoing work to support users, improve documentation, upgrade the accounts system, perform operating system updates and install software.

The Gravitational Wave Data Centre (GWDC) in 2024 is aiming to prioritise alignment with the needs of the LIGO Computing and Software (CompSoft), looking to establish key areas where the GWDC can make direct contributions to the International Gravitational Wave observatory Network (IGWN) computing effort. This will include contributing effort to the Open Science Grid (OSG) and enabling gravitational wave science on OzSTAR – both existing areas of work – as well as continuing to support the key GWDC projects (including work on upgrading the existing infrastructure).



Ngarrgu Tindebeek (back) featuring "Sky Stories" artwork by Mandi Barton.
Credit: Carl Knox, OzGrav/Swinburne

PEOPLE OF OZGRAV - INSTRUMENTATION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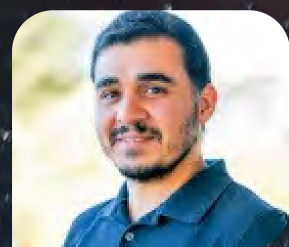
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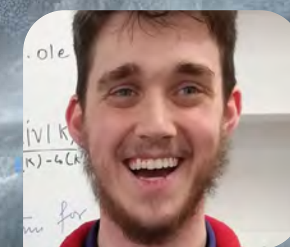
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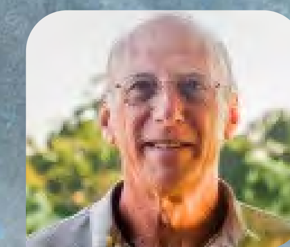
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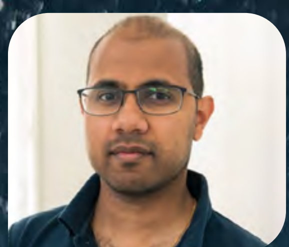
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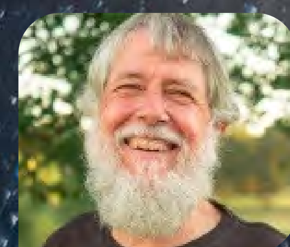
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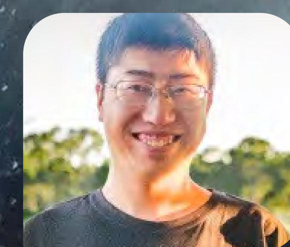
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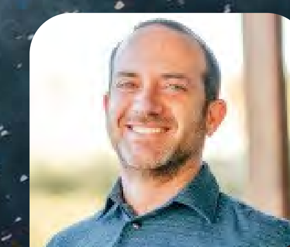
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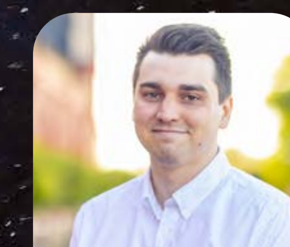
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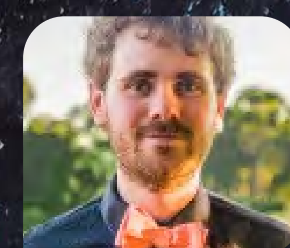
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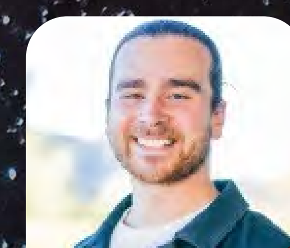
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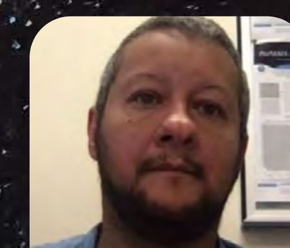
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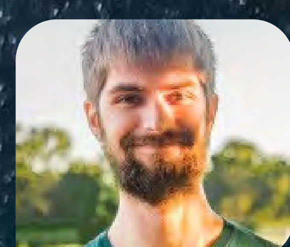
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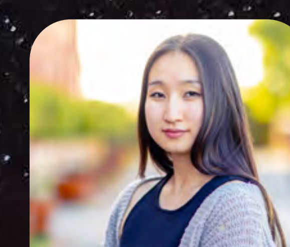
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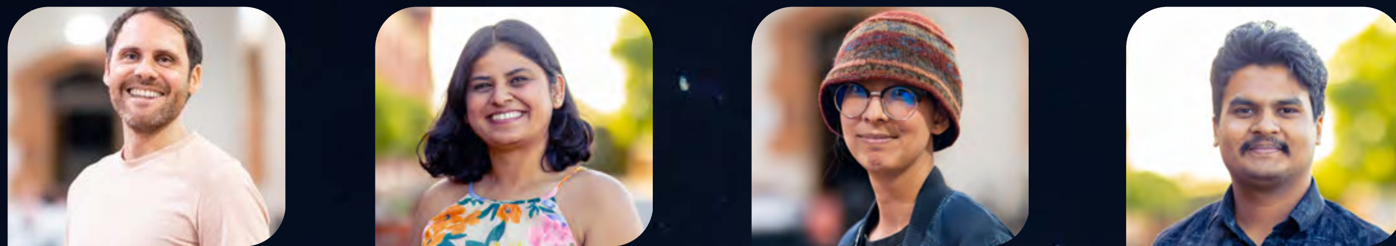
PEOPLE OF OZGRAV - INSTRUMENTATION



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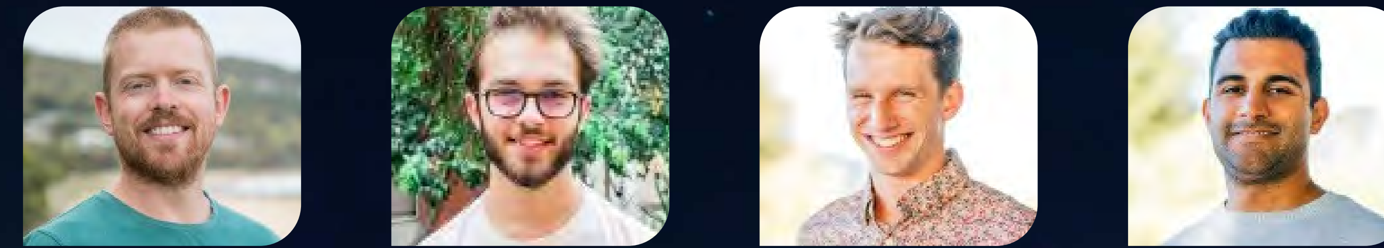

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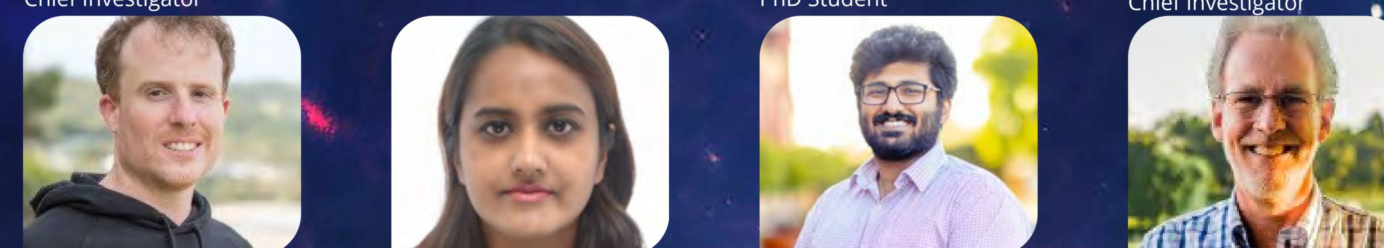

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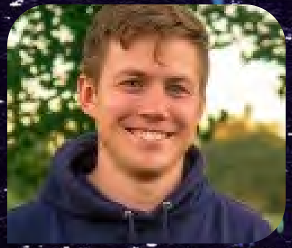

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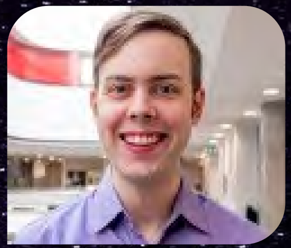

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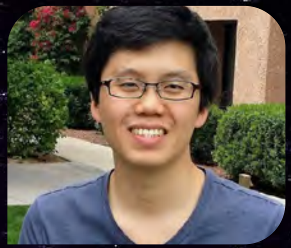

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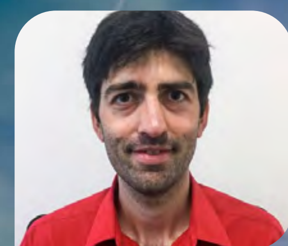
Prof Rob Evans
University of Melbourne
Chief Investigator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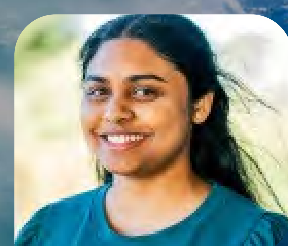
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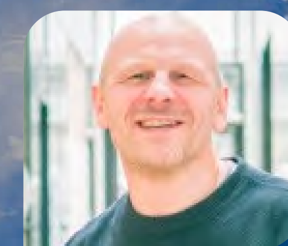
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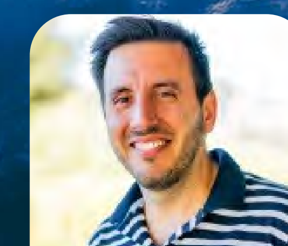
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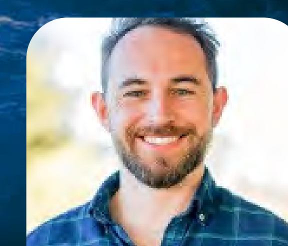
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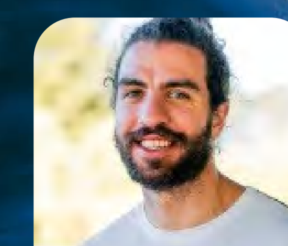
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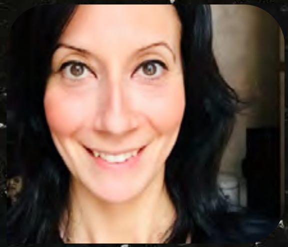
PEOPLE OF OZGRAV - DATA AND ASTROPHYSICS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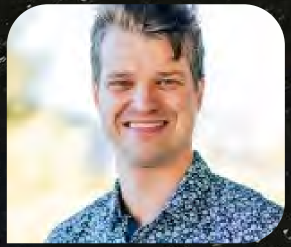
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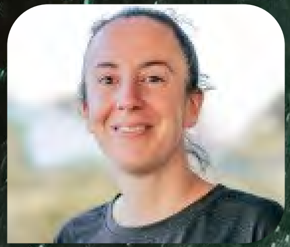
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Distinguished Professor Susan Scott
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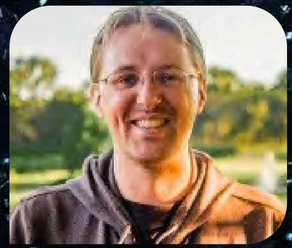
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Supercomputing infrastructure
Gravitational Wave Data Centre


Ruby Chan
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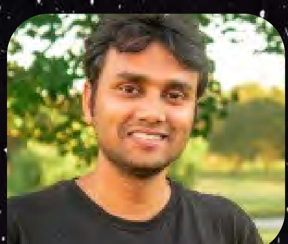
Node administration and Outreach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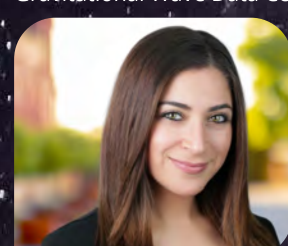
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Node Administration and Events Officer


Deon Hickey
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Lisa Horsley
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Non OzGrav node
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Outreach


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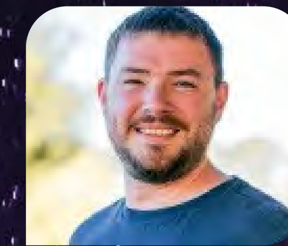
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UX UI Software Engineering
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Undergraduate
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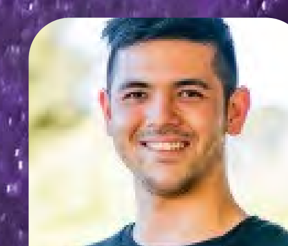
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Dr David Liptai
Swinburne University of Technology Professional Staff

KEY PERFORMANCE INDICATOR (KPI) DASHBOARD

KEY PERFORMANCE INDICATORS

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
Institute of Photonics and Electronics, Czech Academy of Sciences
IPHT - Leibniz Institute of Photonic Technology
Istituto Nazionale di Fisica Nucleare (INFN)
Kavli Institute for Theoretical Physics China
Keck Observatory
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
Observatoire de la Côte d'Azur
Polish Space Agency
Quaisr
Syracuse University
Tsinghua University
UCLouvain
University of Arizona
University of Auckland
University of Birmingham
University of California Riverside
University of Florida
University of Glasgow
University of Hamburg
University of Minnesota
University of North Carolina - Chapel Hill
University of Otago
University of Rome
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
Magellan Power
Promentor P/L
University of Queensland
University of Sydney
Xcalibur Multiphysics

LIGO-Virgo-KAGRA Scientific Collaboration (LVK)

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. 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.

In 2020, KAGRA Japan joined the collaboration and we have become 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 Scientific Congress is composed of over 460 members from 115 institutes in 14 countries/regions.

National and International leadership roles

OzGrav researchers make significant contributions to major national and international collaborations and peak bodies through leadership roles e.g. as chairs of working groups and serving in other key management roles.

- Dan Brown: LSC Adv. Interferometer Configurations WG Chair
- Phillip Charlton: LSC Co-chair of detector characterisation for the stochastic working group
- Eric Howell:
  - Co-chair of GW/FRB search team
  - chair of paper writng team for O3b search for GW counterparts to FRBs (2023 and 2024)
- David McClelland:
  - Australian LIGO Principal Investigator
  - Member of Cosmic Explorer Project Advisory Board
- Jade Powell: LVK Burst working group Chair
- Simon Stevenson:
  - LSC CBC PE Review Coordinator
  - Member of the AAL Science Advisory Committee
- Bram Slagmolen: LSC Seismic Isolation & Suspensions WG Chair
- Ling (Lilli) Sun: LSC Calibration WG Co-chair
- Matthew Bailes:
  - LSC Standards & Conduct Committee Chair
  - Chair of the Gravitational Wace International Committee
- David Ottaway: Chair of the LIGO Program Advisory Committee
- Paul Lasky: AAL Board member
- Eric Thrane:
  - Chair, NCA Time Domain and Multi-Messenger Astrophysics Working Group
  - Chair, IPTA Detection Committee
  - Member, AAL Project Oversight Committee
  - Member, ASA Time-Domain Astronomy Steering Committee
- Daniel Reardon: International Pulsar Timing Array Steering Committee member
- Jeff Cooke:
  - Principal Investigator of the Keck Wide-Field Imager project
  - Principal Investigator of LSST (Australian Data Science)
  - Member of Science 20 Committee as part of the G20 meeting
- Ryan Shannon:
  - Member, International Pulsar Timing Array Steering Committee
  - Member, Parkes Pulsar Timing Array Steering Committee
- Ilya Mandel:
  - Chair, steering committee of the Australian National Institute for Theoretical Astrophysics
  - Vice President, IAU Binary and Multiple Star Systems Commission
  - International Statistics Institute (ISI) Astrostatistics Special Interest Group Management Committee
- Fiona Panther: LVK EM Taskforce chair
- Duncan Galloway: Co-chair of GOTO steering committee

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

FINANCE

	2023 Forecast	2023 Actuals	2024 Forecast
INCOME			
ARC Centre Grant	$5,169,455	$5,169,455	
Institutional cash contribution	$1,152,500	$1,016,849	
Other income		$26,896	
Total Income	$6,321,955	$6,213,199	$-
EXPENDITURE			
Salaries & scholarships	$6,000,686	$5,986,305	$3,078,862
Equipment & Software	$435,783	$144,801	$74,474
Travel, Meetings, Workshops	$1,629,547	$1,478,651	$760,496
Research maintenance and consumables	$381,698	$319,188	$164,164
Outreach, operations and other expenditure	$686,966	$454,451	$233,732
Total Expenditure	$9,134,681	$8,383,396	$4,311,729
Carry-forward from previous year	$6,481,926	$6,481,926	$4,311,729
BALANCE	$3,669,199	$4,311,729	$-

***The 2023 institutional cash contribution was lower than in the original budget. Two nodes had made advance payments in previous years. The total institutional cash commitment over the seven-year lifetime of the Centre was honoured.**

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 the 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 the Australian education, research, engineering and business sectors. This committee is responsible for advising 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 is responsible for overseeing the identification and management of commercialisable technologies developed under the Centre, and advising 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 & Node Leader
Australian National University

Prof David Blair - Outreach Leader
University of Western Australia

Prof Robin Evans - Research Translation Leader
Australian National University

Prof Jarrod Hurley – Node Leader
Swinburne University of Technology

Prof Andrew Melatos – Node Leader
University of Melbourne

Prof Susan Scott - Career Development Leader
Australian National University

Prof Eric Thrane – Node Leader
Monash University

Prof Peter Veitch – Node Leader
University of Adelaide

Prof Chunnong Zhao – Node Leader
University of Western Australia

Prof Tara Murphy (observer)
University of Sydney

Prof Tamara Davis (observer)
University of Queensland

Equity, Diversity and Inclusion Committee Committee

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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
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Dr Kelly Gourdji
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Dr Eric Howell
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