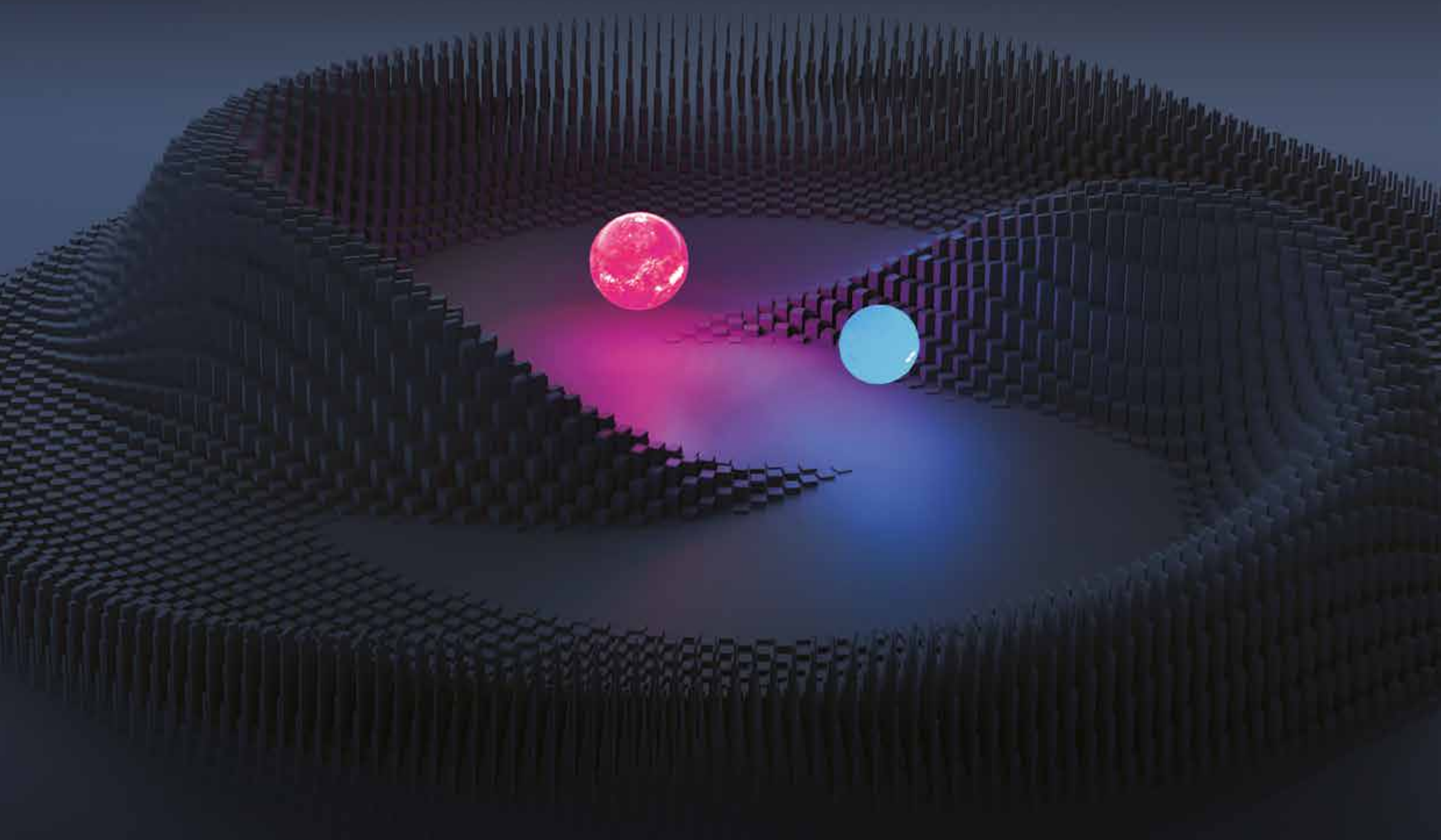


OzGrav

ARC Centre of Excellence for Gravitational Wave Discovery

Annual Report 2018

CONTENTS

OzGrav's vision

To pursue exceptional research and scientific discovery.

To provide world-class research training and leadership.

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

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

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

MESSAGE FROM THE DIRECTOR

It never ceases to amaze me what a good investment in research the Australian Research Council's Centres of Excellence are despite the large fraction of its budget they represent. 2018 was the first full year of OzGrav, and by the end of it the full value of the Centre was clearly apparent. Centres drive collaboration instead of competition, Chief Investigators can concentrate more on performing science rather than grant preparation, and it is a joy for me as Director to host both the weekly video-conferences where we present our science and the annual retreat of our members that facilitate planning. Perhaps the most rewarding validation of our efforts come from our international colleagues, few of which benefit from equivalent programmes in their own countries but many of whom remark about OzGrav's growing international presence and contributions to our field - and whether they can get an OzGrav hoodie!

Gravitational wave astrophysics has been one of the most high-impact areas of astronomy since the discovery of GW150914 was published. Of the top twenty most-cited astronomy papers since GW150914, ten concern gravitational waves. The timing of OzGrav couldn't have been better to capitalise on the "golden years" of gravitational wave astrophysics.

LIGO was being upgraded in preparation for its third major observing run (O3) during 2018, which gave OzGrav astrophysicists a much-needed break to work on the results of earlier runs and modernise data pipelines for the future. Meanwhile, our instrumentalists were busy preparing the LIGO detectors for what promises to be the most exciting run yet. Our colleagues at ANU have been working on some quantum physics "black magic" in the form of quantum squeezing which promises to extend LIGO's sensitivity to well beyond 100 Mpc (about 300 million light years) for neutron star mergers. At UWA Linqing Wen's team is preparing a pipeline for rapid detection of mergers in O3, and our optical astronomers are getting ready to follow-up future neutron star mergers. The hard work of 2018 should ensure that 2019 is our most productive year yet.

OzGrav has been heavily involved in planning for what detectors look like in the future, and are engaged in the third generation design process and science planning, and whether Australia could design and potentially host a high frequency gravitational wave detector in the mid-term future (see section "Planning for Future Detectors").

Our membership has grown steadily, with now over 190 people affiliated with the Centre. Many of our members were recognised for their accomplishments in 2018, including Deputy Director Professor David McClelland - who won the Walter Boas Medal and Quantum Communication, Measurement and Computation Award, and one of the founders of this field, Emeritus Professor David Blair who became a member of the Academy, joining Professor Susan Scott with that honour. It was great to see many of our early and mid-career scientists also winning awards, such as Dr Paul Lasky from Monash who won the Pawsey Medal and even our students like Sara Webb picking up the Violet Louise Bonner Postgraduate Scholarship. I hope you enjoy reading about these and many other highlights in this annual report.

OzGrav Director
Prof Matthew Bailes
Swinburne University of Technology

MESSAGES FROM THE CHAIRS

GOVERNANCE ADVISORY COMMITTEE (GAC)

I would like to congratulate OzGrav on a very productive first full year of operations, which saw highlights across all the Centre programs and activities.

The government's investment in gravitational wave discovery through OzGrav has enabled dramatic growth in Australian capacity in this field. There are now 190+ members of the centre, and OzGrav is committed to supporting their career development. 2018 saw the launch of OzGrav's mentoring program as well as the establishment of an early career researcher committee that helped deliver a successful 2-day workshop to equip ECRs with communication skills and professional confidence.

OzGrav aims to translate its research to industry and other sectors. It was therefore pleasing to see the progress made in 2018, including a new collaboration to use astrophysics techniques to understand eye diseases, a project to develop an earthquake early warning system, and continued growth of a spin-off company. For a discipline driven largely by the quest for knowledge, the breadth of applications of its technology is impressive.

OzGrav also took important steps in 2018 to improve equity and diversity through the implementation of new initiatives, including primary carer grants, an ombuds program, and diversity and inclusion training.

As showcased in this report, OzGrav was busy in 2018 promoting its science to the public. A major milestone was the launch of the OzGrav schools' incursion program. Using Virtual Reality to teach high school kids about OzGrav, the program received glowing testimonials from teachers and students, and hopefully will inspire some of them to pursue STEM disciplines.

OzGrav is pleased to have met or exceeded its targets for almost all Key Performance Indicators in 2018, with its impact being demonstrated by the high collective citation rate of its publications (over 7000) and numerous media articles (over 150) about OzGrav science.

I hope you enjoy reading about OzGrav's achievements in 2018 and plans for the future.

Sincerely,
Prof Ian Young AO

SCIENCE ADVISORY COMMITTEE (SAC)

As the Chair of OzGrav Scientific Advisory Committee (SAC), I was delighted with the scientific progress and international impact OzGrav researchers made during 2018.

During a year when the LIGO detectors were not operating due to upgrades, OzGrav's scientific output was outstanding. Some of the science highlights described herein generated significant media coverage, and put a spotlight on the unique contributions Australia is making to the growing field of gravitational wave astronomy.

An achievement of particular note was the selection of OzGrav-designed software as an official key component of the LIGO data pipeline. This means that future LIGO discoveries will be underpinned by this piece of Australian innovation. Also significant was the release of the full catalog of gravitational wave detections so far, including the most massive black hole merger ever witnessed.

Australia is a key technology partner within LIGO, and in 2018 OzGrav members were busy developing and installing a "quantum squeezer" to increase LIGO's range, and deploying Hartmann cameras to identify optical mode problems and reduce commissioning times. The range for one LIGO detectors has now jumped from 90 megaparsecs to 120 megaparsecs, which should see detections flow twice as fast as in previous observing runs. This sets the stage for a big year of new discoveries in 2019!

This report is rich with additional science highlights, including many that have early career researchers playing key roles. I hope you enjoy the read, and I look forward to the further progress and discoveries that OzGrav will make in 2019.

Sincerely,
Professor Sir James Hough

CENTRE SNAPSHOT

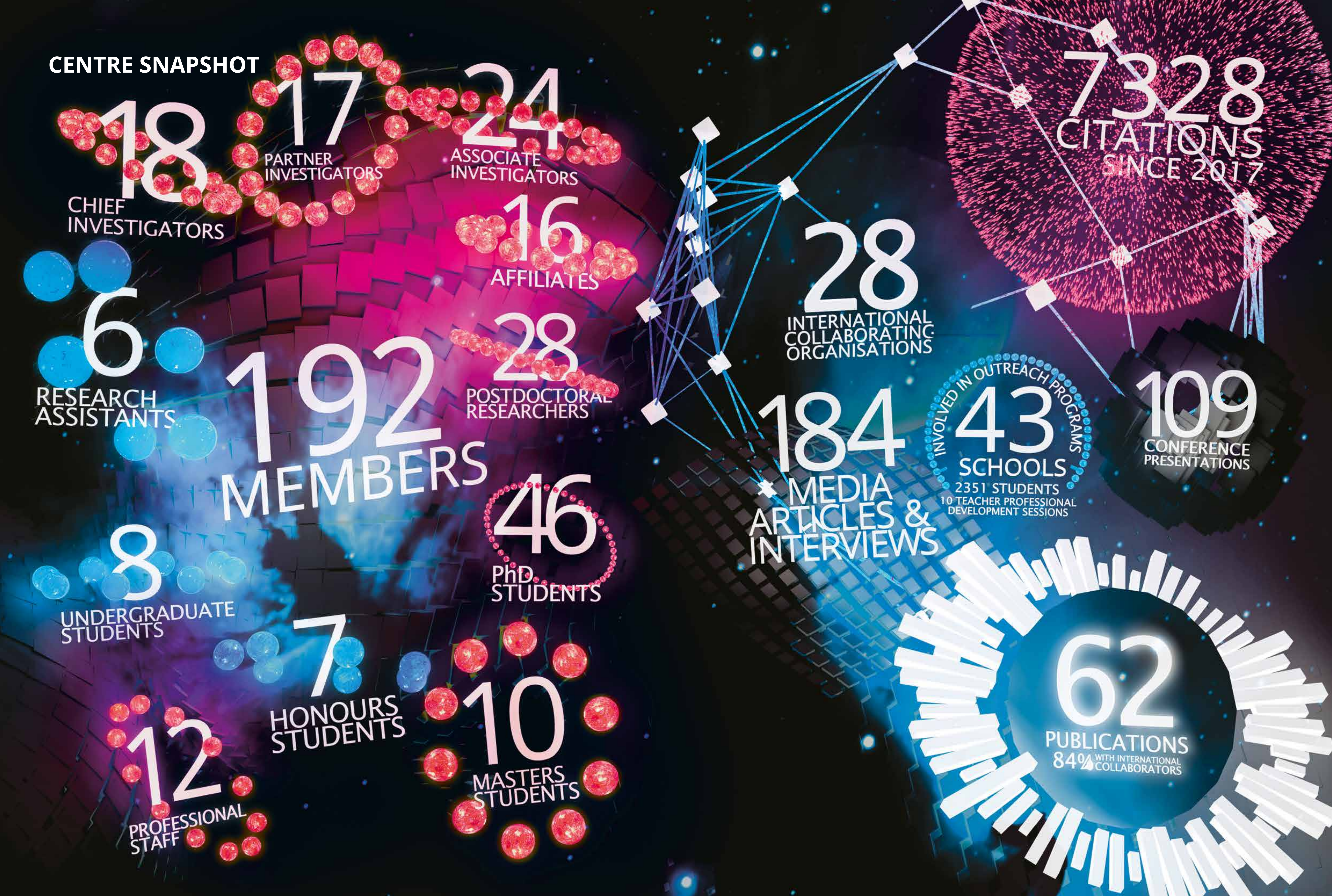


Image: Carl Knox, OzGrav Swinburne

SCIENCE HIGHLIGHTS

APRIL 2018

Stochastic background

More than 100,000 gravitational wave events every year are too faint for LIGO and Virgo to detect individually. However, the gravitational waves from these mergers combine to create a faint background signal that could be detected with a new technique developed by OzGrav.

MAY 2018

GRACE Follow-On launch success

Satellites were successfully launched on board a SpaceX Falcon 9 rocket, carrying laser technology adapted from space-based gravitational wave detectors. The satellite's link acquisition system was initially designed and tested at ANU.

JULY 2018

Einstein's theory passes another test

The universality of free-fall is demonstrated by the orbital motion of a pulsar in a stellar triple system. This particular system consists of one ultra-dense neutron star and two less-dense white dwarf stars, which makes these stars the dream team for testing relativity.

DECEMBER 2018

Full catalog of gravitational wave detections is released

LIGO and Virgo release results from the first two observing runs O1 and O2. The number of gravitational wave events observed hits 11, including the largest black hole collision ever witnessed.

The background hum of space could reveal hidden black holes

Deep space is not as silent as we have been led to believe. Every few minutes a pair of black holes smash into each other. These cataclysms release ripples in the fabric of space-time known as gravitational waves. Now OzGrav scientists Associate Professor Eric Thrane and Dr Rory Smith (Monash University) have developed a way to listen in on these events. The gravitational waves from black hole mergers imprint a distinctive whooping sound in the data collected by gravitational-wave detectors. The new technique is expected to reveal the presence of thousands of previously hidden black holes by teasing out their faint whoops from a sea of static.

By the end of 2018, there had been eleven confirmed gravitational wave events announced by the LIGO and Virgo Collaboration. However there are, according to A/Prof Thrane, more than 100,000 gravitational wave events every year too faint for LIGO and Virgo to unambiguously detect. The gravitational waves from these mergers combine to create a gravitational-wave stochastic (random) background. While the individual events that contribute to it cannot be resolved individually, researchers have sought for years to detect this quiet gravitational-wave hum.

In a landmark paper in the US journal, Physical Review X, the two researchers have developed a new, more sensitive way of searching for the gravitational-wave background. "While the conventional method is likely to require years of design-sensitivity data, we showed that our method is capable of detecting a population of sub-threshold black holes with about one day of data," A/Prof Thrane said.

"Measuring the gravitational-wave background will allow us to study populations of black holes at vast distances. Someday, the technique may enable us to see gravitational waves from the Big Bang, hidden behind gravitational waves from black holes and neutron stars," A/Prof Thrane said.

Dr Smith is optimistic that the method will yield a detection when applied to real data. According to Dr Smith, recent improvements in data analysis will enable the detection "of what people had spent decades looking for." The new method is estimated to be one thousand times more sensitive, which should bring the long-sought goal within reach.

Researchers have access to a new $4 million supercomputer called OzSTAR, launched in March 2018 at Swinburne University of Technology. According to OzGrav Director, Professor Matthew Bailes, "It is 125,000 times more powerful than the first supercomputer I built at the institution in 1998."

The OzSTAR computer differs from most of the more than 13,000 computers used by the LIGO community, according to Dr Smith, including those at Caltech and MIT. OzSTAR employs graphical processor units (GPUs), rather than more traditional central processing units (CPUs). For some applications, GPUs are hundreds of times faster. "By harnessing the power of GPUs, OzSTAR has the potential to make big discoveries in gravitational-wave astronomy," Dr Smith said.

The "Optimal Search for an Astrophysical Gravitational-Wave Background" (Smith & Thrane, 2018) received widespread attention in Australian and international media, including prime-time television, 7:30 Report, ABC, and traditional and online news media such as The Age.

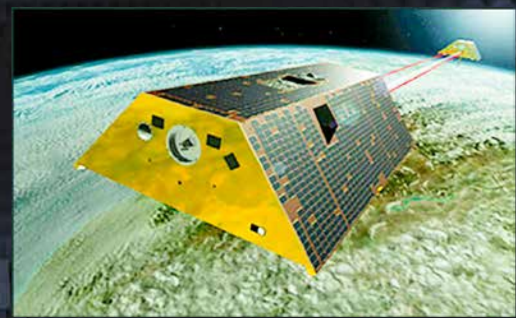
GRACE Follow-on success

In May 2018 the twin GRACE Follow-On (FO) satellites were successfully launched on board a SpaceX Falcon 9 rocket. The satellites were carrying laser technology adapted from space-based gravitational wave detectors.

The core technology at the heart of NASA's Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) mission is based on techniques developed over many years for the LISA (Laser Interferometer Space Antenna) gravitational wave mission. GRACE-FO, like LISA, uses heterodyne interferometry, frequency stabilised lasers and a high dynamic range phasemeter to extract the displacement information. GRACE-FO may one day pay back the favour by testing other techniques that LISA will rely on, such as Time-Delay Interferometry and Arm Locking, that are challenging to fully test in the lab.

The launch was particularly exciting and nerve-wracking for OzGrav's Daniel Shaddock (Australian National University) as 15 years of his work was onboard the rocket. "It was a little bit surreal," Professor Shaddock said. "So many years of your life working on something — it was hard to believe it was actually happening and finally launching. And the most exciting part is still yet to come."

Professor Shaddock developed a retroreflector that uses lasers to measure the world's water reserves from space with unprecedented accuracy. "It measures something that's really important; the presence of water — whether that's frozen form or liquid form — across the entire globe at once. And that's something you can only do from space." "Any large body of water will generate gravity and that gravity can be picked up by GRACE," Shaddock explains.



Images: NASA

For the device to work, two laser beams from two separate satellites — each travelling at thousands of kilometres per hour — need to link with each other from a distance of over two hundred kilometres. The link acquisition system was initially designed and tested at ANU. In the case of the Laser Ranging Interferometer, we can pick up changes in the separation of the spacecraft by ten nanometres. That's ten billionths of a metre — about the diameter of a virus.

GRACE has the extraordinary ability to peer beneath the Earth's surface to weigh groundwater reserves where a third of all freshwater lies. In Australia, GRACE has shown groundwater levels in the Murray-Darling Basin still have not recovered from the Millennium Drought, which ended in 2011. The mission also revealed that freshwater is disappearing from Greenland and West Antarctica faster than any other place on Earth as ice caps melt. GRACE is giving us solid numbers about how much ice is disappearing, how much is ending up in the oceans and also how it is changing our water cycle and our water resources.

Universality of free-fall shown by orbital motion of a pulsar in a stellar triple system

Einstein's theory of gravity, general relativity, predicts that all objects fall in the same way, regardless of their mass or composition. But does this principle also hold for objects with extreme gravity? An international team of astronomers have tested this using three stars orbiting each other: a neutron star and two white dwarfs. Their findings, published in Nature in July 2018, prove that Einstein's theory still passes the test in such extreme conditions.

A hammer and a feather fall with the same acceleration on the Moon. And a light cannon ball hits the ground at the same time as a heavy cannon ball when dropped off the leaning tower of Pisa. Even the Earth and the Moon fall in the same way towards the Sun. Einstein's theory of gravity has passed all tests in laboratories and elsewhere in our Solar System. But most alternative theories predict that objects with extreme gravity, like neutron stars, fall a little differently than weak gravity objects.

Luckily, astronomers have found a natural laboratory to test this theory in extreme conditions: the triple star system called PSR J0337+1715, located 4200 light years from the Earth. "This particular system consists of one ultra-dense neutron star and two less-dense white dwarf stars, which makes these stars the dream team for testing relativity," OzGrav Associate Investigator Dr Adam Deller (Swinburne) says. In this unique system, discovered in 2012, a neutron star is in a 1.6-day orbit with a white dwarf, and this pair is in a 327-day orbit with another white dwarf further away. "The neutron star (radio pulsar) star acts like a clock on the sky. It spins in a very predictable way and each time it sweeps past the Earth we see a little blip of radio emission, which we can treat like the ticks of a clock," Dr Deller says.

If alternative theories of gravity are correct, then the neutron star and the inner white dwarf will fall differently towards the outer white dwarf.

The team of astronomers followed the neutron star for six years using the Westerbork Synthesis Radio Telescope in the Netherlands, the Green Bank Telescope in West Virginia and the Arecibo Observatory in Puerto Rico. "We can account for every single pulse of the neutron star since we began our observations," explains first author Anne Archibald (University of Amsterdam and the Netherlands Institute for Radio Astronomy). "And we can tell its location to within a few hundred meters. That is a really precise track of where the neutron star has been, and where it is going." If the neutron star fell differently from the white dwarf, the pulses would arrive at a different time than expected.

This much more stringent test of gravity was made possible by this unusual triple star system that acts as a natural laboratory. The upcoming biggest radio telescope in the world, the Square Kilometre Array, is expected to find most of the detectable pulsars in our galaxy, including ten times as many millisecond pulsars as are now known. Among these yet undiscovered systems may lurk even more powerful tools for understanding the Universe and testing Einstein's theories.

Scientists reveal largest black hole cataclysmic event yet witnessed

In December 2018 an international group of scientists from the LIGO/Virgo collaboration, including dozens of Australians from OzGrav, announced the detection of the most massive binary black hole merger yet witnessed in the universe. The black hole that resulted from this cataclysmic event GW170729 is more than 80 times as massive as our Sun, and over 10 billion light years away.

The announcement was part of a treasure trove of discoveries revealed in a series of papers about the full catalog of observations of binary black hole and binary neutron star mergers from the first two observing runs of the Advanced LIGO (US) and Advanced Virgo (Italy) gravitational-wave detectors.

According to Dr Meg Millhouse (University of Melbourne) the papers outline a catalogue of all gravitational wave signals "heard" by the Advanced LIGO detectors in the last three years. "These signals are generated by some of the most violent events in the universe, when pairs of neutron stars and black holes – each with many times more mass than our sun – come crashing together," she said.

Dr Simon Stevenson (Swinburne University of Technology) said that the additional information of the other nine binary black holes, "means we are learning things about the population, such as how frequently binary black holes merge in the universe (once every few hundred seconds somewhere in the universe) and whether low mass or high mass black holes are more common. There are many more light black holes (around 5-10 times the mass of the sun) in the universe than heavy black holes (around 30-40 times the mass of the sun), but the heavy ones are 'louder' in gravitational-waves, and easier to 'hear' colliding," he said.

"With each new detection we learn something more about how these extraordinary objects came to be. The detections also help to answer questions about the theory of gravity, the formation of galaxies, and how heavy elements (including gold and platinum) are produced", said co-author Dr Xu (Sundae) Chen (UWA).

Another author, PhD student Colm Talbot (Monash University), in a separate paper described how the detection of these new black holes will assist in understanding the Universe's entire population of black holes. "Each of these black holes formed from huge stars which died in violent explosions called supernovae. By studying these black holes, we act as black hole archaeologists to learn how these cosmic giants die," he said.

One of the key results from these papers is that we find that there seems to be a lack of black holes in these merging binaries more massive than around 45 times the mass of the Sun. One possible explanation for this maximum black hole mass is that stars that would form a more massive black hole undergo a special kind of supernova explosion called a pulsational pair instability supernova. The star would pulse, maybe many times, throwing off its outer layers, before collapsing to form a black hole. This analysis used a method developed by Colm Talbot along with his PhD supervisor OzGrav's A/Prof Eric Thrane and published in the Astrophysical Journal in 2018. Key results included constraints on the black hole mass spectrum and the distribution of black hole spins.

In 2017 Dr Paul Altin (ANU) was part of LIGO's "rapid response team", whose job it is to be ready to receive a detection alert at any time, day or night, in order to quickly analyse the data and decide whether the event is significant enough for an alert to be sent to our partner astronomers for follow-up observations. In 2019 Advanced LIGO comes back online with even higher sensitivity, in part due to the use of quantum squeezing. "Squeezing allows us to get around noise that comes from quantum mechanics, the fundamental theory that governs microscopic particles," he said. The Advanced LIGO squeezer was designed at ANU.

Several OzGrav members spent time in 2018 in the US, installing upgrades to the LIGO detector, including PhD student Nutsinee Kijbunchoo and Dr Terry McRae (ANU). According to Dr Dan Brown (University of Adelaide) the next observing run in 2019 ("O3") aims to use squeezed light to reach the target sensitivity to look for extreme events. "With OzGrav's expertise in squeezed light and adaptive optics for compensating thermal effects from the increased laser power we're making significant contributions towards improving LIGO for the next run," he said.

RESEARCH TRANSLATION HIGHLIGHTS

Earthquake early warning systems

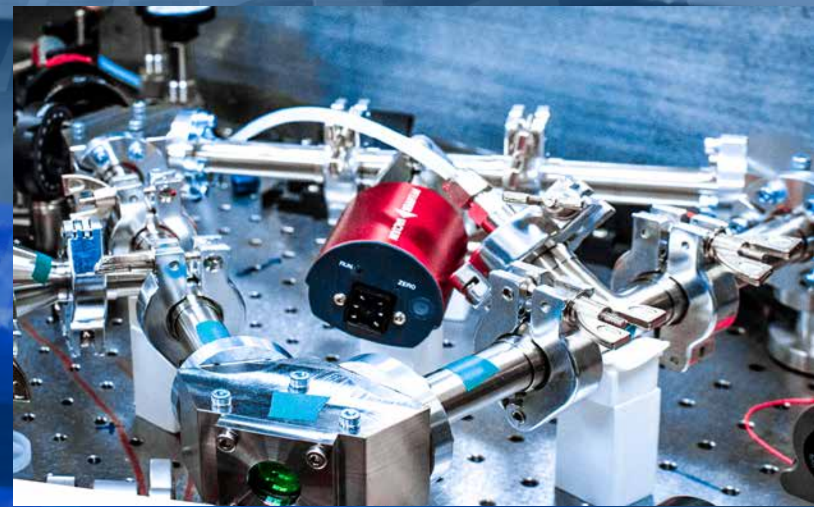
The Earthquake detection project aims to improve the advanced warning time for earthquake early-warning systems using sensor technology developed for gravitational wave detection. The project, led by OzGrav Chief Investigator Dr Bram Slagmolen (ANU), expects to utilise new technology to gain tens of extra seconds of warning, compared to current earthquake early-warning systems. This builds on their development of the TORsion PEndulum Dual Oscillator (TORPEDO). They are investigating the feasibility of implementing this complementary technology into operational earthquake early warning systems. This could provide enormous benefit, as additional seconds of early-warning for damaging seismic waves can save lives.

Image: Bram Slagmolen, OzGrav ANU

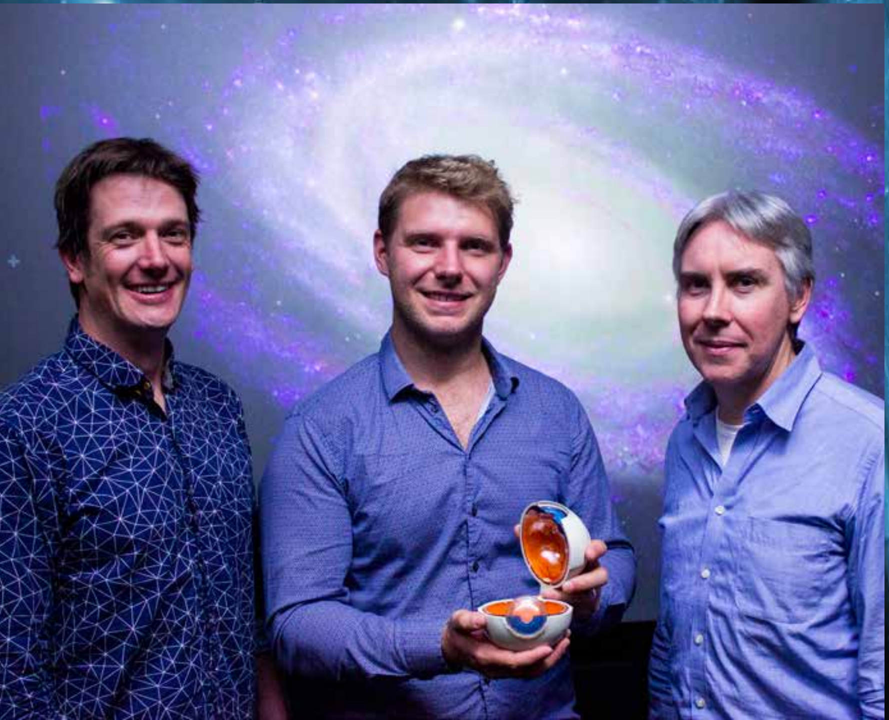
From ophthalmology to mineralogy: industries benefiting from Gravitational Wave sensor technology

Instrumentation techniques directly related to gravitational wave detection, including optical interferometry, signal processing and advanced photodetector designs have been adapted for various projects in collaboration with industry and government. These adaptations find applications in trace gas detection using cavity enhanced spectroscopy; volumetric 3D imaging for ophthalmology and mineralogy using optical coherence tomography; and inertial navigation using a fibre optic gyroscope.

The images below show our current generation ring cavity for carbon isotopic ratio measurements in carbon dioxide for cavity enhanced spectrometry. This project is led by OzGrav's Jong Chow (ANU) in collaboration with Australian Scientific Instruments and the National Measurement Institute. We use similar technologies employed by the Gravitational Wave community to lock an interrogating laser to the cavity, and then extract a quantum noise limited optical absorption readout.



RESEARCH TRANSLATION HIGHLIGHTS



Dr Edward Taylor (Swinburne), Dr Xavier Hadoux (CERA) and Associate Professor Chris Fluke (Swinburne) will apply big data analysis used by astronomers to the field of ophthalmology.

Eyes on the Sky

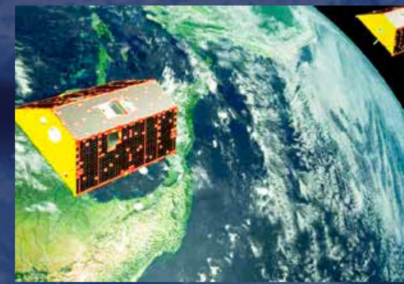
Scientists at the Centre for Eye Research Australia (CERA) have teamed up with OzGrav members and Swinburne University of Technology astrophysicists to better understand the mathematics behind diagnosing eye diseases. The team, led by ophthalmologist Dr Peter van Wijngaarden from CERA and OzGrav's A/Prof Christopher Fluke (Swinburne) will work together to apply the big data analysis used by astronomers in their study of the Universe, to the field of ophthalmology.

CERA researchers want to use these principles to improve their understanding of the data generated with a new type of spectral imaging camera, which provides unique insights into diseases of the eye and brain including Alzheimer's disease.

The collaboration will be formalised thanks to a generous donation from Australian entrepreneur Dr Steven Frisken, CEO of ophthalmic tech company Cylite. He was one of four people jointly awarded the Prime Minister's Prize for Innovation in 2018. Dr Frisken and his colleague Dr Simon Poole received the prize for their work to transform optical telecommunication networks by developing the optical switching technologies that are needed for efficiently connecting the global internet.

Image: Daniel Shaddock, ANU

Spin-off company gets a boost with venture capital funding



OzGrav Chief Investigator Daniel Shaddock (ANU), CEO of Liquid Instruments (Canberra, Australia), started his career as a postdoctoral researcher at NASA's Jet Propulsion Laboratory (JPL) in 2002, working on the Laser Interferometer Space Antenna (LISA), a joint project between NASA and the European Space Agency.

After a cut in funding for LISA, a number of the project's engineers were assigned to the Gravity Recovery and Climate Experiment (GRACE) Follow-On mission, adapting the LISA phasemeter's field-programmable gate array (FPGA) processor. Shaddock's team had gained extensive expertise in signal processing and chip programming, and Shaddock started to look at other applications for this knowledge and technology. The turning point came when one team member figured out how to remotely make an FPGA reconfigure itself for different purposes. FPGAs are computer chips that are not preprogrammed, but designed to be configured by the customer.

With funding from venture capital firms, the team founded Liquid Instruments and set about building a commercial product. This product, Moku:Lab, can switch among eight common electronics test and measurement instruments, including a phasemeter, data logger, and a lock-in amplifier. Because Moku:Lab's hardware is reconfigurable, as the company develops configurations for more instruments, users can simply download them for free. An iPad-based user interface and Wi-Fi capability are also advantages.

The company has identified four target markets including: engineers and physicists in research and development divisions; education, where Shaddock hopes to help attract the interest of more students and enrich science, technology, engineering, and math (STEM) curricula around the world; and industrial markets where electronics manufacturers use various devices to test and measure products coming off the line, with a Moku:Lab at each workstation rather than workers switching between instruments, recording test results at the commands of a central computer.

Images via NASA and Liquid Instruments

Image: James Josephides, CAS Swinburne

EDUCATION AND OUTREACH

OzGrav's Education and Public Outreach programs will inspire and educate the general population about the nature of our Universe and explain how the scientific method works and can be trusted.

Science in Virtual Reality (SciVR)

Download the free SciVR app at www.scivr.com.au

To celebrate National Science Week, OzGrav and Swinburne University of Technology teamed up to bring the latest virtual reality (VR) universe to audiences around Victoria and at Swinburne's campus in Sarawak, Malaysia. The cutting-edge science presented in an immersive environment opened the doors to the universe for new science enthusiasts and seasoned learners as part of this inspiring National Science Week Program.

Immersive Science II: The Invisible Universe (SciVR) was supported by a National Science Week Grant in partnership with the State Library of Victoria. The goal of SciVR was to create a rich VR experience through a free smartphone app developed by the OzGrav outreach multi-media developers Carl Knox and Mark Myers. OzGrav presented two live events with Dr Rebecca Allen and Associate Professor Alan Duffy (OzGrav-Swinburne) leading the audience through virtual tours of the universe, using cardboard VR headsets provided through the National Science Week Grant. Each event was live-streamed to viewing parties hosted at 10 regional libraries as well as to worldwide audiences via YouTube and Twitter. Audience members asked questions of the presenters both live and through the Twitter hashtag #AskSciVR. The OzGrav outreach team also developed educational materials to complement the content in the SciVR app.

EDUCATION AND OUTREACH

Three-Minute Thesis (3MT)

Imagine condensing hours, days and even years of complex research into a short presentation while being judged by an expert panel and lecture theatre full of your peers and strangers. An 80,000 word thesis would take 9 hours to read - they have 3 minutes. It's a great way to train up to deliver the main idea of your PhD thesis research in three minutes, and a great way for the general public to engage with current research. Congratulations to many participants from OzGrav, with particular mentions to Michael Page (UWA) in the UWA 3MT Finals with his talk Schroedinger's cat-flap and the interstellar laboratory, and David McManus (ANU) who made it to the ANU Canberra 3MT Finals with the Music of Gravity – check out their videos on YouTube!

Inset images: Aditya Parthasarathy, OzGrav Swinburne

Astrolight Festival

In 2018 OzGrav once again featured prominently at the AstroLight Festival at Scienceworks. OzGrav was invited to host on the main stage a panel discussion and Q&A on Gravitational Waves. OzGrav researchers Debatri Chattopadhyay (Swinburne), Lucy Strang (University of Melbourne), and Hannah Middleton (University of Melbourne) enlightened audiences as they talked about not only gravitational waves and other exciting developments in astronomy, but also about their personal stories and inspirations. Our outreach team of volunteers hosted five activities in the OzGrav VR zone, sharing the universe in interactive virtual and mixed reality with hundreds of visitors of all ages.

Pub Science events

OzGrav researchers took their stories to local pubs in a series of events focused on bringing science to the public audience in a relaxed and informal setting. OzGrav PhD students Debatri Chattopadhyay and Igor Andreoni (Swinburne) shared snappy eight minute talks as part of Melbourne's Physics in the Pub, and Robert Ward (ANU) shared about Black holes and firewalls at the Canberra Physics in the Pub event, both in May. OzGrav Director Matthew Bailes (Swinburne) shared a longer talk "Watch the fireworks when stars collide" as a speaker for Pint of Science.

AMIGO

Adelaide's Mini Interferometer for Gravitational-wave Outreach (AMIGO) is a tool used to demonstrate the principles of laser interferometry and gravitational wave detection. By visually demonstrating the interference of light and the sensitivity of Michelson interferometers, AMIGO allows us to connect with the general public in new and exciting ways.

OzGrav's Craig Ingram (UoA) has also begun a collaboration with GoogleX to develop portable interferometers to be used in schools and public outreach events.

AMIGO was developed by a team of OzGrav members, with support from OzGrav, the University of Adelaide (UoA) School of Physical Sciences, UoA Faculty of Sciences workshop and the Australia National Fabrication Facility Optofab node.

AMIGO showcased in 2018 at:

- University of Adelaide Open Day for people of all ages. We used a computer simulation of a gravitational wave passing through the LIGO detector to aid us in our discussions with the public. We also used this opportunity to highlight opportunities available within the LIGO collaboration and offered career advice to future students.
- GW170817 celebration event showing potential projects for undergraduate students.
- Photonics Open Day for high school and undergraduate students hosted by the Institute of Photonics and Advanced Seeing (IPAS).
- A demonstration for Year 12 students at University Senior College (USC). This was taken up by the teachers at USC and developed into a major assessment task. The students were encouraged to explore the detection of gravitational waves and its impact of the on global science.

EDUCATION AND OUTREACH

Beyond Perception – exhibition at Scienceworks Museum

“Beyond Perception: Seeing the Unseen” is a ground-breaking and unconventional permanent exhibition designed for teenagers. Exploring the imperceptible worlds of science and technology, this brand new exhibition will look deeper, and see further than ever before. Reflecting the latest and greatest stories from science and technology, this permanent exhibition will immerse teens in large-scale experiences that reveal the invisible fields and forces that surround us, such as gravitational waves, invisible light, sound and aerodynamics, and demonstrates current research which is continuing to uncover amazing hidden worlds around us.

Developed in consultation with OzGrav scientists, including Monash University’s Eric Thrane, Kendall Ackley and Paul Lasky, acoustic engineers and teenagers, Beyond Perception is an intriguing space with a fresh and awe-inspiring new design approach. The OzGrav outreach team was also involved in the design of the black hole formation exhibit, where visitors can stretch fabric with their hands to simulate the warping of space-time and create black holes.

Image: Beyond Perception, Scienceworks

Deeper Darker Brighter

OzGrav supported the exhibition opening of DEEPER DARKER BRIGHTER art exhibition at the Town Hall Gallery in Hawthorn and later for an after-dark evening for the public. Seeking to communicate science via aesthetic means, the exhibition was enhanced by the presence of OzGrav’s Virtual Reality demos which, reinforced the public’s understanding of science via multi-sensory engagement. The exhibition was inspired by OzGrav Chief Investigator Associate Professor Jeff Cooke’s multi-telescope transient observation program Deeper Wider Faster.

Particle/Wave planetarium show

An immersive multimedia experience premiered in the planetarium dome as part of Melbourne International Arts Festival 2018 at Scienceworks.

Particle/Wave is an exploration of art and science showcased under the spectacular dome of the planetarium. Poets, musicians, sound and video artists – alongside OzGrav scientists and outreach team members – collaborated to present a creative glimpse of the incredible story of gravitational waves.

Particle/Wave tells the story of the discovery of Gravitational Waves, ripples in spacetime caused by exploding stars, collisions between neutron stars, and merging black holes. These waves are washing over Earth all the time, but our instruments have not been sensitive enough to detect them until recently.

Director and producer Alicia Sometimes’ aim was to bring this astonishing science to art communities who had never heard about these topics. It has been a great success, and has had concrete impact on audience members, including Zoe, a Year 12 student who was intending to pursue arts at university. According to her mother, Zoe came out of Particle/Wave “walking on air, and she has since changed her university course to include Astrobiology, Introduction to Astronomy, and Introduction to Physics. The show literally changed Zoe’s life”.

Alicia created the show with writers, sound artists, video artists including OzGrav’s Mark Myers and Carl Knox, and OzGrav scientists Kendall Ackley, Alan Duffy and Ling (Lilli) Sun. With support from OzGrav, Museums Victoria, Creative Victoria, Australia Council and Hobsons Bay City Council. The show had a sell-out season at the Melbourne International Arts Festival and will tour Australia and around the world in 2019.

Mission Gravity

In 2018, OzGrav designed, developed and piloted a new school incursion program called Mission Gravity (MG). Driven by overlapping areas between the school curriculum and OzGrav science, and incorporating solid teaching methodologies, Mission Gravity uses cutting edge virtual reality technology to guide students through a virtual mission to the stars. The mission focuses on stellar evolution and the formation of compact objects such as black holes and neutron stars. Working in teams the students decide what parameters are important to measure then, wearing the virtual reality headsets, they travel to a star in a virtual space lab taking measurements as the star evolves in front of their eyes. The virtual reality headsets are wirelessly linked to the Mission Gravity Command Centre and the view of each student, along with their scientific data readout, is projected onto a large screen. The pilot incursions were very successful and well received by both the students and teachers resulting in many requests for return visits.

“Thanks for your wonderful program. All students are talking about it and juniors were asked when can they have the incursion and the teachers are asking for the information and materials. You inspired kids and teachers!! Please let me know when we can book the incursion for next year.”

– Angela, Teacher.

EDUCATION AND OUTREACH

Homeward Bound – Antarctica

OzGrav's Professor Susan Scott (ANU) was selected to take part in the international Homeward Bound leadership program for women in science. Homeward Bound is a ground-breaking leadership initiative, set against the backdrop of Antarctica, which aims to heighten the influence and impact of women in making decisions that shape our planet. One cohort of women is selected each year with the goal of producing, after ten years, a highly networked group of 1,000 women scientists from all over the world who are equipped and ready to take their place at major decision-making tables where critical policies regarding the health of the planet are taken.

The one-year program comprised training in personal assessment and development, leadership style and skills, strategic planning, networking, peer coaching and visibility. In addition to regular group video-conference training meetings, each participant worked with a personal coach throughout the year and was also engaged in numerous media activities. In February 2018, the cohort of 70 women assembled in South America, bound for a 3-week expedition to Antarctica.

Four hours each day were spent on shore visiting a wilderness region, a penguin colony or a research base, or otherwise at sea exploring sea ice, icebergs, seals and whales. Participants saw first-hand the effects of global warming – ice shelfs cracking, sea ice and icebergs melting, the habitat of penguins retracting towards the pole, glaciers retreating and rain where only snow had previously been observed.

The Homeward Bound program was transforming for Prof Scott and the other participants and will greatly enhance their ability to lead and play pivotal roles in STEMM disciplines on a global scale.

Prof Scott shared this expertise and leadership skills to OzGrav via a workshop at the OzGrav Annual Retreat where early career researchers could start to consider leadership from 3 aspects: values, priorities and aspirations. Participants were encouraged to start their own personal strategy map, and looked at things that could get in the way of achieving goals.

Background image: Susan Scott, OzGrav ANU

Einstein First project

Education and outreach activities at OzGrav-UWA have focused on obtaining quantitative data on the effectiveness of Education activities, especially in regard to modernising the school science curriculum to introduce Einsteinian concepts at an early age.

The Einstein-First project (see www.Einsteinianphysics.com) has been developing educational content with activity-based learning based on the use of models and analogies. One of the main problems we are focused on is the development of an Einsteinian curriculum that can be introduced throughout all the years of schooling. To do this we needed to understand at what level students are best able to cope with Einsteinian content.

We held workshops with primary and high school teachers where we introduced our programs, with a view to obtaining advice on 1) the ability of teachers to cope with the material and 2) the ability of children to absorb the concepts introduced. We also asked parents to advise us on their attitude to modernisation of school science. Quantitative results on this work were published.

We also undertook interventions with various age groups, covering hundreds of students, from Year 3 to Year 10. The Einsteinian Physics Education Research Collaboration was formed with six international research groups coming together to pool resources and results. Interventions were the first to combine internationally developed resources with resources developed by the Einstein-First Australian team. These were designed to show an integrated program that combined online material on time dilation (Norway) with models of spatial curvature (Germany) and a graphical introduction of Feynman Path Integral understanding of quantum physics.

At the end of 2018 the OzGrav-UWA team installed an outreach room with permanent set ups for activity-based learning and workshops with schools. We put on several workshops for Japanese exchange program school students and another program was trialed for special needs primary school students.

The Einstein First Team includes OzGrav's David Blair and postgraduate students Jyoti Tejinder Kaur, Rahul Choudhary and Alex Foppoli.

AWARDS AND HONOURS

Pawsey Medal

The Australian Academy of Science awards OzGrav Associate Investigator Dr Paul Lasky (Monash University) from the School of Physics and Astronomy as the winner of the annual Pawsey Medal, awarded to an outstanding researcher in physics. Dr Lasky's research encompasses many different aspects of astrophysics, particularly focussing on the most extreme regions of the Universe including black holes and ultra-dense stellar corpses known as neutron stars.

Image: Australian Museum Eureka Prizes

Eureka Prize

OzGrav Associate Investigator A/Prof Alan Duffy (Swinburne) has been recognised for his contribution to science communication with the Celestino Eureka Prize for Promoting Understanding of Science. The award is given to a scientist who has shared their expertise with a broad audience - informing, enthusing and engaging the public. Alan has made mutliple appearances on TV and radio, as well as SciVR live events as part of National Science Week.

Tall Poppy Award

OzGrav Associate Investigator Dr Andy Casey (Monash) is an enthusiastic and passionate advocate for science and astronomy, including being involved in public observing nights, school visits for primary and secondary students, as well as participating in Science Meets Parliament.

Vice-Chancellor's Research Excellence Award, Swinburne University of Technology

Vivek Venkatraman Krishnan, Igor Andreoni, Dr Jeff Cooke, Prof Matthew Bailes, Andrew Jameson, Wael Farah, Dr Simon Stevenson, Dr Jade Powell, Dr Daniel Price, Dr Stefan Oslowski, Dr Chris Flynn, Dr Ryan Shannon and Dr Adam Deller.

Walter Boas Medal 2017

Awarded in 2018 to OzGrav Chief Investigator Professor David McClelland (Australian National University) by the Australian Institute of Physics.

QCMC18

International Organisation for Quantum Communication, Measurement and Computation (QCMC) Award for outstanding achivements in quantum experimentation to Prof David McClelland (ANU).

2018 Inductee to the WA Science Hall of Fame

OzGrav Chief Investigator Emeritus Professor David Blair (University of Western Australia) was elected to the Academy of Sciences in May 2018. David Blair is an experimental physicist, who has pioneered three separate areas of precision measurement science including 'microwave cavity electro-mechanics' (which make ultra-sensitive displacement measurements that harness electromagnetic springs and self-cooling), and the use of 'whispering gallery modes in sapphire' (for the creation of exceptionally low noise clocks and oscillators).

He won the 2018 Royal Society of Western Australia Medal in July, and in August he was inducted into the Western Australia Science Hall of Fame as part of the WA Permier's Science Awards.

Student Awards

Joshua McCann
Best Presentation at EMS HDR Conference

Sara Webb
Violet Louise Bonner Postgraduate Scholarship for Women

Craig Ingram
IPAS Merry Wickes Transdisciplinary Prize

Nikhil Sarin
Runner-up student talk at Astronomical Society of Australia annual conference

OzGrav 2018 Retreat Awards

Rahul Choudhary
Best student poster

Lucy Strang
Honourable mention for student poster

Huy Cao
Best poster "People's Choice" award

Moritz Huebner
Best under pressure in Media training

Vladimir Bossilkov, Joshua McCann, Michael Page, Joris van Heijningan and Jue Zhang
Space Time Quest winning team

PEOPLE OF OZGRAV - DATA AND ASTROPHYSICS


Prof Matthew Bailes
Swinburne University of Technology
Astrophysics Theme Leader
Centre Director and Chief Investigator
Pulsars, Binary Pulsars, Tests of GR, Binary Evolution, Pulsar Instrumentation


A/Prof Eric Thrane
Monash University
Data Theme Leader
Chief Investigator
Bayesian inference compact binaries stochastic background


Dr Kendall Ackley
Monash University
Postdoctoral Researcher
Gravitational Wave Astronomy, Transient Astrophysics

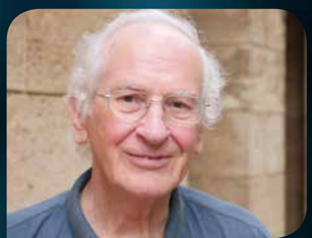

Poojan Agrawal
Swinburne University of Technology
PhD Student
Globular Clusters, Stellar Dynamics, Binaries


Dr Igor Andreoni
Swinburne University of Technology
PhD Student
electromagnetic fast transient discovery


Dr Greg Ashton
Monash University
Associate Investigator
neutron stars, advanced search methods


Sylvia Biscoveanu
Monash University
Associate Investigator
stochastic background GRBs parameter estimation


Dr Joel Bosveld
University of Western Australia
Postdoctoral Researcher
data analysis; optimisation


Dr Ron Burman
University of Western Australia
Affiliate
gamma-ray bursts, supernovae, pulsars


Dr Juan Calderon Bustillo
Monash University
Postdoctoral Researcher
Binary Black Holes, Black Hole Spectroscopy, Parameter Estimation


Debatri Chattopadhyay
Swinburne University of Technology
PhD Student
Compact Binary Coalescence, N-BODY, Population Synthesis


Dr Qi Chu
University of Western Australia
Postdoctoral Researcher
Compact binary coalescence search pipeline


Patrick Clearwater
University of Melbourne
PhD student
gravitational waves, data analysis, virtual laboratories


A/Prof Jeff Cooke
Swinburne University of Technology
Chief Investigator


Dr Neil Cornish
Montana State University
Associate Investigator
Bayesian Inference, General Relativity, Astrophysics


A/Prof David Coward
University of Western Australia
Chief Investigator
gamma ray bursts, optical transients, space debris


Hayden Crisp
University of Western Australia
Masters student
Programming, degenerate stars, GRBs


Prof Jacqueline Davidson
University of Western Australia
Affiliate
Dark Matter; Primordial Black Holes


Dr Benjamin Davis
Swinburne University of Technology
Affiliate
Spiral Galaxy Structure and Evolution; Black Hole Mass Scaling Relations.


Dr Adam Deller
Swinburne University of Technology
Associate Investigator
Radio interferometry, Pulsars, Very Long Baseline Interferometry


Lisa Drummond
University of Melbourne
PhD student
Neutron Stars, Superfluids, Pulsar Glitches


A/Prof Alan Duffy
Swinburne University of Technology
Associate Investigator


Paul Easter
Monash University
Honours Student
Machine Learning, Binary Neutron Stars, Post merger remnant


Prof Rob Evans
University of Melbourne
Chief Investigator
Signal Processing, Control Systems, Electronics, Radar


Wael Farah
Swinburne University of Technology
Affiliate
Machine learning, Data analysis


A/Prof Christopher Fluke
Swinburne University of Technology
Associate Investigator
Visualisation, accelerated computing, GPUs, virtual reality

PEOPLE OF OZGRAV - DATA AND ASTROPHYSICS

Dr Chris Flynn
Swinburne University of Technology
Affiliate
FRBs, pulsars, dark matter, solar twins

Shanika Galaudage
Monash University
Honours student
Neutron stars, Continuous gravitational waves, X-ray binaries

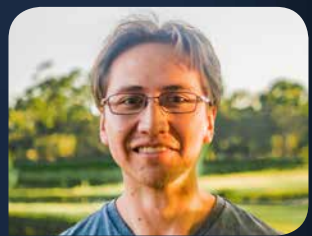
A/Prof Duncan Galloway
Monash University
Chief Investigator
neutron stars, X-ray, merger, transient, astrophysics

Dr Bruce Gendre
University of Western Australia
Postdoctoral researcher
EM observations, GRB, binaries, data analysis, follow-up

Boris Goncharov
Monash University
PhD Student
continuous gravitational waves, neutron stars, gamma-ray bursts

Ben Grace
Australian National University
Honours Student
Mathematics, Physics, Gravitational Waves, Modelling, Theory

Prof Alister Graham
Swinburne University of Technology
Associate Investigator



Francisco Javier Hernandez Vivanco
Monash University
PhD Student
Data analysis, parameter estimation

Dr Eric Howell
University of Western Australia
Associate Investigator

Moritz Huebner
Monash University
PhD student
Parameter Estimation, Bayesian Statistics, Computational Physics

Prof Jarrod Hurley
Swinburne University of Technology
Chief Investigator

Dr David Kaplan
University of Wisconsin-Milwaukee
Affiliate
multi-messenger transients; multi-wavelength wide-field surveys

Manoj Kovalam
University of Western Australia
PhD student
Data Analysis, CBC Search Pipeline, Low Latency Searches, SPIIR

Dr Paul Lasky
Monash University
Associate Investigator
Black holes, Neutron stars, Relativistic astrophysics, Cosmology

Marcus Lower
Monash University
Honours Student
Binary black holes, Parameter estimation, Eccentric inspirals,

Dr Grant Meadors
Monash University
Postdoctoral Researcher
Gravitational waves, data analysis, observation

Prof Andrew Melatos
University of Melbourne
Chief Investigator
LIGO signal processing, relativistic astrophysics

Dr Patrick Meyers
University of Melbourne
Postdoctoral Researcher
Data Analysis, Persistent gravitational waves

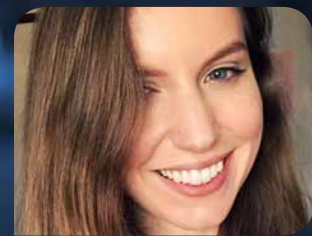
Dr Hannah Middleton
University of Melbourne
Postdoctoral Researcher
gravitational waves, data analysis, outreach

Dr Margaret (Meg) Millhouse
University of Melbourne
Postdoctoral Researcher
Gravitational waves, data analysis, Bayesian inference

Yik Lun (Travis) Mong
Monash University
PhD student
Gravitational waves, Pulsars, Data analysis

Dr Bernhard Mueller
Monash University
Associate Investigator
supernovae, computational fluid dynamics, stellar evolution

A/Prof Tara Murphy
University of Sydney
Associate Investigator
radio astronomy; data analysis; gravitational wave event follow-up



Jacqueline Musiov
Swinburne University of Technology
Undergraduate student
Inquisitive, Analytical, Organised, Transients, Visualisation

Dr Stefan Oslowski
Swinburne University of Technology
Associate Investigator
Pulsars, fast radio bursts, population synthesis

Aditya Parthasarathy
Swinburne University of Technology
Affiliate
Pulsar timing, gravitational wave detection

Dr Jade Powell
Swinburne University of Technology
Postdoctoral Researcher
Gravitational waves, data analysis, astrophysics

Dr Daniel Reardon
Swinburne University of Technology
Postdoctoral researcher
Pulsar timing, interstellar scintillation

Isobel Romero-Shaw
Monash University
PhD student
Numerical modelling, gravitational waves, astrophysics, programming

A/Prof Gavin Rowell
University of Adelaide
Associate Investigator
supernova remnants; pulsar wind nebulae; gamma-ray sources

PEOPLE OF OZGRAV - DATA AND ASTROPHYSICS


Nandini Sahu
Swinburne University of Technology
PhD Student
Galaxy evolution and structure,ISM: supernova remnants, lensing


Nikhil Sarin
Monash University
Honours Student
Neutron Stars, Gamma-ray bursts, post-merger remnants


Prof Susan Scott
Australian National University
Chief Investigator
general relativity, cosmology, gravitational waves


Rahul Sengar
Swinburne University of Technology
PhD student
Relativistic Binary Pulsars, Data Analysis


Dr Ryan Shannon
Swinburne University of Technology
Postdoctoral Researcher
Pulsars Timing Arrays, Radio Transients


Teresa Slaven-Blair
University of Western Australia
PhD student
false-alarm-rate, statistics, multi-messenger, outreach


Dr Simon Stevenson
Swinburne University of Technology
Postdoctoral Researcher
binary stellar evolution gravitational waves


Lucy Strang
University of Melbourne
PhD Student
Multimessenger studies of BNS post-merger remnants


Dr Ling (Lilli) Sun
University of Melbourne
PhD student
Gravitational waves, continuous gravitational waves, data analysis


Colm Talbot
Monash University
PhD Student
data analysis compact binaries


Dr Willem Van Straten
Auckland University of Technology
Associate Investigator
Radio astronomy; high performance computing; machine learning


Sara Webb
Swinburne University of Technology
PhD Student
supernovae, GWs, FRBs, GRBs, Kilonovae


David Weight
University of Western Australia
Undergraduate student
Statistics, Data Analysis, Optimisation, CBC, Programming


Prof Linqing Wen
University of Western Australia
Chief Investigator
signal processing, astrophysics, supercomputing, real-time search


Dr Karl Wette
Australian National University
Postdoctoral Researcher
data analysis pulsars


Dr Christian Wolf
Australian National University
Associate Investigator
optical/IR imaging and spectroscopy, galaxy evolution,


Dr Xingjiang Zhu
Monash University
Postdoctoral Researcher
gravitational waves, pulsars, black holes, neutron stars

Jacob Cameron
University of Western Australia
Undergraduate student
Mathematics, AI, Data Cleaning, Scripting

Dr Andy Casey
Monash University
Associate Investigator
Software infrastructure and data analysis capability for GOTO

Dr Philip Charlton
Charles Sturt University
Associate Investigator
Gravitational waves, stochastic background, chirplets

Liam Dunn
University of Melbourne
Masters Student
data analysis, HPC, gravitational waves, neutron stars

George Howitt
University of Melbourne
PhD student
Neutron stars, pulsar glitches, population synthesis

Sergey Iakovlev
University of Melbourne
PhD Student

Andrea Melchor
Monash University
Undergraduate student
Research Assistant

Dr Matthew Pitkin
University of Glasgow
Affiliate
pulsars, Bayesian inference, data analysis, software

Virinchi Rallabhandi
University of Western Australia
Undergraduate student
Astrophysics, Programming, Theoretical Simulation

Dr Evert Rol
Monash University
Affiliate
gamma-ray bursts

Dr Rory Smith
Monash University
Postdoctoral Researcher
Bayesian inference, high-performance computing, big data

Renee Spiewak
Swinburne University of Technology
Affiliate
Millisecond pulsar timing

Yohanes Sudarmo Dua
University of Western Australia
Masters student

Dr Sofia Suvorova
University of Melbourne
Postdoctoral Researcher

Calley Tinsman
Monash University
Undergraduate student
Research Assistant

Thomas Venville
Swinburne University of Technology
Undergraduate student
Binary neutron stars, kilonovae, pulsars

Zhiqiang You
Monash University
PhD student
data analysis, cosmology

PEOPLE OF OZGRAV - INSTRUMENTATION


Prof David McClelland
Australian National University
Instrumentation Theme Leader
Chief Investigator
squeezing; thermal; interferometry


Dr Vaishali Adya
Australian National University
Postdoctoral researcher
interferometry, control systems, optical layouts, squeezing


Dr Paul Altin
Australian National University
Postdoctoral Researcher
Gravitational wave detection, optomechanics, squeezing


Deeksha Beniwal
University of Adelaide
Masters Student
Mid-IR fibre lasers, Wavefront corrections and actuation


Dr Carl Blair
Caltech - LIGO Livingston
Affiliate
Opto-mechanics, Instrumentation, commissioning


Prof David Blair
University of Western Australia
Chief Investigator
laser interferometers, Einsteinian physics education, vibration isolation


Vladimir Bossilkov
University of Western Australia
PhD Student
high power laser, cavity, instability


Dr Daniel Brown
University of Adelaide
Postdoctoral Researcher
Interferometry, modelling, simulation, commissioning, design


Ben Burridge
University of Western Australia
Masters student
Astronomy, Physics, Mathematics, Statistics, Communication/Outreach


Huy Cao
University of Adelaide
PhD student


Dr Xu Chen
University of Western Australia
Postdoctoral Researcher
optomechanics


Dr Jong Chow
Australian National University
Associate Investigator
Optical interferometry precision instrumentation measurements

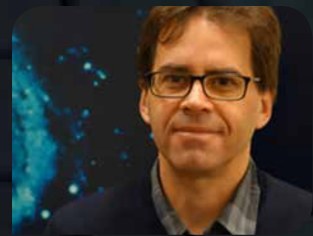

ShinKee Chung
University of Western Australia
Research Assistant
Data Processing, GPUs


Alexei Ciobanu
University of Adelaide
PhD student
modelling, FINESSE, experimental, lasers


Prof Warrick Couch
Australian Astronomical Observatory (AAO)
Affiliate
Extragalactic astronomy and cosmology


Dr Johannes Eichholz
Australian National University
Postdoctoral researcher
Thermal noise, cryogenics, laser stabilization, FPGA, controls


Dr Samuel Francis
Australian National University
PhD Student
Space, interferometry, metrology, instrumentation


Prof Peter Fritschel
MIT Kavli Institute for Astrophysics and Space Research
Associate Investigator
Cosmology, Gravitational Radiation


Daniel Gould
Australian National University
Honours Student
Electronics, Communication


Hui Guo
University of Western Australia
PhD student
Quantum optics; Laser; Programming; Circuits;


Prof Giles Hammond
University of Glasgow
Associate Investigator


Nathan Holland
Australian National University
PhD Student
machine learning, control, torsion pendulum


Craig Ingram
University of Adelaide
Masters student
Instrumentation, Hartmann, optics, teaching, outreach


Vahid Jaberian Hamedan
University of Western Australia
Pre-PhD student
Experimentation


Andrew Jameson
Swinburne University of Technology
Associate Investigator
Software and Systems Engineering, High Performance Computing

PEOPLE OF OZGRAV - INSTRUMENTATION


Rhys Jones
University of Western Australia
Honours Student
low loss optomechanical systems


Prof Li Ju
University of Western Australia
Chief Investigator
Vibration isolation, thermal noise, parametric instabilities


Nutsinee Kijbunchoo
Australian National University
PhD Student
aLIGO, squeezer, instrumentation, optics


Prof Daniel Shaddock
Australian National University
Chief Investigator
laser interferometry, digital signal processing, optical metrology


Paul Sibley
Australian National University
PhD Student
Digital Interferometry, Optical Phased Array, Coherent Beam Combining


Dr Bram Slagmolen
Australian National University
Chief Investigator
Laser, Controls, Suspension, Earthquakes, Noise


Dr Jian Liu
University of Western Australia
PhD Student
Parametric instability, High power laser


Dr Georgia Mansell
Australian National University
PhD Student
Gravitational waves, precision metrology, quantum optics


Joshua McCann
University of Western Australia
PhD Student
low-frequency; seismic; isolation; instrumentation; control


James Spollard
Australian National University
PhD student
Optical phased array, link acquisition, digital signal processing


Layla Steed
Australian National University
Honours Student
Precision measurement, computer programming, experiment


Dr Andrew Sunderland
University of Western Australia
Associate Investigator


David McManus
Australian National University
PhD Student
Newtonian noise, Early Earthquake Warning, Gravimetry, Suspensions


Dr Terry McRae
Australian National University
Postdoctoral Researcher
Metrology, quantum optics, opto-mechanics, photonics


Emeritus Professor Jesper Munch
University of Adelaide
Associate Investigator


Parris Trahanas
University of Western Australia
Masters Student
optomechanics, DEMS, White Light Cavity, optical trap


Dr Joris van Heijningen
University of Western Australia
Postdoctoral Researcher
Controls, Vibration Isolation, Optics, Sensors, Outreach


Prof Peter Veitch
University of Adelaide
Chief Investigator
Lasers, wavefront sensing, adaptive optics


Benjamin Neil
University of Western Australia
PhD student
Photonic Crystal Resonators


Dr Sebastian Ng
University of Adelaide
Postdoctoral Researcher


Prof David Ottaway
University of Adelaide
Chief Investigator


Dr Robert Ward
Australian National University
Associate Investigator
Optics, Controls systems, space instrumentation, interferometry


John Winterflood
University of Western Australia
Postdoctoral Researcher
Vibration isolation, Electronics & Control


Bin Wu
University of Western Australia
Masters student
Astrophysics; Optics; Laser; Gravitational waves


Michael Page
University of Western Australia
PhD Student
Quantum optics, optomechanics, noise


Dr Tarquin Ralph
Australian National University
PhD Student
Digital Interferomentry, Wavefront sensing


Lauren Sarre
Australian National University
Honours Student
optics, quantum, communication, instrumentation, nonlinear


Min Jet Yap
Australian National University
PhD Student
Interferometry, quantum optics, optomechanics, precision metrology


Jue Zhang
University of Western Australia
PhD student
Parametric Instability; Quantum Noise Reduction


A/Prof Chunnong Zhao
University of Western Australia
Chief Investigator
Laser interferometer, Parametric instability, Optomechanics.

INSTRUMENTATION CONT'D

Jiawei Chi
University of Western Australia
Undergraduate student

Ken Field
University of Western Australia
Professional staff
Technician

Perry Forsyth
Australian National University
PhD student
Instrumentation Student Newtonian Noise Seismic

Dr Miftar Ganija
University of Adelaide
Postdoctoral researcher

Andrew Gwatkin
University of Western Australia
Professional staff
Research Assistant

Dean Harvey
University of Western Australia
Professional staff
Technician

Stephen Key
University of Western Australia
Professional staff
Technician

Yoav Naveh
University of Western Australia
PhD student
Vibration Isolation

Dr Lyle Roberts
Australian National University
Postdoctoral researcher
Interferometry Sensing Signal Processing FPGA

Jordan Smith
Australian National University
Honours Student
adaptive-optics, instrumentation, space, lasers

Andrew Woolley
University of Western Australia
Professional staff
Research Assistant

PEOPLE OF OZGRAV - OUTREACH AND PROFESSIONAL STAFF

Dr Rebecca Allen
Swinburne University of Technology
Affiliate
Education/teaching/outreach, Galaxy evolution, Image processing

Jackie Bondell
Swinburne University of Technology
Education and Public Outreach Coordinator

Ruby Chan
University of Western Australia
Node Administration

Rahul Choudhary
University of Western Australia
Masters student
Education and Public Outreach, Einstenian Physics Education

Kim Dorrell
University of Melbourne
Node Administration

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

Alex Foppoli
University of Western Australia
PhD Student
Einstenian Physics Education Research

Howard Golden
University of Western Australia
Affiliate
Geophysics, vibration isolation, gravitational waves

Lisa Horsley
Swinburne University of Technology
Node Administration
outreach programs, science communication

Magdalena Kersting
University of Western Australia
PhD student
theoretical physics, teaching general relativity, learning resources

Carl Knox
Swinburne University of Technology
Digital Media and Marketing Officer
Virtual reality, games, animation, photography

John Moore
University of Western Australia
Observatory Manager
Zadko Observatory
Astronomy, Gravitational Wave Detectors, Technical, Vacuum, Cryogenics

Mr Mark Myers
Swinburne University of Technology
Outreach and Education Content Developer
VR, visualisation, outreach

Erin O'Grady
Swinburne University of Technology
Node Administration
Administration and Event Management

Sareh Rajabi
Australian National University
Node Administration

Kirsty Waring
University of Melbourne
Node Administration

Dr Tejinder Kaur
University of Western Australia
PhD Student
Einstein-First, School curriculum, Einsteinian physics, Modern physics

Chris Samuel
Swinburne University of Technology
Professional staff
High Performance Computing

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. Excellent progress was made in 2018 positioning OzGrav to play a key role in the future of the field.

The instrumentation theme is organised under 6 programs across the audio, milli-Hz, and nano-Hz detection bands:

1. Commissioning (Program leaders: Ottaway and Slagmolen)
2. Quantum (Program leaders: McClelland and Veitch)
3. Low frequency (Program leaders: Slagmolen and Ju)
4. Distortions and Instabilities (Program leaders: Zhao and Ottaway)
5. Space (Program leader: Shaddock)
6. Pulsar Timing (Program leader: Bailes)

The structure has brought national cohesion and cooperation. A major outcome in 2018 was the setting up of a Centre-wide, cross-theme investigation to examine the science case for and technology required to build a highly sensitive detector for the 1 kHz to 4 kHz band. The working title for this investigation is OzGrav-HF (High Frequency).

INSTRUMENTATION

Commissioning (Program leaders: David Ottaway and Bram Slagmolen)

The broad commissioning efforts of the LIGO community focussed on improving the sensitivity and duty cycle of the LIGO detectors in preparation for the O3 observing run which is due to start in early 2019. The initial goal was to start the run with both LIGO detectors having a range that exceeded 120 Mpc (megaparsecs) for inspiral signals from binary neutron stars. Early in 2018 there was a significant vacuum incursion at both sites for the installation of dampers for parametric instability suppression and optical baffles and the replacement of optics whose coatings were not up to specification. OzGrav commissioners who spent considerable time at LIGO Hanford (LHO) are Dan Brown (Adelaide), Alexei Ciobanu (Adelaide), Nutsinee Kijbunchoo (ANU), Terry McCrae (ANU) and Jian Liu (UWA) each spending in excess of 3 months at the LIGO Hanford Observatory during 2018.

The commissioning efforts for the OzGrav community predominantly focussed on the high frequency sensitivity of the LIGO detectors through the installation and commissioning of squeezers to improve sensitivity and the understanding of the mode-matching throughout the detector. Both of these efforts predominantly aim to reduce the impact of the quantum noise which currently limits the performance of the detector above a few hundred hertz. Improving the mode-matching can also reduce other noise sources because it can improve the sensitivity and accuracy of the auxiliary control loop and reduced undesirable noise couplings.

These efforts resulted in new analysis techniques for understanding the performance of the output-mode cleaner and the discovery that there exists a significant difference between the degree of astigmatism in the Hanford (LHO) and Livingston (LLO) output mode-cleaners. Significant effort was also deployed in using the modelling package Finesse to understand the impact of poor mode-matching on the performance. Later in 2018, we focused on commissioning the in-vacuum squeezers. Good progress was made at LLO but significant issues remain at LHO related to power degradation through the coupling fibre from air to vacuum.

The Hartmann sensors that have been developed by the University of Adelaide continue to be used to diagnose hot spots on the Advanced LIGO Core optics. A significant hotspot on one of the ITMs at LIGO Hanford was identified and this optic was subsequently replaced earlier in the year.

Image: Two OzGrav members, Nutsinee Kijbunchoo (left) and Terry McRae (right) at LIGO Hanford site to assist with O3 upgrade.

Quantum (Program leaders: David McClelland and Peter Veitch)

Quantum noise arises from quantum fluctuations imposed on the quadratures (eg amplitude and phase) of an electromagnetic field. Quantum noise can be modified by: changing the laser power and/or wavelength; redistributing fluctuations between quadratures, referred to as squeezing; or modifying the interferometer topology.

Laser Development

The University of Adelaide node has focussed on the development of narrow-linewidth single-frequency Tm-doped fiber master oscillator (MO), the output of which can be amplified using higher power Tm-doped fiber amplifiers. These systems are required to facilitate the development and testing of 2µm (micron/micrometre) optical systems and for the development of high power 2µm lasers for 3G (third generation) detectors. We have demonstrated a 70mW MO that is directly pumped by a laser diode and a 250mW MO that is pumped by the output of an erbium-doped fiber laser (EDFL). Both MOs have line-widths < 200kHz, which is currently limited by the measurement system.

Image: A prototype of the 2µm fiber laser being developed for third-generation detectors with cryogenic silicon mirrors. Credit: Sebastian Ng, OzGrav University of Adelaide.

Squeezing

Our primary goal is the development of a squeezed light source at the 2µm wavelength, producing more than 10dB of locked quadrature squeezing from 10Hz to 10kHz. In 2018 we measured 4dB of quadrature locked squeezing down to 500Hz. We are currently limited by scattered light, laser stability, photodetector noise floor and quantum efficiency. A stable seed laser is under development both at the University of Adelaide and ANU. We have had extensive discussions about the development of high quantum efficiency (QE) photodetectors with our Centre partners at Caltech, and have begun discussions with the Department of Electrical and Electronic Engineering at UWA.

Topologies

i. White-light cavity:

A silicon nitride membrane has the potential to be used as a mechanical resonator in a white-light cavity to broaden the quantum-noise-limited sensitivity bandwidth. However, the membrane itself has low reflectivity. Using a Focused Ion Beam (FIB), we fabricated 0.1mm by 0.1mm Photonics Crystal (PC) on a 1mm by 1mm silicon nitride membrane window. The fabricated PC has high reflectivity at designed wavelength (1064 nm), but has too much optical loss (~10%). Reasons for the high optical loss are not yet known.

ii. Internal squeezing

In 2018 we commenced an experimental activity to test new ideas on quantum enhancement in which the squeezed light source is inserted inside the main interferometer. Analysis of ring cavity squeezers has shown no straight-forward way for their implementation. Work is continuing.

Image: How many physicists does it take to swap an in-vacuum optical fiber? Photo taken during HAM6 vent at LIGO Hanford (left-to-right: Fabrice Matichard, Sheila Dwyer and Hugh Radkins). Credit: Nutsinee Kijbunchoo, OzGrav ANU.

INSTRUMENTATION

Low frequency (Program leaders: Bram Slagmolen and Li Ju)

The low frequency program is aiming to increase the sensitivity and duty cycle of gravitational wave (GW) detectors across the entire frequency band by improving the low frequency stability. This involves instrumentation to measure low frequency seismic noise to estimate Newtonian noise and directly measure Newtonian noise for suppression of seismic noise down to the instrument noise limit. Key technology being developed are the tilt sensor, Torpedo sensor (**Tor**sion **Pe**ndulum **D**ual **O**scillator) and seismic noise array.

The tilt sensor's special flexure design enables it to be operated in arbitrary orientation at very low frequencies. This, combined with the optical walk-off technique, is expected to reach very high sensitivity. The optical readout system was designed and tested in 2018. The mechanical system has been constructed and will be integrated with the optical readout in 2019.

The Torpedo made great progress with the reliable locking of all four optical cavities, which combined provides the signal readout of the instrument. Due to its complex opto-mechanical coupling, transfer function measurements have been taken to reconstruct the current gravitational force sensitivity. During the analyses of these measurements, opto-mechanical cross couplings have become a challenge to mitigate, and are still actively being investigated. We finalised the design of the Torpedo seismic isolation chain. This includes a three-stage pendulum system, with an Intermediate Mass, Penultimate Mass and the Torpedo.

Distortions and Instabilities (Program leaders: Chunnong Zhao and David Ottaway)

We continue to develop new techniques to study distortions and instabilities in advanced interferometers. In the distortion analysis, we have focused on the development of a new mode-matching diagnostic technique, advanced phase camera and low displacement noise deformable mirrors. This work has a significant overlap with our work in Advanced LIGO Commissioning. In instability control we focused on experimental study of angular instability and its control, alternative ways to control parametric instability (PI), and designing future gravitational wave detectors without parametric instability.

The initial Advanced Phase camera demonstration work has been completed. This phase camera represents a significant advance over the first-generation cameras because it has 30 times greater resolution obtained at a maximum scan rate that is 20 times faster and is achieved with no moving parts. This means that if necessary it can be operated when the interferometer is in science mode without the risk of injecting noise signals into the interferometer. We also showed that the performance of this camera is shot noise limited. The increase in acquisition speed means that this camera is now able to monitor the changes in the optical fields of the interferometers at times scales suitable to monitor alignment fluctuations.

For optimum sensitivity the injected squeezed vacuum source must be optically matched to the interferometer which in turn must be matched to the optical mode of the output mode cleaner. We are developing a method of doing this which uses changes in higher mode content to accurately measure this using a single RF photodiode. Extensive numerical simulations using the optical code Finesse have confirm the viability of this method, and construction of a laboratory-based demonstration has commenced. New mode-matching strategies have also been investigated using quasi random noise modulation at University of Adelaide.

At UWA we are setting up a tabletop experiment to study the coupled cavity mode-matching sensing using a wavefront sensing system similar to existing auto-alignment systems but sensing the second order mode components. The technique will be implemented on Gingin suspended coupled cavity for further study.

Accurate mode-matching requires not only a method for measuring mode-matching errors but a means of correcting any errors that are detected. Actuation requires a deformable optical surface that does not introduce excess net mirror motion noise into the interferometer. This immediately rules out existing established methods for achieving phase front correction such as MEMs actuated deformable mirrors. We have developed a number of deformable mirrors and have shown that they correct mode-matching without introducing higher order aberrations. We are currently working with MIT members to evaluate these methods and determine their suitability for incorporation into the Advanced LIGO Plus upgrade.

We studied the angular instability in Gingin east arm cavity. A Simulink model was established with optical torsion spring combined into the local control loop. The experimental results matched the simulation results very well. The model will be useful for designing next GW detectors with high optical power.

After reaching high-gain parametric instability, we investigated PI saturation effects. The results are consistent with theoretical predictions. We then successfully demonstrated the suppression of PI using optical feedback control. We studied the feasibility of designing the next generation detectors without PI through optimising the arm cavity length and the size of the test masses. The conclusion is positive that there exist large enough PI-free windows with optimised detector parameters.

Silicon is one of the promising materials for future GW detector test masses. We plan to build a 3-mirror coupled cavity for studying instabilities and distortions. Polishing the first silicon test mass is completed and two more are in processing.

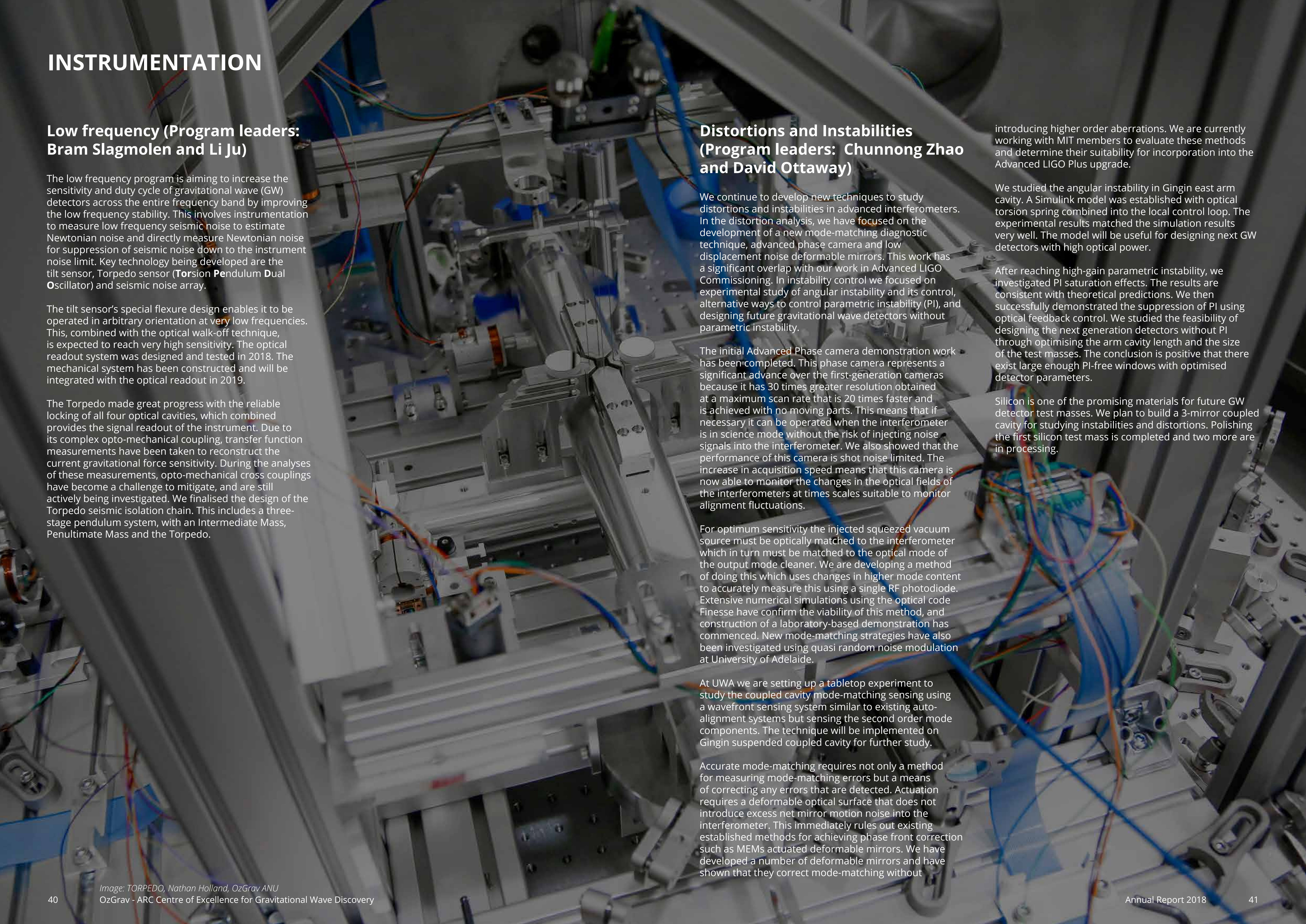


Image: TORPEDO, Nathan Holland, OzGrav ANU

INSTRUMENTATION

Space (Program leader: Daniel Shaddock)

A central theme of OzGrav's Space Program has been the investigation of new architectures for space-based gravitational wave detectors. The research re-evaluates the current approach of relying on passive stability of optical components and mechanical structures and instead examines the potential for sensing and control of critical paths.

Although it is unlikely that these techniques will mature quickly enough to influence the already well-developed LISA mission, there are opportunities to impact other projects such as those proposed by China. In March 2018 Prof Daniel Shaddock (ANU) presented the OzGrav research at the Huazhong University of Science and Technology and at Sun Yat-sen University, China. The ideas presented focussed on a combination of new ideas based on digital enhanced heterodyne interferometry with more mature concepts of time-delay interferometry and high dynamic range phase measurements.

Dr Samuel Francis (ANU-OzGrav PhD in 2017, now with NASA) led the experimental investigation on a new architecture based on a multi-link system for measuring spacecraft displacement and rotation. After testing a prototype system for the multi-link system in 2017, work in 2018 focussed on refining concepts for the optical head. We worked with Macquarie University to develop a monolithic optical head design based on their 3D direct written waveguide technology. The system will continue to be tested in the coming months.

The Australian Space Agency was officially launched. Despite the agency's modest initial funding, we look forward to seeing how the Space Agency can help OzGrav researchers to engage with the broader international space community and potentially partner on a major gravitational wave detector mission.

Pulsar Timing (Program leader: Matthew Bailes)

The Pulsar Timing Instrument for the Square Kilometre Array (SKA) Telescopes is being led by Swinburne University of Technology. In January 2018 the final design of the instrumentation was completed and in February it was subject to Critical Design Review, the final quality milestone in the systems engineering design process. An international review panel assessed the design and awarded it best outcome (pass with no modifications). Completion of this significant milestone is a testament to the major contributions of key OzGrav Associate Investigators: Willem van Straten (Auckland University of Technology), Adam Deller and Andrew Jameson (Swinburne University of Technology). One of the highlights from the review panel was the praise for the extensive field testing of the design prototype at both the ATNF Parkes Radio Telescope (Australia) and the MeerKAT Radio Telescope (South Africa). This practical approach to validation of design through hardware and software prototyping builds upon Swinburne's established practise of designing, constructing and commissioning of instrumentation for Pulsar Timing.

The SKA Pulsar Timing Prototype is built from high-performance software that processes the dual-polarisation data streams in real-time using dedicated high-performance computing hardware. The signal processing software has been extended to utilise GPUs, exploiting the very high memory bandwidth and parallel computational power that this technology provides. This has proven essential in meeting the performance requirements whilst minimizing power and hardware costs.

Early in 2018 the prototype was deployed at the Parkes 64-metre Radio Telescope to process the data stream from the new Ultra-Wideband Low receiver. This enabled real-time pulsar timing (and other capabilities) with almost an order-of-magnitude increase in bandwidth over the previous pulsar timing system. In addition to Pulsar Timing processing, the modular design of the signal processing software has enabled observing capabilities for Pulsar searching, Spectral Line, Continuum and VLBI observing modes. Flexible observing modes and such broad frequency coverage has never been available at centimetre radio frequencies. This will enable new science programs and extend the life of one of the southern hemisphere's most productive radio telescopes.

The same prototype software has been in use at the MeerKAT Radio Telescope in the Karoo Desert of South Africa, the world's premier interferometer at radio frequencies. In partnership with the South African Radio Astronomy Observatory (SARAO), Swinburne has provided the Pulsar Timing instrument "Kronos", integrating it with the SARAO correlator and beam-former, commissioning throughout 2018. The fidelity of the Pulsar Timing prototype has enabled high time and frequency resolution testing of the end-to-end signal processing chain, improving the overall performance and accuracy necessary for the precision measurements that will be required. With commissioning almost complete, the MeerTIME key science project for Pulsar Timing is poised to begin, providing excellent opportunities for OzGrav members to access and exploit premier radio astronomy facilities.

Image: Bram Slagmolen, OzGrav ANU

INSTRUMENTATION

Planning for Future Detectors (Program Leaders: David McClelland and David Ottaway)

A key component of OzGrav's mission is to look into the future of gravitational wave detectors both technically and geopolitically, because discoveries are what ultimately drives the science. Current world "next generation" detector planning under the auspices of GWIC, the Gravitational Wave International Committee, involves the compilation of a science case for the so-called third generation or "3G" detectors and explorations of potential costs, technologies and partnerships. The task has been given to an international committee named the GWIC3G committee. OzGrav Deputy Director Professor David McClelland (ANU) sits on this committee and co-chairs the Instrument R&D subgroup. OzGrav Director Professor Matthew Bailes (Swinburne) co-chaired the science case team on multi-messenger astrophysics.

A 3G detector will attempt to discover sources at 10 times the distance of Advanced LIGO at design sensitivity. The star formation history of the universe and pure geometrical terms mean that instead of finding events every few weeks 3G detectors may find an unbiased sample of sources every few minutes right back until the first stars! But 3G detectors are billion-dollar facilities, and it may be wise to demonstrate some of the technologies required in smaller-scale facilities prior to the 3G detectors of the 2030s. OzGrav is therefore exploring the science case and technologies involved in building a detector with the working title "OzGrav-HF", or OzGrav High Frequency.

The high frequency regime between 1-4 kHz is of significant interest to scientists interested in extreme state of matter. For example, high signal-to-noise measurements of the merger and ring-down phases of a binary neutron star systems promises to allow the determination of the Equation of State of the nuclear matter in neutron stars to high accuracy thereby allowing the precise testing of nuclear matter theories – currently lacking observables.

It is highly likely that such a detector will need to be designed as specialist high frequency detector that deliberately compromises its low frequency performance to achieve the required high frequency performance. The timing is fortuitous since the global community are now beginning to examine how a 40km detector could be made a reality.

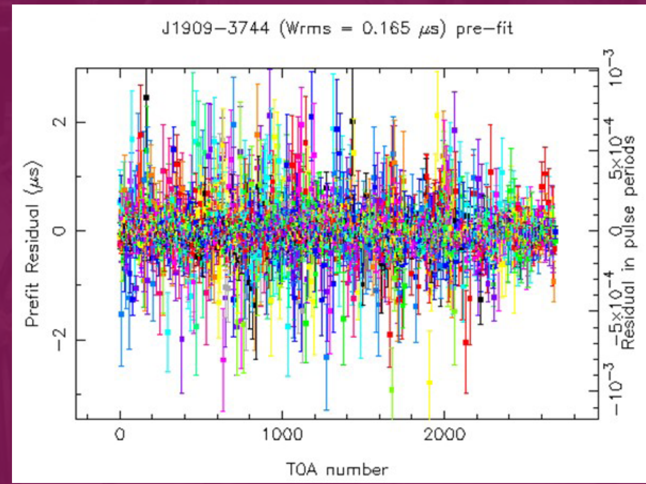
Significant progress has already begun on the strawman design including a decision on wavelength band to be used (2μm) and the core optics choice (Cryogenically cooled silicon mirrors operating at 123K). Seven small working groups have been assembled with the goal of optimising various parts of the interferometer with a feasibility study expected to be completed by the middle of 2019.

Unlike most telescopes/detectors in astronomy, gravitational wave detectors see the whole sky all of the time and collaboration, not competition, is essential to help triangulate source locations, and eliminate degeneracies in source characterisation. OzGrav is keen to support the global 3G effort, through detector R&D, site selection, science planning and by bringing in new collaborators.

Image: Bram Slagmolen, OzGrav ANU

Case study: High Precision Pulsar Timing Arrays

Precise timing was the theme for commissioning observations of pulsars with the Square Kilometre Array precursor MeerKAT radio telescope in 2018. The instrumentation (developed at Swinburne University of Technology) was put to the ultimate test by observing the Galaxy's most sensitive probe of nanohertz-frequency gravitational waves; the millisecond pulsar, PSR J1909-3744. The timing residuals (Figure below) for this pulsar demonstrate the record-breaking sensitivity of MeerKAT, consistently producing 165 microsecond timing precision using 22 sub-bands and just 320 seconds of integration time during observations spanning four months. When averaged in time and frequency, this new instrument will achieve the "jitter limit" of 10 nanoseconds in just one hour of integration. This pulsar, and many others like it, are primary targets for the MeerTIME project that will join the hunt for gravitational waves from objects like binary supermassive black holes as part of OzGrav's science.



DATA AND ASTROPHYSICS THEMES

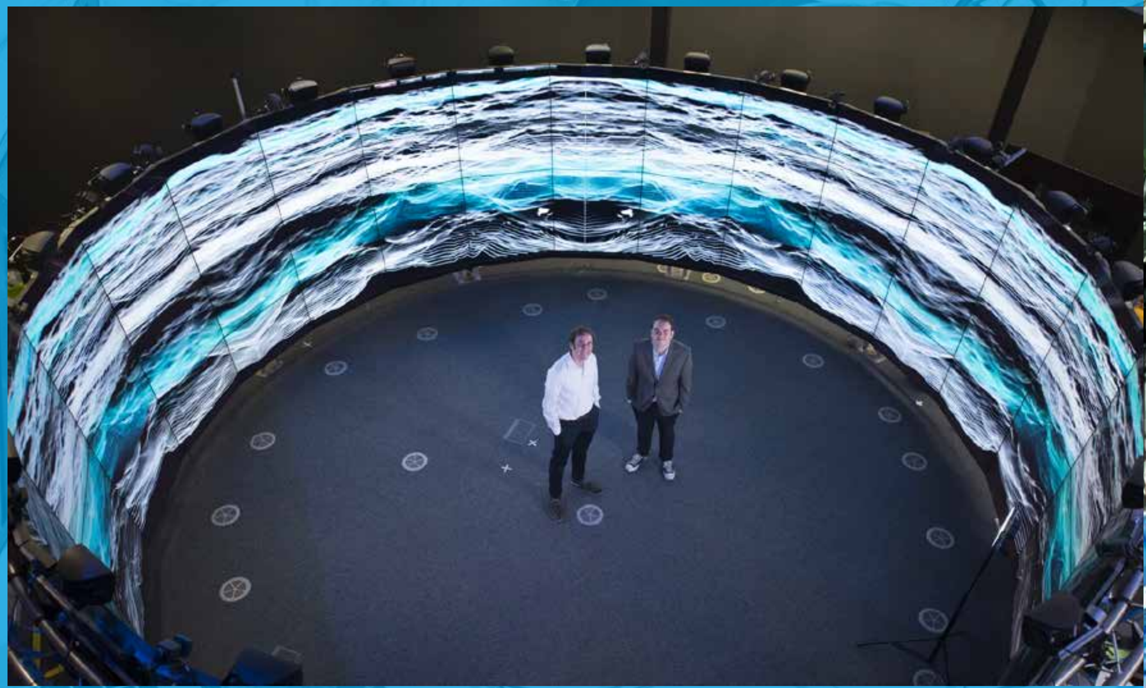
Led by Prof Matthew Bailes (Swinburne) and A/Prof Eric Thrane (Monash).

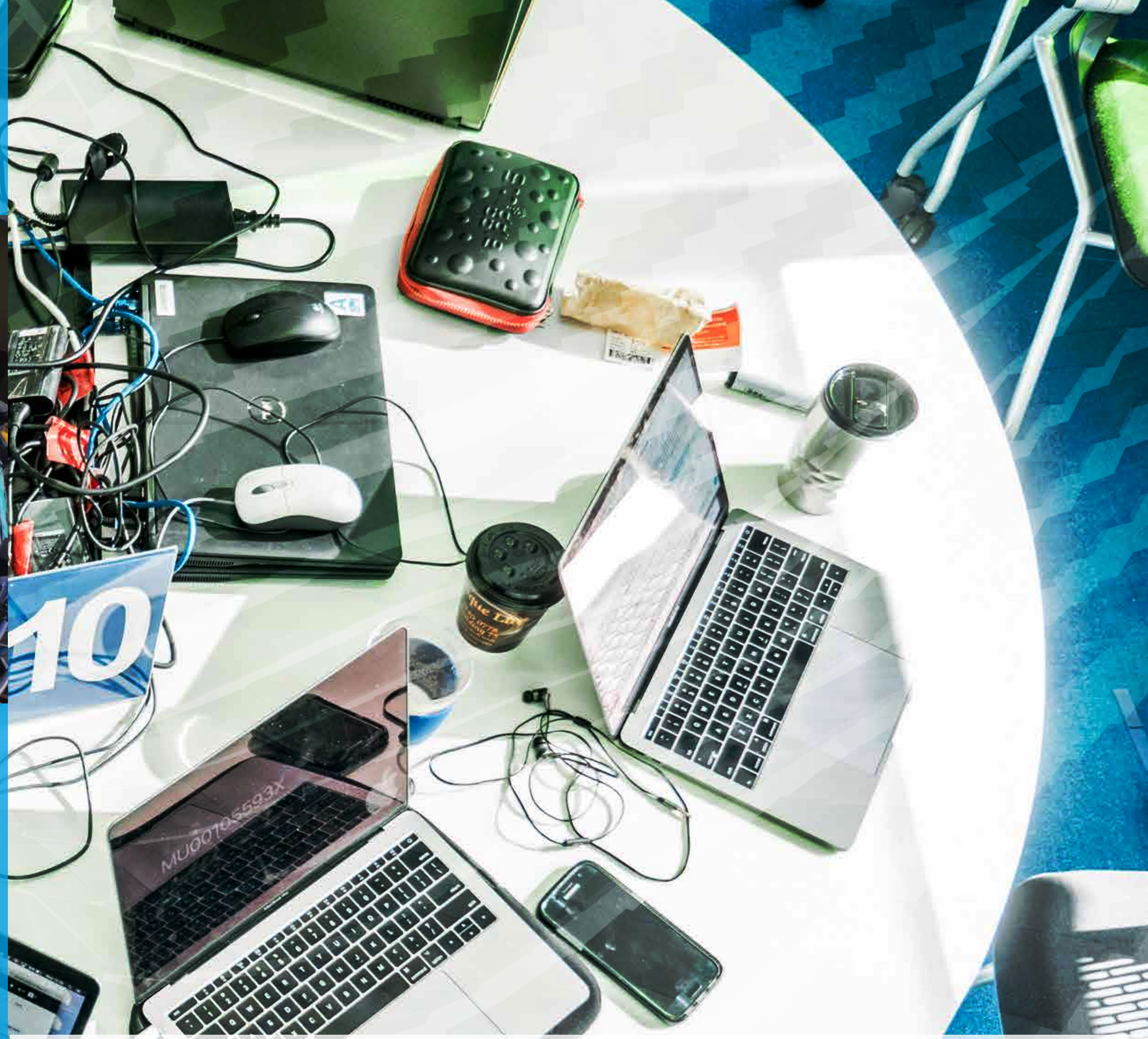
After the first discovery of gravitational waves from a binary black hole (GW150914), and the first discovery of gravitational waves from a binary neutron star (GW170817), we have entered the era of population analysis and regular detections. This year saw the release by LIGO and Virgo of the first ever gravitational-wave transient catalog (GWTC-1), which includes ten binary black hole mergers and one binary neutron star merger.

OzGrav researchers are on the front line of the new directions in gravitational-wave data analysis and astrophysics. Postdoctoral researcher Dr Meg Milhouse (University of Melbourne) contributed to the "burst" analysis for the GWTC-1 catalog, which included the discovery of the most massive, and the most distant, binary black hole merger yet detected. PhD student Colm Talbot (Monash) served on the LIGO/Virgo paper writing team for an analysis describing the binary black hole mass spectrum and the distribution of black hole spins. Meanwhile, Associate Investigator Dr Adam Deller (Swinburne), used very long baseline interferometry to pin down the viewing angle of GW170817, thereby producing new constraint on the Hubble constant.

The outlook for next year is excellent. Chief Investigator Prof Linqing Wen (UWA), working with researcher Dr Qi Chu and others, is readying a low-latency pipeline with a goal of producing the fastest gravitational-wave alerts. Researcher Dr Karl Wette (ANU) was elected Co-Chair of the continuous wave working group, which is tasked with searching for gravitational waves from spinning neutron stars. Wette is working closely with CI Prof Andrew Melatos (Melbourne), CI Prof Susan Scott (ANU) and others to maximise neutron star science in 2019. A team of investigators led by Associate Investigator Dr Paul Lasky (Monash) is developing the Bayesian inference code that will be used by LIGO to infer properties such as the mass and spin of merging black holes and the equation of state of nuclear matter. Finally, the new GOTO telescope, operated by Chief Investigator A/Prof Duncan Galloway (Monash), will join the OzGrav optical follow-up network, including programs led by Chief Investigator Prof David Coward (UWA) and Chief Investigator A/Prof Jeff Cooke (Swinburne), with a goal of carrying out the first observations of the next kilonovae and the MeerKAT and Parkes telescopes will provide exciting new pulsar timing data.

DATA AND ASTROPHYSICS





Inference (Program chairs: Rory Smith and Greg Ashton)

In 2018 members of the inference group coalesced to build a new code for inference: Bilby. Projects across OzGrav had previously identified a need for a flexible and user-friendly code for parameter estimation (PE) and Bayesian inference. Bilby responds to this need by delivering an open-source, extensible code, which can be used for cutting-edge inference of sources detected by ground-based interferometers. Additionally, Bilby provides a general-use library for inference in astrophysics. Already this code has been used by a number of OzGrav members for publications and ongoing projects

The "Optimal Search for an Astrophysical Gravitational-Wave Background", published in 2018 by Smith & Thrane, fundamentally shifted the method and outlook for detecting a stochastic gravitational wave background. During 2018, this work initiated a large scale mock data challenge within the LIGO/Virgo collaboration to test the method. Work is ongoing on this project led by members of the OzGrav inference group.

In July 2018 the Monash node hosted an inference workshop aimed primarily at ECRs from all programs who would like to use inference to do science. Over three days, training was provided on both the theory and practise. On the final day, multiple projects were initiated spanning applications of inference in detector science, building code for transient-GW analysis, and inference for X-ray data from Low Mass X-ray Binaries. A follow-up workshop was also hosted in December at Monash working on the readiness of bilby for O3.

Members of the inference group were awarded grants from the Astronomy Data and Computing Services (ADACS) Software Services in 2018. The first, produced a graphical processor unit (GPU) implementation of LIGO parameter estimation routines. For inference, these routines are repeatedly called in order to infer the properties of the signal; a GPU version was shown to provide speed ups by a factor of 10 and identified further improvement areas. These speedups will greatly improve the ability to analyse large numbers of events expected in the future and leverage the GPU availability on OzSTAR. The second project, a user interface for bilby, delivered a clean and user-friendly web interface through which non-experts can access the latest tools. A follow-up proposal accepted for 2019 intends to extend the functionality and could result in the bilby user interface being the primary method through which production analysis is done.

During the first and second observing runs of LIGO/Virgo, 11 compact binary mergers were observed. Each detection requires experts from a "PE rota" to run inference jobs, check results and fix errors as they arise. This core service work is crucial to the integrity of LIGO/Virgo publications. With improvements in the sensitivity of the detectors, the detection rate in O3 is expected to increase to of order 1/week. This necessarily requires an increase in the number of experts on the PE rota. The inference group of OzGrav has responded to this need by signing up. About 16% of the 100 names on the PE rota are OzGrav members.

GW Data Analysis (Program chairs: Qi Chu and Karl Wette)

The gravitational-wave data analysis program is increasingly synergistic with our other programs including Inference, Relativistic Astrophysics, Population Modelling and Multi-Messenger Observations. A number of OzGrav-sponsored workshops over the past year have facilitated new connections, including an inference workshop hosted at Monash University and a continuous-wave / neutron star workshop, hosted at the University of Melbourne. The cross-program exchange of ideas has led to publications that explore new connections, including work on gamma-ray burst rates led by AI Dr Eric Howell (UWA) and postdoctoral researcher, Kendall Ackley (Monash). Another emphasis over the past year has been improved coordination between the GW Data Analysis Program and the Computing Platform, OzSTAR. Program leaders, Qi Chu (UWA) and Karl Wette (ANU) have led a task force that is working with CI Prof Jarrod Hurley (Swinburne) in order to gain access to LIGO/Virgo data on Australian computers.

Researchers carrying out work in the GW Data Analysis Program have been working to leverage the graphical processor units employed by OzSTAR in order to achieve science targets that would otherwise be computationally challenging. Researchers at Melbourne have developed a graphical processor unit (GPU) optimised algorithm to search for gravitational waves from continuous sources. Meanwhile, OzGrav researchers Qi Chu, Joel Bosveld, and CI Prof Linqing Wen (UWA), led work improving the performance and latency of the SPIIR (Summed Parallel Infinite Impulse Response) low-latency compact binary coalescence (CBC) search pipeline, with participation of OzGrav students Manoj Kovalam, Teresa Slaven-Blair, Shinkee Chung, David Weight and Jacob Cameron (UWA). The latency of the pipeline has been reduced to less than 10 seconds, and its detection efficiency has been extended to beyond 100 megaparsecs. GPU technology has been used extensively in this pipeline that a speed acceleration over 100 times is achieved.

DATA AND ASTROPHYSICS

Pulsar Detections (Program chairs: Ryan Shannon and Hannah Middleton)

Inference as applied to pulsar data sets

In 2017 it was recognised that a weakness in pulsar timing efforts in Australia was the lack of expertise in modern, Bayesian inference techniques, and that OzGrav could play a role in filling this gap. At the 2018 OzGrav inference workshop participants undertook a preliminary investigation of profile-domain timing methods to enhance detection sensitivity. The group prioritised three main streams of future pulsar inference development. These were:

- improving existing pulsar inference codes in collaboration with outside groups (e.g.the Enterprise code being developed by North American Collaborators);
- implementing wide-band timing to account for the large bandwidths of new receivers (such as the Parkes Ultra-wideband-Low (UWL) receiving system and MeerKAT);
- developing actively-supported profile-domain pulsar timing algorithms. The work will involve collaboration across the nodes and with OzGrav Associate investigators at CSIRO (led by Dr George Hobbs)

MeerKAT Pulsar Timing

The group is excited about progress made towards MeerKAT pulsar timing efforts, which is described in detail in the "Pulsar" instrumentation themes. MeerKAT has much greater instantaneous sensitivity than the Parkes 64m radio telescope, although the new UWL receiver does extend the life of the venerable dish. At the time of writing the first official "MeerTime" run is being planned to commence in February 2019.

Parkes Pulsar Timing Array (PPTA)

The second major PPTA data releases "PPTA dr2", is anxiously awaited by the international community. This will be one of the flagship data sets that the group expects to serve as the basis of detection efforts in the coming years. Members of the theme late in the year tried to accelerate the completion of the data set by getting involved in low level data analysis tasks (for example, flagging data for radio frequency interference). We expect that the data set will be complete in early 2019. That being said, a preliminary analysis of the (unmanicured) data set demonstrates its power and is reported as one of the highlights below.

International Pulsar Timing Array

The group retained strong connections to the global international pulsar timing array (IPTA) effort. Dr Ryan Shannon (Swinburne) chaired the IPTA steering committee and served as its member on the Gravitational Wave International Committee (GWIC). Dr Paul Lasky (Monash) co-chaired the IPTA Data Analysis Working Group, the most active group within the IPTA. OzGrav was well represented at the International Pulsar Timing Array science meeting and student workshop held in New Mexico in June, giving 6 talks at the science meeting and delivering two lectures and tutorials at the PhD-level student workshop.

Young pulsars

The group has also investigated the timing noise properties of high spin-down (young) pulsars that have been regularly observed by the Parkes and Molonglo radio telescopes. While these data sets are not suitable for direct detection of gravitational waves, (due to their rotational instability) analysis of such data sets are essential in improving timing methodologies that are applied to the precision timing data sets, and understanding processes that could affect the rotational stabilities of millisecond pulsars. The techniques also benefit searches for audio-band "continuous" gravitational waves from noisy pulsars.

Multi-Messenger Observations (Program chairs: Eric Howell and Kendall Ackley)

This program encompasses both observational electromagnetic follow-up and theoretical studies of the electromagnetic emissions related to gravitational wave sources. Observational follow-ups aim to respond to gravitational wave detections by triggering a global network of telescopes to make observations across the wavelength spectrum. The underlying goal is to probe the nature of these events by combining data from different wavelengths. Theoretical studies in this program build on follow-up observations to provide new insights and predictions of the mechanisms underpinning these extraordinary events.

In the last year the Zadko telescope had a complete recoating of the mirrors, improving the gain in luminosity of around 66%. Infrastructure improvements include installation of a new set of computers for robotization control, a complete re-organisation of the network to improve the reliability of the observatory and recalibration.

During 2018 the GOTO telescope completed commissioning of three of the four mirrors in preparation for ER13 (LIGO Engineering Run 13). There was extensive continued development of the software infrastructure for fully robotic operations. This included a data reduction pipeline written by a team including Evert Rol and Kendall Ackley (Monash), which automatically carries out reduction and calibration of data and populates the detection database. A number of mini-surveys designed to test hardware and software were completed throughout 2018 as well as opportunistic follow-up of transients detected by other projects, including GRBs, Gaia transients, and asteroid observations. This lead to 10 reportable GCN circulars over the past year.

In April 2018 SkyMapper released the most comprehensive multi-colour band southern map of the sky (Southern Sky Survey) which is available for anyone in world online. The map was generated with researchers including Christian Wolf (ANU) using 70,000 individual images from the ANU 1.3-m telescope located at Siding Spring Observatory and contains nearly 300 million stars and galaxy detections. In May 2018 the SkyMapper team published the discovery of the fastest-growing supermassive black hole in the universe.

A cross-node study between UWA and Monash focused on calculating gravitational-wave – gamma-ray burst joint detection rates for O3 and beyond. This study by Eric Howell (UWA), Kendall Ackley (Monash), Antonia Rowlinson (University of Amsterdam) and David Coward (UWA) used Bayesian inference to determine the jet profile of GRB170817 using multi-messenger observations and used it to model future detection rates.

A study investigating X-ray guided gravitational-wave searches for binary neutron star merger remnants was conducted by Nikhil Sarin, Paul Lasky, Letizia Sammut, and Greg Ashton (Monash). This study showed how X-ray afterglow observations of short gamma-ray bursts could be used to conduct more sensitive gravitational-wave searches for post-merger remnants.

Another study by Nikhil Sarin, Paul Lasky, and Greg Ashton highlighted a systematic need for model selection between the fireball and magnetar models of gamma-ray bursts. This study adopted a Bayesian approach to model selection. In a complementary project, Lisa Strang and Andrew Melatos (University of Melbourne) have been working on a model for the mechanism that produces the relatively long-lived X-ray plateaux seen in a large percentage of X-ray afterglow data.

The use of an unsupervised algorithm for identifying point-like sources was developed by Kendall Ackley (Monash). It shows that eliminating objects in the subtracted image which are not point-like and, therefore, not inherently characteristically transient-like in shape reduces the overall number of objects to manually vet. This improves the time it takes for identifying a single optical trigger to a BNS event from or a GRB from Fermi and Swift.

In January 2018 the Deeper Wider Faster (DWF) program (PI: Jeff Cooke, Swinburne) participated in a Swinburne-Japan fast transient workshop for which there were approximately 80 participants from NAOJ Subaru and approximately 40 facilities from all over the globe. There were two DWF runs in February 2018 involving Subaru-HSC and about 30 other simultaneous/follow-up facilities in the radio, infrared, optical, X-ray, gamma ray, cosmic ray and neutrino observing bands; and in June 2018 involving CTIO-DECam and around 20 other simultaneous/follow-up facilities in the radio, infrared, optical, X-ray, gamma ray, cosmic ray and neutrino. In August 2018, there was an IAU Vienna exhibition on StarSound and SOFIA highlighting the data sonification tools developed in collaboration with RMIT.

DATA AND ASTROPHYSICS

Relativistic Astrophysics (Program chair: Paul Lasky)

The Relativistic Astrophysics Program has focused attention on a number of different aspects of neutron-star physics, tests of general relativity using gravitational waves as well as binary and ternary stellar systems, and supernovae physics and gravitational-wave detection.

In the wake of the first detected binary neutron star merger, attention has turned to post-merger remnants, the detection of which would allow for new insight into the behaviour of bulk nuclear matter at densities in excess of those found in the nucleus of an atom. Numerous OzGrav researchers around the country are involved directly and indirectly in the LIGO/Virgo search for gravitational-wave merger remnants, with key contributions to search methodology, result analysis and review, physical interpretation of results, and paper writing. The resulting paper ultimately yielded upper limits on the gravitational-wave emission. Development of physical models, gravitational-wave searches, and an understanding of the post-merger remnant physics and electromagnetic emission is ongoing at a number of institutes, most notably Monash University and the University of Melbourne.

From young to old; garden-variety radio pulsars exhibit unusual rotational phenomena that can potentially be used to probe the cores of these exotic objects. Andrew Melatos' group at the University of Melbourne studies these rotational irregularities through two primary means: by understanding correlations between the size of a glitch and the times between them, and by developing models of neutron star cores to understand the likely mechanisms that drive glitches in the first place.

The dynamics of neutron stars in binary and ternary systems further allows for fundamental tests of gravity. Swinburne's Adam Deller was part of an international team that followed the triple stellar system composed of two white dwarfs and a neutron star named PSR J0337+1715. By tracking the pulsar for five years with radio observations, the team was able to test the principal that bodies full under the influence of gravity independent of their composition; a concept known as the equivalence principle, which is a fundamental tenet of Einstein's gravity. The bodies passed the test with flying colours, and the results were published in the prestigious journal Nature.

Testing gravity with binary systems is a relatively weak-field test compared to measuring gravity at the 'surfaces' of black holes. The direct detection of gravitational waves allows for such tests through a number of mechanisms, including famous tests such as the no-hair theorem that probe whether black holes in the Universe are really those predicted by Einstein's theory of gravity. Other strong field tests include whether black holes receive natal kicks during the inspiral and merger process, that could see them accelerated to large velocities post-merger due to anisotropic gravitational-wave emission. Juan Calderon Bustillo (Monash) led a paper that showed that these black hole kicks can be inferred from gravitational-wave observations, allowing us to calculate the final direction and velocity of the remnant black hole.

Another strong-field effect that can potentially be measured with gravitational waves is that of gravitational-wave memory. This effect is caused by gravitational waves acting as a source term for more gravitational waves, and results in a permanent distortion of spacetime being left behind after a gravitational-wave event. A Monash team led by PhD student Colm Talbot developed new models of this memory that can be used in gravitational-wave memory detection algorithms. They also discovered a new effect, coined 'memory of memory', in which traditional gravitational-wave memory provides a source term for next-order gravitational-wave memory.

Originally touted as primary gravitational-wave candidates for ground-based detectors, supernovae explosions have taken a back seat to close binary mergers. New computational models of supernovae and their corresponding gravitational-wave emission are being studied in OzGrav by Dr Jade Powell (Swinburne), Dr Bernhard Müeller (Monash), and international collaborators, using state-of-the-art three-dimensional simulations. Simulations such as these are being used to develop new gravitational-wave detection algorithms targeted towards supernovae, as well as understand the astrophysics one can learn with a positive detection.

Population Modelling (Program chair: Simon Stevenson)

We now have a population! The past year saw the number of observed gravitational-wave events grow to double-digits, with the release of a catalogue (dubbed GWTC-1) of all binary mergers observed during the first (O1, 2015) and second (O2, 2016-2017) observing runs of Advanced LIGO and Virgo.

OzGrav researchers including PhD student Colm Talbot (Monash) contributed significantly to a paper authored by the LIGO and Virgo Scientific Collaborations analysing the mass and spin distributions of the now emerging binary black hole population.

PhD student Debatri Chattopadhyay (Swinburne) has been utilising the OzSTAR supercomputer housed at Swinburne University of Technology to simulate dozens of globular clusters - dense, spherical balls of tens to hundreds of thousands of stars. These globular clusters may form the binary black holes which are being observed in gravitational waves. Debatri will discuss the relative rates and formation channels of such dynamically formed binary black holes.

PhD student Marcus Lower (Swinburne) showed that although most binary black holes are expected to have circular orbits by the time they are observed merging by ground based gravitational wave detectors, it will be possible to measure the eccentricity for the few percent that will have some residual eccentricity due to their dynamical formation history. This may allow the origin of these mergers to be identified.

2018 also saw OzGrav researchers continue to consider the connection between the extragalactic double neutron star merger GW170817 and the Galactic double neutron star population. Dr Xingjiang Zhu (Monash) led a study showing that gravitational-wave measurements of neutron spins in a few hundred events will enable a measurement of the average lifetime of radio pulsars. The international COMPAS collaboration including existing and incoming OzGrav members also showed how such double neutron star systems form.

In 2019, with the beginning of the third observing run (O3) at enhanced sensitivities, the number of observed black hole mergers will surely grow and quickly exceed the size of known populations of other exotic systems such as the Galactic double neutron star population. This will bring with it new insights, challenges and opportunities for studying the population of gravitational wave events.

DATA AND ASTROPHYSICS

OzSTAR supercomputer (Leader: Prof. Jarrod Hurley)

The Swinburne OzSTAR supercomputer was officially launched on 7th March 2018 by the Swinburne Deputy Vice-Chancellor (Research), Professor Aleks Subic, at a function attended by representatives from the national astronomy community, the technology industry and Astronomy Australia Limited (AAL). The launch included presentations from OzGrav CIs Prof Matthew Bailes and A/Prof Jarrod Hurley (Swinburne). In reality OzSTAR was in full operation from January 2018 onwards (after installation in late 2017) with technical staff performing activities including the installation/optimisation of the slurm workload manager, configuration of the lustre filesystem, setting up the modular software build framework, and initialising OzGrav research projects. Of particular relevance to LIGO activities the LALsuite software was installed in February 2018 (with updates in October) and work began on importing LIGO O1 and O2 data.

OzSTAR represents a significant upgrade over the previous machine that operated at Swinburne from 2012-2018 and was purchased with the help of a national infrastructure grant. OzSTAR possesses a 100Gb high speed/low latency interconnect, 5PB of lustre file system, over 4000 compute cores and significantly 230 Nvidia P100 graphics processing units (GPUs), ideal for many aspects of gravitational wave and pulsar analysis. All of the 115 compute nodes have a minimum of 192GB of RAM and 36 cores.

Uptake of the facility across 2018 has been a testament to the success of OzSTAR with over 60 individual accounts created for OzGrav personnel and collaborators across 13 distinct OzGrav research projects. The combined usage of the facility for these projects was 26% which represents almost 9 million hours of data processing and simulations. The three-dimensional supernova simulations performed by Dr Jade Powell (Swinburne) and Dr Bernard Müeller (Monash) are a prime example of the latter. Many of the users have commented positively about the responsiveness of support personnel and the reliability of the hardware. OzSTAR currently boasts an uptime of 99% and is the main repository of pulsar timing data from the MeerTime telescope in South Africa.

OzGrav ECRs and postdocs had the initiative to set up an "OzSTAR Task Force" that meets regularly with Swinburne staff to facilitate use and provide feedback on the system.

OzSTAR support staff are aligned with the Astronomy Data and Computing Services (ADACS) node at Swinburne – an initiative founded by Astronomy Australia Limited (AAL) and funded through the national astronomy grant administered by AAL. The Swinburne node of ADACS is staffed by 6-7 personnel of which 1.5 provide direct support to OzSTAR operations and thus to OzGrav usage. ADACS also provides software support services with time allocated through a competitive application process. In 2018 time was awarded to OzGrav projects that produced a GPU-based speed-up of signal model routines in LALsuite and the development of a user-friendly interface to the Bilby inference software. Importantly the Bilby development also included the deployment of a workflow that will allow the software to be used effectively on computational infrastructure of all varieties.

Case study: Computational Power

A promising target for searches for continuous gravitational waves is the low-mass X-ray binary (LMXB) Scorpius X-1. A hypothesis which potentially explains the distribution of LMXB spin periods is that the spin-up torque from the accretion disk is balanced by a spin-down torque due to the emission of gravitational waves. Scorpius X-1 is one of the most promising candidates for a continuous gravitational-wave detection, but presents significant data analysis and computational challenges. In particular, the (unknown) spin frequency of Scorpius X-1 is likely to wander randomly on an unknown timescale due to the accretion process.

OzGrav researchers lead by CI Prof Andrew Melatos and students/postdoctoral researchers Patrick Clearwater, Liam Dunn, Lilli Sun, and Sofia Suvorova (Melbourne) have developed a novel search method using the Viterbi algorithm to track a frequency-wandering signal over time at minimal computational cost. This algorithm was then combined with another OzGrav innovation, the J-statistic, which efficiently performs optimal matched filtering of the gravitational-wave data against a template waveform. Finally, a GPU implementation of the J-statistic algorithm dramatically reduced the computational cost of the search by a factor of 100.

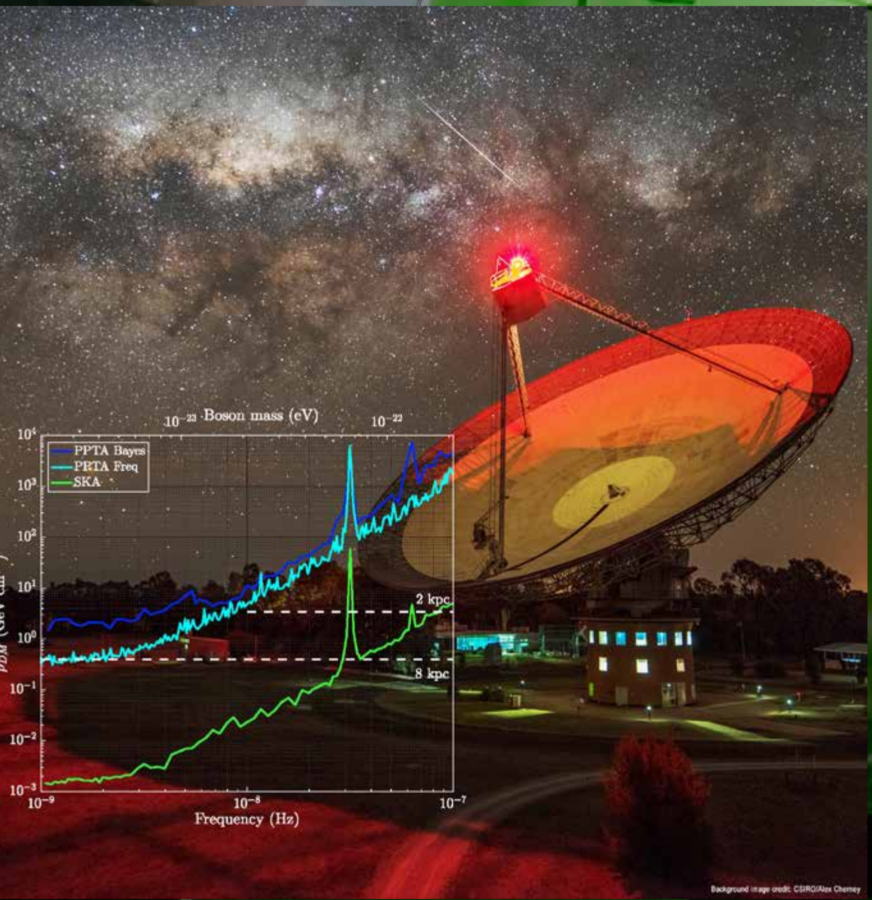
The Viterbi 2.0 (Viterbi + J-statistic) search pipeline was applied to LIGO data from the O2 observing run. The search was completed quickly using the OzSTAR supercomputer at Swinburne, which with its hundreds of GPUs was able to blast through hundreds of trillions of potential waveforms in a matter of weeks, instead of years. This is one of the first LIGO/Virgo searches for gravitational waves where the bulk of the computational power was supplied by OzGrav computing facilities. The Viterbi 2.0 search pipeline will set the most stringent upper limits on gravitational waves from Scorpius X-1 in a forthcoming paper authored by the LIGO-Virgo Collaboration. It is planned for the pipeline to be applied to data from the upcoming O3 observing run to search for Scorpius X-1 and potentially other LMXBs.

DATA AND ASTROPHYSICS

Case study: Bilby (user-friendly Bayesian inference library)

Bilby has been adopted by the PE and CBC chairs of LIGO/Virgo as the new production code for parameter estimation. This establishes OzGrav as the leader in the astrophysical discovery efforts of the LIGO Scientific Collaboration. As the main O3 production code for parameter estimation activities, all measurements of the properties of compact binaries using gravitational waves will be made using software and infrastructure developed within Australia. Moreover, the ADACS/OzGrav development of user-friendly interfaces to Bilby is lowering the entry bar to making astrophysical measurements with gravitational waves. This is facilitating the broader adoption of parameter estimation techniques throughout the LSC, e.g., more scientists are signing up to inference activities.

Throughout 2018, the inference group has published a number of articles on inference in gravitational wave astrophysics. Highlights include work on inferring the mass spectrum of binary black holes, inference of gravitational wave signals contaminated by transient detector noise glitches, inference of the binary neutron star population properties, inference of eccentricity in binary black hole systems, and the astrophysics of core-collapse supernova gravitational wave signals.



Case study: Fuzzy dark matter

The latest data set of the Parkes Pulsar Timing Array (PPTA) was used to place new and independent constraints on the density of fuzzy dark matter in the Milky Way. Fuzzy dark matter is the lightest dark matter that has been proposed, which provides solutions to some big challenges of the standard cold dark matter model. The presence of fuzzy dark matter in the Milky Way was predicted to modulate the times of arrival of pulses from radio pulsars in a periodic way. No such modulations were found in the PPTA data. Therefore, upper limits were derived for the signal amplitude which is proportional to the dark matter density. Whereas the PPTA limits remain above the total dark matter density measured with other methods, it may soon become possible to test the fuzzy dark matter hypothesis with pulsar timing. This work is led by PhD student Nataliya Porayko from Max Planck Institute for Radio Astronomy and OzGrav Postdoctoral Researcher Dr Xingjiang Zhu (Monash), and involves other collaborators and OzGrav members including PI George Hobbs (CSIRO).

Case study: Glitch statistics

University of Melbourne group are using pulsar glitch data to test superfluid vortex models of neutron star matter. "Size-waiting-time Correlations in Pulsar Glitches" (Melatos, Howitt, Fulgenzi) discussed the lack of glitch size-waiting-time correlations in the context of a generic state-dependent Poisson model for glitches, and identified several pulsars for ongoing timing experiments in order to test this theory further. "Nonparametric Estimation of the Size and Waiting Time Distributions of Pulsar Glitches" (Howitt, Melatos, Delaigle) looked at the probability distribution functions of glitch sizes and waiting times for the 5 pulsars with the most recorded glitches, and found observational support for the vortex avalanche model of pulsar glitches. Further timing campaigns with Parkes and Molonglo will increase the size and completeness of the glitch catalogue, improving the robustness of the results from both of these papers and encouraging internode collaboration.

Case study: Unveiling the jet properties of GRB170817A

The binary neutron star merger GW170817 was the gift to astronomy that kept giving throughout 2018, as OzGrav scientists studied its fireball-like afterglow for clues about the nature of the cataclysmic merger. One question rose above all others: had the colliding neutron stars launched a powerful, narrow 'jet' of very fast-moving material that was able to punch clear of the rest of the merger debris? Such jets had been theoretically predicted to accompany the merger of two neutron stars and to create short and powerful gamma-ray bursts; much more powerful than the relatively weak gamma-ray signal associated with GW170817.

The answer was provided by radio observations with the High Sensitivity Array. The team, which included OzGrav AI Adam Deller (Swinburne), were able to provide the sharpest ever images of the radio afterglow. Over the course of 150 days, the position of the radio emission shifted at a rate that appeared to exceed light speed! This seemingly paradoxical situation, called superluminal motion, results when the jet is pointed nearly toward Earth and the material in the jet is moving close to the speed of light.

The results enabled the team to determine the orientation of the merging system on the sky much more precisely than was possible based on the gravitational wave signature alone. The jet had barely grazed the line of sight towards the Earth, explaining why the prompt gamma-ray signal had been so weak. Had the orientation been slightly different, observers on the Earth might have observed a classic gamma-ray burst along with the merger – or, tilted a different way, might not have seen any evidence of the jet and gamma-ray burst at all!

Finally, and excitingly, adding the radio data to the original gravitational wave data results in a considerably improved measurement of the Hubble constant - the rate at which the Universe is expanding - based on GW170817.

Professional Development

In 2018 the OzGrav Professional Development Committee (PDC) comprised the Chair CI Prof Susan Scott, COO Dr Yeshe Fenner, CI Prof Andrew Melatos, CI Prof David Ottaway, postdoctoral researchers Dr Kendall Ackley and Dr Karl Wette and PhD students George Howitt and Joshua McCann. The PDC now has a good balance of seniority, gender and representation across the nodes.

An exciting new development this year was the establishment of the Early Career Researcher (ECR) Committee with founding members Poojan Agrawal, Dr Joris van Heijningen, Dr Terry McRae, Craig Ingram, Dr Grant Meadors and Dr Meg Millhouse. This committee represents the interests and views of our students and postdoctoral researchers and is already playing an important and complementary role to the PDC by suggesting ways that OzGrav can help foster professional opportunities and development for our ECRs.

We rolled out the OzGrav mentoring program for ECRs this year. Participation by mentees and mentors is voluntary and there has been a moderate rate of uptake so far. The feedback we have received from participants has been positive, and so we hope there will be an increase in the uptake rate for the program next year.

A primary focus for the year for both the PDC and the ECR Committee was the long-term planning and eventual running of the two-day ECR part of the OzGrav annual retreat which was held in the Swan Valley of Western Australia on 5-6 December. The program was vibrant and well-rounded incorporating sessions on science communication, science writing for the general public and children, media training, developing leadership and strategic capabilities, delivering great presentations, scientific paper writing, writing and winning grants, and preparing for job interviews. We also held an evening speed-networking session with industry guests. Feedback sought from the ECRs following the retreat indicated that they were pleased with the ECR Workshop part of the retreat and its associated social activities.

Equity and Diversity

The Equity and Diversity Committee welcomed new committee members Dr Grant Meadors and Dr Hannah Middleton in 2018. Grant had extensive experience with the LIGO Allies and was a very active member of the committee, offering Bystander Harassment training sessions at our annual retreat and providing a bridge between OzGrav and LIGO. Grant has recently been awarded a position back in his home country and will be sorely missed on the committee and the wider OzGrav.

A number of initiatives were successfully implemented by the committee in 2018:

- A primary carer's grant scheme was established enabling staff with carer responsibilities to attend workshops and conferences, as well as visit other nodes within OzGrav. Childcare was also offered to staff at the annual retreat.
- Two ombudspeople were appointment that could be contacted if any OzGrav members felt uncomfortable discussing issues like bullying or harassment with OzGrav staff. We were delighted that respected scientists Professor Virginia Kilborn (former President of the Astronomical Society of Australia) and Professor Tamara Davis (ARC Laureate Fellow at the University of Queensland) agreed to take on these roles.
- We successfully submitted an application for a Bronze Pleides award in 2018 (result pending) and are confident of obtaining it based on the work OzGrav has performed to date in this area.
- The schools program "Mission Gravity" and related activities factored in a school's socio-economic and gender status when selecting targeted schools. Many children in rural/semi-rural locations find it difficult to attract experts for incursions, and Lisa Horsley went on a tour of regional schools in late 2018 which was greatly appreciated.

The annual retreat was attended by inspirational female role models including new AI Professor Tara Murphy and Dr Chiara Mingarelli. We also had a dedicated session at the retreat on interpersonal interactions and the role of what some term "microaggressions".

It was clear at the annual retreat that the next generation of scientists are much more aware of equity and gender issues and more comfortable being pro-active in highlighting potential issues.

Gravitational waves is a field that largely grew out of General Relativity and Instrumentation, both historically heavily male-dominated areas. Whilst OzGrav is very proud of the fact that the percentages of its student and postdoctoral population are well above the international average, it is clear that STEM still has tremendous gender issues going forward because before students even enter University, a filter has already been applied to the cohort. A new advanced physics degree established in Australia recently had 40 applications, only 4 of which were female. This highlights the importance of both promoting female role models but also reaching out to children well before they are selecting their University entrance options. Thus OzGrav's Outreach program is important in laying the foundations for physics research of the future.

ACTIVITY PLAN 2019

Instrumentation

Commissioning (Program leaders: David Ottaway and Bram Slagmolen)

Onsite commissioning will be limited this year as a significant fraction of 2019 will be dedicated to the O3 observation run.

Continue to commission the squeezer during commissioning breaks and will be responsible for data quality monitoring channels.

After the end of O3 increase the effectiveness of modematching, improve the effectiveness of the injected squeezed light and increase the circulating power within the interferometer, including advanced phase cameras, single RF detector mode-matching schemes and new types of deformable mirrors.

Continue to work with LIGO commissioning team to understand the impact of the hotspots that have been diagnosed using the Hartmann sensors and possibly find a scheme to reduce their impact.

Quantum (Program leaders: David McClelland and Peter Veitch)

Lasers: complete development of and deliver 50mW MOs to ANU and CIT, and investigate power scaling of the EDFL-pumped MO, and assembly of a first-stage amplifier. Begin development of a cryogenic Ho:YAG MO for use in an injection-locked power oscillator 2µm source.

Squeezers: continue development of 2µm squeezed light source with the goal to measure 6dB squeezing down to 100Hz, aided by the implementation of a new, stable seed laser. Photodetector development will continue with potential candidate materials and designs identified.

Topologies: continue investigation into novel quantum topologies using white light resonators and internal squeezing. For white light cavities, we will explore different manufacture techniques apart from FIB to achieve high reflectivity, low optical loss photonic crystals. We will also explore special patterns to achieve high mechanical Q factor of the photonic crystal.

Low frequency (Program leaders: Bram Slagmolen and Li Ju)

Integrate tilt sensor and test and characterise its performance. Design feedback system for the tilt control for integration into the Gingin isolation system.

Receive the MulitSAS and finalise the assembly and integration into the Torpedo infrastructure, including using the digital control system.

Assemble and test the Intermediate Mass for its principle mechanical resonances. Tweak the Penultimate Mass design so it appropriately integrates the Torpedo with the MultiSAS/MI combination.

Design a low-force isolation platform (to replace the MultiSAS) for next generation Torpedo isolation chain; design and characterise a displacement sensor with a sensitivity of 1 pm/rtHz at 0.1 Hz required for the Torpedo isolation chain; and investigate the use of machine learning techniques to improve the control and readout of the Torpedo.

Seismic array construction. Deploy a small array with ~20 seismometers/geophones at the Gingin site to test data acquisition and analysis. Apply for funding to purchase more seismometers to increase the array size.

Distortions and Instabilities (Program leaders: Chunnong Zhao and David Ottaway)

Continue development of Advanced Phase Camera. Investigate the optimal way of deploying this on a full scale interferometer to investigate the issues with control sidebands and using outside immediate gravitational wave detection application.

The development of the mode-matching scheme will continue with a plan to make a convincing case for implementing this on LIGO detectors post O3.

Continue developing the deformable mirrors in collaboration with the MIT group.

In instability control, study the thermal noise coupling of acoustic mode damper (AMD) at high frequencies for high frequency detectors, and to optimise AMD design and angular control for high frequency detectors.

For the silicon optics, complete the polishing 3 silicon test masses and their mechanical mode Q-factor measurement, to coat 2 silicon test masses with AlGaAs/GaAs, and to prepare fused silicate power recycling mirrors for a coupled cavity at Gingin.

Complete 3 vibration isolators for the coupled cavity.

Space (Program leader: Daniel Shaddock)

Begin development activity for weak light phase locking, which may enable a wider 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.

Frequency stabilising the laser prior to transmitting from the spacecraft is needed to enable future improvements. Such a stabilisation system must have several features that are not standard in conventional frequency stabilisation systems. In particular, the stabilisation system must have a tuneable frequency, but maintain high stability.

Pulsar Timing (Program leader: Bailes)

Transition from commissioning to production for the MeerKAT radio telescope and the commencement of the first MeerTIME observations (are expected to start first half of 2019). Once fully operational MeerKAT will be the most flexible and sensitive observatory for Pulsar Timing science in the world.

SKA telescope will undergo the System Design Review, where the Pulsar Timing Instrument is combined with all other elements of the telescope in a holistic system-level analysis of the design. Swinburne will lead the Pulsar Timing instrument through the final phase the design of this next generation facility as the SKA telescope moves into the construction phase.

Data and Astrophysics

Inference. Program chairs: Rory Smith and Greg Ashton

During 2019 Bilby will be rolled out as production code used by the LSC to measure the astrophysical properties of black holes and neutron stars using gravitational waves. Monash University will host a LIGO-focused parameter estimation meeting. Concluding mock data challenge, then the search will be run on LIGO data with the aim of making the first detection of a gravitational-wave background.

Focus efforts related to inference for pulsar timing and continuous gravitational waves. Support OzGrav experts and add to the growing expertise.

GW Data Analysis. Program chairs: Qi Chu and Karl Wette

An exciting year ahead, with LIGO and Virgo detectors anticipated to begin the O3 observing run with enhanced sensitivity. We will support the detectors by participating in monitoring the data quality of the instruments and report any anomalous disturbances for investigation.

Searches for compact binary coalescences

Due to the anticipated sensitivity improvement of LIGO and Virgo, there could potentially be the detection of up to one binary neutron star coalescence per month, and up to one binary black hole coalescence per week. The SPIIR pipeline will be in place for low-latency CBC searches, aiming to be the first to detect gravitational waves from binary coalescences and provide mass information and sky location information.

Searches for gravitational wave bursts

Continue to carry out analyses with BayesWave during O3, assessing the significance of candidate events and reconstructing compact binary waveforms.

Searches for continuous gravitational waves

With the election of Wette (ANU) to the position of Co-Chair of the CW working group, OzGrav is positioned to take an increasingly lead role in CW science. Searches for continuous gravitational waves from low-mass X-ray binaries, including Scorpius X-1, will continue in O3 using the Viterbi 2.0 algorithm. The feasibility of performing a sensitive, but computationally intensive, all-sky search for gravitational waves using a recently developed algorithm called Weave will also be investigated.

Searches for a stochastic background of gravitational waves

Carry out the optimal search for a gravitational-wave background from compact binaries with LIGO/Virgo data. Once the algorithm has been verified it will be applied to O3 data. There is a good chance that the sensitivity will be sufficient to observe a population of sub-threshold binary black holes.

Pulsar Detections. Program chairs: Ryan Shannon and Hannah Middleton

PPTA dataset, analysis, and workshop: Strengthen the OzGrav pulsar group's work on inference with the second PPTA data release expected in March 2019. Organise a workshop towards this analysis and foster the first searches for gravitational waves in the data set, which we intend on presenting at the 2019 IPTA Science Meeting in June.

First MeerKAT Pulsar Timing Results: MeerKAT is expected to commence regular pulsar timing observations in early 2019 that will enable robust, high fidelity pulsar timing. Early data has already demonstrated that some of the new pulsars discovered in the south have extraordinarily low jitter limits whilst others are very high.

Glitch finding: Working on automated glitch finding and providing a robust estimate of glitch false alarm probabilities based on hidden Markov methods.

Viterbi pulsar searching: Implementing new search techniques to search for relativistic binary pulsars in archival radio datasets of past pulsar surveys at Parkes like SUPERB and HTRU. Signal processing methods used in the search for continuous gravitational waves from rotating neutron stars will be applied to the radio survey data.

IPTA DC2 gravitational wave searches: Increase engagement in International Pulsar Timing Array data analysis. The PPTA has committed to delivering its DR2 to the IPTA when it is complete in early 2019.

ACTIVITY PLAN 2019

Multi-Messenger Observations. Program chairs: Eric Howell and Kendall Ackley

The next LIGO/Virgo run will begin around March 2019 and initiate follow-up for electromagnetic counterparts. Follow-up searches will aim to capture the glow of a kilonova or late time emissions from a gamma-ray burst viewed from a wide angle to the jet axis. Careful electromagnetic follow-up of binary black holes will continue in the hope of gaining some insight on the environment or hosts of these populations.

Early observations from GOTO, Skymapper and Zadko can provide valuable data mapping the evolution of a kilonova. Radio observations through the ATCA, ASKAP and MWA observing programs can provide important insight into the physical properties of the merger/gamma-ray burst and its environment. The High Sensitivity Array will also be monitoring any radio emissions associated with a binary neutron star (black hole-neutron star) merger to put constraints on any jet structure.

The next DWF run scheduled for 23-28 June 2019 and will utilise MeerKAT for searching for FRBs in real time (which may lead to 1-8 detected FRBs during the run), ThunderKAT for radio transients, the South Pole Telescope for wide-field mm and sub-mm real-time fast transients, AST3-2 in the Antarctic for wide-field 24/7 unbroken optical light curves and color info, CTIO DECam for deep, real-time optical fast transients, Astrosat for UV and high-energy transients, HXMT for real-time x-ray and high-energy fast transients, Pierre Auger Observatory for particle and high-energy transients, as well as additional telescopes for follow up, including rapid-response VLT FORS time, SALT, Gemini-Sm and Swift conventional ToOs; and concurrent and/or interleaved observations with SkyMapper, Huntsman, LCOGT, GROWTH, MASTER, SAAO, etc. in the optical and REM in the infrared.

Rapidly and accurately identify which of the transients are novel and which are already known. Work ongoing in the realm of machine learning for automated transient detection with GOTO as well as applications for other optical fast-transient observatories. This will potentially lead to improved response times for truly novel transient events and, in the case for optical follow-up of LIGO/Virgo BNS events, what is the typical population characteristics for sGRBs and kilonovae.

To improve the future prospects of rapid, wide-field optical coverage of the LIGO/Virgo sky regions, GOTO will seek funding to support deployment for a southern node. This will dramatically improve the prospects for an OzGrav-led co-initiative for the identification of the earliest signals from BNS mergers arriving in either hemisphere.

In 2019, SkyMapper will release more data from the Main Survey as part of the Data Release 2 and it will include 120,000 individual images observed over the past four years.

The area of Fast Radio Bursts has rapidly grown in 2018, with over 20 new discoveries made public by ASKAP and CHIME. The sources of these bursts is still unknown and it is hoped that offline GW searches may contribute to this field. Additionally OzGrav researchers have been working on sub-threshold searches for FRBs using the SPIIR pipeline.

Relativistic Astrophysics. Program chair: Paul Lasky

Run a Relativistic Astrophysics workshop in 2019 to encourage internode and interdisciplinary collaboration to exploit the uniquely diverse skill-set and expertise within the various OzGrav nodes.

Develop new gravitational-wave searches that target highly relativistic systems emitting gravitational waves. The development of new models (e.g., for neutron star-black hole systems, tests of general relativity, gravitational-wave emission from isolated pulsars, etc.) can then be used in inference codes such as Bilby to search LIGO/Virgo data sets, or with designated data-analysis algorithms.

Population Modelling. Program chair: Simon Stevenson

Begin third observational run (O3) for Advanced LIGO and Virgo at enhanced sensitivities, with potentially tens of new gravitational-waves being observed.

Develop new techniques and models to explore the population of binary black hole merger properties including their rates, masses, spins, eccentricities and how they vary with redshift and capitalize on the ever growing gravitational-wave catalogue. Ensure sustained OzGrav involvement in Rates and Populations group of the LVC, from development through to contribution to an eventual O3 populations paper.

Analyse the population of O2 binary black hole mergers.

Study optical transients known as Luminous Red Novae as probes of common envelope evolution. Use COMPAS to study the population of Galactic double neutron stars as pulsars. Improve stellar evolution in COMPAS, and speeding up COMPAS simulations using importance sampling named STROOPWAFEL.

Identify sub-populations of gravitational-wave observations using model independent methods.

OzSTAR supercomputer. Leader: Jarrod Hurley

The Gravitational Wave Data Centre will be established at Swinburne in 2019 and will be closely aligned with the Swinburne ADACS node – leveraging off the existing expertise and forming a critical mass of software engineers and hardware experts. Activities will include taking the necessary steps to secure official LIGO Tier 3 Data Centre status for OzSTAR, further development of Bilby to increase the data access and deployment of the application while moving towards a full gravitational wave virtual laboratory, support for Deeper-Wider-Faster operations on OzSTAR and new projects for further GPU code optimisation of key LIGO processing software.

Hardware activities will include a 10% increase of the capacity of the existing Lustre filesystem and the addition of compute nodes housing the latest Nvidia V100 GPUs (hardware procured in late 2018 with installation in early 2019). This will be followed by the installation of a second tier of mass storage which will provide capacity of up to 20 PB and provisioning of a high I/O node customised for rapid processing of pulsar data.

OzGrav and ADACS staff will collaborate to deliver a two-day machine learning workshop focussed on the use of neural networks in gravitational wave astronomy.

Research Translation

- Continue to refine and promote our new research translation seed funding scheme, and mentor our ECRs to take up this opportunity to develop their innovative and entrepreneurial ideas
- The Research Translation Chair will undertake a tour of our nodes to engage closely with our members to identify and advise on technology transfer opportunities
- Continue to deliver briefings to industry, and provide industry internships and industry networking opportunities to our ECRs

Professional Development

- Continue to monitor and develop the OzGrav mentoring program for ECRs
- Expand the OzGrav webinar series including topics of particular interest to ECRs
- Work with the ECR Committee to best tailor our activities and training for the ECRs
- Design an innovative and constructive ECR Workshop for the OzGrav annual retreat

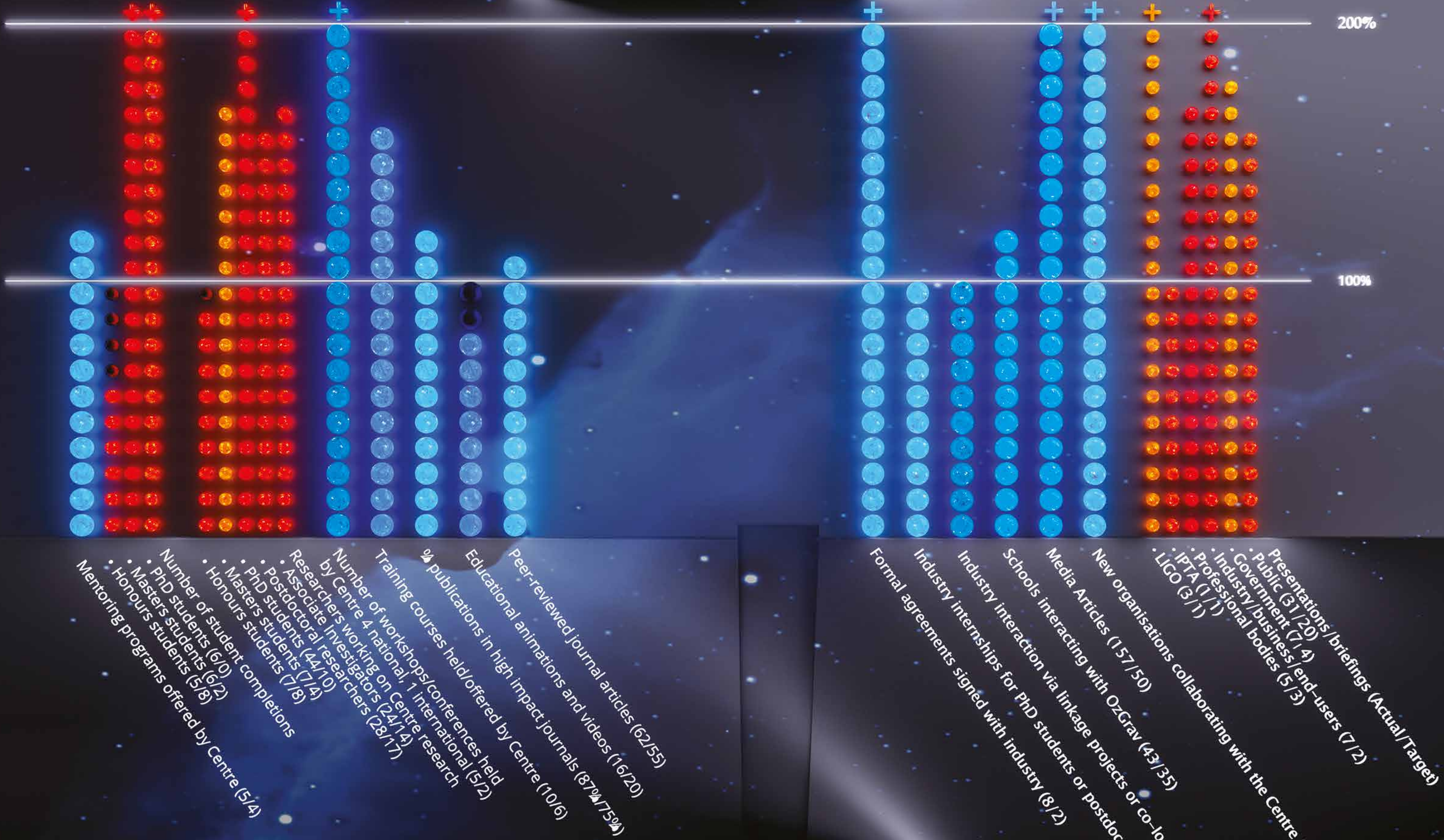
Equity and Diversity

- Conduct annual climate survey to monitor the level of diversity and inclusiveness in the centre and to identify areas for improvement
- Increase engagement with our education and outreach program by people from under-represented or disadvantaged populations
- Implement recruitment and professional development strategies to increase female representation in mid-to-senior level researcher positions in the centre
- Position ourselves so that we are able to meet the criteria for the next level of Pleiades Award in the next round (i.e. Silver Award in 2020)

Outreach

- Build on the success of the pilot phase of the schools incursion program, Mission Gravity, by training members at other nodes to deliver the program. While the first version of Mission Gravity was targeted at high school students, in 2019, we will develop a modified version for primary school kids.
- Enhance our VR app SciVR to improve its accessibility, and use SciVR as the basis for an outreach event at National Science Week
- Increase and broaden teacher engagement to support their content base and professional learning via workshop and conference presentations.
- Continue to engage with science centres such as the Gravity Discovery Centre in WA, where we have built an interactive educational display. In 2019, we will work to make this interactive content available to more museums and outreach centres.
- Continue to provide science communication training for our members throughout the year, including group training and individual assistance.
- Develop impactful media release materials to support the science breakthroughs and discoveries that we look forward to in 2019 when the upgraded detectors resume operations.
- Develop tools to make it easier for members to create interactive and visually stunning presentations for their public and conference talks.

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)
CHIME
Chinese Academy of Sciences Institute of Theoretical Physics
French Space Agency
GOTO Collaboration
GrandMa collaboration
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
MeerTime Collaboration (Manchester, ASTRON, MPIfR, CNRS, SARAO, NRAO, CSIRO, Curtin, AUT, UBC, INAF)
Montana State University
NASA Goddard Space Flight Centre
Tsinghua University
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 Partners and Collaborators

Astronomy Australia Ltd
Australian Astronomical Observatory (AAO)
CGG Aviation
Centre for Eye Research Australia (CERA)
Charles Sturt University
CSIRO Australia Telescope National Facility (ATNF)
International Centre for Radio Astronomy Research (ICRAR)
Liquid Instruments
University of Sydney


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


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

LIGO Scientific Collaboration (LSC)

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 kilometers apart in Hanford (Washington) and Livingston (Louisiana), LIGO exploits the physical properties of light and of space itself to detect and understand the origins of gravitational waves.

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

LSC Working Groups

Boris Goncharov (Monash) running narrowband and broadband radiometer searches for LIGO Stochastic group. Bram Slagomolen (ANU) GWIC 'Site Evaluation' subgroup, responsible for determining the future 3G site requirements for in the big GWIC 3G Science Whitepaper.

A/Prof Eric Thrane was the Review Chair, Burst Group. Grant Meadors (Monash) elected as LVC Allies co-ordinator, and responsibility as a search reviewer.

Hannah Middleton (Melbourne) Editor-in-chief for LIGO Magazine from Nov 2018 (and deputy editor-in-chief before that). Jesper Munch (Adelaide) serves on KAGRA PAB committee.

Karl Wette was elected Co-chair of Continuous Wave Working Group. Ryan Shannon (Swinburne) is Chair of the International Pulsar Timing Array (IPTA). Paul Lasky (Monash) is Co-Chair of the IPTA gravitational-wave working group, and serves on the PPTA steering committee.

Terry McRae (ANU) is DetChar Squeezer subsystem lead. David McClelland (ANU) was LIGO Scientific Collaboration (LSC) Instument Science Lead (until April); serves on the LSC Program Committee; LSC MoU review Committee; OzGrav representative on Gravitational Wave International Committee (GWIC) and GWIC3G R&D Committee Co-Chair.

Vaishali Adya is Postdoc representative for LAAC (Ligo Academic Advisory Council) which is responsible for overseeing and documenting the collaboration's activities in representing and protecting the interests of students and postdoctoral researchers. It also provides education and training activities for new students and postdocs in the collaboration.


Image: Virgo Collaboration


Image: Nutsinee Kijbunchoo, OzGrav ANU

LINKAGES AND COLLABORATIONS

Knighthood in UK Queen's Birthday Honours 2018

Congratulations Prof James (Jim) Hough (University of Glasgow) on being awarded the Gold Medal of the Royal Astronomical Society for his leadership and pioneering contributions to the field of gravitational waves.

Prof Hough was also awarded a knighthood in the UK Queen's Birthday honours 2018. His knighthood was for his leadership role in the detection of gravitational waves. We are extremely fortunate to benefit from Jim's wisdom and experience through his role as Chair of our Scientific Advisory Committee as well as his participation at our events, and (in Australian terms) for being an all-round good bloke.

Charles Hard Townes award

The Optical Society (OSA) is pleased to name OzGrav Associate Investigator Peter Fritschel, Kavli Institute for Astrophysics and Space Research, MIT the 2018 Charles Hard Townes Award recipient. Fritschel is recognized for advances in quantum-limited precision measurement in the Advanced LIGO detectors, leading to the first direct detection of gravitational waves.

"Peter Fritschel has dedicated much of his career to gravitational wave detection. His studies, along with many others, have lead us into the age of multi-messenger astronomy," said Charles H. Townes Award Selection Committee Chair, Giulio Cerullo, Politecnico di Milano, Italy. "We have come a long way in imaging the universe through ground-based laser technology and I am confident that Fritschel and his team will continue to provide us insights into our universe and beyond."

ARC Laureate Fellowship

Member of our Governance Advisory Committee (GAC) Professor Tamara Davis (University of Queensland) was awarded a Laureate Fellowship in August 2018. Dark energy and dark matter are amongst the most profound puzzles facing fundamental physics. This project will substantially advance our understanding of the physics of our Universe, inspiring the next generation of innovators. Congratulations Tamara!

Royal Society Fellowship

OzGrav Partner Investigator Professor Sheila Rowan, director of the University of Glasgow's Institute for Gravitational Research (IGR), has been made a Fellow of the Royal Society for her pioneering work on gravitational wave detection. Professor Rowan led a team of physicists who made key contributions to the international LIGO Scientific Collaboration on the conception, development, construction and installation of sensitive mirror suspensions in the heart of the LIGO detectors in Livingston and Hanford, which were crucial to the first detection.

FINANCE

	2018 Forecast	2018 Actuals	2019 Forecast
INCOME			
ARC Centre Grant	$4,687,523	$4,687,523	$4,881,564
Institutional cash contribution	$1,127,000	$1,142,870	$1,147,000
Other grants and contracts			
Total Income	$5,814,523	$5,830,393	$6,028,564
EXPENDITURE			
Salaries & scholarships	$3,888,747	$3,223,514	$3,860,890
Equipment	$ 581,441	$ 290,029	$ 709,016
Travel and Annual Retreat	$ 662,700	$ 729,264	$ 765,727
Research maintenance and consumables	$ 222,500	$ 485,429	$ 509,700
Outreach, operations and other expenditure	$ 455,181	$ 239,569	$ 251,548
Total Expenditure	$5,810,569	$4,967,805	$6,096,881
Carry-forward from previous year	$3,818,226	$3,818,226	$4,680,813
BALANCE	$3,822,180	$4,680,813	$4,612,497

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 five OzGrav committees; the Governance Advisory Committee, Scientific Advisory Committee, Research Translation Committee, Professional Development Committee, and the Equity and Diversity Committee.

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

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

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

The Research Translation Committee is responsible for overseeing the identification and management of commercialisable technologies developed under the Centre, and advising on strategies and initiatives to support industry engagement and technology transfer.

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

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

The Centre makes excellent use of videoconferencing to facilitate communications and collaboration among our dispersed team and committees. Our weekly centre-wide videoconferences, in particular, have helped galvanise the Centre. These meetings are attended by as many as 40-50 people each week and give members an opportunity to discuss science and share general updates.

OzGrav Executive Committee

Professor Matthew Bailes - OzGrav Director
Swinburne University of Technology

Professor David McClelland - OzGrav Deputy Director
Australian National University

Professor Susan Scott - Career Development Leader
Australian National University

Professor Daniel Shaddock - Research Translation Leader
Australian National University

A/Professor Chunnong Zhao
University of Western Australia

Professor Andrew Melatos
University of Melbourne

A/Professor Eric Thrane
Monash University

Professor Peter Veitch
University of Adelaide

Professor David Blair - Outreach Leader
University of Western Australia

Image: Beyond Perception, Scienceworks

Partner Investigators

Prof Rana Adhikari - Caltech

Dr Douglas Bock - CSIRO

Dr Marica Branchesi - Urbino University

Prof Rong-Gen Cai - Kavli Institute (China)

Dr Brad Cenko - NASA Goddard Space Flight Centre

Prof Karsten Danzmann - Max Plank (Einstein) Institute

Dr George Hobbs - CSIRO

A/Prof Mansi Kasliwal - Caltech

Prof Michael Kramer -Max Planck Institute (Radio Astronomy)

Prof Shrinivas Kulkarni - Caltech

Prof Nergis Mavalvala - MIT

Dr David Reitze - Caltech

Prof Sheila Rowan - University of Glasgow

Dr David Shoemaker - MIT Kavli Institute for Astrophysics and Space Research

Reader Danny Steeghs - University of Warwick

Dr Stephen Taylor - Caltech

Prof Alan Weinstein - Caltech

Chief Investigators, Associate Investigators, Affiliates, 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.

Image: Stargazing Live, ABC

Governance Advisory Committee

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

Dr Gregory Clark
Visiting Fellow, the Australian National University

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

Dr Tanya Hill
Senior Curator, Melbourne Planetarium, Museum Victoria

Dr Chiara Mingarelli
Flatiron Institute's Center for Computational Astrophysics

Dr John O'Sullivan
CSIRO

Prof Aleks Subic
Deputy Vice-Chancellor (Research & Development), Swinburne University

Dr Douglas Robertson
Director, ANU Research Services and delegate of the ANU DVC-R

Prof Matthew Bailes
OzGrav Director

Dr Yeshe Fenner
OzGrav Chief Operating Officer

GOVERNANCE

Scientific Advisory Committee

Prof James Hough - Chair
Professor, University of Glasgow, Director at Institute of Gravitational Research, University of Glasgow

Prof Takaaki Kajita
Professor, University of Tokyo, Director at Institute for Cosmic Ray Research

Prof Vicky Kalogera
E. O. Haven Professor, Northwestern University, Director at Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA)

Prof Barry Barish
Linde Professor of Physics, Emeritus, California Institute of Technology

Dr Joan Centrella
Deputy Director, Astrophysics Science Division, NASA

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

Research Translation Committee

Professor Daniel Shaddock - Chair
Australian National University

Prof Matthew Cuthbertson
Pro Vice Chancellor (Research Development, Innovation and Commercilaisation), Swinburne University of Technology

Dr Fiona Nelms
Director, Technology Transfer Office, Australian National University

Greg Redden
Director Industry Engagement and Commercial, Monash University

Dr Yeshe Fenner
Swinburne University of Technology

Professor Li Ju
University of Western Australia

Professor Robin Evans
University of Melbourne

Professor David Ottaway
University of Adelaide

Equity and Diversity Committee

Prof Matthew Bailes - Chair
Swinburne University of Technology

Prof Li Ju
University of Western Australia

A/Prof Eric Thrane
Monash University

Dr Rob Ward
Australian National University

Dr Yeshe Fenner
Swinburne University of Technology

Dr Jade Powell
Swinburne University of Technology

Dr Hannah Middleton
University of Melbourne

Lucy Strang
University of Melbourne

Dr Grant David Meadors
Monash University

Image: Town Hall After Dark. Credit: ImagePlay

Professional Development Committee

Prof Susan Scott - Chair
Australian National University

Dr Kendall Ackley
Monash University

Dr Yeshe Fenner
Swinburne University of Technology

George Howitt
University of Melbourne

Joshua McCann
University of Western Australia

Prof Andrew Melatos
University of Melbourne

Prof David Ottaway
University of Adelaide

Dr Karl Wette
Australian National University

Early Career Researcher Committee

Poojan Agrawal
Swinburne University of Technology

Dr Joris van Heijningan
University of Western Australia

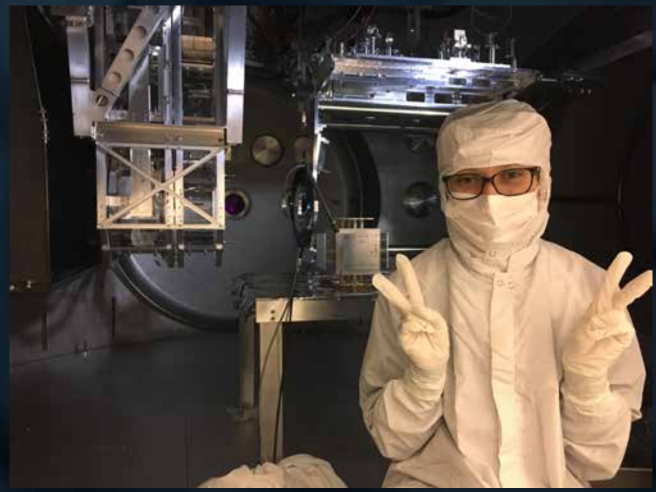
Craig Ingram
University of Adelaide

Dr Grant David Meadors
Monash University

Dr Terry McRae
Australian National University

Dr Meg Millhouse
University of Melbourne

Image: Georgia Mansell hanging out next to an electric field meter prototype and the Y end test mass.



PUBLICATIONS

LIGO Scientific Collaboration Abbott et al. Prospects for observing and localizing gravitational-wave transients with Advanced LIGO, Advanced Virgo and KAGRA. Living Reviews in Relativity. 10.1007/s41114-018-0012-9

LIGO Scientific Collaboration Abbott et al. All-sky search for long-duration gravitational wave transients in the first Advanced LIGO observing run. Classical and Quantum Gravity. 10.1088/1361-6382/aaab76

LIGO Scientific Collaboration Abbott et al. Effects of data quality vetoes on a search for compact binary coalescences in Advanced LIGO's first observing run. Classical and Quantum Gravity. 10.1088/1361-6382/aaaafa

LIGO Scientific Collaboration Abbott et al. GW170817: Implications for the Stochastic Gravitational-Wave Background from Compact Binary Coalescences. Physical Review Letters. 10.1103/PhysRevLett.120.091101

LIGO Scientific Collaboration Abbott et al. First Search for Nontensorial Gravitational Waves from Known Pulsars. Physical Review Letters. 10.1103/PhysRevLett.120.031104

LIGO Scientific Collaboration Abbott et al. Search for Tensor, Vector, and Scalar Polarizations in the Stochastic Gravitational-Wave Background. Physical Review Letters. 10.1103/PhysRevLett.120.201102

LIGO Scientific Collaboration Abbott et al. Constraints on cosmic strings using data from the first Advanced LIGO observing run. Physical Review D. 10.1103/PhysRevD.97.102002

LIGO Scientific Collaboration Abbott et al. Full band all-sky search for periodic gravitational waves in the O1 LIGO data. Physical Review D. 10.1103/PhysRevD.97.102003

LIGO Scientific Collaboration Abbott et al. Search for Subsolar-Mass Ultracompact Binaries in Advanced LIGO's First Observing Run. Physical Review Letters. 10.1103/PhysRevLett.121.231103

LIGO Scientific Collaboration Abbott et al. GW170817: Measurements of Neutron Star Radii and Equation of State. Physical Review Letters. 10.1103/PhysRevLett.121.161101

Abdalla, H., Aharonian, F., Ait Benkhali, F., Angöner, E.O., Arakawa, M., Arcaro, C., Armand, C., Arrieta, M., Backes, M., Barnard, M., Becherini, Y., Becker Tjus, J., Berge, D., Bernhard, S., Bernlöhr, K., Blackwell, R., Böttcher, M., Boisson, C., Bolmont, J., Bonnefoy, S., Bordas, P., Bregeon, J., Brun, F., Brun, P., Bryan, M., Böchele, M., Bulik, T., Bylund, T., Capasso, M., Caroff, S., Carosi, A., Casanova, S., Cerruti, M., Chakraborty, N., Chandra, S., Chaves, R.C.G., Chen, A., Colafrancesco, S., Condon, B., Davids, I.D., Deil, C., Devin, J., DeWilt, P., Dirson, L., Djannati-Ataï, A., Dmytriiev, A., Donath, A., Doroshenko, V., Drury, L.O'C., Dyks, J., Egberts, K., Emery, G., Ernenwein, J.-P., Eschbach, S., Fegan, S., Fiasson, A., Fontaine, G., Funk, S., Füßling, M., Gabici, S., Gallant, Y.A., Gaté, F., Giavitto, G., Glawion, D., Glicenstein, J.F., Gottschall, D., Grondin, M.-H., Hahn, J., Haupt, M., Heinzelmann, G., Henri, G., Hermann, G., Hinton, J.A., Hofmann, W., Hoischen, C., Holch, T.L., Holler, M., Horns, D., Huber, D., Iwasaki, H., Jacholkowska, A., Jamrozy, M., Jankowsky, D., Jankowsky, F., Jouvin, L., Jung-Richardt, I., Kastendieck, M.A., Katarzýnski, K., Katsuragawa, M., Katz, U., Kerszberg, D., Khangulyan, D., Khélifi, B., King, J., Klepser, S., Klúzniak, W., Komin, Nu., Kosack, K., Krakau, S., Kraus, M., Kröger, P.P., Lamanna, G., Lau, J., Lefaucheur, J., Lemière, A., Lemoine-Goumard, M., Lenain, J.-P., Leser, E., Lohse, T., Lorentz, M., López-Coto, R., Lypova, I., Malyshev, D., Marandon, V., Marcowith, A., Mariaud, C., Martí-Devesa, G., Marx, R., Maurin, G., Meintjes, P.J., Mitchell, A.M.W., Moderski, R., Mohamed, M., Mohrmann, L., Moulin, E., Murach, T., Nakashima, S., De Naurois, M., Ndiyavala, H., Niederwanger, F., Niemiec, J., Oakes, L., O'Brien, P., Odaka, H., Ohm, S., Ostrowski, M., Oya, I., Padovani, M., Panter, M., Parsons, R.D., Perennes, C., Petrucci, P.-O., Peyaud, B., Piel, Q., Pita, S., Poireau, V., Priyana Noel, A., Prokhorov, D.A., Prokoph, H., Pöhlhofer, G., Punch, M., Quirrenbach, A., Raab, S., Rauth, R., Reimer, A., Reimer, O., Renaud, M., Rieger, F., Rinchiuso, L., Romoli, C., Rowell, G., Rudak, B., Ruiz-Velasco, E., Sahakian, V., Saito, S., Sanchez, D.A., Santangelo, A., Sasaki, M., Schlickeiser, R., Schössler, F., Schulz, A., Schwanke, U., Schwemmer, S., Seglar-Arroyo, M., Senniappan, M., Seyffert, A.S., Shafi, N., Shilon, I., Shiningayamwe, K., Simoni, R., Sinha, A., Sol, H., Spanier, F., Specovius, A., Spir-Jacob, M., Stawarz, L., Steenkamp, R., Stegmann, C., Steppa, C., Takahashi, T., Tavernet, J.-P., Tavernier, T., Taylor, A.M., Terrier, R., Tibaldo, L., Tiziani, D., Tluczykont, M., Trichard, C., Tsirou, M., Tsuji, N., Tuffs, R., Uchiyama, Y., Van Der Walt, D.J., Van Eldik, C., Van Rensburg, C., Van Soelen, B., Vasileiadis, G., Veh, J., Venter, C., Vincent, P., Vink, J., Voisin, F., Völk, H.J., Vuillaume, T., Wadiasingh, Z., Wagner, S.J., Wagner, R.M., White, R., Wierzcholska, A., Yang, R., Zaborov, D., Zacharias, M., Zanin, R., Zdziarski, A.A., Zech, A., Zefi, F., Ziegler, A., Zorn, J., Zywucka, N., Kerr, M., Johnston, S., Shannon, R.M.. First ground-based measurement of sub-20 GeV to 100 GeV γ-Rays from the Vela pulsar with H.E.S.S. II. Astronomy and Astrophysics. 10.1051/0004-6361/201732153

Archibald, A.M., Gusinskaia, N.V., Hessels, J.W.T., Deller, A.T., Kaplan, D.L., Lorimer, D.R., Lynch, R.S., Ransom, S.M., Stairs, I.H.. Universality of free fall from the orbital motion of a pulsar in a stellar triple system. Nature. 10.1038/s41586-018-0265-1

Barrett, J.W., Gaebel, S.M., Neijssel, C.J., Vigna-Gómez, A., Stevenson, S., Berry, C. P. L., Farr, W. M., Mandel, I.. Accuracy of inference on the physics of binary evolution from gravitational-wave observations. Monthly Notices of the Royal Astronomical Society. 10.1093/mnras/sty908

Bhandari, S., Keane, E.F., Barr, E.D., Jameson, A., Petroff, E., Johnston, S., Bailes, M., Bhat, N.D.R., Burgay, M., Burke-Spolaor, S., Caleb, M., Eatough, R.P., Flynn, C., Green, J.A., Jankowski, F., Kramer, M., Venkatraman Krishnan, V., Morello, V., Possenti, A., Stappers, B., Tiburzi, C., van Straten, W., Andreoni, I., Butterley, T., Chandra, P., Cooke, J., Corongiu, A., Coward, D.M., Dhillon, V.S., Dodson, R., Hardy, L.K., Howell, E.J., Jaroenjittichai, P., Klotz, A., Littlefair, S.P., Marsh, T.R., Mickaliger, M., Muxlow, T., Perrodin, D., Pritchard, T., Sawangwit, U., Terai, T., Tominaga, N., Torne, P., Totani, T., Trois, A., Turpin, D., Niino, Y., Wilson, R.W., Albert, A., André, M., Anghinolfi, M., Anton, G., Ardid, M., Aubert, J.-J., Avgitas, T., Baret, B., Barrios-Martí, J., Basa, S., Belhorma, B., Bertin, V., Biagi, S., Bormuth, R., Bourret, S., Bouwhuis, M.C., Brănzas, H., Bruijn, R., Brunner, J., Busto, J., Capone, A., Caramete, L., Carr, J., Celli, S., El Moursli, R.C., Chiarusi, T., Circella, M., Coelho, J.A.B., Coleiro, A., Coniglione, R., Costantini, H., Coyle, P., Creusot, A., Díaz, A.F., Deschamps, A., De Bonis, G., Distefano, C., Di Palma, I., Domi, A., Donzaud, C., Dornic, D., Drouhin, D., Eberl, T., El Bojaddaini, I., El Khayati, N., Elsässer, D., Enzenhöfer, A., Ettahiri, A., Fassi, F., Felis, I., Fusco, L.A., Gay, P., Giordano, V., Glotin, H., Gregoire, T., Gracia-Ruiz, R., Graf, K., Hallmann, S., van Haren, H., Heijboer, A.J., Hello, Y., Hernández-Rey, J.J., Hößl, J., Hofestädt, J., Hugon, C., Illuminati, G., James, C.W., de Jong, M., Jongen, M., Kadler, M., Kalekin, O., Katz, U., Kießling, D., Kouchner, A., Kreter, M., Kreykenbohm, I., Kulikovskiy, V., Lachaud, C., Lahmann, R., Lefevre, D., Leonora, E., Loucatos, S., Marcelin, M., Margiotta, A., Marinelli, A., Martínez-Mora, J.A., Mele, R., Melis, K., Michael, T., Migliozzi, P., Moussa, A., Navas, S., Nezri, E., Organokov, M., Pavalas, G.E., Pellegrino, C., Perrina, C., Piattelli, P., Popa, V., Pradier, T., Quinn, L., Racca, C., Riccobene, G., Sánchez-Losa, A., Saldana, M., Salvadori, I., Samtleben, D.F.E., Sanguineti, M., Sapienza, P., Schüssler, F., Sieger, C., Spurio, M., Stolarczyk, T., Taiuti, M., Tayalati, Y., Trovato, A., Turpin, D., Tönnis, C., Vallage, B., Van Elewyck, V., Versari, F., Vivolo, D., Vizzocca, A., Wilms, J., Zornoza, J.D., Zúniga, J.. The survey for pulsars and extragalactic radio bursts - II. new FRB discoveries and their follow-up. Monthly Notices of the Royal Astronomical Society. 10.1093/mnras/stx3074

Bhat, N.D.R., Tremblay, S.E., Kirsten, F., Meyers, B.W., Sokolowski, M., Straten, W.V., McSweeney, S.J., Ord, S.M., Shannon, R.M., Beardsley, A., Crosse, B., Emrich, D., Franzen, T.M.O., Horsley, L., Johnston-Hollitt, M., Kaplan, D.L., Kenney, D., Morales, M.F., Pallot, D., Steele, K., Tingay, S.J., Trott, C.M., Walker, M., Wayth, R.B., Williams, A., Wu, C.. Observations of Low-frequency Radio Emission from Millisecond Pulsars and Multipath Propagation in the Interstellar Medium. Astrophysical Journal, Supplement Series. 10.3847/1538-4365/aad37c

Bilous, A.V., Watts, A.L., Galloway, D.K., In'T Zand, J.J.M.. A Millisecond Oscillation in the Bursting X-Ray Flux of SAX J1810.8-2609. Astrophysical Journal Letters. 10.3847/2041-8213/aad09c

Borisov, G., Devogèle, M., Cellino, A., Bagnulo, S., Christou, A., Bendjoya, P., Rivet, J.-P., Abe, L., Vernet, D., Donchev, Z., Krugly, Y., Belskaya, I., Bonev, T., Steeghs, D., Galloway, D., Dhillon, V., O'Brien, P., Pollacco, D., Poshyachinda, S., Ramsay, G., Thrane, E., Ackley, K., Rol, E., Ulaczyk, K., Cutter, R., Dyer, M.. Rotational variation of the linear polarization of the asteroid (3200) Phaethon as evidence for inhomogeneity in its surface properties. Monthly Notices of the Royal Astronomical Society: Letters. 10.1093/mnrasl/sly140

Buckley, D.A.H., Andreoni, I., Barway, S., Cooke, J., Crawford, S.M., Gorbovskoy, E., Gromadzki, M., Lipunov, V., Mao, J., Potter, S.B., Pretorius, M.L., Pritchard, T.A., Romero-Colmenero, E., Shara, M.M., Väisänen, P., Williams, T.B.. A comparison between SALT/SAAO observations and kilonova models for AT 2017gfo: The first electromagnetic counterpart of a gravitational wave transient - GW170817. Monthly Notices of the Royal Astronomical Society: Letters. 10.1093/mnrasl/slx196

Calderon Bustillo, Juan and Clark, James A. and Laguna, Pablo and Shoemaker, Deirdre. Tracking Black Hole Kicks from Gravitational-Wave Observations. Physical Review Letters. 10.1103/PhysRevLett.121.191102

Choudhary, R.K., Foppoli, A., Kaur, T., Blair, D.G., Zadnik, M., Meagher, R.. Can a short intervention focused on gravitational waves and quantum physics improve students' understanding and attitude?. Physics Education.

Coughlin, M.W., Harms, J., Driggers, J., McManus, D.J., Mukund, N., Ross, M.P., Slagmolen, B.J.J., Venkateswara, K.. Implications of Dedicated Seismometer Measurements on Newtonian-Noise Cancellation for Advanced LIGO. Physical Review Letters. 10.1103/PhysRevLett.121.221104

Covas, P.B., Effler, A., Goetz, E., Meyers, P.M., Neunzert, A., Oliver, M., Pearlstone, B.L., Roma, V.J., Schofield, R.M.S., Adya, V.B., Astone, P., Biscoveanu, S., Callister, T.A., Christensen, N., Colla, A., Coughlin, E., Coughlin, M.W., Crowder, S.G., Dwyer, S.E., Eggenstein, H.-B., Hourihane, S., Kandhasamy, S., Liu, W., Lundgren, A.P., Matas, A., McCarthy, R., McIver, J., Mendell, G., Ormiston, R., Palomba, C., Papa, M.A., Piccinni, O.J., Rao, K., Riles, K., Sammut, L., Schlassa, S., Sigg, D., Strauss, N., Tao, D., Thorne, K.A., Thrane, E., Trembath-Reichert, S., Abbott, B.P., Abbott, R., Abbott, T.D., Adams, C., Adhikari, R.X., Ananyeva, A., Appert, S., Arai, K., Aston, S.M., Austin, C., Ballmer, S.W., Barker, D., Barr, B., Barsotti, L., Bartlett, J., Bartos, I., Batch, J.C., Bejger, M., Bell, A.S., Betzwieser, J., Billingsley, G., Birch, J., Biscans, S., Biwer, C., Blair, C.D., Blair, R.M., Bork, R., Brooks, A.F., Cao, H., Ciani, G., Clara, F., Clearwater, P., Cooper, S.J., Corban, P., Countryman, S.T., Cowart, M.J., Coyne, D.C., Cumming, A., Cunningham, L., Danzmann, K., Costa, C.F.D.S., Daw, E.J., Debra, D., Derosa, R.T., Desalvo, R., Dooley, K.L., Doravari, S., Driggers, J.C., Edo, T.B., Etzel, T., Evans, M., Evans, T.M., Factourovich, M., Fair, H., Galiana, A.F., Ferreira, E.C., Fisher, R.P., Fong, H., Frey, R., Fritschel, P., Frolov, V.V., Fulda, P., Fyffe, M., Gateley, B., Giaime, J.A., Giardina, K.D., Goetz, R., Goncharov, B., Gras, S., Gray, C., Grote, H., Gushwa, K.E., Gustafson, E.K., Gustafson, R., Hall, E.D., Hammond, G., Hanks, J., Hanson, J., Hardwick, T., Harry, G.M., Heintze, M.C., Heptonstall, A.W., Hough, J., Inta, R., Izumi, K., Jones, R., Karki, S., Kasprzack, M., Kaufer, S., Kawabe, K., Kennedy, R., Kijbunchoo, N., Kim, W., King, E.J., King, P.J., Kissel, J.S., Korth, W.Z., Kuehn, G., Landry, M., Lantz, B., Laxen, M., Liu, J., Lockerbie, N.A., Lormand, M., Macinnis, M., Macleod, D.M., Márka, S., Márka, Z., Markosyan, A.S., Maros, E., Marsh, P., Martin, I.W., Martynov, D.V., Mason, K., Massinger, T.J., Matichard, F., Mavalvala, N., McClelland, D.E., McCormick, S., McCuller, L., McIntyre, G., McRae, T., Merilh, E.L., Miller, J., Mittleman, R., Mo, G., Mogushi, K., Moraru, D., Moreno, G., Mueller, G., Mukund, N., Mullavey, A., Munch, J., Nelson, T.J.N., Nguyen, P., Nuttall, L.K., Oberling, J., Oktavia, O., Oppermann, P., Oram, R.J., O'Reilly, B., Ottaway, D.J., Overmier, H., Palamos, J.R., Parker, W., Pele, A., Penn, S., Perez, C.J., Phelps, M., Pierro, V., Pinto, I., Principe, M., Prokhorov, L.G., Puncken, O., Quetschke, V., Quintero, E.A., Radkins, H., Raffai, P., Ramirez, K.E., Reid, S., Reitze, D.H., Robertson, N.A., Rollins, J.G., Romel, C.L., Romie, J.H., Ross, M.P., Rowan, S., Ryan, K., Sadecki, T., Sanchez, E.J., Sanchez, L.E., Sandberg, V., Savage, R.L., Sellers, D., Shaddock, D.A., Shaffer, T.J., Shapiro, B., Shoemaker, D.H., Slagmolen, B.J.J., Smith, B., Smith, J.R., Sorazu, B., Spencer, A.P., Staley, A., Strain, K.A., Sun, L., Tanner, D.B., Tasson, J.D., Taylor, R., Thomas, M., Thomas, P., Toland, K., Torrie, C.I., Traylor, G., Tse, M., Tuyenbayev, D., Vajente, G., Valdes, G., Van Veggel, A.A., Vecchio, A., Veitch, P.J., Venkateswara, K., Vo, T., Vorvick, C., Wade, M., Walker, M., Ward, R.L., Warner, J., Weaver, B., Weiss, R., Weßels, P., Willke, B., Wipf, C.C., Wofford, J., Worden, J., Yamamoto, H., Yancey, C.C., Yu, H., Yu, H., Zhang, L., Zhu, S., Zucker, M.E., Zweizig, J.. Identification and mitigation of narrow spectral artifacts that degrade searches for persistent gravitational waves in the first two observing runs of Advanced LIGO. Physical Review D. 10.1103/PhysRevD.97.082002

PUBLICATIONS

Cripe, J., Aggarwal, N., Singh, R., Lanza, R., Libson, A., Yap, M.J., Cole, G.D., McClelland, D.E., Mavalvala, N., Corbitt, T.. Radiation-pressure-mediated control of an optomechanical cavity. Physical Review A. 10.1103/PhysRevA.97.013827

Davis, Benjamin L.; Graham, Alister W.; Cameron, Ewan. Black Hole Mass Scaling Relations for Spiral Galaxies. II. M BH–M *,tot and M BH–M *,disk. The Astrophysical Journal. 10.3847/1538-4357/aae820

De Ugarte Postigo, A., Thöne, C.C., Bolmer, J., Schulze, S., Martín, S., Kann, D.A., D'Elia, V., Selsing, J., Martin-Carrillo, A., Perley, D.A., Kim, S., Izzo, L., Sánchez-Ramírez, R., Guidorzi, C., Klotz, A., Wiersema, K., Bauer, F.E., Bensch, K., Campana, S., Cano, Z., Covino, S., Coward, D., De Cia, A., De Gregorio-Monsalvo, I., De Pasquale, M., Fynbo, J.P.U., Greiner, J., Gomboc, A., Hanlon, L., Hansen, M., Hartmann, D.H., Heintz, K.E., Jakobsson, P., Kobayashi, S., Malesani, D.B., Martone, R., Meintjes, P.J., Michałowski, M.J., Mundell, C.G., Murphy, D., Oates, S., Salmon, L., Van Soelen, B., Tanvir, N.R., Turpin, D., Xu, D., Zafar, T.. X-shooter and ALMA spectroscopy of GRB 161023A: A study of metals and molecules in the line of sight towards a luminous GRB. Astronomy and Astrophysics. 10.1051/0004-6361/201833094

Dreissigacker, C., Prix, R., Wette, K.. Fast and accurate sensitivity estimation for continuous-gravitational-wave searches. Physical Review D. 10.1103/PhysRevD.98.084058

Fang, Q., Zhao, C., Blair, C., Ju, L., Blair, D.G.. Modular suspension system with low acoustic coupling to the suspended test mass in a prototype gravitational wave detector. Review of Scientific Instruments. 10.1063/1.5021503

Foppoli, A., Choudhary, R.K., Blair, D.G., Kaur, T., Moschilla, J., Zadnik, M.. Public and teacher response to Einsteinian physics in schools. Physics Education.

Farah, W., Flynn, C., Bailes, M., Jameson, A., Bannister, K.W., Barr, E.D., Bateman, T., Bhandari, S., Caleb, M., Campbell-Wilson, D., Chang, S.-W., Deller, A., Green, A.J., Hunstead, R., Jankowski, F., Keane, E., Macquart, J.-P., Möller, A., Onken, C.A., Oslowski, S., Parthasarathy, A., Plant, K., Ravi, V., Shannon, R.M., Tucker, B.E., Krishnan, V.V., Wolf, C.. FRB microstructure revealed by the real-time detection of FRB170827. Monthly Notices of the Royal Astronomical Society. 10.1093/mnras/sty1122

Francis, S.P., Lam, T.T.-Y., McClelland, D.E., Shaddock, D.A.. Multi-link laser interferometry architecture for interspacecraft displacement metrology. Journal of Geodesy. 10.1007/s00190-017-1059-1

Galloway, D.K., Zand, J.J.M.I., Chenevez, J., Keek, L., Sanchez-Fernandez, C., Worpel, H., Lampe, N., Kuulkers, E., Watts, A., Ootes, L.. The Influence of Stellar Spin on Ignition of Thermonuclear Runaways. Astrophysical Journal Letters. 10.3847/2041-8213/aabd32

Goncharov, B., Thrane, E.. All-sky radiometer for narrowband gravitational waves using folded data. Physical Review D. 10.1103/PhysRevD.98.064018

Guo, X., Chu, Q., Chung, S.K., Du, Z., Wen, L., Gu, Y.. GPU-acceleration on a low-latency binary-coalescence gravitational wave search pipeline. Computer Physics Communications. 10.1016/j.cpc.2018.05.002

Howell, E.J., Chan, M.L., Chu, Q., Jones, D.H., Heng, I.S., Lee, H.-M., Blair, D., Degallaix, J., Regimbau, T., Miao, H., Zhao, C., Hendry, M., Coward, D., Messenger, C., Ju, L., Zhu, Z.-H.. Host galaxy identification for binary black hole mergers with long baseline gravitational wave detectors. Monthly Notices of the Royal Astronomical Society. 10.1093/mnras/stx3077

Huang, Y., Middleton, H., Ng, K.K.Y., Vitale, S., Veitch, J.. Characterization of low-significance gravitational-wave compact binary sources. Physical Review D. 10.1103/PhysRevD.98.123021

Jaberian Hamedan, V., Zhao, C., Ju, L., Blair, C., Blair, D.G.. Suppression of thermal transients in advanced LIGO interferometers using CO2 laser preheating. Classical and Quantum Gravity. 10.1088/1361-6382/aabceb

Kerr, M., Coles, W.A., Ward, C.A., Johnston, S., Tuntsov, A.V., Shannon, R.M.. Extreme scattering events towards two young pulsars. Monthly Notices of the Royal Astronomical Society. 10.1093/mnras/stx3101

Liu, J., Bossilkov, V., Blair, C., Zhao, C., Ju, L., Blair, D.G.. Angular instability in high optical power suspended cavities. Review of Scientific Instruments. 10.1063/1.5049508

Mahony, E.K., Ekers, R.D., Macquart, J.-P., Sadler, E.M., Bannister, K.W., Bhandari, S., Flynn, C., Koribalski, B.S., Prochaska, J.X., Ryder, S.D., Shannon, R.M., Tejos, N., Whiting, M.T., Wong, O.I.. A Search for the Host Galaxy of FRB 171020. Astrophysical Journal Letters. 10.3847/2041-8213/aae7cb

Mansell, G.L., McRae, T.G., Altin, P.A., Yap, M.J., Ward, R.L., Slagmolen, B.J.J., Shaddock, D.A., McClelland, D.E.. Observation of Squeezed Light in the 2 μ m Region. Physical Review Letters. 10.1103/PhysRevLett.120.203603

Melatos, A., Howitt, G., Fulgenzi, W.. Size-waiting-time Correlations in Pulsar Glitches. Astrophysical Journal. 10.3847/1538-4357/aad228

Meyers, B.W., Tremblay, S.E., Bhat, N.D.R., Flynn, C., Gupta, V., Shannon, R.M., Murray, S.G., Sobey, C., Ord, S.M., Osłowski, S., Crosse, B., Williams, A., Jankowski, F., Farah, W., Krishnan, V.V., Bateman, T., Bailes, M., Beardsley, A., Emrich, D., Franzen, T.M.O., Gaensler, B.M., Horsley, L., Johnston-Hollitt, M., Kaplan, D.L., Kenney, D., Morales, M.F., Pallot, D., Steele, K., Tingay, S.J., Trott, C.M., Walker, M., Wayth, R.B., Wu, C.. Hunting for Radio Emission from the Intermittent Pulsar J1107-5907 at Low Frequencies. Astrophysical Journal. 10.3847/1538-4357/aaee7b

Middleton, H., Chen, S., Del Pozzo, W., Sesana, A., Vecchio, A.. No tension between assembly models of super massive black hole binaries and pulsar observations. Nature Communications. 10.1038/s41467-018-02916-7

Miller-Jones, J.C.A., Deller, A.T., Shannon, R.M., Dodson, R., Moldón, J., Ribó, M., Dubus, G., Johnston, S., Paredes, J.M., Ransom, S.M., Tomsick, J.A.. The geometric distance and binary orbit of PSR B1259-63. Monthly Notices of the Royal Astronomical Society. 10.1093/mnras/sty1775

Mooley, K.P., Deller, A.T., Gottlieb, O., Nakar, E., Hallinan, G., Bourke, S., Frail, D.A., Horesh, A., Corsi, A., Hotokezaka, K.. Superluminal motion of a relativistic jet in the neutron-star merger GW170817. Nature. 10.1038/s41586-018-0486-3

Mooley, K.P., Nakar, E., Hotokezaka, K., Hallinan, G., Corsi, A., Frail, D.A., Horesh, A., Murphy, T., Lenc, E., Kaplan, D.L., De, K., Dobie, D., Chandra, P., Deller, A., Gottlieb, O., Kasliwal, M.M., Kulkarni, S.R., Myers, S.T., Nissanke, S., Piran, T., Lynch, C., Bhalerao, V., Bourke, S., Bannister, K.W., Singer, L.P.. A mildly relativistic wide-angle outflow in the neutron-star merger event GW170817. Nature. 10.1038/nature25452

Page, M., La Fontaine, J., Chen, X., Zhao, C., Ju, L., Blair, D., Pan, H.-W., Chao, S.. Ultra-low dissipation resonators for improving the sensitivity of gravitational wave detectors. Physics Letters, Section A: General, Atomic and Solid State Physics. 10.1016/j.physleta.2017.06.031

Page, M., Qin, J., La Fontaine, J., Zhao, C., Ju, L., Blair, D.. Enhanced detection of high frequency gravitational waves using optically diluted optomechanical filters. Physical Review D. 10.1103/PhysRevD.97.124060

Patruno, A., Wette, K., Messenger, C.. A Deep Pulse Search in 11 Low Mass X-Ray Binaries. Astrophysical Journal. 10.3847/1538-4357/aabf89

Pitkin, M., Doolan, S., McMenamin, L., Wette, K.. Reduced order modelling in searches for continuous gravitational waves - I. Barycentring time delays. Monthly Notices of the Royal Astronomical Society. 10.1093/mnras/sty548

Porayko, N.K., Zhu, X., Levin, Y., Hui, L., Hobbs, G., Grudskaya, A., Postnov, K., Bailes, M., Bhat, N.D.R., Coles, W., Dai, S., Dempsey, J., Keith, M.J., Kerr, M., Kramer, M., Lasky, P.D., Manchester, R.N., Osłowski, S., Parthasarathy, A., Ravi, V., Reardon, D.J., Rosado, P.A., Russell, C.J., Shannon, R.M., Spiewak, R., Van Straten, W., Toomey, L., Wang, J., Wen, L., You, X.. Parkes Pulsar Timing Array constraints on ultralight scalar-field dark matter. Physical Review D. 10.1103/PhysRevD.98.102002

Powell, J.. Parameter estimation and model selection of gravitational wave signals contaminated by transient detector noise glitches. Classical and Quantum Gravity. 10.1088/1361-6382/aacf18

Shannon, R.M., Macquart, J.-P., Bannister, K.W., Ekers, R.D., James, C.W., Oslowski, S., Qiu, H., Sammons, M., Hotan, A.W., Voronkov, M.A., Beresford, R.J., Brothers, M., Brown, A.J., Bunton, J.D., Chippendale, A.P., Haskins, C., Leach, M., Marquarding, M., McConnell, D., Pilawa, M.A., Sadler, E.M., Troup, E.R., Tuthill, J., Whiting, M.T., Allison, J.R., Anderson, C.S., Bell, M.E., Collier, J.D., Gürkan, G., Heald, G., Riseley, C.J.. The dispersion–brightness relation for fast radio bursts from a wide-field survey. Nature. 10.1038/s41586-018-0588-y

Sokolowski, M., Bhat, N.D.R., Macquart, J.-P., Shannon, R.M., Bannister, K.W., Ekers, R.D., Scott, D.R., Beardsley, A.P., Crosse, B., Emrich, D., Franzen, T.M.O., Gaensler, B.M., Horsley, L., Johnston-Hollitt, M., Kaplan, D.L., Kenney, D., Morales, M.F., Pallot, D., Sleap, G., Steele, K., Tingay, S.J., Trott, C.M., Walker, M., Wayth, R.B., Williams, A., Wu, C.. No Low-frequency Emission from Extremely Bright Fast Radio Bursts. Astrophysical Journal Letters. 10.3847/2041-8213/aae58d

Sun, L., Melatos, A., Suvorova, S., Moran, W., Evans, R.J.. Hidden Markov model tracking of continuous gravitational waves from young supernova remnants. Physical Review D. 10.1103/PhysRevD.97.043013

Vigna-Gomez, A., Neijssel, C.J., Stevenson, S., Barrett, J.W., Belczynski, K., Justham, S., de Mink, S.E., Müller, B., Podsiadlowski, P., Renzo, M., Szécsi, D., Mandel, I.. On the formation history of Galactic double neutron stars. Monthly Notices of the Royal Astronomical Society. 10.1093/mnras/sty2463

Wang, L., Steeghs, D., Galloway, D.K., Marsh, T., Casares, J.. Precision Ephemerides for Gravitational-wave Searches - III. Revised system parameters of Sco X-1. Monthly Notices of the Royal Astronomical Society. 10.1093/mnras/sty1441

Wette, K., Prix, R., Keitel, D., Pitkin, M., Dreissigacker, C., Whelan, J. T., Leaci, P.. OctApps: a library of Octave functions for continuous gravitational-wave data analysis. Journal of Open Source Software. 10.21105/joss.00707

Wette, K., Walsh, S., Prix, R., Papa, M.A.. Implementing a semicoherent search for continuous gravitational waves using optimally constructed template banks. Physical Review D. 10.1103/PhysRevD.97.123016

You, X.P., Manchester, R.N., Coles, W.A., Hobbs, G.B., Shannon, R.. Polarimetry of the Eclipsing Pulsar PSR J1748-2446A. Astrophysical Journal. 10.3847/1538-4357/aadee0

Zhao, W., Wen, L.. Localization accuracy of compact binary coalescences detected by the third-generation gravitational-wave detectors and implication for cosmology. Physical Review D. 10.1103/PhysRevD.97.064031

Zhu, X., Thrane, E., Osłowski, S., Levin, Y., Lasky, P.D.. Inferring the population properties of binary neutron stars with gravitational-wave measurements of spin. Physical Review D. 10.1103/PhysRevD.98.043002