LSC LIGO Scientific Collaboration

LIGO MAGAZINE

issue 7 9/2015

Looking for the Afterglow

The Dedication of the Advanced LIGO Detectors

LIGO Hanford, May 19, 2015 p.13

The Einstein@Home Project

Searching for continuous gravitational wave signals p.18

... and an interview with Joseph Hooton Taylor, Jr. !

The cover image shows an artist's illustration of Supernova 1987A (Credit: ALMA (ESO/NAOJ/NRAO)/Alexandra Angelich (NRAO/AUI/NSF)) placed above a photograph of the James Clark Maxwell Telescope (JMCT) (Credit: Matthew Smith) at night. The supernova image is based on real data and reveals the cold, inner regions of the exploded star's remnants (in red) where tremendous amounts of dust were detected and imaged by ALMA. This inner region is contrasted with the outer shell (lacy white and blue circles), where the blast wave from the supernova is colliding with the envelope of gas ejected from the star prior to its powerful detonation.

Image credits

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p. 2 Comic strip by Nutsinee Kijbunchoo

p. 5 Figure by Sean Leavey

pp. 8–9 Photos courtesy of Matthew Smith

p. 11 Figure from L. P. Singer et al. 2014 ApJ 795 105

p. 12 Figure from B. D. Metzger and E. Berger 2012 ApJ 746 48

p. 13 Photo credit: kimfetrow Photography, Richland, WA

p. 14 Authors' image credit: Joeri Borst / Radboud University

pp. 14–15 Image courtesy of Paul Groot / BlackGEM

p. 16 Top: Figure by Stephan Rosswog. Bottom: Diagram by Shaon Ghosh

p. 18 Authors' images from top left, clockwise: Photos courtesy of M. Alessandra Papa, S. Knispel, Franz Fender, MPI for Gravitational Physics

pp. 18–19 Image credit: Benjamin Knispel / MPI for Gravitational Physics

p. 20 Photo courtesy of Benjamin Knispel

p. 21 Image courtesy of MPI for Gravitational Physics / Benjamin Knispel (photo) & NASA (pulsar illustration)

p. 22 Photo credit: Princeton University photo

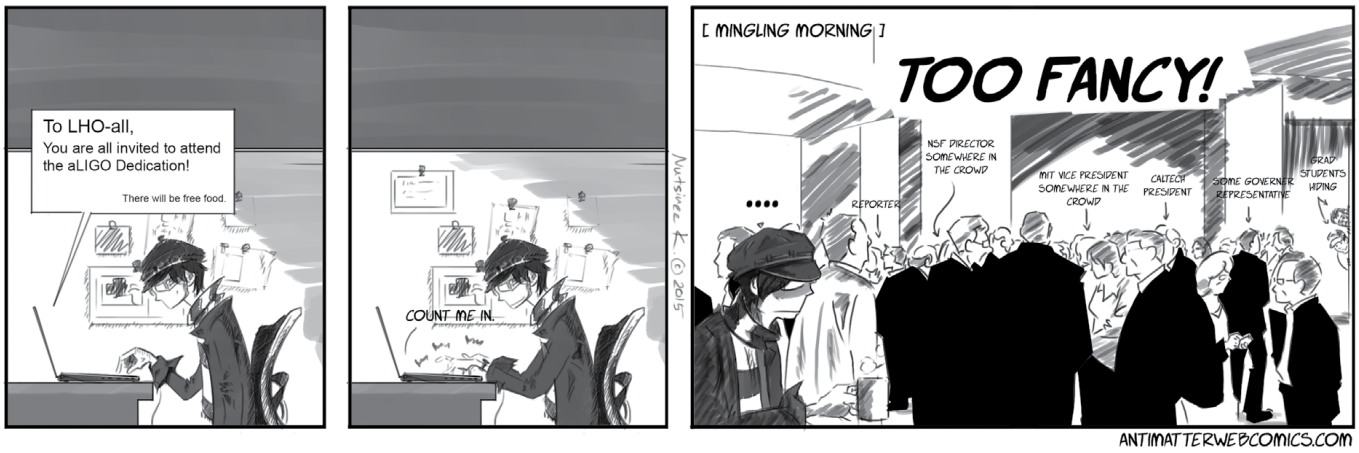
p. 24 Photos courtesy of David Shoemaker and Harald Lück

p. 25 Photo courtesy of UTB

p. 30 Photo credit: Frank Miltner

p. 32 Sketch by Nutsinee Kijbunchoo

Antimatter



Nutsinee Kijbunchoo

Contents

Upcoming Events (compiled by the editors)

The LSC-Virgo September Meeting
Budapest, Hungary,
31 August - 3 September 2015

Spanish Relativity Meeting 2015 (ERE2015)
"Stepping into the second century"
Palma de Mallorca, 7-11 September 2015

The Modern Physics of Compact Stars and Relativistic Gravity 2015
Yerevan, Armenia,
30 September - 3 October 2015

100 year of curved space-time
Vienna, Austria, 5-7 October 2015

Frontiers in Optics/Laser Science
San Jose, California, 18-22 October 2015

Einstein's Legacy
Queen Mary Univerisity of London, 28-29 November 2015

A Century of General Relativity
Harnack House, Berlin,
30 November - 2 December 2015

8th Australasian Conference on General Relativity and Gravitation
Monash University, Australia,
2-4 December 2015

The 28th Texas Symposium on Relativistic Astrophysics
International Conference Centre, Geneva,
13-18 December 2015

GR 100 years in Lisbon
Lisbon, Portugal, 18-19 December 2015

A public web page with a calendar and list of upcoming conferences and meetings that may be of interest to members of the LSC is now available in ligo.org:
https://wiki.ligo.org/LSC/UpcomingConferencesAndMeetings

Welcome to Issue #7 of the LIGO Magazine!

Welcome to the seventh issue of the LIGO Magazine. These are very interesting times for the gravitational wave community, and for other people watching our efforts from the outside: This year will see the launch of the LISA Pathfinder spacecraft and we will report on the project in a series of articles, starting with a brief project overview in this issue. At almost the same time the first science run of the new LIGO detectors will begin, providing new data to analyse and to search! In 'Looking for the Afterglow' and 'A Tale of Astronomers and Physicists' we explore the connections between gravitational wave detection and electromagnetic astronomy. Working closer with other astronomers will bring its own interesting challenges. 'Adventures of an Observational Astronomer' presents a brief glimpse into a different scientific routine.

Another impressive synergy between gravitational waves, radio and gamma-ray astronomy can be found in the overview of the Einstein@Home project. We are proud to feature an interview with Joseph Taylor, one of the winners of the 1993 Nobel Prize in physics for the discovery of the first binary pulsar, PSR B1913+16.

The American Physical Society's Topical Group in Gravitation will become the Division of Gravitational Physics in early 2016 if it retains its current members and recruits a few more. Please join or renew your membership to support this effort.
See http://apsggr.org/?p=222 for more information.

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

Andreas Freise for the Editors

LIGO Scientific Collaboration News

Gaby (Gabriela) González
LSC spokesperson

As we mentioned in the last issue, the future is now: At the time you read this, we'll be a few weeks from starting the first observing run, O1, with the Advanced LIGO detectors. Both LIGO detectors have already achieved a sensitivity better than 3 times the best sensitivity of initial LIGO. Although a detection is not "expected" in O1, we should be ready – so we are putting procedures in place to quickly but thoroughly review an interesting result if it happens. Irrespective of what nature provides, we will publish important results from O1.

This will just be the beginning of a new era: the second Observing run in 2016-2017, with more sensitive LIGO detectors, longer duration and with the Virgo detector joining the network, will have even more interesting results than O1 – but all of us will need to keep our eyes on the prize and keep working hard to make it happen. Detectors improve because lots of people work on them; the data calibration and characterization is essential for the analysis to produce good results; the codes need to be tested, reviewed, and run to produce

results that need to be reviewed and validated: hundreds of people are needed to do this right – we need YOU!

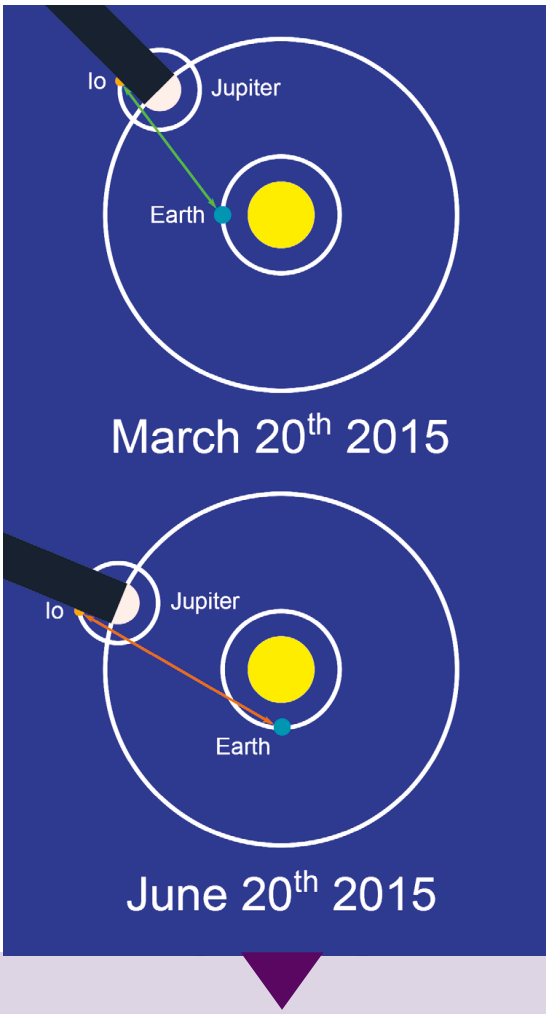
The second cohort of LSC Fellows starts in September – the first group of Fellows not only contributed to the performance of the detectors, but also created a friendly and collegial atmosphere that everybody enjoyed – we are looking forward to hosting many more Fellows at Livingston and Hanford.

I was very happy when I was re-elected as LSC spokesperson in March – THANKS! I promise to honor that trust, working as hard as I can to make the LSC succeed in all its endeavors: not only gravitational wave science, but also its effective communication to the public and the scientific community. I will rely for this on my invaluable ally, Marco Cavaglià, confirmed again as Assistant Spokesperson, as well as all of you in the LSC working groups. Look for announcements in Budapest about all of the newly appointed or re-appointed committee chairs in August – and thank them all for their service.

In other news, the LIGO S6 data set is now publically available through the LIGO Open Science Center. This is very useful for everybody so you should check it out yourself.

I hope you enjoy this issue of the magazine as much as I did – and don't hesitate to contact Marco or me with any question or initiative. We'll be very happy to hear from you.

Gabriela González



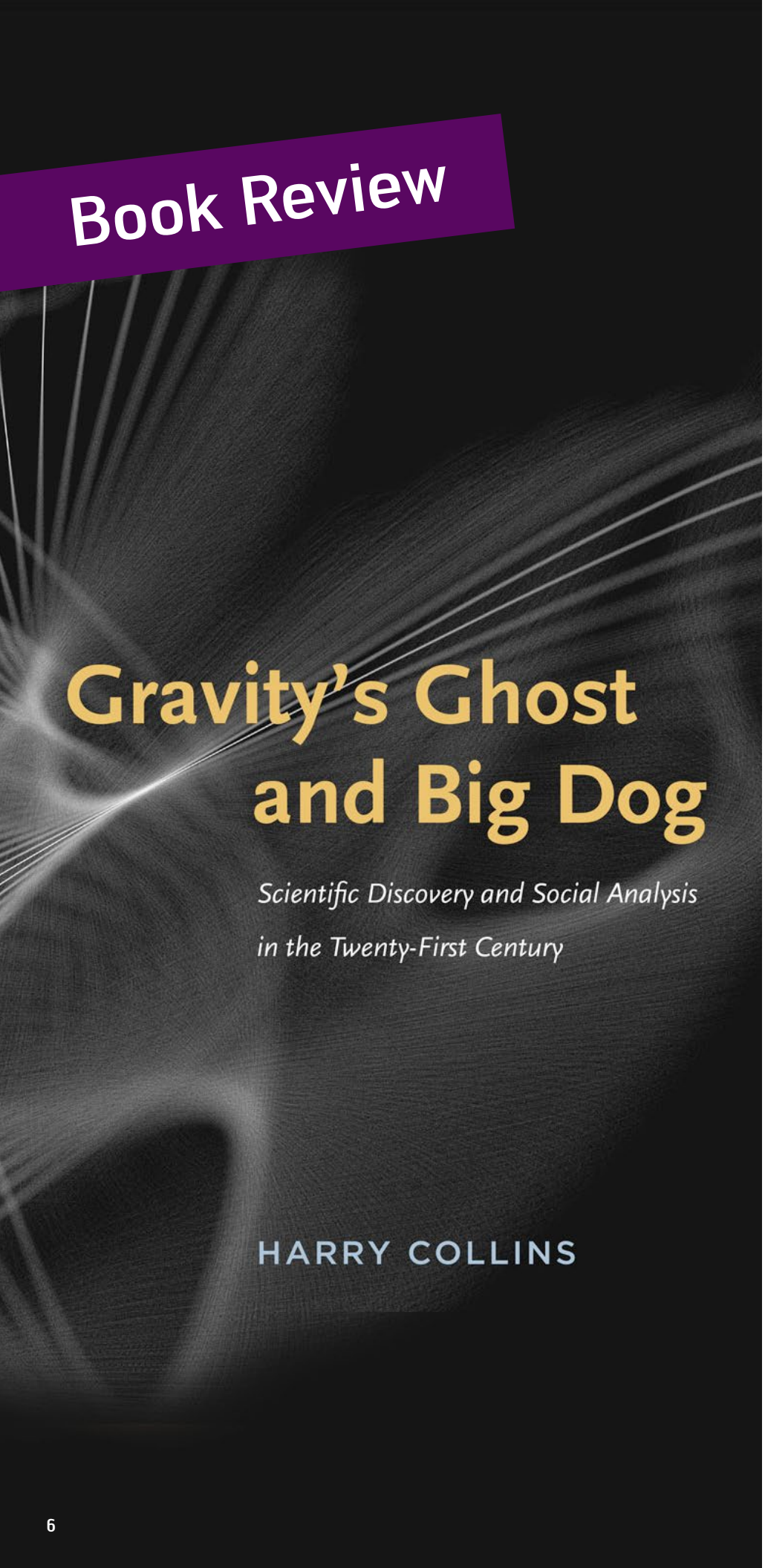
2015 is the International Year of Light, a celebration of the central role that light and light-based technologies play in our everyday lives. The year sees events focussed around how light is integral to our understanding of the Universe, its role in our culture and artistic pursuits, and also the numerous applications in technology and communications.

Ole Roemer (1644-1710) is credited as the first person to have measured the speed of light, but like so many great scientific discoveries, he was not actually looking to make this measurement. Roemer was timing the four Galilean satellites to use them as an accurate celestial clock for the purpose of measuring longitude. A curious discrepancy arose in these observations. The eclipses of the Galilean moons (Io, Europa, Ganymede and Callisto) were consistently later when the planet moved from opposition to conjunction. Roemer actually measured a change of 22 minutes, although today a more accurate value is closer to 17 minutes. This allowed astronomers to make a first estimate of the speed of light. We now term this the Roemer Delay. In the figure above we see that at the two times (March 2015 and June 2015), the distance between the Earth and the point at which Io emerges from the shadow of Jupiter (the eclipse) is different. With a finite speed of light this results in the eclipse happening "later" than expected.

For the International Year of Light, members at the University of Glasgow are working on a citizen science project to make measurements of eclipse timings, in order to estimate the speed of light. A webpage has been set up at http://speedoflight2015.co.uk/ which provides some more information on Roemer's work, information on how to make a measurement, some approximate eclipse timings and also a page for data upload. We already have a number of observations from around the world and are looking for further observations as Jupiter passes conjunction in late 2015. We partnered with Astronomers without Borders who did another observation using the 60" Mount Wilson reflector in late June.

Giles Hammond

Book Review



March 2014, and in a conference hall somewhere near the French Riviera, there is an unscheduled break in the LIGO-Virgo collaboration meeting. We are watching a press conference from Harvard, the BICEP2 team presenting a faint, but definite, signal they have picked up from the far cosmos. We try to decipher their draft paper: "Detection of B-mode Polarization at Degree Angular Scales [..] an excess of B-mode power [..] at a significance of >5σ." Cryptic enough. The press release is more forthcoming: "first direct evidence for cosmic inflation [..] first images of gravitational waves, or ripples in space-time." Those images become front-page news; soon a video appears with a cosmologist sipping champagne to celebrate the confirmation of a speculative theory written down 30 years ago.

Harry Collins' book 'Gravity's Ghost and Big Dog' is on one level a chronicle of the inner workings of LIGO and Virgo, arguing our way from one draft of a paper to the next. But its real subject matter is those moments when a new scientific discovery is claimed, theory becomes experimental fact and the state of human knowledge moves – or seems to move – one step further on a long trail. How do scientists turn readings from their instruments into statements of detection or discovery that will be reported and discussed around the world? Collins is a sociology professor at Cardiff University with a long-standing interest in how scientific progress is really made. He acts as an embedded reporter within LIGO (with full support of the management), trawling our emails, attending our meetings, picking up our specialist language and trying to understand our attitudes and behaviours, if necessary via questioning and argument.

LIGO and Virgo – as Cardiff astronomers would half-jokingly remind us – have not yet detected anything astrophysical, but

Thomas Dent

Thomas Dent is currently a senior scientist at AEI Hannover. He joined LIGO in 2009 via Cardiff University after (n-2) previous jobs in particle physics and cosmology. When not worrying about false alarms in GW searches, his favourite distraction is to cycle up and down absurdly steep hills and eat absurdly large meals, preferably in Italy.

Collins gets his chance when a small group of scientists induce a fake signal in the interferometers without informing the collaborations. 'Blind injections' are tests – to check that data analysis codes put an appropriate little dot on a graph, but more importantly, that the collaboration can draw the appropriate conclusions and go all the way to claiming a detection. The exercise only stops at the last minute to open an 'envelope' unveiling the signal as fake … or, conceivably, real.

The path to detection, with its debates and quandaries, gives Collins both a narrative and a hook for the themes of his sociological analysis. 'Gravity's Ghost' concerns an abrupt blip in LIGO data from September 2007 that was considered for the rôle of first detection, but eventually turned down as being too similar to spurious disturbances in the detectors ('glitches'). When it was revealed as a (fake) signal rather than a glitch, some LIGO scientists were disappointed. Collins wonders if the cautious majority, haunted by implausible detection claims from previous experiments, were setting unrealistically high standards. The section ends with a thoughtful examination of scientific values – among them the willingness for one's findings to be openly debated, as would certainly have happened for a blip with such an uncertain physical interpretation.

'Big Dog' was very different: an audibly and visibly loud signal, apparently from the direction of Canis Major, bearing the fingerprints of a gravitational wave signal from a pair of black holes circling each other. Coming a few weeks before the detectors would be demolished to make way for new hardware, it generated a ripple of excitement: at last something really detectable! The task of justifying and describing it for a wider community was not so straightforward. Collins gives a blow-by-blow commentary on the drafting of the detection paper, piling up evidence that scientific truth is, inevitably, a social construction. (Though, scientists might add, not necessarily less true for that.) At last, LIGO and Virgo unanimously endorsed a detection statement and the 'envelope' was opened. Big Dog was another fake signal – but the champagne that flowed was real.

Was Big Dog a success, as either science or sociology? Collins sees our cautiously hedged detection claim, for such a clear signal, as far from the desired scientific outcome. My data analyst's view: our task is to separate real signals from glitches, but Big Dog behaved as if there was a shot or two of glitch mixed in with the signal, making the results less clear-cut than we hoped – some caveats were inevitable.

And to the data analysts, Big Dog didn't look 'random enough' for a real signal: it was implausibly loud, and arrived too close in time to a tick of the electronic clocks that synchronize LIGO data. Were we, as Collins says, still acting as if the signal was real? Yes and no – we knew our codes needed upgrading for the real first detection, and Big Dog was an impetus to start work on the new framework. And we needed the collaboration to be able to leap over the barrier of caution: otherwise what was the point of the upgraded methods?

But would analysts have pushed towards detection if the signal hadn't been so obvious – and if it hadn't been a probable fake? The email exchanges between pseudonymous scientific characters (Quince, Dogwood...) that Collins quotes read more like a dress rehearsal than a real controversy, and the certainty of an envelope telling us we were right or wrong makes it easy to judge from hindsight.

What became of BICEP2? To be sufficiently certain of a cosmic signal, scientists ruled out contamination from instrumental noise, the Earth, and the Solar System – leaving, finally, polarized light from the Galaxy, for which they had only educated guesses. Still, the bold detection claim was made. But a few months later, a couple of carefully argued papers showed that Galactic dust might be dense enough to account for the entire BICEP2 signal; the results need not imply cosmic gravitational waves after all. So the detection 'bit the dust'.

For Collins, scientific progress is not infallible or inevitable, nor is it a mere set of trends in opinion: science has real content, although this resides more in the expertise of active scientists than in the published record (despite all the attention paid to tiny changes in wording). He values expertise even in cases where experts are wrong, and even if outsiders – including Collins himself? – are hard pushed to tell expertise from merely talking a good game.

The BICEP team's detection was faulted by outside experts, but their expertise in building and operating ludicrously sensitive detectors remains unchallenged and will surely yield valuable results. The question for LIGO's first detection claim will perhaps be not "how certain is the signal?" but "do we have the best possible expertise to support it?"

'Gravity's Ghost and Big Dog: Scientific Discovery And Social Analysis In The Twenty-First Century' (392 pages) is published by University of Chicago Press.

An Astronomer's Tale

Matthew Smith

Matthew Smith is a postdoc at Cardiff University working on galaxy evolution and the interstellar medium. When not thinking about galaxies Matt's passions are for rugby, travelling and his dog Munch.

A troop of kangaroos and The Australia Telescope Compact Array (ATCA), in Narrabri, Australia (August 2012).

In Cardiff we're lucky to have a vibrant coffee break environment where a diverse group of physicists – students, postdocs, and faculty from a varied range of research groups – meet and discuss their current work. Often the astronomers are taunted that trips to make observations at telescopes around the world are just excuses to go on a 'jolly'. Hopefully in this article I can dispel that myth and give you a sense of what a real observing trip entails.

An observing trip really starts six to twelve months before getting anywhere near a telescope. Usually there is competition with many other astronomers worldwide for time on telescopes and over-subscription rates can reach up to a factor of ten. A telescope proposal is just like any other grant proposal; you have to really justify how your observations will produce new science or significantly improve on previous work. The length varies but usually you have only three pages to make your case. Technical details such as the sample size (how many objects you want to observe), map area and sensitivity are important. You can't be too cautious, as the panel judging the proposal will think you will use too much time. Too little time and you run the risk of your data being useless, and the panel might pick up on this flaw in your observing plan. But remember, it takes four times longer to double the sensitivity – it's a real balancing act! After all of these steps, there can be the sudden realisation that the sources aren't visible at night at that time of year or that the

moon is too close. I personally find that working out the required integration time is the hardest part of writing a telescope proposal; this is, how long I must observe a specific source to resolve it sufficiently. It's easy in theory: decide what you want to measure and use a telescope calculator or documentation to work out how long it will take to observe. However, on some occasions I have spent hours bouncing between time estimates of seconds to years. Every single telescope has different terminologies, observational methodology, instrument technologies, and uses different units – I have had to look up the conversion of brightness temperature to Jansky per beam way too many times!

When I'm lucky enough to be awarded observing time – usually after a couple of iterations of the proposal – a number of things need to be prepared before travelling to the telescope. More technical details need to be considered, such as choosing suitable calibrators; a telescope usually has to be calibrated by looking at a standard star, planet, or quasar so that the conversion from counts to flux is known. When all these things have been determined, it's finally time to start planning the trip and obtain any necessary documentation. Unlike conferences, which are often in major cities with nice hotels, telescopes are usually in remote areas where you are limited to the on-site residence and cafeteria. The remoteness means I have been able to see some stunning scenery and wildlife. Before an observing trip to Australia (and having grown up in London) I'd never seen the Milky Way with the naked eye! Sometimes a bit of bravery is required with the cafeteria food, particularly as my stomach isn't used to spicy food for breakfast, lunch and dinner. I also definitely got close to the wildlife, almost walking into a kangaroo in the middle of the night as I was trying to get some lunch or waking up to find a large scorpion sharing my room.

After making the journey to the telescope, the hard work starts. A standard observing session normally lasts around eight hours (about the time a source is overhead). However, I have had fourteen-hour sessions, sometimes with an extra hour to drive up and down a mountain summit. You very quickly fall into a repeated pattern of waking up, eating breakfast (often the same food everyone else is having for dinner), observing, getting back, grabbing some breakfast, and then trying to sleep while the Sun is up – luckily telescope accommodations tend to have good blackout blinds – until it starts all over again. On top of the combined problem of jet-lag and working nights, many telescopes are at high altitudes, which at the very least can make you feel a bit light-headed and dizzy, and has very occasionally led to

Picture taken with a DSLR and 35mm lens whilst observing a top of Mauna Kea in September 2014. The JCMT is shown with the Milky Way.

more serious complications. A colleague of mine once had to be rushed from the top of a mountain to hospital because he had developed a pulmonary edema (i.e. water on the lungs). The first time I experienced altitude there was the added 'fun' of the staircase literally moving, as the telescope and control room rotated atop the building. After working out where the stairs had gone, catching up with them and getting to the top where the control room was located, I was often in need of a good cup of tea!

What I actually do on observing trips varies widely between telescopes. Some telescopes have an operator who controls their basic operations and prevents major errors from occurring. I have always found the operators to be exceptionally helpful. They often go out of their way to help scientists' observing programs, or have nice gestures like keeping tea or coffee supplies going. I'll always remember my first observing trip when the operator and I were trying to fix the telescope, only for him to suffer a serious cut.

While I was trying to get him to find a first-aid kit he proclaimed "No, the science comes first!". When mainly an operator runs the telescope there is time to quickly analyse the results as the data come in to see if the desired sensitivity is being reached. This allows on-the-fly changes to be made if needed, which is especially important if you're using a new instrument or an uncommon observing mode. I tend to do this anyway, as most people know someone who has accidentally used the wrong coordinate system (1950 instead of 2000 coordinates for example) or has looked at a blank patch of sky by forgetting to alter the angular distance correctly. Remember to take off that *cos(declination)* factor!

The most educational telescopes are those where there is no operator and you are left to run everything by yourself. This can be a bit scary and a big learning curve, but I've learned so much about how a specific telescope works by doing this. With no operator around, I've quickly learned how to point, focus and calibrate the telescope, and understood the multitude of readings, from weather to instrument systems temperatures (not the physical temperature of the instrument, but the noise through the whole system). Unsurprisingly, being left on your own leads to interesting situations. Once, while alone at around 4am, a fault occurred in the neighboring control room. This set off a small beeping sound, and two minutes later a phone call came in to that control room (which I didn't answer since it was for a different telescope). Suddenly the fire alarm went off and just as I got outside a massive siren on top of the building bellowed out an awful racket. While I stood outside quite dazed, the system had luckily phoned someone who lived on site to fix the problem.

Regardless of whether an operator is present, there is no better way of getting the most out of the observing program than to interact with the staff at the telescope and host institute. There is a lot of information not written in the manuals, or too buried in documentation, that can really help improve the efficiency and sensitivity of your observation. On some occasions, colleagues and I have been able to feedback this information, which can improve the analysis pipelines for all astronomers. One of the problems facing astronomy is the current move to bigger facilities where you just receive your results, rather than observe yourself. This could lead to diminishing understanding and basic skills for the next generation of observers.

LIGO 2015

Looking for the Afterglow: The LIGO Perspective

As we follow the success of LIGO's commissioning efforts, anticipation is building for the first direct detection of gravitational waves. While there is much to be learned by studying gravitational waves themselves, there is a class of sources for which there is even more to be gained by studying the electromagnetic (EM) radiation emitted alongside the gravitational waves. Binary neutron stars are the most well-understood sources of both gravitational waves and electromagnetic transients. The gravitational-wave signature is a chirp, which when sonified produces the familiar "whoooooop" sound. The precise details of the chirp are primarily determined by the masses and spins of the binary companions. Gravitational waves therefore provide a direct probe of the objects involved in the merger. At the same time, while the LIGO-Virgo network is sensitive to sources from nearly anywhere on the sky, it it difficult to reconstruct the precise position of a source. Typical localizations for the first observation run (O1) are expected to be on the order of a hundred square degrees on the sky, with

this number decreasing to about ten square degrees at the end of the decade.

Binary neutron stars are also thought to be the progenitors of several classes of electromagnetic astronomical transients. Perhaps the most well-known of these are short-hard gamma-ray bursts (GRBs), occurring approximately 1s after merger. Accompanying the GRB on slightly longer timescales – hours to days – are X-ray and optical afterglows resulting from the jet interacting with the circumburst medium. At timescales of weeks to years, this leads to longer-wavelength radio afterglows. Such emission is thought to be directional, making it invisible if not beamed towards the Earth, so many GRBs and their afterglows go unobserved. However, binary neutron stars are thought to produce isotropic emission as well. Ejecta from the merger can undergo r-process nucleosynthesis, leading to a faint optical counterpart peaking in intensity roughly a day after merger. This is referred to as a kilonova. The common theme of these electromagnetic counterparts is that the emission is largely a result of the explosion from the merger interacting with the medium surrounding the binary. As such, astronomical observations primarily yield information about the location of the system, e.g., its redshift, position in the sky, and host galaxy. The combination of this information with details about the central engine from gravitational waves promises to give us a more complete picture of the physics of the progenitors.

There are two approaches to the problem of observing electromagnetic and gravitational radiation from the same event. The first is to use the time and known location in the sky of well-localized, astronomical events, such as GRBs, to perform a deeper search, using a lower threshold for detection, of gravitational-wave data that has already been taken. Such externally triggered searches have led to the most astrophysically interesting LIGO-Virgo publications. A prime example of this is GRB070201, a short-hard gamma-ray burst localized to one of the spiral arms of M31. The LIGO detectors were operating at the time of the GRB with a sensitivity that would have allowed a detection at that distance. A compact binary progenitor was ruled out to a confidence of 99%, which bolstered the case for the event instead being a soft gamma repeater.

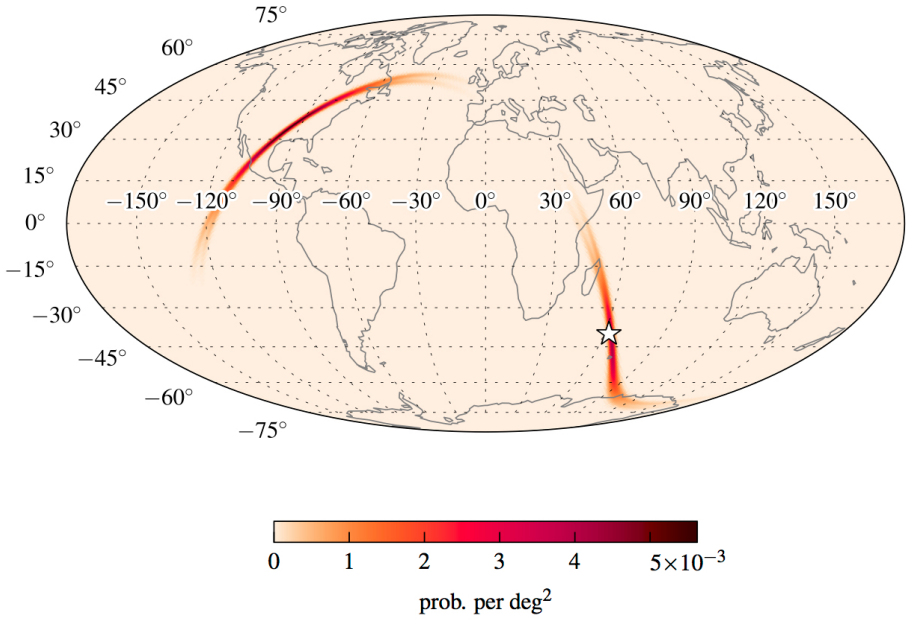
Larry Price

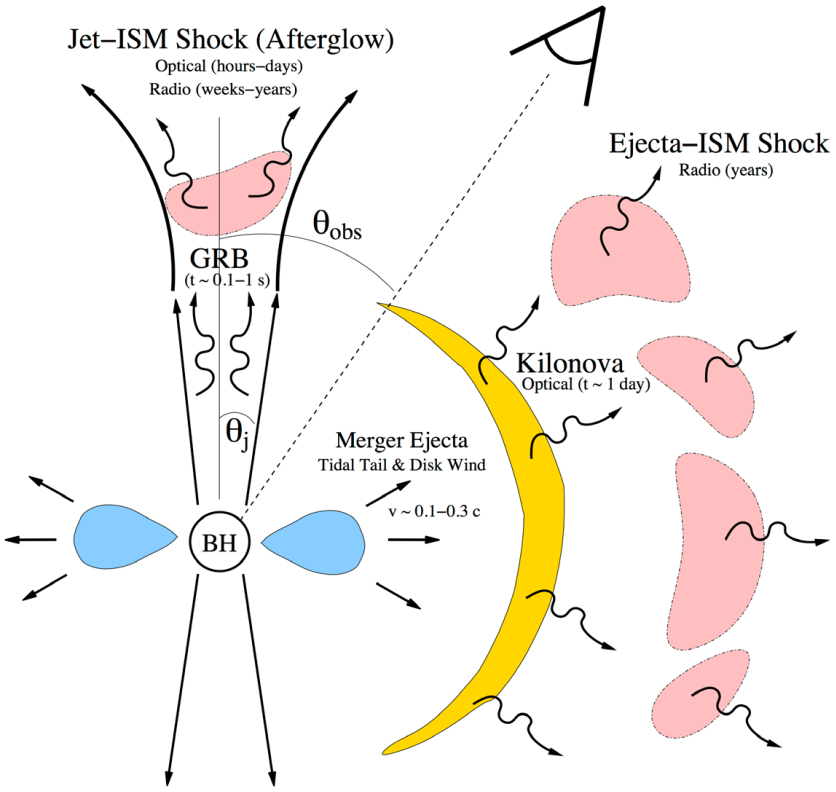
Larry Price is a senior postdoc in the LIGO group at Caltech turned data scientist. When he's not pondering over problems in gravity he's working on a second PhD in Bourbon Studies.

While externally triggered searches will continue to provide interesting results, the wide range of electromagnetic emission and equally wide range of timescales motivates also doing the search the other way around – using gravitational-wave events to trigger electromagnetic observations – what we call EM follow-up.

The final run of the initial LIGO and Virgo detectors (S6/VSR3) saw the first attempt at an EM follow-up campaign. While the limited sensitivity of the detectors made detection, much less EM follow-up, a long shot, the EM follow-up campaign provided an important roadmap for future searches of this type. The initial campaign consisted of 14 astronomy partners spanning radio, optical, and x-ray wavelengths. Each partner was independently provided with a list of coordinates

Localization of a typical binary neutron star coalescence in the (expected) 2015 Hanford-Livingston network. Darker regions indicate a higher probability of finding the source there, and the star indicates the true source location. Even though this particular event is moderately loud, with a network SNR of 15, the 90% confidence region covers 630 square degrees on the sky. A catalog of simulated events in the expected 2015 and 2016 networks can be found online at http://www.ligo.org/scientists/first2years/.





▲ *A pictorial summary of the some of the electromagnetic counterparts expected from binary neutron star mergers (and some neutron star-black hole mergers).*

on the sky that corresponded to the overlap of the gravitational-wave localization with a known galaxy. Such pointing lists were available approximately 30min after the triggers were received, with the largest latency – approximately 20min – coming from a human validation step. Though the process did not result in a detection, important lessons were learned about the challenges involved in a successful EM follow-up campaign.

The primary technical challenge is the mismatch in capabilities of the two types of instruments: the LIGO-Virgo network produces localizations of tens to hundreds of square degrees while a typical telescope covers a much smaller area on the sky. This is a result of the fact that gravitational-wave localization information is mostly obtained from the time of arrival of the signal in each detector. Any two detectors can localize a source to a ring around the line formed by the detectors. For a three-detector network, the source can be localized to the two intersections of the three timing rings which lie on opposite sides of the celestial sphere. The problem becomes more tractable for a four detector network because the six timing rings only intersect at one point, but the first Advanced LIGO observing run will only be a two detector run with localizations of hundreds of square degrees. The use of information obtained from imposing amplitude and phase consistency over the observed signal in multiple detectors improves the sky localization ability somewhat, but the fundamental difficulty remains. This is compounded with the fact that the electromagnetic sky is a busy place. Even for telescopes capable of observing transients in the entirety of gravitational-wave localization regions, covering more area necessarily means observing more transients with no connection to the gravitational-wave event, which in turn increases the difficulty of correctly identifying the counterpart that corresponds to the gravitational-wave trigger.

Other technical challenges are much more easily overcome. By providing alerts in a uniform format to all of our astronomy partners, we're allowing them to tile the error boxes themselves, in whatever way is most efficient for them. In addition, this allows us to perform updates and retractions to alerts. Now instead of requiring human validation before an alert is generated, it can be performed after the alert is sent out and an appropriate update or retraction can be issued. This allows astronomy partners who are interested in observing the earliest counterparts to do so. Additionally, this provides a means for astronomy partners to report on the results of observations.

To date, over 60 groups have signed memoranda of understanding (MoUs) to receive alerts in Advanced LIGO's first observing run, and more are expected. This represents a fairly substantial fraction of the astronomy community who bring with them telescopes of a variety of different capabilities: from large optical telescopes, to radio telescopes, to instruments primarily used for spectrographic follow-up. Historically, much has been learned about GRBs from making use of observations from multiple wavelengths, but EM follow-up presents a much greater challenge. One big question is the extent to which the astronomy community will coordinate observations with such a wide array of instruments. From the perspective of the LIGO-Virgo Collaboration, the best we can do is make tools available to facilitate coordination: in addition to providing the means for issuing and updating alerts, a clearing-house or "bulletin board" for indicating both observations and plans for observing is under development. It remains to be seen how it will be used in practice, but we're hopeful it will help lay the groundwork for fruitful coordination in the era of second-generation gravitational-wave observatories.

The Dedication of the Advanced LIGO Detector

LIGO Hanford

May 19, 2015

Elli King presenting the LIGO Hanford control room.

LIGO marked the completion of the Advanced LIGO program with a commemorative event at the LIGO Hanford Observatory on May 19, 2015. Among the guests were National Science Foundation Director France Córdova, NSF Mathematical and Physical Sciences Assistant Director Fleming Crim and other NSF staff, Caltech President Tom Rosenbaum and Division Chair Tom Soifer, MIT Vice president Kirk Kolenbrander, and MIT Kavli Institute Director Jackie Hewitt. Also in attendance were federal and state government officials and staff, regional and national university leaders, several of LIGO's national and international partners, and representatives from a number of LSC institutions.

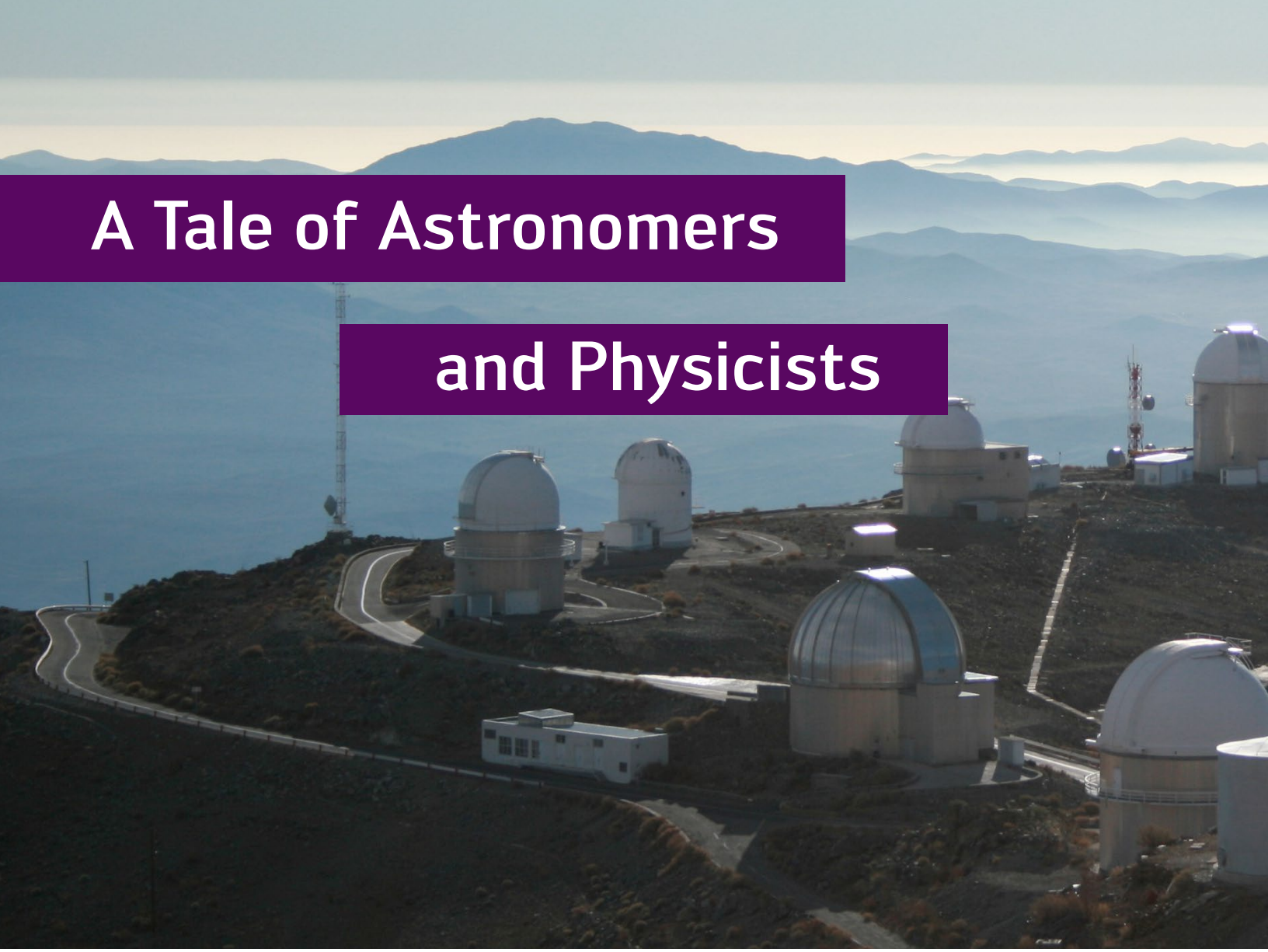
Highlights of the day included an informal opening reception, remarks from several visiting dignitaries, a set of brief talks from Dave Reitze, David Shoemaker, Gaby González and Stan Whitcomb as well as a highly entertaining lunch talk by Rai Weiss that traced the history and development of LIGO and closed with a brief video view of youngsters at work in LIGO Livingston's Science Education Center. Guests participated in tours of the Hanford Observatory after lunch.

This was a really big day for LIGO. For those who were deeply involved in Advanced LIGO construction the event was a chance to celebrate its successful completion, and it was an opportunity for the LIGO Laboratory and the LSC to showcase the remarkable detector and facilities to those who generously support our research. Notably, the day before the dedication the H1 detector logged its best performance to date, operating for more than six hours at an estimated inspiral range of 57 Mpc, a (perhaps not so) fortuitous occurrence.

Dave Reitze

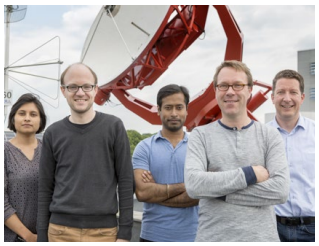
MIT's Rai Weiss presented "A Retrospective on the First 25 Years of LIGO" during lunch at the Advanced LIGO dedication ceremony on May 19, 2015

A Tale of Astronomers and Physicists



Advanced gravitational wave (GW) detectors will soon have a realistic chance of detecting astrophysical sources. As such, many astronomers are becoming interested in GW sources as tools for astrophysics. However, despite very similar educations, astronomers and physicists typically view the world, the Universe and science from different perspectives.

The main reason behind this is that astronomers work with the information they observe from the Universe and often make serendipitous discoveries, whilst physicists design and control their own experiments. A second difference is that physicists, at least in high-energy physics, have reached a point where answers to many big science questions require large-scale dedicated facilities, where only large teams working together can make progress. Although there are of course large observatories in astronomy, these often still operate in such a way that many small or medium-sized teams can use the facility for a fraction of the time to perform their science. Therefore astronomers, in general, are less used to working in very large collaborations. The LIGO-Virgo Collaboration (LVC) is extremely large by astronomical standards, and shares many similar properties to high-energy collaborations. However, in the end, the advanced detectors resemble observatories more strongly than experiments, as the sources are inherently astrophysical in nature and cannot be controlled. Furthermore, there are strong scientific motivations in obtaining simultaneous GW and electromagnetic (EM: gamma-ray, X-ray, optical, infrared, radio) observations such as with our Black-



From left to right: Samaya Nissanke, Steven Bloemen, Shaon Ghosh, Gijs Nelemans, Paul Groot

Some members of the Radboud University astronomy group in the Netherlands joined Virgo in 2012 and our focus is on the detection and characterisation of sources that have both gravitational-wave and electromagnetic signals, in order to answer questions on the formation, evolution and micro-physics of these astrophysical objects.

Overview of the La Silla observatory. The BlackGEM telescopes will be on the GPO dome (second from the left).

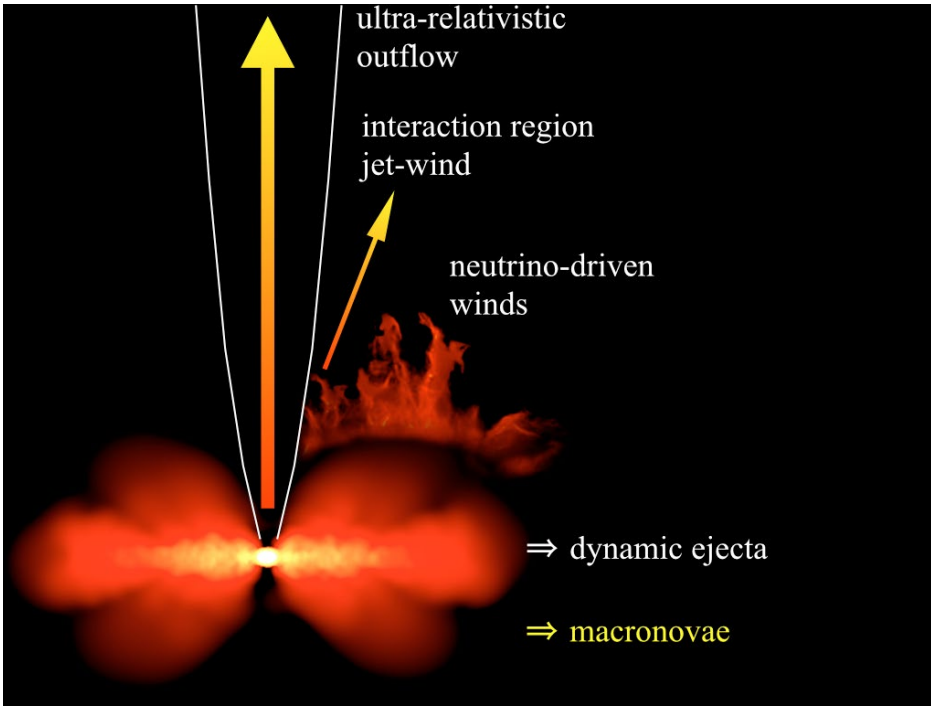
GEM array. Since both communities are interested in the same sources, collaborations between astronomers and physicists thus seem obvious and indeed have been taking place for a long time, but are only now really taking off.

Why are we interested in joint GW-EM astronomy?

Amongst the most promising GW sources are mergers (often called coalescences) of stellar-mass compact objects, either neutron stars or black holes. A significant GW detection of the merger could provide impressively accurate estimates of a combination of the masses of the two stars (the "chirp" mass that sets the time scale of the inspiral), the time of the merger and to a lesser extent the individual masses, the binary orientation and the distance to the source. If the GW source is detected by two or more detectors, a crude position on the sky can also be derived. There is an enormous amount of energy generated by the merger and this, combined with the presence of magnetic fields and (outflowing) matter in the case in which at least one of the stars is a neutron star, should result in EM signatures accompanying the GW merger. These signals can be very diverse (beamed, isotropic, faint, bright, short-lived, long-lasting), and typically have a multi-wavelength character. If such an EM counterpart is detected, the EM data provides additional measurements and will be useful in (further) confirming the GW detection. The EM data may pinpoint the exact location of the source and thus enable studies of the source's local environment. They may also provide the redshift to the source, clues about the composition of the material in or around the source, and potentially help to understand local physical conditions such as gas velocities and densities.

Following up GW sources with EM observatories

The first challenge for EM follow-up work is the poor sky localization of sources observed by GW detectors, yielding vast swaths (for example, 100 square degrees, i.e. 400 full moons) of the sky in which we would need to search for an EM signature. The second is that there is a time



Schematic picture of the different outflows and EM signatures of a double neutron star merger.

window around, or after, the GW detection in which the counterpart is detectable so the observations must be obtained within a wavelength-dependent time window. Third is that even if data are available over the whole region on the sky for which the GW observation is constrained, finding the counterpart remains non-trivial. One reason is the uncertainty over what the counterparts look like – they might be too faint to be detectable even with quite deep and sensitive EM data. The other reason is that there will most likely be many other variable sources in such large areas of the sky that will have to be ruled out as not associated with the GW source. These, often termed 'false-positives', are of course the types of objects and phenomena that astronomers are looking for to answer other science questions. Therefore EM follow-up of GW sources for astronomers is only part of the reason to get involved in this work. These three challenges drive the design of dedicated follow-up facilities, such as BlackGEM.

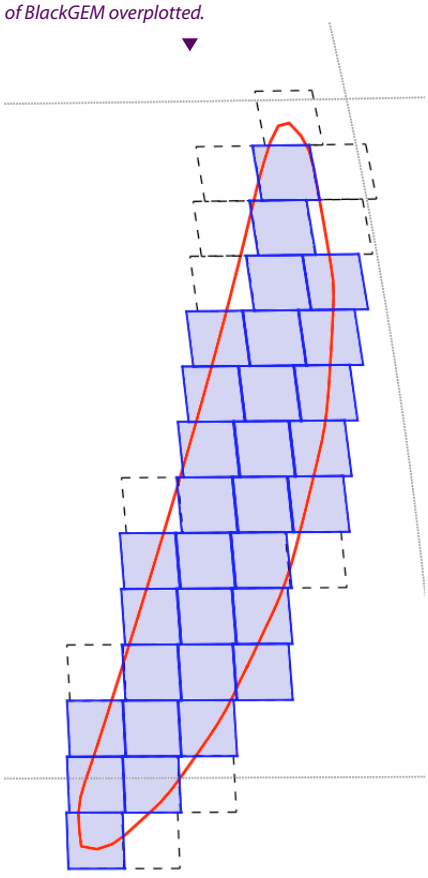
How astronomical facilities work

To understand some of the issues arising in the organization of the EM follow-up, it is worth describing how typical astronomical facilities operate. Observatory facilities (for example the X-ray satellites Chandra and XMM-Newton, large optical telescopes including the Keck and the ESO Very Large Telescopes, and most radio telescopes such as the Very Large Array and LOFAR) are funded by a group of institutions or countries. They have observing rounds of one year or half-year for which proposals are submitted requesting a fraction of the observing time available. A peer review committee ranks the proposals and the top priority proposals are executed. In many cases certain teams (e.g., those that have constructed and contributed instruments to the observatory) are granted some fraction of the observing time that can be used for projects of their choice. Other facilities are dedicated to certain observations, such as the Swift gamma-ray burst satellite and BlackGEM. In many cases the data of dedicated facilities are made publicly available. Most observatory facilities also have the policy of making their data public after a proprietary period of typically one year. This is because it is feasible with a small or medium-sized team to fully analyze a subset of the data and that public data will ensure the most efficient processing and publication of data and results. Only in special cases (such as the Planck satellite) will the data be kept private for an extended period for a consortium to perform the analysis. The argument given is that the data is too complicated to analyze by a medium-sized team immediately. Such a data policy often delays publication of results and is an extreme rarity in EM astronomy.

Data policies

The exceptional nature (and probably to a certain extent the history) of the first direct GW detection naturally implies that the LVC is very careful with the procedures for claiming the first detection(s). In addition, there are probably diverse opinions on whether the GW data can be analyzed by small or medium-sized teams. The GW data

Typical GW error box (red) with the tiling pattern of BlackGEM overplotted.



therefore will initially not be made public. This implicitly also affects how the LVC will coordinate their observations with the astronomers. For what GW candidates should astronomers be involved? Is it the case only for the highly significant ones that are (almost) certainly real detections? Or also for lower confidence triggers? If this is the case, what if the astronomers find an EM source that could be a GW counterpart? For now, the working model proposed has been that astronomers sign a memorandum of understanding with the LVC in which the terms are laid down as to what can and cannot be done with the data provided to them by the LVC. For astronomers, this is a new way in dealing with observational data and indeed in some cases causes conflicts with the general policies of certain observatory facilities. Fortunately, there is now a deep willingness on both sides to make this joint part of GW science a success.

The plan for performing rapid EM followup of GW events

In the current plan the data stream of the advanced detectors will be continuously monitored for possible detections. For candidates with sufficiently high signal-to-noise ratio, the LVC will perform a very rapid analysis of the data that gives a first estimate of the properties of the system, including the sky error box. This information is then transmitted to the EM partners, in a similar way to the process for multi-wavelength follow-up of Gamma-Ray Bursts (GRB). For now it is left to the EM partners to decide on how much coordination there is in the EM follow-up. The LVC will provide a bulletin board for the exchange of information between the teams, because a lot may depend on how well or ill-matched the error box (and position!) is to the EM facilities. Most facilities cannot observe in the direction of the Sun and in practice there are other pointing constraints (the horizon on the Earth, the Earth's shadow from space). For optical/near-infrared telescopes located on the Earth the situation might be somewhat different from the rest because there are relatively many facilities, each with a field of view that is significantly smaller than the typical GW sky error box. Coordination in that case may be stimulated by tools provided by the LVC that quickly show which parts of the sky error box have already been observed and what the next highest priority areas are. However, even for optical telescopes, there are a few facilities, such as ZTF and our own BlackGEM project, that in principle aim at covering the error boxes completely in a homogeneous way within the required time window.

What we will learn from performing joint GW-EM astronomy?

So what will this complicated exercise give us in return? The GW detections alone will give us an unprecedented view into some of the most extreme events in the Universe that probe gravity in new regimes. Simply counting the number of detections determines the rate at which these events happen in the nearby Universe, a number that is currently uncertain by at least two orders of magnitude. The GW properties of the sources largely determine the fractions of the different types of mergers (neutron star-neutron star, neutron star-black hole and black hole-black hole). The chirp mass and individual masses constrain the mass distribution of the neutron stars and black holes in the mergers. A GW detection in association with a short GRB will prove the conjecture regarding their merger progenitors! A set of detections could constrain the properties of supra-nuclear density material that neutron stars are made of, can independently constrain the Hubble Constant and enable strong-field tests of the theory of General Relativity. If corresponding EM detections are made, some of these measurements can be improved and a whole new range of science questions now lie within reach: the EM redshifts can be compared to the GW distances, spectra of counterparts can be compared to merger simulations, and detailed investigations of the merger properties and their environments can test the theories of binary evolution. We are entering a very exciting era!

LIGO 2015

For more details, see

http://www.ligo.org/scientists/GWEMalerts.php

https://astro.ru.nl/blackgem/

http://arxiv.org/abs/1210.6362

BlackGEM Telescope

The challenges of detecting the EM counterpart to a GW detection require rather specific properties of follow-up facilities: large field-of-views, good sensitivity, rapid and long time availability and an efficient way to recognize candidate counterparts. Because there are very few such facilities and none that are presently entirely dedicated to GW follow-up, thus ensuring the rapid and long availability, we at Radboud University are building a dedicated array of optical telescopes, called BlackGEM. The first four telescopes are currently being constructed and should become operational by the end of 2016 at the ESO La Silla observatory in Chile. Each 65 cm telescope has a 2.7 square degree field-of- view and is designed to reach a magnitude of 23 within a 5 minute integration period. The camera of each telescope has six optical filters, which allows rapid characterization and selection of potential counterparts. The aim is to extend the array to 10-15 telescopes to more rapidly and efficiently cover the large sky error boxes. The modularity of the array allows us to extend it later and also gives flexibility to either cover a wide area when all telescopes point at different parts of the sky, or stare deeper in a smaller part of the sky by combining the signals of all the telescopes.

The Einstein@Home Project

M. Alessandra Papa, Benjamin Knispel, Bernd Machenschalk, Holger Pletsch




A senior scientist with her independent research group at AEI Hannover and an Adjunct Professor position at UWM, M. Alessandra has devoted a large part of her scientific life to searching for continuous gravitational wave signals. She hopes that nature will be kind enough to reward her persistence at some point. In her spare time she practices Taiji Chuan, enjoys travelling, DSLR photography and cooking. Also based at AEI Hannover, Benjamin Knispel works as postdoc and press officer, Bernd Machenschalk as a software engineer, and Holger Pletsch leads an independent research group.

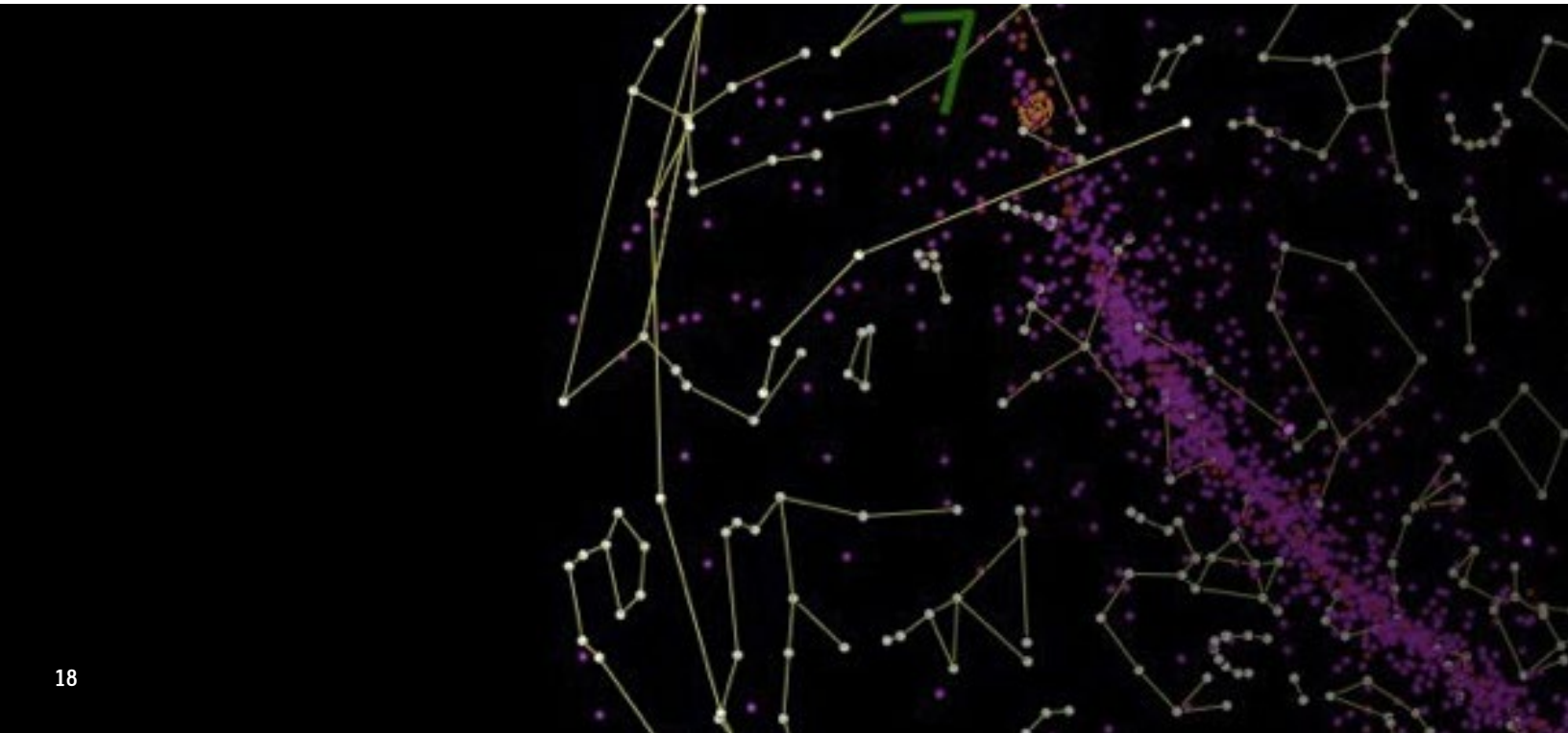
In the context of the APS's activities for the 2005 World Year of Physics, APS Director of Media Relations James Riordon suggested to LIGO management the development of a SETI@Home-type of search for GWs. Bruce Allen thought that the idea was too good an opportunity to let it pass. He accepted leadership of the project and decided that the first search would be for continuous GW signals. For Allen, the main appeal of the SETI@Home paradigm was that it was a working infrastructure having withstood significant stress testing rather than a framework developed in the abstract. David Anderson, the person behind it, was not just a theoretical computer scientist, but someone with real-world experience of very large-scale computing.

Later in 2005, Allen and co-PI's Anderssson and Papa were awarded a grant by the NSF to support the development of the Einstein@Home project. The joint support of NSF and the Max Planck Society made it possible for Einstein@Home to flourish: Since its launch in 2005 it has grown to become one of the four largest computing projects in the world, regardless of whether the metric is number of volunteers, computing power, or scientific output in number of published papers.

The name Einstein@Home was originally suggested by Rejean Dupuis, at the time a LIGO postdoc now working in finance. Since 2008 Einstein@Home has also been searching for radio pulsars and since 2011 for gamma-ray pulsars.

The infrastructure

Although the software that Einstein@Home is based on – Berkeley Open Infrastructure for Network Computing (BOINC) – can manage a small to medium size project, running on a single server computer, a project the size of Einstein@Home requires significantly more effort.



Einstein@Home features about a dozen server machines in two different locations many kilometers apart: UWM in USA, and AEI in Hannover, Germany. At the core there is a large database. Three machines have been specially built and tuned to run this database: an active "master", a "slave" that could easily become the master within minutes, and a spare one for good measure. Each search essentially has its own "download server", from which clients get the data they process.

The whole infrastructure needs to be built, maintained, and constantly fine-tuned to suit the evolving demands of the scientists, while simultaneously adapting to the ever increasing computing power offered by the clients. Almost every new search has its unique requirements, and even a single new feature in the scientific application often requires several changes on the server side. Fixes and improvements to the search codes are incorporated and deployed on-the-fly. Finally, in order to get the maximum computing power from the resources attached to Einstein@Home, constant work is done to leverage improvements in existing and new technologies, like GPUs and mobile devices.

The Einstein@Home searches

Continuous gravitational wave signals

Searches for continuous GW signals are computationally limited and require relatively little data for very long processing times. This makes a volunteer computing project a very good match for the problem.

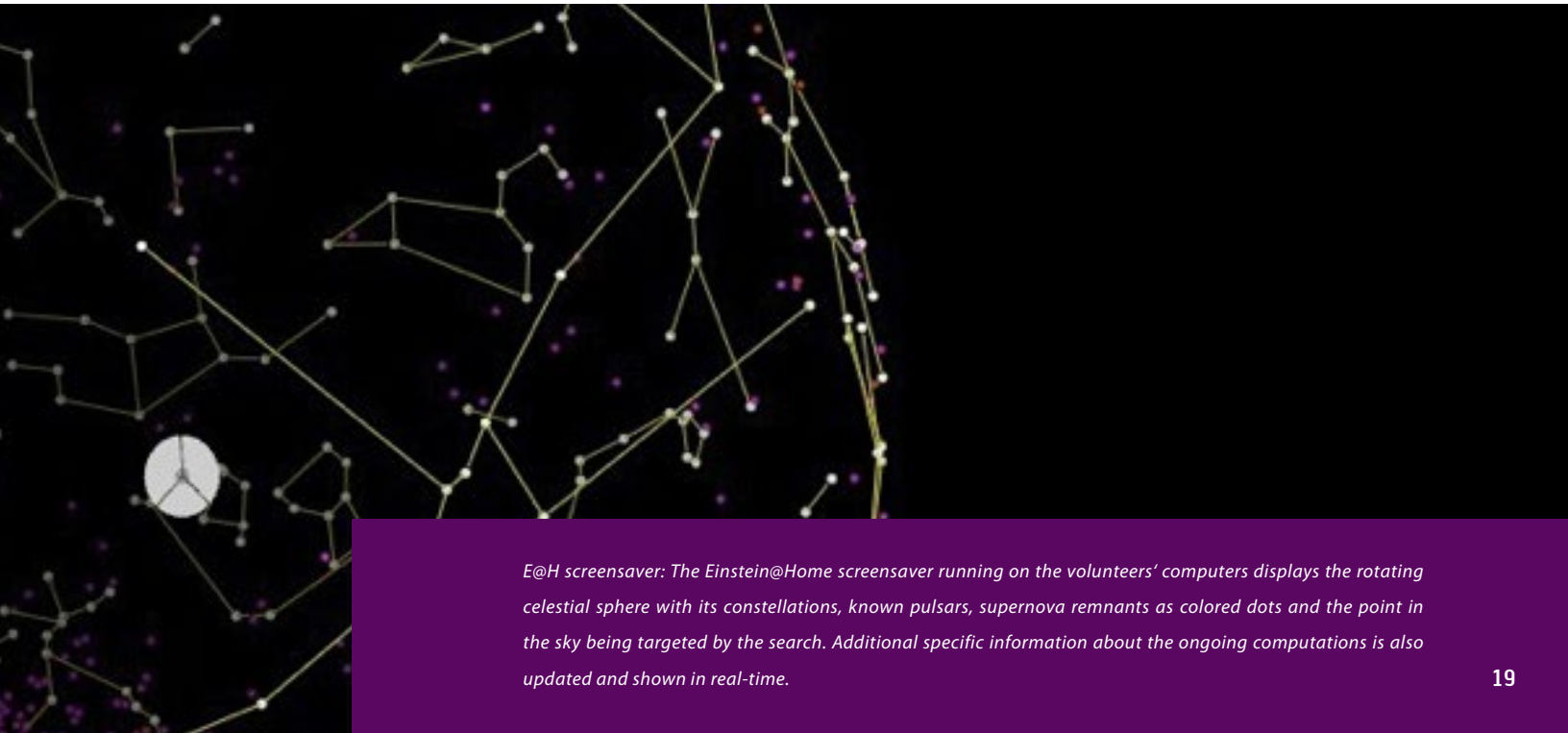
We have always deployed our cutting-edge searches on Einstein@Home. At the time of writing this article, the search "on the air" is the second follow-up stage of candidate-points from an all-sky search. Our efforts are concentrated on a few hundred Hz around the highest sensitivity region of the detector, the so-called "bucket". We have selected the 16 million most promising points from this search and are now performing a hierarchy of follow-up stages. The number of noise-candidates that survive after each stage decreases, as well as the uncertainty in the signal parameter.

Designing, characterizing and profiling the next stage so that the next follow-up is ready to be launched as the current stage completes has put a lot of pressure on the project's data analysis team: Irene Di Palma, Sinéad Walsh, M.Alessandra Papa and Heinz-Bernd Eggenstein meet for several hours every week to discuss results and to assess how these impact the plans for the next stage. A lot of these meetings are via conference calls: Irene is now based in Rome, Sinéad in Milwaukee (USA) and Heinz-Bernd and M.Alessandra are in Hannover. It was a luxury to have everyone under one roof for two weeks at the beginning of May!

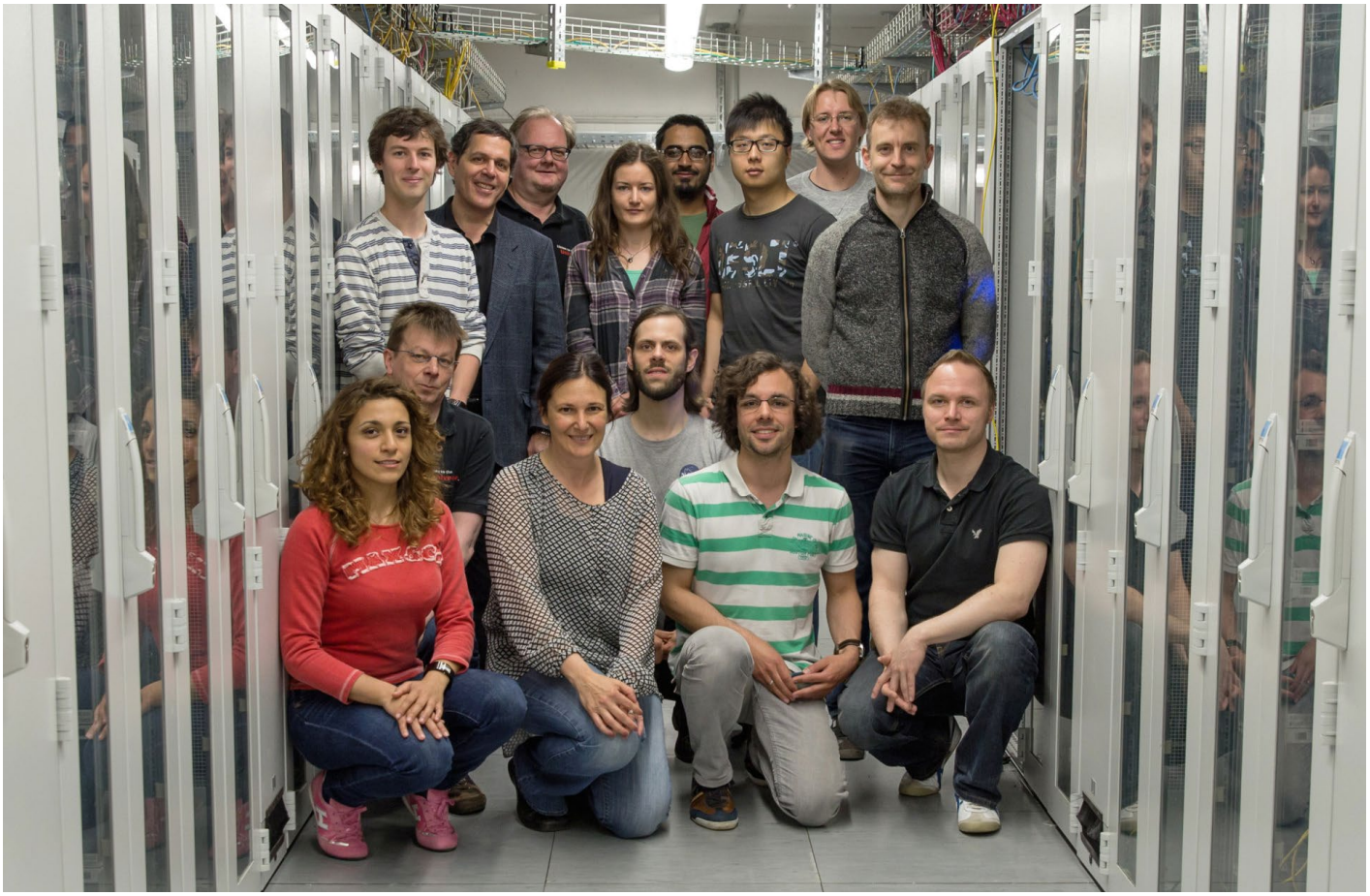
Radio signals

The first (non-GW) extension of Einstein@Home's search efforts for neutron stars was born in early 2008 thanks to a collaboration with James Cordes, an astronomer at Cornell University and at the time chairman of the PALFA consortium. This international project uses data from Arecibo – the largest single-dish radio telescope in the world – to find new pulsars.

In 2008, the PALFA consortium had 4 years of data in hand and expected to collect even more as their dish surveyed our Galaxy with unprecedented sensitivity. Analyzing this huge amount of data would prove to be challenging with the computing power available to the consortium.



E@H screensaver: The Einstein@Home screensaver running on the volunteers' computers displays the rotating celestial sphere with its constellations, known pulsars, supernova remnants as colored dots and the point in the sky being targeted by the search. Additional specific information about the ongoing computations is also updated and shown in real-time.



▲ *Most of the Einstein@Home team in May 2015. From left to right. First row, kneeling: Irene Di Palma, Heinz-Bernd Eggenstein, M.Alessandra Papa, David Keitel, Benjamin Knispel, Oliver Bock. Second row, standing: Colin Clark, Bruce Allen, Bernd Machenschalk, Sinéad Walsh, Avneet Singh, Jing Ming, Karl Wette, Reinhard Prix. Unfortunately Badri Krishnan and Holger Pletsch were travelling when we met to take this photo and so could not be in the picture.*

For pulsars in tight binary orbits – the astrophysically most interesting – the computational challenge was particularly hard: nobody had been able to conduct a proper search. Allen and Cordes soon realized that Einstein@Home's enormous computing power was a perfect match to this problem. Back at the AEI, a small group of postdocs and PhD students, including Knispel, soon turned the idea into reality and within a year were ready to release the new search "into the wild".

In March 2009, the "Arecibo Binary Pulsar Search" was officially launched on Einstein@Home and started to crunch the backlog of data. The search targeted radio pulsars in binaries with orbital periods as short as 11 mins and augments earlier analyses. It borrowed methods from GW data analyses such as a parameter space metric, template banks, and its detection statistics.

At first, known pulsars were re-discovered and provided a useful check for the correct function of the search pipeline. It took a little more than a year until the first new radio pulsar called J2007+2722 was discovered by Einstein@Home in July 2010. This milestone discovery, not only for the project but for volunteer distributed computing in general, was published only a few weeks later in a short paper in Science. J2007+2722 was an unusual pulsar – most likely one ejected from a binary system when its companion star exploded in a supernova. While that paper was being written, Einstein@Home netted a second pulsar, once again of a rare kind. Since then, the project has found a total of 27 radio pulsars in PALFA data from Arecibo Observatory.

Einstein@Home has also analyzed archival data from the CSIRO Parkes radio telescope in eastern Australia. The Parkes multi-beam pulsar survey was conducted in the 1990s and several hundred pulsars were found in its data, which has been re-analyzed several times. Einstein@Home had a go between late 2010 and mid 2011, revealing 24 pulsars that had been missed by previous attempts, six of which were in binary systems.

For the analysis of Parkes data, a search application that runs on the volunteers' graphic cards (GPUs) was used for the first time. This application has improved over time and now runs completely on the GPU, achieving a speed-up factor for the search of about 50.

Since 2013, Einstein@Home's pulsar search also features an Android application that allows volunteers to attach their smartphones

or tablets to the project. While the computing power of each single device is relatively low, their sheer number can compensate for it, and might in fact be the future of distributed volunteer computing.

Currently the radio pulsar search has exhausted the backlog of Arecibo Observatory data and is processing new data as they come in. Also, the archival data set from Parkes is being re-analyzed over an extended parameter space.

Gamma-ray signals

Most neutron stars before 2008 were discovered as radio pulsars, but it was known that some also emitted pulsed high-energy gamma-rays. While the exact mechanism of gamma-ray emission is still unclear, searching for the high-energy emission opens a new discovery window for neutron stars.

In 2008, NASA launched the Fermi Gamma-ray Space Telescope into a low-Earth orbit. One of Fermi's main science instruments is the Large Area Telescope (LAT) which has produced increasingly better source catalogs over the past years. In these, pulsar candidates appear as unidentified point sources with a characteristic energy spectrum.

To identify such sources as pulsars one has to trace the modulation of the gamma-ray photon arrival times by the neutron star's rotation period – the tell-tale sign of the pulsar beam sweeping over the LAT. However, unlike radio pulsars, only very few photons are registered for each source. Typically, the LAT will detect roughly 1000 photons per year and source. In other words, for a 100-Hz pulsar a single photon is registered every 3,000,000 rotations!

This means that the data volume for the search is very small. However, blind searches for periodicities in sparsely-sampled, many-year-long data sets require huge parameter spaces to be scanned at very fine resolution. Since this problem requires spending lots of computing cycles with very little input data, it is perfectly suited for Einstein@Home.

In mid 2011, Einstein@Home started searching for gamma-ray pulsars in Fermi data. This enterprise began with an encounter at a conference. In early December 2010, Holger Pletsch was at the 25th Texas Symposium on Relativistic Astrophysics in Heidelberg. He had completed his PhD at the AEI in Hannover and had developed novel computationally efficient search methods for continuous GWs with Einstein@Home.

In Heidelberg, Pletsch attended a talk on observations of gamma-ray pulsars by Lucas Guillemot, at the time a post-doc at the Max Planck Institute for Radio Astronomy in Bonn. Already the Pletsch & Allen Phys. Rev. Lett. (2009) had pointed out that the proposed GW search method might also be applicable to gamma-ray pulsar searches. But it was during Guillemot's talk that Pletsch decided that he would actively pursue this line of research. Pletsch and Guillemot discussed the idea over dinner on the same evening, did some first "back-of-the-napkin" calculations, and verified the initial hunch.

A close collaboration arose over the subsequent months as they implemented the new search codes and prepared data for a first search run on the Atlas cluster in Hannover. By early 2011, their search had just started running, and immediately began to find pulsars in Fermi data that previous analyses had missed. A few months later, the search effort had discovered ten new gamma-ray pulsars, which at the time was about a third of all such pulsars found through their gamma-emission alone.

This prompt success demonstrated the enormous potential of the new search method.

Since July 2013, the Einstein@Home radio pulsar search is available for Android devices. To attach your smartphone or tablet, download the BOINC App from the Playstore and select Einstein@Home from the list of projects. ▶

It also clearly motivated to move the search onto Einstein@Home, promising yet deeper searches of a larger number of targets. In a coding tour de force, the Einstein@Home developer team spent the summer porting the analysis code to the BOINC environment. By August 2011, the first work units of the Fermi Gamma-ray Pulsar (FGRP) search were sent to the computers of the project's volunteers.

In November 2013, a team of Einstein@Home and Fermi scientists published the discovery of four gamma-ray pulsars, none of which emitted radio waves. Since then, the search method has been enormously refined to further boost its efficiency. Currently, the FRGP search on Einstein@Home is analyzing 6 years worth of Fermi data from 300 "pulsar-like" sources. The latest search also makes use of newly released Fermi data with improved estimates of the Galactic gamma-ray background. Given the previous success, optimism for new discoveries is well warranted.

These gamma-ray pulsars are typically among the most energetic and rather nearby neutron stars. Therefore – closing the loop – these discoveries provide objects that are also promising targets for continuous GWs.

LIGO 2015

An Interview with Joseph Hooton Taylor, Jr.

Professor Joseph Hooton Taylor, Jr. is the James S. McDonnell Distinguished University Professor of Physics, Emeritus, at Princeton University. Together with Russell Hulse he was the winner of the 1993 Nobel Prize in physics for the discovery of the first binary pulsar, PSR B1913+16.

Brian O'Reilly: Discovering a binary pulsar, in that it would allow a determination of the pulsar mass, was important to you in advance of the search that yielded PSR 1913+16. When did you first realize the much greater significance? Was there a Eureka moment?

Joseph Taylor: The first crude solution for orbital parameters told us that relativistic effects should be detectable. Within a few weeks we were convinced that accurate timing measurements might reveal the effects of energy loss through gravitational radiation. The "Eureka moment," if one wants to call it that, was thus spread over several weeks. Perhaps more importantly, it was moderated by a realization that the necessary timing measurements would need to be considerably more accurate than any made up to that time, even though the pulsar was one of the weakest ones known. We were persuaded the goal was worthy, but were not sure it could be achieved.

B: Your search was groundbreaking in its use of computer analysis to discover forty pulsars, and computerized searches have since revolutionized this and other fields. Thinking back on it, do you consider this a seminal moment in the application of computing to science?

J: Yes and no. Our use of a dedicated computer was unusual at the time, and proved highly effective. The algorithms we developed and programmed into our "Modcomp II" mini-computer form the basis of nearly all pulsar searches done since then. But we were hardly unique in exploiting digital computers in these ways. The time was ripe for such developments, and they were taking place in nearly all fields of science.

B: Your study of PSR 1913+16 took place over several decades. From today's perspective it seems unusual that at no point during that time did a competing team beat you to the observations and analyses. Why was that?

J: Other groups made timing observations of the binary pulsar, but it was hard for them to be truly competitive. The huge collecting area of the Arecibo telescope gave us a big advantage over observations made

anywhere else. Moreover, the interesting relativistic effects accumulate in proportion to the square of elapsed time of observations. As discoverers and first observers we had a head start of several years that was very hard to overcome.

B: My previous question was partly out of curiosity and partly because LIGO is tasked with making our data publicly available, in a useable format, on a relatively short timescale after collection. Do you think your analysis would have still been possible in an environment where "Open Data" was the rule?

J: "Open Data" policies make good sense and have served society well when applied to large, expensive group efforts in science. They do not translate well to small, single-investigator efforts. In practice we shared binary-pulsar data with anyone who asked, but the demand was minimal. Others were certainly interested in our results, and sometimes made significant contributions to the higher-level framework within which data were analyzed, but we had very few requests for access to low-level data, details of experimental calibration, etc.

B: We're coming up on the centennial celebration of Einstein's publication of General Relativity. As someone who has made one of the most (if not the most) significant observations what are your thoughts on the impact and significance of the theory?

J: For a hundred years General Relativity has been the best available description of one of the four fundamental forces of Nature. Einstein's theory was and remains a towering intellectual achievement, even though its effects (i.e., departures from the predictions of Newtonian gravity) are so tiny in nearly all familiar situations. However, on a cosmic scale this is not always the case. Most physicists — myself certainly included — would like to understand more about circumstances where strong gravitational fields and/or effects of quantum gravity are present.

B: Do you consider gravitational waves to have already been directly detected by your analysis of PSR 1913+16 or do you think if/when LIGO sees a signal that this will represent the first direct detection? Or do you think it is a moot semantic point?

J: Gravitational waves couple so weakly to matter that any detection will necessarily be "indirect" in many ways. What is "detected," for example, may be a larger-than-statistically-expected number at the output of a lengthy computer calculation, itself based on voltage fluctuations at the output of some complex electronics with a transducer of some kind at its input. The binary pulsar timing experiment detected gravitational waves by measuring the effect of their back-reaction on the orbit of a pair of neutron stars, with radio-frequency electromagnetic waves carrying the resulting information about orbital decay to Earth. Successful measurement of gravitational waves by an Earth-based detector will include one very significant difference: the waves in question will have coupled to something here, at the receiver, rather than there, at the source. The gravitational waves will have been detected after their propagation in that form over some interstellar or even intergalactic distance.

B: LIGO is about to embark on the first observing runs with the upgraded detectors and of course we are expecting to see our first signals in the next couple of years. In some respects LIGO is at a very similar stage to where pulsar searches were 40 to 50 years ago. What are your thoughts on what LIGO might see and its impact?

J: An exciting prospect, indeed! Of course I will be delighted if LIGO's first detected signal is the "chirp" produced by a pair of in-spiraling, coalescing neutron stars – an event nearly identical to the predictable end-point of the PSR 1913+16 system, some three hundred million years from now. But whether or not these are the first signals found, we'll probably also be surprised. Opening a new window on the universe will almost certainly provide some unexpected new sights. One cannot be confident about where such discoveries might lead, but ultimately a deeper, more nearly complete understanding of Nature's most fundamental laws is a reasonable hope and expectation.

B: There are big differences from your pulsar search in terms of the number of personnel involved. What's your perspective on the growth of "big science"?

J: Some science can be done effectively by one person or a very small group; some can't. Arguably it's easier for "small science" to take risks, to go off the beaten track, perhaps to blaze new trails. On the other hand, goals like LIGO's are far beyond the reach of conceivable small-group efforts. Big science, along with its necessary management complexities, becomes a necessity for pursuing such goals. It's analogous to the historical difference between building a house and building a cathedral, or the pyramids. We like to think that human society is capable of both scales of endeavor.

B: Where do you feel the most exciting frontiers are in physics today?

J: In the past half-century cosmology has been transformed from a speculative backwater of astronomy, mostly devoid of experimental data, into an exciting forefront of physics blessed with a wealth of quantitative measurements. We still don't understand the cosmic-scale nature of most of the mass and energy of the universe. To my mind, therein lie some of the most interesting questions in science today.

Obituary for Roland Schilling

Rai Weiss, Maicha Schilling, and Roland Schilling, in Cambridge, Massachusetts in the early 1990's. This photograph was taken at a dinner at the house of David Shoemaker and Virginie Landré, on the occasion of a longer visit by Roland to the MIT Lab.

It was with great sadness that we learned that Roland Schilling had died on 15 May, 2015, after a long and severe illness.

Roland was a founder of our field, and the field of gravitational wave astronomy would not exist in its present form and at the present time without him.

Roland had, for the last four decades, been a dear colleague and friend in the gravitational wave community. His intellect, his critical and yet constructive way of arguing, his great knowledge in physics, electronics and programming were an inspiration to all of us and to the next generation. We are thinking in gratitude of the richness of the science he offered us, and of the many occasions where we enjoyed his company, his wisdom and his humor.

It is tragic that this sad news came just at the time of the dedication of Advanced LIGO, at a gathering that highlighted the success in a worldwide search for better GW detectors. But it was also a timely opportunity for his colleagues to share stories and memories, and to speak of his valuable contributions to our science.

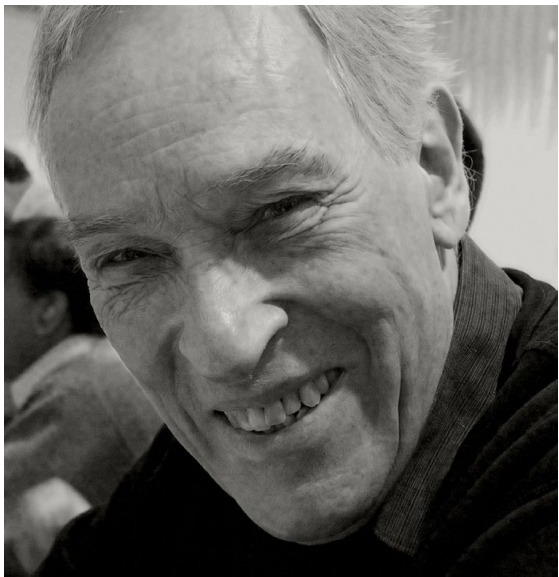
Roland joined the Max Planck Institute for Physics (Astrophysics branch) in 1960, where in the group led by Heinz Billing he was active in the development of new magnetic storage elements for electronic computers, and then of a special-purpose computer for automatic detection and following of tracks in bubble chamber pictures (BRUSH).

In the 1970s, Roland did decisive work in the data taking of Billing's resonant bar detectors, which led to the first significant refutation of Joe Weber's claims of detection of gravitational waves. As a consequence, in the subsequent years the team's focus switched to the interferometric detectors as proposed by Rai Weiss. Roland was an important figure in the design and successful development of the Garching 30 m prototype which in the 1980s had proved the technical feasibility of the interferometric scheme. In this research he invented and developed a multitude of pioneering techniques. His knowledge, especially in optical experimentation and feedback control, was sought also by institutions in the USA (Rai Weiss at MIT) and Japan (Nobuki Kawashima at ISAS), where he stayed for longer visits.

As member of its Study Team he gave important contributions in the concept, design and the documentation of the space project LISA.

The design and optical layout of the German-British detector GEO 600 was greatly furthered by Roland's detailed optical tracing program OptoCad, based on the propagation of Gaussian beams and their alterations (including deformations) by optical components.

His leadership and guidance for younger colleagues is a vital part of his legacy, for which he is gratefully remembered by so many. Some who had the privilege to work as students with him consider him their most important teacher.



We Hear That ...

Those who were fortunate to share discussions, travels, beer garden events and mountain hikes with him will keep these memories forever.

We miss him.

For the first year of my stay in Garching, we all spoke English — I could not speak any German when I arrived, and my colleagues all spoke excellent English. However, at a certain point, Roland pronounced that work would be in German. From then onward, I did my best to participate in German, but always was welcome to fall back on English if needed. However, if I mangled some element of German grammar too terribly, Roland would say 'Falsch!' (with a great and indeed somewhat exaggerated sense of affront at what I had done to his language), all work in the Laboratory would stop, and I would receive a German lesson, complete with questions and practice sentences for the student. Once I had mastered, say, the fact that the genitive case in German is still active and should be used to show possession, we could go back to measuring shot noise with ever greater precision. Roland believed that everything should be done right if it is to be done at all.

David Shoemaker

During my treasured time in Garching, when something did not work I would go to Roland's small office full of papers, books and hardware, and try to explain the problem. It was almost always quickly solved by him asking just the right questions: "what exactly did you do" or "what exactly did you assume". Two phrases I learned from him and that are now in regular use at the AEI: "If you cannot find the source of the noise, increase it!" and "Kaum macht man's richtig, schon geht's!", meaning something like "You do it properly and all of a sudden it works."

Gerhard Heinzel

Recent Graduations

Erika Cowan, previously an undergraduate at Syracuse University working with Duncan Brown, will be starting graduate school at Georgia Tech this Fall.

Jenne Driggers successfully defended her thesis entitled "Noise Cancellation for Gravitational Wave Detectors" at Caltech in May 2015. She has accepted a postdoc at LIGO-Hanford.

Lorena Magana-Zertuche, previously an undergraduate at Georgia Tech working with Deirdre Shoemaker, will be starting graduate school at Syracuse University this Fall.

Jess McIver successfully defended her thesis entitled "The impact of terrestrial noise on the detectability and reconstruction of gravitational wave signals from core-collapse supernovae" at the University of Massachusetts Amherst in May 2015. She will move to Caltech as a postdoc this summer.

Awards

Hsin-Yu Chen, a graduate student at the University of Chicago, is the recipient of a Sugarman Award for excellence in graduate research.

Lynn Cominsky has received the Award for Excellence in Scholarship from Sonoma State University for her dedication to the success of her students.

Martin Hendry received the Royal Society of Edinburgh Senior Public Engagement Prize for his exceptional and sustained track record on science engagement with the general public, schools, societies and science festivals throughout the world.

Stefan Hild received the Royal Society of Edinburgh (RSE) / Makdougall Brisbane Medal, an early career prize, for his outstanding work in the field, and in recognition of his international profile. Dr Hild is also a Member of the RSE Young Academy of Scotland.

Stefan Hild has been appointed to the Global Young Academy. As the voice of young scientists around the world the Global Young Academy provides a rallying point for outstanding young scientists from around the world to come together to address topics of global importance and the role of science in creating a better world. The 200 members are leading young scientists from 58 countries and all continents.

Daniel Hoak, a graduate student at the University of Massachusetts-Amherst, has won a Fulbright U.S. Student Award to spend a year at Virgo. He will be moving to Pisa in October.

James Hough received the 2015 Phillips Award for distinguished service to the Institute of Physics.

Daniel Holz is the recipient of a Quantrell Award.

The LIGO-Livingston outreach team leader **William Katzman** has received the 2014 Distinguished Informal Science Education Award from the Louisiana Science Teachers Association.

Alex Nitz was awarded the Syracuse Physics Department Levinstein Award for outstanding senior graduate student.

Patricia Schmidt, currently a postdoc at Caltech, won the 2015 IOP gravitational physics thesis prize for her thesis entitled "Studying and Modelling the Complete Gravitational-Wave Signal from Precessing Black Hole Binaries".

The 2014 GWIC Thesis Prize was awarded to **Leo Singer** for his thesis "The needle in the 100 deg^2 haystack: The hunt for binary neutron star mergers with LIGO and Palomar Transient Factory."

Sebastian Steinlechner has been awarded a Marie Curie Fellowship at the University of Glasgow to work on "Advanced Quadrature Sensitive Interferometer Readout for Gravitational Wave Detectors".

Syracuse undergrad **Samantha Usman** won an honorable mention in the 2015 Barry Goldwater Scholar's program and is spending summer 2015 with the LIGO-Caltech REU.

The 2014 Stefano Braccini Thesis Prize was awarded to **Yan Wang** for his thesis "On inter-satellite laser ranging, clock synchronization and gravitational wave data analysis".

Career Updates

Riccardo Bassiri has accepted a position as a Physical Science Research Associate at Stanford University. He was previously a postdoc and visiting scholar there.

Justin Garofoli, an operator at LIGO-Hanford during initial LIGO, is now working on Project Loon at Google[x] in Mountain View, California.

Philip Graff, previously a postdoc at the University of Maryland and NASA Goddard Space Flight Center, will be starting a new career outside of academia as a Data Scientist at the Johns Hopkins Applied Physics Laboratory in September 2015.

Syracuse undergrad **Amber Lenon** is spending summer 2015 with the U. Alabama/ NASA REU program.

Antonio Perreca, previously a postdoc at Syracuse University, moved to Caltech in July for another postdoc position.

Michael Pürrer, currently at Cardiff University, has accepted a postdoctoral position at the AEI-Potsdam. He will be moving in September.

Nicolás Smith, after ten years working on the LIGO project (as a SURF student, graduate student at MIT, and now post-doc at Caltech), has accepted a position as an Imaging Scientist at SkyBox Imaging, part of Google.

Larry Price, previously a senior postdoc in the LIGO group at Caltech, is now working as a data scientist at OpenX.

LSC Elections

Gabriela González and **Marco Cavaglià** were re-elected and re-appointed LSC and Assistant Spokesperson, respectively, in March 2015 for a two year term.

Chad Hanna was re-elected as co-chair of the CBC group in March 2015 for a two year term.

Jonah Kanner was elected co chair of the Burst Group in February 2015, replacing Patrick Sutton, for a two year term.

Joey Shapiro Key was appointed chair of the Education and Public Outreach Group in August 2015, continuing the work of Marco Cavaglià and Szabolcs Marka, for a two year term.

Keith Riles was re-appointed co-chair of the Continuous Waves Group in March 2015 for a two year term.

Keith Riles and **Norna Robertson** were elected and re-elected, respectively, as at-large members of the Collaboration's Executive Committee in February 2015 for a two year term.

Peter Shawhan (vice-chair), **Duncan Brown** ("members-at-large"), **Michele Vallisneri** ("members-at-large") and **Jess McIver** (student representative) were elected to the Topical Group on Gravitation Executive Committee earlier this year.

David Shoemaker was appointed co-chair of the Detector Characterization Group in April 2015 until August 2017.

Eric Thrane was re-elected co-chair of the Stochastic Group in March 2015 for a two year term.

General

The International Centre for Theoretical Sciences, Bangalore was awarded a Max Planck Partner Group in Astrophysical Relativity with Parameswaran Ajith as the head. Bruce Allen's division of the Max Planck Institute in Gravitational Physics (Albert Einstein Institute), Hannover is the German partner.

The University of Texas at Brownsville (UTB) becomes University of Texas Rio Grande Valley (UTRGV) in September 2015.

Obituary for Cristina Torres

The editorial staff of the LIGO magazine remembers Cristina Valeria Torres, who passed away March 9, 2015.

Dr. Torres, a 37 year old native of Harlingen, Texas, was a Research Assistant Professor of Physics at the Center for Gravitational Wave Astronomy, in The University of Texas at Brownsville, since 2012.

She received her BA in Physics from UTB in 1999, her MS in Physics from UTEP in 2001 and her PhD in Physics from UT Dallas in 2007. Since 2007 until her appointment at the CGWA she was a senior postdoctoral researcher at the California Institute of Technology in the LIGO Laboratory.

Cristina is remembered as someone who dedicated her enthusiasm and passion to work with physics students and reach out to the general public with her love for science. At the time of her passing she was the Society of Physics Students local chapter advisor. She was a member of the LIGO Scientific Collaboration and a very dedicated mentor and advisor to many physics majors at UTB. She was also the chair of the organizing committee for the Conference for Undergraduate Women in Physics held early this year in Brownsville and the incredible engine motorizing multiple physics and LIGO outreach activities in the region and beyond. Just a week before her death she was staffing the LIGO booth at the APS March meeting in San Antonio. She is fondly remembered as an enthusiastic and energetic colleague by all those who worked with her as a researcher or had the chance to interact with her in many outreach activities.

Cristina Torres with UTB physics majors after observing the partial solar eclipse of October 23, 2014

LISA Pathfinder

The Quietest Place in the Solar System

Martin Hewitson

Martin Hewitson is a staff scientist primarily working on LISA Pathfinder at Leibniz University Hannover. In his ever diminishing spare time, he also endeavours to raise two healthy children, play piano, and maintain a few software applications.

In early 2014, the European Space Agency (ESA) selected two science themes which will form cornerstones of its Cosmic Vision Program. One of these science themes, The Gravitational Universe, envisions the observation of gravitational waves from space, opening a new window on the gravitational wave spectrum, providing access to a rich spectrum of sources, and heralding a new era of observational astronomy. The details of such an observatory have been studied for many years, and over time a mature concept for the mission has emerged. Using laser interferometry to precisely measure the distance between pairs of free-falling test masses, the LISA concept is designed to detect fluctuations in space-time at the level of 1 part in 10^{21} on timescales around 1 hour. At these frequencies, we expect to be able to observe signals from super-massive black hole binaries, extreme mass-ratio inspiral systems, and nearby ultra-compact binaries, amongst others.

With the launch of LISA Pathfinder (LPF) later this year, ESA will take a major step along the road to a LISA-like observatory. LPF will test many of the concepts and technologies needed to build such a gravitational wave observatory in space, paving the way to a detailed design of a LISA-like observatory. The LPF satellite comprises two payload packages: the LISA Technology Package (LTP) provided by the European member states, and the NASA-provided ST7 DRS (Disturbance Reduction System). The European payload is a full system made up of two gravitational reference sensors (which house the free-falling test masses), an optical metrology system, a discharge system, a diagnostic package, and a Drag-free and Attitude Control System. The satellite also hosts two different micro-propulsion systems: a set of cold-gas thrusters provided by ESA to be used with the LTP, and a set of colloidal thrusters provided by NASA.

High precision, high stability sensing

There are three primary sensors on board LISA Pathfinder that provide sensing of 15 of the 18 degrees-of-freedom of the three dynamic bodies: star trackers measure the satellite attitude with respect to the celestial frame; Gravitational Reference Sensors use capacitive sensing to read the position and attitude of the test mass in all degrees-of-freedom; and an optical metrology system (OMS) based on heterodyne interferometry. The OMS uses an ultra-stable silicate-bonded optical bench, providing high precision longitudinal readout of the drag-free test mass with respect to the satellite, and a differential position measurement between the test masses. The OMS also employs differential wavefront sensing to read the attitude of each test mass around the two axes perpendicular to the sensitive (beam) axis.

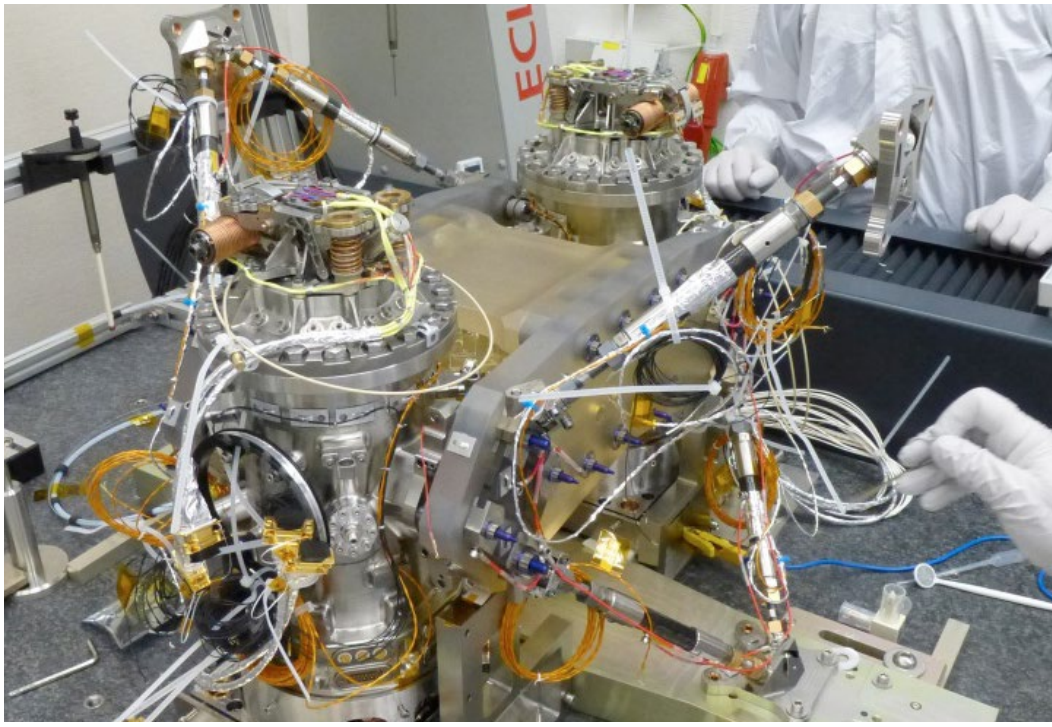
Application of high stability, low-level forces

Two primary actuation systems are in place on LPF. Micro-Newton thrusters are used to apply forces on the satellite with a stability around 0.1 uN/sqrt(Hz) in the measurement band (from 1 to 30 mHz). The second actuation system on LPF acts directly on the test masses and uses electrostatics to apply highly stable forces to the test masses, allowing control of all 6 degrees-of-freedom. Typically forces on the level of nanoNewtons are expected at DC, but in the measurement band, along the sensitive axis, forces at the level of a few femtoNewtons are applied.

The primary science measurement: residual acceleration

There are two main science goals of the LISA Pathfinder mission: to demonstrate a level of test mass free-fall within a factor 10 of what is needed to routinely observe gravitational waves from space; to develop a detailed physical noise model of the system, allowing the performance of any future LISA-like mission to be predicted. Both of these goals require us to

derive the primary science measurement, the residual differential acceleration of the two test masses, from the optical metrology system observations. In the nominal science mode of operation, the system is configured such that the position of the spacecraft relative to the drag-free test mass is sensed interferometrically and is controlled via the micro-Newton thrusters, thus forcing the spacecraft to follow the drag-free test mass. The second test mass is slowly (below the measurement band) forced to follow the first test mass by sensing the differential position interferometrically and applying forces using the electrostatic actuation. From these observations, and accounting for the applied forces, the residual differential acceleration of the two test masses can be estimated. This is very much akin to the calibration routines used in ground-based gravitational wave detectors where the external strain signal is derived from the measured differential arm length fluctuations, accounting for the control forces needed to keep the interferometers at their operating points.



The LTP Core Assembly during integration (© Airbus DS)

Science Operations

After LPF launches, there is a cruise phase of about 2 months as the satellite travels towards its operational orbit around the first Sun-Earth Lagrange Point, L1. Following this, a short industrial commissioning phase will be carried out where all the units needed for the science operations phase will be activated and undergo functional checks. It is at this point that the science operations start.

During the science operations phase, sequences of experiments will be carried out with the aim of establishing a detailed physical model of the system, while at the same time bringing the system to the optimal operating point where the purest level of free-fall can be achieved. To do this, teams of scientists will take shifts at the European Space Operations Centre in Darmstadt where they will analyse the data as it comes down from the satellite and plan and implement the experiments that follow. Due to the short mission lifetime, all experiments are designed and tested in advance and arranged into short, medium and long-term plans. In addition to these front-line analysis teams, other members of the LISA Pathfinder science community will co-locate at remote data centres (such as the one established at the APC in Paris) where they can combine their skills and experience to perform deeper analysis of the data.

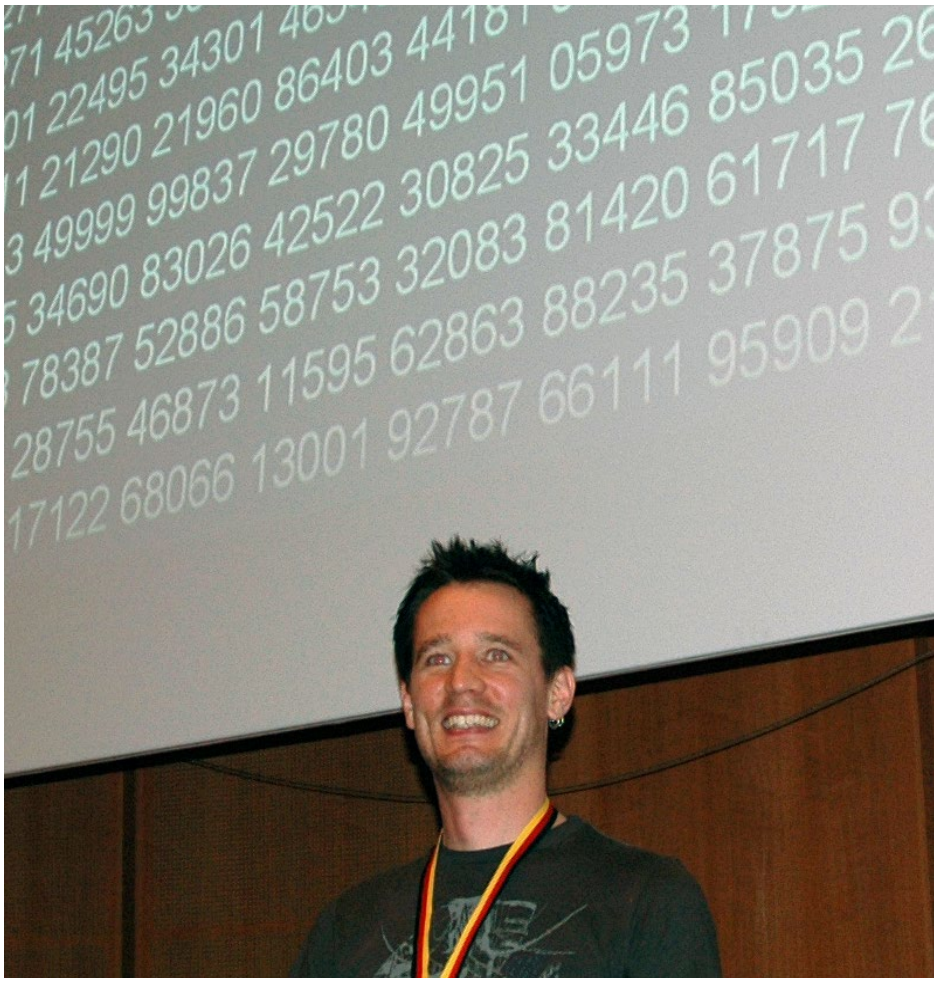
The analysis of the experiments under such time-pressure requires a number of elements to be in place. A robust data analysis toolbox is needed so that confident decisions can be made based on any achieved results. An easy data access system is needed to allow the scientists fast and concurrent access to the raw data as it comes off the satellite, as well as to provide a centralised storage system where analysis results can be exchanged and archived. For each investigation, simulations need to be run to validate the command sequences and the expected system behaviour, and analysis procedures need to be developed to allow the scientists on-duty to step through the analysis and deliver the results in a timely manner.

Approaching Launch

With an expected launch date in mid-November, the activities surrounding the science operations are ramping up with the final definition of the experiments, analysis procedures and pipelines, and the final training of the team. With a successful launch and demonstration of the capabilities of the LISA Pathfinder technologies and concepts, there will be a secure route to LISA, a large-scale, space-based gravitational wave observatory which will deliver the rich science resulting from observations of millihertz gravitational waves.

When I am not Doing Science ...

... I am Memorizing Your Credit Card Numbers!



Jan Harms is a Marie-Curie Fellow working on low-frequency GW detector noise at the University of Urbino. He also drinks his self-made wine and is a big fan of works by Dostoyevsky.

As a young student, I witnessed a discussion that as a scientist you should have seminal papers out before 35, or your ambition will start to be in conflict with the biological degradation of your brain. These worries seemed consistent with another claim that small children learn much faster than grown-ups. Consequently, when I received my Masters degree just after my 26th birthday, I started to feel old myself and worried about my mental future, and so I thought that I need to do something to protect myself. Reading online about these issues, I found that there is a community of mental outlaws, geniuses defying these biological rules. In half an hour, they remember the sequence of almost 4000 binary digits, the order of 52 Poker cards in less than 30s, or associate names and faces of more than 100 people in 15min. The best of them were neither savants nor young. I read that their mental powers rely on a mental trick. The claim is the following; you just need to train a mental feed-through relating complex, often abstract, external information with pictorial, emotional constructs easily digestible by your brain. Practice makes it possible then to quickly translate one type of information into another, and you are ready to do all these feats yourself. To some level, this is how a child's brain works (it is said), and this is how the smart people in former times remembered long stories and speeches.

So during summer 2002, I decided to try this out myself with numbers first. I created images for 100 two-digit numbers from 00 to 99. If I need to remember the sequence 938095, then to me it just means a ball bouncing off a barrel nailed to a tree. Motivated by quick progress, I printed out 1,000 digits of pi, and started to learn them, too. The first 1,000 took quite a while, one week, which was however much less than I expected for a beginner. Going anywhere close to the world-record, which was 42,195 at that time, seemed beyond my patience and ability though, and therefore I switched to training for the more diverting disciplines of the memory championships. The Northern German Championship happened to be in Hannover in 2003, and so I participated, won, got a medal and two nights in a Hilton hotel.

Beginning of 2004, I started to miss pi. This is a side-effect of turning otherwise boring "information" into something nice and beautiful. The first 1,000 digits of pi were all stored in some landscape that I walked more times than any other landscape in the real world. It starts to be your home, the scene involving people and animals can be upsetting, elating, can make

you feel angry, fearful, or happy, and you know this scene in every detail. Emotional binding to the storyline is highly recommended to make it memorable. So I revisited my pi scene and decided to make it larger. The next reasonable step would be to learn another 9,000 digits and try to win the "Everest of Memory Tests". Here, 50 times people call out 5 consecutive digits of pi from anywhere in the first 10,000 digits, and you need to tell the 5 digits before and 5 digits after as quickly as possible. This turned out to be a true challenge, since for the first time I noticed the limitations of my brain. I had to remember so many details of a huge landscape that I started to forget some of them easily. After a while I understood that I had to increase the emotional density of my landscape, and need to add actions of lower instinct such as murder, affection, sex and torture to make this memorable in every detail. Someone calling out 5 digits must activate a unique sequence of first 2, and in a following mental step extended to 3 images (remember that I use one image for 2 digits), so that I enter my pi scene at the correct point. Beyond this, I just had to keep my focus and concentration to make no mistakes when remembering the digits before and after. I tried this at the German Memory Championship in 2007, improved the world-record time by almost a factor 2, won a medal and exhilarating applause.

Here are some conclusions that I drew after years of experience with memorizing. First, everything the brain can do is processing memorized information. There is nothing like "understanding" that could substitute memory. Calculations of addition, multiplication, logarithms and trigonometric functions, which can all be done mentally, are all based on memory. It just does not seem so in many situations, since information is accessed so efficiently by the brain in well-trained tasks that the recall step seems like understanding instead of digging the book inside your brain. Cleverness is an emergent phenomenon, and I am still wondering in some cases how it is created given my premise that it all starts with memorizing. Second, the fact that children learn faster is true on average, but mostly because grown-ups forget how to learn. Any grown-up who intuitively or through practice knows how to learn far outreaches the learning skills of any child up to about 18 years concerning any learning task that I can think of (memory games, languages, text, names,…). Learning is really about good skills. There are certainly age-related factors that start to matter at some point, but you can win World Memory Championships up to an age of 45, and my claim is that much older winners do not exist just because they are getting tired of a life-long competition to be the best memorizer. Well, I already got tired of it, and lost my motivation of learning 1,000,000 digits of pi or the lat/lon of the 10,000 largest cities in the world. I occasionally miss pi and visit my numerical home, still getting angry about the same people there who have not changed at all.

LIGO 2015

The LIGO Magazine

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How does it Work? Parameter Estimation

Detecting gravitational waves is one of the great challenges in experimental physics. A detection would be hugely exciting, but it is not the end of the story. Having observed a signal, we need to work out where it came from. This is a job for parameter estimation!

How we analyse the data depends upon the type of signal and what information we want to extract. I'll use the example of a compact binary coalescence, that is the inspiral (and merger) of two compact objects – neutron stars or black holes (not marshmallows). Parameters that we are interested in measuring are things like the mass and spin of the binary's components, its orientation, and its position. For a particular set of parameters, we can calculate what the wave should look like. (This is actually rather tricky; including all the relevant physics, like precession of the binary, can make for some complicated and expensive-to-calculate waves). If we take away the wave from what we measured with the interferometer, we should be left with just noise. We understand how our detectors work, so we can model how the noise should behave; this allows to work out how likely it would be to get the precise noise we need to make everything match up.

To work out the probability that the system has a given parameter, we take the likelihood for our left-over noise and fold in what we already knew about the values of the parameters – for example, that any location on the sky is equally possible, that neutron-star masses are around 1.4 solar masses, or that the total mass must be larger than that of a marshmallow. We now want to map out this probability distribution, to find the peaks of the distribution corresponding to the most probable parameter values and also chart how broad these peaks are (to indicate our uncertainty). Since we can have many parameters, the space is too big to cover with a grid. Instead, we use computer codes that randomly sample the space and go on to construct a map of its valleys, ridges and peaks. (Doing this efficiently requires cunning tricks for picking how to jump between spots: exploring the landscape can take some time, we may need to calculate millions of different waves). Having computed the probability distribution for our parameters, we can now tell an astronomer how much of the sky they need to observe to have a 90% chance of looking at the source, give the best estimate for the mass (plus uncertainty), or even figure something out about what neutron stars are made of (probably not marshmallow). This is the beginning of gravitational-wave astronomy!

Christopher Berry