OzGrav

ARC Centre of Excellence for Gravitational Wave Discovery

Annual Report 2020

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

OzGrav acknowledges and pays respects to the Elders and Traditional Owners of the land on which our six Australian nodes stand.

OzGrav's vision

To pursue exceptional research and scientific discovery.

To provide world–class research training and leadership.

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

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

MESSAGE FROM THE DIRECTOR

As Director, it brings me great pride to be able to present this, our fourth OzGrav annual report. Apart from the great productivity exhibited by our staff that his report presents - it looks absolutely stunning. At OzGrav I'm very blessed to have such reliable and professional support staff, led by my Chief Operating Officer Dr Yeshe Fenner whose team put together this artistic wonder (take a bow Carl Knox!). Centres of Excellence are a rare opportunity in our professional scientific careers to be able to lay down seven-year plans, build critical mass, and establish long-lasting collaborations and relationships that span the Centre nodes. One of the things that struck me about this report was images of the people of OzGrav, and their love for the science that they perform and explain to the general public through a range of outreach activities - and how much I've missed them in 2020.

It's an incredible privilege to be able to study the universe with gravitational waves and explore the shaking and distortion of the very fabric of space time with black holes and neutron stars.

The third LIGO observing run (O3) was a triumph - detecting gravitational waves almost every week, built upon the hard work of OzGrav and our international colleagues, from the quantum squeezers, to the detection pipelines, parameter estimation and interpretation of the results, our staff were deeply engaged on many levels. This was recognised by the awarding of several prizes, including Australia's most prestigious (The Prime Minister's Prize for Science) going to the OzGrav team consisting of Professors Blair, Scott, Veitch and McClelland.

2020 was OzGrav's fourth year of operation, and in many respects its most challenging due to the global COVID-19 pandemic. Although Australia was incredibly fortunate to avoid the scale of health crisis seen in many other Western countries, our centre was still affected on many levels by COVID's downstream consequences.

Australia's first wave was short, but unfortunately Melbourne, which houses three of our six nodes, had a long and psychologically-challenging second wave, along with a strict lockdown. This physically separated many of our staff and students and made it difficult for us to conduct our research and meetings except via zoom. I was very proud to see how we collectively maintained our productivity, but was conscious of the fact that many of our junior and international students had to deal with social isolation, an almost complete lack of travel and see the toll COVID was taking on many of their home countries from afar. I'd like to think that some of the steps we took to engage with and support our members were helpful, whether it was the Friday dress-up competitions, online wellbeing and resilience workshops, or our COVID-19 grants.

As the vaccine starts to roll out around the globe, I'm optimistic about 2021 and the science we'll tackle during the remaining years of OzGrav. I hope you'll enjoy reading this report about our achievements and plans.

Regards,

Prof Matthew Bailes
OzGrav Director
Swinburne University of Technology

MESSAGES FROM THE CHAIRS

Governance Advisory Committee (GAC)

As Chair of the OzGrav Governance Advisory Committee, I have been delighted that the Centre has continued to perform at the highest level in 2020, despite the very challenging circumstances imposed by the global COVID-19 pandemic.

The Centre is in a very fortunate position to have the resources and agility to be able to provide strong support to its members during 2020. This included directing funds to support members to continue contributing to OzGrav's research priorities and offering mental health and wellbeing support.

OzGrav met or exceeded its targets for almost all Key Performance Indicators in 2020, in some cases by being able to rapidly convert in-person activities to virtual. For instance, the OzGrav education and outreach team did a fantastic job pivoting from in-person delivery of their VR-based schools' program to an interactive online version. Thus the Centre was still able to reach 66 schools either in-person or virtually (beating the KPI target of 40) and inspiring over 5000 students.

The year (2020) was also OzGrav's strongest year in terms of publication outputs and press, with media articles about OzGrav more than doubling from 291 in 2019 to 644 in 2020. This is a measure of the high-impact science the Centre has been undertaking, as well as the public's enormous appetite for exciting astronomy discoveries.

One of the biggest highlights of 2020 was undoubtedly the honour of the Prime Minister's Prize for Science going to the four most senior members of OzGrav, Chief Investigators David Blair, Susan Scott, David McClelland and Peter Veitch. This is Australia's most prestigious award for outstanding research and it sets the scene for many more years of Australian leadership and new discoveries in gravitational wave research.

In addition to producing high impact scientific results, OzGrav aims to translate its research to novel applications with industrial, economic or other social impacts. In this report you can read about OzGrav industry projects ranging from defence to autonomous navigation, public health and more.

Please enjoy this annual report and learning about OzGrav's achievements in 2020 and plans for the future.

Sincerely,

Prof Ian Young AO

Scientific Advisory Committee (SAC)

On behalf of the OzGrav Scientific Advisory Committee (SAC), congratulations to OzGrav on its scientific and technological achievements during 2020.

Although some activities were unavoidably hampered by the coronavirus crisis, by many measures - including the Centre's KPIs – it was one of the most productive years so far for OzGrav. Certainly, the publication rate reached a new high, jumping from 103 in 2019 to 154 in 2020, while the cumulative citations since the Centre commenced in 2017 is over 25,000.

The Instrumentation Theme hit many major milestones in 2020 including: new laser technology that will drive quantum noise below the standard quantum limit; a cross-Theme collaboration to measure LIGO test mass temperature distributions; and a new world record set for weak light phase locking for space applications. In addition, planning for future detectors continued to gain momentum with OzGrav contributing to the Cosmic Explorer global science and network studies, investigating potential Australian detector sites, and publishing a Centre-wide paper outlining the science case and preliminary design for a NEMO – a Nuclear and Extreme Matter Observatory.

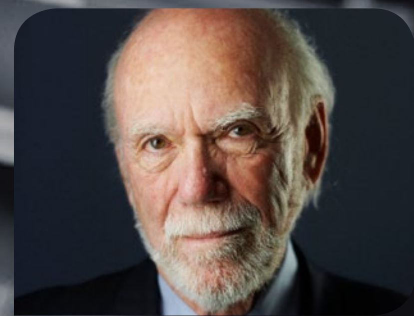
The Data/Astrophysics Theme also had a highly productive year with highlights including: playing a key role in both the detection and interpretation of data via core software packages integrated into the official LIGO-Virgo pipeline; publication of the first strong observation of spinning black holes in binaries; publication of the first direct detection of an intermediate-mass black hole; and the first observation of a neutron star merging with a black hole. OzGrav members – including many early career researchers - have played leading roles in analyzing and writing publications about these new discoveries.

Finally, I would like to personally congratulate the winners of the 2020 Australian PM Prize for Science, David Blair, David McClelland, Susan Scott and Peter Veitch. These Australian pioneers of the field made critical contributions that led to the discovery of gravitational waves, and are wonderful role models for OzGrav's talented cohort of early career researchers.

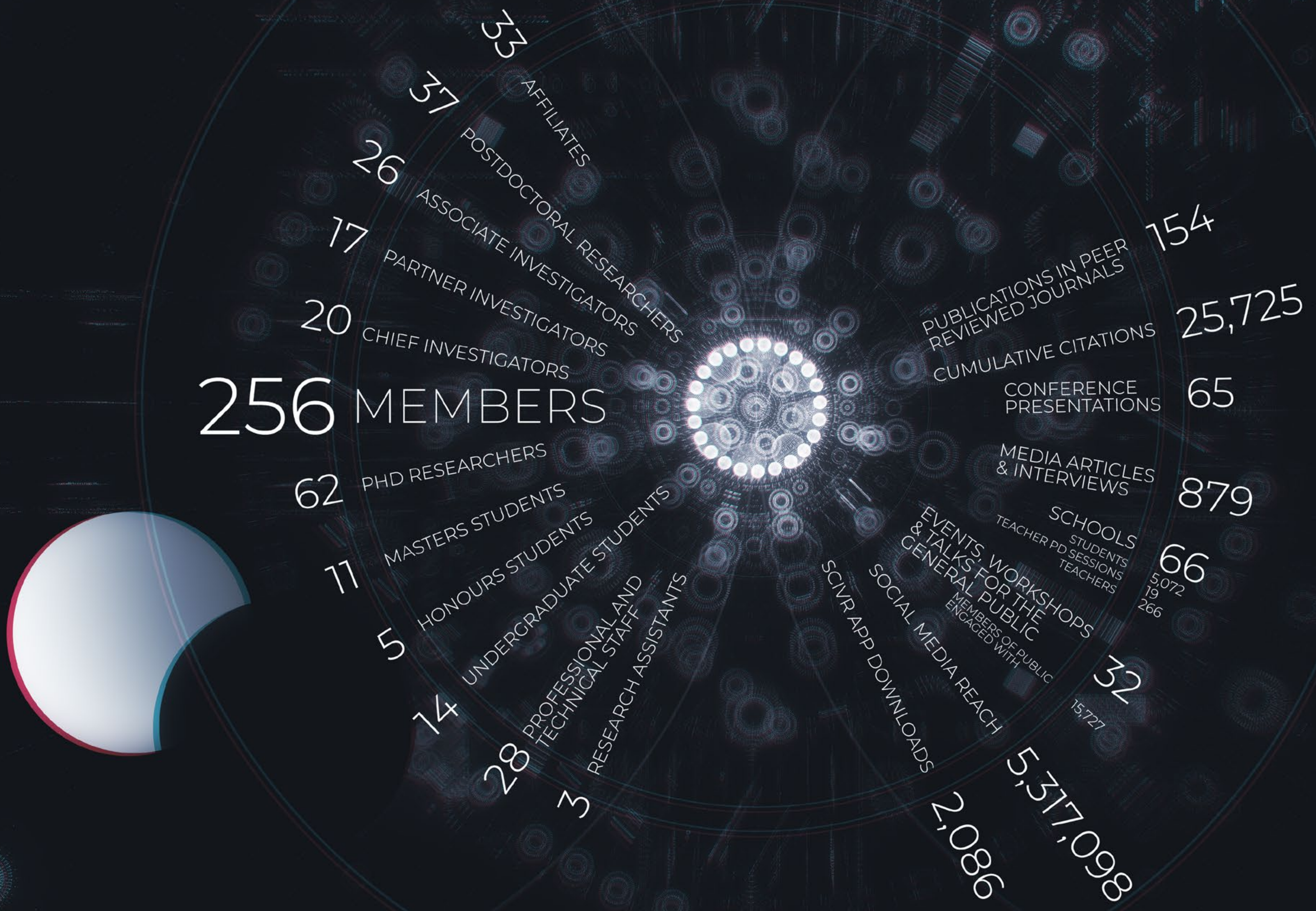
I hope you agree as you read this report, that the future is very bright for OzGrav and the field of gravitational wave research.

Sincerely,

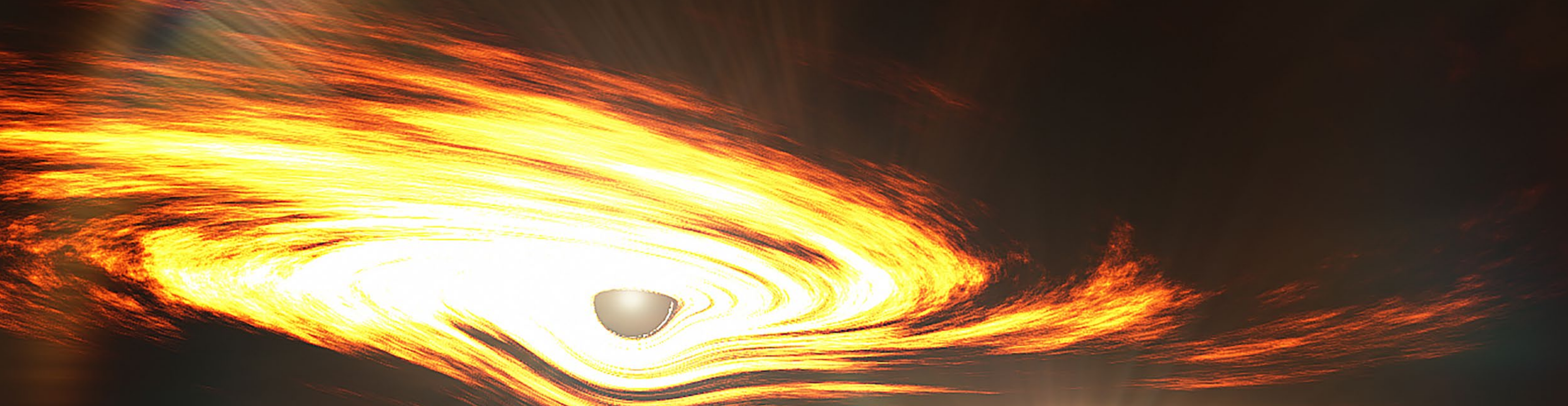
Prof Barry Barish



CENTRE SNAPSHOT



SCIENCE HIGHLIGHTS



First ever intermediate-mass black hole directly observed

The first pair of black holes detected in 2015 were each about 30 times more massive than the Sun. When they merged, the resulting 'remnant' was a black hole that was 60 times more massive than the Sun. Astronomers from the LIGO and Virgo Scientific Collaboration (LVC) reported in 2020 the first ever direct observation of the most massive black hole merger to date. Two black holes collided to form an even more massive object—an intermediate-mass black hole, about 150 times as heavy as the Sun. Researchers from OzGrav contributed to the detection and used the computing resources of the new Gravitational Wave Data Centre to infer the masses of the merging black holes. Juan Calderón Bustillo, co-author and OzGrav postdoctoral researcher at Monash University, reports: "This is the first time we've observed an intermediate-mass black hole, almost twice as heavy as any other black hole ever observed with gravitational waves. For this reason, the detected signal is much shorter than those previously observed. In fact, it's so short that we can barely observe the black hole collision, we can only see its result." The online detection team at the University of Western Australia detected the event, GW190521, seconds after the gravitational wave data were available, and helped generate public alerts for the LIGO Scientific Collaboration.

These 'impossible' black holes have 'forbidden' masses according to what we currently understand about the lives of massive stars. The rare event has prompted researchers to question how the black hole formed, its origins and how the two black holes found each other in the first place. OzGrav PhD student and co-author Isobel Romero-Shaw (Monash University) comments on the perplexing masses: "Black holes form when massive stars die, both exploding in a supernova and imploding at the same time. But, when the star has a core mass in a specific range—between approximately 65 and 135 times the mass of the Sun—it usually just blows itself apart, so there's no leftover black hole. Because of this, we don't expect to see black holes in this solar mass range, unless some other mechanism is producing them." Based on this current study's mass measurements, researchers found that this kind of black hole couldn't have formed from a collapsing star—instead, it may have formed from a previous black hole collision. OzGrav postdoctoral researcher and LVC member Simon Stevenson (Swinburne University of Technology) says: "These 'impossibly' massive black holes may be made of two smaller black holes which previously merged. If true, we have a big black hole made of smaller black holes, with even smaller black holes inside them—like Russian Dolls. We are witnessing the birth of an intermediate mass black hole: a black hole more than 100 times as heavy as the Sun, almost twice as heavy as any black hole previously observed with gravitational waves," adds Stevenson. "These intermediate mass black holes could be the seeds that grow into the supermassive black holes that reside in the centres of galaxies."

Also featured in The ABC, 7 News, The Daily Telegraph, News.com.au and Space Australia.

Artwork: Mark Myers, OzGrav Swinburne

SCIENCE HIGHLIGHTS

Gravitational wave scientists smash quantum noise limits

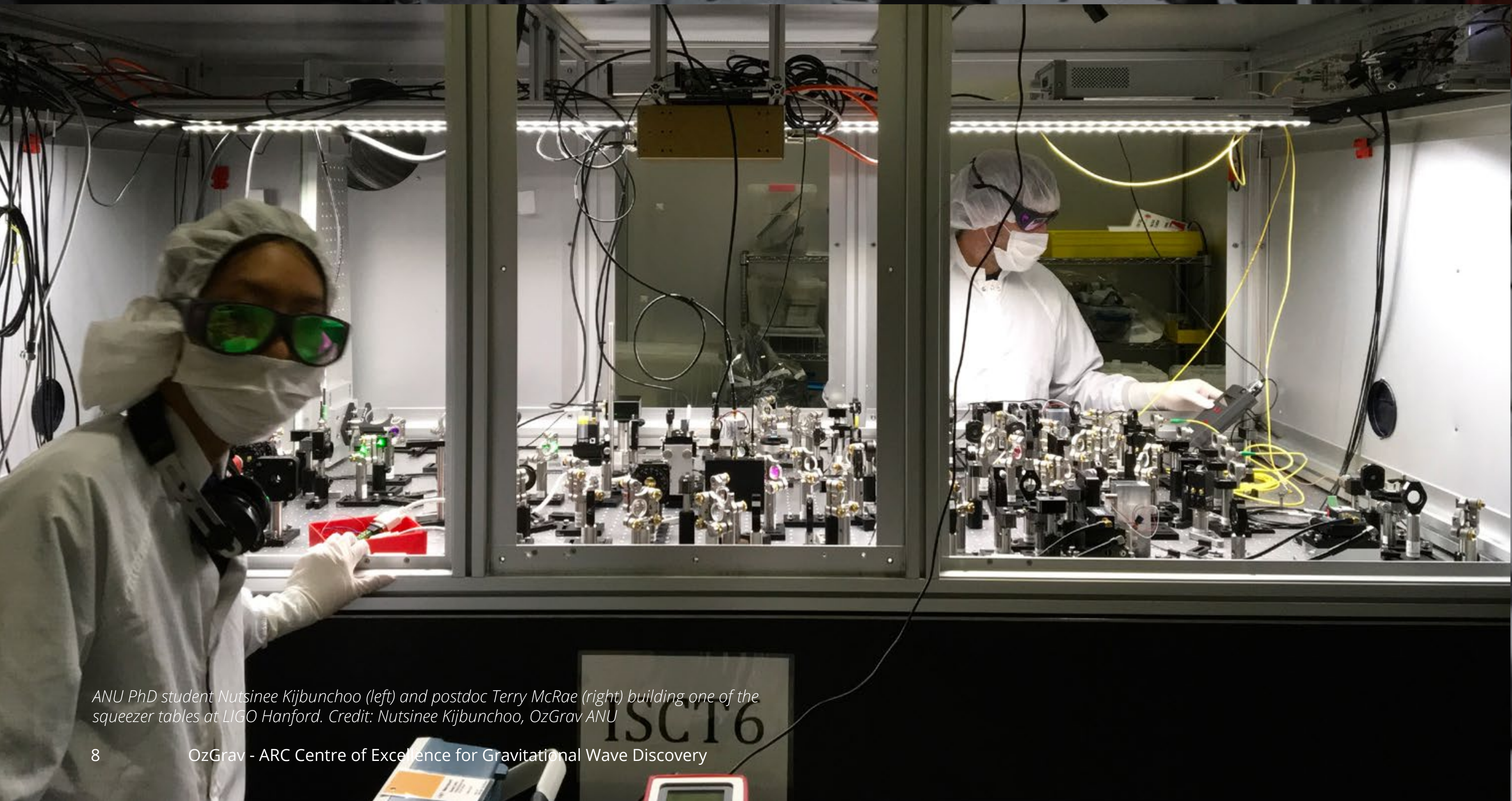
A global team of scientists, including researchers from the ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav) have made a surprising discovery: working out how to break quantum limits. The quantum limit comes from the interaction between light and a test mass, and breaking this limit, just like breaking the sound barrier, once seemed impossible.

The results, published in the prestigious journal Nature, show the standard quantum limit has been breached using squeezed light technology pioneered at the Australian National University (ANU) and refined at Massachusetts Institute of Technology (MIT) on the 40kg test masses in the LIGO gravitational wave detectors. These gravitational wave detectors are the most precise measurement devices ever built, and this result shows that they are now poised to see the effects of quantum physics, which governs the smallest objects in the universe, on human sized objects.

ANU PhD student Nutsinee Kijbunchoo and postdoctoral researcher Dr Terry McRae spent more than a year at the LIGO sites building and commissioning the squeezed light system that led to this quantum physics breakthrough. Dr Carl Blair, from the University of Western Australia (UWA) who was part of the team, said discovering how to break quantum limits was significant for physics and science. "It's amazing to think that sitting in the control room at LIGO, manipulating some controls on a computer you can manipulate the quantum noise of a 40 kg mirror," he said. "We were able to break the limit doing something very mysterious: squeezing the quantum vacuum."

"This result definitively shows that Quantum mechanics applies to the large scale world of multi kilogram objects and not just to atoms, molecules and small microgram scale objects. This ability to make more precise measurements of natural phenomenon has historically been one of the driving forces for technological innovation," said Dr McRae. This leaves many open questions. For example, "will we see quantum quirkiness in the human-scale world some time soon? Like tunnelling through impossible barriers or entanglement where two objects separated by vast distances act like one object?" questioned Dr Blair. Furthermore the use of these techniques have extended the detectors' range by 15 percent and when observing, LIGO and Virgo now see events almost every week. Combined with an increase in the main laser power that carries the gravitational wave signal, that is separate from the squeezed light source, the LIGO detectors can measure a gravitational wave signal, generated by a source such as a binary neutron star inspiral, from about 400 million light years away.

Also featured in Cosmos.



ANU PhD student Nutsinee Kijbunchoo (left) and postdoc Terry McRae (right) building one of the squeezer tables at LIGO Hanford. Credit: Nutsinee Kijbunchoo, OzGrav ANU

Finding NEMO: The future of gravitational wave astronomy

A new study makes a compelling case for the development of "NEMO"—a new a Neutron Star Extreme Matter Observatory in Australia that could deliver on some of the most exciting gravitational wave science next-generation detectors have to offer, but at a fraction of the cost. The OzGrav study coincides with an Astronomy Decadal Plan mid-term review by Australian Academy of Sciences where NEMO is identified as a priority goal.

"Gravitational wave astronomy is reshaping our understanding of the Universe," said one of the study's lead authors OzGrav Chief Investigator Paul Lasky (Monash University). "Neutron stars are an end state of stellar evolution," he said. "They consist of the densest observable matter in the Universe, and are believed to consist of a superfluid, superconducting core of matter at supranuclear densities. Such conditions are impossible to produce in the laboratory, and theoretical modeling of the matter requires extrapolation by many orders of magnitude beyond the point where nuclear physics is well understood."

The study presents the design concept and science case for a Neutron Star Extreme Matter Observatory (NEMO): a gravitational wave interferometer optimised to study nuclear physics with merging neutron stars. The concept uses high circulating laser power, quantum squeezing and a detector topology specially designed to achieve the high frequency sensitivity necessary to probe nuclear matter using gravitational waves. The study acknowledges that third-generation observatories require substantial, global financial investment and significant technological development over many years.

According to Monash PhD candidate Francisco Hernandez Vivanco, who also worked on the study, the recent transformational discoveries were only the tip of the iceberg of what the new field of gravitational wave astronomy could potentially achieve. "To reach its full potential, new detectors with greater sensitivity are required," Mr Hernandez Vivanco said. "The global community of gravitational wave scientists is currently designing the so called 'third-generation' gravitational wave detectors (we are currently in the second generation of detectors; the first generation were the prototypes that got us where we are today)."

Third-generation detectors will increase the sensitivity achieved by a factor of 10, detecting every black hole merger throughout the Universe, and most of the neutron star collisions. But they have a hefty price tag. At about $1B, they require truly global investment, and are not anticipated to start detecting ripples of gravity until 2035 at the earliest. In contrast, NEMO would require a budget under $100M, a considerably shorter timescale for development, and it would provide a test-bed facility for technology development for third-generation instruments. The paper concludes that further design studies are required detailing specifics of the instrument, as well as a possible scoping study to find an appropriate location for the observatory, a project known as "Finding NEMO".

As featured in The Age, Phys.org, and Space Australia.

Background image credit: Nutsinee Kijbunchoo, OzGrav ANU

SCIENCE HIGHLIGHTS

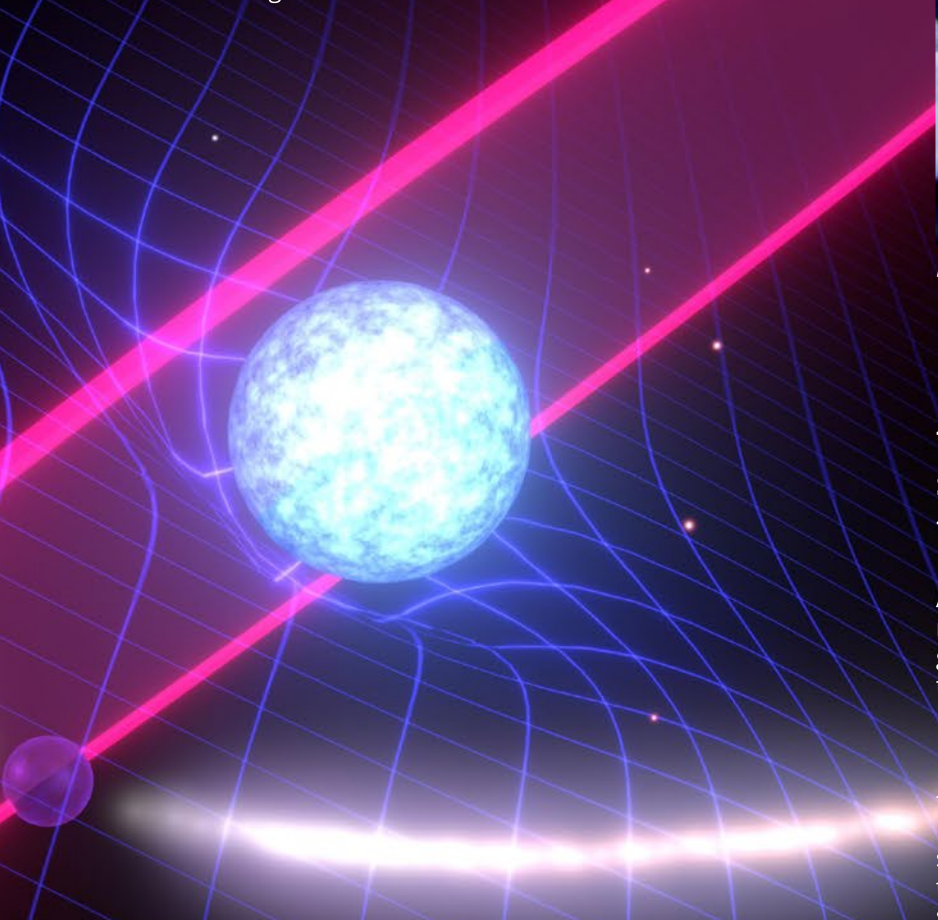
Astronomers witness the dragging of space-time

An international team of astrophysicists led by OzGrav Director Matthew Bailes has found exciting new evidence for 'frame-dragging'—how the spinning of a celestial body twists space and time—after tracking the orbit of an exotic stellar pair for almost two decades. The data, which is further evidence for Einstein's theory of General Relativity, was published in the prestigious journal Science.

More than a century ago, Albert Einstein published his iconic theory of General Relativity – that the force of gravity arises from the curvature of space and time, and that objects, such as the Sun and the Earth, change this geometry. Advances in instrumentation have led to a flood of recent (Nobel prize-winning) science from phenomena further afield linked to General Relativity. The discovery of gravitational waves was announced in 2016, and the first image of the supermassive black hole at the centre of a galaxy was published in 2019.

Almost twenty years ago a team, led by Swinburne University of Technology's Professor Bailes, started observing two stars rotating around each other at astonishing speeds with the CSIRO Parkes 64-metre radio telescope Murriyang. One is a white dwarf, the size of the Earth but 300,000 times its density; the other is a neutron star which, while only 20 kilometres in diameter, is about 100 billion times the density of the Earth.

The system, which was discovered at Parkes, is a relativistic-wonder system that goes by the name 'PSR J1141-6545'. Before the star blew up (becoming a neutron star), a million or so years ago, it began to swell up discarding its outer core which fell onto the white dwarf nearby. This falling debris made the white dwarf spin faster and faster, until its day was only measured in terms of minutes.



Artwork: Mark Myers, OzGrav Swinburne

In 1918 (three years after Einstein published his Theory), Austrian mathematicians Josef Lense and Hans Thirring realised that if Einstein was right all rotating bodies should 'drag' the very fabric of space time around with them. In everyday life, the effect is miniscule and almost undetectable. Earlier this century, the first experimental evidence for this effect was seen in gyroscopes orbiting the Earth, whose orientation was dragged in the direction of the Earth's spin.

A rapidly spinning white dwarf, like the one in PSR J1141-6545, drags space-time 100 million times as strongly. A pulsar in orbit around such a white dwarf presents a unique opportunity to explore Einstein's theory in a new ultra-relativistic regime.

Lead author Dr Vivek Venkatraman Krishnan (Max Planck Institute for Radio Astronomy) was given the unenviable task of untangling all of the competing relativistic effects at play in the system. Frame-dragging of the entire orbit could explain their tilting orbit and the team presents compelling evidence—it shows that General Relativity is alive and well, exhibiting yet another of its many predictions. The result is especially pleasing for team members Bailes, Willem van Straten (Auckland University of Technology) and Ramesh Bhat (ICRAR-Curtin) who have been trekking out to the Parkes 64m telescope since the early 2000s, patiently mapping the orbit with the ultimate aim of studying Einstein's Universe. "This makes all the late nights and early mornings worthwhile," said Bhat.

As featured in The ABC, The Conversation and Scientific American.

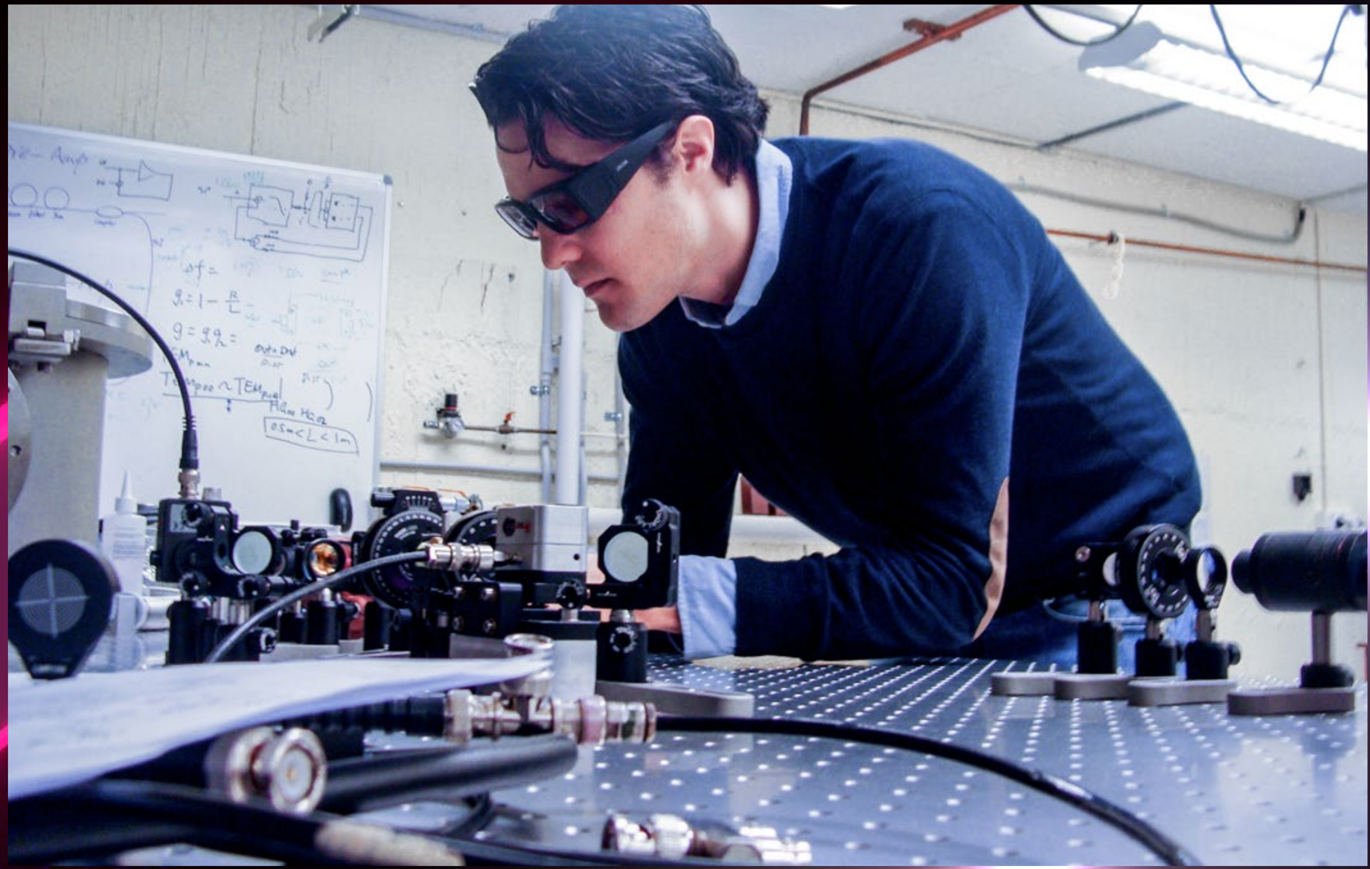


Image: Joris van Heijningan, postdoctoral researcher at UWA. Credit: Mateao van Niekerk

Earth-shaking science in the freezer: Nextgen vibration sensors at cryogenic temperatures

A cutting-edge vibration sensor may improve the next generation of gravitational wave detectors to find the tiniest cosmic waves.

During his PhD, postdoctoral researcher Joris van Heijningen (University of Western Australia) developed the world's most sensitive inertial vibration sensor. Now he proposes a similar design but 50 times more sensitive, at frequencies below 10 Hz, using cryogenic temperatures. This new sensor measures vibrations as small as a few femtometres (a millionth of a billionth of a meter) with a 10 to 100 millisecond period (10 Hz to 100 Hz). He reveals a prototype of the next generation of seismic isolation systems with sensitivity down to 1Hz, using cryogenic temperatures—lower than 9.2 degrees and above absolute zero.

Even though we can't feel it, our planet is always vibrating a tiny bit due to many different events, both cosmic and earthly; for example, from gravitational waves (miniscule ripples in spacetime); ocean waves crashing on the shore; or human activity. According to Dr van Heijningen, some places vibrate more than others and, if you plot these vibrations, they lie between two lines called the Peterson Low and High Noise Models (LNM/HNM). "The best commercial vibration sensors have been developed to have a sensitivity that lies below the LNM. They are sufficiently sensitive to measure all places on Earth with a decent signal-to-noise-ratio," says Dr van Heijningen. To date the Laser Interferometer Gravitational Wave Observatory (LIGO), with its four-kilometre long arms, uses seismic isolation systems to prevent earthly vibrations affecting scientific measurements; however, future gravitational wave detectors demand more advanced and precise vibration sensors.

Scientists are already working on a third generation of detectors that will have the power to detect hundreds of black hole mergers each year, measuring their masses and spins—even more than LIGO, or its European equivalent, Virgo, can measure. In the USA there will be the Cosmic Explorer: a 40-kilometre observatory that will be able to detect hundreds of thousands of black hole mergers each year. Equally as impressive will be the Einstein Telescope in Europe, with its 10-kilometre armed, triangular configuration built underground.

Future detectors will be able to measure gravitational waves at frequencies lower than the current cut-off ~10 Hz, "because that's where the signals from collisions of black holes are lurking," Dr van Heijningen explains. But one of the main issues of these huge detectors is that they need to be extremely stable—the smallest vibration can hamper detections. "Essentially getting the system close to zero degrees Kelvin (which is 270 degrees below zero Celsius) drastically reduces the so-called thermal noise, which is dominant at low frequencies. Temperature is a vibration of atoms in some sense, and this minuscule vibration causes noise in our sensors and detectors," says Dr van Heijningen. At his new position as a research scientist at UCLouvain in Belgium, Dr van Heijningen plans to prototype this sensor design and test its performance for the Einstein Telescope.

As featured on Phys.org.

SCIENCE HIGHLIGHTS

'Discovery of the century' recognised in the Prime Minister's Prize for Science 2020

Four OzGrav scientists have been awarded Australia's most prestigious science award, the 2020 Prime Minister's Prize for Science, for their critical contributions to the first direct detection of gravitational waves—a landmark achievement in human discovery: Chief Investigator Emeritus Professor David Blair (University of Western Australia); Deputy Director Professor David McClelland (Australian National University); Chief Investigator Professor Susan Scott (Australian National University); and Chief Investigator Professor Peter Veitch (University of Adelaide).

The Prime Minister's Prizes for Science are Australia's most prestigious awards for outstanding achievements in scientific research, research-based innovation and excellence in science teaching. 2020's recipients are four pioneering Australian physicists from OzGrav that contributed to the groundbreaking discovery of gravitational wave signals from the collision of two black holes 1.3 billion years ago. This was made possible by decades of research and innovation of the team as part of the Laser Interferometer Gravitational-wave Observatory (LIGO) Scientific Collaboration (LSC). Emeritus Prof David Blair says "It is wonderful to receive the Prime Minister's Prize for Science. It's a fitting tribute to all of the students and scientists who participated in this amazing quest that was finally rewarded with the detection of gravitational waves. This is a prize for physics in Australia."

In 1916 Albert Einstein first predicted the existence of gravitational waves—minute distortions in the fabric of space-time that are non-electromagnetic in nature and spread from their source at the speed of light; however, he believed they would never be detectable. Prof Peter Veitch says "Einstein developed his theory of relativity in 1915, but people questioned whether gravitational waves really existed or whether they were just some sort of mathematical nonsense predicted by the theory. Since then there has been a large advance in our understanding of the Universe, and our research has focused on developing the technologies required to detect Einstein's theorised gravitational waves."

"Over the last few decades, there were many scientists who either didn't believe that gravitational waves existed, or felt that they were simply too small to ever be detected," explains Prof Susan Scott. "We had enormous technological difficulties to overcome – everything had to be about a thousand times better, including the shapes of the mirrors, the frequency of the lasers, the acoustic wringing of the mirrors and the vibration isolation." In September 2015 recent advances in detector sensitivity led to the first direct detection of gravitational waves;

Image credit: Department of Industry

two Advanced Laser Interferometer Gravitational-Wave Observatory (aLIGO) laser interferometers simultaneously detected a signal characteristic of a pair of black holes – 29 and 36 times the mass of the sun – merging into one. This was followed by a further detection in 2017, from the collision of two neutron stars. The first detection of its kind, this event solved a 50-year-old mystery confirming that these mergers are the source of previously observed high-energy gamma ray bursts, and of heavy metals such as gold, platinum and uranium in the Universe.

Prof David McClelland says "This achievement (gravitational wave detection) came about only through long-term investment in basic research and development (R&D) by the Australian Research Council, our universities and many similar organisations around the world. This investment has led to impactful science, impactful technologies and inspired a generation of scientists and engineers." The impact of the first 2015 detection, the acclaimed 'discovery of the century', has been immense, opening up previously unknown parts of the Universe, such as hidden black holes; understanding the origin of gamma ray bursts (and with the potential to discover how supernovae explode); and to even peer back to the beginning of time at the Big Bang.

The legacy of the team's combined research ensures that Australia is now 'front-and-centre' in exploring this brand-new window into the Universe. "The pioneering work of our team over the last quarter of a century has ensured that Australia played a leading role in the first direct detection of gravitational waves," says Prof Scott. "Australia is now in a position to be a powerhouse in the emergent field of gravitational wave astronomy." For OzGrav Director Professor Matthew Bailes (Swinburne University of Technology), the prize is especially pleasing. "This is fantastic recognition of the role Australia has played in opening this new window on Einstein's Universe. I'm thrilled for not only these four pioneers of the field in Australia, but for the future generations of scientists and engineers that will follow in their footsteps."

Emeritus Prof Blair created a large-scale high-optical power research facility in Gingin, Western Australia, to mimic Advanced LIGO interferometers and investigate the subtle interactions between light, sound and heat that would occur in full-scale detectors. His pioneering work predicted that laser light would scatter from sound in the mirrors, causing parametric instability at power levels far below that needed to obtain detector sensitivity. When this theory was validated during LIGO commissioning, Prof Blair sent team members to help implement stabilisation methods that allowed the detectors to achieve sufficient power levels to make the first detection of gravitational waves.

Prof McClelland led the Australian National University team that played a crucial role in designing, installing and commissioning Advanced LIGO's lock acquisition system, and in the construction and installation of Australian hardware for precision routing of the laser beam. His pioneering quantum 'squeezing' technology (now installed in all detectors) is essential for boosting interferometer sensitivity to the current level where signals are detected weekly when in operation.

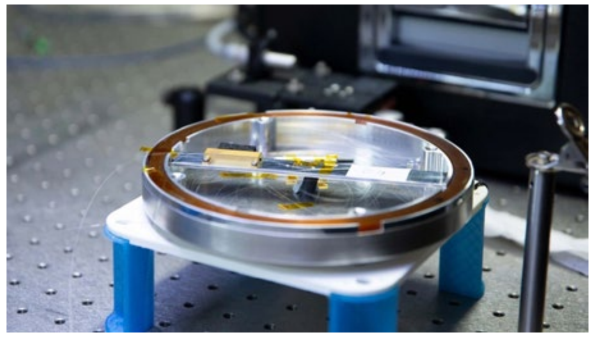
Prof Scott initiated the Australian effort in gravitational wave data analysis in 1998, and led Australian research in digging gravitational wave signals out of detector noise. Her Australian National University team contributed key components to the LIGO Data Analysis System through which the detection signal was processed in 2015, designing and conducting the first gravitational wave search to be carried out under Australian leadership.

Prof Veitch's University of Adelaide team invented and installed critical instrumentation for the Advanced LIGO detectors, namely their Hartman sensors. These sensors provide a solution to a major technological problem – the distortion of the laser beam within the detector – by measuring them simply and with a sensitivity that is 30-times better than any other sensor. The Hartman sensors are used at all stages of the detection process: commissioning, measurement and adaptive correction of the distortions, and optimising the detector sensitivity and stability.

RESEARCH TRANSLATION HIGHLIGHTS

Next-gen navigation technology in a new $8.7 million project

Australian researchers and industry partners are joining forces to develop, design and manufacture the next-generation of optical gyroscopes for high-precision autonomous navigation in a new $8.7 million project.



Gyroscope. Image supplied by ANU

The rapid and transformative development of autonomous vehicles in recent years has seen numerous technological breakthroughs. The deployment of ultra high-performance gyroscopes can enhance their performance in terms of safety and guidance. The use of ultra high-performance gyroscopes can already be found in a wide range of industries including infrastructure management, mining, space sciences, agriculture, and defence. The new project is led by navigation systems manufacturer Advanced Navigation, with research partners The Australian National University (ANU), RMIT University, and commercial partner Corridor Insights. It will develop a new standard for optical gyroscopes, improving precision while reducing cost and size.

OzGrav Associate Investigator Professor Jong Chow from ANU stated that the collaboration is a chance to bring together expertise from around the country: “We have such a broad range of photonics expertise in Australia. This project brings it together, creating a nexus between universities, research and education, industry and government.”

The project has been supported through a $2.8 million Cooperative Research Centre Projects (CRC-P) grant to Advanced Navigation. Chris Shaw, CEO of Advanced Navigation, said the project would translate ground-breaking foundational research at universities to commercialisation, demonstrating Australia’s capability across the advanced manufacturing pipeline. “This project will establish Australia as a leading manufacturer of high-performance, cost-effective navigation solutions,” Mr Shaw said.

At the core of this endeavour is technology developed at the ANU Centre for Gravitational Astrophysics, OzGrav and Department of Quantum Science. The technique, ‘digital interferometry’, combines advanced signal processing with precision optics to create ultra-high-resolution measurements using light.

ANU researcher Chathura Bandutunga said: “We use digital signal processing to encode the lightwaves we use for our measurement. This encoding allows us to enhance the sensitivity of our instruments to rotation.”

While initially developed for measuring gravitational waves in spaceborne gravitational wave detectors, the ANU team has adapted the technology to find a second home in optical gyroscopes.

In parallel, researchers at RMIT’s Integrated Photonics and Applications Centre (InPAC) are undertaking leading research in creating photonic chips - miniaturised optical components, enabling large experiments to be put into a much smaller package. “The clever signal processing developed at ANU allows us to tell apart tiny signals from noise, and our photonic chip technology enables all that functionality to fit on a chip the size of a fingernail,” Distinguished Professor Arnan Mitchell from RMIT said.

“By compressing the light detection technology onto a photonic chip we can shrink ultra high-performance gyroscopes from the size of a bread box to the size of a coffee cup.”

Taking these research ideas through to the field, commercial partner Corridor Insights will pilot the next-generation of optical gyroscope in autonomous infrastructure management, looking for early detection of defects and faults in Australia’s rail network.

Also featured in Space Connect.

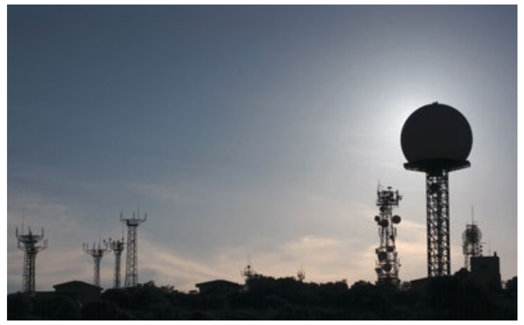
Gravitational-wave technology in the defence industry

Over several decades, defence and astronomy have been closely associated due to the advanced nature of optical and radio frequency (RF) sensors used in astronomical observations, and the need for state-of-the-art technologies in defence.

Radar technology, for instance—which shaped the outcome of World War II—spawned the scientific field of radio astronomy, and some of the largest radio telescopes were subsequently built by ex-World War II radar engineers and scientists. The instrumentation and research infrastructure, such as advanced antenna feed designs and synthetic aperture astronomy, have also subsequently influenced defence capabilities.

Today, this association between astronomy and defence continues to be strong and beneficial with OzGrav Chief Investigators at the University of Melbourne (UM) at the forefront. The team has developed spin-off technologies and expertise shaping defence capability, while enhancing astronomical discoveries. For example, over 40 years OzGrav investigators at UM developed statistical signal processing algorithms to detect acoustic signals in the ocean, which have been further enhanced and used to detect pulsar signals and gravitational waves. There is now the potential to use these techniques to further enhance the acoustic detection of objects in the ocean—an important capability in the navigation of Australia’s naval ships and submarines.

OzGrav Chief Investigators are playing a leading role in a new defence Multi-Function Aperture (MFA) program, developing next-generation phased array technology that will enable wideband simultaneous multi-function RF capability from a common aperture.



Multiple antennas. Image provided by University of Melbourne

The OzGrav team at UM, in conjunction with other Australian universities, is supporting the first phase of this program under a multi-party collaborative agreement with the Defence Science Technology Group, funded by the Next Generation Technologies Fund.

Astronomy is an excellent example of how big science and engineering, in the development of large telescopes and instruments, can drive industry and national capability, especially in areas such as defence. The desire to progress our knowledge of the Universe can keep advancing defence technologies, such as surveillance and information systems. It’s crucial that research funding is maintained to continue the development of large-scale research instruments and to engage scientists and engineers in research and industry as part of that endeavour.

RESEARCH TRANSLATION HIGHLIGHTS

UWA Zadko Telescope helps track ambitious space mission to Mercury

OzGrav scientists from The University of Western Australia (UWA) have worked with the European Space Agency to provide continuous imaging of a space probe passing Earth while on a journey to Mercury. The scientists used the powerful robotic Zadko Telescope in Gingin to capture imagery of the space probe, named BepiColumbo. The probe was launched in 2018 and has since completed one and a half orbits around the Sun, travelling a distance of roughly 1.4 billion kilometres.

Image: The Zadko Telescope was made possible by a generous donation from James Zadko, Director of Claire Energy.
Image credit: Bruce Gendre, OzGrav UWA

Space probe BepiColombo. Credit: ESA

OzGrav postdoctoral researcher Bruce Gendre said BepiColombo would study Mercury's magnetic field and its interaction with the solar wind, offering insight into how the Earth and solar system formed. "In order to keep the space probe on track to reach Mercury in 2025, BepiColumbo performed a 'fly-by' past Earth on 10 April 2020, utilising a gravity assist manoeuvre, which reduces the amount of propellant and thrust needed to complete the mission," said Gendre. "Space navigation is a complex task and requires large quantities of fuel. To reduce fuel consumption and the resulting cost of the mission, space agencies often use gravitational assistance from planets." ESA's Planetary Defence Office is using this fly-by as a test for its capabilities to coordinate the observation of possibly dangerous asteroids. In the southern hemisphere, there are not many telescopes available for this purpose. The Zadko Telescope is partially supported by the UWA Faculty of Engineering and Mathematical Sciences, and OzGrav.

Due to the regional travel restrictions imposed by the WA Government following the COVID-19 outbreak, Gendre was unable to control the Zadko telescope on-site in Gingin and instead operated the telescope remotely from his home in Claremont. "This important contribution to space research helps inspire the engineers and scientists of tomorrow, continuing the legacy of UWA philanthropist James Zadko, who passed away in early 2020," Gendre said.

OzGrav Chief Investigator and Zadko Telescope Director David Coward said tracking the space probe represented a small part of a greater project. "Providing ongoing assistance is part of a broader partnership with the European Space Agency to monitor the space around Earth for potential hazards, including near-earth asteroids," said Coward.

As featured on UWA News.

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.

Public events

In an ever-changing landscape of COVID-19 restrictions, our OzGrav teams across Australia were able to bring science fun to thousands of people in safe and engaging ways.

The UWA team engaged crowds of thousands of people at Perth's Astrofest in March with virtual reality, talks and displays. The lucky Adelaide team were similarly able to provide hands-on science face-to-face including AMIGO (mini interferometer) during the public days of Science Alive at the Adelaide Showgrounds in November, as well as the STEM Science Alive day involving 45 schools. Our Melbourne outreach enthusiasts from Monash and Swinburne provided hands-on experiences supporting the Sean Carrol "Preposterous Universe" tour in February, but then packed away VR headsets for many months during lockdowns.

Holiday programs quickly popped up online, and OzGrav PhD students and researchers gave dozens of online talks, including an OzGrav talk series, and 2 talks for the Australian Institute of Physics, following the Nobel Prize black holes announcement. The Nobel Prize in Physics 2020 was divided, one half awarded to Roger Penrose "for the discovery that black hole formation is a robust prediction of the general theory of relativity", the other half jointly to Reinhard Genzel and Andrea Ghez "for the discovery of a supermassive compact object at the centre of our galaxy."

A model of Einstein watches over AMIGO (Adelaide Michelson Interferometer for Gravitational-wave Outreach). Credit: OzGrav University of Adelaide

UWA demonstrations at Astrofest 2020. Credit: Carl Blair, OzGrav UWA

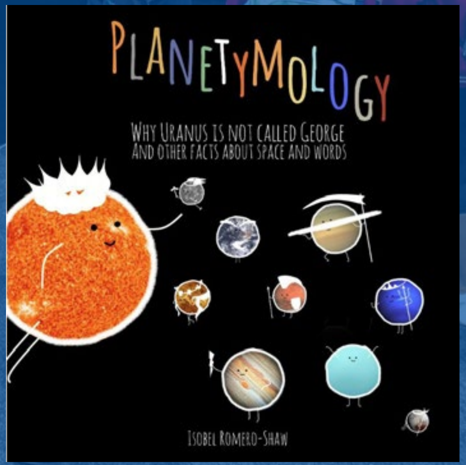
Science Alive! This festival was delayed from National Science Week to November in 2020. Credit: OzGrav University of Adelaide

Planetymology

We're thrilled to announce the launch of Planetymology the book by OzGrav PhD student Isobel Romero-Shaw (Monash). Following her well-received OzGrav public lecture on the topic of The Etymology of the Universe, Isobel continued to pursue her interests in the etymology (origin of words and naming) and published this charming children's book! Isobel tells us more about the inspiration behind the project.

"The inspiration for this book was an amalgamation of various influences," says Isobel. "I'd been reading 'The Incredible Human Journey' by Dr Alice Roberts and 'The Art Instinct' by Denis Dutton, which both got me interested in tracing human migration across the planet and the evolution of different cultures. I then heard on a podcast that the word 'galaxy' comes from the Greek term for the Milky Way, galaxias kyklos, meaning milky circle, and I thought that was just lovely. So I started getting interested in etymology, and when I was given the opportunity to give one of OzGrav's public lectures, I thought I could make use of my new obsession by turning it into a public talk."

"A few weeks later, I gave the OzGrav public lecture on the topic of The Etymology of the Universe, or Star Words. This was well received, and a few weeks after that I gave the same talk to Mount Burnett Observatory. I'd already discussed with OzGrav folks about making the cute planet characters into stickers or something for outreach, and I had in my head the beginnings of an idea for a kid's book based on those characters. When one of the Mount Burnett members asked me what I was planning on doing with the talk next, I realised that I really did want to make it into a book! Making the book was such a fun project, and I really learnt a lot. In a lot of cases I felt like a kid myself, with a new wonder for the history hidden in everyday words. I think science, history and the arts are way too often split into these separate boxes. Kids are told that they're a 'maths person' or a 'bookish person' or an 'arty person', and I don't see why that should be the case when everything is so interesting and interlinked. I am an astrophysicist, and that's often just as much about creativity as it is about logic—most problems need both in order to solve them!"



EDUCATION AND OUTREACH

An Australian Government Initiative

Inspiring Australia

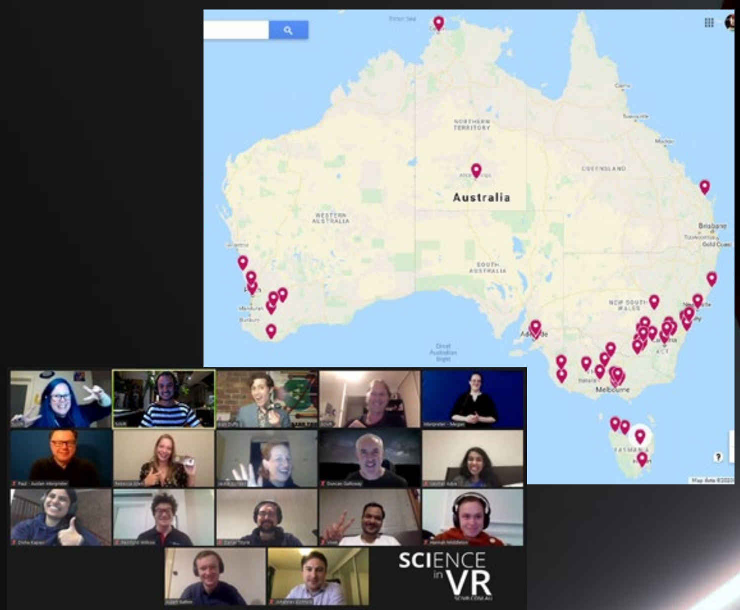
NATIONAL SCIENCE WEEK

national science week 2020

Science in Virtual Reality (SciVR)

The Swinburne SciVR team was well-paced to run a hybrid of face-to-face and online events for 58 libraries and science centres around Australia in 2020. Some locations in WA and SA were able to hold in-person events, while most acted as hubs for people to pick up a mini VR headset to take home and join in online via YouTube. Thanks to funding from National Science Week, thousands of mini headsets, instructions and fun sticker sheets (designed by our fab in-house designer Carl Knox – thanks Carl!) were able to be given away free to enable a wide range of people to participate in our events. Thanks to our superstar presenters Prof Alan Duffy and Dr Rebecca Allen, and our 30 OzGrav students and researchers helping out with the online Q&A. We held a live-streamed adults talk with Auslan interpreters and close captioning, as well as a shorter child-friendly talk.

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



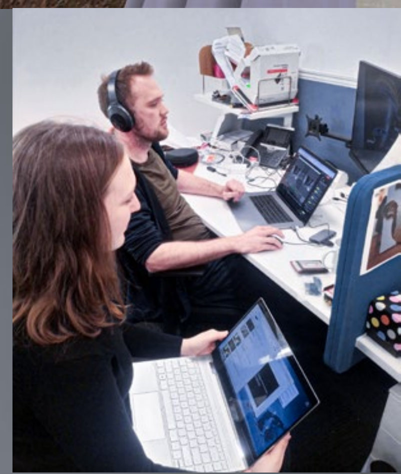

Credit: OzGrav UWA


Credit: OzGrav UWA


Credit: Denamrk Library WA

Minecraft LIGO

Countless hours were put into building a replica LIGO in the computer game Minecraft, by the University of Adelaide OzGrav team (Masters and PhD students, and postdoctoral researchers, with help from Adelaide undergraduate students). This project was funded by the SA National Science Week program, and several talks were held for the general public. Hundreds of people could watch along for a guided tour on YouTube with researchers who work on lasers and some who have installed equipment into LIGO as part of OzGrav ongoing involvement in the LIGO Scientific Collaboration. If participants had the Minecraft game they could follow along inside the virtual space, flying into the air and helping to build (or tear apart). LIGO India also featured some live talks inside the Minecraft LIGO, and there are plans to expand into teacher units.




LIGO Minecraft. Credit: OzGrav University of Adelaide

Adventures Abroad in Science

Chief Investigator Prof Susan Scott (ANU) was interviewed for an online talk "Adventures Abroad in Science" where she discussedher experience in the Homeward Bound leadership program and associated trip to Antarctica.

Satellite Selfie

The ANU OzGrav team participated in the Satellite Selfie during National Science Week. To commemorate the formation of the ANU Centre for Gravitational Astrophysics (CGA), we created a giant CGA sign using old science themed posters and textbooks, that was 'photographed' from space. ANU OzGravvers across various themes and career levels took part in the event to promote science in one of the most creative ways. This satellite selfie is also deemed the world's biggest satellite selfie and was taken by the Maxar satellite at a height of 770 kilometres above the Earth and was part of the National Science Week initiative in the ACT, co-hosted by ANU.


Satellite selfie. Credit: National Science Week

EDUCATION AND OUTREACH

Einstein First project

The team presented at the Inaugural Einstein-First International Workshop at UWA in February. All the talks from this workshop are available at https://www.einsteinianphysics.com/inaugural-int-workshop/.

2020 was a difficult year with COVID-19 restrictions affecting the Einstein-First project because we were unable to readily access schools and teachers. Despite this the team worked hard during the pandemic and made significant progress.

E-F project: Professional development programs and resources for teachers

The team conducted several workshops with primary and high school teachers. The aim of these workshops was to get teachers' feedback on the developed curriculum documents and to revise them as per their comments. Some resources are already available as curriculum documents and modules at www.einsteinianphysics.com with more to come in 2021.

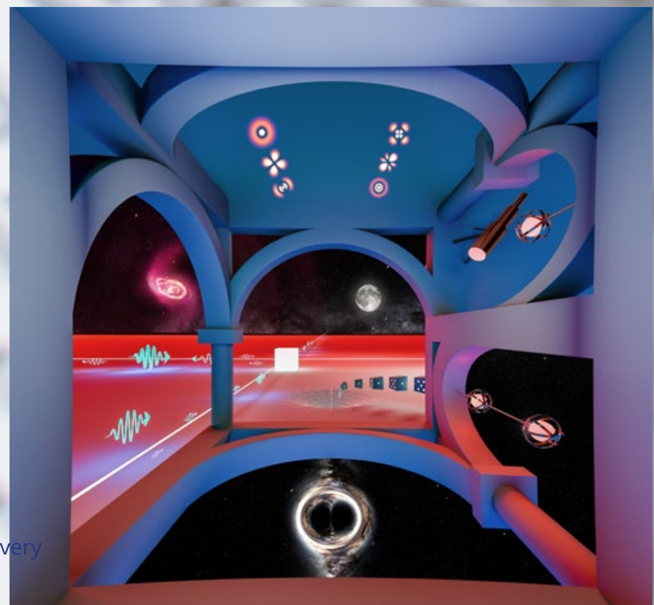
Year 3 Hot Stuff and Year 3 Atom Frenzy
Year 4 May the Force be with You
Year 5 Fantastic Photons and Our Place in the Universe
Year 7 Warp Spacetime

The team also ran workshops at professional development days and the Future Science conference by the Science Teacher Association of Western Australia. We also ran a one-day workshop for our friends at the Gravity Discovery Centre (GDC) in Gingin who share our love of Albert Einstein's work.

Images of Einstein First staff, partner teachers and students. Credit ABC News Eloise Osborne and Briana Shepherd

Physics book goes to publishers

Chief Investigator Prof David Blair (UWA) and OzGrav Affiliate Magdelena Kersting (University of Oslo) lead the internationally collaborative team in publishing their book "Teaching Einsteinian Physics". The book includes chapters contributed by OzGrav team members such as "Patterns and atoms: the structure of atomic matter" and "Teaching quantum physics to high school students using phasor wheels" based on the Einstein-First team's extensive experience delivering engaging workshops to students.



OzGrav's Virtual Universe at the Gravity Discovery Centre

OzGrav are showcasing a new interactive exhibit at the Gravity Discovery Centre (GDC) in Gingin, Western Australia, launched in conjunction with the inaugural Einstein-First International Workshop (18-21 February 2020). As part of the Gingin Science Precinct, the Gravity Discovery Centre (GDC) is a place of learning and wonder. The not-for-profit centre showcases hands-on science exhibits, sharing the latest discoveries in physics and astronomy with a focus on gravity and cosmology. The GDC is the public education interface of the Australian International Gravitational Observatory (AIGO), as well as the Zadko Telescope located on-site. It's also home to the Leaning Tower of Gingin—an impressive engineering feat inspired by the Leaning Tower of Pisa: a 45-metre tall steel structure, leaning at an angle of 15 degrees and held in place by 180 tons of concrete.

Virtual Universe will include multiple interactive screens and artistic projections, weaving the story of gravitational waves and allowing visitors to manipulate the fabric of space-time. Mark Myers and Carl Knox from the Outreach team at OzGrav HQ have created a multi-sensory experience that's both stunning and informative: users can move their bodies to engage with the wall art and content, and visualise gravitational waves to grasp a deeper understanding of the science. The exhibit aims to inspire people from all walks of life and look at gravitational wave science from a fresh, new angle.

Credit: Carl Knox, OzGrav Swinburne

EDUCATION AND OUTREACH

Engaging the public with Virtual Reality (VR)

Magdalena Kersting, University of Oslo

All of us agree that VR is pretty cool. There are exciting opportunities to transform outreach practices by pushing the boundaries of what is possible in the real world. But how exactly do different people engage with a virtual tour such as Bigger Than Big? And how can we develop and identify the benefits of VR?

I set out to answer these questions empirically and joined an OzGrav outreach event at a science festival. I quickly realised that we needed a framework to operationalise VR engagement: we need to know what types of engagement there are to improve our outreach activities.

I drew on the literature and my observations at the festival to suggest a framework of four aspects that reveal essential features that characterise successful use of VR: immersion, facilitation, collaboration, and visualisation. For example, the immersive and visually striking nature of the VR-experiences links the science content to the lived experiences of festival visitors. The OzGrav students and the EPO team, in turn, can use this experience to facilitate deeper engagement. The features of immersion and visualisation also contribute to increased collaboration between the visitors.

Two of my findings are particularly exciting. First, almost all visitors said that the immersive nature of the VR-experience altered their understanding of astronomy. The ability to interact and move within a VR-environment can promote astronomy knowledge by making astronomy experienceable.

Background artwork: Carl Knox, OzGrav Swinburne.
Image below: Science Alive Geelong with Mirage VR demos. Credit: Magdalena Kersting, University of Oslo

Second, facilitation by the OzGrav PhD students and postdoctoral researchers made an essential contribution to the engagement of the visitors. Even better, the engagement through facilitation was mutual with the OzGrav team expressing excitement and satisfaction concerning their role as facilitators. This mutual engagement creates emotional connections that can support science learning further. VR-technology serves as a bridge to connect science experts and non-experts and scientific ideas to the festival visitors' experiences.

Outreach Manager Jackie Bondell prepares for online classes. Credit: Jackie Bondell, OzGrav Swinburne

Mission Gravity Goes Online

Since mid 2018, the OzGrav outreach team has travelled to schools across Australia, using interactive and collaborative Virtual Reality (VR) to bring lessons to students. These workshops cover topics around stars, black holes, neutron stars, white dwarfs, stellar evolution, and how to study these objects using electromagnetic waves and gravitational waves within the framework of the scientific method. Working in teams the students investigated the evolution of the stars over time using OzGrav-developed 'Mission Gravity' virtual reality content. PhD students and postdoctoral researchers from UWA, ANU, Swinburne, Melbourne and Adelaide Universities also join us during these workshops as a great way to train up to explain their science, and share their passion about their career. Students also have the opportunity to participate in a hands-on experiment to understand the concept of 'curvature of space-time fabric' using a gravity well.

The lockdown gave our team the opportunity to redesign our schools incursion Mission Gravity for remote delivery and in 2020 we began offering this program free-of-charge to schools, specifically those schools with students learning remotely. These virtual incursions allowed us to scale our resources across geographic and socioeconomic barriers. In terms 2 and 3, we engaged with well over 100 teachers and students not only across rural areas of Australia but in Europe and North America as well. Even though we may soon be free to visit schools for face-to-face incursions, we will continue to offer these remote programs to ensure OzGrav Education and Outreach content remains accessible to all interested students.

AWARDS AND HONOURS

Pawsey Medal

The Australian Academy of Science awards OzGrav Associate Investigator A/Prof Adam Deller (Swinburne University of Technology) as the winner of the annual Pawsey Medal, awarded to an outstanding researcher in Physics. Associate Professor Deller uses high angular resolution radio imaging to study neutron stars and black holes, the most compact objects in the Universe. To do so, he has developed new instrumentation capable of jointly processing signals from radio antennas spread across the Earth and even on orbiting satellites, which has been adopted by major astronomical facilities world-wide.

American Physical Society Fellowship, and Dirac Medal

OzGrav Chief Investigator Prof Susan Scott (Australian National University) is awarded this Fellowship for groundbreaking discoveries in general relativity and gravitational wave science, advancing our understanding of the singularities and global structure of space-time and the nature of astrophysical signatures in gravitational wave experiments; and for promoting gravitational research worldwide.

Prof Scott is also awarded the Dirac Medal from the University of New South Wales UNSW), which is an international award for Theoretical Physics. Prof Scott is seen here (right) giving a keynote lecture, and accepting the medal from UNSW Dean of Science Prof Emma Johnston (left).

Physical and Chemical Sciences Laureate

Associate Investigator Dr Greg Ashton (Monash University) was awarded the Physical and Chemical Sciences Laureate 2020 by Universal Scientific Education and Research Network (USERN) for his work on black holes, neutron stars and cosmology in the era of gravitational wave astronomy. Each year on November 10th, the Worlds' Science Day for Peace and Development, the USERN prize is bestowed to young scientists in appreciation and recognition of their novel advancement or achievement in scientific education, research, or serving humanity.

Artwork

Carl Knox (Swinburne) had his artwork chosen for the cover of ARC's "Making a Difference" report, based on Greg Ashton and Paul Lasky's work on the Vela glitch (see OzGrav 2019 Annual Report).

Member of the Order of Australia

OzGrav Governance Advisory Committee member Professor Tamara Davis (UQ) was awarded a Member (AM) in the General Division of the Queen's Birthday Honours List 2020 for her service to astrophysics and leading young astronomers.

Postdoctoral Fellowship

We wish PhD graduate Dr Michael Page (University of Western Australia) best of luck as he travels to Japan for a Japan Society for Promotion of Science Postdoctoral Fellowship. His nomination was sponsored by the Australian Academy of Sciences and he continues his work on gravitational waves with Japan's detector KAGRA.

Early Career Researcher Award

Postdoctoral researcher Dr Simon Stevenson has won FSET Early Career Researcher Award 2020 from Swinburne University of Technology.

Lifetime Achievement Award

Internationally renowned astrophysicist Professor Matthew Bailes has been recognised at the 2020 Swinburne University of Technology Vice-Chancellor's Awards with a Lifetime Achievement Award.

Prof Bailes has been central to the development of one of the world's foremost astrophysics and supercomputing centres at Swinburne. Prof Bailes also developed supercomputing at Swinburne, designing the first workstation clusters and making them a university-wide and now national resource. He has more than 25,000 citations and, together with his former student Duncan Lorimer, discovered a new type of cosmic explosion, called fast radio bursts (FRBs).

He pioneered the use of virtual reality for science and education and was involved in the development of three IMAX films, the first of which, Hidden Universe, was Australia's sixth-highest grossing documentary within a year of its release.

AWARDS AND HONOURS

Student Awards

Debatri Chattopadhyay (Swinburne University of Technology) is the winner of the Higher Degree by Research (HDR) Awards 2020 HDR Outstanding Article Award (Faculty of Science, Engineering and Technology) for the paper "Modelling double neutron stars: radio and gravitational waves". Debatri also received a commendation for FSET Awards 2020: Postgraduate Student of the Year.

Congratulations to both Nutsinee Kijbunchoo (Australian National University) and Chayan Chatterjee (University of Western Australia) who both won their respective University Finals of the 3 Minute Thesis (3MT) competition. The Three Minute Thesis (3MT) is an international competition for higher degree research candidates to showcase their research. The catch - they only have three minutes to present and can only use one PowerPoint slide. Nutsinee and Chayan went on to compete against 52 other finalists at the Asia-Pacific finals via video.

Image: Nutsinee Kijbunchoo, OzGrav ANU

Nutsinee is also an avid photographer and videographer, sharing her lab work on lasers and the quantum squeezing system at LIGO. She won the Wiki Science Photo Competition: People in Science 2019 (announced August 2020). The winning image of the People in Science category depicts Georgia Mansell and Jason Oberling at the Pre-Stabilized Laser (PSL) enclosure of LIGO Hanford, wondering what went wrong. A huge thanks to Nutsinee for her contributions to our outreach, social media, newsletters and Annual Reports, including this gem (found in the 2019 OzGrav Annual Report).

Image: Nutsinee Kijbunchoo, OzGrav ANU

Disha Kapasi (Australian National University) was awarded the Dean's Prize for the John Carver Seminar Series, and also received Robert and Helen Crompton Award from the School of Physics to undertake research and training at University of Glasgow for 3 months. We wish her well when international travel is back.

Background image: Aditya Parthasarathy, OzGrav Swinburne

OzGrav 2020 Retreat Awards

Biggest Newsletter and Research Briefs contributors

Juan Calderon Bustillo (Monash), Ilya Mandel (Monash), Marcus Lower (Swinburne), Ryosuke Hirai (Monash) and Xingjiang Zhu (Monash).





Outreach Superstars

Kendall Jenner – University of Adelaide
Debatri Chattopadhyay – Swinburne
Eric Howell and Fiona Panther – UWA
Changrong Liu and Meg Milhouse – University of Melbourne
Isobel Romero-Shaw and Avi Vajpeyi – Monash University
Daniel Toyra and Disha Kapasi – ANU
Dougal Dobie – University of Sydney











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 was pursued under seven programs:

1. Commissioning (Program Chairs: Ottaway and Slagmolen)

2. Quantum (Program Chairs: Ng and Ward)

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

4. Distortions and Instabilities (Program Chairs: C Blair and Ottaway)

5. Space (Program Chair: McKenzie)

6. Pulsar Timing (Program Chair: Bailes)

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

At the beginning of 2020, Drs Robert Ward and Sebastian Ng took over as co-Chairs of the Quantum program, while Dr Carl Blair took on the responsibility of co-Chairing Distortions and Instabilities. A new meeting structure was adopted – moving from weekly to fortnightly meetings with the responsibility for running these meetings rotating around the programs. This has proven very effective.

Despite severe disruptions due to the COVID-19 epidemic, significant progress was made across all 'on-shore' programs. However, no onsite LIGO commissioning was possible. The Quantum program achieved cross-node new architecture for 2 micron lasers and the ability to drive quantum noise below the standard quantum limit in the LIGO detectors. The Low Frequency program made good progress toward realising a 3D tilt sensor, integration of sub-systems for a prototype Newtonian noise sensor and developing and testing analysis algorithms such as beamforming, coherence decay, etc. using the 5-seismometer mini seismic array at the Gingin site. Distortions and Instabilities program made active modematching prototype development, a demonstration of two modematching schemes and a cross-theme collaboration to measure LIGO test mass temperature distributions. The Space program set a new world record for weak light phase locking and development of the tilt locking scheme for space applications. Radio Telescope (Pulsar Timing) activities continue to lead the world, publishing data with the lowest level of jitter noise ever seen in a millisecond pulsar. Finally, our activities in Future Detector Planning continued to expand with OzGrav contributions to the Cosmic Explorer global science and network studies, continuing investigation of potential Australian detector sites, and the publication of a Centre-wide paper outlining the science case and preliminary design for a NEMO – a Nuclear and Extreme Matter Observatory.

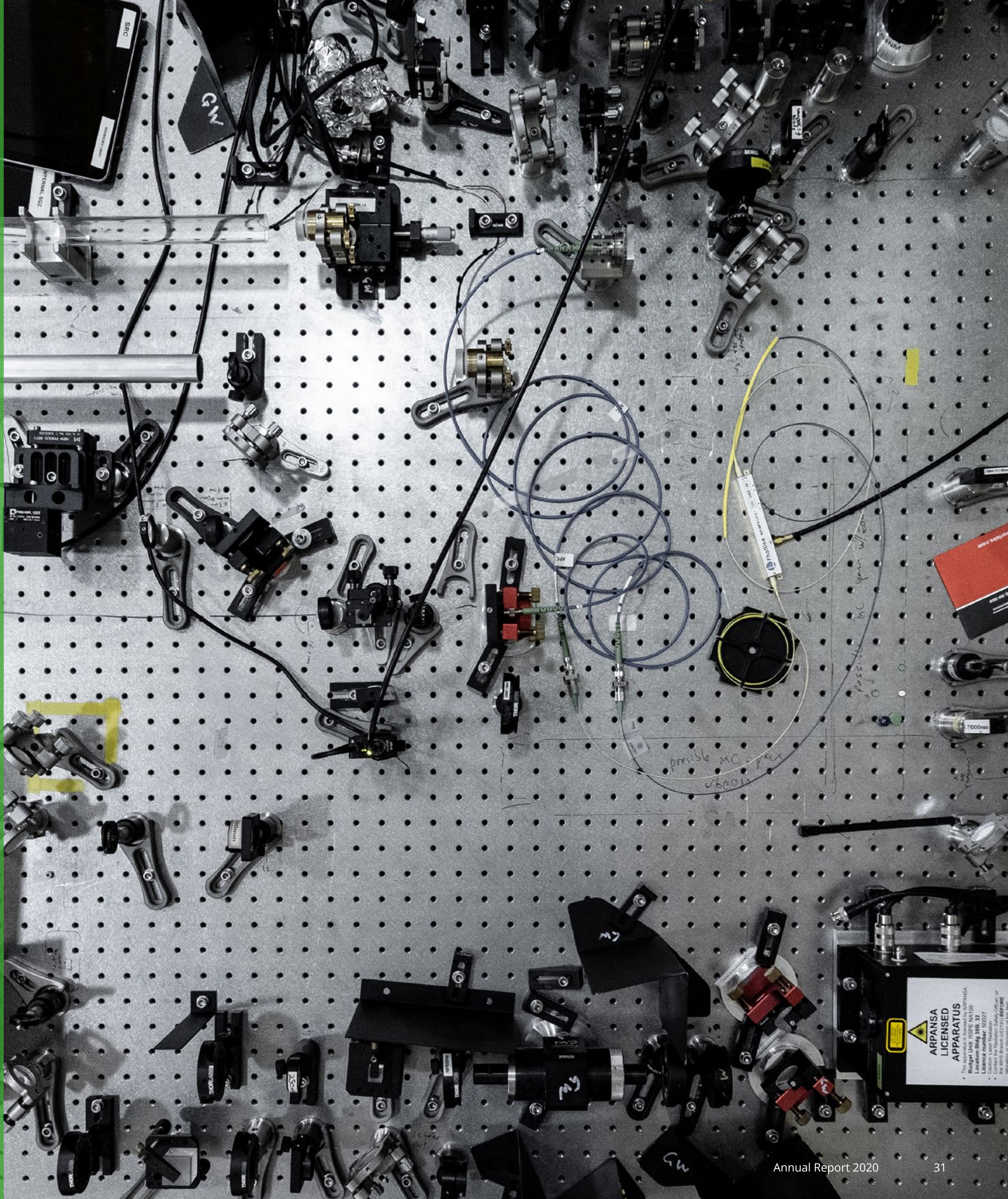


Image credit: Nutsinee Kijbunchoo, OzGrav ANU

INSTRUMENTATION

Commissioning

Program chairs: David Ottaway and Bram Slagmolen

The international travel bans that resulted due to the COVID-19 epidemic massively reduced our ability to contribute to onsite commissioning at the LIGO Observatories in the USA. The onsite presence of OzGrav commissioners reduced from in excess of 950 person days of commissioning in 2019 to zero in 2020. Unfortunately this situation is likely to continue for most of 2021. The commissioning at the US Observatories by US based commissioners has also been curtailed due to significant reduction in the number of personnel allowed onsite due to COVID- 19 restrictions.

In the interim we have been conducting ongoing development of optical systems such as deformable mirrors and optical lock-in cameras that will be deployed at the LIGO sites in 2022. The bright light in all of this is that in the next 3 years the LIGO Observatories are planning two significant upgrades that will extend the reach of the interferometers to in excess of 300 MPc for Binary Neutron Star Mergers. We are planning to make a significant ongoing contribution to commissioning these upgrades when Australians are allowed to travel internationally again.

Quantum

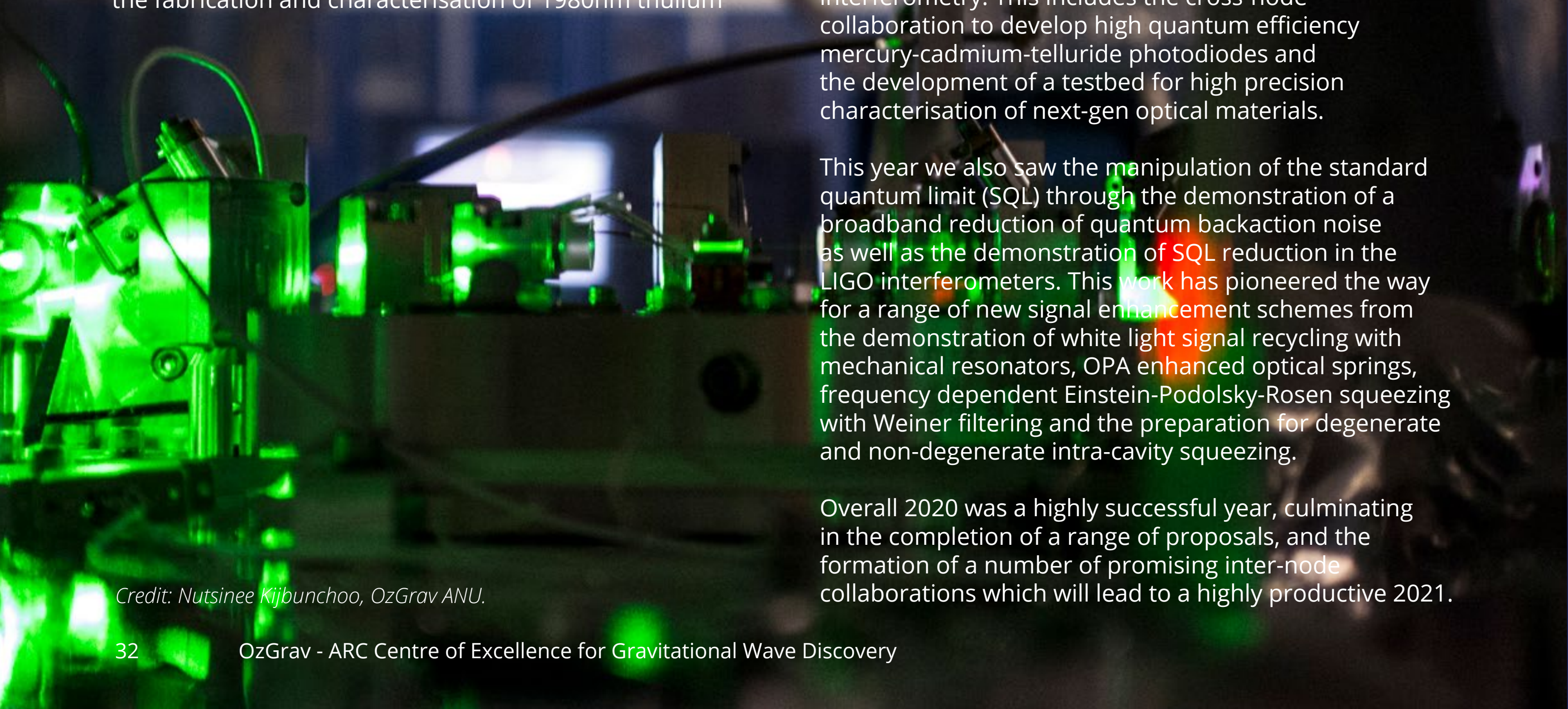
Program chairs: Sebastian Ng and Robert Ward

In 2020 the quantum program continued its pursuit of next generation quantum noise reduction through the development of 2µm (2 micron) squeezed light sources and stable laser systems. Laser development included the fabrication and characterisation of 1980nm thulium DBR cavities with increased stability, DBR frequency actuators, high bandwidth locking schemes and the demonstration of a 5W 2µm laser system for the Gingin test facility. A highlight from this work was the demonstration of a low noise 2µm ECDL which resulted in the cross-node collaboration on an ECDL and thulium preamplifier source for future squeezing experiments.

The development of 2µm quantum noise reduction technology has identified key technologies required in the future improvement of cryogenic silicon interferometry. This includes the cross-node collaboration to develop high quantum efficiency mercury-cadmium-telluride photodiodes and the development of a testbed for high precision characterisation of next-gen optical materials.

This year we also saw the manipulation of the standard quantum limit (SQL) through the demonstration of a broadband reduction of quantum backaction noise as well as the demonstration of SQL reduction in the LIGO interferometers. This work has pioneered the way for a range of new signal enhancement schemes from the demonstration of white light signal recycling with mechanical resonators, OPA enhanced optical springs, frequency dependent Einstein-Podolsky-Rosen squeezing with Weiner filtering and the preparation for degenerate and non-degenerate intra-cavity squeezing.

Overall 2020 was a highly successful year, culminating in the completion of a range of proposals, and the formation of a number of promising inter-node collaborations which will lead to a highly productive 2021.

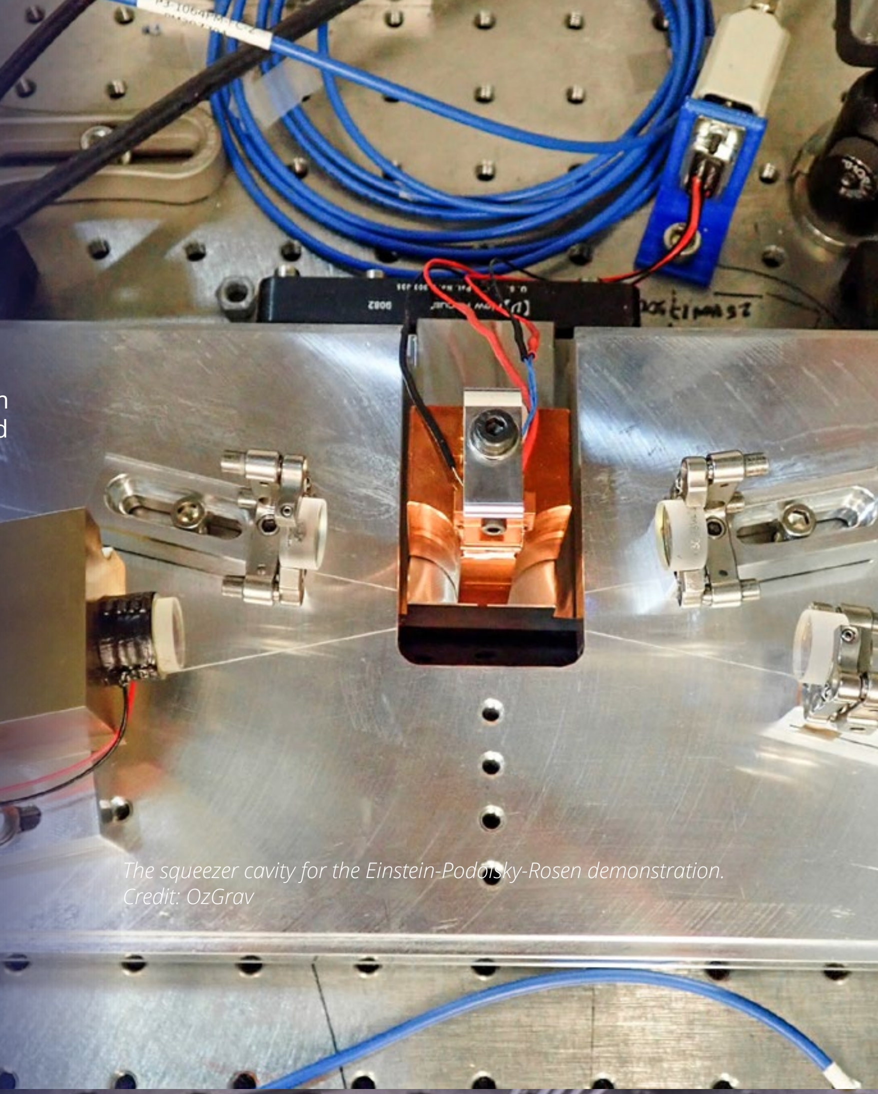


Credit: Nutsinee Kijbunchoo, OzGrav ANU.

Case Study

EPR squeezing using Weiner filtering

Highly sensitive displacement sensors such as gravitational wave detectors are often dominated by quantum noise which limits their sensitivity. Quantum squeezing techniques which are already implemented in the current generation of gravitational wave detectors have shown to reduce quantum shot noise and improve the sensitivity of the detectors in the high frequency regime (>100 Hz). However, in order to reduce quantum noise across the entire measurement band, a frequency-dependent squeezed state is required. To generate such a state, 100m long scale filter cavities are being installed in current gravitational wave detectors. These cavities require additional vacuum infrastructure, have very stringent loss requirements which come with significant technical challenges. The ANU group have demonstrated the generation of frequency-dependent squeezing without the need for such cavities by using Einstein-Podolsky-Rosen (EPR) entangled states. The results of this demonstration were recently published in Nature Photonics. More recently, by exploiting the quantum correlation of EPR entangled states, the ANU group has developed a post-processing technique which optimally reduces the quantum noise with squeezed light. The manuscript containing these results is currently in preparation.

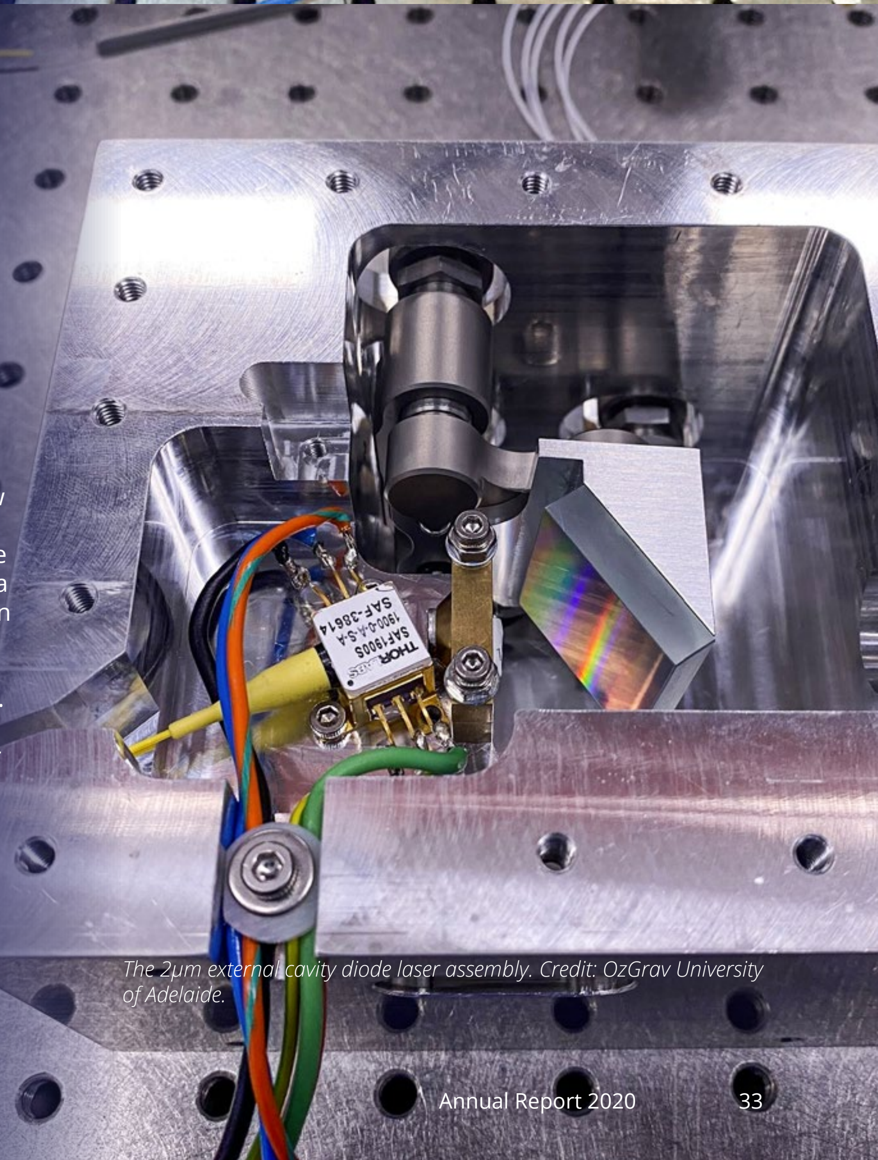


The squeezer cavity for the Einstein-Podolsky-Rosen demonstration. Credit: OzGrav

Case Study

2 micron light sources for quantum squeezing

The development of high power cryogenic silicon gravitational wave detectors necessitates a change in laser wavelength from the 1064nm sources in advanced LIGO. This has prompted research into new ultra stable lasers and squeezed light sources. The ANU team demonstrated a 2µm External Cavity Diode Laser with a 120nm tuning range, 10mW output and a free running linewidth of 20kHz for a 10ms integration time. This resulted in a publication in Optics Express and became the basis of a collaboration between researchers at ANU and University of Adelaide (UofA). Here the ECDL will form the seed laser for a thulium doped amplifier which will increase the output power to level suitable for further squeezing experiments. This collaboration involved researchers from UofA aiding in the assembly of a second ECDL light source in the ANU labs. An all-fibre thulium-doped amplifier system was then designed and has begun initial testing in Adelaide.



The 2µm external cavity diode laser assembly. Credit: OzGrav University of Adelaide.

INSTRUMENTATION

A standalone seismic station deployed in Gingin Gravity Precinct with the data acquisition box and wireless transmitter. The seismometer is buried underground.

Fully assembled tilt sensor. Credit: Joshua McCann, OzGrav UWA

Low frequency

Program chairs: Ju Li and Bram Slagmolen

The tilt sensor (ALFRA) has demonstrated exceptional sensitivity and will be an invaluable tool for stabilising vibration isolation chains at low frequency. Further improvement with thinner flexures and a novel anti-spring design will increase the low frequency sensitivity. An additional coarse shadow sensor readout setup is being designed to improve the ease of locking of the control system. All the design improvements will be incorporated in the second tilt sensor to be constructed in 2021 for complete noise characterisation.

We continue to develop vertical low frequency vibration isolation systems with Euler springs, implemented on Euler-LaCoste preisolator designs that incorporate the low creep materials maraging steel and glassy metal.

We demonstrated inertial damping of the MultiSAS using the Trillium T240 seismometers. The results are limited by not being able to provide active feedback to the suspended Intermediate Mass. This resulted in unwanted resonances which could not be controlled. Even so, the recorded results are fully understood by modeling, which will help inform our path towards full control implementation.

After some delays and challenges involving workshop resources the complete MultiSAS Torpedo isolation and suspension chain has been fabricated. All parts have been cleaned and assembled into the full assembly. We have a full Internal Seismic Isolation Suspension Chain (ISISC), including a MultiSAS, Intermediate Mass, Penultimate Mass and dummy TorPeDO. This included all components for positioning sensors and coil-magnet actuators. The electronics have been tested and installed, including a second new real-time control computing system. The last tests will be undertaken before the 800kg system is craned and installed into our vacuum chamber.

Our other focus is on the characterization of the current TorPeDO sensor. This is done by actively driving the system in a particular way and recording its response. To obtain qualitative measurements, these measurements can take many hours (or days). During this work, we developed a new controls implementation to improve the robustness of the readout of the TorPeDO sensor.

In collaboration with CSIRO and using a 5-seismometer, 400m scale seismic array at the Gingin facility site. We developed and tested analysis algorithms such as beamforming, and coherence, and used it to characterise a range of seismic sources of natural and anthropogenic origin. A weather station was installed to provide wind speed and direction data. The seismic weather vane was able to clearly identify micro-seismic signals correlated with wave buoy data. We also discovered a surprising low-frequency wind signature as low as 0.05Hz. A wireless array connection for real-time data collection was designed and tested with the current 5-seismometer array. A large array with ~30 seismometers (funded by an ARC LIEF grant, plus some on loan from UWA geology department) across km range will be installed in 2021 for developing seismic imaging and low frequency vibration isolation control technique.

The pandemic impacted our program in a variety of ways, the most significant being the lack of personnel exchange between the nodes, limitations on lab access which affected our rate of progress, and the personal toll on individuals.

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 our complicated mechanical and electrical designs. We also appreciate Department of Transport for their kind provision of buoys data from Rottnest Island and Jurien bay, for seismic array study.

Fully assembled Internal Seismic Isolation and Suspendion Chain, with a dummy TorPeDO at the bottom (the round disk). This system weighs about 800kg, and will be moved into a large vacuum tank for full integration. Credit: Bram Slagmolen, OzGrav ANU

Research Assistant Lauren Sarre and Dr Sheon Chua inspecting the recently assembled Penultimate Mass. Delicate balancing and precise mass locations are required to make the suspension work properly. Image credit: Bram Slagmolen, OzGrav ANU

INSTRUMENTATION

Distortions and Instabilities

Program chairs: Carl Blair and David Ottaway

The big successes in 2020 include:

- The active mode matching element prototype development at The University of Adelaide (UofA). This prototype exceeded all requirements and was selected for inclusion in the next LIGO Observing run. This project has now moved to commissioning.
- The experimental demonstration of two mode matching schemes, one using a novel modulated higher order transverse mode and the second using the phase camera.
- A collaboration between Astrophysicists Yuri Levin (Columbia) and Eric Thrane (Monash) and Experimentalist Carl Blair at the University of Western Australia (UWA) developed a new scheme for measuring the temperature distribution in LIGO test masses based on parametric instabilities sensing and control signals.

Significant progress was also made in a number areas. Some achievements compliment 2020 goals and some developed new direction for 2021. These include:

- The interpretation of phase camera images using machine learning.
- Mechanical loss characterisation of the Gingin silicon cavity test masses.
- A published paper demonstrating independent control of optical cavity eigen-frequencies using thermal actuators to deform the mirror surface.
- The development of theory to explain the experimental demonstration of optical feedback control of parametric instability and an improved theory to explain observed parametric instability saturation at Gingin.
- Hartmann sensors for precise substrate absorption estimates to allow for exact evaluation of substrate absorption at third generation detector wavelengths.
- A new Hartmann sensor design to replace existing sensors at LIGO and VIRGO.

Unfortunately this theme was not completely spared from COVID-19 lockdowns and travel restrictions and several projects have been delayed. The phase camera imaging of parametric instability has been delayed till April 2021 due to travel restrictions. The suspension build for Gingin has been delayed due to lockdown; one suspension is complete, the other has parts manufactured and cleaned but is not yet assembled. Several other projects requiring travel to the LIGO sites have also been put on hold.

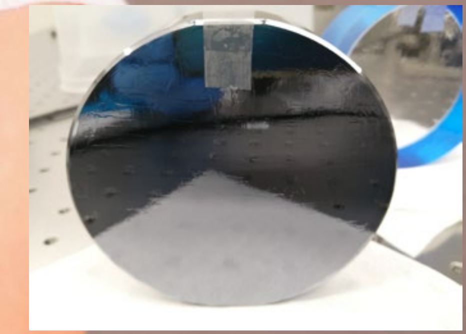
Image: Michael Bishara, OzGrav Swinburne

Case study: Measure the temperature distribution inside Gravitational Wave Detector test masses

The main mirrors or test masses in the aLIGO detectors are 40kg glass cylinders. The gravitational wave signal comes from a change in the test masses apparent position relative to one another. This is measured with fantastic sensitivity by a very powerful ~200kW laser beam. A tiny proportion of the laser power is absorbed in the mirror. This small heating power is however sufficient to distort the test masses through thermal expansion and changes in optical properties. This is a serious problem as the near perfect mirrors become not so perfect resulting in light not going where it is intended to go and ultimately a reduction in detector sensitivity.

Hartmann sensors have been used to estimate this thermal distortion. Thermal actuators then heat the mirror in an opposing manner that balances the original distortion. Recent problems with point absorbers have shown that more careful analysis of thermal distortions is required. In the recently published work, scientists from Monash, Columbia and UWA used techniques from gravitational wave data analysis to show that the signatures of the test mass eigen frequencies which are always present in the detector output that can be used to characterise thermal distortions in the test masses. This will complement existing Hartmann sensor data, allowing better tuning of the detector and potential early identification of thermal distortion issues.

One Gingin isolator. Credit: OzGrav UWA



Gingin Silicon test mass coated with First Contact in preparation for shipment to the coating facility. Credit: Bram Slagmolen, OzGrav ANU

Case Study: Gingin Cryogenic Silicon Coupled Cavity

Thermal noise now is the current fundamental limitation on LIGO detector sensitivity in its most sensitive band around 100Hz. Decades of effort have been spent developing low thermal noise room-temperature mirror coatings. The next generation of this cutting-edge technology will be installed over the next few years to reduce thermal noise. If successful coating thermal noise will be lowered, it will expose substrate thermal noise - an impenetrable barrier for fused silica optics.

Significant additional thermal noise reduction can be achieved at cryogenic temperatures. The Japanese Gravitational Wave Detector, KAGRA uses sapphire test masses that are projected to have very low thermal noise when operated at a temperature of 20K. This is technically very challenging and until these technical challenges are overcome KAGRA operates at higher temperatures with higher thermal noise contribution. A promising middle ground can be achieved using Silicon optics. Silicon has a special property where there is a zero point in thermal expansion at 123K, this results in minimal bulk thermos-elastic noise. This promising concept comes with its own technical challenges, such as the need to use laser wavelengths longer than 1.4μm and crystalline coatings to achieve the full sensitivity benefit. Operating at 120K is significantly easier cryogenic temperature, compared to the 20K required by KAGRA.

The silicon-based technology has not yet been tested in a gravitational wave detector. A technology feasibility study is being conducted at the Gingin High Optical Power Research Facility. This feasibility study will use an 80m coupled cavity that tests cryogenic silicon mirrors with crystalline coatings, the high-power limits in 2μm Silicon cavities and thermal aberration correction.

INSTRUMENTATION

Space Instrumentation

Program chair: Kirk McKenzie

The 2020 Program progressed the two main activities foreseen in the 2019 Report. These are: 1) ultra low-optical power phase locking, and 2) absolute laser frequency knowledge measurement. A third area of laser stabilization research was initiated with two areas being initiated: 3a) Tilt-locking readout of an optical cavity, an alternative to the industry standard readout technique Pound-Drever-Hall Locking, was setup and returned promising initial stabilization results, and 3b) a LISA specific laser stabilization technique: Arm-Locking.

The two absolute laser frequency knowledge milestones, 1) setting up optical cavities and 2) first experimental results were completed. The third milestone of submitting weak-light tracking results for publication was delayed due to some unexpected complexity in the experiment - the program decided to undertake an additional FPGA based hardware simulation before publication of results.

Low-optical power phase tracking: This experiment progressed to pass the previous lowest recorded result, with 15 femtoWatts of light being tracked at a cycle slip rate of 1 per 100 seconds. This represents approximately a factor of 2 lower than the previous effort. This work was presented at the CLEO 2020 and COSPAR 2021 conferences. This work is of critical importance for future inter-spacecraft laser interferometry and will continue into 2021.

Absolute laser frequency knowledge: The experiment was initiated in 2020 and a month-long data-run was initiated just prior to the COVID-19 related shutdown of the ANU campus, yielding long term results that meet the estimated mission requirement for the next GRACE gravity mapping mission. This work has received interest from our NASA collaborators.

Laser stabilization for space interferometers:
The tilt-locking technique was explored for absolute laser stabilization in the LISA frequency band for the first time. We expect tilt-locking to be the first non-RF modulation/demodulation optical cavity readout scheme to show results meeting the GRACE Follow-On laser stability requirement. This work was submitted as an honours thesis and we expect a journal article to follow in 2021.

A detailed study combining the Arm-Locking laser frequency stabilization scheme with an optical cavity redout has been initiated and shown to be compatible with the baseline laser stabilization planned for the LISA mission. The benefits of arm-locking include: no additional hardware is required (since the technique uses the LISA interferometer arms as the frequency reference) and that the additional laser stability (at least 1 order of magnitude improvement across the LISA sensitivity band) means risk reduction for the mission and perhaps an architecture simplification.

Image: Aditya Parthasarathy, OzGrav Swinburne University

Pulsar Timing

Program chair: Matthew Bailes

The system description paper was published entitled "The MeerKAT telescope as a pulsar facility: System verification and early science results from MeerTime". We provide a comprehensive blueprint of how to engineer an array for precision pulsar timing and watch for the digital artifacts that can contaminate pulse profiles and lead to systematic errors. We published data with the lowest level of jitter noise ever seen in a millisecond pulsar.

After consultation with the Xenon Microsystems Technology Group we designed and deployed four servers at the South African SKA site to implement our pulsar timing software. These servers have improved memory bandwidth and CPUs, and ensure that almost no packets are lost during observations. They also possess four very high bandwidth 2TB NVMe drives that allowed the development of baseband capture modes. The first three machines arrived before COVID-19 lockdowns and were installed in February. The final machine was delayed by COVID-19 but is now fully operational.

Planning for Future Detectors

Program chairs: David McClelland and David Ottaway

The Gravitational Wave International Committee for 3G detectors (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 was completed. It will be circulated widely in 2021. A synopsis has been accepted for publication in Nature Physics.

We continued to develop a program to assess potential 3G sites in Australia and carried out an initial Australia-wide survey to identify primary target areas. Software was developed to identify and classify Australian sites that are suitable for hosting a future gravitational wave detector within the Cosmic Explorer (CE) and NEMO concepts. Cosmic Explorer is a proposed third-generation gravitational wave observatory that comprises two detectors, of which one may be located in Australia. The focus so far has been on finding sites within commuting distance of a city, and where a relatively small volume of earth needs to be relocated to create a flat site to site the vacuum tubes that are expected to be of dimension 20-40 km. However, we are gradually including more criteria, such as:

- Noise due to ground motion, varying gravity (Newtonian Noise), wind, and electromagnetism.
- Proximity to existing infrastructure such as electricity grid, roads, and water and sewage systems.
- Risk of earthquakes, flooding, storms and fires.
- Geology, hydrology, and landcover.

In addition we established a national Cosmic Explorer South working group with members from all OzGrav nodes and the US CE team to discuss opportunities. Through this working group we are collaborating with our colleagues from the Cosmic Explorer (US) team on the astrophysics science opportunities of such third-generation detectors, network studies and large infrastructure considerations.

DATA AND ASTROPHYSICS THEME

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

- Inference (Program 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 and Parallel Bilby tools, and 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 only benefit from the recently-funded Gravitational Wave Data Centre based at Swinburne University of Technology.

2019 saw the detection of many exceptional LIGO/Virgo events which were published in 2020. The first strong observation of spinning black holes in binaries was made with GW190412 (which was also the first binary black hole system observed with unambiguously unequal masses). GW190814 contains either the lightest black hole or heaviest neutron star ever observed. GW190521 was formed from LIGO/Virgo's heaviest observed black holes to date, and constituted the first direct detection of an intermediate-mass black hole. Finally, 2020 saw the first observation of neutron star black hole mergers - a landmark discovery in the field. OzGrav members are leading the team within LIGO/Virgo who are analyzing and writing publications about the discovery.

With its third observing run concluded, LIGO/Virgo have detected around 80 gravitational wave events from merging binaries. The latter half of the observing run contains tens of sources which will be published this year. 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

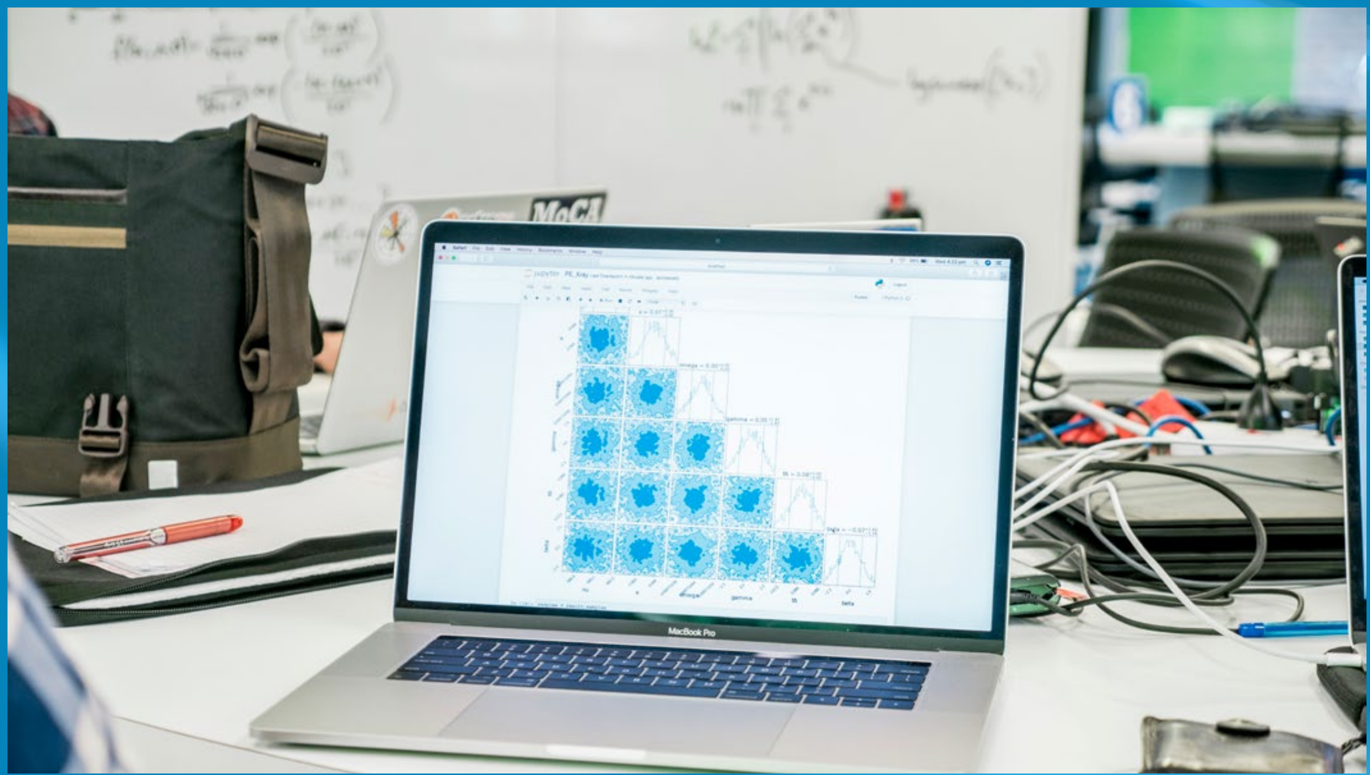
Program chairs: Greg Ashton and Rory Smith

2020 saw the well-established inference program make critical contributions to LIGO/Virgo science. The highly-parallelized variant of the Bilby inference code was rolled out as production code by the LSC 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 O3a/b observing run concurrently with (serial) Bilby. Parallel Bilby was critical for enabling the precise measurement of two of 2019's exceptional gravitational-wave events: GW190814 and GW190412, which marked a number of firsts in the field.

Members of the inference program have had a substantive impact in operational aspects of the LIGO/Virgo collaboration publications. Bilby has been deployed for routine data analysis in O3. We have been leading the inference on the first two neutron star black hole merger observations (made in January 2020), which uses Parallel Bilby as the main code for the analysis. Parallel bilby enables precision measurement on these sources which would otherwise be prohibitively expensive.
We were involved in the inference of the exceptional event GW190521, which provided direct evidence for intermediate mass black holes. Team members have been leading the organisation of inference on the O3b catalogue paper, which will be published in 2021.

Significant steps have been made in inference of compact binary coalescence events. We developed a method for combining multiple observations of binary neutron star mergers to extract the equation of state which was published in 2020 to make the first constraints on the equation of state from multiple observations. We demonstrated how the search for unresolved binary black holes can be used to make inferences on the population properties of black hole binaries. The Parallel Bilby paper was published after internal LIGO/Virgo review of the code, and the code itself was deployed for production. The reanalysis of O1 and O2 events with Bilby was published which helped establish Bilby as a robust code for routine use in LIGO/Virgo. We demonstrated a method to characterize astrophysical binary neutron stars with gravitational waves. GWCloud has been further developed and tested within the Gravitational Wave Data Centre.

In 2020 we continued to innovate on methods that significantly enhance the capability of inference methods. In particular, members of the inference program joined the Cosmic Explorer Consortium, along with OzGrav instrument scientists. We have been contributing to the ongoing Cosmic Explorer trade study to determine the capabilities of next-generation gravitational wave detectors. We have developed the first Bayesian inference methods capable of performing inference on binary neutron stars in third-generation observatories, which will open up future studies in this space.



Bilby in action. Credit: Carl Knox, OzGrav Swinburne

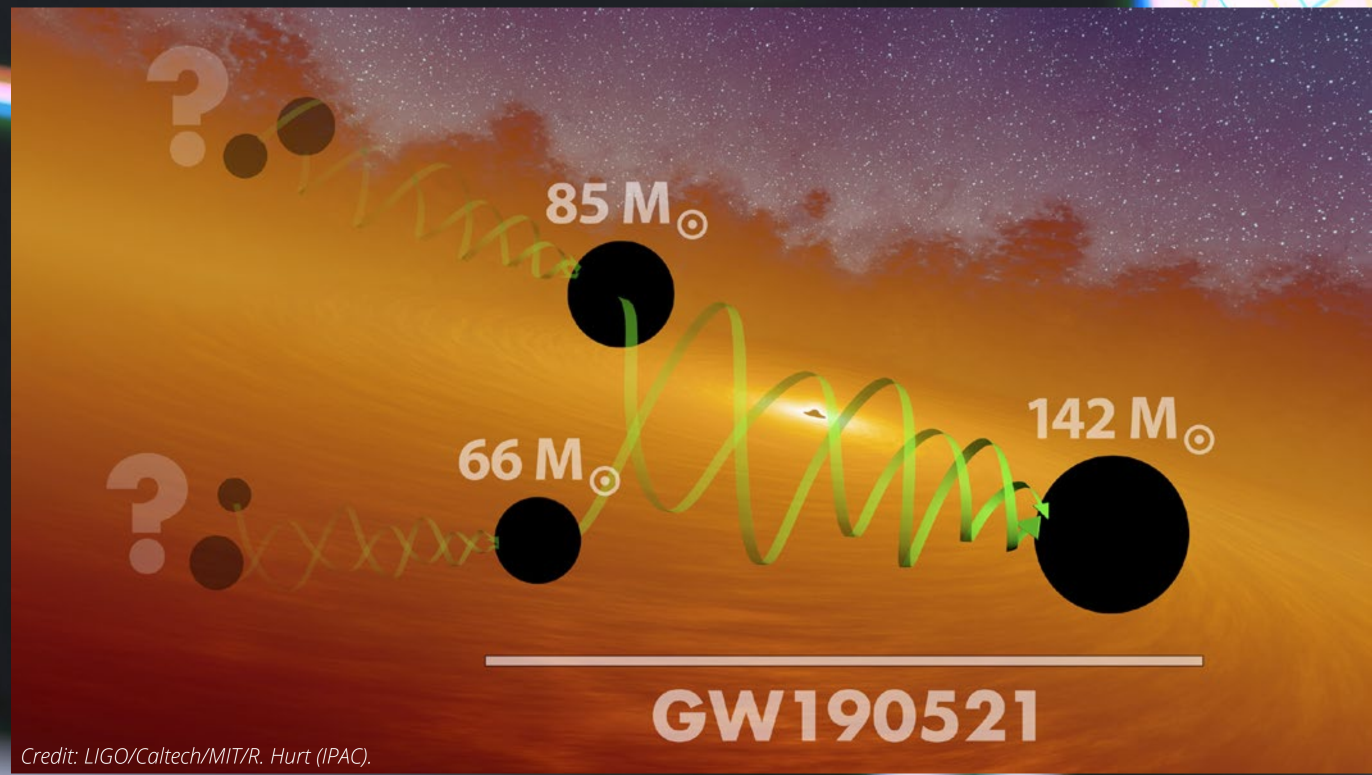
Case study: Exceptional events

OzGrav members were deeply involved in the analysis and paper writing of three of the most exceptional gravitational wave events from O3:

- GW190814, which represents the observation of either the heaviest neutron star or lightest black hole ever observed;
- and GW190412, which was the first unambiguous observation of an unequal mass binary.

Both GW190412 and GW190814 provided the first clear observation for higher-order gravitational-wave modes. The measurements of the properties of GW190814 and GW190412 were made possible by the Parallel Bilby software, which accelerated analyses that would have otherwise taken years. All three events received national and international media coverage.

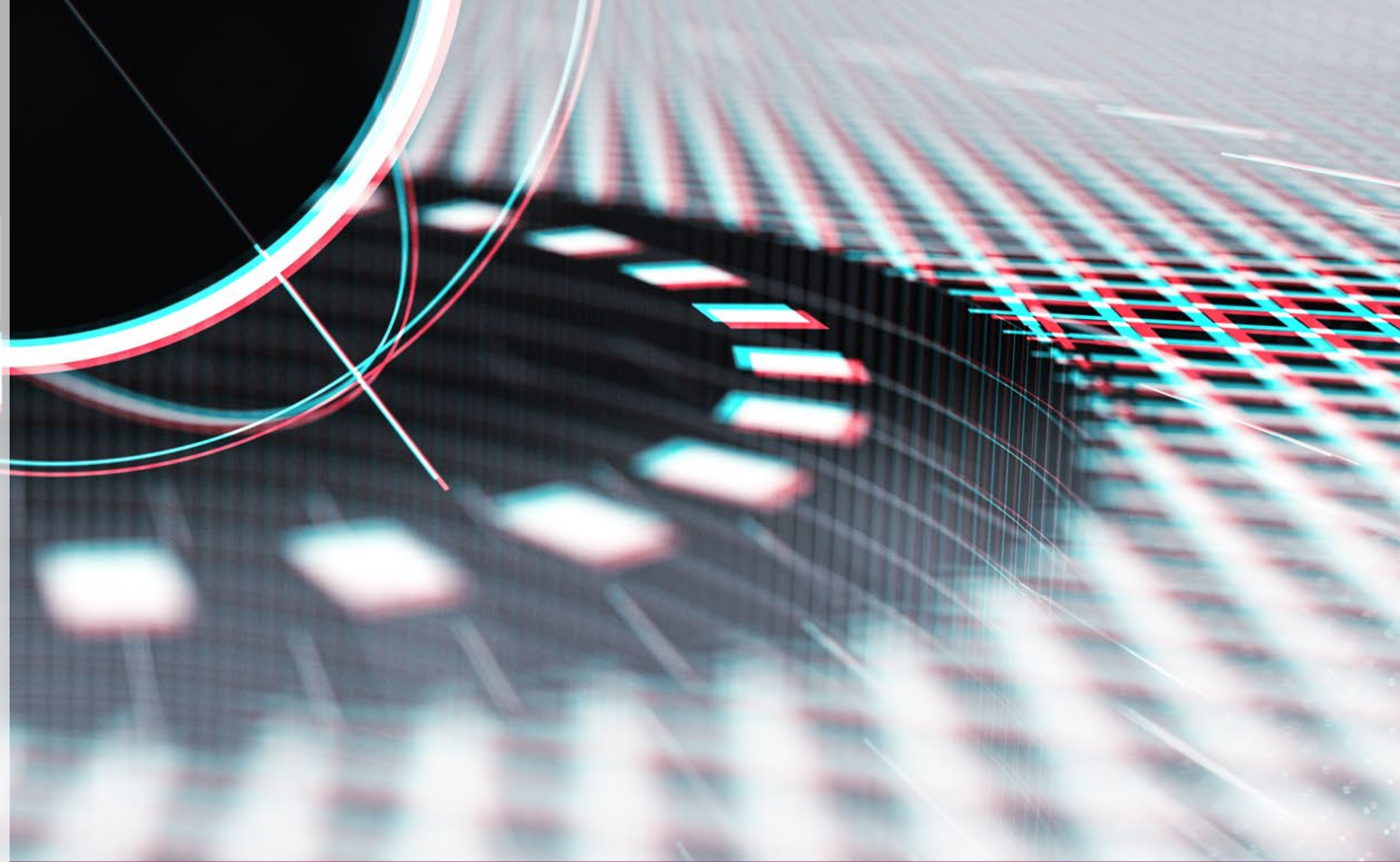
GW190521 is the most massive binary black hole merger observed by LIGO/Virgo to date, with a remnant being an intermediate-mass black hole with a mass around 150 solar masses. These black holes are in the mass range where black holes are not expected to form because their progenitor massive stars are expected to blow themselves apart in pair-instability supernovae. One possibility is that these black holes are themselves the products of previous black hole mergers. The Population Modelling program looked for (and found) evidence of hierarchical binary black mergers. We studied mergers formed dynamically in dense stellar environments like globular clusters using the state-of-the-art N-body code. They suggest that GW190521 may have formed through a series of 7 mergers in a star cluster.



Credit: LIGO/Caltech/MIT/R. Hurt (IPAC).

Background image: Carl Knox, OzGrav Swinburne

DATA AND ASTROPHYSICS



GW Data Analysis Program chairs: Qi Chu and Karl Wette

The main focus of activities in 2020 was the third LIGO-Virgo observing run (O3) which began in April 2019. The run ended one month earlier than scheduled due to the impact of COVID-19. Nevertheless, O3 was highly successful in making scientific discoveries, with active participation and contribution from many OzGrav members within the LIGO-Virgo-KAGRA Collaboration, including: detector calibration, characterisation & data quality; software support; paper analysts, writing team members, project managers, and reviewers; and working group leadership.

The SPIIR team, primarily at UWA, has operated the SPIIR real-time detection pipeline, as a key component of the online public alert infrastructure, throughout the 11 months of the O3 run. Together with other four real-time detection pipelines, 56 public GW alerts were generated that were used for follow-up electromagnetic observations. In June the SPIIR pipeline was used to test the early-warning public alert infrastructure which is among the highest priorities for O4.

The number of GW detections from compact binary coalescence (CBC) sources have tripled with O3, and many exceptional events were discovered. We gained results for deep searches for CBCs using offline cleaned data and the analysis of each O3 exceptional event.

Researchers have been working on new machine learning methods to detect, localise, and estimate parameters of CBC sources with the aim of fast machine learning detection and parameter estimation.

Searches for continuous waves (CWs) using O2 data and the latest O3 data have been published. An O2 Viterbi CW search for five low mass X-ray binaries takes advantage of frequency and orbital parameter measurements from X-ray observations of the five targets to reduce the computational expense. We worked with international collaborators using O2 data to search for CW emission from ultralight boson clouds around the binary Cyg X-1.

We published search results from 12 targets of young supernova remnants using O2 data. A CW search for young supernova remnants using O3 data will be the first to consider potential CW emission from a supernova remnant at dual harmonics. An O3 Viterbi CW search for Scorpius X-1 is being led, and a similar search for 17 low-mass X-ray binaries that had observed accretion events is underway. We are working on a search for GWs from known pulsars in a small band around the electromagnetically measured frequency and spin-down using O3 data.

We worked on stochastic GW detection strategies when correlated magnetic noise is present. This work was applied to the O3 data and will be included in the LIGO-Virgo collaboration work on O3 stochastic background isotropy. We also worked on a method for estimating the accuracy of stochastic background measurement and separate different signals using next-generation detectors.

The GWLab project is developing an online virtual laboratory for GW data analysis. The science component of the project is led by the CW group at University of Melbourne, and the virtual laboratory is being developed by the Gravitational Wave Data Centre (GWDC) at Swinburne. A prototype of the first module, an adaptation of the Viterbi CW analysis pipeline, was developed and is now undergoing testing.

Case Study: The ANU Centre for Gravitational Astrophysics (CGA)

Recognising that gravitational wave discovery is in its infancy, with many decades of rich discoveries to be made, ANU made a long-term commitment to the field with the launch of the Centre for Gravitational Astrophysics (CGA) in 2020. This is a joint Centre between the Research School of Physics and our Research School of Astronomy & Astrophysics, founded to build a world-leading role for Australia in gravitational wave science across instrumentation, data analysis, theory, and astrophysics. The first joint continuing faculty appointment in the CGA was made in 2020 with six new faculty appointments to be made over the next few years.

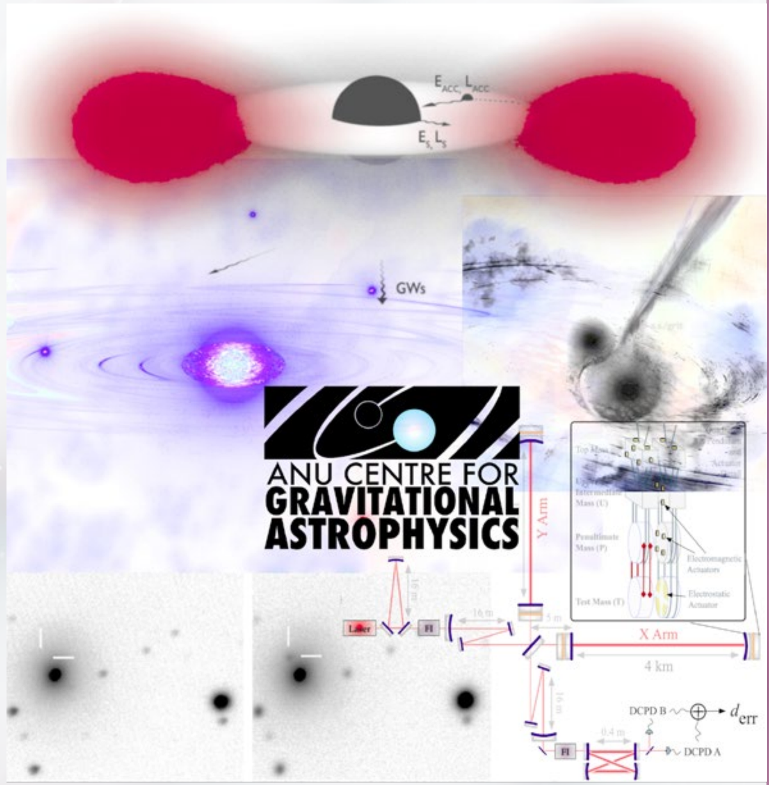


Image credits: R. Brito, V. Cardoso, P. Pani; K. Wette; NSF/LIGO/Sonoma State University/A. Simonnet; N. Kijbunchoo, OzGrav ANU; Andreoni et al, OzGrav; Sun et al, OzGrav.

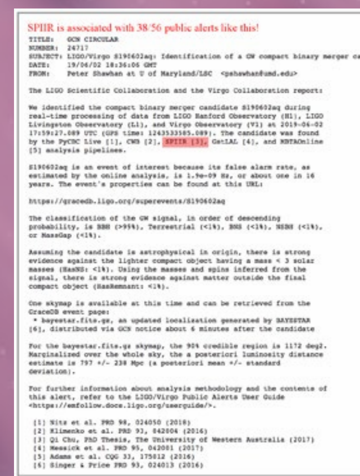
Case study: Summed Parallel Infinite Impulse Response (SPIIR)

The SPIIR team, based primarily at OzGrav-UWA, has spent years of effort to prepare the SPIIR real-time detection pipeline and finally see it play a crucial role in the latest O3 online GW detections. It started about 10 years ago with the invention of the summed parallel infinite impulse response (SPIIR) filters to perform template filtering for CBC searches in real-time. This method has gone through major algorithm improvements over the years so that it can approximate any template filtering result in high precision. It also adopted the major technical advancement from very early on that uses GPUs for acceleration.

A complete pipeline needs to select candidates and estimate the significance of each candidate to be uploaded to the candidate database. SPIIR is the first online pipeline that implemented the coherent candidate selection method with the help of GPUs. This was envisioned as a computational challenge for a long time. This pipeline adopts a novel significance estimation method and achieves expected detection performance.

As online detections are sent to astronomers directly through the public alert infrastructure, it is crucial that online pipelines are producing as few false alarms as possible. Through a year-long code review process with reviewers from within OzGrav and overseas, this pipeline performed numerous tests on online mock challenges and engineering runs. It has evolved to be a well-rounded and robust pipeline against all types of noise impacts.

The pipeline was a key component in the O3 online public alert infrastructure and made significant contributions to O3 discoveries. Of the 56 O3 public alerts, it produced candidates associated with 38 alerts and produced only 2 retractions (false alarms). The overall latency of the pipeline was less than 10 seconds, the fastest of all pipelines. The next breakthrough could be multi-messenger observations triggered by pre-merger alerts from GW detections in O4. During the O4 run, it is expected that there will be at least one BNS detection which can be reported 60 seconds before merger. This is particularly important for facilities with wide fields of view that are suited to following up alerts with large sky localisations, such as SkyMapper in Australia. With GWDC experts joining the SPIIR task force, SPIIR is on track to be ready for the breakthrough.



SPIIR is associated with 38/56 public alerts like this!

TITLE: GCN CIRCULAR
NUMBER: 24717
SUBJECT: LIGO/Virgo S190602aq: Identification of a GW compact binary merger ca
DATE: 19/06/02 18:36:06 GMT
FROM: Peter Shawhan at U of Maryland/LSC <pshawhan@umd.edu>

The LIGO Scientific Collaboration and the Virgo Collaboration report:

We identified the compact binary merger candidate S190602aq during real-time processing of data from LIGO Hanford Observatory (H1), LIGO Livingston Observatory (L1), and Virgo Observatory (V1) at 2019-06-02 17:59:27.089 UTC (GPS time: 1243533585.089). The candidate was found by the PyCBC Live [1], CWB [2], SPIIR [3], GstLAL [4], and MBTAOnline [5] analysis pipelines.

S190602aq is an event of interest because its false alarm rate, as estimated by the online analysis, is 1.9e-09 Hz, or about one in 16 years. The event's properties can be found at this URL:

https://gracedb.ligo.org/superevents/S190602aq

The classification of the GW signal, in order of descending probability, is BBH (>99%), Terrestrial (<1%), BNS (<1%), NSBH (<1%), or MassGap (<1%).

Assuming the candidate is astrophysical in origin, there is strong evidence against the lighter compact object having a mass < 3 solar masses (HasNS: <1%). Using the masses and spins inferred from the signal, there is strong evidence against matter outside the final compact object (HasRemnant: <1%).

One skymap is available at this time and can be retrieved from the GraceDB event page:
* bayestar.fits.gz, an updated localization generated by BAYESTAR [6], distributed via GCN notice about 6 minutes after the candidate

For the bayestar.fits.gz skymap, the 90% credible region is 1172 deg2. Marginalized over the whole sky, the a posteriori luminosity distance estimate is 797 +/- 238 Mpc (a posteriori mean +/- standard deviation).

For further information about analysis methodology and the contents of this alert, refer to the LIGO/Virgo Public Alerts User Guide <https://emfollow.docs.ligo.org/userguide/>.

[1] Nitz et al. PRD 98, 024050 (2018)
[2] Klimenko et al. PRD 93, 042004 (2016)
[3] Qi Chu, PhD Thesis, The University of Western Australia (2017)
[4] Messick et al. PRD 95, 042001 (2017)
[5] Adams et al. CQG 33, 175012 (2016)
[6] Singer & Price PRD 93, 024013 (2016)

Inset image: Fiona Panther, OzGrav UWA
Background image: Carl Knox OzGrav Swinburne

DATA AND ASTROPHYSICS

Pulsar Detections

Program chairs: Hannah Middleton and Ryan Shannon

Millisecond pulsar timing

Early in 2020 we celebrated the second data release from the Parkes Pulsar Timing Array project (PPTA) and associated publication. The release, which provides 14 years of high-quality high-precision timing data, was many years in the making. To make use of the data set it is necessary to develop robust models that characterise the “noise” in the data set, where noise can be astrophysical (spin instability in the neutron stars, turbulence in the interstellar medium) or related to instrumentation. These models are now being used for both searching for gravitational waves, searching for novel forms and dark matter, and for studying individual millisecond pulsars, projects that we expect to complete this year.

The MeerKAT millisecond pulsar (MSP) program has transitioned from a census of all southern millisecond pulsars, to a pulsar timing array program. Currently 80 pulsars are timed every fortnight to a target precision of 1 microsecond or better. The sensitivity and efficiency of MeerKAT are highlighted by the fact that this can be accomplished in less than 12 hours of observing time per epoch. Initial projections indicate the program will be contributing significantly to the sensitivity of the IPTA to gravitational waves in three to five years, impressive considering the 15-year head start of other projects.

Inference as applied to pulsar data sets

OzGrav members have identified a selection of null pulses associated with the Vela 2016 glitch indicating disruption of the neutron star’s magnetosphere thousands of seconds before and after the glitch It is an open problem how and why the magnetosphere is affected by the glitch, but we speculate the nulls are associated with foreshocks and aftershocks around a main starquake during the glitch.

A team characterised the radio pulses emitted from the magnetar Swift J1818.0-1607, and found it possibly belongs to a group of transitional objects that sit between the pulsar and magnetar populations. A follow-up study led to the discovery of dramatic variations in the pulse profile shape and polarisation over a period of 6 months, indicating the radio pulses likely originate from a highly dynamic, sunspot-like region within its magnetosphere. We have been working on a prediction for the gravitational wave background from the Massive Black II cosmological simulation in collaboration with international researchers.

Pulsar searching

A team reprocessed the data of the Parkes High Time Resolution Universe South Low Latitude (HTRU-S LowLat) pulsar survey using sophisticated GPU accelerated search algorithms on OzSTAR supercomputer at Swinburne. So far 60 new pulsars have been discovered, the most compelling of which is a new double neutron star (DNS) system, which has a 1.4 day orbital period but an orbital eccentricity of only e=0.064. This is the lowest eccentricity ever seen in a DNS system and shows some extremely interesting astrophysical consequences i.e., the neutron star radius can be asserted from the DNS with the lowest orbital eccentricity.

Pulsar glitches and young pulsar timing

Pulsar glitch detection with a hidden Markov model has been successfully tested using simulated data. We continued investigating how to link observed sequences of glitches to underlying physical models that track the stress in the neutron star over time. We looked at how long-term observable statistics change when considering glitches caused by history dependent vortex avalanches.

A team has applied Kalman filtering to pulsar timing noise in order to determine the properties of neutron stars. Analysis of data from UTMOST Timing Release I is underway, and work is in progress towards an automatic noise tracker in the UTMOST-2D portal.

Multi-Messenger Observations

Program chairs: Kendall Ackley and Eric Howell

The multi-messenger program within OzGrav aims to obtain new insights on astrophysical phenomena by combining GW data with data from other observational domains, such as the electromagnetic spectrum, neutrinos or cosmic rays. It includes observational, theoretical and data driven themes. Unfortunately, although a handful of candidate binary neutron star events were detected during the O3 run, there were no GW multi-messenger events.

Although the sensitivities of the GW interferometers had increased, allowing greater cosmological volume to be monitored, most of the follow-up observations were for events at the detection threshold (of order 200 Mpc) with large positional sky maps making electromagnetic follow-ups or joint detections challenging. However, the well demonstrated prompt reporting and communication between different facilities that has been well honed during this period will benefit future campaigns.

OBSERVATIONAL: ASKAP

The Australian SKA Pathfinder (ASKAP) telescope was involved in several projects over the past year which also involved participation in O3 follow-up and data analysis. We worked on constraining properties of neutron star merger outflows, the capability of ASKAP to detect prompt radio emission from GW events, the ASKAP survey of radio stars in circular polarization which lead to 23 new detections, as well as a publication on space weather implications on Proxima Centauri using observations from the Zadko telescope and NASA’s TESS instrument in an OzGrav cross-node collaboration.

OBSERVATIONAL: DWF

During 2020 the Deeper-Wider-Faster (DWF) program performed search and follow up observations for BNS and NS-BH EM counterparts and had additional involvement in a number of other events from deep wide-field imaging searches, candidate analysis and searches, and follow up spectroscopy and imaging. DWF used over 20 telescopes worldwide ranging from 1m to 10m optical and infrared telescopes, including Keck, SALT, Gemini, VLT, Palomar, DECam, SOAR, and ANU 2.3m.

DWF ran a successful 6-night coordinated run on Sept 14-19, 2020 for fast transients and FRB counterparts. The pandemic made for a very “interesting” run, coordinating ~25 telescopes all remotely and many simultaneously. DWF detected not one, but two new FRBs in the field of repeating FRB190711. This discovery is unprecedented in a number of ways, including simultaneous observations with multiple wavelengths on the FRBs before, during, and after their bursts and the detection of three FRBs all within about 40 arcmin of each other. No repeat bursts were detected by ATCA, Molonglo, or MeerKAT, thus the localisations of the two are FRBs leave some ambiguity in any deep counterpart search.

OBSERVATIONAL: GOTO

The prototype Gravitational wave Optical Transient Observer (GOTO) in 4-telescope configuration successfully followed up 30 gravitational wave triggers during the first half of the O3 run. GOTO tiled approximately 700 square degrees on average per event, representing over 45 per cent of the LVC probability map. Significant infrastructure development at the La Palma site saw the addition of 4 more telescopes, bringing GOTO closer to full design specifications with approximately 40-square degree field of view, and able to detect new transients down to 21st magnitude (L-band). Further funding has been secured from the UK STFC-PPRP to build a second “GOTO-South” node at Siding Spring Observatory, near Coonabarabran, NSW. The full GOTO network is expected to be operational in 2022, in time for the 4th LVC observing period (O4).

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.

DATA AND ASTROPHYSICS

OBSERVATIONAL: SkyMapper

Skymappers involvement during O3 involved optical (SkyMapper) and WiFeS spectroscopic (ANU) follow-up observation of GW transients. Follow-up searches centred on early kilonovae emissions associated with GW triggers. Similarly, SkyMapper performed follow-up of FRBs discovered by UTMOST's real-time FRB discovery system. Within minutes SkyMapper received details of the coordinates of 3 FRBs. Typically, the time of first observation can be archived 5-10 minutes after receiving an alert. During 2020 the team upgraded the SkyMapper facility for rapid EM follow-up observation of GW triggers. As a new branch of the Main Survey pipeline workflow, AlertSDP is now indispensable in making a prompt response to GW alert, an interactive (web-based) follow-up mechanism, and a near real-time data processing with high credibility.

In early-Feb 2020, the SkyMapper Team released the third data release (DR3) of the SkyMapper Southern Survey, expanding the deep coverage more than twice the fraction of previous data release. Nearly all Southern sky at |b|>10 deg has all uvgriz filters observed by the deeper Main-Survey exposures. In mid-Nov 2020, we installed new detector controllers in SkyMapper to replace some faulty boards, and finally have got a full mosaic for the first time in at least 18 months.

OBSERVATIONAL: Zadko

The Zadko telescope's follow-up of GW alerts during O3 primarily involved collaboration with the Global Rapid Advanced Network Devoted to the Multi-messenger Addicts (GRANDMA). This worldwide network consists 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 performed shifts, ensuring 24 hour monitoring. During O3 GRANDMA has followed up more than 85% of the GW alerts.

Optical instrumentation improvements aimed for O4 GW follow-up have been tested on the European Space Agency's (ESA) space situational awareness program. Zadko telescope has the capability to monitor potentially dangerous asteroids as distant as Mars and dangerous space rocks that may previously have been undetected near Earth. Further work for ESA involved continuous imaging of a space probe, BepiColombo, passing Earth while on a journey to Mercury (see "Science Highlights" section). BepiColombo was launched in 2018 to study Mercury's magnetic field and its interaction with the solar wind, and could provide insight into how the Earth and solar system formed.

An additional collaboration cemented in 2020 involved the French space agency who are building a new global array of receivers for low Earth orbit satellites. The Zadko team is leading the Australian part of the network. The first satellite which will use this new network will be SVOM, to be launched late 2022. SVOM will be a highly versatile astronomy satellite, with built-in multi wave-length capabilities, autonomous re-pointing and dedicated ground follow-up.

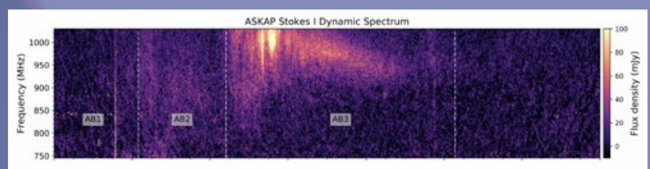
Depiction of a flare-coronal mass ejection event on Proxima Centauri. Credit: Mark Myers, OzGrav Swinburne

Case study:A Flare–Type IV Burst Event from Proxima Centauri and Implications for Space Weather

Space weather events around red dwarf stars, such as explosive ejections of energetic plasma often observed from the Sun, may wipe out any life on their companion planets. However, to date, observations have provided little information about the space weather around other stars. Last year two OzGrav nodes (OzGRAV-UWA and OzGrav-U Sydney) led simultaneous observations with the Australian SKA Pathfinder (ASKAP) telescope, the Zadko telescope, and others including with NASA's TESS space telescope, targeting our closest neighbour: the planet-hosting red dwarf, Proxima Centauri.

The low-frequency radio emission from M-dwarf flares enables a probe of planetary environmental conditions, and therefore, the habitability of their planetary companions. Photometric monitoring with TESS and the Zadko 1m Telescope reveal a large and long-duration flare. Simultaneous spectroscopic monitoring with the WiFeS spectrograph on the ANU 2.3m telescope showed strong enhancements in Hα and other chromospheric emission lines, indicating substantial deposition of energy into the chromosphere. Radio observations with ASKAP reveal a sequence of coincident, intense, and coherent bursts associated with this flare.

Simultaneously, the polarisation and temporal structure of the burst reveals a type IV, or solar-like, radio burst. Solar type IV bursts are characteristically associated with space weather events, such as coronal mass ejections and solar energetic particle events, as they indicate on-going electron acceleration following large flares. By association, they can be used as a tracer of stellar coronal mass ejections. This is the first sign of space weather on another star and has implications for planetary habitability on exoplanets and other M-dwarf systems. The observations revealed the signature of a powerful explosion ejected from the star, indicating that space weather around red dwarfs may be as violent as feared.



Credit: Andrew Zic/University of Sydney/CSIRO

Relativistic Astrophysics

Program chair: Paul Lasky

The field of relativistic astrophysics is devoted to the study of high-energy astrophysics, particularly concerned with extreme energies, velocities, and densities. The increased and rapid development of high-time resolution multi-messenger transient astronomy continues to drive growth in our understanding (and lack thereof) of compact and fast systems.

A prominent and timely example is fast radio bursts (FRBs) and their recently-confirmed connection with highly-magnetised neutron stars. In April 2020, the soft-gamma repeater SGR 1935+2154 was simultaneously caught emitting a fast radio burst and bright x-ray counterpart. While these observations have confirmed the connection between these two enigmatic phenomena, there are still a number of fundamental open questions requiring more observations and deep, thoughtful theoretical consideration. For example, the specific emission mechanism providing the coherent radio emission is not understood; it is not known whether there is a single family of FRBs or separate populations of repeating and non-repeating bursts; and it is not clear how to scale up the total luminosity from the radio burst associated with SGR 1935+2154 to those seen extragalactically. A timely ARC Linkage, Equipment, Infrastructure, and Facilities (LIEF) grant has been awarded for an upgraded backend to the Australian Square Kilometer Array Pathfinder (ASKAP) for the purpose of detecting FRBs.

Gravitational wave observations continue to provide their share of mysteries, ensuring relativistic astrophysicists have no lack of interesting problems to study. Of particular note is the gravitational wave observation GW190814. The secondary mass of this system straddles a confusing region of parameter space, with a well-measured mass of 2.6 ± 0.1 Msolar. Such a mass could imply this is the most massive neutron star measured to date, or the least massive black hole, although both of these interpretations are not without their problems. From a neutron star/nuclear physics perspective, some equations of state can be constructed to account for such a massive system, however these are generally inconsistent with inferences made from the tidal deformability of the first gravitational wave binary neutron star observation GW170817, and terrestrial results from heavy-ion collision experiments. On the other hand, if one interprets the secondary of this system as the least-massive black hole observed to date, then this calls into question our understanding of its formation mechanism. In particular, such an extreme mass ratio (0.11) and component masses are difficult to explain with population synthesis (even if the secondary is a neutron star this is true). Announcement of O3b observations in the coming months, including events initially classified as neutron star-black hole mergers, may or may not provide interesting new insight into the nuclear physics and/or formation mechanisms of systems such as GW190814.

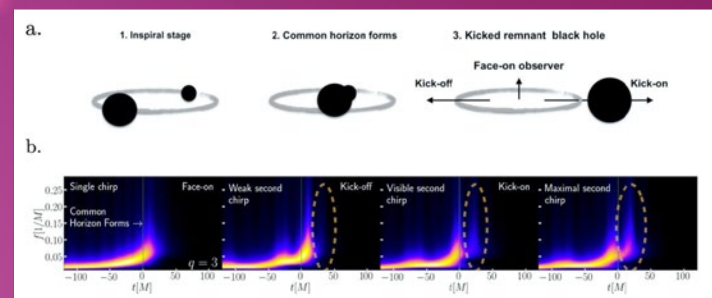
The NANOGrav collaboration's technical announcement of a "common-spectrum process" has certainly caught the attention of pulsar astronomers and relativistic astrophysicists alike. Confirmation of this signal by the PPTA, as well as ongoing international efforts within the IPTA seem to indicate this is real, but the cause of the signal remains unknown. This has provided a new playground for theorists, who have already published more theoretical ideas for the source of the common-spectrum process than there are posterior samples describing it. Whether the signal is really supermassive binary black holes, whip-cracking cosmic strings, primordial fluctuations from inflation, or a result of Planet X, 2021 should see an exciting period of activity trying to understand these observations.

Case study: Two chirps for the price of one

In 2016 the world is abuzz with the announcement of the first detection of gravitational waves from merging black holes. Scientists are celebrating the birth of a new field of astronomy by performing the now-recognisable "chirp": an audio adaptation of the characteristic gravitational wave signal two black holes make when they coalesce and merge.

Sometimes, it seems, when two black holes merge, they chirp not once, but twice or more!

In 2020 we used numerical relativity simulations to show that, if a merging system is observed edge on, the frequency and amplitude of the signal goes up and down a few times before eventually switching off. In other words, the signal chirps several times. This result can in principle allow for detailed studies of the black hole horizons as they merge and eventually settle into their final form. Such studies have the potential to ultimately provide the most stringent tests of general relativity in the ultra-strong field regime.



Credit: Calderon Bustillo, Evans, Clark, Kim, Laguno & Shoemaker

DATA AND ASTROPHYSICS

Population Modelling

Program chair: Simon Stevenson

A highlight for the year was the publication of the second LIGO-Virgo Gravitational-Wave Transient Catalog (GWTC-2), detailing results from the first half of the third LIGO/Virgo observing run (O3a), authored by the LIGO and Virgo collaborations and many OzGrav members. This catalogue presented almost 40 observed gravitational waves. Another ~30 GW candidates were observed in the second half of O3 (O3b).

Among these were a handful of **exceptional** gravitational wave events, **things we have never seen before.**

GW190425 was the second binary neutron star merger observed, and is notable for being more massive than any binary neutron star known in our own galaxy. This raised the question of how such a binary formed, and why we don't see similar binaries in the Milky Way. We suggested that GW190425 may have formed through the evolution of a binary through unstable mass transfer, leading to the formation of a fast-merging binary neutron star. The short lifetime provides a natural explanation for why we haven't seen these binaries in the Milky Way. We showed how we can measure the mass distribution of binary neutron stars observed with both gravitational waves and radio.

GW190814 was the most asymmetric binary merger observed by LIGO/Virgo to date, with the smaller compact object being almost ten times less massive than its companion. This compact object––2.6 times the mass of the sun––lies in the mass gap between neutron stars and black holes and is either the lightest black hole or the heaviest neutron star ever observed. This may have important implications for the maximum mass of neutron stars.

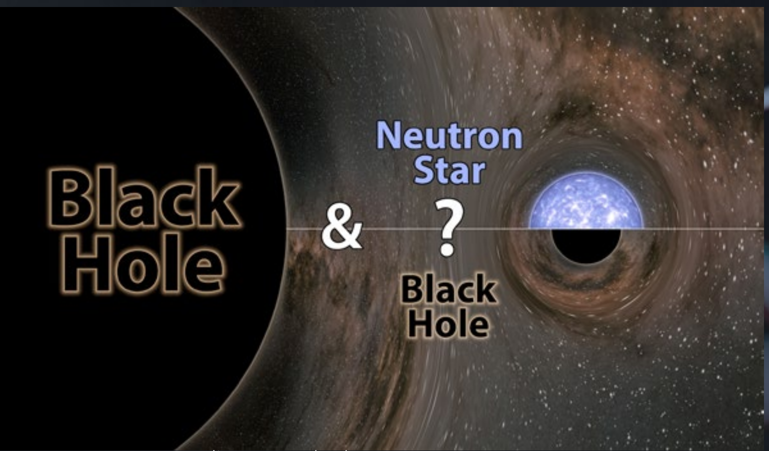


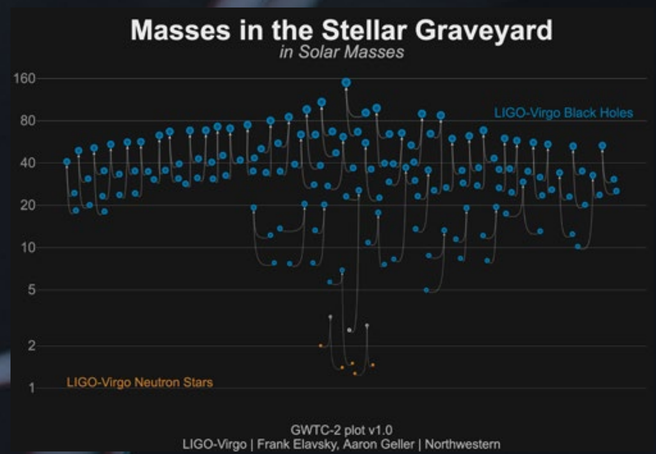
Image credit: LIGO/Caltech/MIT/R. Hurt (IPAC).

Work has continued to develop phenomenological models which can be used to understand the populations of compact object mergers, further developing techniques to infer the population properties of merging compact object binaries when you are unsure how real a given event is. This is important to allow us to drill down into the noise and extract the maximum amount of information from the observed population.

Another highlight of 2020 was the release of the COMPAS binary population synthesis suite (www.compas.science), released publicly in April 2020. We led a study using COMPAS of the population of pulsar-black hole binaries in the Milky Way which may be observable by future radio surveys. We incorporated a model of the evolution of chemically homogeneous evolution of tight, massive binaries in COMPAS. We study what fraction of binary black hole mergers are expected to form in this way, finding that it may be up to 70% of all gravitational wave detections from isolated binary evolution.

We developed a new probabilistic model of the remnant masses of neutron stars and the kicks they receive in core-collapse supernovae and incorporated it into COMPAS. Team members used COMPAS to investigate populations of neutron star and black hole binaries. We developed and published METISSE, a new rapid stellar evolution code which interpolates stellar models on the fly, allowing for a wider variety of stellar models to be used in population synthesis simulations.

A team is investigating the dynamics of hierarchical triple systems and making predictions for the populations of sources observable by the future space based gravitational wave observatory LISA.



Case Study: Populations of compact binaries in the second LIGO-Virgo Gravitational Wave Transient Catalog

As the size of the population of gravitational waves expands, the level of detail that can be extracted about the properties of the population increases. We fit a number of phenomenological models to the data from the first three observing runs in order to understand the distributions of the masses and spins of merging compact binaries, and determine the rate at which they occur in the Universe.

The main features of the black hole mass distribution––a power law in mass––remained consistent with results from the first gravitational-wave transient catalogue (GWTC-1). The observation of GW190521 and other massive black hole binaries however led to the need to revise these models and allow for the existence of higher mass black holes; the collaborations find that less than 3% of black holes in merging binaries have a mass greater than 45 times the mass of the sun.

Modelling by the LVC provides evidence that a substantial fraction (12–44%) of binary black hole mergers have components with spins tilted by more than 90 degrees with respect to their orbit, which is highly suggestive of dynamical formation. This hints that dynamically formed binary black holes contribute significantly to the observed population of binary black holes.

We also present the most precise measurement of the rates of binary neutron star and binary black hole mergers in the universe to date. We found the binary neutron star merger rate to be comparable to that inferred from binary neutron stars observed by radio telescopes in our own Galaxy. We also find that the rate of binary black hole mergers in the universe most likely increases with redshift, but less steeply than the star formation rate increases. This may have implications for the formation of binary black holes.

OzSTAR supercomputer. Credit: Carl Knox, OzGrav Swinburne

OzSTAR supercomputer

Leader: Jarrod Hurley

The Swinburne OzSTAR supercomputer continued to provide vital data and computing resources for OzGrav researchers with 98% uptime across 2020. OzSTAR provides OzGrav researchers with access to approximately 6,000 compute cores, 230 Nvidia P100/V100 GPUs and 6 PiB of storage on a lustre filesystem.

OzGrav usage on OzSTAR in 2020 was spread across 26 distinct research projects and over 120 users. The combined OzGrav usage was 45% of OzSTAR averaged over 2020 which represents 24 million hours of data processing and simulations. The Monash University node was responsible for about half of this usage.

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

- "Rapidly and Optimally Identifying Gravitational Wave Optical Counterparts for GOTO", CI Kendall Ackley (Monash);
- "GPU Acceleration of the DiFX Software Correlator", CI Adam Deller (Swinburne);
- "Optimising Parallel Bilby (pBilby)", CI Rory Smith (Monash);
- "A Web-based Portal for COMPAS", CI Simon Stevenson (Swinburne);
- "Optimisation of the COMPAS Rapid Binary Population Synthesis Code", CI Ilya Mandel (Monash);

where each project was selected through a competitive time assignment process. In total about 40 developer weeks were contributed to these projects. This is in addition to advancements made to the following key projects that receive dedicated support via the GWDC: the SPIIR search pipeline (e.g. a formal workflow for code development and regression tests implemented); the GWCloud parameter estimation interface (e.g. fully functioning workflow implemented with LIGO authentication, job submission, the ability to download results and browse job history); the GWLab laboratory for continuous wave workflows (e.g. prototype developed for the first science module) and the MeerTime access portal for pulsar data (e.g. React user interface deployed with enhanced metadata and visual overview of data, optimised data-transfer pipeline between MeerKAT and OzSTAR).

The OzSTAR environment was enhanced through work to reconfigure and upgrade the OzSTAR network and storage infrastructure. In 2020 we expanded OzSTAR into a second row of racks, moved the storage infrastructure to the new racks and installed a high-performance low-latency network between the storage and compute servers. We also procured the hardware to expand the storage capacity to approximately 12 PiB. The installation of this hardware will be completed early in 2021.

Two big advancements for 2020 were connection of OzSTAR into the Open Science Grid (OSG) and implementation of the process for transferring LIGO data onto OzSTAR using Rucio. We now have the O1-O3 datasets available and data from an entire run can be transferred in no more than a few days across the 10Gb network. With these advancements OzSTAR is essentially operating as a LIGO Tier 3 Data Centre (official certification will occur in early 2021). A further advancement involved the OzSTAR job monitoring system with improvements including the addition of accurate memory usage information which has critically allowed GW users to troubleshoot issues with jobs and optimise their workflow. These updates have also facilitated easy identification of job scheduling bottlenecks, freeing up unused resources and helping the jobs of GW users to begin more quickly.

Finally, in collaboration with the GWDC a Machine-Learning Webinar was delivered. The key speaker was Hunter Gabbard from the University of Glasgow who spoke on "Bayesian parameter estimation using conditional variational autoencoders". The webinar was delivered by videoconference and included a hands-on TensorFlow tutorial.

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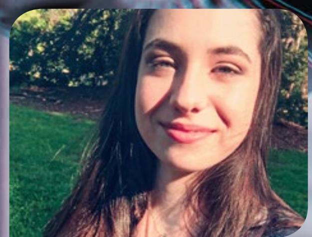
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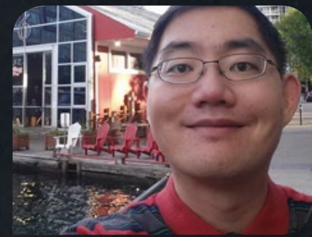
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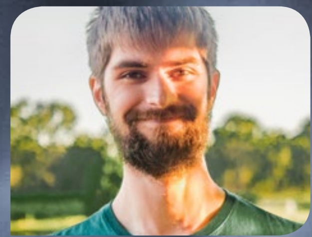
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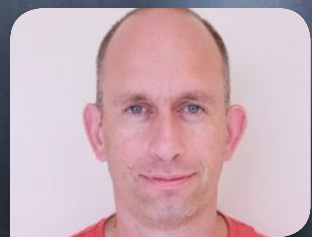
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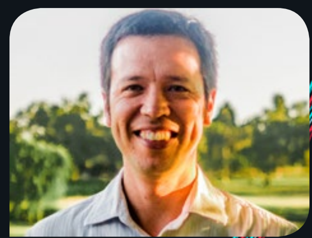

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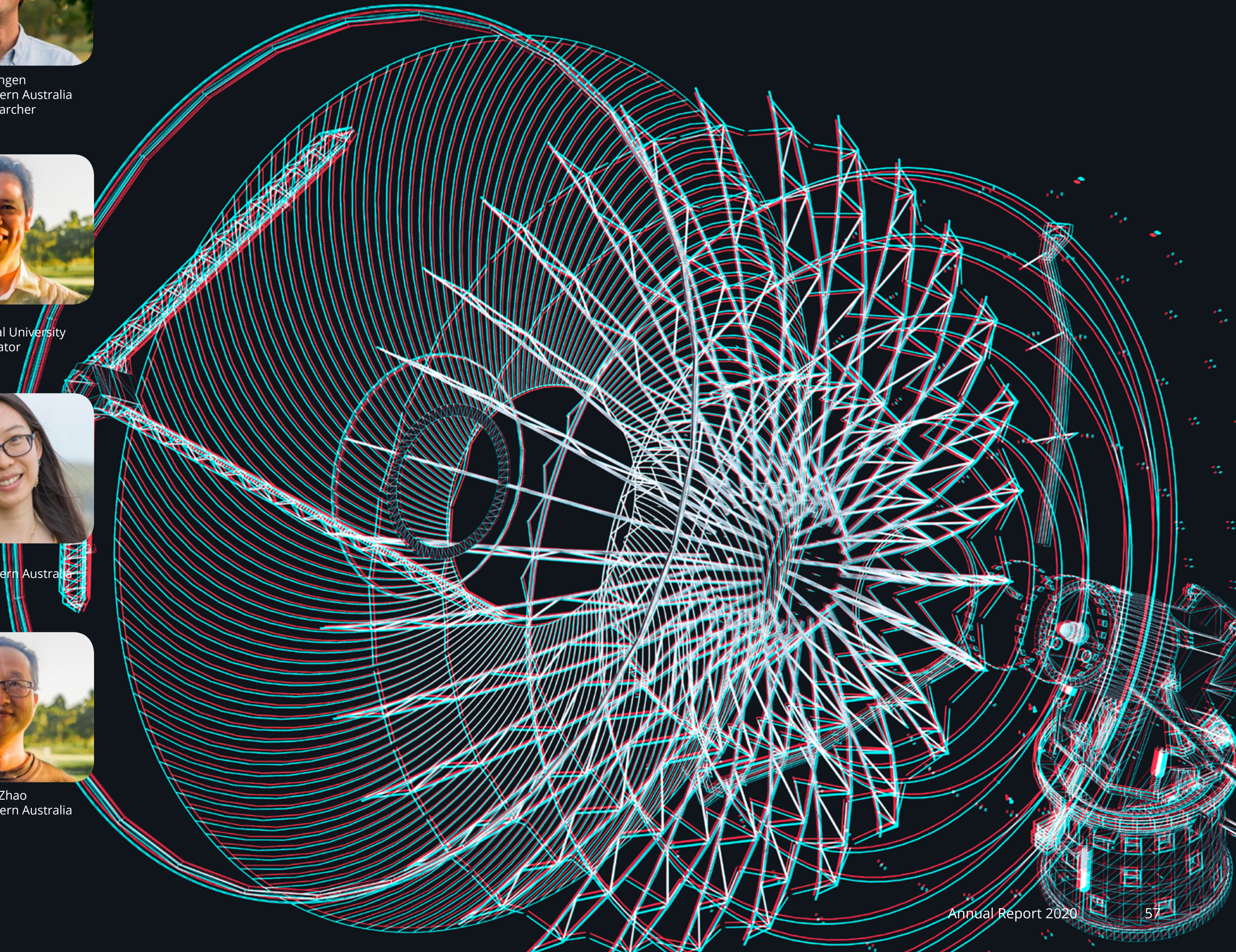

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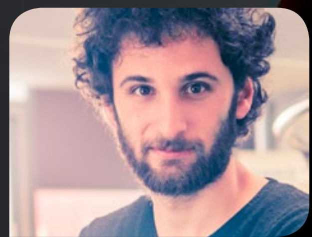

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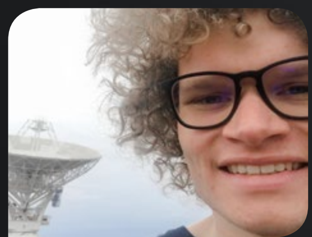

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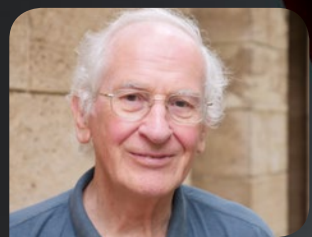

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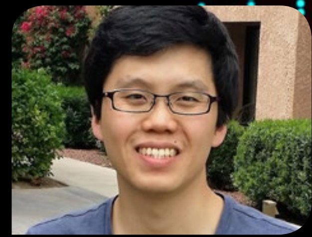

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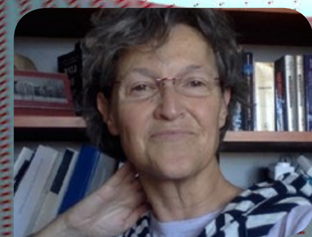

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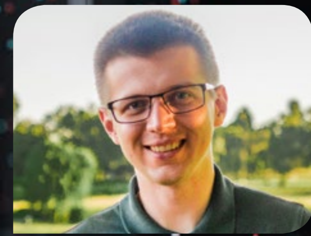
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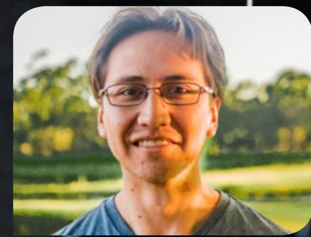
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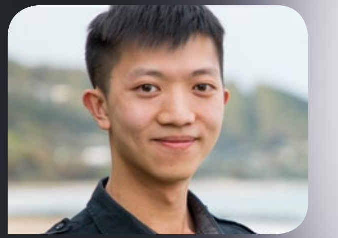
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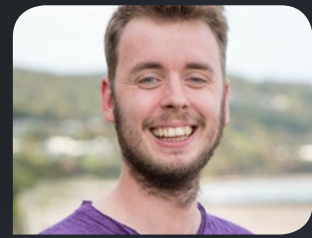
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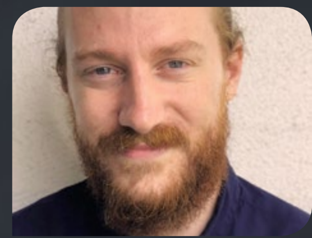
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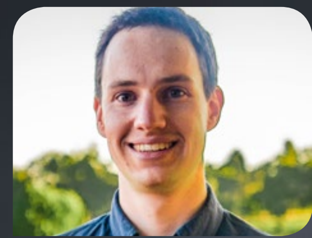
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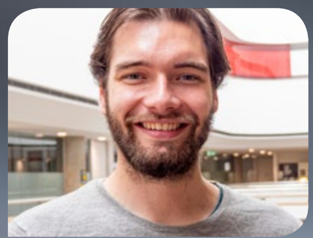
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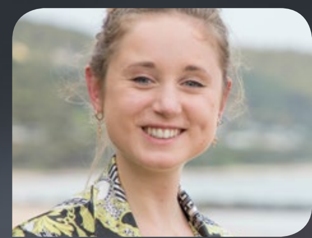
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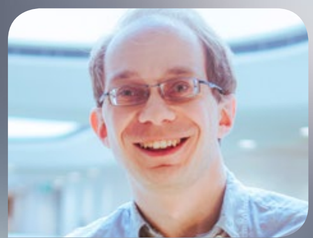
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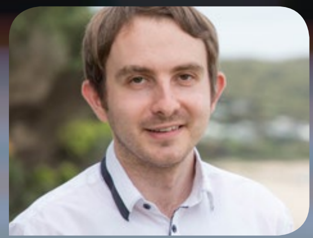
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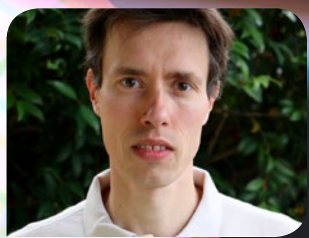
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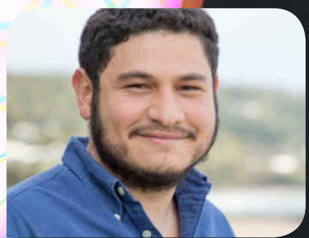
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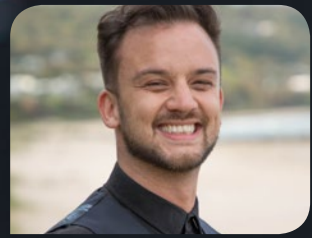

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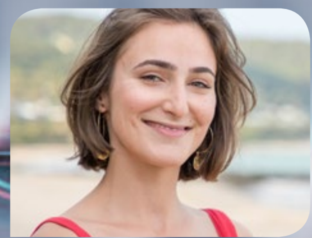

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SUPPORTING OUR MEMBERS DURING THE GLOBAL PANDEMIC

Chief Investigator Dr Paul Lasky (Monash) delivered a gravitational waves talk to a group of Wundergym artists titled 'The Biggest Explosion in the Universe'. Artists created their own work based on Paul's talk, and were fortunate to be able to host a socially-distanced exhibition in Collingwoodin late 2020. Paul (left) is pictured here with Artist Jasmin de Wolf with her artwork (right and below) titled "We don't know how black holes grow." Visit the online exhibition at https://wundergym.co/polly-borland-project-1

The global pandemic that began in early 2020 has impacted our Centre in a wide range of significant ways. Universities are facing financial hardship due to loss of international students. This had led to some freezes on hiring, spending, and other cost-saving measures, which affected our Centre both directly and indirectly. In addition, international travel restrictions have prevented/delayed some of our members from taking up new positions overseas, while also preventing/delaying new international staff & students from commencing work with our Centre. Our important onsite commissioning work at the LIGO sites in the USA has been put on hold and the planned upgrade to Advanced LIGO will take longer than initially forecast.

Restricted access to campus meant that some members had limited laboratory access in 2020 and many members worked from home for most of the year. This limited productivity to varying levels, depending on factors such as an individual's caring responsibilities and how critical lab access is to their research. Our members - like so many people around the world - felt stress and anxiety due to concerns about career continuity, the health of themselves or loved ones, and social isolation.

In 2020, OzGrav prioritised supporting the wellbeing of our members as the top priority, and we responded to the impacts of COVID-19 by:

- Providing mental health and wellbeing support for members, and increasing the frequency of supportive internal communications.
- Using strategic funding and unspent travel budgets to support personnel whose career continuity would otherwise be affected by travel restrictions, to enable them to continue working on high-impact OzGrav projects.
- Keeping informed of, and adhering to, all government and university COVID-safe policies.
- Switching in-person conferences, meetings, and outreach events with virtual options to maintain work networks and collaborations.
- Continuing with any commissioning or lab activities that can be performed remotely, and when research was impacted, we encouraged diverting efforts to other important OzGrav activities such as writing publications and performing modelling studies.

PROFESSIONAL DEVELOPMENT COMMITTEE

In 2020 the OzGrav Professional Development Committee (PDC) comprised Susan Scott (ANU, Chair), Yeshe Fenner (Swinburne, Secretariat), George Howitt (Uni Melbourne), Karl Wette (ANU), Sundae Chen (UWA), Duncan Galloway (Monash), David Ottaway (Adelaide), Kendall Ackley (Monash).

The PDC continued to support and interact closely with the Early Career Researcher Committee (ECRC) (members Poojan Agrawal, Shon Boublil, Zac Holmes, Moritz Huebner, Meg Millhouse, Terry McRae), which plays a major role in putting together the program for the annual ECR workshop, as well as providing important advice and representation on other matters related to training and professional development.

The mentoring program continued to grow throughout 2020, with many new members signing up. Based on feedback from various surveys, we ran a more formal mentoring induction webinar in December, using an external facilitator. We received very positive feedback from those who attended.

The PDC and ECRC organised two webinars throughout the year: one in June 2020 on "How to prepare for your next job interview" with panellists OzGrav CIs Matthew Bailes, Andrew Melatos, David Ottaway, Chair Susan Scott; and one on resilience and self-care during turbulent times in April 2020.

Throughout 2020 the PDC was very mindful of the effects of the pandemic, and the various periods of lockdown, on OzGrav's Early Career Researchers (ECRs). In response, information relating to mental health and wellbeing was posted on the OzGrav website and, through our weekly centre-wide videocons, the ECRs were encouraged to reach out for support where needed. We also established a COVID funding scheme to support personnel whose career continuity would otherwise be affected by travel restrictions, to enable them to continue working on high-impact OzGrav projects.

The PDC and ECRC planned and ran the two-day ECR part of the OzGrav Annual Retreat, on 23-24 November 2020, which was largely a virtual event due to the pandemic. The program was vibrant and well-rounded incorporating sessions on scientific paper writing, applying for jobs, a careers panel, managing stress, and equity and diversity, as well as some virtual social activities. Feedback sought from the ECRs following the retreat indicated that they were very pleased with the ECR Workshop part of the Retreat.

Case study: Mentoring

Through the external internship program IMNIS I (Josh McCann, PhD student at UWA) was assigned an industry mentor for 1 year. This connected me with the Head of Climate change and Energy at Rio Tinto Gerard Danckert. We met monthly for 2-3 hours. Through this not only did I gain new knowledge of Industry but I was able to detail what OzGrav does in both a casual and formal setting. We did have a presentation planned for me to present my work to Rio Tinto staff but this was put on hold due to COVID-19. We have since finished the mentoring year but remain in contact.

Images: Carl Knox, OzGrav Swinburne

EQUITY AND DIVERSITY COMMITTEE

The Equity and Diversity Committee continued to implement OzGrav's Equity & Diversity Action Plan in 2020, while also responding to the Black Lives Matter movement and the impact on our members due to the global pandemic.
The committee's 2020 activities include:

- In response to the impacts of the global pandemic, we ran a webinar on "Resilience during Turbulent Times" and "Resilient Researcher's Stress Survival Kit". We also acknowledged the challenges of this year regularly during our weekly centre-wide Videocon and newsletters, and encouraged node and team leaders to have regular check-ins with staff and students.
- We ran an Acknowledgement to Country Prize, which resulted in the selection of two winning designs created by local Wurundjeri artists. One of the designs is being incorporated into a set of digital assets (e.g. PowerPoint slide, email footer) while the other design is being incorporated into a physical Acknowledgement plaque that will be installed at OzGrav headquarters at Swinburne University. We are hoping to unveil that plaque during National Reconciliation Week in May 2021.
- We launched a monthly Equity & Diversity Journal Club jointly with the Astro3D Centre of Excellence, the first of which focussed on systemic racism and the Black Lives Matters movement. The EDC also discussed at its meetings how OzGrav could make positive changes with respect to systemic racism.
- We delivered our schools program "Mission Gravity" to some regional and low socio-economic schools. While our original plans to run these as in-person events were derailed due to COVID-19, our team did an outstanding job rapidly converting the Mission Gravity experience to remote online delivery. This allowed us to continue to roll out our program at a time when teachers were keen to incorporate new engaging online lessons.
- The Annual Retreat included a round table interactive session on intersectionality, and a talk on how to respectfully engage with indigenous communities.
- OzGrav submitted an application for a Silver Pleiades award to the Astronomical Society of Australia in 2020, which articulated our efforts and progress in supporting diversity and inclusion. The outcome will be announced in 2021.
- One of our nodes (ANU) created and filled a woman-only Level B-D position to help address the gender imbalance in the Australian gravitational wave community.

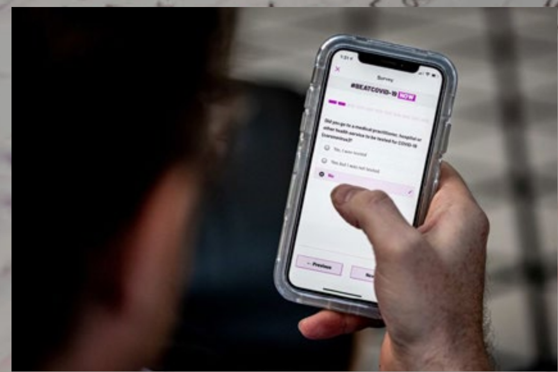
Image credit: Mike Lau, OzGrav Monash

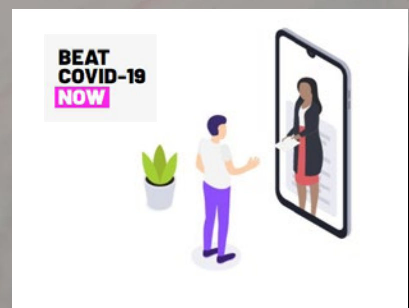
RESEARCH TRANSLATION COMMITTEE

In 2020 the OzGrav Research Translation Committee (PDC) welcomed new member Dr Robin Fieldhouse, head of Major Research Partnerships & Initiatives at the Australian National University, and we thanked departing member Fiona Nelms (ANU) for her contributions.

2020 was a challenging year due to the impacts of the global pandemic. The travel restrictions and lockdowns in Australia significantly limited our opportunities for industry engagement and briefings. Nevertheless OzGrav members managed to make progress on several fronts. Notably, the global challenges of COVID-19 and bushfires were catalysts for new projects applying astronomy expertise to address these crises:

- Supernova detection techniques were exhibited to a national workshop on fire detection and a proof-of-concept demonstrated that new bushfires could be detected by comparing infrared satellite images using astronomical techniques.
- OzGrav members teamed up with public health experts to develop an app to track COVID-19 symptoms and detect possible outbreaks of COVID-19, even before testing takes place. This project also attracted some high-profile media coverage on ABC News online.





Beat COVID-19 Now app. Top image credit: Brendan Esposito, ABC News. Bottom image from Beat COVID-19 Now app https://beatcovid19now.org/

Other Research Translation highlights in 2020 are described elsewhere in this report, including:

- OzGrav members working with industry partners in a $8.7M CRC-P-supported project to develop, design and manufacture optical gyroscopes for high-precision autonomous navigation
- OzGrav Chief Investigators are part of a multi-party collaborative agreement with the Defence Science Technology Group, funded by the Next Generation Technologies Fund, to develop phased array technology to enable wideband simultaneous multi-function RF capability from a common aperture.

We ran an industry/academia panel session at our annual workshop, and organised a workshop to introduce financial modelling experts from the ANZ bank to the data analysis techniques developed by researchers from OzGrav and the Gravitational Wave Data Centre.

An ECR-led project that OzGrav supported though a Research Translation Seed fund made further progress in 2020 and were awarded a small research contract with CMG Operations to explore applications for their LIDAR technology.

In 2020, we produced an Industry Success Stories brochure (available on our website) to showcase OzGrav's achievements in ensuring that new gravitational wave technologies make it out of the lab and into the real world to have lasting impact across a broad range of areas.

Baclground image credit: Michael Bishara, OzGrav Swinburne

ACTIVITY PLAN 2020

Instrumentation

Commissioning. Program chairs: David Ottaway and Bram Slagmolen

Plans on hold due to COVID-19 and international travel bans.

Quantum. Program chairs: Sebastian Ng and Robert Ward

Cryogenic silicon test masses remain a key technology in high frequency and third generation gravitational wave detectors. The development of the Einstein Telescope Pathfinder, Mariner as well as the interest in high frequency detectors compel the continued development of ultra-stable two micron lasers and squeezed light sources. Continuing projects this year will include the demonstration of thulium distributed Bragg reflector master oscillators and their integration with high power thulium fibre amplifiers, the collaborative development of a squeezer pump laser based on the 2µm ECDL designed in Canberra and fibre preamplifier source under construction in Adelaide as well as the integration of the 5W 2µm laser with the Gingin test facility. These lasers sources will aid in the continued development of the 2µm squeezed light source.

A key focus for this year will be research into novel signal enhancement techniques. This will include further investigation of white light cavities with optomechanical filters such as quartz bulk acoustic wave resonators and the demonstration broadband signal enhancement with non-degenerate internal squeezing. A primary aim for 2021 is to expand the collaborative research programs initiated in 2020 including internode collaborations such as light source development, mode matching control and photodiode development.

Deliverables:

- Demonstrate and Characterise high-bandwidth phase lock of broad linewidth laser.
- Assemble and deliver fibre amplifier for squeezing.
- Assemble and characterise medium power thulium amplifier stage.

Low frequency. Program chairs: Ju Li and Bram Slagmolen

Complete characterization of thinner flexure and anti-spring of the tilt sensor. Design and begin construction of second tilt sensor incorporating all upgrades for improved sensitivity and robust operation.

Deploy seismometers to form a large seismic array and the wireless system. Develop effective Seismic data acquisition method. Start array data analysis. Continue to develop feedback/feedforward for the isolation system and evaluate NN noise cancellation strategy.

Improve Tilt sensor characterisation.

Second tilt meter built and noise evaluation.

Current best effort TorPeDO readout (in-air).

Merge TorPeDO with Full Suspension Chain.

Initial readout with TorPeDO fully suspended and under vacuum.

Finalise LaCoste-Euler spring design and test the performance.

Initial performance of the digital enhanced optical interferometry system will be achieved.

Distortions and Instabilities. Program chairs: Carl Blair and David Ottaway

There are two important projects: the Gingin Silicon Coupled Cavity Experiment; and the Compression Fit Mirror (CFM) actuator. We expect to enter the first experimental phase of the Gingin Project in 2021. Phase 3 will be a cryogenic coupled cavity with expected completion in 2023. The CFM has been adopted for LIGOs Observation Run 4 (O4) so will soon transition to a commissioning project.

The imaging of parametric instability with the phase camera has been rolled over into 2021 due to COVID-19 delays. A new collaboration has formed developing CFMs for the recycling cavity of the Gingin Silicon coupled cavity experiment.

New projects include the Gingin scattered light project that will be used to be used to identify excess loss in the Gingin East arm cavity, the experimental demonstration of the temperature distribution estimation technique and subsequent commissioning, and the experimental demonstration of independent optical Eigen frequency control.

Parametric instability simulations and mitigation in NEMO.

Correction thermal errors in the NEMO Beamsplitter.

Coating and characterising Gingin silicon test masses.

Hang first mirrors in Gingin south arm.

Compression fit mirror commissioning.

Phase camera image of parametric instability.

Machine learning interpretation of phase camera images.

Commissioning temperature distribution estimator.

Space Instrumentation. Program chair: Kirk McKenzie

In 2021 the Program will continue on three main activities: 1) continue the activity for weak light phase locking; 2) pursue absolute laser frequency knowledge measurement; and 3) laser frequency stabilization for space based interferometers.

Improved weak light phase locking enables a range of options for future space based gravitational wave detectors, in particular, longer arms which could improve sensitivity or smaller telescopes to reduce payload size and mass. The main task this year is a high fidelity hardware-in-the-loop simulation of phase tracking at low optical powers. Here the FPGA based phasemeter used in the laboratory is fed simulated data, enabling detailed investigation of the phasemeter at well controlled simulated low power tracking.

Knowledge of absolute laser frequency is important for space-based detectors in two ways: 1) To improve acquisition of the laser link between the spacecraft, reducing the number of degrees of freedom from five, (pitch and yaw error, for two spacecraft, and laser frequency difference between spacecraft), to four; and 2) To measure spacecraft separation accurately, and thus gravitational waves amplitude. The laser frequency (or wavelength) is used like a ruler.

For laser frequency stabilization the program will continue to push both Tilt-locking and arm-locking. We expect to be able to have publication quality results before the end of 2021.

Pulsar Timing. Program chair: Matthew Bailes

Key deliverables in 2020 inlcude:

Make MeerTime data available on the gravitational wave data portal.

Adapt UTMOST 2D FRB detector to be a pulsar glitch monitor.

Commence SKA construction for Pulsar Timing.

Image credit: Michael Bishara, OzGrav Swinburne

Future Detector Planning. Program chairs: Matthew Bailes and David McClelland

Complete site selection study report.

Continue CE and CDE South networks study.

Continue Australian site facility study and cost analysis to 50%.

Publish GWC3G study.

Data and Astrophysics

Inference. Program chairs: Greg Ashton and Rory Smith

LIGO/Virgo are preparing for the fourth observing run (O4). To facilitate electromagnetic follow-up of binary neutron star systems, we will develop and deploy rapid Bayesian codes to estimate optimal skymaps in latencies of a few minutes (down from tens of hours). The skymaps will provide electromagnetic astronomers with the smallest region on the sky to search over.

We will continue to analyse O3b candidates within the LVC, with some possibly being exceptional candidate events meriting their own publication.

Bilby and Parallel Bilby will continue to be developed and supported as flagship inference codes of the LVC.

To keep up with the event rate in O4, we will develop reduced order models of state-of-the art binary black hole signals for rapid parameter estimation with (parallel) Bilby. We will develop numerical relativity surrogate models for eccentric binary black holes to facilitate precision measurement. Low latency Bayesian sky localization of binary neutron stars for rapid EM followup in O4+. Reduced order models for binary black hole signals with higher order modes.

The O3b catalogue and O3b populations papers should be released in 2021.

Members joined OzGrav's effort with third-generation detectors, contributing to the Cosmic Explorer design study. We will continue to develop methods for the challenging field of performing inference on gravitational waves in the third-generation era.

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

Members will be analyzing O3 and pre-O3 data, developing new analysis methods and tools, and getting ready for O4.

The team will improve the SPIIR pipeline on the detection performance using new statistical models and improve the latency of the pipeline with new computing techniques. The SPIIR team is going to publish the result for early-warning tests and perform the code review of the new pipeline for O4. We will capitalise on existing CBC techniques and develop new methods to search for FRB coincidences with collaborators from the MWA CRAFT team and using data from the powerful CHIME radio telescope. We will also be contributing to the LIGO/Virgo GRB search paper using O3b data, and completing post-O3 early warning tests and infrastructure.

Many analyses using O3 data are carried through from 2020 and will be published in 2021. These include a Viterbi search for CWs from Scorpius X-1, a Viterbi search for CWs from 17 low-mass X-ray binaries, CW searches for 12 young supernovae remnants, searches for CWs from ultralight boson clouds, a stochastic background isotropy analysis, searches from known pulsars in a narrow frequency band around electromagnetically-constrained rotational evolution, and unmodeled burst searches. Analysis of LIGO open datasets, and development and refinement of new and existing data analysis algorithms will also continue.

ACTIVITY PLAN 2020

Pulsar Detections. Program chairs: Hannah Middleton and Ryan Shannon

Pulsar timing: we intend to complete two high impact studies using MeerKAT. One is an experiment to model the radio eclipses of the relativistic pulsar J0737-3039A by its currently unseen pulsar companion (J0737-3039B; "Pulsar B"). The eclipses provide a novel method to track the rotational phase of Pulsar B without detecting radio pulses from it, as well as enabling studies of the relativistic plasma trapped within its magnetosphere. Another is a scintillation analysis of PSR J0437-4715 to map the structure of the ISM in the direction of this very bright nearby pulsar, and to study the bow shock surrounding the pulsar. We will also develop an automatic data processing pipeline for MeerKAT that will be used to facilitate timing analyses within and outside of OzGrav.

Inference: Work is underway to search the PPTA-DR2 and IPTA data sets for gravitational waves and other spatially correlated processes. We intend to complete a first study early in the year to attempt to replicate the NANOGrav results with the PPTA DR2. Detailed analysis of PPTA and IPTA data sets will continue throughout the year. We will also deliver high precision mass and distance estimates to the millisecond pulsar J0437-4715, which will be used in conjunction with NICER X-ray observation to explore nuclear equations of state.

Young pulsars and pulsar searching: An analysis of 74 pulsars observed over 4-30 years by the Parkes radio telescope by members at Swinburne University, CSIRO, and the University of Melbourne will be wrapped up in early 2021. The project aims to deliver the most complete sample of glitches for these pulsars to date, in addition to exploring whether they are related to the anomalously high braking torques detected in some pulsars. We will also complete the real-time glitch detection system from the UTMOST timing programme. We will collaborate with the population modelling group to discuss the implications of our discovery of the low eccentricity double neutron star system.

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

Although O4 is not due till 2022, preparation will be underway this year for follow-up of GW transients. The observational capabilities available will include: Optical imaging (Skymapper, Zadko, GOTO-South, Huntsman, KMTNet, LSGT, LOCGT), optical spectroscopic (AAT AAOmega, ANU 2.3m WiFeS) , IR imaging (DREAMS), and radio (including VLBI, ATCA, ASKAP, Parkes, Molonglo). There are plans to roboticise the ANU 2.3m instrument, which will enhance the automated follow-up efforts during O4.

Coincident searches for multi-messenger sources are planned with GOTO-ASKAP and GOTO-CTA in preparation for O4 as well as continued collaboration with Caltech-GROWTH BNS and BN-NS counterpart searches with CTIO DECam and ZTF (Swinburne). GRB counterpart searches will be conducted in GOTO data and Zadko will continue its GRB follow-up program.

It is hoped the multi-messenger follow-up management software (ICARE), used by the GRANDMA collaboration, will lead to a coordinated database of EM observations from Australian-led facilities and allow for regular dedicated OzGrav-EM publications. An OzGrav training course is expected to take place in 2021.

The SPIIR pipeline will publish its improvements in early-warning latency and detection performance as well as completing code-reviews for O4 readiness. Additional time will be spent on SPIIR single detector triggering. Further studies will look at machine learning applied to low-latency sky localisation and parameter estimation.

The expected release of Fast Radio Bursts (FRBs) detected by CHIME will significantly increase the number of known sources. We will start a GW-FRB joint search in O3 data. This study will place constraints on progenitor models and the energy emissions from FRBs. We will search for FRB/GW coincidences within a large time window to test all existing theories using CRAFT and public FRB data from the Transient Name Server. Results can either support existing theories, or set upper limits on the event rates of FRBs.

The next DWF run will now be in semester 2021B (Feb - Jul, 2021) and likely in June. We will progress the program enabling developments of the database, and data sonification and visualisation tools. DWF were awarded $300,000 toward progressing the design of KWFI, the wide field imager for Keck to search for and study GW EM counterparts to the furthest distances future GW detectors will be sensitive and to detect non-GW detected KNe to z ~ 1.0.

Another exciting outcome is for ANU to build the DREAMS infrared wide-field survey and transient telescope in Siding Spring Observatory. This will be the first wide-field infrared telescope in the Southern Hemisphere; the Gattini telescope, led by Mansi Kasliwal at Caltech and an OzGrav Partner Investigator, is the only other wide-field infrared telescope and is at the Palomar Observatory in the Northern Hemisphere. DREAMS will be ideal to search and follow up GW counterparts and will fill the only wavelength regime void in the DWF wide-field simultaneous observations.

Phase II of the ASKAP Variables and Slow Transients (VAST) survey will commence in early 2021 as we prepare for the full ASKAP surveys in 2022. We expect key scientific results on radio detection of gamma-ray bursts, supernovae, flaring stars and scintillation of AGN and pulsars.

Relativistic Astrophysics. Program chair: Paul Lasky

There are significant opportunities for the coming years, and hopefully decades to come. The development of the Neutron Star Extreme Matter Observatory (NEMO) concept and design was a collaboration across almost all OzGrav programs, with the relativistic astrophysics program playing significant involvement in driving the science case for such a kilohertz detector. We will work with instrumentalists to understand the potential astrophysics and fundamental physics discoveries of a NEMO detector relies on understanding what sensitivity curves are possible. Likewise, instrumentalists need to understand what frequency band is most interesting, including both bandwidth and required sensitivity.

Main avenues for exploration are to further understand what can be learned about sources with relatively well understood event rates, understanding constraints one can expect on both the "cold" and "hot" equations of state, and their potential differences due to possible phase transitions or the introduction of new physics, important both in terms of gravitational-wave-only and multi-messenger observations. Finally, there is the possibility of more exotic gravitational-wave sources that have not, to this point, been sufficiently considered.

In addition to the above, two significant opportunities present for the coming year that can be driven from new observations. First, the first coincident x-ray burst and fast radio burst unequivocally associating FRBs with highly-magnetised neutron stars provides new opportunities to understand these enigmatic phenomena. Second, the NANOGrav observation described above presents an opportunity for OzGrav scientists to understand if this is truly an astrophysical source of gravitational waves and, if so, what are the progenitors.

"Big questions" in the field in the coming years, in no particular order:

- Understand observational/theoretical constraints on jets launched from binary neutron star and neutron star-black hole mergers, including implications for fundamental physics.
- What are the progenitors of fast radio bursts, and what drives the coherent emission?
- Marrying next-generation pulsar timing and gravitational-wave data with falsifiable models of neutron-star interior physics.
- Understand observational/theoretical constraints on supernovae, and impact on binary evolution.
- Designing and performing tests of general relativity with electromagnetic and gravitational wave observations of black holes.

Population Modelling. Program chair: Simon Stevenson

2021 will see the release of the O3b catalog of gravitational wave results from the second half of LIGO/Virgo third observing run. A priority for OzGrav members will be utilising these results to study the populations of merging compact binaries.

Following the publication of METISSE in 2020, the next step is to implement METISSE into the rapid binary population synthesis codes COMPAS and BSE in order to allow it to be used to make predictions for gravitational wave events.

OzSTAR supercomputer. Leader: Jarrod Hurley

Complete the OzSTAR storage expansion work and finalise the certification of OzSTAR as a Tier 3 LIGO data centre.

Continue to work with the GWDC and OzGrav researchers to make significant contributions to GW software development and data delivery. Primarily across the key projects (SPIIR, GWCloud, GWLab, MeerTime) but also engaging with a wider range of OzGrav members through the expanded software support program. A big focus will be readiness for O4 (data streaming, live searches) and growing the user-bases of the data portals that serve the data products.

Work with the GWDC to provide a Machine Learning Hackathon for OzGrav researchers with an emphasis on industry engagement.

Enable Parkes/Molonglo data through the MeerTime portal.

Enable streaming of KAGRA data to OzSTAR.

Support for LIGO data tools on 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.
- Continue to engage closely with our members at all nodes in order to identify and advise on technology transfer opportunities.
- Run a series of workshops for our ERCs covering a range of topics including industry-related grant opportunities, industry engagement, and personal experience and testimonials.
- Continue to deliver briefings to industry, and provide industry internships and industry networking opportunities to our ECRs

Professional Development

- Continue to monitor and develop the OzGrav mentoring program for ECRs.
- Deliver and grow the OzGrav webinar series including topics of particular interest to ECRs.
- Continue working with the ECRC to best tailor our activities and training for the ECRs, including filling gaps with respect to the node's existing offerings.
- 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.
- Support our ECRs through the continuing effects of the global pandemic.

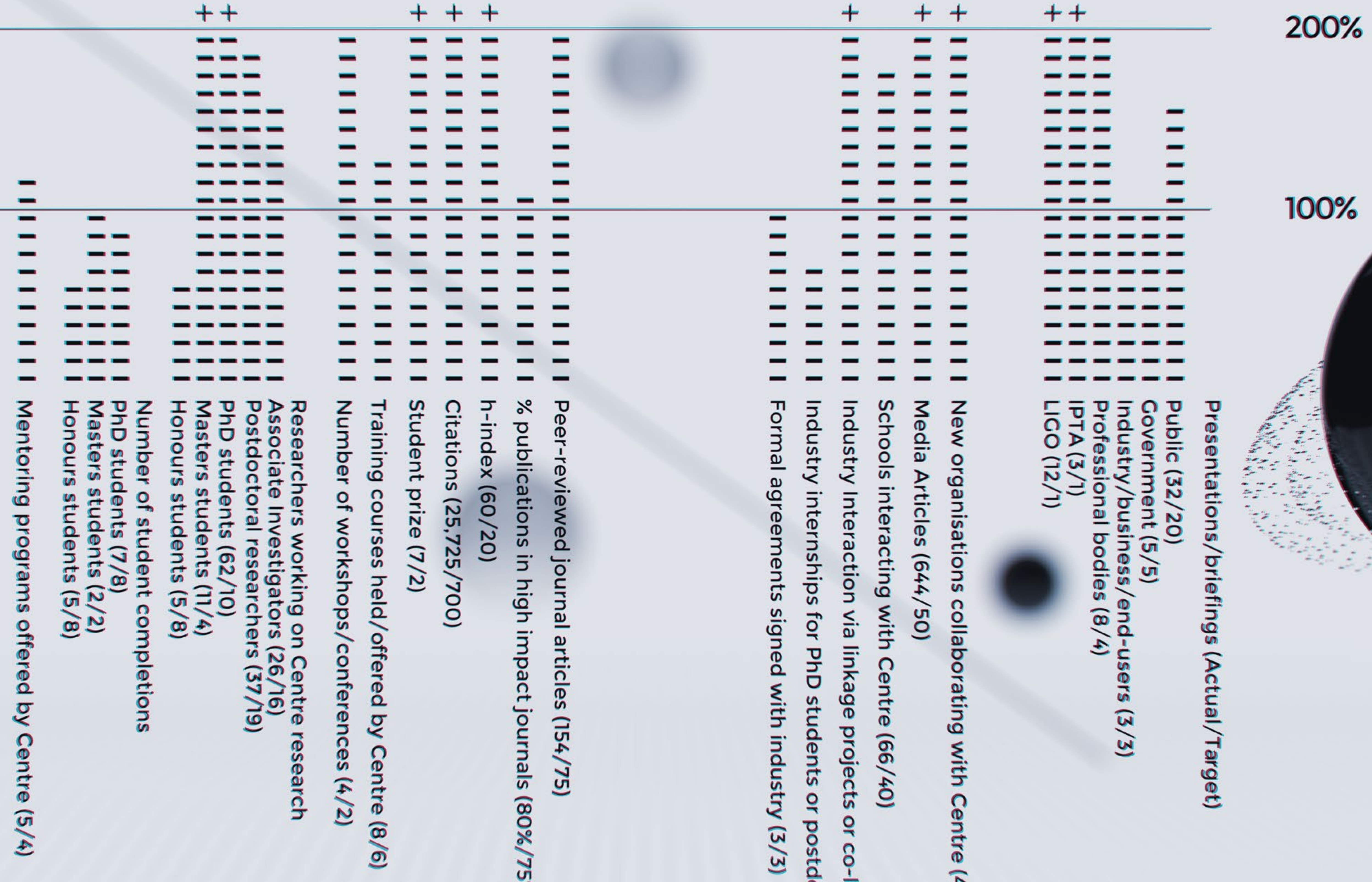
Equity and Diversity

- 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.
- In addition to the E&D Journal Club, we will continue to run webinars on a wide range of topics, e.g. accessibility and destigmatising mental health issues.
- Hold a special lunch event celebrating OzGrav's diversity.
- Increase engagement with our education and outreach program by people from underrepresented or disadvantaged populations, with a particular focus on engaging with schools in indigenous communities.
- Implement recruitment, professional development, and succession planning strategies to increase female representation among our membership at all levels in the centre.
- Continue to implement, update, and evaluate progress against, the OzGrav equity & diversity action plan.

Outreach

- Schools Programs: We will continue to offer our existing face-to-face and virtual incursions, and expanding to include primary schools and virtual experiments. We will also collaborate with our instrumentation and data researchers to develop hands-on educational offerings related to gravitational wave detection and data analysis. The Einstein-First team will continue to expand their curriculum across all year levels.
- Public Outreach: We hope that 2021 allows us to engage with the general public across all node states. We will be adding interactive projections, and we will partner with various public activities across Australia and pilot small-scale OzGrav-led events in regional locations. We plan on offering SciVR as a National Science Week program.
- Member Training: In addition to offering public communication opportunities as part of the ECR workshop and Annual Retreat, we will also offer targeted communication training opportunities for public speaking and media interviews. ECRs will help us to develop our new education content, and can train to deliver these new lessons to students.
- Media and Digital Content: We will continue to support our members with animations, graphics and social media to accompany media articles related to OzGrav work. The outreach team will develop a new documentary this year to bring the story of gravitational waves and OzGrav research to a general public audience.
- Accessibility: We will focus on increasing the accessibility of our content for members of our low-vision and low-hearing communities. We will again provide AUSLAN interpreters as part of our live National Science Week events.

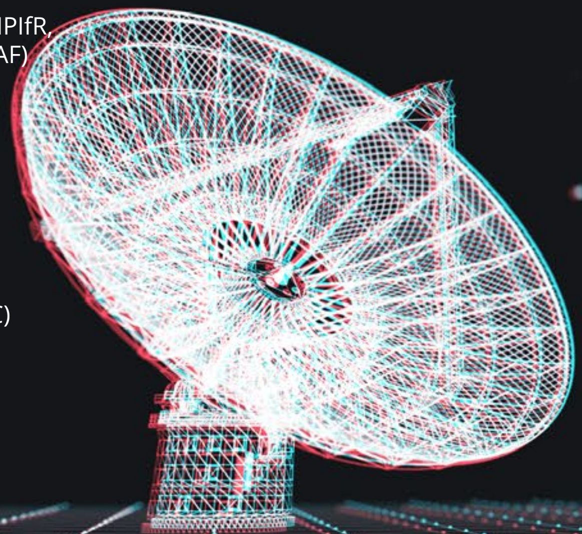
KPI dashboard



LINKAGES AND COLLABORATIONS

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
INFINI.TO: Planetarium of Turin
Kavli Institute for Theoretical Physics China
Laser Interferometer Gravitational-Wave Observatory (LIGO)
Massachusetts Institute of Technology (MIT)
Max Planck Institute for Gravitational Physics (Hannover)
Albert Einstein Institute
Max Planck Institute for Radio Astronomy
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: Carl Knox, OzGrav Swinburne

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

National Partners and Collaborators

Advanced Navigation
Aerometrex Pty Ltd
Arq group
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)
Defence Science and Technology Group (DST)
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) and KAGRA in 2020 (LVK)

LIGO (Laser Interferometer Gravitational-Wave Observatory) is the world's largest gravitational wave observatory and a cutting-edge physics experiment. Comprising two enormous laser interferometers located thousands of kilometres apart in Hanford (Washington) and Livingston (Louisiana), 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 welcomed KAGRA Japan to the observing run O3b in 2020 and beyond, and moved 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/LVK and other international working groups

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

Karl Wette is a Continuous Wave working group Co-Chair. Jade Powell is Chair of the Supernova group. Daniel Brown is the Advanced Interferometer Configurations Chair. Rory Smith is Co-Chair of the Bilby development group (LVK). David Ottaway is a member of the LSC Program Committee and Matthew Bailes is on the LIGO Program Advisory Committee (PAC). Eric Thrane is a member of the LSC Editorial Board, as well as Review Chair for the LIGO Burst Group. Susan Scott is the Amaldi 14 Conference Chair for the Local Organising Committee, with Amaldi 14 scheduled to be held in Australia in 2021.

Members have also contributed to many paper writing and editing teams, including Hannah Middleton for O3b CBC catalog paper, Juan Calderon-Bustillo for GW190521, and Eric Howell co-leading the LIGO FRB search and paper writing team.

Vaishali Adya is the postdoctoral 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.

Inset image: LIGO Magazine cover
Background image: Carl Knox, OzGrav Swinburne

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.

FINANCE 2020

	2020 Forecast	2020 Actuals	2021 Forecast
INCOME			
ARC Centre Grant	$ 4,862,561	$ 4,862,561	$ 4,895,693
Institutional cash contribution	$ 1,165,000	$ 1,165,944	$ 1,130,000
Other grants and contracts		$ 6,490	
Total Income	$ 6,027,561	$ 6,034,995	$ 6,025,693
EXPENDITURE			
Salaries & scholarships	$ 4,051,415	$ 4,144,708	$ 4,559,179
Equipment	$ 502,900	$ 201,513	$ 496,164
Travel, Meetings, Workshops	$ 1,044,398	$ 145,018	$ 313,320
Research maintenance and consumables	$ 670,727	$ 356,528	$ 623,925
Outreach, operations and other expenditure	$ 118,698	$ 123,678	$ 129,862
Total Expenditure	$ 6,388,138	$ 4,971,445	$ 6,122,448
Carry-forward from previous year	$ 4,901,610	$ 4,901,610	$ 5,965,160
BALANCE	$ 4,541,034	$ 5,965,160	$ 5,868,405

GOVERNANCE

The OzGrav Executive Committee, led by the Centre Director, oversees the management, operations, and performance of the Centre across the six collaborating research nodes. 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 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 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 mentoring program.

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

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

OzGrav Executive Committee

Prof Matthew Bailes - OzGrav Director
Swinburne University of Technology

Prof David McClelland - OzGrav Deputy Director
Australian National University

Prof David Blair - Outreach Leader
University of Western Australia

Prof Jong Chow - Research Translation Leader
Australian National University

Prof Jarrod Hurley
Swinburne University of Technology

Prof Andrew Melatos
University of Melbourne

Prof Tara Murphy (observer)
University of Sydney

Prof Susan Scott - Career Development Leader
Australian National University

Prof Eric Thrane
Monash University

Prof Peter Veitch
University of Adelaide

A/Prof Chunnong Zhao
University of Western Australia

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

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

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.

Prof Matthew Bailes
OzGrav Director

Dr Gregory Clark
Visiting Fellow, Australian National University

Prof Tim Colmer
Deputy Vice Chancellor (Research), University of Western Australia

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

Dr Yeshe Fenner
OzGrav Chief Operating Officer

Dr Ella Finkel AM
Science writer and editor, Cosmos Magazine

Background image: Carl Knox OzGrav Swinburne

GOVERNANCE

Governance Advisory Committee continued

Prof Bronwyn Fox
Deputy Vice-Chancellor (Research & Enterprise), Swinburne University of Technology

Dr Tanya Hill
Senior Curator, Melbourne Planetarium, Museum Victoria

Dr Chiara Mingarelli
Flatiron Institute's Center for Computational Astrophysics

Dr John O'Sullivan
CSIRO

Scientific Advisory Committee

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

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

Dr Joan Centrella
Deputy Director, Astrophysics Science Division, NASA

Prof Matthew Evans
Principal Investigator, MIT and LIGO

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

A/Prof Selma de Mink
Associate Professor, Harvard and Smithsonian Center for Astrophysics, Harvard University

Dr Jade Powell
Swinburne University of Technology

Dr Hannah Middleton
University of Melbourne

Lucy Strang
University of Melbourne

Prof Eric Thrane
Monash University

Dr Robert Ward
Australian National University

Background image features OzGrav streetwear tshirt design by Carl Knox, OzGrav Swinburne, depicting a stylised LIGO interferometer, and underneath are symbols for 3 types of gravitational wave mergers: neutron star and neutron star binary; neutron star and black hole binary; and black hole and black hole binary.

Research Translation Committee

Prof Jong Chow - Chair
Physics Education Centre and Deptartment of Quantum Science
Research School of Physics and Engineering
Australian National University

Ros Hore
Director, Industry Research Engagement and Business Development
Swinburne University of Technology

Dr Robin Fieldhouse
Lead, Major Research Partnerships & Initiatives
Australian National University

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

Joshua McCann
Early Career Researcher (ECR) rep
University of Western Australia

Prof David Ottaway
Chief Investigator, University of Adelaide

Tom Schnepple
Senior Commercialisation Officer, Research Development and Innovation Office
University of Western Australia

Prof Len Sciacca
Academic Specialist, Electrical and Electronic Engineering
University of Melbourne

Equity and Diversity Committee

Prof Matthew Bailes - Chair
Swinburne University of Technology

Dr Greg Ashton
Monash University

Dr Qi Chu
University of Western Australia

Dr Yeshe Fenner
Swinburne University of Technology

Professional Development Committee

Prof Susan Scott - Chair
Australian National University

Dr Kendall Ackley
Monash University

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