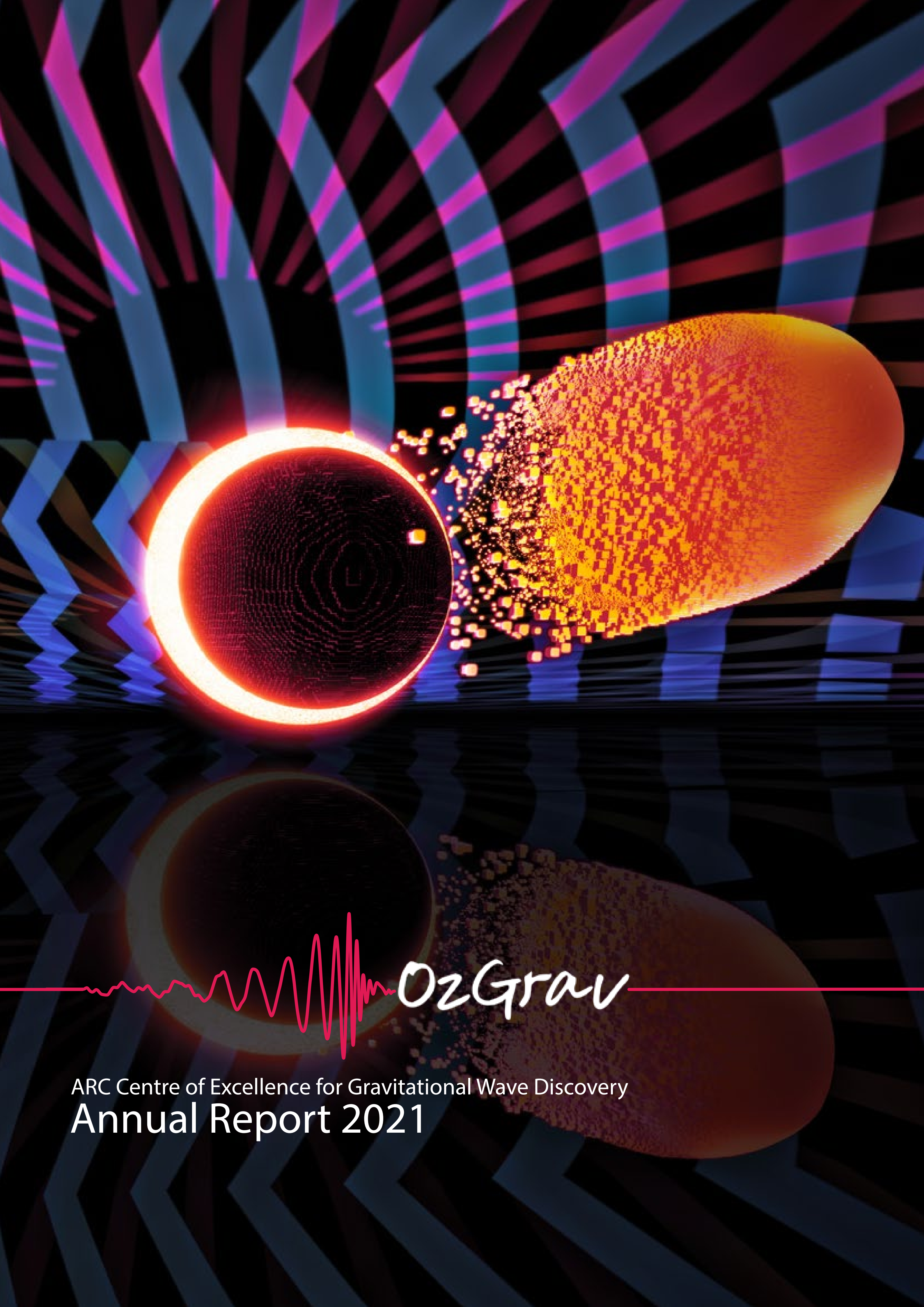
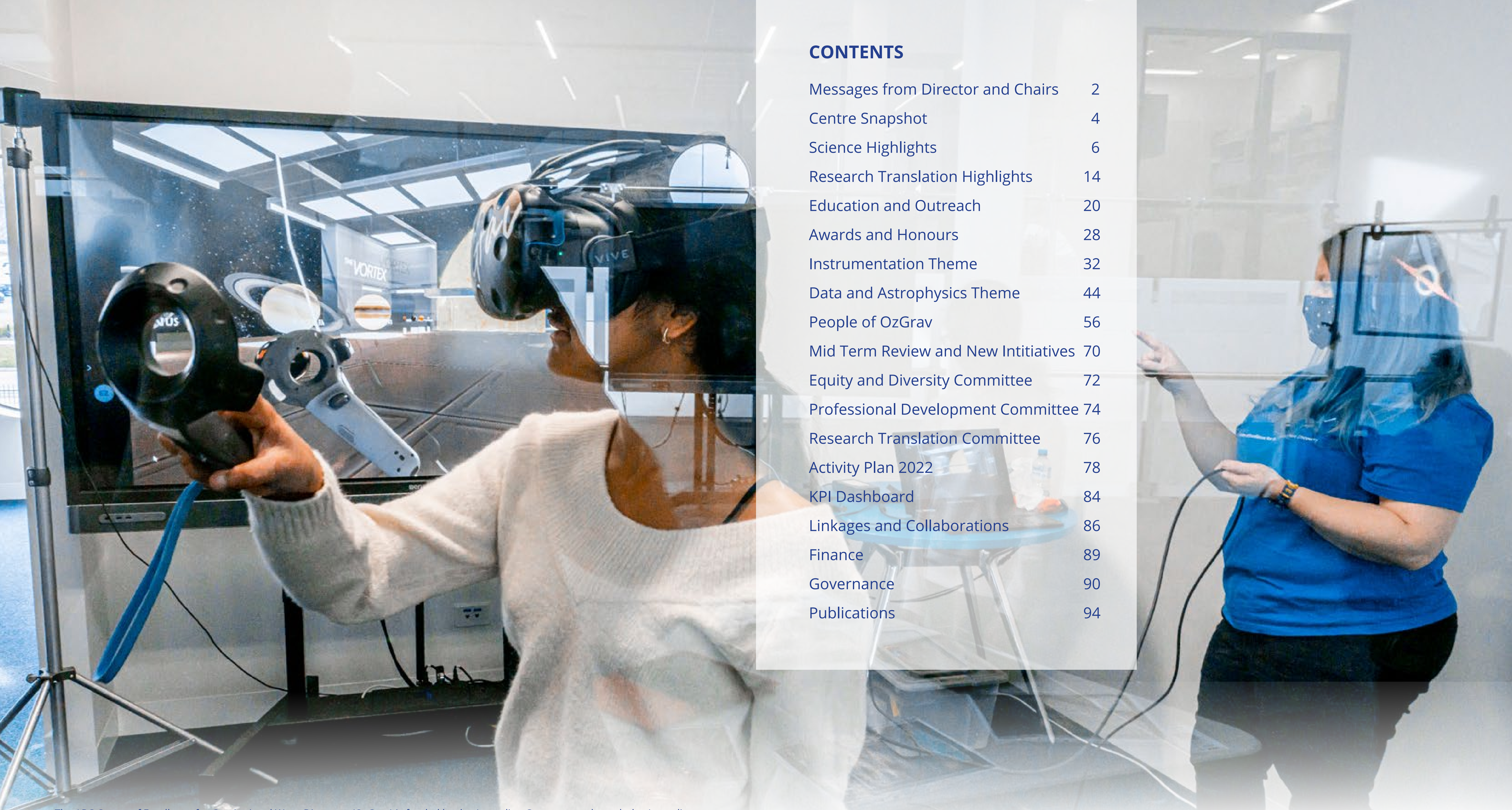


OzGrav

ARC Centre of Excellence for Gravitational Wave Discovery

Annual Report 2021



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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.

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.

Image credit: All background images (unless stated) and artwork with thanks to Carl Knox, OzGrav Swinburne

MESSAGE FROM THE DIRECTOR

Welcome to the fifth OzGrav annual report. As usual it is a visual feast and provides a nice summary of the activities that we've been engaged in over the past year and nicely captures the vibe present across our nodes. I'm grateful to the admin team for all aspects of this year's report, and to all our members for their achievements. Congratulations!

I began my tertiary education at the University of Adelaide (current OzGrav node!) shortly after the first evidence for the existence of gravitational waves had been hinted at in the early 1980s. In that time gravitational waves have gone from a theoretical conjecture to a reality, and we now have over 90 examples of them as neutron stars and black holes collide in the distant Universe that you can read about in this report.

After four decades in the sector I can attest to the immense value that Australian Research Council (ARC) Centres of Excellence provide. Although the hurdle to obtain a Centre is high, once cleared it gives a unique opportunity to plan research for seven years. One of the things the ARC has done very well is to almost fully-fund centre bids, negating the need to have to radically modify the original plans. Another is to insist on an admin team. A Chief Operating Officer with proper support releases our scientists to think about their science in an extremely fiscally-restrained sector where such support is sadly under pressure. Finally, I've noticed that the number of collaborations across our nodes are surging, and I'm confident that these are arising because of the Centre's frequent interactions and growing familiarity between our members. Centres transform our normal other university competitors for funding into colleagues, and lead to professional friendships and familiarity that is extremely healthy. I've never seen an ARC scheme work as well as the Centres at building long-lasting collaborations between institutions. I think this is a combination of the level of funding, the guaranteed admin support, and the longevity of the program.

This year OzGrav was externally reviewed as part of its mid-term ARC process. Over two days the panel met with different groups from within the Centre, and the process and result was very positive. The panel provided positive and constructive feedback on our performance against the objectives of the Centre of Excellence scheme, commenting on our innovative and internationally-recognised research, the strength of our team, and the Centre's cohesion in bringing together a broad set of sub-disciplines. We were grateful for the panel's time and consideration in providing this feedback along with recommendations to help us continue to improve the Centre and support our members at all levels.

In this issue you'll find highlights including the results of our first ever neutron star and black hole merger detections, and the completion and delivery to LIGO of key pieces of instrumentation to improve the detectors, representing the culmination of years of effort. I commend our researchers on their significant achievements during another year that was challenged by the global pandemic, including impressive progress across our science themes, increased momentum and outcomes from our research translation program, and inspiring the general public and engaging students in STEM through our education and outreach efforts.

I hope you enjoy learning about our research and outreach activities.

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

MESSAGE FROM THE CHAIRS

Governance Advisory Committee (GAC)

The past year saw OzGrav achieve several very important milestones, including successfully passing its Mid-Term Review by the ARC. Every Centre of Excellence is required to pass a rigorous performance review by the ARC and a panel including independent experts. As Chair of the OzGrav Governance Advisory Committee, I participated in an interview with the panel to address matters relating to Centre Governance and Management. I was pleased to represent OzGrav and was delighted to see that the panel's report acknowledged the major strides that the Centre has made since its commencement in April 2017. The ARC's report included a number of recommendations for changes to further improve the Centre's performance going forward, all of which OzGrav has adopted and begun to implement. The Centre's responses to the Mid-Term Review report are described on pages 70-71.

Another important activity that took place during 2021 was an intensive effort by the Australian gravitational wave community planning and drafting an Expression of Interest for another ARC Centre of Excellence for Gravitational Wave Discovery to begin in 2023 (the last year of funding for the current OzGrav Centre). Director Matthew Bailes led a large community-wide process to develop the science program for the new Centre bid, which involved White Papers being put forward by members of the broad astronomy and gravitational wave communities and the selection of a new set of CIs for proposed Centre. I wish the community success in the ARC's assessment of this new Centre bid during 2022.

OzGrav met or exceeded its targets for almost all Key Performance Indicators in 2021. Despite the global pandemic continuing to impact members' ability to work and travel, the Centre did very well in interacting with over 100 schools as part of its outreach program, providing extensive professional development training for Early Career Researchers, and continuing to expand its network of collaborating organisations and industry. In particular, it is great to see the inroads OzGrav is making in establishing new industry connections and initiatives, for instance with Australia Post and Google (page 19) and with the data science company, Eliiza (page 16). A core part of the mission of OzGrav is to train a generation of scientists with the skills to be leaders in academia or industry, and you can read about two such examples of Early Career Researchers whose skills have made them prized recruits by industry (page 18).

Finally, I wish to congratulate all involved with OzGrav who won awards and accolades during 2021 (pages 28-31), and to the whole Centre for receiving the Silver Pleiades Award by the Astronomical Society of Australia in recognition of its continued commitment to promoting equity and inclusion.

Please enjoy this annual report, which outlines OzGrav's achievements in 2021 and plans for the future.

Sincerely,
Professor Ian Young AO

Scientific Advisory Committee (SAC)

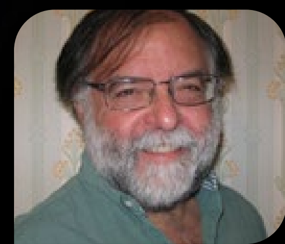
During 2021, I was honoured to be invited to take on the role of Chair of the OzGrav Scientific Advisory Committee. I am grateful for the efforts of my predecessor, Prof Barry Barish, and look forward to helping the collective wisdom of the SAC guide OzGrav towards continued success.

Australian researchers continued their long history of gravitational wave technological innovation during 2021, with highlights including the completion and delivery to LIGO of new adaptive optics systems that will help improve the performance of quantum squeezing, especially at high laser power. A compression fit mirror that was developed in OzGrav over the last few years was also completed and installed at LIGO. OzGrav led the development of new technology that merges quantum particles of sound vibration with photons of laser light, to create amplification in which the merged particles cycle back and forth billions of times without being lost (more details on page 12). Significant progress was also made on investigating new optical methods to enhance signals in future next-generation gravitational wave interferometers.

One of the highlights of 2021 for the international gravitational wave community was the release of 35 new detections in the second stage of the LIGO-Virgo-Kagra observing run three, bringing the total number of confirmed detections to 90. Early Career Researchers from OzGrav made major contributions to important associated publications: the catalog papers (for GWTC-2 and GWTC-3) and the companion "population" papers describing the astrophysical properties of merging binaries.

Another key 2021 publication, announcing the first observations of gravitational waves from neutron star-black hole binaries, had significant OzGrav involvement. The analysis relied extensively on OzGrav-designed software, and key inference calculations were carried out on the OzSTAR supercomputer at Swinburne. The paper writing team included an OzGrav senior scientist.
I would like to acknowledge the significant contributions that OzGrav members at all levels of seniority make to the wider LVK collaboration. As you can see on page 88, OzGrav members lead or contribute to numerous LVK committees, working groups and writing teams, making Australia a highly valued and influential member of this global collaboration.

Sincerely,
Prof Stanley Whitcomb



CENTRE SNAPSHOT

AFFILIATES 39

POSTDOCTORAL RESEARCHERS 35

ASSOCIATE INVESTIGATORS 32

PARTNER INVESTIGATORS 18

CHIEF INVESTIGATORS 20

MEMBERS 275

PHD RESEARCHERS 72

MASTERS STUDENTS 16

HONOURS STUDENTS 8

UNDERGRADUATE STUDENTS 4

PROFESSIONAL AND TECHNICAL STAFF 27

RESEARCH ASSISTANTS 4

155 PUBLICATIONS IN PEER REVIEWED JOURNALS

63 (41%) PAPERS WITH OZGRAV STUDENTS/POSTDOCS AS FIRST AUTHORS

38,749 CUMULATIVE CITATIONS

126 CONFERENCE PRESENTATIONS

522 MEDIA ARTICLES & INTERVIEWS

107 SCHOOLS

5,305 STUDENTS

99 TEACHERS

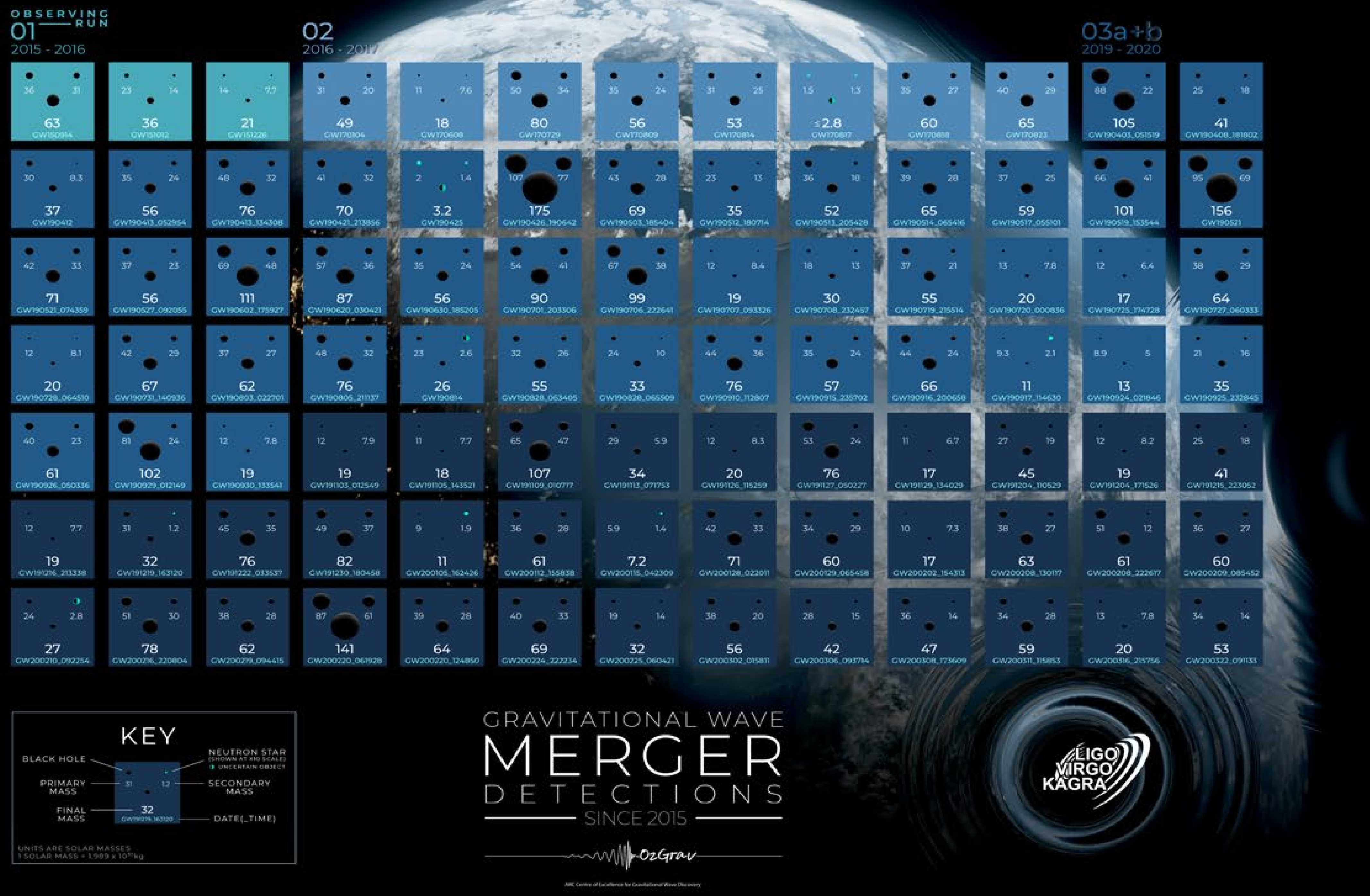
39 EVENTS, WORKSHOPS & TALKS FOR THE GENERAL PUBLIC

16,934 MEMBERS OF PUBLIC ENGAGED WITH

466.2 MIL POTENTIAL MEDIA REACH

2,825 SCIVR APP DOWNLOADS

SCIENCE HIGHLIGHTS



Largest number of gravitational wave detections to date

The gravitational wave universe is teeming with signals produced by merging black holes and neutron stars. An international team of scientists, including Australian OzGrav researchers, present 35 new gravitational wave observations in December 2021, bringing the total number of detections to 90!

All of these new observations come from the second part of the Laser Interferometer Gravitational-Wave Observatory (LIGO) Observing Run Three, called "O3b", which was an observing period that lasted from November 2019 to March 2020. There were 35 new gravitational wave detections in this period, a vast improvement on LIGO's first observing run in 2015 yielding 3 gravitational wave events. Of these new observations, 32 are most likely to come from pairs of merging black holes, 2 are likely to come from a neutron star merging with a black hole, and the final event could be either a pair of merging black holes or a neutron star and a black hole. The mass of the lighter object in this final event crosses the divide between the expected masses of black holes and neutron stars and remains a mystery.

Highlights - the numbers in the names are the date and time of the observation:

- Two mergers between possible neutron star - black hole pairs. These are named GW191219_163120 and GW200115_042309;
- A merger between a black hole and an object which could either be a light black hole or a heavy neutron star called GW200210_092254;
- A massive pair of black holes orbiting each other, with a combined mass 145 times heavier than the Sun (GW200220_061928);
- A pair of black holes orbiting each other, in which at least one of the pair is spinning upright (GW191204_171526);
- A pair of black holes orbiting each other which have a combined mass 112 times heavier than the Sun, which seems to be spinning upside-down (called GW191109_010717);
- A 'light' pair of black holes that together weigh only 18 times the mass of the Sun (GW191129_134029).

The different properties of the detected black holes and neutron stars are important clues as to how massive stars live and then die in supernova explosions. "It's fascinating that there is such a wide range of properties within this growing collection of black hole and neutron star pairs", says study co-author and OzGrav PhD student Isobel Romero-Shaw (Monash University).
"Properties like the masses and spins of these pairs can tell us how they're forming, so seeing such a diverse mix raises interesting questions about where they came from."

Not only can scientists look at individual properties of these binary pairs, they can also study these cosmic events as a large collection - or population. "By studying these populations of black holes and neutron stars we can start to understand the overall trends and properties of these extreme objects and uncover how these pairs came to be" says OzGrav PhD student Shanika Galaudage (Monash University) who was a co-author on a companion publication: 'The population of merging compact binaries inferred using gravitational waves through GWTC-3 P2100239'. In this work, scientists analysed the distributions of mass and spin and looked for features which relate to how and where these extreme object pairs form. Shanika adds, "There are features we are seeing in these distributions which we cannot explain yet, opening up exciting research questions to be explored in the future".

Detecting and analysing gravitational wave signals is a complicated task requiring global efforts. Initial public alerts for possible detections are typically released within a few minutes of the observation. Rapid public alerts are an important way of sharing information with the wider astronomy community, so that telescopes and electromagnetic observatories can be used to search for light from merging events - for example, merging neutron stars can produce detectable light. Says Dr Aaron Jones, OzGrav Postdoctoral Researcher from the University of Western Australia, "It's exciting to see 18 of those initial public alerts upgraded to confident gravitational wave events, along with 17 new events".

All of these detections were made possible by the global coordinated efforts from the LIGO (USA), Virgo (Italy) and KAGRA (Japan) gravitational wave observatories. Between the previous observing runs, the detectors have been continually enhanced in small bursts which improves their overall sensitivity. Says Disha Kapasi, OzGrav PhD student (Australian National University), "Upgrades to the detectors, in particular squeezing and the laser power, have allowed us to detect more binary merger events per year, including the first ever neutron star-black hole binary recorded in the GWTC-3 catalogue. This aids in understanding the dynamics and physics of the immediate universe, and in this exciting era of gravitational wave astronomy, we are constantly testing and prototyping technologies that will help us make the instruments more sensitive."

The LIGO and Virgo observatories are currently offline for improvements before the upcoming fourth observing run (O4), due to begin in late 2022. The KAGRA observatory will also join O4 for the full run. More detectors in the network help scientists to better localise the origin or potential sources of the gravitational waves. "As we continue to observe more gravitational-wave signals, we will learn more and more about the objects that produce them, their properties as a population, and continue to put Einstein's theory of General Relativity to the test," says Dr Middleton.

Also featured in The Guardian, Space Australia, Canberra Times and Perth Now.

Feature image by Carl Knox, OzGrav Swinburne, released by LVK as a poster.

Approaching zero: super-chilled mirrors edge towards the borders of gravity and quantum physics

The LIGO gravitational wave observatory in the USA is so sensitive to vibrations it can detect the tiny ripples in space-time called gravitational waves. These waves are caused by colliding black holes and other stellar cataclysms in distant galaxies, and they cause movements in the observatory much smaller than a proton.

Now we have used this sensitivity to effectively chill a 10-kilogram mass down to less than one billionth of a degree above absolute zero. Temperature is a measure of how much, and how fast, the atoms and molecules that surround us (and that we are made of) are moving. When objects cool down, their molecules move less.

“Absolute zero” is the point where atoms and molecules stop moving entirely. However, quantum mechanics says the complete absence of motion is not really possible (due to the uncertainty principle).

Instead, in quantum mechanics the temperature of absolute zero corresponds to a “motional ground state”, which is the theoretical minimum amount of movement an object can have. The 10-kilogram mass in our experiment is about 10 trillion times heavier than the previous heaviest mass cooled to this kind of temperature, and it was cooled to nearly its motional ground state.

How it works

LIGO detects gravitational waves using lasers fired down long tunnels and bounced between two pairs of 40-kilogram mirrors, then combined to produce an interference pattern. Tiny changes in the distance between the mirrors show up as fluctuations in the laser intensity. The motion of the four mirrors is controlled very precisely, to isolate them from any surrounding vibrations and even to compensate for the impact of the laser light bouncing off them.

This part may be hard to get your head around, but we can show mathematically that the differences in the motion of the four 40-kilogram mirrors is equivalent to the motion of a single 10-kilogram mirror. What this means is that the pattern of laser intensity changes we observe in this experiment is the same as what we would see from a single 10-kilogram mirror.

Although the temperature of the 10-kilogram mirror is defined by the motion of the atoms and molecules that make it up, we don’t measure the motion of the individual molecules. Instead, and largely because it’s how we measure gravitational waves, we measure the average motion of all the atoms (or the centre-of-mass motion).

There are at least as many ways the atoms can move as there are atoms, but we only measure one of those ways, and that particular dance move of all the atoms together is the only one we cooled.

The result is that while the four physical mirrors remain at room temperature and would be warm to the touch (if we let anyone touch them), the average motion of the 10-kilogram system is effectively at 0.77 nanokelvin, or less than one billionth of a degree above absolute zero.

Squeezed light

Part of OzGrav’s contribution to LIGO was to design, install and test the “quantum squeezed light” system in the detector. This system creates and injects a specially engineered quantum field into the detector, making it more sensitive to the motion of the mirrors, and thus more sensitive to gravitational waves.

The squeezed light system uses a special kind of crystal to produce pairs of highly correlated or “entangled” photons, which reduce the amount of noise in the system.

What does it all mean?

Being able to observe one particular property of these mirrors approach a quantum ground state is a by-product of improving LIGO in the quest to do more and better gravitational wave astronomy, but it might also offer insights into the vexed question of quantum mechanics and gravity.

At very small scales, quantum mechanics allows many strange phenomena, such as objects being both waves and particles, or seemingly existing in two places at the same time. However, even though the macroscopic world we see is built from tiny objects that must obey quantum phenomena, we don’t see these quantum effects at larger scales.

One theory about why this happens is the idea of decoherence. This suggests that heat and vibrations from a quantum system’s surroundings disrupt its quantum state and make it behave like a familiar solid object.

In order to measure gravitational waves, LIGO is designed to not be affected by heat or vibrations from its surroundings, but LIGO test masses are heavy enough for gravity to be a possible cause of decoherence.

Despite a century of searching, we have no way to reconcile gravity and quantum mechanics. Experiments like this, especially if they can get even closer to the ground state, might yield insight into this puzzle. The work, published in Science, is an important step in the ongoing quest to understand the gap between quantum mechanics — the strange science that rules the universe at very small scales — and the macroscopic world we see around us. Plans are already underway to improve the experiment in more sensitive gravitational wave observatories of the future. The results may offer insight into the inconsistency between quantum mechanics and the theory of general relativity, which describes gravity and the behaviour of the universe at very large scales.

From an article written by OzGrav Chief Investigator David McClelland, OzGrav Associate Investigator Robert Ward and OzGrav Postdoctoral Researcher Terry McRae from the Australian National University. Featured in The Conversation, Cosmos Magazine and Science Mag.

Image: Installation of the TorPeDO multi-stage isolation and suspension chain at ANU. Bram Slagmolen and Nathan Holland are checking if all clean and sensitive parts are covered. Credit: Sheon Chua, OzGrav ANU

SCIENCE HIGHLIGHTS

Milestone discovery

An entirely new phenomenon in the Universe was revealed in 2021: the death spiral and merger of the two most extreme objects in the Universe—a neutron star and a black hole. The observations were officially announced in July 2021 by the Laser Interferometer Gravitational-Wave Observatory (LIGO), in the USA, and the Virgo gravitational wave observatory in Italy. A milestone for gravitational wave astronomy, the discovery will now allow researchers to further understand the nature of the space-time continuum and the building blocks of matter.

The first observation of the neutron star-black hole merger was made on 5th January 2020 when gravitational waves—tiny ripples in the fabric of space and time—were detected from the collision event by LIGO and Virgo. When masses collide in space, they shake the whole Universe, sending out gravitational waves, like ripples on the surface of a pond. Detailed analysis of the gravitational waves reveal that the neutron star was around twice as massive as the Sun, while the black hole was around nine times as massive as the Sun. The merger itself happened around a billion years ago, before the first dinosaurs existed, but the gravitational waves only just reached Earth.

Remarkably, on 15th January 2020 another merger of a neutron star and a black hole was observed from gravitational waves. This neutron star and black hole also collided around a billion years ago, but they were slightly less massive: the neutron star was around one and a half times as massive as the Sun, while the black hole was around five and a half solar masses.

Dr Rory Smith, an astrophysicist with OzGrav at Monash University, who co-led the international team of scientists in this discovery, explains: "It's an awesome milestone for the nascent field of gravitational-wave astronomy. Neutron stars merging with black holes are amongst the most extreme phenomena in the Universe. Observing these collisions opens up new avenues to learn about fundamental physics, as well as how stars are born, live and die."

Thousands of international scientists teamed up for this world-first detection, with Australia playing a leading role. "From the design and operation of the detector, to the analysis of data, Australian scientists are working at the frontiers of astronomy," adds Smith. The SPIIR pipeline, at the University of Western Australia (UWA)—Australia's only realtime gravitational wave search pipeline—detected a neutron star-black hole event in real-time for the first time. SPIIR is one of five pipelines that alerts astronomers around the world within seconds of gravitational events, so they can try to catch the potential flash of light emitted when a neutron star is torn apart by its companion black hole.

The Zadko telescope, also based at UWA, was one of the Australian facilities that searched for a counterpart to the merger event and, despite a well-organised search, the team led by Dr Bruce Gendre and Eloise Moore could not secure a localised source. "During the next observing run, many more of these events are expected, providing more opportunities for SPIIR to catch them in real-time, and for astronomers to observe the light from these extreme events," says OzGrav Postdoctoral Researcher Dr Fiona Panther (UWA).

Black holes and neutron stars are two of the most extreme objects ever observed in the Universe—they are born from exploding massive stars at the end of their lives. Typical neutron stars have a mass of one and a half times the mass of the Sun, but all of that mass is contained in an extremely dense star, about the size of a city. One teaspoon of a neutron star weighs as much as all of humanity.

"This is a confirmation of a long-standing prediction from binary stellar evolution theory which predicted these systems should exist!" explains Dr Simon Stevenson, OzGrav Postdoctoral Researcher at Swinburne University of Technology.

This article is an extract from the original media release. Also featured on The Australian, The Financial Review, The ABC, Channel 10 News,Cosmos Magazine and more

Image: Artist's impression of a black hole swallowing a neutron star. Credit: Carl Knox, OzGrav Swinburne

SCIENCE HIGHLIGHTS

New technology to improve world’s most sensitive scientific instruments

A new technology that can improve gravitational wave detectors, one of the most sensitive instruments used by scientific researchers, has been pioneered by physicists at the University of Western Australia in collaboration with an international team of researchers. If it could be implemented in the world’s existing gravitational wave detectors, it would allow them to achieve a sensitivity that was previously thought only to be achievable by building much bigger detectors.

The research was led by the ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav) at UWA, in collaboration with the ARC Centre of Excellence for Engineered Quantum Systems (EQUS), the Niels Bohr Institute in Copenhagen and the California Institute of Technology (Caltech) in Pasadena.

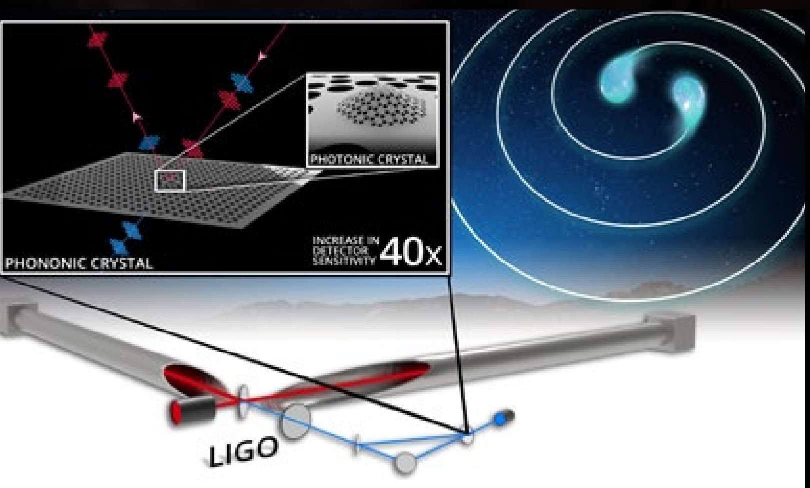
OzGrav Chief Investigator Prof David Blair, from UWA, says the technology merged quantum particles of sound vibration called phonons with photons of laser light, to create a new type of amplification in which the merged particles cycled back and forth billions of times without being lost.

“More than a hundred years ago Einstein proved that light comes as little energy packets, which we now call photons,” says Prof Blair.

One of the most sophisticated applications of photons are gravitational wave detectors, which allow physicists to observe ripples in space and time caused by cosmic collisions. ”Two years after Einstein’s prediction of photons, he proposed that heat and sound also come in energy packets, which we now call phonons. Phonons are much trickier to harness individually in their quantum form because they’re usually swamped by vast numbers of random phonons called thermal background,” says Prof Blair.

OzGrav Affiliate Dr Michael Page says the trick was to combine phonons and photons together in such a way that a broad range of gravitational wave frequencies could be amplified simultaneously. “The new breakthrough will let physicists observe the most extreme and concentrated matter in the known universe as it collapses into a black hole, which happens when two neutron stars collide,” says Dr Page.

Credit: Carl Knox, OzGrav Swinburne



Prof Blair says the waveforms sounded like a brief scream that was pitched too high for current detectors to hear. “Our technology will make those waveforms audible, and will also reveal whether the neutrons in neutron stars get split up into their constituents called quarks when they are in this extreme state,” he says. “The most exciting thing about seeing nuclear matter turn into a black hole is that the process is like the reverse of the Big Bang that created the Universe. Observing this happen will be like watching a movie of the Big Bang played backwards.”

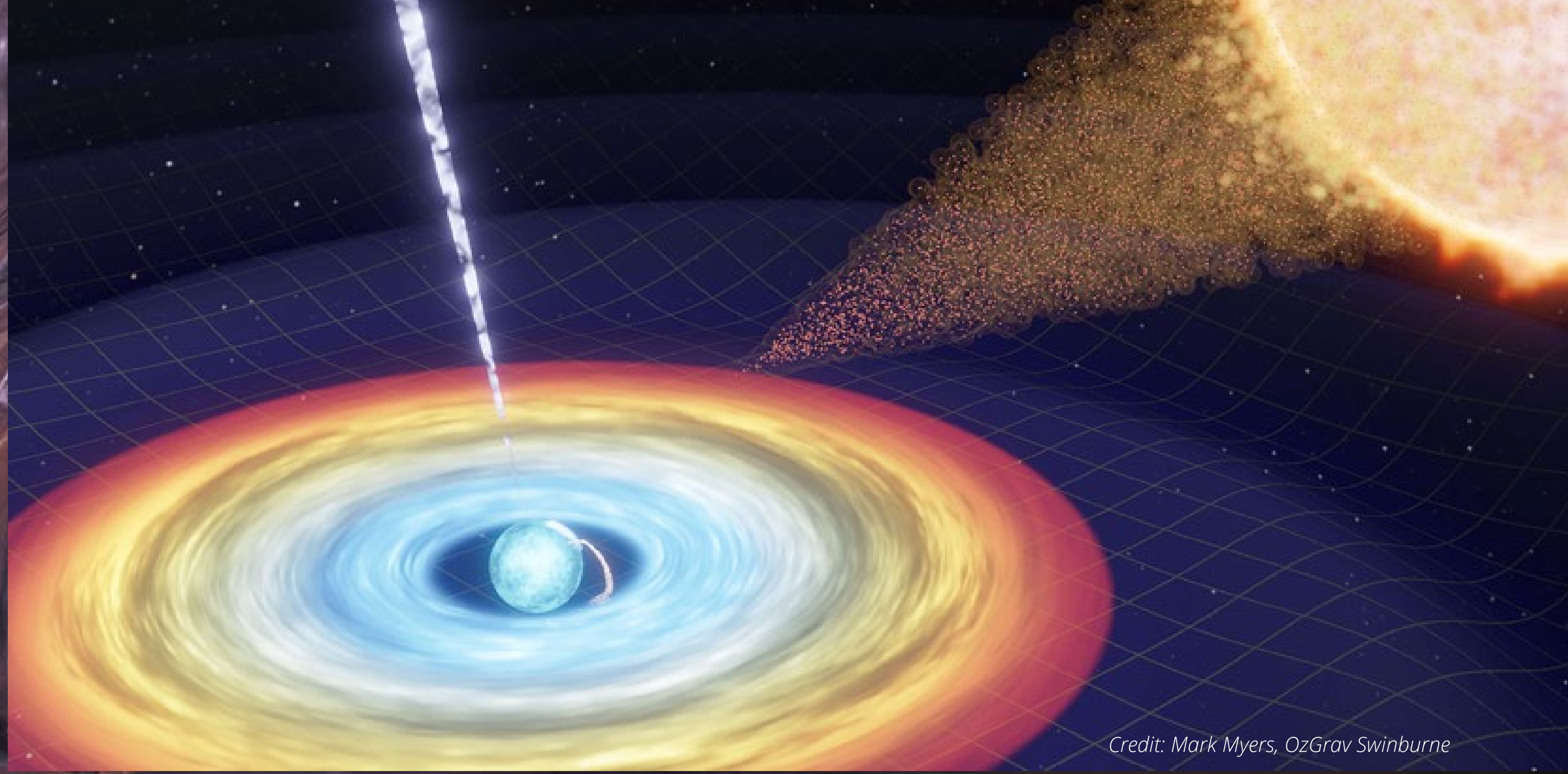
From the original media release written by UWA Media Office. Prof David Blair also wrote an article featured in The Conversation.

New insights into the elusive continuous waves from spinning neutron stars

Five years on from the first discovery of gravitational waves, an international team of scientists, including from OzGrav, are continuing the hunt for new discoveries and insights into the Universe. Using the supersensitive, kilometre-sized LIGO detectors in the USA, and the Virgo detector in Italy, the team have witnessed the explosive collisions of black holes and neutron stars. Recent studies, however, have been looking for something quite different: the elusive signal from a solitary, rapidly-spinning neutron star.

Take a star similar in size to the Sun, squash it down to a ball about twenty kilometres across, and you’d get a neutron star: the densest object in the known Universe. Now set your neutron star spinning at hundreds of revolutions per second and listen carefully. If your neutron star isn’t perfectly spherical, it will wobble about a bit, and you’ll hear a faint “humming” sound. Scientists call this a continuous gravitational wave.

So far, these humming neutron stars have proved elusive. As OzGrav Postdoctoral Researcher Karl Wette from the Australian National University explains: “Imagine you’re out in the Australian bush listening to the wildlife. The gravitational waves from black hole and neutron star collisions we’ve observed so far are like squawking cockatoos—loud and boisterous, they’re pretty easy to spot! A continuous gravitational wave, however, is like the faint, constant buzz of a faraway bee, which is much more difficult to detect. So we’ve got to use a few different strategies. Sometimes we hone in on a particular direction—for example, a flowering bush where bees are likely to congregate. Other times, we close our eyes and listen keenly to all the sounds we can hear, and try to pick out any buzzing sounds in the



Credit: Mark Myers, OzGrav Swinburne

background. So far, we haven’t had any luck, but we’ll keep trying! Once we do hear a continuous gravitational wave, we’ll be able to peer deep into the heart of a neutron star and unravel its mysteries, which is an exciting prospect.”

A collaborative study with OzGrav has taken a closer look at the remnants of exploded stars, called supernovae. OzGrav PhD student Lucy Strang from the University of Melbourne explains: “Our search targets fifteen young supernova remnants containing young neutron stars. We use three different pipelines: one optimized for sensitivity, one that can handle a rapidly evolving signal, and one optimized for one likely astrophysical scenario. This is the first LIGO study covering all three of these scenarios, maximising our chance of a continuous wave detection. Continuous gravitational waves are proving very difficult to detect, but the same properties that make them elusive make them appealing targets. The exact form of the signal (i.e. its frequency, how rapidly the frequency changes, how loud it is, etc.) is dependent on what neutron stars are made of.”

OzGrav Associate Investigator Lilli Sun from the Australian National University says: “Young neutron stars in supernova remnants are promising targets to look for those tiny continuous gravitational waves, because they haven’t spent a long enough time to relax and smooth out the asymmetries introduced at their birth. Although no signal has been detected in O3 (LIGO Observing Run 3), we set interesting constraints on the neutron star properties. If such a signal can be detected in future observations when the detectors are more sensitive, it will shed light on the fascinating structure of a neutron star.”

OzGrav postdoctoral researcher Carl Blair from the University of Western Australia says: “Gravitational waves are being used to probe the most exotic objects in the Universe. Neutron stars, composed of matter collapsed in on itself like a giant atomic nuclei, have to be one of the most exotic. We don’t know that much about neutron stars because they’re so small and strange. Are they hard or soft? And when they spin fast as they collapse, do they wobble away that energy in the form of gravitational waves?”

In addition, recent studies announced by the international research team have focussed on pulsars. Pulsars are like giant spinning magnets, except they’re billions of times stronger than the ones stuck to your fridge. So strong, in fact, that the magnetic field distorts the shape of the neutron star, and may lead to a tell-tale hum of continuous gravitational waves. While the recent studies did not pick up anything, they found tight constraints on how loud the “hum” could be, which, in some cases, are starting to challenge theoretical predictions.

OzGrav PhD student Deeksha Beniwal from the University of Adelaide says: “O3 observations also provide an opportunity to test out different pipelines—such as different search methods for continuous wave signals—in realistic environments.”

OzGrav postdoctoral researcher Meg Millhouse from the University of Melbourne says: “Continuous gravitational waves from neutron stars are much smaller than the gravitational waves LIGO and Virgo have seen so far. This means we need different techniques to detect them. And, because these are long lasting signals, we need to look at lots of data which can be very difficult computationally.”

Scientists estimate that there are billions of neutron stars in the Milky Way with a faint murmur of continuous gravitational waves. Further studies have therefore taken an “ears wide open” approach, combing through the LIGO and Virgo data for any hint of a signal. The results so far suggest that these murmurings are extremely quiet and out of the detectors’ “ear” range. However, as detector technology becomes more advanced and sensitive, the first ever detection of continuous gravitational waves could soon become a reality.

Original media release from OzGrav. Also featured in Cosmos Magazine, IFL Science, Space Australia and Sci Tech Daily.

ANU spin-off Liquid Instruments launches new hardware

From gravitational wave science to global technology company: Liquid Instruments is a Canberra start-up bringing NASA technology to the world. Liquid Instruments (LI) Pty Ltd, a spin-off company from the Australian National University (ANU), is revolutionising the $17B test and measurement market.

Test and Measurement devices are used by scientists and engineers to measure, generate and process the electronic signals that are fundamental to the photonics, semiconductor, aerospace and automotive industries. The LI team has raised more than US$25M in Venture Capital investment, and now has more than 1000 users in 30 countries.

LI was founded by researchers from the gravitational wave group at ANU to commercialise advanced instrumentation technology derived from both ground and space-based gravity detectors. Former OzGrav Chief Investigator Prof Daniel Shaddock (ANU), CEO of Liquid Instruments, began as an engineer at NASA's Jet Propulsion Laboratory in 2002, working on the Laser Interferometer Space Antenna (LISA), a joint project between NASA and the European Space Agency. The work on LISA's phasemeter was the genesis for forming Liquid Instruments. LI's software-enabled hardware employs advanced digital signal processing to replace multiple pieces of conventional equipment at a fraction of the cost and with a drastically improved user experience. Their first product Moku:Lab provides the functionality of 12 instruments in one simple integrated unit.

On 23 June, the company launched two new hardware devices, the Moku:Go—an engineering lab in a backpack for education, and the Moku:Pro – a multi-GHz device for professional scientists and engineers. Like the Moku:Lab, this revolutionary new hardware includes a suite of instruments with robust hardware features giving a breakthrough combination of performance and versatility.

Daniel Shaddock says: "Moku:Pro takes software defined instrumentation to the next level with more than 10x improvements in many dimensions - it's a new weapon for scientists. Moku:Go takes all the great features of Moku:Lab but reduces the cost by 10x to make it more accessible than ever before. We hope it will help train the next generation of scientists and engineers in universities around the world."

MokuGo: an engineering lab in a backpack. Credit: Liquid Instruments

Liquid Instruments CEO and former OzGrav Chief Investigator Prof Daniel Shaddock at the ANU launch of Moku:Go and Moku:Pro.

The new Moku:Pro hardware with iPad user interface undergoing testing in the OzGrav lab at ANU. Credit: Liquid Instruments

Using one-hundred-million-year-old fossils and gravitational-wave science to predict the Earth's future climate

A group of international scientists has used gravitational wave astronomy to study ancient marine fossils as a predictor of climate change. The research, published in the journal Climate of the Past, is a unique collaboration between palaeontologists, astrophysicists and mathematicians – to improve the accuracy of a palaeo thermometer, which can use fossil evidence of climate change to predict what is likely to happen to the Earth in coming decades.

OzGrav Chief Investigator Prof Ilya Mandel, from Monash University, and colleagues, studied biomarkers left behind by tiny single-cell organisms called archaea in the distant past, including the Cretaceous period and the Eocene.

Marine archaea in our modern oceans produce compounds called Glycerol Dialkyl Glycerol Tetraethers (GDGTs). The ratios of different types of GDGTs they produce depend on the local sea temperature at the site of formation. When preserved in ancient marine sediments, the measured abundances of GDGTs have the potential to provide a geological record of long-term planetary surface temperatures.

To date, scientists have combined GDGT concentrations into a single parameter called TEX86, which can be used to roughly estimate the surface temperature. However, this estimate is not very accurate when the values of TEX86 from recent sediments are compared to modern sea surface temperatures.

"After several decades of study, the best available models are only able to measure temperature from GDGT concentrations with an accuracy of around 6 degrees Celsius," says Prof Mandel. "Therefore, this approach cannot be relied on for high-precision measurements of ancient climates."

Prof Mandel and his colleagues at the University of Birmingham in the UK have applied modern machine-learning tools—originally used to create predictive models of merging black holes and neutron stars—to improve temperature estimation based on GDGT measurements. This enabled them to take all observations into account for the first time rather than relying on one particular combination, TEX86. It also produced a far more accurate palaeo-thermometer.

Using these tools, the team extracted temperature from GDGT concentrations with an accuracy of just 3.6 degrees—a significant improvement, nearly twice the accuracy of previous models. According to Prof Mandel, determining how much the Earth will warm in coming decades relies on modelling, "so it is critically important to calibrate those models by utilising literally hundreds of millions of years of climate history to predict what might happen to the Earth in the future," he says.

Also featured in Cosmos magazine, Sci Tech Daily and Phys.org.

Eliiza Partnership to enhance knowledge sharing and professional development between academia and industry

Australian-owned data science company Eliiza announced the launch of a new business unit, Eliiza Research, a partnership with OzGrav aimed at enhancing Australia's capabilities in machine learning and artificial intelligence associated with gravitational wave astronomy.

This partnership will look to capitalise on the historic first detections of gravitational waves to understand the extreme physics of black holes and warped spacetime. It will inspire the next generation of scientists and engineers in this area while also giving the talent at Eliiza the ability to apply their skills to this area of research.

The partnership was formed following an initial piece of research undertaken on Noise Characterisation, where Eliiza's data science team developed a multi-label sound classifier that was able to accurately identify various anthropogenic, animal, and natural noise sources. The aim was to understand and improve detector characterisation data quality, and therefore reduce low-latency false alarms through accurate signal and glitch estimation. Eliiza Research's first task will be to deliver a technical document and presentation showing the proof-of-principle that this noise characterisation method can be successfully applied to LIGO/Virgo data (gravitational wave and black hole data).

Associate Professor Paul Lasky, Monash University and OzGrav Chief Investigator, says "The advanced techniques developed in the initial research have the potential to lead to new cross-disciplinary applications in communications and engineering, contribute to Australia's science and research priorities, and bring economic value to broader information and communication industries in Australia. We are thrilled to be working alongside Eliiza to leverage their knowledge of Machine Learning and industry while supporting their team's learning and development."

Eliiza CEO James WIlson says "This partnership provides a platform for our team to work on ground-breaking research, away from the corporate projects that they embed themselves in for months. This provides a great balance to their work, whilst also helping to develop future talent from within the research community and highlighting the pathways that are available in the industry. Personally, I am excited to provide industry insights back into OzGrav."

There are potential ECR development opportunities, which include hybrid PhD programs that incorporate industry internships, as well as post-PhD career opportunities for data scientists, astrophysicists, and instrumentalists alike. Eliiza will provide OzGrav researchers with coaching, mentoring and networking to assist with a career path for corporate work in the future.

Lead Data Scientist at Eliiza, Kathryn Collier, says "To work alongside the next generation of technologists across so many institutions via OzGrav is exciting. I am looking forward to building relationships with the next crop of data scientists, and bridging the academia and corporate gap, especially for women and gender minority groups."

BepiColombo in cruise configuration. Credit ESA / ATG medialab

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

Optical observations of BepiColombo as a proxy for a potential threatening asteroid

BepiColombo is a joint mission between the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA) designed to study the planet Mercury. Launched in late 2018, its complex trajectory involved a fly-by past Earth on April 10, 2020.

We took advantage of the event to organise a coordinated observing campaign. The main goal was to compute and compare the observed fly-by orbit properties with the values available from the Mission Control. The method we designed could then be improved for future observation campaigns targeting natural objects that may collide with our planet.

The incoming trajectory of the probe limited the ground-based observability to only a few hours, around the time when it was closest to Earth. The network of telescopes we used has been developed by ESA's NEO Coordination Centre (NEOCC) with capabilities to quickly observe imminent impactors, thus presenting similar orbits. Our team successfully acquired the target with various instruments such as the 6ROADS Chilean telescope, the 1.0 m Zadko telescope in Australia, the ISON network of telescopes, and the 1.2m Kryoneri telescope in Corinthia, Greece.

The observations were difficult due to the object's extremely fast angular motion in the sky. At one point, the telescopes saw the probe covering twice the size of the moon in the sky each minute. This challenged the tracking capabilities and timing accuracy of the telescopes. Each telescope was moving at the predicted instantaneous speed of the target while taking images, "tracking" the spacecraft. Field stars appeared as trails, while BepiColombo itself was a point source, but only if the observation started exactly at the right moment.

Because the probe was moving so fast, any date errors of the telescope images translate into position errors of the probe. To reach a precise measurement of 0.1 metres, the date of the images needed to have a precision of 100 milliseconds.

The final results were condensed into two measurable quantities that could be directly compared with the Mission Control ones, the perigee distance, and the time of the probe's closest approach to Earth. Both numbers were perfectly matched, proving our method a success:

it calculated a more accurate prediction of BepiColombo's orbit; it also provided valuable insights for future observations of objects colliding with Earth:

- A purely optical observing campaign can provide trajectory information during a fly-by at sub-kilometre and sub-second levels of precision.
- A similar campaign would lead to a sub-kilometre and sub-second precision for the time and location of the atmospheric entry of any colliding object.
- Timing accuracy below 100 milliseconds is crucial for the closest observations.
- It's possible to organise astrometric campaigns with coverage from nearly every continent.

Written by OzGrav researcher Dr Bruce Gendre, University of Western Australia.

Skills translation into industry

Dr Qi Chu

Qi began her education by studying telecommunication engineering and computer science. After visiting Prof Linqing Wen and Prof David Blair's groups at the University of Western Australia (UWA), she became extremely interested in physics, particularly gravitational waves. She took on a PhD project in UWA and later became an OzGrav and UWA postdoc. For the last ten years, Qi worked on low latency searches of gravitational wave signals and participated in many exciting new discoveries with LIGO and Virgo. During this time she worked with talented people from LIGO and OzGrav and gained many transferrable skills for both industry and academia. These skills include reasoning and deduction skills, data analysis and reporting skills, and interpersonal skills.

In 2021 Dr Qi Chu started her new role as a data scientist at Australia's largest natural gas provider, Woodside, in Perth. She's currently onboarding a data science team to work on various data rendering and optimisation projects from Woodside's natural gas production process. Industry has been adapting to the new era of big data technology and artificial intelligence, including traditional resource companies like Woodside or BHP. There's more investment in new data infrastructures and technologies to transform data-driven organizations. Researchers from academia are particularly welcome to bring in new perspectives and skills to this transformation.

Dr Joshua McCann

Josh has been interested in space and astronomy since he was a child, getting space and planet books from the library, and watching shows like Star Trek (first introduction to a gravitational wave). Despite an interest in space, he was more interested in using his hands as a teenager, which led him to leave school in Year 11 and pursue an electrical apprenticeship. He completed this and grew more and more interested in engineering, which spurred him onto undertaking an Electrical Engineering Degree.

On completing Honours in Electrical Engineering, he returned to work as an electrical engineer. During the 2nd year of this position, he came across an advertisement for PhD students at the University of Western Australia (UWA) in gravitational wave (GW) science. They were looking for instrumentation engineers. This was his chance to finally combine his interest in space with his profession as an engineer. In 2017 he started a PhD at UWA, and focused on the design, build and testing of a ground rotation sensor, specifically designed to help measure and in turn reduce tilt and translation coupling in GW seismic isolation systems. The sensor the UWA team developed, called the ALFRA, was successful in receiving further funding, with aims to provide the sensors to LIGO.

Dr McCann's new role as lead/senior design engineer came about through industry contacts and word-of-mouth via previous work colleagues. Now he leads an electrical engineering team in the electrical design and construction gyroscopic stabilisers for ships. His role involves a large portion of research and development, specifically around new products the company plans to provide, where Josh's problem-solving skills learnt during his PhD and with OzGrav really come into play. Dr McCann says "Most of my PhD felt like problem-solving and teaching myself skills to overcome technical challenges. So now, I can do this type of thinking intuitively and apply it to an industry setting."

Image: Astronomers spot bizarre, never-before-seen activity from one of the strongest magnets in the Universe. Artist's impression of the active magnetar Swift J1818.0-1607. Credit: Carl Knox, OzGrav Swinburne

Australia Post Data Science Internships in alliance with the Google-Cloud Students-as-Partners program

OzGrav has joined a partnership with Australia Post (AP) and Google to provide competitive industry internships in data science. It is aimed at PhD or Masters students studying for a technical degree with a significant quantitative, statistical or data science component. Interns are paid to work full-time to complete a 3-month data science project with Australia Post with a key focus around applying advanced mathematical models to generate innovative solutions to complex business problems. An objective is to make interns Google Cloud career-ready and provide them with the opportunity to work on a challenging industry problem, gaining Industry/Business experience, business communication skills, and grow their professional network within AP and Google.

The first pilot internship program was launched in late 2021, and an OzGrav PhD student who applied is being on-boarded by Australia Post in 2022. They will have the chance to work on deep quantitative problems and innovate within a real commercial setting and impact. They will also get exposure to a modern cloud platform (Google Cloud Platform, i.e. GCP) and modern ways of developing commercial data science solutions/products. Part of the interview process also requires them to successfully complete formal GCP training (20 – 30 hours).

Says Borislav Savkovic, Data Science Manager with AP "This is a very exciting program as it's providing commercial experience to our PhD candidates and helping keep deep talent within Australia, i.e. creating local opportunities for our talented PhD students in the commercial world."

Project areas at Australia Post include:

Network optimisation - Graph theory optimization to achieve improved network utilisation;

Anomaly detection - Cyber security applications to detect anomalies within our data and network;

Call centre - Statistical and NLP analysis of the reasons for customer calls and optimal intervention strategies;

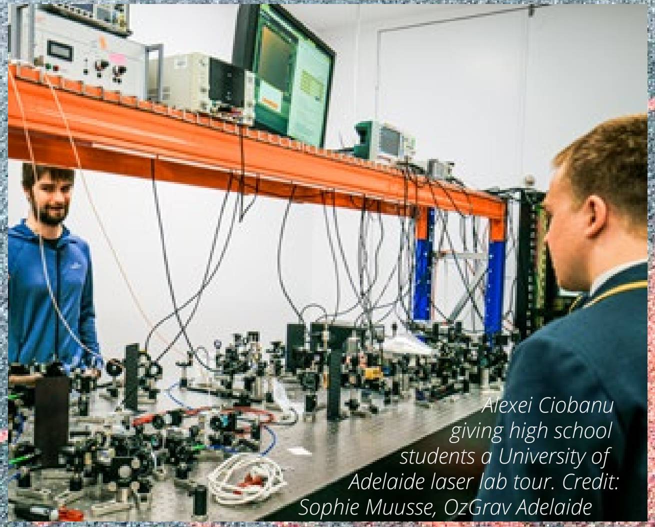
Forecasting - Large scale forecasting underpinned by big data, with varying forecasting horizons;

Efficiency in facilities - Utilization of mathematical optimisation algorithms to improve throughput in our facilities and operations;

Machine Learning (ML) Computer Vision - Applications to uplift accuracy and efficiency of computer vision algorithms for parcel processing.

EDUCATION AND OUTREACH

Credit: World Science Festival



Alexei Ciobanu giving high school students a University of Adelaide laser lab tour. Credit: Sophie Muusse, OzGrav Adelaide

All over Australia

Despite changing restrictions and lockdowns due to COVID-19, OzGrav members presented sessions all over Australia, both in person and online, to share our research with schools, special interest groups and the general public. Holiday programs were popular again, and we thank partners such as libraries, science centres, Tech Schools, PrimeSci, LabRats and YMCA Space Squad for their perseverance in difficult times to bring sessions to locations in both metro and regional areas.

We participated in University Open Days, hosted school groups in our labs, and developed Work Experience programs to inspire the next generation of scientists. We are particularly excited about the expanding Australian Space Industry, hosting events for students in the South Australian Space School and Space Industry Network work experience students. We were also involved in larger events such as the World Science Festival in Brisbane (including satellite events in regional Queensland towns such as Toowoomba and Gladstone), Astrofest in Perth, Astro-Rocks Fest in Mount Magnet, and Science Alive! Adelaide.

Non-touch interactions and projections

OzGrav continues to look for ways to take our science out of the lab and make it accessible for a wide range of people. We have some great VR and online programs, and in 2021 we looked at ways to engage people in fun science experiences without touching equipment. OzGrav Digital Media Artist Carl Knox (Swinburne) and Education and Outreach Content Developer Mark Myers (Swinburne) have been developing ways to set up cameras to recognise people's movement and hand gestures to control interactive content, rather than a mouse, keyboard or VR remote. Carl has been developing light projections as a way for multiple people to engage together in a fun shared experience, and find ways to make the engagement last longer with wider reach, for example by people taking photos and sharing on social media. We are experimenting with making equipment robust enough to travel, and training more outreach volunteers to set up equipment and explain the science. Despite cancelled plans due to lockdowns in 2021, we built partnerships and took experiences to regional areas, such as Twisted Science Echuca and Bendigo Science and Technology Centre. OzGrav Outreach Officer Lisa Horsley (Swinburne) and Communications and Media Officer Lu Spadafora (Swinburne) are continuing to work with OzGrav members to run science communication training sessions. We train, encourage and support Masters, PhD students and postdoctoral researchers to share their science through written articles, TV and radio interviews, public talks and hands-on science demonstrations.

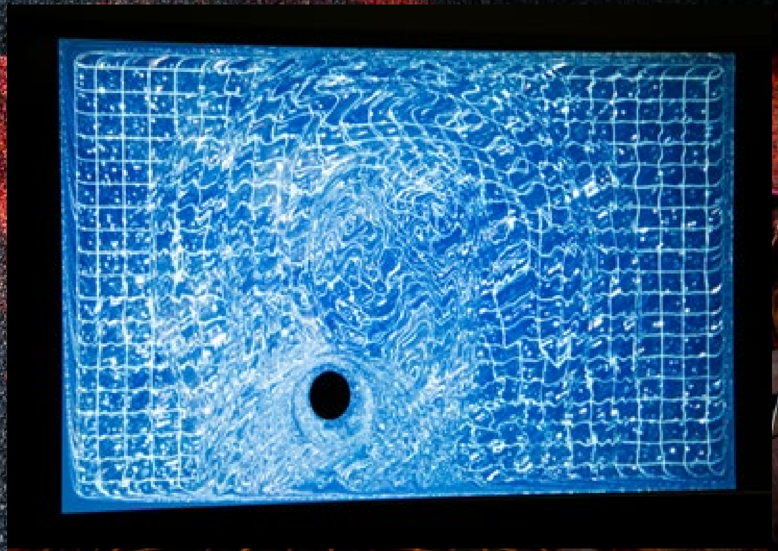
Live talks and podcasts

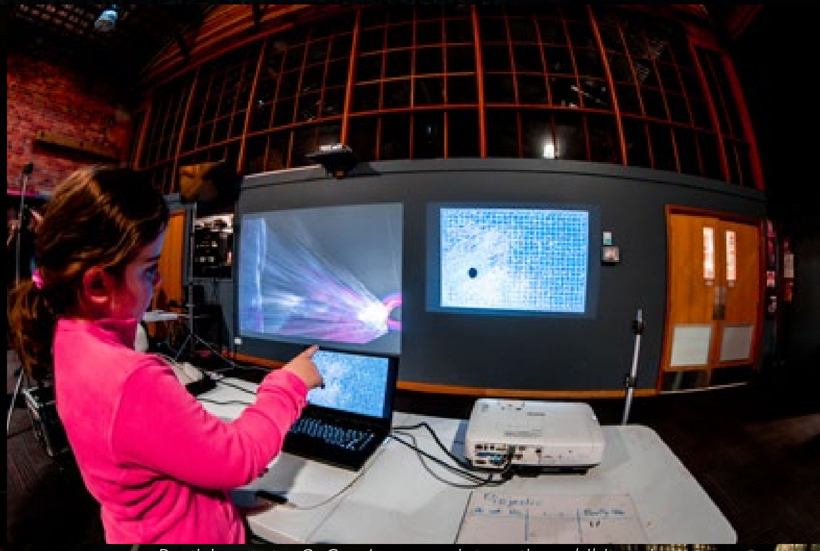
Nutsinee Kijbunchoo (ANU) shared her science and cartoons at a Science in the Pub event. Nutsinee is a PhD student and has worked on lasers at LIGO in the USA. Follow Antimatter for more comics and art.

Chayan Chatterjee (UWA) appeared as a guest on the talk show ' The Uncertainty Principle Presents: Science After Dark' at the Perth Fringe Festival in January 2021. He appeared as a guest on two podcasts - 'Astrophiz', and 'Curiosity Killed the Rat' as part of Pint of Science, Perth. He was also the Western Australia finalist of FameLab 2021.

Fiona Panther (UWA) appeared on the 'Astrophiz' podcast, and the Mug of Science show, hosted by Tom Carruthers. Eric Thrane (Monash) appeared on children's science podcast "Solvelt for Kids" with "How Do Scientists LISTEN to Black Holes?" Karl Wette (ANU), Lucy Strang and Meg Millhouse (Uni Melbourne) appeared on the IOP World of Physics podcast to discuss recent CW searches. Ling Sun has worked on the ultralight boson search and was also on a podcast interview by Trekzone.

Each year the SA branch of the Australian Institute of Physics awards the Bronze Bragg Medal to high scoring students in SACE Stage 2 Physics and Higher Level Physics in IB in SA. The award is named after William Henry Bragg and William Lawrence Bragg who shared the 1915 Nobel Prize in Physics. The lecture started with the presentation of the medals at St Peters College Adelaide, then Professor Susan Scott (ANU) beautifully linked Einstein's field equations with the geometry of spacetime to the distribution of matter within it.





Participants try OzGrav's pop-up interactive exhibits using cameras and motion detectors at Discovery Science and Technology Centre, Bendigo. Credit: Carl Knox, OzGrav Swinburne

EDUCATION AND OUTREACH

National Science Week

SciVR and Space beer collaboration with Burnley Brewing

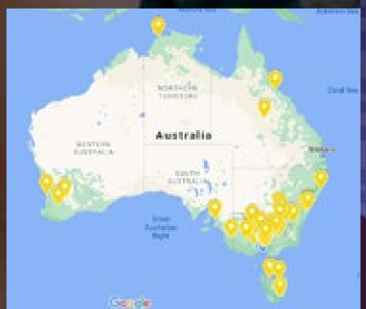
It was great to be partnering with 55 regional libraries and science centres including Swan Hill Regional Library to bring space science to the public during the 2021 National Science Week. SciVR is a mobile phone app and livestream event that takes you on the hunt for things that go boom. We explore the universe and origins of explosions in space, tracking events as they happen with Prof Alan Duffy and Dr Rebecca Allen – astronomers and science communicators at Swinburne University of Technology. New content this year includes the Mars rover Perseverance and helicopter Ingenuity.

Burnley Brewing in Richmond, Melbourne, created a space beer “Red Giant IPA” made with galaxy hops to be shared during our SciVR space talk. Unfortunately due to lockdowns the live pub talk couldn’t go ahead, but people who lived within a 5km radius could grab some takeaway food and drinks to enjoy from home while watching the live online talk.

In and around city and statewide lockdowns, some libraries and science centres were able to host in-person SciVR events for people to watch the talk together and share their excitement about space science. Some libraries acted as hubs for people to pick up their free mini VR headset and stickers before the event, and watch the livestream from the safety and comfort of their home. Participants could send in questions to be answered live on YouTube and Twitter.

We have made some accessibility updates to this event over time, including working with Auslan sign language interpreters for the past 3 years. We include a section on Indigenous astronomy to help audiences appreciate the discoveries our ancestors made over thousands of years. This project received grant funding from the Australian Government as part of National Science Week.

Download the free SciVR app to your smartphone or tablet, or watch back the video and hear questions answered, from the SciVR website www.scivr.com.au.



Credit: Google Maps

Credit: Burnley Brewing

Space+Time images showing on large TV in foyer at UWA.
Credit: UWA

Space+Time

Binary Coalescence Project ‘Space+Time’ is a collaboration between OzGrav astrophysicist Dr Linqing Wen at UWA and artists from Perth and Melbourne, led by Aiv Puglielli. #StoryBursts was funded by a National Science Week Major Grant and supported by the City of Melbourne Arts Grants. In August an audiovisual track was launched online in response to the research outcomes of Dr Linqing Wen (UWA). Facilitated by creatives in Mandarin and English, the virtual interviews which took place between Dr Wen (Perth) and Aiv (Melbourne) explored the first principle understanding of the idea of ‘binary coalescence’ in astronomy, as observed in the research of gravitational waves and the origins of the universe. It ran across screens at the UWA Science Barry J Marshall Library and in the foyer of the Department of Physics building, as well as online.

National Science Quiz

Does grass grow at night? Is an empty roller-coaster faster than a full one? Moved online due to Melbourne’s lockdowns, over 1000 people watched the panel session hosted by Charlie Pickering, and competed from home for cash and prizes. Hosted and delivered by ACEMS (ARC Centre of Excellence for Mathematical and Statistical Frontiers) in partnership with several other ARC Centres of Excellence, the quiz covered a range of maths, chemistry, biology and physics topics, with video experiments to show the answers. Watch back any time on YouTube.

Credit: ACEMS

Science Alive! Adelaide (Nov)

Science Alive really is all kinds of awesome. 13,000 people in Adelaide joined in and discovered how science and technology influence our everyday lives. The event was pushed back from National Science Week in August to November due to COVID-19 restrictions. Friday was the Science Alive STEM Day Out, providing Year 7-12 students a window into the wide variety of STEM careers now available. Saturday and Sunday were the family days, where everyone could chat to our researchers and PhD, Masters and Undergraduate students, try virtual reality (VR), find out about LIGO (and don’t get too close to the laser). We send a huge thanks to all the people who helped explain AMIGO (Adelaide Michelson Interferometer for Gravitational-wave Outreach) and took people on VR experiences across the exhausting 3 days.

Science Alive! is the largest, single, interactive, mobile science exhibition in Australia. With over 60 exhibitors including all the big names in science and technology, people could experience interactive and dynamic displays, plus spectacular science shows and performances for all ages. There’s something to spark the curiosity in all of us!

It helps to build our community’s awareness of the scope and importance of science and technology in our everyday lives, inspiring future generations of science and technology professionals. There’s no better event to experience first-hand all fields of science and technology.

Credit: Meaghan Coles


Booth set up at Science Alive Adelaide. Thanks to our volunteers explaining LIGO science and showing VR demos. Credit: Kendall Jenner, OzGrav Adelaide


University of Adelaide PhD student Deeksha Benwial (left) explains laser interferometry using AMIGO at Science Alive in Adelaide. Credit: OzGrav

EDUCATION AND OUTREACH

Astrofest Perth

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

astronomy wa
ASTROFEST
AN ASTRONOMY FESTIVAL OF EPIC PROPORTIONS

ASPIRE UWA remote school sessions and Astro Rocks Fest at Mount Magnet

Aspire UWA works with more than 70 partner schools and communities in regional Western Australia and Perth to raise aspirations for tertiary education. They encourage students who would not normally consider university to see the benefits and opportunities that university study offers. Partner schools value their unique relationship with Aspire UWA, and activities are tailored to each school, and each year group accordingly. Younger students enjoy active exploration of different disciplinary areas, while the reality of studying at university is reinforced for older students through explanation of pathways, support services and networks, academic revision workshops, and exposure to some of WA's best and brightest minds.

We thank ASPIRE and ICRAR for their financial support towards our first endeavour to reach out to WA regional and rural schools and communities with the ASPIRE team in September 2021. The ICRAR team had a great time connecting with the people in Mount Magnet at their annual Astro Rocks Fest, as well as our new and old friends from Aspire/The University of Western Australia, ASTRO 3D, CSIRO, SKA Observatory, Astro Photography Australia, Gravity Discovery Centre and Observatory, Astrotourism WA, Fireballs in the Sky, and Scitech.

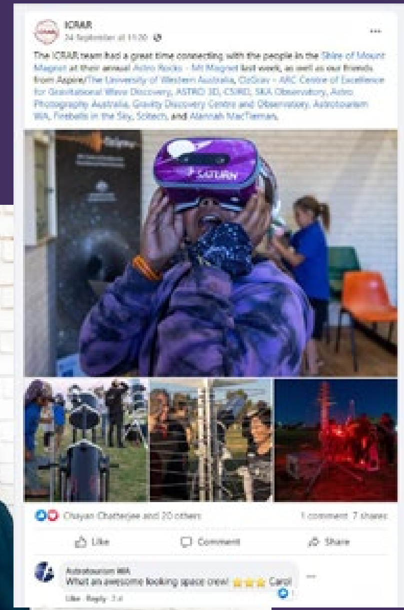
It has been a worthwhile science communication experience for new OzGrav volunteer Fariha Islam who noticed the huge disparity of resources available between city and rural/regional schools. We thank Sasha from ASPIRE, Greg from ICRAR, and Teresa Slaven-Blair from OzGrav and Astro3D, who were very supportive and encouraging of Fariha's efforts to offer outreach in a very different and challenging environment.

Reflections from Outreach volunteer Fariha Islam.

The trip overall was very eye-opening and wholesome. I would highly recommend students to take on opportunities like this. The people I went on the trip with were very helpful and caring. Even during my presentation/ sessions I got plenty of support to ensure everything was running smoothly. I would also recommend any Physics student to take on this opportunity because I have learnt so much from Greg, Teresa and Sasha alone and as well as the other members that joined us later.

Another learning aspect of this trip was figuring out how to communicate science which not a lot of us worry about doing in our everyday life. I had a couple of students ask some interesting questions and being there on the spot and finding a way to communicate the complex ideas in easy everyday language was a bit of a challenge at first. But hearing Greg communicate over the first couple of days was a huge learning curve for me as I was able to observe him and apply it when I am asked questions. I would highly recommend future students to make thorough observations of everyone when they are doing their work.

At the Astro Rocks Fest people really enjoyed having a look at the headsets. The stall was very popular among kids exploring the solar system. I am so glad I decided to take on this opportunity because it was not only fun and exciting but was a huge learning curve for me. Having company of people who have similar interests as me was very encouraging as a woman in STEM.

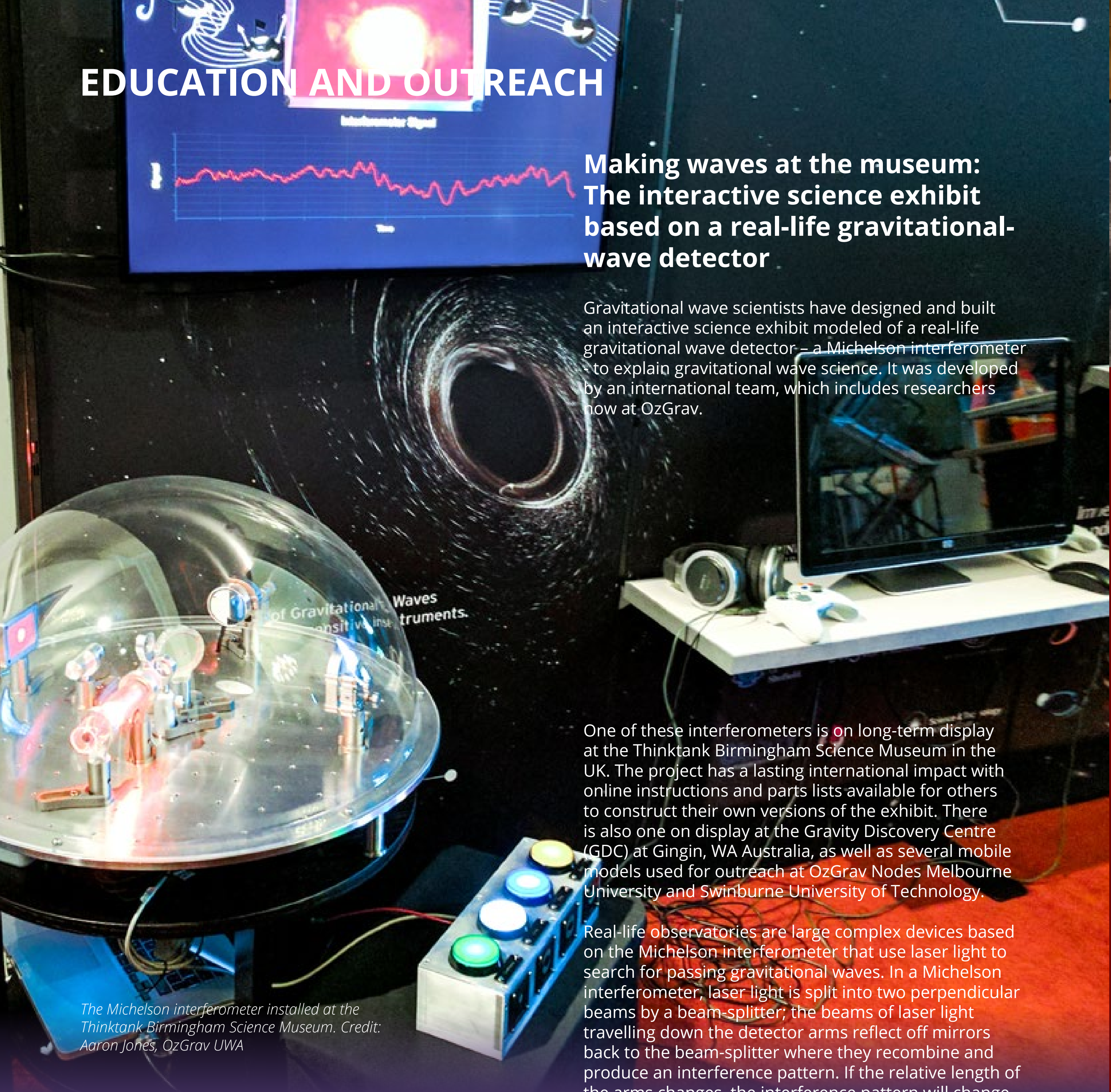


Volunteer Fariha Islam. Credit: Astro Rocks Fest

All photos on this page are from Astrofest Perth.
Credit: Ruby Chan, OzGrav UWA

Astrofest Perth. Credit: Ruby Chan, OzGrav UWA

EDUCATION AND OUTREACH



Making waves at the museum: The interactive science exhibit based on a real-life gravitational-wave detector

Gravitational wave scientists have designed and built an interactive science exhibit modeled of a real-life gravitational wave detector – a Michelson interferometer – to explain gravitational wave science. It was developed by an international team, which includes researchers now at OzGrav.

One of these interferometers is on long-term display at the Thinktank Birmingham Science Museum in the UK. The project has a lasting international impact with online instructions and parts lists available for others to construct their own versions of the exhibit. There is also one on display at the Gravity Discovery Centre (GDC) at Gingin, WA Australia, as well as several mobile models used for outreach at OzGrav Nodes Melbourne University and Swinburne University of Technology.

Real-life observatories are large complex devices based on the Michelson interferometer that use laser light to search for passing gravitational waves. In a Michelson interferometer, laser light is split into two perpendicular beams by a beam-splitter; the beams of laser light travelling down the detector arms reflect off mirrors back to the beam-splitter where they recombine and produce an interference pattern. If the relative length of the arms changes, the interference pattern will change. The exhibit model cannot detect gravitational waves, but it's extremely sensitive to vibrations in the room!

The Michelson interferometer exhibit uses lab-grade optics and custom-made components, drawing people in to take a closer look. In a museum 'Exhibits need to be easily accessible with self-guided learning,' explains OzGrav postdoc Dr Hannah Middleton, one of the project leads from the University of Melbourne.

'We've developed custom interactive software for the exhibit through which a user can access explanatory videos, animations, images, text, and a quiz. Users can also directly interact with the interferometer by pressing buttons to input a simulated gravitational wave, and produce a visible change in the interference pattern.'

Featured in Phys.org.

The Michelson interferometer installed at the Thinktank Birmingham Science Museum. Credit: Aaron Jones, OzGrav UWA

Chirp App

Chirp is an outreach app that provides real-time notification of Gravitational Wave events. Within a few seconds of a gravitational wave event, the source parameters are analysed and converted into public-friendly text. Chrip is a joint project between OzGrav at University of Western Australia and the University of Birmingham in the UK. UWA leads the development of all real-time components and data storage. The app is available from LaserLabs CIC (www.laserlabs.org/chirp.php).

Work is continuing on updating the Chirp app. At UWA we have an Engineering Masters Student in Computer Science working on a V2 of the real-time infrastructure. We started formalising legal arrangements in coordination with the Research Commercialisation office at UWA.

Book launch. Credit: David Nicolson

Hands-on activities at Book launch. Credit: David Nicolson

Teaching Quantum Physics to High School students

There is a growing interest in introducing quantum physics at an early age in schools because of its applications in emerging technologies, such as quantum computers. To make it accessible to school students, the Einstein First program presents a novel way of exploring basic quantum mechanical phenomena, such as matter-wave interference, diffraction, and reflection.

Our graphical approach, based on Feynman path integrals, offers insights into the quantum world in which observations represent quantum probability density. We combine tactile tools called phasor-wheels with real-life analogies and videos of single-quanta interference and employ elementary mathematics to teach these concepts.

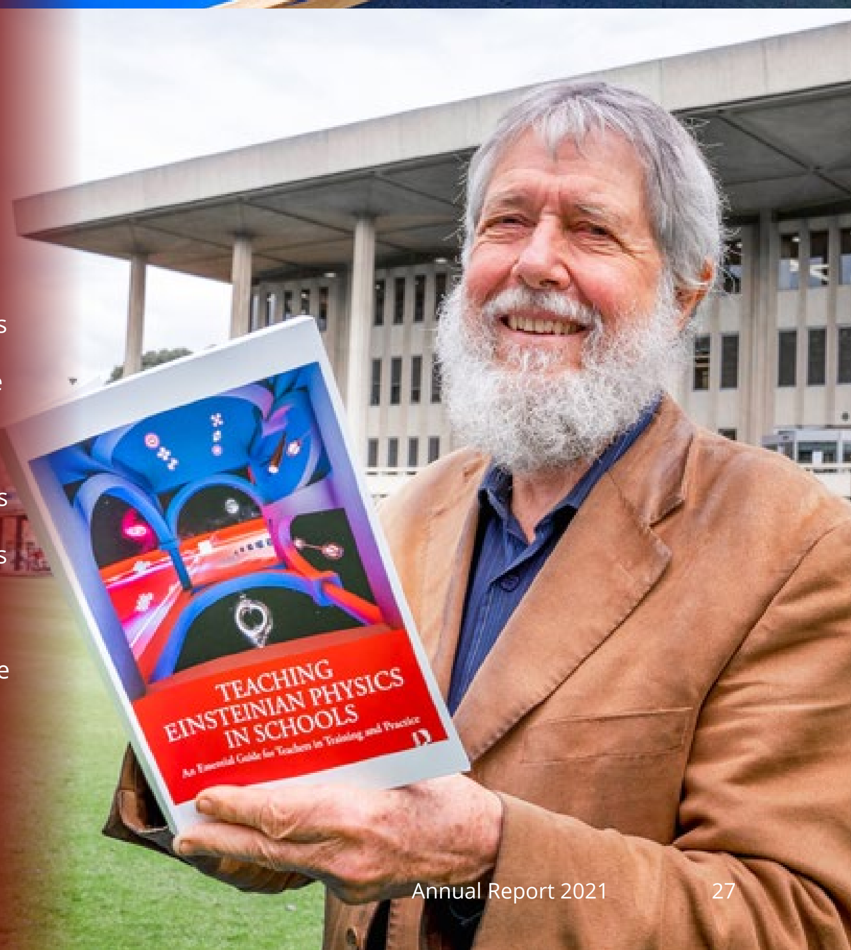
Our approach uses practical, hands-on tools for teaching, making it appealing to students from high school (Year 9 and above). The engaging material encouraged active participation and students found it easy to understand these abstract scientific concepts.
Article by Rahul Choudhary (UWA).

Spacetime demonstration. Credit: Ruby Chan, OzGrav UWA

Book Launch

As part of the Einstein-First Project at the University of Western Australia, the book "Teaching Einsteinian Physics in Schools" was launched in National Science Week to revolutionise school science. Science luminaries - including Chief Investigator Prof Susan Scott (ANU) and Chief Investigator Prof David Blair (UWA), two of the 2020 winners of the Prime Minister's Prize for Science - announced this campaign to take school science from the 19th Century and place it firmly in the 21st Century. The new book introduces Einsteinian science to teachers at the level needed for both primary and middle school. It advocates complete replacement of obsolete concepts with the Einsteinian concepts that underpin all modern technology.

The launch event went really well, with about 150 people who attended in person, plus those joining online. We collected approximately 50 pre-orders for the book and have been able to create some new connections for partner schools and make contact with potential new industry supporters for the Einstein First project.



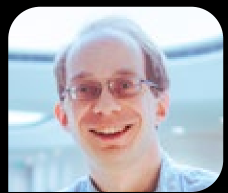
AWARDS AND HONOURS

Julian Carlin was awarded the Geoff Opat Seminar Series Best Talk 2021 by the University of Melbourne.

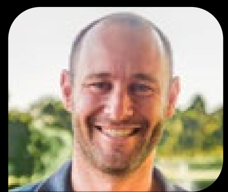



The Newcomb Cleveland Prize of the American Association for the Advancement of Science (AAAS) is annually awarded to authors of outstanding scientific papers published in the Research Articles or Reports sections of Science. In February 2021 it was awarded to the paper Bannister et al. (2019) including OzGrav members Deller, Shannon, Flynn and Oslowski, for best paper of the year in the journal Science (June 2019-June 2020) that presented the discovery of the first localised one-off FRB: 'A single fast radio burst localized to a massive galaxy at cosmological distance'

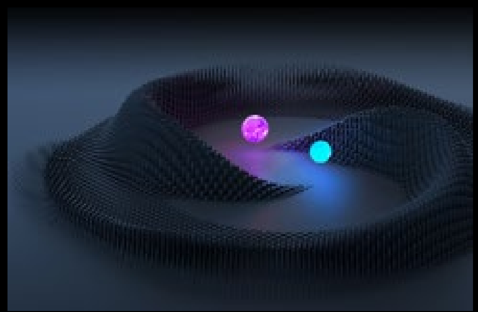
Congratulations to OzGrav Affiliate Dr Rebecca Allen (Swinburne University) who has been selected by the Australian Institute of Policy and Science to receive a prestigious Young Tall Poppy Science award. The awards honour up-and-coming scientists who combine world-class research with a passionate commitment to communicating science.



Dr Bernhard Müller (Monash) won a 2021 Australasian Leadership Computing Grant from National Computational Infrastructure (NCI) Australia. The grant will fund research on 'High-resolution Core-Collapse Supernova Simulations', with both OzGrav Associate Investigators Dr Jade Powell (Swinburne) and Prof Alexander Heger (Monash) working on the project.



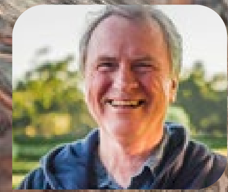
In November Paul Lasky was named Australia's Top Researcher in Condensed Matter Physics by the Australian Newspaper.



Carl Knox's (Swinburne) image "Waves" is selected to be presented in an installation named "The Art of Outer Space" as part of [Figure 1.A.] 2021. Carl's work was chosen from 221 images submitted from 120 artists in 18 countries, representing 63 institutions This installation will complement the main exhibition and features two images and a video all of which are created by artists collaborating with scientists. The work will be exhibited in the gallery Forum of Hôtel de Ville, Lausanne Switzerland from 23rd-30th August 2021. See more at www.figure1a.org

Susan Scott (ANU) received an Honorable Mention - Gravity Research Foundation 2021 international Awards for Essays on Gravitation, with her essay: "What Actually Happens when You Approach a Gravitational Singularity?

OzGrav Postdoctoral Researcher and Population Modelling Program Chair Dr Simon Stevenson (Swinburne) was awarded an ARC DECRA (DE22) for his project Discovering the origins of gravitational waves.

Congratulations to Susan Scott and David McClelland on their elevation to "Distinguished Professor" status at ANU. A well-deserved recognition for their life-long contributions to gravitational wave research.

The Thomas Ranken Lyle Medal is a career award that commemorates the contribution of Sir Thomas Ranken Lyle, FRS, to Australian science and industry generally and in particular to his own fields of physics and mathematics. The purpose of the medal is to recognise outstanding achievement by a scientist in Australia for research in mathematics or physics. In 2021 it was awarded to Distinguished Professor David McClelland (ANU and OzGrav Deputy Director). It is terrific to see David's tremendous contributions to quantum squeezing and gravitational wave discovery recognised with this honour on top of the other accolades he has received since the creation of OzGrav!

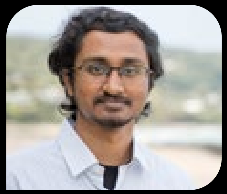
Professor David Blair (UWA) is internationally recognised for his extensive achievements in experimental physics. A reception was held in June 2021 at Scitech in recognition of his contribution to Science, including the prestigious 2020 Prime Minister's Prize for Science, and his 2018 induction into the WA Science Hall of Fame.

Congratulations to Tamara Davis (University of Queensland) on receiving the 2021 ASA prize-winning Robert Ellery Lectureship for outstanding contributions in astronomy or a related field. Tamara is a member of the OzGrav Governance Advisory Committee (GAC) and we are grateful for her enthusiasm and expertise.

Congratulations to former OzGrav Chief Investigator Prof Daniel Shaddock (ANU), founder and CEO of Liquid Instruments, who was announced as the 2021 ACT Chief Minister's Pearcey Entrepreneur Award.

OzGrav won a Silver Pleiades Award by the ASA, for our continued commitment to promoting equity and inclusion. The Silver Pleiades recognises organisations with a sustained record of at least two years 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.

AWARDS AND HONOURS

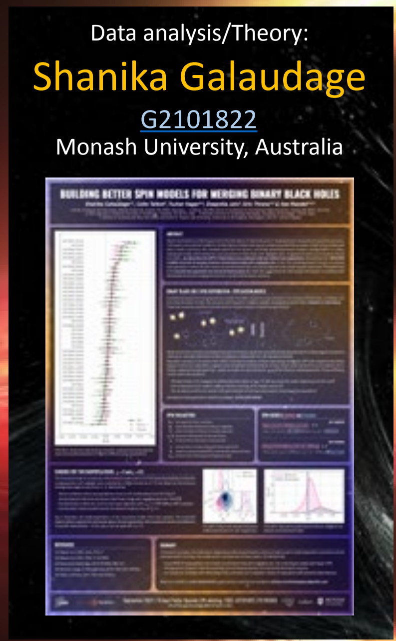


Chayan Chatterjee (UWA PhD student) is building on his science communication skills from the 2020 Three Minute Thesis UWA finals win, making it to the finals of FameLab Western Australia in 2021. Chayan won this year's J-P Macquart Best Student Talk Award at ANITA21, awarded by the Australian National Institute for Theoretical Astrophysics.

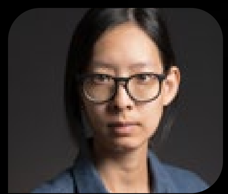
Rahul Choudhary (UWA PhD student) won a UWA iPrep Award for a paid industry project.

Dougal Dobie (PhD student at University of Sydney and now Postdoctoral Researcher at Swinburne) has won the 2021 School of Physics prize for the best PhD Thesis at the University of Sydney.

Congratulations to Shanika Galaudage (Monash University PhD student) on winning the September 2021 international LVK meeting poster prize for Data Analysis / Theory. Her poster is titled "Building Better Spin Models For Merging Binary Black Holes."



Congratulations to Disha Kapasi (ANU PhD student) who has been selected to represent ANU students in the 10th Anniversary edition of the Global Young Scientists Summit (GYSS) where she will interact with Nobel Laureates and world-renowned scientists.



The Warsash Science Communication Prize in Optics is open to student members of the Australian and New Zealand Optical Society (ANZOS) whose Honours, Masters or PhD research work has been accepted for publication in a refereed journal in the past year. A submission consists of a 300-word summary of the published research, written in the style of a New Scientist article or similar, explaining the significance of the applicant's research project to a general reader outside the field. Selection criteria include High-quality research in Optics, and Ability to seize and sustain the reader's interest. Ntusinee Kijbunchoo's submission (ANU PhD student) "The Bumpy Little World: How Quantum Engineered Vacuum Increased Gravitational Waves Detection Rate" was the overwhelming favourite of the panel and has been awarded a combined 2020/2021 Warsash Science Communication Prize. It will be featured in an upcoming edition of the ANZOS Newsletter.

Ethan Payne (Monash Masters student then ANU Research Assistant) has received an honourable mention for the Bok Prize for outstanding research in astronomy or a closely related field, by an Honours student or eligible Masters student at an Australian university.

Ethan Payne (now studying his PhD at Caltech) received the 2021 LIGO Laboratory Award for Excellence in Detector Characterization and Calibration for his outstanding work improving the incorporation of LIGO detector calibration errors into gravitational-wave parameter estimation analyses.

Congratulations to Isobel Romero-Shaw (Monash University PhD student) for winning Monash's Norris Family Award for Outstanding Author Contribution by a Graduate Research Student to a published Quality Scholarly Research Output for the paper "GW190521: Orbital eccentricity and signatures of dynamical formation in a binary black hole merger."

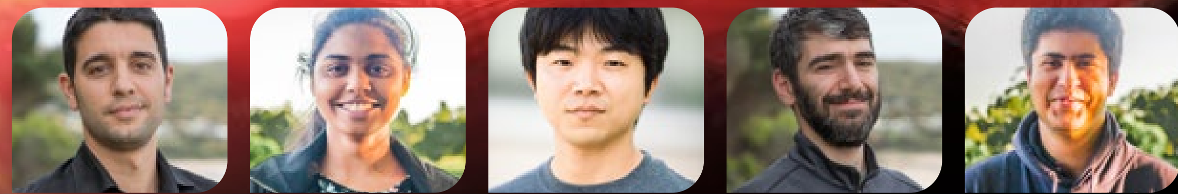
Congratulations to Colm Talbot (former PhD student at Monash University) on receiving the Charlene Heisler Prize for most outstanding PhD thesis in astronomy or a closely related field, for his Doctoral Thesis: "Astrophysics of Binary Black Holes at the Dawn of Gravitational-Wave Astronomy."

Congratulations also go to Colm for winning Monash University's Vice-Chancellor's Commendation for thesis excellence for his thesis.

OzGrav 2021 Retreat Awards

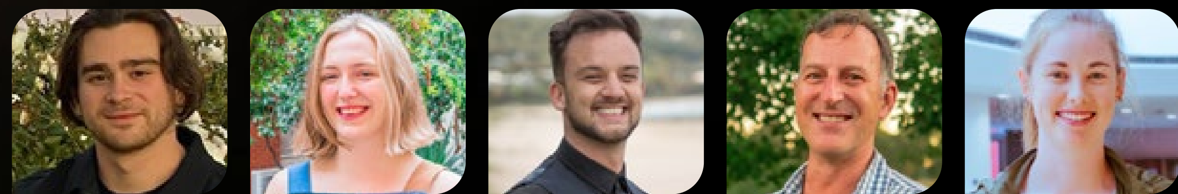
Biggest contributors to newsletters and research briefs

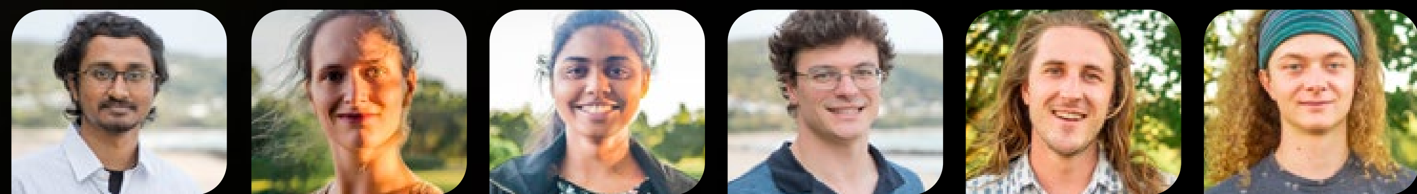
Juan Calderon Bustillo (Monash), Shanika Galaudage (Monash), Ryo Hirai (Monash), Ilya Mandel (Monash) and Nikhil Sarin (Monash)



Outreach Superstars

Zac Holmes and Sophie Muusse – University of Adelaide
Carl Knox and Mark Myers - Swinburne University of Technology
Kyla Adams and Chayan Chatterjee - University of Western Australia
Lucy Strang – University of Melbourne
Shanika Galaudage and Reinhold Willcox - Monash University
Dan Gould and Ben Grace – Australian National University





INSTRUMENTATION THEME

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

The instrumentation theme is pursued under seven programs:

1. Commissioning - Program chairs: Dr Daniel Brown (Adelaide) and Dr Bram Slagmolen (ANU)

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

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

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

5. Space Instrumentation - Program Chair: Prof Kirk McKenzie (ANU)

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

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

Background image: Associate Investigator Dr Ling (Lilli) Sun (ANU) in the laser lab. Credit Tracey Nearmy ANU.

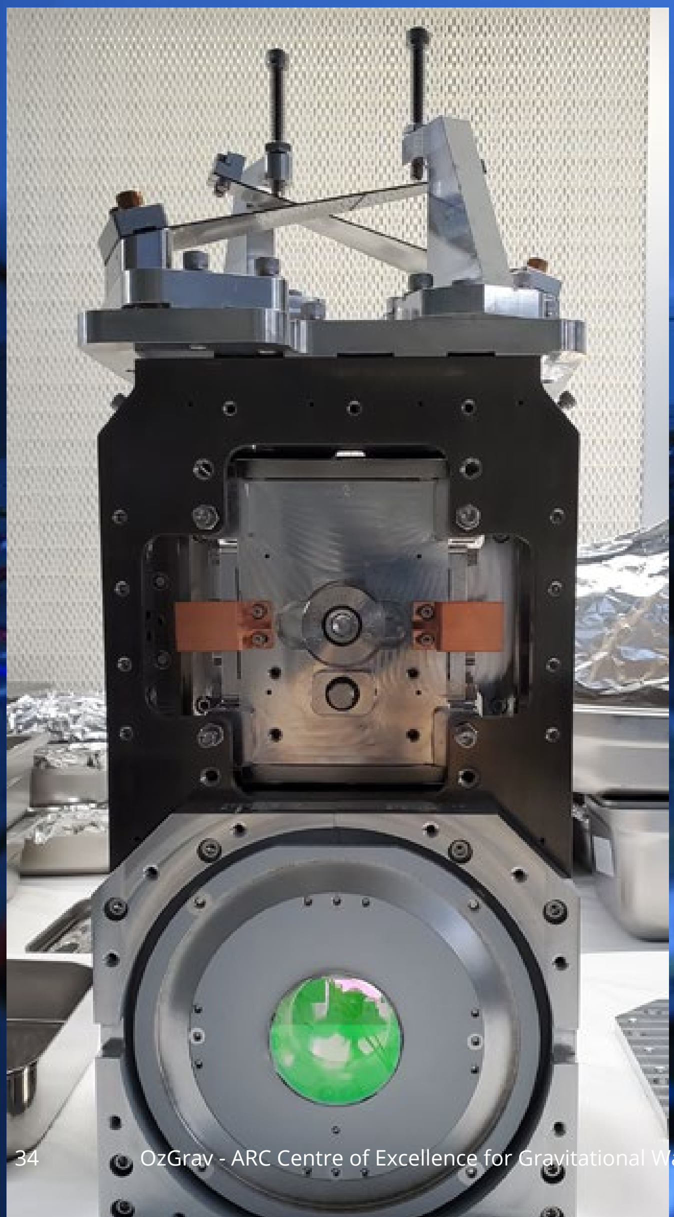
INSTRUMENTATION THEME

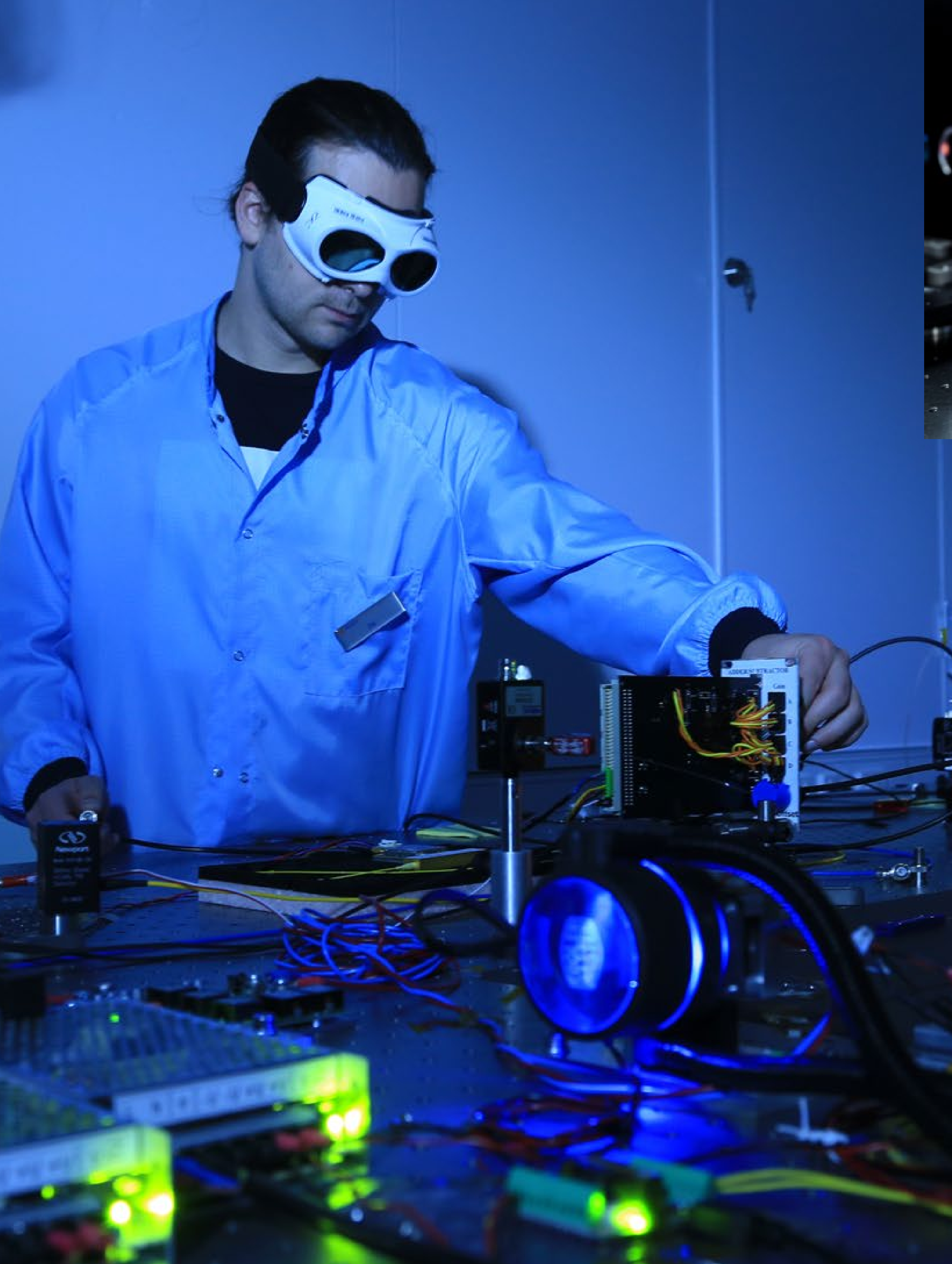
Commissioning

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

The LIGO Observatories incurred reduced activities due to the COVID-19 pandemic, which resulted in delays in constructing new infrastructures on the sites (chamber installation, 300m beam tube for filter cavity). This in turn pushed the need for commissioning activities to the later months of the year at LIGO Livingston (LLO) and scheduled to start in Jan 2022 for LIGO Hanford (LHO).

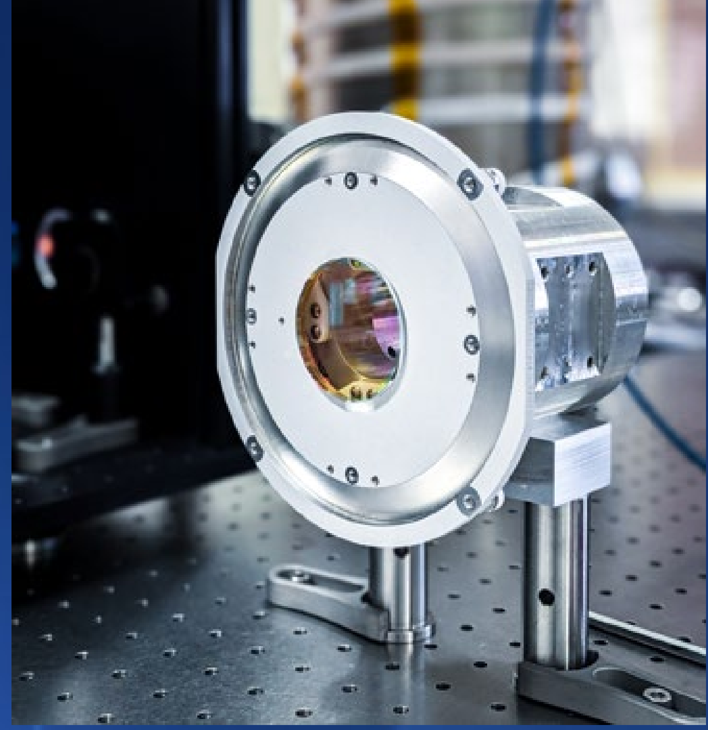
The continued international travel bans that resulted due to the COVID-19 pandemic massively reduced our ability to contribute to onsite commissioning at the LIGO Observatories again during 2021. Despite this, significant efforts have been underway in Adelaide to build, characterise, and deliver the new thermal adaptive wavefront control systems to LIGO. The first of these was delivered to LIGO Livingston at the start of 2022.





Inset image: T-SAMS suspension has just been assembled at LIGO Livingston. Credit Karla Ramirez, LIGO

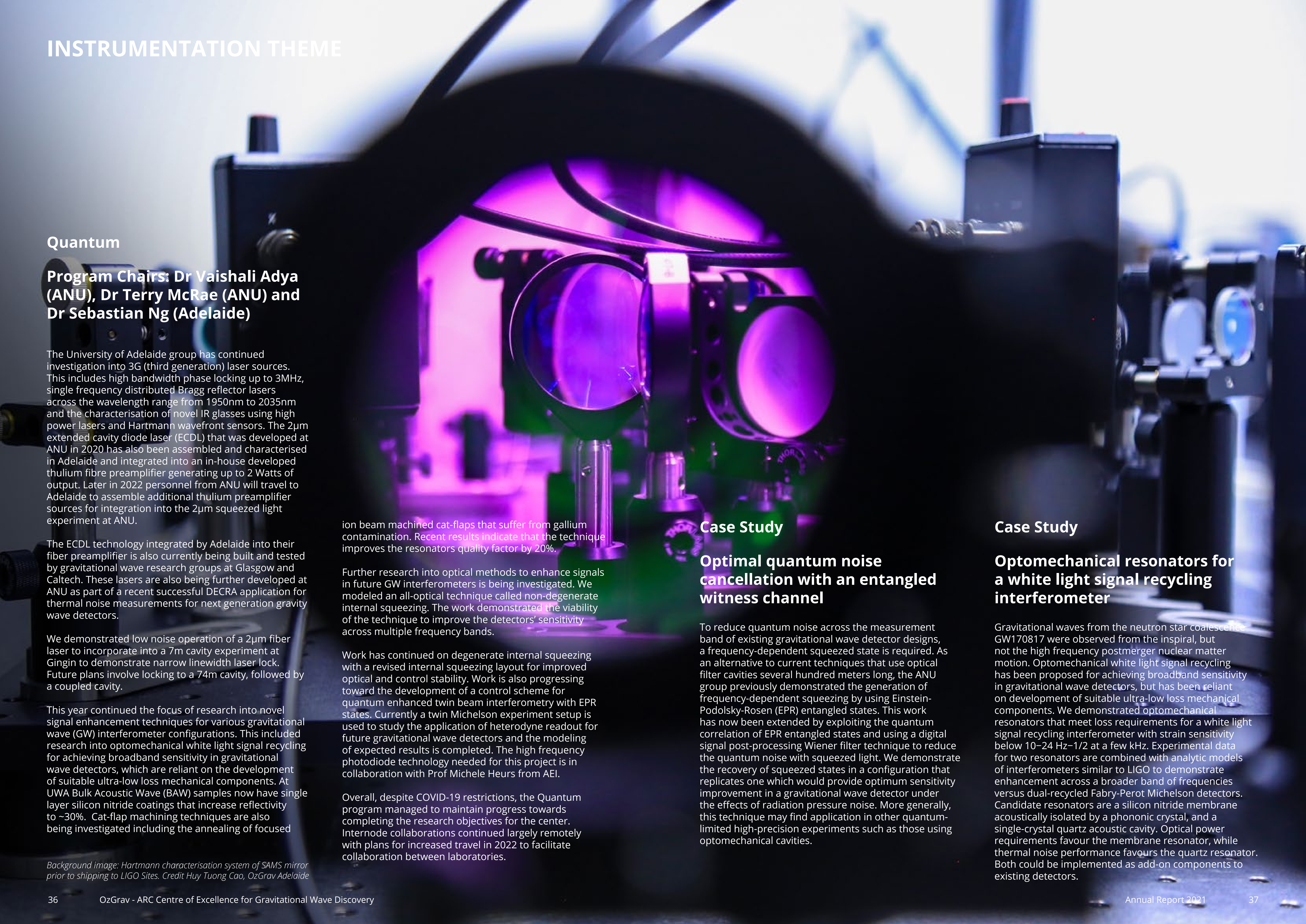
Background image: Zac Holmes (Adelaide) characterising the thulium-doped fibre preamplifier. Credit: Huy Tuong Cao, OzGrav Adelaide



T-SAMS installed into HTDS suspension. Credit: Huy Tuong Cao, OzGrav University of Adelaide

Case Study

The first of an adaptive optics, conceptually realised by researchers at OzGrav Adelaide node, has been finalised and delivered to LIGO Livingston Observatories at the end of December 2021. These are mirrors with radii of curvature that can be tuned with varying temperature. The deformable mirror is referred to as the Thermal Suspended Active Matching Stage (T-SAMS). These mirrors, together with the piezo-actuated mirror (P-SAMS) developed at MIT LIGO Lab, are integrated into a double pendulum suspension to form a new class of suspension system which house optics that can actively be tuned to correct mode-mismatch in gravitational wave interferometers. The HTDS system, which houses the T-SAMS will be installed in HAM6 at the antisymmetric port of the detector before the output mode cleaner. This should enable improving mode-matching from the interferometer to the output mode cleaner. Three other suspensions which house the P-SAMS (HPDS) have been installed in the new frequency-dependent squeezing system. The T-SAMS mirror is a product of two years of design and refinement from its initial concept, started in early 2019. During 2021, the fabrication of these mirrors started at the University of Adelaide instead of at LIGO Lab per its initial plan due to the impact of COVID-19. A new facility was constructed to allow these assemblies to meet LIGO standards. Testing of the first delivered unit with the University of Adelaide Hartmann sensor shows a large actuation range with a highly linear response to temperature change. Further testing using the ZYGO at Caltech has further verified its performance. The installation of the first mirror is scheduled for January 2022 at Livingston. A second unit is currently undergoing assembly and will be delivered to LIGO Hanford Observatory in late January. The installation of these new active optics aim to address the mode mismatch loss which degrades the performance of squeezing, especially at high laser power operation. The next few months will see OzGrav members' continual effort in commissioning these optics integrated into the detectors, making an Australian direct contribution towards LIGO A+ design sensitivity.



Quantum

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

The University of Adelaide group has continued investigation into 3G (third generation) laser sources. This includes high bandwidth phase locking up to 3MHz, single frequency distributed Bragg reflector lasers across the wavelength range from 1950nm to 2035nm and the characterisation of novel IR glasses using high power lasers and Hartmann wavefront sensors. The 2µm extended cavity diode laser (ECDL) that was developed at ANU in 2020 has also been assembled and characterised in Adelaide and integrated into an in-house developed thulium fibre preamplifier generating up to 2 Watts of output. Later in 2022 personnel from ANU will travel to Adelaide to assemble additional thulium preamplifier sources for integration into the 2µm squeezed light experiment at ANU.

The ECDL technology integrated by Adelaide into their fiber preamplifier is also currently being built and tested by gravitational wave research groups at Glasgow and Caltech. These lasers are also being further developed at ANU as part of a recent successful DECRA application for thermal noise measurements for next generation gravity wave detectors.

We demonstrated low noise operation of a 2µm fiber laser to incorporate into a 7m cavity experiment at Gingin to demonstrate narrow linewidth laser lock. Future plans involve locking to a 74m cavity, followed by a coupled cavity.

This year continued the focus of research into novel signal enhancement techniques for various gravitational wave (GW) interferometer configurations. This included research into optomechanical white light signal recycling for achieving broadband sensitivity in gravitational wave detectors, which are reliant on the development of suitable ultra-low loss mechanical components. At UWA Bulk Acoustic Wave (BAW) samples now have single layer silicon nitride coatings that increase reflectivity to ~30%. Cat-flap machining techniques are also being investigated including the annealing of focused ion beam machined cat-flaps that suffer from gallium contamination. Recent results indicate that the technique improves the resonators quality factor by 20%.

Background image: Hartmann characterisation system of SAMS mirror prior to shipping to LIGO Sites. Credit Huy Tuong Cao, OzGrav Adelaide

Further research into optical methods to enhance signals in future GW interferometers is being investigated. We modeled an all-optical technique called non-degenerate internal squeezing. The work demonstrated the viability of the technique to improve the detectors' sensitivity across multiple frequency bands.

Work has continued on degenerate internal squeezing with a revised internal squeezing layout for improved optical and control stability. Work is also progressing toward the development of a control scheme for quantum enhanced twin beam interferometry with EPR states. Currently a twin Michelson experiment setup is used to study the application of heterodyne readout for future gravitational wave detectors and the modeling of expected results is completed. The high frequency photodiode technology needed for this project is in collaboration with Prof Michele Heurs from AEI.

Overall, despite COVID-19 restrictions, the Quantum program managed to maintain progress towards completing the research objectives for the center. Internode collaborations continued largely remotely with plans for increased travel in 2022 to facilitate collaboration between laboratories.

Case Study

Optimal quantum noise cancellation with an entangled witness channel

To reduce quantum noise across the measurement band of existing gravitational wave detector designs, a frequency-dependent squeezed state is required. As an alternative to current techniques that use optical filter cavities several hundred meters long, the ANU group previously demonstrated the generation of frequency-dependent squeezing by using Einstein-Podolsky-Rosen (EPR) entangled states. This work has now been extended by exploiting the quantum correlation of EPR entangled states and using a digital signal post-processing Wiener filter technique to reduce the quantum noise with squeezed light. We demonstrate the recovery of squeezed states in a configuration that replicates one which would provide optimum sensitivity improvement in a gravitational wave detector under the effects of radiation pressure noise. More generally, this technique may find application in other quantum-limited high-precision experiments such as those using optomechanical cavities.

Case Study

Optomechanical resonators for a white light signal recycling interferometer

Gravitational waves from the neutron star coalescence GW170817 were observed from the inspiral, but not the high frequency postmerger nuclear matter motion. Optomechanical white light signal recycling has been proposed for achieving broadband sensitivity in gravitational wave detectors, but has been reliant on development of suitable ultra-low loss mechanical components. We demonstrated optomechanical resonators that meet loss requirements for a white light signal recycling interferometer with strain sensitivity below 10^{-24} Hz$^{-1/2}$ at a few kHz. Experimental data for two resonators are combined with analytic models of interferometers similar to LIGO to demonstrate enhancement across a broader band of frequencies versus dual-recycled Fabry-Perot Michelson detectors. Candidate resonators are a silicon nitride membrane acoustically isolated by a phononic crystal, and a single-crystal quartz acoustic cavity. Optical power requirements favour the membrane resonator, while thermal noise performance favours the quartz resonator. Both could be implemented as add-on components to existing detectors.

INSTRUMENTATION THEME

Image: Installation of the TorPeDO multi-stage isolation and suspension chain at ANU.Credit: Sheon Chua, OzGrav ANU

Low Frequency Newtonian Noise Mitigation

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

Even with reduced laboratory access the TorPeDO experiment installed the 500kg Isolation and Suspension Chain in position in the vacuum tank. For many months prior the installation, the four-stage pendulum system has been methodically built, assembled and tested. We finalised complex measurements which took many weeks to obtain, which will take some time to analyse and present the performance of the low-frequency dual torsion experiment.

We assembled a free-space optical measurement setup to test the performance of the digital interferometer technique, with a goal to use this as a contactless displacement sensor in the Isolation and Suspension Chain.

We worked on upgrading the prototype rotation sensor–ALFRA. The Mark-2 ALFRA features a compact design with a more robust flexure, and easy tuning. Optimisation of the flexure with finite element modelling was completed. Test flexures were successfully machined. The new design also incorporates a shadow sensor/actuator together with the interferometric sensing to improve the dynamic range of the system. The Mark-2 is finishing the conceptual design.

With the ARC LIEF grant, we obtained 20 new compact seismometers (Trilium Horizon), and low frequency geophones (SmartSolo). Together with UWA existing 20 seismometers, this will allow us to construct a large (kilometer size) seismic array at the Gingin site for seismic imaging, vibration isolation system control and conduct Newtonian noise cancellation research. A special stand-alone bushfire-proof design is made to adapt the array environment at the Gingin site. A Wi-Fi remote data acquisition system was also designed for the purpose of near real time seismic imaging. A mini-seismic array was deployed near the Gingin research facility. We did initial site characterisation of the low coherency of the wind-induced seismic motion.

Distortions and Instabilities

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

The major highlight of this year was that the compression fit mirror that was developed in OzGrav over the last few years has been completed and it has been installed for testing in the LIGO Livingston observatory. We eagerly await the results from this installation which will hopefully significantly improve the mode matching between the Signal Recycling Cavity and the Output Mode Cleaner which will lead to improved quantum noise suppression from squeezed light injection.

The other major advancement was that COVID-19 restrictions were lifted long enough that members of the University of Adelaide Team were able to travel to visit the University of Western Australia team to undertake our long-awaited parametric instability imaging experiment. This experiment was a success and we used our optical lock-in camera technology to image the optical mode generated by parametric instability for the first time. This demonstration will become increasingly important as the optical power levels in the interferometer increase and it becomes increasingly important to develop new parametric instability suppression strategies.

COVID-19 led to a significant delay in crystalline coating on silicon test masses because the coating material to be transferred to the test mass will be made in US through Thorlabs, while the facility that can cope with large area and thick test mass (30mm thick) is in Jena, Germany. While we are waiting for the crystalline coatings, we polished 2 fused test masses and coating with normal optical coating at 2μm (2 micron) wavelength. Since the Gingin 80m pipe in the south arm crashed accidentally, we are building a 7m cavity with fused silica test masses suspended with initial LIGO small optics suspension and using a 5W 2μm laser as the light source. The laser is set up at Gingin and the vacuum system is ready. All parts are available and we expect the first 2μm cavity in March.

The analysis of parametric instability in NEMO has been completed. Significant instability will appear in NEMO if no control is applied. However a slight change to the end test mass radius of curvature and recycling cavity Gouy phases will prevent the instability. We started the acoustic damper design for NEMO, but no results yet.

We built a silicon birefringence mapping system using a photoelastic modulator and a 2μm laser source. The initial measurements of the birefringence of a FZ silicon show 10^-8/cm of refraction index changes. However, the results of a MCZ silicon sample from Caltech show 100 times larger refraction index changes than FZ silicon. Caltech informed us that this is not a good sample.

We have continued our numerical studies on the implications of thermal induced aberrations in the beam splitter. We have shown that if 2 micron lasers are used in either Voyager or NEMO then the aberrations induced in a silica beam splitter will be a significant limiting factor. Introducing a passive compensating plate that makes the thermal aberrations common mode can increase the power levels which can be achieved before aberrations limiting by a factor of 2. Unfortunately this is not sufficient to guarantee the reliable operation of NEMO or Voyager and new solutions to the beam splitter issue need to be found. This could involve either shortening the wavelength used to 1.55μm, changing the material used in the beam splitter to CaF2 or developing compensation strategies for the beam splitter. The current state of technical readiness of 1.55μm lasers is higher than 2μm detectors.

Our study on rapid decomposition of optical modes in an interferometer using both amplitude and phase and machine learning showed significant performance advantages compared with the more traditional integral based modal decomposition approaches.

We have developed an improved photo-thermal 'deflection' technique in which the pump absorption is measured using a differential Hartmann wavefront sensor and an off-axis probe beam. We demonstrated, for the first time ever, that the optical absorption coefficient for ZBLAN at 2μm is 50 ppm/cm with an uncertainty due to random error of 1pm/cm. Importantly, this measurement is independent of scatter loss in the ZBLAN, which is crucial for improving the optical quality of that IR glass.

Inset image: UWA and University of Adelaide colleagues working at Gingin (via Zoom). Credit: Mitchell Schiworski, OzGrav Adelaide.

Background image: our home built 2μm laser at Gingin High Optical Power Facility (UWA). Credit: Aaron Jones and Ben Gaudin, OzGrav UWA

Space Instrumentation

Program Chair: Prof Kirk McKenzie (ANU)

In 2021 the Space Instrumentation Program continues on the three themes 1) weak light phase tracking, 2) absolute laser frequency knowledge measurements, and 3) laser frequency stabilization for space-based interferometers.

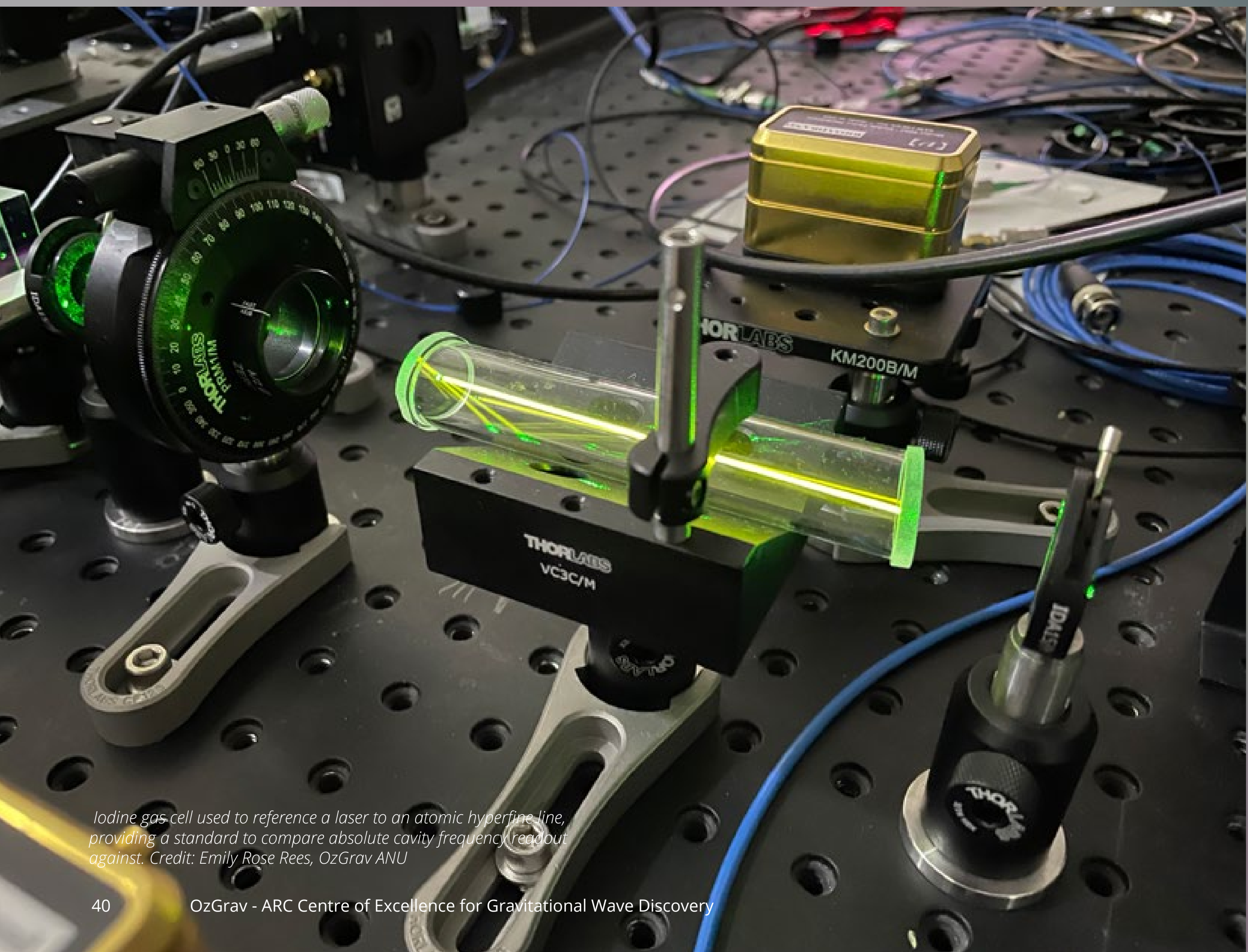
Of the four Space program milestones set out in the 2020 Annual report, three were completed on time or early, and a fourth is delayed and will be completed in 2022. We published journal articles on absolute frequency knowledge experimental results and laser stabilisation, as well as absolute frequency knowledge and tilt-locking. An Arm-locking laser stabilisation article was submitted. We completed FPGA-based simulation of weak-light phase tracking, clearing the way for an optical test in 2022. Research was delayed on weak-light tracking results due to some unexpected complexity, with expected new findings and optical results in mid to late-2022.

Low-optical power phase tracking: Improved weak light phase locking enables a range of options for future space-based gravitational wave detectors, in particular, longer arms which could improve sensitivity or smaller telescopes to reduce payload size and mass. The main achievement this year was a detailed study of our phasemeter feedback loop parameterisation and cycle slip dynamics under a hardware-in-the-loop simulation. Here the FPGA-based phasemeter used in the laboratory was fed simulated data, enabling detailed investigation of the phasemeter as well controlled simulated low power tracking. This prepares our phasemeter for a full optical testbed campaign in 2022.

Absolute laser frequency knowledge: Knowledge of absolute laser frequency is important for space-based detectors in two ways: 1) To improve acquisition of the laser link between the spacecraft, reducing the search over degrees of freedom from five to four; removing laser frequency difference between spacecraft to leave just pitch and yaw errors. And 2) to calibrate the scaling of detected phase into units of true displacement, and thus gravitational waves amplitude. An experimental program is ongoing with results of an absolute frequency readout accurate to 1 ppb in 2021.

Laser stabilisation for space interferometers: For laser frequency stabilisation, results from the tilt-locking work in mid-2021 showed performance comparable to the standard Pound-Drever-Hall locking. Performance exceeded GRACE-FO requirements and is close to meeting the LISA requirements. This completes a milestone to finalise tilt-locking and wraps up our ongoing work on this topic for now.

A detailed study combining the Arm-Locking laser frequency stabilisation scheme with an optical cavity redout was finalised and shown to be compatible with the baseline laser stabilisation planned for the LISA mission. Using the LISA arms as an ultra-stable reference, the existing mission hardware can be resourcefully used to augment the current cavity only stabilisation system. The benefits include risk reduction and possible architecture simplifications with no additional hardware and at least an order of magnitude improvement across the LISA sensitivity band.



Iodine gas cell used to reference a laser to an atomic hyperfine line, providing a standard to compare absolute cavity frequency readout against. Credit: Emily Rose Rees, OzGrav ANU

Case Study

The Experiment Must Go On — Using Moku:Lab During Lockdown

While the COVID-19 shutdowns in 2020 and 2021 were disruptive for the Space program experiments and in particular the student projects, an attempt was made to maximise the output by various work arounds. The OzGrav Space Program worked with the Australian start-up company Liquid Instruments to take results over the COVID-19 shutdown.

At the onset of COVID-19 pandemic, Dr Andrew Wade and Dr Kirk McKenzie of the Center for Gravitational Astrophysics at the Australia National University (ANU) were warned that a full shutdown of their lab was imminent, and could last for months. They needed to quickly configure their setup and ensure long-term data collection was possible. After a few calls and emails with the Liquid Instruments team, their experiment was up, running, and remotely accessible.

"We (ANU) had set up a long running measurement to track the stability of an optical frequency reference against a time standard," said Dr Wade. "We needed to log slow drifts of our device under test using the Moku:Lab's Lock-in Amplifier and wanted to check in on the progress of the experiment every few days. Ideally we wanted a month-long segment of uninterrupted data."

The equipment itself was not necessarily the problem. "We have a lot of legacy equipment that can collect and digitise data," Dr Wade explained. Instead, the larger hurdle was accessing the data once it was collected. "Extracting the data from these legacy instruments, often involves many layers of "hacks" to check in and access data remotely over a computer network." Even though their lab has a custom-built ADC/DAC system for collecting data, the short and urgent timeline meant a lot of overhead and a steep learning curve for configuration that the research team could not afford to take on.

Dr Wade's research lab already had a few Moku:Labs, and he immediately saw the potential to incorporate them into their experiment. "Moku:Lab offered an easy-to-use interface that could be learned, configured and deployed in our setup in a matter of hours," he said. "The data logger is also built into a number of instruments on the Moku:Lab making it easy to log signals from, for instance, the Laser Lock Box and directly from the ADC inputs."

Even with Moku:Lab's flexibility, there were limitations to the solution in the face of months of lockout. The research team had set up a measurement to run for a 240-hour period (the default maximum). About a week after the lab entered full shutdown, Dr Wade emailed the Liquid Instruments team directly to inquire about maximising the log time. Immediately recognising that this was a solution that stood to benefit many of our customers facing limited lab access, Liquid Instruments started working together on a solution. Within a few days, a beta update to the iPad app had been implemented. This update was done entirely in the firmware, with no modification to any of the hardware.

"We now have an excellent set of data that is 33 days of uninterrupted collection," said Dr Wade. "It allowed us to be productive in the lab even through the COVID-19 shutdown. Liquid Instruments worked with us to provide a solution quickly that meant that lab equipment wasn't sitting idle when we were not able to physically present."

Moku:Lab. Credit: Nutsinee Kijbunchoo, OzGrav ANU

INSTRUMENTATION THEME

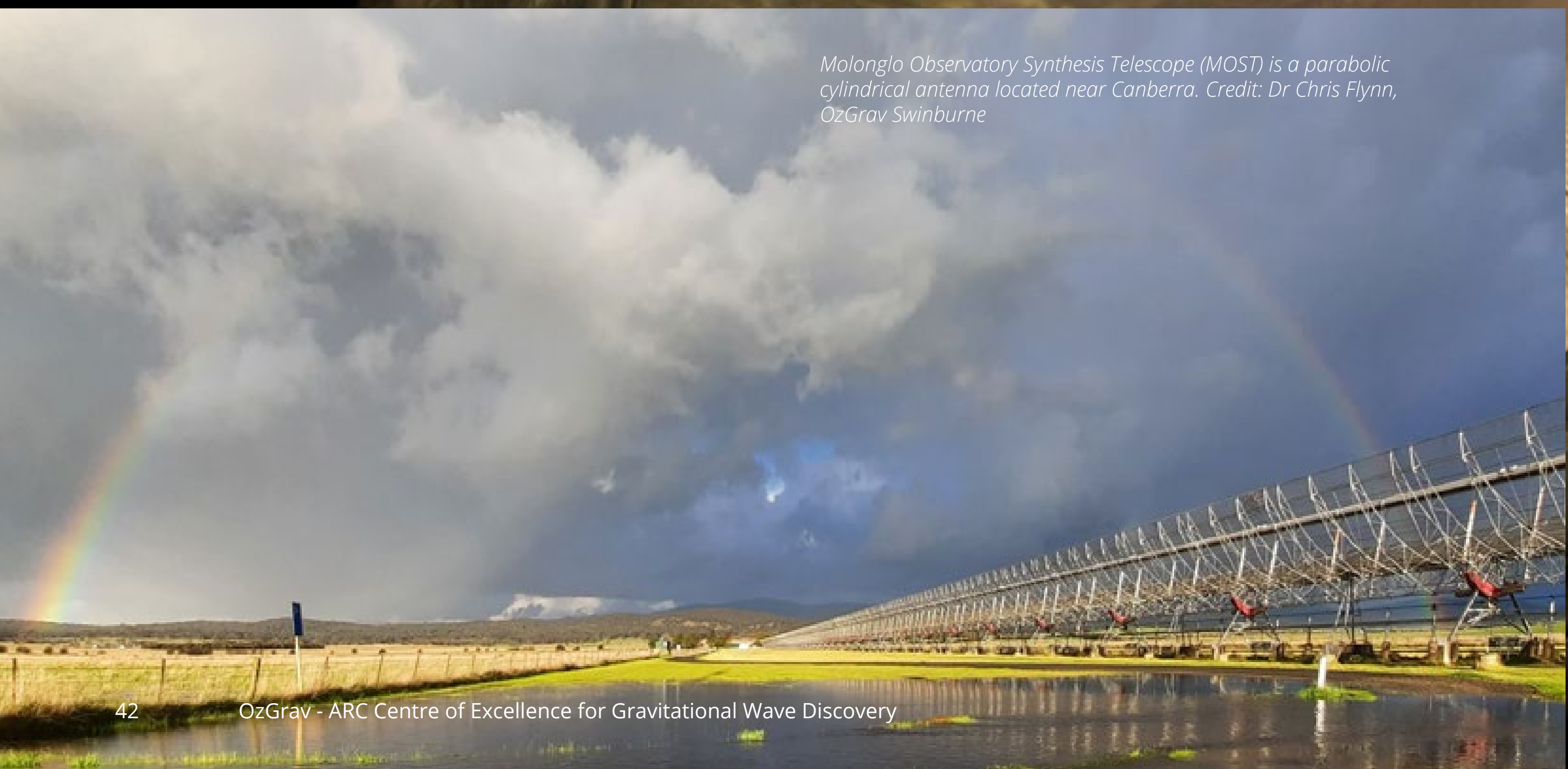
Pulsar Timing

Program Chair: Prof Matthew Bailes (Swinburne)

In 2021 we successfully formed a spin-off company "Fourier Space Pty Ltd" to work in advanced signal processing for radio astronomy, satellite communications and related activities. The company was successful at winning the contract for the pulsar processors for the Square Kilometre Array, and has already succeeded at gaining design contracts from the CSIRO for phased array feed work, the ASKAP telescope and a satellite communications company.

We also developed a new pulsar timing engine for the (previously defunct) north-south arm of the Molonglo Observatory in a collaboration between Swinburne University of Technology and the University of Melbourne. The new telescope observes approximately 170 pulsars each week and automatically search for glitches by the University of Melbourne's pipeline.

The team achieved all of its 2021 goals including the deployment of the pulsar timing portal with the help of the Gravitational Wave Data Centre.



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

Future Detector Planning

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

Our efforts developing the science case and technical design for an Australian next-generation detector called NEMO has led to our design being tabled alongside the US Cosmic Explorer and the EU Einstein Telescope as one of the key next-generation detector opportunities. Importantly, OzGrav is playing a key role in the global interferometer modelling effort and we will ensure that our members continue to lead the international next-generation detector R&D roadmapping efforts.

We will also increase our focus on building and galvanising our reputation with European colleagues, noting that the Einstein Telescope (ET) was recently approved for inclusion in the European Strategy Forum on Research Infrastructures (ESFRI) 2021 Roadmap. For instance, we have recently added leading European GW physicist Professor Stefan Hild to our Scientific Advisory Committee, and we are exploring options for Australian involvement in the multi-billion-dollar GW LISA observatory by adapting the work performed for the Grace Follow-on mission. We are also ensuring that OzGrav members join the ET Science Collaboration with a goal to taking on R&D work packages.

University of Adelaide Masters student Thomas Roocke is assisting with the clean and bake of the SAMS assembly. Credit: Huy Tuong Cao, OzGrav Adelaide

DATA AND ASTROPHYSICS THEME

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

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

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

DATA AND ASTROPHYSICS THEME

Inference

Program chair: Dr Rory Smith (Monash)

In 2021 the inference group contributed to core LIGO-Virgo-KAGRA discoveries. Notably, the first observations of neutron star–black hole binaries was led by Rory Smith along with colleagues in the LVK, and the third gravitational-wave transient catalogue was published with significant OzGrav involvement. Groups in OzGrav continued to lead methods for inference on unmodelled bursts, stochastic backgrounds, pulsar timing and supernovae.

The LVK collaboration published the first observations of gravitational waves (GW) from neutron star–black hole binaries; the first observations of these kinds of astronomical systems. The paper was led by Rory Smith (Monash) for the LVK, and relied extensively on OzSTAR and OzGrav lead codes.The primary results were produced using the OzGrav-developed parallel Bilby inference library. The data analysis to produce the measurements of the properties of the binaries were largely performed on OzSTAR.

We worked on how Bayesian model selection can improve detection prospects for unmodeled GW bursts when including more GW detectors in the network.

We worked with international collaborators on inferring the properties of the super massive black hole binary population using the speculative pulsar timing array detection from NANOGrav.

Work continued on methods for inferring physical properties of neutron stars using radio and GW data, and stochastic background parameter estimation.

A hybrid model was developed involving a denoising autoencoder and Convolutional Neural Network (CNN) to accurately predict mass posteriors of binary black hole events at unprecedented speeds.

A denoising autoencoder model was developed to extract pure, noise-free BBH gravitational wave waveforms from stationary Gaussian and real noise. We applied conditional variational autoencoder models for gravitational wave parameter estimation.

We interpreted the spins of the second-observed neutron star–black hole binary. We explored the alternative-interpretation of GW190521 as the merger of exotic "Proca stars" (or "boson stars").

We wrote a review article for Nature Physics about machine learning methods for inference in gravitational-wave astronomy. We wrote an article on methods for inference in third-generation gravitational-wave detectors.

We lead a successful ADACS project to help prepare parallel Bilby for production readiness in LVK's fourth observing run.

Case Study

The discovery of neutron star–black hole binaries was an OzGrav highlight for 2021, impacting many areas of astrophysics, and programs in OzGrav (inference, astrophysics, GW data analysis). The discovery was facilitated by the development of OzGrav-lead inference methods, and was led by Rory Smith (Monash) on behalf of the LVK.

The discovery of neutron star–black hole binaries completes the trio of compact binaries that LIGO/Virgo have long been searching for. It opens up a new avenue to study compact binary formation, nuclear matter at extreme pressures and densities, and relativistic astrophysics.

The discovery received international and national media attention. Pleasingly, the "rainbow swirl" graphics produced by Carl Knox (Swinburne) were featured in a host of international media. OzGrav scientists were highlighted in various print, traditional and social media, including ABC's Radio National Breakfast and Melbourne's 9News TV.

Carl Knox's artwork appears with the LVK announcement of the first detected merger of a neutron star and black hole, captured here on ABC News Breakfast. Credit: Hannah Middleton, OzGrav Melbourne.

SPIIR UWA team lunch

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

OzGrav members led or contributed to a large number of projects in 2021 across the fields of continuous waves, short-duration bursts, compact binary coalescenses and detector calibration, with many results from the analysis of O3 data coming to fruition.

A large number of searches were published in 2021, including:
A search for GWs in O3 data from accreting millisecond X-ray pulsars;
A continuous wave (CW) search targeting Fomalhaut b in O2;
A search for GWs on O3a data from young supernova remnants;
A search for GWs from Scorpius-X1;
A narrowband search for GWs from known pulsars;
An all-sky search for GWs in a narrow frequency band;
A search for GWs from ten H.E.S.S. TeV sources (collaboration between University of Adelaide and University of Melbourne);
The search for short-duration unmodelled gravitational wave bursts.

The third gravitational wave transient catalog (GWTC-3) was released in late 2021, bringing the total count of GW events detected by the LVK to 90, with a number of contributions from OzGrav data theme members. Hannah Middleton (Melbourne) and Isobel Romero-Shaw (Monash) were part of the paper writing team for GWTC-3, including work on data release coordination. Meg Millhouse (Melbourne) also used unmodelled GW reconstruction methods to contribute to data quality checks, removing instrumental glitches from data surrounding GW signals prior to parameter estimation. Fiona Panther and Manoj Kovalam (UWA) were members of the paper review team.

Eric Howell (UWA) co-lead the LVK search for GW counterparts from FRBs using data from the CHIME/FRB project, and Teresa Slaven-Blair and Eric Howell (UWA) participated in the X-pipeline unmodelled search for both the O3 LVK FRB and GRB searches as analysts.

The SPIIR group at UWA is currently upgrading their online gravitational wave detection software in preparation for O4. This work will potentially improve the sensitivity of the pipeline. We have been working on early warning detections for binary mergers. Results are out from a Mock Data Challenge for early warning alerts involving SPIIR (conducted in 2020). We also worked on SPIIR's forecast for early warning alerts from binary neutron star mergers in O4.
The SPIIR software development team across UWA and ADACS/Swinburne is working towards improving the existing codebase. These changes include code optimisation, better workflow and software version upgrades.

In 2021 the UWA machine learning group focused on real-time detection and parameter estimation of gravitational wave signals using deep learning, including developing Convolutional Neural Network (CNN) models trained on SPIIR data products, to distinguish real gravitational wave signals from noise. Details of their parameter estimation projects can be found under the Inference theme report.

We contributed to the horizon study of Cosmic Explorer (CE). OzGrav members from multiple nodes have produced a continuous-waves and signal-processing demonstration for use in undergraduate laboratories.

The GWLab project to develop an online virtual lab progressed, with the first module undergoing user testing and the second module under development by the Gravitational Wave Data Centre (GWDC) at Swinburne. In addition, the GWDC has now rolled out GWCloud - a searchable repository for the creation and curation of gravitational-wave inference results, as well as providing support for optimising and maintaining the SPIIR pipeline.

Case Study

Ultralight boson particles, predicted by many beyond Standard Model theories to solve problems in particle physics, high-energy theory, and cosmology, could form clouds around rapidly rotating black holes. The existence of boson clouds may alter the formation and evolution of binary black hole systems in ways that can leave an imprint on the population. For example, the formation of boson clouds can rapidly spin down the remnant black holes created by mergers due to the significant amount of energy extracted by the clouds through superradiance, a mechanism that amplifies the boson fields. As a result, remnant black holes from subsequent black hole mergers are less likely to be kicked out of densely packed clusters. This may lead to an increased recycling of remnant black holes into future generations of merger events. As the number of merger events significantly increases as gravitational-wave detectors become more sensitive, we will be able to search for key signatures of boson clouds using hierarchical inference on the population.

Lockdown did not stop new ideas and discussions about exciting science. With the support of the OzGrav COVID Strategic Fund, Ethan Payne, a graduating OzGrav Honours student at Monash, started working with OzGrav AI Dr Ling (Lilli) Sun (ANU), and OzGrav CIs Dr Paul Lasky and Prof Eric Thrane (Monash) to explore these conjectured boson clouds. As an outstanding student, Payne has been facing delays and difficulties in pursuing his PhD overseas due to COVID. The OzGrav funds provide full support for him to continue his research during the unexpected longer transition between Honours and PhD, making this new collaboration possible in these difficult days. This project couples two of the main astrophysics and data themes within OzGrav: Relativistic Astrophysics and Inference. Dr Sun (ANU), has been studying boson clouds and the associated evolution of black holes for the last couple of years, and the Monash group has significant expertise in inference on the black hole population. This exciting work will explore a new approach to search for imprints of ultralight bosons using gravitational waves and populations of binary mergers, paving the way for future cosmic probes of fundamental physics.

Images for a media release regarding OzGrav Associate Investigator Dr Ling (Lilli) Sun (ANU) during her work searching for ultralight boson particles. Credit: Tracey Nearmy, ANU

Pulsar Detections

Program chairs: Dr Hannah Middleton (Melbourne) and A/Prof Ryan Shannon (Swinburne)

Pulsar timing data sets

OzGrav continues to play leading roles in pulsar timing with MeerKAT and Murriyang (Parkes) telescopes. The MeerTime Millisecond Pulsar Timing program has matured. In August we created a census of 189 millisecond pulsars as observed by MeerKAT. The observationally focused paper presents high fidelity pulse profiles delivered by MeerKAT for this largest census. The observations have informed the MeerKAT MSP timing program, and will also form the Square Kilometre Array pulsar timing program. Work also continued on developing a pipeline to automatically reduce pulsar timing data with the MeerKAT telescope. An automatic glitch detection pipeline was developed for UTMOST. We started groundwork for a third Parkes Pulsar Timing Array data release .

Pulsar inference

In 2021 we made great progress on applying modern inference tools to a variety of pulsar datasets. One of the highlights was our search for gravitational waves of the Parkes Pulsar Timing Array second data release (see case study). This year, we completed a timing analysis of this data set, measuring new pulsar parameters, and providing more accurate measurements than those reported previously. We had a detailed analysis of the properties of a large sample of young pulsars timed with Murriyang, and analysed the single pulse properties of PSR J1909-7344. Using baseband data collected with the Swinburne-designed PTUSE pulsar timing system, we showed that the pulsar emission showed mode changing, regularly seen in young pulsars. We then developed a technique that could account for the mode changing in the observations and improve the achieved timing precision.

Pulsar Searching

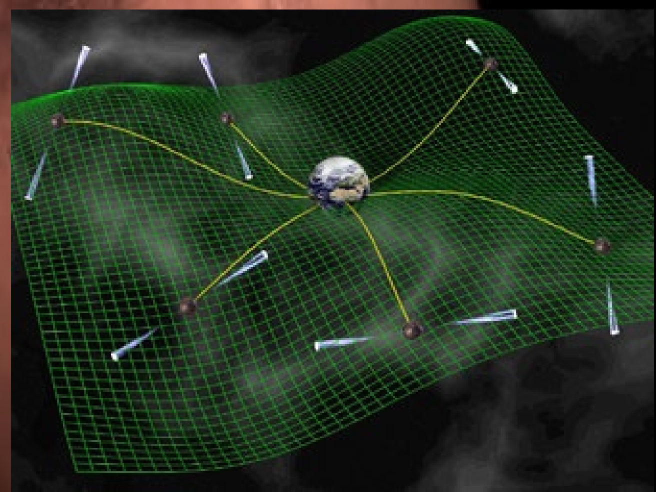
We completed a reprocessing of the High Time Resolution Universe low Galactic latitude survey, a major Galactic-plane pulsar survey undertaken with Murriyang in the 2010s. In total, 72 pulsars were discovered, including a new double neutron star system. We then used this pipeline to reprocess the venerable Parkes Multibeam Survey discovering 14 new pulsars. Timing analysis of all the discoveries are ongoing at Parkes.

OzGrav Postdoctoral Researcher Dr Andrew Cameron (Swinburne) organised the Australasian Pulsar Telecon, a fortnightly zoom meeting bringing together pulsar and FRB researchers in Australia, New Zealand, and India. OzGrav Postdoctoral Researcher Dr Daniel Reardon (Swinburne) co-organised a pulsar timing data analysis workshop for students from Africa and India. Reardon and a group of African students are now analysing MeerTime millisecond pulsar data sets to measure new neutron star masses through Shapiro delay observations.

The timing analysis of PSR J0437-4715 is waiting on finalisation of the NICER analysis to represent a pair of high impact publications. Technical issues that delay modelling the eclipses in the double pulsar system have been overcome and we expect the project to be completed in the next few months. The MeerTime data reduction pipeline is nearly complete with only the final automation tasks to be finished in early 2022.

Case Study

Excitement continues to grow (and interest intensify) in the search for nanohertz-frequency gravitational waves, following the 2020 claim by the North American Nanohertz Frequency Observatory for Gravitational Waves (NANOGrav) of a common-spectrum process in their 12.5 year data set. A common spectrum process is a signal that has common noise properties between pulsars but is uncorrelated between pulsars, and is predicted to be the precursor to a gravitational wave detection which is spatially and temporally correlated. In 2021 OzGrav members used the same approaches applied to the Parkes Pulsar Timing Array (PPTA) second data release, a data set we prepared in 2020. Like NANOGrav, we also found strong Bayesian evidence for a common spectrum process in the Parkes data set. However we are more cautious about the interpretation of the results. We raised concerns that the methodology could suffer from "model misspecification", demonstrating strong Bayesian evidence in favour of a common spectrum process in simulated data sets containing none. The Parkes data set showed tantalising hints of the spatial correlations expected of the gravitational wave background. In the next year OzGrav will play a leading role in nanohertz frequency gravitational wave searches by producing data releases for PPTA and MeerTime, and conducting gravitational wave searches for the PPTA and IPTA.



Artist's conception of a pulsar timing array. The gravitational wave background induces correlated timing variations in pulsars distributed throughout space. Credit: David J Champion

Multi-Messenger Observations

Program chairs: Dr Katie Auchettl (Melbourne) and Dr Jielai Zhang (Swinburne)

The focus of this program is to take advantage of all available astrophysical domains, ranging from gravitational waves, electromagnetic, neutrinos and/or cosmic rays, to obtain new insights into a wide range of astrophysical phenomena. Due to the inherently interdisciplinary nature of this work, there is significant overlap between this program and other OzGrav programs that are part of the OzGrav observational, theoretical and data-driven themes of the centre.

With O4 starting in 2022 there has been significant work by the community in preparation for the upcoming run, which will continue over 2022.

Observational: Australian SKA Pathfinder (ASKAP) telescope and radio follow-up.

ASKAP, which played an important role in O3 follow-up and data analysis, began preparation for the beginning of full ASKPAP survey science. In this role, they have recently released the vast-tools package and a pilot survey. They have discovered a number of interesting transients/variable radio sources, along with radio follow-up of a number of optical transients ASKAP also published their comprehensive radio follow-up of two LIGO O3 events. OzGrav's very own Dr. Dougal Dobie's thesis "Radio follow-up of gravitational wave events" was awarded the inaugural University of Sydney School of Physics prize for best PhD thesis. Congratulations Dougal!

Observational: Deeper Wider Faster (DWF)

DWF continued its simultaneous multiwavelength observation program to search for fast transients on timescales of days to sub-second. DWF coordinated two successful observing runs each lasting six half nights in 2021 in June and September. Publications include on flare stars, light curve analysis for transients, GRB follow-up ("A blast from the infant Universe: the very high-z GRB 210905A") using the Dark Energy Camera (DECam) on the CTIO Blanco telescope, and GW190814 EM counterpart searches. In addition, we followed up the short GRB 210919A in search of a kilonova or supernova counterpart using NIRC2 on the Keck telescope, two epochs with DECam via a DWF collaboration, and the LSGT telescope at SSO.

Good progress has been made with the Australian-led Keck Wide Field Imager (KWFI). KWFI is a wide field optical imager optimised for UV sensitivity designed for the 10m Keck telescopes. Its planned 1 degree diameter field of view, extreme sensitivity, fast filter exchange system, flip in secondary mirror system for rapid optical and infrared spectroscopic follow up will make KWFI the premier GW follow-up instrument for the foreseeable future. KWFI

DATA AND ASTROPHYSICS THEME

will be 10-200x more sensitive than other wide-field GW follow-up telescopes and will cover 2/3rds of the Southern Hemisphere and all the Northern Hemisphere. KWFI has succeeded in receiving Keck Observatory, CARA board SSC, and Swinburne funding totalling more than $700,000 for design and development.

Observational: GOTO

The Gravitational-wave Optical Transient Explorer celebrated some significant milestones during 2021. During the first half of the year, observing continued with the single "prototype"-phase mount at the Roque de los Muchachos Observatory on La Palma. The LIGO-Virgo network was not operating all year, so there were no opportunities to follow up our highest-priority compact object merger transients. Instead, our nightly survey operations were punctuated by follow ups of gamma-ray bursts detected by the Fermi satellite, and a new capability for following up IceCube transients. We continue to work with Monash Postdoctoral Researcher Kendall Ackley as she was appointed to a Postdoctoral position with our project partner Warwick University.

In the second half of the year we undertook a major equipment upgrade, thanks to the funding from the UK STFC. We replaced the prototype mount by a new version fabricated by Astro Systeme Austria (ASA), and installed a second mount in the existing second dome on La Palma. Each mount was fully kitted out with 8 ASA 40cm optical telescope assemblies (OTAs), which completes our northern installation and will allow us to reach our target combined field of view of ~80 square degrees. Commissioning was interrupted by the Cumbre Vieja eruption on La Palma, which began in September and lasted through to mid-December. The ash and gas plumes at time prevented access to the site, also closing the airport on occasion. Winter weather has prevented much further observing, but the new hardware has us well placed for resuming survey and followup operations in 2022.

Observational: SkyMapper

SkyMapper has implemented a new software pipeline (called Alert Science Data Pipeline) to receive alerts, schedule observations and examine the incoming real-time data stream for transient candidates. At any time, once a position of a likely kilonova candidate is identified, we can manually switch from the search phase to a continuous high-cadence monitoring by clicking a button in the web-interface. Until the end of O3, we classified transient candidates with a random forest classifier trained on earlier supernova survey data. Later, we added a new classifier (XGBoost) and new training sets. We attain high completeness of 98% and purity ~91% across a wide magnitude range. Along with this, we improve our internal filtering scheme to reduce the number of candidates greatly before the stage of human vetting. Lastly, we added features (Candidate Dweller) to the web interface that trigger interaction with the telescope scheduler for follow-up modes that we anticipate to use during the next GW observing run. This mode is designed to probe the colour of a source quickly after an initial detection is made and to help assess its likelihood of being a kilonova from a BNS merger.

Observational: Zadko

Unfortunately 2021 has been a year with a number of difficulties for the Zadko Observatory. Several key elements of the system have been broken, such as the camera or the rain detector. This required significant work from the observatory team to restart and improve telescope operations, however the combination of delays related to COVID-19 and reduced funding for maintaining the Observatory has meant observations could not be taken, or the timescale for repairs have increased. Currently the observatory is waiting for repairs of the CCD camera to be completed.The Zadko team has started to investigate sources of funding and partnership, aimed at increasing the cash flow of the observatory for unexpected repairs.

The view of the Milky Way as seen by the GOTO observatory. Credit: Krzysztof Ulaczyk (Warwick)

Observational: General

We coordinated multiwavelength observations to search for the host galaxy of CHIME FRB190425A in collaboration with researchers from ICRAR-Curtin. Dr Fiona Panther (UWA) organised the OzGrav EM Followup workshop in May 2021 and presented results from the Australian EM followup survey associated with this meeting at the 2021 ASA AGM. We worked on gamma-ray emission from subluminous supernovae, and two OzGrav summer students worked on characterising positron annihilation in kilonovae with implications for observers and improving simulations that involve positron microphysics, including developing a library of annihilation linewidths that can be used by gamma-ray observers.

Case Study

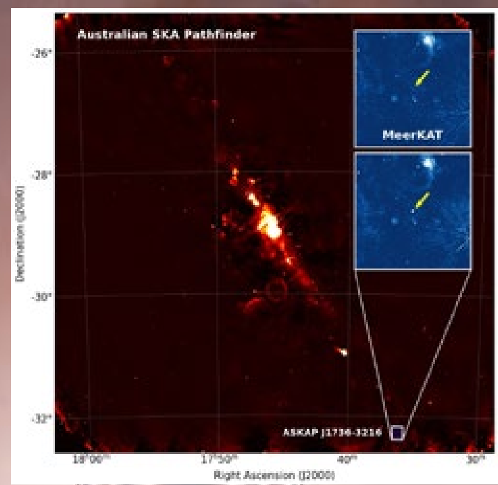
The ASKAP telescope was involved in several projects over the past year including those related to O3 follow-up and data analysis. ASKAP has been conducting a survey of the Southern radio transient sky, called the Variables and Slow Transients Survey (VAST). In early 2020, a source called ASKAP J173608.2-321635 was discovered in the direction of the centre of our Galaxy, the Milky Way. The highly polarised nature of this new transient makes it part of a rare 1% of all radio sources.

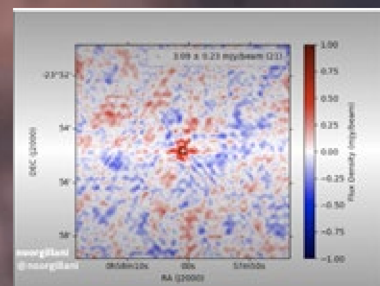
This object was followed-up with observations in multiple wavelengths on three continents and in space, but still remains a mystery. This mystery has garnered a lot of media attention too including on The Conversation, Earth Sky, and ScienceAlert to name a few.

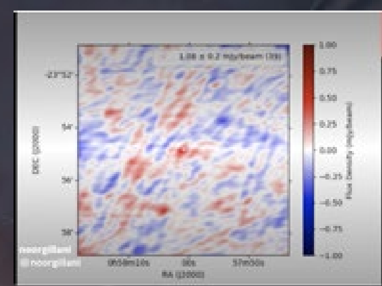
The mystery is yet to be resolved as the two most likely candidates that might be circularly polarised are unlikely candidates: stars and pulsars. Stars are unlikely because they should be bright in the optical and infrared, but no detection was made at these wavelengths. Pulsars are ruled out because of the lack of the tell-tale lighthouse periodic light that indicates pulsars.

ASKAP made another exciting discovery published in 2021 where it observed five distant galaxies to twinkle their light passed through the turbulent gas of the Milky Way. These five galaxies were the only ones that twinkled out of 30,000 galaxies imaged by ASKAP, making this a rare phenomena. The highlight of this discovery was that the turbulent gas had not otherwise been known.

The two images show radio images of one of the galaxies taken at two times, showing different brightnesses. If this happens quickly over time, this is what creates the twinkle effect. Using these observations, the geometry and properties of this turbulent gas could be derived, and it was the very first time a gas cloud has been studied in this way. This discovery also received a lot of media attention, including with The Conversation, space.com and Geeky.news.







Relativistic Astrophysics

Program chair: Dr Ryo Hirai (Monash)

New discoveries and new measurements are the main driver of relativistic astrophysics research. The past year was packed with new exciting observations that gave us opportunities to improve our understanding of high-energy astrophysical phenomena.

The main highlight of 2021 was the announcement of the discovery of gravitational waves from two neutron star-black hole (NSBH) merger events by the LIGO/Virgo/KAGRA collaboration including many members of OzGrav. Since 2015, there have been many detections of binary black holes (BHBH) and several binary neutron stars (NSNS). The addition of the NSBH flavour to the stellar graveyard was yet another huge milestone for gravitational wave astronomy, marking the transition of the field from the initial discovery phase to the next stage. The inferred merger rate of NSBH systems are on the higher side of theoretical expectations, although there are large uncertainties both on the observational and theoretical sides. Further detections in the future may allow us to start strongly constraining the theoretical models of various binary evolution processes, as well as the supernova mechanism.

Another impactful observational result was the revision of the black hole mass in the high-mass X-ray binary, Cygnus X-1. Cyg X-1 was the first discovered black hole candidate and has been thoroughly studied for decades. A group of Australian astronomers including several OzGrav members used VLBA measurements to revise the distance to Cyg X-1, leading to a revision of the black hole mass from ~15Msun to ~21Msun. Although this may not look like a significant change, this new measurement poses serious challenges to binary evolution theory, especially on wind mass loss. The high mass of the black hole implies that the mass loss rate is a factor ~5-10 times lower than current wind prescriptions. This significantly different mass loss rate could have a huge impact on the formation rate of other objects such as merging binary black holes. However, extra care must be taken when comparing detection rates of high-mass X-ray binaries and binary black holes, as there are strong observational biases towards tight orbit X-ray binaries according to our new wind accretion models.

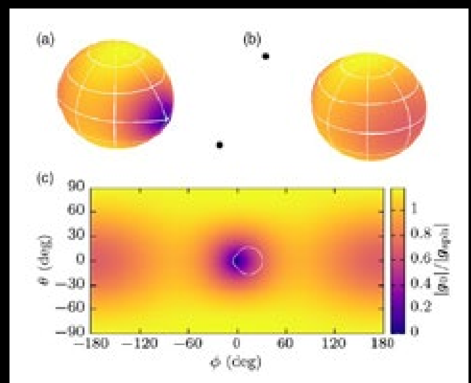
The more traditional measurements of pulsars continue to be extremely valuable for understanding neutron star properties. We were awarded 57 hours of observation with the Green Bank 100m telescope to monitor the relativistic binary pulsar PSR J1757-1854. The timing results showed signs of geodetic precession and also the proper motions were used to set limits on the radiative test of gravity. Pulsar glitches can be used to probe the inner structure of neutron stars. A group of OzGrav members established new efficient methods to discover glitches from observational data. These detections may eventually be useful for understanding the nature of superfluids inside neutron stars. More exotic matter such as quarks or hyperons could be present in neutron stars and could be probed from their cooling curves.

Multi-messenger astronomy is becoming a powerful approach in high-energy astrophysics, as proven by the success with the famous GW170817 binary neutron star merger event. The information from gravitational waves and neutrinos as well as the different wavelengths of electromagnetic signals give us extra dimensions into the way we see events. X-ray emission from short gamma-ray bursts can help us estimate stellar and shock parameters. We discussed how neutron star collapse times can be measured with future gravitational wave detectors. We showed how the combination of gamma-ray burst observations with a NEMO-like gravitational wave detector can significantly contribute to our understanding of neutron star mergers. Supernova explosions are another promising target for multi-messenger astronomy. Multidimensional hydrodynamical simulations can aid us in predicting the multi-messenger signatures from deep inside massive stars.

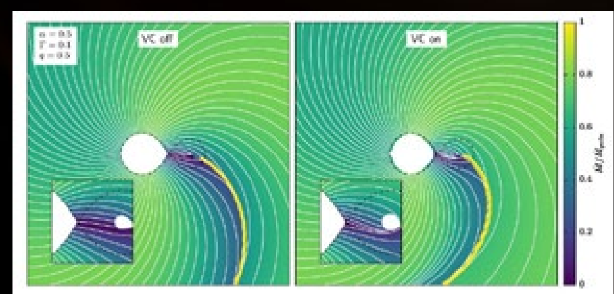
Case study: How stellar winds can create discs around black holes

After nearly 60 years since the discovery of Cygnus X-1, only a handful of high-mass X-ray binaries have been detected. Many more of them were expected to exist, especially given that many binary black holes (the future states of high-mass X-ray binaries) have been discovered with gravitational waves in the past few years. There are also many binaries found in our Galaxy that are expected to eventually become a high-mass X-ray binary. So, we see plenty of both the predecessors and descendants, but where are all the high-mass X-ray binaries themselves hiding?

One explanation states that even if a black hole is orbited by a massive star blowing a strong wind, it does not always emit X-rays. To emit X-rays, the black hole needs to create an accretion disc, where the gas swirls around and becomes hot before falling in. To create an accretion disc, the falling gas needs 'angular momentum', so that all the gas particles can rotate around the black hole in the same direction. However, we find it is generally difficult to have enough angular momentum falling onto the black hole in high-mass X-ray binaries. This is because the wind is usually considered to be blowing symmetrically, so there is almost the same amount of gas flowing past the black hole both clockwise and counter-clockwise. As a result, the gas can fall into the black hole directly without creating an accretion disc, so the black hole is almost invisible.



But if this is true, why do we see any X-ray binaries at all? In our paper, we solved the equations of motion for stellar winds and we found that the wind does not blow symmetrically when the black hole is close enough to the star. The wind blows with a slower speed in the direction towards and away from the black hole, due to the tidal forces. Because of this break of symmetry in the wind, the gas can now have a large amount of angular momentum, enough to form an accretion disc around the black hole and shine in X-rays. The necessary conditions for this asymmetry are rather strict, so only a small fraction of black hole + massive star binaries will be able to be observed.



Population Modelling

Program chair: Dr Simon Stevenson (Swinburne)

Despite being another challenging year due to the COVID-19 pandemic, we remained productive. A milestone for the OzGrav Population Modelling program in 2021 was our contribution to the publication of the most recent edition of the catalogue of gravitational wave transients observed by Advanced LIGO and Virgo through the end of the third observing run (GWTC-3). The total number of gravitational waves observed now stands at 90, including neutron star black hole mergers for the first time. This has allowed for some of the most detailed studies of the population of merging compact objects to date (see Case Study).

These studies are typically performed using simple parameterised phenomenological models. Many of these models were originally developed within OzGrav, and a considerable amount of work goes on to extend and enhance these models, as well as applying them to the latest observations. We worked on the phenomenological modelling of populations of gravitational wave mergers, and performed a combined analysis of the double neutron star (DNS) population observed both through radio observations of pulsars, and gravitational-wave observations. They find that the heavy DNS GW190425 may not be an outlier.

We introduced an improved model for the distribution of binary black hole spins, accounting for the possibility of a subpopulation with negligible spins, as expected from some binary evolution models. The team used this model to show that up to 90% of merging binaries may contain black holes with negligible spin.

Work continues on searching for signs of eccentric binary mergers. We argue that two gravitational-wave events show evidence for eccentricity, suggesting that more than 27% of the observed binary black holes may have dynamical origins.

Another major focus of the OzGrav Population Modelling Program is the COMPAS (Compact Object Mergers: Population Astrophysics and Statistics) rapid binary population synthesis suite. A highlight for this group in 2021 was the writing of a journal article detailing the COMPAS code, representing a culmination of years of work by a large group of people. Additionally, a web portal to interact with the COMPAS code and results—GWLandscape—is currently under development with the Gravitational Wave Data Center (GWDC) and should be available for use in 2022.

We studied the distribution of pulsar velocities using COMPAS, focusing in particular on the population of low-velocity pulsars that may be associated with electron-capture supernovae. We describe predictions for the populations of neutron star and black hole binaries from a large set COMPAS models. We examine the impact of

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uncertainties in binary evolution and the cosmic star formation history on the model predictions, and examine which models are in agreement with observations.

The common envelope phase is an enigmatic, yet vitally important phase of massive binary evolution. Throughout 2021 we conducted several investigations into the workings of the common envelope in massive binaries, including a detailed study of the role of the equation of state on the outcome of the common envelope using a set of three-dimensional hydrodynamics simulations. We also used a set of one-dimensional stellar models to study the stellar response after stripping as a model for common-envelope outcomes.

Another important aspect of massive stellar evolution is their high mass-loss rates. ARC Future Fellow Prof Ilya Mandel (Monash) and collaborators revised the mass of the Galactic high-mass X-ray binary Cygnus X-1, and used this revised mass to place new constraints on the amount of mass loss from stripped stars. We examined physical and numerical uncertainties in the evolution of massive stars. These models are an important step on the road to producing the next generation of population synthesis codes.

Case study: The population of merging compact binaries inferred using gravitational waves through GWTC-3

The large population of 90 gravitational-wave sources observed through GWTC-3 allows for the strongest population analysis to date. The LIGO, Virgo and KAGRA Collaboration (LVK) study the population of merging compact binaries using a range of phenomenological models designed to capture the mass and spin distributions of compact object binaries, as well as how the total merger rate changes with redshift. OzGrav members were involved throughout the production of GWTC-3 and the companion population analysis, from searching for and detecting gravitational waves, to characterising them, to extracting population information.

GWTC-3 includes the two previously observed binary neutron stars and the two neutron star black hole mergers. All other sources are likely binary black holes (though this is not clear for a few sources, such as GW190814). The large scale properties of the population, such as the overall binary black hole merger rate, are in agreement with previous findings from GWTC-2.

With the larger number of observations, structure in the mass distribution on smaller scales is starting to become apparent. One example is the presence of local overdensities ('bumps') in the mass distribution at around a primary mass of 10 and 30 solar masses (see Figure 1). These features in the mass distribution may be related to the formation of the gravitational wave sources, and should be explained by future population models.
The apparent presence of a maximum black hole mass around 45 solar masses was one of the key results from earlier population analyses, as it matched theoretical expectations of the absence of massive black holes due to pair-instability supernovae. The discovery of GW190521 demonstrated that while such massive binary black holes may be rare, they do in fact exist. Several more similar high mass binary black hole mergers were observed in GWTC-3. In this most recent analysis there is therefore no strong evidence for an upper mass gap in the black hole mass distribution.

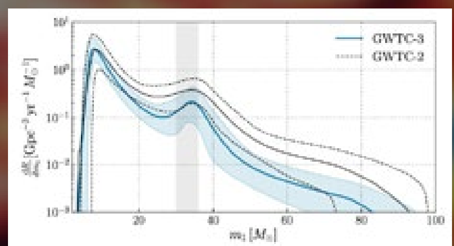


Figure 1: The mass distribution of the primary black hole (m1) in merging binary black holes inferred from gravitational-wave observations. The blue band shows the new results from GWTC-3, whilst the results in black are from GWTC-2 for comparison. Highlighted is the local overdensity of systems with primary masses around 35 solar masses (image from Abbott et al. 2021).

The larger number of observations, and larger typical distances (due to the increased sensitivity) has improved the cosmic reach of the population, allowing for investigations into how the rate of binary black hole mergers changes with redshift. This paper concludes that the binary black hole merger rate increases with redshift, as expected due to the increasing star formation rate.

OzSTAR Supercomputer

Leader: Prof Jarrod Hurley (Swinburne)

The Swinburne OzSTAR supercomputer continued to provide vital data and computing resources for OzGrav researchers with 99% uptime across 2021. OzSTAR provides OzGrav researchers with access to approximately 6,000 compute cores and 230 Nvidia P100/V100 GPUs. Importantly, in 2021 we finalised the expansion of the lustre filesystem from 6 PiB to 12 PiB, providing additional storage capacity to meet the future needs of OzGrav researchers.

OzGrav usage on OzSTAR in 2021 was spread across 26 distinct research projects and over 130 users. The combined OzGrav usage was 33% of OzSTAR averaged over 2021 which represents 18 million hours of data processing and simulations. Healthy usage was reported across the Monash, Melbourne, Swinburne and UWA nodes.

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

"MPI Parallelisation of a Boltzmann Solver for Supernova Simulations";
"Collaboration on Shared Codebases";
"Getting Parallel Bilby Production-ready for the LIGO 4th Observing Run ";
"Parallelising FINESSE v3 for Gravitational Wave Detector Design and Inference Problems";
where each project was selected through a competitive time assignment process. In total about 36 developer weeks were contributed to these projects. This is in addition to advancements made to the following key projects that receive dedicated support via the GWDC: the SPIIR search pipeline; the GWCloud parameter estimation interface; the GWLab laboratory for continuous wave workflows; the MeerTime access portal for pulsar data; and the GWLandscape environment for population synthesis of gravitational wave sources.

Integration of the GWCloud parameter estimation interface with the CIT cluster at CalTech was a big highlight as this important milestone meant that researchers could now run jobs either on OzSTAR at Swinburne or at CalTech via the same interface, expanding the reach of GWCloud across the international LIGO community.

ADACS/GWDC staff ran training sessions in the use of the git software development and version control environment as part of the OzGrav ECR workshop in November 2021. Two sessions were run in parallel: git101 for beginners and git201 for advanced users. There were 56 attendees in total.

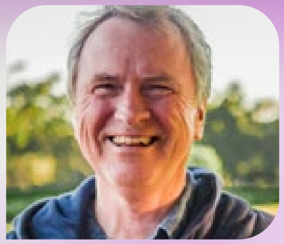
OzSTAR and the GWDC played a critical role in underpinning the parameter estimation of NSBH events reported by other OzGrav Programs. This involved working with researchers to optimise workflows and prioritise access to resources. More generally, OzSTAR was utilised as the prime computational engine for GW events announced in 2021.

Case study

In collaboration with the GWDC a Machine Learning (ML) Hackathon was run in March 2021 across two days. The goal of this hackathon was to provide a fun, collaborative learning experience for GW researchers to learn about ML, with a focus on using the knowledge of ML practitioners to work with others who had little to no experience and try to see what teams could achieve in just two days with data they had not seen before. The hackathon was well attended with 35 participants, including 7 people from Europe, and there was a range of ML experience levels from no experience at all to regular users. The participants were grouped into 7 teams based on skills, regions and, if possible, their research institution. We provided the teams with a list of six datasets taken from Kaggle with no formal tasks assigned; teams just had to decide what they would do with that data but were encouraged to look at the solutions already submitted on Kaggle. There were four astronomy related datasets (Galaxy Zoo, Gravity Spy, Finding Pulsars, and Predicting Hazardous Asteroids) and two non-astronomy related datasets (Worldwide COVID-19 Vaccination Progress, and Predicting Rain in Australia). The use of non-astronomy related datasets was to help participants to realise that the skills they have can be used outside of astronomy should they choose not to stay within astronomy-related research. Presentations from three ML experts also formed part of the program.

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

PEOPLE OF OZGRAV - INSTRUMENTATION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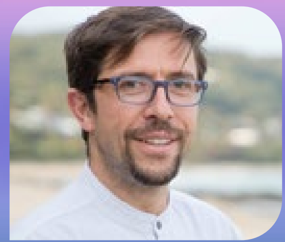
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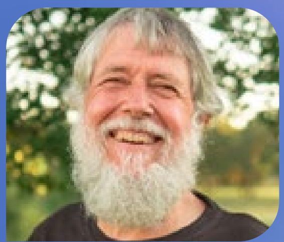
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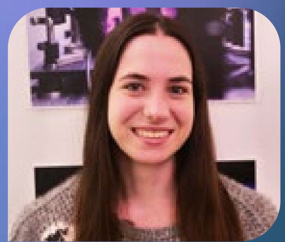
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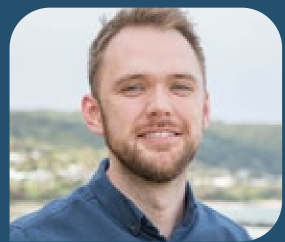
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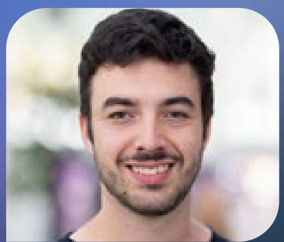
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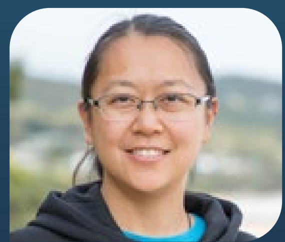
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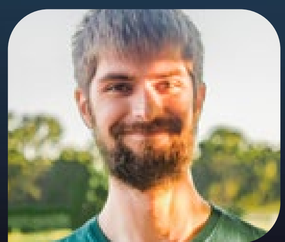
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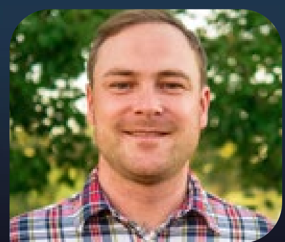
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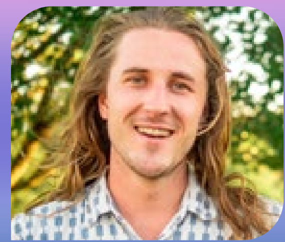
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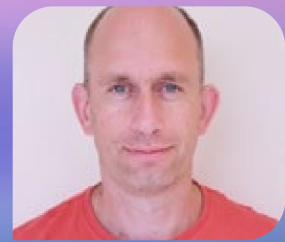
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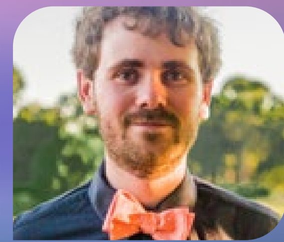
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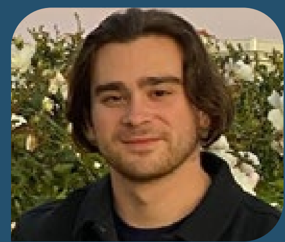
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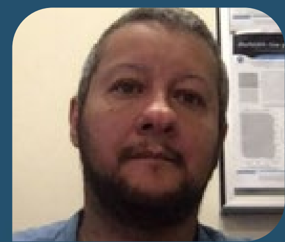
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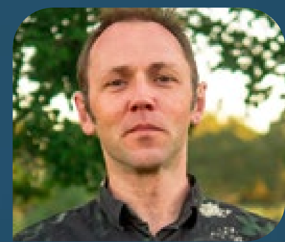
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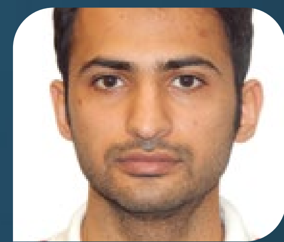
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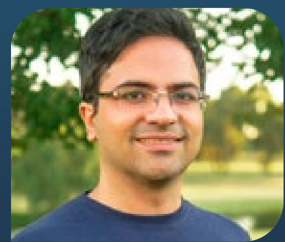
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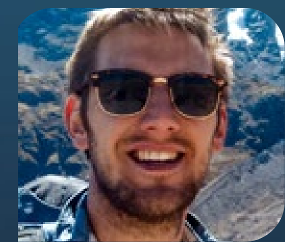
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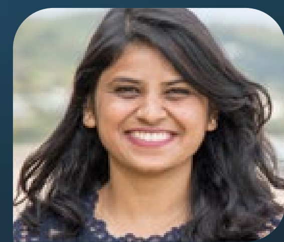
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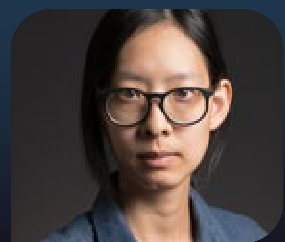
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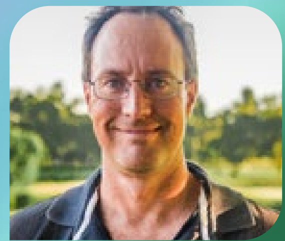
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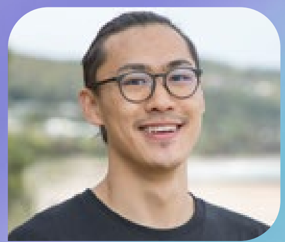
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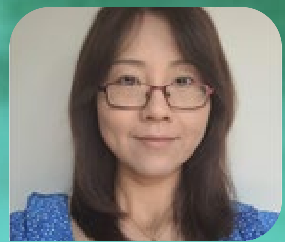
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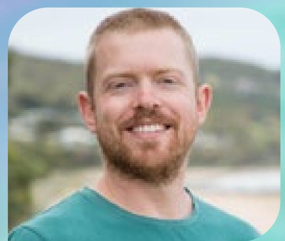
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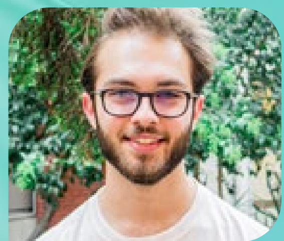
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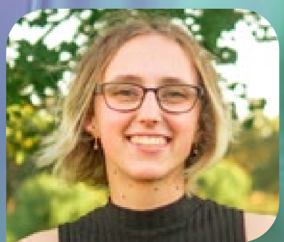
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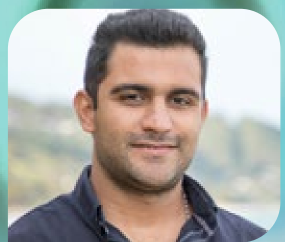
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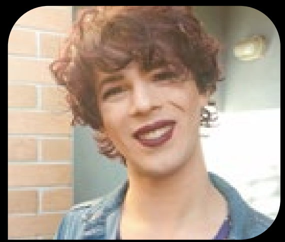

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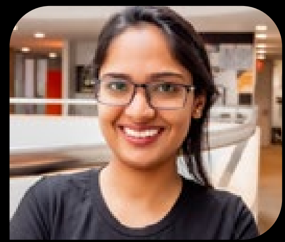

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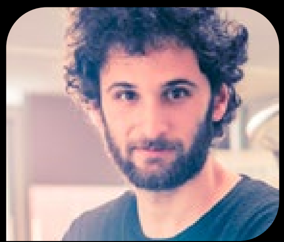

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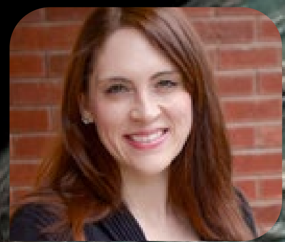

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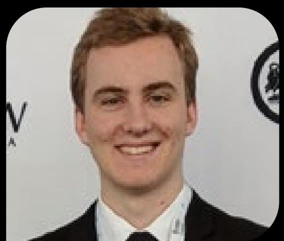

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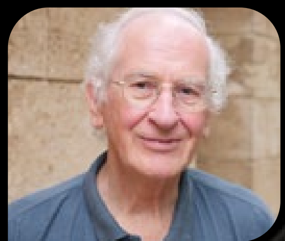

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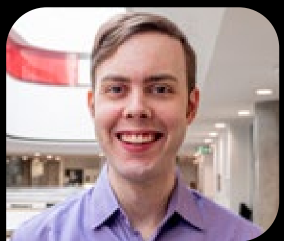

Dr Andrew Cameron
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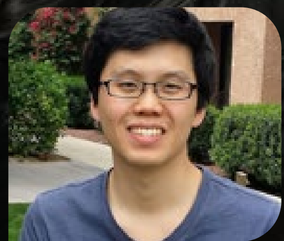

Dr Seo-Won Chang
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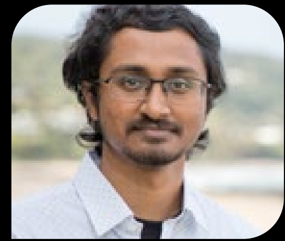

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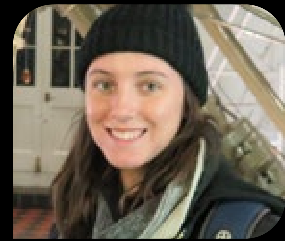

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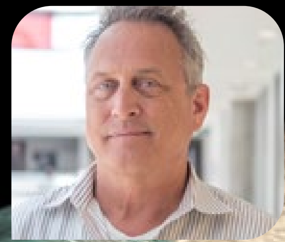

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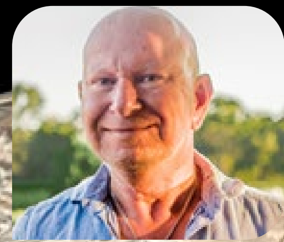

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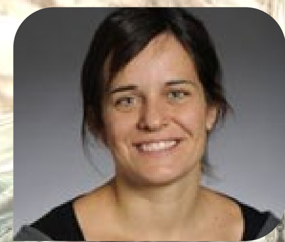

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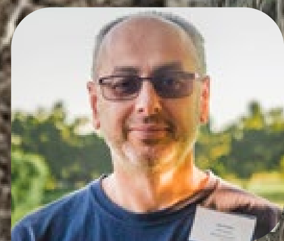

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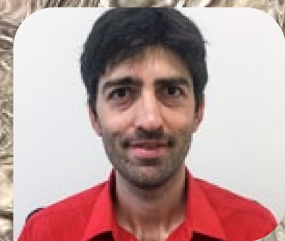

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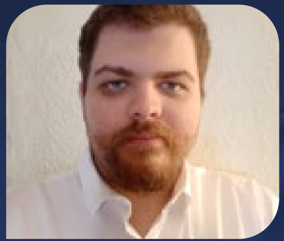
PEOPLE OF OZGRAV - DATA AND ASTROPHYSICS


Isaac Finaldi-Baratieri
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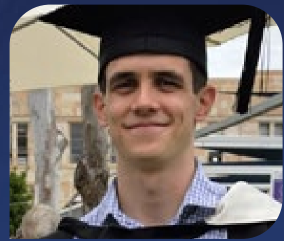
Jim Freeburn
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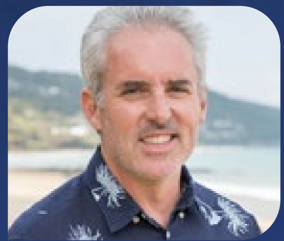
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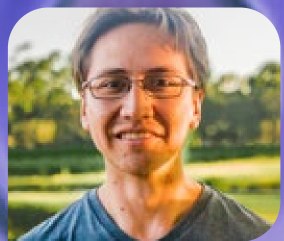
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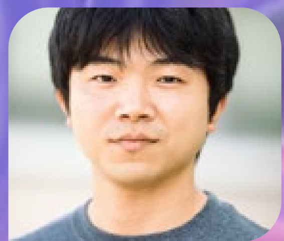
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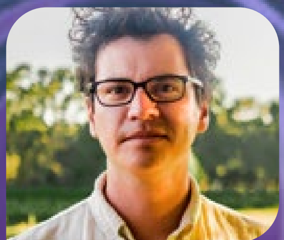
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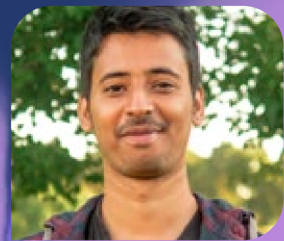
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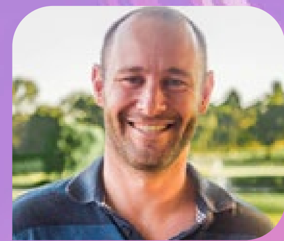
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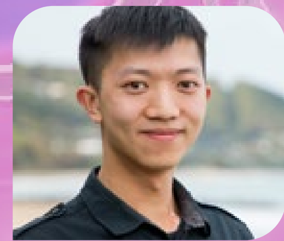
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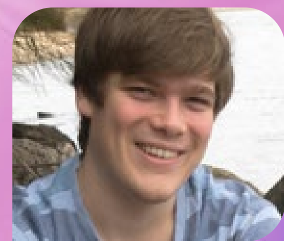
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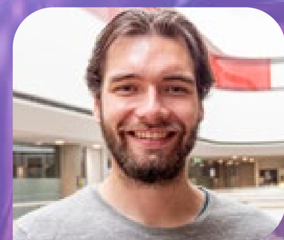
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PEOPLE OF OZGRAV - DATA AND ASTROPHYSICS

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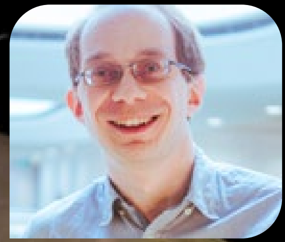

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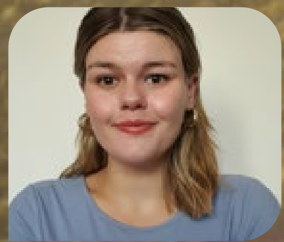

Sonja Panjkov
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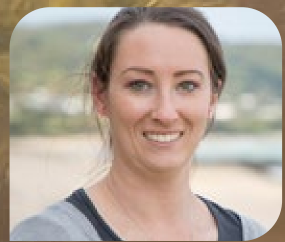

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Australian National University
Research Assistant

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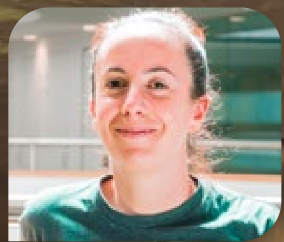

Dr Jade Powell
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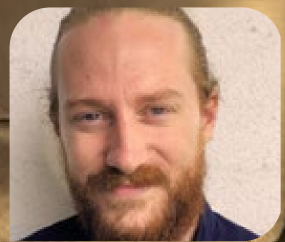
Associate Investigator



Joshua Pritchard
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Dr Jeff Riley
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Isobel Romero-Shaw
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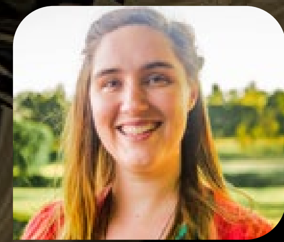

Teresa Slaven-Blair
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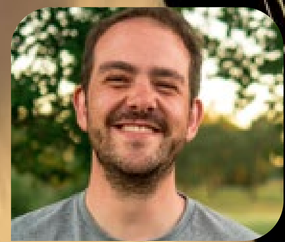

Dr Rory Smith
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Postdoctoral Researcher

Dr Simon Stevenson
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Postdoctoral Researcher

Lucy Strang
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PhD Student

Dr Sofia Suvorova
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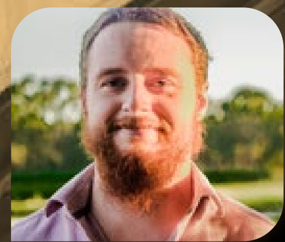

Dr Colm Talbot
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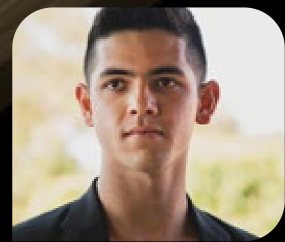

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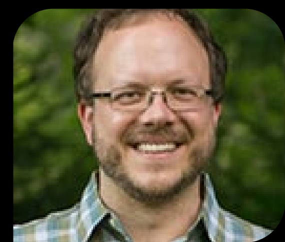

A/Prof Willem Van Straten
Auckland University of Technology
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Andres Vargas
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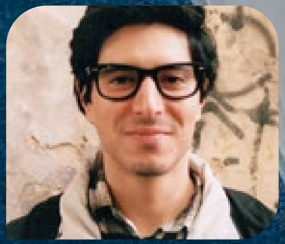
PhD Student

PEOPLE OF OZGRAV - DATA AND ASTROPHYSICS



Dr Alejandro Vigna Gomez
Niels Bohr Institute
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Dr Serena Vinciguerra
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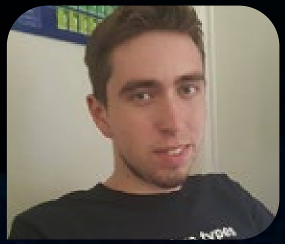

Kris Walker
Monash University
Honours Student

Yuanming Wang
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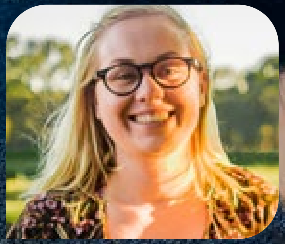

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Students interact with Carl Knox's gravitational wave projections. 2 people can participate, moving their bodies around the space as the black holes follow them with tracking. As the black holes move, the gravitational waves travel out through the grid of spacetime. Credit: Carl Knox, OzGrav Swinburne.

PEOPLE OF OZGRAV - OUTREACH AND PROFESSIONAL

Kyla Adams
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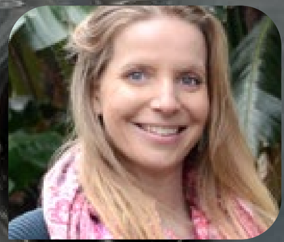

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Shon Shachar Boublil
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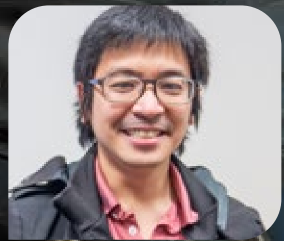

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Lisa Horsley
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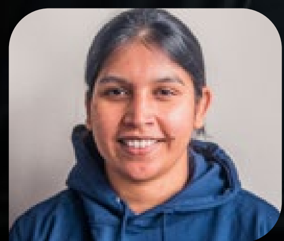

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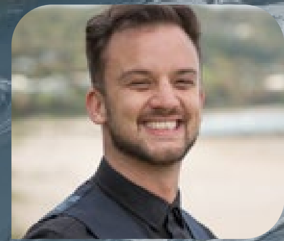

Carl Knox
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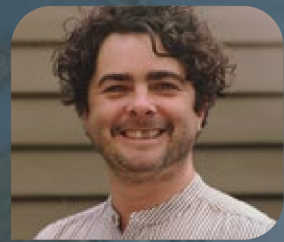

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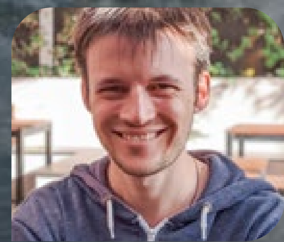

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MID TERM REVIEW AND NEW INITIATIVES

Each ARC Centre of Excellence must undergo a very thorough review of its performance against the objectives and expectations of the Centre of Excellence program. Centres must successfully pass this review for their funding to continue. The OzGrav Mid-Term Review was originally scheduled for 2020, but due to the impacts of COVID it was moved into 2021.

The Mid-Term Review was a valuable opportunity to take stock of what we have achieved over the first four years of the Centre's operations, and consider where there is room for further growth and improvement to secure a bright future for our field. Reflecting on our achievements, we were proud to see that the Australian gravitational wave community has grown from around 70 in 2016 to more than 250, and that Australia is playing an increasingly influential role in the international gravitational wave community, including in the planning and R&D for future detectors. As the Centre has grown, so has the level of cohesion between what were previously disparate groups, leading to a growing number of cross-nodal projects and a healthy and positive Centre morale.

It was a useful and heartening process to document and discuss our accomplishments with the ARC through our written submissions and interviews with the Review panel. These interviews were grouped by member/stakeholder type: Centre Management, Senior Researchers, Postdocs, Students, PIs and other stakeholders, and Board members, and the panel also separately met with the Director and the Swinburne DVC-R.

We thank all the individuals who were interviewed by the Review panel. Special thanks to our postdoc and student representatives (Meg Millhouse, Daniel Reardon, Kendall Ackley, Seb Ng, Fiona Panther, Johannes Eichholz, Julian Carlin, Debatri Chattopadhyay, Isobel Romero-Shaw, Deeksha Beniwal, Joshua McCann, Disha Kapasi) who the panel were particularly impressed with, noting that they were well-spoken, passionate, interacted positively with each other, and were able to talk across disciplines with a working understanding that demonstrates the cohesiveness within the Centre.

The panel subsequently provided OzGrav with a comprehensive report of their assessment of the Centre's performance against the Review's Terms of Reference. Overall, the report gave a very positive appraisal of the Centre's performance and progress to-date. The panel commended the Centre on its growing international presence, technical and research achievements, supportive environment for early career researchers, public outreach achievements, highly effective operational team, and achievements in the translation of gravitational wave science to broader applications within industry and other disciplines.

The Review panel also provided a number of constructive and well-considered recommendations, designed to help the Centre build on its previous work to further strengthen the Centre and the sector, and to further support its members. OzGrav drafted an action plan to respond to each of the recommendations, sparking many new activities, initiatives and goals, including:

- Increased efforts engaging with the global future detector planning activities to maximise opportunities for Australia to develop technology for, and potentially host, a future detector.
- Hosting more workshops and events to bring OzGrav members together with industry and other potential partners, to explore possibilities for joint projects and research translation into other sectors.
- Expanding our mentoring program by growing the pool of industry mentors available to our members, encouraging those in the program to have open and transparent conversations about career challenges and set-backs, and ensuring that our mentors and senior researchers are themselves receiving support and mentoring.
- Providing more professional development opportunities to mid and senior career researchers, and ensure succession planning and implementation is occurring at all levels for all categories of member.
- Providing more training on Research Translation and commercialisation, and increasing the promotion and uptake of our Research Translation Seed grants.
- Working with industry partners to provide more industry/academia hybrid career options, and internship opportunities in a range of sectors from instrumentation to data science.
- Striving to approach gender parity across the Centre, through a range of specific actions designed to improve women-representation from the student level all the way through to the CI, PI and Advisory Committee levels.
- Setting more ambitious Key Performance Indicators and benchmarks to push the Centre towards stretched targets.
- Launching new targeted funding opportunities.

Georgia Bolingbroke, PhD student at University of Adelaide, is assembling and testing the distributed Bragg reflector laser. Credit: Huy Tuong Cao, OzGrav Adelaide

New funding opportunities for OzGrav members

Research and Innovation Grant

This funding is to enable our students and Postdoctoral Researchers to undertake new and innovative projects. The funds are aimed at empowering early career researchers to pursue novel ideas, to give them support and freedom to pursue ideas and publish them as first-author papers. These projects may be pure research or innovative projects to apply technology or skills to other real-world applications. Applications from teams of students/postdocs are welcomed, with cross-nodal teams especially encouraged.

Professional Development Grant

This grant aims to enable OzGrav students and Postdoctoral Researchers with priority to people from underrepresented groups to participate in activities and training to improve their professional development skills. The grant may go to individuals for their development and training, and in some cases we may offer the requested training as a group event to the wider OzGrav ECR cohort, if appropriate.

Hardship Grant

This scheme is intended to support OzGrav students and Postdoctoral Researchers facing financial difficulty or loss of income/employment as a result of extraordinary circumstances (e.g. impacts of the pandemic leading to unforeseen financial difficulties, gaps in employment, etc). The funds are intended to allow the recipient to work effectively on OzGrav research.

These new funding schemes complement our existing OzGrav funding opportunities that include:

Research Translation and Commercialisation Seed grants are aimed at stimulating, fostering and supporting research translation and commercialisation activities that apply OzGrav-developed techniques or technologies to solve industrial or other practical challenges.

Primary Carer grants support OzGrav primary carers to participate in research activities that they would otherwise not be able to undertake due to their caring commitments.

International visitor funding brings leading international scientists to collaborate on OzGrav projects, visit multiple nodes, and give seminars and public talks during their visit.

Event sponsorship is available for events that are relevant and beneficial to our members.

Vacation scholarship program brings bright young minds to work with our researchers, with at least half of the students coming from underrepresented groups or working with a supervisor from an underrepresented group in STEM.

ECR travel awards for student and postdoc placements at Nodes, travel for conferences, and site visits to collaborators institutions.

Work Experience student at University of Adelaide works at the laser table. Credit: OzGrav Adelaide

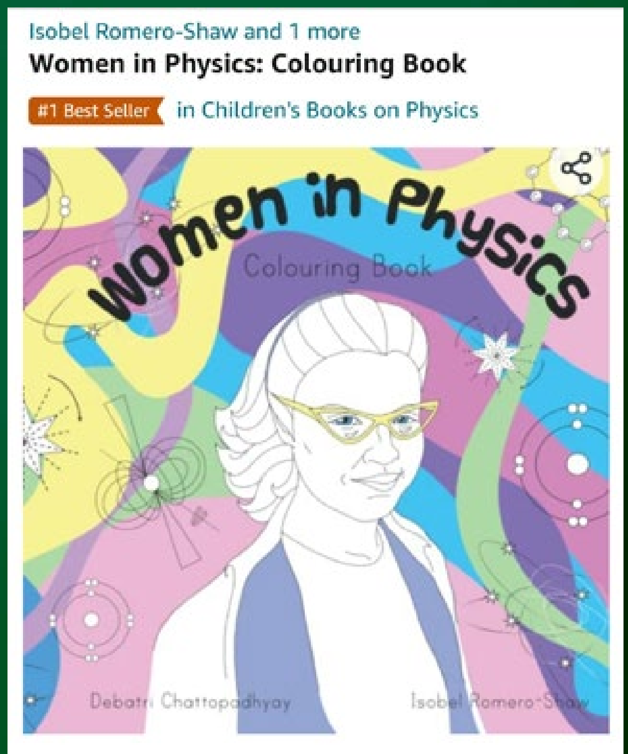
EQUITY AND DIVERSITY COMMITTEE

In 2021, OzGrav saw a number of highlights and achievements that advanced our Equity, Diversity and Inclusion goals.

OzGrav PhD students Isobel Romero-Shaw and Debatri Chattopadhyay collaborated on a colouring book called "Women in Physics" encouraging girls to follow their science passions and learn about the amazing women who changed the course of history. It features 17 influential women in physics, fun facts, science snippets, creativity prompts, and much more.

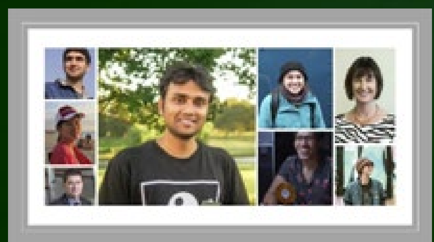
"Embark on a journey through time with some amazing women who changed the course of history with their physics research! Meet the women who wrote the first computer program... discovered how atoms spontaneously combust... worked out what the Sun is made of... discovered a giant black hole at the centre of our galaxy... and many more!"

It is available on Amazon.



Space Industry Newtork (a program linked with Space Discovery Centre Careers) Work Experience students at the University of Adelaide did some research and data analysis, then created and delivered a presentation. Credit: OzGrav Adelaide

OzGrav held a Diversity Day Lunch on Friday 21st May in celebration of World Day for Cultural Diversity for Dialogue and Development. There was a Centre-wide video conference with talks from 9 of our members about their background, cultures and challenges. Each Node held a special lunch, where a diverse range of cuisines were provided and members were encouraged to bring along a dish that reflects their cultural background.



OzGrav received a Silver Pleiades Award from the Astronomical Society of Australia (ASA) in recognition of our continued commitment to promoting equity and inclusion. The Silver Pleiades recognises organisations with a sustained record of at least two years 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. Prof Matthew Bailes says "I'm indebted to our very active Equity and Diversity committee and to everyone in OzGrav for their efforts that led to this success."

"The efforts that OzGrav have demonstrated over the past two years are commendable and we wish to encourage your continued commitment to promoting equity and inclusion. We would specifically like to highlight that the Pleiades Awards review committee found the range of activities and the engagement of the E&D committee members to be impressive." - The IDEA Chapter Steering Committee.

In order to increase opportunities for underrepresented people to engage in OzGrav research, in 2021 we launched a scheme to Centrally-fund 50% of a PhD stipends if the student is from an underrepresented group or working with underrepresented supervisors. We also launched a scheme to Centrally-fund a vacation scholarship program where at least half of the students were from underrepresented groups or working with underrepresented supervisors.

Our current Equity and Diversity action plan sets a target of 50% female gender representations of all new recruits/members. This is an ambitious target, given that the pool from which we draw our new recruits/members is male-dominated, especially in the instrumentation disciplines. Nevertheless, in 2021 over 40% of our new recruits were women.

In 2021 our Equity & Diversity Journal Club continued, covering topics including: accessibility, Black Lives Matter, intersectionality, and Women in Physics in developing countries. At our annual retreat, our equity and diversity session explored the topics of neurodiversity and autism, and culturally safe workplaces for indigenous Australians. This session was very well attended (over 80 people) and got glowing feedback from our post-event survey.

PROFESSIONAL DEVELOPMENT COMMITTEE

In 2021, OzGrav continued to refine and implement our Professional Development Program, led by Prof Susan Scott and supported by our PD Committee. Our PD webinar series ran throughout 2021, with sessions on resilience, stress management, career planning and networking, tips for job interviews, managing difficult conversations, and career development inside and outside of academia. We also ran a mentoring networking session for people in our mentoring program. Each year we try to target topics that our ECRs are most interested in, as indicated by surveys and feedback from our Early Career Researcher Committee, and we use appropriately skilled and credentialled facilitators.

Two of the biggest events on our calendar each year are our 3-day Annual Retreat and 2-day ECR workshop. The ECR workshop program is designed by our ECR Committee, with input from our PD Committee. In 2021 the program included plenty of social and ice-breaker activities, tips on using virtual platforms for collaboration and meetings, science communication, software development training, and a Career panel Q&A with special guests offering a breadth of experience from academia, finance, government, science communication, industry, commercialisation and start ups. Our panel guests shared their career paths, challenges, curve balls, and highlights.

In 2021, OzGrav launched a Research and Innovation Grant scheme to support our students and early career researchers to pursue novel ideas. This scheme will strongly incentivise collaborations, as team projects will have access to a higher level of funding, and priority will go cross-nodal projects. This fund will encourage members to publish the results as short-author papers.

In 2021 we also launched a new Hardship grant scheme, and a Professional Development funding scheme that will complement the PD workshops, webinars and training that we already provide to members as part of our multi-layered Professional Development Program. The hardship grant scheme is effectively an expansion of our previous COVID scheme. This scheme will support our members to continue pursuing their careers despite experiencing hardship (e.g. due to financial or employment impacts caused by extraordinary circumstances). The Professional Development scheme supports individual PD training or courses with priority given to members from underrepresented groups in STEM. Both new schemes are open to OzGrav students and postdocs.

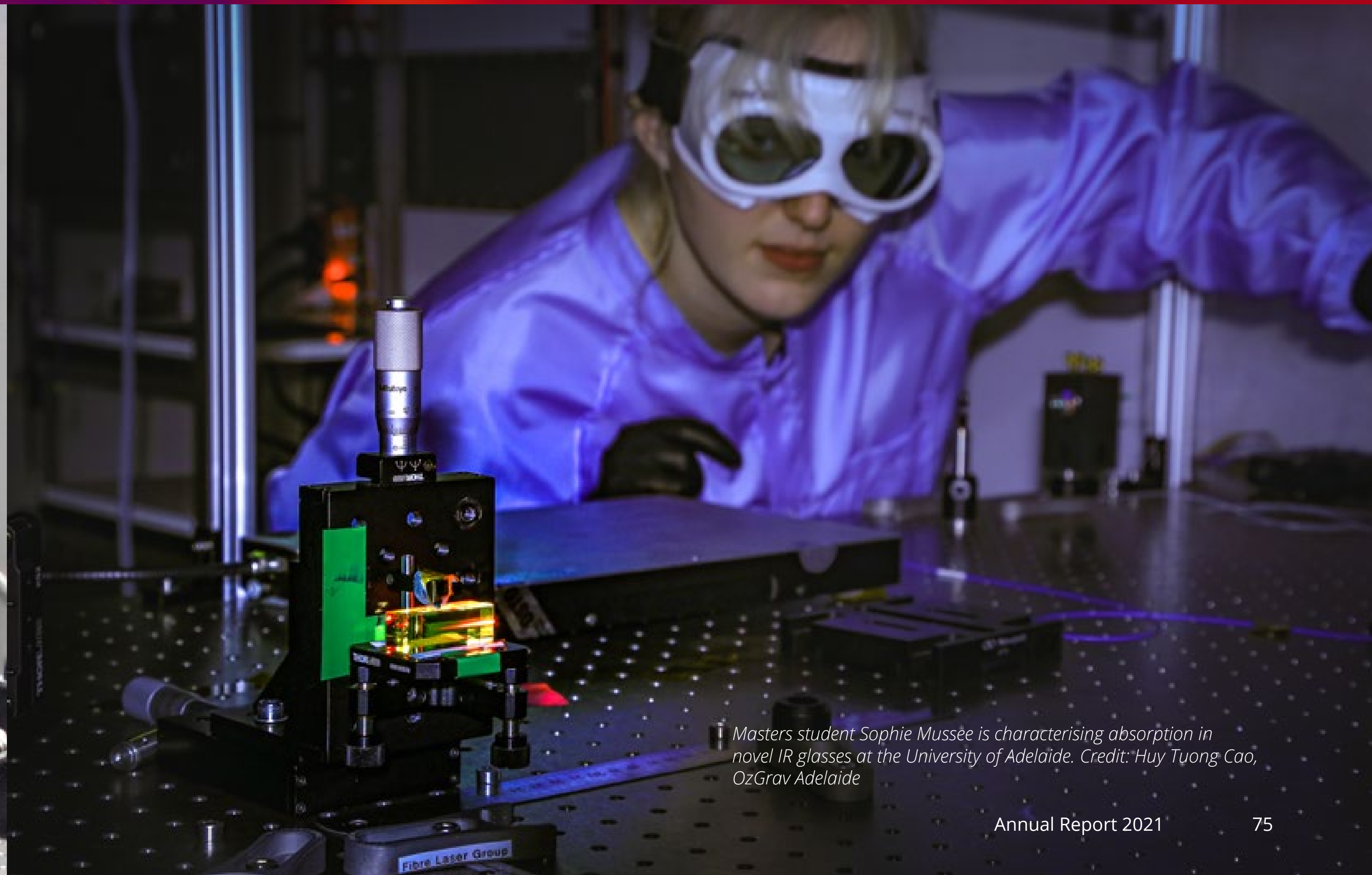
Mentoring program

One-on-one discussions with mentors is a very important setting for providing support to Early Career Researchers, and is a key complement to the facilitated webinars and workshops that we regularly run. We rolled out updated mentoring program guidelines in September 2021. We have also begun to grow our pool of mentors from outside academia. We are reaching out to dozens of potential new mentors that have been recommended by our investigators and other industry connections.

Updates to our mentoring program in 2021:

- Mentors to have conversations about resilience, challenges and setbacks in each meeting, and for mentors to openly share their own experiences navigating difficult terrain throughout their careers.
- At least 30% of our mentors to come from other sectors or industry, by drawing on our industry connections, our growing alumni network, members of the Astronomical Society of Australia, and through our CI and PIs' collaborators from outside our field. We expanded our pool of mentors to include external people from different sectors and with greater diversity.
- Build into the mentor program the option to have two mentors: e.g one from academia and one from industry, or one from inside and one from outside OzGrav.
- Feedback survey to go out annually, including giving them options to change mentor, have an additional mentor, express interest in doing an industry placement.
- Send out reminders to catch up every 4 months, with suggestions for topics to discuss.

Work Experience student at University of Adelaide works at the laser table. Credit: OzGrav Adelaide



Masters student Sophie Mussee is characterising absorption in novel IR glasses at the University of Adelaide. Credit: Huy Tuong Cao, OzGrav Adelaide

RESEARCH TRANSLATION COMMITTEE


Suspended from the crane is the full TorPeDO isolation and suspension chain. Careful lifting over the optical table in the ANU Laboratory, on its way to its new home. (with Min Jet Yap, Nathan Holland and Bram Slagmolen). Credit: Sheon Chua, OzGrav ANU

We thank Prof Jong Chow (ANU) who stepped down from the role of OzGrav Research Translation Committee Chair in 2021, following a very productive period at the helm of our RT Program. Jong passed the baton over to our Chief Investigator Prof Rob Evans (Uni of Melbourne) to take advantage of his outstanding depth and breadth of industry experience and his strong commitment to mentoring the next-generation of researchers.

We took this opportunity to refresh the membership of our Research Translation Committee and to bring in industry members to provide new and complementary perspectives. In late 2021, our new RTC comprised OzGrav members: Prof Rob Evans (Chair), Dr Carl Blair (UWA), Dr Yeshe Fenner (Swin), Dr Aaron Jones (UWA), and Dr Seb Ng (Uni Adelaide). In addition, we appointed to the RTC: Dr James Murray, an industry engagement specialist from Astronomy Australia Ltd, James Wilson, the CEO of the data science company Eliiza, Dr Doris Grosse, Instrument scientist at the ANU Institute for Space, and Dr Andrew Sutton, an OzGrav alumni who has recently moved into industry.

In 2021 we were delighted with the number and breadth of Research Translation highlights that came about as a result of our Centre's people and programs. Some of these are described in more detail on pages 14-19 of this report. For instance, we have developed new relationships with Australia Post and Google for internships for students/postdocs considering industry work. This will give our ECRs an opportunity to work on short ~3 month data science projects to tackle real-world problems, while giving them a taste for working in industry.

More than 20% of our recent Early Career Researcher alumni have moved into industry positions. We are delighted that they have all agreed to stay connected with OzGrav, and to share their industry experience with our members. We have invited them, and all our alumni with industry experience, to join our mentoring program as mentors. We have been using our weekly videoconferences, monthly newsletter, and ECR workshops to highlight research translation opportunities and industry career pathways.

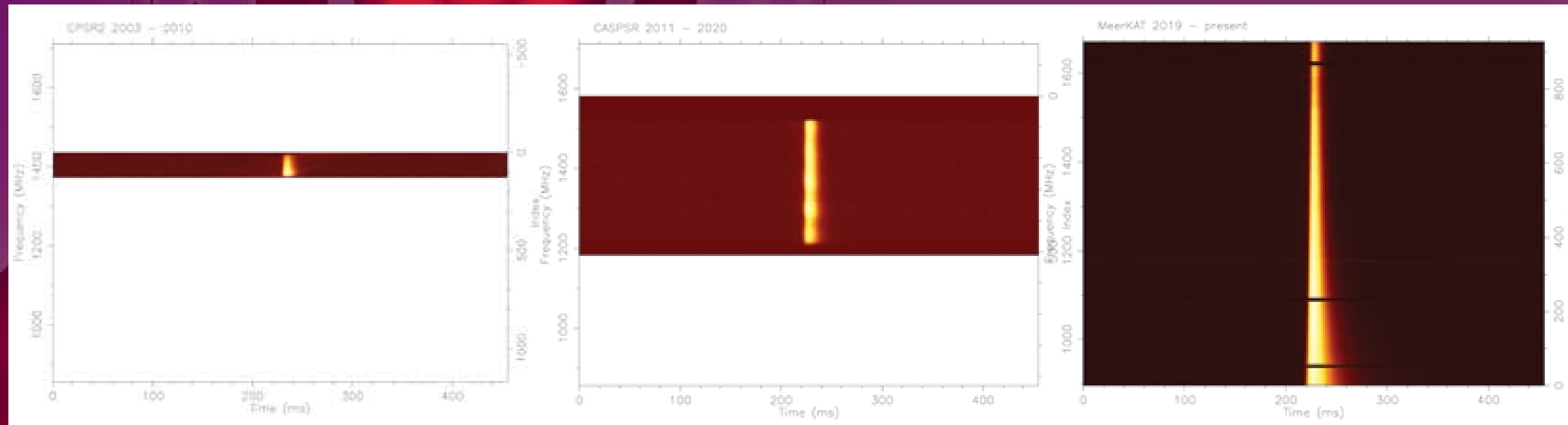
In 2021 we awarded two new Research Translation Seed grants: 1) to the Einstein First educational program with the goal of enabling them to commercialize their product to yield revenue, scale-up, and to ultimately become self-sustaining, 2) to a team involving Monash, Swinburne and ANU members in partnership with the data science company Eliiza, to use machine learning to improve the classification of noise and glitches in the LIGO data, and boost the sensitivity of our signal detection pipelines.

Case study: new company Fourier Space Pty Ltd

Fourier Space is a new spin-off company from Swinburne that offers expertise in high performance digital signal processing and its use in astronomical instrumentation. Over the last 15+ years the team have designed, developed, and commissioned many generations of successively more capable, bespoke, high-time-resolution processing instruments for the iconic Parkes radio telescope. In more recent years, they have developed expertise in interferometry (beamforming and correlation), fast transient detection, spectrometry and baseband recording techniques. Software instruments have been designed and deployed by the team at some of the most capable observatories, including MeerKAT, Keck and UTMOST.

The development of the Pulsar Timing instrument for the MeerKAT radio telescope has been a most important recent development that has contributed to the foundation of Fourier Space. The instrument design, construction and commissioning has been supported by OzGrav and conducted at Swinburne and it now enables the timing of pulsars at the world's most sensitive radio interferometer. Gravitational wave searches with MeerKAT pulsar data will continue to provide rich dataset through the MeerTIME Key Science Program (led by Matthew Bailes) and will deliver direct benefits to OzGrav researchers for years to come.

At the heart of this work is the capability to receive extremely high data-rate streams from telescope systems and process them, in real-time, using the latest Graphics Processing Units (GPUs). This hardware is typically deployed on modest supercomputers, built from commercial-off-the-shelf servers, which reduces cost of ownership, complex systems engineering and deployment timescales. Software libraries and algorithms that unlock the massive memory bandwidth and processing capabilities of GPUs have been developed to enable rapid development and deployment of coherent signal processing software. This software is available for licensing and can be coupled with consulting services to provide complete pipelines and systems. The team have also laid the foundations for many core software libraries and developed critical applications that are made available to the radio astronomy community. Fourier Space are now leveraging their experience and existing software infrastructure to pursue opportunities in developing the next generation of astronomy instrumentation on facilities such as the Square Kilometre Array. The future for Fourier Space includes commercialisation opportunities outside of astronomy, with a focus to translate expertise digital signal processing research to applications in space and communications sectors.



Observations of pulsar J1644-4559 performed with 3 generations of pulsar timing instrumentation at L-band; CPSR2 (2001-2010), CASPSR (2011-2020), MeerKAT (2019-present). The plots show the dedispersed pulsar flux, folded at the pulsar period (455 milliseconds). The maximum processable bandwidth from each instrument is shown in the same scale: CPSR2 64MHz, CASPSR 300 MHz and MeerKAT 856MHz. The broadening at low frequencies is due to interstellar scattering.

ACTIVITY PLAN 2022

Instrumentation

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

The global COVID-19 situation is continually changing. We hope that 2022 will allow scientists from OzGrav to return in person to the sites. We also plan to explore the feasibility of remotely commissioning the LIGO detectors in preparation for O4, making optimal use of timezones and the recent upgrades in infrastructure allowing for easier remote access to the sites. We will help bring Filter cavities online and generate frequency dependent squeezing.

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

The Quantum program is continuing to focus on the development of 2µm lasers to aid the research into cryogenic silicon test masses and the use of squeezed light for broadband and high frequency sensitivity for third generation gravitational wave detectors.

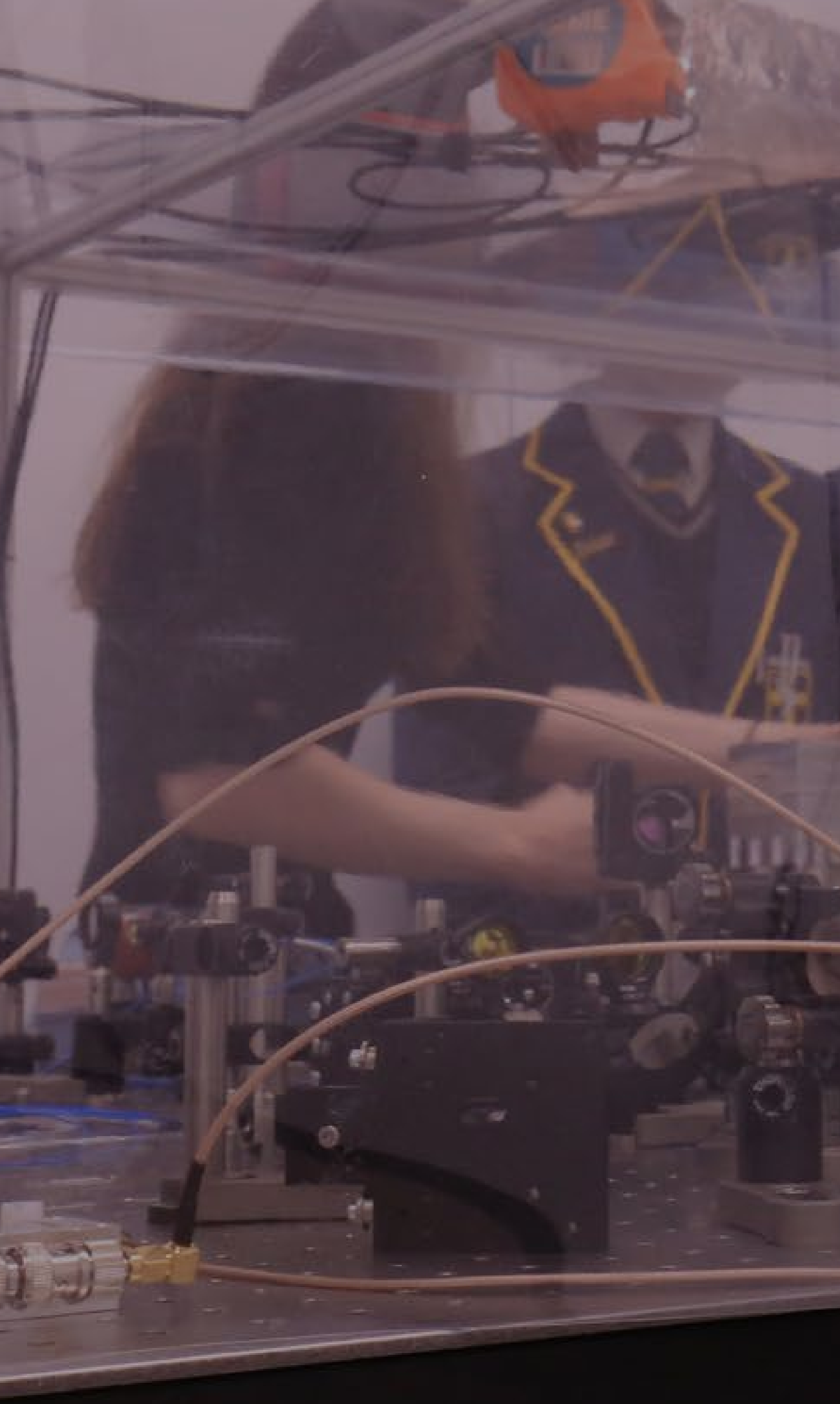
We would like to integrate the ECDL and fiber amplifier into the 2µm squeezed light experiment and test the combined noise performance and recover squeezing at the 1984 nm wavelength. Initial modeling has shown parametric amplification can mitigate issues regarding poor photodetector efficiency in our 2µm squeezed light source. We are building a parametric amplifier and would like to test this idea in the coming year.

We would like to begin testing the performance of the internal squeezer in the first quarter of 2022 and aim to see non classical effects. Ultimately we would like to investigate the possibility of running the system in a non-degenerate mode. By the end of the year the development of a control scheme for quantum enhanced twin beam interferometry with EPR states should be near completion. The University of Western Australia is continuing its development of optomechanical negative dispersion filters with the focus on silicon nitride membranes acoustically isolated by a phononic crystal, and single-crystal quartz acoustic resonators.

We aim to have 2µm Squeezer laser installation complete by July, with measurement of internal squeezing by September. The 2µm OPA will be installed by December.

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

The main goal for 2022 for the TorPeDO experiment is to commission the full Isolation and Suspension Chain. This requires us to bring each of the four pendulum stages to its operating point, using controls implementations. Parallel to this is the phase locking of the four sensing-lasers against a fifth laser, to mimic the characteristic of a single laser. Each of the four sensing-lasers will be directed into one of the four TorPeDO cavities, with locking achieved by September. With this we will have the first full performance test of the suspended TorPeDO system by December. The TorPeDO-DI development will be integrated into the TorPeDO systems once performance has reached the design target.



University of Adelaide PhD student Georgia Bolingrbroke runs a laser lab tour for high school students. Credit: Sophie Muusse, OzGrav Adelaide

For the rotation sensor project, the goal is to have 2 x Mark-2 rotation sensors constructed and preliminary characterised in 2022. The Mark-2 ALFRA final design is to be completed by April, and manufactured by July. Preliminary result of the performance of ALFRA is expected in December.

In 2022, we expect to have the large seismic array deployed and remote data acquisition completed ready for data analysis and vibration feedback/feedforward control.

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

Work on BS aberrations will be complete by April. By May we will lock a 2µm laser to a 7m suspended cavity and characterise the pre-stablised 2µm laser. A suspended silicon test mass cavity will be complete by December. We will finish a study on PI Mechanical Mode mapping. By December we will complete characterisation of Birefringence of Silicon Sample using Photoacoustic technique.

Space Instrumentation - Program Chair: Prof Kirk McKenzie (ANU)

The program will continue in its three main themes of weak light phase tracking, robust minimal hardware absolute laser frequency knowledge measurements, and laser frequency stabilisation for the space-based interferometer. We will assemble a new high finesse cavity reference testbed by May, and submit absolute frequency results against atomic reference by June.

Weak light phase tracking is an essential enabling technology for future space-based gravitational wave detectors and a central theme of our work. The main task this year is a high fidelity optical test of our updated and fully characterised phasemeter. We will pre-stabilise a pair of lasers and track an attenuated optical beat note at the 10s of femtowatt level. We will sweep our phase meter parameters to demonstrate our models of cycle-slipping against experimental realisation: demonstrating the benefits of laser pre-stabilization combined with optimal phasemeter tuning. We expect a publication in the third quarter of 2022.

Absolute laser frequency readout will be essential for calibrating displacement in space-detectors. We will progress this work with comparisons of our cavity readout technique against an absolute iodine reference. We will also conduct an implementation of our readout scheme on a finesse 100k ultra-stable cavity (factor ten higher than previously).

For the laser frequency stabilisation work we will start construction of a fibre-based proof-of-principle experiment to test our arm locking in a delay-line style frequency reference. A blended feedback control tying optical frequency stability to both a cavity and fibre delay line will ultimately be used to experimentally confirm our simulations.

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

Four simultaneous PTUSE machines will be operational at SKA-SA site by March. By the end of June, operations of North-South arm pulsar timing program at Molonglo Observatory will be routine via a new AARNET fibre link. The Timing array Data Release 1 for MeerKAT is expected by the end of June 2022.

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

Pursue an Australian next-generation detector called NEMO, alongside the US Cosmic Explorer and the EU Einstein Telescope (ET) as one of the key next-generation detector opportunities. We will ensure that OzGrav members continue to lead the international next-generation detector R&D roadmapping efforts. We are also ensuring that OzGrav members join the ET Science Collaboration with a goal to taking on R&D work packages.

We are exploring options for Australian involvement in the multi-billion-dollar GW LISA observatory by adapting the work performed for the Grace Follow-on mission.

Data and Astrophysics

Inference - Program chair: Dr Rory Smith (Monash)

In 2022 the program will be primarily focussed on (i) delivering core parameter estimation codes and methods for the LVK's upcoming fourth observing run, and (ii) the general development and application of methods and techniques for broad problems and discoveries in astronomy. Concretely for (i) we will provide production ready codes for highly parallelised inference on individual compact binary mergers (parallel Bilby), and the rapid optimal sky localization of binary neutron star mergers (SKYLR) by December.

With LVK observations resuming in very late 2022, there will likely be a stronger emphasis on analysis of historical data, theoretical methods, and third-generation detectors.

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

In 2022 there will be a strong focus on wrapping up the last results from O3, with attention turning toward preparations for O4, slated to begin in late 2022. We will co-lead the O3b GW/FRB search and analysis.

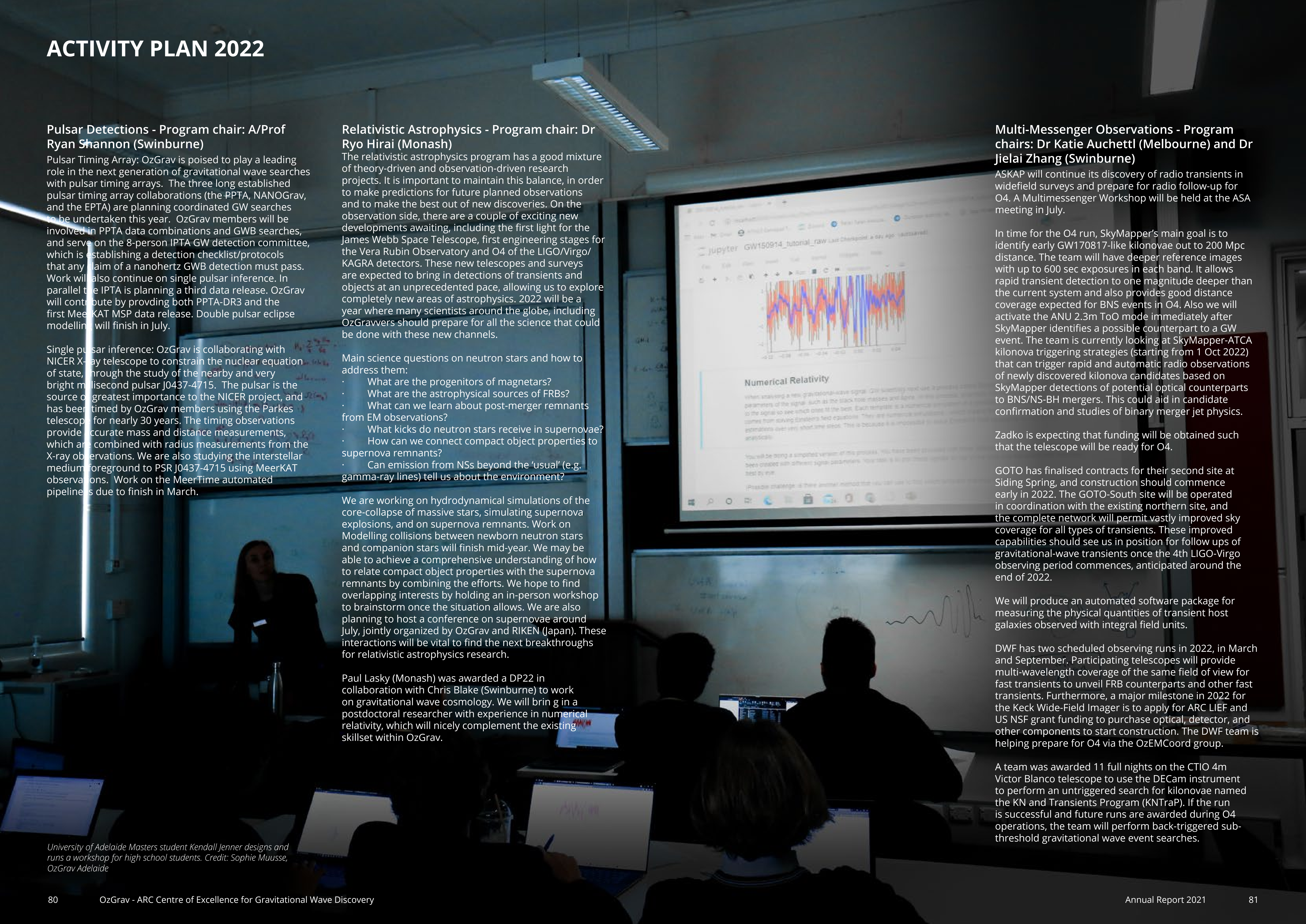
We will prepare Viterbi and associated search management tools for O4 data. We will also work on a new Viterbi-based search method for vector bosons.

We will complete work on localisation of BBH, BNS and NSBH signals. We will extend our current localisation model to predict posteriors of all 15 parameters of GW signals in real-time.

We will work on Machine Learning in Gravitational Waves Mock Data Challenge, and have a Mock data challenge for optimal search for astrophysical stochastic background.

We will have SPIIR early warnings for NSBH by May, develop SPIIR software for O4 by August, and review SPIIR code until October.

ACTIVITY PLAN 2022



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

Pulsar Timing Array: OzGrav is poised to play a leading role in the next generation of gravitational wave searches with pulsar timing arrays. The three long established pulsar timing array collaborations (the PPTA, NANOGrav, and the EPTA) are planning coordinated GW searches to be undertaken this year. OzGrav members will be involved in PPTA data combinations and GWB searches, and served on the 8-person IPTA GW detection committee, which is establishing a detection checklist/protocols that any claim of a nanohertz GWB detection must pass. Work will also continue on single pulsar inference. In parallel the IPTA is planning a third data release. OzGrav will contribute by provding both PPTA-DR3 and the first MeerKAT MSP data release. Double pulsar eclipse modelling will finish in July.

Single pulsar inference: OzGrav is collaborating with NICER X-ray telescope to constrain the nuclear equation of state, through the study of the nearby and very bright millisecond pulsar J0437-4715. The pulsar is the source of greatest importance to the NICER project, and has been timed by OzGrav members using the Parkes telescope for nearly 30 years. The timing observations provide accurate mass and distance measurements, which are combined with radius measurements from the X-ray observations. We are also studying the interstellar medium foreground to PSR J0437-4715 using MeerKAT observations. Work on the MeerTime automated pipeline is due to finish in March.

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

The relativistic astrophysics program has a good mixture of theory-driven and observation-driven research projects. It is important to maintain this balance, in order to make predictions for future planned observations and to make the best out of new discoveries. On the observation side, there are a couple of exciting new developments awaiting, including the first light for the James Webb Space Telescope, first engineering stages for the Vera Rubin Observatory and O4 of the LIGO/Virgo/KAGRA detectors. These new telescopes and surveys are expected to bring in detections of transients and objects at an unprecedented pace, allowing us to explore completely new areas of astrophysics. 2022 will be a year where many scientists around the globe, including OzGravvers should prepare for all the science that could be done with these new channels.

Main science questions on neutron stars and how to address them:

- What are the progenitors of magnetars?
- What are the astrophysical sources of FRBs?
- What can we learn about post-merger remnants from EM observations?
- What kicks do neutron stars receive in supernovae?
- How can we connect compact object properties to supernova remnants?
- Can emission from NSs beyond the 'usual' (e.g. gamma-ray lines) tell us about the environment?

We are working on hydrodynamical simulations of the core-collapse of massive stars, simulating supernova explosions, and on supernova remnants. Work on Modelling collisions between newborn neutron stars and companion stars will finish mid-year. We may be able to achieve a comprehensive understanding of how to relate compact object properties with the supernova remnants by combining the efforts. We hope to find overlapping interests by holding an in-person workshop to brainstorm once the situation allows. We are also planning to host a conference on supernovae around July, jointly organized by OzGrav and RIKEN (Japan). These interactions will be vital to find the next breakthroughs for relativistic astrophysics research.

Paul Lasky (Monash) was awarded a DP22 in collaboration with Chris Blake (Swinburne) to work on gravitational wave cosmology. We will brin g in a postdoctoral researcher with experience in numerical relativity, which will nicely complement the existing skillset within OzGrav.

Multi-Messenger Observations - Program chairs: Dr Katie Auchettl (Melbourne) and Dr Jielai Zhang (Swinburne)

ASKAP will continue its discovery of radio transients in widefield surveys and prepare for radio follow-up for O4. A Multimessenger Workshop will be held at the ASA meeting in July.

In time for the O4 run, SkyMapper's main goal is to identify early GW170817-like kilonovae out to 200 Mpc distance. The team will have deeper reference images with up to 600 sec exposures in each band. It allows rapid transient detection to one magnitude deeper than the current system and also provides good distance coverage expected for BNS events in O4. Also we will activate the ANU 2.3m ToO mode immediately after SkyMapper identifies a possible counterpart to a GW event. The team is currently looking at SkyMapper-ATCA kilonova triggering strategies (starting from 1 Oct 2022) that can trigger rapid and automatic radio observations of newly discovered kilonova candidates based on SkyMapper detections of potential optical counterparts to BNS/NS-BH mergers. This could aid in candidate confirmation and studies of binary merger jet physics.

Zadko is expecting that funding will be obtained such that the telescope will be ready for O4.

GOTO has finalised contracts for their second site at Siding Spring, and construction should commence early in 2022. The GOTO-South site will be operated in coordination with the existing northern site, and the complete network will permit vastly improved sky coverage for all types of transients. These improved capabilities should see us in position for follow ups of gravitational-wave transients once the 4th LIGO-Virgo observing period commences, anticipated around the end of 2022.

We will produce an automated software package for measuring the physical quantities of transient host galaxies observed with integral field units.

DWF has two scheduled observing runs in 2022, in March and September. Participating telescopes will provide multi-wavelength coverage of the same field of view for fast transients to unveil FRB counterparts and other fast transients. Furthermore, a major milestone in 2022 for the Keck Wide-Field Imager is to apply for ARC LIEF and US NSF grant funding to purchase optical, detector, and other components to start construction. The DWF team is helping prepare for O4 via the OzEMCoord group.

A team was awarded 11 full nights on the CTIO 4m Victor Blanco telescope to use the DECam instrument to perform an untriggered search for kilonovae named the KN and Transients Program (KNTraP). If the run is successful and future runs are awarded during O4 operations, the team will perform back-triggered sub-threshold gravitational wave event searches.

University of Adelaide Masters student Kendall Jenner designs and runs a workshop for high school students. Credit: Sophie Muusse, OzGrav Adelaide

ACTIVITY PLAN 2022

Monash University PhD student Mike Lau runs a virtual reality workshop for high school students at Casey Tech School. Credit: Carl Knox, OzGrav Swinburne

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

With no new gravitational-wave data expected until late in 2022, the goals of this year will differ from those of previous years, with more focus on developing models, extracting information from current observations.

Development of detailed N-Body models of star clusters will be complete by March.

The METISSE team will continue Binary evolution implementation throughout the year. We continue development of extended and improved phenomenological models for the population of merging compact object binaries.

The first public availability of GWLandscape is expected in December.

OzSTAR supercomputer - Leader: Prof Jarrod Hurley (Swinburne)

A major activity and highlight for 2022 will be the design, procurement and installation of OzSTAR v2 which will succeed OzSTAR as the primary GW data and computing engine in Australia. In late 2021 $5.2M of funding was awarded through the Victorian Higher Education State Investment Fund for the installation of OzSTAR v2 by the end of 2022.

An important deliverable is to secure the next round of funding for the GWDC. Current funding will only take us through to July 2022. If further funding is not secured we will need to delay or halt progress on development projects which will limit Australian involvement in O4 science. We will work closely with AAL to secure further funding to avoid this scenario.

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

Professional Development

Deliver and grow the OzGrav webinar series including topics of particular interest to Early Career Researchers.

Expand our PD Program to provide more PD and mentoring opportunities to Mid Career and senior researchers.

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

Once travel permits, roll out a new and invigorated program of in-person events, node placements, international placements, distinguished visitor programs, cross-disciplinary workshops, and industry networking events. This program will be developed in consultation with our ECRs, advisory committees and industry partners.

Support our researchers through the continuing effects of the global pandemic, and encourage a culture of openness and transparency about set-backs and career challenges, in accordance with the recommendations from our Mid Term Review.

Continue the promotion of ECRs and MCRs into the role of Program Chairs, with the appropriate mentoring from node and theme leaders.

Continue to grow the pool of mentors in our mentoring program, including people from industry and other sectors, and encourage more senior OzGrav researchers to be part of the program as mentees as well as mentors.

Run a mentor/mentee networking and speed-meet-a-mentor event.

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

Equity and Diversity

Continue to implement, update, and evaluate progress against, the OzGrav equity & diversity action plan.

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

In addition to the E&D Journal Club, run webinars on a range of topics, e.g. accessibility and destigmatising mental health issues.

Hold a special event celebrating OzGrav's diversity.

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

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

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

Research Translation Committee

Our Research Translation Committee has crafted an action plan for 2022 to lift our members' interest in, and exposure to, research commercialisation, intellectual property identification and protections, and broad industry engagement. The plan incorporates a bottom-up approach to educate and empower our members to explore RT of their ideas, alongside top-down strategic approaches to identify projects and technologies with the greatest potential for translation and commercialisation. Key elements of the 2022 action plan are:

Provide training in commercialization and Intellectual Property that includes information about each institution's specific processes and resources. Provide pitch session training.

Hold a series of seminars by researchers who have commercialized technology, started companies, or had major industry engagement. The aim is to inspire OzGrav researchers, excite them about the possibilities of research commercialization, and educate them on the various processes.

Work with each Node to create an OzGrav capability statement listing the Centre's key capabilities, skills and technologies that may be relevant to industry. Engage an astronomy research commercialisation expert to further drill down into these capabilities to identify those with most promise, and help map our skills and technologies to real-world industry challenges.

Support our members to increase uptake of Research Translation Seed grants, through a combination of better promotion of the grants, and creating an initial less onerous Expression of Interest stage for applicants to discuss their idea before proceeding to a full proposal. Offer an industry mentor to grant recipients.

Hold OzGrav-meets-industry networking and pitchfest events. Deliver briefings to industry, and provide industry internship opportunities.

Outreach

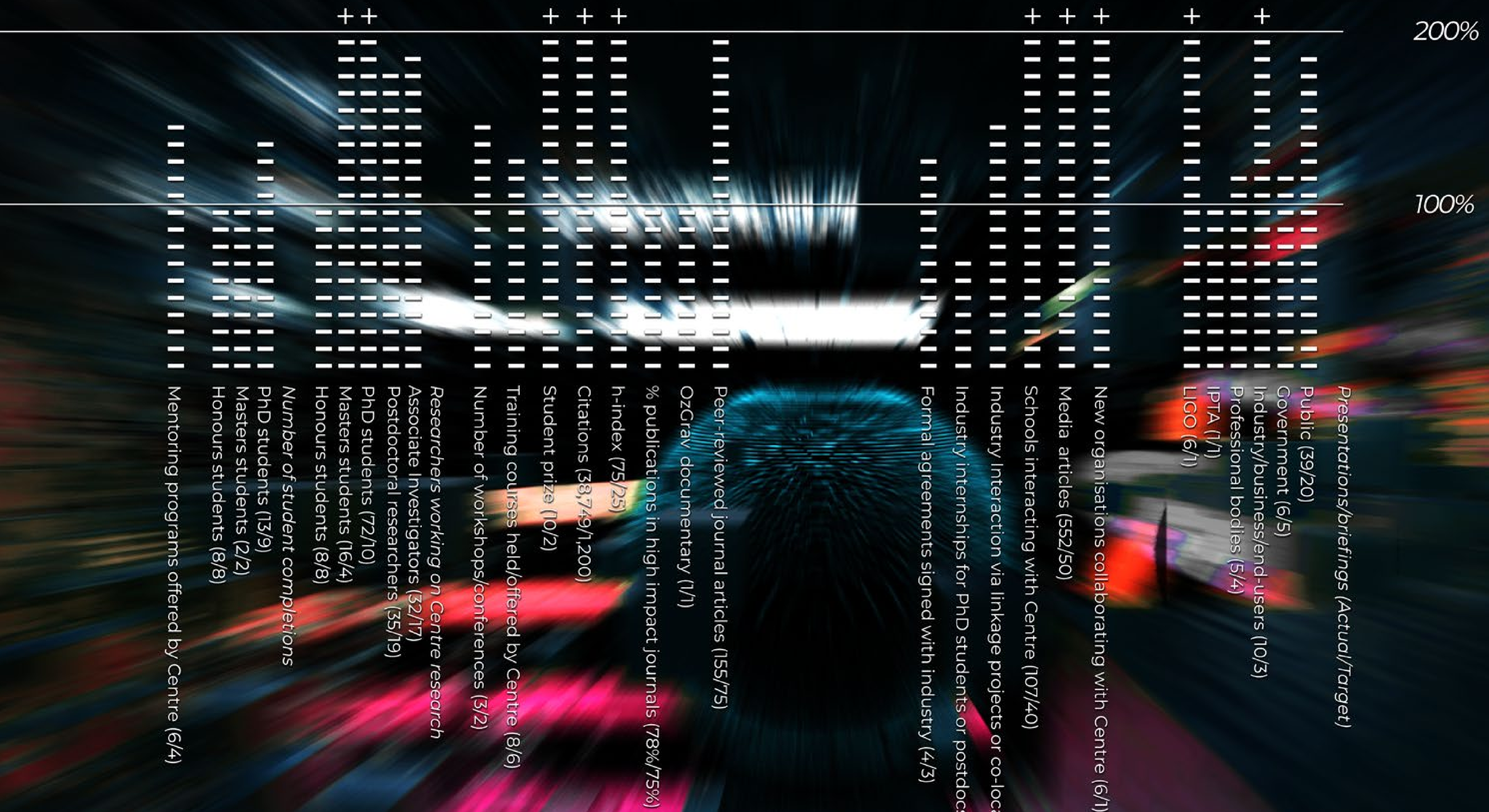
Schools Programs: We will continue to offer our existing face-to-face and virtual incursions. Additionally, we will pilot our new Gravity Explorer XR interface to introduce additional physics lessons for schools. We will also collaborate with our instrumentation and data researchers to develop hands-on educational offerings related to gravitational wave detection and data analysis. The Einstein-First team will continue to expand their curriculum across all year levels.

Public Outreach: We hope that 2022 allows us to engage with the public across all node states. We will continue to pilot interactive projections and will create a new VR guided tour using the resources from the Gravity Explorer project. We will also work to make the University of Adelaide-developed Minecraft LIGO a more accessible and widely utilised asset. We will also provide opportunities for our members to meet the public at events specifically targeted in regional locations.

Member Training: In addition to offering public communication opportunities as part of the ECR workshop and Annual Retreat, we will also offer targeted communication training opportunities for public speaking and media interviews.

Media and Digital Content: We will continue to support our members with animations, graphics and social media to accompany media articles related to OzGrav work. The outreach team will develop resources to support the promotion of the 2021 OzGrav documentary.

KPI dashboard



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
European Space Agency (ESA)
Flawless Photonics
French Space Agency
GOTO Collaboration
GrandMa collaboration
INFINI.TO: Planetarium of Turin
Kavli Institute for Theoretical Physics China
Laser Interferometer Gravitational-Wave Observatory (LIGO)
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
Tsinghua University
University of Birmingham
University of Florida
University of Glasgow
University of North Carolina - Chapel Hill
University of Otago
University of Science and Technology China (USTC)
University of Tokyo
University of Urbino
University of Warwick

National

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

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

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

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

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

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

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

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

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

Image: Virgo detector, Italy. Credit: Virgo Collaboration

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

LINKAGES AND COLLABORATIONS

LSC/LVC/LVK and other international working groups

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

Congratulations to OzGrav Chief Investigator Dr Bram Slagmolen (ANU) for being elected to the position of Technical Advisor to the LSC Oversight Committee. Karl Wette (ANU) is a Continuous Wave Working Group co-chair. Ling Sun is a LIGO Calibration Working Group co-chair. Vaishalia Adya (ANU) is a LAAC postdoctoral representative. Jade Powell (Swinburne) is co-chair of the Core-collapse Supernova Group. Daniel Brown (University of Adelaide) is Advanced Interferometer Configuration chair.

Eric Thrane (Monash) is a member of the LIGO Editorial Board. David McClelland (ANU) is a member of LVK editorial board, a member of the LIGO speaker board, and a Partner Investigator for the LIGO Scientific Collaboration. Rory Smith (Monash) led the paper writing team for the neutron-star-black-hole discoveries. Manoj Kovalam (UWA) is a Low Latency liaison for the SPIIR group. Hannah Middleton (University of Melbourne) is LIGO Magazine Editor-in-Chief. Gregory Ashton (University of Portsmouth) is Compact Binary Coalescence (CBC) co-chair. Ryan Shannon (Swinburne) serves on ATNF Users' Committee, as well as NRAO Science Review Panel.

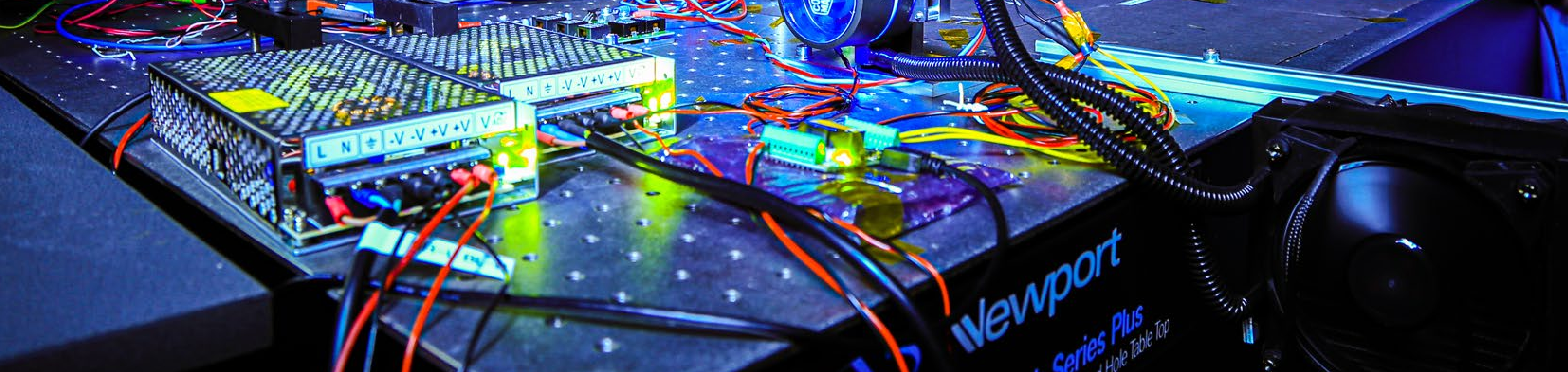
LIGO Magazine

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

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

FINANCE

	2021 Forecast	2021 Actuals	2022 Forecast
INCOME			
ARC Centre Grant	$ 4,895,693	$ 4,895,693	$ 4,884,868
Institutional cash contribution	$ 1,130,000	$ 1,159,060	$ 1,114,000
Other income		$ 5,542	
Total Income	$ 6,025,693	$ 6,060,295	$ 5,998,868
EXPENDITURE			
Salaries & scholarships	$ 4,559,179	$ 4,074,655	$ 4,987,707
Equipment	$ 496,164	$ 399,271	$ 376,498
Travel, Meetings, Workshops	$ 313,320	$ 70,074	$ 907,500
Research maintenance and consumables	$ 623,925	$ 353,580	$ 766,269
Outreach, operations and other expenditure	$ 129,862	$ 130,132	$ 262,588
Total Expenditure	$ 6,122,448	$ 5,027,712	$ 7,300,562
Carry-forward from previous year	$ 5,965,160	$ 5,965,160	$ 6,997,742
BALANCE	$ 5,868,405	$ 6,997,742	$ 5,696,048



Background image: PhD student Zac Holmes works on the laser table at the University of Adelaide. Credit: Huy Tuong Cao, OzGrav Adelaide

GOVERNANCE

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

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

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

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

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

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

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

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

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

OzGrav Executive Committee

Prof Matthew Bailes - OzGrav Director
Swinburne University of Technology

Prof David McClelland - OzGrav Deputy Director
Australian National University

Prof David Blair - Outreach Leader
University of Western Australia

Prof Robin Evans - Research Translation Leader
Australian National University

Prof Jarrod Hurley
Swinburne University of Technology

Prof Andrew Melatos
University of Melbourne

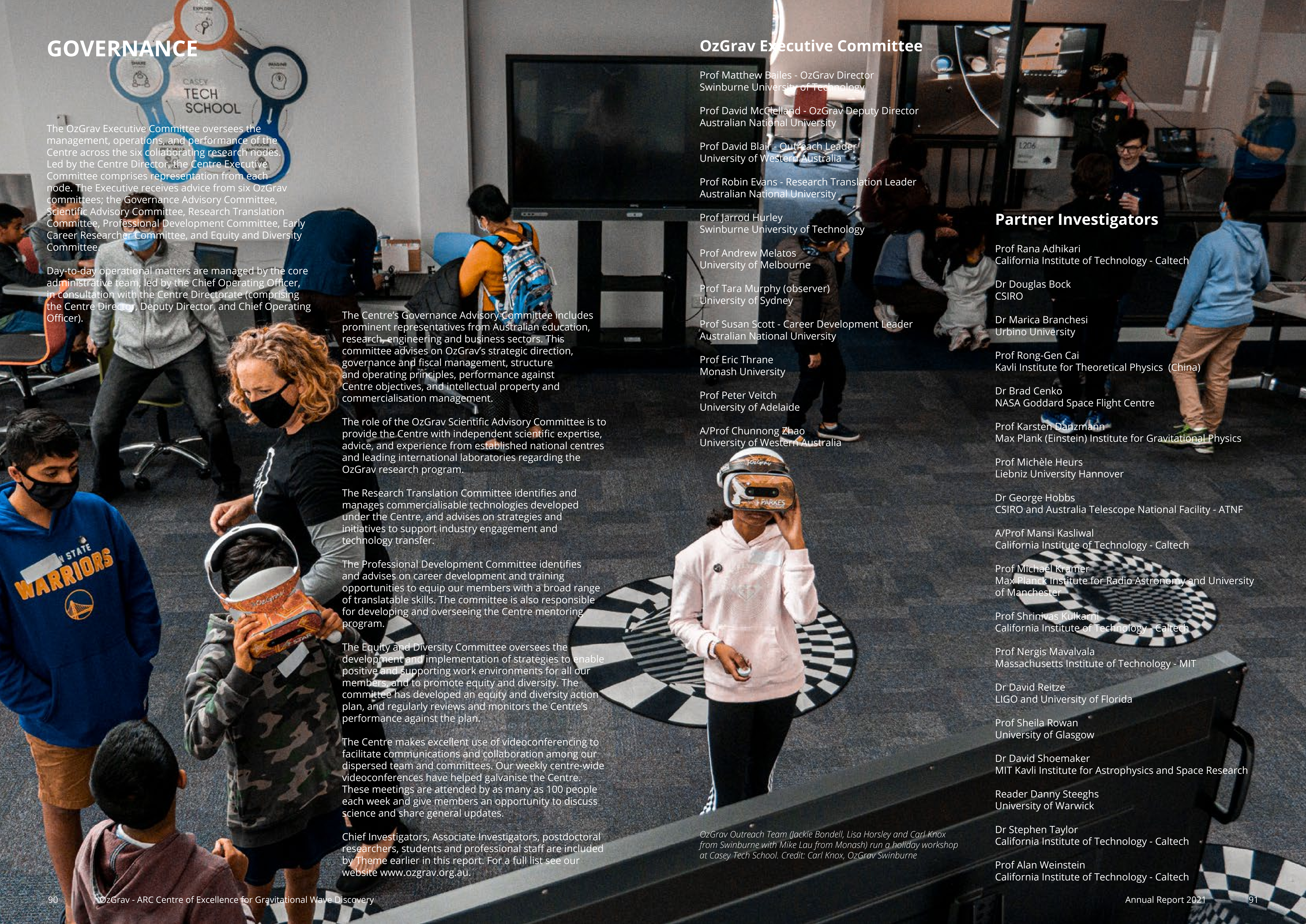
Prof Tara Murphy (observer)
University of Sydney

Prof Susan Scott - Career Development Leader
Australian National University

Prof Eric Thrane
Monash University

Prof Peter Veitch
University of Adelaide

A/Prof Chunnong Zhao
University of Western Australia



OzGrav Outreach Team (Jackie Bondell, Lisa Horsley and Carl Knox from Swinburne with Mike Lau from Monash) run a holiday workshop at Casey Tech School. Credit: Carl Knox, OzGrav Swinburne

Partner Investigators

Prof Rana Adhikari
California Institute of Technology - Caltech

Dr Douglas Bock
CSIRO

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Urbino University

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

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NASA Goddard Space Flight Centre

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

Prof Michèle Heurs
Liebniz University Hannover

Dr George Hobbs
CSIRO and Australia Telescope National Facility - ATNF

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California Institute of Technology - Caltech

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Max Planck Institute for Radio Astronomy and University of Manchester

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California Institute of Technology - Caltech

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Massachusetts Institute of Technology - MIT

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Prof Sheila Rowan
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Reader Danny Steeghs
University of Warwick

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Prof Alan Weinstein
California Institute of Technology - Caltech

GOVERNANCE

Governance Advisory Committee

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Kernot Professor of Engineering at the University of Melbourne, Chief Executive with Conviro Pty Ltd and President, Cloud Campus Pty Ltd.

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OzGrav Director, Swinburne University of Technology

Dr Gregory Clark
Visiting Fellow, Australian National University

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

Dr Yeshe Fenner
OzGrav Chief Operating Officer, Swinburne University of Technology

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Dr Tanya Hill
Senior Curator, Melbourne Planetarium, Museum Victoria

Prof Virginia Kilborn
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Dr John O'Sullivan
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Dr Sarah Pearce
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LIGO, American Physical Society (APS) and Optical Society (OSA)

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Dr Andrew Sutton
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CEO, Eliiza Data Science

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Lucy Strang
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Prof David Ottaway
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Dr Karl Wette
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Australian National University

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Chayan Chatterjee
University of Western Australia

Dougal Dobie
Swinburne University of Technology

Pratyasha Gitika
Swinburne University of Technology

Zac Holmes
University of Adelaide

Disha Kapasi
Australian National University

Christine Yi Shuen Lee
University of Melbourne

Masters student Tom Roocke assisting with the clean and bake of the SAMS assembly at the University of Adelaide. Credit: Huy Tuong Cao, OzGrav Adelaide

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Masters student Zac Holmes runs a workshop with AMIGO for high school students at the University of Adelaide. Credit: Sophie Muusse, OzGrav Adelaide

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