

# LIGO MAGAZINE

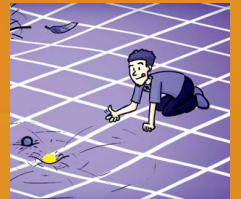
issue 9 8/2016

## LIGO does it again!

03:38:53 UTC, 26 December 2015

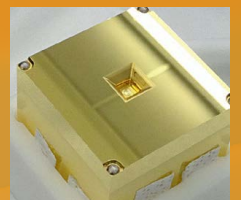
Science Communication:  
Excitement or Accuracy?

The Making of Physics Fans p.14



A Green Light for LISA

The First LISA Pathfinder Results p.26



... and interviews with Stan Whitcomb, and Peter Michelson

**S**napshot of a numerical relativity simulation of a binary black hole coalescence mimicking the properties of GW151226. The image shows the remnant black hole shortly after the merger and the characteristic gravitational wave signal as detected on the 26th of December 2015.

Numerical-relativistic Simulation: S.Ossokine, A.Buonanno (Max Planck Institute for Gravitational Physics) and the Simulating extreme Spacetime project;

Scientific visualization: T. Dietrich, R. Haas (Max Planck Institute for Gravitational Physics)

Inset of Cartoon: Screenshot from video by Jorge Cham, "Piled Higher and Deeper" [www.phdcomics.com](http://www.phdcomics.com)

Inset of LPF Test Mass: Courtesy of RUAG Space, Switzerland

### Image credits

Photos and graphics appear courtesy of Caltech/MIT LIGO Laboratory and LIGO Scientific Collaboration unless otherwise noted.

**p. 3** Comic strip by Nutsinee Kijbunchoo, <http://antimatterwebcomics.com>

**pp. 6-7 Numerical simulation:** Numerical-relativistic Simulation: S.Ossokine, A.Buonanno (Max Planck Institute for Gravitational Physics) and the Simulating extreme Spacetime project; Scientific visualization: T. Dietrich, R. Haas (Max Planck Institute for Gravitational Physics)

**p. 10** Photo courtesy of Stan Whitcomb

**p. 13 Top:** Photo by Kai Staats. **Bottom:** Photo by Phil McCarten, © 2016 American Astronomical Society

**pp. 14-16** Screenshots from video by Jorge Cham, "Piled Higher and Deeper" [www.phdcomics.com](http://www.phdcomics.com)

**p. 17** Photos courtesy of Chris Messenger and the Glasgow Outreach Team

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**p. 36** Image by Nutsinee Kijbunchoo



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## Antimatter



Nutsinee Kijbunchoo

# Welcome to the LIGO Magazine Issue #9!



A handwritten signature in blue ink that reads "Andreas Freise". The signature is written in a cursive, flowing style.

Welcome to the ninth issue of the LIGO Magazine. After providing an impressive 70 pages of special content in the previous issue regarding the detection, we have now settled back to the regular length of the magazine, but the content still follows along the same lines. We have since announced and celebrated both the second detection of a gravitational wave and the total score for black hole binaries in Advanced LIGO's first scientific observation run. Simon Stevenson looks at the astrophysical implications of this in 'Astrophysics with gravitational wave observations'. The Magazine is just one of the many activities in the collaboration dedicated to making our work more transparent and accessible. In 'The Making of Physics Fans', Joey Key and Martin Hendry describe the outreach and public engagement work around the detection announcements, and this issue also highlights a few examples of the many ongoing activities, such as the collage of tweets about the detection, in 'The Glasgow Mosaic' by Chris Messenger and with 'Gravitational waves in the Science Museum' by Anna Green. The main aim of the magazine, however, is not outreach as such but to provide information to the members of our collaboration. We often like to do this in the form of interviews and are pleased to feature two interviews in this issue, one with Stan Whitcomb and another with Peter Michelson.

On a more personal note, this is the last issue of the Magazine with myself as editor-in-chief. After almost five years and now nine issues I will hand over this role to Jocelyn Read in December. It has been a privilege and a lot of fun to be part of the team that created, designed and defined the LIGO Magazine; have a look at the masthead on the last page of each issue to see the full list of editors. For the Magazine to be interesting and relevant we will continue to rely on your input and your help. Please send comments and suggestions for future issues to [magazine@ligo.org](mailto:magazine@ligo.org).

*Andreas Freise for the Editors*

# LIGO Scientific Collaboration News

In the last issue of the magazine, the first after the discovery of GW150914, we said in these pages “September 14, 2015 marks the end of a long journey and the beginning of a new adventure”. Indeed we’ve started to travel our way into the era of gravitational wave astronomy, where the exciting road is created with each new step, including the very significant GW151226 event, our second definite detection of gravitational waves. As a collaboration, we have had many exciting months celebrating the discoveries. LIGO’s momentous detection of gravitational waves was recognized with a special Breakthrough prize and the Gruber cosmology prize, shared with Ron Drever, Kip Thorne and Rai Weiss. We gave talks in conferences, told our colleagues and the public, and more importantly, told our families who hopefully understand better now our passion – please remember to give back time to your dear ones if you have not already, after times of stress and overtime for many of us.

The new road has many uncertainties, and that is part of the excitement: Although we have written several articles already with results from the first Observing Run O1, we are still analyzing the data taken in September 2015-January 2016 – “upper limits” are now seen as preparing the road for future detections. We are preparing to take data again later this fall in O2, with people working hard in the instruments and in the control rooms of all observatories, and analyses now better prepared (and anxious!) for more detections.

Being in a new era, and with the collaboration having grown to more than 1,000

members (we crossed that threshold in 2015), we are also beginning to review our scientific goals and the best LSC structure to support those goals – keep in touch with your Council representatives about conversations on these topics.

The LSC thanks all members for their work, especially those who volunteer time for helping to run the many working groups and committees in the collaboration. Apart from the elected leaders and representatives listed in later pages in this magazine, we thank both incoming and leaving chairs of the following important committees: Alessandra Corsi and Stefan Hild in Presentations and Publications, taking over from Sergey Klimenko and Badri Krishnan; Duncan Macleod in Remote Participation, taking over from David Shoemaker; B. Sathyaprakash as co-chair of the LSC Speakers Board (with Fred Raab). We also thank Barry Barish for accepting to chair an appointed “LSC Observational-era Revisions Committee”, as well as the members of that committee. We have a very special acknowledgement to Andreas Freise, who will be retiring as LIGO magazine editor-in-chief, with Jocelyn Read taking over soon. Andreas gracefully took what was just an idea, and converted it into essential reading for LSC members and a professionally produced publication, highly sought by the general public, colleagues and administrators in our institutions. Everybody wants to read the LIGO magazine! Please join me in thanking Andreas for the large amount of time and effort he spent in a job exceptionally well done. Thanks Andreas!

*Gabriela González and Marco Cavaglià*



Gaby (Gabriela) González  
LSC spokesperson

A handwritten signature in blue ink that reads "G. González".

## Astrophysics with Gravitational Wave Observations

*Simon Stevenson*



*is a final year PhD student at the University of Birmingham in the UK. He is trying to work out what we may be able to learn about the lives of massive stars in binaries from gravitational-wave observations. He is looking for a job if you are hiring.*

**G**W151226 is the second direct observation of gravitational waves ever, and the second ever observation of a binary black hole merger. GW151226 was detected at 03:38:53 UTC on Boxing day (26th December 2015) in Europe, meaning it was early evening on Christmas day in the USA where the detectors are.

Avid readers of the LIGO magazine may have noticed an Easter Egg in the GW150914 comic in the previous issue! It was an unexpected holiday present for everyone in the LIGO and Virgo Scientific

Collaborations, whether they were celebrating Christmas or not. Many people ended up working hard over the Christmas holidays, operating the detectors and analysing the data. In fact, things have been non-stop for many of us for all of the last 6 months since the last issue of the LIGO magazine.

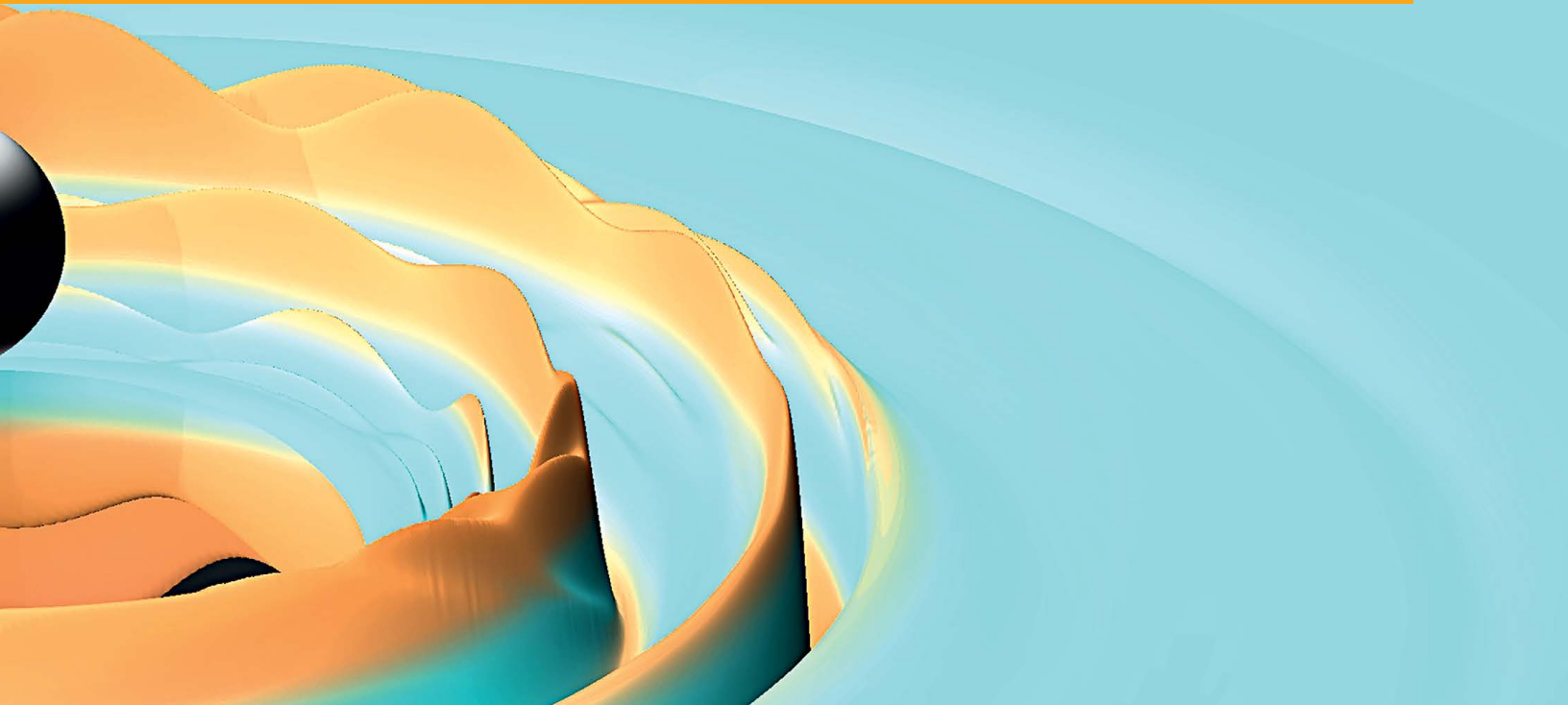
### **The younger sibling**

In many ways GW151226 is very similar to the first detection, GW150914 (its more famous elder sibling). Many of the meetings, revelations, decisions, discussions and arguments that accompanied writing the paper for GW151226 were remarkably similar to those we had writing the first paper for GW150914.

Both of the gravitational-wave events LIGO has observed so far have been caused by two black holes colliding to form a bigger black hole. Both mergers happened over a billion light years away!

There are also some important differences between the first detection and the second. The black holes in GW151226 are much lighter than those in GW150914, having masses around 14 and 8 times the mass of the sun, compared with 36 and 29 times the mass of the sun in the first detection. Is this important? Does this tell us something about how these black holes formed? We do not know the answers to these questions at the moment, but time will tell. Certainly it tells us that binary black holes form and merge with a large range of masses.

GW151226 was also a longer and quieter signal than the loud and short GW150914. It lasted for ~60 gravitational-wave cycles (corresponding to the final ~30 orbits of the two black holes around one another), over a period of a second, compared to the 8 cycles and 0.1 seconds of GW150914. There was one more possible detection of gravitational-waves from a binary black hole merger during the first



▲  
*Numerical-relativity simulation of the gravitational waves emitted by GW151226, the black hole binary detected on 26 December 2015 by Advanced LIGO.*

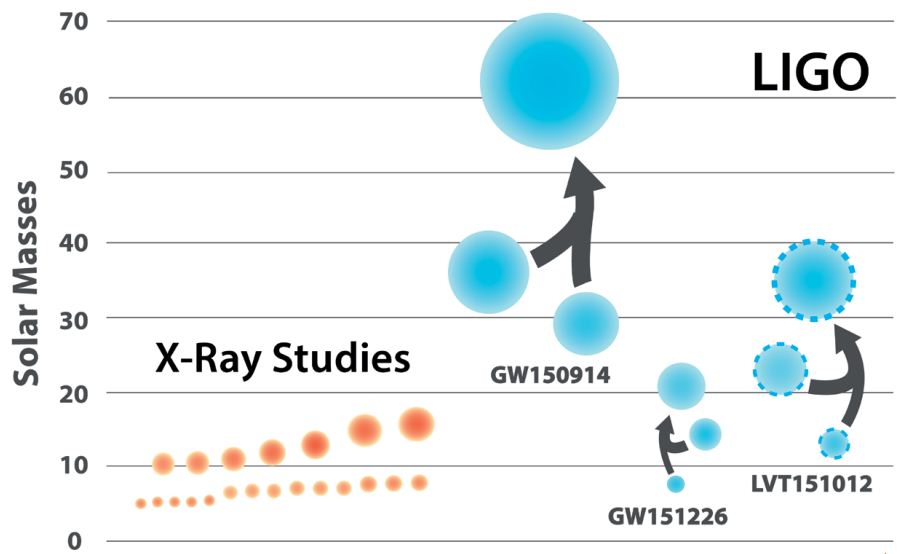
observing run, called LVT151012. However the chances that the wiggles in the data we saw could be caused by random noise fluctuations is high enough that we weren't completely sure it was real, unlike the other other two.

**How to form a binary black hole**

Stellar mass black holes - what we call black holes with a mass a few to a few tens the mass of our sun - are what is left over at the end of a massive star's life. It may start its life as much as a hundred times the mass of our sun. Stars this massive do not live for very long: only a few million years. Granted, that is a lot longer than you or I will stick around, but it is a small fraction of the life of a more normal star like the Sun. These stars are extremely rare; one star in 1000 will have a mass greater than 20 times the mass of our sun. Only fitting for stars that are so extreme in other aspects of their lives; they are extremely bright and hot, they live fast and they die young, sometimes in explosive ways! The death of one

of these massive stars can leave behind a black hole, like an astronomical gravestone. To form a binary black hole, you have to

have two of these massive stars. We actually do not know exactly how GW151226 and GW150914 formed, that is one of the



▲  
*This cartoon shows all of the stellar mass black holes that we know about, and have reliable mass measurements for. In the bottom left corner are the black holes known from observations of x-ray binaries, where a black hole is tearing mass off of a more normal star and emitting lots of x-rays in doing so. These black holes are all in our galaxy, and all have masses lower than around 20 times the mass of the Sun. In the upper right corner we see, for each event LIGO has witnessed, the mass of the two black holes that merged together, and then the mass of the black hole they formed. Most of these black holes are more massive than the ones we know in our galaxy but they are also much further away. Astronomers think that it is easier to form more massive black holes earlier in the universe when the gas the stars formed from contained fewer elements heavier than helium.*

exciting things we are hoping to learn more about with future gravitational-wave observations. Astronomers have two reasonable ideas which can both explain the observations, and many more exotic ones are being discussed every day. These formation scenarios differ in the location we think the binary black holes formed, and whether the black holes have been together for all their lives.

Binary black holes can be formed from what we call ‘isolated binary evolution’ in the galactic field. That is, you have two massive stars which are born together, but far from any other stars. They live their whole lives together. They share everything, even their

*Measured physical parameters of the three most significant events observed by Advanced LIGO in Observing Run 1.*

gaseous envelopes at times, and stick together through thick and thin, even extremely violent explosions which try to tear them apart. When both stars have grown old and died, you have two black holes which are orbiting each other on an extremely short period orbit, which decays due to emission of gravitational-waves, eventually leading the two black holes to merge together forever.

The alternative scenario involves black holes formed from massive stars in an extremely dense stellar environment such as a globular cluster. These black holes die alone and spend all their deaths trying out different partners, and not finding one to their liking. They keep changing partners many times, becoming closer and closer with their partners until they eventually find one they will spend the rest of eternity with, and

merge together. We call binary black holes formed this way ‘dynamically formed’, since the constant switching of partners comes about almost entirely due to N-body Newtonian dynamics.

## Colliding black holes throughout the universe

Black holes are colliding throughout the universe remarkably often. In fact, they collide so often that we expect gravitational waves from black holes colliding somewhere in the universe to pass through the earth every 15 minutes! Most of these gravitational waves are too weak by the time they reach LIGO to ever be detected.

Attentive readers of the recent LIGO discovery papers will have noticed that we quote many of our results with error bars and talk about “90% credible intervals”. For example we quote the measured mass of the heavier black hole in the GW150914 merger as being within a 90% credible interval of 31.0 to 40.0 times the mass of our sun. Now it would be great if we could quote an exact mass, but this is never going to be possible. There will always be some uncertainties in any measurement we make with LIGO due to the presence of detector noise and uncertainties in our models. However, what exactly does it mean when we say that the mass has a 90% credible interval of 31.0 to 40.0? One might think that it means that the mass of the black hole is definitely within this interval but that isn’t true. It means that 90% of the time the actual measured mass will lie in the quoted interval. So when we detect ten binary black hole mergers, which may happen much sooner than we initially thought, we will determine the 90% credible intervals for the mass of the heavier black holes. We expect that the real mass will lie within the quoted interval 90% of the time, so one of the black holes will have a mass outside of the range quoted. The problem is, we have no way of knowing which one that will be!

Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio	23.7	13.0	9.7
False alarm rate (yr <sup>-1</sup> )	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
Significance	$> 5.3 \sigma$	$> 5.3 \sigma$	$1.7 \sigma$
Primary mass ( $M_{\odot}$ )	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	$23^{+18}_{-6}$
Secondary mass ( $M_{\odot}$ )	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	$13^{+4}_{-5}$
Chirp mass ( $M_{\odot}$ )	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$15.1^{+1.4}_{-1.1}$
Total mass ( $M_{\odot}$ )	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$	$37^{+13}_{-4}$
Effective inspiral spin	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
Final mass ( $M_{\odot}$ )	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	$35^{+14}_{-4}$
Final dimensionless spin	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.66^{+0.09}_{-0.10}$
Radiated energy ( $M_{\odot}c^2$ )	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Luminosity distance (Mpc)	$420^{+150}_{-180}$	$440^{+180}_{-190}$	$1000^{+500}_{-500}$
Source redshift $z$	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$	$0.20^{+0.09}_{-0.09}$
Sky localization (deg <sup>2</sup> )	230	850	1600



Since we saw two binary black hole mergers in Advanced LIGO's first observing run, we are able to predict we may see around 10 in the second observing run, which should begin any day now!

'One binary black hole merger is an event; two is a population'. This is a phrase that has been repeated many times over the last few months as we began to study not only single gravitational wave events, but the properties of all binary black holes in the local universe. As we observe more and more, we will be able to work out what the typical masses and spins of binary black holes are. This in turn will teach us about the ways they form, and they will shed light on the lives of massive stars.

### What will we discover next?

What will be next for LIGO to discover? Will we observe gravitational-waves from a massive star we see exploding in our galaxy as a supernova? Maybe two neutron stars will merge together and cause a Gamma Ray Burst or Kilonova which is detected by SWIFT at the same time as it is by LIGO. Maybe that event would even show evidence of a black hole tearing apart a neutron star as they merge.

Perhaps the next black holes we see will be even heavier than the ones we have detected so far, so called intermediate mass black holes, which are thought to live at the centers of globular clusters. Or maybe

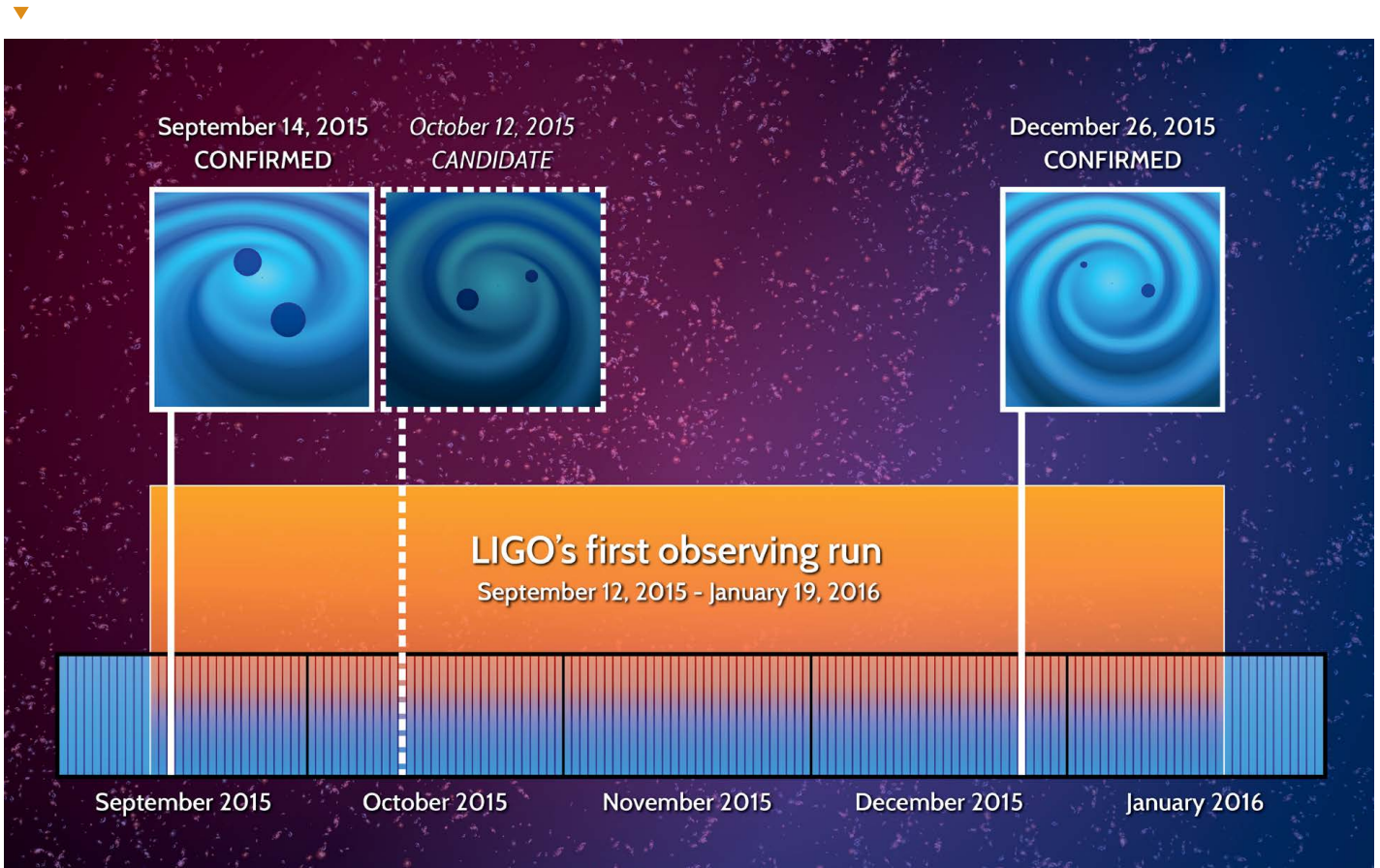
we will see precessing black holes dancing around each other in the final seconds of their lives.

We could even see repeating gravitational-waves from a spinning neutron star, in the same way as we see periodic pulses of radio waves from pulsars.

Hopefully we detect all of these things and even more over the next few years. Each one promises to revolutionise our understanding of the universe! Even better, maybe LIGO will see something we have not even thought of.

LIGO<sub>2016</sub>

Timeline showing Advanced LIGO's first observing run which ran from 12th September 2015 to 19th January 2016. On it we can see the times of the two detections, GW150914 (14th September 2015) and GW151226 (26th December 2015). It's interesting and scary to see how lucky we were; if we had begun observing just a few days later, we wouldn't have detected GW150914. If we had finished observing before Christmas as originally planned, we wouldn't have detected GW151226!



## Bringing about Gravitational Wave Astronomy

*Stan Whitcomb*



*Stan is, or was (no one is quite sure), the Chief Scientist of the LIGO Laboratory, a position that sounds important without having any real responsibility. He*

*has been with LIGO longer than all but a few current members of the LSC, has held almost every position imaginable in the organization, and is currently in his eighth or ninth office on campus. Almost everyone in the LSC has heard that he did something important for LIGO, but whatever it was, it happened long before they joined the effort.*

**A** glimpse of the founding years of the field of gravitational wave detection, seen through the eyes of one of the longest-serving members of the LIGO Scientific Collaboration.

Describe the early-career path that pointed you toward gravitational-wave detection. Who were some of the individuals that you found to be particularly influential along the way?

I actually came to gravitational-wave detection from astronomy. As an undergraduate physics major, I had started to drift toward astrophysics by doing a senior thesis in cosmic ray detection. Robbie Vogt was my undergraduate advisor, and he supervised my senior thesis. (As a side oddity, my senior thesis dealt with the design of a cosmic ray electron telescope that took even longer than LIGO to make its first detection!). He was the one who suggested I do my graduate studies at the University of Chicago (where he earned his Ph.D.).

There I met the person who had the biggest influence on my career: my thesis advisor, Roger Hildebrand. When I arrived at the University of Chicago, Roger was just establishing a new research effort in infrared astronomy. A high energy physicist up until then, he had taken a position in the University administration for a few years (basically, the U of C was broken, and someone had to fix it). When he was finally able to give that up, he discovered that high energy physics had changed, and he no longer found it fun. Without a track record in astronomy, he was struggling to start a group, and I brought something very valuable to that effort - my own funding (since he didn't have any money to pay for a graduate student). I dove in and by the time I graduated, I considered myself to be a real card-carrying astronomer.

*With David Shoemaker, circa 1995. That's my inbox that's visible on the desktop (the real desktop, not the Windows 95 desktop), and my auxiliary inbox behind it. Boxes of Sun Microsystems hardware are visible behind David.*



Those six years were wonderful. Roger didn't teach me astronomy facts, since he didn't really know them any more than I did, but he taught me critical thinking. Equally importantly, he taught me how to write. We would go back and forth over the manuscripts we wrote, until I learned that brief and simple was always appreciated. He also taught me personal qualities; how to be honest, how to do the right thing, and how to care about others, though anyone who knows us both will quickly agree that I never mastered those qualities as well as he did.

Robbie Vogt reappeared in my life about the time I was graduating from Chicago, this time as the Caltech Physics, Mathematics and Astronomy Division chair. While visiting Chicago to give a colloquium, he told me about Caltech's new initiative in gravitational-wave detection (by this time, the cosmic ray detector I had designed had been launched, but still was not detecting anything, though its companion detectors were racking up some interesting results). Kip Thorne had convinced the faculty to back a new initiative in GW detection and they had selected Ron Drever to lead that effort. However, Ron was allowed to spend half of his

time at the University of Glasgow and Caltech wanted another faculty member on campus who could watch over the group between Ron's visits. I fell in love with the challenge of making such a precise measurement and the potential for creating a new field of astronomy. I applied and eventually became THE assistant professor of physics (the only non-tenured member of the physics department at that time).

**Here's a comment from Peter Saulson: "We're all optimists in this business, otherwise we wouldn't be here. Here's proof that I'm an optimist. In 1983, while I was a postdoctoral scholar with Rai Weiss, I asked him how long it was likely to take before we discovered a gravitational wave signal. Rai worked it out for me: one year to convince the NSF to fund LIGO, two years for construction, one year for commissioning to design sensitivity, and one more year to observe until we found signals." What was your level of optimism in the early years?**

If anything, we on the West Coast were more optimistic (i.e., less realistic) even than our MIT colleagues. I had been hired into a tenure track position, and I was convinced that I would make my tenure case five years later not based on gravitational wave detection, but on doing astronomy with gravitational waves. It quickly became obvious to me that the experimental work was going to consume all of my effort, and my connections to the astronomy world began to fade. We built the 40 m laboratory and the first prototype interferometer. The main thrust of the work was to prove the feasibility of building a sensitive Michelson interferometer with Fabry-Perot cavities in the arms. We were making decent progress, achieving about an order of magnitude improvement in sensitivity about every 9 months or so, which we celebrated with bottles of champagne.

**You departed from gravitational wave detector development for a time, and then returned. What activities did you pursue during this interlude, and what brought you back?**

It took me some time to realize that the management that had been put in place for the

joint Caltech-MIT effort was not going to work, and that there was nothing I could do to influence people to do anything different. This was the era of the infamous Troika. I decided to bail out before Caltech had to make the inevitable unfavorable tenure decision for me. I landed a research position at one of the local LA aerospace companies and spent the next six years working on a variety of electro-optical systems. Some turned into hardware, and some did not.

In late 1990, Robbie contacted me and asked if I would be interested in returning to LIGO as his Deputy. The Troika had been replaced by a more sensible management structure with Robbie as the overall project director, and the group had written the LIGO construction proposal. LIGO had just been approved by the NSB (National Science Board) and the push was on to get congressional approval. Site selection was beginning, and serious facility design and detector design would need to start. I had never lost my fascination with the challenges and potential of GW detection, so I jumped at the opportunity to rejoin. I reconnected with the 40 m lab, worked on site selection, developed specifications for the facilities, and led the design of the initial detector.

**In your view, what were the key factors that led to a positive outcome for the LIGO construction proposal?**

I believed then, as I do now, that truly visionary science initiatives can appeal to the Congress as much as to the general public. Robbie had an extraordinary ability to communicate the excitement of GWs to non-specialists, and he made full use of that ability to excite the interest of key congressional members and their staffs.

I believe that there were two very important factors in the decision to fund LIGO that are not widely recognized today. First, the technical challenges and the cost challenges could be separated to a large degree. The highest cost items in the '89 proposal were relatively well-known technologies—the buildings and the vacuum system—and the possibility that these

might cost significantly more than estimated was relatively small. The higher-risk items in terms of technical performance were relatively low cost; these could be reworked if needed with relatively little cost impact.

Second, LIGO assembled the cost proposal on very solid engineering. No facilities like this had ever been constructed, and the design included several new or unusual features. Robbie and Bill Althouse assembled an excellent team of engineers with backgrounds in the design and construction of real facilities – Boude Moore, Larry Jones, Fred Asiri, names that most people in the LSC won't recognize but who played a crucial role. Their work was well organized, systematic, and detailed. The fact that the final costs accurately matched the cost estimates in the proposal is a tribute to the entire proposal engineering team.

In all of the hoopla surrounding GW150914, I have felt that one of the greatest oversights was the lack of recognition of the role that Robbie played. He turned a rather disjointed science effort into a real project, built and supervised an amazing engineering team, and sold a very speculative project to the NSF and Congress based on its merits. There are many in the history of LIGO who have played important roles, but in the majority of cases (my own included), it was a matter of being in the right place at the right time—if that person had not been there, another individual would have arisen to do nearly as well. I think that if Robbie had not been present, it is unlikely that anyone else could have done the job he did. There were complications subsequently, but without Robbie at the time, I believe LIGO (as it exists today) would never have come into being.

**You were once the LIGO Laboratory Deputy Director, bridging the directorships of Barry Barish and Jay Marx. Did you enjoy your tenure as Deputy? What were some significant outcomes during this period?**

Enjoy? No, not at all. I did feel that the work was important, which gave me satisfaction, but it

# Interview with Stan Whitcomb

was one of the most stressful times in my life. I had to deal with some difficult issues during that time, including a pretty significant budget cut for the LIGO Laboratory. Overall, the job of Deputy Director has (almost) all of the stresses and frustrations of the Director's job, and (almost) none of the perks and joys. We were lucky that someone as capable as Albert Lazzarini was willing to take this on when I left.

However, several things began during my tenure as Deputy Director that I remember with pride. We successfully transitioned into observing mode and started S5 (Science Run 5). We received our first Advanced LIGO funding, and we built the Science Education Center at LLO (LIGO Livingston Observatory). Preparations for the very successful announcement of the first detection originated when I told Jay (over pizza one night during his first few weeks as Director) that I thought there was a possibility that we might make a first detection in S5 and he needed to be ready for such an event. (This admonition might have been a bit premature. At this point, LIGO's detection was nearly ten years away, although that cosmic ray detector I designed was only five years from making its first real detections.)

**International collaboration and the growth of the international detector network have been very important to you. What is your current assessment of the international enterprise in our field? Of LIGO India specifically?**

My interest in international collaboration comes from my long-held desire to see the beginning of GW astronomy. You can't do GW astronomy without source locations and without full polarization information. These require a global network. As a practical matter, a global network requires international collaboration, at least when projects reach the scale of LIGO.

We have known from the early days that a global network would be needed. Indeed, the selection of the US sites was made with that in mind, with one of the main site selection criteria being the area of the triangle formed by the two LIGO sites and a possible European detec-

tor (a measure of the angular resolution of the three detectors working together). However, it was not easy to forge international collaborations at that time, with each project barely meeting milestones and keeping the funding agencies satisfied, so we went along, sort of collaborating, sort of competing. It wasn't until we reached the stage where LIGO and Virgo were about to operate at a sensitivity at which detections became more likely that we had the incentive to really begin collaborating.

I am quite certain that the next few years will see fruitful collaboration among LIGO Virgo, KAGRA and LIGO-India, and that this will lead to full exploitation of their capabilities. There will be hiccups in the process, of course, but the rewards are too great to tolerate anything less than success.

Bigger challenges will arise when the community begins to seek funds for next-generation facilities. I believe that the funding agencies will want to see that the community has planned the entire network in an optimal fashion. I can't imagine that any funding agency would invest in a major new facility that needs international partners, unless reasonable assurances exist that those partners will operate at the appropriate sensitivity. Consequently, people will need to give up some control over their local facilities, and that won't be an easy decision to make. LIGO Laboratory and IndIGO are going through a smaller version of this process regarding LIGO-India, so far without too much drama, but the collaboration is still in the early stages.

**Were you satisfied with the process that LIGO used for crafting the GW150914 detection paper? The LVC might make at least one detection per month during observation runs over the next couple of years, but we needed five months to prepare the case for GW150914. Will it be possible to achieve a steady state between LIGO's inputs and outputs?**

There were many things that I liked about the GW150914 process, and a few that I didn't, but in the end the real test is the final product. The

detection paper is a very good paper, and we wrote it relatively quickly and with a lot of pressure and distraction.

I am not so worried about future papers, as long as we recognize that our future publications are not likely to achieve anything close to this level of visibility and scrutiny. The GW150914 paper was written for the broader physics and astronomy communities, and it had to be a bit different. From now on, we will be writing mostly for researchers in fields that are closely related to our own. Future papers won't need to be as perfect as this one. As long as we remember that, I don't think that we will fall behind. Also, we will eventually get beyond the point where every new event gets its own paper.

**What lies ahead for you?**

Ah, the \$64 question. Of course, none of us can know the future. Most of the LSC already knows that I retired the day after GW150914 passed through our detectors. That event disrupted my plans a bit. But now I can get back on track. Maybe some kite-flying. Maybe some bridge.

Maybe I will become a novelist. I have an idea for a thriller about the Director of a major science project which seems in danger of not meeting its (rather speculative) goals, resulting in cancellation of future funding. S/he secretly recruits a couple of brilliant grad students to generate a couple of false events that will guarantee future funding for years to come. The whole scheme comes apart when the plodding Chief Scientist nearing the end of his career is called to investigate the reality of the detection and begins to suspect foul play. The Director offers him a sweet deal to retire and keep quiet. I haven't quite decided how it ends, but maybe with a bit more thought, I can come up with something surprising.

Interview by Dale Ingram

LIGO<sub>2016</sub>

# The First Two Detections: Press Conferences



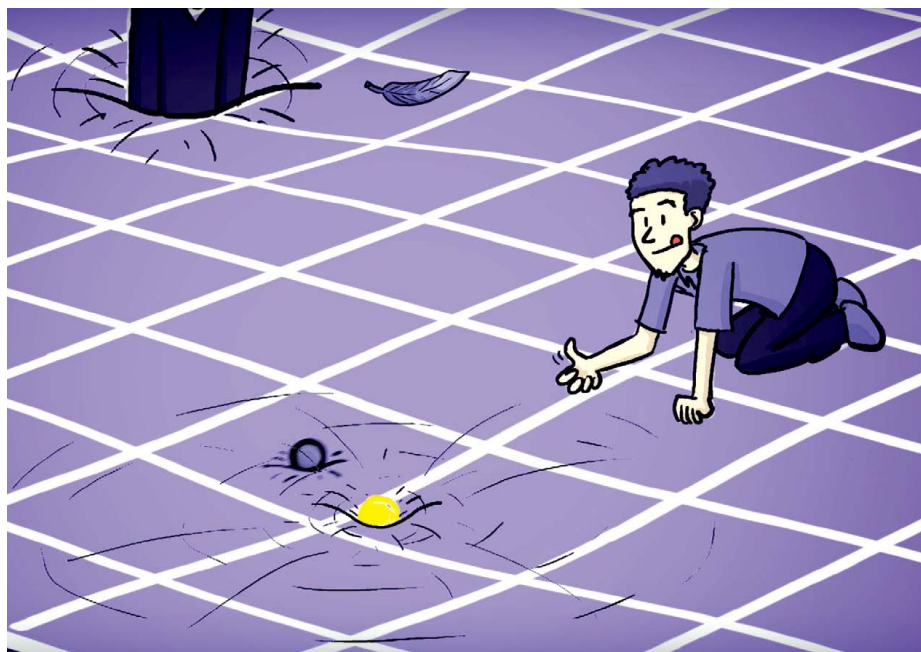
▲ France A. Córdova, Director of the National Science Foundation, Dave Reitze, Gabriela González, Kip Thorne, Rai Weiss during the press conference announcing the first detection of gravitational waves, Washington–DC, February 11, 2016.

▼ Gabriela González, Fulvio Ricci and Dave Reitze - Press Conference: The Latest News from LIGO, Wednesday June 15, 2016.



## Science Communication: Go for Excitement or Accuracy?

**O**n February 11, 2016 the LIGO Scientific Collaboration and Virgo Collaboration (LVC) announced the first ever direct detection of gravitational waves and the first observation of a binary black hole merger, followed by an announcement on June 15, 2016 of a second detection of gravitational waves from a smaller binary black hole merger. The physics community has been working toward these discoveries for 100 years, since Einstein's theory of General Relativity predicted gravitational waves and black holes in 1916, and they represent a huge scientific breakthrough. Science is an inherently careful and skeptical pursuit, however, and the discovery of gravitational waves is an especially salient example of work that takes dedication and patience by generations of scientists.



*Marbles on a rubber sheet representing a planet orbiting a sun. Screenshot from "Gravitational Waves Explained", "Piled Higher and Deeper" by Jorge Cham [www.phdcomics.com](http://www.phdcomics.com)*

So how does this slow and meticulous scientific culture share the visceral excitement of a breakthrough moment? How can the importance of the discovery be communicated to a public that is familiar with neither the underpinning theory nor the remarkable technology that made it possible? In short, how can the entire history of the field of gravitational wave astronomy be condensed in a manner that maximizes interest and impact for non-experts while not compromising scientific accuracy and rigour?

Modern modes of communication require swift reactions, distilled messages, and new content backed up by in-depth coverage of the human, historical, and fundamental science stories. To assess the impact of the news of a scientific discovery it is important to differentiate between the public being excited and the public's understanding being enhanced. Efforts on both fronts are valid and important



*ultimate frisbee, especially with physicists.*

### *Joey Shapiro Key*

*is the Director of Education and Outreach for the Center for Gravitational Wave Astronomy at the University of Texas Rio Grande Valley. She likes playing*



*Paul Franklin's "Interstellar" Oscar and briefing the Queen on the Hubble expansion.*

### *Martin Hendry*

*is Professor of Gravitational Astrophysics and Cosmology at the University of Glasgow. Recent career highlights include holding*

but it is harder to evidence the latter: a genuine increase in public understanding.

That said, we can surely agree that everyone should be able to appreciate something about how important and exciting physics is, regardless of their academic background, social demographic, or native language. The discovery of gravitational waves and the merger of two black holes are awe-inspiring events, even for those who do not have a deep understanding of general relativity. One can love a Mozart symphony or a Renoir portrait without expertise in symphonic writing or impressionist painting. Similarly, the beauty of Olympic athletics can be shared with a worldwide audience, including a majority of people who do not participate in any particular sport.

The Education and Public Outreach Working Group of the LVC worked on a range of projects leading up to the announcement of our

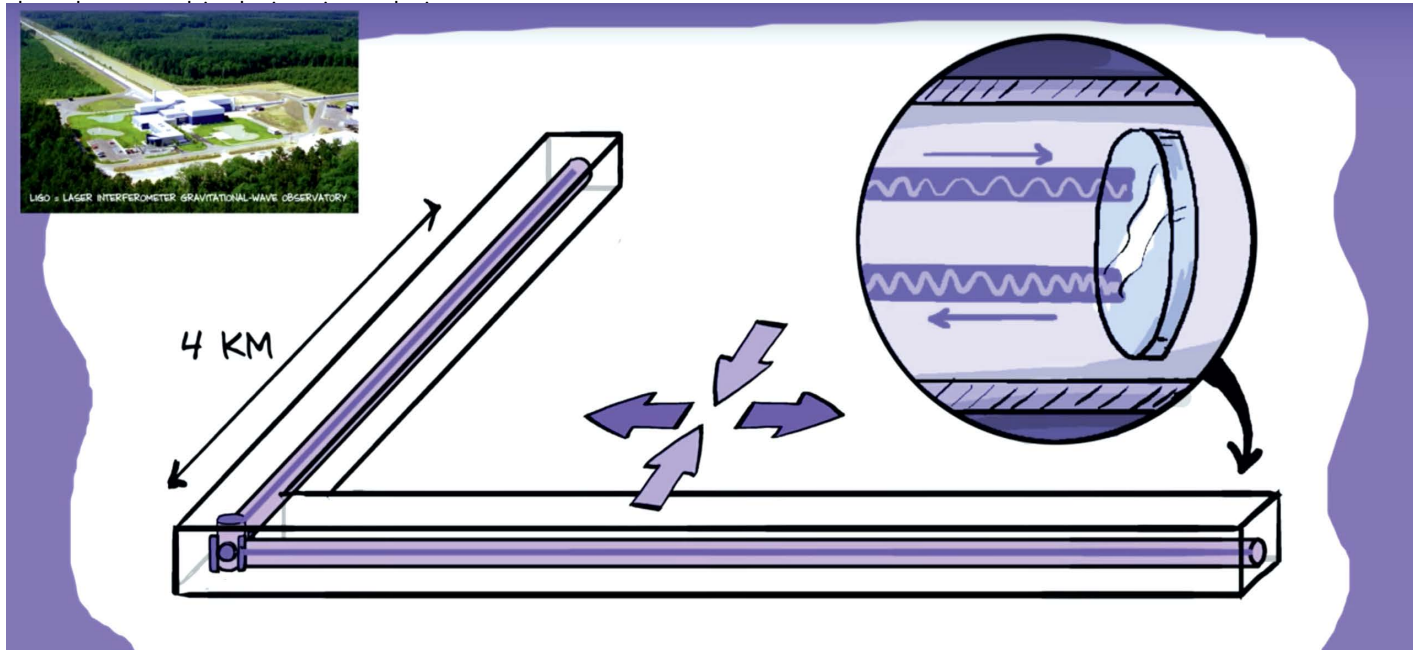
discoveries with the goal of conveying both the excitement and importance of our discoveries and (as best we could) how those discoveries had been made possible.

To meet these goals we decided from the outset that some scientific accuracy would have to be compromised. With little or no math we almost

mathematics like our interferometer animations, designed to give even the casual viewer some clear insight into what gravitational waves are and how we detected them. In parallel, we prepared in-depth material designed to address more detailed questions about the science and technology behind gravitational wave detection – principally making this material available

These included, for example, a [question@ligo.org](mailto:question@ligo.org) address that since February has attracted hundreds of email enquiries from across the globe, posing the Collaboration some highly challenging and perceptive questions.

Finally, our strategy highlighted the importance of not just our scientific breakthroughs



Sketch of the LIGO interferometer including a schematic drawing of laser light bouncing off the mirror. Screenshot from “Gravitational Waves Explained”; “Piled Higher and Deeper” by Jorge Cham [www.phdcomics.com](http://www.phdcomics.com)

which may be imperfect but can nevertheless convey core ideas. For example ‘ripples in the fabric of spacetime’ is the commonly-used analogy for gravitational waves, but what does the ‘ripple’ actually represent in this context? Waves on the surface of a rubber sheet or trampoline do not stretch and squeeze the distances on the sheet, so the analogy doesn’t work in detail to explain the effect of a passing gravitational wave on the LIGO interferometers. Indeed, physicists themselves were confused about the nature of gravitational waves for 40 years, and took an additional 60 years to build an experiment capable of detecting them!

So the LVC adopted a multi-level approach. We developed accessible resources using commonplace (if imperfect) analogies such as the stretched rubber sheet, and simplified sche-

via our website. A key example here was our science summaries: in-depth articles written without technical language but conveying the essential scientific arguments and conclusions presented in our detection papers. Other LVC products included translations of the press release into 18 languages, an educator guide for teachers, new high-resolution simulations representing the gravitational lensing and gravitational wave signatures of the black hole merger, and tutorials for using the public LIGO data through the LIGO Open Science Center.

We also sought to promote our outreach efforts vigorously using social media, formulating a comprehensive plan that would direct followers to the very latest news, provide clear pathways to more in-depth resources and offer opportunities to engage directly with LVC researchers.

themselves, but also the scientific methodology that underpinned them. We emphasised three key messages here:

**first**, that detecting gravitational waves was incredibly difficult and a quest that many had thought impossible (in the words of LIGO Executive Director Dave Reitze, the equivalent of the Apollo “Moonshot”). Thus our success was a triumph for the long-term vision and investment of the NSF and other national funding agencies; **second**, that our discovery relied on the teamwork and cooperation of many hundreds of scientists and engineers from dozens of countries across the globe – mirroring the modus operandi of many contemporary ‘big science’ projects; **third**, (to quote Carl Sagan) that “extraordinary claims require extraordinary evidence”, so the five month delay between our detection and its announcement involved a huge amount of

# The Making of Physics Fans

meticulous analysis, leaving no stone unturned in the quest to convince ourselves that we detected a real signal.

Were all of these efforts successful? Let's consider some raw figures around the impact of our discovery – which we believe are quite remarkable.

The LIGO Twitter top tweet had 639K impressions, 4116 retweets, and 2996 likes. From Feb 8 to March 8 the account had 4.7M impressions, 15.4K likes, 17.4K retweets, 30.3K link clicks, and gained 19.2K new followers. The top LIGO Twitter mention was from @POTUS: "Einstein was right! Congrats to @NSF and @LIGO on

sure; nevertheless we believe there are strong indicators of our success here too – from the quality and consistency of the questioning in our NSF LIGO US congressional hearing (widely lauded for its "bipartisan praise") to the YouGov survey conducted in the UK, in which one third of respondents thought that the discovery mattered "a fair amount" or "a great deal". More specific examples include our February 12 LVC Reddit 'Ask Me Anything' session that generated 923 comments, answering an unprecedented >90% of the questions asked, and sparked a separate thread discussing the LVC AMA on [reddit.com/r/bestof](https://reddit.com/r/bestof).



*Analogy of the matched filtering procedure to extract the signal from the noise. Screenshot from "Gravitational Waves Explained"; "Piled Higher and Deeper" by Jorge Cham [www.phdcomics.com](http://www.phdcomics.com)*

Newspaper and television news coverage of the gravitational wave detection included front page articles on the New York Times, CNN, and the BBC. A total of 961 newspaper front pages from February 12 featured the discovery according to the Newseum, which listed the "Discovery of Gravitational Waves" as one of four dates in 2016 so far deemed to be of historical significance – and the only positive historical news day selected in the last 6 months.

Caltech media reported 70 million aggregate impressions on all tweets using the #gravitationalwaves, #LIGO, and #EinsteinWasRight hashtags. The LIGO Scientific Collaboration Facebook page top post reached 665K people, 15K likes, and 2.8K shares. From Feb 8 to March 8 the page reached 1.5M people, 7.3K shares, 42.4K reactions, and gained 8.7K new followers.

detection gravitational wave – a huge breakthrough in how we understand the universe" with 80K engaged, 9.5K retweets, and 21K likes.

So it seems clear that our detection generated enormous impact and excitement. Also impressive was the breadth of our impact – across a range of cultural icons not traditionally associated with fundamental physics: from tweeting birds in a New Yorker cartoon to "News from Lake Wobegone" on A Prairie Home Companion; from a Superbowl MVP sketch on Saturday Night Live to Brian Greene demonstrating a Michelson Interferometer on The Late Show with Stephen Colbert (a segment that attracted 2.2 million views on YouTube).

What about the depth of our engagement? As we noted already this is much harder to mea-

sure; nevertheless we believe there are strong indicators of our success here too – from the quality and consistency of the questioning in our NSF LIGO US congressional hearing (widely lauded for its "bipartisan praise") to the YouGov survey conducted in the UK, in which one third of respondents thought that the discovery mattered "a fair amount" or "a great deal". More specific examples include our February 12 LVC Reddit 'Ask Me Anything' session that generated 923 comments, answering an unprecedented >90% of the questions asked, and sparked a separate thread discussing the LVC AMA on [reddit.com/r/bestof](https://reddit.com/r/bestof).

Perhaps most striking of all are the third party individuals and groups, with no formal connections to the LVC, who have composed and performed material about our discovery. Examples range from the 8th grader science projects sent to [question@ligo.org](mailto:question@ligo.org) to the work of poet and non-scientist Missy Assink – who read her new composition 'GW150914, or a love story between two black holes' at Spoken Word Paris in March 2016 – and a plethora of other videos on YouTube created to highlight the detection. Both the energy and enthusiasm of these presenters and the remarkable scientific quality of their content demonstrate to us the deep impact and learning that the excitement of our discovery has generated. There is a wave of new physics fans sweeping across the world.

## References

- YouGov survey in the UK (<https://yougov.co.uk/opi/share/surveys/results/survey/b8db9270-d173-11e5-a405-005056900127>)
- PhD Comics on gravitational waves (<https://www.youtube.com/watch?v=4GbWfNHtHRg>)
- Brian Greene on The Late Show with Stephen Colbert (<https://www.youtube.com/watch?v=ajZojAwfEbs>)
- Missy Assink (<https://about.me/missyassink>)
- Spoken Word Paris (<https://spokenwordparis.org/>)



~ 75 hours of child's play ...

# The Glasgow Mosaic

Chris Messenger

on behalf of the Glasgow outreach team. Chris is a Lord Kelvin Adam Smith Fellow at the University of Glasgow.

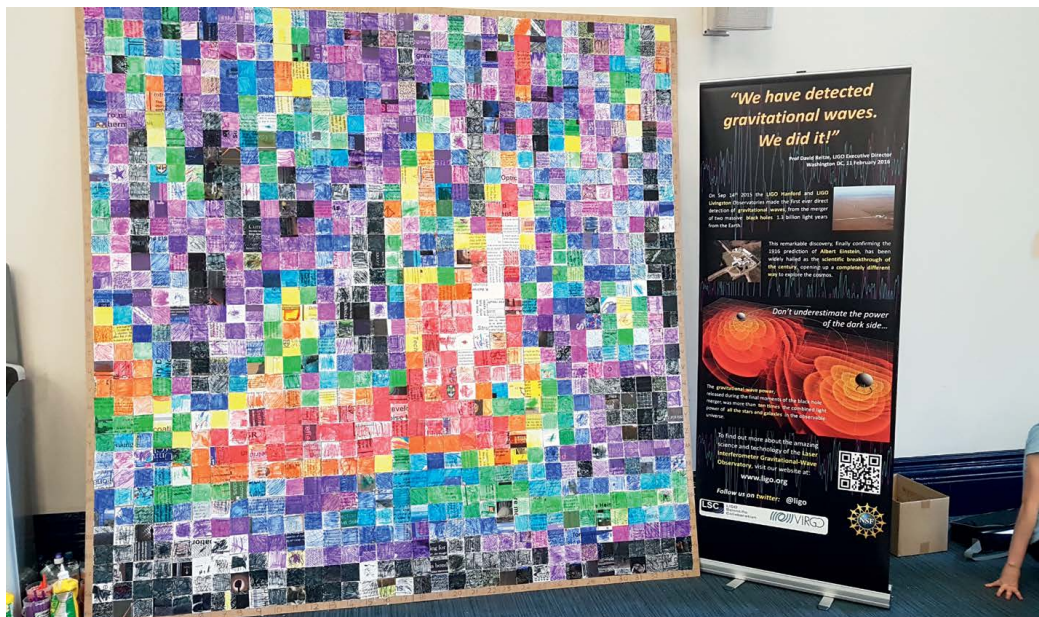


**W**e set about making a collage depicting the time-frequency map of the “Event” asking members of the public (mostly children) to colour-in small square “pixels” to be placed on a larger (2.4 x 2.4 metre) image. Each pixel was 7 x 7 cm and so we needed  $34 \times 34 = 1156$  pixels in total. It took ~75 person-hours to complete and required hundreds of participants. This was all done over the course of a few public outreach events held in Glasgow.

One of the features of the project is that the pixels themselves are small pieces of our research posters. These posters have been hidden in the corners of offices for years and secretly document the research efforts of the Institute for Gravitational Research (IGR) here at Glasgow. The pixels are coloured-in with felt-tip pens so that the text and plots of the original posters shows through when you get close up to it. Whilst the first collage is complete we are in the process of framing and then displaying it. The image is of the H1 signal and we are planning to also do the same for L1 soon.

LIGC 2016

Colourful public engagement by the Glasgow outreach team, pictured left to right (top image): Andrew Spencer, Peter Murray, Karl Toland, and Brynley Pearlstone.



... it's fun but also hard work!

# Social Media Impact of LIGO Detection

**Joel Achenbach** @JoelAchenbach  
"That's the chirp we've been looking for" LIGO! LIGO! LIGO! [Yes, I felt the cosmos move]

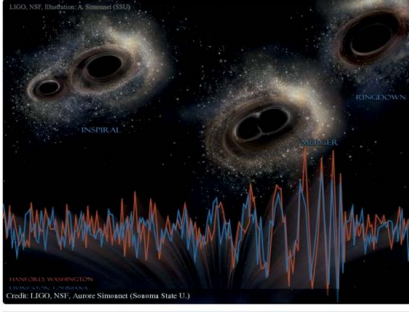


Cosmic breakthrough: Physicists detect gravitational waves from violent black hole merger. The detection was hailed as a triumph for a controversial, exorbitantly priced, billion-dollar physics experiment and as confirmation of a key prediction of Albert Einstein...  
washingtonpost.com

RETWEETS 1 LIKES 5

12:44 AM - 12 Feb 2016

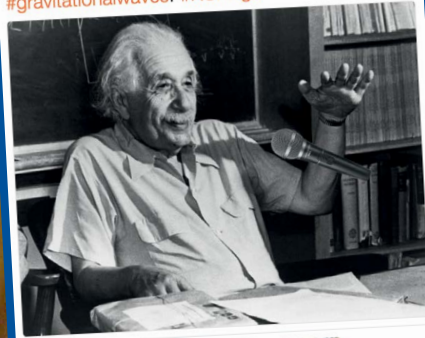
**Astro Pic Of The Day** @apod  
LIGO Detects Gravitational Waves from Merging Black Holes: [apod.it/160211](http://apod.it/160211) by @NSF



913 RETWEETS 781 LIKES

5:00 PM - 11 Feb 2016

**Albert Einstein** @AlbertEinstein  
If Einstein were alive, he'd totally do a mic drop after today's #LIGO conference on #gravitationalwaves. #NSFLigo



1,144 RETWEETS 1,175 LIKES

5:19 PM - 11 Feb 2016

**Brian Greene** @bgrgreen  
It's real. Gravitational waves have been detected. Our understanding of the universe takes a giant leap forward. #LIGO

539 RETWEETS 662 LIKES

5:24 PM - 11 Feb 2016

**Stephen Hawking** @shuttleCDRKelly  
My congratulations to the LIGO team on their discovery of gravitational waves. It is a result that is at least as important as the discovery of the Higgs Boson. It includes the first observation of gravitational waves, and of two black holes colliding and merging. With LIGO's increased sensitivity, we can expect many more detections, all improving our knowledge about how the universe works.

These experimental observations are consistent with my theoretical work on black holes in the 1970s. As a theoretical physicist, I have spent my life contributing to our understanding of the universe. It is thrilling to see predictions I made over 40 years ago such as the black hole area and uniqueness theorems being observed within my lifetime. -SH

22,523 shares 2.3k comments

**Angry Birds** @AngryBirds  
Those #gravitationalwaves seem mighty familiar... #LIGO



46 RETWEETS 93 LIKES

10:14 PM - 11 Feb 2016

**Kamala Harris** @KamalaHarris  
The universe speaks! Incredible discovery by @Caltech & the #LIGO team which will inspire generations to come. [bit.ly/1TbpKFE](http://bit.ly/1TbpKFE)

10 RETWEETS 21 LIKES

11:22 PM - 11 Feb 2016

**Mark Kelly** @ShuttleCDRKelly  
Scientists have heard & recorded the sound of two black holes colliding, proving Albert Einstein right. #LIGO



133 RETWEETS 317 LIKES

11:01 PM - 11 Feb 2016

**HuffPost Science** @HuffPostScience  
Scientists have just caught up to Einstein's brilliance #LIGO #gravitationalwaves [huff.to/20qY6om](http://huff.to/20qY6om)



14 RETWEETS 22 LIKES

12:00 AM - 12 Feb 2016

**LIGO** @LIGO  
The birth of gravitational wave astronomy!



426 RETWEETS 520 LIKES

10:23 AM - 11 Feb 2016

**GW150914** @lamgw160914  
I am GW150914, the first gravitational wave detected on Earth by #LIGO on September 14, 2015. I was announced today! #gravitationalwaves

**Narendra Modi** @narendramodi  
Historic detection of gravitational waves opens up new frontier for understanding of universe!

1,957 RETWEETS 3,730 LIKES

**EGO-Virgo** @ego\_virgo  
La scoperta che apre una nuova finestra sull'Universo!! #ondegravitazionali !! @LIGO @UffComINFN @CNRS

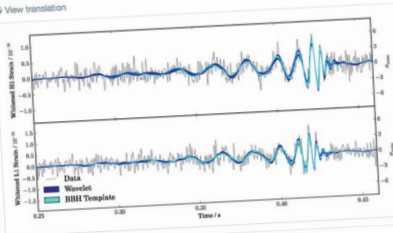


Focus @Focus\_it  
Scoperte le #ondegravitazionali: tutto quello che c'è da sapere @ego\_virgo @LIGO -> focus.it/scienza/scienz...

32 RETWEETS 22 LIKES

5:12 PM - 11 Feb 2016

**Shit relativists say** @RelativistsSay  
Eppur si muove, again: #LIGO #GravitationalWaves



RETWEETS 5 LIKES

Background image of sim card courtesy of Georgy90

**National Science Fdn** @NSF

We detected **#gravitationalwaves**. We did it! - David Reitze, **@Ligo** Exec. Director

RETWEETS 150 LIKES 164

4:56 PM - 11 Feb 2016

**CNN en Español** @CNNEE

Gabriela González **@LIGO**: La detección que hemos medido es la primera observación directa de dos agujeros negros fusionándose — **@camilocnn**

RETWEETS 33 LIKES 28

11:32 PM - 11 Feb 2016

**President Obama** @POTUS

Einstein was right! Congrats to **@NSF** and **@LIGO** on detecting gravitational waves - a huge breakthrough in how we understand the universe.

RETWEETS 9,464 LIKES 21,214

12:43 AM - 12 Feb 2016

**Neil deGrasse Tyson**

Posted by Jeffrey Simons, StarTalk Social Media Director:  
New Video from StarTalk Radio: Neil deGrasse Tyson explains **#GravitationalWaves** discovery. With Charles Liu & Eugene Mirman: <https://www.youtube.com/watch?v=OxiiipD7dsw>

Like Comment Share

5.9k

1,363 shares

156 comments

**Yihua** @xuyihua

LIGO激光干扰仪耗时10年终于捕获到13亿光年外2个约太阳30倍质量的黑洞相互吞噬时释放的穿越时空的微弱引力波，正式确认爱因斯坦整100年前，即1916年广义相对论中的预言。上帝粒子引力波，这两年真是物理的丰收年。

In Milestone, Scientists Detect Gravitational Waves As Black Holes Collide  
A U.S.-led team says it has seen waves in space-time from two black holes merging together. It is the first time humanity has directly detected such waves. npr.org

RETWEETS 26 LIKES 10

5:35 PM - 11 Feb 2016

**Sean Carroll** @seanmcarroll

Holy crap what a beautiful plot. I'm a bit verklemt. **#LIGO**

RETWEETS 508 LIKES 390

7:38 AM - 11 Feb 2016

**The White House OSTP** @whitehouseostp

Did you hear about **@NSF's** announcement confirming **#gravitationalwaves**? It changes how we can observe the universe! **#LIGO**

RETWEETS 54 LIKES 77

8:31 PM - 11 Feb 2016

**BMBF** @BMBF\_Bu

Forschungsministerin **#Wanka**: "Ein grandioser Erfolg für die Grundlagenforschung" **#Gravitationswellen @LIGO @mpi\_grav**

„Der Nachweis der Gravitationswellen eröffnet ein neues Fenster zum Universum, das uns den Blick bis zurück zum Urknall erlaubt. Das ist eine Jahrhundertentdeckung und ein grandioser Erfolg für die Grundlagenforschung. Deutsche Forschungsgruppen haben zu dieser Entdeckung maßgeblich beigetragen – das zeigt die herausragende Position Deutschlands als Wissenschaftsstandort.“

Johanna Wanka, Bundesministerin für Bildung und Forschung [www.bmbf.de](http://www.bmbf.de)

RETWEETS 31 LIKES 31

4:41 PM - 11 Feb 2016

**SA Scientific American** @sci.am

With gravitational wave discovery, **#** promises to open a new era of astro [bit.ly/1muJmA](http://bit.ly/1muJmA)

RETWEETS 282 LIKES 243

11:42 PM - 11 Feb 2016

**茂木健一郎** @kenichiro-moji

その時に鍵となるのが、実は英語である。英のwikiの重力波のページはこちらだが、[en.wikipedia.org/wiki/Gravitational...](http://en.wikipedia.org/wiki/Gravitational_waves) 数式も入るし、今回のLIGOの成果もすでに書かれていて、とにかく早くてくわしい。日本語の真だど、こうはいかない。

RETWEETS 80 LIKES 147

11:34 PM - 11 Feb 2016

**Jeff Bezos** @JeffBezos

Hope, somewhere in space-time, Einstein is seeing this. [wapo.st/20OwPIg](http://wapo.st/20OwPIg) **#LIGO**

Cosmic breakthrough: Physicists detect gravitational waves from violent black-hole collisions. The detection was hailed as a triumph for a controversial, exquisitely crafted, billion-dollar physics experiment and as confirmation of a key prediction of Albert Einstein's theory of general relativity. [washingtonpost.com](http://washingtonpost.com)

RETWEETS 377 LIKES 626

1:41 PM - 11 Feb 2016

**((Steve Israel))** @PipSteveIsrael

On Wed **@HouseGOP** voted to cut **@NSF** grants. Today, **#LIGO** funded by **@NSF** biggest physics discovery in 100 yrs [goo.gl/UK3vh](http://goo.gl/UK3vh)

RETWEETS 1 LIKES 1

11:42 PM - 11 Feb 2016

**Mark Zuckerberg** @zuck

Scientists just confirmed the detection of gravitational waves. This is one of the biggest discoveries of modern science. Albert Einstein is one of my heroes, so I've been following this announcement closely. Einstein first predicted gravitational waves 100 years ago in his Theory of General Relativity. Gravitational waves are ripples in the fabric of space-time created by the movement of mass. These are mostly too small to be detected, so we need to look for waves that begin with massive events like the Big Bang, the collapse of stars and the collision of black holes. By analyzing the information contained in gravitational waves, we can now open up an entirely new view of the cosmos -- potentially shedding light on the very earliest moments of the universe, as well as the creation and growth of black holes. It's inspiring to think about all the lives and effort, generation after generation, that have gone into uncovering this insight about our universe. It's inspiring to think about all the lives and effort, generation after generation, that have gone into uncovering this insight about our universe. It's inspiring to think about all the lives and effort, generation after generation, that have gone into uncovering this insight about our universe.

RETWEETS 282 LIKES 243

11:42 PM - 11 Feb 2016

**IN2P3 Les 2 infinis** @IN2P3\_CNRS

Avez-vous déjà entendu une onde gravitationnelle? Eux oui! **@LIGO @ego\_virgo**

MIROIRS, MES BEAUX MIROIRS, DITES-MOI QUI A LA PLUS BELLE ONDE GRAVITATIONNELLE?

RETWEETS 1,125 LIKES 950

7:41 PM - 11 Feb 2016

**XKCD Comic** @xkcdComic

Gravitational Waves [xkcd.com/1642/](http://xkcd.com/1642/) [m.xkcd.com/1642/](http://m.xkcd.com/1642/)

THE GRAVITATIONAL WAVE DETECTOR WORKS! FOR THE FIRST TIME, WE CAN LISTEN IN ON THE SIGNALS CARRIED BY RIPPLES IN THE FABRIC OF SPACE ITSELF!

EVENT: BLACK-HOLE MERGER IN ORION (50 M<sub>SUN</sub>)

EVENT: ZEPHYRUS THE PARTY WOULD LIKE TO CONNECT ON LINKEDIN

EVENT: BLACK-HOLE MERGER IN ORION (20 M<sub>SUN</sub>, 50 M<sub>SUN</sub>)

EVENT: PORTAGE OFFER FROM TRANQUILITY GRUVE

EVENT: ZEPHYRUS THE PARTY WOULD LIKE TO CONNECT ON LINKEDIN

EVENT: MEET LOVELY SINGLES IN THE LOCAL GROUP 'DMIGHT'

RETWEETS 1,125 LIKES 950

7:41 PM - 11 Feb 2016

**早川 悠** @fickidiascom

LIGOが重力波を観測

RETWEETS 30 LIKES 127

12:42:28

## Gravitational Waves in the Birmingham Science Museum

Anna Green

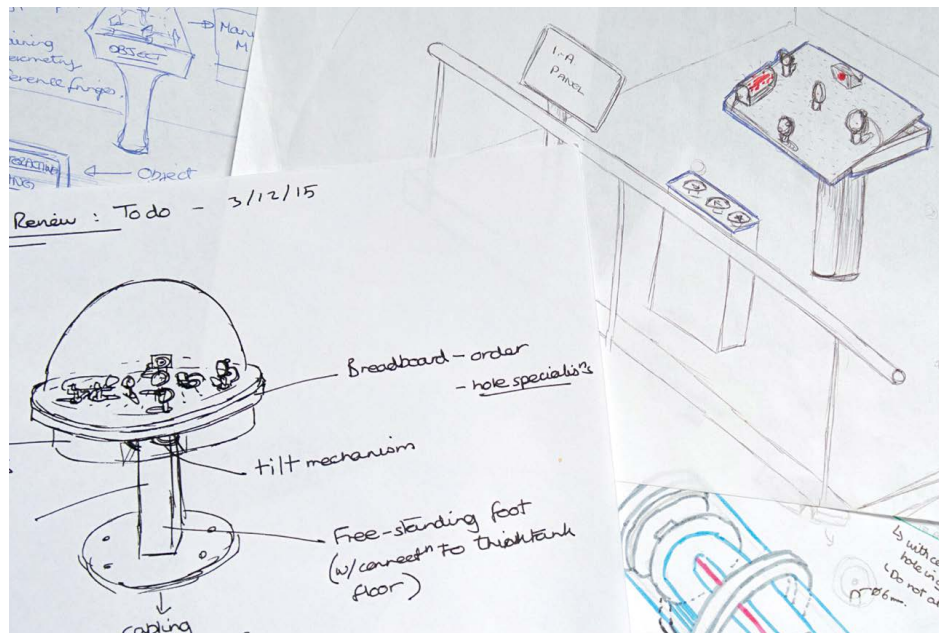


is a PhD student at the University of Birmingham, studying radiation pressure effects. When not working, she spends her time attempting to memorise simple origami patterns and playing the flute - sometimes during a good ceilidh.

The 'Thinktank' is a vibrant place, full of buttons to push, levers to pull, stars to gaze at and robots to instruct: this is Birmingham's Science Museum. Opened in 2001, it houses over 200 hands-on exhibits and artefacts, ranging from the historical to the cutting edge - while a Spitfire fighter plane hangs from the high ceiling of the 'Move It' gallery, a short walk upstairs via 'We Made It' - a gallery focused on Birmingham's rich history of manufacturing, leads you to the 'Futures Gallery' where one can learn about modern medical techniques, argue heartily (if futilely) with the 'Robo Thespian', or, now, learn about gravitational waves.

The Astrophysics and Space Research group at the University of Birmingham has a strong outreach programme, which has included developing apps and games like 'Space Time Quest' and 'Pocket Black Hole' as well as leading workshops with local schools and being invited to attend numerous science events, such as the British Science Festival and BBC Stargazing Live. We first visited the Thinktank in 2014 with an event called 'Teen Takeover', to which we brought our usual mix of computer games, hands-on activities, and enthusiastic volunteers. From this, our relationship with the museum began to develop, led by fellow student Hannah Middleton. This included two similar 'Meet the Expert' days, and in December 2014 the thought emerged to develop a longer-term exhibit for the museum.

We were very excited to explore this idea, and quickly settled on developing a 'super-shiny Michelson' - a simple model to demonstrate how gravitational wave detectors work, with



The 'super shiny Michelson' at Birmingham's Thinktank museum. **Top image:** Anna Green and Hannah Middleton make final adjustments to the finished exhibit; **Bottom:** sketches made throughout the development process.

a high focus not only on functionality but on aesthetics too. Our benchmark then became our existing Michelson model: how could this be improved upon to better showcase the work our collaboration does? How could we make an exhibit that made sense even if none of us were there to explain it?

The project began with market and funding research. It immediately became apparent that when the priority is 'shininess', some standard parts are no longer an option. As effective as our favourite suppliers' mirror mounts were, black anodised parts didn't fit the bill - so many of the components used became the vacuum-compatible versions. Much of the design became entirely bespoke, an aspect that I particularly enjoyed as it harked back to my school days studying Product Design. We decided early on that an exposed laser tube would greatly enhance the look of the piece, as well as showing the public what's happening 'under the hood'. This did, however, complicate the health and safety requirements: an open 1000V tube is not exactly public-friendly! So we designed a transparent housing for it, and encased the whole breadboard inside an acrylic bubble.

Alongside the hardware, developments began on the user interface to accompany the interferometer. After an extensive search we found the existing tools for creating interactive displays either prohibitively expensive or offering only limited functionality. Our newest PhD student, Sam Cooper, thus started the development of a completely new piece of software for the exhibition based on commonly used and easily accessible components: the exhibit uses the 'node.js' package and is cross-platform, currently running on a Raspberry Pi 3 with an Arduino Uno allowing interaction with the interferometer itself. Throughout the project we held regular meetings with our research group and the museum itself, each time generating new ideas to trial - which was no mean feat! However the result is an exhibit which is compatible with both the Thinktank's technological

constraints and the capabilities we require, for now and the future.

After testing our workshop's capabilities by requesting a circular breadboard almost too large for their machines, the focus turned to the media content of the exhibit. Since we could not be there in person for a long-term installation piece like this, we decided to record videos, accompanied by additional material to click through and a quiz. Filming the videos was an adventure in itself, most of us having never been in front of the camera before. The final three videos focused on the Michelson itself, introducing gravitational waves, and the first detection.

As with all projects, the day marked for completion came around all too quickly and there was a Herculean effort by all to get the 'i's dotted, 't's crossed, screws tightened and circuits soldered. The installation itself happened across two days, the first focused on fitting the hardware into the Futures Gallery and the second on integrating the software. It was exciting to see that there was already interest in the new piece, both from school groups and other locals visiting on their lunch breaks, while we were still attempting to tighten too-small bolts upside-down and performing live demonstrations of software tuning.

The exhibit is running well now, and was officially launched on the 7th July. The 'super shiny Michelson' will stay in its new home for at least the next year, ready for people to 'send a gravitational wave' to the detector by clicking the mouse, causing one of the mirrors to shake. We are already working on upgrades to the software, including investigating a touchscreen version for when the Michelson returns to us.

It has been a big project for us, in which I think we have more than surpassed our benchmark. For now, we look forward to visiting the gallery and spotting some of the Thinktank's 260,000 annual visitors learning a little something about gravitational waves!



Members of the Birmingham outreach team during the first day of installation. *Top and Middle: fitting the leg and feeding cabling from the Michelson and Pi to the Thinktank's main system; Bottom: a snug fit inside the control box, which houses everything used to control the exhibit from the laser power supply to the Raspberry Pi and Arduino.*

## Gravitational Waves: A Neat Problem to work on



*Peter Michelson*

*is currently a Professor of Physics at Stanford University as well as the Physics Department Chair. He is also the principal investigator of the Large Area*

*Telescope (LAT) on the Fermi Gamma-ray Space Telescope. In the 1980's he led a gravitational wave bar detector project at Stanford University.*

**T**his interview was conducted on April 24, 2015, before the first detection was made.

**Brett Shapiro:** What inspired you to build a gravitational wave bar detector?

**Peter Michelson:** It started with Joe Weber, that's who built the first bar detectors. And then Bill Fairbank and Bill Hamilton among others felt that if the detectors were cooled to low-temperature, the closer to absolute zero you can get then the mechanical thermal noise in the detector will be reduced and that makes a better, more sensitive detector. One of the challenges was of course matching the bar antenna to an electromechanical transducer and amplifier readout operating near the quantum limit and also vibration isolating it.

I thought it was a neat problem to work on. I actually started out working in superconductivity and condensed matter experimental physics studying SQUID devices, and those had an application as part of the readout of the gravitational wave detector. Detecting gravity

waves is an ambitious undertaking. It's pretty fundamental physics. So that's how I got into it.

**B:** Did you have any collaborations with other bar detector groups?

**P:** Yeah we did, with the group at LSU led by Bill Hamilton at the time, and with the group in Italy at the University of Rome that eventually built a detector at CERN. In the early days the leaders of the Rome effort were Guido Pizzella, and Edoardo Amaldi. Amaldi was already emeritus when I got involved, but he was a very active senior scientist in Europe and started the effort in Italy.

We collaborated with them on coincidence experiments. The detector developments were mostly done independently, but the vision of the advantages of a low temperature detector were shared. Of course the detectors were optimized to look for impulsive events from gravitational collapse of a massive star. In those days the canonical source was a supernova collapse. These days the canonical source is a coalescing binary system. It is a little easier to understand what the waveform is going to look like in the binary case. But anyway, that was the vision in those days. So we did a series of coincidence measurements with them and published some papers on that.

**B:** Your current work still involves objects that may be sources for gravitational waves. Do you hope to make use of any of the data from future LIGO observations?

**P:** Long duration gamma ray bursts are very likely due to the core collapse of massive stars

when they form a black hole. It is likely that a rotating black hole forms in the core of a collapsing massive rotating star and then you get a relativistic jet of emission that extracts rotational energy and converts it to an outward jet of radiation; the result is a gamma ray burst. Short duration gamma ray bursts are probably also the birth signals from a black hole, but from the coalescence of a binary system such as 2 neutron stars. For this reason, short duration gamma-ray bursts likely generate gravitational radiation; these are the focus for LIGO. So if one could do a coincidence experiment where LIGO sees something and the FERMI observatory or any other gamma ray burst observatory sees a coincident gamma ray burst, that's a pretty dramatic development.

And it is also a nice cross check because the localization and detection is done by two different methods. LIGO has an antenna pattern on the sky that is very different than that of a gamma ray burst detector. With the Large Area Telescope on Fermi, if the burst has very high energy emission then we can localize it better than a tenth of a degree on the sky or something like that. If the burst is detected by the GBM instrument on Fermi that is sensitive in the MeV band and is the most likely place the first coincident detections would come from, then the Fermi localization would be a few degrees. I think the cross correlation of Fermi and LIGO will be fantastic. Coincident detection of a short duration gamma ray burst would be proof that they are indeed coalescing binary systems. That would be awesome.

**B:** Do you think the advanced detectors coming on line will soon make a direct detection?

**P:** I would bet money on it. What odds will you give me? LIGO will eventually detect gravitational radiation. When I was directly working on gravity wave detectors back in the 1980s everybody used to say 'within 10 years we're going to detect gravity waves'. We kept saying that and saying that. I think people say that now, but I believe now that is actually what will happen.

**B:** As the PI for a large collaboration, what are the challenges you find in running the organization, and do you have any advice for the LVC?

**P:** Well you guys seem to be doing pretty well. With the Fermi LAT, we're very much in operations and data analysis mode now and doing science. So it is a little different than when we were constructing the telescope. We now have a collaboration of 400 members, but we have different membership categories reflecting the fact that many members have other, complementary science interests that they are part of. So we have full members, who were either part of building the instrument and maintaining it and running it. That group is about 40% of the total group. After launch, additional full members joined who would bring expertise that benefited the collaborations ability to do science and who are willing to spend most of their time on Fermi science. In addition the Fermi LAT collaboration has members who spend much less than 50% time on Fermi science, but they bring something, say multi-wavelength data, for example a radio observer or optical astronomer, and they have an interest in collaborating that benefits the Fermi science and the collaboration. These members are Affiliated Scientist members. This gives them access to our analysis tools and collaboration meetings and to interaction within the collaboration. And they contribute directly to analysis that goes into papers; they're actually coauthors on the papers they contribute to. So we have a very nice mechanism to reach out in the world and collaborate with the people that want to collaborate with us. And it recognizes they have other research interests but they bring something to the scientific agenda of the collaboration and the mission. This has worked extremely well.

It was a little bit challenging before we launched. When we were putting the collaboration together we had two cultures. A particle physics culture, and an astronomy or astrophysics culture. At the time they were rather different. Particle physics had already grown to where typical collaborations were very large. At the time of our initial discussions about membership and publication policies we were at the level of 200 members, for particle physics that is on the small side. In any case, it was typical in particle physics experiments that authorship on papers was inclusive to all members and the authors were listed alphabetically. In astronomy it was typical that investigations involved a much smaller group with authorship on papers restricted to those who worked directly on the analysis in the paper. The authorship was not necessarily alphabetical.

We realized that there was a challenge with either approach. So we worked out something that recognizes the strengths of both approaches. We successfully formulated a publication policy and membership policy that recognizes that those two different approaches exist and can in fact be synergistic if they're managed the right way. So we have basically key papers that we designate as category 1, that are done more in the particle physics mode; everybody who contributed to the collaboration, the full members of the collaboration, are entitled to be coauthors on those papers. But they are not obligated to be; they must opt in. For full members who have contributed to building and operating the instrument this is important recognition of their crucial contributions to the science. Even though many of these individuals may

not have directly participated in the final steps of analysis reported in a paper, they're entitled to be an author on the paper. That's different than the typical astrophysics model. We also decided that category 1 papers are alphabetical. Naturally, we also have category 2 papers that typically are follow ups or narrower scope papers. The authorship is a smaller group that is involved directly in the analysis specific to the paper.

We also have a publication board that manages that process. All of the publications, whether they're the category 1 or category 2 papers, they all go through a very rigorous internal review in the collaboration. We have a lot of expertise and we call on that to improve the papers. And then we submit them to a journal. We've rarely had a paper come back from a journal with any serious issues. The papers are typically accepted fairly quickly. It just takes longer to submit them because we've gone through a process to get them to a level of readiness that we can stand behind.

It is important that we figured all of this out before we had the first bit of data. If we waited until we had data and then we started thinking of how to do this it would have been chaos. So we said look, let's think this through, talk about it, discuss it, and write down our plans. And that was very important. We didn't just wait until data started coming and then suddenly have big arguments about how we are going to put 200 names on a paper and what does the author list look like. We got that worked out ahead of time.

Interview by Brett Shapiro

LIGC<sub>2016</sub>

# Hans Bethe's Last Prediction

I have many fond memories of Hans Bethe. In February of 1987, I ran up from my office in Cornell's Laboratory of Nuclear Studies (LNS) to tell him about a new, spectacular supernova, 1987A. I found Hans in the elevator, before I ever got to his office. "Indeed nature has made me a present before I die," he responded, with a great smile.

**H**appily he took it easy and kept on working for many more years after that! I felt privileged to be able to enjoy the company of such an exceptional physicist during my time at Cornell, between 1984 and 1988. I was the new kid on the block, still in my 20's, and he was one of the greatest scientists I had ever met. We had many discussions over lunch at the campus cafeteria, on everything from physics to politics. Nuclear disarmament was a topic dear to Hans, years after his role in the Manhattan Project. We batted ideas back and forth about how (or even whether) disarmament could be accomplished. Once, we even bet on how many warheads Reagan and Gorbachev might part with! Hans was pessimistic and I was happy to win, but both of us were even happier when the disarmament took place.

We always had interesting visitors at LNS. During one of these visits, Hans, Jay Orear, and I were having lunch with a guest (it was Dick Garwin, if I remember correctly). At one point in the lively conversation that followed, the



*Hans Bethe (1906-2005) was a Professor of Physics at Cornell University from 1935. He was awarded the 1967 Nobel Prize in Physics for contributions to the theory of nuclear reactions, especially his work on energy production in stars.*

older gentlemen started reminiscing about how they had made the H-bomb work. I started asking questions about the process, and they answered them. We delved into technical details, over some drinks, until someone said, "Oops, Riccardo, this is still classified! Keep it to yourself!" I did, of course, but I enjoyed having a chance to learn technological history from those awesome thinkers.

In the spring of 1988, while I was working on the CLEO experiment at Cornell, Hans gave an impromptu LNS seminar explaining where the Sun's missing neutrinos were hiding. The high density of electrons in the Sun's core, he explained, slows down electron neutrinos just a little bit. As they emerge from the denser core on their way to the Sun's surface, they speed up to  $c$ , their in-vacuum velocity. The surprise is that electron neutrinos, created during fusion that occurs deep in the Sun's core, "flip" and become muon neutrinos at, and only at, the specific depth where their speed and wave function exactly matches that of muon neutrinos. The muon neutrinos eventually reach Earth, where they pass through Earth-based

detectors totally undetected. Electron neutrinos are therefore produced just as his solar model predicted, but the ones born below that critical depth transform into muon neutrinos and "disappear" from our detectors. The puzzle was solved! What's more, given the measured fraction of missing neutrinos, Hans was able to determine that neutrinos do have a small mass, a topic of much debate over the years. He was even able to estimate the difference in mass between the two kinds of neutrinos. He concluded, however, that neutrinos' mass could not account for the existence of dark matter.

That seminar in 1988 was one of the most inspiring scientific talks I've attended. Hans' way of using simple reasoning to advance our understanding of the universe left a deep impression on me and contributed to my decision to research gravitational waves. The last time I saw Hans Bethe was in 1997. Not long before I transited from Virgo to LIGO, I visited Cornell, my second alma mater (my first one is the University of Pisa). During my return as a visitor, I was invited to give an LNS "donut club" colloquium, to talk about upcoming developments in gravitational wave observatories. While I was getting ready to give my talk at the podium, I asked Dave Cassel, then Associate Director of LNS, about Hans. Hans had kindly attended the seminars I had given during my years at Cornell (no doubt due more to my antics than to my poor man's physics), so I inquired if he might be present that afternoon as well. Dave told me that, unfortunately, Hans had stopped coming to the Institute years earlier (he was now 91 years old); it would be unreasonable to expect him to attend my colloquium.

The seminar room was now getting full. As I connected my computer to the projector for the presentation, Hans suddenly walked in, with his usual slow and deliberate demeanor. He sat at his usual place, which had magically become vacant: second row, to the left of the speaker. After quietly acknowledging everyone's respectful surprise and admiration, he smiled and waved to me!



Overwhelmed, I could barely wave back to him. I must have presented the entire lecture about gravitational wave detectors directly to him, oblivious to the rest of the audience. I discussed the working principles and challenges of the gravitational wave detectors under construction, and gave many technical details. I explained how we optimized both Virgo and LIGO to detect binary neutron star in-spirals, because we understood that such sources must exist, given Hulse and Taylor's observations in 1974.

Hans made no questions or comments until the very end, after everyone else had had the opportunity to ask questions. When people were slowly starting to leave, he stood up; with his usual German politeness, he asked if he could say a few words. Everybody scrambled back to their seats. In the sudden silence that followed, Hans very kindly praised a seminar that had beautifully illustrated, in his own words, the "outstanding experimental prowess" needed to detect gravitational waves. He was confident that we would succeed in finding them. For the next 15 minutes, he gave us a great, impromptu lecture, and he made a prediction about gravitational waves, one which he and Jerry Brown would publish the next year.<sup>1</sup> For the entire quarter of an hour, I stood in front of him, in rapt attention, while he made his points.

He told us a marvelous story about the evolution of a pair of twin stars. The first one to change evolves into a red giant, then goes supernova and collapses into a neutron star. The second one follows suit, within about a million years, but when it reaches its own red giant stage it engulfs its companion (the first neutron star). During this period, the tiny neutron star starts eating the red giant from within, gaining mass until it becomes overweight and collapses into a black hole. He explained how little this thinning would affect the second red giant's core, which would continue its own evolution into a supernova and then a neutron star. His grand finale was that we would

soon detect ripples in space-time caused by gravitational waves, but he did not believe that twin neutron star mergers were the most promising source for what we would observe. His prediction? We would first, or at least more frequently, detect black hole-neutron star mergers, the starring characters in his story.

As for me, I was deeply moved! One of the greatest physicists of our time had kindly given what was surely one of his last lectures to me! It was long after our first discussion of collapsed stars in 1987, but the echoes of those days and of his many seminars on stellar evolution remain with me. Almost twenty years later, the two LIGO observatories have finally detected gravitational waves, a very gratifying result. I'm sure Hans would be very pleased to hear about this – gravitational wave astronomy has finally started! He would consider it another present to himself, this time from our efforts, not from nature!

As it turns out, the first detections involved double black hole signals, where each black hole weighs tens of solar masses. With their larger mass and stronger signals, black hole mergers have authoritatively taken the stage. Even so, Hans' reasoning is probably right for today's stars, but he could not bring his idea to the logical conclusion that new observations now indicate. In the earlier, low metallicity era of the Universe, when supernovae had not yet forged the other atoms all the way to iron, large stars made only of hydrogen and helium were prevalent, much more transparent, and more likely to collapse into black holes than to explode into supernovae and shed most of their mass. Lacking the sudden mass loss of a supernova event, those ancient binary stars were more likely to become heavier, tightly bound black hole binaries than binary systems produced in later times. Such fundamentally different evolution may produce more black hole inspirals than previously expected.

Events involving neutron stars, with their puny 1.4-solar-mass weight, are proving to be more difficult to detect, but the show has just begun

to unfold. Instrument sensitivity will continue to improve, and it remains to be seen whether black hole-neutron star mergers are actually more numerous than binary neutron star mergers, as Hans predicted. Time will tell, and I am still betting that Hans' last prediction was correct. And there is a new twist: during the plunge phase neutron stars get shredded and matter is ejected to carry away excess angular momentum. It has recently been noted that this baryonic matter is then free to dissociate into heavy elements. Who knows, the small black holes predicted by Hans may help to explain the puzzle of the heavy elements above iron, all the way up to uranium!

Looking back, I realize that Hans gave me a gift greater than scientific knowledge. When I was just a new kid on the block and Hans was the greatest scientist at Cornell, there could not have been a greater contrast between us. Nevertheless, Hans was always willing, even happy, to discuss anything with a young scientist like me, a friendship which I have never forgotten. I feel like I contracted a debt of honor, and I have tried to pay it forward ever since. Over time, as I have developed science projects of my own, I have always enjoyed including the next generation of students in my work. I learned from him, never to reject any one of them. Involving many young scientists and engineers in my endeavors has given me the strength to accomplish much more than I could have on my own. Thanks Hans!

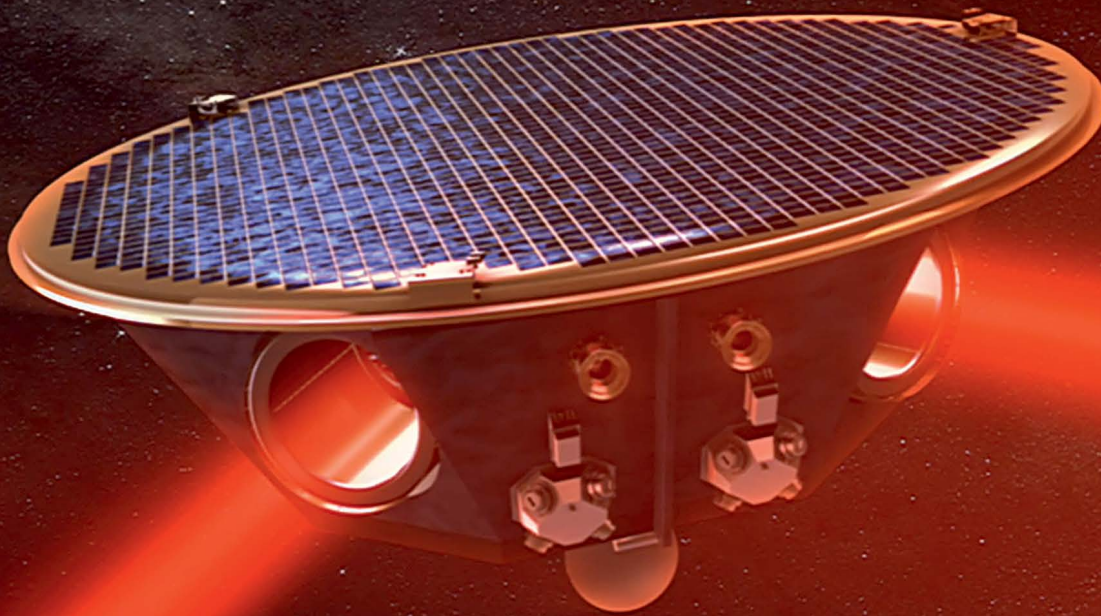
LIGO<sub>2016</sub>



*Riccardo DeSalvo is a senior resident scientist working on dielectric coatings and advanced materials at the California State University of Los Angeles. He also oversees teaching laboratories and develops techniques and materials for haptic virtual reality.*

<sup>1</sup>Bethe, Hans A., and G. E. Brown., "Evolution of binary compact objects that merge." *The Astrophysical Journal* 506.2 (1998): 780.

# The First LISA Pathfinder Results



## A Green Light for LISA

**B**efore launch, if you had asked people in the LISA Pathfinder team what performance they expect from the instrument, many would have been cautiously optimistic. Indeed, projections from modelling and ground tests suggested that the performance would be better than requirements. However, anyone who's been involved in the building, commissioning and operation of any complex instrument will tell you that the road to best performance is a long and difficult one. This makes the early results obtained on LISA Pathfinder even more special: the instrument has operated much better than requirements since switch-on, working essentially flawlessly out-of-the-box. These first results are presented below, along with some discussion of the impact they have on the future of gravitational wave observations, particularly in space.



*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.*



*William Joseph Weber*

*is a Southern Californian working on gravitational wave observation from space at the Università di Trento in Italy, where he is Associate Professor*

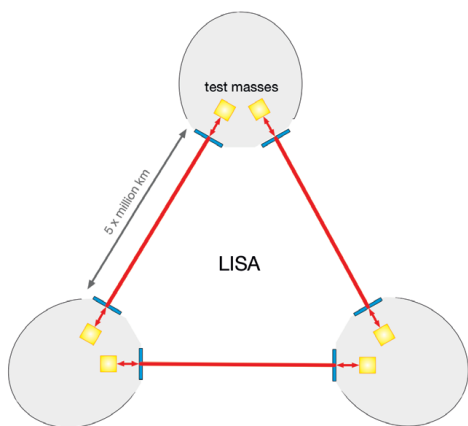
*in Physics. He is looking forward to taking his wife and two children hiking in the Dolomites, as soon as LISA Pathfinder permits it.*

▲  
*Artist's impression of a LISA spacecraft showing two laser arms, each pointing to spacecraft several million km away.*

### **Observing gravitational waves from space**

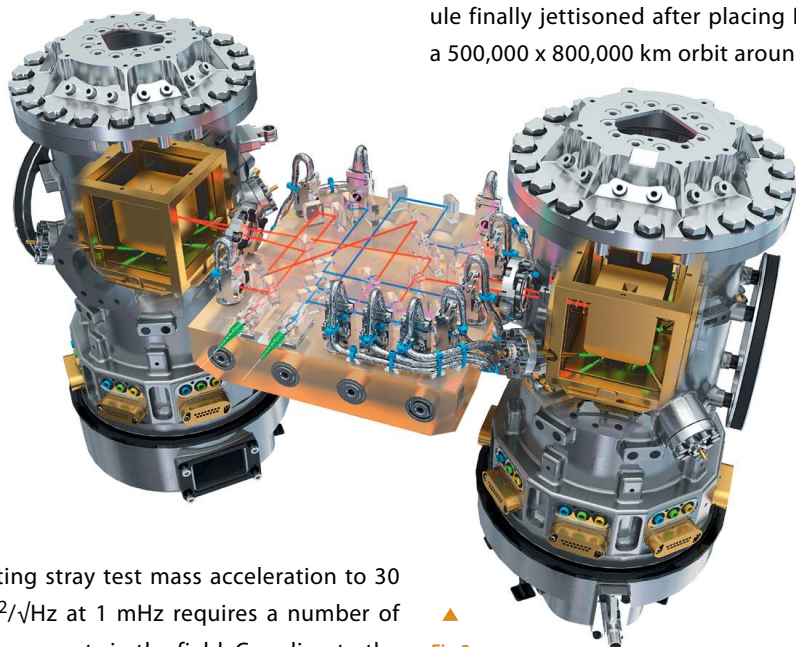
With the direct detection of a merging black-hole binary system in September of 2015, the Advanced LIGO detectors have given a first glimpse of the future of astronomy, where observations of gravitational processes will expand our understanding of the Universe enormously. Just like the electromagnetic spectrum, the systems which emit gravitational waves cover a vast range of frequencies. The signal seen by LIGO, GW150914, is at the lower end of the human audio band, around 100Hz. Such signals are emitted by the acceleration of objects with several tens of solar masses. Signals from more massive systems, such as the merging of galaxies, have frequencies much lower, and the band around a millihertz is expected to be

a rich source of gravitational waves from a variety of astronomical systems. The observation of signals with these frequencies is currently only considered feasible from space, and for this reason the science community has spent several decades studying and designing a space-based observatory, comprising 3 satellites in heliocentric orbits, forming an equilateral triangle with each satellite separated by millions of kilometres. Reference test masses free-fall inside satellites at the corners of the triangle, such that the constellation has 3 ‘arms’, each formed from a pair of free-falling test masses. The relative motion of the test masses at the end of each arm is modulated as a gravitational wave passes through the constellation. Along one arm, this relative motion is synthesised from three interferometric observations: the motion of each test mass relative to its parent spacecraft, and the inter-satellite motion. By combining the relative test mass motion of the three links using a method called Time Delay Interferometry (TDI), different interferometric combinations can be formed, resulting in an observatory that will be sensitive to gravitational waves in the millihertz band at a level similar to that achieved by ground-based observatories in the audio band.



▲ *Fig.1: The LISA concept of a space-based gravitational wave observatory comprising 3 links formed by 3 pairs of free-falling test masses.*

The European Space Agency embarked on the LISA Pathfinder mission in order to address many of the technical challenges inherent to the creation of an orbiting gravitational wave observatory, with a direct demonstration in space. The two main requirements of the LISA Pathfinder mission were to place a test mass in free-fall at the sub-femto-g level and to observe the residual acceleration using an interferometric readout with pico-meter resolution, all on time-scales of minutes to hours.



▲ *Fig.2: A CAD rendering of the core instrument on LISA Pathfinder.*

Limiting stray test mass acceleration to  $30 \text{ fm/s}^2/\sqrt{\text{Hz}}$  at 1 MHz requires a number of advancements in the field. Coupling to the noisy motion of the host satellite must be drastically reduced; there is no mechanical contact between test mass and spacecraft, and the satellite is “drag-free” controlled, with micro-thrusters, to follow the reference test mass. Test mass acceleration must be measured relative to other free-falling test masses, not the satellite. In LISA this is done by synthesizing a measurement between test masses in distant spacecraft. On LPF, this is done with a second, “witness” test mass inside the same satellite. While this second test mass must be free of stray accelerations at the same level as the first, it also has to be forced, with a weak electrostatic suspension, to maintain a stable three-body dynamical system. These two

test masses (TM) form a miniature LISA arm, with their relative acceleration measured with a heterodyne interferometer readout of their relative motion.

### On-station at L1

At 04:04 UTC on December 3rd, LISA Pathfinder was launched on a VEGA rocket from Kourou. A series of 6 orbit raising manoeuvres, performed with a propulsion module, pushed LPF onto a trajectory towards the 1st Sun-Earth Lagrange Point (L1). A 50 day journey followed, with the propulsion module finally jettisoned after placing LPF into a  $500,000 \times 800,000 \text{ km}$  orbit around L1.

During the cruise phase, with the two TMs still safely held by their launch lock mechanisms, one subsystem after another was turned on for the first time, coming to life and allowing a first check-out of much of the apparatus. The big highlight of this phase was the interferometer “first light”, which revealed a differential displacement measurement with  $7 \text{ fm/s}^2/\sqrt{\text{Hz}}$  precision, already meeting the mission requirement, in spite of a roughshod alignment of the caged TM which allowed only 3% contrast – a far cry from the 98% contrast achieved a month later with free-falling TMs, with performance addressed in the next section.

# The first LISA Pathfinder results

Early February featured the simultaneous venting to space of the TM housings and the “decaging” of the TMs, passing them from the kiloNewton-level launch lock to a roughly Newton-level suspension between two “fingers”. This allowed final checkout of the all-axis nm-level sensing needed for spacecraft control. On February 15 and 16th, the two TM were released into free-fall, not to be mechanically touched again for months and forced electrostatically, at the nanoNewton level, to follow the spacecraft. In the following days, these TM control forces diminished as the system was eased into the final measurement configuration, with the spacecraft “drag-free” controlled, with cold-gas micro-thrusters, to follow the test masses, which remain virtually free of applied forces down to mHz frequencies.

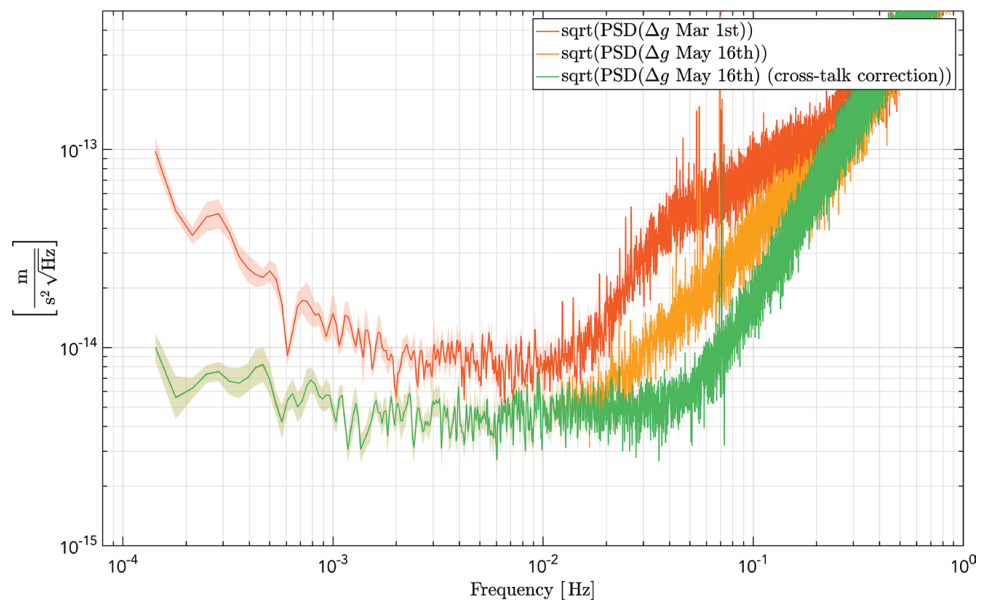
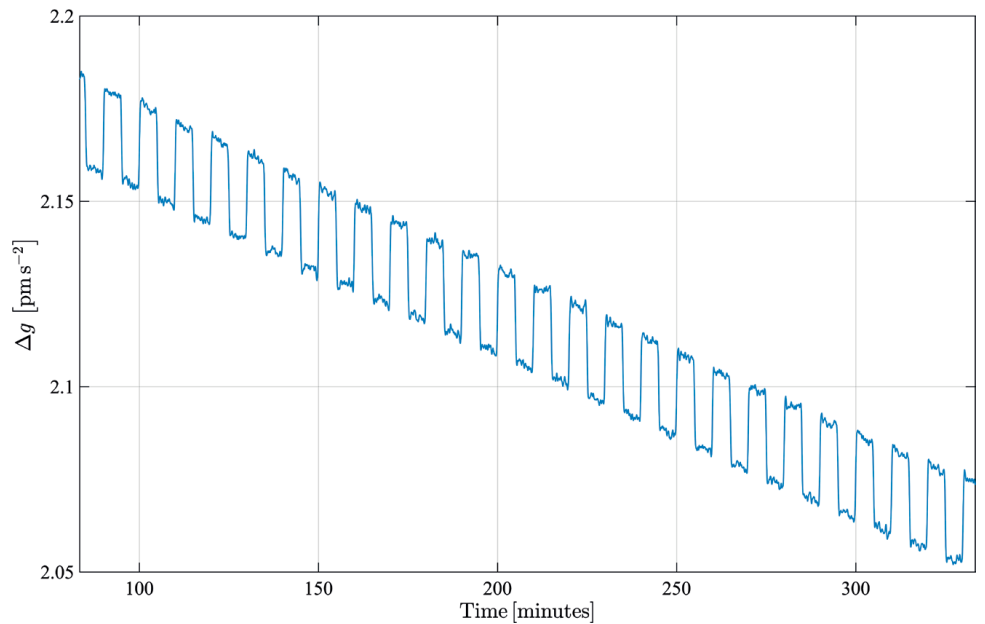
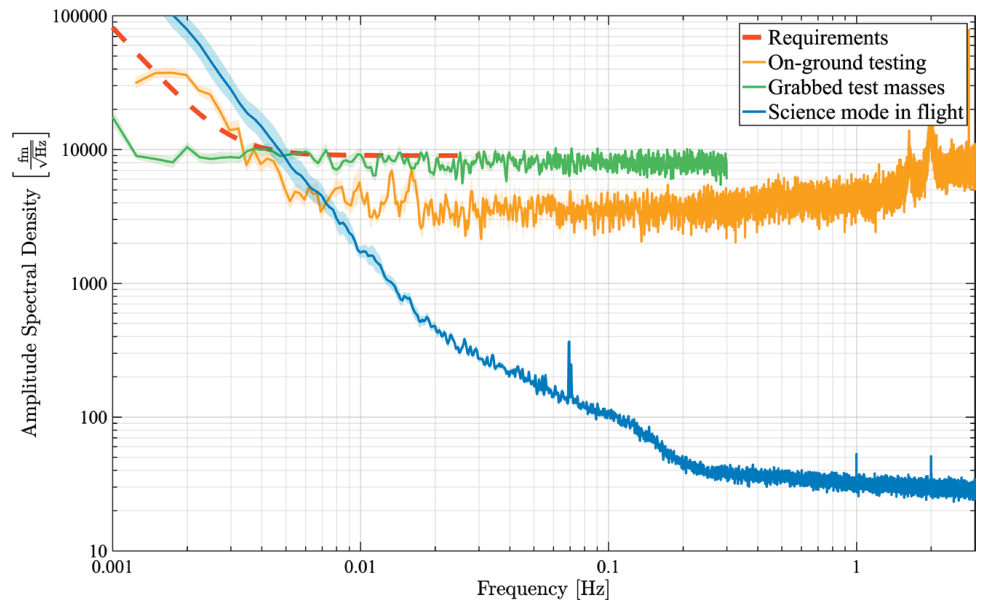
## The measurement campaign

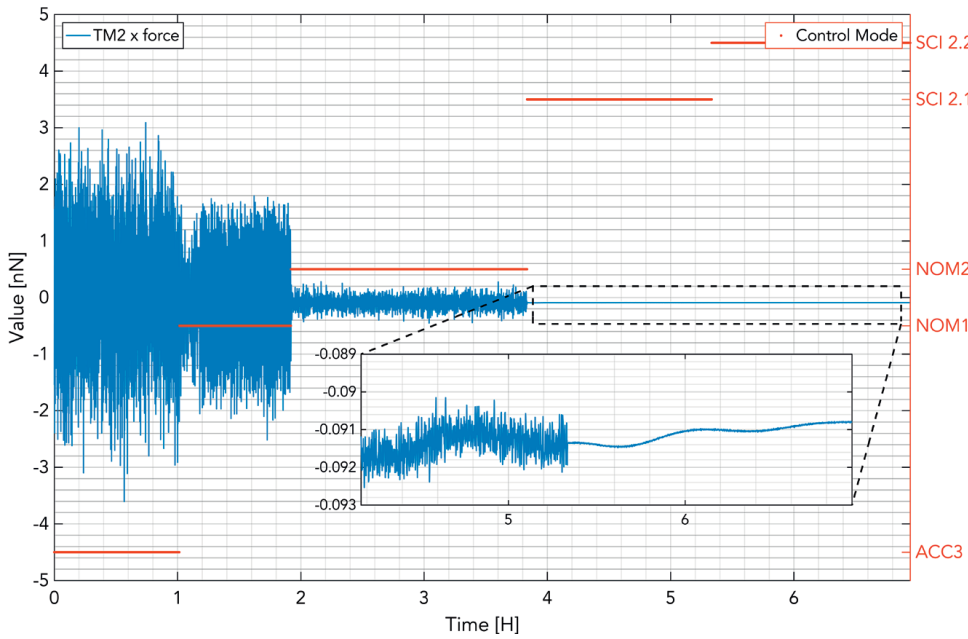
With the commissioning program finishing on the designated hour on February 29th, the first long noise measurement of the science operations commenced. From the outset, the relative acceleration performance met the requirements (“March 1” curve in Fig. 5). But the campaign to reach the best operating conditions was only just beginning.

*Fig.3 Top: Performance of the differential interferometer at different times. The measurement with grabbed test masses is made with very low contrast (~3%) due to alignment. The on-ground test data is made with fixed, but nominally well aligned mirrors in place of free falling test masses. For the flight data, where the test masses are free-falling, the noise below about 200 mHz is real test mass motion. In this condition, we can only observe the interferometer noise at frequencies above 200 mHz.*

*Fig.4 Middle: Differential test mass acceleration measurement, with a roughly 20 fm/s<sup>2</sup> signal caused by modulation of the laser beam power by 0.1%.*

*Fig.5 Bottom: Evolution of the differential acceleration measurement over the course of science operations. The first curve (March 1st) shows the performance right at the start of operations. The second curve shows the performance on May 16th, and the third is the same data with corrections for cross-talk taken into account.*





The measurement program that has followed was designed over many years by scientists in the LPF collaboration, and is aimed both to optimise the noise performance and to build a physical model of all noise sources relevant to LISA. With the promising March 1 measurement in hand, the measurement plan was fine tuned to first address the leading noise sources and continues to evolve over the mission.

The current noise (May 16), and its improvement since March 1, can be largely summarised in 4 effects:

- The noise floor above 60 mHz is set by the interferometer performance, currently at the 35 fm/ $\sqrt{\text{Hz}}$  level, two orders of magnitude better than achieved on ground. The broad bump observed initially between 10 and 100 mHz has been traced to coupling of spacecraft motion into the IFO readout, and has been reduced, first by improving the test mass alignment and then by calibration and time-series subtraction of the residual effect.
- The flat noise in the mid-frequency band is consistent with Brownian noise from molecular impacts on the TM, decreasing over time – by roughly a factor two over the measurement period – as the residual

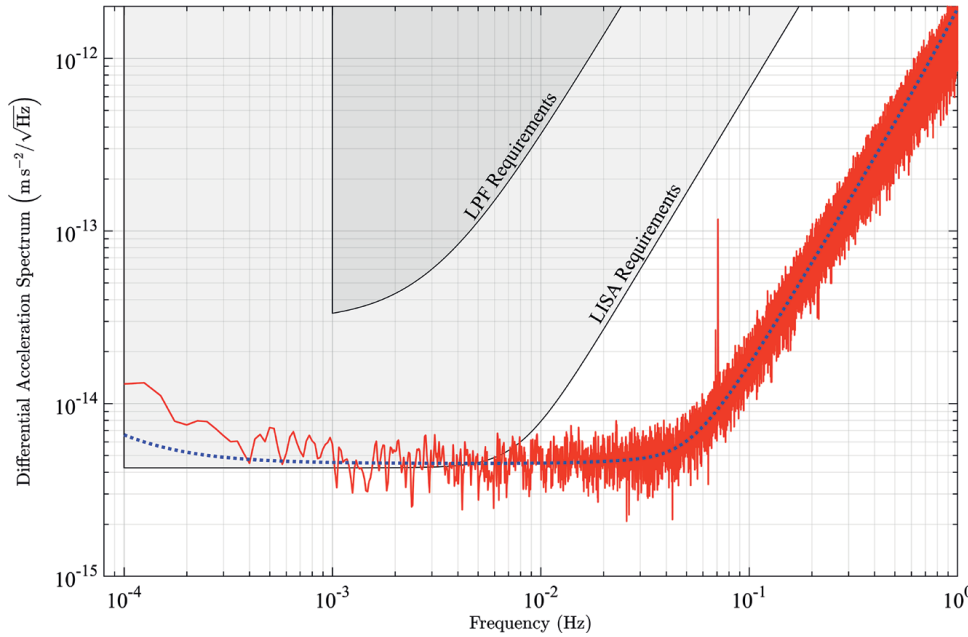


Fig.6 Top: Illustration of applied force on TM2 during the first transition from the ACC3 accelerometer mode (where the test masses are forced to follow the satellite), into a drag-free science mode, with the spacecraft forced to follow TM1, with TM2 force with roughly -90 pN to compensate the DC differential acceleration of the two test masses.

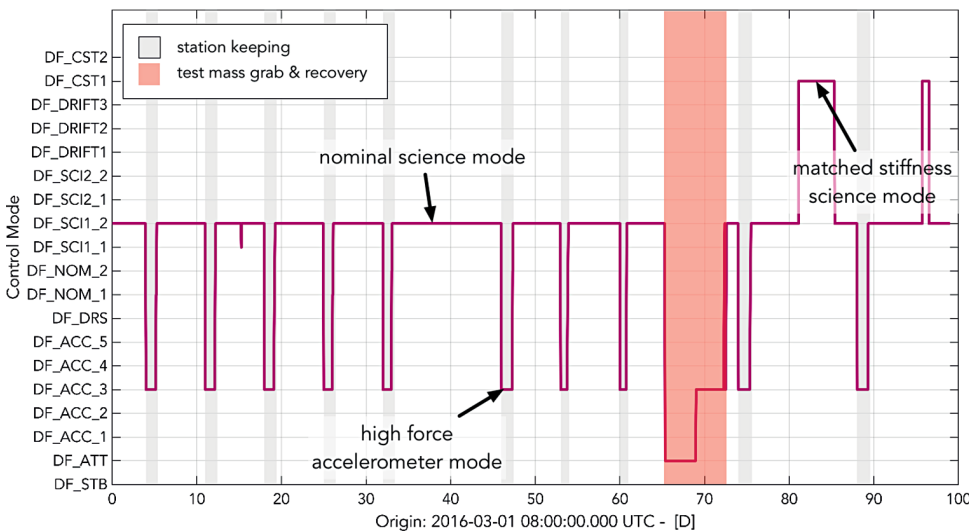


Fig.7 Middle: The high-performance measurement of differential test mass acceleration achieved on LISA Pathfinder. The data is taken from a science measurement made between May 16th and 19th. The figure shows the current level of our understanding in the form of our total error budget represented by the blue dashed line.

◀ Fig.8 Bottom: Overview of the primary control mode showing the science time, the time spent in accelerometer mode for station keeping, and two 'special' periods of custom mode where the actuation on TM1 was active but unused, thus matching the 'stiffness' coupling to the spacecraft.

gas around the TM slowly pumps away, following the system being vented to space in early February. The current noise floor could be explained by roughly  $6 \mu\text{Pa}$  of  $\text{H}_2\text{O}$ .

- The noise initially dominating around and slightly below 1 MHz has been reduced by decreasing the force authority of the TM2 electrostatic suspension, which decreases the force noise associated with gain fluctuations in the actuation electronics. The reduction in force authority is possible because of the nearly perfect gravitational balance on the spacecraft, with a measured residual DC differential acceleration between the two TMs of order  $10 \text{ pm/s}^2$  throughout the mission, compared to a “budgeted” imbalance of  $650 \text{ pm/s}^2$ .

- The “low frequency tail”, excess noise from 0.1 – 0.5 MHz, has been observed to decrease dramatically and apparently independently of our experimental “tinkering” with the measurement setup. This may be related to some relaxation mechanism, either in the decaying pressure around the TM or in some mechanical effect, but remains under investigation.

The current noise floor thus is pushing near to the goals of the original LISA observatory at all frequencies above 0.5 MHz, and even at the 0.1 MHz low-frequency band edge, the noise is a factor 3 above the LISA goal. Dissecting this noise measurement – using dedicated measurements to understand and project the noise contribution of all relevant sources onto Fig. 4 – is the remaining task of the mission and will be described in future papers.

## **Towards an observatory in space**

The results of LISA Pathfinder are a major step towards a gravitational wave obser-

vatory in space. The relative acceleration of two free-falling test masses has been shown to be low enough to allow us to access the full, rich low-frequency science program of LISA. The roughly  $5 \text{ fm/s}^2/\sqrt{\text{Hz}}$  result represents a several order of magnitude improvement over what has been achieved at MHz frequencies in geodesy missions, with the Pathfinder measurement campaign allowing consolidation of a physical model of disturbances, allowing confidence in the robust design of the reference test mass system.

On the interferometry side, LISA will require both a “long-arm” measurement of the inter-satellite motion and two “short arm” measurements between the free-falling test mass and its satellite. This second, local measurement, has been demonstrated on LISA Pathfinder at a level almost 2 orders of magnitude better than needed for LISA, making this aspect of the design extremely robust.

In addition to the acceleration noise and interferometric sensitivity numbers, perhaps equally important to the final space observatory is the reliability with which the LISA Pathfinder instrument has achieved such sensitivity benchmarks; uninterrupted science mode operation for up to two weeks at a time has been demonstrated, allowing for routine, long-term operation needed to maximize observation time with LISA.

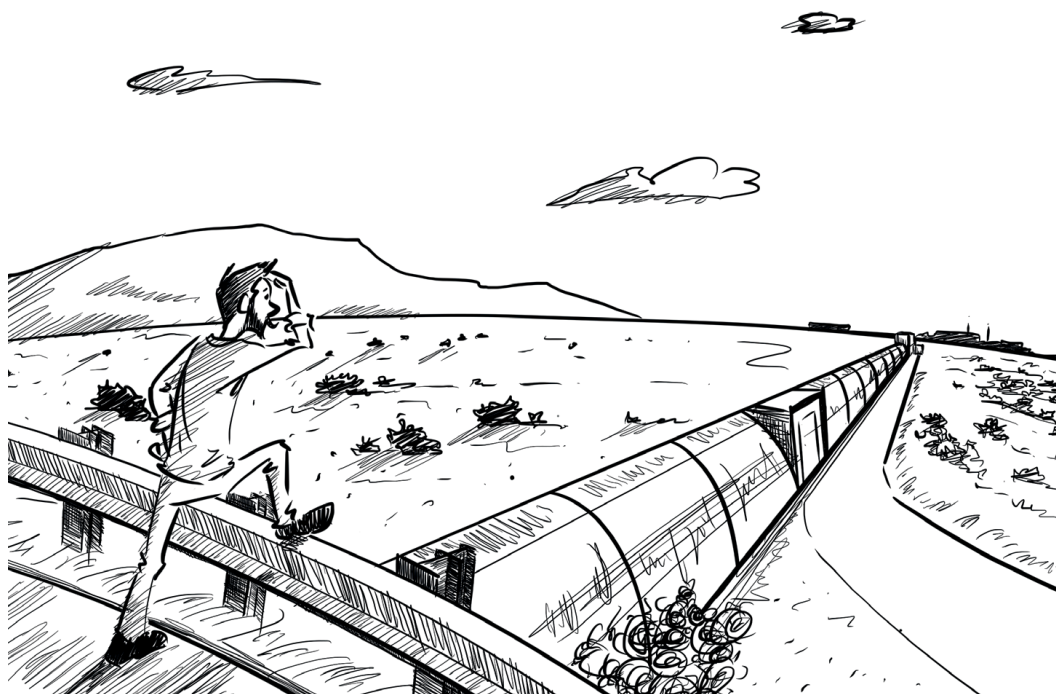
Putting this all together, the time is right to finalise the design of the LISA observatory, build it and fly! The door is open to the revolutionary science promised by a gravitational wave observatory in space.

## Demystifying Inspiral Range and Detection Rates

Ilya Mandel



is a Professor of Theoretical Astrophysics at the University of Birmingham, UK. He agrees with Lord Byron that the future is a serious matter — but, fortunately, it never comes.



**D**oes the horizon distance of LIGO have something to do with black-hole event horizons? Is a SenseMon range best used for cooking or for playing golf?

We often talk about gravitational-wave detectors as “listening” for gravitational waves rather than “seeing” them. Unlike a typical telescope, which needs to be pointed at a specific source, our detectors can hear gravitational waves from all over the sky. But gravitational-wave emission is not isotropic: for a compact binary, more power is emitted perpendicular to the binary’s orbital plane than in the plane. Detectors are not uniformly sensitive either. They are best at detecting overhead sources, and are completely insensitive to sources located in the detector plane at a 45-degree angle to the detector arms.

The horizon distance is a measure of a detector’s sensitivity to gravitational wave sources. It is the distance at which gravitational waves from a source in an optimal orientation would yield an expected signal-

to-noise ratio (SNR) of 8. An optimal orientation for a binary is face-on and directly overhead a detector. We typically define the horizon distance for a compact-object binary composed of two canonical 1.4 solar-mass neutron stars.

This horizon distance can then be related to the sensitive volume in which a detector is expected to measure an SNR of 8 or greater from the same neutron-star binary. This is done by averaging over the binary’s possible orientations and locations on the sky, both of which are assumed to be isotropically distributed. The sensitive volume is not a ball and is in fact peanut-shaped.

The SenseMon range is defined as the radius of a ball whose volume is equal to the sensitive volume. It turns out to be equal to the horizon distance divided by 2.26. The SenseMon range is a useful detector sensitivity monitor, which is projected onto the LIGO control room walls — hence the name. For a design-sensitivity advanced LIGO detector the horizon distance is about 450

megaparsecs (a megaparsec, Mpc, is about 3 million light years). The corresponding SenseMon range is about 200 Mpc. Hence, we might expect that a network of two LIGO detectors operating at this sensitivity will have a sensitive volume equal to a ball with the SenseMon range as its radius. In this case, for canonical neutron star binaries it is about thirty million cubic Mpc. If there is one neutron star binary merging in a cubic Mpc every million years, we would expect to detect around thirty binary neutron star mergers per year.

Our Universe is expanding, so when we consider distant sources, we have to take cosmology into account when computing gravitational waveforms, volumes, and comparing time intervals at source and detector. Therefore, a SenseMon range is not very useful for detection rate estimates as our sensitivity reaches cosmological distances. And, of course, the surveyed volume is much larger for heavier binaries than for those canonical 1.4 solar mass neutron stars.

## Recent Graduations

**J**uan Calderon Bustillo, previously a grad student at University of Balearic Islands, joined the GaTech LIGO group as a postdoctoral fellow in March '16.

**T**imo Denker of the Quantum Control group at AEI Hannover defended his thesis, "High-precision metrology with high-frequency nonclassical light sources" on June 17th, 2016.

**H**unter Gabbard, previously a physics undergraduate student at the University of Mississippi, will be joining AEI Hannover under Andy Lundgren.

**C**arl-Johan Haster of University of Birmingham defended his thesis, "Compact, diverse and efficient: globular cluster binaries and gravitational wave parameter estimation challenges" and is taking a postdoctoral position at the Canadian Institute for Theoretical Astrophysics in September 2016.

**T**omoki Isogai completed his Ph.D. at MIT earlier this year and has taken an industry position in Japan.

**D**avid Kelley defended his PhD thesis at Syracuse University and began a new job at Block Engineering in Marlborough, MA doing R&D for mid-infrared spectroscopy to quickly and accurately identify chemicals on distant surfaces.

**TJ** Massinger earned his PhD from Syracuse U and is taking a postdoctoral position at LIGO Caltech in summer 2016.

**E**ric Oelker defended his PhD thesis in July at MIT and is heading off to JILA to do a post doc in Jun Ye's group.

**D**irk Schütte of the Quantum Control group at AEI Hannover defended his thesis "Modern control approaches for next-generation inter-

ferometric gravitational wave detectors" on July 8th, 2016.

**M**aximilian Wimmer of the Quantum Control group at AEI Hannover defended his thesis "Coupled nonclassical systems for coherent backaction noise cancellation" on June 24th, 2016.

**A**lex Urban earned his PhD from UW-Milwaukee and is taking a postdoctoral position at LIGO Caltech in summer 2016.

## Career Updates

**M**ohammad Afrough joined the LIGO group at the University of Mississippi as a graduate student in physics working with Professor Kate Dooley.

**D**uncan Brown was named the inaugural Charles Brightman Professor of Physics at Syracuse University for his leadership role in the LIGO project, his excellence in teaching and mentoring, and his contributions to campus research computing.

**T**ito Dal Canton, formerly a postdoc at AEI Hannover, joined the NASA Goddard Space Flight Center group as an NPP fellow.

**P**aul Fulda, formerly a postdoc at the University of Florida, began a Visiting Scientist position at the NASA Goddard Space Flight Center in August.

**J**oey Shapiro Key will join the University of Washington Bothell as an Assistant Professor of Physics starting in September.

**R**yan Lang, a postdoc at UWM, is starting a tenure-track position in the fall at Hillsdale College in Hillsdale, MI.

**S**heila Rowan was appointed Chief Scientific Adviser to the Scottish Government on June 13, 2016.

**B.S.** Sathyaprakash is moving from Cardiff to Penn State in August/September 2016 but he will continue to work part time (0.25 FTE) at Cardiff.

**P**atricia Schmidt will be moving from LIGO Lab Caltech to Radboud University in the Netherlands, Working with Gijs Nelemans and Samaya Nissanke, in fall 2016.

**S**ebastian Steinlechner is moving from the University of Glasgow to the University of Hamburg, to join Roman Schnabel's group as a postdoctoral researcher, beginning 1st of August.

**A**mber L. Stuver began her term on the APS Forum on Outreach and Engaging the Public Executive Committee as a member-at-large. She was also appointed to the APS Committee on Informing the Public. She is currently vice-chair of the AAPT Space Science and Astronomy Committee and will be Chair next year.

**S**alvatore Vitale will join the physics faculty at MIT in January 2017.

## Awards

For their fundamental contributions to the first detection of gravitational waves, **Bruce Allen, Alessandra Buonanno and Karsten Danzmann** from Max Planck Institute for Gravitational Physics are being honored with the Lower Saxony State Award 2016.

UTRGV REU student **Dieddra Atondo** has been selected to present her research poster 'BayesWave Analysis for LIGO External Trigger Generation' at the Emory University-Laney



Graduate School STEM Research and Career Symposium September 18-20, 2016.

**Lynn Cominsky** received the Wang Family Excellence Award for her extraordinary commitment to student achievement and exemplary contributions in her fields. She also received the American Astronomical Society's Education Prize and the American Astronautical Society's Sally Ride Excellence in Education Award for her work in bringing STEM education to K-12 and college classrooms.

**Ronald Drever, Kip Thorne, and Rainer Weiss** were awarded The Gruber Cosmology Prize, a Special Breakthrough Prize in Fundamental Physics, The Shaw Prize in Astronomy, and the The Kavli Prize in Astrophysics for conceiving of and designing LIGO, resulting in the first direct detection of gravitational waves. The Gruber prize recognizes the entire LIGO team, and The Breakthrough Prize is shared with 1012 contributors to the detection of gravitational waves, including 1005 authors on the first detection paper.

**Marty Fejer** was elected to the National Academy of Sciences.

**Hunter Gabbard** from the University of Mississippi was awarded a Fulbright Fellowship from the U.S. Department of State to work at AEI Hannover.

**James Hough** received an honorary Doctor of Science degree in June from the University of Glasgow in recognition of his "outstanding contribution to one of the most significant scientific discoveries of the century".

**Nergis Mavalvala** was elected a Fellow of the International Society on General Relativity and Gravitation for her innovative contributions to the development of squeezed quantum states of light and classical optomechanics techniques, and their application

to the quantum enhancement of km-scale interferometers for the detection of gravitational waves.

**Hafizah Noor**, a graduate student at the Institute for Gravitational Research at the University of Glasgow, was made the "Youth Icon" of Malaysia by the Malaysian Deputy Prime Minister in May.

**Norna A. Robertson** was elected a Fellow of the International Society on General Relativity and Gravitation for her pioneering contributions to the development of interferometric gravitational wave detection especially in the areas of laser stabilization, test-mass suspension systems, and test-mass charging.

**Sheila Rowan**, Director of the Institute for Gravitational Research in Glasgow, has been awarded the Hoyle Medal and Prize in recognition of her work in gravitational waves.

**Susan Scott** was elected to the Australian Academy of Science in May as one of 21 New Fellows for the Academy in 2016.

**Borja Sorazu**, a postdoctoral fellow at the Institute for Gravitational Research at the University of Glasgow, has been given the Aixé Getxo! award (in the category of Innovation and Scientific Culture) from his home area of Getxo in the Basque Country, Spain, in recognition of his contributions to the gravitational waves discovery.

**Kip Thorne** was elected a Fellow of the International Society on General Relativity and Gravitation for his wide-ranging achievements in gravitational physics, including foundational contributions to our understanding of black holes and gravitational waves, and for his essential role in the development of gravitational wave astronomy.

## General

As part of the Glasgow science festival a poet, comedian and musician visited the School of Physics and Astronomy, talking to physicists and astronomers. The resulting "cosmic cabaret" featured a journey into the cosmos and a space-themed variety night:

'Keep Breaking it Down' - <https://www.youtube.com/watch?v=Ac2htH1Pfsk>

'LISA' - [https://www.youtube.com/watch?v=cz9Zo0coW\\_k](https://www.youtube.com/watch?v=cz9Zo0coW_k)

'Save as Universe' - <https://www.youtube.com/watch?v=XZBmFkECS50>

## LSC Elections

**Roman Schnabel** was re-elected chair of the Quantum Noise working group (QNG) in August 2015.

**Matt Evans** was re-elected chair of the Advanced Interferometer Configurations (AIC) Working Group in September 2015.

**Volker Quetschke** was re-elected chair of the Lasers and Auxiliary Systems group in September 2015.

**Gregg Harry** was elected co-chair of the LIGO Academic Affairs Council (LAAC) in November 2015, replacing Jocelyn Read.

**Beverly Berger** was elected senior-member of the LIGO Academic Affairs Council (LAAC) in November 2015.

**Christopher Berry** and **Paul Fulda** were elected postdoctoral representatives of the LIGO Academic Affairs Council (LAAC) in November 2015.

**Sarah Gossan** was elected the Graduate Student Member of the LIGO Academic Affairs Council (LAAC) in November 2015.

**John Veitch** was re-elected co-chair of the CBC Working Group in February 2016.

**Brian Lantz** was re-elected chair of the Suspensions and Isolation Working Group (SWG) in March 2016.

**Ian Martin** was re-elected chair of the Optics working group (OWG) in March 2016.

**Alicia Sintès** was elected co-chair of the CW Working Group in March 2016, replacing Graham Woan.

**Siong Heng** was re-elected co-chair of the Burst Working Group in March 2016.

**Nelson Christiansen** was re-elected as co-chair of the Stochastic working group in March 2016.

**Barry Barish** and **Peter Saulson** were re-elected “members at large” for the LSC Executive Committee in February 2016.

**Dennis Coyne** was elected chair of the new Controls Systems Working Group (CSWG) in July 2016.

LIGO<sub>2016</sub>

## Detection: A Poem

Andrew Steane

*Andrew is a Professor of Physics at the University of Oxford, U.K. His research work is mostly in quantum information theory and laser manipulation of atomic systems. For his co-discovery of quantum error correction he was awarded the Maxwell Medal and Prize of the Institute of Physics in 2000.*



### LIGO, September 14, 2015

*How express this dazzling of the dark?  
This pull and twist that wound the sheets  
of time  
And pulsed that taught fabric,  
Inscribed its eye-blink cry,  
Its pin-prick shout  
That for a sudden breath  
Outshone the universe?*

*Twin globules of sloping space,  
Vacuum-cleaners of the vacuum,  
Each slides and slips the gentlest  
Swirling paths into its timely maw.  
How feel and say what jagged  
edge is this?  
Its massive daggered heart  
is folded down,  
Inexorably collapsed, glutted on itself,  
Drawing down the curled-up horizon  
Where time runs in.*

*So two mercurial blobs  
Insensibly embraced across the  
Depths of space some eon time ago,  
Began their friendless waltz  
In automatic tune,  
Curling weights of folded space  
Falling to their given final gyre.*

*To these globs, empty of thought,  
No forgiveness applies,  
And so we forgive their insatiable hunger.*

*Harbingers of their own doom,  
Their grace is mathematical.  
Warping each other's space  
In utter obliviousness,  
They rush into their own vortex  
In massive neither joy nor fear.*

*Then as each distends to swallow the other  
Their sudden death is born,  
Scratching its rising scream  
Into the world's field,  
Pitching into the foundations the  
Three-solar gravity-quake that  
Throbbled the surface of the dark.*

*How express the murmur of that sound  
A billion years away?  
The ant's tread upon the moth's wing  
On the far side of an impossible moon?  
The weight of pin-prick winter light in a  
cold dawn?  
How show the stillness of the hanging  
Mirror, its poised mass,  
The thunder of the laser light?  
The vacuum strained one thousand  
Billion billionth part  
And shook the foundations of our thought.  
A ripple in the mind  
That said,  
"Behold! Behold the void that sings!"  
And to each human countenance  
A smile of grace it brings.*

Andrew Steane<sup>1</sup>

<sup>1</sup>With a line from Stevie Smith

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# LIGO: A Big Pool of Diversity

LIGO is a big pool of diversity. The first detection opened an opportunity for many to bring science to their homes and communities. The press release was translated into 21 different languages.

**Corey Gray (Siksika Nation)**

“As far as I know, this is the first time a scientific discovery has been translated into a Native American language. I wanted to reach out to Native youth and to help them see that science is cool, and people like them are involved.”

**Max Isi (Uruguay)**

“I was invited to do a TV interview and 5 radio interviews remotely. After the media frenzy I received messages from several teenagers and young people in Uruguay saying that our discovery was very inspiring and encouraged them to pursue careers in science, this was very rewarding!”

**Darkhan Tuyenbayev (Kazakhstan)**

“My vacation back home turned into a series of interviews and seminars. Not only university students and faculty attended the seminars but also high school students. I believe they were excited to find out that there was someone from Kazakhstan who contributed to the discovery.”

**Nutsinee Kijbunchoo (Thailand)**

“Scientists in Thailand are rare. Women scientists are even rarer. When the public found out that someone from Thailand was involved in the discovery, LIGO went viral. I did several live broadcast interviews hoping to inspire Thai youngsters and show them that being part of a big scientific discovery isn't just a dream.”

The first detection went viral not only in LVC-member countries but all around the world!

