LIGO Scientific Collaboration

LIGO MAGAZINE

issue 12 3/2018

The Dawn of Multi-Messenger Astronomy: GW170817

First Detection of Gravitational Waves awarded Nobel Prize in Physics 2017

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... and a squeezing roadtrip to the Virgo detector.

Visualization of a neutron-star merger superimposed on a coherent spectrogram of LIGO-Virgo gravitational-wave data made by Matt Evans and Jess McIver. Simulation image from Tim Dietrich (Max Planck Institute for Gravitational Physics, Friedrich Schiller University Jena, BAM collaboration).

Image credits

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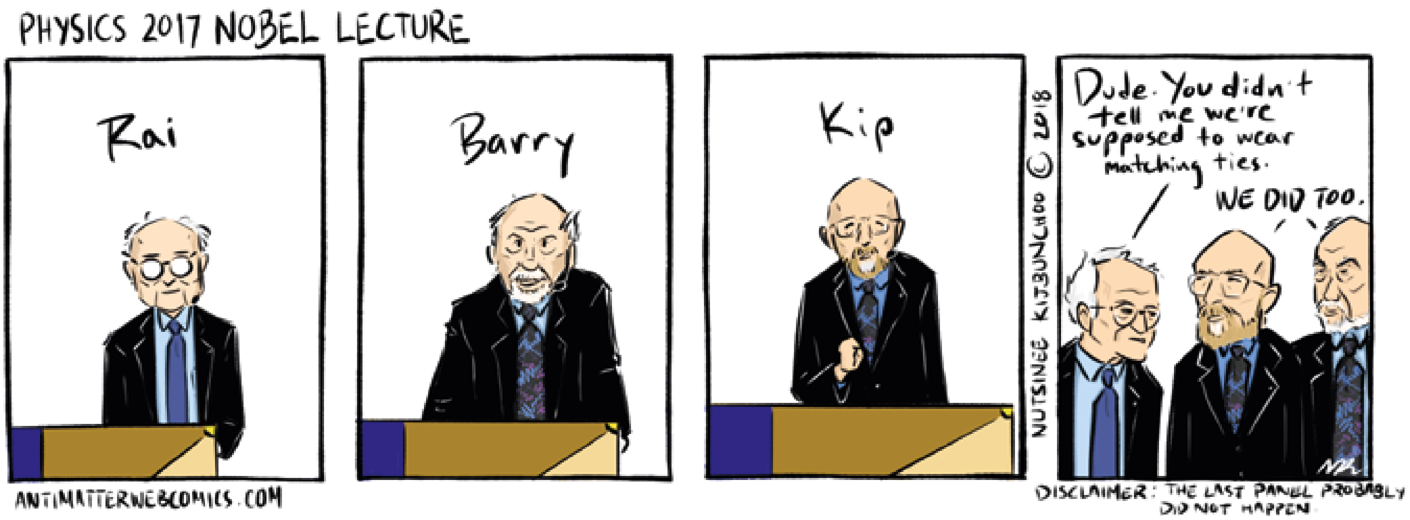


Welcome to the LIGO Magazine Issue #12!

Jocelyn Read

HMiddleton

It's been a breathtaking six months since our last issue, which went to print just before the universe sent the collaboration into a whirlwind of activity that lasted into the Fall. With Virgo joining in LIGO's detections, the first merging neutron-star system, and a Nobel prize, there's lots to cover this issue—and we'll have more stories from this year to come after we take a little more time to catch our breath.

Jocelyn would very much like like to thank Hannah Middleton, Deputy Editor-in-Chief, who stepped up to take the lead on this issue. We've pulled together several stories from the electromagnetic follow-up efforts across the spectrum of light, with reports from our LIGO colleagues Hsin-Yu Chen and Alessandra Corsi as well as astronomers Stephen Smartt and Nial Tanvir. Katerina Chatziiioannou leads us through one of the new questions of physics that GW170817 addresses: what is the neutron-star equations of state? Of course, we cannot forget our binary black holes, with two new announcements featured, and Geoffrey Lovelace (with a beautiful layout by Alex DeMaio) introduces the concepts of numerical relativity which underpin our merging black hole models. We also bring you some of the glamour of the gravitational-wave Nobel prize ceremony, and the excitement of the GW170817 press conference from student Maya Kinley-Hanlon.

It takes the joint work of many volunteers to write, illustrate, and edit each issue of the LIGO Magazine, and I am always amazed by what comes together from their efforts. If you are interested in joining our team, please get in touch! If you have any ideas, suggestions, or stories, please send us an email at magazine@ligo.org.

Jocelyn Read and Hannah Middleton, for the Editors

LIGO Scientific Collaboration News

This last six months has been eventful, indeed! Our last magazine update for August 2017 was written just as Virgo was joining the O2 run...but before the 14th of August. Since that update, the establishment of the LIGO-Virgo network was realized, along with the observation of the BBH GW170814 and the truly momentous observation of a binary neutron star merger, GW170817.

The subsequent exploitation of the science by the LIGO and Virgo Collaborations was very rich in results, with 10 full-collaboration papers and a number of short-author-list papers from the collaborations. There were also many challenges, with an unprecedented publication pace and the interactions with the greater Astrophysics community. The lessons we learned are helping the Collaboration prepare and plan for Observing Run 3 (O3), and that is the focus of a great number of Collaboration members.

The commissioning of the LIGO detectors is moving forward well. Key changes are a shift to new 70W lasers, introduction of frequency-independent squeezing, replacement of some test masses, implementation of test mass dampers to reduce parametric instabilities, and a myriad of smaller actions to e.g. reduce scattered light. We plan to meet the sensitivity goal of 120 megaparsec binary neutron star reach for both detectors by late 2018. This improvement in sensitivity, coupled with better Virgo sensitivity, will lead to a significantly higher event rate.

That, in turn, is making us confront how to publish our observations in ways that maximize the scientific output for both for gravitational waves per se and in synergy with electromagnetic and neutrino observers, and also give collaboration members a chance to reap the rewards of their commitments to the LSC.

The plan to release Open Public Alerts in O3 is driving ideas on how to simplify our relationships with electromagnetic astrophysical observers and on new ‘science based’ Memorandum of Understandings (MoU) with that community. It is also driving our ability to responsibly deliver low-latency triggers to the public, in terms of the mechanics, the detector characterization, and establishing confidence and skymaps on short time scales. All of these of course depend deeply on the central activity of pipeline development and improvement.

In parallel, we are working to bring about changes in the Collaboration to make it better suited to the post-detection environment. The Observational-era Revision Committee report has guided this activity, with the Program Committee recently formed, the Executive Committee pivoting to the Management Team, and the Council taking on more of the decision-making of the Collaboration. The new organization will be firmly in place and operating by the start of O3. A revised MoU with Virgo is being negotiated now, and is expected to bring the two collaborations policies and procedures into ever closer alignment.

Lastly, the recognition by the Nobel Committee of the importance of what the LSC has accomplished, with Rai, Barry, and Kip as our inspirations, is very gratifying. This is just one of the many awards won by individuals and by the LSC for the accomplishments recently achieved but won over decades of effort. We have established a new field! And it is just the beginning.

David Shoemaker and Laura Cadonati

David Shoemaker
LSC Spokesperson

Laura Cadonati
LSC Deputy Spokesperson

Laura Cadonati

GW170817 –

A binary neutron star inspiral

An Advanced LIGO test mass at the Livingston detector. To reduce scattered light, there can be no contamination on any optical surfaces.

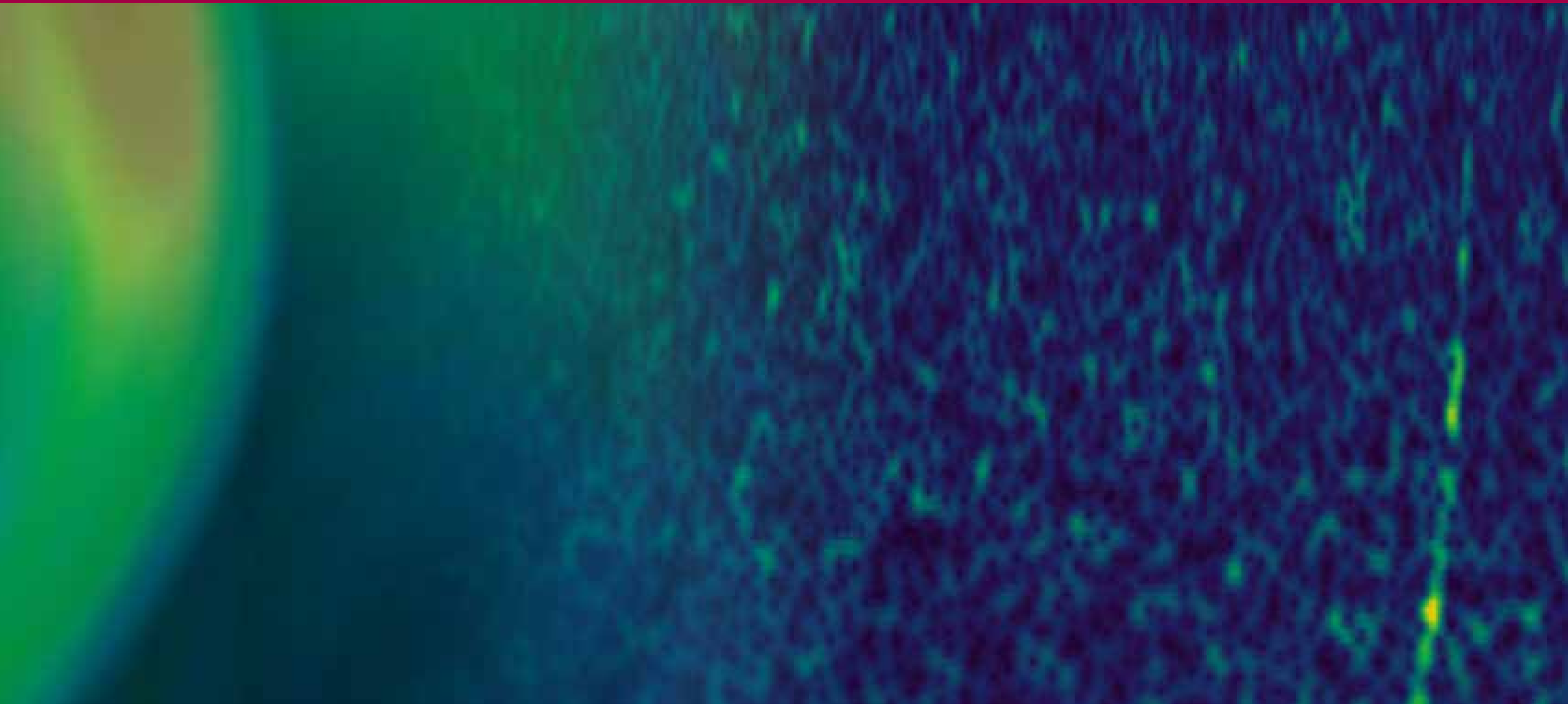
On 17 August 2017, at 12:41:04 UTC, the LIGO–Virgo gravitational wave detector network registered a signal from a new type of source. This was the inspiral of two compact stellar remnants: neutron stars. This binary neutron star event came just three days after the first joint LIGO-Virgo detection of a binary black hole merger, GW170814 (see page 23).

Neutron stars orbiting around each other in binary systems have been observed before using radio telescopes. One of the most famous examples of this is the Hulse-Taylor binary, which was discovered in 1974. Over 40 years, observations of this system have shown that the two neutron stars are slowly spiralling together due to the emission of gravitational waves. However, it will take approximately 300 million years before the Hulse-Taylor binary will merge, creating a signal similar to the one LIGO just observed for GW170817.

The observation of GW170817 came during the second observing run — the two LIGO detectors had started observations on 30 November 2016, and Virgo had just joined on 1 August 2017. Multiple detectors allow gravitational wave astronomers to measure where on the sky a signal comes from; the more detectors, the better they can locate the region on the sky. For this binary neutron star event, the source localization was found to an oblong region roughly 2 degrees across, and 15 degrees long, covering about 28 square degrees (this is roughly the size and shape of a banana, held at arm's length). The location of this area on the sky is in the constellation Hydra, centered near the naked eye star Psi Hydrae.

The dawn of multi-messenger astronomy

Just 1.7 seconds after the signal passed our detectors, a gamma-ray burst known as GRB170817A was detected by Fermi-GBM. Strong signals like GW170817 or GRB170817A are often called “triggers” because they initiate other astronomy activities. In the case of this event, the gravitational wave and gamma-ray triggers generated alerts sent out to the astronomical community, sparking a follow-up campaign that resulted in many detections of the fading light from the event, located near the galaxy NGC 4993. To read more about multi-messenger astronomy, see pages 9-16.

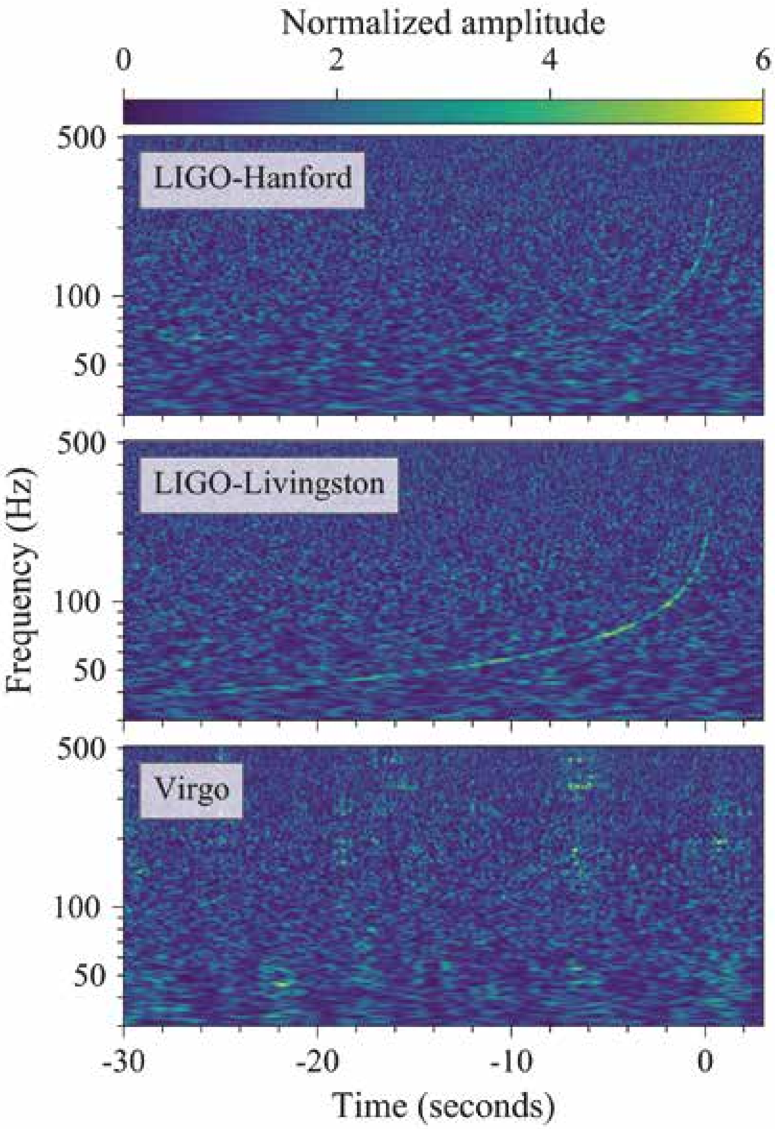


A close-up of our cover image: a simulation of two neutron stars about to merge, just as the two surfaces come into contact, overlaid on the gravitational-wave data.

The Gravitational Wave Signal

Gravitational waves from a binary neutron star can be visible to our detectors for a minute or more. In GW170817, about 100 seconds before the neutron stars merged they were separated by about 400 kilometers, but completed about 12 orbits every second. With every orbit, gravitational wave wave emission brings the stars closer together. As the orbits shrink, the stars move faster and faster, and the strength and frequency of the gravitational waves increases. The process accelerates until the stars merge and form a single remnant.

From the figure on the right, the signal is clearly visible for both LIGO detectors, but not the Virgo detector. This is an important aspect of the localization on the

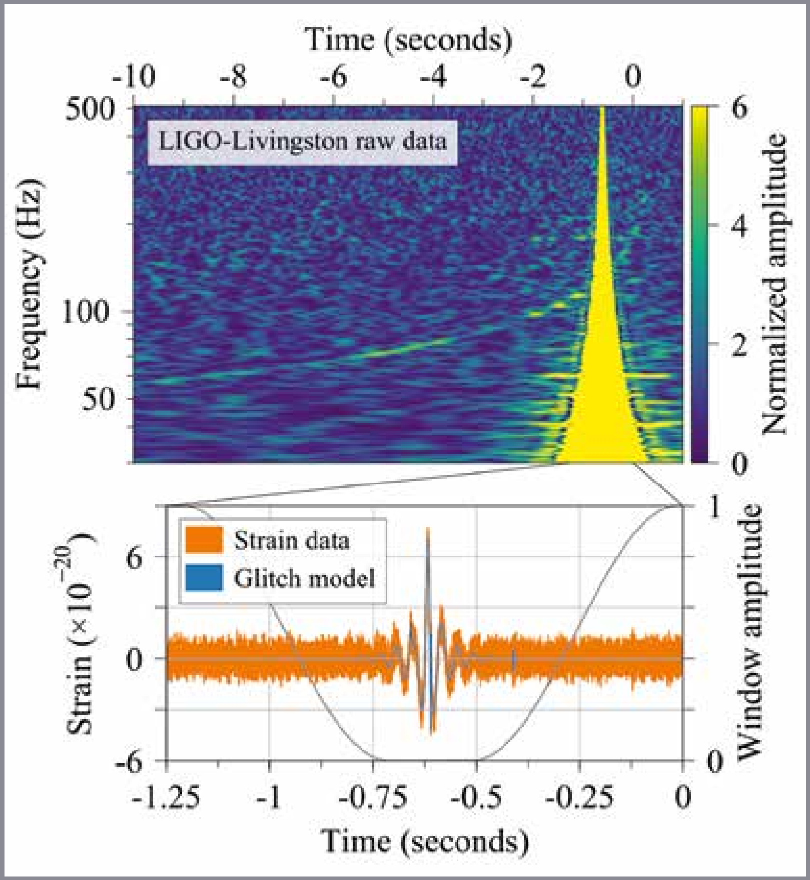


sky. Every detector has regions of the sky where it cannot see signals as easily as in other places. Because the signal was easily visible in both LIGO detectors, but not in Virgo, the implication is that the signal came from one of the places in the sky where it was hard for Virgo at that particular moment, a fact that helps tremendously with the localization.

The masses of the individual objects can be calculated from the gravitational wave signal. For GW170817, each neutron star has a mass between 0.86 and 2.26 mass times the mass of the Sun. Neutron stars can also be spinning on their axis, however the spin cannot be measured very well for this event. Spin effects change the gravitational-wave signal in a way that is similar to how unequal mass changes the signal. If we assume the objects are spinning slowly, then the data is equally well described by masses between 1.17 and 1.60 solar masses. In either case, these masses are consistent with the masses of all known neutron stars, which is one of the reasons we think this is a binary neutron star system.

The distance to the source of the gravitational waves was measured to be about 130 million light-years. By looking for galaxies that are in a similar location and distance as GW170817, a probable host galaxy can be identified as NGC 4993.

For more information about this observation see: https://www.ligo.org/science/Publication-GW170817BNS/index.php



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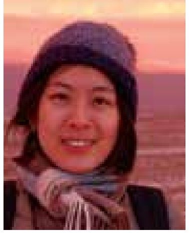
The top panel shows the glitch in the LIGO-Livingston data, and also clearly shows the binary chirp as well. The lower panel shows the strain (the quantity used to describe the strength of signals in LIGO and Virgo) of the glitch in time. It is narrow (lasting only about 1/4 of a second), but very strong. Mitigation reduces the glitch tothe level of the orange trace away from the glitch time, which is the background noise that is always present in detectors like LIGO.

The automated LIGO software did not initially generate an alert for the Livingston data, despite the fact that the signal is visible to the human eye. The problem was caused by a burst of noise — analogous to a pop of static in your stereo speakers — close to the end of the signal. That short burst of noise is called a “glitch” by detector scientists. This glitch was loud enough to potentially affect the detector’s measurement, and an associated warning prevented any nearby triggers from being automatically registered for LIGO-Livingston. In order to correctly evaluate the properties of the signal, a careful removal procedure was used to remove the glitch, but not the signal.

Glitches happen in gravitational wave detectors all the time; ones like the glitch cleaned from the GW170817 data happen once every few hours. If you would like to find out more about glitches and get involved in their identification and classification please visit the GravitySpy citizen science project at *http://gravityspy.org.*

The light from gravitational-wave events

Hsin-Yu Chen



is a Black Hole Initiative Fellow at Harvard University. Besides looking for electromagnetic counterparts, she is recently into jazz piano.

Observing the sky with gravitational-waves, electromagnetic-waves, and astroparticles jointly brings about an immense amount of information that can shed light on many mysteries in the Universe. This way of studying astrophysics with multi-messenger observations has been even more strongly yearned for after the first detections of gravitational-waves from binary black hole mergers. To ensure and facilitate the collaboration between the gravitational-wave and the broad astronomy communities, a group of LVC members reached out to non-gravitational-wave astronomers and developed the gravitational-wave event real time communication programme.

Every now and then a loud and/or shining event rings out somewhere in the Universe for a very short period of time. Among them there are LIGO's targets, such as compact binary mergers and supernova. Unlike the nearly omnidirectional LIGO observatories, many telescopes can easily miss the target if they don't point to the right direction at the right time. If we would like to capture gravitational-wave transients not only with LIGO but also observe other emissions from the same source, we need to share information promptly. For example, the event time and location on the sky are two essentials.

During the first and second observing runs of Advanced LIGO-Virgo, we learned and got surprised by different types of events. When an event candidate happened, a group of experts on the interferometers, the data quality, the signal search pipelines, and electromagnetic follow-up gathered online and made a fast decision on the validity of the candidate. If approved, the candidate was distributed to collaborating astronomers within a few tens of minutes, along with our best knowledge about the candidate at that time (starting from the third observing run, this process is going to be more automatized). All these efforts were to insure our fellow astronomers got the best chance to catch any possible counterpart emission.

GW170817 is what we have been waiting for.

It happened among the shower of gravitational-wave candidates in August 2017. Many of us were eagerly following-up/cheerfully celebrating the first LIGO-Virgo-triple detection, GW170814. The alert of GW170817 struck our phones like normal morning alarms (as a matter of fact the alerts rang Eastern US phones fairly often at dawn at the end of observing run 2). It was the opening of a memorable day.

The Dark Energy Camera mounted on the Victor M. Blanco 4-meter Telescope at the Cerro Tololo Inter-American Observatory in the Chilean Andes followed-up GW170817 and made one of the independent discoveries of the kilonova AT2017gfo.

A day long call gathered people to check and generate the initial alert 40 minutes after the event. A few hours later we sent out the first three detector sky map, and then an updated sky map shortly after the sunset in Chile, where lots of major optical telescopes are located. This smooth and swift response enabled the discovery of the kilonova and hence the follow-up of multi-wavelength afterglows.

The discovery of the electromagnetic counterpart of binary neutron star mergers allows us to study the system in a complementary manner. For example, the measured gravitational-wave waveform tells us the mass of the system, while the brightness and color of the kilonova emission suggests the amount of mass being ejected from the system. These observations also work together jointly. For example, we measured the cosmological parameters by combining the distance inferred from gravitational-wave signal and the redshift of the group of galaxies associated to the kilonova.

Capturing the gravitational-wave "sound" and the electromagnetic light of GW170817 is like moving from radio to television — another wide window is opened and it is lots of fun. Now we are looking forward to catching more episodes from the Universe in the near future. Stay tuned!

LIGO 2018

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Hsin-Yu Chen in front of the Victor M. Blanco 4-meter Telescope at the Cerro Tololo Inter-American Observatory.

What is the r-process?

Only the lightest elements (like hydrogen and helium) emerged from the hot early universe. Elements up to iron are produced by fusion in the cores of massive stars, but additional protons or neutrons must be captured by their nuclei, in some energetic process, to make the heaviest elements we find in our universe. This neutron capture can happen slowly (s-process) or rapidly (r-process). The r-process produces radioactive nuclei that can decay to elements like gold. The astrophysical location of these reactions had often been assumed to be supernovae, but observations of GW170817's aftermath gave spectroscopic evidence for another proposed site: material ejected from merging neutron stars.

The multi-messenger revolution of 2017

Stephen Smartt

Stephen Smartt is Professor of Astrophysics at Queen's University Belfast and has led several transient sky surveys. He led one of the early papers on the kilonova associated with GW170817, which inconveniently occurred during his Dublin marathon training programme. When he's not working or running he and his wife Sarah watch their 3 children play sport and rock music

The digital revolution changed the direction of survey astronomy around the turn of the decade in 2010. Wide-field digital cameras (covering about 10 square degrees on 1 to 2-metre telescopes) were employed as dedicated optical time domain surveys. Projects harnessed the power of high performance computing facilities to process data and image subtraction methods rapidly produced catalogues of moving asteroids, variables and transients. High energy astronomy has been using gamma ray and x-ray satellites for many years, with impressively fast ground-based follow-up providing redshifts and energetics of the optical and near-infrared counterparts to gamma bursts and x-ray flares. In the last few years the exciting discoveries of high energy neutrinos and fast radio bursts together with upcoming cosmic ray experiments and the arrival of Advanced LIGO and Virgo promised a new dawn of multi-messenger astronomy combining non-photonic messengers with a range of multi-wavelength facilities. The dawn broke on 17th August with the gravitational wave signature of GW170817 followed by a weak gamma-ray burst (GRB) and the immediate pinpointing of the exact location of the source (given the official International Astronomical Union transient name designation AT2017gfo: where AT stands for "astronomical transient") in galaxy NGC4993 using optical and near-infrared light.

We couldn't have hoped for a more auspicious start to multi-messenger astrophysics. A distance of only 40 megaparsecs, combined with a detection of the source in gamma rays, x-rays, optical, near-infrared, and radio was astounding. This is a possible game changer for those of us working in transient and time domain surveys, and the big question now is the rate of these events. If the event rate of these neutron star mergers within the distance of 100 megaparsec is as high as a few per year (and the most optimistic rates are 20 per year) then it would define the direction of our electromagnetic telescope survey strategies for many years. Experience has shown us that it takes major time and effort to chase gamma-ray bursts and supernovae across the electromagnetic spectrum, commandeering the largest telescopes on earth and in space within minutes to hours of the events and combining this rich data set to determine the physics of these explosions. If the neutron star-neutron star (NS-NS) merger rates are toward the upper limit of the LIGO-Virgo estimated rates (albeit uncertain from just one event!) we will have our hands full for many years to come. Throwing our precious resources at a few events per year is already a major task for any group, since the telescope proposals need to be written, the observations designed in advance, then triggered, reduced, analysed,

Artist's impression of merging neutron stars. ESO/L. Calçada/M. Kornmess.

modelled and written up rapidly. For two months in late summer 2017, many of us did nothing else but work day and night on the wealth of electromagnetic data from the transient source AT2017gfo associated with GW170817. If we get multiple objects like this per year, it will sap much of our human resources to keep up – transient astronomy will be duly changed for good, and we will be delighted.

On the other hand, we may have just been lucky last year with GW170817. At the nearby distance of 40 megaparsecs, and having a gamma ray jet directed along our line of sight (albeit a weak one), this could be a once in a decade type of event. The lowest rates of NS-NS mergers from constraints based on the recent LIGO data (observing runs O1 and O2) imply roughly 0.8 events per 10 years within 40 megaparsecs. The association of long gamma ray bursts with supernovae was spectacularly shown in 1998 with the GRB980425 and its associated supernova SN1998bw, also at a distance of just 40 megaparsecs. While there have been many more GRBs associated with supernovae, none have been closer than 100 megaparsecs in the 20 years since. The thought that we may have a decade long wait for another GW170817 event is a little sobering. The answer lies in true rates of NS-NS mergers and we are excited to see how this plays out in the next LIGO-Virgo observing run O3. It could be as high as 20 per year within 100 megaparsecs, and the electromagnetic signature of an AT2017gfo type event would still be very accessible from the x-ray through to the radio. Locating such a transient within a sky map of 50 to 500 degrees will likely be quite straightforward, particularly now that we know what we are looking for. It could also be as low as 1 per year, which would not be such a game changer.

And what do we now make of the electromagnetic signals from GW170817? The first wave of papers on this “kilonova” that appeared on October 16th were written quite rapidly, and applications of models to the data were a first initial step at understanding what we saw. The early hot blue flux in the ultraviolet and optical rapidly gave way to a much cooler emitting source. Many interpreted this as a two-component model with the latter source composed of heavy r-process ejecta (the lanthanides in the periodic table – see r-process box on page 10). However this is not a unique solution and the theoretical uncertainties in opacity, radioactive powering and trapping of the decay products are still being worked on. The nature of the jet that produced the gamma-rays, x-ray and radio is still being hotly debated. Even without another event we will likely be working on the models and interpretation of this well into 2019 and beyond. We might expect a very different signature from the next one, and can hope for a neutron star–black hole merger to complete the set in O3. A truly exciting era in time domain astrophysics has arrived.

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The first electromagnetic counterpart to a gravitational wave source in NGC4993. ESO/A.J. Levan, N.R. Tanvir.

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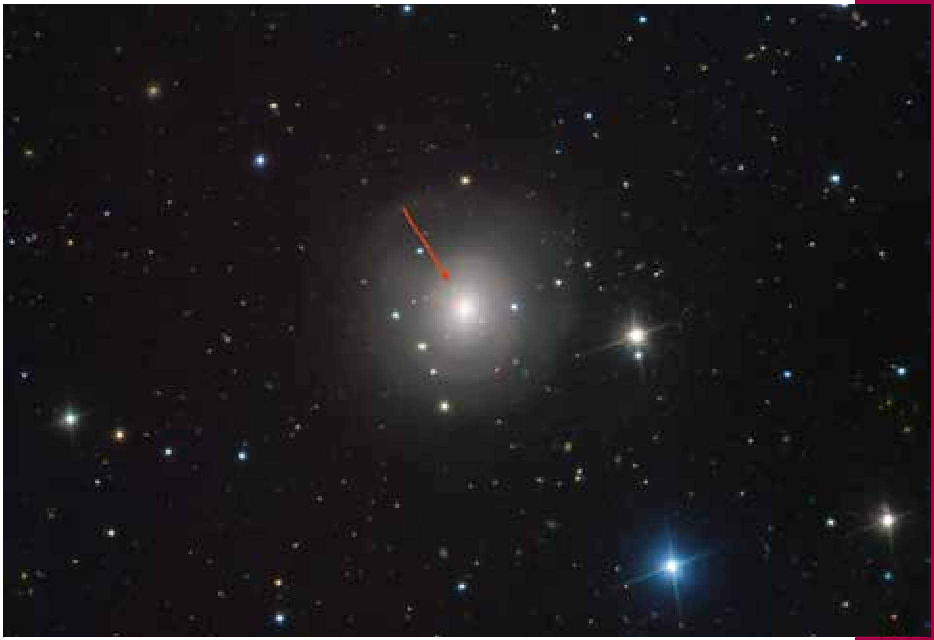
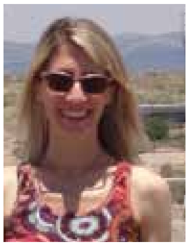


A delayed radio glow

Alessandra Corsi



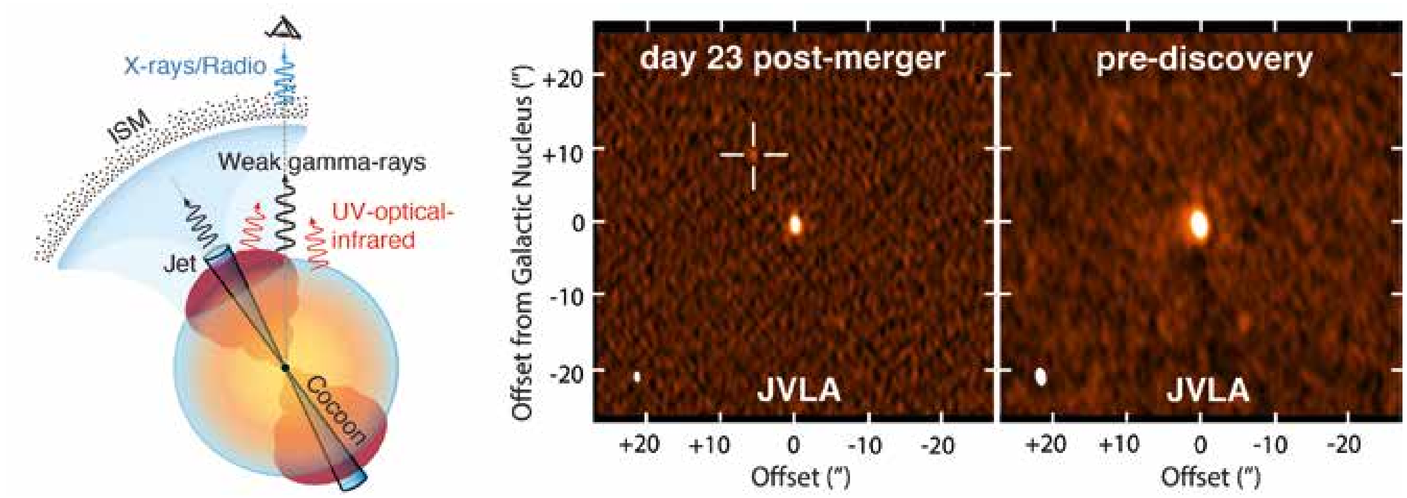
works at Texas Tech University on multi-messenger studies of gamma-ray bursts using LIGO and the Jansky Very Large Array. In her spare time she enjoys going to the theater (ballet shows are the best), decorating the house, and feeding prairie dogs.

After the LIGO and Virgo detectors caught the first gravitational wave "chirp" from the collision of a pair of neutron stars (GW170817), a global network of telescopes spanning the entire electromagnetic spectrum was mobilized in search for light from the cosmic smash-up (Abbott et al. 2017).

While confirming the hypothesis of an association between neutron star mergers and short gamma-ray bursts (GRBs), GW170817 also opened a new puzzle: the energy emitted in gamma-rays was about four orders of magnitude smaller than what we would have expected from a typical short GRB. Could this be an intrinsically faint event, or could it be that we were observing the GRB jet off-axis (like a tilted flash light, see figure below)? This last scenario was appealing, since astronomers had been searching for off-axis GRBs, unsuccessfully, for about two decades… Like when a flashlight is tilted, in an off-axis GRB we can see behind the main beam, and learn how the fastest jets we know of in the universe interact with their surroundings. To confirm the off-axis GRB hypothesis, observations at wavelengths other than gamma-rays were needed.

Optical telescopes in the Southern hemisphere were the first to reveal what came after the gravitational waves and gamma rays (Coulter et al. 2017). About 10 hours after the merger, a bright optical transient consistent with the location of GW170817 was discovered in a galaxy called NGC 4993. This is an early-type galaxy at about 130 million light years (40 megaparsecs) from Earth. The bright optical counterpart to GW170817 was also independently detected by several other teams and telescopes. The optical discovery opened yet another puzzle: the visible light from GW170817 was much brighter than expected from the afterglow of an intrinsically weak or off-axis GRB! This, together with further observations in the ultra-violet (UV) and infrared (IR), revealed that the bright optical/UV/IR counterpart was not coming from the fast jet that produced the gamma-rays, but from a "kilonova" associated with the radioactive decay of heavy r-process nuclei (see r-process box p.10 and e.g. Evans et al. 2017, Valenti et al. 2017 for further information).

Although the discovery of the kilonova emission was incredibly exciting, we were still missing the opportunity of probing the very first off-axis GRB jet. Given that



The left panel shows a schematic representation of the relativistic jet, cocoon, and more isotropic neutron rich debris formed in the binary neutron star collision. The eyeball at the top of the image marks our point of view from Earth. On the right hand side, the first panel shows the radio counterpart to the binary neutron star merger GW170817 marked by the crosshairs. The brighter radio source visible in this panel, and in the pre-discovery image in the second panel, is the far away galaxy that hosted the merger. These two snapshots were taken by the Karl G. Jansky Very Large Array (NRAO/NSF), one of the most sensitive radio telescopes on Earth. This figure is adapted from Hallinan, Corsi et al. 2017 and Kasliwal et al. 2017.

the UV/optical/IR emission was dominated by the kilonova, that meant that radio and X-rays were the only remaining messengers that could possibly be used to probe this jet. After 16 long days (and many sleepless nights!) since the neutron star merger, our team at Texas Tech University was one of two teams who independently discovered the faint radio glow from GW170817 (Hallinan, Corsi, et al. 2017) in images taken with the Karl G. Jansky Very Large Array, one of the most sensitive radio telescopes on Earth. After showing up on day 16, the radio counterpart to GW170817 grew brighter. The crosshairs in the central panel of the figure show the radio transient at day 23 after the merger compared with the same view before the event. The radio emission of the far away galaxy that hosted the merger is also clearly detected in this image, and in the pre-discovery one (right panel of the figure). The delayed turned-on in the radio emission, together with a similarly delayed turn-on in X-rays (Troja et al. 2017), confirmed the hypothesis of an off-axis jet. After 20 years of searching, we had finally formed our very first view of a relativistic jet observed from the side! The radio observations, in particular, reveal the presence of mildly relativistic and pressurized material, a cocoon, formed in the interaction of the jet with the neutron rich debris (left panel of figure and Mooley et al. 2018).

In summary, GW170817 was not “just” the first binary neutron star merger ever observed in gravitational waves, but it was a fantastic opportunity that nature gave us to probe many “firsts”: the first gamma-ray flash observed off-axis (thus the weak gamma-ray signal), the first direct observation of a kilonova (thus the unexpectedly bright optical transient), the first view of a cocoon formed by a relativistic jet seen from the side (thus the delayed turn on in radio). This story of a faint GRB, a bright optical transient, and a delayed radio glow marks the start of a completely new way of doing astronomy!

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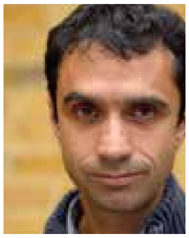
A lucky beginning

On August 16th 2017 I was taking part in a panel discussion on the prospects for electromagnetic (EM) observations of gravitational wave (GW) detections at the PAX2017 meeting in Amsterdam.

Nial Tanvir

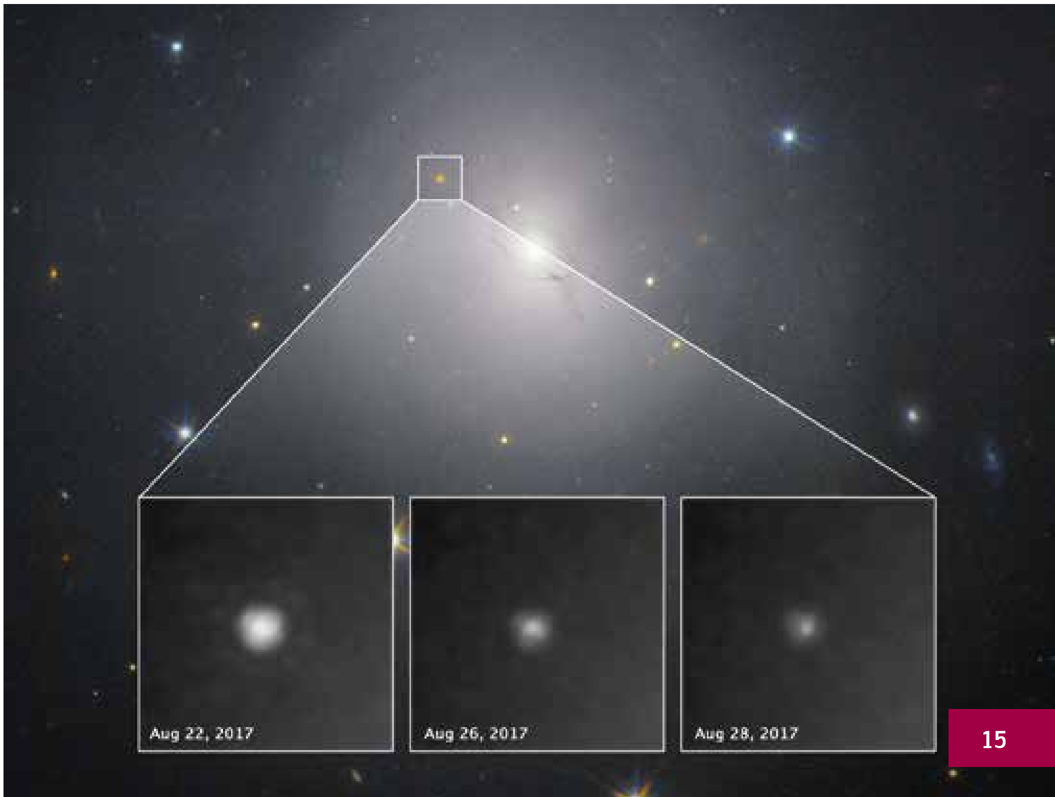


is a professor of astronomy at the University of Leicester, and is particularly interested in using explosive transients to study extreme physics and galaxy evolution. He is PI of the VINROUGE collaboration for gravitational wave follow-up with the VISTA near-infrared telescope, and of the STARGATE collaboration, for GRB follow-up at ESO. When opportunities arise, he enjoys hiking and photography.

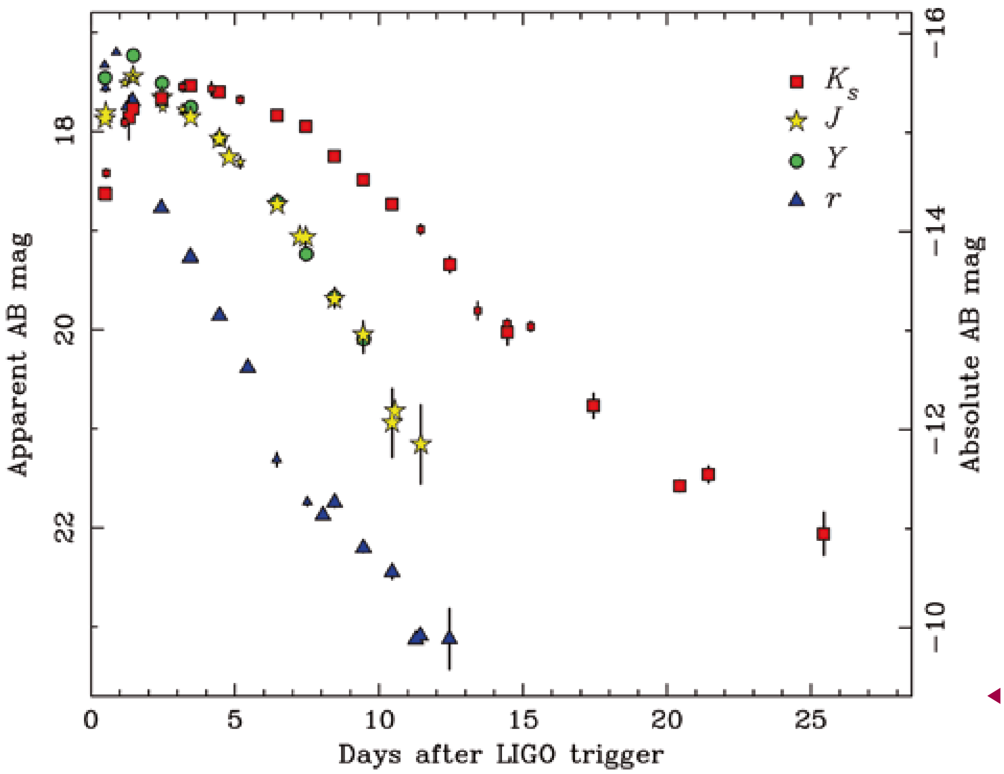
My mind was rather distracted by the binary black-hole in-spiral event GW170814, the first to benefit from joint LIGO/Virgo observations occurring only two days earlier. We were in the process of conducting near-infrared mapping using the ESO VISTA telescope of a section of the error region for the location of the source on the sky, and this had just been refined, hence demanding a change of strategy. I recall one of the questions asked to the panel was whether we expected much of a role for gamma-ray satellites like Fermi in the GW follow-up game. As far as I remember, my response was that, while the rate of short gamma-ray bursts within the Advanced-LIGO horizon was low, such a simultaneous gamma-ray signal was the one EM counterpart that would be unmistakable, and certainly there should be a detection eventually even if it took a few years to happen. By contrast, other putative EM signals, infrared, optical and radio, might turn out to be fainter and harder to identify in large GW error regions than the optimistic predictions suggested.

Remarkably, within 24 hours of this discussion the first combined gravitational wave and short-gamma-ray burst signal from a binary neutron star merger had occurred, and within 48 hours the counterpart had been identified across the full range of ultra-violet, optical and infrared wavebands. When the initial electronic notices had appeared, in the early afternoon UK time, announcing a high-confidence binary neutron star merger event, GW170817, with a coincident gamma-ray burst trigger by Fermi, it had seemed too good to be true. Indeed, the first email I sent to my collaborator Andrew Levan was just three words long: the first two may not be appropriate to repeat for the gentle readers of the LIGO Magazine, but the last one was just the question “serious?”. Of course, despite these doubts, we took it seriously, and immediately began planning optical and infrared searches. The very limited visibility of the field, only roughly an hour at the beginning of the night from southern hemisphere observatories, presented a challenge, but we benefited from the rapid determination of a revised “three detector” error region by the early evening and a low inferred distance estimate of about 40 megaparsecs. This restricted the number of likely host galaxies for this signal to just double figures. Nonetheless, our instincts at this stage were still to be cautious,

The source of GW170817, galaxy NGC 4993 as seen by the Hubble Space Telescope.



by Nial Tanvir



The light curves of kilonova AT2017gfo in bands ranging from the optical r-band, where the peak brightness occured in the first day, to the near-infrared K-band, where the peak occured after several days. This illustrates the evolution from blue to red colours, indicative of an emerging „red" kilonova, which likely represents light from ejecta that is rich in heavy elements including lanthanides. Data are taken from Tanvir et al. 2017 ApJ 848 L27, Kasliwal et al. 2017 Science 358 1559, Drout et al. 2017 Science 358 1570, Valenti et al. 2017 ApJ 848 L24

and to assume that any counterpart might be faint and require fairly deep observations in multiple colours to identify. The strategy we decided upon was to use the wide field VISTA telescope to target two 1.5 square degree fields within the GW error region for the source location on the sky, that had the highest concentration of possible host galaxies, using three filters and with repeated observations to search for variability. In parallel we requested imaging of several other galaxies with the ESO/VLT. Observations were to begin in twilight after sunset, to maximise the amount of data obtained.

To cut a long story short, by the time the large VISTA data-sets had been transferred from Chile in the early hours of the morning of the 18th August the report of a bright new optical transient in the galaxy NGC 4993 seen by the Swope telescope had already appeared, so we immediately set about measuring its infrared properties from our imaging. In parallel we performed a search for other possible transients in our data, developed the strategy for further observations the following night, and triggered our Hubble Space Telescope program.

Monitoring the transient source over the next couple of nights already revealed the marked changes in colour, from blue to red, that were the expected hallmark of a `kilonova'/`macronova' produced by the ejecta from merging neutron stars. The coincidence was too great for this to be anything other than the counterpart of the gravitational wave and gamma-ray source. Henceforth the priority was to gather as much data as possible before the source became too close to the Sun in mid-September.

The results of this global campaign have been the stuff of many articles and news reports, although, in fact, analyses and even further data gathering are still on-going. A key conclusion is that the behaviour of the `kilonova' confirms them as being the site of substantial r-process nucleosynthesis (see p.10), which suggests they are likely a major, if not dominant, source of heavy elements such gold and platinum in the universe. The nature of the relativistic component of the ejecta, that led to the gamma-ray emission, has provoked much debate, and it is still unclear how this event relates to more conventional short-GRBs. Ongoing observations from radio to X-ray will help resolve this. One thing we can say is that the absence of any similarly low-redshift and intrinsically faint transient amongst the well-localised short-GRBs suggests that comparable events are quite rare, and that we must have been very lucky to have seen one so early in the three detector GW era.

I remain astonished by the profound progress made in such a short time, and the richness of the phenomenon that was GW170817 and its accompanying `kilonova'. It is hard to imagine a more auspicious start to the GW-EM multi-messenger era.

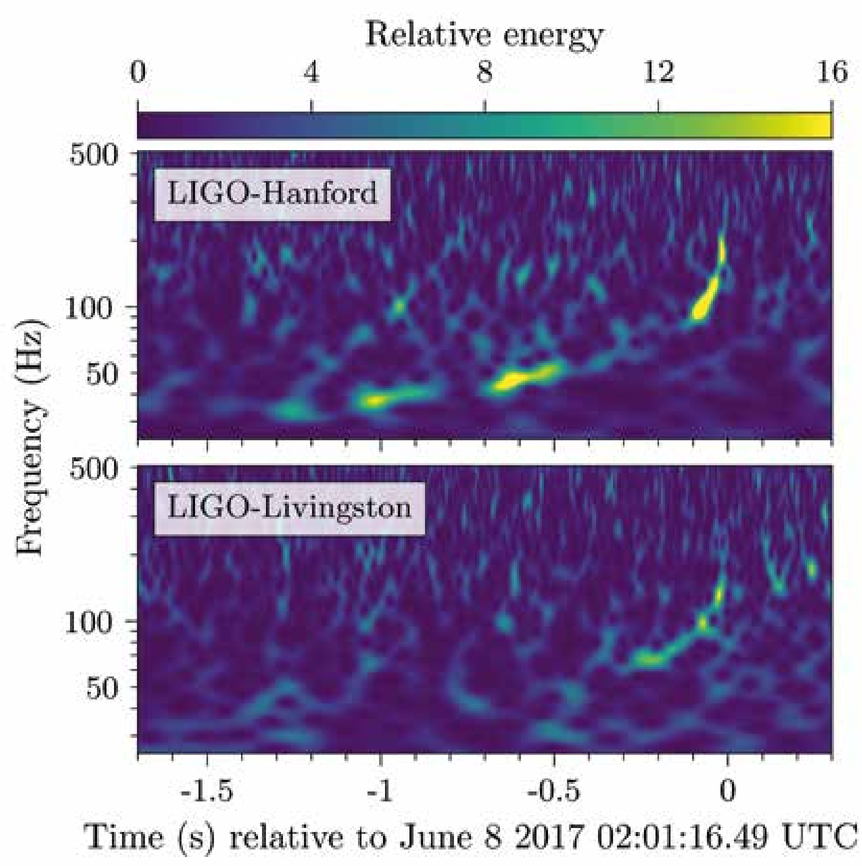
GW170608

The lightest binary black hole so far?

On June 8, 2017 at 02:01:16 UTC (in the evening of June 7, 2017 in North America) gravitational waves were observed from the spiralling together and collision of two black holes. The signal was observed by both LIGO detectors in Livingston, Louisiana and Hanford, Washington during their second observing run. The gravitational wave signal came from a distance of around 1.1 billion light years and the system it originated from may be the lightest black hole binary system observed so far. The masses of the two black holes were around 12 and 7 times the mass of the Sun.

For more information about this observation see: https://www.ligo.org/science/Publication-GW170608/index.php

LIGO 2018



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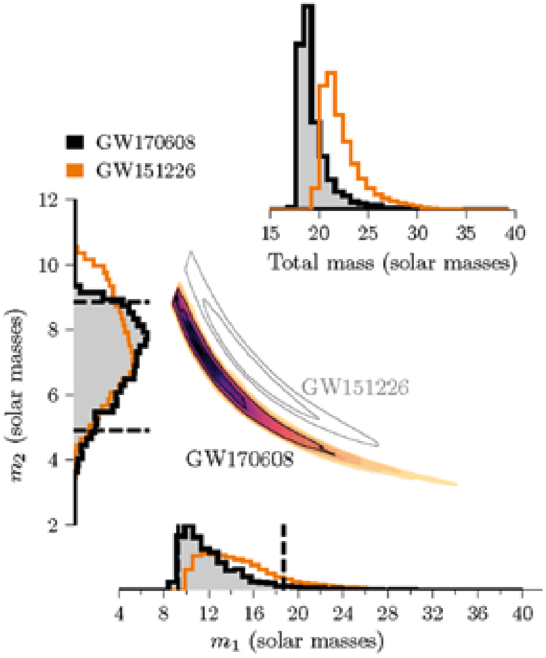
__Top:__ The time-frequency representation of the signal as seen by LIGO Hanford (top) and LIGO Livingston (bottom). The colors indicate the amount of energy at any given time/frequency, going from blue (low) to yellow (high). The curve from the lower left to the upper right, clearly visible in the Hanford data and hinted at in the Livingston data, is the gravitational wave signal from the black hole inspiral.



◀

__Left:__ The main plot shows the probability distribution for the masses of the two black holes in the binary (m_1 and m_2), in units of the mass of the Sun. The higher-mass black hole mass distribution (m_1) is shown on the horizontal axis, while the distribution for the lower-mass black hole (m_2) is on the vertical axis. Also shown is the probability distribution for the masses of the previously detected low-mass black hole binary, GW151226 for comparison. The inset plot at the upper right shows the probability distribution for the total mass in the black hole binary ($m_1 + m_2$), comparing GW170608 with GW151226.

What is Numerical Relativity?

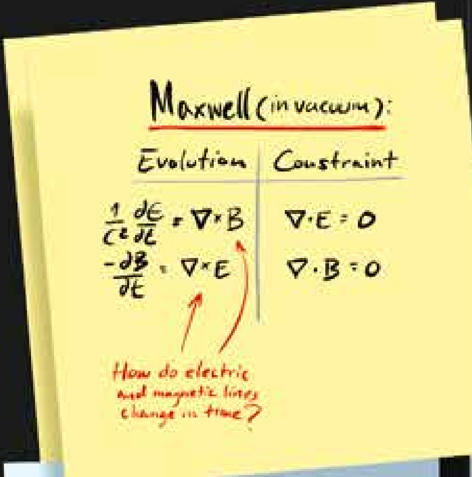
Geoffrey Lovelace is an associate professor in the Department of Physics and the Gravitational-Wave Physics and Astronomy Center at Cal State University, Fullerton. In his spare time, he enjoys taking dubious gaming advice from his nine-month-old son.

STEP ONE

Numerical relativity solves Einstein's equations for the warped spacetime surrounding black holes. This is notoriously challenging, in part because the equations are so strongly nonlinear: the warped spacetime around a binary black hole is more than just the sum of the warping caused by the two individual black holes.

Step Two

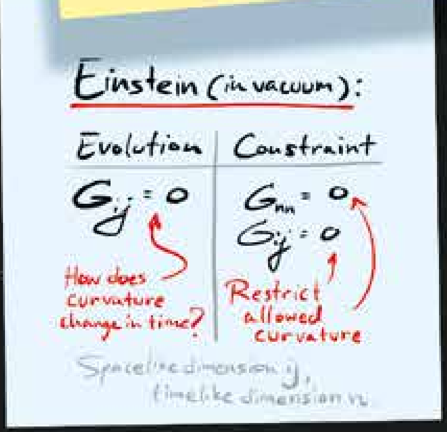
Our calculations divide spacetime up into a stack of "slices." Each slice is space at a moment in time, like an individual still frame image in a movie. Spacetime is the whole movie. When you split spacetime into slices like this, Einstein's equations split into constraint equations and evolution equations. Evolution equations, with time derivatives, say how spacetime changes from one moment to the next. Constraint equations restrict the form this spacetime takes, similar to how $\nabla \cdot B = 0$ in Maxwell's equations says there are no magnetic monopoles.



Maxwell (in vacuum):

Evolution	Constraint
$\frac{1}{c^2}\frac{\partial E}{\partial t} = \nabla \times B$	$\nabla \cdot E = 0$
$-\frac{\partial B}{\partial t} = \nabla \times E$	$\nabla \cdot B = 0$

How do electric and magnetic lines change in time?



Einstein (in vacuum):

Evolution	Constraint
$G_{ij} = 0$	$G_{nn} = 0$ $G_{ij} = 0$

How does curvature change in time?

Restrict allowed curvature

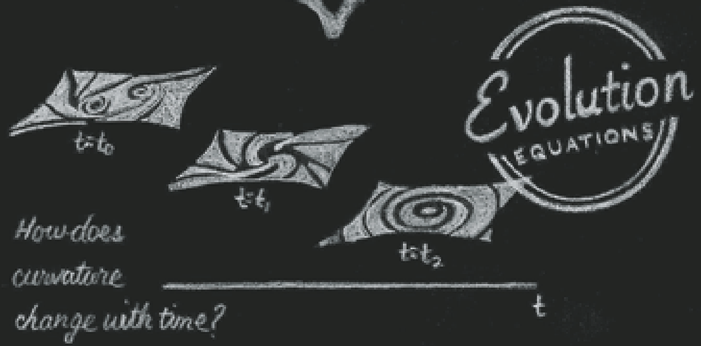
Spacelike dimension ij, timelike dimension n by Geoffrey Lovelace

STEP THREE

The initial curved space at time t=0 comes from solving constraint equations. It's a lot like solving a much harder version of the Laplace equation. Numerically, it typically involves a series of large (1 million x 1 million) matrix inversions.

STEP FOUR

Next, the calculation solves the evolution equations to step forward to a later time. The gist of these methods is as follows: if you have a curved space now, and you know how quickly it's changing in time, you can compute what the space will be doing a short time later. Then, rinse and repeat. This comes down to a solving a set of coupled, ordinary, nonlinear differential equations.



STEP FIVE

Once you solve for all the slices covering the time when the black holes spiral together, merge, and ring down, you can look at the part of the slices far away from the black holes and read out the gravitational waves as they travel outward. You can also compute things like how the black holes' masses and spins change, or how their warped spacetime would lens light from background stars.

Step Six

There are plenty of complications: Black holes have singularities inside, so you have to figure out a way to deal with that. Some codes cut out ("excise") a hole inside each black hole's horizon, while other codes adopt coordinates that make sure the singularities never touch the part of the space you're solving for.

Don't simulate this part
(here there be singularities)!
∞ = BAD

STEP SEVEN

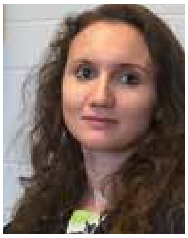
There are many different ways to write Einstein's equations after splitting them into space and time components, and many of them behave badly numerically. For instance, for some formulations, even if the initial snapshot satisfies the constraints to round-off error (say 1 part in 10^15), that initially small constraint violation grows exponentially in time, until you're no longer even close to satisfying the constraints. One last challenge is that the calculations take a long time. Different black holes with different masses and spins give different gravitational waves. So we have to do these calculations many times to model all the different kinds of binary black holes that LIGO might see. And binaries where one hole is much smaller than the other, or the black holes are spinning rapidly, are still technically challenging enough that in many cases, no one has yet been able to model them at all. ■

What is the equation of state?

Extreme conditions in Neutron Stars

Neutron star interiors are the scene of matter's final defense against gravity before total gravitational collapse into a black hole. Two pillars of modern physics, Quantum Chromodynamics and General Relativity, are driven to the edges of our understanding in the extreme conditions found within neutron stars, where even nucleons can break apart.

Katerina Chatziioannou



is a postdoctoral fellow at the Canadian Institute for Theoretical Astrophysics at the University of Toronto. Besides studying gravitational waves from compact binaries, she enjoys long bike rides in the mountains and insists on attempting to learn German.

From the perspective of nuclear physics, the neutron stars are one the most extreme environments in which matter exists in our Universe. Matter within neutron stars can come in many forms, its exact nature becoming increasingly uncertain with depth. Neutron star crusts contain nuclei and electrons at relatively low densities. The densities encountered at the cores of neutron stars are many times larger than the nuclear density, challenging our understanding of matter in beta-equilibrium. Nucleons themselves seem to falter, giving rise to phase transitions to exotic states where the presence of strange quarks are possible. In addition to being extremely dense, neutron star matter is also very cold (despite being the highest temperature superconductor known) meaning the typical energies are well below the Fermi energy. The composition, density, and temperature extremes encountered in neutron star cores are completely unattainable in laboratories on Earth, and as such have considerable uncertainty.

It is those unattainable conditions and uncertainties that the equation of state of neutron stars describes. The equation of state is a relation between the pressure and the density—temperature is usually negligible—under conditions that look nothing like what we have seen in terrestrial experiments, making the equation of state one of the most intriguing puzzles of modern physics.

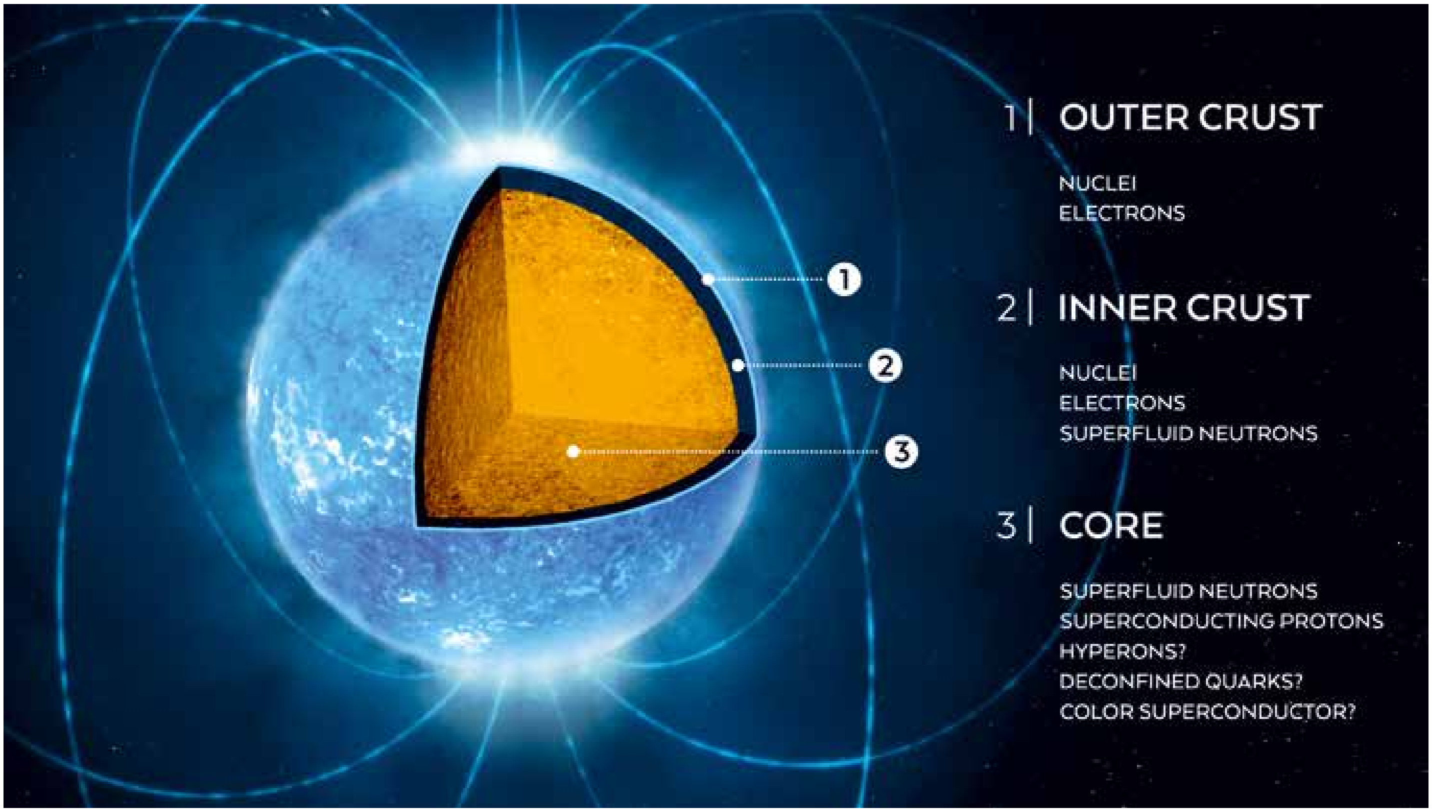
From the perspective of astrophysics, the neutron star equation of state determines the masses and sizes of neutron stars. Sizes can vary by almost a factor of two (predicted radii range from 8km to 15km), directly affecting observables such as the outcomes of supernova explosions, neutron star mergers, the production of short gamma ray bursts, and the production of heavy elements. Different masses signal the division between neutron stars and black holes, characterize neutron star populations, and affect their formation and evolution paths. In short, studying the neutron star equation of state amounts to simultaneously studying physics at both extreme microscopic and macroscopic levels.

Despite decades of efforts by both nuclear physicists and astrophysicists, many uncertainties remain, and the precise matter composition of neutron star cores is unknown. Nuclear physicists expect that the high energies encountered within neutron star interiors might give rise to phase transitions in the form of more hadronic degrees of freedom or exotic forms of matter.

One option is the formation of strange quarks that are heavier than the up and down quarks that make up neutrons and protons. Another option is to form Bose-Einstein condensates. The possibilities abound: hyperon condensates, kaon condensates, pion condensates, color superconducting phases, or even pure 'strange quark stars' made entirely of quarks. All these options not only increase the complexity of the problem, but also impose so-far-insurmountable obstacles for first principle Quantum Chromodynamics calculations.

These additional matter degrees of freedom have considerable consequences for the equation of state. The production of additional types of matter leads to a drop in pressure, resulting in lower neutron star masses; the equation of state 'softens'. The reconciliation of this theoretical mass decrease and the observed lower limit on the maximum mass is known as the 'hyperon puzzle'. As heavier neutron stars are observed, it becomes harder to construct equation of state models with phase transitions.

Along with determining the composition of neutron-star matter, we need to model its interactions. The theoretical nuclear community is leading the way on this front. Phenomenological 2-body and 3-body interaction potentials, approximate n-body interactions derived from Quantum Chromodynamics us-



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Structure of neutron star interiors: from the outer crust that is supported by electron degeneracy pressure to the inner core that is supported by neutron degeneracy pressure and possible exotic matter. Schematic from A. Watts et al 2016 Rev. Mod. Phys. 88, 021001.

ing chiral effective field theory, and relativistic mean-field theory are all employed to model the properties of dense matter in beta-equilibrium. But this endeavor is difficult. Nuclear experimental data probe regions with far lower densities and higher temperature than neutron stars and currently n-body approximations are limited to 3-body interactions.

But it's not all bad. In spite of all these sizeable obstacles, we already know a great deal about the equation of state. We know that, coupled to the general relativistic structure equations for spherical objects in equilibrium (Tolman-Oppenheimer-Volkoff equations), it uniquely determines the properties of a neutron star, such as its mass, radius and tidal deformability.

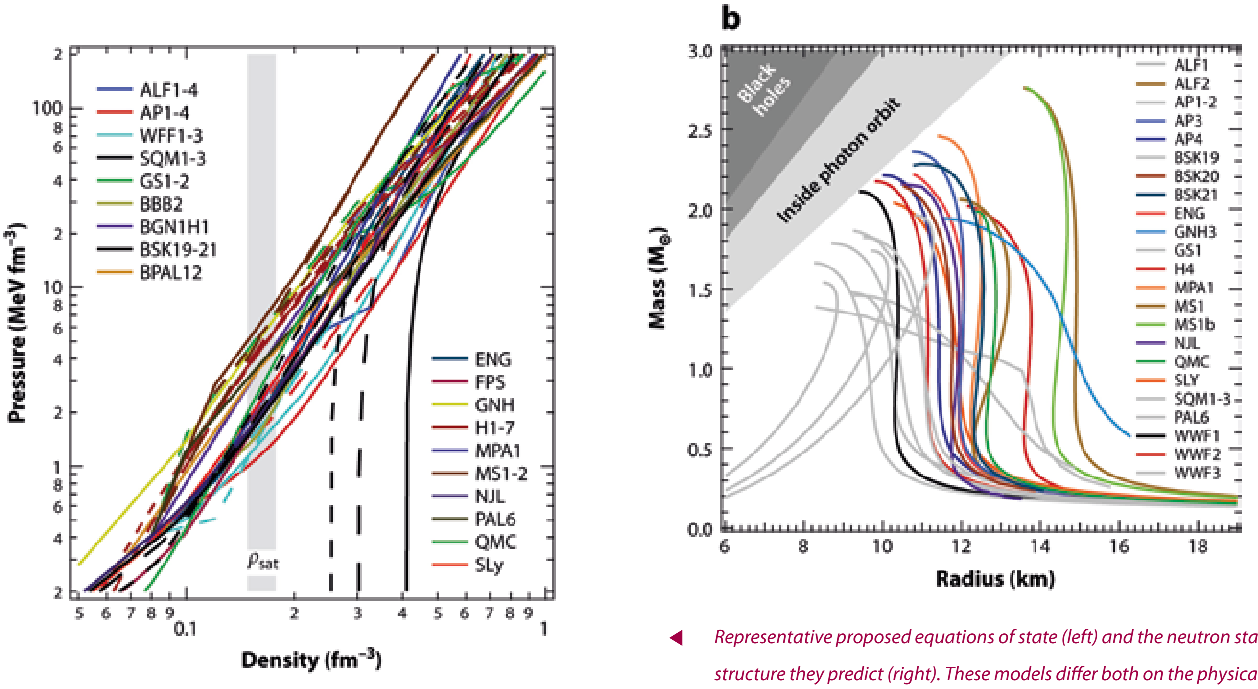
We know that the macroscopic properties of neutron stars depend on the microscopic details of their composition in more-or-less straightforward ways: the maximum mass is determined by the conditions at particularly high density, the radius depends on the conditions at a more moderate density, while the slope of the mass-radius relation is decided by the conditions in the middle. This simple correspondence makes the comparison of astrophysical and nuclear physics data possible.

We know that a number of macroscopic quantities are related to each other in a way that is agnostic about the equation of state. Examples include the moment of inertia, rotational quadrupole moment and tidal deformability of the star; or the maximum nonrotating and the maximum uniformly rotating mass. Despite the complicated physics that enters the construction of the equation of state, its basic properties must be simple.

We know that imposing "causality," a speed-of-light limit on the sound speed inside a neutron star, leads to an upper limit on the mass of about 3 solar masses. We know that the smallest rotational period allowed by causality and the star not tearing itself apart is about 0.6ms.

Both nuclear physics experiments and astrophysical observations shed more light on the properties of neutron stars. On the nuclear physics side, scattering data, neutron skin thickness measurements, nuclear masses and charge radii, giant dipole resonance data, dipole polarizability measurements, and heavy-ion collisions offer guidance about the microscopic properties of neutron stars.

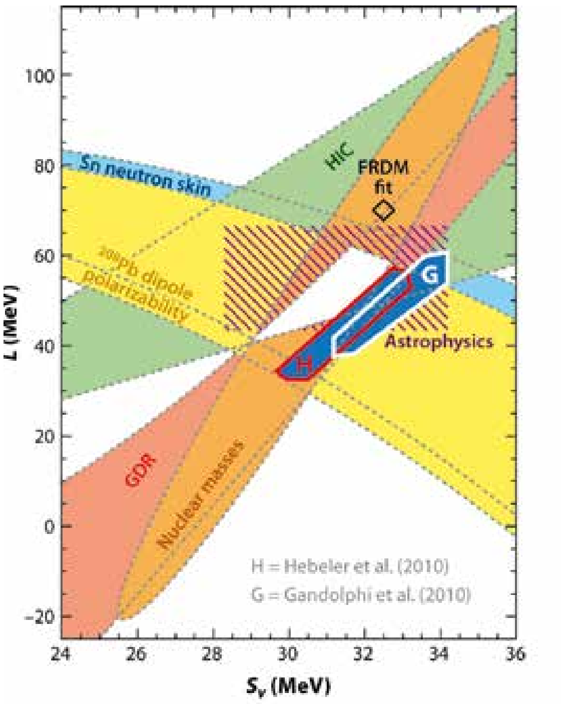
On the astrophysics side, mass measurements through radio and X-ray measurements of neutron stars in binary systems,



Representative proposed equations of state (left) and the neutron star structure they predict (right). These models differ both on the physical and the mathematical/computational level. Figure from F. Özel and P. Friere 2016, Annu. Rev. Astron. Astrophys. 54:401-440.

radii measurements through thermal X-ray emission and X-ray bursts, and observations of neutron star cooling, pulsar glitches, and quasiperiodic oscillations of accreting neutron stars offer information about the macroscopic properties of neutron stars. Attempts to compare and combine nuclear physics and astrophysics constraints suggest the two communities are gradually converging to a consistent picture.

Only a few months ago, the first binary neutron star merger observed through gravitational waves and electromagnetic radiation allowed for new constraints on the radius of the stars. In the near future NICER, a NASA mission of opportunity mounted on the International Space Station and observing hot spots on neutron star surfaces in X-rays, will attempt to measure their radii even more precisely. We are tantalizingly close to solving this longstanding puzzle.



The interface between astrophysical observations and nuclear theory experiment expressed through the properties of the nuclear symmetry energy that quantifies the behavior of the energy away from saturation and neutron-proton symmetry. Figure from JM. Lattimer 2012 Annu. Rev. Nucl. Part. Sci. 62:485-515.

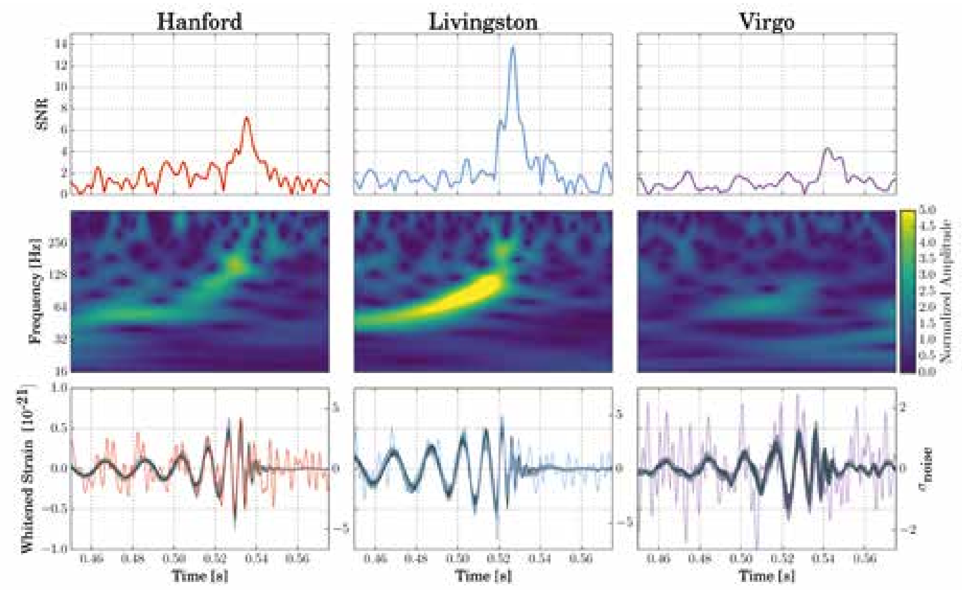
GW170814:
The first triple detector observation of a binary black hole coalescence

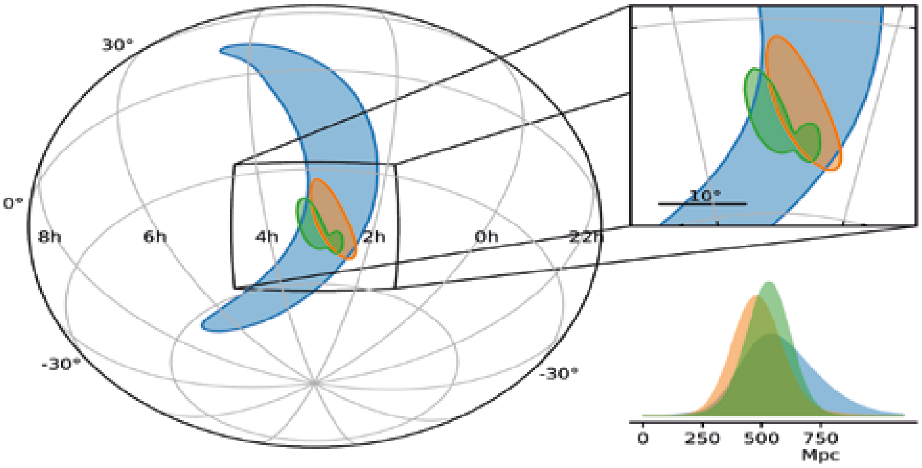
On August 14, 2017, at 10:30:43 UTC, Advanced Virgo saw its first gravitational wave detection from the coalescence of a pair of black holes, which was also observed by the twin Advanced LIGO detectors. The observation, called GW170814, is the first confirmed gravitational-wave event to be observed by three detectors.

On August 1, 2017, the Advanced Virgo detector joined the Advanced LIGO second observation run, which ran from November 30, 2016 until August 25, 2017. This detection illustrates the enhanced capability of a three-detector global network (comprising the twin Advanced LIGO detectors plus Advanced Virgo) to localize the gravitational-wave source on the sky.

The signal came from the coalescence of two black holes, which each had masses of around 30 and 25 times the mass of the sun, respectively. The event occurred at a distance of 1.1 to 2.2 billion light years away.

For more information about this observation see: https://www.ligo.org/science/Publication-GW170814/index.php





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Top: *For each of the three observatories. Top row: the signal-to-noise ratio over time. Middle row: the time-frequency representation of the strain data. Bottom row: the gravitational wave strain over time with the best waveforms from matched filtering (black-solid) and unmodelled search methods (grey bands) superimposed.*

Bottom: *Localization of GW170814's source on the sky. The left part of the figure represents the sky, where the coloured regions show the most likely areas to contain the source of the GW170814 signal. The blue area shows the rapid localization based on the observations of the two LIGO detectors only. The addition of Virgo leads to the orange region, a much improved localization area. The green region is the result of the full parameter estimation analysis using all three detectors—an area of 60 square degrees. The top-right insert shows a zoom-in of the sky map and the bottom-right shows the likely distance to the source in megaparsecs using the three difference analyses.*

Nobel Prize in Physics 2017 for the first direct detection of Gravitational Waves

"I'm positively delighted that the Nobel Committee has recognized the LIGO discovery and its profound impact on the way we view the cosmos. This prize rewards not just Kip, Rai, and Barry but also the large number of very smart and dedicated scientists and engineers who worked tirelessly over the past decades to make LIGO a reality."

David Reitze

While from the outside, it may seem surprising that this Nobel Prize was awarded a scant 2 years after the discovery of gravitational waves (often, Nobel Prizes are awarded many years after discoveries), for the three laureates, it actually comes at the culmination of decades of effort. LIGO may have only recently detected gravitational waves, but its journey to doing so began nearly 45 years ago.

So, while this Nobel Prize is being awarded barely two years after LIGO's historic detection, it acknowledges 45 years of effort: from conception, through design, planning, testing and prototyping, through decades of research and engineering, invention and innovation, advances in computing, lasers, and optics, and especially the championing and advocating of three remarkable men: Barry Barish, Kip Thorne, and Rai Weiss. There can be no doubt; their recognition by the Nobel Committee is well earned.

To learn more about the Nobel Prize in Physics 2017 visit: https://www.ligo.caltech.edu/news/ligo20171003

◄ *Barry Barish, Rai Weiss, and Kip Thorne enjoy the applause from a full house after their lectures at the Aula Magna (Great Auditorium) in Stockholm University.*

Nobel Prize Celebrations

Watching the televised award ceremony from a room at the Grand Hotel.

> It was a very exciting weekend of celebration. A once in lifetime experience. We were feeling like a big family gathered together to honor the success and recognition of decades of collaborative work.
>
> Alicia Sintes

Stockholm by night

Items donated to the Nobel Museum. From Barry, the photo diode from Livingston that made the GW150914 detection; from Kip, an anti-light scattering device he invented. Rai's donation is a large box photo detector from the 1970's, which had not yet arrived.

> What a magic, unforgettable week.
>
> Les Guthman

A group photo of the gathered LIGO/Virgo folks in the Grand Hotel.

collected by Hannah Middleton


Barry Barish giving his Nobel Lecture.


Some of the LIGO instrument scientists in Sweden.

It was an amazing opportunity to celebrate LIGO and Virgo's achievements, all dressed up and no talk slides at all - just party and smiles!

Gabriela González

It was amazing ! I am very happy and proud to have had this opportunity. The gravitational wave revolution is now…so my hope is that this will not remain a "once in the life experience".

Pia Astone

Rai,Barry and Kip at the award ceremony.

A memorable experience, and such a pleasure to share it with so many colleagues.

Bernard Schutz

The signatures of Barry Barish, Rai Weiss and Kip Thorne on a chair in the Nobel Museum.

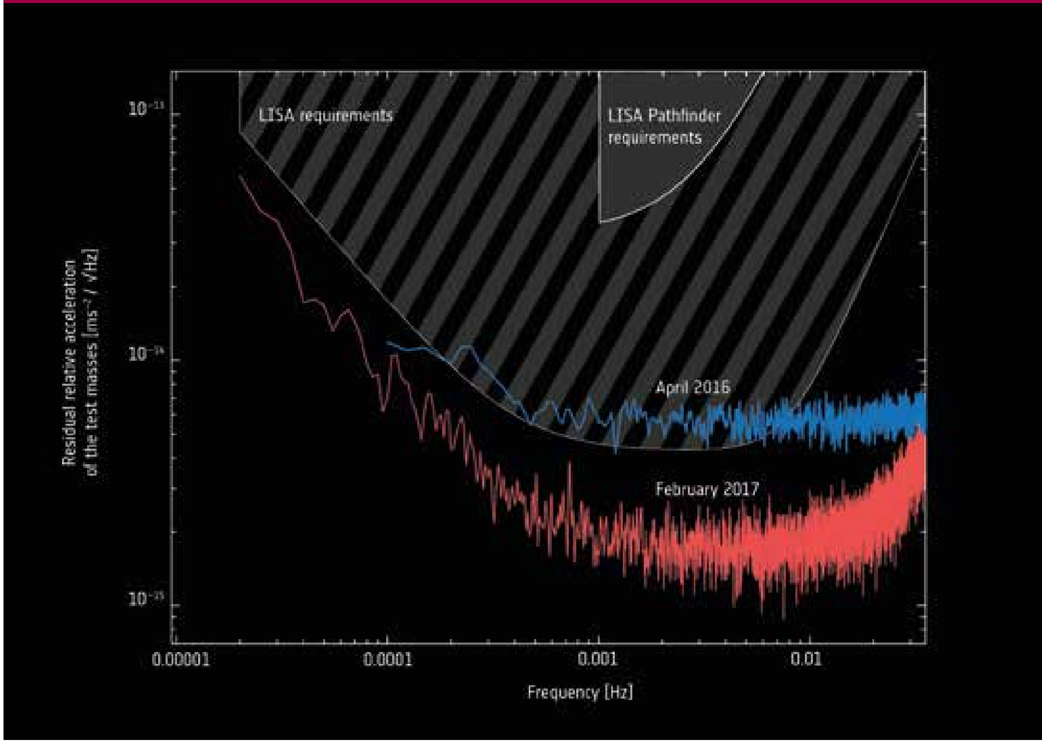
What a great privilege to join friends and colleagues at this high point in our long journey, celebrating such shiny recognition of our leaders' inventiveness, foresight and doggedness!

Joe Giaime


Group photograph at the Grand Hotel on the night of the Royal Dinner.

LISA Pathfinder: The quietest place in space

New LISA Pathfinder results exceed requirements for future gravitational-wave observatory LISA by far.



▲ *Analysis of the LISA Pathfinder mission results towards the end of the mission (red line) compared with the first results published shortly after the spacecraft began science operations (blue line). The initial requirements (top, wedge-shaped area) and that of the future gravitational wave detection mission LISA (middle, striped area) are included for comparison, and show that it far exceeded expectations.*

The final results from the ESA satellite LISA Pathfinder (LPF) were published on 5 February 2018 (https://journals.aps.org/prl/a-stract/10.1103/PhysRevLett.120.061101). Using data taken before the end of the mission in July 2017, the LISA Pathfinder team significantly improved first results published in mid 2016. LPF now has exceeded the requirements for key technologies for LISA, the future gravitational-wave observatory in space, by more than a factor of two over the entire observation band.

While the first LPF results already exceeded the LISA requirements at high frequencies (above 0.01 Hz), the new publication shows that the requirements are beaten by more than a factor of two all the way down to 0.00002 Hz – the entire LISA frequency band.

How to create the quietest place in space
A combination of several effects allowed the LPF researchers to further improve the initial results, reduce the remaining noise sources, and create an even quieter environment for the two cubic gold-platinum test masses:

- After several more months of venting the test mass vacuum chambers to space, their residual gas pressure – which previously limited the measurements – dropped by a factor 10.
- The availability of more data improved the understanding of the small inertial force acting on the cubes caused by the spacecraft's orbit and how it was orientated in space. Improved control in LISA will reduce this effect further.
- A more accurate calculation of the electrostatic forces of the onboard electrical systems and magnetic fields has also now eliminated a systematic source of low-frequency noise.
- Statistical analysis has allowed scientists to remove the effects of additional sporadic events ("glitches") to measure the noise at even lower frequencies than expected.

This demonstration of near-perfect free fall of two test masses over a wide frequency band is a critical benchmark for the LISA mission and future multi-messenger astronomy in collaboration with other (electromagnetic-wave) observatories.

The first ever laser interferometer in space
In addition, the laser interferometer, the first ever in space, performed more than 100 times better than its requirements, and 30 times better than ever in ground-based laboratories. It enabled the detailed investigation of subtle tiny noise sources and artefacts, thus further accumulating experience and building confidence in the laser interferometry for LISA. The design and construction of the precise optical measurement system was led by scientists of the University of Glasgow, the Max Planck Institute for Gravitational Physics and Leibniz Universität researchers in Hannover.

The Laser Interferometer Space Antenna is scheduled for launch into space in 2034 as a mission of the European Space Agency (ESA). It is supported by many ESA member states as well as NASA and many scientists working together across the Atlantic. LISA passed its Mission Definition Review (MDR) on 22 January 2018 with flying colours.

A squeezed-light source for the Virgo gravitational-wave detector

After more than one year of work, Henning Vahlbruch and Moritz Mehmet from the AEI Hannover completed their latest generation squeezer. It is an advanced version based on the technology that GEO600 has successfully been using for the last seven years. In January, Henning and Moritz along with Harald Lück delivered it to Cascina and installed it at the Virgo site. The squeezer was completely assembled and tested on a 1 m^2 breadboard in a clean room lab in Hannover. To survive the 1300 km road trip to Cascina, great care was taken to realise a rugged design.

We considered the safest option to be transporting the squeezer on our own in a small rental truck. While still inside the clean room, the squeezer was doubly wrapped in a dust-tight plastic sheet and stowed in a flight case; it was then placed inside a wooden box with packing foam for shock protection. This box together with a 19" rack containing all the electronics needed for operating the squeezer was "expertly" stowed together with all the other items you need for such a trip (e.g. bicycles for riding along the Virgo arms!). On Thursday, January 11th, we set off southward.

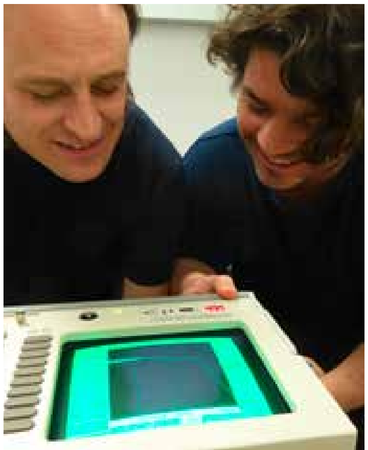
by Harald Lück, Moritz Mehmet, and Henning Vahlbruch

After the trip across the Alps, we arrived at the Virgo site in the afternoon of Friday, January 12th. Together with our Virgo colleagues Franco Carbognani, Jean-Pierre Zendri and Marco Vardaro we immediately started unloading the truck. The large crane in the Virgo central building was used to lift the flight case across the hall, where it was gently placed close to the detection lab and left to reach thermal equilibrium over night.

The next morning we installed the squeezer and its electronics rack in their intended locations. The optical table and cables to the detection electronics room on site were very well prepared prior to our arrival, such that the installation work went very smoothly. For reactivation of the squeezer, only minimal realignment was required and subsystem checks started on Saturday evening. Sunday was dedicated to fine alignment of the entire setup. In the evening we could observe that the squeezer performed as well as it did in the Hannover lab.

Interfacing of the squeezer to the Advanced Virgo detector is currently being undertaken by the Virgo squeezer integration team. This squeezer will improve the detection capabilities of Advanced Virgo in time for the next observation run.

LIGO 2018



Once again, LIGO makes history

Maya Kinley-Hanlon

will graduate from American University in May with a BS in Physics. She has been a research assistant for Professor Gregory Harry in his LIGO Lab for three years and is currently the President of the Society of Physics Students and the Art Student's Guild. In her spare time, she enjoys going on trail rides with her horse Goldie.

This summer, LIGO once again made history. The Laser Interferometer Gravitational Wave Observatory saw signals from two neutron stars colliding, the morning of August 17, 2017. As a student reporter for The SPS Observer, I got to attend the official announcement of the discovery on October 16th.

It was thrilling to be in the same room as 30 journalists from such a wide array of publications. I was sitting next to a reporter from the LA Times. None of us, at the time, knew what would be announced, simply that it was a discovery that would rock the astronomical community. Suddenly, a hush came over the room as the panelists silently filed in. After the introductions were made, France Córdova, Director of the National Science Foundation (NSF), took the podium. "Today," she said, "we are thrilled to announce that scientists have detected gravitational waves coming from the collision of two neutron stars."

David Reitze, executive director of the LIGO lab at Caltech, then took the podium. "We have, for the first time, seen both gravitational waves and light from the collision of two dense, dense, stars," he said. "This time... we all did it." It is that message that resonated as each panelist spoke. What was possibly the most amazing feat of this discovery is not just its impact, but also the fact that it was a collaboration between LIGO, Virgo and over 70 astronomical observatories in the world, with both ground- and space-based detectors.

▲

The panel discussing the gravitational wave detection and electromagnetic follow-up observations. From left to right: David Reitze, France Córdova, David Shoemaker, Jo van Den Brand, Julie McEnery, Marica Branchesi and Vicky Kalogera.

LIGO deputy spokesperson Laura Cadonati mentioned that nature has been benevolent with LIGO throughout the entire process. The strong initial signal of two black holes merging was a clear announcement to the world that the science of LIGO was successful. And while the detection of a binary neutron star merger was an expected detection, it announced a revolutionary new era of multi-messenger astronomy. The binary neutron star merger was the first to be seen and gave a description for the amount of gold and platinum that exists in the universe. Additionally, because neutron stars are so dense, their collision is bright and able to be seen by not only gravitational wave detectors, but by telescopes around the world, including gamma-ray and x-ray detectors. Being able to study this event by looking at gravitational waves and light together will allow astronomers to learn even more about our universe.

The LIGO Collaboration has grown up over the past 20 years, along with the researchers who have dedicated their lives to it. Until the initial discovery of gravitational waves in 2015, LIGO efforts were hardly known by the public and viewed with skepticism by more established astronomy communities. The researchers of LIGO pushed on, not because they hoped to gain fame, but because they believed in what they were doing. This made the collaboration one of community and support, which was clearly evident during the press conference. Every scientist on the LIGO panel echoed each other that this most recent discovery was one made and celebrated by a community.

This article was originally published in the SPS Observer (Society of Physics Students) in 2018. The original article can be found here: https://www.spsnational.org/sites/default/files/files/publications/observer/2018/SPS-Observer-Winter-2018-web.pdf

by Maya Kinley-Hanlon

After a celebratory dinner, I sat with astronomer and researcher Vicky Kalogera and Laura Cadonati, talking about the importance of such a large collaboration. Kalogera, who came from a pure astronomy background, talked about how before she joined LIGO she was used to very small groups, and she grew to understand that you cannot achieve results like these without a collaboration of this size. "No individual group can reach this kind of achievement," she said "We need each other."

Towards the end of dinner, Cadonati and LIGO spokesperson David Shoemaker were pushed to give a toast. "This is a celebration of a remarkable result of observations of LIGO, and a really joyous combination of both this collaboration and our electromagnetic partners that has turned out remarkably well," Shoemaker said. Cadonati added, "We want to thank you for this amazing endeavor...It has not always been easy, but the very fact that we got 3500 authors on the same paper, 70 papers in the archives today, and we took down the journal web servers," she said to cheers and applause from the room, "is an amazing accomplishment. I look forward to all of you giving talks to the general public and raising enthusiasm for gravitational wave astrophysics, gravitational wave cosmology, gravitational wave nuclear physics, and the good things that will come. Thank you everyone, and welcome to the new era." With that, the room erupted into thunderous applause.

What keeps LIGO researchers going is the hunt for more discovery. Kalogera put it simply: "No matter what, research is about questions." This is what we can all keep in mind as we find the efforts we want to dedicate our lives to. I'm thankful to have begun my career in research within the LIGO Collaboration. Hopefully, no matter what we choose to study, we are surrounded by as much support and joy!

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Solar eclipse across the USA

▲

Taken using a Nikon D5200 and a 300mm zoom lens on a fixed tripod. Exposure is 1/400 sec at ISO 1600. Maximum aperture. Location: Clarksville, TN. Marco Cavaglia

▲

I moved my camera out of focus while taking the solar-filter off. A tip is to tape your camera to fix the focus – out of excitement (and in the darkness), you are surely not going to look back at the focus once totality begins! Archisman Ghosh

▲

The photo has been taken through a test piece of LIGO black glass mounted on a 80X zoom digital camera. This type of black glass is used for some of the stray light baffles and beam dumps at both observatories. In this case camera magnification was used only to help live streaming on a small digital display. Taken at Caltech.

Alena Ananyeva & Madeleine Kerr.

Career Updates

Kate Dooley has moved from University of Mississippi to Cardiff University, joining **Hartmut Grote**, who moved from the Albert Einstein Institute in January. They are building up an experimental gravitational wave group there.

Maxime Fays graduated from Cardiff and moved to a postdoc position at the University of Sheffield, where he is working on signal processing technologies applied to magnetocardiograph data analysis in the gravitational wave group.

Paul Fulda, currently at the Goddard Space Flight Center, will join the University of Florida as an assistant professor in April 2018.

Sean Leavey started work in December as a postdoc at the Albert Einstein Institute in Hannover, helping to commission the 10m prototype SQL experiment.

Denis Martynov moved from the MIT Kavli Institute to the University of Birmingham as a faculty member, where he will be working on experimental quantum optics and design of future gravitational wave detectors.

Grant Meadors, previously a postdoc in the continuous waves group at the Albert Einstein Institute in Hannover, moved to Monash University in January to take up a Research Fellow postdoc position, as part of the ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav).

Hannah Middleton has finished her PhD at the University of Birmingham, and has just started a postdoc at the University of Melbourne as part of the ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav).

Miriam Cabero Müller successfully defended her thesis, entitled "Gravitational-wave astronomy with compact binary coalescences: from blip glitches to the black hole area increase law", at the Albert Einstein Institute in Hannover in February.

M. Alessandra Papa has established an Independent Research group at AEI Hannover. The group will comprise between 15 and 20 scientists and focuses on searching for continuous gravitational waves.

Brett Shapiro, formerly a postdoc at Stanford University, accepted a position as a Guidance and Control Engineer at the Johns Hopkins Applied Physics Lab in Laurel, MD. He is currently working on the Parker Solar Probe, scheduled to launch next summer to study the sun up close.

Rory Smith, previously a senior postdoc at Caltech, joined the Faculty of Science at Monash University as a Lecturer in September 2017. He is also a member of the ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav).

Awards

The Relativity and Gravitation Group at the University of the Balearic Islands was awarded the **City Gold Medal of Palma de Mallorca**. The award was approved by the City Council on December 21st and the ceremony took place on December 31st during the Festa de l'Estendard.

Parameswaran Ajith from ICTS-TIFR, Bangalore, was named a CIFAR Azrieli Global Scholar by the Canadian Institute for Advanced Research. This involves a research support of CAD100k and membership to CIFAR's "Gravity and Extreme Universe" program.

Alessandra Buonanno has received the Leibniz Prize, the most prestigious award of the Deutsche Forschungsgemeinschaft, for her key role in the first direct observations of gravitational waves.

Neil Cornish, from Montana State University has been named a Montana University System Regents Professor, the most prestigious designation for a Montana professor.

Dennis C. Coyne, Peter K. Fritschel, and David H. Shoemaker will share the 2018 Berkeley prize in recognition of their leadership roles in the development of the Advanced LIGO detectors.

Karsten Danzmann received the Stern-Gerlach Medal of the German Physical Society, their most prestigious award for experimental physics, for his crucial contributions to the development of gravitational-wave detectors.

Peter Fritschel received the OSA 2018 Charles Hard Townes Award for advances in quantum-limited precision measurement in the Advanced LIGO detectors, leading to the first direct detection of gravitational waves.

Daniel George, from the University of Illinois at Urbana-Champaign, was awarded 1st place in the ACM graduate student research competition at the Supercomputing Conference (SC17) for his research titled "Deep Learning with HPC Simulations for Extracting Hidden Signals: Detecting Gravitational Waves". This work was featured as a demo in the NVIDIA booth at SC17 and also received the Best Poster Award at the 24th IEEE conference on HPC, Data, and Analytics in December 2017.

Abhirup Ghosh from ICTS-TIFR, Bangalore, received the Ramkrishna Cowsik Medal of the Tata Institute of Fundamental Research (TIFR), given across the TIFR system for the best paper published in the last three years to researchers under the age of 35.

Les Guthman was the only American inducted as a Fellow of the Royal Canadian Geographical Society in the class of 2017.

Michèle Heurs received the Leibniz Universität Hannover prize for excellent teaching for 2017.

James Hough was awarded the Gold Medal of the Royal Astronomical Society for his contribution to the science of gravitational waves over the last four decades.

Vicky Kalogera was awarded the 2018 Dannie Heineman Prize for Astrophysics for her fundamental contributions to advancing our understanding of the evolution and fate of compact objects in binary systems, with particular regard to their electromagnetic and gravitational wave signals.

Paul Lasky was awarded the 2018 Pawsey Medal from the Australian Academy of Sciences, for outstanding contributions to science by an early career researcher.

Stephen C. McGuire, Southern University, has been elected to the Edward Bouchet Abdus Salam Institute (EBASI) Council of the International Center for Theoretical Physics (ICTP) in Trieste, Italy.

Cody Messick was given the "Rising Star Alumni Award" by his alma mater, Clark College, which recognises young researchers that have "exhibited exceptional service to the college, exemplary service to the community and have had personal and professional achievements".

Emma Osborne, from Southampton University, won the Newcomer Award at the SEPnet Public Engagement Awards held in December, after being a finalist for the Institute of Physics Early Career Communicator award in November.

Nergis Mavalvala, **Roman Schnabel and David McClelland** will be given the QCMC 2018 Award for outstanding achievements in quantum experimentation.

Stan Whitcomb was awarded the 2018 C.E.K Mees Medal from the OSA for pioneering interdisciplinary contributions to the development of the LIGO gravitational-wave interferometers.

New LSC Positions

Collaboration members who have taken on new leadership positions in the LSC organization:

Odylio Denys Aguiar is the new LIGO Academic Advisory Committee senior member.

Stefan Danilishin is the new Quantum Noise working group chair.

Kate Dooley is the new LIGO Academic Advisory Committee co-chair.

Ben Farr is a new co-chair of the Compact Binary Coalescence (CBC) Working Group.

Andreas Freise is the new Technical Advisor to the Oversight Committee.

Ray Frey is a new co-chair of the Burst Analysis Working Group

Carl-Johan Haster is the new LIGO Academic Advisory Committee postdoc representative.

Stefan Hild is the new Advanced Interferometer Configurations working group chair.

Nutsinee Kijbunchoo is the new LIGO Academic Advisory Committee grad-student representative.

Brian Lantz is the new Instrument Science Coordinator.

Joe Romano is a new co-chair of the Stochastic Background Working Group.

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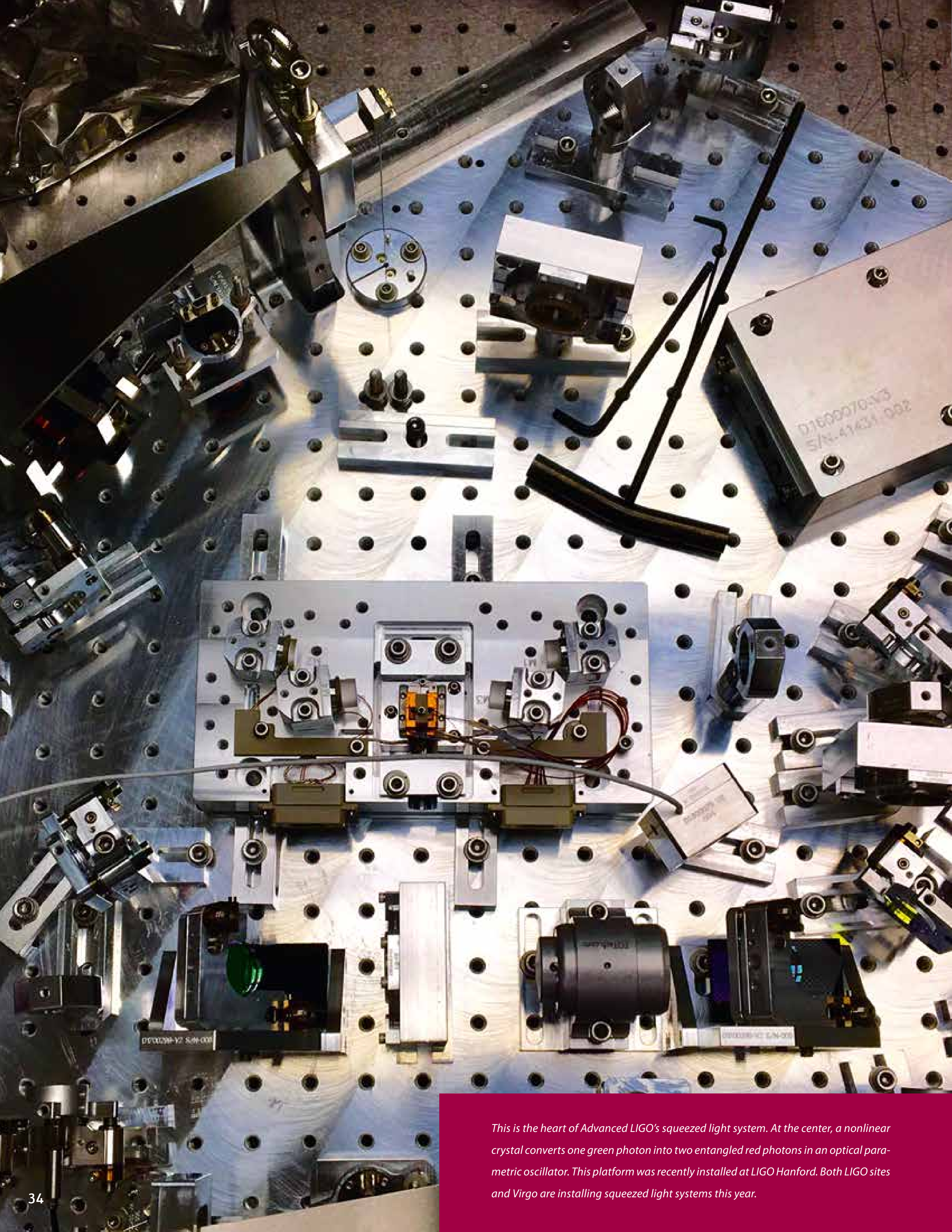

This is the heart of Advanced LIGO's squeezed light system. At the center, a nonlinear crystal converts one green photon into two entangled red photons in an optical parametric oscillator. This platform was recently installed at LIGO Hanford. Both LIGO sites and Virgo are installing squeezed light systems this year.

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What is a neutron star?

by Ansel Neunzert

Neutron stars are relatively small, extremely dense objects, with masses greater than the Sun's, and diameters of about 20km. They result from massive stars collapsing, creating such high-pressure conditions in the core that most of the protons and electrons are forced to combine into neutrons.

Since the 1960s, astronomers have detected electromagnetic radiation coming from neutron stars. Some, called pulsars, are rotating stars that emit a beam of radiation, so that the star appears to "pulse" each time the beam sweeps by Earth. The fastest known pulsar rotates 716 times every second! Neutron stars can also emit radiation that does not pulse. For example, some stars are accreting: matter is falling onto the star, generally from an orbital companion. Accretion can release energy in the form of observable radiation, and is probably also what "spins up" some pulsars to their high frequencies, by transferring angular momentum from the orbit to the star.

What don't we know about neutron stars?

A lot of things! For one, we don't know the neutron star equation of state: the exact relation between pressure, volume, temperature, and other thermodynamic quantities within such an object. The life cycle of a neutron star is also not fully understood. How, in detailed terms, do pulsars achieve their high spin frequencies? How fast can a neutron star possibly spin, and what sets that upper limit? How many neutron stars exist that we have not (or cannot) observe electromagnetically? How many of them are in binary systems?

Neutron stars and gravitational waves

There are at least three big reasons why neutron stars are interesting for gravitational wave astronomy: First – as we saw last year – colliding neutron stars create a burst of gravitational waves. And unlike black hole mergers, they also create a bright burst of electromagnetic radiation. Second, neutron stars are expected to emit gravitational waves even when they're not colliding. A neutron star with a small "bump" or other asymmetry could generate weak but continuous gravitational waves (which we also search for in LIGO data). And third, the regular blinking of pulsars could turn them into a kind of gravitational wave detector in their own right: something called a pulsar timing array. A very low frequency gravitational wave passing by Earth should cause observers to note tiny changes in the pulse frequencies of stars across the sky.