# SPACE TIMES

OzGrav

April 2022

# Welcome

Welcome to another edition of Space Times!

I've been coming up for air after submitting a full application for another Centre of Excellence focussed on gravitational waves that would start next year if successful. The Centres represent one of the best value-for-money investments of the Australian Research Council and I'm very confident that the community has put forward the best possible case for continued funding.

Recently I was part of a committee discussing the advantages and disadvantages of in-person and hybrid scientific meetings/ conferences in gravitational waves in the post-pandemic world, just before my first overseas trip for over two years. The panel felt that in-person meetings are sorely missed, more for the informal interactions and the removal of distractions for a week than the talks presented. They acknowledged that online meetings often meant larger audiences, much less CO2 emissions, greater equity, less costs and no jetlag. I personally find that the biggest downside of global online conferences is that your day job and family responsibilities don't end just because you are "at an online conference" and that attempts to cater for all the different time zones completely remove the ability to just think about physics for an uninterrupted period.

Somewhat ironically then, this newsletter represents another distraction, but one I hope you will enjoy reading.

Yours sincerely - Matthew Bailes (OzGrav Director)

*Our Director on the last leg of the 235 km Peaks Challenge in March, having defied 4500m of gravitational potential energy to complete the course near the summit of Falls Creek almost 12 hours after the starting gun had fired and about 3 hours after OzGrav members Adam Deller and Daniel Reardon.*

# NEWS IN BRIEF

- Our fantastic new annual report for 2021 is here! Thanks to Lisa for a brilliant job coordinating the whole process and compiling the report, Carl Knox for the wonderful graphics, and all our members for your contributions to the report and to OzGrav throughout 2021. Download a copy here
- Prof Tamara Davis (USyd) is a movie! You can check out "Carbon - The Unauthorised Biography" here.
- Congratulations to a team from University of Adelaide who were awarded an OzGrav Research Transation Seed grant to investigate laser-based technology for killing weeds. The application is led by Zac Holmes (PhD Student), and includes Dr Seb Ng, Prof Peter Veitch, Emir Prof Jesper Munch, as well as partners from the Uni Adelaide School of Agriculture, Food & Wine.
- Congratulations to Prof Susan Scott (ANU) who has been appointed as the first Australian Editor-in-Chief of the international journal Classical and Quantum Gravity!
- The latest issue of the LIGO Magazine is available now!

**Editor-in-chief:** Luana Spadafora
Subscribe or submit your contributions to lspadafora@swin.edu.au

*Background image by Carl Knox, OzGrav-Swinburne University*



## RESEARCH HIGHLIGHT

### Graphics processing unit implementation of the F-statistic for continuous gravitational wave searches

One promising source of gravitational waves, not yet detected, is rapidly rotating neutron stars. Neutron stars are hyperdense leftovers from stellar evolution, formed from the core of stars of a certain weight class (not too light, not too heavy). Instead of collapsing all the way to a black hole, they stop just short, ultimately packing the mass of the Sun into a ball about 10 kilometers across. Neutron stars are known to spin rapidly, up to hundreds of revolutions per second, and they are so fantastically dense that even a small (millimeters high!) mountain will emit continuous gravitational waves (CWs) that are potentially detectable by LIGO.

However, detecting these gravitational waves is no mean feat. Although they are continuously emitted (as opposed to gravitational waves from merging neutron stars and black holes, which last no longer than a few minutes), they are very quiet, and digging these signals out of the noise is very challenging. The task is complicated by the fact that we often have to search over a wide range of gravitational wave frequencies and sky locations, since we do not know where a gravitational wave-emitting neutron star might be in the sky, or how fast it might be spinning. All of these facts combine to create a computational challenge which is formidable – many searches for these continuous gravitational waves are limited by the available computing power.

This motivates us to make these searches as computationally efficient as possible, and to take advantage of all resources available. One important resource which has so far been under-utilised in CW searches is graphics processing units (GPUs). Although initially designed, as their name suggests, for crunching numbers in service of producing 3D graphics, over the last twenty years they have proven themselves to be equally useful in many scientific applications, often providing significant speedups over CPUs. Most supercomputing clusters are now equipped with some number of high-powered GPUs for exactly this reason.

Our recent paper presents the implementation of one very common method used in CW searches, the "F-statistic", on GPUs. We show that, using our implementation, one GPU can do the work of 10–100 CPU cores, unlocking a significant new source of computational power to be used in analyses using the F-statistic. We also show that achieving these speeds does not require sacrificing sensitivity, which is extremely important given the faintness of the signal we're looking for. Finally, as a demonstration of the utility of this new implementation in a real-world context we run a small search for continuous gravitational waves from four recently discovered neutron stars spinning between 200 and 400 times per second. The search consumes 17 hours of GPU time, in contrast to the 1000 hours of CPU time which would have been required to run the equivalent search. This work will allow more CW searches to take advantage of the computing power offered by GPUs in the future and continue to push towards the first detection of continuous gravitational waves.

Written by OzGrav PhD student Liam Dunn, the University of Melbourne.

# A new technique to discover the brightest radio pulsar outside our own galaxy

When a star explodes and dies in a supernova, it takes on a new life of sorts. Pulsars are the extremely rapidly rotating objects left over after massive stars have exhausted their fuel supply. They are extremely dense, with a mass similar to the Sun crammed into a region the size of Sydney. Pulsars emit beams of radio waves from their poles. As those beams sweep across Earth, we can detect rapid pulses as often as hundreds of times per second. With this knowledge, scientists are always on the lookout for new pulsars within and outside our Milky Way galaxy.

*Credit: Carl Knox, OzGrav-Swinburne University*

In recently published research in the Astrophysical Journal, we detail our findings on the most luminous radio pulsar ever discovered outside the Milky Way. This pulsar, named PSR J0523-7125, is located in the Large Magellanic Cloud – one of our closest neighbouring galaxies – and is more than ten times brighter than all other radio pulsars outside the Milky Way. It may be even brighter than those within it.

**Why wasn't PSR J0523-7125 discovered before?**

There are more than 3,300 radio pulsars known. Of these, 99% reside within our galaxy. Many were discovered with CSIRO's famous Parkes radio telescope, Murriyang, in New South Wales. About 30 radio pulsars have been found outside our galaxy, in the Magellanic Clouds. So far, we don't know of any in more distant galaxies. Astronomers search for pulsars by looking for their distinctive repeating signals in radio telescope data. This is a computationally intensive task. It works most of the time, but this method can sometimes fail if the pulsar is unusual: such as very fast, very slow, or (in this case) if the pulse is very wide.

A very wide pulse reduces the signature "flickering" astronomers look for and can make the pulsar harder to find. We now know PSR J0523-7125 has an extremely wide beam, and thus escaped detection.

The Large Magellanic Cloud has been explored by the Parkes telescope several times over the past 50 years, and yet this pulsar had never been spotted. So how were we able to find it?

**An unusual object emerges in ASKAP data**

Pulsar beams can be highly circularly polarised, which means the electric field of light waves rotate in a circular motion as the waves travel through space. Such circularly polarised signals are very rare, and usually only emitted from objects with very strong magnetic fields, such as pulsars or dwarf stars. We wanted to pinpoint unusual pulsars that are hard to identify with traditional methods, so we set out to find them by specifically detecting circularly polarised signals. Our eyes can't distinguish between polarised and unpolarised light. But the ASKAP radio telescope, owned and operated by Australia's national science agency CSIRO, has the equivalent of polarised sunglasses that can recognise circularly polarised events. When looking at data from our ASKAP Variables and Slow Transients (VAST) survey, an undergraduate student noticed a circular polarised object near the centre of the Large Magellanic Cloud. Moreover, this object changed brightness over the course of several months: another very unusual property that made it unique. This was unexpected and exciting, since there was no known pulsar or dwarf star at this position. We figured the object must be something new.

We observed it with many different telescopes, at different wavelengths, to try and solve the mystery. Apart from the Parkes (Murriyang) telescope, we used the space-based Neil Gehrels Swift Observatory (to observe it at X-ray wavelengths) and the Gemini telescope in Chile (to observe it at infrared wavelengths). Yet we detected nothing. The object couldn't be a star, as stars would be visible in optical and infrared light. It was unlikely to be a normal pulsar, as the pulses would have been detected by Parkes. Even the Gemini telescope didn't provide an answer. Ultimately, we turned to the new, highly sensitive MeerKAT radio telescope in South Africa, owned and operated by the South African Radio Astronomy Observatory. Observations with MeerKAT revealed the source is indeed a new pulsar, PSR J0523-7125, spinning at a rate of about three rotations per second. Our analysis also confirmed its location within the Large Magellanic Cloud, about 160,000 light years away. We were surprised to find PSR J0523-7125 is more than ten times brighter than all other pulsars in that galaxy, and possibly the brightest pulsar ever found.

**What new telescopes can do**

The discovery of PSR J0523-7125 demonstrates our ability to find "missing" pulsars using this new technique. By combining this method with ASKAP's and MeerKAT's capabilities, we should be able to discover other types of extreme pulsars – and maybe even other unknown objects that are hard to explain. Extreme pulsars are one of the missing pieces in the vast picture of the pulsar population. We'll need to find more of them before we can truly understand pulsars within the framework of modern physics. This discovery is just the beginning. ASKAP has now finished its pilot surveys and is expected to launch into full operational capacity later this year. This will pave the way for even more discoveries, when the global SKA (square kilometre array) telescope network starts observing in the not-too-distant future.

*Written by OzGrav PhD student Yuanming Wang, OzGrav Associate Investigator Tara Murphy, and Prof. David Kaplan (University of Wisconsin-Milwaukee). This is an edited extract from the original article on The Conversation. Also featured in CSIRO and Space Australia.*

# OzGrav 2.0 - Bid update

Over the past 1.5 years, there has been an intensive effort by the Australian gravitational wave community to plan for, and develop, an application for another ARC Centre of Excellence that focusses on gravitational waves to commence in 2023. This effort culminated in the submission of an 875-page application on 22 March 2022 to the ARC, involving 23 Chief Investigators, 12 Partner Investigators, and 22 Associate Investigators.

The new Centre aims to build on the success of OzGrav, with a mission to use gravitational waves to make critical discoveries about the fundamental nature of relativistic gravity, ultra-dense matter and cosmology, and to position Australia as a leading player in the gravitational-wave megascience instruments of the 2030s and 2040s.

The Centre is built around six Key Projects:
1. Optimisation: Maximise the science returns of gravitational-wave observatories in the 2020s
2. Detection: Discover and interpret gravitational-wave sources and high-energy electromagnetic transients
3. Gravity: Probing the nature of gravity and extreme spacetime
4. Extreme Matter: The physics of ultra-dense matter
5. Cosmos: Determine fundamental properties of the Universe
6. Future Tech: Develop key technologies for next-generation detectors

The proposed Director Matthew Bailes and proposed Deputy Directors Tamara Davis and David McClelland led a large community-wide process to develop the science program for the new Centre. The process included community workshops; a call for White Papers that elicited 30 Papers; selection of the named investigators; and extensive consideration and refinement of the research program. Our high-level plans were documented in an EOI to the ARC in 2021. It was short-listed from a large field of over 100 EOIs to a smaller pool of 17 bids that were invited to submit a full proposal. We expect to receive assessor reports on our full proposal in May-June, with interviews to follow in July-August and the final outcome known in Q4 of 2022. Good luck team!



*Background image by Carl Knox, OzGrav-Swinburne University*



## Simulating the complicated lives of stars, from birth until death

Scientists from the ARC Centre of Excellence for Gravitational Wave Discovery and the University of Cologne (Germany) have developed new simulations of stars' complicated lives, boosting research on how new stars are born and how old stars die. These stellar evolution simulations, called the BoOST project, can be used to predict how often gravitational waves should be detected—gravitational waves (ripples in space-time) are expected to happen when the death throes of two stars merge. The project can also help to study the birth of new stars out of dense clouds in space.

Not all stars are the same. Sure, they all look like tiny, shining points on the sky, but it's only because they are all so far away from us. We only see stars that are close and bright enough. The rest, we may see with telescopes. If you use a telescope to measure the colour of a star, it turns out that some stars are rather red, some are blue, and some are in between. And if you measure their brightness, it turns out that some are brighter than others. This is because a star's colour and brightness depend on its heaviness and age, among other things. It's a complex theory that has been developing since the age of the first computer simulations in the 1950's. Today, we have computer simulations that can predict how a star lives its complicated life, from birth until death. This is called 'stellar evolution' and applies to the stars that are close enough for us to observe with telescopes.

But there are stars so far away that even the largest telescopes can't view them clearly; there are stars hiding inside thick clouds (yes, such clouds exist in space); and there are dead and dying stars that used to exist once upon a time. Is there a way to study these unreachable stars to observe similarities and differences from those that we can actually see? Stellar evolution simulations can help here because we can simulate any star—even the stars we can't see. For example, stars that were born soon after the Big Bang used to have a different chemical composition than those stars that we see today. From computer simulations, we can figure out how these early stars looked like: their colour, brightness etc. What's more, we can even predict what happens to them after they die. Some of them become black holes, for example, and we can tell the mass of this black hole based on how heavy the star had been before it exploded. And this presents more opportunity for discovery! For example, it's possible to predict how often two black holes merge. This gives us statistics about how many times we can expect to detect gravitational waves from various cosmic epochs. Or, when trying to understand how stars are born out of dense clouds, we can count the number of hot bright stars and the number of exploding stars around these cloudy regions. Both hot bright stars and explosions change the clouds' structure and influence the birth of new stars in delicate ways.

Lead scientist on the study Dorottya Szécsi from the University of Cologne says: 'Much like the theory of stellar life got a boost in the 1950's from computerization, we hope our BoOST project will contribute to other research fields, because both the birth of new stars and the ultimate fate of old stars depend on how stars live their complicated and very interesting lives'. "Given the importance of massive stars in astrophysics, from determining star formation rates to the production of compact remnants, it is essential that our theoretical models of stars keep pace with advancements in observations," says OzGrav postdoctoral researcher and study co-author Poojan Agrawal.

Written by Dorottya Szécsi (Nicolaus Copernicus University) and OzGrav Alumnus Poojan Agrawal (Carnegie Mellon University).

# Continuous gravitational waves in the lab

Gravitational-waves are ripples in space-time created by distant astronomical objects and detected by large complex detectors (like LIGO, Virgo, and KAGRA). Finding gravitational-wave signals in detector data is a complicated task requiring advanced signal processing techniques and supercomputing resources.

Due to this complexity, explaining gravitational-wave searches in the undergraduate laboratory is difficult, especially because live demonstration using a gravitational-wave detector or super-computer is not possible. Through simplification and analogy, table-top demonstrations are effective in explaining these searches and techniques.

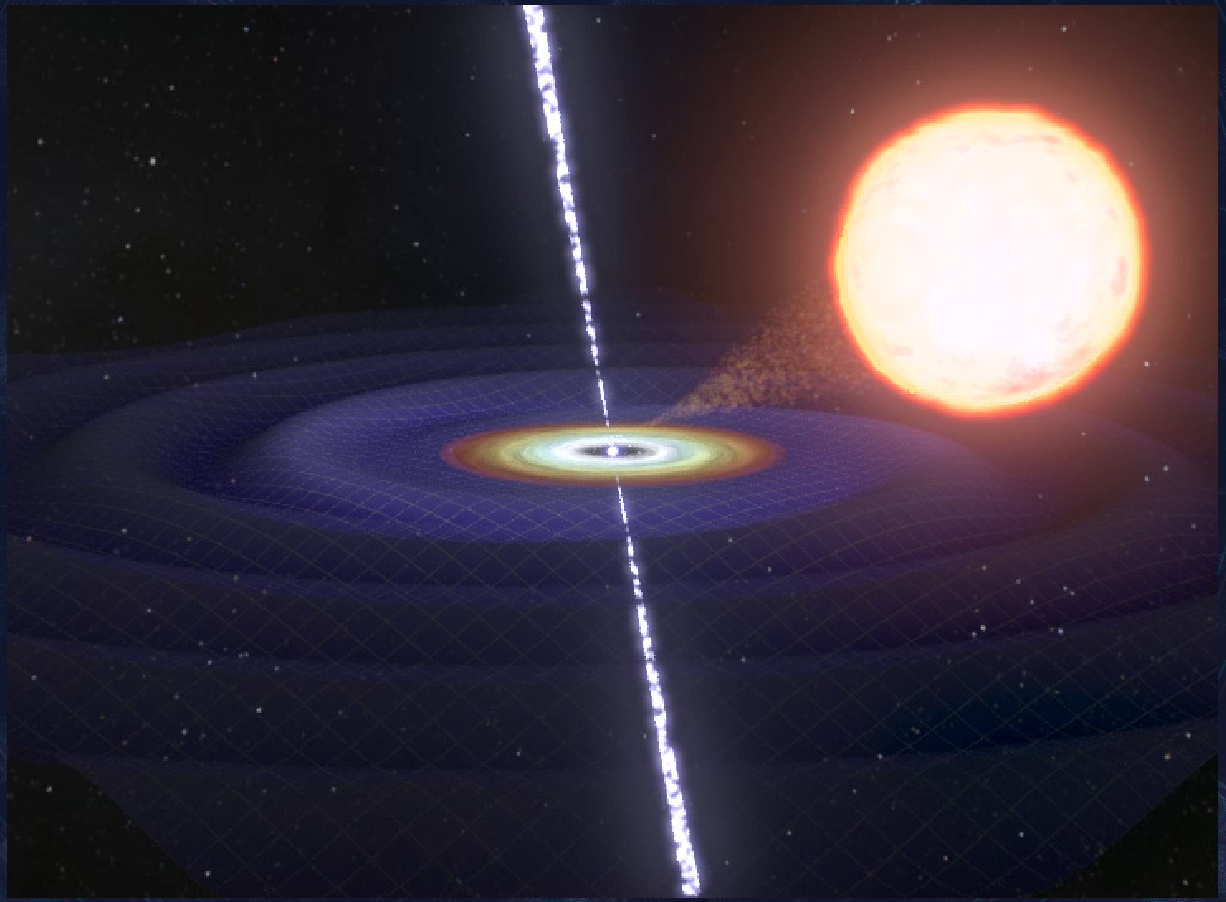
A team of OzGrav scientists, across multiple institutions and disciplines, have designed a table-top demonstration with data analysis examples to explain gravitational-wave searches and signal processing techniques. The demonstration can be used as a teaching tool in both physics and engineering undergraduate laboratories and published in the American Journal of Physics.

Lead author of the project James Gardner (who was an OzGrav undergraduate student at the University of Melbourne during the project and now a postgraduate researcher at the Australian National University) explains: “This demonstration offers some charming insights into a live field of research that students like me should appreciate for its recency compared to the age of most ideas they encounter”.

**Table-top gravitational-wave demonstrations**

Gravitational wave detectors are very complicated and huge — laser light is sent down tubes kilometres long! But the workings of a gravitational-wave detector can be demonstrated using table-top equipment. Researchers at the University of Adelaide have developed AMIGO to do just that! Deeksha Beniwal, co-author of this study and an OzGrav PhD student at the University of Adelaide explains: “With AMIGO, the portable interferometer, we can easily share how LIGO uses the fundamental properties of light to detect ripples from the most distant reaches of the universe.”

This work expands on the portable interferometer demonstration with a selection of examples for students in both physics and electrical engineering. Changrong Liu, co-author of this study and an OzGrav PhD student in electrical engineering at the University of Melbourne, explains: “This project offers a great opportunity for electrical engineering students like me to put some of their knowledge into the real and exciting physical world”.



*Artist's illustration of continuous grav tiational waves - Mark Myers, OzGrav-Swinburne University.*

**Explaining the hunt for continuous gravitational waves**

To demonstrate searching for signals with the table-top set up, the team first needed to make some fake signals to find! This is where the analogy of sound comes in: audio signals are used to mimic gravitational waves interacting with the detector. The team focused on demonstrating the hunt for continuous gravitational waves, a type of gravitational wave that hasn't been detected yet.

Hannah Middleton, co-author of the study and an OzGrav Associate Investigator (at the University of Birmingham), explains: “Continuous waves are long-lasting signals from spinning neutron stars. These signals should be present in the detector data all the time, but the challenge is to find them. This demonstration is directly inspired by the techniques developed by OzGrav physicists and electrical engineers in the hunt for continuous gravitational waves!“

A continuous wave signal can be slowly changing in frequency, so the audio signals used in this demonstration also change in frequency. ”We show, through using sound as an analogue to gravitational waves, what it takes to detect a wandering tone: a long signal that slowly changes pitch like whalesong,” explains Gardner.

Prof. Andrew Melatos, co-author of this study and leader of the OzGrav-Melbourne node explains: “We hope that undergraduate educators will emphasize the cross-disciplinary spirit of the project and use it as an opportunity to speak more broadly to students about careers at the intersection of physics and engineering. The future is very bright career-wise for students with experience in cross-disciplinary collaboration”

Written by OzGrav Assoc. Investigator Hannah Middleton (University of Birmingham) and OzGrav postgrad researcher James Gardner (ANU)

Reference: “Continuous gravitational waves in the lab: Recovering audio signals with a table-top optical microphone” by James W. Gardner, Hannah Middleton, Changrong Liu, Andrew Melatos, Robin Evans, William Moran, Deeksha Beniwal, Huy Tuong Cao, Craig Ingram, Daniel Brown and Sebastian Ng, 23 March 2022, American Journal of Physics. DOI: 10.1119/10.0009409

As featured in SciTech Daily.





Background image by Carl Knox, OzGrav-Swinburne University

# Mount Burnett Open Day!

It was fantastic to get back to some in-person science outreach and join many other volunteers for the Mount Burnett Observatory Open Day on Saturday 26 March. The event celebrated 50 years of the Monash Dome, and visitors young and old were able to look through observatories and telescopes. It was a festival atmosphere with a BBQ, various science activities, and OzGrav's VR tour and games about gravity, black holes and gravitational waves. A big thank you to our volunteers, including Pratyasha and Evgeni who tried out some science outreach alongside experts Reinhold, Avi, Mohsen and Lisa.


*Mount Burnett Observatory. Credit: Ronald Fritz*

# Menzies Creek Primary Stargazing

Mohsen, Shanika and Lisa joined OzGrav Chief Investigator Eric Thrane and his children for a special stargazing night at Menzies Creek Primary School on 6 April. Several volunteers from Mount Burnett Observatory brought their telescopes out to the oval, while OzGrav hands-on science activities were noisily crowded in a classroom. The special event capped off several weeks of Year 3 and 4 learning about space, and they were excited to show their rocket designs to friends and families. Eric also gave a special talk earlier in the week, showing students a gravity experiment and describing how we detect gravitational waves.

Eric said: "The children and families had so much fun and learned a lot. It has been a tough couple of years for the school with community events mostly cancelled due to the pandemic. This stargazing event for the year 3/4 students and their families really brought out the community spirit. I can't tell you how much this means to the Menzies Creek community!"




*Background image by by Carl Knox, OzGrav-Swinburne University*

# OzGrav Associate Investigator Dr Hannah Middleton

I work on gravitational wave data analysis, such as searching for continuous waves from spinning neutron stars and trying to learn about massive black hole binaries with pulsar timing array results. I also enjoy outreach and I know many of you have been pestered by me to write for the LIGO Magazine!

I started working on gravitational waves during my PhD in Birmingham (UK). The opportunity to travel to conferences and see a bit more of the world was wonderful and at the end of my PhD, I headed for the University of Melbourne to join OzGrav as a postdoc.

Being able to move to the other side of the world and live in Australia for a few years has been amazing. OzGrav has a great community and I've enjoyed the chance to meet and work with many of you over the years. I've loved exploring Australia (although not as much as I'd hoped to) and in my free time I enjoy photography and getting out for walks in the countryside. This was one of my favourite things about living in Australia - at any moment I might see a bird or bug that was totally new to me to attempt to photograph!

As many OzGrav-ers will be only too aware of, being far away from family during the pandemic has been tough. Not only that, job hunting has been pretty tricky too. With my postdoc contract coming to an end, I applied for the OzGrav COVID funding scheme and was very happy to be offered a place at Swinburne during 2021. I was still missing my family dearly, but having some job security and being able to continue working with OzGrav was a huge relief. Although the lockdowns meant I couldn't get over to Hawthorn as much as I would have liked, it was great to work with the Swinburne team on a project about the sensitivity of the MeerTime pulsar timing array - and learn a bit about pulsar observations along the way.

Late last year I moved back to the UK - a strange experience during lockdown, but a comfortable flight with only 23 passengers on one of the planes. I'm now working at the University of Birmingham on data analysis for the LISA mission as well as being an OzGrav Associate Investigator, so I hope to continue working with many of you in the future.



*Background image by Carl Knox, OzGrav-Swinburne*

# Acknowledgement of Country plaque project

We're delighted to share this special project that will be unveiled at OzGrav HQ - Swinburne University.

Due to COVID stalling progress, this project started a few years ago with the intention of installing an Acknowledge of Country (AoC) at our OzGrav offices at Swinburne University. Initially we were going to do something fairly simple, but after consulting with our Swinburne Indigenous liaison group, we decided to run this as a prize for a local Indigenous artist to design the AoC artwork with OzGrav science as inspiration.

One of the winning designs was by Wurundjeri Elder Uncle Colin Hunter, which we wanted to use for the physical plaque. The other design was by a Wurundjeri artist Judy Nicholson (who has sadly since passed away) that we are using for our electronic AoC.

Initially we were just going to get a company to etch Uncle Colin's design onto glass or metal but Colin was very keen to create the artwork himself by burning it onto wood and painting it as per the traditional style of his Wurundjeri people. His ongoing enthusiasm for the project has been amazing.

We are deeply grateful to Uncle Colin for his engagement in this project and for the final (massive!) artwork, which will soon be installed in at the Hawthorn campus of Swinburne University.

Following the installation, we will be hosting an official unveiling event, with Uncle Colin as our VIP guest of honour.

# International collaboration offers new evidence of a gravitational wave background

The results of a comprehensive search for a background of ultra-low frequency gravitational waves have been announced by an international team of astronomers including scientists from the ARC Centre of Excellence for Gravitational Wave Discovery: Ryan Shannon, Daniel Reardon, Matthew Bailes, Stefan Oslowski and Boris Goncharov.

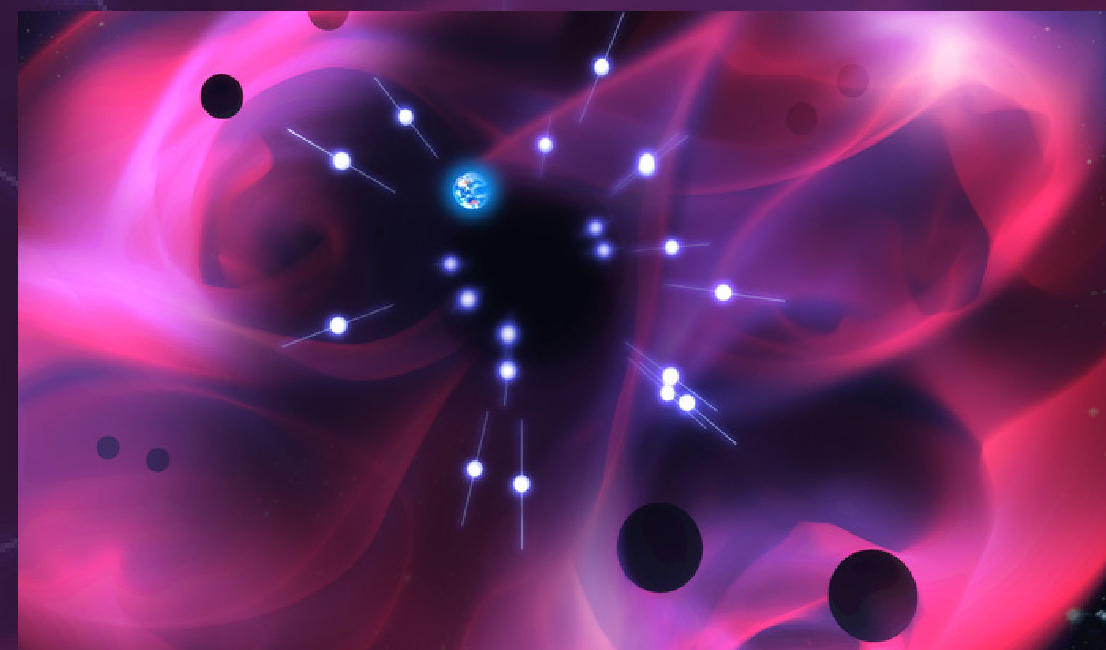
These light-year-scale ripples, a consequence of Einstein's theory of general relativity, permeate all of spacetime and could originate from mergers of the most massive black holes in the Universe or from events occurring soon after the formation of the Universe in the Big Bang. Scientists have been searching for definitive evidence of these signals for several decades.

The International Pulsar Timing Array (IPTA), joining the work of several astrophysics collaborations from around the world, recently completed its search for gravitational waves in their most recent official data release, known as Data Release 2 (DR2).

This data set consists of precision timing data from 65 millisecond pulsars – stellar remnants which spin hundreds of times per second, sweeping narrow beams of radio waves that appear as pulses due to the spinning – obtained by combining the independent data sets from the IPTA's three founding members: The European Pulsar Timing Array (EPTA), the North American Nanohertz Observatory for Gravitational Waves (NANOGrav), and the Parkes Pulsar Timing Array in Australia (PPTA).

These combined data reveal strong evidence for an ultra-low frequency signal detected by many of the pulsars in the combined data. The characteristics of this common-among-pulsars signal are in broad agreement with those expected from a gravitational wave "background".

The gravitational wave background is formed by many different overlapping gravitational-wave signals emitted from the cosmic population of supermassive binary black holes (i.e. two supermassive black holes orbiting each other and eventually merging) – similar to background noise from the many overlapping voices in a crowded hall.



*An array of pulsars around the Earth embedded in a gravitational wave background from supermassive black hole binaries. The signals from the pulsars measured with a network of global radio telescopes are affected by the gravitational waves and allow for the study of the origin of the background. Credit: Carl Knox, OzGrav-Swinburne University*

This result further strengthens the gradual emergence of similar signals that have been found in the individual data sets of the participating pulsar timing collaborations over the past few years.

OzGrav Associate Investigator Dr Boris Goncharov from the PPTA cautions on the possible interpretations of such common signals: "We are also looking into what else this signal could be. For example, perhaps it could result from noise that is present in individual pulsars' data that may have been improperly modeled in our analyses."

To identify the gravitational-wave background as the origin of this ultra-low frequency signal, the IPTA must also detect spatial correlations between pulsars. This means that each pair of pulsars must respond in a very particular way to gravitational waves, depending on their separation on the sky.

These signature correlations between pulsar pairs are the "smoking gun" for a gravitational-wave background detection. Without them, it is difficult to prove that some other process is not responsible for the signal. Intriguingly, the first indication of a gravitational wave background would be a common signal like that seen in the IPTA DR2. Whether or not this spectrally similar ultra-low frequency signal is correlated between pulsars in accordance with the theoretical predictions will be resolved with further data collection, expanded arrays of monitored pulsars, and continued searches of the resulting longer and larger data sets.

Consistent signals like the one recovered with the IPTA analysis have also been published in individual data sets more recent than those used in the IPTA DR2, from each of the three founding collaborations. The IPTA DR2 analysis demonstrates the power of the international combination giving strong evidence for a gravitational wave background compared to the marginal or absent evidences from the constituent data sets. Additionally, new data from the MeerKAT telescope and from the Indian Pulsar Timing Array (InPTA), the newest member of the IPTA, will further expand future data sets.

Given the latest published results from the individual groups who now all can clearly recover the common signal, the IPTA is optimistic for what can be achieved once these are combined into the IPTA Data Release 3. Work is already ongoing on this new data release, which at a minimum will include updated data sets from the four constituent PTAs of the IPTA. The analysis of the DR3 data set is expected to finish within the next few years.

*This is an edited extract from the original media release on Eureka Alert.*





*Background image by Carl Knox, OzGrav-Swinburne University*

## Rates of compact object coalescences

How often do pairs of black holes and/or neutron stars collide? And how do such systems form in our Universe? Many researchers have studied these open questions for decades, with an explosion of interest since 2015, when the LIGO and Virgo detectors observed the first of such collisions through gravitational waves. In recent years, new gravitational-wave and electromagnetic observations have been used to constrain the frequency of black holes and neutron star collisions, whilst increasingly sophisticated models of neutron star and black hole mergers forming through a variety of evolutionary channels produced a range of theoretically predicted rates. It was therefore an opportune time for us (Ilya Mandel and Floor Broekgaarden) to review the existing observational and theoretical knowledge of compact-binary coalescence rates that is now published in Living Reviews in Relativity "Rates of Compact Object Coalescences". It includes a comparison of the predicted and observed rates from over 200 papers published in the last decade, as well as a review on the different observational methods and formation channels.

Written by Floor Broekgaarden, PhD candidate Centre for Astrophysics, Harvard University

## Merging stellar-mass binary black holes

When two black holes orbit each other in a binary, the emission of gravitational waves will ultimately drive them to merger (and, hopefully, a detection by OzGrav!). However, in order for two black holes weighing in at 30 solar masses, such as those comprising the very first gravitational-wave event GW150914, to merge within the current age of the Universe, they must start out quite close together: no more than a quarter of the distance from the Earth to the Sun. On the other hand, the massive stars from which such black holes form expand to more than ten times this size during their evolution. Thus, getting such black holes into a sufficiently tight orbit to allow them to merge by emitting gravitational waves is a bit like fitting a large peg into a tiny hole that is much smaller than the width of the peg. Yet we now know that black holes merge regularly. How do they manage? There are a few very intriguing possibilities, from black-hole match-making clubs (globular clusters) to magical Abracadabra wands that tell stars not to expand (chemically homogeneous evolution). In Merging stellar-mass binary black holes, recently published in Physics Reports, Ilya Mandel and Alison Farmer attempt to provide accessible explanations for the challenges and excitement of merging black holes.

Written by OzGrav Chief Investigator Ilya Mandel, Monash University



# About OzGrav

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.

The mission of OzGrav is to capitalise on the historic first detections of gravitational waves to understand the extreme physics of black holes and warped spacetime, and to inspire the next generation of Australian scientists and engineers through this new window on the Universe.

OzGrav is part of the international LIGO-Virgo collaboration. LIGO is funded by 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-OzGrav) making significant commitments and contributions to the project. Nearly 1300 scientists from around the world participate in the effort through the LIGO Scientific Collaboration. The Virgo Collaboration is composed of approximately 350 scientists from across Europe. The European Gravitational Observatory (EGO) hosts the Virgo detector near Pisa in Italy, and is funded by Centre National de la Recherche Scientifique (CNRS) in France, the Istituto Nazionale di Fisica Nucleare (INFN) in Italy, and Nikhef in the Netherlands.

The Kamioka Gravitational Wave Detector (KAGRA), formerly the Large Scale Cryogenic Gravitational Wave Telescope (LCGT), is a project of the gravitational wave studies group at the Institute for Cosmic Ray Research (ICRR) of the University of Tokyo. It will be the world's first gravitational wave observatory in Asia, built underground, and whose detector uses cryogenic mirrors. The design calls for an operational sensitivity equal to, or greater, than LIGO. The project is led by Nobelist Takaaki Kajita who had a major role in getting the project funded and constructed.

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