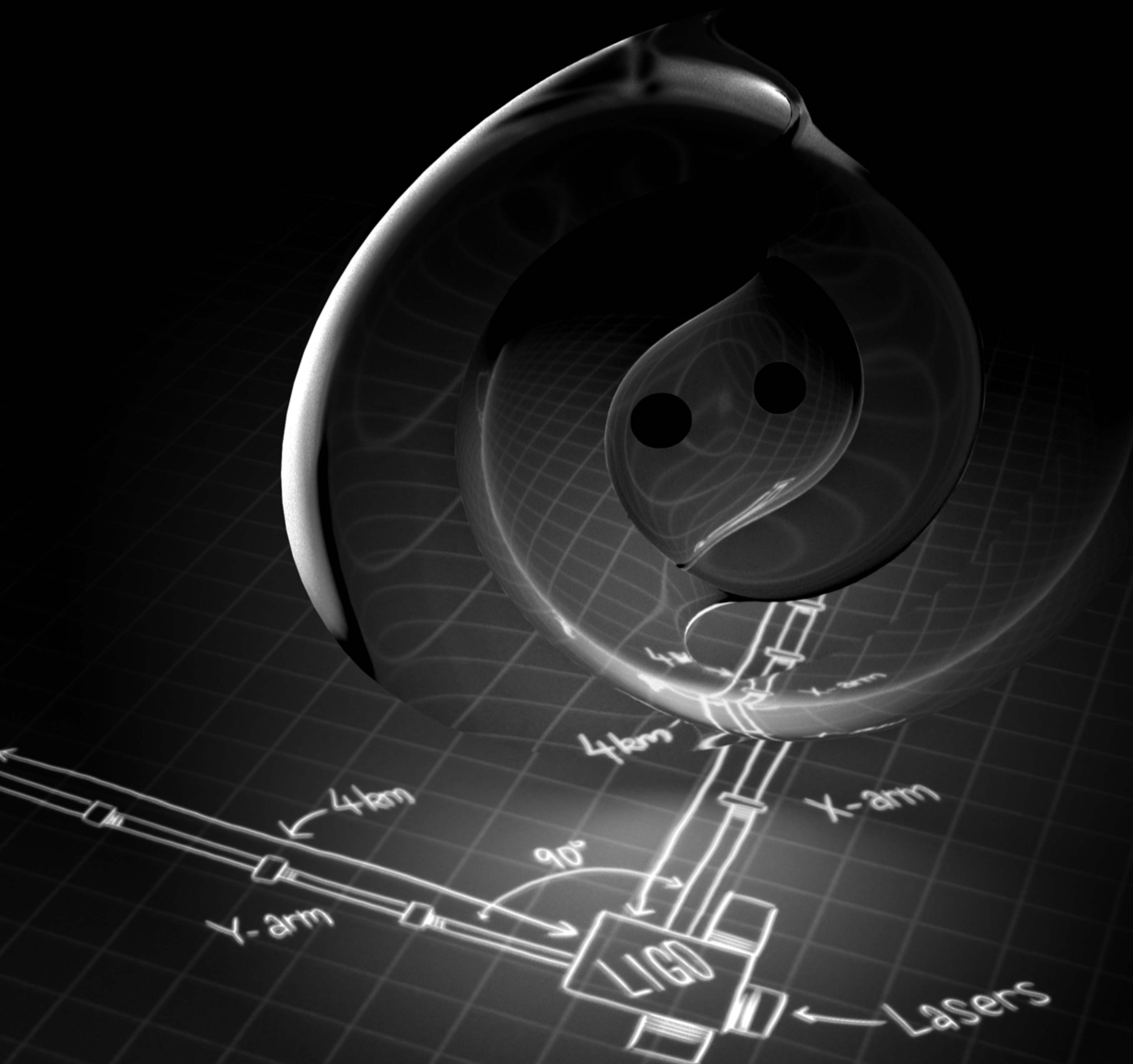


OzGrav

ARC Centre of Excellence for Gravitational Wave Discovery

Annual Report 2019

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.

CONTENTS

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

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

MESSAGE FROM THE DIRECTOR

In April 2019 the LIGO and Virgo gravitational wave detectors turned back on for the third observing run, "O3", after an extended down-time for detector enhancements and we got to listen to more of the gravitational Universe than ever before thanks to the tireless work of OzGrav instrumentalists and our international colleagues. I was fortunate to be able to visit the Hanford detector for the first time in 2019 and the scale of these instruments has to be seen to be believed.

In just 4 years since the dawn of gravitational wave astrophysics, the detectors are now seeing over 8 times as much of the Universe, detecting a new source of gravitational waves about once per week, and providing many surprises as this new window of the Universe is being exploited to learn new physics.

In this year's report you can read about how OzGrav's instrumentation team helped implement some "quantum magic" on the lasers, worked on phase cameras and instabilities that have helped extend LIGO's reach into the ever more-distant Universe. But our work is not confined to the detector. In O3 the SPIIR (Summed Parallel Infinite Impulse Response) pipeline from the University of Western Australia (UWA) is running 24/7 to detect gravitational waves and had its first successes shortly after O3 commenced. We also had the exciting news that the "BILBY" (Bayesian Inference Library) parameter estimation (PE) tool developed at Monash will be LIGO's PE tool of choice in the future, and new funding was obtained via Astronomy Australia Limited from the Federal Government to enhance our compute capabilities via the creation of a Gravitational Wave Data Centre run for us by Astronomy Data And Computing Services (ADACS) at Swinburne University of Technology.

Our Associate Investigator A/Prof Adam Deller used his software correlator "DiFX" to map the expansion of the cosmic fireball from the neutron star merger and published his work in Nature Astronomy. This remarkable feat won Adam the Astronomical Society of Australia (ASA) Peter McGregor prize for his leading role in developing the software correlator. Congratulations also to all our members who received awards in 2019 for their achievements, including nine students winning a trove of competitive awards, two members being awarded ARC Future Fellowships, and the Deputy Director David McClelland being elected as a Fellow of the Australian Academy of Sciences.

Nothing captures the public's imagination like black holes, and in 2019 the UWA outreach team secured an ARC Linkage grant to take their Einstein First education project to even greater audiences. We're just putting the finishing touches on our first OzGrav documentary which accurately captures the passion of our staff as they help explore this new dimension of the Universe.

We bid farewell to Research Translation chair Dan Shaddock whose spin-off company Liquid Instruments secured a large venture capital investment and is expanding its operations. We were fortunate to secure the services of Associate Investigator Jong Chow to take over leading our Research Translation Program, and in 2019 he toured our nodes explaining how our staff can pursue commercial spin-offs and commercialise their IP.

The Centre held its annual retreat in the beautiful seaside town of Lorne in November, and we were able to plan our research for the coming year. In anticipation of a bright future for this rapidly growing field, we have been planning for how we might build pathfinders to ultimately enable us to build detectors with 10-100x the reach of the current generation. We look forward to our Centre's mid-term review in July 2020, which will hopefully lead to an even more successful second half of OzGrav and beyond.

OzGrav Director
Prof Matthew Bailes
Swinburne University of Technology

MESSAGES FROM THE CHAIRS

GOVERNANCE ADVISORY COMMITTEE (GAC)

As Chair of the OzGrav Governance Advisory Committee, I have been delighted with the progress and growth of the centre during 2019, noting that it met or exceeded its targets for almost all Key Performance Indicators.

As you may read in this report, OzGrav members were the recipients of a trove of competitive awards in 2019. This is testament to the quality and impact of their research. Congratulations to all award winners, including OzGrav Deputy Director David McClelland who was elected as a Fellow of Australian Academy of Science and OzGrav Director Matthew Bailes who was awarded the prestigious Ellery Lectureship. There were a large number of students and early career researchers who won awards, showing that the future is bright for this field of science.

OzGrav aims to translate its research to industry and other sectors, and in 2019 it launched a Research Translation Seed Funding program. In this report you may read about the exciting work being done by the first recipients of OzGrav seed funding, early career researchers James Spollard and Lyle Roberts, who are applying gravitational wave technology to make autonomous vehicles safer. The spin-off benefits of gravitational wave research can be surprising, and it's great that OzGrav members are being encouraged to think outside the box about other uses of their skills and technology.

One important milestone in 2019 was the publication of a White Paper authored by OzGrav Chief Investigators, outlining a possible path towards a future gravitational wave detector based in Australia. The White Paper feeds into the process of developing the Australian Astronomy Decadal Plan, which will be released in mid-2020 and helps guide government's infrastructure investments.

Gravitational wave astronomy involves compute-intensive data analysis to detect faint signals and interpret them. These activities received a major boost in 2019 with the commencement of the Australian Gravitational Wave Data Centre, based at Swinburne University and co-located near OzGrav headquarters.

I hope you enjoy reading about OzGrav's achievements in 2019 and plans for the future.

Sincerely,
Prof Ian Young AO

SCIENCE ADVISORY COMMITTEE (SAC)

On behalf of the OzGrav Scientific Advisory Committee (SAC), I highly commend OzGrav on its scientific achievements during 2019.

This report showcases the progress and highlights across the OzGrav science programs spanning instrumentation, data analysis, and astrophysics. There are now more than 200 members of OzGrav who are making important and substantial contributions to the field of gravitational wave astronomy.

A big highlight for 2019 was switching the LIGO-Virgo detectors back on after major upgrades that improved sensitivity by 40%. The upgrades included an innovative technique called "quantum squeezing" developed at the Australian National University, and new sensor systems developed at University of Adelaide.

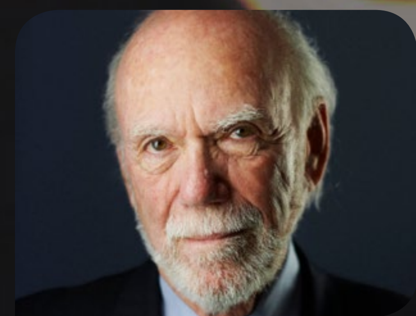
In addition, in 2019 two key pieces of OzGrav-developed software were implemented by the LIGO-Virgo Scientific Collaboration: low-latency detection software built at UWA, and a parameter estimation tool built at Monash University.

There are many additional science highlights given throughout this report, including many that have early career researchers playing key roles.

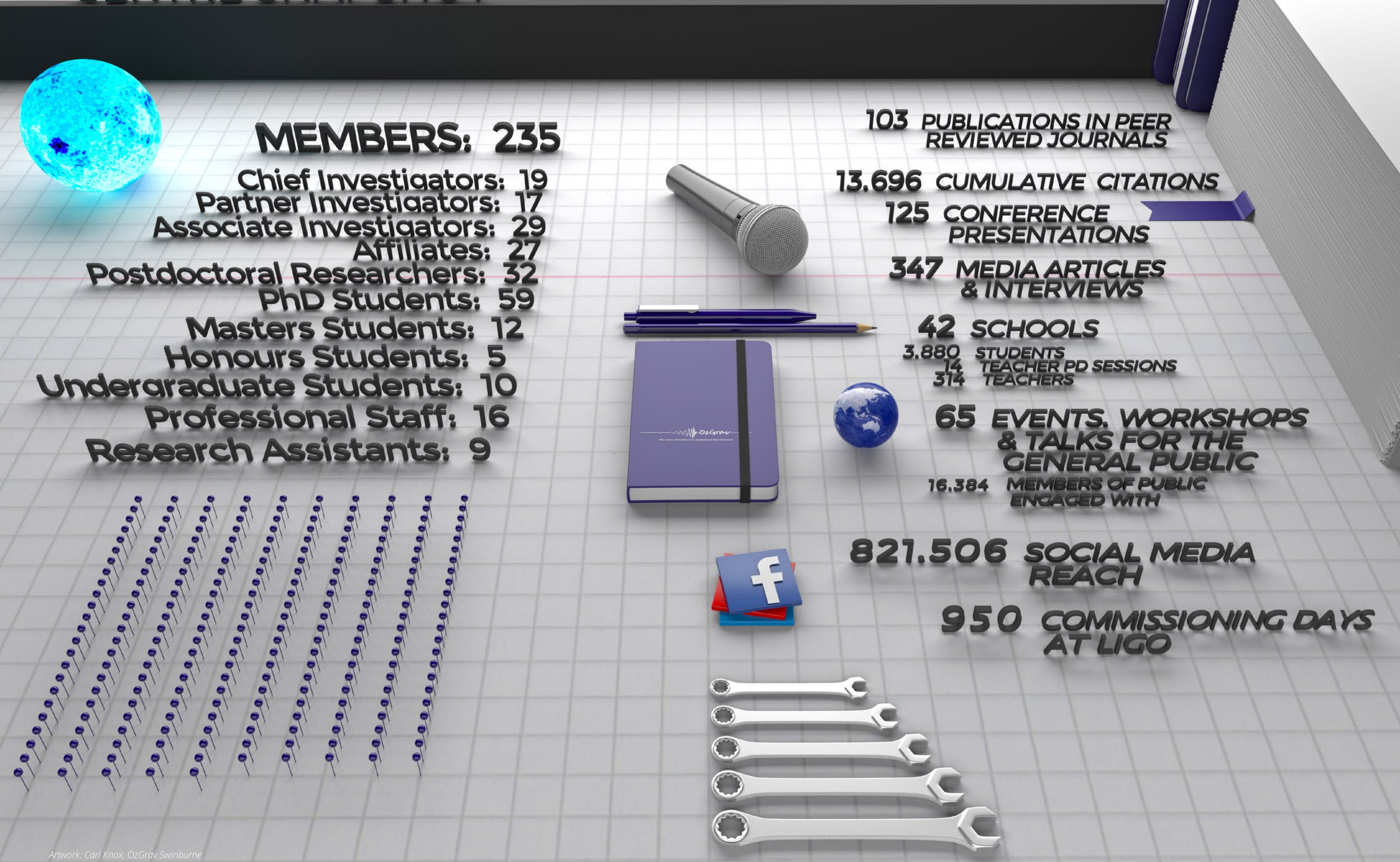
The centre is scientifically very productive, with its publications having been cited over 13,000 times since OzGrav commenced in 2017. It is also pleasing to see that OzGrav's science and discoveries are having an impact more broadly, with OzGrav featuring in hundreds of media articles/interviews, and engaging with thousands of students and members of the public during 2019.

I look forward to OzGrav's continued success in 2020.

Sincerely,
Prof Barry Barish



CENTRE SNAPSHOT



Artwork: Carl Knox, OzGrav Swinburne

SCIENCE HIGHLIGHTS

A glimpse into the past, present and future: Hubble constant measured by neutron star fireball

The Hubble constant is one of the most fundamental pieces of information that describes the state of the Universe in the past, present, and future. It tells us how fast the Universe is expanding—a valuable piece of information in science's search for answers.

The two best ways of estimating the Hubble constant are based on: the background hiss of the Universe left over from the big bang (the 'Planck' observations of the cosmic microwave background radiation) and on massive stars blowing themselves to pieces in the distant Universe ('type 1a supernovae' observations). According to the measurements of the exploding stars, the Universe is expanding a bit faster than the measurements of the background hiss would indicate, and the difference is now very significant. So, either one of them is incorrect or something is missing in our understanding of physics and cosmology. We'd like to know what is really happening in the Universe, so we need a third, independent check.

This is where the merger of two neutron stars can shed some light. Neutron star mergers are phenomenally energetic events—two stars, each more massive than the Earth's Sun, whip around each other hundreds of times per second before colliding and producing an enormous blast of material, light and gravitational waves. In 2017, gravitational waves and light were first detected from a neutron star merger that had occurred 130 million years ago, in an event scientists refer to as GW170817.

Scientists realised that a burst of gravitational waves can be used as a 'standard siren': based on the shape of the gravitational wave signal, we can tell how 'bright' the event should have been in gravitational waves. We can then measure the actual brightness of the event and work out what the distance must have been. However, this only works well if we know how the merging stars were oriented on the sky (edge on, face on, or somewhere in between).

The gravitational wave data itself can't accurately tell whether a merger was nearby and edge on, or distant and face on. To answer that question, a team including OzGrav Associate Investigator Adam Deller used radio telescopes to take a super-high-resolution movie of a narrow but powerful jet of material left behind after two neutron stars merged in the GW170817 event. The resolution of the radio images was so high, if it was an optical camera, it would see individual hairs on someone's head 10 km away. By examining the miniscule changes in this radio-emitting bullet of gas (compared against models developed by supercomputers), the angle of the jet and the orientation of the merging neutron stars was found.

Using this information, Deller and the team could tell how far away the merging neutron stars were and, by comparing this with how fast their host galaxy is rushing away from the Earth, they could finally work out the prized Hubble constant. Despite this incredible result, which was published in Nature Astronomy in July 2019, the current measurement is still not good enough to distinguish between 'Planck' vs 'Type 1a supernovae'. Further observations of merging neutron stars will soon lead to a more accurate Hubble constant.

As featured in Cosmos Magazine, The ABC, CNET and Phys Org

Artwork: James Josephides - Swinburne Astronomy Productions (SAP)

Advanced Australian instrumentation underpins upgraded LIGO detectors

In April 2019, advanced LIGO switched back on for its third observing run, taking advantage of major upgrades to the detectors that improve sensitivity by 40%, allowing scientists to see events out to an average of 550 million light-years away, or more than 190 million light-years farther out than before! Innovative Australian instrumentation has contributed to this dramatic improvement in performance.

One of the key innovations is a technique called “squeezing” that reduces levels of quantum noise that can mask faint gravitational-wave signals. The technique was developed at the Australian National University (ANU). Says OzGrav’s Professor David McClelland who leads this effort at ANU, “manipulating the quantum world to enhance the sensitivity of the world’s biggest laser interferometers will enable the deepest searches yet for new gravitational wave sources”. OzGrav researchers have also spent time in the US installing the instrumentation, including PhD student Nutsinee Kijbunchoo who says “with every improvement in our squeezing technology, we can push further out into Universe. Seeing the range jump to more than 100 megaparsecs for the first time after injecting squeezing was one of the most exciting moments of my PhD!”

Over at University of Adelaide, OzGrav postdoctoral researcher Dan Brown has also been working on developing new systems to improve LIGO’s performance. Says Dr Brown, “The group at Adelaide have been developing a variety of new sensors and adaptive optics to compensate for thermal effects from the detector’s increased laser power. Myself and students have spent much of the last year onsite at LIGO helping to prepare these systems for the next observation run, and now I’m eager to see what new discoveries they’ll enable”.

One of the challenges in gravitational wave discovery is being able to rapidly point telescopes at the source of the waves, in order to observe any emitted light before it fades. Most of the previous discoveries were found in the data with a delay of a few minutes. According to University of Western Australia’s Dr Qi Chu, “We expect the coming run to surprise us with faster detections, and we have developed a fast search pipeline to look for gravitational waves from double merger sources. Our pipeline will be processing data directly from LIGO and Virgo during this run, and will send alerts to other astronomers within seconds.”

Understanding the physical and astronomical implications of detected events is done with sophisticated software that utilises state-of-the-art data-analysis techniques. New software developed at Monash University will begin operating on LIGO and Virgo data in this observing run. “It’s truly exciting to know that all new gravitational-wave events will be studied using software written and conceived in Australia” said Monash University Senior Lecturer Dr. Paul Lasky. “We’re obviously excited to see what new black hole and neutron star collisions the new observing run will bring, but even more excited to see what other surprises the Universe will throw at us in the coming twelve months.

A quantum leap that’s been decades in the making

Scientists detected ripples from such an event for the first time about four years ago, following forty years of tireless work from a collaboration of thousands of people around the globe.

ANU Professor and OzGrav Deputy Director David McClelland and his team had a big role to play in the discoveries, and their work stands to make an even bigger impact in the future.

A paper published in the prestigious journal Physical Review Letters in Dec 2019 outlined exciting results from the team’s work to help improve the sensitivity of laser interferometers in the United States that can detect ripples in space and time from these violent smashes in the Universe.

These ripples, known as gravitational waves, are minuscule and many of them can be easily drowned out by so-called quantum noise in the laser’s surrounding vacuum that is pushing the interferometer’s mirrors around and making measurements fuzzy.

The ANU researchers’ method, called ‘squeezing’, dampens quantum noise to help make measurements more precise. The LIGO detectors were recently taken offline for upgrades to improve their range and precision, including with the enhanced squeezing capability.

ANU-OzGrav members Ms Nutsinee Kijbunchoo and Dr Terry McRae spent a year at the Hanford Observatory as lead members of the LIGO installation and commissioning team, along with OzGrav alumni Dr Georgia Mansell. Ms Kijbunchoo was one of the three female graduate students who led the quantum squeezing improvement of the advanced LIGO gravitational wave observatory reported in Physical Review Letters.

Ms Kijbunchoo, along with MIT’s Maggie Tse and Haocun Yu, used technology pioneered at ANU and refined at MIT to improve the detector’s performance by more than 15 per cent.

“When we injected squeezing into the Hanford detector for the first time, the range improvement even before the optimisation was jaw dropping,” said Ms Kijbunchoo.

Professor McClelland, , who is based in the ANU Research School of Physics, recalls the day 15 years ago when his then graduate student Kirk McKenzie burst into his office to announce that they had made, for the first time anywhere, the type of squeezing needed for gravitational-wave detectors.

“The achievement this year is the fulfilment of a dream we had 17 years ago, but it is also just the beginning,” Professor McClelland said. “Within a few years we expect the quantum enhancement to be more than a factor of three, increasing the rate at which gravitational waves are detected by around 30. We will be seeing gravitational waves on a daily basis. It has been great pleasure to work with so many gifted students and researchers who should all be rightly proud of what they have achieved.”

As featured on ABC news and ABC radio. This is an extract from the ANU media release.

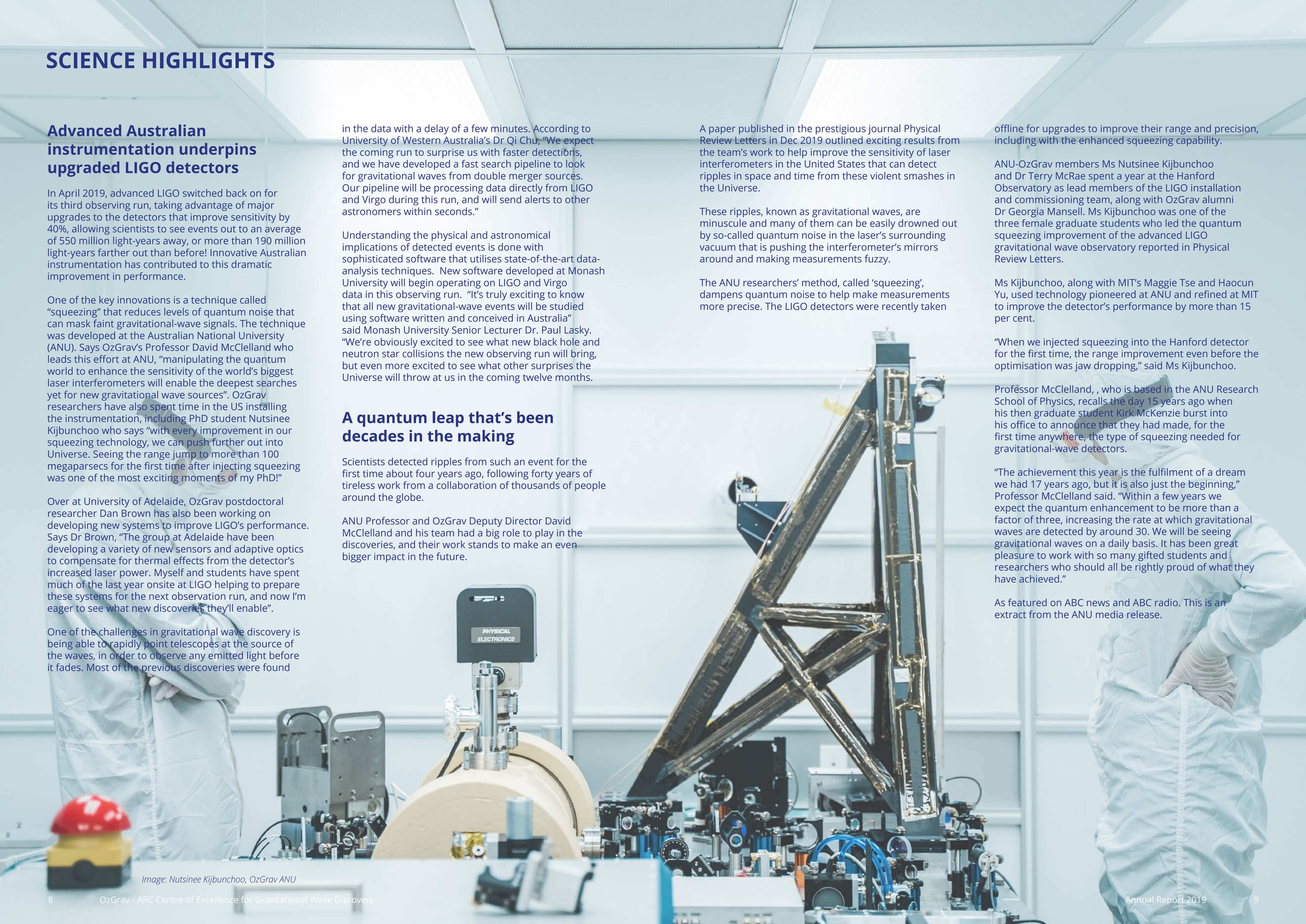


Image: Nutsinee Kijbunchoo, OzGrav ANU

Glitch in neutron star reveals its hidden secrets

Neutron stars are among the densest objects in the Universe, and they rotate extremely fast and regularly. Until they don't. Occasionally, these neutron stars start to spin even faster, caused by portions of the inside of the star moving outwards. It's called a 'glitch', and it's a rare glimpse into what lies within these mysterious objects. In a paper published in Nature Astronomy in August 2019, a team from OzGrav at Monash University; McGill University, in Canada; and the University of Tasmania, studied the Vela Pulsar: a neutron star in the southern sky, 1,000 light years away from Earth.

According to the paper's first author OzGrav-Monash Associate Investigator Greg Ashton, only 5% of pulsars are known to glitch—Vela 'glitches' approximately once every three years. This makes Vela a prized jewel among the 'glitch hunters' like Ashton and his colleague, OzGrav-Monash Associate Investigator Paul Lasky. By re-analysing data from observations of the Vela glitch in 2016—taken by co-author Jim Palfreyman from the University of Tasmania—Ashton and his team found that during the glitch, the star started spinning even faster before relaxing down to a final state.

According to Lasky, this observation (done at the Mount Pleasant Observatory in Tasmania) is particularly important because, for the first time, scientists got invaluable insights into the interior of the star, revealing that the inside of the star actually has three different components. 'One of these components, a soup of superfluid neutrons in the core, moves outwards first and hits the rigid crust of the star causing it to spin up. But then, a second soup of superfluid that moves in the crust catches up to the first causing the spin of the star to slow back down. This overshoot has been predicted a couple of times in the literature, but this is the first real time it's been identified in observations,' says Lasky.

Another observation defies explanation: 'Immediately before the glitch, we noticed that the star seems to slow down its rotation rate before spinning back up. We have no idea why this is, and it's the first time it's ever been seen! We speculate it's related to the cause of the glitch, but we're honestly not sure,' says Ashton. He suspects this paper will spur some new theories on neutron stars and glitches.

As featured in The Age, Sydney Morning Herald, Science Daily, Universe Today and Space.com.

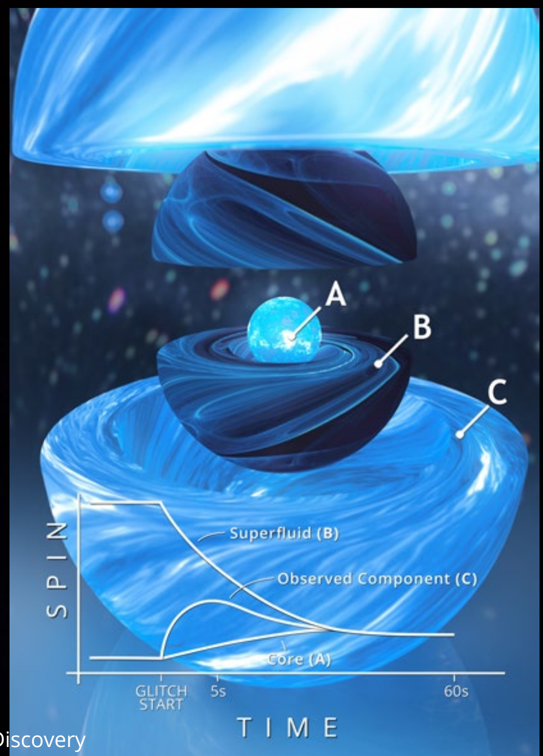


Photo and artwork: Carl Knox, OzGrav Swinburne

Using deep learning to pinpoint gravitational waves

Following the recent overwhelming success of deep learning and artificial intelligence in research, industry and medicine, OzGrav researchers from the University of Western Australia (UWA), have built a deep learning model to pinpoint where in the sky gravitational wave signals have come from.

The model can localise the source of gravitational waves produced by colliding pairs of black holes potentially as much as a thousand times faster than any other technique.

Gravitational waves are small ripples in the space-time continuum caused by colossal stellar events such as colliding black holes.

The need for speed and accuracy is particularly important in the context of gravitational wave localisation—scientists need to tell a global network of telescopes where to point on the sky as quickly as possible, so they can see any electromagnetic light that may also have come from the gravitational wave event.

The current algorithm used to locate gravitational wave sources in real time takes a few seconds to process. More accurate methods usually take several hours to compute. The light generated by gravitational wave events can be very short-lived at certain wavelengths, like short gamma ray bursts, which last a mere 2-3 seconds, so scientists need methods that can rapidly process huge data as fast and accurately as possible.

The idea behind deep learning is simple: it's an algorithm designed to mimic the functioning of neurons in our brain to carry out tasks, like categorising observed stimuli. This is done by making the network learn the correlations between a labelled input dataset and the output it is trying to predict.

Just like electric signals or synapses flow through neurons in our brain, the input information provided to an Artificial Neural Network travel through layers of nodes (usually several layers deep), with each layer introducing some non-linearity to the input.

This non-linearity helps the network learn complex features of the data. The 'learning' happens through a rigorous 'training' of the network. During the training, the predictions of the network are compared with the true values, and the parameters of the network are adjusted to minimise any erroneous gaps.

Chatterjee and the team successfully trained the Artificial Neural Network to learn the input data for source localisation. The data was pre-processed to extract the important physical parameters from simulated gravitational wave signals, injected into 'random noise'. The network classified these signals into several classes and accurately identified the source direction of the gravitational waves. The model localised the test samples much faster than other methods and at a low computational cost. The researchers plan to extend this work for pairs of merging neutron stars and neutron star-black hole systems.

Chatterjee says: 'Hopefully the methods we introduce can also be translated to other areas of research and industry and help further untap the seemingly limitless potential of deep learning and artificial intelligence'.

OzGrav-UWA Chief Investigator Professor Linqing Wen who led the study says: 'The future is wide open for gravitational wave discovery using the machine learning technique'.

Also featured in Space Australia.

RESEARCH TRANSLATION HIGHLIGHTS

Making safer self-driving cars using Gravitational Wave Detection Technology

Two scientists from the ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav) and the ARC Centre of Excellence for Engineered Quantum Systems (EQUS), at the Australian National University (ANU), are using technology originally developed to detect gravitational waves—the small ripples in the space-time continuum caused by colossal stellar events such as colliding black holes—to make self-driving cars safer..

Postdoctoral Research Fellow Dr Lyle Roberts and PhD Researcher James Spollard are developing a light detection and ranging (LiDAR) sensor that measures not only how far away objects are, but also how fast they are moving. This work is being supported through the OzGrav Research Translation Seed Funding scheme that is open to OzGrav members.

LiDAR is considered to be a crucial technology for self-driving vehicles as it provides highly detailed three-dimensional maps of the surrounding environment. LiDAR works by scanning a laser beam around the vehicle and analysing the light that reflects off the surrounding objects.

Conventional LiDAR sensors typically only map the distance to surrounding objects. However, the LiDAR sensor developed by the researchers measures many attributes of the light simultaneously, including frequency, which gives it the ability to measure distance as well as velocity.

By measuring velocity, Roberts and Spollard aim to help self-driving cars achieve super-human perception. This is important because road networks have been designed for over a hundred years to be navigated by humans, not robots. According to Spollard, 'in order for self-driving cars to be safer than human drivers, they require better-than-human perception. Autonomous vehicles are about 99% of the way there, but it's that last 1% that really matters.'

The human brain's visual cortex—which processes information produced by the eyes—is highly efficient at prioritising object based on movement, Roberts explains. 'Objects that move within our field-of-view are more difficult to anticipate and therefore considered a higher priority than stationary objects. When driving, we tend to pay more attention to things that move because they are more likely to be hazardous.' By giving autonomous vehicles the ability to measure velocity, they intend to improve the safety of self-driving by enabling them to prioritise objects based on movement.

This LiDAR technology makes clever use of a technique that is being used in the Nobel-Prize winning detection of gravitational waves. Director of OzGrav Professor Matthew Bailes says: 'At OzGrav, we're really excited to support real-world applications of gravitational wave technology. Lyle and James's LiDAR technology is just one of many examples of cutting-edge gravitational wave research having spin-off benefits to society and industry.'

'This is a great example of an application inspired by quantum technology research, where the control techniques and precision needed at the quantum level can be rolled out into industrial and consumer technologies,' says EQUS Director Professor Andrew White.

As featured in the Herald Sun, Adelaide Advertiser and Courier Mail.

Background image: James Spollard and Dr Lyle Roberts in their research lab at ANU co-funded by ARC Centres of Excellence OzGrav and EQUS. Inset image: Car testing with LIDAR. Images supplied from ANU OzGrav and EQUS

RESEARCH TRANSLATION HIGHLIGHTS

OzGrav scientists in Perth help defend the Earth from dangerous asteroids

The Zadko Telescope has been contracted by the European Space Agency to provide observations of asteroids – in particular Near Earth Objects (NEOs) – to the SSA-NEO segment of ESA's Space Situational Awareness program for the Southern Hemisphere. The project includes scientists from the University of Western Australia (UWA) and the University of Poznan in Poland who will use the powerful Zadko Telescope at the Gravity Precinct in Gingin, to survey the skies from a Perth vantage point.

The contract is part of a global strategy to provide advanced warning of future impacts of asteroids or comets. This contract focuses on two aspects: performing follow-up astrometric (position) observations with existing optical telescopes in the Southern hemisphere and ensuring the delivery of properly formatted image data to the databases of the NEO Coordination Centre; and development of a software tool to quickly submit observation requests to multiple observatories in case of urgency, e.g. for follow-up of imminent impactors.

UWA Associate Professor and OzGrav Chief Investigator David Coward said the Zadko telescope had the capability to monitor asteroids as far away from Earth as Mars and dangerous space rocks that may previously have been undetected near Earth.

"There are thousands of rocks that orbit the Sun close to Earth and monitoring their activity is hugely important for the protection of our planet," Professor Coward said. "It's the smaller space rocks between 10 and 100 metres in diameter where current surveillance is missing. These rocks are often termed 'city destroyers' and you need to have high precision telescopes, like the Zadko telescope, to monitor these threats. The Zadko telescope's location is pivotal and provides a fantastic resource to monitor what could be a significant threat to our planet's survival."

In 2019, a 100-metre-wide asteroid was detected just hours before it came within 70,000 kilometres of Earth, and in 2013 a fireball entered Earth's atmosphere over Russia at 600,000 kilometres per second, resulting in sonic blasts that shattered countless windows and injured more than 1000 people.

Zadko Observatory Manager John Moore said the contract was perfectly timed. "It comes after the telescope has just had significant upgrades including a new mirror coating which has improved its sensitivity ten times to what it was previously," he said.

The Zadko Telescope is supported by the UWA Faculty of Engineering and Mathematical Sciences and the Australian Research Council Centre of Excellence for gravitational wave discovery (OzGrav).

This article was originally published on UWA's website and featured in The West Australian.

Image: Bruce Gendre, OzGrav UWA

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.

Image: Carl Knox, OzGrav Swinburne

Science in Virtual Reality (SciVR)

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

The Science in Virtual Reality (SciVR) free app and livestream event expanded again in 2019, reaching 27 locations including OzGrav nodes and partner sites, and covering every state and territory in Australia. It was again a great celebration of the latest science including live detection updates from LIGO and Virgo, as well as the famous first image of a black hole. Anyone can download the free SciVR app at www.scivr.com.au to their smartphone and engage with the VR content as Alan Duffy and Rebecca Allen take people on a journey through the universe to celebrate National Science Week.

The app was more accessible from updates made through informed consultation by accessibility experts. It has improved usability for vision-impaired audiences, we added live closed-captioning for the livestream viewing parties, and we worked with deaf consultancy Auslan Consultants to bring in two excellent science enthusiast interpreters for our Mountain Goat Brewery live event. Another feature was to expand the solar system scene in the app allowing for a tool that could be utilised from classrooms to couches.

Image: Geoff Crane, National Science Week

Image: Mohsen Shammohamadi, OzGrav Swinburne

EDUCATION AND OUTREACH

Pub Science events

OzGrav researchers took their stories to local pubs in a series of events focused on bringing science to the public audience in a relaxed and informal setting. Hannah Middleton (Melbourne) kicked things off in January speaking about little green men and cosmic lighthouses in Canberra. Robert Ward (ANU) and Paul Lasky (Monash University) talked about recreating the collision of two black holes, in which two invisible things give out more energy than the rest of the galaxy. OzGrav PhD students Poojan Agrawal (Swinburne University) and Reinhold Willcox (Monash) alongside Postdoctoral Researcher Meg Milhouse (University of Melbourne) regaled the packed venue with eight-minute talks as part of Melbourne's Physics in the Pub in May. Pint of Science covered many venues across Australia, and we had many OzGrav researchers and outreach staff sharing science: Lucy Strang and Stefan Oslowski at Royal Melbourne Hotel, Matthew Bailes and Jackie Bondell at Spotted Mallard Melbourne, Juan Calderon Bustillo at Exchange in Melbourne, and Linqing Wen in Fremantle (SOLD OUT).

LIGO Outreach

In July Jackie Bondell (Swinburne University) was invited by Amber Strunk, the Education and Public Outreach Director at LIGO - Hanford Laboratory to present two workshops related to OzGrav's Mission Gravity as well as a more general session on incorporating technology in curriculum design at the LIGO International Physics and Astronomy Educator Program. At this program there were 22 teachers from 11 different countries. In addition to sharing OzGrav developed resources with an international audience of Physics educators, Jackie also learned about modern Physics education programs being developed by her counterparts at LIGO and at Perimeter Institute and participated in thoughtful conversations about equity in STEM education. Since the time of this workshop, Jackie has incorporated some of these lessons into newly developed teacher professional development (PD) programs she has delivered to over a hundred teachers in Australia.

Image: Carl Knox, OzGrav Swinburne

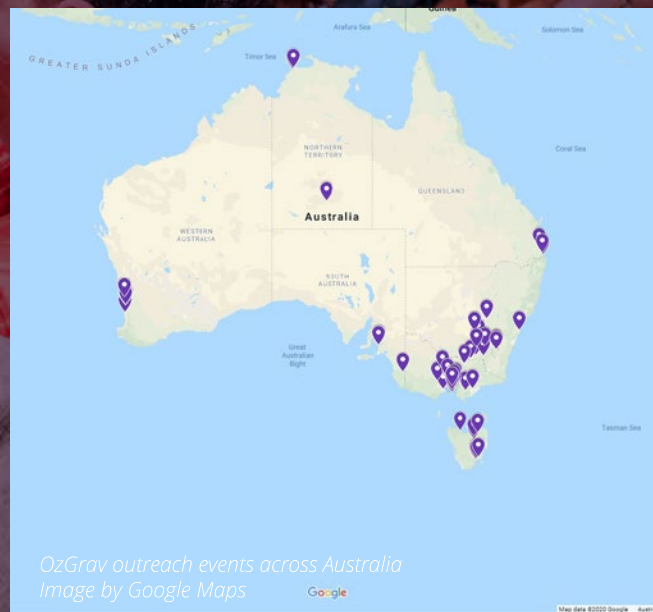
Image: David McClelland, OzGrav ANU

Public events

OzGrav members love to chat about black holes and gravitational waves! You may have seen us having fun with science demos and VR around the country at events like Astrofest in Perth, World Science Festival in Brisbane, and Science Alive in Adelaide. We love inspiring the next generation of scientists with lab tours, school holiday programs and special interest presentations such as Scouts and Astronomy groups.

We helped Parkes Radio Telescope celebrate 50 years since the Apollo Moon Landing with 10,000 people at Parkes Dish Open Days in July. It was a great treat to be able to share the science of neutron stars, pulsars and gravitational waves with the majestic Dish right outside the display tent. It was also a great chance for some of our staff to climb up onto the Dish itself, with a once-in-8-years opportunity for guided tours.

In July and August we helped out at University Open Days for our respective universities, chatting with future students and parents about STEM options. We love celebrating science as part of National Science Week in August every year, with both our own SciVR events around Australia and we join in with partner events too. We're also writing and being interviewed for traditional and online media too, and although it can be a bit daunting with a camera or microphone aimed at us, we're greatly encouraged by the interest from media outlets and the general public.



OzGrav outreach events across Australia
Image by Google Maps

Images: Aditya Parthasarathy, OzGrav Swinburne

EDUCATION AND OUTREACH

AMIGO

The LIGO detectors consist of two interferometers spaced 3,000 kilometres apart in the USA. Each L-shaped facility has two four-km arms positioned at right angles to the central building. Lasers traverse along each arm and bounce back from mirrors and, by exploiting the wave nature of light, these ripples in space-time can be detected. The sensitivity of these devices is such that scientists can measure a change in length as small as 1/10,000 the width of a proton, representing the incredibly small scale of the effects imparted by passing gravitational waves. Essentially, LIGO can be thought of as ears listening for gravitational waves, or even as a skin trying to feel the slightest of movements.

Students from OzGrav at the University of Adelaide have developed a 'mini LIGO' dubbed AMIGO (Adelaide's Mini Interferometer for Gravitational-wave Outreach) through the generous support in part by OzGrav and the University of Adelaide. They use AMIGO to demonstrate the properties of light and principles of precision measurement to students of all ages. Craig Ingram, a post-graduate student at the University of Adelaide said: 'Many [students] would normally run a mile if you tell them that you were going to talk to them about physics. Instead [with AMIGO] we end up with the students wide-eyed and engaged.'

In the 12 months since the outreach program started in Adelaide, the researchers have delivered the program to thousands of students across the country. This includes a highly successful exhibition at the World Science Festival in Brisbane. During this two-day event, Deeksha Beniwal and Georgia Bolingbroke—two integral members of the AMIGO outreach team—interacted with over a thousand members of the general public.

In January 2019 Ingram was invited to Google X headquarters in California (home to the developers of technologies such as Google Glass and WAYMO driverless cars) to explain the fundamental properties of light using AMIGO. According to Ingram, it is only after understanding the fundamental nature of light that we can develop new technologies that Google X are investigating, such as quantum computing.

Submarine project fell off the back of a truck and into the hands of Centre Alliance Senator Rex Patrick, pictured.

But his Freedom of Information request to see those

Senator Patrick said the CEP documents guided France, Japan and Germany as they prepared their bids to design the Future Submarines and include details on the Aus-

CEP documents for any other purpose other than for my parliamentary duties.

"They've spent $150,000 trying to protect documents that are not sensitive, and I say

marines. While he was sent a section that had been heavily redacted, someone in Defence accidentally also sent him the full version.

He argues Defence is keep-

tions, and for other Senate Committee work."

Defence said it would be inappropriate to comment while the tribunal was considering the matter.

Amigos, let's do the space-time warp again

CLARE PEDDIE
SCIENCE REPORTER

THREE young Adelaide scientists have built a new "friend" to help make physics fun.

AMIGO is Adelaide's Mini Interferometer for Gravitational-wave Outreach. It's a tabletop demonstration of the technique used to detect ripples in the fabric of space-time, which were first foreseen by Albert Einstein.

University of Adelaide PhD students Craig Ingram, Deeksha Beniwall and Huy Toung Cao designed and built the tabletop demo that was on show last week for the Third Goodwood Scout Group.

"Hopefully we show that physics is hard but it's interesting and it's worth the effort," Mr Ingram said.

"The reward is ultimately amazing, when you discover new things that haven't been seen before. Potentially we can look back to the beginning of the universe using gravitational waves."

The interferometer has an eye-safe laser source split in two. Light is sent down two long "arms" then bounced back off mirrors and recombined. Any disturbance or vibration will cause the light waves to fall out of sync and cancel each other out when they come back together. The same principle applies in the world's biggest laser interferometer gravitational-wave observatory in the US. The L-shaped facility has two 4km-long arms positioned at right angles to the central building. "As gravitational waves pass through the Earth, they shrink and stretch the Earth in different directions and we see that warping of space-time," Mr Ingram said.

Scout Jonathon King, 14, said he liked learning about space.

DEMONSTRATION: Scientist Craig Ingram shows AMIGO to scouts Jonathon King, 14, and Isaac Thyer, 12. Picture: MARK BRAKE

Mr McEwen, pictured, said he had tried three times to brief Mr Knoll about what he characterised as a departure from the approved funding methods.

"Advice on each occasion from your office was that my request would be referred to your diary committee," the letter said. "I heard no more."

Labor's local government spokesman Tony Piccolo said Mr Knoll needed to explain why he had refused to meet with Mr McEwen. "It's somewhat troubling and disturbing that Mr Knoll has refused to meet with Mr McEwen on three separate occasions," he said.

"When a commissioner has to resign from the commission, it raises serious questions about the minister's competence about managing the local government portfolio."

Mr McEwen was an independent MP for the South-East seats of Gordon and Mt Gambier. He was a minister in the former Labor government from 2002 to 2009.

The Grants Commission role earned him an annual fee of $13,570.

A spokesman for Mr Knoll said: "Mr McEwen met with relevant departmental staff on a number of occasions and, ultimately, it is the commission's role to make recommendations to the minister through the appropriate mechanisms."

The AMIGO interferometer consists of an eye-safe laser which is split and bounced through the use of strategically placed mirrors and laser beams. The desktop AMIGO, along with less technical props like ropes, is used to illustrate the wave nature of light and '...in turn what gravitational waves are and how they are detected,' Beniwal said.

'It's a really cool way to show how the fundamentals of physics can be used to teach us about how the Universe works.'

As featured in the Adelaide Advertiser

Inset images: Adelaide Advertiser and University of Adelaide
Background image: Carl Knox, OzGrav Swinburne

Mission Gravity

Expanding on the development of Mission Gravity in 2018, we delivered more sessions of our school incursion program, and trained more presenters and researchers. Mission Gravity uses cutting-edge virtual reality (VR) technology to guide students through a virtual mission to the stars. The mission focuses on stellar evolution and the formation of compact objects such as black holes and neutron stars. Working in teams wearing the virtual reality headsets, students travel to a star in a virtual space lab taking measurements as the star evolves in front of their eyes. The virtual reality headsets are wirelessly linked to the Mission Gravity Command Centre and the view of each student, along with their scientific data readout, is projected onto a large screen.

"Aside from using the virtual reality goggles, the best part of the excursion was seeing how Physics concepts learnt in the classroom can be applied in science inquiries. It was also interesting to see the amazing impact technological advances have had on our ability to understand space-time and the implications of Einstein's theories."

Year 11/12 student.

"The OzGrav program was a very effective way of learning about the stars and universe. The virtual reality component of it was engaging and enjoyable. It was really easy to understand the concepts that were discussed by having a visual representation. We got so much out of it and I was able to understand ideas that I previously struggled with."

Year 11/12 student.

We've created a web browser-based version for teachers to use in conjunction with the supplemental materials that have been developed to support the delivery of the content. This content will be freely available to teachers via an in-development OzGrav teacher's portal. If you're interested in learning more or getting involved in the Mission Gravity program, please contact epo@ozgrav.org

EDUCATION AND OUTREACH

Teacher Professional Development

Parkes

Astronomy from the Ground Up in May 2019 was a teachers' workshop sponsored by CSIRO and hosted at the Parkes Radio Telescope. Present at this workshop were 20 secondary teachers from around Australia. The goal of the workshop was to introduce teachers to science topics related to Astronomy and introduce them to activities they can deliver in their own classroom lessons. The first session was an Overview of Gravitational Wave Detection and a second session introduced teachers to OzGrav's Mission Gravity and the Use of VR in the Physics Classroom. As a result of this opportunity, Mission Gravity was introduced in classrooms in regional VIC, NSW, and WA. In addition to sharing OzGrav's education and outreach content, Jackie Bondell (Swinburne) also learned new ideas for outreach activities from her counterparts at CSIRO and Edith Cowan University.

Darwin

CONASTA is the annual conference for Australian Science Teachers, and is open to primary and secondary teachers from all across Australia, as well as school lab technicians. Lisa Horsley (Swinburne) teamed up with Renee James (Sam Houston State University) in Darwin in July, running a workshop for 15 teachers and outreach professionals, covering gravitational waves and implementing the science into senior science classes. Attendees were delighted to hear about the research happening right now in Australia, supporting the international efforts at LIGO, and this information will inform career path choices. The VR demos were also a hit! We showed the "gravity well" demo and gave out 10 pieces of lycra for lucky teachers to use straight away in their classrooms, as well as the free SciVR app.

New Zealand

As part of the 10th Australasian Conference on General Relativity and Gravitation (ACGRG10) in Wellington, NZ in December 2019, the Einstein-First Project and OzGrav Education and Outreach were invited to host respective half-day workshops for New Zealand-based Physics teachers.

OzGrav PhD student Shon Boublil (UWA) presented the workshop: Einstein's Theory of Gravity: Free Fall and Bending Space-Time, highlighting the central importance of introducing Einsteinian concepts earlier in the science curriculum via the use of quality models and analogies. He introduced the teachers to accessible classroom activities such as a series of lessons utilising the space-time simulator with the goal of building sufficient familiarity so the teachers can bring these lessons to their classes.

"This event was a wonderful collaboration between departments and members of the OzGrav team. I had a beautiful time at the University of Victoria in Wellington and met a lot of physicists and teachers that have a common interest in finding novel ways of bringing Einsteinian physics in the curriculum." Shon Boublil

OzGrav Education and Outreach Coordinator Jackie Bondell (Swinburne) presented: Gravitational Waves in the Secondary Classroom and Virtual Reality in Physics Education. She reviewed the recent advancements in gravitational wave science and introduced the teachers to hands-on activities to introduce students to major concepts related to gravitational wave detection and multi-messenger astronomy. She also led teachers through the OzGrav Mission Gravity program using interactive virtual reality.

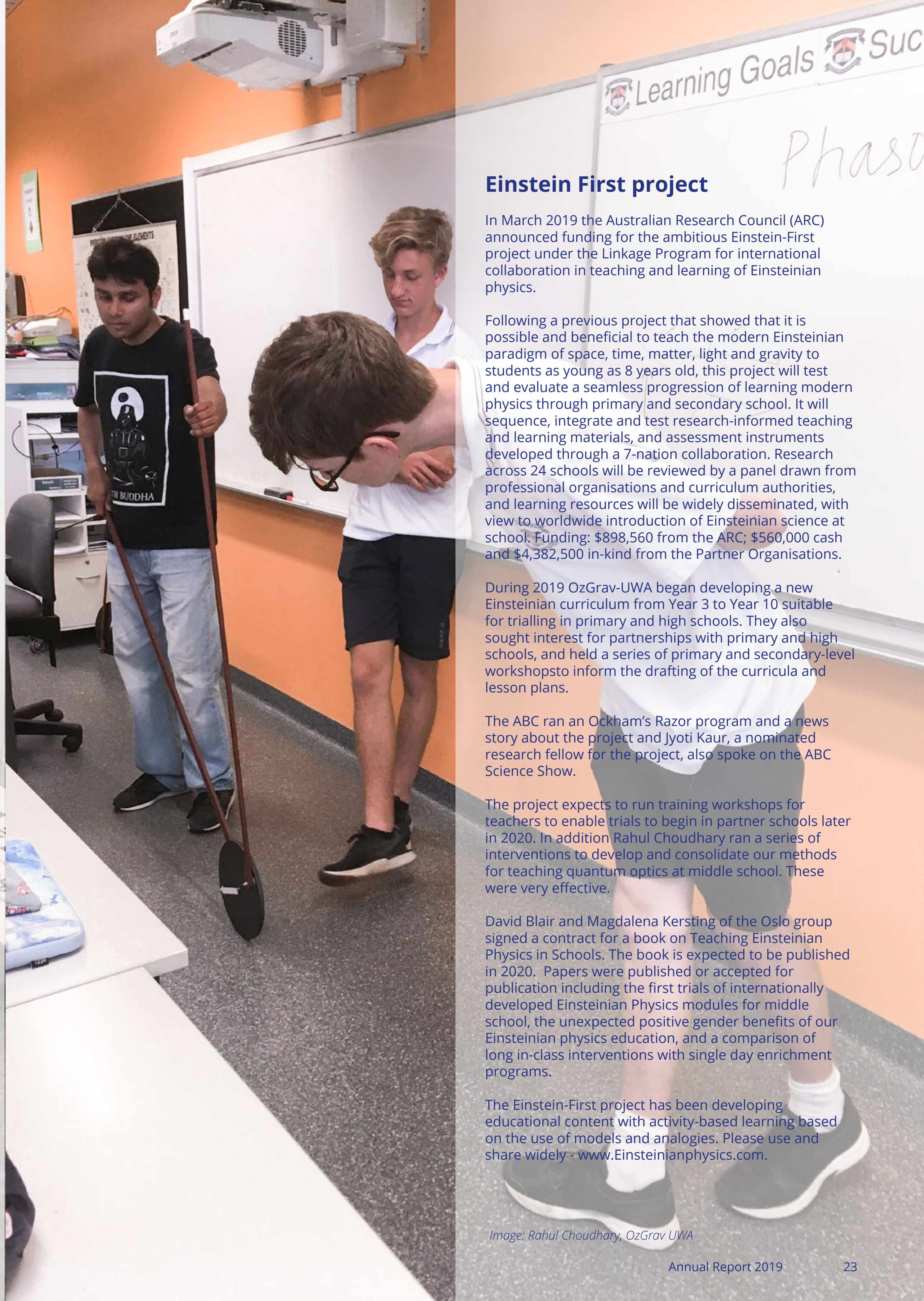
Teaching Tibetan monks astrophysics

Ilya Mandel (OzGrav Monash University) travelled to the Gaden monastery outside of Hubli in the southern region of India, where he spent a fortnight training current and future geshe—monks with the equivalent of a PhD—in their studies. Started in 2006 by Emory University in the US and the Dalai Lama, the aim of the Emory-Tibet Science Initiative is designed to give Tibetan monks university-level science training across a variety of disciplines.

The first-year curriculum includes basic introductory material in physics, biology, neuroscience and the philosophy of science and the teaching is undertaken by visiting academics from around the world. By year four, the monks receive an introduction to quantum physics, 'and by their final year the curriculum extends to astrophysics and cosmology,' says Mandel. The training isn't all one way, as scientists can observe Tibetan Buddhist approaches to study, meditation, and debate.

Mandel explains the monks 'are expert logicians, able to quickly find flaws in any argument, so the sorts of approximations and over-simplifications we typically provide in introductory lectures in the Western curriculum don't fly: the monks are guaranteed to spot the logical inconsistencies.'

Image: Deeksha Beniwal, OzGrav Adelaide



Einstein First project

In March 2019 the Australian Research Council (ARC) announced funding for the ambitious Einstein-First project under the Linkage Program for international collaboration in teaching and learning of Einsteinian physics.

Following a previous project that showed that it is possible and beneficial to teach the modern Einsteinian paradigm of space, time, matter, light and gravity to students as young as 8 years old, this project will test and evaluate a seamless progression of learning modern physics through primary and secondary school. It will sequence, integrate and test research-informed teaching and learning materials, and assessment instruments developed through a 7-nation collaboration. Research across 24 schools will be reviewed by a panel drawn from professional organisations and curriculum authorities, and learning resources will be widely disseminated, with view to worldwide introduction of Einsteinian science at school. Funding: $898,560 from the ARC; $560,000 cash and $4,382,500 in-kind from the Partner Organisations.

During 2019 OzGrav-UWA began developing a new Einsteinian curriculum from Year 3 to Year 10 suitable for trialling in primary and high schools. They also sought interest for partnerships with primary and high schools, and held a series of primary and secondary-level workshopsto inform the drafting of the curricula and lesson plans.

The ABC ran an Ockham's Razor program and a news story about the project and Jyoti Kaur, a nominated research fellow for the project, also spoke on the ABC Science Show.

The project expects to run training workshops for teachers to enable trials to begin in partner schools later in 2020. In addition Rahul Choudhary ran a series of interventions to develop and consolidate our methods for teaching quantum optics at middle school. These were very effective.

David Blair and Magdalena Kersting of the Oslo group signed a contract for a book on Teaching Einsteinian Physics in Schools. The book is expected to be published in 2020. Papers were published or accepted for publication including the first trials of internationally developed Einsteinian Physics modules for middle school, the unexpected positive gender benefits of our Einsteinian physics education, and a comparison of long in-class interventions with single day enrichment programs.

The Einstein-First project has been developing educational content with activity-based learning based on the use of models and analogies. Please use and share widely - www.Einsteinianphysics.com.

Image: Rahul Choudhary, OzGrav UWA

AWARDS AND HONOURS


Congratulations to Ryan Shannon and Ilya Mandel for being awarded ARC Future Fellowships. These Fellowships run for four years and include salary and research support.

Ilya's project is on Shining Gravitational Waves on Binary Astrophysics.

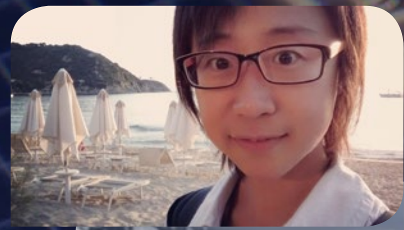
Ryan's project is on Transforming Fast Radio Bursts Into An Astrophysical Tool.

This is a wonderful testament to the quality and impact of their research, and a great result for OzGrav.

Paul Lasky, Simon Stevenson, Eric Thrane and Xingjiang Zhu.
Named as "Rising stars" in the Early Achievers leaderboard by The Australian newspaper. These are Australia's top 40 researchers who are less than 10 years into their careers.




In May David McClelland was elected as a Fellow of Australian Academy of Science.
"In 2016, the LIGO and Virgo Collaborations announced the first direct detection of gravitational waves, opening up a new window for astronomy and cosmology. David McClelland was a vital contributor to this success as Australia's leading audio-band gravitational wave scientist and Chair of the Instrument Science/Advanced Detector program in the 1000-strong LIGO Scientific Collaboration. He led the ANU team that played a crucial role in designing, installing and commissioning Advanced LIGO's acquisition system, which brings the interferometers into operation. His pioneering quantum science experiments that beat the previous low-frequency limit for squeezing light by three orders of magnitude were also essential for improving gravitational wave detection sensitivity."




OzGrav alumna Lilli (Ling) Sun won the LIGO detchar prize and Pat Meyers was one of three honorable mentions.

2019 Award for Excellence in Detector Characterization and Calibration, awarded by LIGO Laboratory on 29 Nov 2019 https://www.ligo.caltech.edu/news/ligo20191129

Lilli also travelled to Antarctica with the 4th cohort of women in the Homeward Bound STEM leadership program. www.homewardboundprojects.com.au

Adam Deller on behalf of the DiFX collaboration collected the Peter McGregor Prize awarded by the Astronomical Society of Australia (ASA).

Awarded to the DiFX collaboration for excellence in astronomical instrumentation. DiFX is used to process radio interferometer data, and was used for numerous results. Inside OzGrav, it contributed to two Nature papers in 2018. Outside OzGrav DiFX was used to image the black hole event horizon last year.


Rory Smith won an Institute for Computational and Experimental Research in Mathematics (ICERM) Research Fellowship awarded by Brown University. This award supports a three month visit to ICERM's (Brown University) fall 2020 semester program on Advances in Computational Relativity

Matthew Bailes awarded Ellery Lectureship by ASA.
The ASA recognises outstanding contributions in astronomy or a related field by the award of Robert Ellery Lectureships.

OzGrav was awarded a Bronze Pleiades Award for equity and diversity by ASA in July valid for 2 years. Congratulations on your achievements towards creating a better working environment for all astronomers. The panel was impressed by the breadth of current and planned activity to promote gender equity, and support for mental health awareness.

THE PLEIADES AWARDS
Bronze
2018

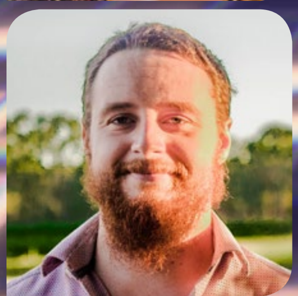
AWARDS AND HONOURS









Student Awards

Magdalena Kersting
Hartle Award for Best Oral Talk by a Student in the Outreach and Education Strand @ GR22/Amaldi13
International Society on General Relativity and Gravitation (ISGRG)

Magdalena Kersting
Best Oral Presentation of a Young Researcher in Physics Education @ GIREP 2019
Groupe International de Recherche sur l'Enseignement de la Physique

Huy Tuong Cao
Dean's Commendation for Doctoral Thesis Excellence
University of Adelaide

Dougal Dobie
Faculty of Science Postgraduate Research Prize for Outstanding Academic Achievement
University of Sydney

Dougal Dobie
Award for Postgraduate Excellence in Physics
Australian Institute of Physics (NSW Branch)

Isobel Romero-Shaw
Best Student Talk
Astronomical Society of Australia

Lucy Strang
Best Student Talk
Australian Institute Of Physics

Lucy Strang
Jean Laby Women In Physics Travel Award
University of Melbourne

Lucy Strang
Faculty of Science Travelling Scholarship
University of Melbourne

Deeksha Beniwal
Travel Grant for KOALA 2019 IONS-KOALA

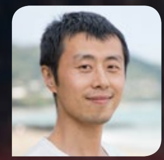
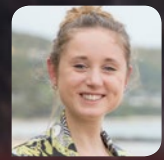
Craig Ingram
Travel Grant for Frontiers in Optics 2019/OSA student leadership conference

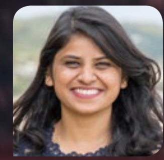
Sara Webb
Directors Excellence In Outreach
Swinburne University

Poojan Agrawal
Directors Excellence In Outreach
Swinburne University

Colm Talbot
Postgraduate publication award
Monash University

OzGrav 2019 Retreat Awards



Best Poster - People's Choice Award

Hengxin Sun - University of Western Australia (UWA)
Isobel Romero-Shaw - Monash University (Monash)
Jue Zhang - UWA
Disha Kapasi - Australian National University (ANU)

Best Sparkler Talks

Deeksha Beniwal - University of Adelaide (Adelaide)
Nathan Holland - ANU
Alexei Ciobanu - Adelaide
Boris Goncharov - Monash
James Leung - University of Sydney

ECR Workshop Teamwork and Communication Winning Team

Deeksha Beniwal - UoA
Huy Tuong Cao - Adelaide
Johannes Eichholz - ANU
George Howitt - University of Melbourne (Melbourne)
Coen Neijssel - Monash

Outreach Superstars

Hannah Middleton and Patrick Clearwater - Melbourne
Deeksha Beniwal and Craig Ingram - Adelaide
Reinhold Willcox and Paul LAsky - Monash
Sareh Rajabi and Vaishali Adya - ANU
Poojan Agrawal - Swinburne University of Technology
Ruby Chan and Rahul Choudhary - UWA



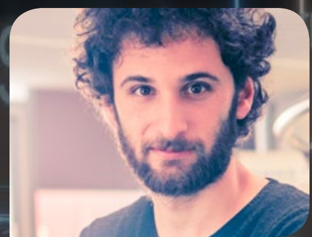

PEOPLE OF OZGRAV - DATA AND ASTROPHYSICS

Prof Matthew Bailes
Swinburne University of Technology
Astrophysics Theme Leader
Centre Director and Chief Investigator

A/Prof Eric Thrane
Monash University
Data Theme Leader
Chief Investigator

Dr Kendall Ackley
Monash University
Postdoctoral Researcher

Poojan Agrawal
Swinburne University of Technology
PhD Student



Dr Igor Andreoni
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Affiliate

Dr Greg Ashton
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Associate Investigator

Adrian Barbuio
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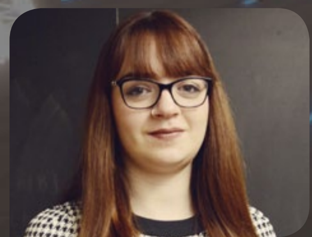
Honours student



Sylvia Biscoveanu
MIT
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Dr Ron Burman
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Affiliate

Ben Burridge
University of Western Australia
Masters student

Dr Juan Calderon Bustillo
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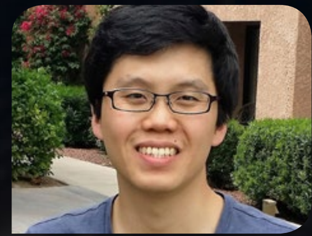
Postdoctoral Researcher

Julian Carlin
University of Melbourne
PhD Student



Dr Seo-Won Chang
Australian National University
Postdoctoral researcher

Dr Philip Charlton
Charles Sturt University
Associate Investigator

Chayan Chatterjee
University of Western Australia
PhD student

Debatri Chattopadhyay
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Dr Qi ChiChi Chu
University of Western Australia
Postdoctoral Researcher

Teagan Clarke
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Undergraduate student

Patrick Clearwater
University of Melbourne
PhD student

A/Prof Jeff Cooke
Swinburne University of Technology
Chief Investigator

Dr Neil Cornish
Montana State University
Associate Investigator

A/Prof David Coward
University of Western Australia
Chief Investigator

Hayden Crisp
University of Western Australia
Masters student

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University of Western Australia
Affiliate

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A/Prof Adam Deller
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PEOPLE OF OZGRAV - DATA AND ASTROPHYSICS

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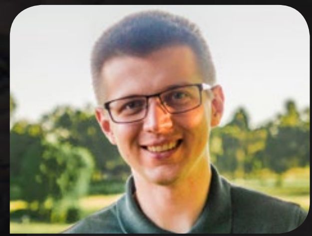
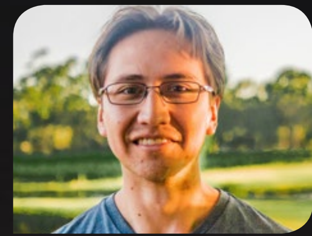


Boris Goncharov
Monash University
PhD Student

Prof Alister Graham
Swinburne University of Technology
Associate Investigator



Francisco Hernandez Vivanco
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Liam Dunn
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Masters Student

Paul Easter
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Prof Rob Evans
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Dr Ryosuke Hirai
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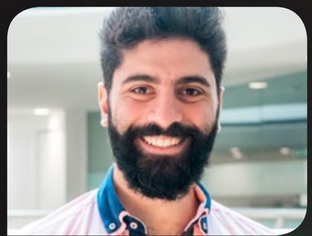
Postdoctoral Researcher

Dr Eric Howell
University of Western Australia
Associate Investigator

George Howitt
University of Melbourne
PhD Student



Wael Farah
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Affiliate

Dr Matteo Fasiello
Institute of Cosmology and Gravitation, Portsmouth
Affiliate

A/Prof Chris Fluke
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Moritz Huebner
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Prof Jarrod Hurley
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Chief Investigator

Dr Clancy James
ICRAR - Curtin University
Affiliate

Dr Chris Flynn
Swinburne University of Technology
Affiliate

Dr Garry Foran
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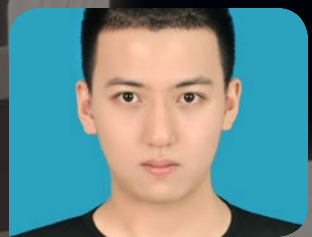
PhD student



Yusheng Gai
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Dr David Kaplan
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Affiliate

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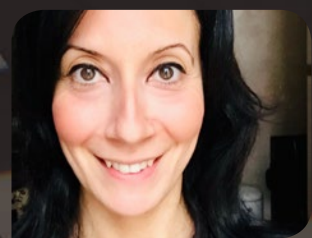
Chief Investigator

Dr Bruce Gendre
University of Western Australia
Postdoctoral researcher

Mike Lau
Monash University
PhD student



A/Prof Paola Leaci
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James Leung
University of Sydney
PhD student

PEOPLE OF OZGRAV - DATA AND ASTROPHYSICS


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Monash University
Chief Investigator


Dr Grant Meadors
Los Alamos National Laboratory
Affiliate

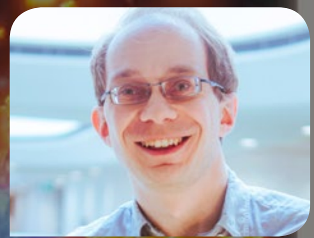

Prof Andrew Melatos
University of Melbourne
Chief Investigator


Dr Patrick Meyers
University of Melbourne
Postdoctoral Researcher

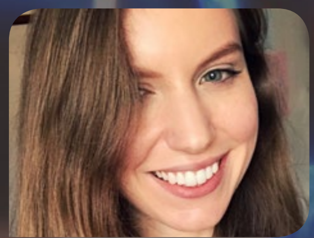

Dr Hannah Middleton
University of Melbourne
Postdoctoral Researcher

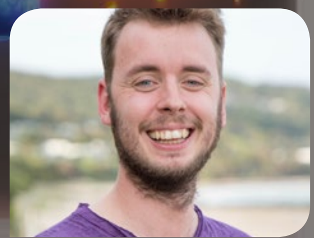

Dr Meg Millhouse
University of Melbourne
Postdoctoral Researcher


Travis Yik Lun Mong
Monash University
PhD student


Dr Bernhard Mueller
Monash University
Associate Investigator


Prof Tara Murphy
University of Sydney
Associate Investigator


Jacqueline Musiov
Swinburne University of Technology
Undergraduate student


Coenraad Neijssel
Monash University
PhD student


Dr Stefan Oslowski
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Associate Investigator


Aditya Parthasarathy
Swinburne University of Technology
Affiliate


Ethan Payne
Monash University
Undergraduate student


Dr Jade Powell
Swinburne University of Technology
Postdoctoral Researcher


Joshua Pritchard
University of Sydney
PhD student


Dr Daniel Reardon
Swinburne University of Technology
Postdoctoral researcher


Dr Jeff Riley
Monash University
PhD student


Isobel Romero-Shaw
Monash University
PhD student


Dr Ashley Ruiter
University of New South Wales Canberra
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Nandini Sahu
Swinburne University of Technology
PhD student


Prof Susan Scott
Australian National University
Chief Investigator


Rahul Sengar
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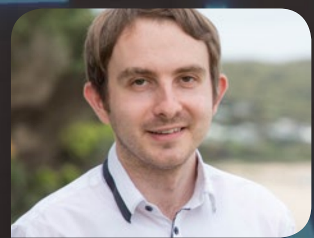
PhD student


Dr Ryan Shannon
Swinburne University of Technology
Postdoctoral Researcher


Teresa Slaven-Blair
University of Western Australia
PhD student


Dr Rory Smith
Monash University
Postdoctoral Researcher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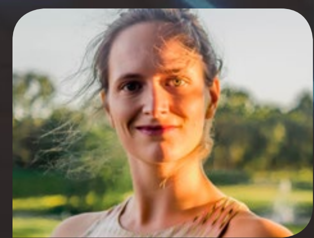
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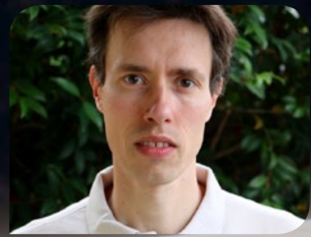

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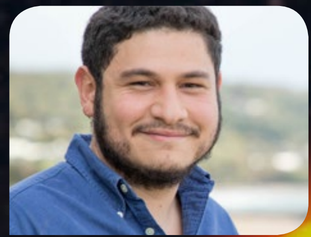

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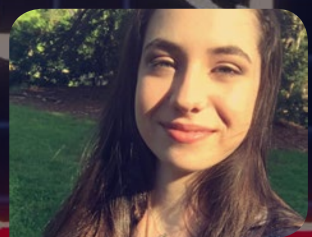

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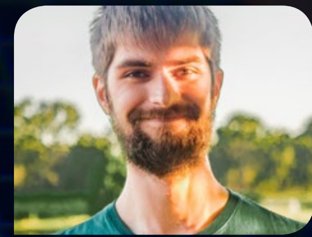

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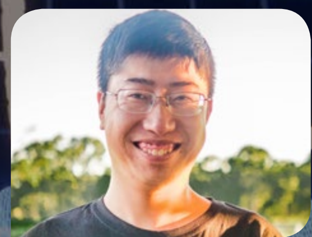

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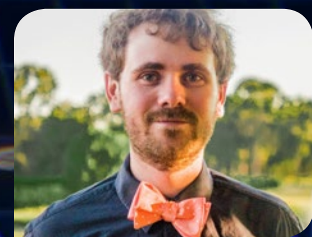

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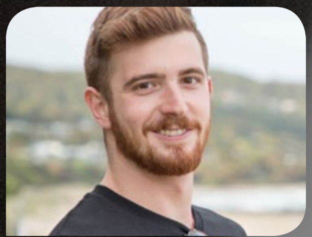
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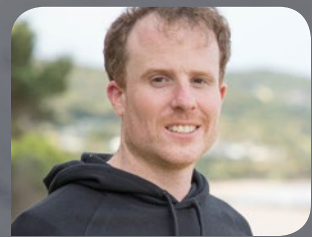
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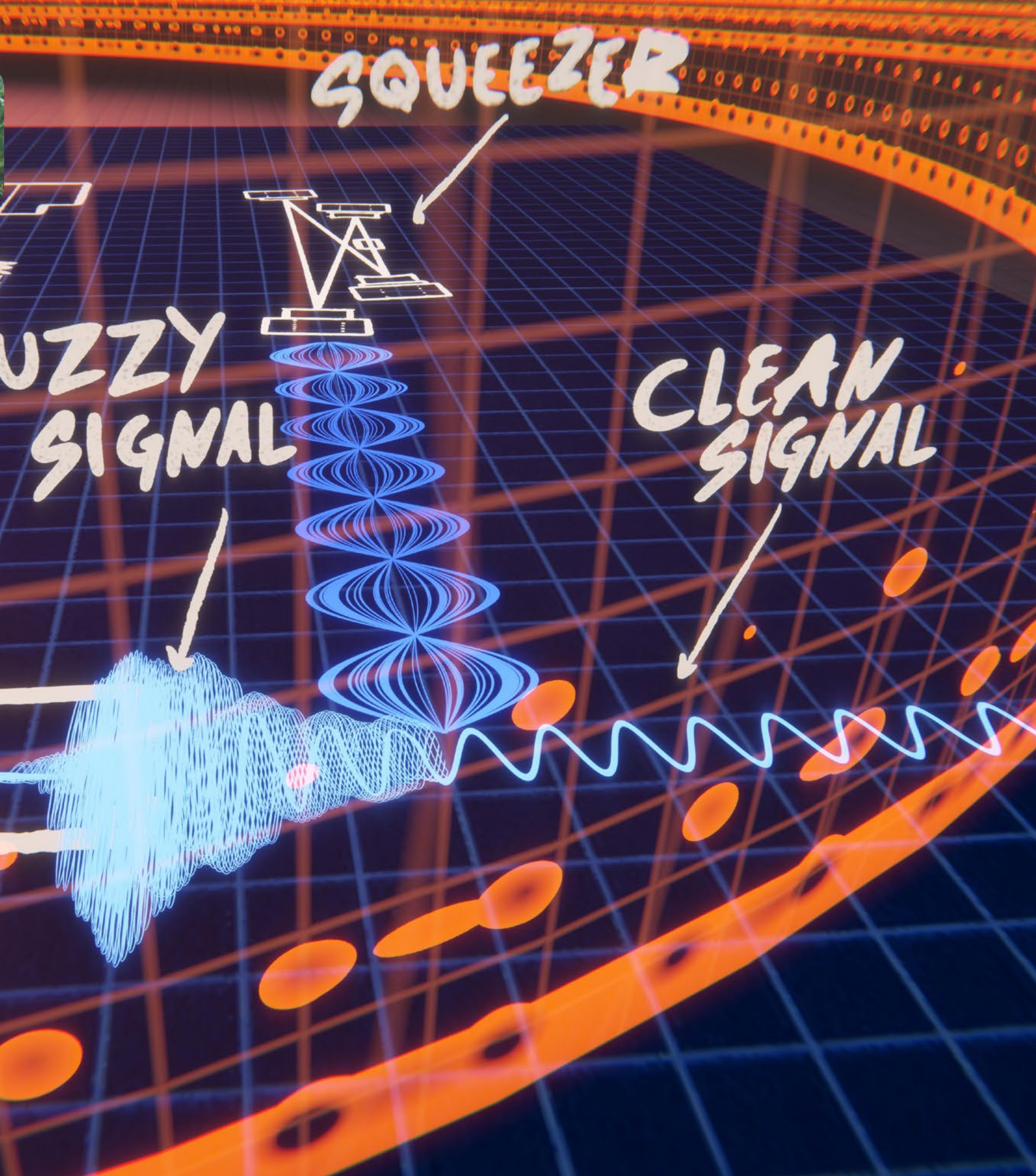
Background image: Nutsinee Kijbunchoo, OzGrav ANU

PEOPLE OF OZGRAV - INSTRUMENTATION

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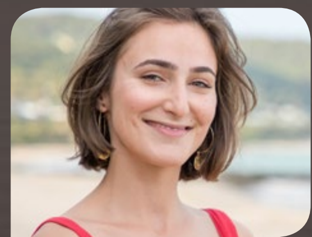

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INSTRUMENTATION THEME

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

The instrumentation theme added a seventh program this year:

1. Commissioning (Program Chairs: Ottaway and Slagmolen)

2. Quantum (Program Chairs: McClelland and Veitch)

3. Low frequency (Program Chairs: Slagmolen and Ju)

4. Distortions and Instabilities (Program Chairs: Zhao and Ottaway)

5. Space (Program Chair: McKenzie)

6. Pulsar Timing (Program leader: Bailes)

7. Future Detector Planning (Program Chairs: McClelland and Ottoway)

Great progress was made across all programs. Commissioning saw our OzGrav team feature in the stable operation of squeezing in Advanced LIGO, accompanied by a significant range increase, and make major inroads into understanding optical loss. The Quantum program produced the first controlled squeezing at the 2 micron wavelength and a new architecture for 2 micron (2μm) lasers. The Low Frequency program made steady progress toward realising a prototype Newtonian noise sensor and the setting up of a seismic noise array at the Gingin site. Distortions and Instabilities program saw the development of new mode matching control, the testing of a phase camera at LIGO Hanford and the design of a parametric instability free optical cavity. In Space, we saw the launch of the GRACE Follow-on satellites testing spacecraft laser ranging needed for future GW missions. We welcomed a new Program Chair, Kirk McKenzie, who joined OzGrav as a Chief Investigator from the Jet Propulsion Laboratory taking over from Daniel Shaddock. Pulsar Timing activities continue to lead the world with the commencement of MeerTime Key Science Project observations and the close-out of the Square Kilometre Array (SKA) pre-construction project. Finally our activities in Future Detector planning ramped up with OzGrav contributions to global science and design studies, the development of the high frequency detector architecture and studies of possible Australian sites for third generation detectors.

In 2020, we are supporting two of our early-to-mid-career researchers to develop their leadership experience and take on the co-chair role for the following programs: Quantum (Dr Robert Ward, replacing Prof David McClelland) and Distortions and Instabilities (Dr Carl Blair, replacing Prof Chunnong Zhao).

Finally we would like to thank Prof Daniel Shaddock who had to step down from OzGrav this year with the ramp of his company Liquid Instruments. Daniel was a key member of the OzGrav team and was crucial in its early development, and we continue to benefit from his wisdom and advice.

Image: Nutsinee Kijbunchoo, OzGrav ANU

INSTRUMENTATION

Commissioning

Program chairs: David Ottaway and Bram Slagmolen

The available commissioning time at the sites was limited in 2019 because the third observing run (O3) took up a significant fraction of the year. Despite this, the OzGrav community provided a large contribution to ongoing commissioning efforts at both LIGO sites (LIGO Hanford and LIGO Livingston observatories). We contributed in excess of 950 days at the sites from 10 different early career researchers from five of our six nodes. Successful participation in completely remote commissioning was performed for the first time within OzGrav by PhD Student Nathan Holland (ANU).

Our stated objectives for 2019 were to commission the squeezers and work towards improving the modematching of the interferometers using advanced phase cameras, single RF detector modematching and new deformable mirrors.

The commissioning of the squeezers at the two observatories has resulted in 14.5 Mpc increase in range at which a standard binary neutron star inspiral can be detected at LIGO Hanford Observatory and a 17 Mpc increase at the LIGO Livingston Observatory. We aimed for a 3 dB reduction in high frequency quantum noise and have currently achieved 2.2 dB at LIGO Hanford and 3.1 dB at LIGO Livingston. This translates to an approximately 50% increase in detection range. This represents a significant advancement in our potential to understand the nuclear make-up of neutron stars through improved measurements of the tidal deformity of neutron stars during the inspiral phase of neutron star coalescence.

OzGrav commissioners have spent a considerable amount of time improving the modematching and the optical modes within the optical cavities which will result in better control of the interferometers and remove an important constraint on squeezing. Detailed studies on the modematching between the interferometer and the output mode cleaner showed that around 10-20% of the losses are not well understood. In addition measurements showed that the LIGO Hanford output mode cleaner is more astigmatic than original design. New techniques are currently under development to understand this situation better. OzGrav researchers have also spent considerable time developing a new phase camera for imaging differing optical fields within the interferometer. This phase camera was developed within the Instabilities and Distortions theme and was trialled for the first time on a full-scale interferometer during a commissioning break at LIGO Hanford. Studies showed that the RF sidebands, at the input, change shape and curvature during power-up of the interferometer. However the light fields within the power recycling cavity do not explain the significant loss in the crucial 9 MHz sidebands.

Many new commissioners undertook their first visit to the LIGO site this year and worked on a number of important tasks. These ranged from improving and understanding the calibration procedures, improving the automation of the alignment of the interferometer and improving the damping control of suspension to speed-up lock reacquisition. We thank Carl Blair, Vladimir Bossilkov, Dan Brown, Huy Tuong Cao, Xu Chen, Alexei Ciobanu, Nathan Holland, Nutsinee Kijbunchoo, Terry McRae and Ethan Payne for their contributions commissioning the LIGO interferometers.

Image: Nutsinee Kijbunchoo, OzGrav ANU.

Case study: Phase Camera

Further improvements in the detectors sensitivity relies on being able to store ever more optical power within the interferometer. One of the main goals for O3 was to increase the injected power, the initial goal going from ~20W to 50W. However, during commissioning of the Hanford detectors we found that increasing the circulating power resulted in significant thermal distortions from point absorbing defects within the test mass mirror coatings.

Achieving optimal control of the interferometers relies on the many optical beams used for sensing the position of the suspended mirrors having identical shapes. When thermal deformations are introduced this overlap in shape between the beams is degraded. To study how the beams are changing in shape a special type of camera, known as a Phase Camera, is required to image them.

The OzGrav team at University of Adelaide developed an advanced Phase Camera prototype and tested this device at the Hanford detector in a commissioning break. During this test we demonstrated that the device operates and introduces no additional noise. The optical science and control beams in the power recycling cavity were studied at various thermal states, during which the change in shape of the beams were observed. However, the measured change in shape of the control beams did not account for the total loss of control signals that was observed. Thus by using this new sensor we were able to rule out one potential cause of the problems we are experiencing. Looking forward we hope to use these new phase cameras as sensors to monitor beam shapes and generate control signals that can be used with new wavefront actuators to further enhance the performance of the interferometers.

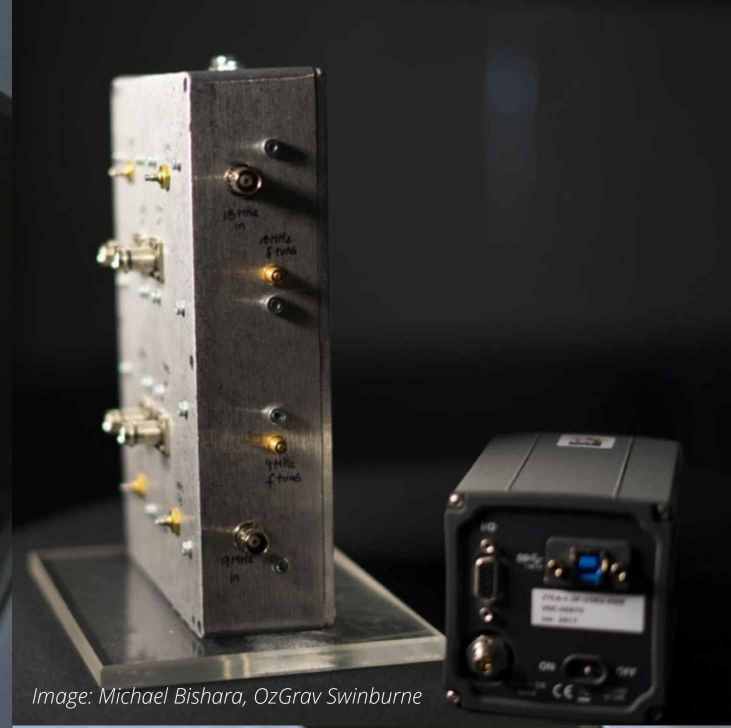
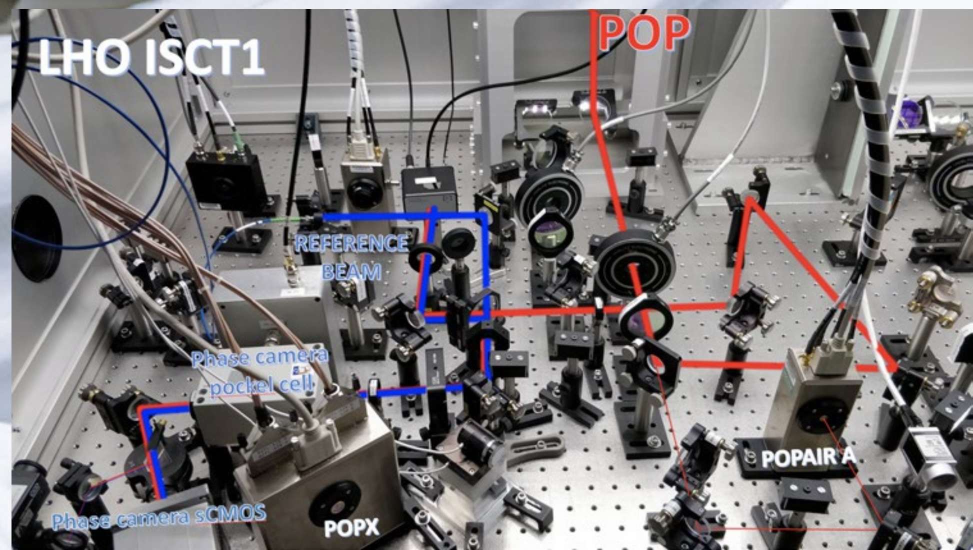


Image: Michael Bishara, OzGrav Swinburne



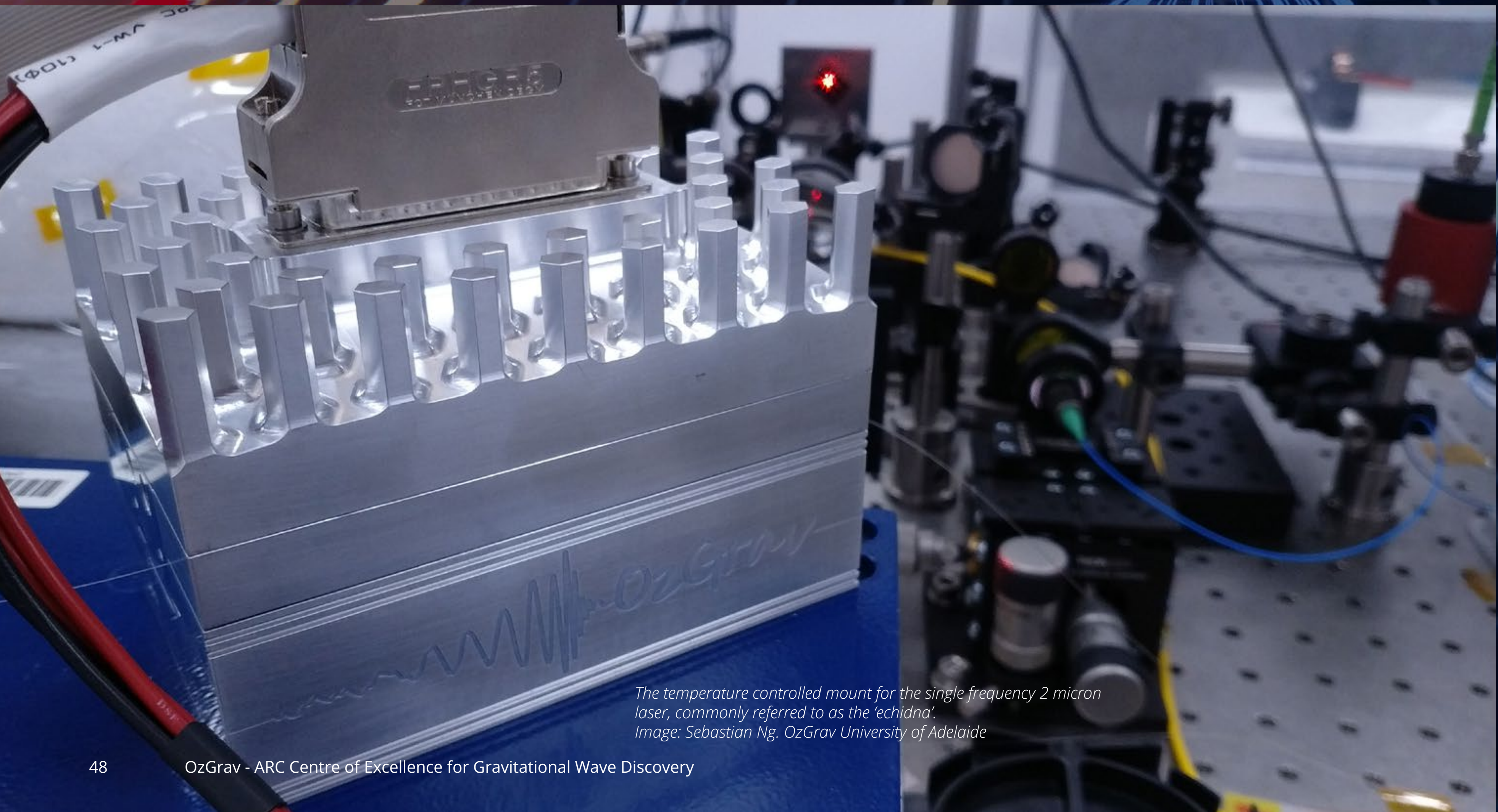
Quantum

Program chairs: David McClelland and Peter Veitch

Thulium-doped fibre lasers are a candidate for the laser source for third-generation gravitational wave detectors. The University of Adelaide team has continued the development of a thulium-doped fibre master oscillator and designed and fabricated a laser head to provide the environmental isolation required for stable laser operation. Characterisation of this master oscillator has indicated promising results but also revealed the need for a redesigned fibre cavity to improve laser stability. Updated cavities are currently being fabricated by collaborators at DSTG. Power scaling of this master oscillator has begun with an initial demonstration of a thulium-doped fibre amplifier.

Squeezing generation at 2µm is a key focus of the program, to reduce quantum noise in future gravitational wave detectors. The ANU team has produced the first squeezed light at 2µm, and in 2019 the level of squeezing produced in the experiment was determined to be 11dB. This level of squeezing cannot be directly measured due to two principle reasons: there are no photodetectors with high enough quantum efficiency to measure it, and the 2µm laser source used to generate the squeezing has too much phase noise. In 2019 progress was made on both these challenges. A coherent locking field was added to the 2µm squeezing experiment to measure and control the squeezing ellipse orientation--this enabled the measurement of 4 dB of squeezing with a stable spectrum. Higher quantum efficiency photodetectors are being pursued via two collaborations: one with Caltech and one with UWA, each with different semiconductors (IndiumAntinimide and HgCdTe, respectively). A low-noise 2µm seed laser was also developed at the ANU, with frequency noise performance superior to commercially available lasers - this design will form the basis of a new collaboration with the University of Adelaide.

Study of advanced squeezing methods also continued at 1µm where the technology is mature. These included the conclusion of a tabletop experimental demonstration of EPR-entanglement based squeezing which can be used to generate frequency dependent squeezing, and a theoretical and experimental study of the quantum noise effects of including a nonlinear element in a "long signal recycling cavity" (the experiment is underway).



The temperature controlled mount for the single frequency 2 micron laser, commonly referred to as the 'echidna'.
Image: Sebastian Ng. OzGrav University of Adelaide

Low frequency

Program chairs: Ju Li and Bram Slagmolen

Several novel designs were incorporated into the tilt sensor such as soft supports, compact eddy current damping and anti-spring. The tilt sensor construction was completed and testing starts early 2020.

For future vertical vibration isolation solutions, new contoured designs for Euler springs were investigated. Contouring allows us to remove material where it is not needed and thus increase the blade internal modes which spoil isolation performance. Using ANSYS modelling, we came up with a design and these were fabricated and successfully tested using glassy metals.

We received the MultiSAS, a soft isolation platform, from InnoSeis BV, and installed it in a clean tent in our laboratory. Initial testing showed that the system is working with a basic control and feedback system from the digital control system. The 140 kg Intermediate Mass, made from Aluminium-Bronze, Aluminium and Stainless-Steel, has been made in the mechanical workshop, and suspended from the MulitSAS.

Very productive discussion and visits by researchers from University of Melbourne and UWA to ANU included progress on implementing advanced control and feedback topologies, such as H-infinity methods. This implementation can make the performance of the controllers more robust, in particular for the complex suspension systems under development at ANU and UWA.

A 5-seismometer mini-array was deployed near the Gingin lab, and the team successfully applied for ARC LIEF funding to acquire more seismometer/geophone. We started trial data acquisition and analysis with the mini-array, and gained excellent experience for a future large array.

The program chairs want to thank the professional staff in the mechanical workshop and the electronics workshop at ANU and UWA for their tireless effect in manufacturing the complicated mechanical designs we come up with.

Inset images: Bram Slagmolen and Ju Li, OzGrav ANU and UWA

INSTRUMENTATION

Distortions and Instabilities

Program chairs: David Ottaway and Chunnong Zhao

The Distortions and Instabilities program made significant advances in 2019 including: the development of new mode matching control, the testing of a phase camera at LIGO Hanford and the design of a parametric instability free optical cavity. New information about non-uniform absorption in mirror coatings also now drives a new line of research in this program area.

A prototype design for the active mode matching elements for Advanced LIGO's squeezed light filter cavity was completed. OzGrav is playing an active role in the development and testing of prototypes. Currently there are two concepts being investigated: one uses thermal actuation and the other uses piezo actuation. Development of these actuators will continue in parallel until a down-select is made in mid-2020.

The phase camera development continues. Phase cameras were installed in the Advanced LIGO Hanford Detector during the October 2019 commissioning break. They worked well and produced interesting results on the circulating modes of the carrier field and the control sideband fields in the power recycling cavity. The results show how the fields change as the mirrors warm from the absorbed laser power. A more detailed description of these tests is included in the Commissioning section, since this technology has now transitioned to a commissioning tool. Development of machine learning techniques has also commenced to increase the amount of useful information that can be extracted from the phase camera images.

A parametric instability free gravitational wave detector arm cavity was designed and the process for a complete gravitational wave detector design process was established. Thermal transients cause the conditions for parametric instability to change in a complicated way. Over the last few years OzGrav members have developed a method for minimizing these transients. This technique was demonstrated at LIGO Livingston and allowed the laser power circulating in the arms to be increased from 100kW to 170kW. A new technique for avoiding parametric instability by simply changing one problematic optical mode frequency was developed, thereby adding an extra tool in the growing arsenal of parametric instability control strategies.

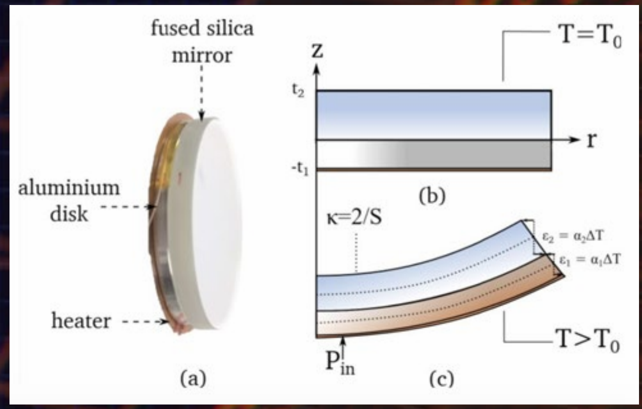
The silicon optics for the Gingin coupled cavity were characterized. There were some surprises with higher than expected mechanical loss which resulted in some delays while detailed investigation of the mechanical loss were undertaken. One of the suspensions for these test masses is complete and preparations for building the second suspension are almost complete.

Finally a technique for investigating non-uniform absorption, devised at the University of Adelaide is being used at Caltech to investigate test masses prior to and post-installation. This technique will allow test masses to be validated relatively quickly prior to installation. Test masses with very uniform coating absorption will allow optical power to be increased in the detectors and thereby allow improved sensitivity.

Case study: Mode matching elements

The University of Adelaide team has been collaborating with MIT to develop active mode matching elements. There are two design principles being developed: one that uses piezo actuators to deform a mirror; and one that uses a thermal actuator to deform a composite mirror composed of materials with different thermal expansion coefficients. The Adelaide group led the design and prototyping of the thermal actuator project. The description of an initial design has been accepted for publication in Applied Optics.

The thermal actuator is composed of the fused silica mirror, an aluminium disk and heating elements. The higher thermal expansion coefficient of aluminium results in the mirror being distorted into a convex shape when it is heated by the resistive heating elements. Materials for the thermally actuated mirror are being validated at Caltech and the performance of the actuators are being tested in preparation for a down select in technology in mid 2020.



INSTRUMENTATION

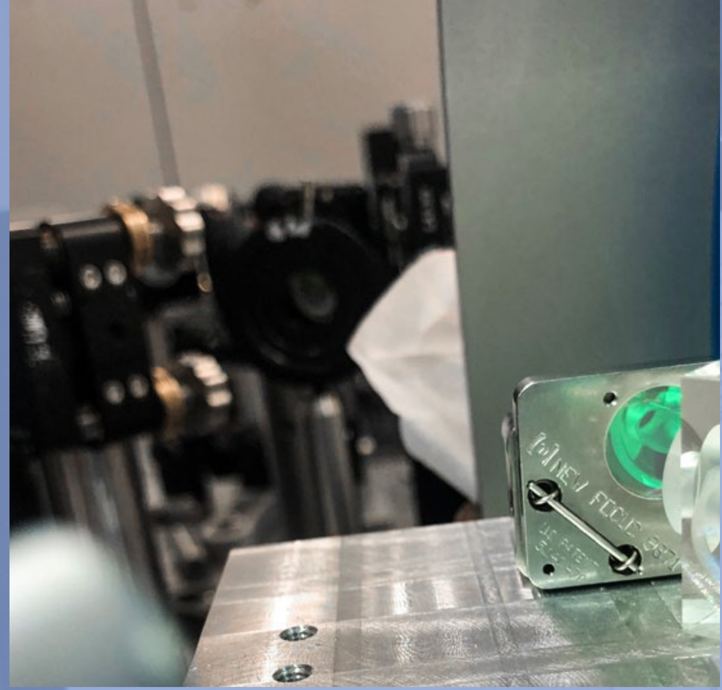
Space Instrumentation

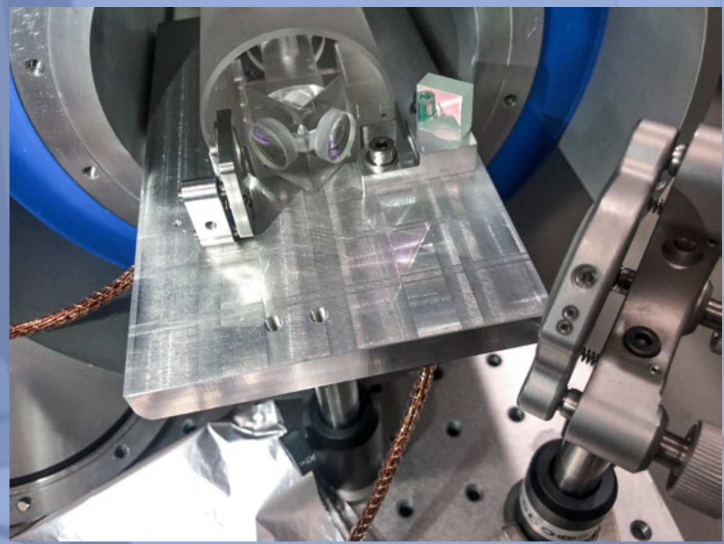
Program chair: Kirk McKenzie

LISA (Laser Interferometer Space Antenna), led by the European Space Agency (ESA) will measure gravitational waves by tracking changing spacecraft separation. In 2019 the OzGrav Space Program built on its capability to perform these core tracking measurements in the context of very low received optical power. The motivation for this work comes because space-based laser interferometers receive almost vanishingly small amounts of light from the distant spacecraft (picoWatts is typical). Tracking lower optical power increases the robustness of current planned space-based detectors, such as LISA, and opens up new possibilities for other detector architectures.

This low-optical power tracking work was pursued in 2019 as planned in the 2019 OzGrav report; the two planned milestones have been achieved: 1) First experimental results were recorded at a record low power level, and 2) confirm the model predictions: low optical power tracking is improved by frequency stabilizing lasers, compared with free-running lasers. These initial results were presented at the 2020 SPIE Photonics West conference in San Francisco, CA and the work is ongoing.

Senior Fellow Kirk McKenzie was recruited to lead OzGrav's Space program in May 2019. Dr McKenzie returned to ANU after working at NASA's Jet Propulsion Laboratory (JPL) for the previous 11 years. He brings a unique capability and experience to OzGrav as he has held senior space-flight instrumentation roles at JPL, including the NASA Instrument Manager of the GRACE Follow-On Laser Ranging Interferometer, and Instrument Scientist for the NASA LISA Phasemeter development. The OzGrav Space Program also appointed postdoctoral fellow Dr Andrew Wade, returning to the ANU after a 3-year fellowship in the Adhikari Lab, at the California Institute of Technology.





The Space Instrumentation program is pushing the limits of precision laser tracking. Optical cavities are used to stabilize the laser frequency: enhancing very low-power phase tracking and enabling new possibilities in space-based detector configurations. Images provided by Kirk McKenzie, OzGrav ANU

Case study: Laser Lockbox

Space Program expertise used to test Australian start-up Liquid Instruments device

The OzGrav Space Program worked with the Australian start-up company Liquid Instruments to test their Moku:lab instrument - the laser lockbox. The Space Programs' precision laser stabilization testbed was ideal to push the Moku:lab through its paces, which it passed with flying colours. The Liquid Instruments Moku:lab is currently used to routinely achieve performance near the fundamental limit of laser stabilization to an optical cavity.

Inset image: Moku:lab. Image credit: Nutsinee Kijbunchoo, OzGrav ANU
Background image: Tarquin Ralph (OzGrav alumni now wokring at Liquid Instruments) uses Moku:lab. Image credit: Nutsinee Kijbunchoo, OzGrav ANU

INSTRUMENTATION

Pulsar Timing

Program chair: Matthew Bailes

The 2019 plan had three key milestones. The first was to commence regular MeerTime Key Science Project observations by June 2019. In a sign of a strong project this objective was achieved four months early. As of 1 February 2020 MeerTime has recorded 762 hours of data from 972 unique pulsars. Many of these are of interest to OzGrav, including the celebrated double pulsar, many other relativistic binary pulsars and over 80 millisecond pulsars.

The second milestone was to submit the first MeerTime paper by October 2019. Dr Simon Johnston led a paper on the thousand pulsar array that was submitted to PASA in December 2019. This paper describes one of the four major pulsar projects that comprise MeerTime, the "Thousand Pulsar Array" and uses PT-USE, the pulsar timing prototype developed at Swinburne for the Square Kilometre Array.

The final milestone was to close out the SKA pre-construction project by the end of 2019. The final reports for this project were completed and the money expended by November 2019 by A/Prof Adam Deller and his team.

2019 was an important year for validating the hardware our team has been developing over the past four years on the SKA progenitor MeerKAT, a 64-dish array in the Karoo, South Africa. MeerTime was nominally awarded some 5000 hours over the first five years of MeerKAT operations, and SARAO managed to support us strongly in 2019. In just under a year we have already recorded 762 hours of data and astronomers from Australia, the UK, Germany, Italy, South Africa, New Zealand, USA and Hungary are all working on processing these data to validate the system and do new science.

The prototype pulsar processors are now five years old and we realised that new technologies had come to market that could increase their functionality and performance. Specifically new CPUs can catch more packets of data without loss, and new disk drives enable us to record baseband data. In late 2019 we ordered three new servers with enhanced hardware and these will be commissioned in 2020 at the SKA site where MeerKAT is located.

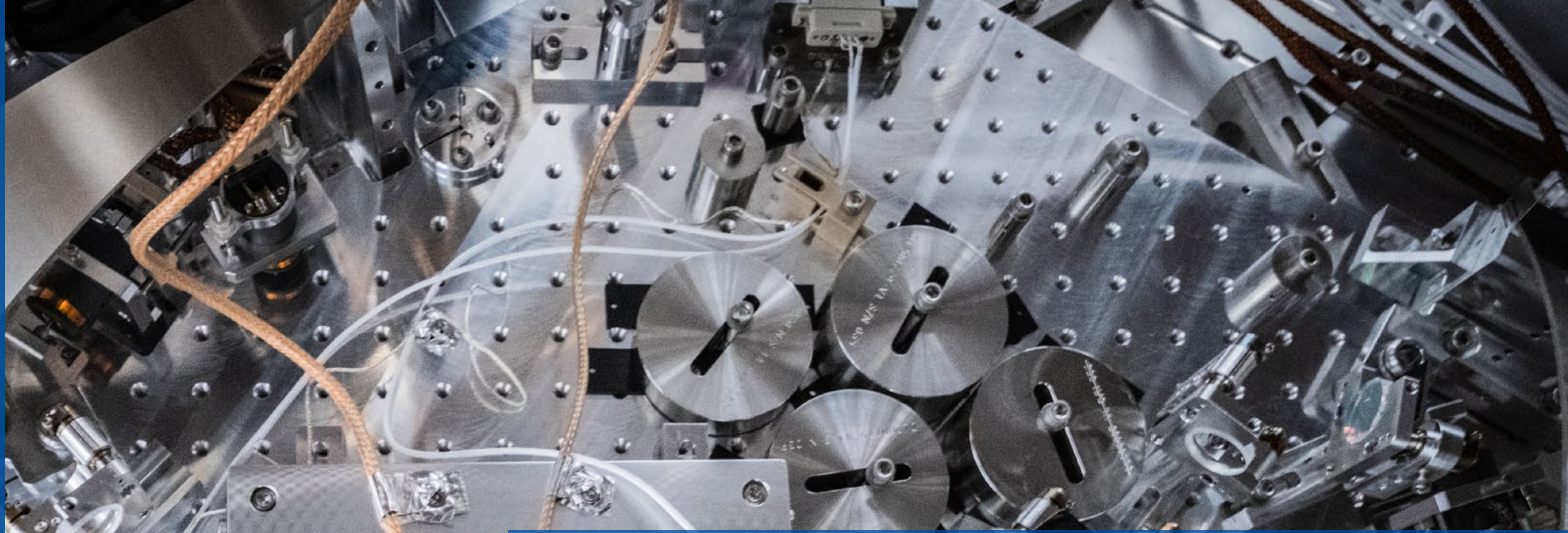


Image: Nutsinee Kijbunchoo, OzGrav ANU

Planning for Future Detectors

Program chairs: David McClelland and David Ottaway

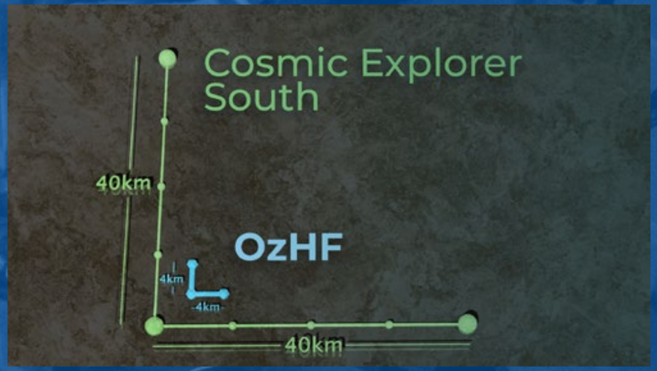
2019 was an important year for the development of the science case for the so-called third-generation or 3G detectors. An international team organised by the Gravitational Wave International Committee (GWIC) developed the science case for a global third generation ground-based gravtiational wave (GW) network and examined the research and development that needs to deliver the required sensitivity. Professor Bailes led the development of the multi-messenger science case with co-leads Mansi Kasliwal and Samaya Nissanke. Professor McClelland led the Research and Development study with Harald Lueck from the Albert Einstein Institute in Germany. The GWIC report is expected to be released in 2020.

There are currently two concepts for 3G detectors. The European team is spearheading the case for a triangular underground detector with 10 km arms known as the Einstein Telescope (ET) whereas the USA team are proposing the development of a "super-LIGO" with 40 km arms they call Cosmic Explorer. At such lengths the curvature of the Earth becomes significant, and suitable sites problematic. Nevertheless these instruments would detect mergers to the edge of the Universe in a very unbiased manner.

Most of the key science projects for such detectors are compromised unless the sources are detected at three sites, so in addition to a European and US-based observatory it would be advantageous to have a third site, preferably in the Southern hemisphere and located in a stable continent with ample spare land. Australia would be worthy of consideration.

At OzGrav we have been pursuing a two-pronged strategy with regard to future detectors. In the short-term we have a working group exploring the merits of a high-powered high-frequency detector to explore neutron star mergers and the equation of state of nuclear matter. Nicknamed OzHF, this concept has brought together theorists and experimentalists alike to see if it is both economic and scientifically worth pursuing on short timescales. 3G detectors will want to increase laser power and OzHF might be a way to de-risk future 3G detectors by validating the instrumentation required.

The long game might be to build OzHF at the site of a future southern 40km detector in the late 2030s. In 2019 we commenced a study of potential sites for such a detector and wrote a White Paper outlining a possible path forward to an Australian-based detector. The White Paper was a submission into the Australian Astronomy Decadal Plan Mid-Term Review, and the vision it painted was picked up by major Australian media.



NEWS

Giant site search is a matter of gravity

AMAZING SPACE

DATA AND ASTROPHYSICS THEME

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

- Inference (Program chairs: Greg Ashton and Rory Smith)
- Gravitational Wave (GW) Data Analysis (Program chairs: Qi Chu and Karl Wette)
- Pulsar Detections (Program chairs: Hannah Middleton and Ryan Shannon)
- Multi-Messenger Observations (Program chairs: Kendall Ackley and Eric Howell)
- Relativistic Astrophysics (Program chair: Paul Lasky)
- Population Modelling (Program chair: Simon Stevenson)
- OzSTAR supercomputer (Leader: Jarrod Hurley)

The observational foundation for OzGrav's science stems from the LIGO-Virgo gravitational wave (GW) detectors and the Parkes 64m and MeerKAT radio telescopes. All of these facilities have undergone significant enhancements that have extended their sensitivities in the last year by our OzGrav instrumentation teams and their international collaborators. OzGrav now has a key role in the interpretation of the GW data from LIGO/Virgo via the Bilby tool, and for the first time the SPIIR pipeline has been detecting binary coalescences on live data. Searches for bursts and continuous wave sources are in full swing. This work will benefit from the recently-funded Gravitational Wave Data Centre based at Swinburne University of Technology.

The Parkes pulsar timing array had its second major data release after a big push by OzGrav staff and collaborators, and GW detection efforts for nHz sources are ramping up across OzGrav. The MeerKAT telescope commenced regular pulsar timing observations in February 2019, and has already recorded over a month of pulsar timing data and OzGrav personnel helped interpret the glitch of a nearby pulsar.

At other wavelengths both national (e.g. SkyMapper, Zadko) and international optical telescopes have been on stand-by to track down the optical counterparts of neutron star mergers, and funding has been secured for a GOTO-South telescope by Monash University.

Finally, gravitational wave detections are opening new opportunities to learn about the evolution of binary stars and in the future may even peer into the cores of exploding stars.

Image: Carl Knox, OzGrav Swinburne

DATA AND ASTROPHYSICS

Inference

Program chairs: Greg Ashton and Rory Smith

2019 marked a transitional year for the inference program: from development to deployment. The next-generation inference code Bilby (Bayesian Inference Library) was rolled out as production code by the LIGO/Virgo Collaboration (LVC) to measure the astrophysical properties of black holes and neutron stars using gravitational waves. After thorough testing and review, the code was deployed in the O3b observing run concurrently with its predecessor. We anticipate a transition period during which both codes will be used and eventual wholescale adoption. Already this effort has borne fruit: Bilby was used for verification in the detection of GW190425.

Members of the inference program have had a substantive impact in operational aspects of the LIGO/Virgo collaboration publications. OzGrav members are on several paper writing teams and instrumental in the analysis, inference and astrophysical interpretation for papers such as the O1+O2 populations paper and GW190425 discovery paper. A/Prof EricThrane is a member of the editorial board. In total our members are directly involved in the analysis of thirteen of the events detected in O3 so far.

OzGrav hosted the 2019 LIGO/Virgo parameter estimation face-to-face meeting in February at the Monash node. Funding supported 32 participants with 12 international visitors. This unique opportunity highlighted the strength of OzGrav within the wider gravitational wave community as experts in inference. It also provided an opportunity to develop collaborations with international visitors, especially to junior members less able to travel to international conferences.

Significant steps have been made in inference of compact binary coalescence events. We developed methods to extract the neutron star equation of state from gravitational-wave observations from multiple binary neutron star mergers. OzGrav members developed a method for combining multiple observations to extract the equation of state which will be deployed in 2020 to make the first constraints on the equation of state from multiple observations. In addition we demonstrated how a background of unresolved binary neutron star gravitational-wave signals could be detected using aLIGO, developed and deployed a search for signs of eccentricity, and furthered the search for the memory effect.

We set ourselves the challenge to continue extending the scope of the inference program beyond compact binary coalescence inference from gravitational wave merger data. OzGrav and collaborators have made significant strides in inferring neutron star physics from glitch statistics, worked on post-merger inference, and there has been strong developments in inferring and predicting the behavior of X-ray afterflows. We continue work applying inference to extract astrophysics from core collapse supernovae. Additionally, the Bilby inference code is gaining recognition in astrophysics: in 2019 it was cited by 7 non-gravitational-wave papers ranging from radio pulsar timing to fast radio bursts.

In 2019 we continued to innovate on methods that significantly enhance the capability of inference methods by improving the scalability of our algorithms. We demonstrated how GPUs could be used to accelerate inference on individual and populations of gravitational waves by several orders of magnitude. We developed a massively-parallel implementation of Bilby which can be deployed at scale on CPU clusters to obtain near-linear speedup with the number of CPUs. This "parallel bilby" code is under review by the LVC group and will be deployed in O3b to analyze events where the most accurate, but expensive, signal models are needed. by signing up. About 16% of the 100 names on the parameter estimation (PE) rota are OzGrav members.

Case study: Second binary neutron star merger

The first LIGO/Virgo detection paper from the O3 observation run, GW190425, is likely the second binary neutron star merged ever detected. Members across the OzGrav Inference team were involved in the analysis from the start, analysing the data, reviewing results, and writing the paper. Moreover, the Bilby software was used for verification of the results: the first citation for Bilby in a detection paper! A press release was issued quoting OzGrav early career researchers Adya, Zhu, Stevenson and Ashton. Ashton was interviewed by Adelaide radio fiveaa and the paper was picked up by multiple news sites worldwide.

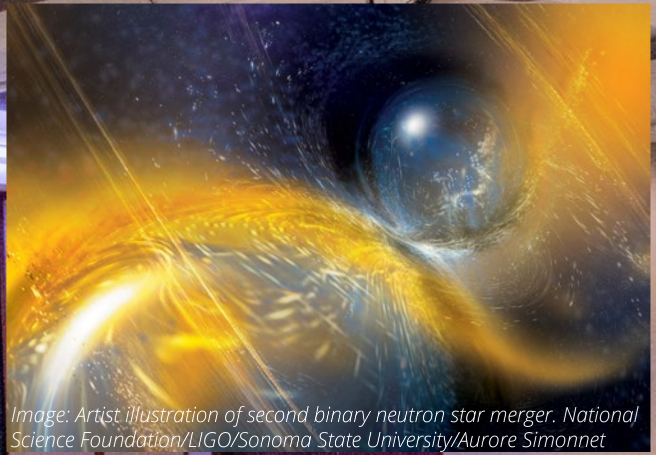


Image: Artist illustration of second binary neutron star merger. National Science Foundation/LIGO/Sonoma State University/Aurore Simonnet

Case study: Gravitational wave memory

OzGrav-Monash members Hübner, Talbot, Lasky, and Thrane's paper "Thanks for the memory: measuring gravitational-wave memory in the first LIGO/Virgo gravitational-wave transient catalog" (accepted for publication in Phys. Rev. D) was highlighted on space.com. With facilities like LIGO and Virgo, we can now detect the strongest ripples in space-time as they wash over the Earth. But gravitational waves leave behind a memory — a permanent bend in space-time — as they pass through, and we are now on the verge of being able to detect that too, allowing us to push our understanding of gravity to the limits. This paper marks the culmination of significant effort to develop theoretical understanding, waveforms, and finally predict that the gravitational wave memory effect will be observable in the early A+/Virgo+ era (more enhancements to Advanced LIGO and Virgo detectors from 2024 onwards).

Background image: Carl Knox OzGrav Swinburne

DATA AND ASTROPHYSICS

GW Data Analysis Program chairs: Qi Chu and Karl Wette

2019 saw the completion and publication of many observational papers from the LIGO and Virgo observatories' 2nd observing run ("O2") led by or with contributions from OzGrav members. Meg Millhouse led the O2 all-sky short-duration GW burst search. Jade Powell contributed to the O1/O2 search paper for GW bursts from supernovae. Patrick Clearwater and Andrew Melatos completed the analysis for the O2 Sco-X1 CW search using a hidden Markov model, which used critical GPU code developed by Liam Dunn. Patrick Meyers, Colm Talbot, and Boris Goncharov lead and completed the O2 search for a directional stochastic background.

The 3rd observing run ("O3") of the LIGO and Virgo observatories commenced in April 2019. OzGrav members have fully participated in detector characterisation and data analysis activities related to the O3 run. Meg Millhouse contributed to the O3 all-sky short-duration GW burst search. Jade Powell contributed to the O3 search for GW bursts from supernovae. The SPIIR low-latency detection pipeline, led by Linqing Wen, Qi Chu, and the UWA SPIIR team, participated in producing open public alerts for candidate GW detections from the O3 run; 50% of this effort has been supported by OzGrav. Meg Millhouse helped with some of the (unmodeled) waveform reconstruction for the O3a catalog paper. Patrick Meyers served as a mentor for detector characterization data quality shifts. Andrés Vargas, Julian Carlin, and Hannah Middleton helped with identifying known and unknown lines for the O3 pulsar searches.

OzGrav members have also contributed to service and leadership of the LSC/Virgo Collaboration, including Jade Powell chairing the LSC supernova group, Eric Thrane serving as review chair of the LSC/Virgo burst working group, Karl Wette serving as co-chair of the LSC/Virgo continuous wave working group, and Juan Calderon Bustillo, Grant Meadors (OzGrav alumnus), Jade Powell, Simon Stevenson, Eric Thrane, and Karl Wette serving as internal reviewers for LSC/Virgo analyses and papers. OzGrav PhD students and postdocs make significant contributions to LSC/Virgo leadership through serving as lead analyst/author of many LSC/Virgo observational papers, as well as serving in LSC/Virgo Collaboration management roles; this provides valuable leadership training for OzGrav early-career researchers in the GW data analysis program.

OzGrav members also pursued research in a wide variety of areas related to GW data analysis, which resulted in many papers submitted and/or accepted for publication. Topic include machine learning (Jade Powell), joint GW and X-ray detection (Pay Meyers, Andrew Melatos, Sofia Suvorova), a search for GWs from LMXBs beyond Sco X-1 (Hannah Middleton, Patrick Clearwater, Andrew Melatos, Liam Dunn), an O2 Viterbi CW search for supernova remnants (Meg Millhouse, Lucy Strang, Andrew Melatos), a GPU version of the CW F-statistic (Liam Dunn, Patrick Clearwater, Andrew Melatos, Karl Wette), reconstruction of GW supernova signals with dynamic time warping (Sofia Suvorova, Jade Powell, Andrew Melatos), continued high-precision observations of the orbit of Sco X-1 which is critical to CW searches (Duncan Galloway), a search for X-ray pulsations from Sco X-1 in support of CW searches (Shanika Galaudage, Duncan Galloway, Karl Wette), a statistically optimal search for the population of sub-threshold binary black holes (Colm Talbot, Rory Smith, Francisco Vivanco Hernandez, Eric Thrane, Sylvia Biscoveanu), a new Bayesian search for intermediate-mass black holes (Avi Vajpeyi, Rory Smith, Eric Thrane), a new search for gravitational-wave memory (Atul Divakarla, Paul Lasky, Eric Thrane), a search targeting CWs associated with gamma-ray sources in the HESS telescope catalogue (Deeksha Beniwal, David Ottaway, Andrew Melatos, Patrick Clearwater), and a new semi-coherent search method for long-duration signals from a post-merge binary neutron star (Ben Grace, Karl Wette, Susan Scott).

OzGrav data analysts have also applied their skills more widely in interdisciplinary collaborations with the OzGrav instrument science theme, providing signal processing and data analysis services for suspensions experiments at ANU and UWA, the seismic array at UWA, LIDAR spin-off technology developed at ANU for autonomous vehicles and other applications, and optimisation of the proposed OzHF high-frequency gravitational wave detector, itself a major OzGrav interdisciplinary project.

Case study: OzGrav leadership of LSC/Virgo observational papers

In 2019 three flagship papers from the 2nd observing run ("O2") of the LIGO and Virgo observatories were led by OzGrav members.

Meg Millhouse (University of Melbourne) led the O2 all-sky search for short-duration GW burst signals. This search was sensitive not only to GW signals from the merger of binary black holes, but also from as-yet undetected GW signals from supernovae, pulsar glitches, cosmic string cusps - and potentially some completely new physical phenomena. Cosmic string cusps, in particular, were targeted by the search using a modelled search. While no GW bursts were detected, the search was able to place sensitive upper limits on the possibility of GW bursts, which in turn are able to constrain theoretical models. The search was published in Physical Review D.

Patrick Clearwater and Andrew Melatos (University of Melbourne) led the O2 Sco-X1 CW search using a hidden Markov model. This search was the first LSC/Virgo search to run entirely on the OzGrav OzSTAR supercomputer hosted at Swinburne University of Technology. Liam Dunn (University of Melbourne) developed GPU code for the search which was critical in reducing its runtime from months to weeks. The search also relied on optical observations of the Scorpius X-1 orbit published by Duncan Galloway (Monash University) and collaborators. The internal reviewers for the search were Grant Meadors (Monash University, OzGrav alumnus) and Karl Wette (Australian National University). The search set sensitive upper limits on continuous gravitational waves from Scorpius X-1, which are robust to potential stochastic spin wandering of the signal, and was published in Physical Review D. Patrick Clearwater is now employed by the OzGrav-affiliated Australian Gravitational Wave Data Centre, and so OzGrav will continue to benefit from his software engineering expertise.

Patrick Meyers (University of Melbourne) was lead author of the O2 search for a directional stochastic background, alongside Colm Talbot and Boris Goncharov (Monash University). This search looked for a persistent background "hum" of gravitational waves from different points in the sky, which could have come from a non-spherical neutron star, or from a cloud of exotic axion particles around a black hole, or from something new. A feature in the data which initially looked like a promising candidate turned out to not be consistent with a gravitational wave. The search set upper limits on persistent gravitational waves 1.5 times more sensitive than previous searches.

Background image: Carl Knox OzGrav Swinburne

DATA AND ASTROPHYSICS

Pulsar Detections

Program chairs: Hannah Middleton and Ryan Shannon

Parkes Pulsar Timing Array (PPTA): We took a leading role in completing the much anticipated second major PPTA data release "PPTA dr2". The data set shows evidence for correlated ephemeris noise which is limiting the sensitivity to gravitational waves. We are currently undertaking an extensive noise analysis of the data set. The PPTA has provided the data set to the International Pulsar Timing Array for further gravitational wave searches.

International Pulsar Timing Array: The group retained strong connections to the global international pulsar timing array (IPTA) effort. Ryan Shannon (Swinburne) served on the IPTA steering committee as immediate PTA steering committee, and Xingjiang Zhu (Monash) joined the committee. Daniel Reardon (Swinburne) started as co-chair the IPTA Gravitational Wave Analysis Working Group, replacing previous co-chair Paul Lasky (Monash). This working group is undertaking gravitational wave searches of these data sets. OzGrav was well represented at the International Pulsar Timing Array science meeting and student workshop held in India in June, giving nine talks at the science meeting and delivering five lectures and tutorials at the PhD-level student workshop.

MeerKAT Pulsar Timing: The team is excited about the progress made towards MeerKAT pulsar timing efforts (see "Pulsar" instrumentation program). MeerKAT has much greater instantaneous sensitivity than the Parkes 64-m radio telescope, although the new UWL receiver does extend the life of the venerable dish. As of writing the MeerTime project has nearly 3000 unique observations of over 900 pulsars, totalling over 700 hours of integration time. The first papers on millisecond pulsars will be published in mid-2020.

Inference as applied to pulsar data sets: Efforts increased to improve capabilities in modern inference, holding an inference workshop and hack week in May. The program has gained expertise in using modern inference tools through participation in the IPTA hack weeks. The team gained expertise in using domain standard tools such as Enterprise and is now looking into developing it for use with our data sets.

Pulsar searching: We refocused pulsar search efforts on reprocessing of the High Time Resolution low-latitude south survey, a Galactic-plane search for pulsars. Armed with a state-of-the-art pipeline, the reprocessing has over 40 "gold" class pulsar candidates which will be confirmed and monitored through future Parkes observing.

Pulsar glitches: The underlying causes leading to pulsar glitches are unclear. We investigated the statistics of the sizes of pulsar glitches and the waiting times between glitches. Sizes and waiting times can be used to falsify broad classes of theories describing the build-up and release of stress during the glitch process. A method of detecting pulsar glitches with a hidden Markov model has been developed and tested. It will be applied in earnest to astronomical data in 2020. There is work underway to use local period estimation as an aid to pulsar glitch detection (possibly also in collaboration with the UTMOST pulsar team). We are modeling pulsar glitches as superfluid vortex avalanches in neutron star interiors.

Case study: Pulsar glitches

Pulsar glitches are sporadic, abrupt increases in the rotational frequency of a pulsar. While these events have been seen since the 1970s, the underlying physical mechanism causing them is still unclear. Meta-models, such as the ones explored here provide an avenue for linking entire classes of physical models to precise, falsifiable predictions that are compared to observations in individual pulsars. For example, the strong cross-correlation between glitch sizes and the waiting time until the next glitch seen in PSR J0537-6910 is indicative of an underlying physical process in which stress steadily builds in the system until a constant threshold is reached, at which point a fraction of that stress is released in a glitch, and the process repeats.

One model for the cause of pulsar glitches is due to superfluid vortex avalanches in the interior of neutron stars. We developed a code to test the feasibility of the vortex avalanche model of pulsar glitches. The code simulates the motion of vortices in a decelerating 2D container in the presence of pinning sites. This work finds evidence that this system undergoes avalanche behaviour, with qualitatively similar statistics to the observed pulsar glitch waiting time distribution.

Multi-Messenger Observations

Program chairs: Kendall Ackley and Eric Howell

The goal of the Multi-Messenger Program is to probe the nature of GW events that could have corresponding electromagnetic emissions by combining data from different wavelengths. The program encompasses both observational electromagnetic follow-up and theoretical studies. Observational follow-ups aim to respond to gravitational wave detections by triggering a global network of telescopes to make observations across the wavelength spectrum. Theoretical studies seek to build on follow-up observations to provide new insights and predictions of the physical mechanisms and processes driving these extraordinary events.

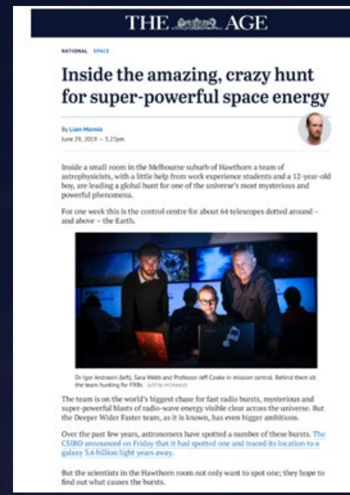
Although there have been a handful of promising compact binary mergers including at least one neutron star, the positional sky maps have been large and the GW events have been quite distant in comparison to GW170817, closer to the observational GW horizon. Both these factors have made follow-up quite challenging for electromagnetic facilities. Despite the lack of follow-up discoveries, a highly encouraging aspect of the campaign so far has been the organisation and prompt reporting between different facilities. This bodes well for the remainder of the campaign and beyond.

Case study: Data Sonification

OzGrav PhD student Garry Foran (Swinburne) isn't the first blind astrophysicist but his work, with his supervisor—OzGrav Chief Investigator Jeff Cooke (Swinburne) —is truly unique: developing novel tools that use sound to study distant galaxies and detect the fastest explosions in the universe.

'When Garry came, we were looking for ways to try to analyse the data faster and better, and sound came up as an option. We started learning that there are many areas of sound that haven't been exploited, and that you can hear certain information faster than you can see it.' said OzGrav Chief Investigator Jeff Cooke.

As part of OzGrav's research program called Deeper Wider Faster (DWF), we started to work with data sonification to help Garry hear the spectra of data that the rest of us see on our computers and hear the complex sounds of multiple parameters at once. These tools have not only made astronomy more inclusive for visually-impaired scientists, they've also opened the door to more efficient ways of processing data and even helped sighted astronomers make new discoveries. Garry featured online prominently on data sonification including an interview on Radio FM4 along with Jeff Cooke, and Garry presented an exhibition of DWF data sonification at the IAU symposium 358 in Japan.



THE AGE

NATIONAL SPACE

Inside the amazing, crazy hunt for super-powerful space energy

By Liam Mannix
June 29, 2019 — 5.27pm

Inside a small room in the Melbourne suburb of Hawthorn a team of astrophysicists, with a little help from work experience students and a 12-year-old boy, are leading a global hunt for one of the universe's most mysterious and powerful phenomena.

For one week this is the control centre for about 64 telescopes dotted around – and above – the Earth.

Dr Igor Andreoni (left), Sara Webb and Professor Jeff Cooke in mission control. Behind them sit the team hunting for FRBs.

The team is on the world's biggest chase for fast radio bursts, mysterious and super-powerful blasts of radio-wave energy visible clear across the universe. But the Deeper Wider Faster team, as it is known, has even bigger ambitions.

Over the past few years, astronomers have spotted a number of these bursts. The CSIRO announced on Friday that it had spotted one and traced its location to a galaxy 5.6 billion light years away.

But the scientists in the Hawthorn room not only want to spot one; they hope to find out what causes the bursts.

OBSERVATIONAL: DWF

During 2019 the Deeper Wider Faster (DWF) program (led by Jeff Cooke, Swinburne) ran two successful 6-night coordinated DWF runs. DWF includes 65 telescopes around the globe; the two 2019 runs involved a number of telescopes coordinated to search for fast transients and FRB counterparts in the same field at the same time, with detections in real time. Simultaneous observation telescopes included MeerKAT and ThunderKAT in South Africa, and Parkes and Molonglo in Australia in the radio searching for FRBs and transients; mm/submm searches with the South Pole Telescope, Antarctica; optical searches with DECam, Chile, MeerLICHT, South Africa, AST3-2, Antarctica and MASTER, South Africa. High energy searches included HXMT, space telescope (X-ray), HESS, Namibia (gamma-ray) and Pierre Auger, Argentina (high-energy particle/photons).

DWF successfully ran real time data processing and analysis (in seconds to minutes) and candidate identification using software developed by the DWF team and international collaborators to perform human visualisation in the mission control room on the Swinburne campus. DWF also coordinated telescopes to monitor the target fields for long duration events and performed follow up spectroscopy and imaging.

Along with the research team, DWF included undergraduate students, high school students, and the general public, including 12 year-old "Astro-Blake" as part of our citizen science work, bringing DWF to the public to inspire young scientists. Jeff Cooke contributed to a range of media stories on science on radio and in print news, and also led a fundraising event for the Royal Children's Hospital, Melbourne, with a talk, science discussion, and astronomy artwork sales.

DWF are presently exploring the data to detect kilonovae to redshift z ~ 0.5, well beyond the LIGO/Virgo horizon, to better understand the optical behaviour of the KN population. DWF were also involved in search and follow up observations for binary neutron star (BNS) and neutron star – black hole (NS-BH) EM counterparts as well as some involvement in a number of other events from deep wide-field imaging searches, candidate analysis and searches, and follow up spectroscopy and imaging.

DATA AND ASTROPHYSICS

OBSERVATIONAL: ZADKO

During O3 the Zadko telescope has been a member of the Global Rapid Advanced Network Devoted to the Multi-messenger Addicts (GRANDMA) worldwide network of 25 telescopes with photometric and/or spectroscopic facilities across 19 observatories, 26 institutions and groups from nine countries. As part of the observing program, Zadko astronomers committed to perform shifts, ensuring 24-hour monitoring, and during O3 GRANDMA has followed up more than 85% of the GW alerts. UWA node has also been involved in developing and maintaining the GRANDMA database, storing all results and observations, and implementing a web interface for all data and operations.

During 2019 there have been a number of technical issues to overcome to facilitate the observation program. Zadko's mirrors have had to be recoated and recalibrated, the camera has been replaced and updates and reconfiguration of the robotic system has been completed. Despite these obstacles, Zadko was able to perform interesting follow-up observations of BBH and BNS mergers, GRB sources, as well as some dedicated observation programs

We have been actively engaging with international companies with a strong interest in space situational awareness. This theme is motivated by the requirement to protect and monitor space assets, both corporate and government owned. Ariane group is a major French aerospace company engaged in space situational awareness and OzGrav will host satellite monitoring equipment at the UWA Zadko Observatory. The initial contract has developed into an industry and research training program. An industry pilot program in 2018 funded an undergraduate from France to be trained at UWA in satellite identification.

OBSERVATIONAL: SkyMapper

Before O3, SkyMapper set up a rapid-response and real-time processing system (AlertSDP: ALERT Science Data Pipeline) to automatically follow up LIGO/Virgo alerts of GW events involving binary neutron stars (BNS). To perform an end-to-end test of the software that includes GW alert handling, improved scheduling, image processing, transient detection and database management, SkyMapper carried out gamma-ray burst (GRB) follow-up drills. In April 2019, the SkyMapper team released the deep multi-colour data set collected as part of the SkyMapper Southern Sky Survey, with information about over 500 million unique astrophysical objects down to 22 magnitude and more cross-matched external catalogues. This near complete i-band sky-map for Southern Hemisphere is used as reference images for the kilonova search, making us find an optical counterpart quickly to get into monitoring mode of that source.

A study highlighted how often M dwarf stars have energetic outbursts as these are the main contaminants in searches for fast extragalactic transients. One important conclusion was that, reassuringly for SkyMapper, SkyMapper expects no M dwarf flares to confuse i-band searches for kilonovae from GW events.

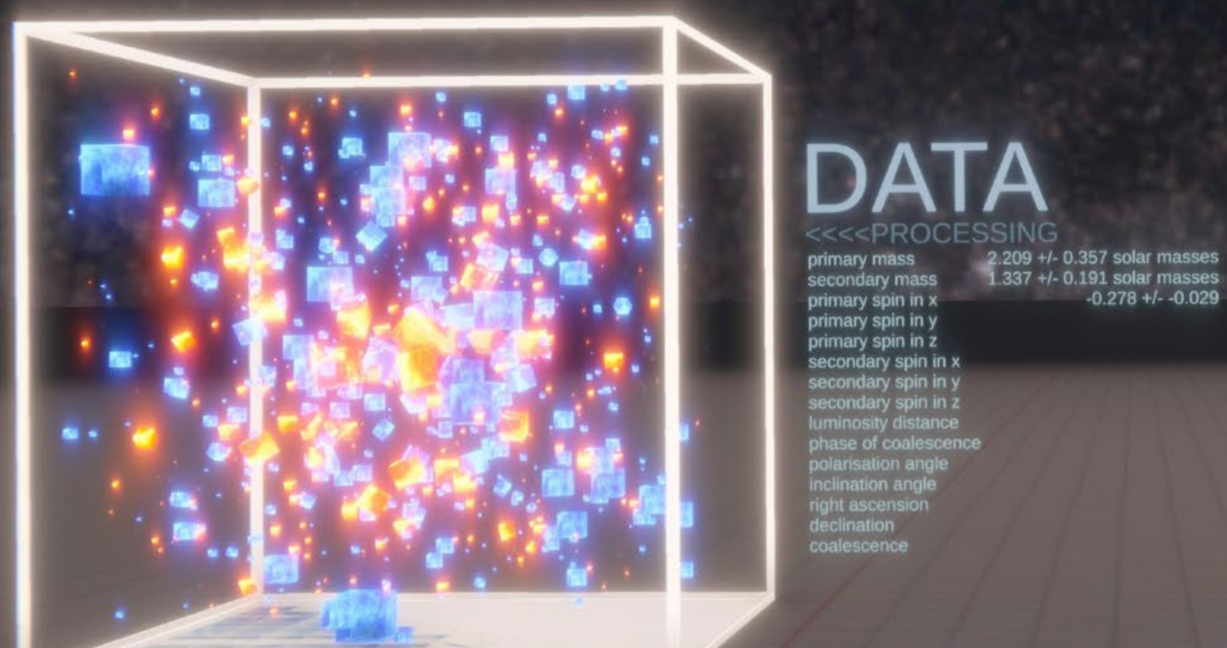



Image: ZADKO teelscope

THEORY PROJECTS

Collaborative study between OzGrav-UWA and Murchison Widefield Array (MWA) researchers examined how fast radio burst (FRB)-like signals could be detected in low-frequency radio observations if triggered by the aLIGO/Virgo gravitational wave detectors. We worked on reduction in response time by triggering on `negative latency' GW alerts. Using a proposed new MWA observational mode capable of viewing 25% of the sky, an FRB-like burst from an event similar to GW170817 could be detected at O3 sensitivity.

Work continued on model selection between the fireball and magnetar models of gamma-ray bursts, adopting a Bayesian approach to model selection. Collaboration continued using Bayesian methods for detecting the geometry of short GRBs using coincident electromagnetic and GW observations. We also worked on a model for the mechanism that produces the relatively long lived X-ray plateaux seen in a large percentage of X-ray afterglow data. This feature is understood to be produced through energy injection from a newly born magnetar.

OBSERVATIONAL: GOTO

The prototype Gravitational wave Optical Transient Observer (GOTO) in 4-telescope configuration successfully ran observations of 29 gravitational wave triggers during the first half of the LIGO/Virgo Collaboration (LVC) O3 run. GOTO tiled approximately 700 square degrees per event, representing over 45 per cent of the LVC probability map. The latter half of the year saw approximately 23 more gravitational wave triggers of which GOTO followed weather permitting. Significant infrastructure development saw the addition of 4 more telescopes installed, bringing GOTO closer to full design specifications. Additionally, when not searching for GW counterparts, GOTO participated in opportunistic follow-up of transients detected by other projects, including Fermi and Swift GRBs, IceCube and high-energy neutrino alerts, and asteroid observations.

Highlight

$6 million in funding has been secured from the STFC-PPRP to begin building a GOTO-South 8-telescope node in Australia for the upcoming year. It would be a duplicate of the La Palma GOTO instrument (see image below), and would be housed at Siding Springs near Coonabarabran in NSW. This improves our chances of finding electromagnetic counterparts to binary neutron star mergers.


The first GOTO dome at Roque de Los Muchachos observatory on La Palma. Image: Krzysztof Ulaczyk, University of Warwick

DATA AND ASTROPHYSICS

Relativistic Astrophysics

Program chair: Paul Lasky

The field of relativistic astrophysics is undergoing numerous changes and challenges thanks to the welcome arrival of new and interesting observations of highly-relativistic systems.

Gravitational wave observations of many more black hole mergers in the third aLIGO/Virgo observation run are being used to challenge our understanding of gravity in the most dynamic regions of high spacetime curvature.

Gravitational wave observations of binary neutron star mergers, precision x-ray observations of pulsar J0030+0451, radio observations of glitching pulsars, and multi-wavelength afterglows of short gamma-ray bursts are enabling us to peer deeper into the heart of neutron stars than ever before. The as-yet unpublished putative observations of gravitational waves from neutron star-black hole mergers in 2019 provide new opportunities to probe these exotic regions of spacetime in the coming year.

All the while, the increased number and type of fast radio bursts is shedding some light on their progenitors which must be highly-compact systems, although their precise origin is still a subject of much debate.

Relativistic astrophysics is a multi-faceted field that relies not only on observations such as those mentioned above, but also on complicated and complex modelling of physical phenomena. We continue to drive supernova modelling forward, understanding the complex three-dimensional fluid mechanics that ultimately leads to gravitational waves being (hopefully) detected by ground-based gravitational-wave detectors. This complements existing and ongoing efforts to detect and perform parameter inference on such signals.

Pulsar glitches have received their share of attention this year, including grass-roots modelling of superfluid vortex dynamics, statistical analyses of glitch waiting times and size distributions, new glitch detection methods, and inference of the 2016 Vela glitch to understand the spin evolution of the star during the glitch (see Science Highlights at beginning of report).

NEWS

TUESDAY, AUGUST 13, 2019

Glitch key to stellar effort

Dr Greg Ashton (right) with colleague Dr Paul Lasky. Photo: Eddie Jim

Liam Mannix
Science reporter

What lies in the heart of a neutron star?

Patient observation – and a sudden glitch – have allowed Australian astronomers to peer inside one of these extreme objects [illegible]rst time.

What they found was something deeply strange: a dense liquid of subatomic particles that behave according to strange physical laws.

[illegible]

sun and you crush it down to about 10 kilometres in radius."

Neutron stars generate very powerful magnetic fields, which channel the star's radiation into a thin beam. As the star spins, the beam spins too.

Australian scientists have been watching the spinning beam coming from a neutron star known as Vela – and waiting for a glitch.

Vela, and other neutron stars, rotate with great regularity. But sometimes the rotation speeds up or [illegible]

Mount Pleasant, outside Hobart. Then they watched, and waited.

And suddenly, there it was. The star's spin slowed down, and then sped up until it was racing, before settling into its normal rhythm. The whole thing lasted about 13 seconds.

Dr Ashton's team did some detective work about what could be causing the glitch, which they published today in *Nature Astronomy*.

Inside the star, they speculate, the neutrons are crushed together so hard they start behaving like a fluid.

[illegible]

The team believes the glitch is caused by the superfluid at the core of the star moving outwards and hitting the star's outer crust, causing it to start spinning faster.

Then the middle layer, also a superfluid, catches up to the outer layer, causing the star to slow down.

"They have found tantalising evidence that this neutron star has done something unexpected – immediately before spinning up the star unexpectedly and briefly slowed down," says Dr Ryan Shannon, a [illegible]

Background image: Carl Knox OzGrav Swinburne

Population Modelling

Program chair: Simon Stevenson

In the past year, the COMPAS collaboration (www.compas.science) has covered a diverse range of topics. The team is currently working hard to release the COMPAS software publicly in 2020. We implemented the evolution of pulsars in COMPAS, and used this to study the population of double neutron stars observable with radio and gravitational-wave observatories.

We explored various aspects of double neutron star populations, including double neutron stars that will be observable in the Milky Way by the future space based gravitational-wave observatory LISA. LISA will observe tens of double neutron stars, and will be able to use measurements of their orbital eccentricity to determine their formation mechanism.

Predictions for the rates and properties of compact binary mergers depend crucially on the poorly constrained metallicity specific star formation rate---that is, the fraction of star formation at a given redshift that occurs at a given metallicity. This may open up the possibility of constraining the metallicity specific star formation rate using gravitational-wave observations in the future.

We explored the spins of binary black holes. We showed that the first born black hole in such binaries is expected to be very slowly spinning, whilst the second born black hole may be either slowly spinning or rapidly spinning. The deciding factor is whether the progenitor binary -consisting of a black hole and a helium star - has a short enough orbital period for the helium star to be tidally spun up. We studied the population of merging binary black holes in which at least one of the black holes was formed from a progenitor which underwent a particular kind of supernova known as a pulsational pair-instability supernova.

We worked with collaborators on an algorithm called STROOPWAFEL which uses importance sampling to make population synthesis simulations up to 100 times faster. We studied the dynamical formation of primordial binary black hole binaries in small clusters, and they are unlikely to be observed with gravitational waves. We published a study showing how we will be able to identify subpopulations of gravitational-wave sources using machine learning when we have hundreds of detections. We developed a method for performing population inference with a catalogue of gravitational-wave sources including marginal events. This will be crucial for obtaining unbiased mass, spin and rate distributions using the catalogue from O3 and beyond.

Case Study: Common Envelope Evolution

Common envelope evolution is a rapid phase of binary evolution where a compact star orbits inside the extended envelope of its companion star, dramatically reducing the orbital separation of the binary. It is a key stage of binary evolution for the formation of gravitational-wave sources such as double neutron stars and binary black holes, but is still poorly understood. OzGrav members published several papers in 2019 aiming to increase our understanding of common envelope evolution.

We used the rapid binary evolution code COMPAS to study the population of luminous red novae---optical transients associated with common envelope evolution. Work with collaborators showed that the Large Synoptic Survey telescope will observe hundreds of luminous red novae every year, which will quickly allow the physics of common envelope evolution to be probed.

In a separate study we used COMPAS simulations combined with hydrodynamical simulations to study the population of superluminous supernovae which result from stellar mergers containing a compact object (neutron star or black hole) during common envelope evolution.

We studied common envelope evolution involving black holes using three dimensional hydrodynamical simulations. This showed that black holes accrete very little mass during common envelope evolution, and are unlikely to be significantly spun up. This means that the masses and spins of black holes being observed through gravitational waves may be the ones the black holes were born with.

Image below: The luminous red nova V838 Mon, thought to be associated with two merging stars in a common envelope event. Credit: NASA, ESA and H.E. Bond (STScI)

DATA AND ASTROPHYSICS

OzSTAR supercomputer

Leader: Jarrod Hurley

The Swinburne OzSTAR supercomputer continued to provide vital data and computing resources for OzGrav researchers with 99% uptime across 2019. Two new compute nodes were added, each with two Nvidia V100 graphics processing units (GPUs), and nodes from the previous gSTAR machine were repurposed into OzSTAR, bringing capacity to over 6,000 compute cores and 300 GPUs. Storage was increased by 20% to a total of 6 PiB to provide capacity for pulsar data from the SKA precursor MeerKAT facility.

OzGrav usage was spread across 17 distinct research projects and over 100 users. The combined OzGrav usage was 37% of OzSTAR averaged over 2019 which represents 16 million hours of data processing and simulations.

OzGrav researchers also took advantage of the software support services offered by Astronomy Data and Computing Services (ADACS) - an initiative founded by Astronomy Australia Limited (AAL) and funded through the National Collaborative Research Infrastructure Strategy (NCRIS) grant. Each project was selected through a competitive time-assignment process. The Swinburne node of ADACS worked on the following OzGrav related projects in 2019:

- “Bilby”, CI Paul Lasky (Monash), 7 weeks;

- “DWF Portal and Database”, CI Jeff Cooke (Swinburne), 13 weeks;

- “Building on the Bilby-UI”, CI Patrick Clearwater (Melbourne), 7 weeks.

In 2019 we signed an agreement with AAL to establish a Gravitational Wave Data Centre (GWDC) at Swinburne as an extension of the existing ADACS node. Funding is $2.63M from the NCRIS scheme for an initial two-year period with the possibility of further funding for future years. The GWDC will provide the infrastructure, training and support to enable gravitational wave researchers nationally to lead the discovery of events from the latest data on an international scale and to maximise the scientific impact of these discoveries.

Key projects include:

- optimisation and development of the SPIIR time-domain search pipeline to process data using the GPU capabilities of OzSTAR;

- establish GWCloud to perform and manage rapid parameter estimation of GW events leveraging the existing Bilby parameter estimation software and create a data validation portal for non-LIGO scientists to then be developed into a full Virtual Laboratory for gravitational wave detection;

- stream, store, process and publish data from the MeerKAT Square Kilometre Array (SKA) precursor facility;

- establish OzSTAR as a recognised LIGO Tier 3 Data Centre.

To date we have formed a GWDC Science Advisory Panel from representatives of the national GW community to oversee GWDC activities, conducted a workshop at the OzGrav retreat and hired five staff members. We expect to be fully staffed by mid-2020.

Background image: Carl Knox OzGrav Swinburne

Highlight

$2M of new funding announced via AAL and the Australian Government to establish an Australian Gravitational Wave Data Centre. It will process data from mega-science facilities like the Advanced LIGO gravitational wave detectors in the US and the forthcoming Square Kilometre Array (SKA) mega-radio telescope being constructed in Australia and South Africa.

OzSTAR logo credit: Carl Knox OzGrav Swinburne

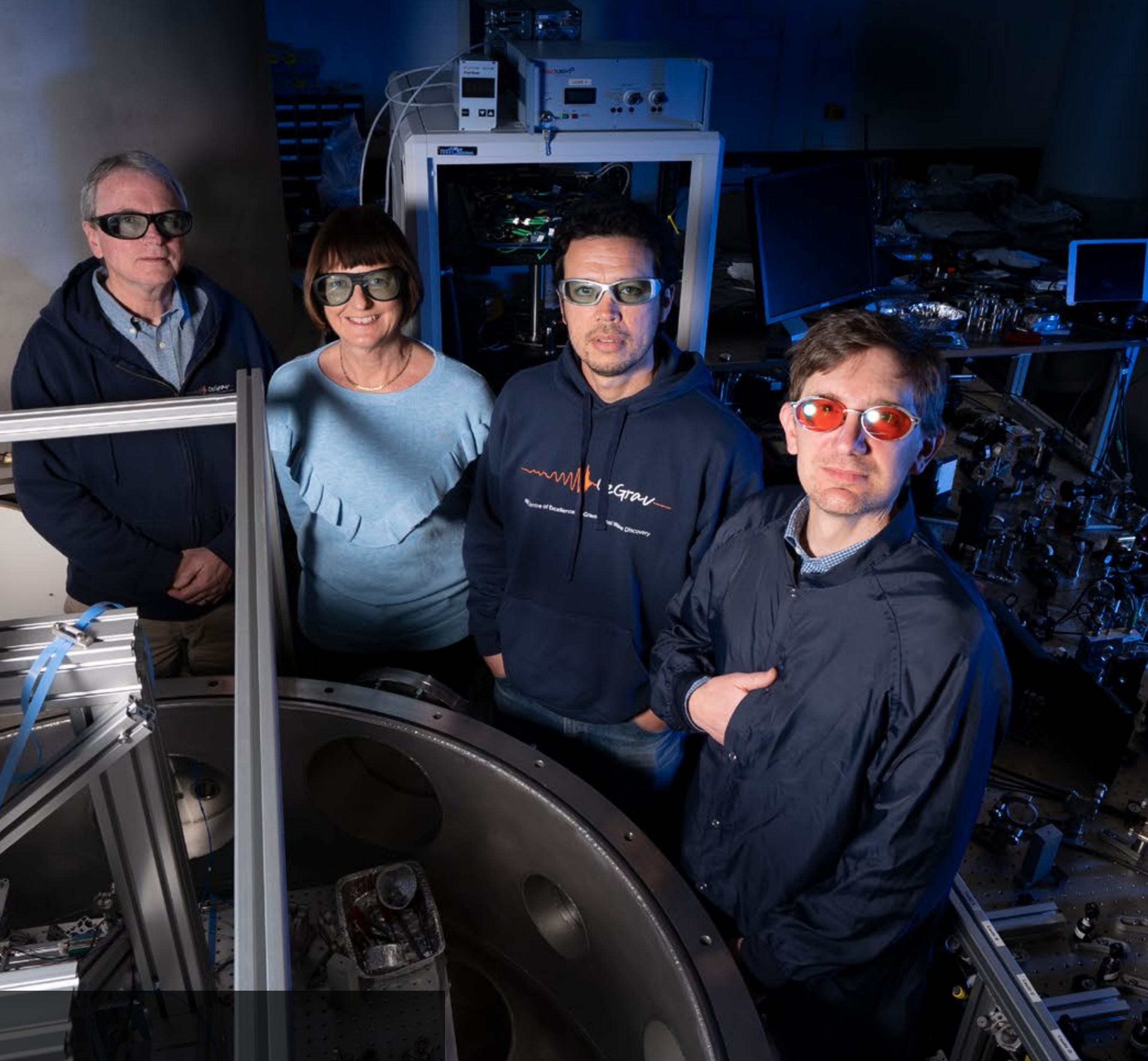
PROFESSIONAL DEVELOPMENT COMMITTEE

In 2019 the OzGrav Professional Development Committee (PDC) welcomed new members Sundae Chen (UWA) and Duncan Galloway (Monash) to the committee, and thanked departing members Joshua McCann (UWA) and Andrew Melatos (Melbourne).

The PDC continued to support and encourage the work of the Early Career Researcher (ECR) Committee (founding members Poojan Agrawal, Dr Joris van Heijningen, Dr Terry McRae, Craig Ingram, Dr Grant Meadors and Dr Meg Millhouse), that plays a major role in putting together the program for the annual ECR workshop, as well as provide important advice and representation on other matters related to training and professional development. The ECRC helped organise several webinars throughout the year including one on how to prepare yourself for a career in industry.

The mentoring program continued to run throughout 2019, with many new members signing up. Based on feedback from various surveys, we will run more formal mentoring induction webinars beginning in 2020, using an external facilitator.

A primary focus for the year for both the PDC and the ECR Committee was the long-term planning and eventual running of the two-day ECR part of the OzGrav annual retreat which was held in Lorne, Victoria, 18-22 Nov 2019. The program was vibrant and well-rounded incorporating sessions on leadership skills, science and grant writing, media training, career advice, and a panel discussion with ex-astronomers who have moved into other sectors. 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 social activities.



Case study: A new Centre for Gravitational Astrophysics at ANU

In December 2019 the Australian National University (ANU) announced the birth of the Centre for Gravitational Astrophysics (CGA). The ANU recognised the extraordinary global success of the gravitational wave detection project and the subsequent development of the fields of gravitational wave physics, astrophysics and multi-messenger astronomy, and was keen to ensure that the University would play a prominent role in these areas in the coming decades.

The CGA will commence in January 2020 and will span the Research School of Physics and the Research School of Astronomy and Astrophysics at ANU. The ANU node of OzGrav will be part of the CGA and play a leading role in the new Centre. The inaugural Director of the CGA will be the OzGrav Deputy Director Professor David McClelland.

The CGA has a broad vision and will include all aspects of experimental gravitational wave detection, gravitational wave theory, astrophysics and data analysis, and the follow-up and analysis of gravitational wave events through multi-messenger astronomy. There is a strong commitment written into the goals of the CGA to achieve excellent gender equity throughout the Centre including new staff appointments. To this end we have already advertised a female-only position and are excited to announce that, as a result of this search, Dr Ling (Lilli) Sun will be joining the CGA in the second half of 2020. We currently have a second female-only staff position advertised and several further staff appointments will be advertised in 2020.

EQUITY AND DIVERSITY COMMITTEE

The Equity and Diversity Committee welcomed new committee members Dr Greg Ashton (Monash) and Dr Chi Qu (UWA) in 2019, and farewelled Dr Grant Meadors (who left Monash to take up a position back in the USA after contributing enormously to this committee) and Prof Ju Li (UWA).

A number of initiatives were successfully implemented by the committee in 2019:

- We were delighted to be awarded a Bronze Pleiades award by the Astronomical Society of Australia in 2019, in recognition of our efforts to support diversity and inclusion.
- We conducted our inaugural climate survey, which provided considerable feedback on the experiences of members within the centre. Overall, the feedback was very positive and reassuring. The survey did reveal a range of areas for improvement that we are now endeavouring to address.
- Our primary carer's grant scheme continued to enable staff with carer responsibilities to attend workshops and conferences, as well as visit other nodes within OzGrav. Childcare was also offered to staff at the annual retreat.
- We delivered our schools program "Mission Gravity" in a range of low socio-economic communities, including a regional road tour that received glowing testimonials from teachers, students and parents.
- The annual retreat included a diversity breakfast session and round table interactive session, where people shared experiences, scenarios, and suggestions for how to handle instances of inappropriate behaviour.
- ANU advertised a number of female-only positions, with the recruitment process still underway for several of these.

While OzGrav is proud of the fact that the percentages of its student and postdoctoral population are above the international average, unfortunately, over the first three years of the centre's lifetime we haven't achieved the improvements in gender balance that we have been striving for. Therefore, a large focus for the committee and the centre in the next year is to be more pro-active in recruiting women candidates at all levels.

Image: Lannon Harley ANU

Background image: Carl Knox OzGrav Swinburne

Case study: OzGrav's Carer Grant Scheme

OzGrav is strongly committed to the equitable and inclusive treatment of all its members and colleagues, and to the elimination of discrimination and barriers of disadvantage. Striving to create a culture of acceptance, OzGrav actively promotes a culture that is inclusive for everyone, regardless of their background or individual characteristics, such as race, religion, sexuality, gender, disability, carer responsibilities, and mental or physical health.

To impart these values, OzGrav offer a carer grant scheme that allows people with primary carer responsibilities to participate in conferences or travel to work with collaborators. This is designed to be flexible and may be used to cover, for example, childcare costs and travel of dependent children to accompany the primary carer.

We interviewed Associate Investigator Eric Howell, based at the University of Western Australia (UWA), on how the scheme has helped him in his work and family life.

1. Can you tell us about your work with OzGrav and how you came to join as an AI?

I had been working in both gravitational wave and gamma ray burst (GRB) astrophysics as part of and since my PhD. I had obtained an ARC DECRA Fellowship around the time OzGrav was set up, so it was natural to join as an AI.

2. How has OzGrav's carer grant scheme assisted you and your family?

My wife Shirley became disabled after she suffered a brain haemorrhage in 2007—we also have a five-year-old boy, Brian. My wife made a remarkable recovery, learning to speak and move again, during a year spent at a rehabilitation centre. Although she is reasonably independent, at home she still needs a lot of help, especially with our young son. She also requires transportation to several appointments. Travelling and collaborating is important in my research but organising overseas and domestic trips has always been highly challenging. As we have no family in WA this involved juggling trips around Shirley's mother, who lives in Brisbane, or my sister, in Melbourne. The OzGrav carer grant has been really helpful, allowing me to take my family to domestic research trips and bring my mother-in-law down to assist in Melbourne when I go on international trips. It's still quite challenging to juggle everything, but the carer grant has been a fantastic help for me.

3. What opportunities have you been able to take thanks to the scheme?

It's really helped with existing and new collaborations: spending time at the Monash node working with Kendall Ackley, and at the University of Amsterdam; and attending LIGO-Virgo-KAGRA meetings, which was never possible before. The latter meetings have been of paramount importance in meeting and presenting to members of the GRB/Fast Radio Bursts (FRB) group, resulting in involvement in GRB search papers and setting up a future gravitational wave search for FRBs as part of the Canadian Hydrogen Intensity Mapping Experiment (CHIME). Such activities would have been very difficult without face-to-face interactions.

4. What do you think of OzGrav's overall culture and approach to diversity and inclusion?

OzGrav's overall culture and approach to diversity and inclusion is a real breath of fresh air. The carer grant is only one of OzGrav's many fantastic initiatives. When I talk to researchers from other organisations they're always really impressed with the level or diversity and support within OzGrav. In addition to these initiatives, OzGrav are always seeking new levels of support for their members—this is to be highly commended.

RESEARCH TRANSLATION COMMITTEE

In 2019 the OzGrav Research Translation Committee (RTC) welcomed new members Tom Schnepple (UWA), Les Sciacca (Melbourne), Eric Thrane (Monash), and Early Career Researcher representative Joshua McCann (UWA) to the committee, and thanked departing members Robin Evans (Melbourne), Greg Redden (Monash) and Li Ju (UWA) for their contributions.

During 2019, the RTC chair Professor Jong Chow undertook a very productive tour of all six OzGrav nodes to discuss research translation ideas, opportunities and challenges with our members. Opportunities that were discussed and documented by the RTC chair included: space debris tracking with the Zadko telescope; geophysics applications of a tilt sensor; broader application of education and outreach content and software; and application of OzGrav's parameter estimation software to financial modelling and other data challenges. As a direct result of these discussions, new industry connections were made in several projects.

OzGrav's first recipients of research translation seed funding made excellent progress during 2019 on their project to apply OzGrav technology to the autonomous vehicle industry. This project, led by James Spollard and Lyle Roberts from ANU, generated some media attention in News Ltd press.

We also ran an industry/academia panel session at our annual workshop and organised a webinar for our early career researchers on preparing yourself for a career in industry.

While OzGrav's research is motivated by the quest to understand physics and the Universe, it is very pleasing to see the spin-off applications of our world-leading technology and skills. 2019 saw great progress made on technology transfer projects, and we hope you enjoy reading about several highlights featured in this annual report.

Image: Carl Knox, OzGrav Swinburne

WHAT IS A GRAVITATIONAL WAVE?

Gravitational waves are distortions in the fabric of space and time caused by the movement of massive objects, like sound waves in air or the ripples made on a pond's surface when someone throws a rock in the water. But unlike sound waves or pond ripples, which spread out through a medium like water, gravitational waves are vibrations in spacetime itself, which means they move just fine through the vacuum of space. And unlike the gentle drop of a stone in a pond, the events that trigger gravitational waves are among the most powerful in the universe.

Detecting gravitational waves on Earth was a challenge that took roughly a century to complete, since the ones that wash through the planet are incredibly tiny.

Einstein's general theory of relativity first predicted the existence of gravitational waves, which the famous scientist himself noted in 1916. Though Einstein later doubted the waves' existence, we have had indirect evidence of them since the 1970s.

In 1974, astronomers Joe Taylor and Russell Hulse tracked a pair of spinning stellar corpses called pulsars. As the pair of pulsars spun around each other, they grew closer together, which indicated that they were giving off energy. Calculations made clear that this energy loss came in the form of gravitational waves—a discovery that won Taylor and Hulse a Nobel Prize in 1993.

The first direct detection of gravitational waves took place on September 14, 2015, when the USA Laser Interferometry Gravitational-Wave Observatory—aka LIGO—detected the rumble that two colliding black holes gave off 1.3 billion years ago. Scientists formally announced the success in February 2016. In 2017, three of LIGO's founding scientists were honored with the Nobel Prize in physics.

Starting in the 1970s, physicists including Rainer Weiss, Kip Thorne, and Barry Barish sketched out the idea that later became LIGO. The observatory consists of two facilities: one in Louisiana, the other in Washington State. Each L-shaped facility consists of two arms 4 kilometres long that meet at a right angle.

By bouncing lasers back and forth within each arm, physicists can measure their lengths with an accuracy so astonishing, it would be like measuring the distance between us and Alpha Centauri—the closest star outside our solar system—to within a hair's width. When a gravitational wave passes through Earth, it slightly stretches one of the arms and compresses the other. Those length changes alter the time it takes the laser beams to bounce back and forth, which in turn changes the pattern the beams make where they meet. By tracking the shifting patterns through time, researchers can watch a gravitational wave ripple through the facility.

LIGO has two facilities so that both detectors can try and spot the same event, in effect checking each other's work. In addition, the difference in time between each detection reveals which direction the gravitational waves came from, helping astronomers hoping to pinpoint the source in the sky.

Since 2007, Virgo Scientific Collaboration (detector in Italy) and LIGO have agreed to share and jointly analyze the data recorded by their detectors and to jointly publish their results. We look forward to having KAGRA (detector in Japan) join O3 observations in 2020.

Excerpt from National Geographic.

ACTIVITY PLAN 2020

Image: Chathura Bandutunga PhD student at ANU

Instrumentation

Commissioning. Program chairs: David Ottaway and Bram Slagmolen

The LIGO O3b observing run will terminate on 30 April 2020, after which the interferometer will undergo upgrades to LIGO A+. OzGrav scientists will visit the sites to contribute to this 18-month upgrade scheme.

- Phase camera measurement prior to LHO ITM swap, before and after.
- Squeezing upgrade to install the filter cavity to implement frequency dependent squeezing control
- Squeezed light source rebuild to improve performance and reliability.
- Measurements and characterisation of the optical losses at the output of the LIGO interferometers.
- Opportunistic contributions to the thermal compensation system during increased optical input power.

Quantum. Program chairs: David McClelland and Peter Veitch

The University of Adelaide aims to continue the development of thulium laser systems. This includes the characterisation of updated laser cavity designs and the initial amplification stage, additional power scaling with a second-stage amplifier and investigation into high-speed laser frequency control. Adelaide also plans to work closely with ANU on the development of 2µm seed lasers for high power amplification and squeezing.

The ANU plans to continue development of 2µm seed lasers with Adelaide, as well as perform tests of newly developed 2µm photodetectors. The EPR-entanglement experiment can be improved through the implementation of a Wiener filter in post-processing for optimal squeezing recovery, and the ANU plans to conduct this experiment in 2020. Finally, the ANU plans to complete the table-top based internal squeezing experiment with a three-mirror coupled cavity.

Deliverables:

- Assemble and characterise Thulium fiber master oscillator.
- Assemble and characterise 1W thulium fiber MOPA.
- Assemble second-stage thulium fiber amplifier.
- Test of HgTeCd photodetectors.
- Demonstrate internal squeezing.
- Wiener filtering squeezing recovery.

Low frequency. Program chairs: Ju Li and Bram Slagmolen

The tilt sensor will be characterised with existing flexures. We also plan to upgrade it with glassy metal modular flexure (Euler spring design), which is expected to have better performance than the current aluminium flexure with much higher tensile strength.

We will purchase new seismometers and deploy the larger array. Investigate practical wireless data acquisition options, and start meaningful seismic imaging data analysis.

We will investigate methods of incorporating seismic array information into the low frequency feedback/feedforward scheme.

We aim to demonstrate the inertia damping of the MultiSAS using our inertia sensors, and characterise the suspension and isolation chain by recording the response of the suspended Intermediate and Penultimate mass.

With the Torpedo in-air and without sufficient isolation, a best-effort high sensitive Torpedo performance measurement will be made. When deemed achievable, this setup will be put under high vacuum to record an improved performance measurement.

Once the suspension and isolation chain has been characterised, and the Torpedo performance measurements have been recorded, the Torpedo sensor will be merged with the suspension and isolation chain, inside the large vacuum tank. Once combined the whole system will need to commissioned to become operational.

Distortions and Instabilities. Program chairs: David Ottaway and Chunnong Zhao

In 2020 the program will focus on three areas: First thermal effects in high power laser interferometer gravitational wave detectors will continue to be studied. Second, the development of active mode matching elements for the correction of beam shape will continue. Finally, a collaboration between the UWA and University of Adelaide nodes will enable the imaging of the low intensity optical fields resulting from parametric instability to be achieved for the first time.

There are several experiments running in each focus area. Thermal effects are being investigated for the next generation gravitational wave detectors by measuring different materials' optical absorption at 2µm. A novel mode matching sensing scheme is being tested. Finally the Gingin East arm cavity will be used to characterize scattering from mirror surface thermal deformation due to non-uniform absorption.

The primary focus area in beam shape correction is the development of the SAMs prototypes with LIGO.

The phase camera will allow the optical mode shape driving parametric instability to be characterized. This will help resolve an observed discrepancy between theory and experiment regarding the order of the optical mode responsible for parametric instability at Gingin. Additionally a new control strategy will be tested in the Gingin east arm. Finally simulation will be used to determine the requirements for parametric instability control on future gravitational wave detectors such as OzHF.

There is also the ongoing development of a 80m pair of coupled optical cavities with silicon optics at the Gingin High Optical Power Test Facility south arm. These cavities will be used for a variety of project goals in 2021, including demonstrating coupled optical cavity mode matching control. Large area AlGaAs coating uniformity and performance in a suspended cavity. Silicon optic characterization.

Space. Program chair: Kirk McKenzie

In 2020 the Space Instrumentation Program will pursue two main activities 1) continue the activity for weak light phase locking, and 2) pursue absolute laser frequency knowledge measurement.

Improved weak light phase locking may enable a wider range of options for future space based gravitational wave detectors, in particular, longer arms which could improve sensitivity or smaller telescopes to reduce payload size and mass. First results confirm that frequency stabilising the laser prior to transmitting from the spacecraft enables lower optical power to be used without losing tracking, and record low power looks to be achievable.

Knowledge of absolute laser frequency is important for space-based detectors in two ways: 1) To improve acquisition of the laser link between the spacecraft, since the laser frequency must be known to ensure interference. This reduces the number of degrees of freedom from five, (pitch and yaw error, for two spacecraft, and laser frequency difference), to four. And 2), To measure spacecraft separation accurately, and thus gravitational waves amplitude. The laser frequency (or wavelength) is used like a ruler. Knowledge of absolute laser frequency will give absolute calibration of the amplitude of the gravitational wave and could be useful to determine the source distance with improved accuracy.

Pulsar Timing. Program chair: Matthew Bailes

Key deliverables in 2020 inlcude:

Submit MeerTime system description paper.

Commission new servers.

Develop new baseband capture mode.

Future Detector Planning. Program chairs: David McClelland and David Ottaway

2020 will see the completion and publication of the GWIC3G study examining the science case for the next generation of observatories, coordination of the key research and development activities required and frameworks to efficiently manage and operate the next generation GW network. In parallel with this activity we will develop a program to assess potential 3G sites in Australia and carry out an initial Australia-wide survey to identify primary target areas. We will work closely with similar activities being undertaken in the USA. We will complete and publish our first level study of the science case for a high frequency detector in a detector network and the feasibility of the technology. We will study the merits of building an Australian HF detector at a site deemed suitable for a full 3G installation.

Data and Astrophysics

Inference. Program chairs: Greg Ashton and Rory Smith

Members across OzGrav are already assigned to run analysis on events in O3a and contribute to the LIGO/Virgo O3a catalogue. New events in O3b will be assigned to OzGrav members and we anticipate a few of these being exceptional events meriting their own publication: this will necessarily involve input from the OzGrav analysts.

Romero-Shaw is leading a LIGO/Virgo-wide effort to produce a Bilby catalogue for the O1+O2 events. This will showcase the new features and provide a reference point for future development.

Parallel Bilby will be reviewed and deployed for production analyses. This will enable inference using the most accurate GW models that are otherwise too expensive to use. We will continue to validate the search for the stochastic background from binary black hole mergers and deploy the actual search in 2020. As more binary neutron star mergers are observed, we will use Monash-led methods to combine data on the tidal deformability and mass of neutron stars to infer the equation of state.

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

2020 will be a continuation of 2019 activities related to the O3 observing run, scheduled to complete in May 2020, and the completion and publication of new gravitational-wave results using the O3 data. The SPIIR pipeline will continue to produce open public alerts for GW detection candidates until

ACTIVITY PLAN 2020

the end of the run, and the UWA SPIIR team will participate in producing the O3a CBC catalogue paper, with many other OzGrav members also contributing. Several O3 CW papers will be led by OzGrav members, as well exploring a new Bayesian radiometer for stochastic searches, and continue contributing to O3 GW burst searches. Prospective O3 papers include work on supernova search, targeted pulsar CW search, all-sky short-duration GW burst, and CW Viterbi search for Sco X-1 and other LMXBs.

OzGrav members will contribute to the science and leadership of the LSC/Virgo Collaboration, continuing to serve as internal reviewers for LSC/Virgo analyses and papers, co-chair committees and serve as mentors for detector characterisation data quality shifts.

Pulsar Detections. Program chairs: Hannah Middleton and Ryan Shannon

2020 promises to be a big year for the group. OzGrav is organizing the 2020 International Pulsar Timing Array (IPTA) conference and student workshop, which will bring ~ 100 astronomers and students to Australia in June. The science meeting will be held in Hobart and the student workshop will be held at Swinburne University, Melbourne. We expect to complete searches for gravitational wave signals in PPTA and IPTA data sets this year, and help in deliver a third IPTA data set.

The MeerTime timing project is in full swing and the first exciting results from that project will be published in 2020. We expect to observe at least 60 millisecond pulsars every fortnight for the purpose of gravitational wave detection. The final strategy will be decided by two important pathfinding projects: a census of southern millisecond pulsars and a study of pulse jitter. These projects will inform on the ultimate achievable timing precision for the projects.

Several projects related to pulsar glitches are being led by members of the University of Melbourne group in collaboration with the UTMOST pulsar team. This work will continue into 2020.

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

DWF are planning two runs in 2020, one for Aug/Sep planned with Parkes and/or ASKAP and one in Dec/Jan with MeerKAT. DWF will have major facilities like HESS, HXMT, and others searching for high-energy fast transients, the South Pole Telescope searching for mm/sub-mm fast events, and DECam and other optical/infrared telescopes searching for fast optical events.

In O3b, the SkyMapper team will do rapid searches for gravitational-wave-detected kilonovae to understand its early blue emission and evolution, and follow-up spectroscopy to confirm the nature of candidates associated with GW signals. Current ongoing work is testing improvements to the real-bogus classification in terms of completeness and reliability of transient detection. Data Release 3 (DR3) of the Southern Survey with increased sky coverages and depths in all six filters will allow more complete and real-time monitoring of transient sources to be found in the GW sky localization region.

OzGrav UWA will continue ongoing negotiations to facilitate an industry partnership in space research with SVOM (Space-based multiband astronomical Variable Objects Monitor); this is a joint mission of the China National Space Administration (CNSA) and the Centre National d'Études Spatiales (French space agency CNES) detecting and studying gamma ray bursts. This is an opportunity for OzGrav researchers to directly participate in an international satellite research mission to identify and install small satellite receivers in Australia, and providing science time using the satellites for OzGrav scientists to perform their own research.

We will be working with members of the NASA team to determine joint GW/GRB detection rates for proposed cube satellites (assuming A+ sensitivity and beyond for the GW detectors). Work is ongoing inferring and predicting the behaviour of X-ray afterglows using Bilby, and developing a robust Random Forest algorithm for the detection of optical transients in GOTO data. OzGrav will contribute to theoretical studies related to EM followup observations, and SPIIR low-latency sky localisation. A Multimessenger workshop will be held mid-2020.

The expected release of Fast Radio Bursts detected by CHIME during O3 will initialise a search in GW data. Eric Howell, on behalf of the LIGO GRB/FRB search team has been leading an initiative to share data between LIGO/Virgo and the CHIME/FRB project.

Relativistic Astrophysics. Program chair: Paul Lasky

There are many opportunities to continue to increase capabilities and inter-node collaborations in the Relativistic Astrophysics programme in 2020. The ever-increasing diversity of fast radio bursts continue to indicate that the one or two populations are both due to neutron stars, potentially even newly-born millisecond magnetars. Collaborations between the University of Melbourne and Monash OzGrav groups, who are experts in the dynamics, electromagnetic and gravitational-wave emission mechanisms of such systems provides natural collaboration opportunities with the groups pioneering the detection of fast radio bursts with Parkes and ASKAP.

Other opportunities include the possibility of studying black hole-neutron star mergers if indeed the initial low-latency gravitational-wave announcements indicating LIGO and Virgo may have measured such events turn out to be true. Collaborations between various groups and the Adelaide University nuclear physics group provides an opportunity to understand and target equation of state measurements with gravitational-wave and electromagnetic observations. Continued OzGrav collaborations on pulsar physics and inference, supernovae inference and physics are particularly encouraged, as well as joint inference, populations, and relativistic astrophysics work. A workshop is planned for late 2020 which should see increased capabilities as well as increased science output.

Population Modelling. Program chair: Simon Stevenson

The key goal for 2020 for the population modelling program will be to exploit the results of Advanced LIGO and Virgo's third observing run (O3). We expect a population of around 100 gravitational wave detections by the end of O3.

As part of this, we will ensure sustained OzGrav involvement in Rates and Populations group of the LVC, from development through to contribution to an eventual O3 populations paper.

COMPAS code has been rewritten, and work will now explore binary black holes formed through chemically homogeneous evolution before the public release of COMPAS in 2020, as well as enhanced stellar evolution code METISSE in 2020.

OzSTAR supercomputer. Leader: Jarrod Hurley

To continue to meet the data and computing requirements of OzGrav we will enhance the OzSTAR supercomputer environment in 2020 by upgrading the internal network and decoupling the storage and compute components to increase performance now, and future proof the system for expansion to meet demand. This will include an expansion of the lustre filesystem to 10PB capacity in 2020. The investment from Swinburne for this work is $1.2M. This hardware investment will also enable extremely high I/O capability for pulsar data processing and a high-availability data relay machine at the SKA-mid site to facilitate nano-Hertz GW detection. We will aim to have OzSTAR certified as a Tier 3 LIGO Data Centre making it the first GPU-based system in the LIGO suite.

On the software side the GWDC will become fully staffed in 2020 and make significant contributions to GW software development and data delivery. The identified key projects (SPIIR, GWCloud, MeerTime/pulsars) will continue to be the focus, however, we expect to initiate a small projects scheme in 2020 through which individual OzGrav researchers can apply for professional assistance. We also plan to bring our GPU hardware and software expertise to the LIGO community to assist in accelerating search and analysis codes. We will run a GW-focussed Machine Learning workshop, and optimise the pipeline for data transfer between SKA-mid and OzSTAR.

Research Translation

- Continue to oversee and promote our research translation seed funding scheme, and mentor our ECRs to take up this opportunity to develop their innovative and entrepreneurial ideas.
- The Research Translation Chair will continue to engage closely with our members at all nodes in order to identify and advise on technology transfer opportunities.
- Continue to deliver briefings to industry, and provide industry internships and industry networking opportunities to our ECRs.

Professional Development

- Recommend changes to address any climate survey feedback relevant to career development.
- Continue to monitor and develop the OzGrav mentoring program for ECRs.
- Deliver and grow the OzGrav webinar series including topics of particular interest to ECRs, including preparing for job interviews and the next stage in your career.
- Continue working with the ECR Committee to best tailor our activities and training for the ECRs.
- Run induction sessions for the mentors and mentees and further expand uptake of the mentoring program.
- Design an innovative and constructive ECR Workshop for the OzGrav annual retreat.

Equity and Diversity

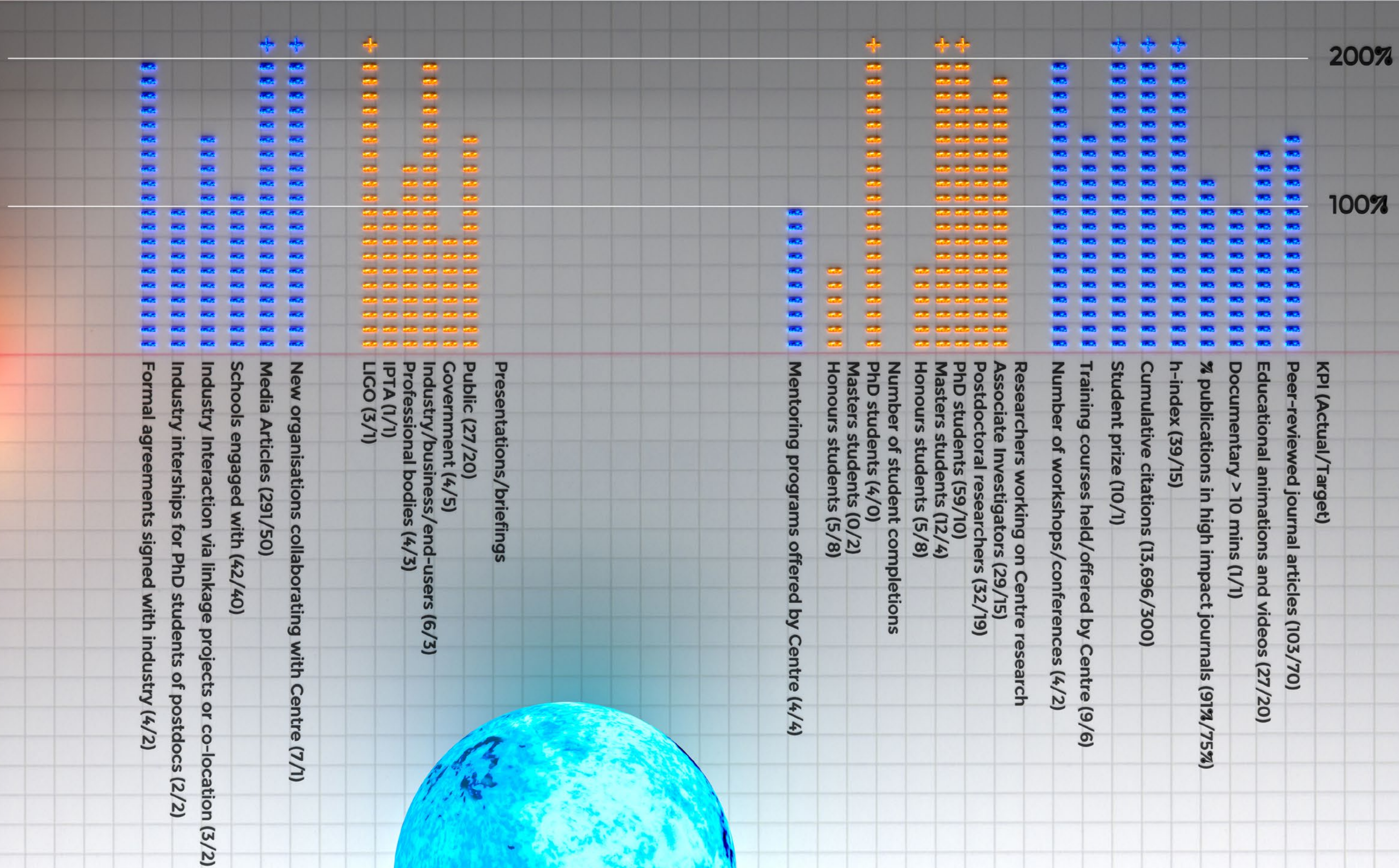
- Continue to implement, update, and evaluate progress against, the OzGrav equity & diversity action plan.
- Implement improvements in response to the results from our first annual climate survey that was conducted and reviewed in 2019.
- Conduct our second annual climate survey to monitor the level of diversity and inclusiveness in the centre, assess changes over time, and identify further areas for improvement.
- Increase engagement with our education and outreach program by people from underrepresented or disadvantaged populations.
- Implement recruitment and professional development strategies to increase female representation among our membership at all levels in the centre.
- Increase and broaden our focus on inclusiveness beyond gender.
- Position ourselves so that we are able to meet the criteria for the next level of Pleiades Award in the next round (i.e. Silver Award in 2020).

Outreach

- Schools: Expand offerings for OzGrav-delivered education programs to align with both the primary schools curriculum as well as the Einstein-First contemporary Physics programs. Expand geographic delivery to more regional areas across Australia via collaborations in more states.
- Educators: Increase educator engagement across more areas of Australia using a 'train the trainer' model. Develop online training modules for more educators in remote locations to incorporate into their own classrooms.
- Public events: Upgrade the SciVR app while increasing the geographic reach of our live events to even more regional locations using our strong relationships with libraries in states and territories across Australia. Focus on key public outreach events to engage with a broader cross-section of visitors from regional locations around Australia.
- Media and communications: Develop impactful media release materials to support the science breakthroughs and discoveries following the successful O3 LIGO / Virgo run. Continue to promote the work of our early career researchers and communicate our science and technology to the public and key stakeholders.
- Museums: Complete updated exhibit at the Gravity Discovery Centre that will be part of the science centre's permanent collection, including striking wall art. These elements will be offered to node universities and other science centres for incorporation of gravitational wave science in their public displays.

Background image: Carl Knox OzGrav Swinburne

KPI DASHBOARD



Artwork: Carl Knox OzGrav Swinburne

LINKAGES AND COLLABORATIONS

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

International Partners and Collaborators

Airbus Ariane Rocket GeoTrack Group
AstroParticle and Cosmology Laboratory (APC)
Auckland University of Technology
California Institute of Technology (Caltech)
Centre National De La Recherche Scientifique (CNRS)
CHIME
Chinese Academy of Sciences Institute of Theoretical Physics
European Space Agency (ESA)
French Space Agency
GOTO Collaboration
GrandMa collaboration
Kavli Institute for Theoretical Physics China
Laser Interferometer Gravitational-Wave Observatory (LIGO)
Massachusetts Institute of Technology (MIT)
Max Planck Institute for Gravitational Physics (Hannover) Albert Einstein Institute
Max Planck Institute for Radio Astronomy
MeerTime Collaboration (Manchester, ASTRON, MPIfR, CNRS, SARAO, NRAO, CSIRO, Curtin, AUT, UBC, INAF)
Montana State University
NASA Goddard Space Flight Centre
Tsinghua University
University of Birmingham
University of Florida
University of Glasgow
University of North Carolina - Chapel Hill
University of Otago
University of Science and Technology China (USTC)
University of Tokyo
University of Urbino
University of Warwick

Background image: Nutsinee Kijbunchoo, OzGrav ANU

National Partners and Collaborators

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

LIGO Scientific Collaboration (LSC) incorporating the Virgo Collaboration in 2019 (LVC)

LIGO (Laser Interferometer Gravitational-Wave Observatory) is the world's largest gravitational wave observatory and a cutting-edge physics experiment. Comprising two enormous laser interferometers located thousands of kilometres apart in Hanford (Washington) and Livingston (Louisiana), 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.

The LIGO Scientific Collaboration now works closely with the Virgo Collaboration, with some joint papers released by the LIGO and Virgo Collaborations (LVC). We look forward to welcoming KAGRA to the observing run O3b in 2020 and beyond, where we move to the LIGO – Virgo – KAGRA collaboration (LVK).

Image supplied by LIGO Scientific Collaboration

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

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

Image: Virgo Collaboration

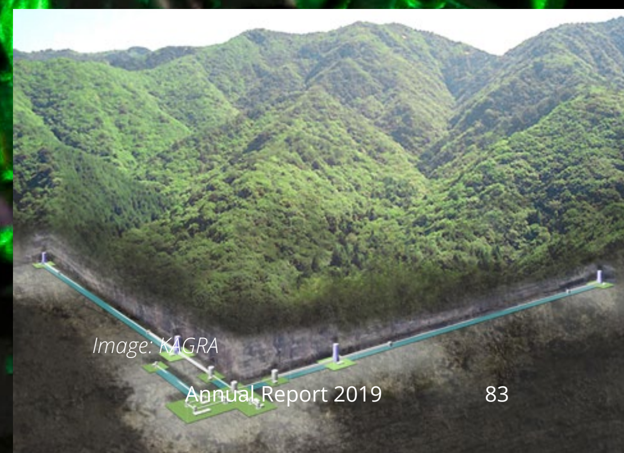


Image: KAGRA

LINKAGES AND COLLABORATIONS

LSC/LVC and other international working groups

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

OzGrav members have also contributed to service and leadership of the LSC/Virgo Collaboration. Jade Powell is chair of the LSC Supernova group. Karl Wette is Co-chair of LIGO/Virgo Continuous Wave Working Group. Meg Millhouse ran Burst short-duration all sky calls. Juan Calderon Bustillo, Grant Meadors (OzGrav alumnus), Jade Powell, Simon Stevenson, Eric Thrane, and Karl Wette serve as internal reviewers for LSC/Virgo analyses and papers. Hannah Middleton is the Editor-in-chief for LIGO Magazine from Nov 2018 (and deputy editor-in-chief before that).

Jesper Munch serves on KAGRA PAB committee. Eric Thrane was the LIGO/Virgo Burst Working Group Review Chair, and member of the Editorial Board. Andrew Melatos and Susan Scott are LSC Council members. David McClelland serves on the LSC Program Committee; LSC MoU review Committee; OzGrav representative on Gravitational Wave International Committee (GWIC) and GWIC3G R&D Committee Co-Chair.

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

Ema Dimastrogiovanni and Matteo Fasiello are members of the LISA consortium and the LISA cosmology working group. Matteo is involved in characterization and predictions of primordial gravitational waves and of modifications of general relativity. Paola Leaci is a Continuous-Wave working group co-chair.

Ryan Shannon and Xingjiang Zhu serve on the International Pulsar Timing Array (IPTA) steering committee.

Background image: Nutsinee Kijbunchoo, OzGrav ANU

LIGO Magazine

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

Hannah Middleton (OzGrav Postdoctoral Researcher at University of Melbourne) has been the Editor-in-Chief since 2018 and prior to that was Deputy Editor-in-Chief from 2014-2018. She leads a team of editors based all around the world. Together they discuss topics for each issue, commission and edit articles and make sure everything is ready for each issue to be published at the LIGO/Virgo/KAGRA meetings. It's fantastic that an OzGrav early career researcher has been appointed to such an important role, with big reach both internally and externally.

Additional OzGrav editors: Nutsinee Kijbunchoo, Deeksha Beniwal, Kendall Ackley.
OzGrav 2019 authors: Qi Chu, Joris van Heijningen, Patrick Clearwater, Letizia Sammut and George Hobbs.

"The magazine is of course a big team effort! From the authors to the editors and illustrators (particularly OzGrav's Nutsinee Kijbunchoo) everyone has to work together to achieve an issue every 6 months. I've really enjoyed the opportunity to work with this team and to 'meet' (by email at least!) so many people, including interviewing Jocelyn Bell Burnell for the 50th year anniversary of her discovery of pulsars and Jennifer Wiseman, the NASA Senior Project Scientist for Hubble. I find it so rewarding to see an issue go from nothing to a finished magazine. I enjoy our discussions with editors to figure out what topics will be exciting and timely for the next issue and particularly love to find out about and include articles of people's personal stories and experiences." Hannah Middleton

Images: Hannah Middleton, OzGrav Uni of Melbourne

FINANCE 2019

	2019 Forecast	2019 Actuals	2020 Forecast
INCOME			
ARC Centre Grant	$4,881,564	$4,881,564	$4,824,974
Institutional cash contribution	$1,147,000	$1,194,632	$1,165,000
Other grants and contracts		$3,573	
Total Income	$6,028,564	$6,079,770	$5,989,974
EXPENDITURE			
Salaries & scholarships	$3,860,890	$3,833,587	$4,051,415
Equipment	$709,016	$278,887	$502,900
Travel, Meetings, Workshops	$765,727	$994,665	$1,044,398
Research maintenance and consumables	$509,700	$638,787	$670,727
Outreach, operations and other expenditure	$251,548	$113,046	$118,698
Total Expenditure	$6,096,881	$5,858,972	$6,388,138
Carry-forward from previous year	$4,680,813	$4,680,813	$4,901,610
BALANCE	$4,612,497	$4,901,610	$4,503,446

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 have helped galvanise the Centre. These meetings are attended by as many as 80 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 David Blair - Outreach Leader
University of Western Australia

A/Professor Jong Chow - Research Translation Leader
Australian National University

Professor Andrew Melatos
University of Melbourne

Prof Tara Murphy (observer)
University of Sydney

Professor Susan Scott - Career Development Leader
Australian National University

A/Professor Eric Thrane
Monash University

Professor Peter Veitch
University of Adelaide

A/Professor Chunnong Zhao
University of Western Australia

Partner Investigators

Prof Rana Adhikari - Caltech

Dr Douglas Bock - CSIRO

Dr Marica Branchesi - Urbino University

Prof Rong-Gen Cai - Kavli Institute (China)

Dr Brad Cenko - NASA Goddard Space Flight Centre

Prof Karsten Danzmann - Max Plank (Einstein) Institute

Dr George Hobbs - CSIRO

A/Prof Mansi Kasliwal - Caltech

Prof Michael Kramer -Max Planck Institute (Radio Astronomy)

Prof Shrinivas Kulkarni - Caltech

Prof Nergis Mavalvala - MIT

Dr David Reitze - Caltech

Prof Sheila Rowan - University of Glasgow

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

Reader Danny Steeghs - University of Warwick

Dr Stephen Taylor - Caltech

Prof Alan Weinstein - Caltech

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

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.

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OzGrav Director

Dr Gregory Clark
Visiting Fellow, the Australian National University

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

Dr Yeshe Fenner
OzGrav Chief Operating Officer

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Science writer and editor, Cosmos Magazine

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Senior Curator, Melbourne Planetarium, Museum Victoria

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Flatiron Institute's Center for Computational Astrophysics

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CSIRO

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

Prof Ian Smith
Vice-Provost, Research & Research Infrastructure, Monash University

Prof Aleks Subic
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Background image: Carl Knox OzGrav Swinburne

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Lucy Strang
University of Melbourne

A/Prof Eric Thrane
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Dr Robert Ward
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Image: Carl Knox, OzGrav Swinburne

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Monsah University

Craig Ingram
University of Adelaide

Dr Terry McRae
Australian National University

Dr Meg Millhouse
University of Melbourne

Image: Harley Lannon, ANU

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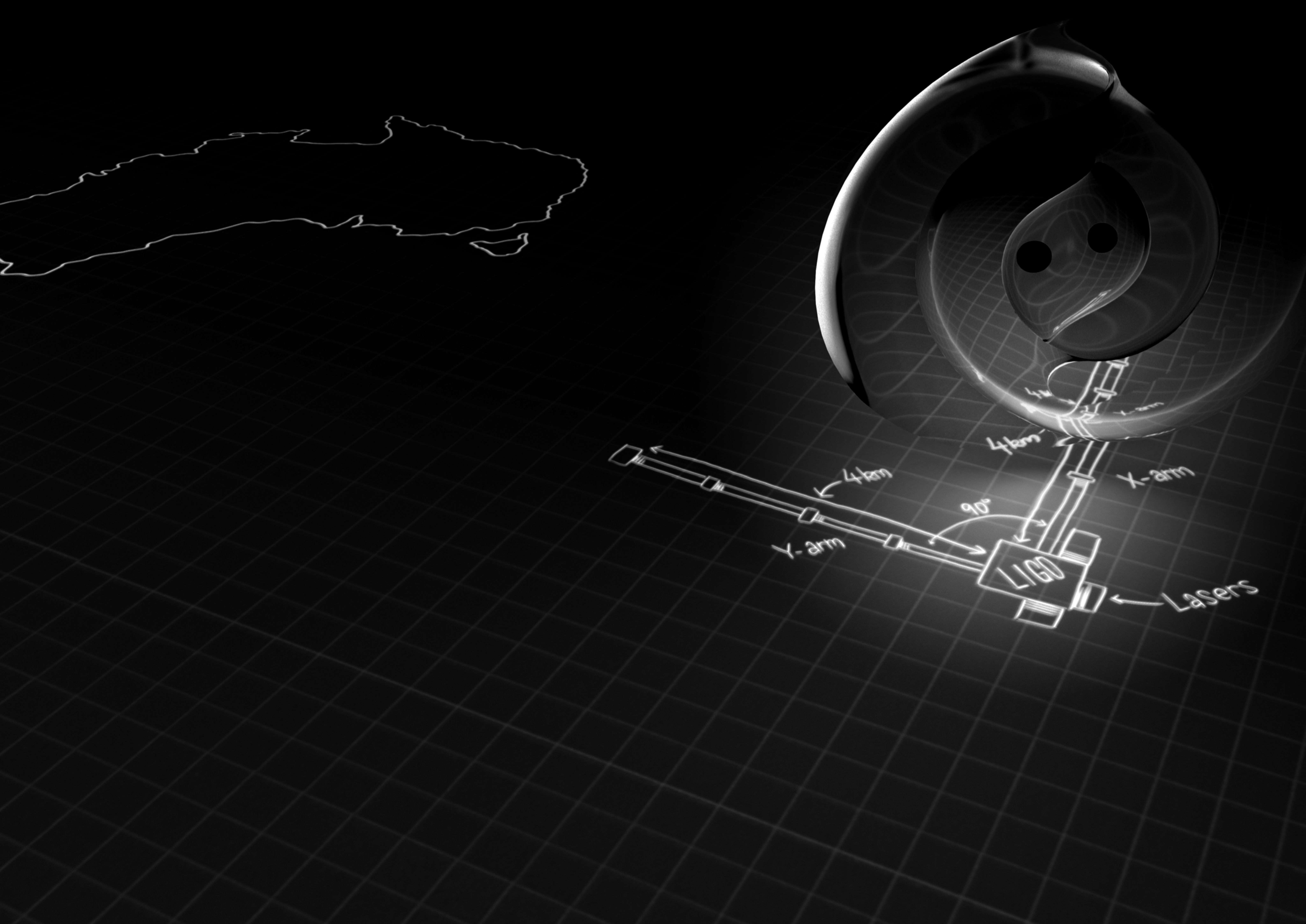
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