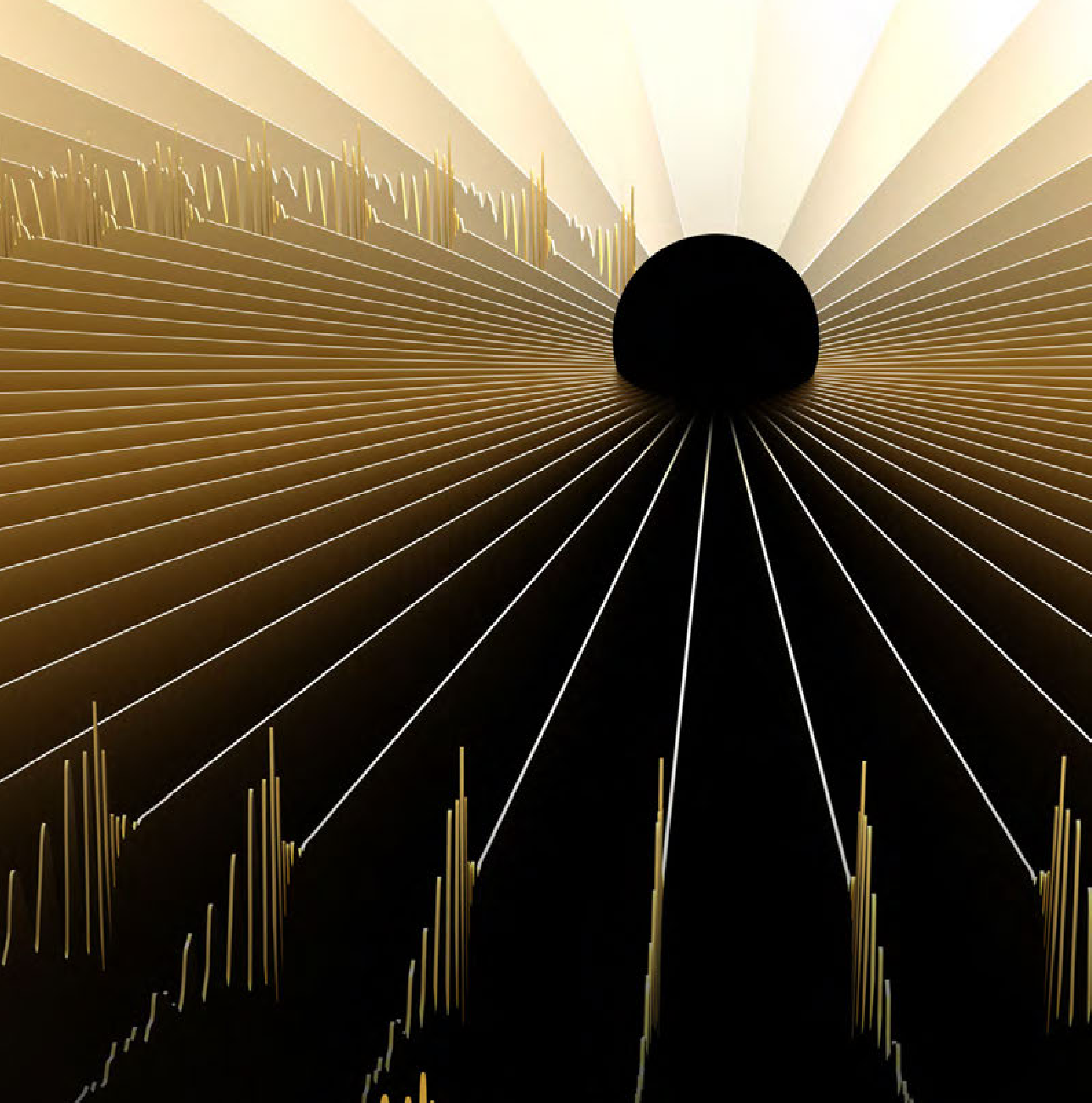

OzGrav

ARC Centre of Excellence for Gravitational Wave Discovery

Annual Report 2017

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.

Swinburne University of Technology · Australian National University · Monash University · The University of Adelaide

The University of Melbourne · The University of Western Australia · CSIRO · AAO

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MESSAGE FROM THE DIRECTOR

In 1981 as a young undergraduate at the University of Adelaide, I would take great joy in perusing the books in the astrophysics section in the library. My favourite book, “Black Holes, White Dwarfs and Neutron stars”, represented the intersection between science fiction and science fact. It described the then brand new field of relativistic astrophysics, driven by the first observations of neutron stars and black holes by the X-ray and radio telescopes of the 1960s and 70s. These instruments enabled the discovery of neutron stars and black holes, which had only been theoretical conjectures in the early 20th century. The popular science book was written in a manner which made these discoveries accessible to anyone with a basic knowledge of high school physics, and I was hooked.

By 1984 I was studying relativistic astrophysics in my Honours year, and my project concerned the binary pulsar - two neutron stars locked in a tight orbit - that was to provide the definitive evidence for the existence of gravitational waves and provide the 1993 Nobel Prize in physics to its discoverers, Russell Hulse and Joseph Taylor. They predicted that in 300 million years the binary pulsar would merge and unleash a burst of gravitational waves. There was good reason to believe that similar systems existed in other galaxies, and the Laser Interferometer Gravitational-Wave Observatory (LIGO) was designed and built to detect the cosmic gravitational waves produced by such mergers.

In 2014 when OzGrav was first mooted, the Advanced LIGO with improved detectors was nearing completion. The predecessor LIGO had not detected anything, and the decades long hunt for gravitational waves had yielded no fruit. The OzGrav team of instrumentalists, data processors and astrophysicists had to come up with a proposal that was optimistic, but realistic about the technical challenges and statistical uncertainties. One of the unique features of our OzGrav collaboration was the bringing together of the gravitational wave and pulsar communities. The pulsar astronomers provided a census of our own galaxy’s pulsar content, and the instrumentalists gave a realistic estimate of the range the new LIGO detector could see neutron star mergers. Based on estimates of the merger rates at that time, it was by no means assured that the detection of gravitational waves would occur during the lifetime of OzGrav. Nevertheless, I insisted that OzGrav’s name should encompass the goal of the Centre, that of Gravitational Wave Discovery. Our proposal described how we had the skills and expertise to help build and tune the detectors, process the data, use Australia’s telescopes to follow-up neutron star mergers, and astrophysicists to interpret the results.

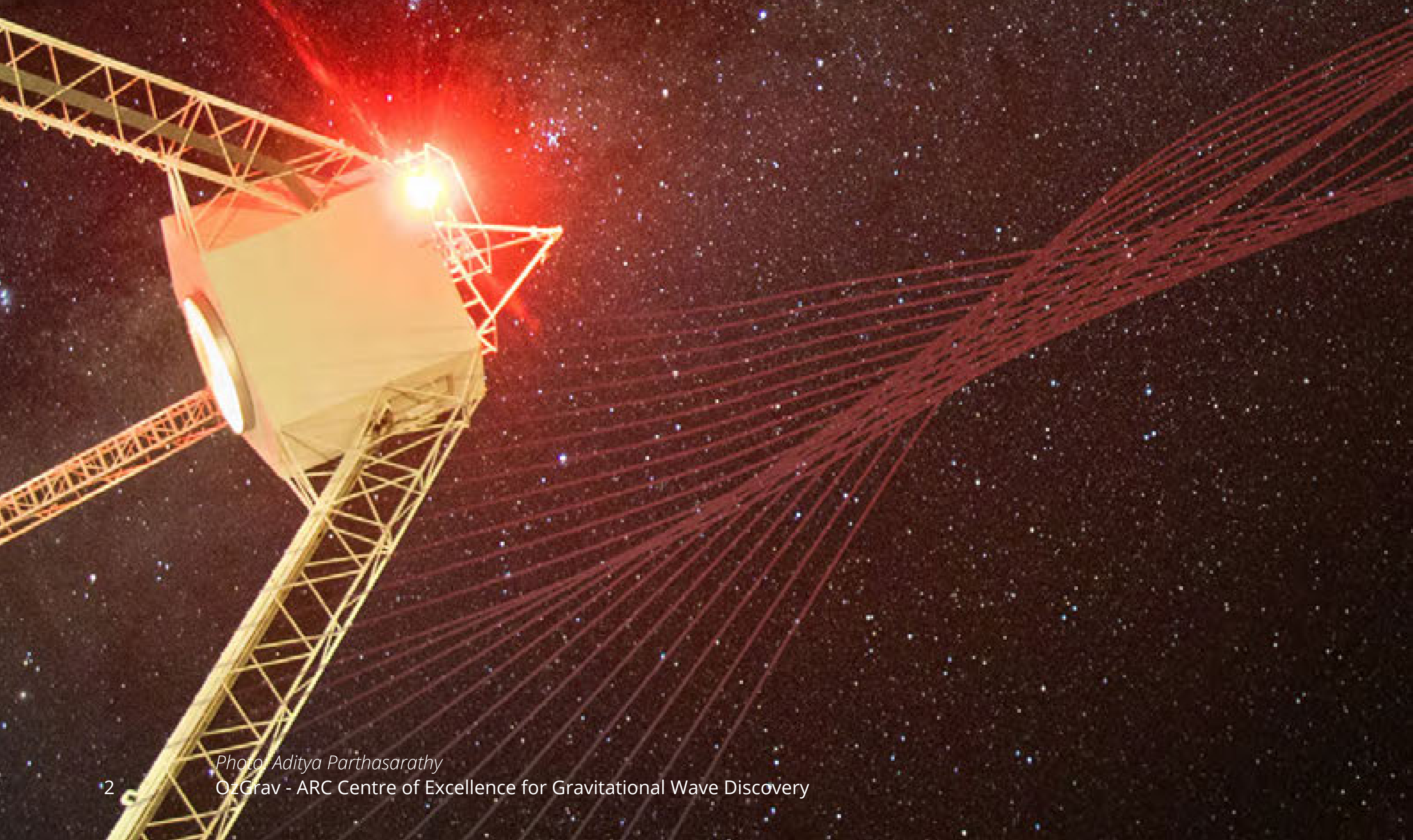


Photo: Aditya Parthasarathy

Remarkably, almost as soon as Advanced LIGO was turned on in September 2015, it unveiled its first source, a pair of 30 solar mass black holes in their final few orbits. This not only provided an impetus to give the go-ahead for OzGrav, but it captured the scientific community and public's imagination. The ARC Centre of Excellence for Gravitational Wave Discovery, OzGrav, started operations in April 2017, just over a year after the first detection of gravitational waves was announced and is perfectly timed to be a part of the exciting first decade of gravitational wave astrophysics.

For me the highlight of our first year came with the landmark discovery on 17 August 2017 of merging neutron stars in a nearby galaxy, in an event known as GW170817. I was fortunate enough to be at the LIGO Scientific Collaboration's meeting at CERN where the results were first discussed. It wasn't hard to feel like you were witnessing a part of scientific history. That single event revealed: the first neutron star merger; proof that the speed of light and the speed of gravitational waves were identical; the origin of short-duration gamma-ray bursts; the origin of the r-process elements (like gold and platinum); a new way to estimate the expansion rate of the Universe; and the first observations of a kilonova.

For many of my OzGrav colleagues who have been involved in the development of gravitational wave detectors for decades, the last couple of years has been confirmation that gravitational waves not only exist, but will be discovered in even greater numbers than initially expected.

A new window on the Universe has been opened, which is leading to new insights into the Universe. The excitement of the next generation of exceptionally talented students and postdocs we've attracted to OzGrav is infectious.

The dreams presented in a popular science book from the 1980s are now a reality, and I am looking forward to 2018 being a year of continued growth and consolidation for OzGrav, as we work with the global community to further understand the extraordinary physics behind gravitational waves.

OzGrav Director
Prof Matthew Bailes
Swinburne University of Technology

MESSAGES FROM THE CHAIRS

GOVERNANCE ADVISORY COMMITTEE (GAC)

ARC Centres of Excellence are large, ambitious projects and OzGrav is no exception. The Centre brings together very diverse scientific communities to pursue world-leading research, while preparing its members for a range of career paths, and using their scientific discoveries to inspire the public about physics and technology.

A robust governance framework is critical to maximizing the success of a Centre, and I am pleased with OzGrav's progress in its first year to put in place the appropriate and necessary structures for management and oversight. If that wasn't enough to keep OzGrav busy in 2017, the scientists were also part of a global team of researchers responsible for with an almost unprecedented series of major discoveries, the highlight of which was undoubtedly the discovery of colliding neutron stars. These events helped to galvanize the Centre and its programs, while garnering considerable national and international media attention. In its first year OzGrav certainly made its mark.

The Centre should be pleased with its progress against its Key Performance Indicators, particularly in regards to its scientific output (74 peer-reviewed publications) and impact (472 citations). The Centre will benefit enormously from the wisdom of OzGrav's Scientific Advisory Committee, chaired by international leader in gravitational waves Prof Jim Hough, the former Director and now Associate Director of the University of Glasgow's Institute for Gravitational Research, whose advice will help OzGrav target its efforts to make unique and significant international contributions.

In 2017, the Centre also established committees to develop and oversee its important Equity and Diversity, Professional Development, and Research Translation programs. The Centre began rolling out elements of these programs, including inclusive and family-friendly policies and practices, and a workshop to provide training, career advice, and commercialisation know-how to the early career researchers.

In 2017, the OzGrav Education and Outreach team made impressive progress creating visualisations and virtual reality experiences designed to promote and explain gravitational wave science to people of all ages. It was great to see their efforts recognized with a 2017 Swinburne Vice-Chancellor Community Engagement Award.

There were many other awards bestowed upon OzGrav researchers last year, as you may read in these pages. For the field as a whole, none was bigger than the 2017 Nobel Prize for Physics being awarded to three pioneers in the search for gravitational waves, including a member of OzGrav's Scientific Advisory Committee, Prof Barry Barish.

It is hard to imagine a more successful start for OzGrav, and I hope you enjoy reading about OzGrav's achievements to date and future plans.

Sincerely,
Prof Ian Young

Photo: Aditya Parthasarathy

SCIENCE ADVISORY COMMITTEE (SAC)

On behalf of the OzGrav Scientific Advisory Committee (SAC) I am delighted to congratulate the OzGrav leadership and researchers on their achievements in their inaugural year. OzGrav's establishment phase has come amidst a whirlwind of major scientific breakthroughs in gravitational wave physics, to which OzGrav members have made significant contributions.

I am pleased and honored to be Chairing this committee that comprises such an esteemed group of international experts in physics. The SAC now boasts not one, but two Nobel Laureates! These are: Prof Takaaki Kajita, who shared the 2015 Nobel Prize in Physics for discovering neutrino oscillations; and Prof Barry Barish who received the 2017 Nobel Prize with colleagues Profs Rainer Weiss and Kip Thorne, for their role in the 2015 discovery of gravitational waves.

Australian groups - now part of OzGrav - were responsible for many of the technological and scientific innovations that made it possible to measure the tiny distortions in space-time caused by gravitational waves. It took decades of hard work and incremental advances in instrumentation before the 2015 breakthrough. It is therefore hard to comprehend the rapid advances in the field in the last two years. The birth of OzGrav could not be timelier. In August 2017, just four months after the Centre formally commenced, a new era of gravitational wave astronomy dawned when a cosmic event – the coalescence of a neutron star binary system - was observed for the first time not only in gravitational radiation but across the electromagnetic spectrum from gamma rays to radio waves.

This new era in science naturally brings together the researchers across OzGrav's three Themes: Instrumentation, Data and Astrophysics. It also triggered OzGrav members to embark on a review of its scientific program structure and priorities to ensure that its experts are focused on the highest impact science that exploit OzGrav's advantages. At our first meeting in early 2018, the SAC was pleased to advise on and endorse OzGrav's research programs and plans. The SAC was also impressed by the new supercomputing facility that OzGrav has dedicated access to, which has great potential to support the gravitational wave community's data and computing requirements.

OzGrav researchers are part of the LIGO Virgo Collaboration (LVC), a thousand-person strong global scientific effort. The ability of OzGrav to maximize its global scientific impact will rely on the strength and relevance of its collective expertise. To this end, I congratulate OzGrav on attracting a growing pool of talented early career researchers. I was pleased to meet many of them at the inaugural OzGrav retreat in November 2017, where the breadth and depth of talent in the Centre was apparent.

The future for OzGrav looks bright, and I wish OzGrav a productive and successful 2018.

Sincerely,
Prof James Hough

MAJOR HIGHLIGHTS

4 JANUARY

3RD BLACK HOLE MERGER

A pair of black holes collided in the distant universe, sending gravitational ripples through the cosmos. 3 billion years later, these tiny ripples were measured here on Earth, providing clues about where and how they formed.

6 APRIL

OZGRAV IS BORN (GW170604!)

A special day for OzGrav. Not only our official commencement, but we also held our first outreach event as part of Stargazing Live, attended by 5000+ people. Our Centre has grown dramatically, reaching over 130 members in our first year.

17 AUGUST

NEUTRON STAR MERGER

The scientific world shook with the landmark discovery of a colliding pair of neutron stars. This was the first time a cosmic event was "heard" through gravitational waves and "seen" through telescopes. It marked the dawn of a new branch of science: GW multi-messenger astronomy.

3 OCTOBER

NOBEL PRIZE IN PHYSICS

The momentum of the new field of gravitational wave astronomy is striking. Less than two years since gravitational waves were first discovered, the Nobel Prize in Physics was awarded to three pioneers of this exciting new field, including our Scientific Advisory Committee member Prof Barry Barish.

9 NOVEMBER

OZGRAV LAUNCH

Minister for Education Simon Birmingham officially launched OzGrav at Swinburne University of Technology, joined by many guests including Nobel Laureate Brian Schmidt. The event also showcased new virtual and augmented reality educational software being developed at OzGrav.

The mission of the ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav) is to capitalise on the historic first detections of gravitational waves to understand the extreme physics of black holes and warped spacetime, and to inspire the next generation of Australian scientists and engineers through this new window on the Universe.

In Einstein's theory of General Relativity, spacetime is dynamic. It can be warped into a black hole. Accelerating masses create ripples in spacetime known as gravitational waves (GWs) that carry energy away from the source. Recent advances in detector sensitivity led to the first direct detection of gravitational waves in September 2015. This was a landmark achievement in human discovery and heralded the birth of the new field of gravitational wave astronomy.

The Centre brings together the Australian gravitational-wave, astrophysics, and pulsar communities in a focused national program. Through this Centre Australian scientists and students have the opportunity to fully participate in gravitational wave astronomy on an international stage. There is a great deal of excitement both within and outside of OzGrav about the new era of gravitational-wave astrophysics, and the timing of OzGrav's birth could not have been better. The following pages showcase the major highlights for the Centre and the field in 2017.

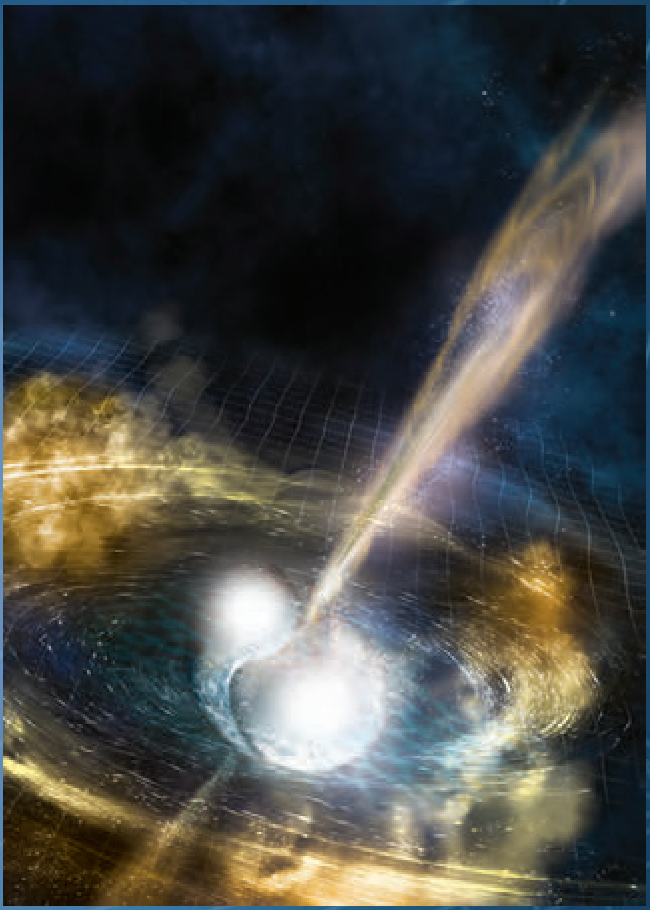


Image: Artist illustration of binary neutron star merger. National Science Foundation/LIGO/Sonoma State University/Aurore Simonnet

The Nobel Prize in Physics 2017

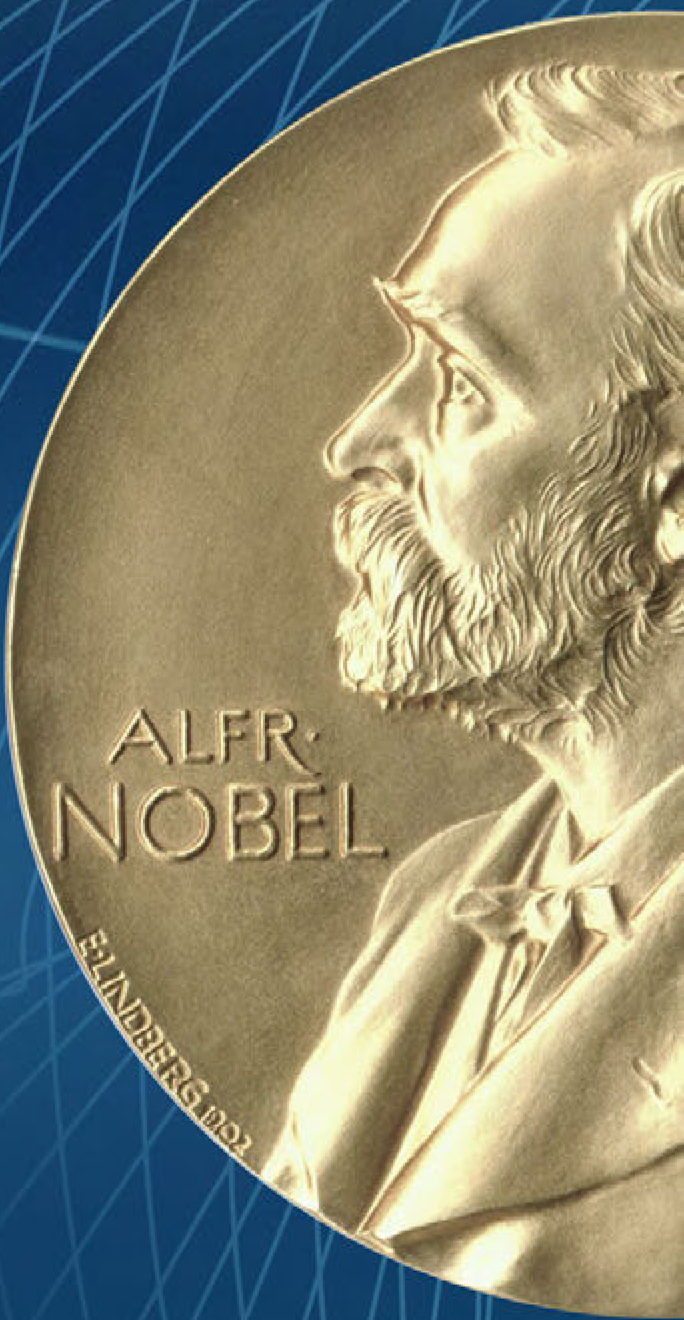
The Royal Swedish Academy of Sciences announced on 3 October 2017 that it had awarded the Nobel Prize in Physics 2017 with one half to Rainer Weiss from the LIGO/VIRGO Collaboration and the other half jointly to Barry C. Barish (member of the OzGrav Scientific Advisory Committee) and Kip S. Thorne, both also from the LIGO/VIRGO Collaboration, “for decisive contributions to the LIGO detector and the observation of gravitational waves”.

The 2017 Nobel Laureates have, with their enthusiasm and determination, each been invaluable to the success of LIGO. Pioneers Weiss and Thorne, together with Barish, the scientist and leader who brought the project to completion, ensured that four decades of effort led to gravitational waves finally being observed.

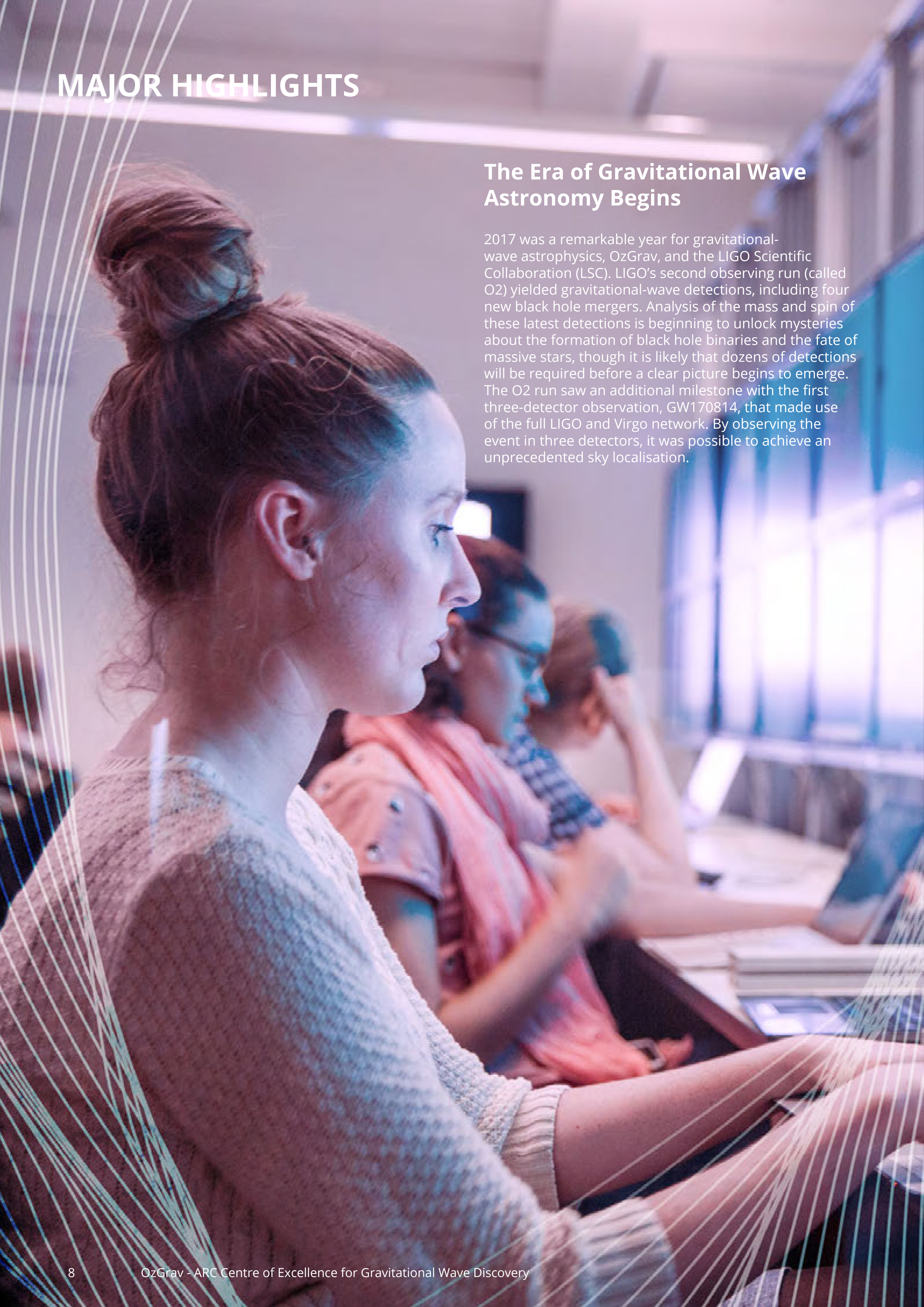
In the mid-1970s, Rainer Weiss had already analysed possible sources of background noise that would disturb measurements, and had designed a detector, a laser-based interferometer, which would overcome this noise. Early on, both Kip Thorne and Rainer Weiss were firmly convinced that gravitational waves could be detected and bring about a revolution in our knowledge of the universe.

Gravitational waves spread at the speed of light, as Albert Einstein described in his general theory of relativity. They are created when a mass accelerates, or a pair of black holes rotate around each other. Einstein was convinced it would never be possible to measure them. The LIGO project’s achievement was using a pair of gigantic laser interferometers to measure a change thousands of times smaller than an atomic nucleus, as the gravitational wave passed the Earth.

According to the Nobel Prize Committee, “So far all sorts of electromagnetic radiation and particles, such as cosmic rays or neutrinos, have been used to explore the universe. However, gravitational waves are direct testimony to disruptions in spacetime itself. This is something completely new and different, opening up unseen worlds. A wealth of discoveries awaits those who succeed in capturing the waves and interpreting their message.”



MAJOR HIGHLIGHTS



The Era of Gravitational Wave Astronomy Begins

2017 was a remarkable year for gravitational-wave astrophysics, OzGrav, and the LIGO Scientific Collaboration (LSC). LIGO's second observing run (called O2) yielded gravitational-wave detections, including four new black hole mergers. Analysis of the mass and spin of these latest detections is beginning to unlock mysteries about the formation of black hole binaries and the fate of massive stars, though it is likely that dozens of detections will be required before a clear picture begins to emerge. The O2 run saw an additional milestone with the first three-detector observation, GW170814, that made use of the full LIGO and Virgo network. By observing the event in three detectors, it was possible to achieve an unprecedented sky localisation.

Just three days later, the LIGO-Virgo network made the first-ever observation of gravitational waves from the violent collision of two neutron stars. The spectacular event, referred to as GW170817, occurred about 130 million years ago and created a cosmic fireworks display. Teams including LIGO, Virgo and OzGrav, used about a hundred instruments at roughly 70 observatories to track down and watch the cataclysm in multiple wavelengths of light, allowing astronomers to scrutinize the source of these cosmic ripples for the first time.

The GW170817 binary neutron star merger was the ideal stress test of OzGrav's electromagnetic capabilities, and it was wonderful to see the spirit of cooperation and collaboration between the OzGrav nodes, culminating in a paper led by Swinburne OzGrav PhD student Igor Andreoni, and Monash postdoctoral researcher Kendall Ackley, and featuring data from the Australian National University (ANU) and University of Western Australia (UWA) facilities. During the height of this activity, over fifty people from OzGrav were joining in for weekly Data/Astrophysics teleconferences, eager to learn the latest news about the merger.

The observation of GW170817 and the associated burst of high-energy gamma-rays are likely to be long remembered as a pivotal discovery. At first glance, it appeared to solve a long-standing mystery about what causes short gamma-ray bursts, with merging neutron stars being the culprit. While this may prove to be the case, the implications of GW170817 has raised more questions than it answered, such as: Is GW170817 a normal gamma-ray burst that we viewed off-axis, making it appear far dimmer than expected? Or did we observe slightly beamed gamma-ray emission from a cocoon? How do we best understand the 1.7 second delay between the gravitational-wave and gamma-ray signals? OzGrav researchers contributed to the LIGO-Virgo Gamma-Ray Burst (GRB) GW170817 companion paper, helping to interpret the results and leading the review effort.

The GW170817 merger of two neutron stars created one new short-lived bright star. This phenomenon, known as a kilonova, was first observed eleven hours after the merger event, and has become one of the best-studied transient astronomical events. Electromagnetic observations of the event, including those by OzGrav researchers, are beginning to provide clues about a number of important topics including: the abundance of heavy elements, the possibility of a hyper-massive neutron star remnant, and the dynamics of kilonovae. As the sensitivity of LIGO and Virgo improves, OzGrav looks to enhance its role in the multi-wavelength observation of binary neutron star counterparts.

OzGrav researchers and collaborators announced this discovery at a press conference on 17 October 2017 in Canberra, joined by the ARC CEO Professor Sue Thomas and Australia's Chief Scientist Dr Alan Finkel.

MAJOR HIGHLIGHTS

The discovery garnered major media coverage, through which OzGrav members outlined to the public the important science implications of GW170817, which include:

- The observation of an electromagnetic counterpart facilitated a gravitational-wave based measurement of the Hubble parameter and the age of the Universe. This paves the way to an era of precision gravitational-wave cosmology. OzGrav researchers contributed to the review of this result.
- We now know that somewhere in the Universe, thousands of binary neutron stars coalesce every day. As a result, it is likely that advanced detectors can detect a hum of weak binary neutron star signals, which are too weak to observe individually, but which combine to create a stochastic background.
- It is not known if GW170817 left behind a black hole or a hyper-massive neutron star. Detection of gravitational waves from a hyper-massive neutron star would provide key insights into the equation of state of nuclear matter. OzGrav researchers co-led a LIGO-Virgo search for post-merger gravitational waves. While the search produced no evidence of a signal, it provides a starting point on which to build a more sophisticated search.
- Resolving a debate about the origin of gold and other heavy elements in the cosmos.

OzGrav Launch

After the announcement of GW170817 in October 2017, and the global interest it generated not only within the scientific community but amongst the general public, only a couple of weeks remained to get ready for the official launch of the Australian Research Council Centre of Excellence for Gravitational Wave Discovery.

MC Prof Brian Schmidt, 2011 Nobel Prize winner and ANU Vice Chancellor, hosted the OzGrav launch event with a special message from 2017 Nobel Prize winner Prof Barry Barish. Prof Matthew Bailes wowed the audience with a presentation involving a mix of advanced VR, augmented reality and animations. It was an immersive and technically complex presentation that came together seamlessly thanks to the efforts and talents of outreach wizards Mark Myers and Carl Knox. The audience were taken on a tour of the history of Newton's gravitation, Kepler's planetary motion and Einstein's relativity, culminating in the detection of gravitational waves and the binary neutron star merger event.

The event finished with the Federal Minister for Education and Training, Senator Simon Birmingham, officially launching OzGrav, and joining guests at the reception to explore a virtual universe.


CELEBRATING
25 YEARS OF
UNIVERSITY
EDUCATION

CENTRE SNAPSHOT

17 PARTNER INVESTIGATORS

19 CHIEF INVESTIGATORS

19 ASSOCIATE INVESTIGATORS

134 MEMBERS

6 HONOURS

6 AFFILIATES

2 Pre-PhD

7 MASTERS

32 PhD

9 PROFESSIONAL STAFF

17 POST DOCS

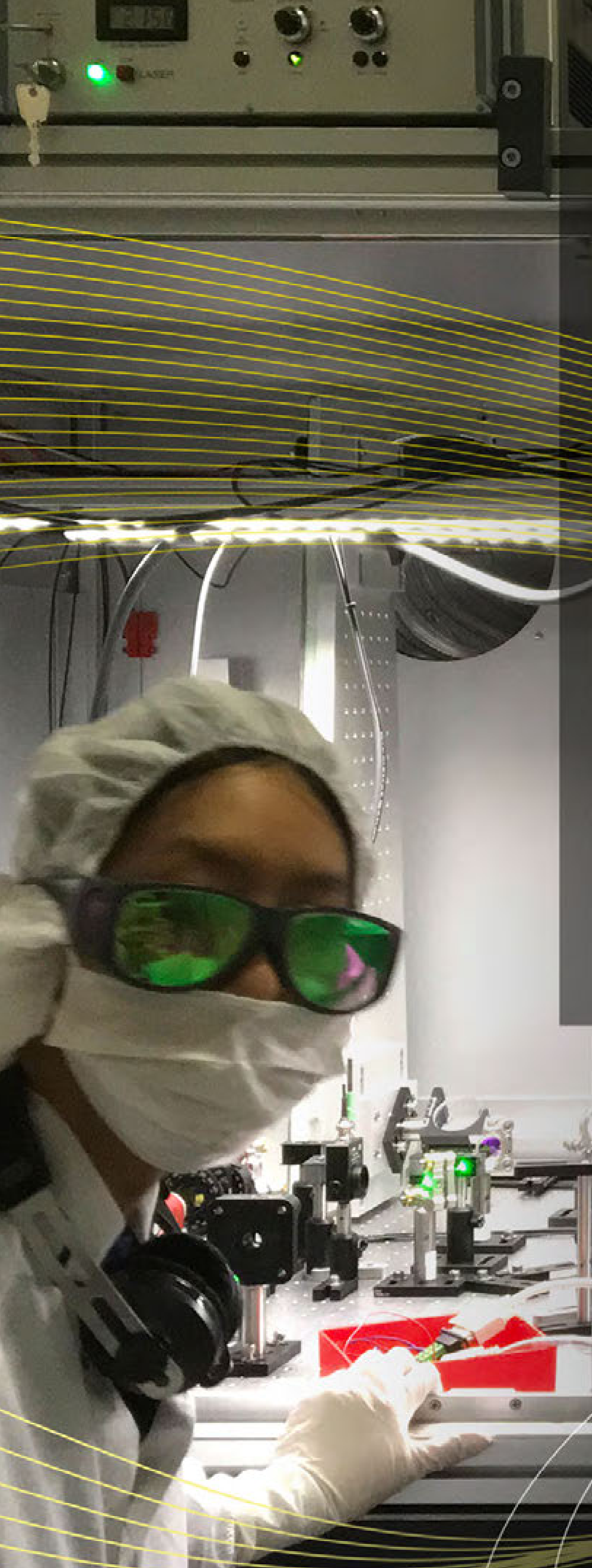
74
PUBLICATIONS

472
CITATIONS

215
MEDIA ARTICLES

19
INTERNATIONAL COLLABORATING ORGANISATIONS

36
OUTREACH EVENTS



INSTRUMENTATION THEME

OzGrav's Instrumentation Theme, led by Chief Investigator Prof David McClelland (Australian National University) 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 2017, which is positioning OzGrav to play a key role in the future of the field.

The original proposal identified four programs - Advanced LIGO, Beyond Advanced LIGO, Space, and Radio Telescopes with many projects under these programs. During 2017, we successfully trialled a modified structure, grouping activities by technologies and techniques into six programs, whose progress is outlined below. This has provided opportunities for joint cross-nodal leadership, promoted collaboration and cohesion, and fostered a more global vision.

The OzGrav Instrumentation theme is composed of six programs across the audio, milliHz, and nanoHz detection bands.

1. Commissioning (Program leaders: Ottaway and Slagmolen)

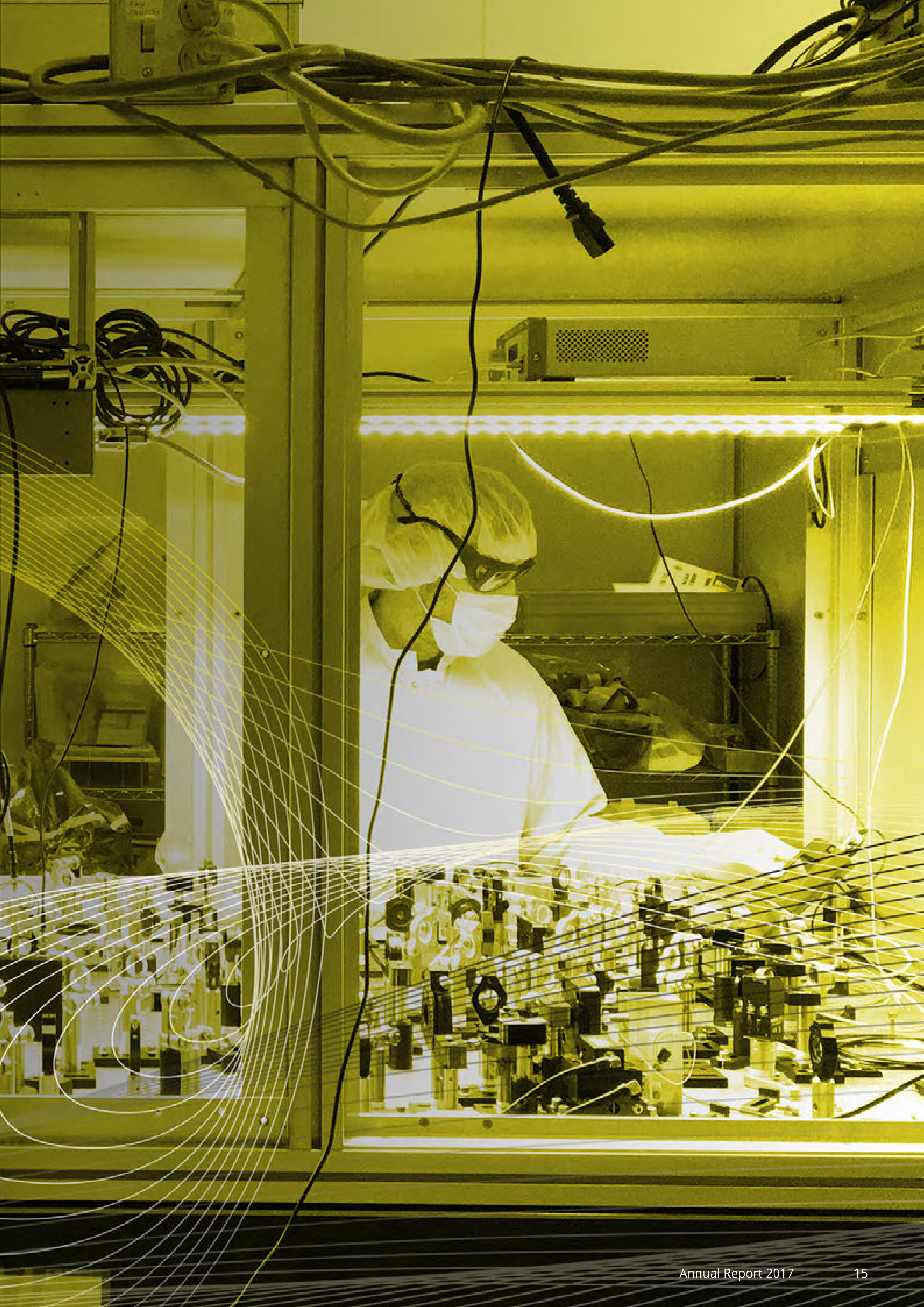
2. Quantum (Program leaders: McClelland and Veitch)

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)



INSTRUMENTATION

Commissioning (Program leaders: Ottaway and Slagmolen)

Throughout the year OzGrav provided commissioning personnel to the LIGO observatories, ranging from PhD students to post-docs and academics. A major commissioning highlight was the use of the University of Adelaide's Hartmann optical wavefront sensor to diagnose a major absorption hot spot on one of the input test masses at the LIGO Hanford Observatory. This hot spot caused a major differential absorption in the power-recycling and signal-recycling cavities and is likely to be responsible for some of the unexplained effects seen in that interferometer, including large susceptibility to input mode fluctuations. This input test mass has now been replaced. Further investigations are underway to investigate the anticipated improvement on the performance of the Hanford detector.

In preparation for the Squeezed Light Source installation into the LIGO detectors, OzGrav scientists from the Australian National University (ANU) began assembling the squeezing injection tables at both the Livingston and Hanford Observatories. LIGO's third observation run (O3) beginning in late 2018 will utilise squeezed light injection, pioneered at the ANU and MIT, to improve the LIGO detectors' performance.

Quantum (Program leaders: McClelland and Veitch)

Quantum noise refers to the uncertainty of a physical quantity that is due to its quantum origin. The OzGrav Quantum program plans to reduce quantum noise by developing high power, highly stable lasers and vacuum-squeezed light sources.

Laser development for advanced detectors operating at 1μm is now very mature. However, lasers at 2μm, with the power and stability required for planned new detectors such as LIGO-Voyager, do not exist. 2μm laser development is a key OzGrav focus, and this year we made progress on the development of the master oscillators (MO). We designed a Tm:fiber MO that will be core-pumped by the output of an Er:glass fiber laser; developed the Er:glass fiber pump laser; and designed and commenced fabrication of reference cavity for diagnostic breadboard. We assembled a Tm:fiber pump system for the Ho:YAG MO.

OzGrav has been a leader in forging the development of 1 μm squeezed light sources in the kHz band required for use in the current and near future detectors such as Advanced LIGO and its upgrade A+. OzGrav and LIGO are currently installing squeezers designed by OzGrav in the LIGO vacuum envelopes (see Commissioning). Whilst there are a few lasers that operate at 2μm (we are working on one with the properties required) there are no squeezed light sources. In 2017 we built the first squeezed light source in the 2μm band and demonstrated operation in the kHz band. Whilst the system works there are problems to be solved before a highly squeezed state can be generated.

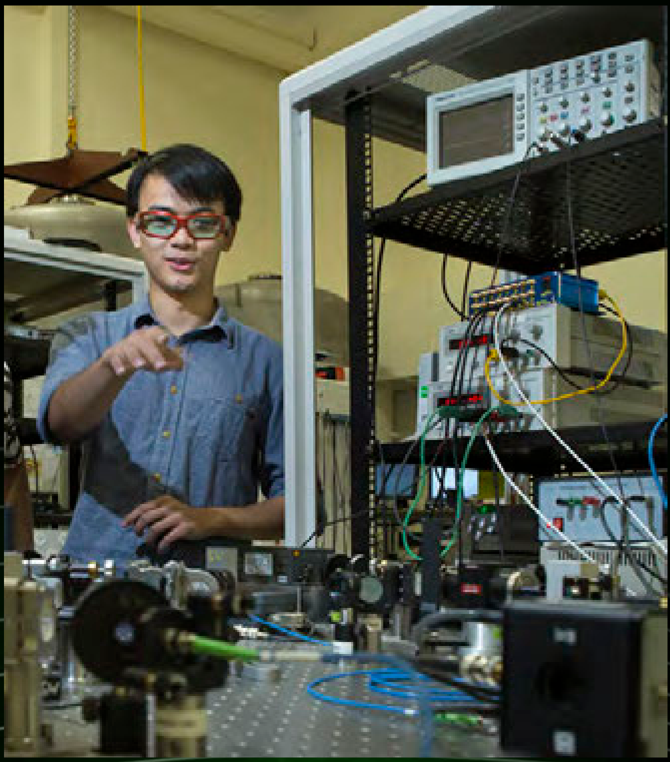
Low frequency (Program leaders: Slagmolen and Ju)

One key objective is to improve the low frequency isolation performance of the existing isolators towards future low frequency isolation system research. In 2017 we focused on developing an Advanced low frequency rotation accelerometer (tilt sensor). We designed the "walk-off" tilt sensor base on previous study, and analyzed its performance. We commenced the construction of a seismometer array for ground motion (including tilt) analysis and feedback/feedforward. We completed the data acquisition and analyzing procedure and started preliminary data analysis. We investigated several possible improvement for the existing vibration isolation system at the Gingin laboratory.

Another key objective is to develop an instrument to directly measure Newtonian Noise caused by the direct gravitational coupling between masses moving around the interferometer (such ground motion and atmospheric motion) and the interferometer test masses. The system being investigated is a TORsion PEndulum Dual Oscillator I (TORPEDO) with which local gravity gradients are detected by monitoring the differential motion between two independently-hung torsion bars. In 2017 the main stage was hung in air, brought under control with local sensors and the optical control strategy demonstrated.

INSTRUMENTATION

Instabilities and Distortions (Program leaders: Zhao and Ottaway)



Parametric instabilities (PI) arise from the excitation of acoustic modes of the mirrors from circulating optical field modes. Left unchecked such PI will prevent interferometer operation. In 2017 at our Gingin Research Facility, we investigated factors affecting cavity circulating power. It was found that the angular radiation pressure modified the test mass local control loops, thus we reduced the control loop phase margin. aLIGO experienced the similar effect in the angular control. After carefully optimising the local control loop, the cavity circulating power was increased to ~20kW, and 5 unstable acoustic modes at frequencies near 350kHz were observed with maximum gain ~4.

We developed a system to identify the unstable acoustic modes by mapping the amplitude distribution of the beat note between the cavity fundamental mode and the high order mode. This information is required to implement feedback control to suppress the parametric instability. We studied a thermal transient compensation scheme by pre-heating the test mass. A proof-of-principle experiment was done at Gingin laboratory, with experimental results consistent with the prediction of the simulation. We completed a further study of the implementation of the thermal transient compensation on aLIGO detectors. We installed a Hartmann wavefront sensor for monitoring the thermal tuning of the test mass radius of curvature.

Another issue accompanying increasing laser power is thermally induced distortions. In 2017 we undertook a number of activities to measure and compensate for such distortions using deformable mirrors. We collaborated with Dr Aidan Brooks from Caltech to develop a new type of deformable mirror that relies on the differential thermal expansion of a metal and a glass to produce a near perfect quadratic profile mirror change. An alternative method of obtaining a tuneable lens involves using the absorption of mid-infrared lasers to develop a quadratic temperature profile within a fused-silica substrate. We assembled and tested a 1 Watt Er:ZBLAN laser whose wavelength (2.7-2.9 µm) matches the strong OH absorption feature found in standard fused-silica glass. A proof-of-concept demonstration showed a clean quadratic profile but wavelength changes within the laser added significant noise to the system.

A critical part of optimizing the mode matching between various cavities of the interferometers is measuring the spatial quality of the resonating sidebands. Previously this has been achieved using a so-called phase camera. The first generation of this device relied on scanning an extended beam over a small photodiode and measuring the spatially dependent beat note. Unfortunately, such a device cannot be used in second generation detectors since its beam scanning nature couples noise back into the interferometer. We commenced the development of a modulation free phase camera.

Finally we ramped up our expertise and effort in interferometer simulation. We studied parametric instability in the next generation detectors using FEM simulation; and studied the coupling of input mode beam jitter to the gravitational wave channel using a full Finesse Model.

INSTRUMENTATION

Space (Program leader: Shaddock)

Following the exceptionally positive recent results from Laser Interferometer Space Antenna (LISA) Pathfinder that demonstrated the performance of the intraspacecraft interferometry, the field is eagerly awaiting the launch of the GRACE Follow-On mission which will demonstrate interspacecraft laser interferometry over 200km. Although the scientific goals of GRACE FO are very different, there is a high degree of overlap of the technology, techniques and personnel. OzGrav members were involved in defining the architecture of the mission and prototyped some of the key technologies under the Australian Space Research Program funding several years ago. More recently, we partnered with the NASA Jet Propulsion Laboratory (JPL) scientists to devise tests of Time-delay interferometry, a technique critical to the LISA measurement, that can be carried out on the GRACE FO mission. Dubbed LISA Experience from GRACE Optical Payload (LEGOP) the project is developing tests of arm locking and time delay interferometry (TDI), two frequency stabilisation techniques, that could be performed on GRACE-FO in collaboration with JPL scientists.

Attention now has turned to the next generation of space interferometry missions, with PhD student Samuel Francis publishing a demonstration of a new multipoint architecture to simplify the construction and operation of future space interferometers. Samuel completed his PhD in 2017 following an experimental demonstration of the new architecture along with tests of several key components and enabling techniques. A significant challenge with space interferometry is acquiring the laser links at startup (link acquisition).

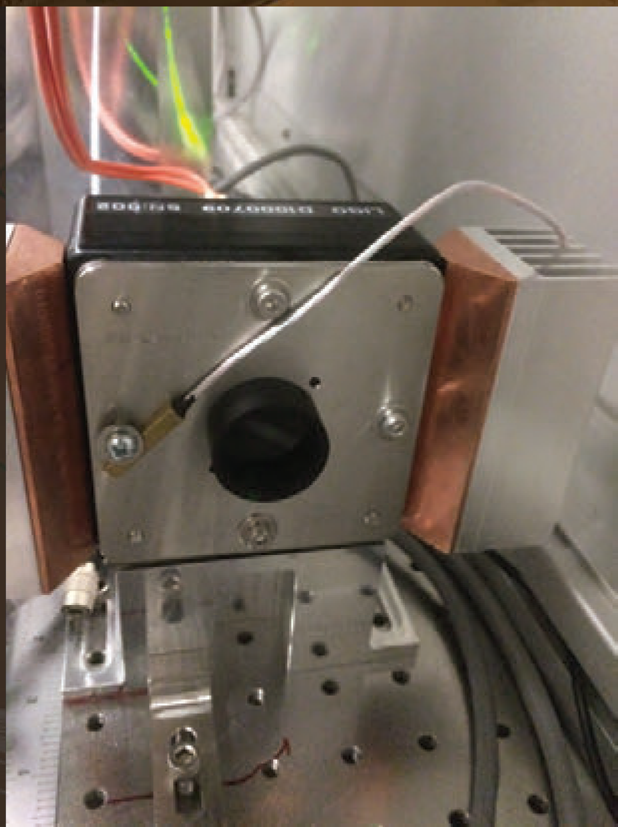
There is great interest in China in gravitational wave detection in both the ground and space-based detector fields. OzGrav CI's Prof David Blair (UWA) and Prof Daniel Shaddock (ANU) gave invited talks at the International Symposium on Gravitational Waves at the Chinese Academy of Science in May 2017 and discussions were held regarding the proposed Tiaji gravitational wave detector. Prof Shaddock visited Sun Yat-Sen University to discuss the potential for Australian-Chinese collaboration on the TianQin project, a less expensive proposal to put three spacecraft in orbit around the Earth.

Pulsar Timing (Program leader: Bailes)

OzGrav Associate Investigator and ARC Future Fellow Dr Adam Deller led the development of the Square Kilometre Array Pulsar Timing Sub-element (PST) with a team from Swinburne University of Technology and Auckland University of Technology. A prototype for the PST was developed and successfully deployed at the MeerKAT radio telescope in the Karoo in South Africa. With just 16 elements of the 64-dish MeerKAT telescope the team has already managed to observe a number of radio pulsars, in conjunction with the Parkes radio telescope in Australia, that validated the exceptional system temperature of the MeerKAT receivers (18K). When MeerKAT is completed in mid-2018 OzGrav scientists will be well-placed to monitor the Universe for the presence of supermassive black hole binaries with a precision not previously possible in the Southern hemisphere.

Case study: Commercialisation

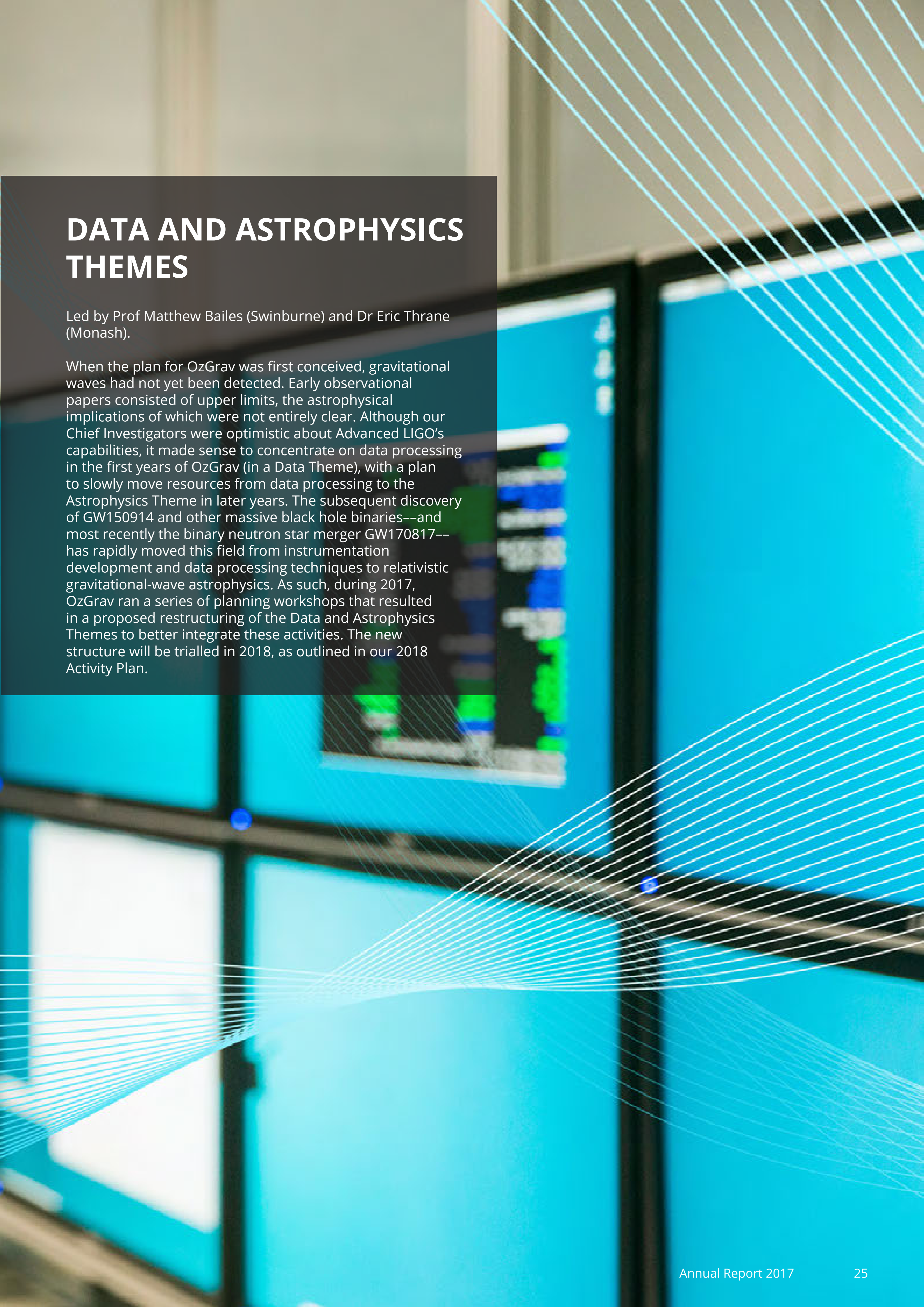
Commercialisation of the Hartmann wavefront sensor technology developed for the Advanced LIGO gravitational wave detectors is being investigated by OzGrav's University of Adelaide node in collaboration with Lastek Pty Ltd, an Adelaide photonics company, and the assistance of a Photonics Catalyst Program grant from the South Australian Government. The Hartmann sensor technology is being used to develop an instrument that yields both the wavefront and intensity profile of an incident laser beam from a single measurement. While a profiler for visible and near infrared wavelengths is being developed currently, the Hartmann IP can be used at any wavelength for which a suitable pixelated camera is available. Such systems could be used for a wide range of laser applications, including remote sensing and Light Detection and Ranging (LIDAR), free space laser communications, advanced manufacturing and the development of new infrared laser sources.



Case study: Spin-off Company

Liquid Instruments (LI) Pty Ltd was founded by researchers from the gravitational wave group at the ANU to commercialise advanced instrumentation technology derived from both ground and space-based gravity detectors. LI is looking to disrupt the test and measurement industry with a new class of software-enabled hardware. The company has raised $2.1M in seed funding and are about to pass $1M in cumulative sales revenue. They now employ 17 staff in the US and Australia; many of them are former researchers and students who have transitioned to industry.

LI employs advanced digital signal processing to replace multiple pieces of conventional equipment at a fraction of the cost and with a drastically improved user experience. Their first product Moku:Lab provides the functionality of 10 instruments in one simple integrated unit. Moku:Lab is certified in all major markets with distributors covering 30 countries. In September 2017, the company transitioned to a large, top-tier manufacturing partner so they can scale production dramatically.



DATA AND ASTROPHYSICS THEMES

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

When the plan for OzGrav was first conceived, gravitational waves had not yet been detected. Early observational papers consisted of upper limits, the astrophysical implications of which were not entirely clear. Although our Chief Investigators were optimistic about Advanced LIGO's capabilities, it made sense to concentrate on data processing in the first years of OzGrav (in a Data Theme), with a plan to slowly move resources from data processing to the Astrophysics Theme in later years. The subsequent discovery of GW150914 and other massive black hole binaries––and most recently the binary neutron star merger GW170817–– has rapidly moved this field from instrumentation development and data processing techniques to relativistic gravitational-wave astrophysics. As such, during 2017, OzGrav ran a series of planning workshops that resulted in a proposed restructuring of the Data and Astrophysics Themes to better integrate these activities. The new structure will be trialled in 2018, as outlined in our 2018 Activity Plan.

DATA RESEARCH THEME

LIGO Pipelines (Program Leader: Melatos)

2017 was another great year for the LIGO Scientific Collaboration's (LSC) search for gravitational waves from compact binary coalescences with four events being published. Three of these were from black hole pairs with masses ranging from roughly 10-30 times the mass of our Sun. Toward the end of the second observing run (O2), the European Advanced Virgo detector joined the detector network for the first time. This enabled the LIGO and VIRGO teams to "triangulate" the location of the black hole merger GW170814 to just 60 square degrees, much smaller than LIGO alone can accomplish. A typical LIGO-only localisation can span many hundreds of square degrees. The undoubted highlight of the astronomical year was LIGO's detection of the first binary neutron star merger, GW170817, which united OzGrav and the world's astronomers in the chase for a fading fireball at a multitude of wavelengths.

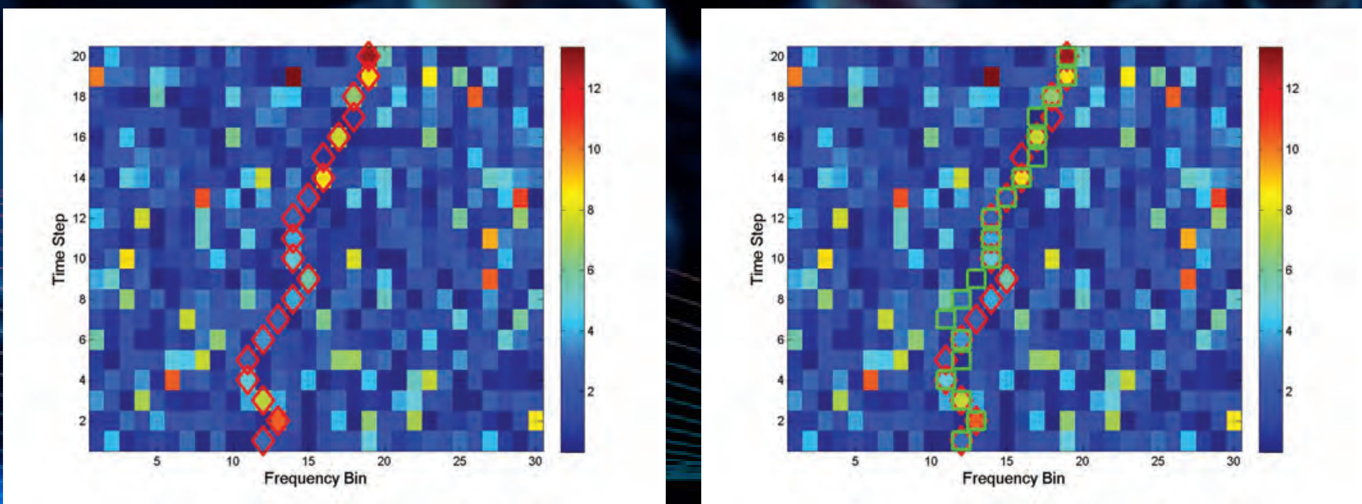
GW170817 united the previously disparate pulsar, gravitational wave and optical follow-up research efforts within OzGrav. GW170817's progenitor was a highly evolved version of the binary pulsars that had been discovered by our pulsar astronomers over many decades, but instead of its orbital period measured in hours it was mere tens of milliseconds when first detected by LIGO, and at merger just a millisecond or so.

The detection of gravitational waves from black holes and neutron stars has led to an explosion of work studying the population properties of compact binaries. Postdoctoral researcher Dr Simon Stevenson (Swinburne University of Technology), PhD student Colm Talbot (Monash University), and Chief Investigator (CI) Dr Eric Thrane (Monash) published a series of papers investigating how gravitational-wave measurements of binary black hole spin can be used to learn how and where black hole binaries form. The new techniques are currently being applied to LIGO data. Postdoctoral researcher Dr Xingjiang Zhu (Monash), working in collaboration with other OzGrav researchers, investigated how gravitational-wave measurements of neutron star spin might be used to probe phenomena such as magnetic field decay in neutron stars. Dr Thrane and Associate Investigator (AI) Dr Paul Lasky explored how binary black hole detections can be used to test the famed no-hair theorem. AI Dr Eric Howell (UWA) contributed content to the Gamm Ray Burst companion paper to GW170817, while CI Dr Eric Thrane (Monash) and CI Prof Yuri Levin (Monash) reviewed the paper for the LIGO Burst Group.
Chief Investigator (CI) Prof Linqing Wen and her postdoctoral researchers Dr Qi Chu and Dr Joel Bosveld at University of Western Australia (UWA) have been developing a time-domain gravitational wave (GW) pipeline (SPIIR) that provided independent confirmations of O2 merger events like the June 8 binary black hole merger. SPIIR was also demonstrated to successfully process 3-detector data from the LIGO-Virgo network. The pipeline is able to achieve latencies (gaps between events and detection) of only 30 seconds. In 2017 the group worked with international LSC collaborators on a range of projects including: further optimising the code for GPU technology; using 3rd generation detectors for cosmology; and a proposed new mechanism for generating electromagnetic counterparts from a coalescing system comprising two black holes and a star.

Achieving the first detection of a continuous source of gravitational waves is a key goal of OzGrav's LIGO Pipelines program. CI Prof Andrew Melatos's group at the University of Melbourne (UoM) has introduced signal tracking based on hidden Markov models (HMMs) to the LIGO Scientific Collaboration (LSC), adapting algorithms from engineering applications like mobile telephony and speech recognition to OzGrav's mission. PhD student Lilli Sun (UoM) reported the results of a HMM search for the low-mass X-ray binary (LMXB) Scorpius X-1 in Advanced LIGO O1 data as lead author of an LSC paper. The search is the first to track stochastic wandering of the unknown LMXB signal frequency and produced a record low upper limit on the signal strength at the time of publication. UoM group also published method papers demonstrating how to improve the HMM's performance four-fold by tracking LMXB orbital parameters (as part of PhD student Patrick Clearwater's thesis) and how to modify the HMM to track neutron stars in young supernova remnants (SNRs) efficiently. The HMM method is ideally suited to tracking rapidly evolving postmerger signals from binary neutron star mergers. CI Professor Scott's group at the Australian National University (ANU) plays a central role in LSC searches for continuous-wave signals from isolated neutron stars, many of which also emit radio pulsations. OzGrav postdoctoral fellow Karl Wette (ANU) continued the development of algorithms and infrastructure for the Einstein@Home volunteer distributed computing project in preparation for high-sensitivity all-sky searches in Advanced LIGO O3 data in 2018. Wette also published a method paper on efficiently correcting for the Earth's orbit in continuous-wave searches, including relativistic effects.

AI Dr Letizia Sammut (Monash) co-led an investigation into the implications of GW170817 for a stochastic background from binary neutron stars. This work was featured as an Editor's Suggestion in Physical Review Letters. Rory Smith and Eric Thrane developed a new method for detecting the stochastic background from binary black holes, which is shown to reduce the time to detection from years to days. AI Dr Sylvia Biscoveanu (Monash) developed a method to test the general relativity prediction that gravitational waves are either plus- or cross-polarised. These results were published in Physical Review X.

In 2017, all three binary black holes were detected by searches for gravitational wave bursts. Burst tools provided morphology-independent waveform reconstructions of the detections, and were used to search for residual gravitational wave energy after the signals were subtracted from the data. For the binary neutron star detection, burst tools were used to reconstruct and remove the glitch that occurred in the LIGO Livingston detector. The OzGrav group at Monash University contributed to the burst search for a neutron star remnant that could emit gravitational waves following the neutron star merger. The Swinburne



Hidden Markov models (HMMs) are adept at finding very weak signals in noise. Each cell in the diagram is coloured according to the likelihood that a simulated signal has been measured at that frequency and at that time. It is impossible by eye to identify a contiguous sequence of brightly coloured cells that stretch from the bottom of the diagram (start of observation) to the top (end of observation). The left panel shows the best guess (i.e. the path with the highest likelihood) generated by the HMM as a trail of red diamonds. The right panel overplots the true, simulated path as a trail of green squares. The HMM does a superb job!

DATA AND ASTROPHYSICS

University of Technology and Monash University groups are developing tools for accurate parameter estimation of future gravitational wave signals that are contaminated by glitches. OzGrav is active in preparing for the detection of other sources of gravitational wave bursts, such as core-collapse supernovae. Dr Jade Powell (Swinburne) has shown how the explosion mechanism of a supernova signal can be determined with a gravitational wave detection.

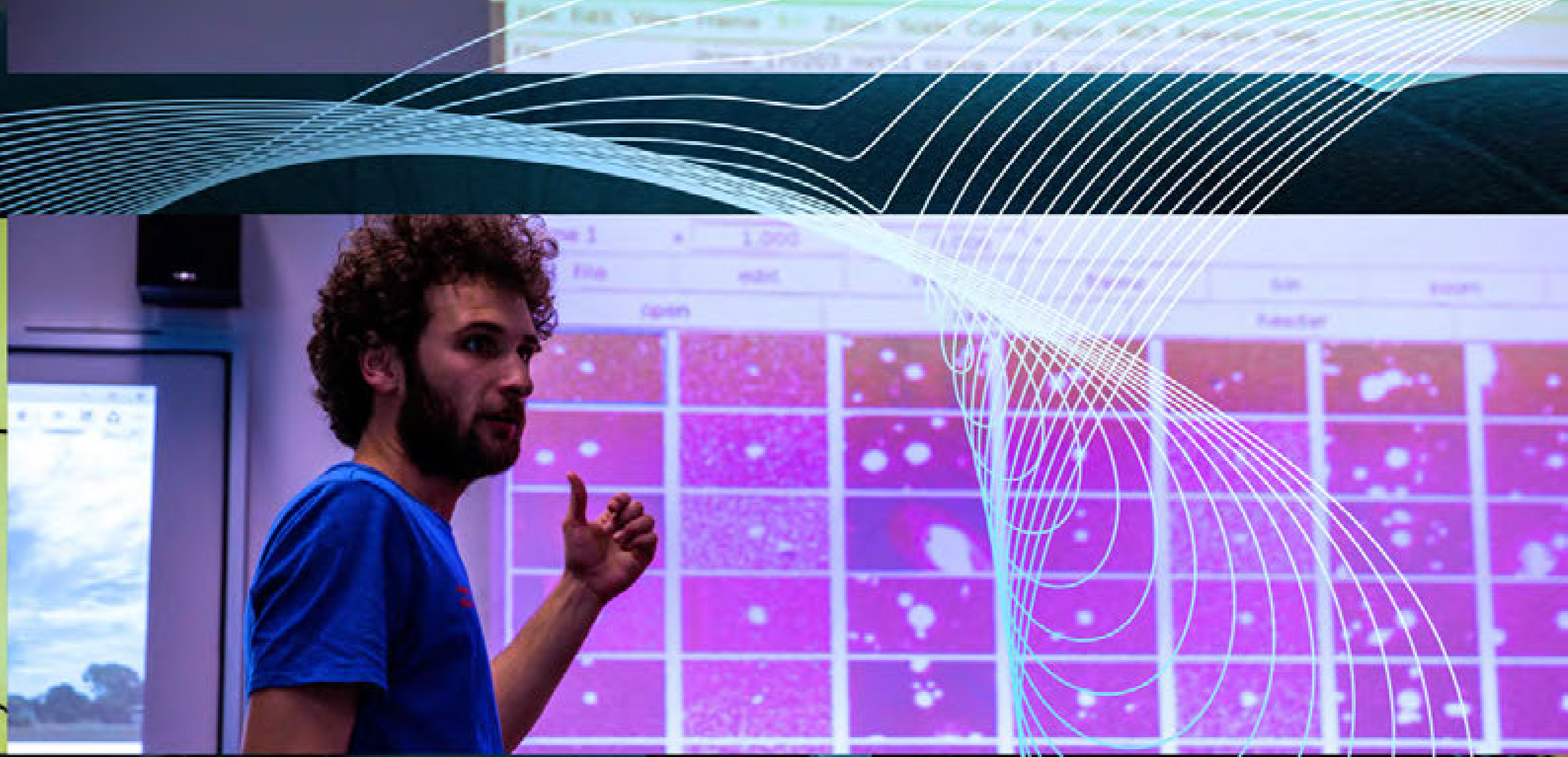
Astrophysical inferences about GW170817 rely on Bayesian parameter estimation. In order to understand systematic errors, the event was analysed and reanalysed with different assumptions and using different waveform models. PhD student Colm Talbot (Monash) and incoming OzGrav postdoctoral researcher Hannah Middleton (University of Melbourne) assisted by volunteering to carry out some of the O2 parameter estimation runs. The entire parameter estimation effort was made possible by reduced order methods, which decreased computation times from months to hours. AI Dr Rory Smith (Monash) played a significant role in the development and implementation of these reduced order methods.

Pulsars (Program leader: Bailes)

OzGrav is fortunate to have many members of the Parkes Pulsar Timing Array (PPTA) among its cohort. Until recently the Parkes telescope was the only large-aperture radio telescope dedicated to astronomy in the Southern hemisphere with a pulsar processor. This gives the PPTA a unique view of the rich Southern hemisphere's millisecond pulsar population that are essential for detecting the gravitational waves generated by supermassive black hole binaries. In 2017 the collaboration prepared for its second major data release (dr2) and Monash University student Daniel Reardon used the perturbations imposed on the radio signals by the interstellar medium to determine the geometries of the millisecond pulsar PSR J0437-4715. We successfully used 25% of the MeerKAT telescope (South Africa) to perform its first pulsar observations. Our long-term timing of a relativistic binary pulsar provided strong evidence for Lense-Thirring precession. New techniques that invoke interstellar scintillation are proving remarkably robust in determining pulsar inclination angles.

OzGrav aims to cross-fertilise the pulsar and audio band gravitational-wave communities. Some steps have already been taken towards this aim with the inclusion of CI Prof Linqing Wen's group into the PPTA prior to the existence of OzGrav. This was strengthened with the movement of Dr Xingjiang Zhu from a PhD position at UWA to a Monash OzGrav postdoctoral researcher position where he has been examining the constraints we can place on the population of supermassive black hole binaries using the PPTA data. Dr Ryan Shannon (Swinburne), with a deep background in PPTA, was recruited from CSIRO, and is well-positioned to drive PTA science for OzGrav. Dr Hannah Middleton (Melbourne) is also an expert in this area, joining OzGrav for 2018.

One of OzGrav's goals is to continue to survey the sky to conduct a census of the radio pulsar population to discover new millisecond pulsars for gravitational wave detection and extremely relativistic objects to test theories of relativistic gravity. The first pulsar surveys were incapable of discovering anything but the brightest pulsars, and relatively primitive chart recorders. As technology has improved digital techniques have become commonplace and modern surveys record Terabytes of data that are processed and reprocessed with advanced algorithms. Two exciting objects were detected, with papers now submitted for publication in 2017: a new millisecond pulsar with a planetary mass companion (Spiewak et al. 2018) and the most accelerated binary pulsar (Cameron et al. 2018).



Supercomputing (Program leader: Hurley)

Supercomputers come in many guises and their optimal design is intimately linked to the types of problems the computer has to address. OzGrav recognised the importance of a strong supercomputing platform to back up our scientists and engineers as they search for needles in cosmic haystacks. CI Prof Jarrod Hurley (Swinburne) worked with a range of OzGrav personnel and vendors to design a machine to suit OzGrav's data challenges. The result was OzSTAR, a machine provided by Dell-EMC and boasting over 1 Petaflop of supercomputing power via 230 Nvidia P100 Graphics Processing Units (GPUs), a fast path to over 5 Petabytes of disk space, a high-speed low-latency interconnect and a generous (192 GB) allocation of Random Access Memory (RAM) per server. OzSTAR was delivered in late 2017 and its first users are now performing tests of the system. The new supercomputer will be one of the fastest in Australia and preliminary benchmark tests have placed OzSTAR within the top 500 worldwide. It will perform real-time searches for gravitational waves, process optical images from telescopes around the world and simulate dense clusters of stars that may produce binary mergers.

A machine as complex as OzSTAR requires support from a range of experts to keep the machine's uptime to the standards required for real-time data analysis. Prof Hurley oversees several experts that maintain and develop the batch queues, optimise disk performance and create and administer accounts. OzSTAR's predecessor (gSTAR) boasted an uptime of over 99%.

OzGrav has recently hired the first of its system engineers Chris Samuel to aid users in the efficient use of supercomputers and benefits from Associate Investigator's Andrew Jameson's real-time processing expertise to develop pulsar processors.

DATA AND ASTROPHYSICS

ASTROPHYSICS THEME

Observations (Program leader: Cooke)

It was not until the last month of the O2 run that the first binary neutron star merger was witnessed by LIGO in the astronomical highlight of the year. CI A/Prof Jeff Cooke (Swinburne) helped coordinate OzGrav's response to the merger, gained Director's Discretionary Time, and wrote successful Target of Opportunity proposals to enable 9 radio, infrared, and optical telescope facilities worldwide to acquire data on this event before it faded. This work was summarised in the Australian GW170817 summary paper led by student Igor Andreoni (Swinburne) and postdoctoral researcher Dr Kendall Ackley (Monash) and featured data from UWA's Zadko telescope (CI A/Prof David Coward), ANU's SkyMapper (Associate Investigator A/Prof Christian Wolf) and 2.3 m telescopes, the Anglo-Australian Telescope (AAT) and overall 14 different instruments. A highlight was the sequence of images from ANU's SkyMapper telescope that showed the fireball cooling and fading with days of its discovery.

Part of OzGrav's strong response was due to previous collaborations on Fast Radio Burst (FRB) follow-up between Swinburne, ANU and UWA facilities and the novel "Deeper, Wider, Faster" project led by Prof Cooke that now involves 25-40 major astronomical facilities at all wavelengths (radio through gamma-ray), as well as particle and gravitational wave detectors. Prof Cooke has submitted over 15 successful competitive telescope time request proposals (radio through gamma-ray) resulting in awarded time for 2 DWF observing runs (10 days) in the first half of 2018.

In a collaboration with overseas Partner Investigator Steeghs, Dr Duncan Galloway (Monash) is helping to construct the Gravitational-wave Optical Transient Observer (GOTO) telescope specifically designed to discover transients associated with GW merger events.

Sources (Program leader: Bailes)

It is currently unclear whether the binary mergers LIGO is witnessing are coming from very massive binaries in galaxies or from the dense swarms of stars known as globular clusters in which black holes are fed in partner exchanges and slowly grow until they meet with another black hole and spiral together. The best way to address this uncertainty is to generate simulations of these complex systems using advanced algorithms on modern supercomputers such as OzSTAR. Professor Hurley's new PhD student Debatri Chattopadhyay has been exploring how often this occurs in nature by simulating dozens of star clusters.

Low-mass X-ray Binaries (LMXBs) are potential sources of detectable gravitational waves if accretion leads to non-spherical mass distributions. OzGrav brings together theoretical (CI Professor Melatos at UoM), signal processing (CI Professor Rob Evans at UoM), observational expertise (CI Dr Duncan Galloway at Monash) and new postdoctoral researcher Dr Karl Wette at ANU to place new limits on gravitational waves being generated from sources such as Scorpius X-1.

OzGrav is fortunate to have Associate Investigator Professor Alister Graham (Swinburne), an expert on the masses of supermassive black holes and the scaling relations between galaxy parameters and the underlying supermassive black holes that our pulsar timing arrays are hoping to detect.

DATA AND ASTROPHYSICS

Gravity (Program leader: Scott)

Our search programs and parameter estimation codes rely on the accurate generation of gravitational wave waveform comparisons worked on in collaboration with the LIGO Scientific Consortium.

The Monash team realised that the black hole mergers being detected by LIGO may be leaving behind a permanent imprint in the space-time continuum; a "gravitational-wave memory". Although individual events do not allow an unambiguous detection of this effect, they demonstrated that once we have a few dozen events their combined signature may well be detectable. Memory should be detectable before the conclusion of OzGrav if improvements in LIGO's sensitivity continue.

Binary pulsars offer the opportunity to test General Relativity (GR) in different ways than LIGO. When a binary pulsar is first discovered, the masses and orientation of the binary are rarely known. It is only after the patient monitoring of the system for months and sometimes years that post-Keplerian effects offer additional information that permits a breaking of degeneracies that enable astronomers to test GR and deliver parameters like neutron star masses. Monash student Daniel Reardon has made remarkable progress on obtaining independent estimates of pulsar transverse velocities that have enabled him to orient binary pulsars with respect to the Earth to astounding precision. These new constraints offer new tests of GR.

Case study: The Aftermath of a Neutron Star Collision

One of the most exciting scientific discoveries of 2017 was the coincident detection of gravitational waves and electromagnetic radiation from the collision of two neutron stars (referred to as GW171817). OzGrav scientists played key roles in the LIGO/Virgo data analysis, electromagnetic follow-up, and physical and astrophysical interpretation of all the observational data. One specific area of involvement spanned multiple OzGrav nodes, and has given rise to an ongoing collaborative effort that is being driven, in large part, by contributions downunder. The unifying question is what is left behind after two neutron stars collide? A simple question that is very complex to solve.

Potential answers to this question are: 1) a black hole, 2) a neutron star that eventually collapses to form a black hole (anywhere from <1 second to 10,000 seconds following the merger), or 3) an eternally stable neutron star. Each of these different outcomes has a different signature in terms of both electromagnetic observations and potential gravitational-wave observations from the post-merger remnant. For example, the lifetime of a nascent neutron star is imprinted on the colour evolution of the kilonova signal. It is the hunt for potential post-merger gravitational waves that brought together researchers from three OzGrav nodes.

For a number of years OzGrav AI Dr Paul Lasky (Monash) has been working to predict both the gravitational-wave and electromagnetic signatures of post-merger events. At the time of the event, Dr Lasky had three OzGrav honours students (Kyla Adams, Paul Easter and Nikhil Sarin) working on various aspects of the problem. Together, they ascertained what the specific gravitational-wave signal should look like for a long-lived (>10 seconds) neutron star.

Meanwhile, OzGrav postdoctoral researcher Dr Karl Wette (ANU), PhD student Lilli Sun (University of Melbourne) and CI Prof Andrew Melatos (Melbourne) have been developing algorithms to search for persistent gravitational waves from much older neutron stars. They quickly realised that the University of Melbourne (UoM) algorithm could also be used to search for gravitational waves from the putative neutron star created in GW170817. Dr Wette quickly ported the waveform models into the correct data format and generated test software injections, which Sun was able to successfully recover. The endeavor from OzGrav scientists to hunt for a GW170817 post-merger remnant starts from there.

DATA AND ASTROPHYSICS

Case study: New dimensions in fast Big Data and leading-edge data analysis

Sound is being used to enhance and accelerate discovery in several new ways. OzGrav CI Jeff Cooke and collaborators are developing a tool to convert data into sound (sonification) to exploit the unique capabilities of human hearing to analyse Big Data sets faster and more efficiently, to enable 10-20 parameters of the data to be analysed at once coherently, and to pick out signals buried within the noise. For Big Data, we are developing a tool, StarSound, initially for the Deeper, Wider, Faster (DWF) program data. DWF coordinates over 40 telescopes worldwide and in space to detect and study the fastest explosions in the Universe (milliseconds-to-hours duration) including those created by gravitational wave events. DWF performs simultaneous observations using electromagnetic (radio through gamma-ray) telescopes and multi-messenger facilities and processes the data in real time (seconds). In order to rapidly follow up the detected fast events before they fade, the data need to be analysed very quickly. Sound enhancement aims to speed up this process, increase efficiency, enable a faster analysis of outliers and interesting events and, ultimately, those events that will receive follow up observations.

In addition, we are also exploring the use of higher-order harmonics of tones (those that enable the human ear to distinguish a flute from a trumpet, for example) to present multiple properties of a given object in a single tone. Assigning different parameters to different harmonics can enable quick identification of relationships that exist between them and a holistic understanding of their properties. Finally, we are exploiting the 'cocktail party' effect, where human hearing can selectively focus on a familiar sound in a crowd, sometimes when the signal is fainter and lower than the 'noise'. This property is proving valuable in finding specific signals in very low signal-to-noise data.

Above: Screenshot of the StarSound computer interface that enables data sonification (credit Jeff Hannam, RMIT; Jeff Cooke, Swinburne)

Case study: Radio observations illuminate gravitational-wave event

OzGrav AI Dr Adam Deller was a member of an international team whose discovery brought scientists one step closer to understanding the physics of binary neutron star mergers and the universe at large.

Their discovery, showed that the super-fast jet launched during the cataclysmic event of a neutron star merger slammed into material surrounding the merging neutron stars and inflated a bubble-like cocoon.

The findings, published in Nature, contradict a popular theory describing the aftermath of the recently observed neutron star merger — namely, that the beam-like jet thought to be associated with highly energetic phenomena called gamma-ray bursts had been seen directly, immediately after the merger.

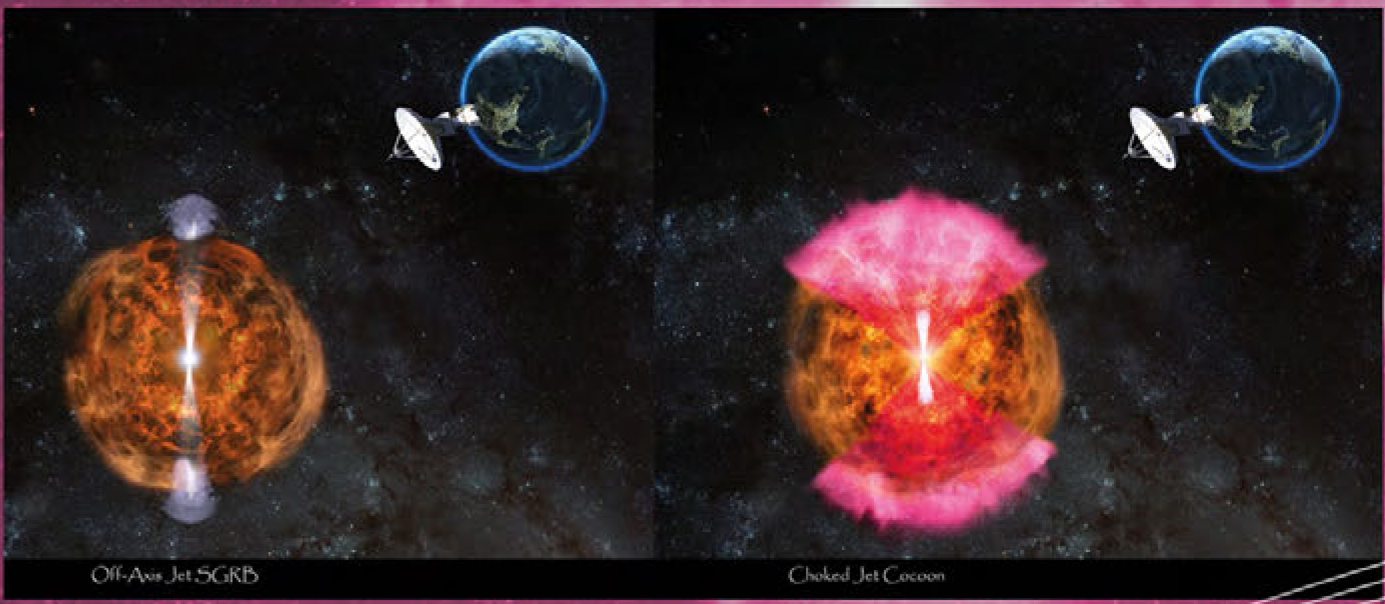
“The burst of gamma-rays from this merger didn’t come directly from a highly relativistic jet that grazed our line of sight; instead, they came from a more slowly moving outflow of material that had absorbed some of the jet’s energy,” says Swinburne astronomer Dr Adam Deller (Associate Investigator, OzGrav).

“We confirmed this by studying the radio emission produced by this outflowing material weeks and months after the merger.”

Dr Deller believes this finding will impact astronomy in two important ways. “The ‘canonical’ model of what happens when neutron stars merge will be revised and improved, and when LIGO detects more binary neutron star mergers in the future, we now expect to see an ‘afterglow’ counterpart more frequently than previously expected, which will help us pin down their locations and is good news for learning more about the extreme physics of these merger events.”

The findings were made possible by the cooperative efforts of a team of astronomers and facilities world-wide, and Dr Deller stresses the importance of having radio telescopes in Australia and the world monitoring these events.

“As we’ve kept our radio telescopes trained on the site of this event, we’ve continued to learn more and more about the nature of the explosion that accompanied the neutron star merger,” he says. “Having a suite of radio telescopes world-wide, including in Australia, has underpinned this monitoring effort. By observing at a range of times and radio frequencies, we’ve learnt much more about the explosion than any one facility could have provided alone.”



AWARDS AND HONOURS

Vice-Chancellor's Community Engagement Award – Swinburne University

Alan Duffy, Carl Knox and Mark Myers

SciVR is a virtual reality app created as part of National Science Week 2017 by OzGrav AI Dr Alan Duffy and the OzGrav outreach team's Carl Knox and Mark Myers at Swinburne University of Technology. The free app allows anyone with a phone and VR headset to explore the Universe, from our own solar system to distant colliding black holes. It has been downloaded by over 4000 users and provides an immersive and accessible experience that OzGrav used during 2017 to teach and thrill the public about the wonders of the cosmos.

Vice-Chancellor's Award for Excellence in Media and Outreach – Australian National University

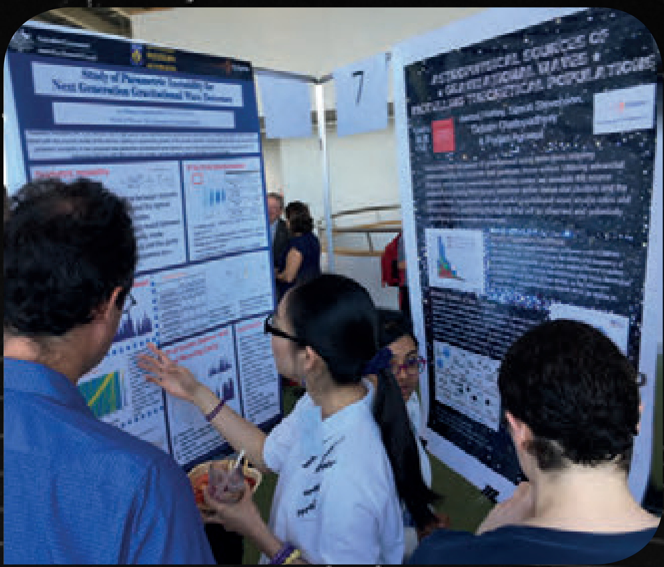
Susan Scott, David McClelland and Christian Wolf

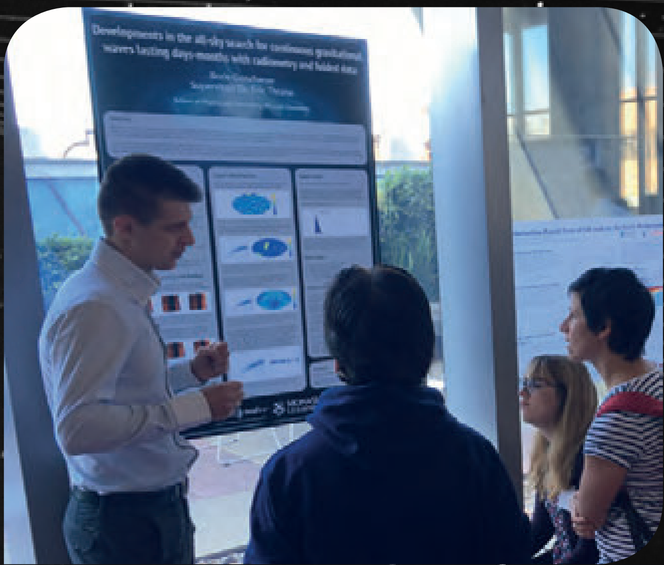
ANU's Gravitational-Wave Astronomy team received this honour for their involvement in the landmark first detection of ripples in space and time, known as gravitational waves, from the collision of two dense neutron stars generated an enormous amount of media interest. The team helped to prepare media materials and were tireless in their efforts to explain the significance of the discovery to journalists.

Emeritus Professor Honour - The University of Western Australia

David Blair

The title of "Emeritus Professor" was awarded to Australian gravitational wave legend Winthrop Prof. David Blair at the University of Western Australia's Academic Board Dinner in November 2017 to acknowledge his meritorious and longstanding service to the University. David Blair's connection with UWA began as a student graduating with first class Honours in physics in 1968. He travelled overseas to complete his PhD at the University of East Anglia and then to the USA to join others in the search for gravitational waves. He returned to UWA in 1976 where he began work to build the first southern hemisphere gravitational wave detector and this day continues to work with Asian and European collaborators to make this dream a reality. In 2017, David Blair was also honoured by his nomination for WA Scientist of the Year as well as for the Prime Minister's Prize for Science.





Medal awarded in May to people involved with the gravitational wave discovery.

Student Awards

Nikhil Sarin
MoCA Prize for Best Astrophysics Honours student - Monash University

Sylvia Biscoveanu
Leroy Apker Award for Undergraduate Research Finalist - American Physical Society

Alexei Ciobanu
Travel grant from IONS KOALA

Min Jet Yap
Best student talk at ACGRG9

George Howitt
Dr Alan Kenneth Head Travelling Scholarship from University of Melbourne

OzGrav 2017 Retreat Awards

Boris Goncharov
Best student poster

David McManus
Honourable mention for student poster

Debatri Chattopadhyay
Best poster “People’s Choice” award

Joshua McCann
Best student talk

Lilli (Ling) Sun
Honourable mention for student talk

Honourable Mentions

Prof Susan Scott, who was “highly commended” in the ANU Impact Award for Reach and Influence

Prof David Blair, Prof David McClelland, Prof Susan Scott and Prof Peter Veitch, who were shortlisted for the 2017 Prime Minister’s Prize for Science and were invited to the Awards Presentation Dinner on 18 October 2017 held in The Great Hall at Parliament House, Canberra

PEOPLE OF OZGRAV - DATA AND ASTROPHYSICS

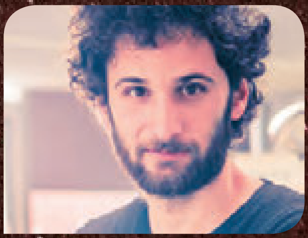
Prof Matthew Bailes
Swinburne University of Technology
Astrophysics Theme Leader
Centre Director and Chief Investigator
Pulsars, Binary Pulsars, Tests of GR, Binary Evolution, Pulsar Instrumentation

Dr 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

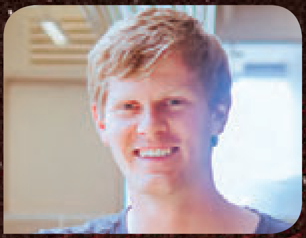
Kyla Adams
Monash University
Honours Student
postmerger neutron stars, equations of state

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



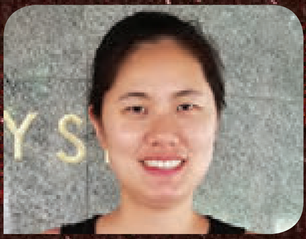
Igor Andreoni
Swinburne University of Technology
PhD Student
electromagnetic fast transient discovery

Sylvia Biscoveanu
Monash University
Associate Investigator
stochastic background GRBs parameter estimation



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

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

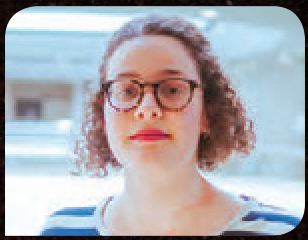
Shin Kee Chung
University of Western Australia
Pre-PhD Student
Data Processing, GPUs


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

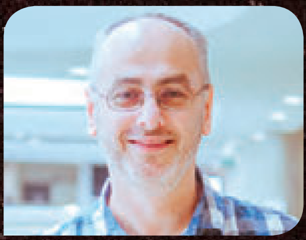

A/Prof Jeff Cooke
Swinburne University of Technology
Chief Investigator


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


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


A/Prof Christopher Fluke
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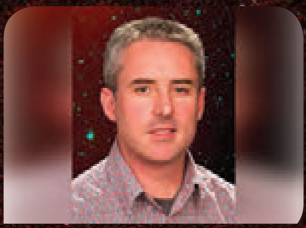
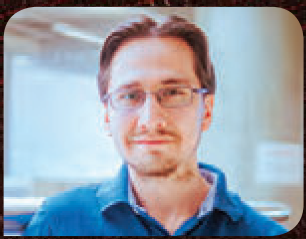
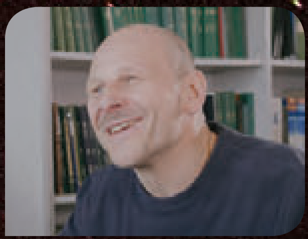
Associate Investigator
Visualisation, accelerated computing, GPUs, virtual reality


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


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


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


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


Prof Jarrod Hurley
Swinburne University of Technology
Chief Investigator


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,


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


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


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


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


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


Dr Letizia Sammut
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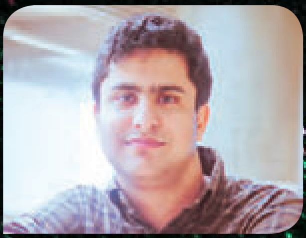
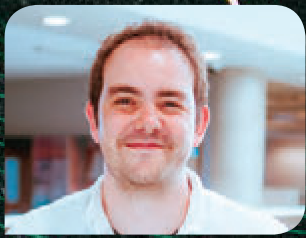
Associate Investigator


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

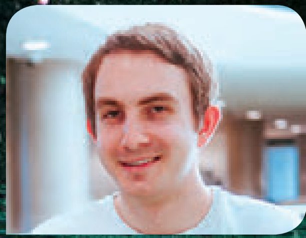

Prof Susan Scott
Australian National University
Chief Investigator
general relativity, cosmology,
gravitational waves


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

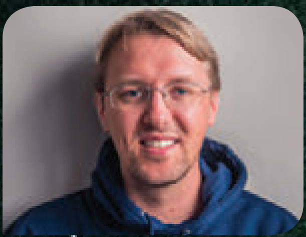


Dr Simon Stevenson
Swinburne University of Technology
Postdoctoral Researcher
binary stellar evolution gravitational waves

Ling Sun
University of Melbourne
PhD student
Gravitational waves, continuous gravitational waves, data analysis

Colm Talbot
Monash University
PhD Student
data analysis compact binaries

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

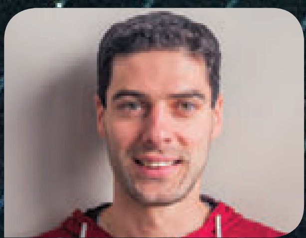
Dr Andrew Casey
Monash University
Associate Investigator

Sergey Iakovlev
University of Melbourne
PhD student

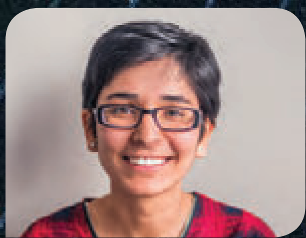
Dr Sofia Suvorova
University of Melbourne
Postdoctoral Researcher

PEOPLE OF OZGRAV - INSTRUMENTATION

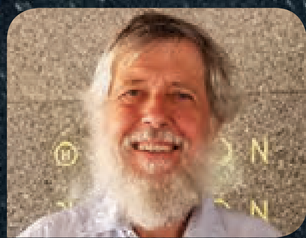
Prof David McClelland
Australian National University
Instrumentation Theme Leader
Chief Investigator
squeezing; thermal; interferometry



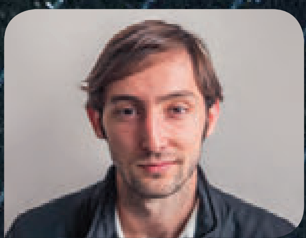
Dr Paul Altin
Australian National University
Postdoctoral Researcher
Gravitational wave detection, optomechanics, squeezing



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



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

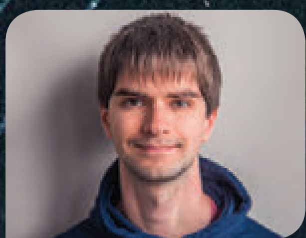


Vladimir Bossilkov
University of Western Australia
PhD Student
high power laser, cavity, instability

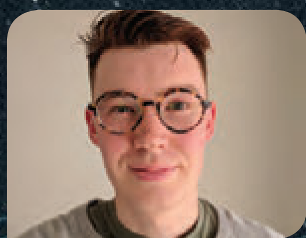
Dr Daniel Brown
University of Adelaide
Postdoctoral Researcher
Interferometry, modelling, simulation, commissioning, design

Huy Cao
University of Adelaide
PhD student

Dr Xu Chen
University of Western Australia
Postdoctoral Researcher
optomechanics



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

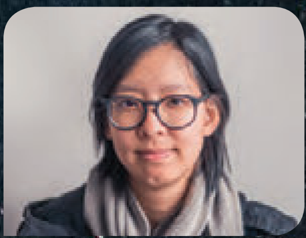


Samuel Francis
Australian National University
PhD Student
Space, interferometry, metrology, instrumentation

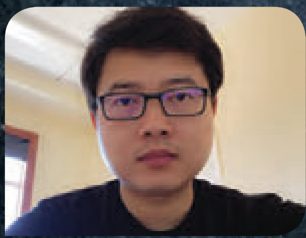
Nathan Holland
Australian National University
PhD Student
machine learning, control, torsion pendulum

Vahid Jaberian Hamedan
University of Western Australia
Pre-PhD student

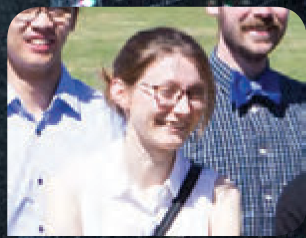
Prof Li Ju
University of Western Australia
Chief Investigator
Vibration isolation, thermal noise, parametric instabilities



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



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



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

Joshua McCann
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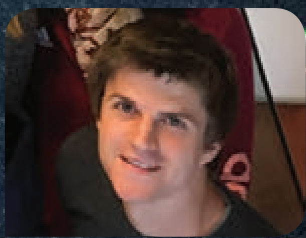
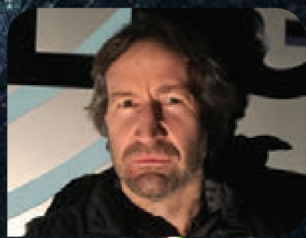
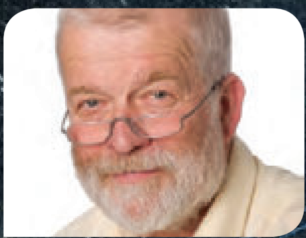
PhD Student
low-frequency; seismic; isolation; instrumentation; control



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

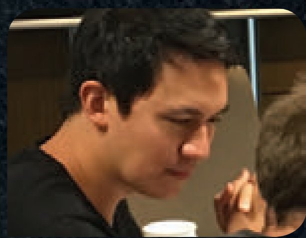


Terry McRae
Australian National University
Postdoctoral Researcher
Metrology, quantum optics, opto-mechanics, photonics

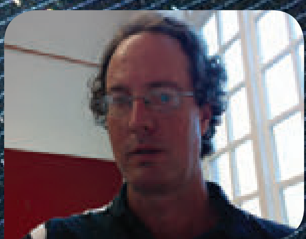


Emeritus Professor Jesper Munch
University of Adelaide
Associate Investigator

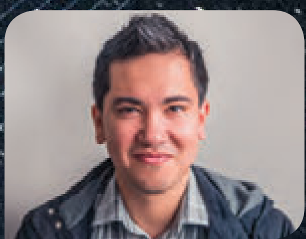
Yoav Naveh
University of Western Australia
PhD Student
Vibration Isolation



Dr Sebastian Ng
University of Adelaide
Postdoctoral Researcher



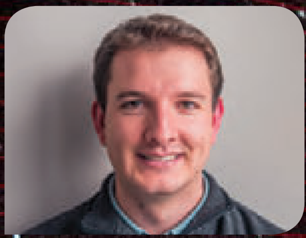
Prof David Ottaway
University of Adelaide
Chief Investigator



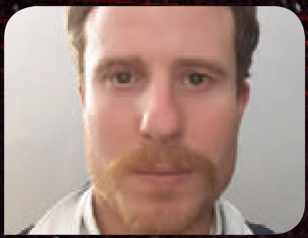
Michael Page
University of Western Australia
PhD Student
Quantum optics, optomechanics, noise

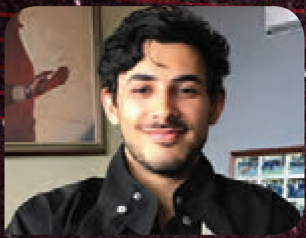
Tarquin Ralph
Australian National University
PhD Student
Digital Interferomentry, Wavefront sensing


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 Andrew Sunderland
University of Western Australia
Associate Investigator


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


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


Dr Robert Ward
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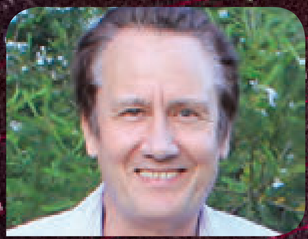
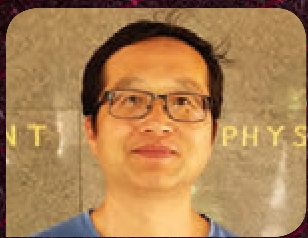
Optics, Controls systems, space instrumentation, interferometry


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


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



A/Prof Chunnong Zhao
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Laser interferometer, Parametric instability, Optomechanics.

Yohanes Dua
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Masters student

Perry Forsyth
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Instrumentation, Newtonian Noise, Seismic

Dr Miftar Ganija
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Mitchell Herrick
University of Adelaide
Masters Student
Laser Design

Craig Ingram
University of Adelaide
Masters Student
Instrumentation Hartmann

Jarrah Mik
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Fibre lasers and Cavities

Benjamin Neil
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Honours Student

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

PEOPLE OF OZGRAV - PROFESSIONAL AND OUTREACH

Ruby Chan
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Node Administration

Rahul Choudhary
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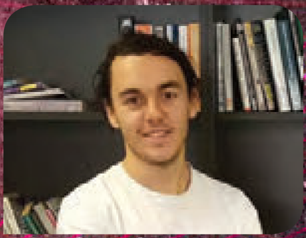
Education and Public Outreach,
Einstenian Physics Education Research

Kim Dorrell
University of Melbourne
Node Administration

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



Alex Foppoli
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PhD Student
Einstenian Physics Education Research

Lisa Horsley
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Node Administration
outreach programs, science communication

Carl Knox
Swinburne University of Technology
Digital Media and Marketing Officer
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John Moore
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Observatory Manager
Zadko Observatory
Astronomy, Gravitational Wave Detectors, Technical, Vacuum, Cryogenics

John Moschilla
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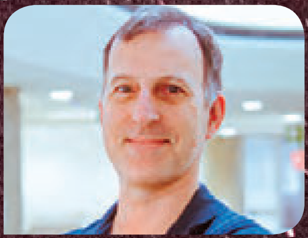

Mr Mark Myers
Swinburne University of Technology
Outreach and Education Content Developer
VR, visualisation, outreach

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

Kirsty Waring
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Node Administration

Tejinder Kaur
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PhD Student
Einstein-First, School curriculum, Einsteinian physics, Modern physics


OzGrav
VIVE

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.

EDUCATION AND OUTREACH

Outreach Summary

- 29 outreach events plus 6 events for 29 schools
- 75 teachers involved in Professional Development Program on Einsteinian Physics and General Relativity run by Einstein Physics Education Research Collaborators and Einstein-First project Group
- 1089 people involved in seminars, workshops and tours, and thousands attending 13 public events around Australia
- Tours at Gingin Research facility and Gingin Discovery Centre
- 3 cafes and bars
- 5 classrooms
- 11 university events (including Swinburne, UWA, ANU, Curtin)
- 4 public places and science museums

Outreach modes

Animations
Videos
Public talks and lectures
Workshops
Virtual Reality (VR)
Mixed Reality (MR) with green screen
SciVR app
Black hole simulator


ITAL

EDUCATION AND OUTREACH

StarGazing LIVE at Federation Square

2017 was a busy year for the Education and Public Outreach (EPO) team at OzGrav HQ. After an initial investigation into virtual reality (VR) as an outreach tool, the first public demonstration was assembled for the StarGazing LIVE event at Federation Square, Melbourne on 6th April 2017 (which happened to also be OzGrav's "birthday"!). During the course of the evening hundreds of participants experienced via fully immersive VR, merging black holes, a simulation of galaxy evolution, standing on the top of Parkes telescope, and much more. Telescopes were also set up for viewing the Melbourne night sky, with a team of keen OzGrav students, staff, and colleagues on hand to answer questions from curious minds.

Science in Virtual Reality (SciVR)

The SciVR app was created by OzGrav AI A/Prof Alan Duffy (Swinburne) and the OzGrav outreach team's Carl Knox and Mark Myers. It is a gateway to a universe of science, bringing the cosmos to anyone with a mobile phone and VR headset. The team also created and released special SciVR headsets made of high quality Google Cardboard and fitting most smartphones.

The app and headsets were used in two huge live events by Dr Alan Duffy and Dr Katie Mack during Australia's annual National Science Week:

STATE LIBRARY, MELBOURNE: A family-friendly tour of the cosmos on 13th August where we gave everyone SciVR headsets to take them from the beautiful heritage Library into the equally beautiful surrounds of space.

MOUNTAIN GOAT BREWERY: One for the adults, with a beer in hand they explored the Universe on 17th August, providing everyone with a SciVR headset to take them from the cool inner-city brewery to even cooler outer-space. There was also a recorded livestream event so anyone around regional Australia could join in the experience.

As a prelude to National Science Week, the SciVR app was first unveiled at an OzGrav display at Swinburne's Open Day, which included VR, and the addition of a green screen to allow for a Mixed Reality (MR) demonstrations.

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

Wholesome Show

As part of National Science Week, on the evening of Wednesday 16th August CI Prof Susan Scott (ANU) was one of four scientists to take part in the live "The Wholesome Show" entitled "Scientists Who Bloody Love Their Jobs" which took place during a lively evening at the Wig and Pen Pub in Canberra. This is the podcast:

http://wholesomeshow.com/live/2017/5/16/the-wholesome-show-scientists-who-bloody-love-their-jobs

Strictly Science

CI Prof Susan Scott was one of eight "entertainers" to take part in the final event for National Science Week in Canberra on Saturday 19th August 2017 which was a science cabaret called "Strictly Science" aka "Liz Lea Dance presents Science, Sex and Sass". She gave a light-hearted presentation about gravitational waves and black holes then introduced the dance group Fresh Funk who gave an artistic interpretation of how the "Dance Off" between the two black holes might look accompanied by a musical recording incorporating the recorded voices of Susan and Brad Tucker talking about the detection event but presented in rap form!

EDUCATION AND OUTREACH

Astrolight Festival

On the night of the Mountain Goat Brewery SciVR demonstration something unexpected happened – the first binary neutron star merger - GW170817! This resulted in a very intense couple of months creating animations and support material for the major press release, a day of filming for the 7:30 Report, and preparing for another public event, Astrolight Festival at ScienceWorks (Melbourne). Astrolights is a huge Astronomy and Light Festival that typically attracts thousands of people of all ages, run in partnership with 15 Victorian science organisations and universities. At this event the OzGrav outreach team showcased animations, videos, Virtual Reality (VR), Mixed Reality (MR) with green screen, the SciVR app with VR headsets, and the black hole simulator. Over 1000 people attended the event.

TEDxCanberra

CI Prof Susan Scott was one of 18 speakers at the annual TEDxCanberra event held over a full day on 16th September at the Canberra Theatre. She spoke about "The story behind the detection of gravitational waves on Earth". Training for the event commenced months earlier with each speaker being assigned a personal coach. The rules imposed on these talks were; less than 18 minutes long, no Powerpoint presentation to support the talk (and prompt the speaker!) and no stepping out of the small circular patch of red carpet in the centre of the stage.

The Canberra Theatre was full early on the Saturday with 1,000 eager faces ready to absorb the diversity of ideas and stories with which they would soon be presented. Prof Scott opened the lineup, and the audience were very fresh and receptive to the general scientific notions discussed. The talk program was interspersed with various entertainers. The talk has been posted on YouTube.

Pint of Science

Ever wanted to have a pint with a cutting-edge scientist? Now is your chance!

Pint of Science is an international not-for-profit festival that is held annually in pubs right across the world. During this event, patrons have the opportunity to hear about the 2017 frontiers of scientific research from some of Melbourne's brightest minds in the best way that Melbourne knows how - over the comfort of a pint. Pint of Science is a fun, interactive and informative event. Additional OzGrav demonstrations were given at Pint of Science utilising a mixture of VR and interactive, animated scenes.

EDUCATION AND OUTREACH

Einstein First project

OzGrav's Einstein First Project led by CI Prof David Blair (UWA) is an education project seeking to introduce Einsteinian physics seamlessly throughout the school curriculum. In 2017, five postgraduate students were involved in developing and testing exciting new ways to introduce Einsteinian thinking from early on in the school curriculum. These programs allow students to learn experientially, and in 2017 we engaged with many hundreds of school students from Year 5 to Year 10, and with primary and secondary school teachers. Gravitational wave detectors and the discovery of gravitational waves from coalescing black holes provides a perfect context for teaching about general relativity and quantum mechanics. By bringing students into contact with young PhD students we also try to teach that science is for everyone and that scientists are ordinary people with interesting lives.

At early ages we concentrate on a few key questions like what is space? what is time? what is light? and what is gravity? Our goal is to open the minds of both children and teachers to the fact that a) there are answers to the above questions, b) the answers are not trivial and c) in most cases the answers are different from those taught by most teachers.

To understand space, we focus on geometry and arithmetic with questions like what is a straight line? Once we have explored the concept of a straight line we are ready to do experimental geometry on different surfaces. Through simple experiments (like using upturned woks to explore the geometry of triangles!) students discover that the laws of geometry depend on the shape of the surface. At Year 7 levels and above students enjoy learning that the standard formulae of geometry are only approximations because space is curved.

To understand light, we first introduce students to the concept of photons, particles of light. We use soft toy bullets to mimic photons and the recoil of toy interferometer mirrors to teach about the momentum of photons, Here we create foundational thinking about mathematics that goes beyond normal arithmetic, to determine where photons will arrive in experiments where light can take two alternative paths. They will experiment with this using simple experiments with lasers. The most interesting results obtained so far from the Einstein-First project are the following:

- Students are entirely receptive to the foundational ideas
- Knowledge testing before and after interventions show that student learning outcomes are independent of their prior knowledge.
- Girls attitudes to science improve more than the boys, from much lower prior attitudes to near equality with the boys after the programs.

Einstein First and Gingin Science Festival Hands on Science at AIGO 19 and 20 Aug 2017. Photos: David Nicolson

Homeward Bound

In February 2017, CI Prof Susan Scott was selected to participate in the 2018 Homeward Bound program which is a ground breaking leadership, strategic and science initiative and outreach for international women scientists, set against the backdrop of Antarctica. This initiative aims to heighten the influence and impact of women with a science background in order to influence policy and decision making as it shapes our planet.

Currently 80 international women scientists are undertaking a year-long state-of-the-art program to develop their leadership and strategic capabilities, using science to build conviction around the importance of their voices. This program will culminate in the largest-ever female expedition to Antarctica, departing in February 2018, with a focus on the leadership of women and the state of the world. The three week expedition to Antarctica incorporates intensive onboard leadership, strategic, science and visibility training delivered by a highly qualified and experienced international team.

The Homeward Bound vision is to equip a 1000-strong global collaboration of women with a science background to lead, influence and contribute to policy and decision making as it informs the future of our planet within 10 years.

Image (left): Homeward Bound 2017/18 participants from the ACT: Madeline Mitchell, CSIRO Agriculture and Food, Canberra; Aparna Lal, Spatial Epidemiology, ANU; Nicole Fetchet, Outreach Science Communicator, Questacon, Canberra; CI Prof Susan Scott

RESEARCH TRANSLATION

OzGrav's research is at the forefront of science and technology in a range of areas, from instrumentation and measurement techniques to advanced data analysis and supercomputing. An important goal of OzGrav is to translate these research techniques and technologies to other areas of science, to industry, and to benefit society in general. In 2017 a Research Translation Committee was established to coordinate, encourage and support such translational activities. The Committee is chaired by Chief Investigator Prof Daniel Shaddock (ANU) and consists of representatives from all nodes of OzGrav, with a mix of researchers and university commercialization experts. The committee meets several times a year and reports to the OzGrav Executive committee on research translation and commercialisation performance.

OzGrav employs several strategies to foster translation activities, such as embedding of commercial partners in OzGrav nodes, via co-location of offices, and student internships with partner organisations. In 2017 the start-up company Liquid Instruments renewed a contract with the ANU to house their 12 member R&D and engineering team in the ANU OzGrav premises. In return Liquid Instruments has trained several interns from the ANU physics and engineering undergraduate programs, several of which have since joined OzGrav. Another key strategy, also employed by Liquid instruments and OzGrav, is to encourage joint appointments of university research staff with commercial partners. Three OzGrav researchers now work part-time for Liquid Instruments.

The colocation and joint appointment arrangements have been a great success, fostering strong links between academic and industrial staff. OzGrav anticipates adopting similar arrangements at other nodes, including with a spin out company at Swinburne University that was founded in 2017 by OzGrav Director Prof Matthew Bailes to commercialise IP from the centre's education and outreach program, by creating educational content for the Virtual/Mixed/Augmented Reality marketplaces.

OzGrav strives to ensure that its postdoctoral scientists and students are commercialisation- and innovation-savvy, and equipped with translatable skills. Therefore, as part of our 2017 annual Early Career Researcher (ECR) workshop, we held a day-long Research Innovation and Entrepreneurship workshop attended by 45 of our early career researchers. The workshop walked ECRs through the steps from having an idea to market production, culminating in teams delivering short pitches about their entrepreneurial idea.

PROFESSIONAL DEVELOPMENT

During 2017 we established the OzGrav Professional Development Committee (PDC) initially comprising the Chair CI Prof Susan Scott and CI Prof Andrew Melatos and CI David Ottaway. As the year progressed and OzGrav appointed various new postdoctoral fellows the PDC was enlarged to include three Early Career Researchers (ECRs) from three different OzGrav nodes. The initial priority of the PDC was to determine a suitable mentoring program for all ECRs in OzGrav. The establishment of this program was initiated in 2017 and will be further developed this year.

The second main priority for 2017 was to put together a high quality 2-day program for the ECR portion of the week long first annual retreat of OzGrav held at Swinburne University in November. An interactive Research Innovation and Entrepreneurship workshop, a programming training module, an OzGrav app brainstorming competition held throughout the lunch hour, and sessions such as “Building your personal brand to market yourself as a scientist” and “Tips for writing successful grants” were held. The highly popular career stories, advice, and panel discussion with panel members Prof Sheila Rowan and Prof Giles Hammond from University of Glasgow, and Dr Chiara Mingarelli from Flatiron Institute’s Center for Computational Astrophysics in New York completed the program. Feedback sought from the ECRs following the retreat indicated that they were very pleased with the ECR Workshop part of the retreat and its associated networking activities.

Case study: From Industry to Research

A reflection from Joshua McCann

At the beginning of March 2017 I found myself in a conference room on the fourth floor of the physics building at the University of Western Australia. It was my first week as a PhD student and I was taking part in a weekly group meeting for the UWA Gravity Wave group. As if I wasn't already feeling overwhelmed enough joining this team of dedicated researchers, we were then informed by one of our Professors that we would all be part of the new ARC Centre of Excellence for Gravitational Wave Discovery OzGrav!

Having come from industry as an electrical engineer I was often in environments where open communication was minimal and exploring new ideas was frequently disregarded. While I understand that industry has the goal of profit and doing what works tends to get the results, becoming a researcher at UWA and within OzGrav has finally given me the opportunity to explore new possibilities and contribute to a field that is at the forefront of our times.

The first OzGrav retreat and ECR Workshop exposed me to many of the facets of the research that is required for discovering gravitational waves from low frequency seismic isolation to the search for continuous gravitational wave signals. While these topics were mind bogglingly exciting I found the biggest take away from the weeklong conference to be the importance of collaboration. Although we come from different institutions we are all working toward the same goals. This is what I believe brings about discoveries in science and often contrasts my experiences of industry which keeps its cards to its chest. In summing up my first year out of industry and into research, I feel so thrilled and privileged to have joined Australia's finest researchers in the field of Gravitational Waves in OzGrav and can't wait to contribute and collaborate.

EQUITY AND DIVERSITY

There is a growing awareness of the importance in the STEM and physics communities of Equity and Diversity. In 2017, OzGrav's Equity and Diversity Committee was established to tackle these matters, chaired by Director Prof Bailes and drawing members from a broad cross-section of the Centre.

Internationally, there is a low percentage of women participating in gravitational wave science, and in Australia there were only two tenured female staff who were members of the LIGO Scientific Collaboration at the time that the OzGrav bid was being developed, both of whom are OzGrav Chief Investigators. The formation of OzGrav helped us gain a third female Chief Investigator (Associate Professor Ju Li at the UWA node). When recruiting, OzGrav highlights many of our family-friendly policies, gleaned from a review of best practice and examples learned from Director Bailes' former membership of the ARC Centre of Excellence for All-Sky Astrophysics (CAASTRO).

In 2017, we implemented the first of many Equity and Diversity initiatives, including offering childcare to all delegates to the annual retreat and conducting an unconscious bias training session. We ensured that some of the most inspiring women in gravitational wave science attended our annual retreat and early career researcher workshop, and that our advisory boards feature many leading women in science. We also sponsored CI Prof Scott to attend an in-depth leadership training course with 80 other future female leaders, and we have made every attempt to ensure our weekly theme videoconferences are at family-friendly times.

In 2017, OzGrav had higher than average percentage of female new postdoctoral recruits for this field of science. Importantly, some of these applicants actively listed elements of OzGrav's equity and diversity policies as motivation for applying for positions with the centre.

ACTIVITY PLAN 2018

Instrumentation

Commissioning

2018 promises to be an exciting year for the Australian presence at the LIGO sites. The aLIGO interferometers will use squeezing for the first time. OzGrav will continue to provide significant support for the commissioning of this critical hardware at both LIGO sites, helping to bring the LIGO detectors to a sensitivity at which the range for binary neutron star events is around 120Mpc. This will trigger the commencement of LIGO's third observing run, during which we will continue to support OzGrav LIGO fellows on site. It is hoped that experienced OzGrav commissioners will be available at the sites to help supervise new OzGrav commissioners from all OzGrav nodes and take some of the load off the local staff.

Quantum

We will continue to develop Tm:fiber MOPA and Ho:YAG ILPO systems with output powers ca. 100W.

We will improve our 2μm squeezed light source toward delivering a factor of 10 times (inferred) quantum noise reduction and commence an investigation into improving photodiode quantum efficiency.

Low frequency

We plan to build the first tilt sensor with piezo feedback, test it at the isolator at our UWA lab before installing it on the isolators in vacuum at the Gingin facility.

We will move the TORsion PEndulum Dual Oscillator system into vacuum and install a pre-isolation stage as a low displacement suspension platform.

Instabilities and Distortions

Parametric instabilities continue to be a major issue. This year we will study feedback controls for PI suppression and continue our study of resonant damper systems. We will commence work on building a 3-mirror suspended cavity with fused silica test mases at 1064nm initially. In preparation for studying instabilities at 2μm we will install a 2μm laser with output power of the order of 10W, and frequency stabilise it to a reference cavity.

Research on new techniques to measure distortions will focus on the completion of a mechanical scanning free phase camera.

We will continue our work on automatic mode-matching, investigating a number of platforms including: new bi-material tuneable mirror in a Tip-Tilt mirror platform; measurement of the fundamental absorption of OH free Fused-Silica in the wavelength band between 1.9-2.1μm to assess suitability; and the development of new high speed spatial modulators.

We will commence an investigation of what fundamentally limits the circulating power in advanced detectors. This will take a completely unified approach across the theme.

Space

This year we will begin to address the challenge associated with link acquisition between the spacecraft of a space-based gravitational wave detector. We will characterise different laser beam steering approaches. We plan to test these and other acquisition strategies under real-world conditions by operating laser links over longer distances. Due to the arm lengths involved, these tests cannot be conducted in the lab, and we plan to collaborate with researchers from ANU's research school of Astronomy and Astrophysics to demonstrate link operations over 10s to 100s of metres.

Pulsar Timing

The Zadko Telescope is a one-metre telescope funded by a generous donation from James Zadko to UWA. Here are some UWA OzGrav members with James Zadko (centre).

When MeerKAT is completed in mid-2018 OzGrav scientists will be well-placed to monitor the Universe for the presence of supermassive black hole binaries with a precision not previously possible in the Southern hemisphere. In February 2018 the PST passed its critical design review paving the way for its successful construction as part of the SKA.

Data and Astrophysics

We will work under six new programs from 2018 on:

- Electromagnetic Observations
- Pulsars
- LIGO
- Relativistic Astrophysics
- Population Modelling
- Inference

Expand involvement in 3G Science Working Groups, especially through activities in the Population Modelling and Inference Programs.

Electromagnetic Observations

We will continue to perform optical follow-ups of neutron star mergers with the Zadko, GOTO, SkyMapper and other telescopes. The GOTO telescope in La Palma will be fully commissioned to detect optical counterparts of gravitational-wave events in the northern hemisphere.

We will search for pulsations in X-ray and radio data to benefit continuous gravitational-wave searches.

We will provide precision ephemerides for gravitational-wave searches.

We will organise and optimise all OzGrav-related EM facilities worldwide for GW follow up during LIGO/Virgo operational run O3. Grow Deeper Wider Faster (DWF) to include over 60 facilities and expanding the energy range for transient detection and study, making it the largest collaborative telescope program in the world. 2 scheduled ground-breaking DWF runs in the first half of 2018, coordinating simultaneous observations of

ACTIVITY PLAN 2018

~20 multi-wavelength facilities, real-time supercomputer data processing, and follow-up observations by ~25 facilities.

Pulsars

Using MeerKAT telescope (with approximately 7x the performance of Parkes) we will monitor millisecond pulsars to detect the gravitational-wave background from supermassive binary black holes. We will search for evidence of ultra-light dark matter. We will complement this with data from a new ultra-wideband receiver from the Parkes radio telescope.

We will use the MeerKAT to monitor relativistic binaries to tests theories of relativistic gravity and determine the masses of southern neutron stars.

The broadband nature of the PKS and MeerKAT receivers will allow us to use a novel new method to determine neutron star inclination angles and masses more accurately.

The new OzSTAR supercomputer will house archival surveys that we will search for accelerated pulsars.

LIGO

We will ramp up research related to the interpretation of LIGO binary black hole and binary neutron star detections. This includes activities such as participation in LIGO parameter estimation runs following detections, hierarchical modeling to study the population properties of binary black holes, tests of general relativity including a search for gravitational-wave memory, and detection of a population of individually unresolvable binary black holes.

We will continue to be heavily involved in continuous-wave searches for gravitational waves from isolated neutron stars.

The newly constructed OzSTAR cluster will facilitate expanded effort in low-latency searches for gravitational waves from binary neutron stars with a focus on methods optimised for GPU acceleration.

Detector characterisation will be consolidated to leverage our broad expertise in instrumentation, commissioning and Big Data techniques.

Our involvement in the LIGO Burst and Stochastic data analysis groups will continue, as we search for the stochastic background from binary black holes.

Population Modelling

The Galactic relativistic binary pulsar population will be modelled and we will use the location of merger events to better constrain kicks while enhancing our understanding of pulsar selection effects. Pulsar selection effects will be incorporated into the binary population modelling.

We will simulate GW signals from accurate models of core-collapse events with Associate Investigator Mueller.

We will use the OzSTAR supercomputer to perform extensive modelling of globular cluster populations. These studies will help us to understand the properties of binaries that form dynamically.

Inference

In 2018, our inference program will ramp up significantly. We will develop and improve Bayesian inference and parameter estimation tools that answer questions posed in our Relativistic Astrophysics Program.

Easy-to-use, user-friendly, well-documented parameter estimation tools will be developed in order to expand the number of OzGrav researchers fluent in parameter estimation.

There will be an increase in the number of researchers involved with core LIGO parameter estimation activities including parameter estimation shifts (following detections) and development / maintenance of parameter estimation pipelines. We will continue to develop and implement optimisation techniques such as reduced order modelling and reduced order quadrature.

Participation in Global 3G Design study

In addition to the above Instrumentation, Data and Astrophysics activities, OzGrav members will play key roles in global efforts to plan and design future gravitational wave detectors. OzGrav will work with the international community, including leading some of the primary design study sub-committees, in order to:

Develop the science case for the next generation of observatories

Coordinate key research and development themes and programs that will lead to technological breakthroughs needed to achieve design goals

Make recommendations for frameworks to efficiently manage and operate the next generation GW network.

Education and Outreach

In 2018, the OzGrav schools incursion program will bring a collaborative and interactive lesson to varied schools, incorporating innovative digital technology and major scientific themes.

We will develop a TED-style public lecture with engaging animations that our researchers will be trained to deliver, in order to communicate our science to the public.

We will continue to participate in public outreach at state and national science events using Virtual and Augmented Reality content, and will work with the Gravity Discovery Center to build interactive exhibits focusing on the science of black holes and gravitational waves. We will also continue developing and deploying the Einstein First project led by Prof Blair.

The diverse faces of OzGrav will be showcased through videos and people profiles that we promote. We will run science communication workshops to not only help OzGrav members communicate their science, but to also ensure that communication is accessible to a diverse audience.

Equity and Diversity committee

In 2018, we will launch a carer grant scheme to support our members with primary carer responsibilities to attend workshops and conferences.

We will ensure that our schools and outreach programs target under-represented groups in science and disadvantaged communities.

We will appoint trained ombudspeople to listen to the concerns of our members.

We will strengthen links with LIGO's equity committee to share policies and best practices.

Our target is to win a bronze Pleiades award in 2018 and gold by the end of OzGrav and also to consider equity issues beyond gender and race.

Professional Development committee

The OzGrav mentoring program will be fully rolled out and operational in 2018.

We will provide our early career researchers with training on a range of topics including science communication and preparing for the next stage in their career.

We will design an inspiring and empowering program for our early career researcher annual workshop, incorporating elements of the 2018 Homeward Bound leadership program.

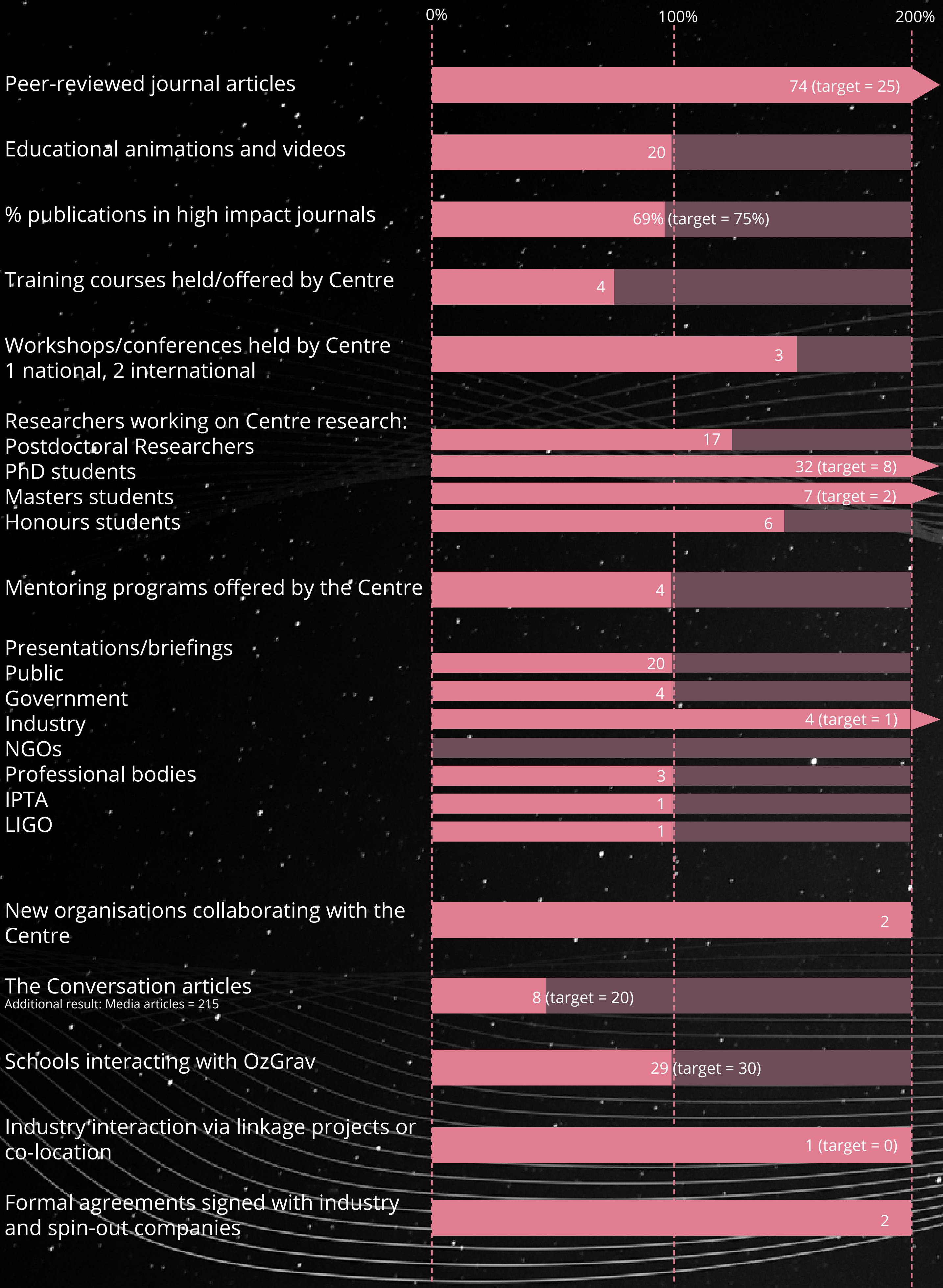
Research Translation committee

A competitive grant program will be launched in 2018 to provide seed funding for pre-commercialisation activities by our members.

We will work with our nodes to monitor and advise on technology transfer opportunities.

Regular industry briefings will be held by OzGrav, and we will facilitate joint appointments of industry and research staff, and industry internships for our early career researchers.

KPI DASHBOARD



Hierarchy of Eddies art installation at RMIT Gallery, 2017. Photo: Mark Ashkanasy

LINKAGES AND COLLABORATIONS

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

National Partners and Collaborators

CSIRO Australia Telescope National Facility (ATNF)
Australian Astronomical Observatory (AAO)
Charles Sturt University
International Centre for Radio Astronomy Research (ICRAR)
Astronomy Australia Ltd

International Partners and Collaborators

Auckland University of Technology
Laser Interferometer Gravitational-Wave Observatory (LIGO)
Massachusetts Institute of Technology (MIT)
University of Glasgow
California Institute of Technology (Caltech)
Max Planck Institute for Gravitational Physics (Hannover)
Albert Einstein Institute
University of Warwick
Kavli Institute for Theoretical Physics China
Max Planck Institute for Radio Astronomy
NASA Goddard Space Flight Centre
University of Urbino
AstroParticle and Cosmology Laboratory (APC)
University of Science and Technology China (USTC)
University of Tokyo
Tsinghua University
University of Otago
MeerTime Collaboration (Manchester, ASTRON, MPIfR, CNRS, SARAO, NRAO, CSIRO, Curtin, AUT, UBC, INAF)
LIGO Scientific Collaboration (LSC)

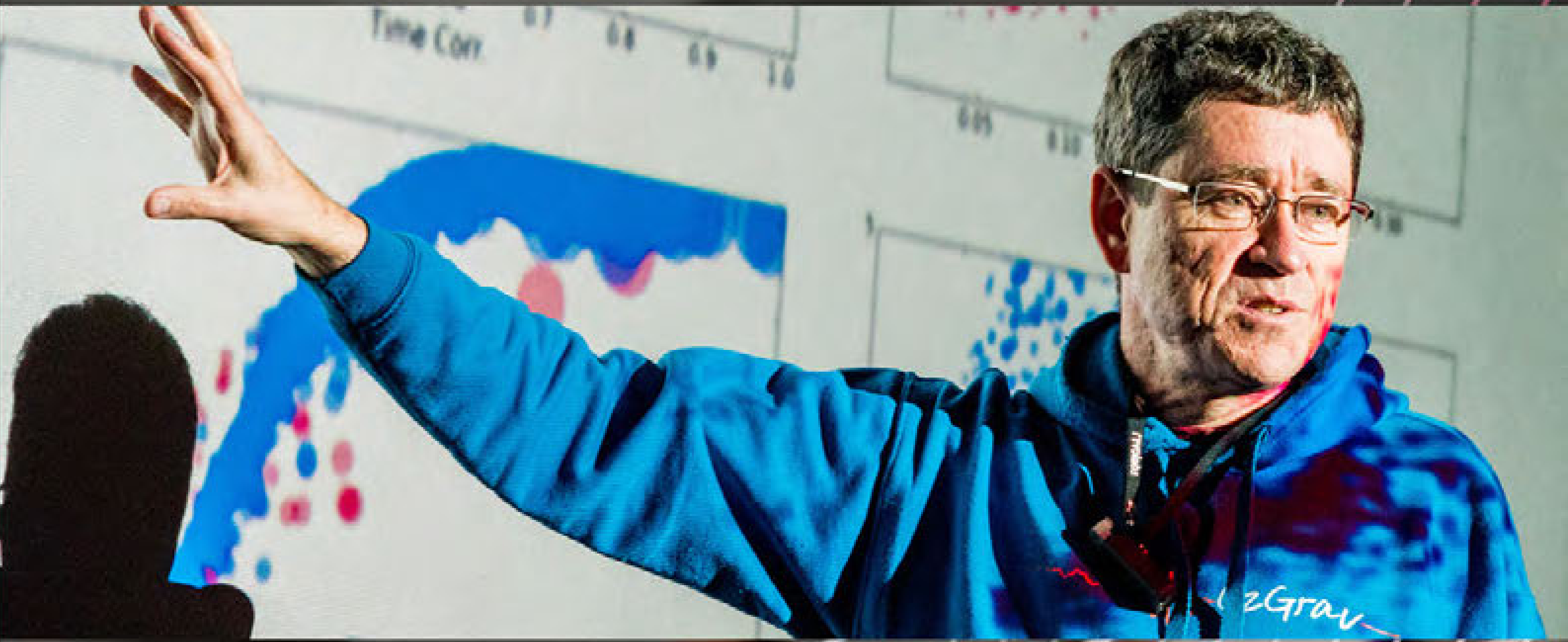
LIGO Scientific Collaboration (LSC)

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

In 2017, AI Dr Letizia Sammut (Monash) served as co-Chair of the Stochastic Data Analysis group and CI Dr Eric Thrane (Monash) served as Review Chair for the Burst Data Analysis group. Nutsinee Kijbunchoo (ANU) was elected as a graduate student representative to LAAC (LIGO Academic Affairs 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.



Nature's 10 - Ten people who mattered in 2017

OzGrav PI Marica Branchesi – Merger Maker

An astronomer helped scientists make the most of a historical gravitational-wave event.

For a few weeks starting on 17 August, it seemed as if every telescope on Earth and in space was looking in the same direction. Prompted by the latest detection of gravitational waves by facilities in Italy and the United States, some 70 teams of astronomers rushed to capture the first direct observations of the collision between two inspiralling neutron stars. What they saw solved several astrophysical mysteries at once, including the nature of certain γ-ray bursts and the origin of the Universe's heavier elements.

This effort was the result of years of preparation spearheaded by Marica Branchesi, a member of the Virgo collaboration, which operates the gravitational-wave detector near Pisa, Italy. Branchesi bridged the divide between observational astronomy and the physics-heavy realm of gravitational-wave research — fields that, until recently, had little reason to work together. "Marica has been the key communicator between astronomers and physicists," says Gabriela González, a physicist at Louisiana State University in Baton Rouge and the former spokesperson for Virgo's partner, the collaboration that runs the US-based Laser Interferometer Gravitational-Wave Observatory (LIGO).

LINKAGES AND COLLABORATIONS

Collaborations and Conferences

Australasian Society for General Relativity and Gravitation Conference

The University of Western Australia (UWA) hosted the Australasian Society for General Relativity and Gravitation Conference in November 2017 with international keynote speaker Prof Tsvi Piran who gave talks on “GW170817 and its EM counterparts-predictions and implications” and “Neutron Stars, Gravitational Waves and the Origin of Gold”. Other keynote speakers included OzGrav Director Prof Matthew Bailes and Nobel Laureate Prof George Smoot III. The Conference attracted the attention of many of our Asian collaborators. One highlight of the Asia-Australia collaboration has been the proposal for a joint Australian and Chinese Academy of Sciences workshop on future gravitational wave detectors.

Interdisciplinary Big Data workshop

OzGrav hosted its first interdisciplinary workshop in July 2017 with the not-for-profit company, Centre for Eye Research Australia (CERA). CERA is one of Australia’s leading eye research centres. Just like OzGrav, CERA is facing challenges associated with this new era of big data. The workshop program brought together about 50 researchers from CERA, Swinburne, and OzGrav to explore new cross-disciplinary collaborations in the area of Big Data. Several continuing collaborations were seeded by this event.

Gravitational Wave Advanced Detector Workshop 2017

GWADW is a major event on the international gravitational wave calendar, and OzGrav was delighted to host the 2017 workshop. GWADW 2017 was attended by about 100 international researchers from 9 countries, who gathered on Hamilton Island to discuss advanced instrumentation for future gravitational wave detectors. We had a rocky start as on 28th March Cyclone Debbie, a category 4 storm, made landfall in Queensland, and Hamilton Island was on the direct path of the storm. The hotel sustained a lot of damage, which was mostly cleaned up and fixed prior the workshop commencement on 7th May.

The GWADW 2017 workshop opened with a discussion on 'What is the known science case for future generations of detectors?'. From this we explored questions like 'How does the science case depend on the network of detectors?', 'Is it desirable for the detectors to have the same response?' and 'Will there be an ongoing role for second-generation detectors?' and since the LISA space-based mission will possibly be launched around the same time as future detectors come online, 'What will be the interaction of future ground-based detectors and space-based detectors'. Significant time was devoted to key design issues for future detectors including control strategies, quantum and thermal noise abatement, and extending the range of detectors to lower frequencies.

Future Gravitational Wave Detectors

In 2017, OzGrav-UWA led an international study on the science benefits of creating new gravitational wave detectors of 8km arm length with approximately 4 x the strain sensitivity of the Advanced LIGO nominal strain sensitivity. Modelling was undertaken for new detectors in China and Australia. The results of this analysis, which was led by Eric Howell and included collaborators in Glasgow and China showed that this step in sensitivity, using the known technologies already in use, combined with modest improvements to reduce low frequency noise could allow binary black hole sources to be detected from about 50% of the observable universe, corresponding to signals at the rate of ~ 1 per hour. It was also shown that the angular resolution of a network that included two new detectors and other detectors at the Advanced LIGO design sensitivity would be capable of uniquely identifying the host galaxies of the brightest sources.

Prof Wen of UWA together with Prof Zhao of the University of Science and Technology of China, studied the capacity of the proposed 3rd generation gravitational wave detectors in measuring the expansion rate of our Universe. In particular, the possibly significant effect of the low-frequency sensitivity of the future detectors was highlighted.

FINANCE

	2017 Actual	2018 Forecast
Income		
ARC Centre Grant	$ 4,716,750	$ 4,687,523
Institutional cash contribution	$ 1,119,101	$ 1,127,000
Other grants and contracts	$ 70,985	
TOTAL INCOME	$ 5,906,836	$ 5,814,523
Expenditure		
Salaries & scholarships	$ 1,354,284	$ 3,888,747
Equipment	$ 129,845	$ 581,441
Travel and Annual Retreat	$ 331,129	$ 662,700
Research maintenance and consumables	$ 115,003	$ 222,500
Outreach, operations and other expenditure	$ 158,349	$ 455,181
TOTAL EXPENDITURE	$ 2,088,610	$ 5,810,569
Carry-forward from previous year	-	$ 3,818,226
Balance	$ 3,818,226	$ 3,822,180

OzGrav members were involved in other grants during 2017 worth a total of $21.7M.

Photo: Aditya Parthasarathy

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

Professor David Blair - Outreach Leader
University of Western Australia

Professor Andrew Melatos
University of Melbourne

Dr Eric Thrane
Monash University

Professor Peter Veitch
University of Adelaide

GOVERNANCE

Partner Investigators

Prof Warrick Couch - AAO

Dr George Hobbs - CSIRO

Dr Douglas Bock - CSIRO

Dr David Reitze - Caltech

Prof Rana Adhikari - Caltech

Prof Shrinivas Kulkarni - Caltech

Prof Alan Weinstein - Caltech

Prof Sheila Rowan - University of Glasgow

Prof Rong-Gen Cai - Kavli Institute (China)

Prof Karsten Danzmann - Max Plank (Einstein) Institute

Prof Nergis Mavalvala - MIT

Dr Marica Branchesi - Urbino University

Dr Brad Cenko - NASA Goddard Space Flight Centre

Prof Michael Kramer - Max Planck Institute (Radio Astronomy)

Reader Danny Steeghs - University of Warwick

A/Prof Mansi Kasliwal - Caltech

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

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

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

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

Kirsty Cleland
Swinburne Innovation Precinct, Swinburne University of Technology

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

Photo: Aditya Parthasarathy

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
Unversity of Western Australia

Dr Eric Thrane
Monash University

Dr Rob Ward
Australian National University

Dr Yeshe Fenner
Swinburne University of Technology

Dr Jade Powell
Swinburne University of Technology

Professional Development Committee

Prof Susan Scott - Chair
Australian National University

George Howitt
University of Melbourne

Joshua McCann
University of Western Australia

Dr Karl Wette
Australian National University

Prof Andrew Melatos
University of Melbourne

Prof David Ottaway
University of Adelaide

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