



LIGO
Scientific
Collaboration



LIGO MAGAZINE

issue 15 9/2019



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Sometime after sunrise 19 June 2019
at the Japanese gravitational-wave detector

Getting KAGRA ready p.11



DON'T PANIC!
Gravitational waves can find new planets

LISA data in exoplanetary studies p.20



... and One Hundred Years of Testing: Celebrating the 1919 solar eclipse centenary p.31

Front cover

At LIGO Hanford, team members (left-to-right: Fabrice Matichard, Sheila Dwyer, Hugh Radkins) install in-vacuum equipment as part of the squeeze-light upgrades.

Top inset: One of the 3 km arms of KAGRA, the Japanese large-scale cryogenic gravitational wave detector.

Bottom inset: An artistic representation of a white dwarf binary orbited by a Jupiter-like planet by Simonluca Definis.

Image credits

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Cover: Main image by Nutsinee Kijbunchoo. Top inset from KAGRA / ICRR University of Tokyo. Bottom inset by Simonluca Definis.

p. 3 p3. Comic strip by Nutsinee Kijbunchoo (including image from the Event Horizon Telescope Collaboration).

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p. 29-30 Photos by Letizia Samutt.

p. 31 Solar eclipse photograph and text excerpt from Dyson, F. W., Eddington, A. S., & Davidson, C., Phil. Trans. R. Soc. Lond. 220, 291–333 (1920). Philosophical transactions of the Royal Society of London. Series A, Containing papers of a mathematical or physical character by Royal Society (Great Britain). Reproduced with permission of The Society in the format Republish in a journal/magazine via Copyright Clearance Center.

p. 32 Eclipse map from Robin Catchpole / Graham Dolan / The Nautical Almanac for the year 1919 (www.royalobservatorygreenwich.org/articles.php?article=1283).

p. 32-33 Eclipse re-enactment photo by Clifford Will. Valencia performance photo from the High Conservatory of Dance of Valencia.

Sobral overhead view and lens photo from Daniela Klebis, communication coordinator of the SBPC (Brazilian Society for Scientific Research).

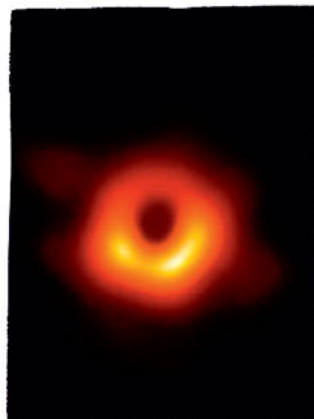
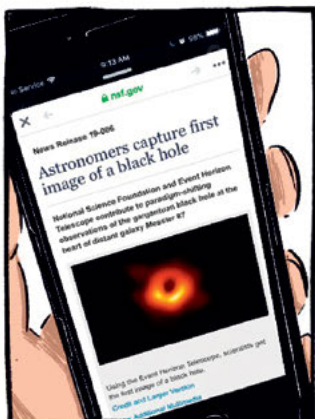
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Back cover: Illustration by Nutsinee Kijbunchoo (with text from Qi Chu).



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Antimatter



Welcome to the LIGO Magazine Issue #15!



H.Middleton

Welcome to the fifteenth issue of the LIGO Magazine! Observing Run 3 (O3) is well underway and brings with it public alerts for gravitational wave candidates as we hear from Christopher Berry in “Gravitational Wave Astronomy Live”. The universe is never sleeping and Qi Chu tells us about getting up in the middle of the night to check on gravitational wave events as well as making sure the public alerts go out smoothly in “Are you ready? Public Alerts for O3”. Take a look at the back page to see what a typical alert looks like. KAGRA is planning to join observations before the end of O3 and we hear how the progress is going in “Getting KAGRA Ready”.

Last July, the LIGO Lab welcomed an international group of teachers to the LIGO Educators Program and we hear from Amber Strunk and Kim Burtnyk on the program activities. In “LIGO to ANSTO” we catch up with Letizia Sammut on her work at the Australian Synchrotron. Looking to space-based gravitational wave observatories, NASA’s Ira Thorpe tells us about LISA progress from the NASA perspective. There’s lots to look forward to from LISA as we hear in “Don’t Panic! Gravitational waves can find new planets”.

This year marks the centenary of the historic 1919 solar eclipse observations used to test Einstein’s general relativity. In “Celebrating the 1919 solar eclipse centenary” we hear about the one hundred year anniversary events around the world. We also hear from Nathan Johnson-McDaniel and Anuradha Samajdar about the tests of general relativity made possible with gravitational waves observations in “Putting general relativity to the test”.

As always, please send comments and suggestions for future issues to magazine@ligo.org.

Hannah Middleton, for the Editors

News from the spokesperson

The four months since I became LSC spokesperson have been a whirlwind. That my first month overlapped with the start of the O3 Observing Run certainly contributed to the excitement. Thus far in O3, we have surveyed more than a million Mpc^3 years of spacetime for binary neutron-star collisions and issued public alerts in low-latency for 22 transient gravitational-wave candidates. As we wrap up the last of our O1-O2 observational papers, we are also moving full steam ahead on O3 observational papers including an accelerated publication on the candidate S190425z. It is gratifying to see the analysis and interpretation of the data proceeding apace even with the substantial increase in event rate. The LSC continues to deliver improved instruments, excellent science, and high-quality data that is being used by the broader community. Thank you all for making this possible!

With the construction of new ground-based detectors underway in Japan and India, the future holds tremendous promise. The Japanese KAGRA team is working to join LIGO and Virgo in taking data before the end of O3. Our plans for detector improvements and observing runs stretch into the middle of the next decade at which point the global gravitational-wave observatory network will include five detectors: LIGO-Hanford, LIGO-Livingston, Virgo, KAGRA and LIGO-India. With every instrumental improvement, the increased number of compact binary detection will deepen our understanding of black holes, neutron stars, and cosmology, and enable stricter tests of general relativity. We can also anticipate the detection of other sources, perhaps a supernova, cosmic string cusp or a spinning neutron star.

There are also challenges. It's easy to think of the LSC as a bureaucracy that exists independent of its members. It is not. The LSC was formed more than twenty years ago to bring together the large, diverse, and committed team needed to make the first detection of gravitational waves. The LSC Charter and Bylaws establish the responsibilities and rewards associated with membership in the LSC; these documents establish a social contract between all LSC members. In order to flourish in this new era of gravitational-wave astronomy, however, and to ensure that our ambitious plans can be realized, we need to change our Charter and Bylaws to address challenges with accountability, authority, coordination, and credit.

The development of an LSC Program that follows from our science goals and distinguishes infrastructure and operations (InfraOps) from long-term research (LTR) is a major step towards understanding what our shared scientific goals are. A Management Team, structured to streamline day-to-day decision making, replaced the Executive Committee in June 2019. And the Bylaws Committee has been considering changes to the LSC Bylaws since the start of the year. We will discuss those changes during the September LIGO-Virgo meeting.

Regardless of structural changes to the collaboration over the coming months and years, there is one thing that will not change. As hateful and intolerant rhetoric and actions increase around the world, the LSC remains committed to being an inclusive collaboration that is free from discrimination and harassment. Thank you for working to set an example of what a great collaboration can look like!



Patrick Brady
LSC Spokesperson



Observing Run 3:

Gravitational-wave astronomy live

LIGO and Virgo's third observing run (known as O3 to its friends) has seen a big change in how we share our science. Alerts issued when we find new gravitational-wave candidates are now shared straight-away with everybody. This has enabled more astronomers than ever before to hunt for the elusive counterparts that might accompany a gravitational-wave signal. It also allows the general public to follow the excitements and disappointments of gravitational-wave science as it happens. With O3 producing more candidates than ever before, it is a great time for gravitational-wave astronomy.

I was waiting in-line at airport security on 18 May when my phone buzzed. I had a message from GraceDB, our Gravitational-wave Candidate Event Database. We had a new detection candidate S190518bb. And this candidate could be a binary neutron star! Binary neutron stars are especially exciting, as there is the potential of there being light, as well as gravitational waves produced by the merger. This light fades quickly, so it's imperative that we analyse the signal quickly. GraceDB wouldn't just be contacting scientists within LIGO and Virgo, but sending out a notice to the GCN service, which distributes this information to astronomers around the world (see p. 18 and the back cover for more information).

The initial notice contains the results of our first analyses of the data. Details are given in the box on p.9. These calculations have been designed to be as fast as possi-

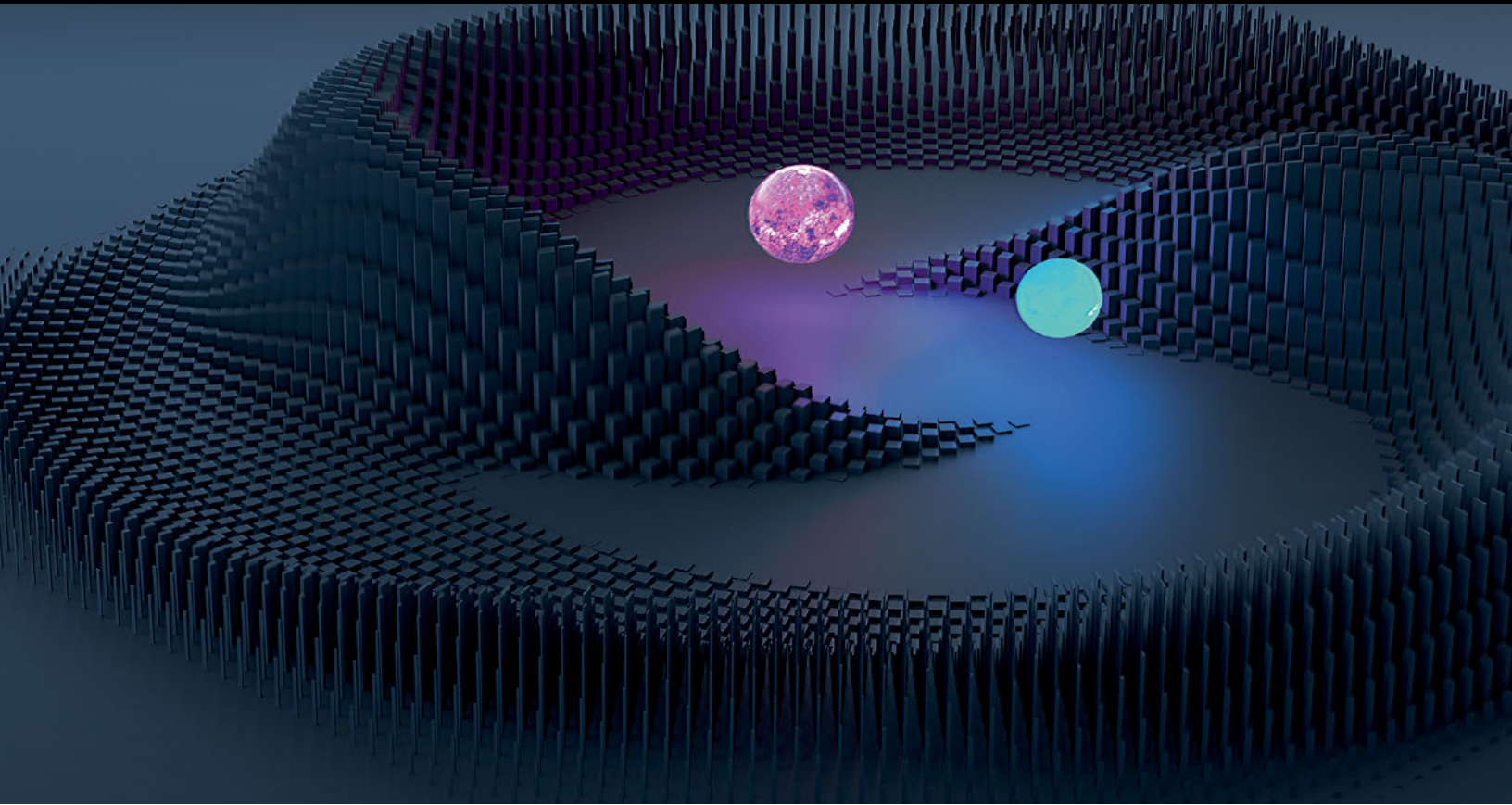


Christopher Berry

is a research professor at Northwestern University working on understanding the astrophysics of gravitational-wave sources. He is a big fan of cake, and usually picks Yoshi when playing

Mario Kart. Find him on Twitter [@cplberry](#) or visit [cplberry.com](#)

ble, so that we can share results as rapidly as we can. More detailed analyses are then performed to refine our understanding. While waiting in-line I quickly checked the results on my phone. A false alarm rate of 1 per 3 years, corresponding to a 75% probability of being a neutron star (and a 25% probability of being just noise), was interesting, but not a sure thing. Then I saw the localization: the source was localised to be in a small area on the sky and really close by. This is exactly what as-



tronomers would hope for! However, this made me a little worried. Unfortunately, it was now my turn to go through the security scanners, so I'd have to wait to investigate further.

After clearing security, I grabbed my laptop and logged onto the airport wifi. I wanted to dig into the results. The false alarm rate indicated that this was a quiet signal. Quiet signals are usually from far away sources, and have large uncertainties on the sky position. This event, however, seemed to be nearby and was well localized. My suspicion was that it must be loud in one of our detectors, but quiet in the others. In this case, the good localization on the sky then reflects the small area where a couple of the detectors were not sensitive to signals, and so would only record a weak signal. Something like this

happened for our first binary neutron star detection GW170817. In that case Virgo didn't see anything, allowing us to pin down the source's direction. While these situations of a loud signal in only one detector do happen, it can be easier to be fooled by a glitch when you're only relying on a single detector. Glitches are a loud burst of noise from something misbehaving in or around our detectors. Looking over our analysis reports, I saw that this was indeed the case. There didn't appear to be anything in Livingston or Virgo, but there was a loud something in Hanford. Unfortunately, that something was clearly a glitch. Alas, this was a false alarm!

After getting an alert, a team of experts assembles to check the state of the instruments, that all the analysis software is working properly, and that we are confident that our results make sense. In the



Artistic representation of a binary neutron star merger by Carl Knox. Carl has a background in 3D animation and currently works as a digital content creator at OzGrav, ARC centre of Excellence for Gravitational Wave Discovery in Melbourne. You can follow him on Instagram @knoxcarl or visit his website carlknox.com.

time it took me to get through security, they had been through various checks, and come to the conclusion that this alert was due to a glitch. In this case, a retraction is sent to alert everyone not to waste their time on this event, and sure enough, it was there waiting for me when I checked. The whole flurry of activity, from first identification to sending the retraction was over in just 30 minutes.

The excitement on 18 May may seem disappointing – we didn't find a gravitational-wave – but it was an excellent illustration of what goes on when we are analysing events. Scientists always need to check their work to make sure it is correct.

03 LIVE: Unlocking gravitational-wave astronomy

WHAT IS IN A NAME?

OUR GRAVITATIONAL-WAVE CANDIDATES HAVE NAMES LIKE S190412M OR S190518BB, BUT WHAT DO THESE MEAN?

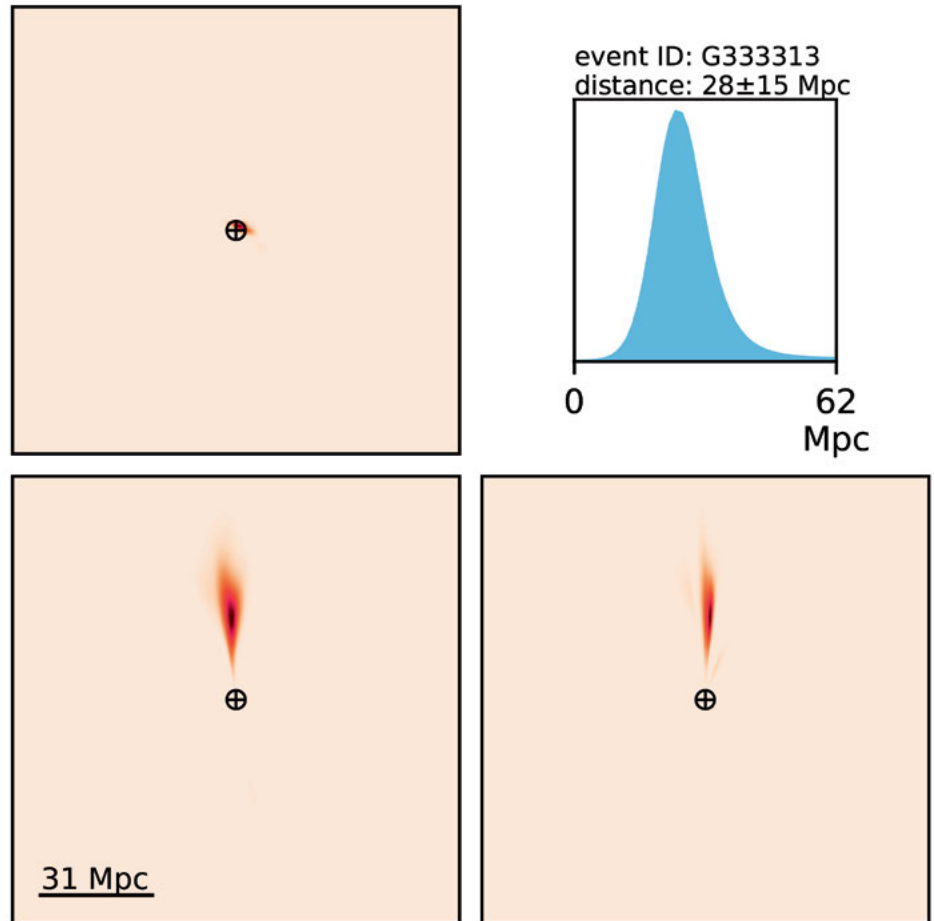
THE “S” STANDS FOR “SUPEREVENT” (NOT “HOPE”). OUR DETECTION PIPELINES LOOK AT THE DATA AND FLAG INTERESTING TIMES AS EVENTS. SINCE WE HAVE MULTIPLE DETECTION PIPELINES, THE SAME STRETCH OF DATA CAN GET FLAGGED AS MANY DIFFERENT EVENTS. THIS CAN GET CONFUSING! THEREFORE, IN O3, WE GROUP TOGETHER EVENTS THAT HAPPEN AROUND THE SAME TIME AS A SUPEREVENT. THIS HAS MADE LIFE MUCH EASIER.

THE NEXT 6 DIGITS REFER TO THE DATE. “190412” MEANS 2019 APRIL 12TH, AND “190518” MEANS 2019 MAY 18TH. WE USE THE SAME FORM WHEN REFERRING TO OUR GRAVITATIONAL-WAVE DETECTIONS. IF S190412M CHECKS OUT AFTER ALL OUR IN-DEPTH ANALYSIS, IT WOULD BECOME GW190412.

THE LETTERS AT THE END REFER TO THE ORDER EVENTS WERE ADDED TO OUR DATABASE. THE FIRST ONE OF THE DAY IS “A”, THE SECOND ONE IS “B”, THE 27TH IS “AA”. WE KEEP TRACK OF LOTS OF LOW SIGNIFICANCE SUPEREVENTS, WHICH ARE ALMOST CERTAINLY FALSE ALARMS, IN OUR DATABASE. WE ONLY SEND OUT ALERTS WHICH HAVE A GOOD PROBABILITY (AROUND 9 IN 10 TIMES) OF BEING A REAL SIGNAL.

Most of the time, this work isn't visible. However, in this case it was important, and we got it done quickly and efficiently!

Sharing our alerts with the world is a big change compared to previous observing runs. Now everyone can share in our ex-



Three-dimensional localization for the 18 May gravitational-wave candidate. The top right panel shows the probability distribution for the distance to the source averaging over all directions. The distance is measured in units of megaparsec (Mpc), where 1 Mpc = 3.3 million light-years. The most probable distance is around 30 Mpc. The other three panels show three different views of the full three-dimensional localization. Darker red indicates a more probable location, and the \oplus symbol indicates the position of the Earth. The most probable location is confined to one narrow direction.

citement as we find new events of interest, and disappointment when further analysis shows that these aren't to be. As we provide updates you can see how our understanding evolves as we perform more detailed analyses – hopefully everyone will get an appreciation of how much time and effort goes into understanding our data, and why it is so important to do this (as first analyses can miss important details)!

In our first two observing runs, we only told the world about our detections once we had all the analysis wrapped up. Alerts were still issued to astronomers so that they could look for counterparts, but only if they signed up to a special, private system. We waited to make the announcement because we wanted to be sure that we had everything right.

Gravitational-wave detection has not had a smooth past. Famously, Joseph Weber,



FALSE ALARM RATE (OR FAR FOR SHORT)

THE FALSE ALARM RATE IS CALCULATED BY OUR DETECTION PIPELINES, THE ANALYSES WHICH LOOK FOR SIGNALS IN OUR DATA. OUR DATA CONTAINS LOTS OF DIFFERENT SOURCES OF NOISE AS WELL AS (HOPEFULLY) GRAVITATIONAL-WAVE SIGNALS, AND THE DETECTION PIPELINES HAVE TO DISTINGUISH THE TWO. THE DETECTION PIPELINES LOOK FOR SOMETHING SIGNAL-LIKE IN THE DATA. IF THERE IS A REAL SIGNAL, YOU WOULD EXPECT IT TO BE IN MULTIPLE DETECTORS. NOISE SHOULD BE DIFFERENT IN DIFFERENT DETECTORS, BUT RARELY YOU'D GET SOME RANDOM NOISE IN MULTIPLE DETECTORS WHICH DO LOOK LIKE A SIGNAL. THE FALSE ALARM RATE IS HOW OFTEN YOU'D EXPECT TO SEE SOMETHING THIS SIGNAL-LIKE DUE TO A LUCKY COINCIDENCE OF RANDOM NOISE. A FALSE ALARM RATE OF 1 PER CENTURY MAKES IT HIGHLY PROBABLE THAT YOU HAVE A REAL SIGNAL, WHEREAS A FALSE ALARM RATE OF 1 PER DAY SHOULD HAPPEN BY CHANCE 1 PER DAY AND IS PROBABLY SAFE TO IGNORE.

SOURCE PROBABILITIES

THE FALSE ALARM RATE IS A GOOD FIRST PIECE OF INFORMATION ABOUT WHETHER THERE IS A SIGNAL THERE. HOWEVER, IT IS NOT THE FULL PICTURE. IT IS CALCULATED ASSUMING THAT THERE IS ONLY NOISE. TO WORK OUT THE PROBABILITY OF IT BEING REAL, WE NEED TO ADD IN THE POSSIBILITY OF THERE ACTUALLY BEING GRAVITATIONAL WAVES. FOR EXAMPLE, IF WE EXPECT TO SEE 1 GRAVITATIONAL WAVE PER YEAR, THEN SOMETHING FLAGGED BY THE DETECTION PIPELINES AS HAVING A FALSE ALARM RATE OF 1 PER YEAR IS EQUALLY PROBABLE TO BE REAL OR NOISE. IN THIS CASE WE WOULD SAY THAT THE PROBABILITY OF THE SOURCE BEING TERRESTRIAL (MEANING SOME RANDOM NOISE IN OUR DETECTORS INSTEAD OF A REAL ASTROPHYSICAL SOURCE) IS 50%.

THE INFORMATION WE GIVE IN OUR ALERTS IS MORE DETAILED THAN JUST THE PROBABILITY OF BEING NOISE VS BEING REAL, AS WE KNOW THAT THERE ARE DIFFERENT CATEGORIES OF GRAVITATIONAL-WAVE SOURCE. WE EXPECT TO SEE MOST SIGNALS FROM BINARY BLACK HOLES, AND FEWER FROM BINARY NEUTRON STARS. THEREFORE, WE BREAK UP THE PROBABILITIES INTO DIFFERENT CLASSES. BINARY BLACK HOLE, BLACK HOLE-NEUTRON STAR, BINARY NEUTRON STAR, AND MASS GAP. BINARY BLACK HOLE MEANS TWO BLACK HOLES MERGING (WE'VE SEEN 10 OF THESE BEFORE O3, SO WE'RE FAIRLY CONFIDENT WE KNOW HOW MANY TO EXPECT); BINARY NEUTRON STAR MEANS TWO NEUTRON STARS (WE'VE SEEN ONE OF THESE BEFORE O3, SO WE'RE NOT TOO CERTAIN HOW MANY WE SHOULD EXPECT TO SEE), AND BLACK HOLE-NEUTRON STAR MEANS ONE BLACK HOLE AND ONE NEUTRON STAR (WE DIDN'T SEE ANY OF THESE BEFORE O3, SO WE ONLY HAVE A MAXIMUM FOR HOW MANY WE SHOULD SEE). THESE THREE CATEGORIES SHOULD SEEM TO COVER EVERYTHING, BUT THE COMPLICATION IS THAT WE'RE NOT EXACTLY SURE WHERE THE TRANSITION FOR NEUTRON STARS TO BLACK HOLES OCCURS. IT HAS BEEN SUGGESTED THAT DUE TO THE WAY STARS EXPLODE, THERE IS A GAP BETWEEN THE HEAVIEST NEUTRON STARS AND SMALLEST BLACK HOLES. THEREFORE, WE INCLUDE THE EXTRA MASS GAP CATEGORY FOR THINGS IN THIS RANGE (PERHAPS WITH OUR OBSERVATIONS WE'LL BE ABLE TO FIGURE IT OUT).

TO CATEGORISE THE DIFFERENT SOURCES, WE USE MASSES ESTIMATED FROM THE DETECTION PIPELINES. THE DETECTION PIPELINES ARE DESIGNED TO NOT MISS SIGNALS, RATHER THAN TO GET THE MASSES PERFECTLY CORRECT. THEREFORE, THERE'S SOME UNCERTAINTY ON THE MASSES. WE FOLD THIS INTO THE CALCULATION OF OUR PROBABILITIES, WHICH IS WHY THERE'S OFTEN A PROBABILITY FROM LOTS OF DIFFERENT CLASSES. WE HAVE TO WAIT FOR MORE DETAILED ANALYSES TO GET BETTER INFORMATION ON THE MASSES.

LOCALIZATION

IF YOU WANT TO FOLLOW-UP A GRAVITATIONAL-WAVE CANDIDATE, YOU NEED TO KNOW WHERE TO POINT YOUR TELESCOPE. ALERTS PROVIDE AN INITIAL ESTIMATE OF WHERE THE SOURCE IS. WE GIVE A THREE-DIMENSIONAL MAP, SHOWING THE MOST PROBABLE DIRECTIONS ON THE SKY, AND MOST PROBABLE DISTANCES. GRAVITATIONAL-WAVE DETECTORS ARE SENSITIVE TO SIGNALS FROM PRETTY MUCH ANY DIRECTION, SO IT CAN BE HARD TO LOCATE THE SOURCE OF A SIGNAL: THIS IS WHERE HAVING MULTIPLE DETECTORS REALLY HELPS!

THE FIRST LOCALIZATION IS BASED ON INPUT FROM THE DETECTION PIPELINES. WE THEN PERFORM MORE DETAILED CALCULATIONS TO DOUBLE-CHECK THIS, WHICH CAN TAKE SEVERAL HOURS.

03 LIVE: Unlocking gravitational-wave astronomy

who pioneered the first gravitational-wave detectors in the 1960s, claimed that he had made a detection which could never be reproduced by anyone else. This

high profile claim kick started the field, as many groups worked to build their own detectors to see if they could reproduce his results. However, it also created a bad

first impression. To convince the world that LIGO had detected gravitational waves, and not repeat Weber's mistake, we had to have every detail pinned down. For our first detection, this took about 5 months of exhaustive work. More detections followed. With each we grew in confidence, we gained experience in analysing signals and understanding the behaviour of our detectors. Then we got our first binary neutron star—this was accompanied by a counterpart observed across the entire spectrum of light, from gamma-rays to radio, so there could be no doubt that it was a real detection!

As we move into O3, we have shown that we do know how to detect gravitational waves. There's no problem in sharing our alerts now. Some might not turn out to be relied upon following careful analysis, but we have proved that our analyses are trustworthy, and that we will get everything figured out in the end.

The world is a different place now that we are making frequent gravitational-wave detections. It took 100 years from Einstein's prediction of gravitational waves to us having the technology able to measure them. Less than four years since our first detection, we now we have a new detection candidate about once per week. Soon gravitational-wave detection will be an everyday occurrence, and that is awesome!

When I used to give a talk about gravitational waves, I always used to make sure my phone was on silent. I would be extremely embarrassed to get a call in the middle of my talk! Now, however, I have to leave it on. A message from GraceDB could come at any time, and if I miss it my talk could be out of date before I finish.

GRAVITY SPY

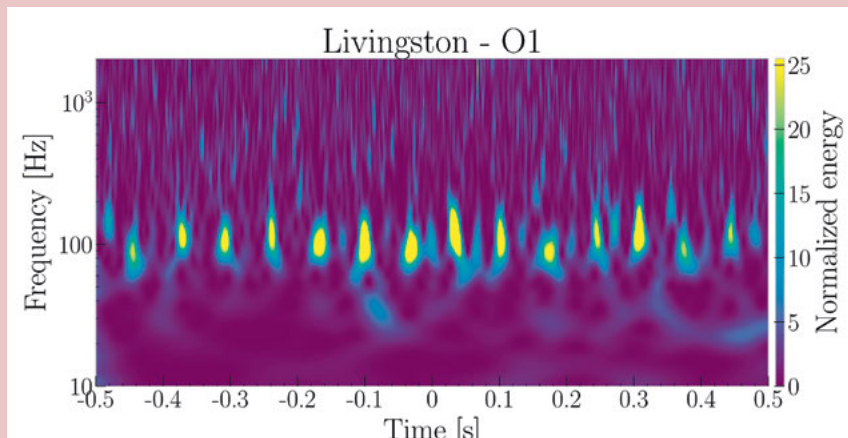
GRAVITATIONAL-WAVE DETECTORS ARE EXTREMELY COMPLICATED MACHINES. THEY MAKE AMAZINGLY PRECISE MEASUREMENTS. THEY ARE ALSO SUSCEPTIBLE TO A RANGE OF DISTURBANCES, WHICH WE CALL GLITCHES [1]. GLITCHES CAN BE CAUSED BY A SYSTEM IN THE DETECTOR MISBEHAVING (OFTEN SOME LIGHT IS REFLECTED OFF SOMETHING IT SHOULDN'T), OR DUE TO AN ENVIRONMENTAL DISTURBANCE (INCLUDING THIRSTY RAVENS[2]). SOME SOURCES OF GLITCHES REMAIN A MYSTERY.

IDENTIFYING GLITCHES HELPS US TRACK DOWN THEIR CAUSES, AND THE MORE WE SEE OF A PARTICULAR TYPE, THE EASIER IT IS TO DISTINGUISH THEM FROM A POTENTIAL REAL SIGNAL. GRAVITY SPY IS A CITIZEN SCIENCE PROJECT WHERE YOU CAN HELP US CLASSIFY GLITCHES. THE CLASSIFICATIONS MADE BY THE GRAVITY SPY VOLUNTEERS HELP US TRAIN OUR DATA ANALYSIS ALGORITHMS, INCLUDING THOSE USED TO QUICKLY SPOT IF THERE IS A PROBLEM WITH THE QUALITY OF OUR DATA AROUND A CANDIDATE EVENT.

EACH TIME WE UPGRADE OUR DETECTORS, THERE IS THE POTENTIAL FOR NEW TYPES OF GLITCHES TO EMERGE. GRAVITY SPY CITIZEN SCIENTISTS HAVE BEEN ESPECIALLY HELPFUL IN O3. SO FAR, THEY HAVE IDENTIFIED THREE NEW CLASSES! PERHAPS YOU COULD DISCOVER A NEW CLASS TOO?

[1] GRAVITYSPY.ORG

[2] HUMANSOFLIGO.BLOGSPOT.COM/2018/10/THIRSTY-RAVEN.HTML



An example of a Scratchy glitch. The plot shows a time-frequency representation. The colors indicate the amount of energy at any given time/frequency going from blue (low) to yellow (high).

Sometime after sunrise: 19 June 2019

Summer 2019 marks a milestone for the Japanese gravitational-wave detector KAGRA. Thanks to a heroic effort of the whole KAGRA team, the initial hardware installation work is essentially wrapped up. It is time to start locking the entire interferometer in its design configuration and obtain the first sensitivity spectrum of the differential arm length - the gravitational wave channel. That first spectrum will lay out the remaining noise reduction work required before starting observations with KAGRA.

In the meantime, the schedule pressure is high. LIGO and VIRGO started their long O3 observation run back in April (see p.6 and p.18 for news of Observing Run 3). KAGRA would like to join that run before it is over with a scientifically interesting sensitivity. This tight timeline is the reason one of the authors (Stefan) decided to join the KAGRA team for the better part of the summer this year, helping with commissioning KAGRA's lock-acquisition sequence.



▲ Celebrating the first lock of the dual-recycled Michelson interferometer - the central part of the KAGRA interferometer. The goal was achieved in the morning of June 19, 2019, sometime after sunrise. In the KAGRA control room from left to right: Yutaro Enomoto, Keiko Kokeyama, Masayuki Nakano.

History of KAGRA

But how did we get here? After project approval in 2010, the KAGRA tunnel excavation started back in May 2012. As soon as the tunnel was ready, the hardware installation began, leading to the demonstration of a 3-km Michelson interferometer at room temperature as part of iKAGRA in April 2016. The main purpose was to check the alignment of the infrastructure, to install and test the digital control system, and to gain the experience operating a km-scale interferometer. After iKAGRA, the installation of the cryogenic interferometer called baseline-KAGRA (bKAGRA) began. In May 2018 the 3-km Michelson interferometer was operated with a cryogenic, 13-m tall suspension and sapphire test masses. Since then, all of the suspensions have been installed and cooled down to cryogenic temperatures - the first km-scale gravitational-wave detector to do so. The first issue caused by the cryo-

genic mirrors was already encountered. The y-arm finesse was found to be far too low due to Nitrogen-deposition at low temperatures. Fortunately, the finesse recovered after raising the temperature, and the issue is now under control.

Commissioning KAGRA

Acquiring lock - that is getting light to resonate in all the cavities - requires an intricate control system dance. Green light is used to "pre-lock" the arm cavities and move them off-resonance as seen by the infrared light. Next, the central, dual-recycled Michelson interferometer (DRMI), consisting of the beam splitter, the two recycling mirrors and the two input test masses, has to be locked on the infrared light. The final step then is slowly bringing the arm cavities to resonance, achieving full light build-up in the arms. Fortunately, much of this process is very similar to the LIGO lock acquisition procedure.

The arm length stabilization system (ALS) was commissioned back in December, after the cryogenic suspension installation finished. Both arms were separately locked on green light with exactly twice the frequency of the main infrared laser. Unlike LIGO, the green light is injected from the corner, simplifying the arm length stabilization system. Holding the arms off-resonance for the infrared light and bringing them slowly to resonance was successfully demonstrated. The ALS locking procedure is automated using the Guardian automation software developed for LIGO, and the system is ready for the full interferometer commissioning.



Masayuki Nakano is a Postdoc at the University of Toyama. He has worked on KAGRA from 2014, when nothing was in the tunnel except for stones, soil, and water. The picture is at the laser room in 2014.



Stefan Ballmer is an Associate Professor at Syracuse University with some experience commissioning initial LIGO, initial Virgo, Advanced LIGO and now KAGRA. His Japanese has improved a lot this summer.

Then, in June, it was time to lock the central dual-recycled Michelson (DRMI) interferometer. While the sensing and actuation hardware all worked as designed, we ran into an old enemy - low-finesse optical cavities. KAGRA's design, compared to Advanced LIGO, requires higher arm cavity build-up factors, or finesse (~1500), but comparatively lower central interferometer finesse. Low-finesse cavities pose additional problems: The fringe takes up a bigger fraction of the free spectral range of the cavity. That is also true for higher order modes. As a result, depending on the transverse mode spacing and alignment state of the cavity, there is a significant chance that the Pound-Drever-Hall error signal from a higher order mode disturbs the desired one from the fundamental mode. This leads to "mode-hops" and glitches.

Indeed, the first KAGRA power recycling cavity locks were plagued by such glitches, which in effect disturbed the signal recycling cavity error signal and prevented solid DRMI locking. The as-installed transverse mode spacing in the power recycling cavity turned out to be exactly one-sixth of the free spectral range, leading to a co-resonance of the sixth-order transverse mode and the aforementioned glitches. Two days after diagnosing the problem, one of the mode-matching mirrors in the folded recycling cavity (PR2) was moved by 2mm, fixing the co-resonance issue, and leading to the first DRMI lock (Fig.1).

With the dual-recycled Michelson interferometer locked, the next big goal is full interferometer locking. While naturally we expect some technical hurdles along the way, that goal should still be achievable in this fall.

Working at KAGRA

Usually the first question asked about commissioning KAGRA is about the experience with working underground. Actually, the practical impact on day-to-day work is not as big as one might think. Sure, there is the 10min drive from the control room to the mine entrance, and there are safety protocols to follow (emergency lights, oxygen monitor, and so on). But level tunnel access and electric commissioning cars capable of driving inside the mountain make access quite straightforward. Indeed, once in the corner hall, one tends to forget fairly rapidly that all this is happening inside a mountain. On the other hand, the advantage of sitting under ground becomes obvious during mode cleaner locking – the mirrors have to be actively pushed for the cavity to move through fringes that the control system can grab.

The KAGRA control room experience is remarkably similar to LIGO's. Indeed, all key control software is identical, guaranteeing a seamless transition for someone with previous LIGO commissioning experience. Furthermore, many technical discussions are happening in English, making the language barrier surprisingly easy to bridge.

Finally, we would be remiss not mentioning the beautiful mountain valley surrounding the Mozumi control room area - KAGRA definitely wins the scenic beauty prize among gravitational-wave detectors. Of course, this location comes with a commute of 30 to 60min to the nearest hotel. But that hotel always comes with a hot spring to relax at the end of a long day.



Technical Update by the authors – July 24 2019:

Since the article was written, KAGRA commissioning was continuing full-steam, progressing further towards a fully locked interferometer. Monday July 22, 2019 saw the first extended lock of the central power-recycled interferometer with both arms held off-resonance by the arm length stabilization system (ALS). Work started on the “CARM reduction sequence”, slowly bringing the arms on resonance. The dual-recycled configuration still struggles with “mode-hops” – jumps in the error signal due to partial co-resonance of higher order modes – disturbing the signal recycling mirror error signal. This is a disease of low-finesse cavities and was also experienced in Hanford’s signal recycling cavity. Just as in Hanford, better angular control of the optics is expected to cure the problem.

Also, as some of you might have heard, a birefringence issue with the sapphire input test masses was discovered: on single-bounce off the back surface of the input test mass

~6-10% of the incident s-polarization light is converted to p-polarization – mostly in a “butterfly-shaped” mode. Maybe surprisingly, the impact of this loss for full locking is less severe than naively expected: (i) The phase conjugation experienced when reflection off an arm cavity instead of a simple input test mass means that the losses of forward- and backward-propagating beams almost cancel interferometrically, leading to a loss-reduction in full lock. This cancellation was experimentally verified in a single-arm lock. (ii) The KAGRA arm finesse is about 1400 - about 3x higher than LIGO’s, making recycling cavity losses comparatively less critical. (iii) Since the p-polarization is in a higher-order mode, its resonance condition can independently be tuned by adjusting the power recycling cavity round-trip Gouy phase.

At the time of this update, the authors remain optimistic that a KAGRA full lock can be achieved by this fall.

A century of testing general relativity

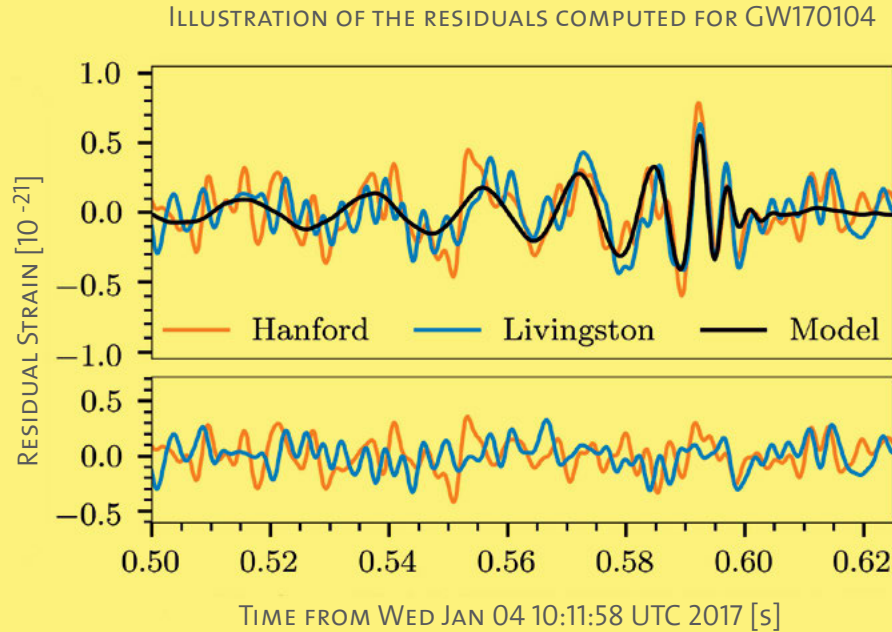


Illustration of the residuals computed for GW170104. The top panel shows the gravitational wave strain over time detected by the Hanford (orange) and Livingston (blue) observatories. The black trace shows the best-fit model waveform from general relativity. After the model waveform is subtracted from the data, the remaining residual should contain only noise if the data is consistent with GR. The lower panel shows the residuals from each observatory, which are consistent with being noise.

Putting general relativity to the test

In the century since the observations of the gravitational bending of light by Eddington and collaborators, general relativity (GR) has passed a wide variety of experimental tests. These tests have ranged from precision laboratory experiments to equally precise observations of astronomical objects from the Solar System to distant galaxies. Eddington himself (in 1922) laid the foundations for the framework in which most Solar System tests are carried out. The observations of the mergers of binaries of black holes and neutron stars

with gravitational waves by LIGO and Virgo now let us test GR in some of the most extreme conditions in the universe, with high speeds and strongly warped spacetime. Additionally, pulsar timing of neutron stars in binaries provides complementary constraints on the motion of relativistic binaries further from merger, where they can be observed for many years. Recently, astronomers have also been able to test GR by observing the region around a supermassive black hole in a nearby galaxy using the Event Horizon Telescope.

Nathan Johnson-McDaniel



is a research associate at the Department of Applied Mathematics and Theoretical Physics at the University of Cambridge, currently focusing on tests of general relativity and related waveform modeling. Nathan also enjoys playing the viola and cycling through the beautiful English countryside.

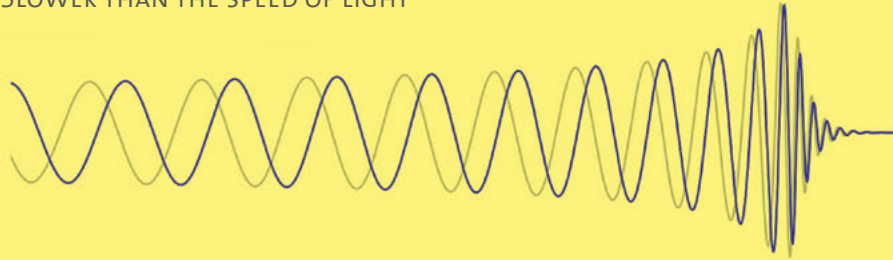
Anuradha Samajdar



is a postdoctoral fellow at Nikhef in Amsterdam and works on data analysis aspects of tests of general relativity. In her spare time, she enjoys travelling and reading crime thrillers.



SLOWER THAN THE SPEED OF LIGHT



FASTER THAN THE SPEED OF LIGHT



Illustration of the deformations of general relativity binary black hole waveforms (in grey in the background) due to dispersive propagation, both faster and slower than the speed of light.

with gravitational wave observations

Although GR remains a very successful theory of gravity and so far reproduces all observations, some missing links remain, especially in the regime where quantum phenomena become dominant, leading to no viable quantum theory of gravity. In addition, puzzles around dark matter and dark energy remain. Thus, one expects to find deviations from the predictions of GR in sufficiently extreme regimes.

While the very observation of gravitational waves means that another one of GR's predictions is borne out by experiment, there are many other possible theoretical descriptions of gravity that predict gravi-

tational waves very similar to those of GR. It is thus necessary to make very precise comparisons of the predictions of GR (given by exacting analytic calculations and high-accuracy supercomputer simulations) with the observations. We detail these tests here:

The most basic test we perform is to consider whether there is anything besides noise left over in the residual signal we obtain after subtracting the best-fit GR waveform from the data. We model the residual signal as noise specific to each detector and a signal that is coherent in all detectors. The coherent signal is de-

scribed using a superposition of wavelets (short oscillatory functions). We compute the signal-to-noise ratio (SNR) of the coherent part of the residual signal as a measure of how much of the total signal is not described by the GR waveform. By comparing the residual SNR with the SNRs one obtains from pure noise around each detection, we find that the residuals are consistent with coming from noise.

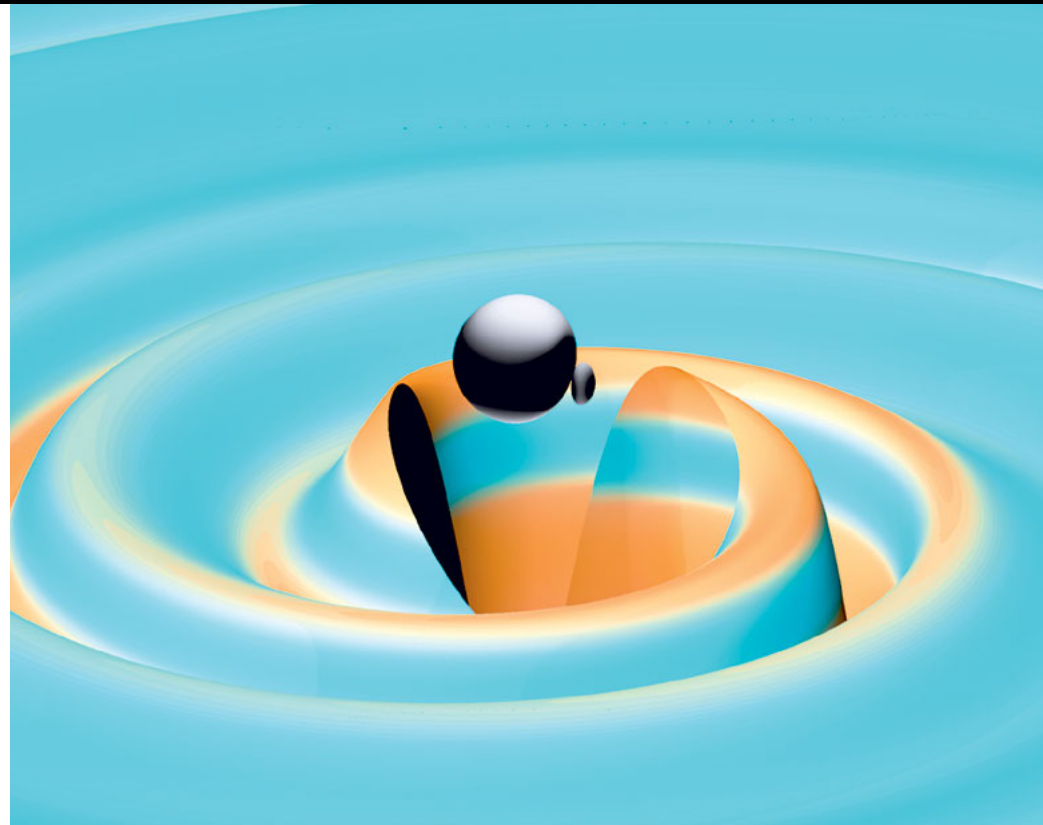
We also check that the low- and high-frequency parts of the signal are in agreement. The low- and high-frequency pieces roughly correspond to the early and late times (inspiral and merger) of the signal,

A century of testing general relativity

due to the chirping nature of the waveform. This test can only be applied to the seven highest-mass binary black hole signals we detected, since for lower-mass binaries (including the binary neutron star) the merger occur at higher frequencies, where the detector noise is larger. The test considers the agreement of the mass and spin of the final black hole since these parameters are inferred fairly precisely from the signals. If the signal is consistent with GR, the final mass and spin estimated from the two portions of the signal should agree to the level expected from noise fluctuations. This is indeed what we find.

We now turn to tests that introduce deviations into GR waveforms and constrain these deviations from GR. We use this method to try to detect any generic violations of the theory in the absence of waveforms from a consistent alternative to GR. We probe the signal in two regimes, the highly dynamical, strong-field regime where the source generates gravitational waves, and the weak-field regime where the emitted gravitational waves propagate from the source to the detector.

In the first test, we verify that the way the gravitational waveform is generated by the source follows GR. The emission of gravitational waves by binaries in GR can be described by a combination of analytical techniques describing the initial stage when the component objects of a binary are far apart and numerical methods when the two components come closer together and form a single object. In order to check for deviations from the predictions of GR, we introduce a deformation parameter in each of the parameters in the waveform model (either the analytically calculated coefficients or the coefficients of fits to the numerical simu-



lations). These deformation parameters are zero in GR, and we check the values given by the data for consistency with the GR value of the parameter.

We have applied this test to all 10 binary black holes and the binary neutron star, and find them all to be consistent with the predictions of GR. Additionally, we have combined results from all the binary black holes detected with a high significance, giving the best bounds obtained to date for possible deviations from GR's predictions in the strong field regime. In all but two cases, these bounds are much better than the bounds obtainable from radio observations of binary pulsar systems, which have much smaller speeds, but have been observed for many years.

We now turn to the propagation test. In GR, gravitational waves travel at the speed of light regardless of frequency, without

Visualization of a numerical simulation of a binary black hole coalescence consistent with GW151226 shortly before the merger. The image shows the horizons of the black holes and the gravitational waves the system emits.

the dispersion effects that one finds for electromagnetic waves travelling through matter. In such dispersive propagation, a wave's speed depends on its frequency, which creates phenomena such as rainbows. We can check if the gravitational waveforms we observe are deformed by dispersion effects or travel without dispersion, as GR predicts. Various alternative theories predict such dispersive propagation. In particular, if the graviton (the gravitational analogue of the photon) has a mass, then low-frequency gravitational waves travel slower than high-frequency gravitational waves.

We consider a parameterized dispersion relation which determines how the speed of

the gravitational waves depends on their frequency. The additional term in this dispersion relation is characterised by an amplitude parameter which is 0 in GR. The LIGO-Virgo observations of binary black hole signals and the binary neutron star signal, allow us to constrain the amplitude parameter to be close to the GR value. In particular, we bound the graviton mass to be at most 5×10^{-23} eV/c², by combining together the constraints from all the binary black holes detected with a high significance. This means that if the graviton has a mass, this mass has to be extremely small compared to all known massive particles: The lightest known massive particles are the three neutrinos, of which at least two must have masses greater than zero, and the two more massive neutrinos have masses greater than 0.009 eV/c².

In addition to checking the consistency of the gravitational waveform with the predictions of GR, one can perform additional tests in cases where one observes both gravitational and electromagnetic radiation. This is the case for the binary neutron star GW170817, which was also seen as the gamma-ray burst GRB 170817A and with other signals across the electromagnetic band. The gamma-ray burst was observed 1.74 ± 0.05 seconds after the end of the gravitational wave inspiral signal. This short difference in arrival times, compared to the long travel time from the source to Earth

(about 130 million years), and the short time between the expected times of emission of the two signals (less than 10 seconds, in most astrophysical scenarios), lets us put stringent constraints on any differences in the speed of gravitational and electromagnetic radiation. We find that these have to travel at the same speed to better than one part in 10^{14} . We thus very strongly constrain proposed alternative theories that predict different speeds, effectively ruling out many of these theories.

For GW170817, one can also compare the amplitude of the observed gravitational waves with the expected value given by the system's masses and spins (which can be determined from the signal's frequency evolution) and the distance to the source obtained from electromagnetic observations. This allows one to constrain proposals where gravity also propagates in extra dimensions that are otherwise inaccessible to us, while electromagnetic radiation propagates only in the four spacetime dimensions we know and love. We find that the data are consistent with gravity also propagating in only four dimensions.

Finally, one can use the precise sky location of the source of GW170817 obtained from electromagnetic observations to check whether gravitational waves produce the expected relative stretching and squeezing of the arms of all three interferometers.

Here we compare the prediction of GR with alternative predictions and find that the GR prediction is favored by factors of greater than 10^{20} . One can also perform the same analysis for the binary black holes that are observed by all three detectors, still favoring GR, but much less strongly, due to the lack of a precise sky localization.

These tests are just the beginning of the constraints we can hope to place on possible deviations from GR with gravitational waves. In fact, particularly for the waveform tests, these results are in some ways comparable to the initial constraints on the bending of light carried out by Eddington and collaborators – showing consistency with the predictions of GR, but not yet sensitive enough to distinguish very small deviations from these predictions. As current detectors become more sensitive, and new detectors are built, we will be able to repeat the tests discussed here with louder signals, and a wider variety of binary parameters. Additionally, many more tests are in development, including the theoretical developments that will allow us to construct accurate waveform models for the merger of compact objects in alternative theories of gravity, and thus compare the predictions of these theories with the predictions of GR. We will continue to put GR to more and more sensitive tests and may even eventually uncover evidence of its breakdown.

Are You Ready? Public alerts for O3



Qi Chu

is a research fellow at the University of Western Australia node of ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav). She is currently working

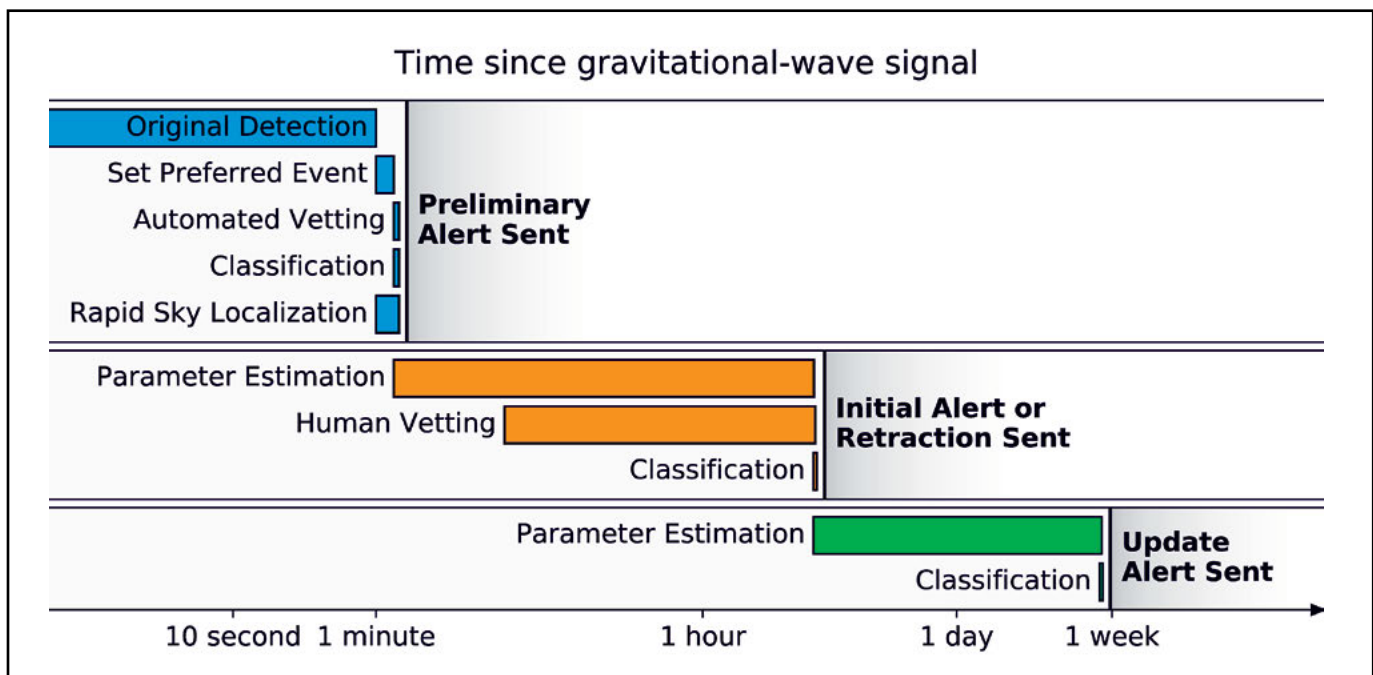
on one of the online compact binary detection pipelines and figuring out how to get back to sleep after late night event alerts.

Since initial LIGO, the collaboration has been preparing for joint observation of gravitational waves (GWs) and electromagnetic counterparts to draw the full picture of the most violent phenomena in the Universe: double neutron star or black hole mergers. The effort includes establishing a system to process data and detect GWs in real time. Less than two years after the first GW detection, the first joint observation took place with a gamma-ray burst from a binary neutron star merger.

The GW signal was so strong that the source was localized to an area that was 5% of the localization for the first GW event detection. This enabled the global observation campaign to trace the source to a specific galaxy and allowed targeted observation from radio to X-ray bands for weeks.

Will we be lucky enough to see joint observations in Observing Run 3 (O3) and beyond? Chances are good. In the last month of Observing Run 2, the rate of event detections was once per week. The event rate for O3, with an over 30% increase in sensitivity, should only be higher. One of the main challenges for joint observations is to capture the rapidly decaying electromagnetic or neutrino emissions during the merging process. This requires that there is no delay of the information flow from the GW detections to the astronomers.

The timeline of public alerts of gravitational-wave events [2]. A "preliminary" alert is automatically sent out once any detection pipeline finds a significant signal that passes the real-time data quality check, and the source type and location are rapidly estimated. This should cost less than one minute. A rapid response team with instrumentation and software experts checks the quality of the trigger and send out an "initial" or "retraction" alert. This can take a few minutes to several hours depending on how "clear" the event is. In the days following the alert, there may be a few "Update" GCN notices to provide more information on the source type and localization of the event.



Preparation for public alerts in O3

The “Low-latency” group of the LIGO Scientific Collaboration and Virgo Collaboration had been working on automating and testing the real-time infrastructure for months before O3 began. The system consists of data delivery tools, data characterization and quality tools, detection pipelines, sky localization pipelines, the event database and so on. The group performed two real-time mock data tests in August and October 2018 and participated in two engineering runs in December 2018 and March 2019, and finally the real-time production of “public alerts” was ready for O3 (see figure). Public alerts appear in the public page of GraceDB [1] and are immediately communicated through NASA’s Gamma-ray Coordinate Network (GCN).

First public alert in O3

The first O3 GW event, S190408am, occurred eight days after the start of O3. Being a recipient of GraceDB significant triggers, I was woken up at 2:18am local time by a series of phone calls. Struggling to fight off drowsiness, I joined a crowd of thirty-ish excited people on Teamspeak. We were expecting to witness the first automated “preliminary” alert, but something got stuck and needed to be fixed manually. Regardless, the first alert was out in about half an hour. The public alert system was continually perfected and practiced during following events.

As the time of writing, four months into O3, twenty public alerts have been published, more detections than the last two runs combined. Events occur randomly, sometimes there are multiple in a day, sometimes it is very quiet for a whole month. Most of the time, the signals detected are binary black hole mergers that are loud and clear. But sometimes, we find marginal signals that require the rapid response team to carry out a series of checks. So far, we have caught our second binary neutron star merger signal and a promising variety of signals from binary black hole mergers. There is no electromagnetic counterpart identified yet. In the eight months ahead, who knows what other surprises are in store for us?

Take a look at the back cover to see an annotated example of a public alert.

[1] <https://gracedb.ligo.org/superevents/public/O3/>

[2] <https://emfollow.docs.ligo.org/user-guide/index.html>

GraceDB also collects and displays external alerts, such as from Gamma Ray Bursts.

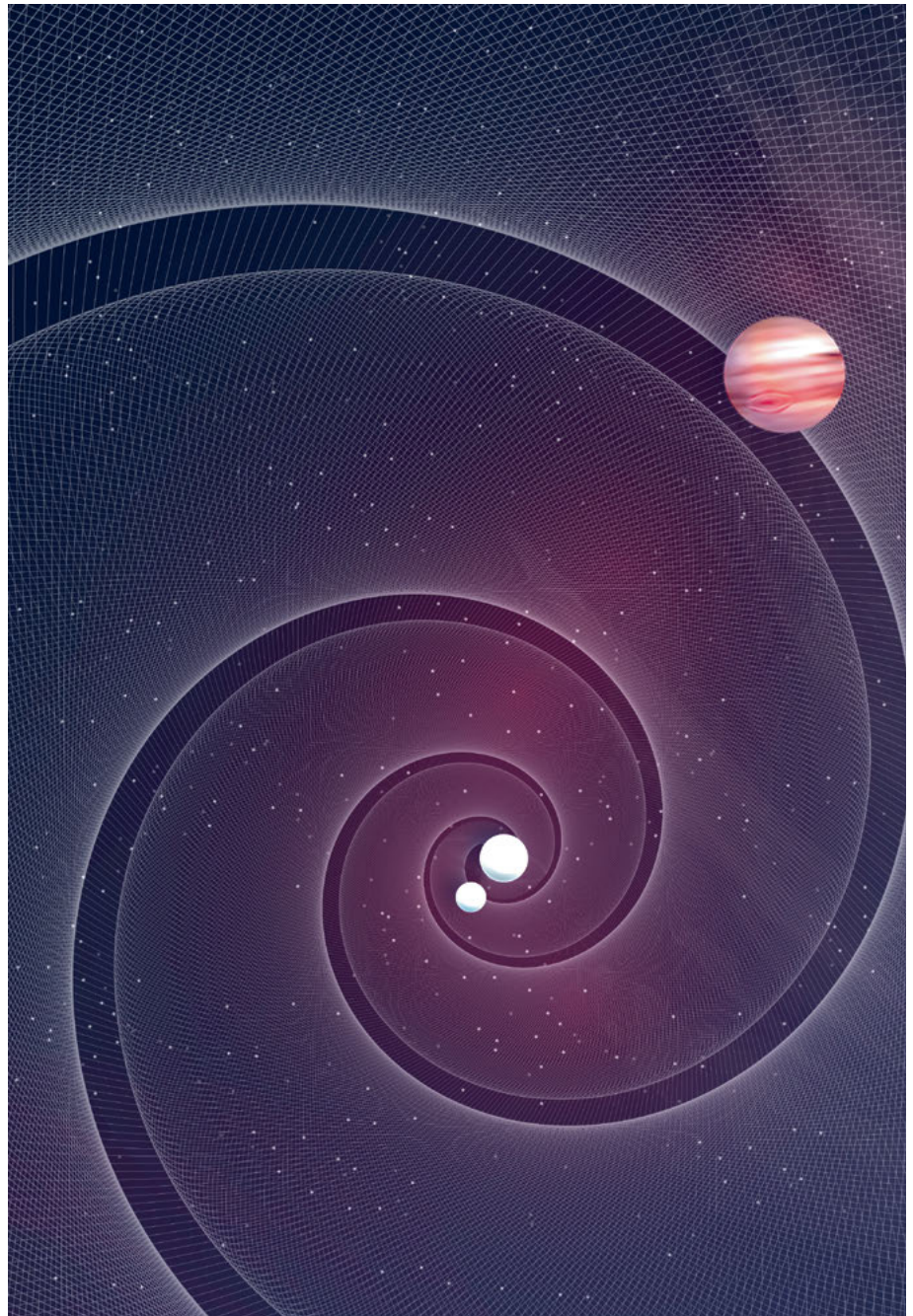
Gravitational waves can find new planets

An artistic representation by Simonluca Definis showing a white dwarf binary emitting gravitational waves and a Jupiter-like planet orbiting around it.

“Out of the utter blackness stabbed a sudden point of blinding light. It crept up by slight degrees and spread sideways in a thin crescent blade, and within seconds two suns were visible, furnaces of light, searing the black edge of the horizon with white fire.”

This is what Zaphod and Arthur, two of the main characters in Douglas Adams’s novel “The Hitchhiker’s Guide to the Galaxy”, see from three hundred miles above the surface of the mythological planet Magrathea. There long before their arrival, the second greatest computer ever created took seven and a half million years to answer The Ultimate Answer to Life, The Universe and Everything. The answer, of course, was 42. To find Magrathea, by then a long disappeared world whose memory soon passed into the obscurity of legend, Zaphod and Arthur use the “Heart of Gold”, a brand new state of the art spaceship equipped with the so-called “Infinite Improbability Drive”, the only technological means at their disposal able to localize the planet and bring them there.

In the future we, humans, will have another way to find Magrathea: gravitational waves! According to the quote above, Magrathea is a planet orbiting a binary star burning with “white fire”. If we interpret this as two stars emitting



white light, contrary to our Sun, which is yellow in the visible band, we can well suppose that Magrathea is orbiting a white dwarf binary. White dwarfs are old stars, with sizes similar to the Earth, that have experienced the Red-Giant phase, ejected the outer envelopes of their atmosphere, and that are now undergoing the last stage of their life, where they slowly fade out, and finally die. Our Sun itself will become a white dwarf in around 8 billion years.

Compact white dwarf binaries represent one of the main target sources for the future Laser Interferometer Space Antenna (LISA), a space mission designed to observe gravitational waves. LISA is expected to detect tens of thousands of such white dwarf binaries everywhere in our galaxy and even in nearby galaxies. The gravitational wave signal emitted by these binaries is almost monochromatic, meaning that the frequency of the wave is basically constant. This implies that the signal itself will evolve very slowly during the 4 years of nominal duration of the LISA mission, contrary to gravitational wave signals currently observed by the LIGO and Virgo detectors whose frequency changes by an order of magnitude in few seconds or minutes. The gravitational waves emitted by a white dwarf binary will thus be boringly simple throughout the whole observational period of LISA, unless of course something perturbs such a signal.

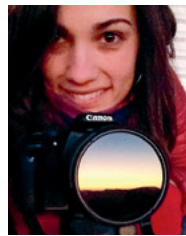
A planet such as Magrathea, on a wide orbit around the white dwarf binary, will force the center of mass of the binary star to move itself on a smaller Keplerian orbit around the common



Nicola Tamanini

is a postdoc at the Max Planck Institute for Gravitational Physics (Albert Einstein Institute) in Potsdam. His research focuses on exploring the cosmological, astrophysical and fundamental

physics implications of gravitational wave astronomy. He is a member of both the LIGO Scientific Collaboration and the LISA Consortium, and is currently chairing the LISA Early Career Scientist (LECS) group.



Camilla Danielski

is a postdoc at the Department of Astrophysics (AIM, CEA-Irfu) in Saclay, Paris. Her research focuses on exoplanets, with particular interest on the characterisation

of their atmosphere through transit and direct imaging techniques. She is an associate of the LISA Consortium and a member of the ARIEL Consortium.

center of mass of the three body system. Consequently the frequency of gravitational waves emitted by the white dwarf binary will be periodically shifted towards higher and lower values due to the well-known Doppler effect. Such a modulation can be detected by LISA and it provides a new method for detecting exoplanets.

This technique can be viewed as the gravitational wave analogue of the common radial velocity method, which employs traditional telescopes and standard electromagnetic waves. The results we presented in Tamanini & Danielski (Nature Astronomy, 2019) suggest that LISA will be able to detect circumbinary exoplanets above 50 times

the mass of the Earth orbiting within a few astronomical units (the distance between the Earth and the Sun) from the white dwarf binary. Furthermore LISA will have the potential to detect these exoplanets everywhere within our galaxy and even in nearby galaxy, overcoming the limitations in distance of electromagnetic telescopes and possibly leading to the discovery of the first extragalactic bound exoplanet.

LISA observations might thus have profound implications for exoplanetary formation and evolution theories. Finding these planets would show that such worlds can survive and/or form again from either the material ejected by their stars during the Red-Giant phase, or the remnants of the close-in planets that instead got destroyed by the atmospheric expansion of their inner binary. This said, even a null result would provide interesting information! Finding no planets at all would in fact tell us that these kind of planets simply do not exist all across the Galaxy, and that the life of a massive planet naturally ends before this stage of stellar evolution.

Given that so far no data have been acquired on such a population of exoplanets, and that current theoretical models cannot provide accurate predictions because of the lack of observations, LISA data will definitely bring a major advance in exoplanetary studies.

For us, humans, gravitational waves could well turn out to be the key to find the legendary planet Magrathea.

IPA – LIGO Lab's International Physics and Astronomy Program

LIGO's fascinating scientific discoveries and world class engineering continue to generate intense public interest. While this interest has increased since the observation of binary black hole merger GW150914, outreach at LIGO started long before this historic detection. LIGO founders have long believed in the importance of sharing our science and engineering with the world. In addition to public tours, both LIGO observatories lead a wide range of outreach activities with students and teachers. The far reaching impact of these activities, from awakening a student's interest in a STEM related career to contributing to the scientific literacy of the public at large, make them well worth the investment.

Education and outreach programs like LIGO's that focus on modern physics topics such as General Relativity, face several challenges, particularly when working with primary and secondary students and teachers. One such challenge is a lack of modern physics topics found in curricula around the world. Fortunately, the breadth of science and engineering represented in LIGO means that, with a little thought, one can find many entry points for introducing gravitational-wave science and detectors in almost any curricula.

A more substantial hurdle those doing outreach must face is the lack of exposure many teachers have to modern physics topics. In 2009 only 35% of US physics



Plotting her next DIY project.

Amber Strunk

is the Education and Outreach Coordinator at LIGO Hanford Observatory. When she is not spreading the exciting physics of gravitational waves she is spending time with her two sons and plotting her next DIY project.



She loves tortoiseshell cats, coffee, chocolate, and landscape photography...pretty much in that order.

Kim Burtnyk

is the LIGO Laboratory Technical Writer and Editor, aka LIGO Cat Herder. She studied Science Communication at ANU and is devoted to helping scientists communicate more effectively with non-expert

teachers had majored in physics or physics education, while another 11% had minored in these subjects according to AIP[1]. A full 54% of teachers had little to no physics background whatsoever! It is easy to imagine the difficulty these teachers face when attempting to integrate gravitational-wave science into their lessons, or even understanding where these topics fit in their curriculum.

While a plethora of professional development (PD) opportunities for teachers exist, only a handful around the world focus on modern physics. Exceptional programs such as CERN's High School Teacher Program and Perimeter Institutes Einstein Plus Workshop

2019 IPA participants engage in classroom activities.





▲ Gabriele Vajente prepares to lead teachers into the laser and vacuum equipment area.

provide exemplary examples of what PD programs for modern physics can accomplish.

Gravitational-wave researchers, working alongside LIGO's experienced educators, are uniquely positioned to bridge the gap in the experience of teachers and current physics research. Additionally, the observatory sites can provide a one-of-a-kind experience for teachers to not only help them better understand the science we do, but to highlight the expanse of STEM related careers present at many large scientific experiments, from science and engineering to the important business office, all of which are needed to make experiments like LIGO successful.

LIGO's International Physics and Astronomy (IPA) program for educators was born out of the knowledge that there was a need for such programs and that LIGO is well positioned to provide an invaluable experience for teachers.

2018 marked the inception of the IPA program. The program gives high school teachers an opportunity to feed their own curiosity, deepen their modern physics knowledge, and collaborate with colleagues from around the world, all while immersed in the environment of a gravitational wave observatory. By providing teachers with these opportunities, we not only deepen their content knowledge but we also provide an environment where

they can foster their passion for physics and physics teaching.

Our goal was to provide educators with a unique personal and professional learning experience within the context of a scientifically historic location. The value of attending a program on-site at a major research facility cannot be underestimated, and such immersion is known to solidify and embed learning in powerful ways.

"LIGO IPA is the first truly collaborative PD experience I have ever had as a teacher. Being with American teachers & International teachers who have a strong passion for Physics education was restorative for me. Thank you for being intentional about creating spaces for community with our colleagues as well as with the LIGO scientists. I stepped away from the program refreshed, renewed, and excited for another 10 years of teaching Physics!"

– Ashley, IPA 2019

"The LIGO IPA was an awesome experience. I enjoyed meeting teachers from all over the world and hearing captivating talks from a range of specialists. I can't believe that I had the opportunity to tour the LIGO facilities with one of the lead engineers. By participating in the program, I now have a number of strategies to implement more modern physics into the classroom. It was definitely worth coming all the way from Australia for the program!"

– Lachlan, IPA 2019

The program is advertised on the LIGO Laboratory website[2], social media, and teacher networks in several countries. Interest in the program has been extremely high. In 2018, 66 applications were received from teachers in 14 countries. In 2019, 79 applications were received from an astounding 23 countries! This remarkable response in just the first two years, clearly illustrates the need for programs like this, not just in the United States, but around the world, and the desire teachers everywhere have to further their own knowledge and become better educators.

The application process is competitive. Interested teachers must submit a written application and create a one minute video explaining what they love about modern physics. Applications are reviewed by a rotating committee of LVC (LIGO Collaboration and Virgo Collaboration) members, and the top-rated 24 applicants are invited to join the program.

The 2019 IPA program was held in July. On Sunday, July 14, 24 teachers from 11 different countries enjoyed a fun and relaxed evening of pizza and conversation, giving them the opportunity to meet each other before the program started. Since they'd spend the next 5 days together working in groups and actively discussing science and pedagogy, allowing teachers to get to know each other in a relaxed social environment is a great way to ensure that teachers are ready to jump into a whirlwind week of physics and camaraderie!

Wasting no time Monday began with a talk about the basics of General Relativity by Dr. Greg Mendell, followed by an overview of LIGO by Dr. Fred Raab. Throughout the week, teachers learned about dark matter, radioactivity, electro-magnetic astronomy, multi-messenger astronomy, and kilonovae straight from the experts. Between talks, teachers participated in hands-on workshops led by Dion Skitsko of the Perimeter Institute, Amber Strunk of LHO (LIGO Hanford Observatory), and Jackie Bondell of OzGrav. The content covered in workshops is correlated to that heard in talks making a direct and almost immediate connection between concepts and activities.

While participants from both years extolled the benefits of the program, they weren't the only ones to benefit. The program also positively impacted LIGO scientists and engineers. LIGO Staff Scientist Gabriele Vajente, who led the 2018 IPA participants on an in-depth tour of LHO, said "I found it extremely stimulating to have to explain what we do in terms that are understandable for non-specialists. It's an opportunity to take a step back and look at our work from a different perspective. I always find that this exercise gives me better insight on aspects of physics and of our detectors, aspects that I often take for granted but are far from obvious (even for LIGO scientists)."

What can YOU do?

There are several ways you can support LIGO's IPA program and teachers. First, help us get the word out to teachers in your region and in countries all over the world. If

you already work with teachers or just have a Twitter account, consider spreading the word about the program.

You can also consider financially supporting a teacher from your region. The IPA program requires substantial investment by the LIGO lab. Even with this investment, teachers must pay a \$300 registration fee and support their own travel to the site. Two selected participants were unable to join the program this year due to lack of funding for their travel. Look into what grants and funding may be available to remove this burden for teachers in your area. If you know of such opportunities, please contact Amber Strunk so she can share these resources with teachers.

Partner with LIGO Hanford! There are so many ways for you to partner with the program, from translating lessons, giving a talk, or leading a workshop. If none of these are possible, you could support an additional spot for a teacher from your region. The program is currently limited to 24 teacher due to limited funding. If you are interested in understanding what it would take to open additional places in the program please contact Amber Strunk.

Gravitational-wave science is an international endeavor and we want our program to be representative of our own diverse community.

[1] www.aip.org/statistics/data-graphics/percent-physics-teachers-physics-degree

[2] www.ligo.caltech.edu

LISA takes gravitational wave revolution into space

Fresh off the dramatic successes of the early observing runs of Advanced LIGO and Advanced Virgo, the gravitational wave community is already looking toward the future and facilities that will expand our view through this new window on the Universe. On the ground, these visionary projects are known as “third generation” observatories and may feature longer arms, subterranean facilities, more powerful lasers, cryogenic test masses, advanced coatings, and other improvements. A parallel, and scientifically complementary, tactic is to move the observatory to space where the environmental disturbances associated with a living, breathing planet can be avoided and there are billions of kilometers of vacuum to be had for free (launch vehicle not included). The Laser Interferometer Space Antenna (LISA) will be the first space-based gravitational wave observatory and will complement its Earth-bound cousins by observing in the millihertz band - a regime expected to host a rich variety of astrophysical sources.

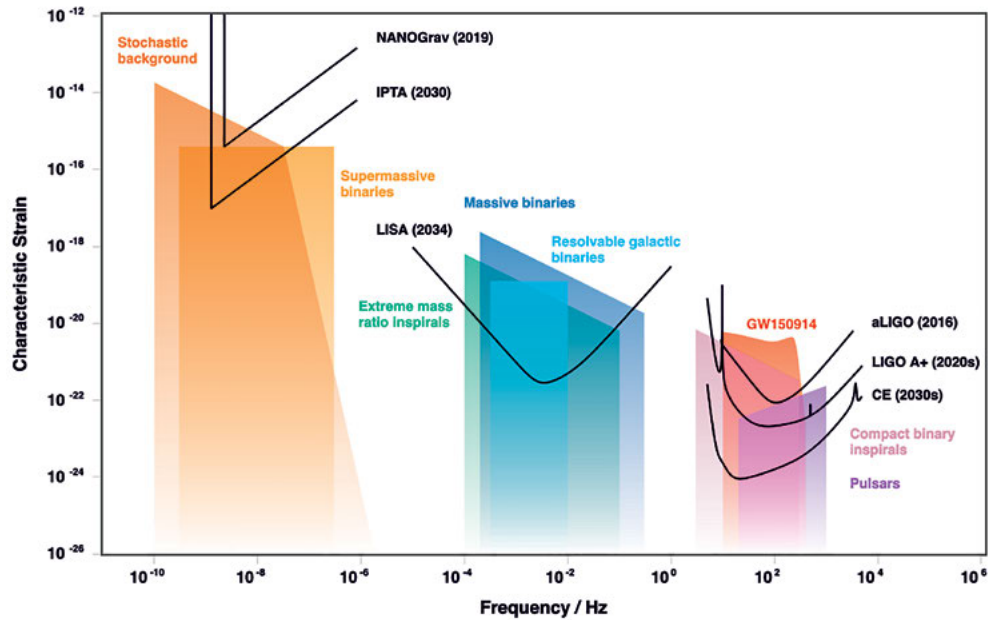


Fig.1: The colored blocks show the expected gravitational wave amplitude and frequency for different sources of gravitational waves. The black lines indicate the sensitivity of different instruments to search for gravitational waves in each frequency range (the lower the line, the better the sensitivity). Produced using gwplotter.com.

The case for space

Astronomers observing in the electromagnetic spectrum have a full suite of instruments that can be trained on objects of interest. The goal of gravitational wave astronomers is to achieve similarly broad coverage using a range of facilities. Figure 1 shows a comparison of instrument sensitivities and expected source amplitudes across 15 decades of gravitational wave frequency[1]. Ground-based detectors such as Advanced LIGO and its 3rd-generation descendants cover the upper end of the band which is primarily sensitive to signals produced by objects in the range of 1-100 solar masses. Pulsar Timing Arrays (PTAs) are sensitive at nanohertz frequencies and will observe both stochastic and isolated signals from truly supermassive black holes of billions of solar masses. Space-based interferometers are well-suited to covering the gap between PTAs and terrestrial interferometers, with the frequency of peak sensitivity primarily determined by the length of the interferometer arms. While concepts with a wide

range of arm lengths have been considered, LISA has selected 2.5 million kilometer arms, which places the peak sensitivity at frequencies around 1 millihertz with an overall measurement bandwidth ranging from 0.1mHz to 100 mHz.

LISA expects to detect tens of thousands of sources ranging in distance from white dwarf binaries in the Milky Way to mergers of massive black holes in the distant reaches of the universe, far beyond any electromagnetic signals observed to date. Figure 2 shows the characteristic strain of some of these signals along with the LISA instrument sensitivity (green line). The most nearby, and most numerous, sources are compact binaries -- binary systems containing one or more compact stellar remnants -- in the Milky Way. Millions of such systems are expected to radiate gravitational wave power within LISA's sensitive band as they slowly inspiral over millions of years. Of these, a fraction of the loudest and most actively-evolving

The case for space ...

Ira Thorpe



is the NASA LISA Study Scientist at the Goddard Space Flight Center outside Washington, DC and previously worked on LISA Pathfinder operations and optical interferometry. He enjoys

cycling both with and without his wife and kids and travels back to his hometown of Santa Fe, NM to get his regular chile fix.

systems numbering in the tens of thousands will be uniquely identified by LISA with measurements of masses, sky locations, and distances (purple dots in Figure 2). A handful of such systems have already been identified through electromagnetic observations (blue asterisks), providing a set of guaranteed multimessenger sources. The remaining unresolved compact binaries produce a foreground signal (grey region in Figure 2) which exceeds the instrument noise for some frequencies, making LISA the first foreground-limited gravitational wave observatory.

Moving outwards, the next most distant sources are black hole binaries of the type currently being observed by Advanced LIGO and Advanced Virgo (grey and black lines at the lower right of Figure 2). At ear-

ing possibility of multiband gravitational wave astronomy with applications in fundamental physics as well as the astrophysics of these objects.

The next most distant LISA source will be Extreme Mass-Ratio Inspirals (EMRIs), with typical redshifts of 1-2.

As many of the post-Keplerian orbital effects are ramped up to extreme levels (the reddish traces near the lower part of Figure 2 represent multiple simultaneously-evolving frequencies from a single EMRI source). The gravitational waveform is similarly complex and precisely encodes the interaction between the two objects. Such systems represent one of the best imaginable laboratories for conducting precision tests of gravity.

LISA's greatest reach will be for mergers of massive black holes, scaled-up versions of the black hole signals now being regularly observed by the ground-based detector network. Relative to LIGO's signals, LISA signals are scaled up in amplitude and stretched out in time by the ratio of the total mass of the merging objects -- a factor of roughly a hundred thousand to a million. This results in signals that are so powerful that they can be detected at redshifts exceeding 30 for optimal mass ranges. Probing these very early epochs may help unlock the mystery of how the massive black holes observed in distant quasars formed and developed and in turn, how galaxies themselves assembled. Figure 2 shows traces of three example massive black hole binaries (red-yellow-black curves) at a redshift of 3, with total masses of 10^5 , 10^6 , and 10^7 times that of our Sun. Such systems could be used for tests of GR by comparing waveforms with numerical relativity templates, and for multimessenger observations with x-ray or other electromagnetic telescopes.

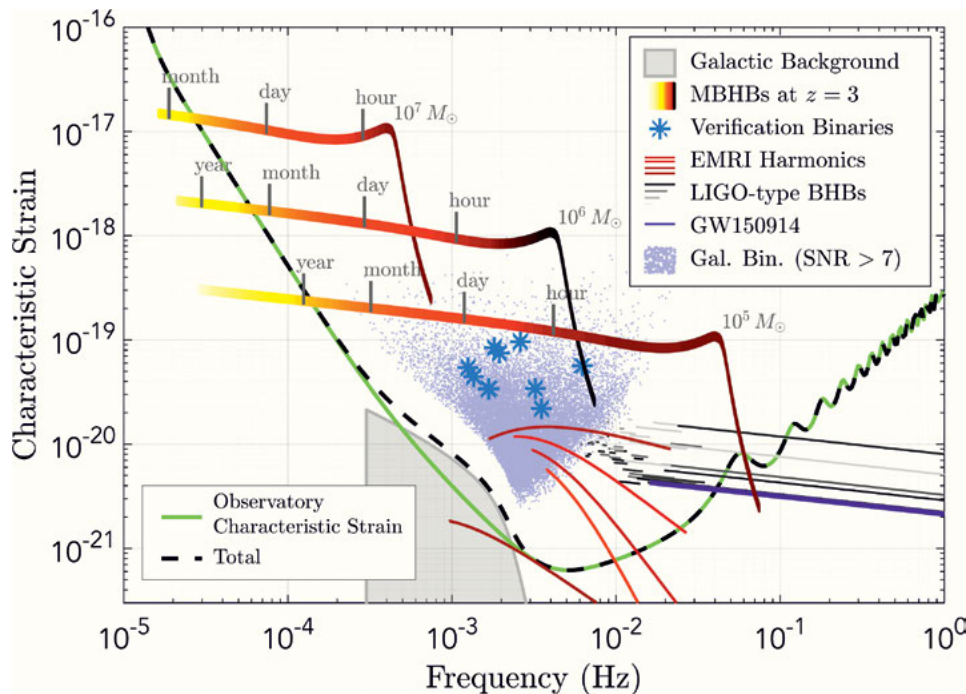


Fig.2: The characteristic strain for some example gravitational wave signals in comparison to the LISA sensitivity curve in green.

lier epochs in their evolutions, systems like GW150914 (blue line) will radiate in the LISA band with the time gap between exiting the upper end of the LISA band and merging in the terrestrial band measured in weeks. This opens up the excit-

As the name implies, an EMRI occurs when a smaller black hole falls into a larger black hole. The resulting orbit is highly com-

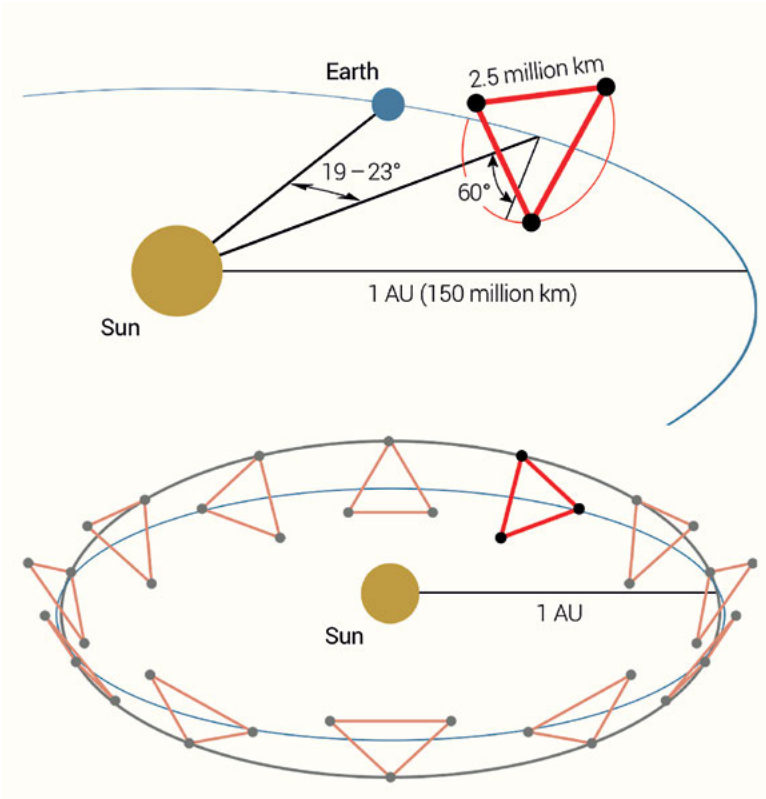
LISA Concept and Technologies

The LISA instrument is distributed over a constellation of three spacecraft arranged in an approximately equilateral triangle. This arrangement is enabled by a class of heliocentric orbits that permit such a constellation to persist for years to decades with no station-keeping maneuvers

required (see Figure 3). Both the Earth-constellation distance and the constellation size are adjustable design parameters with impact on sensitivity, transfer propulsion costs, communications, and mission lifetime. LISA's 2.5Mkm arms at roughly 20° behind the Earth deliver a compelling science case.

sensitive axes, such as the line of sight between each pair of LISA spacecraft, the test masses are allowed to drift completely free while a control system commands the spacecraft to follow using its micropropulsion system. This technique of drag-free flight was successfully demonstrated by LISA Pathfinder, a European Space Agency (ESA) led mission with the express purpose

LISA is sensitive to similar strain amplitudes as LIGO but with a baseline that is a million times larger. This boosts the effective displacements for LISA signals into the picometer range, requiring an interferometric resolution of "only" a millionth of the one micron optical wavelength. On the other hand, the immense distances prevent light from being efficiently transferred between the spacecraft, making it impossible to implement a true Michelson-like architecture. Instead, LISA operates more like a network of optical transponders. Each of the six LISA test masses is associated with a laser, an optical bench, and a telescope. Light from the laser is brought to the optical bench where a portion of it is mixed with light from the second payload assembly on the same spacecraft. Light is exchanged with the far spacecraft via the telescopes, which both expand the transmitted beam to reduce diffraction loss as well as focus the received beam on the optical bench. Out of roughly 2W of transmitted laser light, a few hundred picowatts are received, enough to make an interference with the local beam and measure the resulting phase difference at microcycle precision. A portion of the local beam is also reflected off of the test mass to probe its position. Because of the large mismatches in optical pathlength the interference patterns are dominated by laser frequency noise resulting in fringe rates of MHz or more. Doppler shifts resulting from relative motion between the spacecraft contribute similarly-sized signals. A high dynamic range heterodyne receiver known as a phasemeter is used to track and record each of these signals, which are then transmitted to the ground. On the ground, the signals are adjusted in time and combined to produce an output which has the noise-cancelling properties of an equal-arm interferometer. This process, called Time Delay Interferometry, is what allows LISA to tolerate arm lengths



▲
Fig.3: The arrangement of the three LISA spacecraft.

At its core, LISA relies on the same basic measurement principle as LIGO – optical interferometry to measure distance fluctuations between widely separated, freely-falling test masses. There are, however, some important differences. Since LISA does not need to suspend its test masses against the pull of Earth's gravity, no mechanical suspension is required. Each LISA test mass, a 4cm cube of a Gold-Platinum alloy with a mass of about 2kg, is free to fall inside a hollow housing with gaps on all sides of a few millimeters. Along the most

of validating technologies for LISA which operated from 2015 through 2017. Figure 4 (overleaf) shows the measured amplitude spectral density of test mass acceleration measured by LISA Pathfinder relative to the LISA requirement. Each LISA spacecraft will contain two test masses based on the Pathfinder design with one oriented towards each of the other two spacecraft in the constellation.

The interferometric design of LISA differs significantly from LIGO. On the one hand,

The case for space ...

that differ by tens of thousands of kilometers and which vary over the mission. While no dedicated technology demonstrator is planned for LISA's long-baseline interferometry technologies, many of the components and techniques were validated by the successful operation of the Laser Ranging Interferometer instrument on board the US/German Gravity Recovery and Climate Explorer Follow On (GRACE-FO) mission.

As is typical for ESA missions, contributions to both the instrument and scientific operations are expected from a number of ESA member states as well as international partners. The LISA Consortium (www.lisamission.org) has been formed to organize these contributions to payload and science and currently has more than 1000 members from several dozen countries. NASA has convened a LISA Study Office to

the spacecraft and payload design as well as the split of responsibilities amongst the partners, LISA will proceed to the implementation phase.

Some of us LISA veterans can remember a time when researchers working on LIGO and LISA would engage in a good-natured, but serious, debate about which instrument would make the first detection. In the early 2000s, the answer was not as clear as it might seem in hindsight. When working on one of the recent LISA formulation activities, I called up from my laptop a memo on LISA orbits that had been written in 2003 so that I could compare that analysis with a new one. The memo assumed a LISA launch in 2014 with science operations beginning in January 2015. Had that assumption been maintained, LISA would have detected signals, possibly including GW150914 itself, a few months before September 14th, 2015. That certainly would have made for some lively GWIC meetings in the Fall of 2015!

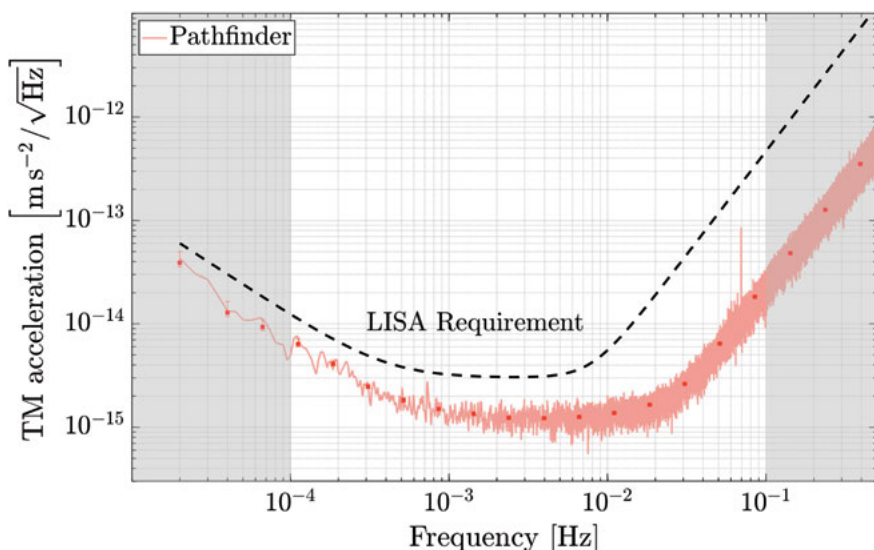


Fig.4: The LISA Pathfinder mission had the aim of validating technologies for LISA. This shows the LISA Pathfinder test mass (TM) acceleration (red line) exceeded the requirements needed for LISA (black dashed line).

Status and Outlook

LISA was selected in 2017 as a large-class mission in the Cosmic Vision Programme of the European Space Agency (ESA). The mission concept retains all of the essential features of the NASA/ESA LISA mission which was studied from 2004-2011, including a full three-arm triangular constellation which allows direct measurement of gravitational wave polarization and also provides some redundancy in the gravitational wave measurement. The mission is in its early formulation stage, with an assumed launch date of 2034.

coordinate pre-project activities including technology development, identification of potential hardware contributions, and foundational work to support US contributions to science and data analysis. NASA is supporting the development of five individual technologies including lasers, ultra-stable telescopes, test mass charge-control devices based on the UV photoelectric effect, high dynamic-range phasemeters, and colloidal micropropulsion systems. Following the consolidation of

While there is certainly some disappointment that LISA isn't yet operating alongside its terrestrial cousins, I think all of us recognize that the community's experiences from LIGO, PTAs, LISA Pathfinder, GRACE-FO, and elsewhere will help make for a successful LISA that will further expand our view into the gravitational wave universe.

For more information on LISA visit

sci.esa.int/lisa,
lisamission.org,
and lisa.nasa.gov.

From LIGO to ANSTO and a new world of acronyms...



Working at Australia's Nuclear Science and Technology Organisation (ANSTO).

Like many, when I decided to take on a PhD, I was unsure where it could or where I wanted it to take me. I just knew I was interested in gravitational waves so studying them sounded good to me (for a few years at least). My first exposure to the concept of gravitational waves came in 2006, when it was listed on the topic list for the research component of my third-year undergraduate physics course. From a young age I was interested in astronomy. Some of my earliest memories were from going for walks in the evening with my father, who was an avid amateur astronomer. He would point out planets and constellations and explain how the Earth's rotation and orbit are the result of gravity.

When I saw gravitational waves on the list, I was intrigued. I spent the next

semester teaching myself general relativity (which was not formerly taught at my university until honours level) in order to understand (or at the very least unpack) the simplistic (but heavily loaded) Einstein's field equations. I learnt about the types and various detectors around the world, and also first found out about LIGO.

Although the prospect of detecting gravitational waves seemed onerous and still a long way off, the idea of an entirely new observational window on the Universe really inspired me, and I wanted to be a part of it.

During my PhD I developed a data analysis pipeline to search for a continuous signal from neutron stars in Low Mass X-ray Binary systems. I continued to write and run search pipelines as a

Post-Doc, instead searching for the stochastic gravitational wave background.

Developing and testing analysis code and scripts in a multitude of computer languages, while installing and maintaining software packages on various operating systems, combined with an advanced understanding of physics and science in general, provided me with a desirable skill set in the field of Scientific Computing.

Counting my PhD and first post-doc, I was coming up to 10 years with LIGO. Although I had enjoyed my time in the collaboration, I was also feeling ready to try something new. There was an opportunity for a Senior Scientific Software Engineer at the Australian Synchrotron. This job would allow me to combine my passion for science and my experience in computer programming and software development in order to facilitate leading edge science for the benefit of the broader community.

As part of the Scientific Computing team at the Australian Synchrotron, I am responsible for designing and developing the software solutions for the operational and scientific outcomes of the facility.

A synchrotron is a light-source that generates extremely bright light by accelerating electrons to almost the speed of light, and deflecting using magnetic fields. At each deflection, very intense light is emitted, which is a million times brighter than the sun.

The scientific research and innovation output of the Synchrotron span



hugely diverse fields, ranging from medicine, biomedicine, advanced materials, agriculture, defence science, environmental sustainability, food and food technology, forensic science, energy industry, mining, cultural heritage, planetary science, and electronics, among many others

Due to the broad range of scientific applications of the facility, and the many specialised “beamlines” or experiments, my work is both interesting and highly varied.

The systems developed and maintained within Scientific Computing range from helping to communicate with and move technical hardware (motor, mirrors, cameras, etc), to enabling users of the facility to access and analyse their data. Within the first few months of starting my job, I had already updated a web interface to view the robot arm that mounts a sample holder on one of the experi-

ment beamlines, and started to develop an interface for users to be able to manage the experimental data they have access to on our system.

And for the multitude of problems, there are usually a multitude of possible solutions. My job involves staying up-to-date with and on top of the ever changing and advancing programming tools and software engineering. This means I am constantly learning and applying new tools and technologies, making my job varied and fast-paced, and often requiring me to work on multiple projects at once.

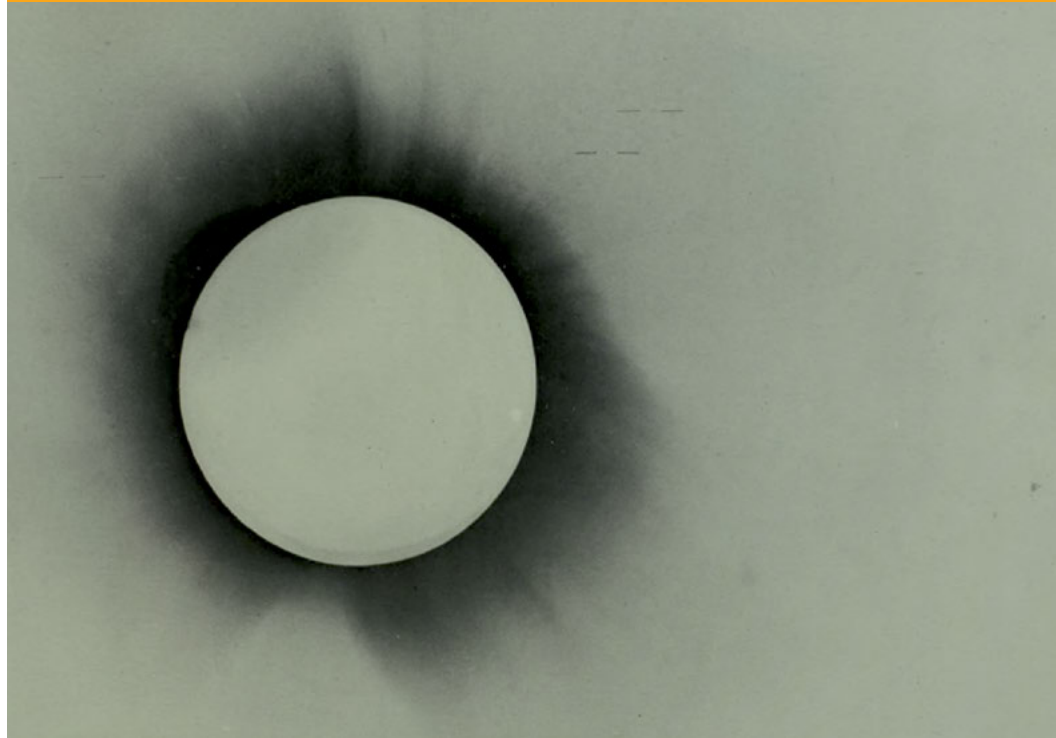
Being part of a team also means there is lots of collaboration, usually involving multidisciplinary groups. This teamwork and collaboration is something I really enjoy, and I am happy to be able to continue after the collaborative experience at LIGO.

Celebrating the 1919 solar eclipse centenary

2019 is a big year in the history of General Relativity as it marks the centenary of the solar eclipse on May 29 1919 which provided one of the first major tests of Einstein's theory - bringing relativity firmly into the public eye and turning Einstein into a global celebrity.

One of the key predictions of General Relativity is that the path of a light ray is deflected as it passes close to a massive object. The aim of the 1919 observations was to measure the deflection of light from distant stars observed close to the limb of the Sun and to compare the results with Einstein's prediction. A total solar eclipse presented a unique opportunity to do this since at any other time the brightness of the Sun would render such starlight too faint to see.

The path of totality for the 1919 eclipse spanned the Atlantic Ocean and crossed the continents of Africa and South America. Two expeditions were planned to observe the eclipse: one to the island of Principe off the west coast of Africa led by Arthur Eddington and Edwin Cottingham and the other to Sobral in Brazil led by Andrew Crommelin and Charles



▲
One of the photographs of the 1919 eclipse taken with the 4-inch lens at Sobral from the 1920 paper by Dyson, Eddington and Davidson

Davidson. The analysis of the observations was presented by Frank Dyson, Eddington and Davidson at a meeting held at the Royal Society on 6 November 1919, and the authors found that there was: "little doubt that a deflection of light takes place in the neighbourhood of the sun and that it is of the amount demanded by Einstein's generalised theory of relativity, as attributable to the sun's gravitational field"[1].

These results were widely reported in the world's press, for example making the front pages of the London Times and the New York Times that same week, and helped to catapult Albert Einstein and General Relativity to global prominence. In the hundred years since, many further observations have been (and will continue to be) made to put general relativity to the test, including of course the observation of gravitational waves. Take a look at p.14 to find out more about testing general relativity with LIGO and Virgo observations of gravitational waves. In the next

hundred years, what adventures and tests are waiting for us regarding gravity?

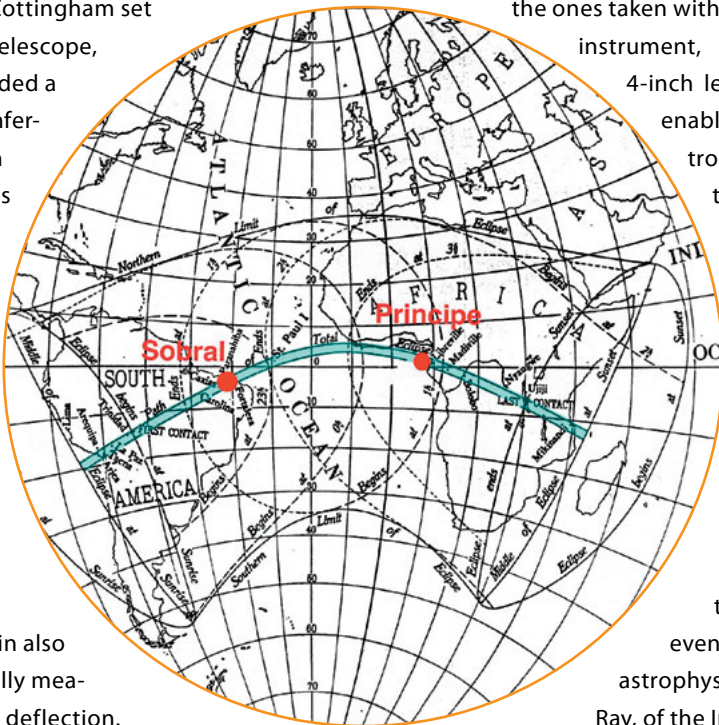
Around the world, events have been taking place to celebrate the centenary of the historic 1919 eclipse observations.

Principe Island Celebrations (Clifford Will)

In late May, the tiny island of Principe was invaded by scientists, teachers and students aiming to celebrate the measurements of the deflection of starlight carried out there by Arthur Stanley Eddington and Edwin Cottingham exactly 100 years earlier. The activities included a two-day scientific conference "Eddington at Sundry", outreach and educational activities for students from Sao Tomé & Principe and Portugal, and other social events. The conference featured talks ranging from tests of general relativity to the latest results from LIGO and Virgo. The President of Portugal, Marcelo Rebelo de Sousa, even showed up for the event (the two-island nation is a former Portuguese colony).

[1] Dyson, F. W., Eddington, A. S. & Davidson, C. Phil. Trans. R. Soc. Lond. 220, 291-333 (1920).

On May 29, the celebrations took place at the Sundry Farm, a former coca plantation, now a high-end resort, where Eddington and Cottingham set up their telescope, and included a video conference with celebrants in Sobral, Brazil, where the other British team of Charles Davidson and Andrew Crommelin also successfully measured the deflection.



▲ Path of the 1919 solar eclipse. The blue line is the path of totality. The map has been adapted by Robin Catchpole and Graham Dolan from the *Nautical Almanac for the year 1919*. For more information on the story behind this map, see www.royalobservatorygreenwich.org/articles.php?article=1283

Sobral Celebrations (Riccardo Sturani)

Celebrations in Sobral (Ceará, Brazil) also took place from May 28th until May 30th, including the live connection with Principe Island. The bad weather at Principe Island prevented Eddington and Cottingham from making good measurements of the light deflection and only two of the pictures taken there could be used, making the observation taken in Sobral decisive for proving the theory of General relativity. However the pictures taken with the main telescope in Sobral (a 13-inch

device) were not clear, probably due to a deformation of the lens due to the heat, and finally the decisive pictures had been the ones taken with the space instrument, with a 4-inch lens, which enabled the astronomers to take 7 pictures of 7 stars close to the Sun. Among the invited scientists to the event, the Irish astrophysicists Tom Ray, of the Institute of Advanced Studies in Dublin, presented to the public the 4-inch lens and 8-inch coelostat of the telescope which recorded the images during the eclipse which belong to Dunsink Observatory. They had been lost and were found again 70 years later in the store of the Dunsink Observatory, and were loaned to the museum of Sobral where they were on display until July 2019.

Valencia Celebrations (Isabel Cordero-Carrión)

In July 2019 from 7th to 12th Valencia (Spain) was the meeting point for researchers in Relativity and Gravitational Waves during the celebration of the 22nd International Conference on General Relativity and the 13th Edoardo Amaldi Conference on Gravitational Waves. As an outreach activity during these conferences, on Monday July 8th in the Botanical Garden of the Univer-

Isabel Cordero-Carrión



is Associate Professor in the University of Valencia (Spain). Her research lines are Applied Mathematics and Astrophysics, with special interest in Numerical Relativity and Gravitational Waves. She is an amateur musician and flamenco dancer, loves mixing science and art and likes playing soccer with her friends and love living close to the Mediterranean sea.

Martin Hendry



is Professor of Gravitational Astrophysics and Cosmology at the University of Glasgow, where he is also Head of the School of Physics and Astronomy. In 2015 Martin was very proud to be awarded an MBE for his services to the public understanding of science.

At the University of Valencia, we celebrated the anniversary of the British expeditions to Sobral and Principe to test Einstein's theory of General Relativity during the eclipse of 1919. The first activity of the day was a round table in the Auditorium with Luis Carlos Bassalo Crispino (Pará University, Brazil) and Gon-

▼ Eclipse re-enactment to welcome people to Principe.

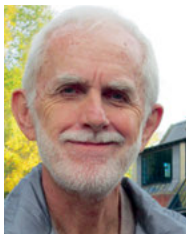


Riccardo Sturani



is professor at the International Institute of Physics (IIP, Natal, Brazil), he's a LIGO/Virgo collaboration member since November 2011 and his main expertise is in the interplay between field theory methods and the General Relativistic description of binary dynamics.

Clifford Will



is Distinguished Professor of Physics at the University of Florida, and a Chercheur Associé at the Institut d'Astrophysique de Paris. He works on the experimental foundations of general relativity, gravitational radiation theory, and relativistic orbital dynamics.

zalo Olmo (University of Valencia, Spain), experts in the topics of the eclipse in 1919 and General Relativity, and Isabel Cordero-Carrión (University of Valencia, Spain) as moderator, in which the main details of the theory of General Relativity, the historical context, the motivations of the expeditions

and the measured results were discussed with a lot of enthusiasm.

Although it was hailing the day before, which is quite unusual for Valencia weather in July, on Monday 8th evening we had a very clear sky, and it was possible to go to an external square of the Botanical Garden where a group from the High Conservatory of Dance of Valencia did a performance inspired in curves, trajectories and the deflection of light, created especially for this occasion. Moreover, the Valencia Astronomical Association brought a few optical telescopes and the assistants had the opportunity to observe the Moon, Jupiter with their satellites, and several additional objects.

Participants from the conferences as well as the public in general were able to know more about one of the first major tests of Einstein's theory, the eclipse in 1919, and to enjoy a nice evening mixing science and art in a wonderful environment.



In Valencia's Botanical Garden there was a performance by the High Conservatory of Dance of Valencia inspired by the deflection of light.

LIGC₂₀₁₉

Left image: Bird's eye view of the celebrations in Sobral. Right image: The 4-inch lens and 8-inch coelostat of the telescope which recorded the eclipse images. They were presented to the public of Sobral having been lost and found in the Dunsink Observatory storage after 70 years.



LIGC₂₀₁₉

Career Updates

Ian MacMillan has graduated from Georgetown in Physics and will be starting his Ph.D. at Caltech this Fall.

Sudarshan Karki, Paul Schale and Vinny Roma have all recently graduated with their PhDs from Ray Frey's research group at the University of Oregon. Their theses can all be found on the DCC.

Kyung Ha Lee, Grégoire Lacaille, Mariela Masso Reid, Daniela Pascucci and Brynley Pearlstone have all graduated from the Institute for Gravitational Research at Glasgow University. Kyung is starting a postdoc at Stanford University, Grégoire and Mariela are now postdocs at Glasgow University, Daniela is starting a postdoc at Nikhef, and Brynley has branched out into the field of science communications.

Jan Gniesmer has graduated from Hamburg University with his PhD on "Advanced Techniques for Squeezed-Light-Enhanced Gravitational-Wave Detection". He continues as a postdoc at Hamburg in the group of Roman Schnabel.

Sarah Gossan, Max Isi, Zach Korth, Masha Okounkova, Surabhi Sachdev and Vijay Varma have all graduated with their PhDs from the California Institute for Technology. Sarah is now at CITA (University of Toronto), Max is now at MIT/LIGO and the Flatiron Institute along with Masha, Zach is now an Engineering Physicist at Senseker Engineering, Surabhi is now at Penn State, and Vijay will remain at Caltech as a postdoc.

Jian Liu has been awarded his Ph.D. at the University of Western Australia and is now working as a postdoc in the AEI 10m prototype group in Hannover, Germany.

Carl Blair has joined the University of Western Australia after a successful DECRA application, moving from LLO. He is working on "Advanced Technologies for Next Generation Gravitational Wave Detectors".

Vaishali Adya joined the Australian National University as a post-doctoral researcher in November 2018 to work on squeezed light sources and experiments for current and future gravitational wave detectors.

Zoheyr Doctor received his PhD from the University of Chicago, and is headed to the University of Oregon for a postdoc with Ben Farr.

Jessica Steinlechner and Sebastian Steinlechner are joining Maastricht University as assistant professors, to work on the Einstein Telescope Pathfinder.

Matt Pitkin has moved from the University of Glasgow to begin a lectureship position at Lancaster University.

T.J. Massinger has moved from a postdoc at Caltech to a new position at MIT/LIGO.

Ansel Neunzert has completed their PhD at the University of Michigan, and will be starting as a lecturer at the University of Washington Bothell in the fall.

Jess McIver has recently moved from Caltech to join the faculty at the University of British Columbia.

David Reitze has succeeded Sheila Rowan as the Chair of the Gravitational Wave International Committee (GWIC).

Awards

The GWIC/Braccini prize for 2018 was awarded to **Jonathan Cripe**, for his thesis "Broadband Measurement and Reduction of Quantum Radiation Pressure Noise in the Audio Band".

The Bakerian Medal and Lecture 2020 has been awarded to **Sir James Hough** for his work on "suspensions systems for the test masses used in laser interferometry, pivotal to the successful detection of gravitational waves". The award will be presented at the Royal Society's Premier Awards Dinner in October 2019.

Bernard Schutz has been elected member of the US National Academy of Sciences, and was also recently awarded the 43rd Eddington Medal for his 1986 work on determining the expansion of the Universe with gravitational-wave and electromagnetic observations.

Denyz Melchor, an undergraduate at California State University Fullerton, was awarded the Barry Goldwater Scholarship as well as the California Pre-Doctoral Sally Casanova Scholarship.

Isobel Romero-Shaw was awarded the Best Student Talk at the Astronomical Society of Australia (ASA) meeting in July 2019 for her presentation on 'Eccentricity in Gravitational Wave Transients'.

Maya Fishbach received a William Rainey Harper Dissertation Fellowship.

Hossein Masalehdan was awarded a SPIE education/research scholarship for studies in the field of optics and photonics.

New LSC positions

Daniel Williams has been elected as LVC Allies chair (June 2019).

Stuart Reid was elected as the Optics working group chair (March 2019).

Patrick Brady was elected as the LSC Spokesperson (March 2019).

Vuc Mandic has been elected as co-chair of the stochastic working group (March 2019).

Marco Cavaglia has been elected as Burst working group co-chair (March 2019).

Other News

From the CSIRO Parkes Observatory

50 years ago, the Parkes radio telescope helped send images of humankind's first steps on the Moon around the world. During the weekend of 20th-21st July, the 50th anniversary of the Apollo 11 mission was celebrated at the CSIRO Parkes Observatory. Thousands of visitors from all around Australia got the chance to visit the telescope, to interact with astronomers and engineers, and even to control the telescope through the PULSE@Parkes program! - Shi Dai (CSIRO)

LIGO 2019

A rare sight of two vacuum chambers open at the same time for part of the squeezer installation at LIGO Hanford. ▶

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Gravitational wave public alerts - what do they mean?

A unique GCN ID number

Yay! A Detection!

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

→ EM advocate on shift (one of the people who checked the detection)

The LIGO Scientific Collaboration and the Virgo Collaboration report:

Significance of the detection

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.

Standard Header

Event time, Detectors that were online, and real time pipelines that identified the event.

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> ← Link to the detection

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

Classification of the event source

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%).

Probability of having REMNANT after merger

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).

Estimated sky location and distance of the event source

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] Klimentenko 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)