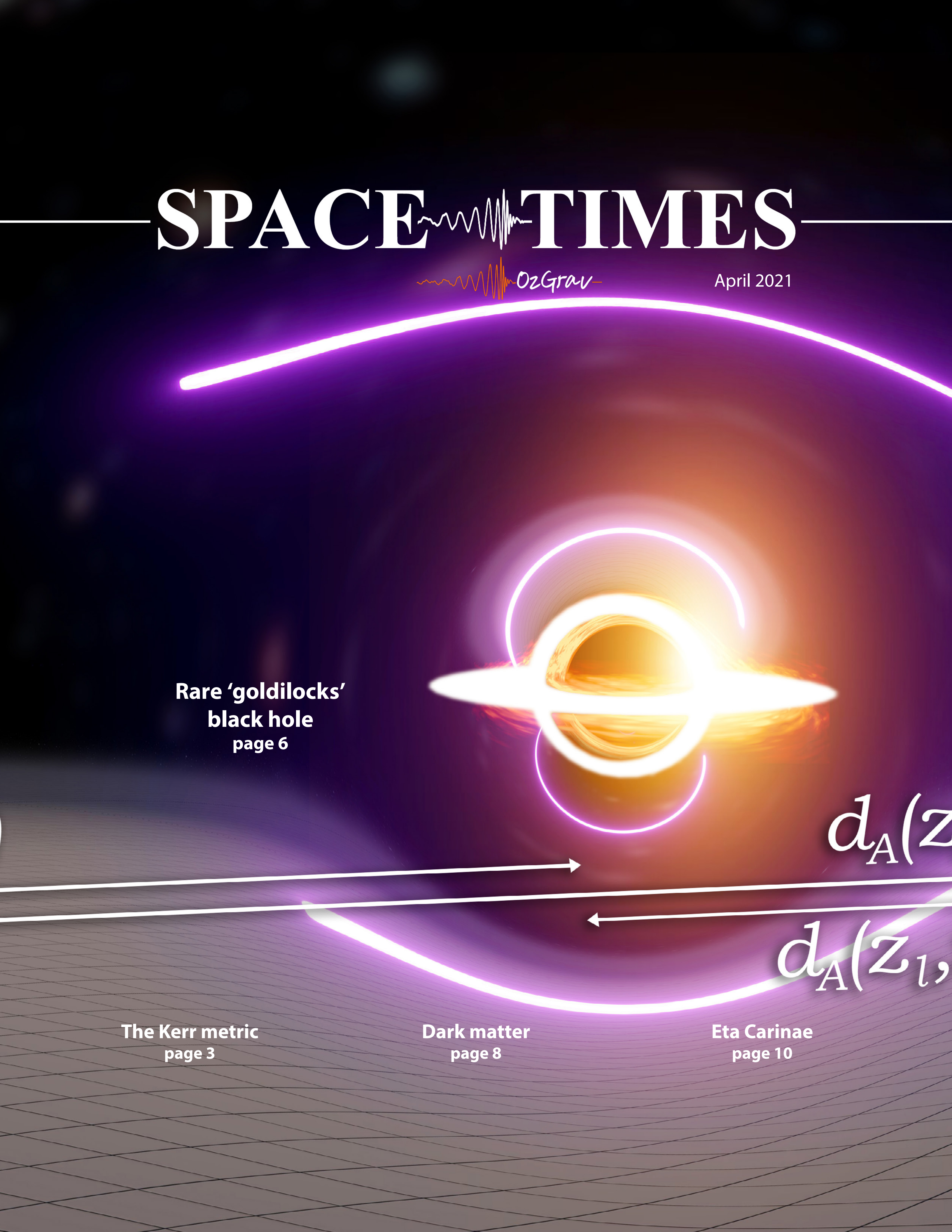
SPACE TIMES

OzGrav

April 2021



Welcome

Dear Colleagues,

One of my main duties as Director over the past six months has been organising the documentation, presentations and interviews for the Australian Research Council's mid term review of OzGrav which occurred in early April. I found the review extremely gratifying as it gave me time to reflect on the achievements of the OzGrav team and where the community and the field were in 2015, in contrast to today.

As I was thumbing through the annual reports, one image particularly struck me as exemplifying the essence of OzGrav. It pictures one of our Monash PhD students and the partner of another (from Swinburne) volunteering their time to show members of the public the wonderful science of neutron stars, black holes and gravitational waves about which we're all so passionate. It's clear that everyone is greatly enjoying the event, the OzGrav VR technology is working beautifully, and the science they're describing is the result of a lot of hard work from across our nodes.

I find such images extremely uplifting, and this one in particular energized me prior to the Director's presentation to the review committee. I couldn't have been happier with how the review went and wanted to thank everyone in OzGrav for making the review process a joy, especially Yeshe's admin team who organised it all and made it go like clockwork.

Finally, congratulations to Professors David McClelland and Susan Scott from ANU on their elevation to "Distinguished Professor" status.

Hope to see you all soon.

Regards - Matthew
OzGrav Director

NEWS IN BRIEF

- Congratulations to OzGrav Chief Investigator Ilya Mandel on his feature article selected by the Editorial Board of Classical and Quantum Gravity (CQG) as one of the journal's Highlights of 2019-2020. Articles featured in the Highlights are chosen by the Board for their high interest, novelty and significance. The full collection can be accessed here.
- Congratulations to Susan Scott and David McClelland for being promoted Distinguished Professors by ANU. A well deserved recognition for their life-long contributions to gravitational wave research.
- Issue 18 of the LIGO magazine is now live. It's a bumper edition with tons of contributions from OzGrav members! A big thanks for OzGrav postdoc and Editor-in-Chief Hannah Middelton.
- The 14th Edoardo Amaldi Conference on Gravitational Waves (Amaldi14) will be taking place virtually on July 19-23, 2021.

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

RESEARCH HIGHLIGHT

Testing Einstein's theory of gravity from the shadows and collisions of black holes

General relativity, Einstein's theory of gravity, is best tested at its most extreme--close to the event horizon of a black hole. This regime is accessible through observations of shadows of supermassive black holes and gravitational waves--ripples in the fabric of our Universe from colliding stellar-mass black holes. For the first time, scientists from the ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav), the Event Horizon Telescope (EHT) and the LIGO Scientific Collaboration, have outlined a consistent approach to exploring deviations from Einstein's general theory of relativity in these two different observations. This research, published in Physical Review D, confirms that Einstein's theory accurately describes current observations of black holes, from the smallest to the largest.

One of the hallmark predictions from general relativity is the existence of black holes.The theory provides a specific description of a black hole's effect on the fabric of space-time: a four-dimensional mesh which encodes how objects move through space and time. Known as the *Kerr metric*, this prediction can be related to the bending of light around a black hole, or the orbital motion of binary black holes. In this study, the deviations from the Kerr metric were linked to features in these black hole observations.

In 2019, the Event Horizon Telescope generated silhouette images of the black hole at the centre of the galaxy M87, with a mass several billion times that of our Sun. The angular size of the shadow is related to the mass of the black hole, its distance from Earth and possible deviations from general relativity's prediction. These deviations can be calculated from the scientific data, including previous measurements of the black hole's mass and distance.

Meanwhile, since 2015 the LIGO and Virgo gravitational-wave observatories have been detecting gravitational waves from merging stellar mass black holes. By measuring the gravitational waves from the colliding black holes, scientists can explore the mysterious nature and metrics of the black holes. This study focussed on deviations from general relativity that appear as slight changes to the pitch and intensity of the gravitational waves, before the two black holes collide and merge.

Combining the measurements of the shadow of the supermassive black hole in M87 and gravitational waves from a couple of binary black hole detections, called GW170608 and GW190924, the researchers found no evidence for deviations from general relativity. Co-author of the study and OzGrav research assistant Ethan Payne (Australian National University) explained that the two measurements provided similar, consistent constraints. "Different sizes of black holes may help break the complementary behaviour seen here between EHT and LIGO/Virgo observations," said Payne. "This study lays the groundwork for future measurements of deviations from the Kerr metric."

Written by OzGrav research assistant Ethan Payne, the Australian National University.

Background image: Carl Knox, OzGrav-Swinburne

FACES OF OZGRAV

Dr Michael Page

OzGrav Associate Investigator and Postdoctoral researcher at NAOJ National Astronomical Observatory of Japan, Tokyo.

Like everyone else who has written for Faces of OzGrav, I have always had an interest in every discipline of science from a young age. I actually started out my scientific career as a Chemistry student, but when I found myself reading more about electronics and quantum mechanics than what I was supposed to be doing, I eventually decided I was set on becoming a Physicist.

My work in gravitational waves started at the University of Western Australia. I was mainly involved in the design of the white light cavity, a highly ambitious type of gravitational-wave detector that uses optomechanical filters to achieve a broadband sensitivity increase. I was fortunate to be in gravitational wave research during the discovery in 2015, as well as the formation of OzGrav. Everyone in OzGrav also has invaluable opportunities to learn from experts abroad--In my case I travelled to England, France and America and learned many things in my own field and adjacent areas of research. I found this to be greatly helpful in understanding what I was doing and what I wanted to do in the future. Indeed, during my research trip to the University of Birmingham, well before I graduated, I was already resolved in what I was going to do, and eventually managed to get it.

Recently I became a JSPS Postdoctoral Fellow at the National Astronomical Observatory of Japan, one of the leading nodes of the KAGRA collaboration. I'm currently working on the frequency dependent squeezing (FDS) experiment with the 300 metre TAMA filter cavity, as well as the design of FDS for the KAGRA detector. I'm working more on control and commissioning compared to my previous work, which was mostly focused on quantum optics. So far, I've been trying something new every day of my postdoc and I'm also motivated to shake up my old habits. The more time I spend on my research, the more I'd like my future to be "in the moment" aspect of gravitational wave detection.

In my free time I'm usually taking pictures of the Tokyo cityscape or transcribing guitar songs. Of course, sometimes I visit the KAGRA site out in the wilderness, with plenty of scenic photo ops there as well.

Upcoming prizes & awards

- Australian Optical Society Awards - nominations close 30 April 2021
- Australian Academy of Science Awards - nominations close 1 May 2021
- 2021Australian Museum Eureka Prizes - nominations close 28 May 2021
- The AIP Walter Boas Medal - nominations close 1 June 2021
- The AIPS TH Laby Medal for Excellence in Physics - nominations close 1 July 2021

A French visit to Gingin

Picture from left to right: Dr Buce Gendre (OzGrav scientist and Zadko Systems Manager); Eloise Moore (undergrad OzGRav associate and Zadko Scholar); Mr Frederic Flipo, Honorary Consul for France, Perth; His Excellency, Mr Jean-Pierre Thebault, Ambassador of France; Associate Professor David Coward (OzGrav CI)
Mr John Moore (Gingin Gravity Precinct Manager and OzGrav support staff); Wg Cdr Franck Arnaudon, French Air Force Deputy Defence Attaché, Canberra

A French embassy delegation from Canberra visited OzGrav at the University of Western Australia (UWA) 12 April. The Ambassador (His Excellency, Mr Jean-Pierre Thebault) requested a meeting with the Zadko Telescope team at the Gingin Gravity Precinct. The diplomatic delegation were introduced to UWA OzGrav activities. The Ambassador was keen to discuss big science questions, ranging from "Is there life beyond Earth?" and "What is dark energy?". He expressed particular enthusiasm for space related activities, joint projects with the French Government scientific bodies, French National Centre for Scientific Research and National Centre for Space Studies, and student exchanges between UWA and french universities.

In addition the Ambassador was briefed on the OzGrav participation in the Space Variable Objects Monitor satellite mission that will study gamma ray bursts and other transients.The Ambassador recommended that the OzGrav members at the meeting provide a briefing to the French Scientific Attache in Canberra to initiate possible joint projects.

Background image: Pixabay

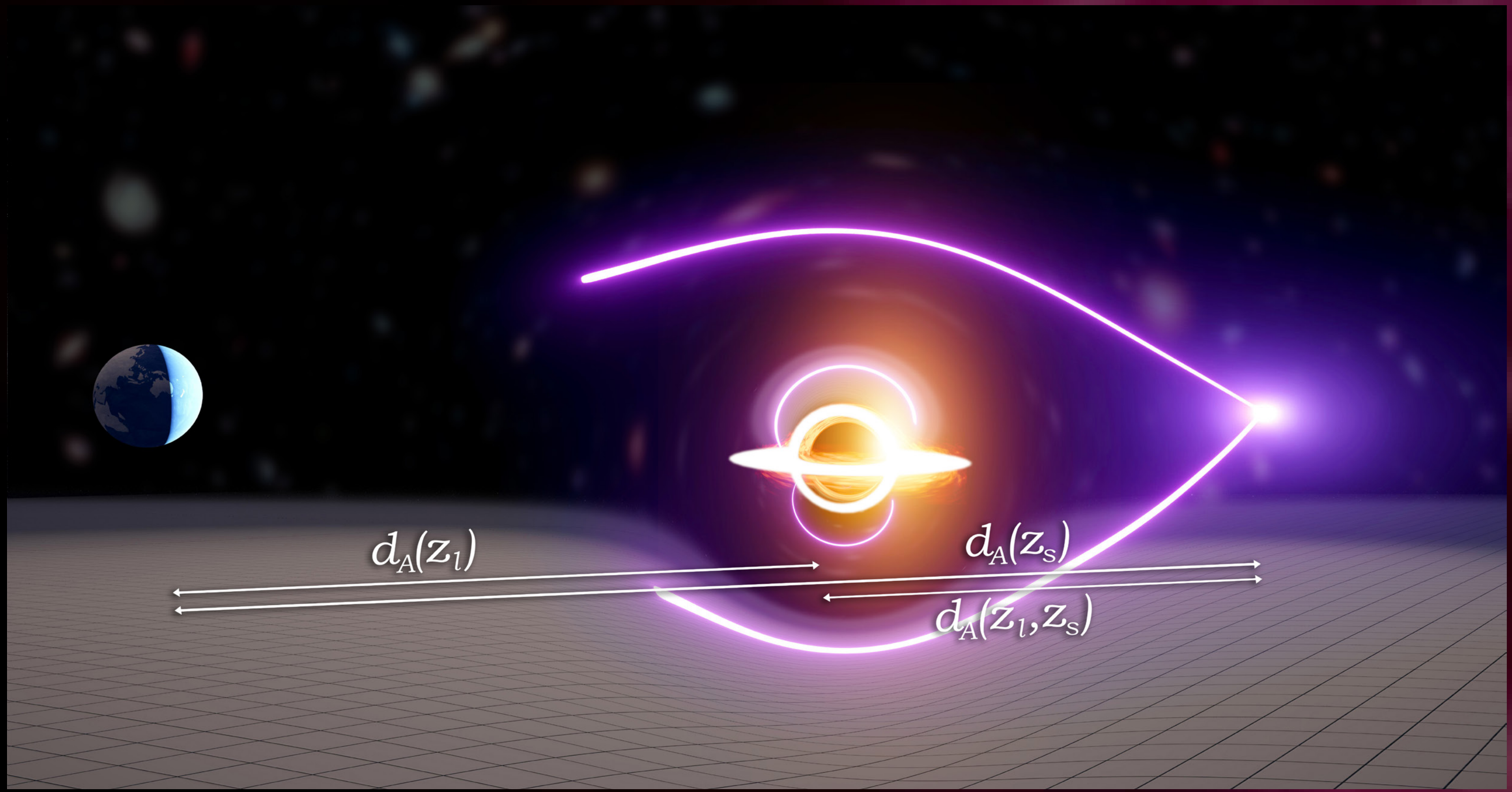
Astronomers discover rare 'Goldilocks' black hole from intergalactic blasts

New observations of the first black hole ever detected have led astronomers to question what they know about the Universe's most mysterious objects. Published in the journal *Science,* the research shows the system known as Cygnus X-1 contains the most massive stellar-mass black hole ever detected without the use of gravitational waves.

Cygnus X-1 is one of the closest black holes to Earth. It was discovered in 1964 when a pair of Geiger counters were carried on board a sub-orbital rocket launched from New Mexico. The object was the focus of a famous scientific wager between physicists Stephen Hawking and Kip Thorne, with Hawking betting in 1974 that it was not a black hole. Hawking conceded the bet in 1990. In this latest work, an international team of astronomers used the Very Long Baseline Array—a continent-sized radio telescope made up of 10 dishes spread across the United States—together with a clever technique to measure distances in space.

OzGrav Chief Investigator and study co-author Prof Ilya Mandel, from Monash University, says the black hole is so massive it's actually challenging how astronomers thought they formed. 'Stars lose mass to their surrounding environment through stellar winds that blow away from their surface. But to make a black hole this heavy, we need to dial down the amount of mass that bright stars lose during their lifetimes,' says Prof Mandel. 'The black hole in the Cygnus X-1 system began life as a star approximately 60 times the mass of the Sun and collapsed tens of thousands of years ago,' he says. 'Incredibly, it's orbiting its companion star—a supergiant—every five and a half days at just one-fifth of the distance between the Earth and the Sun. These new observations tell us the black hole is more than 20 times the mass of our Sun—a 50 per cent increase on previous estimates.'

Second study author Dr Arash Bahramian from the Curtin University node of the International Centre for Radio Astronomy Research (ICRAR) says this was an exciting discovery, resulting from a collaboration between astronomers focused on different observational and theoretical aspects of black holes, coming together for a new extensive and rigorous look at a known but previously elusive black hole. 'It is exciting that we can measure so precisely so many aspects of the system, like its distance from us, its motion and speed through the Galaxy, and the binary motion of the black hole and the star around each other,' says Dr Bahramian. 'Our new distance estimate caused an interesting domino effect, leading us to new measurements for the mass and spin of the black hole, which in turn led to fascinating new insights about how stars evolve and how black holes form.'



An artist's impression of a lensing event. Light (purple) bends around an object in space, like a black hole, splitting into different paths -- one arrives faster than the other. Credit: Carl Knox, OzGrav-Swinburne University

Lead researcher James Miller-Jones also from ICRAR says over six days the researchers observed a full orbit of the black hole and used observations taken of the same system with the same telescope array in 2011. 'This method and our new measurements show the system is further away than previously thought, with a black hole that's significantly more massive,' says Prof Miller-Jones.

In a separate but related development University of Birmingham PhD candidate Coenraad Neijssel, affiliated with OzGrav and Monash, led a companion paper to this work simultaneously published in the Astrophysical Journal. 'Using the updated measurements of the system properties, we were able to unwind the previous history of the binary as well as predict its future,' says Coenraad. 'Precise observations like this are critical for improving our understanding of the evolution of massive stars.'

This article is an edited of the original media release written by Silvia Dropulich at Monash University Media Office. Also featured in the New York Times and The Daily Mail.

Background image: James Josephides, Swinburne University

Did LIGO and Virgo observe **dark matter?**

A recent study by an international team of scientists—led by the Galician Institute of High Energy Physics, the University of Aveiro, and including OzGrav researchers—shows that the "heaviest black hole collision" ever observed might be something even more mysterious—dark matter.

Gravitational waves are ripples in the fabric of space-time that travel at the speed of light. Predicted in Einstein's General Theory of Relativity, they originate in the most violent events of our Universe, carrying information about their sources. Since 2015, humankind can observe and interpret gravitational waves thanks to the two Advanced LIGO detectors (Livingston and Hanford, USA) and the Advanced Virgo detector (Cascina, Italy). To date, these detectors have already observed around 50 gravitational-wave signals which originated in the coalescence and merger of two of the most mysterious entities in the Universe—black holes and neutron stars—deepening our knowledge of the Universe.

Gravitational wave astronomy could eventually provide us with evidence for previously unobserved or unexpected objects and shed light on current open issues, like the nature of dark matter—a discovery that may have already happened.

In September 2020, the LIGO and Virgo collaborations (LVC) announced the gravitational-wave signal called GW190521. The signal was consistent with the collision of two black holes of 85 and 66 times the mass of the Sun, which produced a final 142 solar mass black hole—this was the first-ever detected intermediate-mass black hole. This discovery was extremely important as intermediate black holes were long considered the missing link between two well-known black-hole families: the stellar-mass black holes, that form from the collapse of stars, and the supermassive black holes, that hide in the centre of almost every galaxy.

Despite its significance, the observation of GW190521 posed an enormous challenge to scientists' understanding of stellar evolution: the life and death of stars is significantly more massive than our Sun. If this is correct, the heaviest of the two colliding black holes shouldn't have occurred as the end-result of the gravitational collapse of a massive star.

In an article recently published in Physical Review Letters, a team of scientists lead by OzGrav alumnus Dr Juan Calderón Bustillo, (now "La Caixa Junior Leader - Marie Curie Fellow", at the Galician Institute of High Energy Physics) and Dr Nicolás Sanchis-Gual, a postdoctoral researcher at the University of Aveiro and at the Instituto Superior Técnico (University of Lisbon), together with OzGrav researchers from Monash University Dr Rory Smith and Avi Vajpeyi, and collaborators from the University of Valencia and The Chinese University of Hong Kong, has proposed an alternative explanation for the origin of the signal GW190521: the collision of two exotic compact objects known as boson stars. Such hypothetical stars are among the simplest exotic compact objects proposed, and present as well-founded dark matter candidates. Within this interpretation, the team estimated the mass of a new particle constituent of these stars: an ultra-light boson with a mass billionths of times smaller than that of the electron.

> **"If confirmed by subsequent analysis of this and other gravitational-wave observations, our result would provide the first observational evidence for a long-sought dark matter candidate".**

Dr Nicolás Sanchis-Gual, explains: "Boson stars are objects almost as compact as black holes, but they don't have a 'no-return' surface, or event horizon. When they collide, they form a boson star that can become unstable, eventually collapsing to a black hole, and producing a signal consistent with what LIGO and Virgo observed. Unlike regular stars, which are made of what we commonly know as matter, boson stars are made up of what we know as ultralight bosons. These bosons are one of the most appealing candidates for constituting dark matter, which forms ~27% of the Universe."

The team compared the GW190521 signal to computer simulations of boson-star mergers and found that these explain the data slightly better than the analysis conducted by LIGO and Virgo. The result implies that the source would have different properties than stated earlier. Dr Calderón Bustillo explains: "First, we wouldn't be talking about colliding black holes anymore, which eliminates the issue of dealing with a forbidden black hole. Second, because boson star mergers are much weaker, we infer a much closer distance than the one estimated by LIGO and Virgo. This leads to a much larger mass for the final black hole, of about 250 solar masses, so the fact that we have witnessed the formation of an intermediate-mass black hole remains true".

The team found that even though the analysis tends to favour "by design" the merging black-holes hypothesis, a boson star merger is actually preferred by the data, although in a non-conclusive way. Professor José A. Font from the University of Valencia says: "Our results show that the two scenarios are almost indistinguishable given the data, although the exotic boson-star one is slightly preferred. This is very exciting since the computational framework of our current boson-star simulations is still fairly limited and subject to major improvements. A more evolved model might lead to even larger evidence for the boson-star scenario and would also allow us to study similar gravitational-wave observations under the boson-star merger assumption".

This result would not only involve the first observation of boson stars, but also that of their building block, a new particle known as ultra-light boson. Such ultra-light bosons have been proposed as the constituents of what we know as dark matter, which makes up around 27% of the observable Universe. Professor Carlos Herdeiro, from University of Aveiro says that "one of the most fascinating results is that we can actually measure the mass of this putative new dark-matter particle, and that a value of zero is discarded with high confidence. If confirmed by subsequent analysis of this and other gravitational-wave observations, our result would provide the first observational evidence for a long-sought dark matter candidate".

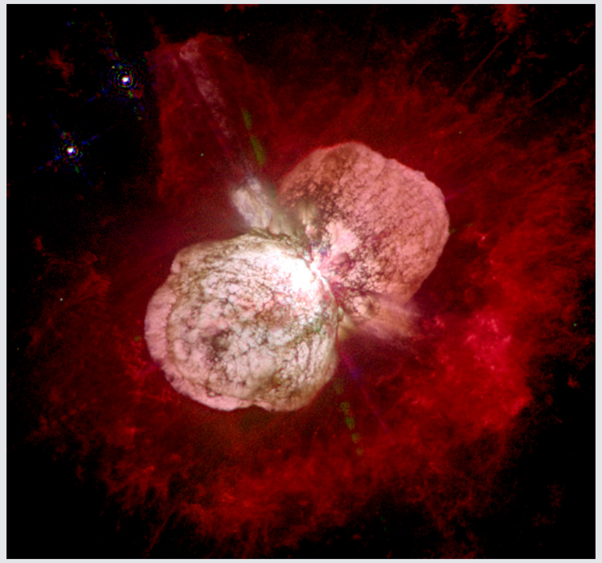
OzGrav researcher Dr Rory Smith adds: "Gravitational-wave astronomy is still very much in its infancy. However, the fact that we are already able to start drawing connections between gravitational-wave observations and fundamental particle physics is a remarkable sign of how powerful this new field is. Even if future observations rule out boson stars as real astronomical objects, we should expect many new and exciting discoveries in the future".

Written by Dr Juan Calderón Bustillo. Also featured on Space Australia.

Background image by Ralf Kaehler

RESEARCH HIGHLIGHT

Simulating the complicated history of Eta Carinae



Optical image of Eta Carinae (Credit: NASA/STScI/ESA)

Eta Carinae is an extraordinary star that has fascinated mankind for decades. It's surrounded by an expanding 'Homunculus nebula', shaped like an hourglass. This nebula was expelled in an energetic explosion called the 'Great Eruption' that occurred in the 1840s, when Eta Carinae became the second brightest star in the sky and was visible to the naked eye for over a decade.

There are other clusters of bullets outside the Homunculus nebula, that were shot out several centuries before the Great Eruption. Eta Carinae itself is extremely massive with a mass more than 100 times the Sun and is orbited by another star that has a mass about 30 times the Sun on a highly eccentric orbit. With all these and many more peculiar features, scientists have been puzzled for a long time on how the star exploded and created the surrounding messy nebula.

Out of many other proposed models, our recently published study focused on one hypothesis that the star system used to be a triple system that eventually became unstable and caused a stellar merger. As more detailed observations are made, this scenario is becoming increasingly popular but has lacked detailed theoretical investigations so far.

In this work we performed the first comprehensive set of detailed theoretical calculations for this scenario. We first carried out three-body dynamical simulations to see how a triple system becomes unstable and eventually two of the stars collide. We started with a stable system in which one star is in a wide orbit around the other two stars which are in close orbit. Once the most massive star approaches the end of its life, it expands and starts transferring matter to its companion. This makes the system unstable and causes two of the stars to merge within a few thousand years. We found that before the final merger, the stars can wildly swap their positions and encounter each other at close distances, grazing each other's surfaces.

We carried out additional N-body simulations to see how a star responds to these close encounters. Part of the surface material can be peeled off and sent away as narrow sprays. Combining the orbital dynamics and close-encounter simulations, we found that the multiple grazing encounters—that occur centuries before the merger—can reproduce the messy structure outside the Homunculus nebula.

We also carried out hydrodynamical simulations to see how the outflow from the stellar merger is shaped into the hourglass shape we see today. We proposed a new scenario that takes similar ideas for how the triple-ring nebula for the supernova SN1987A was formed. As the stars merge, a huge amount of energy is released inside the star, causing the Great Eruption. But unlike supernovae, a large fraction of the energy and mass remains in the star. This energy slowly leaks out over the following century as strong bipolar winds. The wind sweeps up the inner parts of the explosion ejecta and forms a hollow shell-like structure. Our simulations show that with this scenario, we can closely reproduce the shape and size of the Homunculus nebula.

Our combination of simulations successfully reproduces the main features of Eta Carinae's surrounding nebula and provides strong support to the stellar-merger-in-a-triple scenario. This not only gives us insight into the origin of Eta Carinae, but also many other astronomical objects that can be created through mergers in triple systems. For example, some massive black holes found by LIGO (GW190521) are considered to have been created this way. Using the rich information from Eta Carinae, we can learn much more about the formation of exotica in our Universe.

Written by OzGrav Postdoc Ryosuke Hirai, 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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