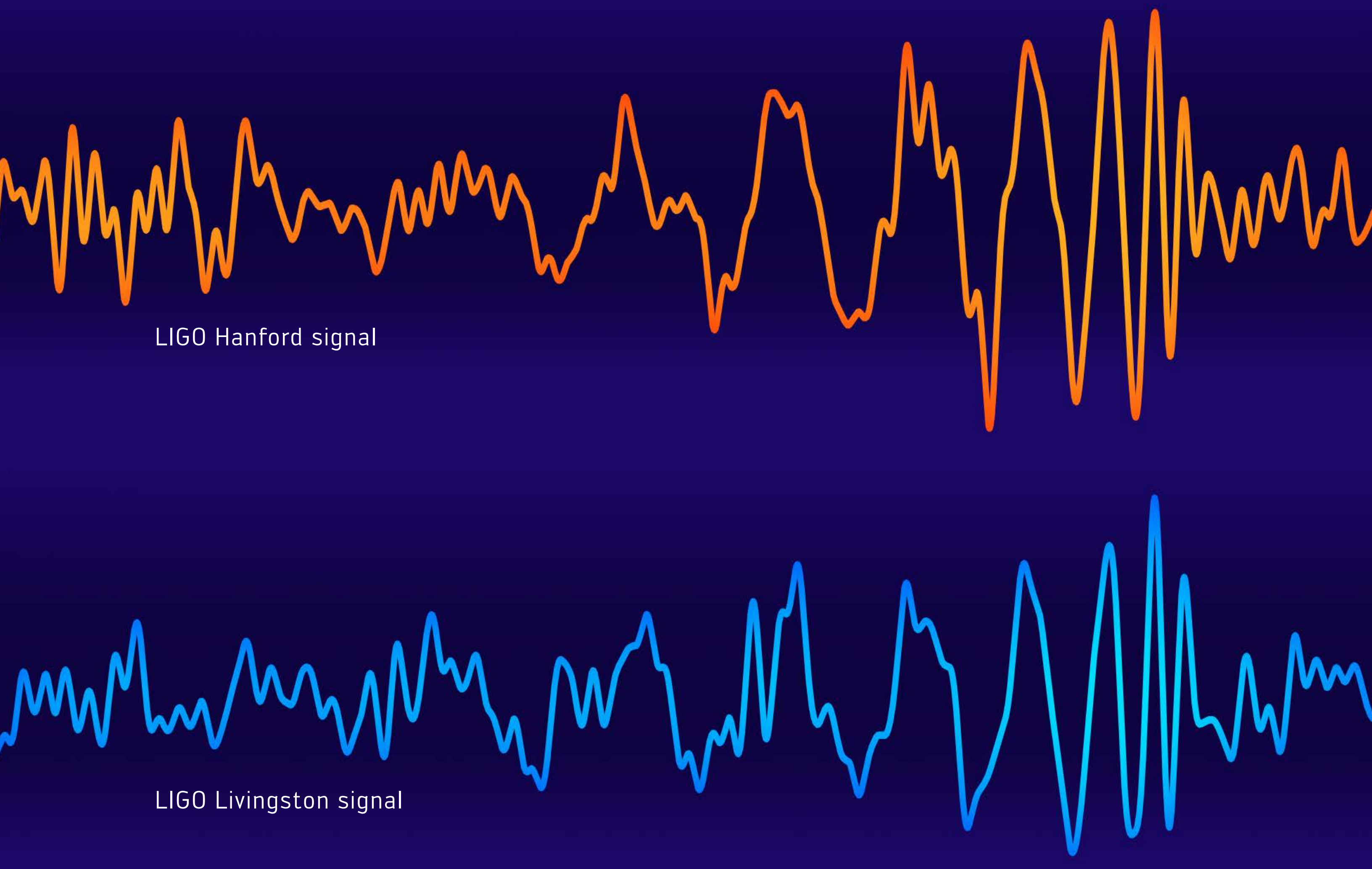
LIGO Scientific Collaboration

issue 8 3/2016

LIGO MAGAZINE

First detection!

9:50:45 UTC, 14 September 2015



The front page shows the first detection of a gravitational wave by LIGO. The orange (top) and blue (bottom) lines show the filtered data collected by the Hanford and Livingston observatories, respectively. The data from each detector is bandpass filtered between 35 Hz and 350 Hz, with additional notch filters used to suppress strong instrumental spectral lines.

The back cover and "the waveform explained" show the modeled signal at the LIGO Hanford observatory. The trace is not a line but a band; the width indicates the 90% uncertainties in the black hole binary signal constructed using the posterior samples from the coherent follow-up analysis from both the Hanford and Livingston observatories. The posterior samples provide a distribution for the system parameters from which a signal can be generated for each set of parameters. Then the central 90% of the signals at each sample time are highlighted to produce the trace shown. All model waveforms are bandpass filtered between 35 Hz and 350 Hz, with additional notch filters used to suppress strong instrumental spectral lines. The width of the band indicates the range of plausible signals given our noise model.

The title, the back cover and the 'waveform explained' have been provided by Ben Farr, currently a McCormick Fellow at the University of Chicago, Christopher Berry, currently a Postdoctoral Research Fellow at the University of Birmingham and Nutsinee Kijbunchoo who is currently an operator at LIGO Hanford.

Image credits

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

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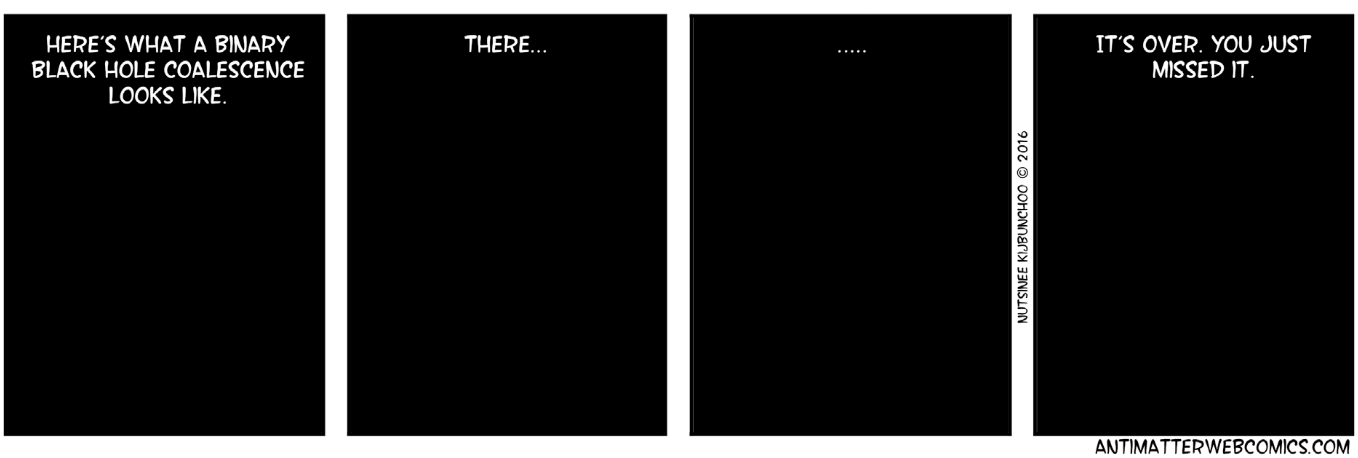


Nutsinee Kijbunchoo

Welcome to the LIGO Magazine Issue #8!

Welcome to the eighth issue of the LIGO Magazine. You might have heard it on the news: a gravitational wave has been detected by LIGO. Many of us have worked years or decades towards this moment, and now is the time to celebrate this very special achievement. The era of gravitational wave astronomy has now truly begun and our work and our science has suddenly become much more visible to colleagues and also to the public.

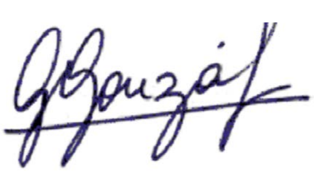
This issue was prepared at the time when the scientific papers on the detection were still being written, and when most groups were working hard to prepare new material for the public announcement. We are very grateful to our contributors whose time and effort made it possible to now present some stories and images that you might not have seen before. Our title, the back cover and the several articles in the magazine are all about GW150914, the first gravitational wave signal detected by the LIGO observatories. In `The Transition of Gravitational Physics – From Small to Big Science' we complete the story on the origins of LIGO from the personal perspective of an NSF officer at the time. Throughout the magazine we have collected quotes, thoughts and reactions from a small number of people. We believe that their thoughts and stories are representative of the very many people who contributed so much to LIGO, but who cannot all be presented here. And while we are celebrating the ground-based detection, LISA Pathfinder is very successfully demonstrating the technology for a space-based detector. Read more about this in 'LISA Pathfinder: going operational'.

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

Andreas Freise for the Editors

LIGO Scientific Collaboration News

Gaby (Gabriela) González
LSC spokesperson



September 14, 2015 marks the end of a long journey and the beginning of a new adventure. On that day, a feeble ripple of space time was turned into a visible (and audible!) signal by our LIGO detectors, two of the most incredible devices ever built by humankind. That ripple of space time briefly crossing paths with Earth after a billion year long voyage through the depths of space brought us GW150914, the first ever direct detection of a gravitational wave. GW150914 brings to a conclusion the long journey to directly detect gravitational waves. It also opens the way to a new adventure: gravitational-wave astronomy.

Since 2008, when Advanced LIGO was funded, many people were involved in installation and commissioning to make the Advanced LIGO detectors a reality - this was hard work, invisible to most people outside the LIGO detectors, but of course the heart of the discovery. Since 2010, the LSC has been not only analyzing initial LIGO and Virgo data, but also tuning search codes to make the best of the Advanced LIGO detectors data to come, and trying them in seven (!) engineering runs.

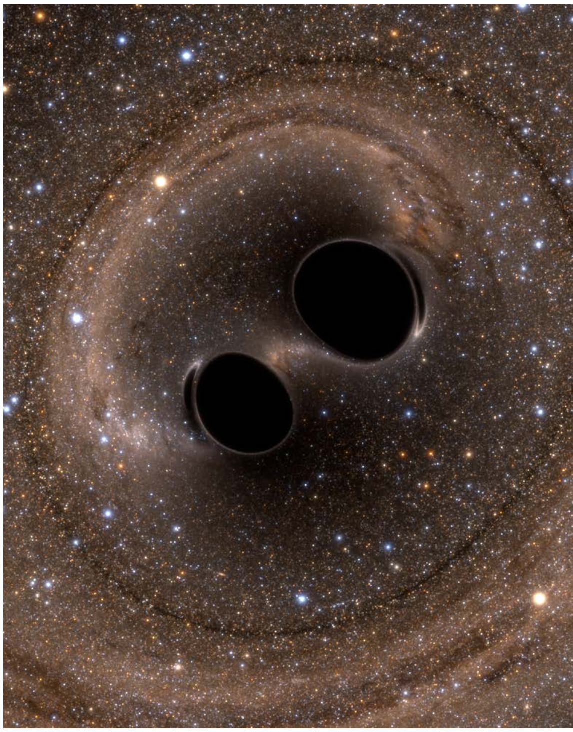
The last chapter in the story leading to GW150914 began on August 17, 2015. At 8:00 a.m. PDT, the green light was given to start ER8, the last Engineering Run before O1, the first observing run with Advanced LIGO. The H1 and L1 detectors were over 3 times more sensitive than the initial LIGO detectors to the coalescence of neutron stars, but our expectations for a first detection in O1 were low. However, we also knew that nature sometimes likes to play with us. So we worked hard to be ready; when you start looking, you never know what you might find! In the weeks leading to the planned start date of the first observing run, the Hanford and Livingston labs were buzzing with the many activities required to deliver stable detectors and achieve long, robust lock stretches of data. Installation and commissioning technicians, engineers and scientists were working around the clock to make the detectors ready for the upcoming observing run. 24-hr coverage in control rooms began on August 10. While LSC fellows, control room operators, and the laboratory scientific staff joined by 'detcharians' were monitoring and calibrating the instruments, analysts across the LSC finalized the codes required to analyze the data. After a many months discussion, we approved in August our "Detection Procedure". As the end of ER8 approached, stable and reliable locking of the interferometers with a BNS range of ~80 Mpc was now routine.

Then September 14 came. The first gravitational-wave signal ever seen by LIGO was not a binary neutron star chirp. It was the chirp of two massive black holes colliding at half the speed of light, found by an online code looking for unmodeled events. Fascinating. Nature had indeed surprised us! In a matter of hours, analysts started analyzing the event, the detector characterization group began looking at data artifacts that could rule it out, instrumentalists wondered who could plant a double blind injection in the detectors, and the LSC management scratched their heads to figure out the next step: there was no room for mistakes, we had to be sure this was a detection before we could announce it to the world. This would take months and a lot of work!

We took more data, and analyzed it in several different independent ways. The Detection Committee was now put to work not in "preparation" mode any more, but for real. The highest priority was now to collect the data needed for validating the candidate event. Just one month after the event, on October 22, a first LVC-wide meeting informed the collaborations that a detection case for GW150914 was being assembled, so we could start "Step 2" of the detection procedure. The next day, a Paper Coordination Team was appointed to draft the discovery paper - even while the analysis results were still being reviewed. In parallel, the Education and Public Outreach group put together many resources, including how to explain what a black hole merger is to school children. What happened in the weeks that followed is recent history – a swirl of faster and frenzied activities much like the inspiral of the two black holes culminating with Dave Reitze's "We did it!" on February 11, 2016.

We did it indeed: we discovered gravitational waves, and we did it all together. The road has been long, starting in the 70s with the vision and later, in the 90s, with the funding, and always with people collaborating and moving forward, getting stronger through differences and discussion. The discovery has the world in awe, looking at the sky in a different way - and we should all be very happy and proud.

This is the beginning of an even more exciting road ahead: detectors with improving sensitivity, more observing runs, more detectors (Virgo!), more detections and likely



A physically accurate gravitational lensing visualization of a binary black hole merger.

more surprises, more interest in what we find and who we are. While we celebrate our first detection, let's get our hands and heads together again, and keep opening this new window on the universe.

Here's to you, and to the gravity-bright universe!

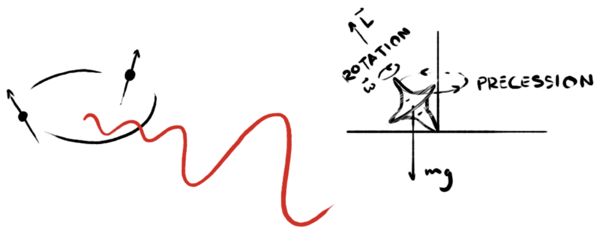
Gabriela González and Marco Cavaglià

The waveform explained

[BLACK HOLE]

A BLACK HOLE IS ONE OF THE SIMPLEST OBJECTS IN THE UNIVERSE. IT HAS ONLY TWO CHARACTERISTICS: ITS MASS (WHICH DETERMINES ITS SIZE), AND ITS SPIN (HOW MUCH SPACETIME SWIRLS AROUND).

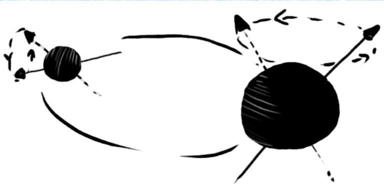
WHEN YOU HAVE TWO BLACK HOLES IN A BINARY SYSTEM, THINGS GET MORE COMPLICATED. WE NOW HAVE THE MASSES AND SPINS OF BOTH BLACK HOLES. THE SPINS STAY THE SAME SIZE DURING THE ORBIT, BUT THEIR DIRECTIONS WOBBLE AROUND IN A PROCESS CALLED PRECESSION. THE GRAVITATIONAL WAVES REACHING EARTH FROM THE BINARY ALSO DEPEND ON WHERE THE BINARY IS AND WHICH WAY IT IS ORIENTATED.



[SPIN]

AS THE BLACK HOLES ORBIT EACH OTHER, THEIR SPINS CHANGE DIRECTION. THIS ALSO CAUSES THE ORIENTATION OF THE ORBIT TO TOPPLE BACKWARDS AND FORWARDS A LITTLE. THIS PRECESSION LEAVES AN IMPRINT ON THE GRAVITATIONAL WAVES: THEY BECOME LOUDER AND QUIETER AS THE SPINS WOBBLE AROUND. THE PRECESSION DEPENDS ON DIRECTIONS OF THE TWO SPINS, COMPARED TO EACH OTHER AND COMPARED TO THAT OF THE ORBIT. THE SPIN OF THE MORE MASSIVE BLACK HOLE HAS A LARGER EFFECT THAN THAT OF THE SMALLER ONE.

WE DON'T SEE MUCH SIGN OF PRECESSION IN GW150914. THIS MAY BE BECAUSE SPINS ARE SMALL, ITS INCLINATION MEANS THE WOBBLES AREN'T VISIBLE, OR A COMBINATION OF BOTH. SINCE THE INSPIRAL IS SHORT, WE WOULD NOT EXPECT TO SEE A LARGE EFFECT IN ANY CASE.

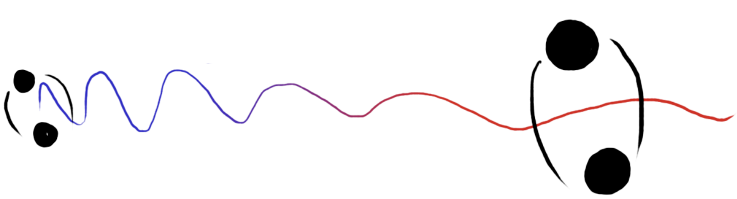


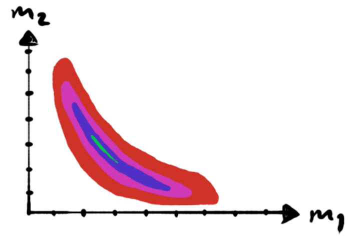
[REDSHIFT]

THE EXPANSION OF THE UNIVERSE AFFECTS GRAVITATIONAL WAVES IN A COUPLE OF WAYS. AS THE UNIVERSE EXPANDS, IT STRETCHES THE WAVES TRAVELLING THROUGH IT. THIS IS WELL KNOWN IN ASTRONOMY AND IS CALLED REDSHIFT, AS IT MAKES VISIBLE LIGHT MORE RED. TO HAVE A LARGE EFFECT, THE WAVES MUST HAVE TRAVELLED A LONG WAY.

THE FIRST EFFECT IS THAT THE FREQUENCY OF THE WAVE CHANGES. THIS HAS THE SAME IMPACT AS CHANGING THE MASSES: **THINGS FURTHER AWAY APPEAR MORE MASSIVE**. THE SECOND EFFECT IS TO CHANGE THE AMPLITUDE, WHICH IS THE SAME AS CHANGING THE DISTANCE: WE OFTEN TALK ABOUT THE LUMINOSITY DISTANCE, WHICH ABSORBS THIS EFFECT, BUT ISN'T THE SAME AS IF WE MEASURED THE DISTANCE TO THE SOURCE USING A TAPE MEASURE.

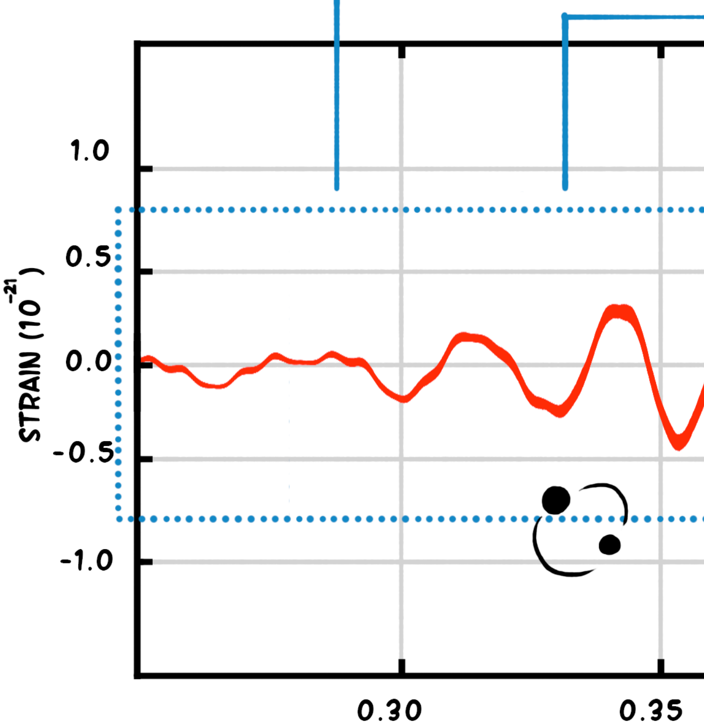
IF WE GET ENOUGH MEASUREMENTS OF HOW GRAVITATIONAL WAVES ARE REDSHIFTED, WE COULD POSSIBLY LEARN SOMETHING ABOUT HOW THE UNIVERSE IS EXPANDING.

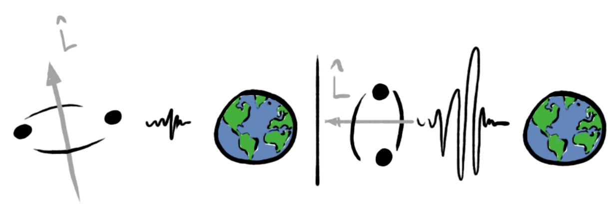




[CHIRP MASS]

THE WAY THE SIGNAL CHANGES DURING THE INSPIRAL IS PRIMARILY FIXED BY A COMBINATION OF THE BLACK HOLE MASSES WE CALL THE CHIRP MASS. IF WE SEE LOTS OF CYCLES OF INSPIRAL, WE CAN MEASURE THE CHIRP MASS REALLY WELL (BETTER THAN A FRACTION OF A PERCENT). WHEN THINKING ABOUT WHAT WE CAN LEARN FROM GRAVITATIONAL WAVES, PEOPLE OFTEN FIRST THINK ABOUT THE CHIRP MASS.





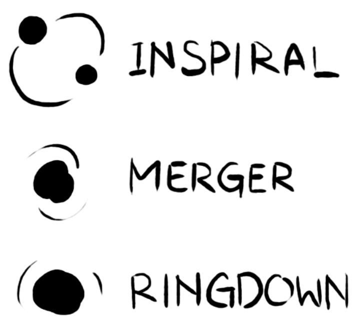
[INCLINATION]

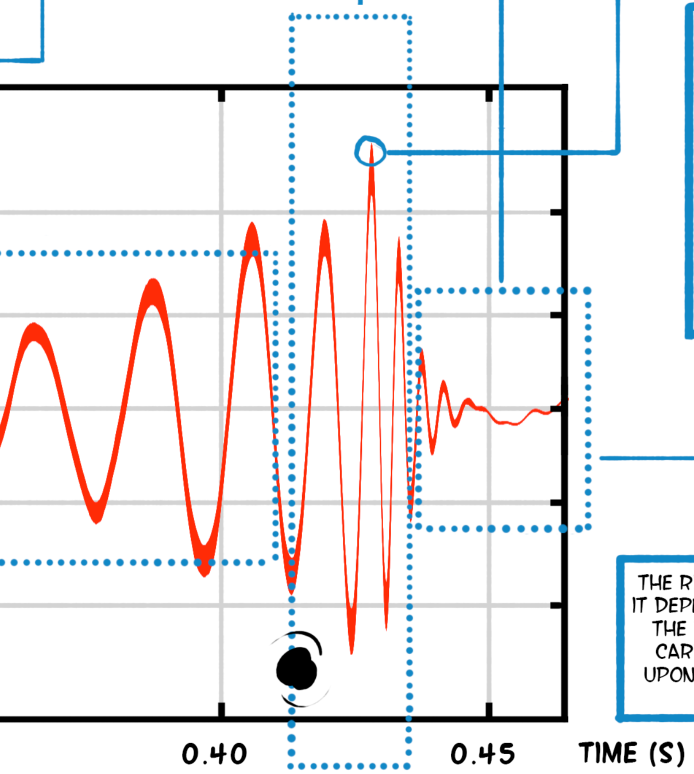
THE WAY THE BINARY IS FACING THE EARTH DETERMINES THE GRAVITATIONAL WAVES WE SEE. IF IT IS EDGE ON, THE SIGNAL IS QUIETER, BUT IT IS EASIER TO SPOT SMALL CHANGES CAUSED BY THE BLACK HOLES' SPINS. IF IT IS FACING US, THE SIGNAL IS LOUDER, BUT IT'S HARDER TO TELL IF THE ORBIT WOBBLES BECAUSE OF PRECESSION. WE HAVE A GREATER CHANCE OF DETECTING A FACE-ON BINARY BECAUSE THEY CAN BE DETECTED FROM FURTHER AWAY.

[STAGES]

ONE OF THE REASONS WE DIVIDE UP THE GRAVITATIONAL WAVE SIGNAL IS BECAUSE DIFFERENT TECHNIQUES CAN BE USED TO CALCULATE THE WAVES AT DIFFERENT POINTS. THE EARLY **INSPIRAL** CAN BE CALCULATED USING POST-NEWTONIAN THEORY (THIS STARTS WITH NEWTON'S THEORY OF GRAVITY AND ADDS LITTLE EXTRA BITS TO ACCOUNT FOR HOW THINGS CHANGE IN GENERAL RELATIVITY). THE **RINGDOWN** CAN BE CALCULATED USING BLACK HOLE PERTURBATION THEORY (THIS STARTS WITH THE FINAL SHAPE OF THE BLACK HOLE, AND SEES HOW IT REACTS TO SMALL CHANGES). THE **MERGER** CAN ONLY BE CALCULATED USING NUMERICAL RELATIVITY (SIMULATIONS OF THE FULL EQUATIONS OF GENERAL RELATIVITY WHICH TAKE LOTS OF COMPUTING POWER); THIS HAS ONLY BEEN POSSIBLE IN THE LAST 10 YEARS, SO THE MERGER WAS THE LAST PART OF THE PUZZLE.

IF WE HAD A BINARY CONTAINING NEUTRON STARS INSTEAD OF BLACK HOLES, THE INSPIRAL WOULD BE MUCH THE SAME, BUT THERE WOULD NOT BE THE SAME MERGER AND RINGDOWN. THE SIGNAL WOULD BE MUCH MESSIER, POSSIBLY FEATURING NEUTRON STARS BEING RIPPED APART, BEFORE COLLIDING AND COLLAPSING TO A FINAL BLACK HOLE.





[AMPLITUDE]

THE SIZE OF THE SIGNAL, ITS AMPLITUDE, DEPENDS ON HOW FAR AWAY THE BINARY IS. IF THE DISTANCE WERE TWICE AS BIG, THE AMPLITUDE WOULD BE HALF. THE QUIETER A SIGNAL IS, THE HARDER IT IS TO DETECT, AND THE LESS WE CAN LEARN ABOUT ITS PROPERTIES.

HEAVIER SYSTEMS PRODUCE LOUDER GRAVITATIONAL WAVES AS THERE IS MORE MASS MOVING AROUND TO CREATE THE WAVES.

THE SIGNAL AMPLITUDE DEPENDS UPON THE WAY THE BINARY IS FACING (ITS INCLINATION), AND ITS POSITION IN THE SKY: THE DETECTORS ARE NOT EQUALLY SENSITIVE TO GRAVITATIONAL WAVES FROM ALL DIRECTIONS (THE SIGNAL IS LOUDEST WHEN THE SOURCE IS DIRECTLY ABOVE OR BELOW A DETECTOR.

$$h(t) = \frac{G m v^2}{c^4 r}$$

[RINGDOWN]

THE RINGDOWN PART OF THE SIGNAL COMES FROM THE FINAL BLACK HOLE, SO IT DEPENDS UPON ITS MASS AND SPIN. THE FINAL MASS IS ALMOST THE SAME AS THE TOTAL MASS OF THE TWO INITIAL BLACK HOLES (SOME ENERGY IS LOST, CARRIED AWAY BY THE GRAVITATIONAL WAVES). THE FINAL SPIN DEPENDS UPON THE SPIN OF THE INITIAL BLACK HOLES AND HOW THEY WERE ORBITING AROUND EACH OTHER WHEN THEY MERGED.

[TOTAL MASS]

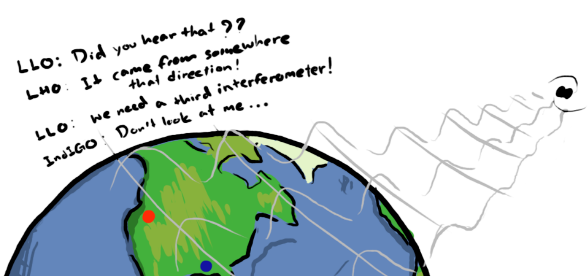
THE TOTAL MASS OF THE SYSTEM DETERMINES HOW LONG IT TAKES FOR THINGS TO HAPPEN. HEAVY SYSTEMS ARE BIGGER, AND SO CHANGE MORE SLOWLY. THE GRAVITATIONAL WAVES ARE AT LOWER FREQUENCIES, WHICH MEANS THAT LIGO CAN ONLY SEE THE FINAL PARTS. LIGHTER SYSTEMS PRODUCE GRAVITATIONAL WAVES AT HIGHER FREQUENCIES, SO WE CAN MEASURE MORE OF THE INSPIRAL.

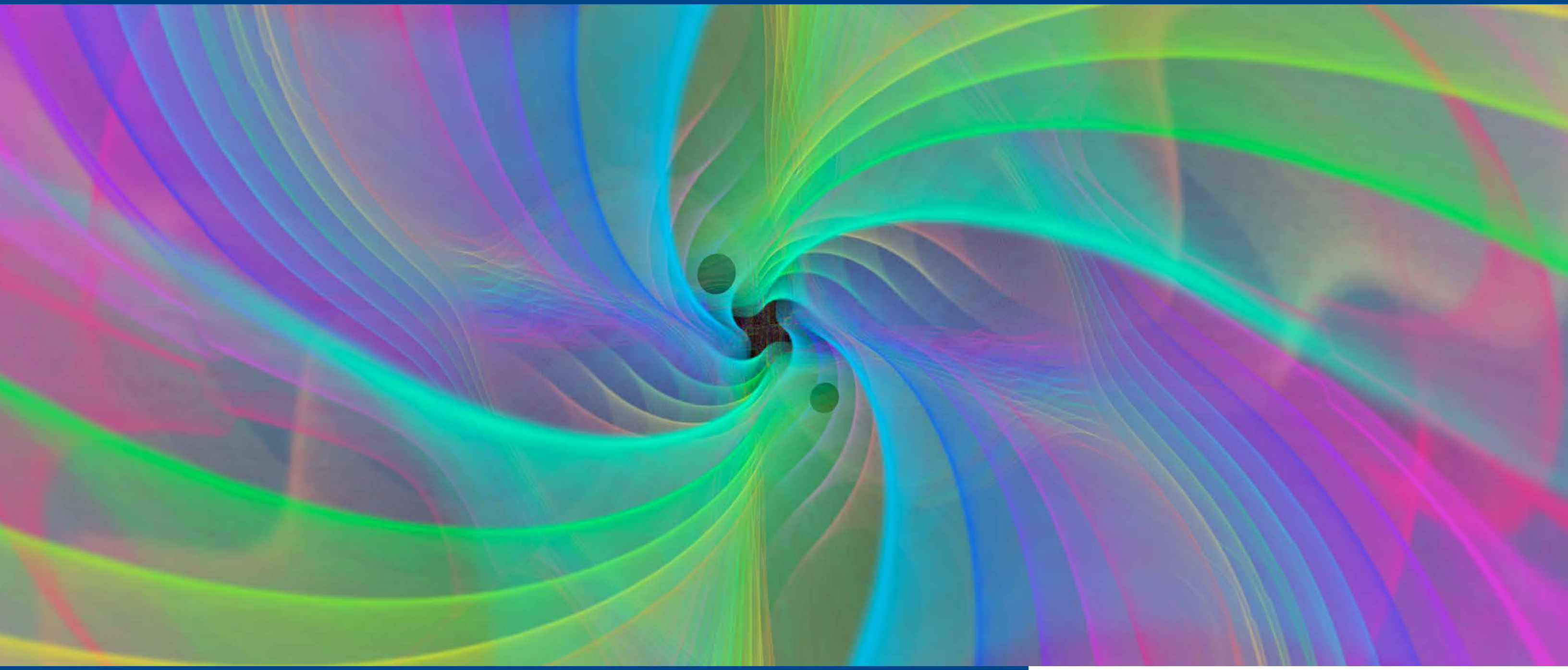
THE TOTAL MASS OF THE SYSTEM SETS WHICH PARAMETERS ARE MOST EASILY MEASURED. FOR REALLY MASSIVE SYSTEMS WE MEASURE THE TOTAL MASS BEST (AS WE ONLY SEE THE MERGER AND RINGDOWN), BUT FOR LIGHT SYSTEMS, LIKE BINARY NEUTRON STARS, WE MEASURE THE CHIRP MASS BEST (AS WE ONLY SEE THE INSPIRAL). GW150914 IS SOMEWHERE IN THE MIDDLE.

[SKY]

WITH MULTIPLE DETECTORS, WE CAN WORK OUT WHICH DIRECTION THE GRAVITATIONAL WAVES CAME FROM BY LOOKING AT THE TIMES WHEN THE SIGNALS ARRIVED AT EACH DETECTOR. THIS IS SIMILAR TO HOW YOU CAN LOCATE THE SOURCE OF A SOUND USING YOUR EARS.

WE CAN GET SOME EXTRA INFORMATION ABOUT THE DIRECTION FROM HOW LOUD EACH SIGNAL IS (SINCE EACH OF THE DETECTORS HAS ITS BEST SENSITIVITY IN A DIFFERENT DIRECTION), AND WHERE THE WAVE IS IN ITS CYCLE.





Timeline of GW150914

Numerical-relativity simulation of the gravitational waves emitted by GW150914, the black hole binary detected on 14 September 2015 by Advanced LIGO.

About 1 billion years ago: Two black holes merge, releasing approximately 3 solar masses of energy in the form of gravitational waves. These waves start spreading through the universe at the speed of light. They will be the first gravitational waves detected by LIGO, GW150914.

About 100,000 years ago:
GW150914 enters the Milky Way.

Berlin, Germany - November 25, 1915:
Albert Einstein presents his General Theory of Relativity to the Prussian Academy of Sciences. GW150914 is 99 years, 9 months, and 20 days away.

MIT - April 15, 1972: Rai Weiss
Publication of Quarterly Progress Report No. 105 outlines the concept behind LIGO. GW150914 is 43 years, 4 months and 30 days away.

1992: The epoch of LIGO construction begins, leading to the realisation of the two observatories LIGO Livingston (LLO) and LIGO Hanford (LHO).

2002: The two initial LIGO detectors and the GEO 600 detector start their first period of scientific data taking, 'Science Run 1'.

Hanford, Washington and Livingston, Louisiana - October 20, 2010:
With the end of the sixth science run, the era of the first generation detectors ends, without the detection of a gravitational wave. At the same time the installation of Advanced LIGO begins with the decommissioning of the initial LIGO detectors. Two upgraded 4 km instruments will be installed at LIGO Hanford and LIGO Livingston. GW150914 is 4 years, 10 months and 25 days away.

LLO - May 27, 2014:
The second-generation detector at LLO, called L1, is locked fully for the first time. GW150914 is 465 days away.

Deinstallation of an Initial LIGO seismic isolation platform at LHO.

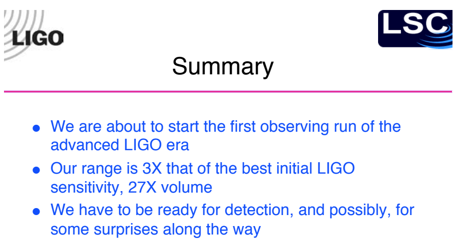
LHO - December 3, 2014:
The detector at Hanford, H1, is now fully locked. Commissioning and noise hunt-

The detection of gravitational waves was the result of decades of work by hundreds of people. This timeline has contributions from a small number of collaborators, with interesting stories to tell; it is in no way meant to amplify their roles above those of the rest of the LIGO and Virgo Scientific Collaborations.

ing proceeds on both detectors, slowly but steadily improving their performance, in the drive towards the first observation run, O1.

LHO – September 9 2015, 22:00 UTC – Mike Landry:

An all-hands meeting was convened at LHO, describing expectations for the O1 run, operator and LSC Fellows coverage, alerts, the Rapid Response Team. The final bullet of the presentation read "We have to be ready for detection, and possibly, for some surprises along the way." GW150914 is 5 days away.



Final slide of the LHO all-hands meeting of Sep 9, 2015

Teamspeak JRPC Channel - September 10, 2015 – Lisa Barsotti:

The best-attended Joint Run Planning Committee call of the year started with an evaluation of readiness to begin O1 on Monday, September 14th, as originally scheduled. Leaders of groups representing different aspects of the run were asked to give a "GO/NO GO" to proceed. Run coordination: GO! Detectors: GO! Commissioning: GO! "This is going to be easy", I thought while chairing my first meeting. Jeff Kissel then reported for Calibration, saying the measurements would be completed on-time but more time would be required for a reliable on-line calibration, crucial for sending alerts to partners. Also, technical issues were complicating hardware injections. Both Detector Characterization and Data Analysis groups stressed that hardware injections were crucial for validating data quality and analysis pipelines, especially with respect to on-line analyses. The JRPC call ended with a large fraction of the groups asking for a few more days to complete these tasks...so... NO-GO! A new tentative date to start the run: September 18th. "Not a big deal, just a few more days. It's not like we are going to detect gravitational waves on day one..." GW150914 is ~4 days away.

LLO - September 11, 2015 - 15:00 UTC - Brian O'Reilly:

We had a meeting of site personnel where we talked about event alerts and how we needed to be ready for a detection. At the time there was a minor stir from the fact that a Gamma Ray Burst Alert #18263 related to Short GRB 150906B had explicitly mentioned the Advanced LIGO detection horizon. I remember trying to not overstate the chances of a detection but to emphasize that our mindset for this run should be different. GW150914 is ~3 days away

September 13, 2015 – 14:00 UTC:

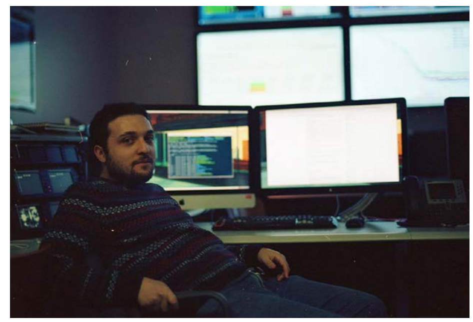
GW150914 is now closer to Earth than Voyager 1. It is ~18 hours away.

LLO - September 13, 2015 - Gaby Gonzalez, Les Guthman and the Documentary Project Team:

Gaby: I remember telling Les that we were very excited about starting to take data, we didn't expect to see anything, but we never knew - I even mentioned that we knew so little about black holes, that it was possible we'd see those in the run… GW150914 is ~12 hours away

LHO - September 13-14, 2015 – Stefan Ballmer and Evan Hall:

Nearing midnight, sitting in the Hanford control room, Evan and I finished measuring the output mode cleaner mode-matching. There were more measurements to be done before "hands-off" for the official start of the observation run. But, no rush - the run start had been delayed by a week. Those measurements could wait until the morning. It was time to declare the interferometer undisturbed and go home. GW150914 is less than 3 hours away.



Evan Hall

LLO - September 14, 2015:

Joe Betzwieser: I had, (along with Shivaraj Kandhasamy and Adam Mullavey) just finished updating the real-time calibration model with our latest numbers. We had finished taking measurements on the interferometer between 07:30 and 08:00 UTC (2:30 to 3:00 am), and had been analyzing the data. I left the site just after my last logbook entry of the night around 09:05 UTC (04:05 am local time). GW150914 is less than an hour away.

LLO - September 13-14, 2015 – Anamaria Effler and Robert Schofield

Anamaria: I had traveled to Hanford the week before the event for a week of environmental noise coupling tests with Robert Schofield and then we both traveled

◀ *Interview with Gaby Gonzalez at LLO on Sunday Sept. 13, about 12 hours before the detection. Left to right: Christine Steele, editor; John Armstrong, Director of Photography; Gaby; Les Guthman, Director and Producer.*

to Livingston. As luck goes, we didn't finish all the tests we had in mind and were still injecting until 2am on that Monday the 14th. We then worked from the control room until 4am. We wanted to make sure our data were sufficient for what we deemed important tests before embarking on others. We discussed if we should do "car injections" where we take a GPS watch and drive a big car next to the buildings, applying the brakes violently every five seconds exactly, so we can see if we can extract the pattern in DARM. This helps us place limits on traffic near the detector. It's a quick test so doesn't require too much "awakeness" and we could've knocked it off our list. But the GPS watch had unsynched from the satellites and somehow that was the last straw and we said "fine, let's just call it done and go, we can live without this test". I distinctly remember (because I was asked many times the next few days), looking at my car clock as I was driving off and seeing it was 4:35am, remembering it was off by 3 minutes, and being annoyed.

As Anamaria and Robert leave the site GW150914 is less than 20 minutes away.

LLO Electronic Logbook – September 14, 2015, 09:05 UTC – William Parker:

LLO General
william.parker@LIGO.ORG - posted 04:05, Monday 14 September 2015 (20526)
IFO Status

Operating Mode: Observing

Range: 68 Mpc

seismic is quiet; weather is clear

Livingston, Louisiana

- September 14, 2015 - 09:50:45 UTC: GW150914 is detected by the Livingston instrument, L1.

Hanford, Washington

- September 14, 2015 - 09:50:45 UTC: GW150914 is detected by the LIGO Hanford instrument, H1. This coincident detection occurs ~7 ms later than at L1, within the light travel-time between the two sites.

Having interacted briefly with the LIGO test masses, GW150914 propagates onwards essentially undisturbed.

LLO – September 14, 2015, 09:53:51 UTC – Alex Urban, Reed Essick:
The Coherent WaveBurst (cWB) data analysis algorithm detected GW150914. An entry was recorded in the central transient event database (GraceDB), triggering a slew of automated follow-up procedures. Within three seconds, asynchronous automated data quality (iDQ) glitch-detection follow-up processes began reporting results. Fourteen seconds after cWB uploaded the candidate, iDQ processes at LLO reported with high confidence that the event was due to a glitch. The event was labeled as "rejected" 4 seconds afterward. Automated alerts ceased.

Processing continued, however. Within five minutes of detection, we knew there were no gamma-ray bursts reported near the time of the event. Within 15 minutes, the first sky map was available.

At 11:23:20 UTC, an analyst follow-up determined which auxiliary channels were associated with iDQ's decision. It became clear that these were un-calibrated versions of h(t) which had not been flagged as "unsafe" and were only added to the set of available low latency channels after the start of ER8. Based on the safety of the channels, the Data Quality Veto label was removed within 2.5 hours and analyses proceeded after restarting by hand.

AEI Hannover – September 14, 2015, 10:00 UTC – Marco Drago and Andy Lundgren:
Marco: I was in my office that day as usual, working on a paper, when I received a mail from the pipeline regarding an event. I was not really surprised, the alert threshold was near 1 event per day, so I was convinced it was a typical noise event. My colleague Gabriele and I reviewed the coherent event display. Just looking at the time-frequency plot, it was clear that this event was coming from a binary coalescence. The SNR was so loud that we were convinced that it was an injection. However, I did not find any declared injections at that time, so I went to Andy's office to ask him. I remember that my first sentence was not "We have an event", but, "Is someone making a CBC injection?" Andy said no, so I told him that there was a very nice event. He asked me for the GPS time and I realized I had left it in my office! So crazy. Andy made Omega scans, found there was no standard hardware injection, and confirmed the event in the data. He then knocked on the wall to call Collin from his office (it was quite funny) and we started to call the CBC people and inform them.

Andy called the laboratories to ask the detector status. I am not sure that we told them about the event, we were not sure who to ask for information. Andy's office in a short time became full of people looking at the event. Someone asked: "What do we do now?" At a certain point I went back to my office to start the email, "Very interesting event…"

LLO control room phone – September 14, 2015, 10:27 UTC – Andy Lundgren calls operator William Parker:

AL: Hi, this is Andy from DetChar. Is anyone online?

WP: Yes, Livingston Control Room here.

AL: We're tracking an event here. What is the current state of the detector? Is everything running nominally? Are there any injections being done?

WP: We've got a good strong lock, everything is normal. There's no injections.

September 14, 2015 - 10:55 UTC - Email to Burst Group:

*From: Marco Drago <marco.drago@*******.de>*
Subject: [burst] Very interesting event on ER8
*Reply To: burst@******.org*

Hi all,
cWB has put on gracedb a very interesting event in the last hour.
https://gracedb.ligo.org/events/view/G184098
This is the CED:
https://ldas-jobs.ligo.caltech.edu/~waveburst/online/ER8_LH_ONLINE/JOBS/112625/1126259540-1126259600/OUTPUT_CED/ced_1126259420_180_1126259540-1126259600_slag0_lag0_1_job1/L1H1_1126259461.750_1126259461.750/

Qscan made by Andy:
https://ldas-jobs.ligo.caltech.edu/~lundgren/wdq/L1_1126259462.3910/
https://ldas-jobs.ligo.caltech.edu/~lundgren/wdq/H1_1126259462.3910/

It is not flag as an hardware injection, as we understand after some fast investigation. Someone can confirm that is not an hardware injection?
-Marco

Gainsville, Florida– September 14, 2015, 12:00 UTC – Sergey Klimenko:

September 14 morning I was checking e-mails. I saw the Coherent WaveBurst (cWB) alert. Alerts were expected, what was not expected was the unusually high signal-to-noise ratio of 24, way above any background event. It reported a clean chirp in both detectors with the chirp mass of 27.6 Solar Masses. My first impression was that this was a hardware injection but digging deeper I realized this was not the case. "Big Dog deja vu" - I thought - "but much more spectacular!". After some cross-checks and consultations, it was clear that we needed to start the detection checklist. After 8 AM people woke up and the e-mail floodgates broke wide open.

Richland, Washington – September 14, 2015 12:00 UTC - Mike Landry:

Waking on Sep 14 I checked emails, finding Marco Drago's message on the "Very interesting event". With such a high SNR, I assumed this would prove to be a hardware injection, quite possibly a test blind injection. I had an email conversation with Gaby and David Shoemaker at 6:30 in the morning in which, looking at the experimental logs for the past couple of days, we thought it highly likely a blind injection test. David confessed the following misgivings about such a test process. From his email that morning: "I find the blind injections are really a lot like telling someone sailing across the ocean in a small boat with only periodic internet connection that you love them, and waiting to hear back what they think, and to discover after days, weeks, or months they were just kidding around." As I sit here now, writing this, I am happy that the universe ultimately responded in a generous and loving way.

I drove to the lab, speeding and amped up, and cornered Jeff Kissel, our local LHO blind injector. Having myself been a member of the blind injection team in the past, I knew I could not ask him if he made a blind injection the night prior, but I could ask : "Are we in a blind injection phase right now?". I did so, pretty emphatically. He answered "no", as he did to "did you make a regular injection", "did you make a blind injection test on regular channel", and finally for good measure, "did you make any injection at all?". Hearing Jeff say no to all these questions was astonishing.

I phoned Gaby to confirm with her that I could tell the 9:00am Detector Characterization meeting that the cWB candidate was not due to a blind injection. I got her voicemail. Because we were not in a blind injection phase (which requires notifying the collaboration - blind injectors can't take the LSC completely by surprise), and in order to get the event response moving, I said so, in Detchar. There was no blind injection. I took that meeting standing up, in the small conference room at LHO. At about 9:20 I left the meeting for a little while, walked down to the control room, and we initiated the first of our Rapid Response Team (RRT) responses to gravitational wave triggers. I asked Jeff Kissel to write an event (EVNT) log on the blind and regular injection channels. Patrick Thomas checked the badge reader logs to assess access to the experiment halls. Sheila Dwyer and commissioners looked for ADC overflows, timing and issues on site. The CDS group looked at remote logins. These were the first of many event logs in the new password-protected "EVNT" logbook, on GW150914.

LLO - September 14, 2015, 13:00 UTC – Brian O'Reilly:

When I got to the control room the night shift operator, William Parker, informed me that someone had called to ask about our status because there was an event. The audio was bad, and William thought the person who called was named Eric. I spent a few days looking for the right Eric or Erik, until we figured out that it was

Andy Lundgren calling from Germany. We had a film crew on-site and they were there for the morning meetings. We talked about the alert, but didn't dwell on it, except to emphasize that alerts like this were to be expected through O1 and that we needed to be very systematic in our approach to them.

There was some confusion due to the data quality ("iDQ") veto of the signal. Sergey Klimenko sent an email at 11:15 UTC, which I read after our 13:20 UTC morning meeting in the control room:

From: Sergey Klimenko
Subject: [burst] Fwd: action required for GraceDB event : G184098(burst_cwb_allsky)
*Reply To: burst@****.org*
Why this event has been rejected by iDQ! - this is a nice inspiral with Mchirp = 27 Mo.
Sergey.

We have a 09:00 AM (1400 UTC) meeting at LLO with group managers/senior staff. At this meeting I mentioned the event. There was not much excitement. We were following up, I mentioned that I would poll the site by email to find out who was at the site in the hours before and after the event, and what activities they were engaged in. There was a feeling that it was a blind injection, and I got that reaction from several people when I showed them the spectrogram. I remember Carl Blair, one of the LSC Fellows, said something to the effect that it looked so good it had to be an injection.

Recall that at the September LVC meeting someone (I think it was J. Kissel) communicated to Gaby that "there would be a blind injection test in ER8" (quote may not be exact). So I was convinced that this was the promised test.

At 11:00 Central I joined the DetChar call. I distinctly remember when Mike Landry said "It is not a blind injection", on the call. The reaction in the room at LLO was very pronounced.

That set in motion a blur of events. We quickly decided to freeze the detector. We have a meeting on Monday afternoons to go over the tasks for Tuesday maintenance. At that meeting we canceled all maintenance activities (Rai Weiss told me later that from his vacation home in Maine he saw these cancellations and worried that something had gone very wrong). Of course something had gone very right, and we spent the next 4+ weeks making sure we collected enough background to be able to say so with confidence.

In talking with Joe Giaime (The Head of the Livingston Observatory) over that day and the next couple of days he was still not convinced. Dave Reitze was to visit LLO on Wednesday and the plan was to ask him directly if this was a blind injection. When Dave did show up I brought this up at a meeting on September 16th. Dave said very clearly that as far as he knew it was not a blind injection. And he should have known.

Dave Reitze on blind injections

LHO - September 14, 2015 - 22:00 UTC - Mike Landry and Fred Raab:
Fred came to my office in the afternoon, and I pulled up the Omega scans of the event for

Our LIGO colleagues have done an outstanding job for reaching such an unbelievable sensitivity. I deeply admire their capacity, well knowing how difficult it is. The detection of this black hole coalescence brings also, in my opinion, the first true experimental evidence of black holes, all that on top of the gravitational wave detection. A great job. I hope that Virgo will follow in operation very soon for creating, together with LIGO, the first gravitational wave observatory.
- Adalberto Giazotto

*Beautiful! Congratulations to all of us who finally succeeded inventing, designing, planning, building and operating these crazy instruments. I will not regret the last 35 years of my scientific career. My consideration to those scientists in our research institutions, NSF, CNRS, INFN, MPI, etc, for having accepted to support our expensive and risky projects more than 20 years ago. And my special thanks to Rai Weiss and to Peter Bender, who attracted me to this field. - **Alain Brillet***

*GW150914 arrived at our detectors on Sept 14th 2015. On February 11th 2016 we announced our discovery to the world. In 180 days the instrument scientists performed hundreds of checks on the detectors to establish that they were operating reliably, the data analysts carried out multiple searches and established detection confidence beyond any reasonable doubt, the signal was scrutinised inside out, its parameters estimated, consistency with general relativity tested, astrophysical consequences drawn, 12 papers were written in concert. I am proud at how all this came together. It does justice to all the past years of hard work and non-detections and to this wonderful gift of Nature that GW150914 has been. - **Maria Alessandra Papa*** both instruments. “That’s it!” he exclaimed. “That’s either a signal, or an injection”.

LHO - September 14, 2015 - Miquel Oliver:
The experience of being at the LIGO Hanford Observatory site for the detection was so unreal, it’s hard to explain. On the event day we Fellows woke up to a rain of email, so, intrigued, we drove to the site with the aim of understanding what was going on. Was it possible that the blind injection phase had already started during an engineering run?

The answer came as soon as we got to the site. Jeff Kissel published a logbook entry: the event was not a blind injection! At that point a tsunami of excitement and more and more questions started.

I Skype called Alicia Sintes, my adviser. She wanted to know what was the impression on the site and I immediately said that uncertainty was in everyone’s mind but people at the site knew that it was not a blind injection. The feeling that something big had happened was all over the place.

In the days that followed, the cautious excitement and quiet celebrations grew. Although at times we couldn’t quite believe it, we found no better explanation. It seemed we had detected gravitational waves for the first time in history!

LLO September 16, 2015 - Anamaria Effler and Robert Schofield - reflecting on what would have happened if they had continued PEM injections on Sep 14th:
Anamaria: I breathed a giant sigh of relief knowing that we were off site already and that we didn’t do the last few tests. But knowing how close we were…

Robert: If we had decided to go back into the experimental halls and finish everything, then we might have missed the detection, or at least made vetting a lot harder. I didn’t realize until much later that because Anamaria and I had been to both sites, working around the ESDs, just before the detections, we were prime suspects in the event that the detection was a malicious injection.

Albert Einstein Institute Golm (40km from Berlin) - October 5 2015 - Ian Harry:
It was my turn to chair the weekly Monday teleconference. This was no normal teleconference though; today we were to see for the first time the results of the offline searches. There was some nervousness. We were sure the September 14 event was real, but what if we had missed a bug in our search codes? Luckily this did not happen, the event was louder than our ability to measure background, and we were able to claim with very strong confidence that this was a detection. My part in making the first gravitational-wave detection was now done. I could now focus on trying to find second and subsequent signals. It was strange how in a space of 3 weeks we had transformed from a collaboration expecting to make “no detection” statements in the next two years to a collaboration starting to write a “first discovery” paper along with many accompanying papers exploring various astrophysical aspects of this detection. Next time I tell a graduate student that this is an exciting time to be in gravitational waves, I won’t need to cross my fingers behind my back. Except, what if this really was a blind injection? What if someone just said it wasn’t, or didn’t know? Should the first detection really be this loud? Should it really have masses this high?

AEI Hannover - October 5, 2015 - Tito Dal Canto:
As I started TeamSpeak, joined the usual Monday telecon and scrolled down the list of attendees, I felt a shivering down my

I can’t imagine a better source for the first gravitational-wave detection by LIGO than the one we found. When I realized that the signal we detected wasn’t a test or an error but the real thing, it really left me breathless. We spent years studying sources that we thought would create the most extreme wave patterns: pairs of massive black holes in the process of merging. And that’s exactly the kind of signal we detected. It perfectly matches our predictions for how two black holes draw near each other, move around each other and ultimately merge. It also gives us a remarkable opportunity to see how gravity operates under such extreme conditions. It’s such an enormous discovery that it’s difficult to anticipate all the repercussions for gravity, fundamental physics and astrophysics, but its echoes will be reverberating in those fields for many, many years. With so many black holes around us generating gravitational waves, the Universe suddenly seems full of sounds that we couldn’t even hear just a few short months ago! - ***Alessandra Buonanno***

This is an amazing discovery. We barely turned on the Advanced LIGO instruments for the first time, and a whopping big signal popped up. And no ordinary signal, it was a pair of 30 solar masses black holes crashing into each other. This breaks new ground on so many fronts: Measurement of gravitational wave strain by the LIGO detectors, observation of the orbital evolution and coalescence of the heaviest known stellar-mass black holes, leading to the birth of an even heavier black hole, all consistent with General Relativity. In a word: “WOW!“ - **Nergis Mavalvala**

What??? our predictions were right? the optimistic ones??!! - ***Vicky Kalogera***

After 35 years in this field, I couldn’t have hoped for a better first detection - two black holes and a whopping signal to noise!
- ***Norna Robertson***

spine: it was one of the longest attendance lists I had ever seen, and in a few minutes I was going to present the results of the PyCBC analysis of the data containing GW150914.

PyCBC is software developed for offline, wide parameter space search for coalescing compact binaries in Advanced LIGO. Although GW150914 had been already reported by the online searches, the result of the offline CBC searches represented an important ingredient in the whole analysis. I couldn't wait to see the result. I wondered how the event would look through PyCBC's glasses. Which part of the template bank would pick up the event? Would we be surprised by a weaker event missed by online pipelines? The possibility that the event would not show up at all crossed my mind.

I presented the PyCBC results, and others presented the corresponding GSTLAL results. I typed the necessary command, the Atlas web server survived the most benevolent DDoS attack ever and the plots revealing GW150914 became visible. There were no surprises, but we felt we needed to celebrate anyway. After the telecon, the AEI CBC group gathered in my office and finally enjoyed the long-awaited detection whisky.

Les Guthman and the MIT crew:
This image (below left) is a moment of history from our footage - the frame when the box was opened and Rai Weiss recognized the GW candidate was unquestionably real. He is surrounded by David Shoemaker behind him, Mike Zucker behind David, Nergis across the table. Salvatore Vitale sits next to her, Erik Katsavounidis stands behind Rai, with Ryan Lynch. The box opening on October the 5th marked the end of the preliminary investigations and the start of the detailed analysis of the gravitational wave candidate GW150914.

Salvatore Vitale: Opening the champagne at MIT box opening telecon. None of those bottles got thrown away, but rather kept as souvenirs!

One of the nice outcomes of all of this is that it will be a lot easier to explain to our friends and family what we've been doing all these years! - ***Lisa Barsotti***

When the event came up and we started to discuss it among colleagues, I especially remember the first conversation Stan and I (as detection committee chairs) had about it and he asked what I thought. "I wouldn't trade a gold plated event in ER8 for a marginal event in the middle of O1". And I haven't changed my mind obviously! - ***Frederique Marion***

Like many people in the collaboration, I've been working towards this moment of discovery for my entire scientific career - more than 20 years - and it feels fantastic to have not only got here, but to truly feel that we are now at the start of something huge - it's terrific. - ***Sheila Rowan***

Twenty years ago when Advanced LIGO was still a dream, right through the long and challenging design and construction phases, I would not have believed how successful it would be, with the most wonderful observation of a binary black-hole system right at the very start of operation. - ***Ken Strain***

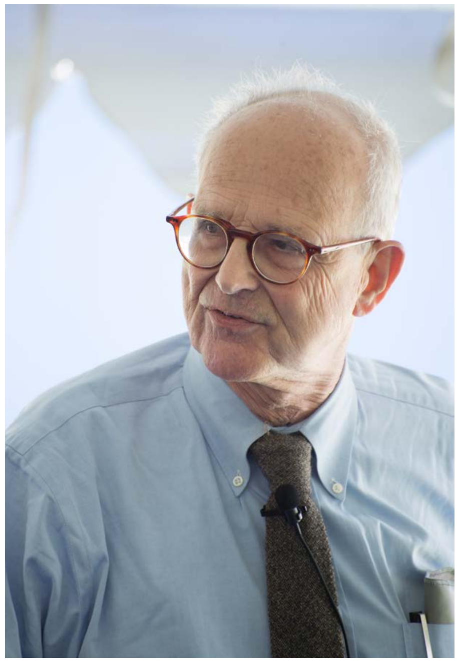
When I convinced myself The Event was real, my heart skipped a beat, and I cried too. Being part of a groundbreaking discovery, earlier and more perfect than I ever expected, is an incredibly powerful experience. Congratulations and thanks to all of you who have made it possible. - ***Laura Cadonati***

First day back in work after defending PhD. So much for an easy start! - ***Duncan Meacher***

This led to a series of sleepless nights, but they made for the most satisfying time I've had in research so far. - ***Surabhi Sachdev***

Thoughts and Reactions

Rai Weiss



Where were you when you heard about the first detection and what did you think at the time?

I was in Maine on vacation with my wife and son and his wife. We had a date with Peter Saulson and his wife to go kayaking along the Maine coast. By chance Richard Isaacson, was also going to join us. Richard is a student of Misner's, he wrote an important paper showing that gravitational waves did carry energy and were real physical things. He was the discipline chief for gravitational physics at the NSF at the critical time when interferometric detection of gravitational waves was being proposed. He was absolutely central to the NSF taking the gamble to first develop and then fund LIGO. After getting permission from the LIGO directorate, Peter and I told Richard about the "event". He looked quite skeptical and plied us with perfectly sensible questions - "how do you know it isn't due to…" - but after seeing the data and a pretty thorough grilling, we all went out to a really memorable dinner, toasted the "event" and talked about the good and bad old times.

When did you start to work in the field of gravitational wave detection? Who introduced you to the field?

It is a long story. It began when I was a starting faculty member at MIT and was asked to teach a general relativity course. The time was 1968 and I had just started a new research group in the physics department to work on experimental gravitation and observational cosmology. I hardly knew GR and was typically one day ahead of the students (they may have been ahead of me in the tensor calculus). The class wanted to know more about the Weber experiments. These were the measurements Weber made with the excitation of aluminium bars. I had a terrible time understanding the interaction of a bar with a gravitational wave. I thought I could understand and calculate how a pair of objects travelling along neighboring geodesics changed their separation when a gravitational wave came by. The next idea was to measure this separation using the time it took light to go between the objects. The math was reasonably easy. I gave it as a problem to the students. Later I thought about it some more and realized that one could actually make a sensitive gravitational wave detector this way. That was the beginning of LIGO in my thinking.

Were you surprised about black holes being our first source?

I was wishing it would be black holes as they are totally Einstein objects - Newtonian gravity cannot explain them - they are nature's gift to test the Einstein field equations in the strong field limit and it looks like Einstein was right again!

Working in a new field that for very long had no signals must have been challenging at times. Did you ever think of switching to another field?

I have worked in various fields including atomic clocks and the cosmic background radiation as well as gravitational waves. All of them are wonderful and fun to work on. You go nuts if all you think about is the end result. What keeps one going is the problems at hand and the interesting people you work with in solving them.

When you think back, what moment stands out as the most significant in the development of gravitational wave science?

Clearly Weber's idea that one could try to measure gravitational waves directly was important. The really significant event was Hulse and Taylor's discovery of the binary pulsar system and the subsequent exquisite analysis over many years of the dynamics of the system. All derived by just looking at the arrival time of the pulsar pulses. The key finding was the decay of the orbit due to loss of energy by the system to the radiation of gravitational waves.

Dinner table at Bass Harbor, clockwise from lower left are: Rebecca Weiss, Ben Weiss, Peter Saulson, Sarah Saulson, Richard Isaacson, Rai Weiss and Carla Chrisfield.

What are your hopes and expectations for the future of gravitational wave astronomy?

I think we may have actually opened a new way to look at the Universe. It seems black holes are more ubiquitous than had been thought. We knew that most galaxies have a big one in their centers. It may even be necessary for the evolution of galaxies as we see them to have a central black hole. One direction of research we now know about is the mass spectroscopy of black holes. This is interesting for both gravitational physics as well as astronomy. An important question has now become the source of these stellar mass black holes: are they a relic of the formation of the first stars in the Universe or are they born in later times in rich clusters of stars?

If we can bring the detector to design sensitivity, we may well begin to see binary neutron star coalescences. These will teach us something about the nuclear interaction as well as astronomy. We should not forget about supernovae: gravitational waves will provide key information about the dynamics of the implosions that cannot be determined by any other means. And, there is good reason to expect surprises, we know so little about the dark (not electromagnetic) universe.

At some point with even more sensitive detectors than Advanced LIGO we will be able to use gravitational wave sources to learn about cosmology. If there is a population of black holes extending to the time of the formation of the earliest stars, it should be possible to map the geometry of the Universe by observing the same type of signals we have just uncovered at different distances.

Rainer Weiss is a cofounder of LIGO and emeritus Professor of Physics at MIT. The Gravitation and Cosmology group at MIT has been working on interferometric detection of gravitational waves since the late 1960s. The group has trained many of the scientists now working on LIGO.

Ron Drever (middle) with (left to right) Harry Ward, Jim Hough and Sheila Rowan. Ron started the gravitational wave research effort in Glasgow in the 1970s. In 1984 he moved full time to Caltech where he co-founded LIGO. Included in his many contributions are his work on resonant cavity systems and the eponymous Pound-Drever-Hall technique. Ron is delighted to send the LIGO team his congratulations and his best wishes for the ongoing work in the exploration of gravitational waves at this very exciting time.

James Hough

What made you choose the field of gravitational wave detection as a research topic?

I had just finished my PhD - this would be about 1971 - and pulsars had just been discovered a few years before by Jocelyn Burnell. So pulsars were very big. I had done my PhD in nuclear physics but I didn't find it particularly exciting at the time. Ron Drever was here, and he thought we would detect x-rays from pulsars by looking at phase fluctuations in low frequency radio waves. So we set up an experiment to do that: to look at the phase of radio waves from a transmitter in Germany, and looking for phase fluctuations at the same kind of frequency as a known pulsar - I think it was CP1133. Just before that, around 1969 or 1970, Joseph Weber had set up his gravitational wave detectors and was beginning to report having seen events. It became very interesting, this field of gravitational waves, because this was something new, a little bit like the new pulsars a few years before. So at that point Ron Drever thought it would be a good idea to see if we could build some gravitational wave detectors.

Did you ever think of giving up and moving to a different topic?

I never really thought of giving up. We had two big funding scares where we thought the group would get shut down, but I never thought of leaving. What keeps you going in these long experiments is the spin-off technologies, particularly from when I started. My real expertise was lasers.

Pound-Drever-Hall (-Hough!) locking?

Yes, I was involved in that quite a bit. It was great fun, stabilising lasers. If you ask me what my favourite piece of experimentation was, I would say laser stabilisation. The most fun I ever got was taming lasers. Some lasers were very untamable!

When did you hear about the first detection?

We were on a telephone call with Sathya [Cardiff GEO PI] discussing the fact that there had been a gamma ray burst and wondering if, you know, there was any sign in the data of that event. During that telephone call it became clear - I think Marco Drago and Andy Lundgren had sent some sort of email - so it was all really exciting, and that was when I first heard.

What moment stands out as the most significant in the development of gravitational wave science?

Maybe it was when our first silica suspension in GEO was hung, and didn't fall down. We realised that we could make an interferometer with fused silica. I think for me that probably is the most significant.

Was that a vast improvement in noise performance over steel wires?

Oh yes. When you look now at Advanced LIGO it is a very large factor improvement in thermal noise over initial LIGO around about 20 Hz or so, because it is now silica.

What are you looking forward to, now that we have made the first detection?

I'm looking forward to seeing Advanced LIGO get down to its design sensitivity. With the event rates right now, it's roughly one a month. But I think we've got about a factor of 3 to go to get to design sensitivity, so that would give about a factor of 30, so instead of seeing one a month we might get to see one a day! That's when it will get really exciting. Hopefully we will also see NS/NS and NS/BH binaries as well as BH/BH pairs.

What are your hopes and expectations for the future of gravitational wave astronomy?

What I would really like to be able to do is to see far enough out into the universe to be able to check that the expansion is still accelerating, and check that there really has to be something like dark energy, and that it's not some artifact from relying on supernova brightness to give you the distance scale. You see we have always wanted to feel that we are doing real astronomy. And we are already: we have seen black hole binaries, which is remarkable. If this had been an NS/NS binary discovery, people would be saying "great, you have discovered gravitational waves from a source you expected." But at the same time we have also seen black holes - that's remarkable!

Jim is Professor of Experimental Physics at the University of Glasgow. As Director of the Institute for Gravitational Research he co-founded GEO-600 and has worked on a range of topics including laser stabilisation and low-noise materials. In his spare time he enjoys high performance sports cars, photography, model railways and short wave radio.

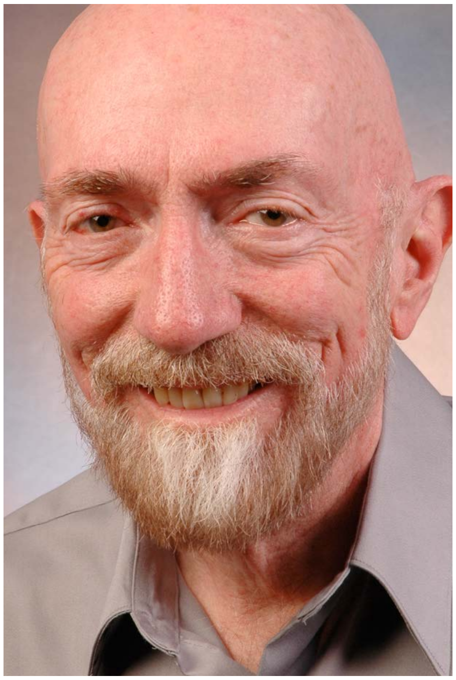
Kip Thorne

Where were you and what did you think when you heard about the first detection?

I was working at home. Christian Ott alerted me by email several hours after the signal arrived, and pointed me to the event display. I looked at the time-frequency plots and felt a sense of profound satisfaction. This was probably it: the first detection, after four decades of hard work.

Were you surprised about black holes being our first source?

No. The distance to which LIGO can see a compact binary is approximately proportional to the binary's mass, so the volume of the universe searched is approximately proportional to the mass cubed - and black hole binaries have much larger masses than neutron star binaries. Beginning in the 1980s, when we started planning LIGO, I thought it likely that this would more than compensate for the fewer number of black hole binaries than neutron star binaries in the universe, making black hole binaries be detected before neutron star binaries.



What made you choose gravitational wave detection as a research topic?

In 1972 I became convinced that gravitational wave science had the potential to revolutionize our understanding of the universe, and so I began developing a vision for this field of research [see W.H. Press and K.S. Thorne, "Gravitational-Wave Astronomy," Annual Review of Astronomy and Astrophysics, 10, 335-374 (1972)].

When you think back, what moment or period stands out as the most significant in the development of gravitational wave science?

None more significant than others: It required a long, sustained effort, over four decades.

When you started, how and when did you imagine the first gravitational wave detection to happen?

In the late 20th century. I wasn't at all sure what kind of detector would succeed first.

What are you looking forward to, now that we have achieved the first detection?

Exploring the warped side of the universe!

Kip Thorne is a cofounder of LIGO and the Feynman Professor of Theoretical Physics, Emeritus at Caltech. In addition to mentoring students and scientific research, Professor Thorne's career has spanned writing and film, including work on the recent movie Interstellar as science advisor and executive producer.

Albrecht Rüdiger

A Wish Come True

Heinz Billing was just recently honored, at the age of 101.5 years, by being awarded the Deutsches Verdienstkreuz (German Order of Merit First Class) for his pioneering work at the dawn of the computer era. He not only made the art of computing arrive in Germany, but his inventions were recognized internationally.

And years later, in the early 1970s, he again was in the front line of a new field. He was urged by the scientists of the Max Planck Institute for Astrophysics to clarify the soundness of Joe Weber's claims of having detected gravitational waves. He turned his Department for Numerical Computers into one of the first groups to repeat Weber's bar experiment, hiring Walter Winkler for that research. Luckily, he heard of an experiment in Frascati, led by Karl Maischberger, that followed identical paths. Under Billing's leadership, these two groups performed a coincidence experiment that was the most sensitive, the longest and the best analyzed room-temperature resonant-mass experiment of that time. The analysis (Kafka, Schnupp) very clearly refuted Weber's claims.

For attaining better sensitivities, Billing was faced with making the decision whether to go into cryogenic resonant-mass antennas or follow the interferometric scheme put forward by Rai Weiss. He made the right decision, albeit with an argument that later turned out to be incorrect: he feared that going into cryogenics would mean "big science", i.e., very costly, whereas at that time interferometry was considered the less expensive scheme. Now with the cost of one advanced interferometric antenna we could easily build a dozen cryogenic detectors.

And another good decision was made at that time, again ironically on false assumptions: to go ahead with the delay-line scheme of Rai Weiss. This gave the Munich (and later Garching) prototypes a head start into many pioneering features. As Walter Winkler established in his thesis, this required big mirrors to cope with stray light, seemingly a disadvantage. It did allow, however, the use of mirror suspension in wire slings, leading to a vast reduction of thermal noise. The scheme had built-in beam recombination right from the start, and thus the realization of power recycling (Schilling, Drever) was easily implemented, long before the Fabry-Perot prototypes could follow suite. But the delay line scheme turned out to be a dead-end road, ironically because the mirrors losses were getting too small: Photons scattered by only small angles would give rise to stray fields building up in the delay line for long time spans, leading to serious noise problems.

Even after Billing's retirement, his spirit endured in the Garching group and led to many discoveries and improvements that later became standard in the actual detectors.

Once I closed my talk with the words that to see gravitational waves would require patience and, for our generation, actually longevity. Karsten Danzmann once asked Billing what he would yet like to witness in his life, and Billing answered "to see the detection of gravitational waves". We congratulate Billing on having reached that goal, thanks to the sensational observation of the merger of two stellar mass black holes, on the day 2015-09-14.

▲ *Heinz Billing with a bar detector.*

Albrecht Rüdiger entered Heinz Billing's Department for Numerical Computers in 1957, for research on novel computer components, developing a special computer for fully automatic track detection in bubble chamber pictures, and in the late 1970s joined the gravitational wave detection group under Billing. He was the GEO representative in establishing the LIGO Scientific Collaboration in the late 1990s.

It takes a worldwide village

▲ *Some of the many faces of the LSC collaboration. Clockwise: Sheila Rowan, Sanjeev Dhurandhar, Laura Cadonati, Karsten Danzmann, David McClelland, Marco Cavaglià, Fulvio Ricci and Dave Reitze. Middle: View into the central building of the GEO600 gravitational wave detector at Ruthe near Hannover, Germany.*

LIGO research is carried out by the LIGO Scientific Collaboration (LSC), a group of more than 1000 scientists from universities around the United States and in 14 other countries. More than 90 universities and research institutes in the LSC develop detector technology and analyze data; approximately 250 students are strong contributing members of the collaboration. The LSC detector network includes the LIGO interferometers and the GEO600 detector. The GEO team includes scientists at the Max Planck Institute for Gravitational Physics (Albert Einstein Institute, AEI), Leibniz Universität Hannover, along with partners at the University of Glasgow, Cardiff University, the University of Birmingham, other universities in the United Kingdom, and the University of the Balearic Islands in Spain.

LIGO was originally proposed as a means of detecting gravitational waves in the 1980s by Rainer Weiss, professor of physics, emeritus, from MIT; Kip Thorne, Caltech's Richard P. Feynman Professor of Theoretical Physics, emeritus; and Ronald Drever, professor of physics, emeritus, also from Caltech.

Virgo research is carried out by the Virgo Collaboration, consisting of more than 250 physicists and engineers belonging to 19 different European research groups: 6 from Centre National de la Recherche Scientifique (CNRS) in France; 8 from the Istituto Nazionale di Fisica Nucleare (INFN) in Italy; 2 in The Netherlands with Nikhef; the Wigner RCP in Hungary; the POLGRAW group in Poland and the European Gravitational Observatory (EGO), the laboratory hosting the Virgo detector near Pisa in Italy.

The discovery was made possible by the enhanced capabilities of Advanced LIGO, a major upgrade that increases the sensitivity of the instruments compared to the first generation LIGO detectors, enabling a large increase in the volume of the universe probed – and the discovery of gravitational waves during its first observation run. The US National Science Foundation leads in financial support for Advanced LIGO. Funding organizations in Germany (Max Planck Society), the U.K. (Science and Technology Facilities Council, STFC) and Australia (Australian Research Council) also have made significant commitments to the project. Several of the key technologies that made Advanced LIGO so much more sensitive have been developed and tested by the German UK GEO collaboration. Significant computer resources have been contributed by the AEI Hannover Atlas Cluster, the LIGO Laboratory, Syracuse University, and the University of Wisconsin-Milwaukee. Several universities designed, built, and tested key components for Advanced LIGO: The Australian National University, the University of Adelaide, the University of Florida, Stanford University, Columbia University of New York, and Louisiana State University.

▲ *The Advanced Virgo detector at Cascina near Pisa, Italy.*

GW150914
TIMELINE
1.4 BILLION YEARS AGO
SEPTEMBER 14TH, 2015
HA HA! I EXIST!!
09:50:45 UTC
LHO Rapid Respond Team
WE'VE GOT AN EVENT
LEMME SEE!
YES. LIVINGSTON CONTROL ROOM HERE.
We're tracking an event here. Is everything running nominally? Are there any injections being done?
We've got a good strong lock, everything is normal. There's no injections.
Thank you.
WAIT. WHAT??
NOW WHAT??
IT'S *PROBABLY* A BLIND INJECTION.
Week 0
~~Malicious~~ BLIND Injection Department
IT WASN'T US.
THERE'RE FOUR OF US BY THE WAY.
IT'S NOT A BLIND INJECTION?!
HOLY SHIT!!
WHAT DO WE DO?
WHAT HAPPENED?
CODE FREEZE!
IT'S A BINARY BLACK HOLE!
WE HAD A DETECTION!!!
GUYS, PLEASE KEEP THE NEWS AMONG LSC MEMBERS ONLY.
Week 1
IT'S ALREADY ON TWITTER!
THAT A*STRONOMER
WHO THE F@*K IS THIS GUY??
Week 2-3
ALMOST HALF OF THE CHECKLIST ARE DETCHAR ITEMS!
IT'S A NECESSARY EVIL <3
DETECTION COMMITTEE
Week 4
FIND WHOEVER LEAKED THE RUMOR.
AND MAKE AN OFFER HE/SHE CAN'T REFUSE.
DISCLAIMER: THIS NEVER HAPPENED (I THINK).
Week 5
LVC-wide Telecon
DAC: THE SIGNAL IS REAL!
EVERYBODY PLEASE MUTE!!
NUTSINEE KIJBUNCHOO © 2016
Email Sent
To: [gw150914]
Subject: P150914-v1
Week 6-8
Paper draft circulates
OOF!

Week 9
PEM CHECKLIST
GO
LDAS ARCHIVE STATUS
ARCHIVE IS A GO.
PCAL EXCITATION CHECK
GO GO GO.
Week 10-11
STILL REVIEWING DETCHAR ITEMS.
WELL, HERE'S V-7
Email Sent
Week 12
DAMN IT
RE: CAN WE CHANGE THE TITLE?
DETCHAR CHECKLIST IS GO!
+MANY OTHERS
Week 13
SHOULD WE INCLUDE G197392 IN THE PAPER?
WE CAN'T CLAIM A DETECTION WITH THAT ONE.
G197392
But I'm REAL too
Week 14
Merry Christmas!
OOPS. ALMOST FORGOT LIGO.
FROM LHO STAFFS WHO WORKED DUIRNG THE HOLIDAY.
BETWEEN WEEK 15-16, A SECOND WAVE OF RUMORS HIT THE COLLABORATION.
HOLY SH*T! IT'S EVERYWHERE!
NOT AGAIN...
I'M LYING TO MY MOM!
SOMEBODY TAGGED ME ON FACEBOOK. WHAT DO I DO?
IGNORE! IGNORE!!
HOURS OF PRODUCTIVITY WERE LOST.
NO THANKS TO THE JERK WHO LEAKED THE INFO.
Week 16
DETECTION PAPER IS A GO.
BUT I STILL THINK WE SHOULD --
IT'S 587 YES, 5 NO. JUST SHUT UP.
WE F@*K!NG DID IT!
LIGO VIRGO
February 2016
PARTY!!!!
+900 OTHERS

Told ya.

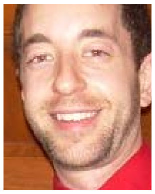
A Tool for Testing

▲
Vincent Roma in the Data Mass Storage Room, LIGO Hanford on maintenance day

What are blind injections?

Jeffrey S. Kissel

When the LIGO detectors are taking data, we often intentionally move the mirrors to create a brief signal that looks much like an expected gravitational wave would. This process is called 'injection' and is an essential tool for testing the entire detection pipeline – from interferometer performance to data analysis software. In previous observational runs, a very small number of these injections had been performed about which the majority of the scientists in the collaboration do not know any detail; most importantly the exact number, time, or astrophysical source parameters. Due to their blind nature, prior to the upcoming Advanced LIGO observation era, the collaboration formed a committee – the Blind Injection Committee.



Jeffrey S. Kissel is the control systems engineer at the LIGO Hanford Observatory. His primary role is to design, understand, commission, and improve all control systems in the LIGO detector to ensure the highest level detector robustness. In his time away from the detector, he also enjoys using the right half of his brain while playing drums, swing dancing, and as a member of the local city governments Arts Commission.

This committee was charged to refine a policy for making such injections to ensure such a process would retain integrity in the future. The committee subsequently developed several documents which were presented during the September 2013 collaboration meeting in Hannover. At the following meeting in March 2014, in Pasadena, the collaboration voted on and accepted the policy via representative council.

In June 2015, the Collaboration's spokesperson, Prof. Gabriela Gonzalez (Gaby), asked four collaboration members, including myself, to form the Blind Injection Team to enact the approved policies. Having learned from past blind injection experience, information about the team and the required infrastructure were deliberately not kept secret – they were simply "not well advertised." Any communication with the collaboration was to be filtered through Gaby. However, again, the number, time, and astrophysical parameters of the injections remained in confidence with the Blind Injection Team alone. Once the infrastructure was ready, the collaboration was only to know the observation period over which there may have been blind injections – a "blind injection phase."

From June up through September 2015, the Blind Injection Team worked "with" the Calibration and Hardware Injection teams, to make blind injections possible. In fact, half of the Blind Injection Team were key players in the calibration of the detectors (a process in which models of the interferometer control systems are used to turn raw detector output into a strain signal more digestible by search algorithms) and the installation of infrastructure for "regular" hardware injections at both observatories. Indeed, due to various complications in implementing said infrastructure, the Calibration, Hardware Injection, and Blind Injection teams went so far as to ask for a one-week delay in the start of the run. This was on Thursday Sept 10 2016 14:30:00 UTC. With the request granted, the run was tentatively delayed from Sept 14 2015 15:00:00 UTC to Sept 21 15:00:00 UTC. All teams continued to work through the weekend, going to sleep that Sunday "night" (in truth, the Livingston observatory's staff were still working on calibration installation at 2-3am local, Sept 14 2015 ~07:00-08:00 UTC), assuming we would continue preparation for data taking in the following week, and that blind injections, and the subsequent blind injection phase, would be ready "when they're ready."

While these teams were asleep, GW150914 arrived in the data stream.

I arrived, groggy and tired, at the Hanford observatory's regular Monday morning site meeting, only to be bombarded by our site's run coordinator, asking "Are we in a blind injection phase?!" to which I quickly replied "No," having no idea yet that we'd had such an incredibly loud event candidate overnight. As the news slowly sunk in – desiring to immediately quell further questioning and internal rumors – I posted to our internal electronic logbook:

EVNT Logbook:
12:25 Monday 14 September 2015, Jeff Kissel
There were NO Transient Injections during G184098 Candidate Event. Other than continuous wave injections which were ongoing in L1, there were NO hardware injections – blind or otherwise – during event candidate G184098.

In the days and weeks immediately following, the interferometer configuration was locked down to preserve the detectors' integrity. As such, no further work on the injection system could be done because it might have detrimentally changed the detectors. The official start of the run was moved up to Friday Sept 18th, at the recommendation of the collaboration and in light of the observation of GW150914. The afternoon prior (Sept 17th) the Blind Injection Team received the request from Gaby to stand down, with the intention of picking up where we left off at a future, as-yet-undetermined, date. In the new year, I'd asked Gaby, on behalf of the Blind Injection Team, if we were to resume its function. She said: "Although it's not official (since it requires a change in an approved LSC policy), I strongly suggest you don't think about blind injections any more… We will not do blind injections during [this observational period], and probably not any more." Indeed, she was merely following the recommendation of the approved Blind Injection Committee's policy: "[...] Blind injections [...] should be in operation during [observation] runs from the beginning of [the first observation run] until public dissemination of the first detection." Happily, the first detection defined the beginning of the first observation run!

We couldn't have asked for a more exciting reason to cease-and-desist!

LIGO 2016

That day was my birthday. In the morning (Korean time), my five-year old daughter told me to come home early because she was preparing a cake to celebrate my birthday. When the event happened (18:53, KST), I was driving home. During a party with my daughter (19:55, KST), I received Marco's first message via e-mail. It felt like receiving a birthday present from God. - ***John Oh***

Lost the bet to Chad and Kipp. Have to buy them a bottle of whiskey. - ***Tjonnie Li***

Slept through my alarm on the morning of the alert, haven't slept since... - ***Cody Messick***

Someone said it's our job to kill this event. If we can't kill it, it's an event. My attitude is if I wanna sleep, I'll kill the event, if I wanna win a nobel prize, I'll elevate the event. Our job is to do neither. - ***Alan Weinstein***

You thought we had a lot of work up until this point. It is just starting. - ***Patrick Brady***

I was getting into the shower when an alert went off (I took my phone everywhere during O1) and while I was looking at the gracedb page Leo phoned to ask if I could get on a call. I couldn't right away, because I had to go and get dressed again first. It literally caught me with my pants down. - ***Kipp Cannon***

The Monday sources call was hijacked to talk about the event where Collin posted omega scans. It looked ridiculously like a chirp. - ***Sarah Caudill***

GW150914 moments

Understanding the characteristics of the LIGO Detectors

Laura Nuttall / Jess McIver

Laura Nuttall and Jess McIver are postdoctoral scholars at Syracuse University and Caltech respectively. They have been friends and colleagues (most notably in the LIGO detector characterization group) since they started their PhDs in 2009.

Despite the LIGO detectors being 'twins', in that they contain the same components assembled 3000 km apart, they certainly have their own personalities and characteristics. When someone asks what the quality of the data looks like from the detectors, it's far too broad a question and the answer typically changes on an hourly timescale. As a result, collaboration members both on- and off-site routinely monitor the output of the detectors, checking that the data are of sufficient scientific quality to analyze and looks typical for the current environmental conditions. Should something look amiss, data quality experts begin diagnostic investigations. This is the work of the LSC Detector Characterization group.

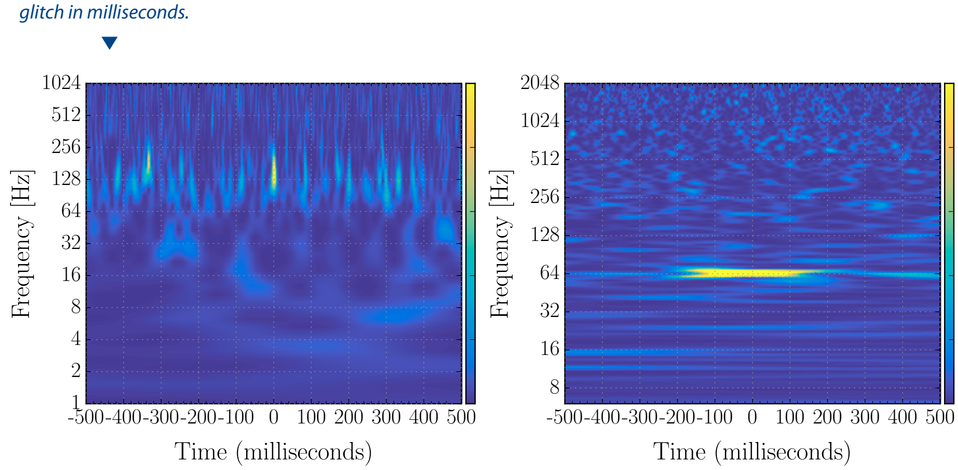
Both LIGO detectors are staffed 24 hours a day, 7 days a week by operators whose main responsibility is to keep the interferometers operating in their usual configuration and producing good quality data. In fact, they have to push a button to indicate when the detector is in this configuration, and it is these times that are analyzed for gravitational wave signals by search pipelines.

In an ideal world, the data would look the same on any given day across the frequency band the detectors are sensitive to (typically a few to thousands of Hz). In reality, a combination of waves crashing on beaches, people driving cars, trucks or trains near the sites, and hiccups in electronics and instrumentation produce 'glitches' in the data. Glitches can mimic a gravitational wave signal, making it harder for the gravitational wave search algorithms to distinguish a true signal from noise. Ideally, any noise sources that produce glitches in LIGO data are fixed or removed; data quality analysts work closely with the commissioning team, providing leads to address the root causes. Failing this, data quality researchers can flag the times of known problems.

Many thousands of monitors covering almost every aspect of the observatories and detectors are recording a wide range of interferometer and environmental behavior along with the gravitational wave strain data. These auxiliary channels are used to look for correlations between a potential noise source and the gravitational wave strain channel. A recent example is a series of glitches observed in the gravitational wave strain channel at ~60Hz every ~74 minutes at the Hanford observatory (see Figure 1). This regular glitching was initially found to correlate with magnetometers at the Y-end station of the interferometer. This key clue led investigators to discover the root cause: a refrigerator compressor cycling. Disabling the refrigerator completely removed these glitches from the data!

There are families of glitches that we frequently see but have not yet discovered the cause of. For example, a class of glitches we have named 'blip' glitches appear at both sites which have a 'teardrop' shape in the time-frequency plane. These glitches

Figure 1: *Examples of glitches (left) caused by trucks and (right) caused by a refrigerator, both at LIGO-Hanford. Both plots are time-frequency spectrograms, normalised by average signal energy. The time axes are centered around the glitch in milliseconds.*



never appear at both interferometers at the same time, and differ just enough from the expected signature of a true gravitational wave signal that the searches can distinguish between them. However the distinction can be subtle. Take a look for yourself in Figure 2. Can you pick out the gravitational wave signal from a blip glitch? Remember, a gravitational wave signal produced from two neutron stars or black holes colliding sweeps upward in the time frequency plane.

Despite the many quirks of our interferometers, we understand their characteristics and their behavior in different environmental conditions. Data quality researchers can then highlight times when the detectors are known to be adversely affected by noise. This information is fed back to the gravitational wave search pipelines in the form of data quality flags. These flags can be used to completely remove data from an analysis if the data are sufficiently understood and egregious, for example in the event of a hardware failure. Data quality flags can also be used to down rank any potential candidates an analysis identifies as significant during these imperfect operating periods.

The gravitational wave event GW150914 occurred just before the official start of the Advanced LIGO observing run. However the detectors were both in their nominal state at the time of the event, and the data looked clean and typical for data we have seen throughout the first observing run. When this event was identified as significant, scores of people conducted an exhaustive series of checks and investigations to rule out any possibility GW150914 was an instrumental or environmental artifact. We checked every auxiliary channel of the interferometer and found nothing to suggest either detector made this signal. No known glitch classes like those previously described occurred at this time. Moreover no data quality flags tracking known noise features were active anywhere close to the event. Instrument scientists and commissioners even tracked the gravitational wave signal through the interferometer, to see if the signature appeared as expected at each stage as it would if it was of true astrophysical origin. It did.

We now focus our attention on the next challenge: to understand our detectors after further upgrades, and to improve our monitoring techniques to be ready for the improved sensitivity of the second observing run. In addition, collaborations are now being made with the citizen science project Alder Zooniverse to create 'Glitch Zoo', a project which will allow the public to help in our work to characterize and eliminate glitches in our interferometers is coming soon. Will you help us in this effort?

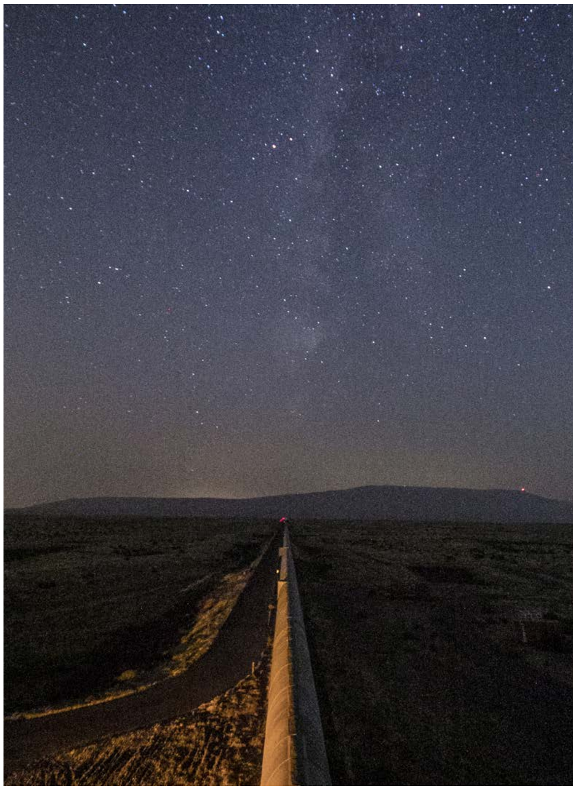
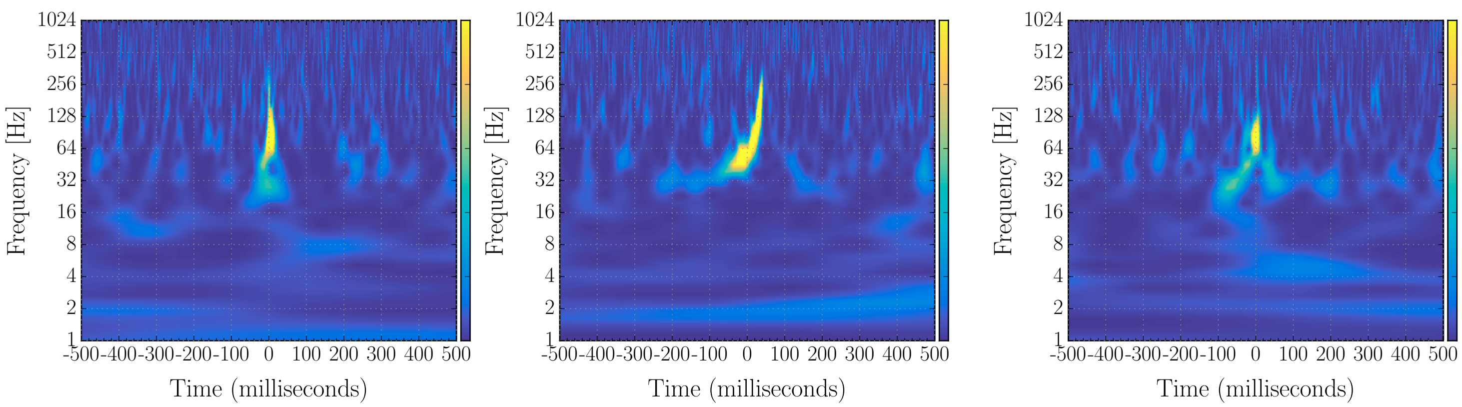


Figure 2: *Time-frequency plots, normalised by average signal energy, of 2 blip glitches and event GW150914. The time axes are centered around the glitch in milliseconds. Can you tell which are the glitches and which is a true gravitational wave signal? (Answer - event GW150914 is in the middle).*

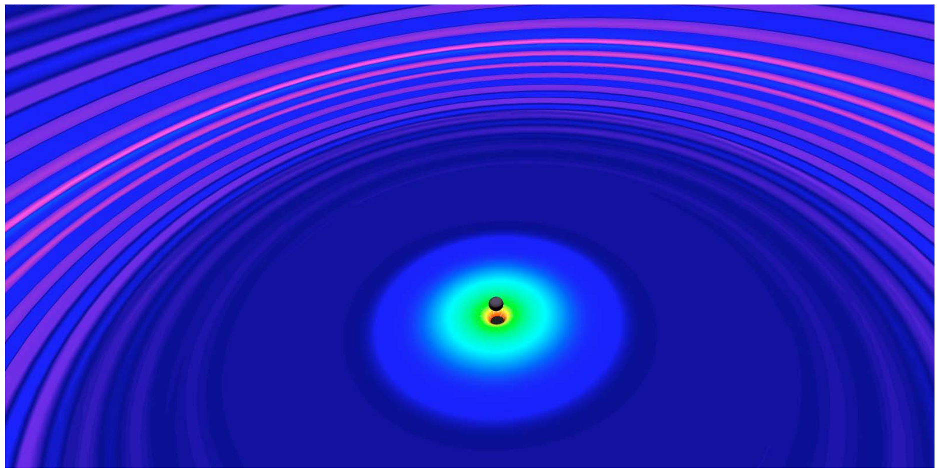


Black Hole Conversations

Shane Larson / Mark Hannam

Shane Larson is a research associate professor in CIERA at Northwestern University and an astronomer at the Adler Planetarium in Chicago. He has about half a million Lego bricks and three cats, and enjoys building telescopes and remotely piloted submarines.

Mark Hannam is currently a Professor at Cardiff University, while he works out what to do when he grows up.



Simulation of GW150914, showing the ringdown just after merging.

A discussion of black hole astrophysics and what LIGO's first detection means for the future of gravitational wave astronomy.

Shane: I spend most of my days thinking about ultra-compact binaries in all their various combinations: white dwarfs, neutron stars, black holes. My background was originally at much lower gravitational wave frequencies – which will be covered by the LISA observatory, so I'm always thinking about events from the perspective of how a source emerges into the graveyard of compact binaries from their stellar phases and how they evolve over time. Of particular interest to me is, as our catalog of observations grows, what will this tell us about the entire population of compact binaries.

Mark: My background is in numerical-relativity simulations of binary black holes, but now I mainly work on using those simulations to make models of gravitational wave signals. Most of the effort goes into thinking about which simulations to perform and how to use the results and whether the models we have are good enough and how to make them better.

Shane: We have spent years expecting the first source we see would be a neutron star binary. We kind of expected that as we slowly crept out in distance, we would eventually see our first detection – it would be a detection, but maybe a marginal one. But here we find ourselves where astronomy usually finds itself – the Universe has surprised us, not with something we cannot understand but with something unexpected. I think what is going to surprise everyone the most is that The Event is a solid detection.

Mark: I have spent the last decade hoping that the first detection will be a binary black hole, and writing on grant applications that binary black holes are "one of the most promising sources for the first detection" well aware that the "bread and butter" sources for Advanced LIGO are binary neutron stars and the binary black hole merger event rate is so uncertain that there was a chance we would never see one with Advanced LIGO at all.

In the first day or two I did not pay much attention to the event - I assumed it was a glitch or some other problem that would go away. After that I assumed it must be an injection, even after the official statement was made that it was not a hardware injection, I (and a number of others I talked to) thought, "Well, they would say that, wouldn't they?" In the end it was only time that got rid of my scepticism – my scepticism in someone engineering a blind injection overcame my scepticism that it was a signal. But I am not sure when I will finally completely erase the nagging suspicion that someone is going to suddenly say, "Surprise!" Hopefully by the time the paper is published...

Shane: I missed the first flurry of emails about the event on September 15; I did not hear anything until almost midnight. But it immediately sent me into a tizzy of back of the envelope calculations. In my Moleskine journal I carry everywhere, there is a page marked "TOP SECRET" dated 16 September 2015 12:17am CDT, followed by a couple of pages of calculating from the rough parameters of the trigger to population parameters, and attempts to estimate the rates. A fevered burst of excitement that, obviously has not let up!

Mark: I hope we can remember what it was like during these strange, hectic frustrating months. They are a turning point in our field and an experience to savour. Only a few months before this, we were cautious and uncertain. What if we do not detect anything? That was a real concern. Now all that is behind us, but we should not forget what it was like. This is a unique experience, passing from doubt and uncertainty (which lasted for decades), to knowledge. Most of us will not have that experience ever again in our lives.

Shane: The curious thing to me, being on the inside of the collaboration, is watching the world outside. There are clearly people who have pieced together that something big is afoot, either because of rumors or because they have read between the lines. Some of them cannot help but pry – "What can you tell us (wink wink, nudge nudge)?" Others of them clearly do not want to put those of us in the collaboration in a bad position – "We will talk about this after you leave the room."

Mark: In December I was at the Texas Symposium in Geneva, and it was a strange (and delicious) experience to have the secret knowledge of our discovery. There was a lot of talk about the potential of gravitational wave astronomy and all the questions we can hope to answer: do binary black holes exist, and do black holes exist with many tens of times the mass of the Sun? Will we be able to detect the signal of a ringing black hole and make the most direct observation of a black hole? For most of the people there, these were questions they could only dream of answering – but the LVC members in the audience already knew the answer! It is a stark reminder of just what an incredible thing we have done, and how it will transform science. In a few months' time, meetings like that will be completely different.

Shane: I have a nine-year-old, so keeping secrets is something I practice a lot. The hardest part is not keeping The Event secret, but rather having to feign ignorance when our curious colleagues outside the collaboration ask questions! After everyone knows, I imagine a lot of conversations where I have to paraphrase Mr. Spock – "I did not lie; I evaded, I deflected, I pivoted!" I can hardly wait for everyone to hear the news –- once our friends in astronomy hear the news, departmental teas and colloquium cookie-fests and water cooler chatter are going to be filled with wide ranging discussions about the implications of The Event. It (and all the events that follow) are finally going to move us to the time we have all been waiting for –- when gravitational waves are as much a part of our toolbox as photons. The near future is going to be awesome!

Mark: At the Texas Symposium Michael Kramer gave a talk on the incredible measurements that have been possible with pulsars, in particular the double pulsar binary. One of the wonderful things they have been able to observe is precession of the neutron-star spins. I cannot wait until we can do the same with gravitational waves from black-hole binaries. It could be that The Event was a highly precessing binary, but due to its configuration we cannot tell for sure. We can hope in the future that we observe configurations where these effects can be measured, and we will be able to observe far more extreme examples than in the double binary pulsar. That is the source that I am most looking forward to. (Some people have commented to me that we were unlucky in the orientation of The Event, but it is hard to agree: we had quite enough luck for one observation!)

Shane: This event is awesome from the perspective of studying gravitational wave sources because it is the first entry in our catalog, and the catalog is only going to get bigger from here on out. For decades now we have been synthesizing and simulating populations trying to guess the LIGO event rate, but here we are with the first data in hand that can observationally constrain all our theoretical rambling. That, to me, has always been one of the greatest goals –- to get to that point that we always describe science as operating at, a back and forth interplay between theory and observations that together move our whole understanding of the field forward.

Mark: You mentioned the rates, and how we are no longer arguing and waving our hands in the dark, and can work with actual observations. We used to make guesses on how many detections we would have per year. But that is going to change. It is not the counting that is interesting, it is the details of the individual sources. The first observation gives us our first ever black-hole binary. The next strong source might be a neutron-star binary – and then there is very different science that you can do. The next one might be a pulsar, and it is different science again. That is not just a tally of three signals, but three very different scientific observations that each provide unique information.

Shane: Black holes have become an accepted part of astrophysics. Their properties, as we understand them, explain many observed astrophysical phenomena ranging from quasars to x-ray binaries. Curiously though, before The Event, we have never seen a black hole! Up to now, everything we knew about black holes is derived from observing how they interact with everything else. To me, that is the most exciting thing about this – this is the beginning of the era where we can study black holes themselves!

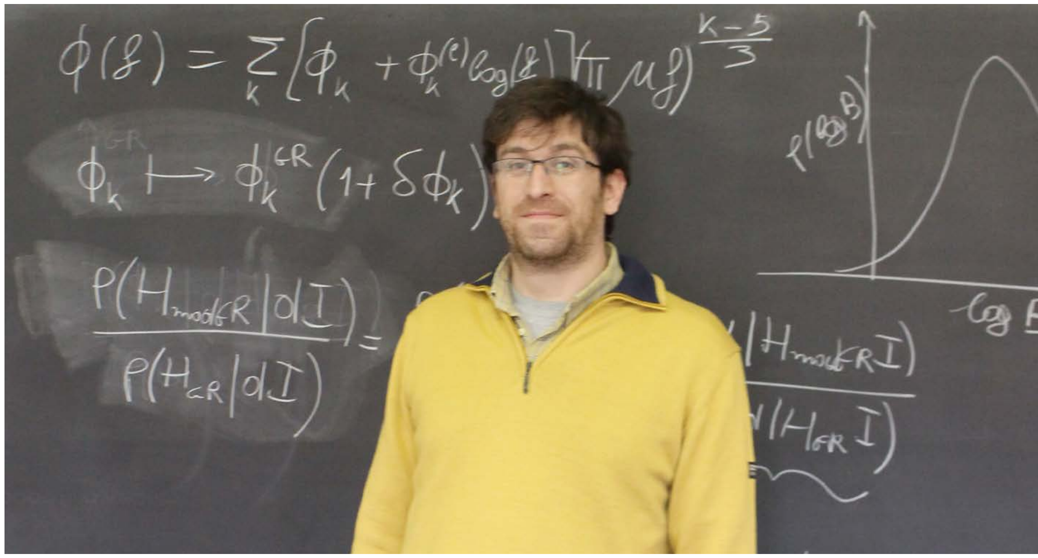
Mark: People will probably look back on our predictions for the field, and be amazed at how short-sighted and unimaginative we were. I certainly hope so!

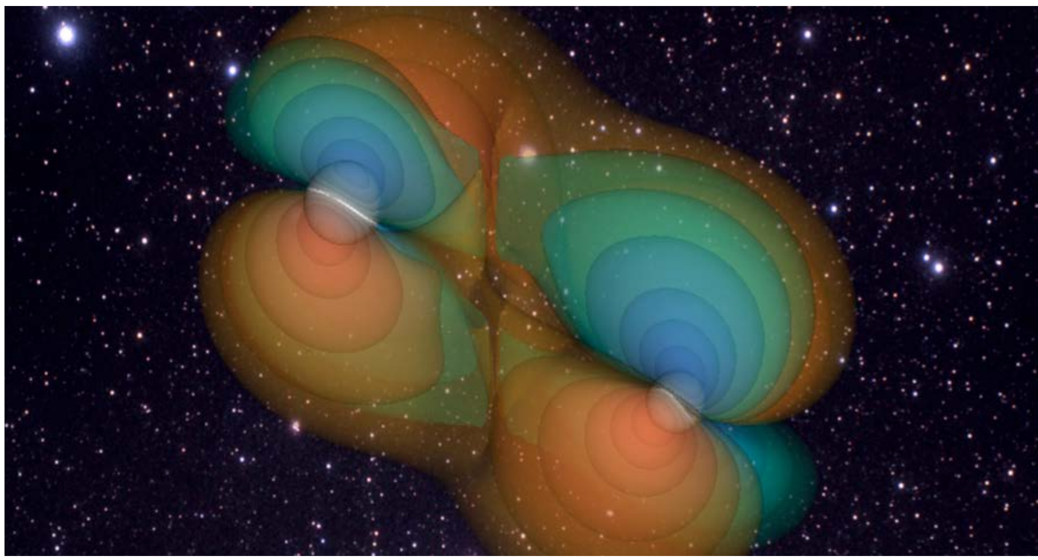
Shane: I think I am always overly optimistic about signals because I am a firm believer in the notion that the Universe just does not care what our expectations are –- our experience is so limited and colored by our long history with electromagnetic telescopes that there are going to be surprises. Big surprises! There always have been in astronomy, and this certainly is no exception. So here we are, with a big freakin' signal right out of the gates, and my ears hurt from smiling so much.

Testing General Relativity

Walter Del Pozzo

Walter Del Pozzo is a postdoctoral fellow at the University of Birmingham where he works on tests of strong field gravity from GW observations. He plays guitar and writes his own music. He also hates cheese.





Numerical relativity simulation of a binary black hole merger with parameters matching those of GW150914.

GW150914 is an amazing discovery. Not only because it opens the era of gravitational wave astronomy, but it also provides the unique opportunity to gain insights into the inner workings of Einstein's theory of general relativity. Think of a gravitational wave as a melody being played on a piano. As the melody goes on, its pitch keeps increasing and each new note is uniquely defined by those played before.

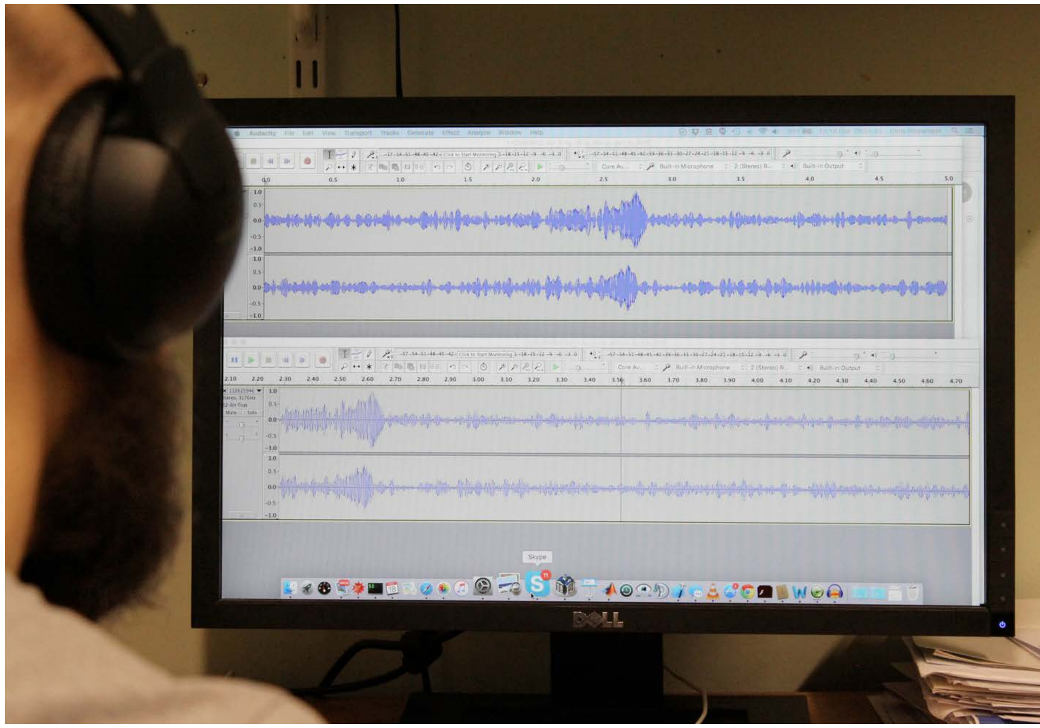
General relativity is our understanding of the scale on which Nature's piano plays its melodies. When two black holes collide, we expect a very specific kind of signal which is different from the signal from two neutron stars colliding. General relativity is the tool that allows the distinction between the two. But how do we know that general relativity gives us the correct interpretation of the melodies heard by LIGO?

Today, we know that whatever might be wrong with general relativity is going to be small, we have observed gravitational waves after all. But we do not know if general relativity is correct all the way to the moment in which two black holes merge and form a new one. So LIGO scientists have come up with several ways of testing if general relativity predicts the gravitational wave signals we observe correctly. For example, we can compare the low frequency part of the signal (the inspiral) with its high frequency part (the merger and ringdown) and look for global dissonances between the two parts of the signal. If the low pitch notes and the high pitch ones do not fit together, then we find indications that our scale set by general relativity is not quite right.

We have checked thoroughly for violations of general relativity in GW150914, but as far as we can tell, or as far as we can hear, we found no dissonances that would indicate a failure of general relativity. Once again general relativity comes out just fine! But GW150914 is just the first gravitational wave melody we have heard, and we will keep listening, who knows what surprises Nature has in store.

LIGO 2016

Listening to The Event



Chris Messenger working on audio files of GW150914.

Chris Messenger

Chris Messenger is a Lord Kelvin Adam Smith Fellow at the University of Glasgow.

Everything seemed to be happening very quickly during the first week following the Event with countless emails and preliminary follow-up analyses. As an LVC member that does not usually get his hands dirty with the analysis of real data, there was a nagging feeling that I should contribute something to this historic discovery, however small. Then it struck me, let's hear what this event sounds like.

I'd been working with a student on an audio based gravitational wave outreach project over the summer. The idea was to find out if the general public could hear the characteristic chirping sounds of compact binary coalescences in real data if it was converted into sound. In fact, we knew that they could, since "sonifying" our expected signals has long been a useful tool in communicating gravitational wave science to the public. What we didn't know was how far into the universe people could hear gravitational waves. The project was a success and it left me with a set of software tools designed for producing and manipulating gravitational audio files from real gravitational wave data.

Before I had time to start applying this to the Event data another flurry of emails arrived and in this set, amongst the parameter estimation, and EM follow-up subject headings, there was one email mentioning audio files. Progress was happening so quickly and I'd been beaten to it. However, despite my minor initial disappointment I was eager to hear the signal so I plugged in my headphones and pressed play.

Bear in mind at this point that this gravitational wave had traversed ~400 Mpc over the last ~1 billion years before arriving at Earth and we were some of the first few people EVER to hear it. It was amazing, but despite the high signal-to-noise ratio it was unfortunately quite difficult to hear because of the relatively low frequency content of the signal (due to its source being particularly massive). The general consensus was that it actually sounded very much like a single gravitational wave "heart beat".

So, I saw an opportunity and decided to try doing a few different things to the data which resulted in stumbling on the idea of shifting the signal to higher frequencies. Our outreach project had taught me that humans are generally more sensitive to sounds at higher frequencies. One way to think of this is that it is analogous to false colour enhancements applied to astrophysical images. This is where the wavelengths of light imperceptible to humans are shifted into our visual band to create images from telescopes operating in the x-ray, radio, and infrared bands.

After a few attempts and handful of different filtering parameters the original "heart beat" was transformed into the classic "chirp" like signal we've all been waiting for. My very small contribution had been made.

Compact Binaries

Gianluca M Guidi

Gianluca is assistant professor at the University of Urbino and INFN associate. He is the Virgo co-chair of the LIGO-Virgo CBC group. While working on GW Data Analysis, he dreams of wandering through the landscapes of Africa with a good book and an orchestra.

John Veitch

John is an Ernest Rutherford Fellow at the University of Birmingham and co-chair of the CBC group. Before Sept 14th he spent his free time on his exhaustive study of heavy metal music.

Chad Hanna

Chad is an Assistant Professor of Physics at Penn State University and co-chair of the CBC group. Before September 14, Chad spent his time dreaming of the first detection and the bet with Tjonnie Li that he would win. After September 14, he wonders where his prize is.

An interview with Chad Hanna, John Veitch and Gianluca M Guidi, the current co-chairs of the LIGO-Virgo Compact Binary Coalescence Group The Interview was conducted by Hannah Middleton and Andreas Freise. Transcript by Alejandro Vigna-Gómez.

Hannah: How did you hear about the detection?

John: I remember it was Monday morning about 12:00 in the UK when I first heard about the Event through an email to the gravitational wave burst mailing list saying that there was an interesting candidate. It was what would have been the first day of O1 (Observing Run 1) had we not decided we were not quite ready to go, so it was still technically Engineering Run 8 (ER8) time. My initial thought was that it must be a hardware injection, just because it was still engineering time and given how loud it was it was clear that it was something that was interesting. Chad, were you awake at the point when it came in?

Chad: No I was not and did not have my automated phone alerts set up yet. So the first I knew about the event was on my walk into the office at around 7:30 or 8:00 eastern time by which point some email excitement had already grown. Like John, I responded with some incredulity - I thought this is probably a hardware injection, it's funny how one responds to these sorts of things. How about you, Gianluca?

Gianluca: Well when I first heard about it I did not stand up shouting ... I kept reading the emails and I said to my Virgo colleague: "Hey, it seems we have found something!". But as it was during ER8, we did not know clearly what was going on with the blind injection program. So I was not so excited, I expected something to go wrong because it was quite an incredible thing!

John: I think the initial reaction is just disbelief because we were so used to having basically little expectation of detecting something. It sounds ridiculous now that we were initially just like "ah no, it can't possibly be real, there must be some rational explanation for this!" The first thing that really sort of shocked me was the time-frequency plots showing the really nice chirp (see 'Understanding the characteristics of the LIGO detectors' on page 24), and then I thought okay it's got to be a hardware injection.

Gianluca: Yes, it was reading Marco and Sergey's emails about the trigger and it's very nice chirp-like structure that I first realized that something was going on. If I remember well, the trigger was erroneously vetoed at first, so, after Sergey asked why and pointed out the very interesting features, a bunch of emails went around checking the vetoes and spreading interest in the event. Then the number of emails kept growing and growing .....

John: With all this excitement, people directly asked the hardware injectors whether there were any injections in ER8 time. When I saw the email come in from the hardware injectors saying there were no hardware injections in ER8, at that point it hit me that this is going to be serious and I did get a slight sort of adrenaline rush! I was leaving work at that point to go home and meet Eleanor my wife and I just could not quite sit still all evening and I think it was not til a couple of days later when I would really calm down!

Hannah: How long did it take for you to believe the signal was real?

Gianluca: I believed that it was real when Gaby confirmed that the blind injection program was not started and the preliminary checks did not see any spurious signal injected. There was still someone among my Virgo colleagues who was not really convinced about the absence of a blind injection, but I began to think that we finally did find them, or better, we found it, this gravitational wave coming from these two black holes which were really there, spinning and coalescing out there in the far sky. So, the event became the Event, with its own "personality" to be appreciated and uncovered, searching farther in what we knew and in what it was telling us.

Chad: At that time I still did not believe, I thought that it was in fact a double blind injection of some type or another. It took me several weeks, with presentations from the likes of Matt Evan and others about how this was not an injection, to finally start to come round to the idea. At this point I certainly believe that everything is exactly what we think it is and it is extremely exciting.

John: Yeah, I think there is a distinction between what you think and what you feel. When I saw this initial denial that this was a hardware injection, I really felt that this was something exciting, but in my head I was thinking "well they're probably lying". It was not until I looked at all of the evidence that I really convinced myself that there is no way it could have been a hardware injection. And even then I think several weeks after I still was not completely sure they weren't going to open an envelope on us at some point and say "aha, I got you!" But I think I am pretty convinced now.

Hannah: Were you surprised that the first source we saw was a binary black hole?

Chad: Honestly, I've always personally felt that binary black holes (BBH) could be the wild card. It is not what people have put the most confidence in simply because there is observational evidence for compact binary neutron stars (BNS) and the BBH waveforms are more complicated. So I think we were less confident about finding BBH, but people were very good at exploring other areas too and even in initial LIGO we started a serious BBH search.

We have been pleasantly surprised that we have confirmed we can pull these signals out of the noise. There are a lot of unknowns in the astrophysics for the rates of BBH mergers, but if there is a larger population of them, you can see them so very very far away. So, I am not extremely surprised that it was a BBH. I think we were really really fortunate that this first event was a very loud and clean signal which will give us confidence in how to proceed to get the best out of the data for these sorts of systems.

Gianluca: I was not really surprised either. It is true that it was not the most expected source, but in fact it was the one whose existence and coalescing rate were subject to the largest uncertainty.

Personally, I would have preferred a BNS or a neutron star - black hole binary, so that the event follow up through electromagnetic (EM) observations could have more probability of finding success – and it was what I was working on ....

John: For O1 BBH actually had the highest potential rate, so I remember thinking we could go with BBH before seeing BNS, and that does seem to be what has happened. We have got lucky and nature has smiled upon us, also not just that they were black holes but they were very heavy. I mean the distance that you see these things is mind boggling compared to how far we can see BNS which is basically the local universe. We have gone from not being able to see anything to seeing out to cosmological distances.

One of the things that has really surprised us with the new detectors is just how good the data has been and how long the locks have been compared to initial LIGO. The next generation of detectors could be looking out to the earliest era of star formation and I wouldn't expect there to be any sources before that.

Hannah: What do you think the future will be like for this field?

Chad: I'm hopeful that the impact is such that we see a great expansion of the field. We have already observed things that have simply never been possible with other channels and it's going to be a huge success for fundamental physics of course. But I really think that having signals this loud means the most in the long term for gravitational wave astronomy and the fact that maybe we really can use gravitational waves to observe the Universe on a regular basis. People have always talked about this but now it has become very clear that it is real and I think we will see more research being put into new advanced detectors and into more sources to look for. It is hard to imagine that the general interest from the entire community and beyond will not lead to things that we cannot even anticipate and lead to those things way sooner than I think any of us had thought.

Gianluca: From the wider point of view, as always when big discoveries are made, I feel that it is a big success for all of us as human kind. It may seem childish, but at the end these discoveries define what we are and what we want to be. Scientifically, we confirm in a brilliant way one century of "difficult" research and begin the start of a new era of astronomy and fundamental physics. In both realms - and this is a sign of the wide importance of the discovery - we have the possibility of looking where we could not ...before.
Gravitational waves are so different from EM waves that they can really open new perspectives on known phenomena but also raise new mysteries - and how exciting is this!

John: I think we have been extremely lucky, literally on the first morning of the first day of what would have been the first observing run, we have got not only a detection but a detection that is not just a gravitational wave and not just a system that we know exists – it is a new type of system that has never been observed in nature before. We have hit the jackpot in lots of different ways, it is incredible!
But you do not just stop after the first detection, you want to start to catalogue all the different type of sources – see how they form, whether we can categorise them into different classes. We are doing a new type of astronomy in a sense in the black hole area. Likewise if we do start seeing binary neutron stars it is exciting in a different way, we will

start to understand a bit more about gamma ray bursts. That would be something I would really like to see coming out of this generation of detectors, I think that is an optimistic goal, but I am feeling optimistic these days.

Chad: I just want to go on the record that I bet a bottle of whisky that we would have our first three sigma event before Halloween last year, so I feel quite vindicated!

John: So I can go one better that that, in that my wife Eleanor predicted that it would happen on the first morning of the first day and she was wrong only because we changed the definition of the first day!

Andreas: Has the detection changed your roles as CBC co-chairs?

Chad: We came into this in what others might have been calling the "dark period": between initial LIGO and advanced LIGO when we did not have active data and what was needed was to get the group pulling together to have everything in place for the beginning of Advanced LIGO. So our duties were not always fun, lots of documents to be written and telecons about plans and plans of other plans. There were certainly things that could have been slightly more prepared but overall I feel we went into O1 more ready to detect GW than the group had ever been before. People really used the time between initial LIGO and now to commission not only the detectors, but how to do data analysis, how to do both detection and parameter estimation, to come up with new waveform models and incorporate them into searches. Everyone was extremely active in anticipation that all our hard work was going to pay off, and, I gotta say, I am proud of the entire group for sticking through all of that when there was not exciting data to have and I hope that at least the majority of them feel that all the hard work in the interim years, did in fact pay off. I think it is people's attention to detail and willingness to stick things out during the "dark period", even when it was not easy, that has got us where we are. I do not necessarily feel that responsible for it, of course we tried our hardest to keep the group pulling in one unified direction towards this goal, but really the people in the group were just tremendous scientists and we were lucky to be leading such a group of tremendous scientists.

Gianluca: Being such a large group, with so many different initiatives going on, the chairs' work is more of organization, but this requires also the understanding of the research problems approached inside the group; thus it is quite demanding. It is difficult to say if something has changed after the Event: everything is going in a different way now, but we are in a new and emergency situation. To understand which type of work and dynamics there will be in the CBC group in the detection era we need to wait until after these first detections have been digested.

John: It is really a dynamic situation at the moment. Before the detection there was a lot of focus on getting things just right and I think now people can focus less on the codes and more on the science. It is the first time I have ever done anything like this. You are trying to direct the efforts of these talented people, but also trying to hang on and keep up and keep an eye on different parts to make sure things are not being neglected. I have to say I do go through waves of feeling exasperated and feeling excited. Once we have the first set of results behind us it will feel less rushed and more, I don't know, euphoric.

Chad: I concur, it has been an emotional rollercoaster. We've been talking on teleconferences at hours when neither one us should have been on teamspeak. There was a lot of loss of sleep this semester. Sometimes because there was a lot of tense stuff going on and a lot of pressure and sometimes it really was just because I was too excited to sleep. I think you have to take both in a role like this. The question is when I average over the experience will I be overall excited and happy with the whole thing? Absolutely. It is hard to imagine that I won't be despite the rough patches.

John: Yeah absolutely, it has been very difficult at times, but also just fantastic, watching the results coming out. It's a privilege to be a part of it.

Chad: Looking to the future, I see the potential for this collaboration to do great things going forward. A lot of people have settled on niches that are really critical pieces of the big picture and are doing them well. I have hopes that we'll continue to flourish by not being complacent. We'll continue to advance all of our science, techniques, and the things we search for. But we will also learn to take data, get basic results out quickly and "wow!" the entire astrophysics community with the overnight transformation from a sceptical experiment to one of the most interesting and profound observatories of the century. I look forward to that the most. I look forward to this overnight change where we are just constantly revealing new mysteries from nature everyday to the rest of the world.

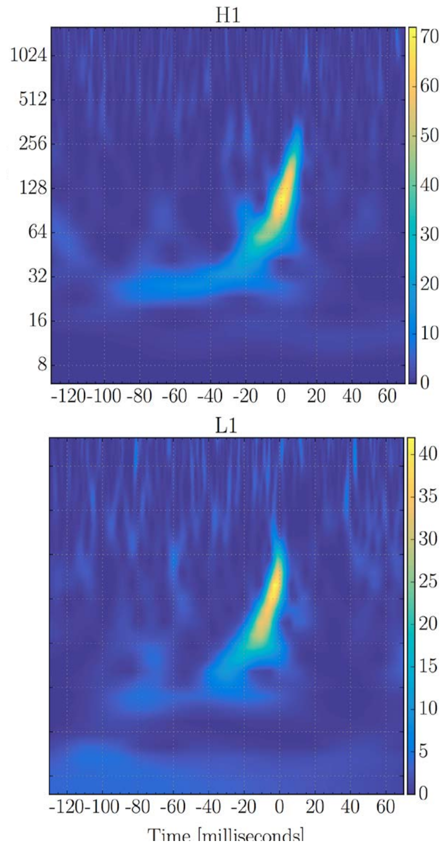
John: I think Chad put that very well. He was looking at the future, I think it is also a nice coincidence that this is a hundred years after the creation of GR and it is just amazing that when Einstein first proposed the existence of GW, he said they would never be detected. It is a tribute to the work that has been done over a century. In developing the instruments, practically every single component of the detectors has been invented from scratch and a lot of data analysis signal processing were invented from scratch. It is just a fantastic achievement. And there are a lot of people who should be very proud.

The Journey of a Gravitational Wave Signal

A long time ago in a part of space far, far away, two black holes collide - creating another, more massive black hole whilst emitting enormous amounts of gravitational waves. These waves travel at the speed of light, gradually getting weaker. They arrive at Earth where the LIGO detectors are operating nominally, about to start their first observing run. The gravitational waves cause the space-time in each of the LIGO-Livingston arms to stretch and squeeze, and 7 ms later the same thing happens at LIGO-Hanford. This stretching and squeezing causes a phase change in the laser light resonating in the arms, which registers as an electronic signal at the output of the interferometer.

In the weeks leading up to an observing run, many measurements are made at each LIGO site which allow the calibration team to accurately convert this electrical signal in to the dimensionless gravitational wave unit - strain. This is defined as the change in the length of the detector arms caused by a gravitational wave divided by the length of the arms themselves.

Strain data from each interferometer are transferred in close to real time to a central location, where several "low latency" data analysis algorithms are ready, waiting. Only when both LIGO detectors are operational at the same time do these algorithms begin searching through the data to find a gravitational wave signature. These analyses search for modeled and unmodeled gravitational wave signals, and have their own methods for identifying a signal. However should any analysis identify a potentially interesting signal an alert is sent out to collaboration members.



Normalized spectrograms of GW150914 in LIGO-Hanford (top) and LIGO-Livingston (bottom).

The collaboration has a team of scientists on standby, 24 hours a day, 7 days a week, waiting for any alert sent through this system. Mobile phone alerts and emails are sent to the rapid response team within minutes of a gravitational wave signal being recorded by each interferometer. This team immediately meets to decide if there are any reasons to suspect the validity of the signal. For example, a list of instrumental monitors are checked and discussions are had with experts on site to ensure the interferometers were operating nominally. If no problems are found, a further team then starts the process to notify astronomers of the possible identification of a gravitational wave signal so they can point their telescopes and capture any potential electromagnetic counterpart.

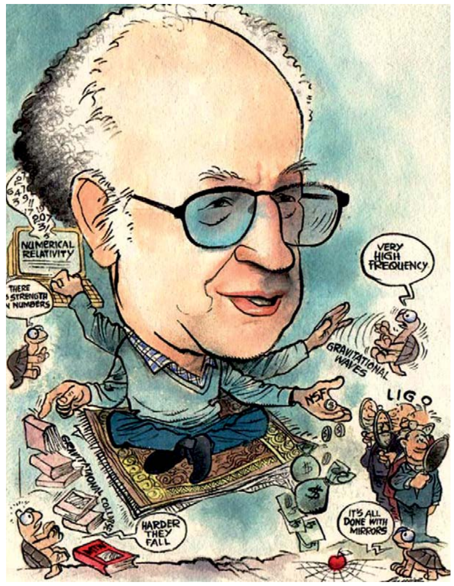
The "low latency" algorithms give the collaboration a first glimpse into the parameters of a signal, such as the masses of the original compact objects or where the signal came from on the sky. Parameter estimation algorithms are then launched on the data around the signal to help pinpoint the parameters to a greater certainty. In addition, offline analyses use large periods of data to confirm and search for further gravitational wave signals. Typically the offline searches use at least 5 days of coincident data which ensures any signal can be found to a statistically significant level to claim a detection.

These offline analyses are conducted in a blind fashion, meaning that any gravitational wave signals an analysis might identify are not presented in the initial output of the analysis pipelines. Instead, these pipelines split the data between "foreground" and "background". Foreground data may include a gravitational wave signal, and their results are placed in a so-called "closed box". Background data are data which cannot possibly include a real gravitational wave signal, and is used to estimate the probability of anything in the foreground being of astrophysical origin. It is these data that scientists evaluate to check an analysis was conducted in the manner intended. Once these checks have been completed, the "box" can be opened. In practice this is simply changing permissions on a webpage, but this process is very exciting. This is usually done during a teleconference with the rest of the collaboration, where hundreds of scientists are constantly refreshing a webpage to see if any of the offline pipelines identified a signal to detection significance. In the case of this event, the box opening occurred on a Monday, 3 weeks after the signal initially arrived at the detectors. From this moment the signal was identified as a possible detection and the previously agreed procedure for a detailed analysis was started.

- *Laura Nuttall*

The Transition of Gravitational Physics – From Small to Big Science

You can change history, but history demands that, in return, you must pay a price. This is a partial account of the long, non-scientific ordeal that the LIGO originators and their successors had to endure to achieve their ambitious dream. It presents a view as seen from inside the National Science Foundation (NSF), their partner in this adventure.



The author as seen by C. V. Vishveswara, who also first predicted quasi-normal modes of black holes in 1970. Richard Isaacson is a retired NSF Program Director for Gravitational Physics, and is currently researching the weavings of Arabs in Uzbekistan during the 19th century.

First steps

After 15 years of R&D, design studies, and prototyping, the team at Caltech and MIT had arrived at the stage where facility construction might begin to be seriously considered. At this point, the proponents of this project had to endure a rite-of-passage to further advance their dream and to attract the large funding needed to enable the new era of Big Science in Gravitational Physics. Each step forward in the scientific community or the governmental funding process required the interruption of exciting progress in laboratory research or conceptual insights. Creating a consensus for a large facility necessitated a lateral diversion of effort by the project's scientific, engineering, and management teams, and especially the scientific spokesmen for the project, Ron Drever and Kip Thorne at Caltech, and Rai Weiss at MIT. Endless dog-and-pony shows each demanded another week of preparation. Of course, as a mole for the scientific community within NSF, I too had to interrupt my normal work to prepare arguments to justify LIGO at internal governmental planning meetings on management and budget. (These ran the gamut from stultifying to terrifying.) Such events became ever more frequent and stressful for all concerned as external attention focussed on the project and its ambitious goals and budget. In the end, the process actually added real value to the final plans for the LIGO facilities and its research program. During this process, Rai and I met occasionally, as we were to do many times over the years, spending afternoons walking around Walden Pond where we could be uninterrupted, and informally discussed the problems and opportunities ahead.

Following the annual NSF review of progress in December 1989, a credible construction proposal was organized by Robbie Vogt of Caltech and submitted to NSF, to build the major research facilities that we now know as the LIGO project. However, it would still take several years of further review, justification, negotiation, and revision to the planned activities before any actual construction funding could arrive. (See Fig. 1.)

A construction proposal this ambitious was initially evaluated with the usual mail peer review panel, which was supplemented with an expanded review with a visiting commit-

2/88	NSF site visit and review of LIGO project
10/88	Presentation to NSF Physics & Astronomy Advisory Committees
12/89	LIGO construction proposal to NSF
2/90	NSF site visit and review of LIGO project
4/90	NSB approves LIGO construction proposal
10/90	Presentations to NSB:
	Cost Risk Analysis
	Site Selection Procedures and Criteria
	NSB approves Site Selection Process
11/91	Presentation of LIGO site evaluation to NSF Review Committee headed by John Slaughter, former NSF Director
	Caltech technical evaluation of all 19 sites (171 pairs) sent to NSF
2/92	Site choices announced
5/92	Cooperative Agreement with Caltech signed

Fig.1

tee that made a site-visit to the project for an in-depth examination of critical issues such as plans, personnel, technology, and readiness. Eventually, these reviews concluded with highly supportive recommendations. With these in hand, in April of 1990, the NSF director Erich Bloch went forward to the National Science Board seeking approval to move to the next step.

The National Science Board (NSB) had been following the planning for this project for several years. After a thorough discussion of the latest reviews and the funding needed, the NSB provisionally approved a LIGO construction project, subject to a satisfactory clarification of some further considerations. The Board was still concerned about two critical points: they wanted to hear more about how the risks of such a novel enterprise were going to be handled by management, and how the costs would be kept under control. So the NSB invited the LIGO group to come back and explain this to them in greater detail. Also, since the proposal did not identify the actual sites for the two LIGO facilities needed, the NSB wanted to hear and approve the details of the site selection process. (Of course, the NSB would also have a final chance to see and approve the results of any search before they were made public.) Erich Bloch provisionally initiated planning for LIGO funding in the next available budget cycle, Fiscal Year 1992 (FY1992), assuming the project's response to these remaining issues would be satisfactory.

In October of 1990, the LIGO team returned for the expanded discussions requested by the NSB. The discussion of risk was finessed by Vogt arguing that the high risk elements were relatively low-cost, e.g. the optical systems. These had negligible costs compared to the conventional construction items. (Activities such as pouring 4 km of concrete are not generally associated with high risk.) So, while the scientists might have difficulties achieving expected performance with some initial optical configuration, the design for flexible components allowed systems to be redone or improved with a relatively low cost penalty. For the site selection process, Caltech, proposed to run the site competition and carry out the technical evaluation of the proposed sites and their possible pairings, then present the results to NSF for approval and final selection.

Following these presentations, the NSB fully approved proceeding toward facility construction. Importantly, however, this NSB decision to proceed said nothing about having the money to pay for it! These funds needed to be requested by the President (through the Office of Management and Budget, the OMB), and would, as usual, come from Congress, and require special justification and approval from the four relevant Congressional committees as well as years of lead time. The delay was not a serious problem, as major construction activity would take time to start up, while project staff was assembled, and plans and subcontracts prepared.

In November of 1991, John Slaughter, a former NSF Director, headed a committee to review the Caltech site evaluations and retrospectively validate that it was all done sensibly. The leading site-pair combinations (out of all of the 171 possible pairs of 19 proposed sites) were approved by the Slaughter committee, and sent with a full analysis to Walter Massey, the then-current NSF Director, for a final selection. After internal review, Massy's final decision was to choose the Hanford and Livingston sites. This was made public in February 1992, and a Cooperative Agreement for the construction project was signed by NSF and Caltech in May 1992.

What were the key points in this Cooperative Agreement? NSF was supporting the construction of an observatory to open a new field of science (hence the O in LIGO), not just a one-shot experiment to detect the signals predicted by Einstein in 1916. This made the facility more costly, because of the necessity to provide flexibility for a multi-investigator and multi-instrument facility. This facility had to last for more than 20 years, and have a long baseline. (This concept of an observatory really upset much of the Astronomy community. They wondered how you could possibly build an observatory before any gravitational wave signal was seen; moreover they were certain that the funding would surely come out of their own next request.) Another feature that NSF understood was that there would necessarily be a two-phase construction activity. In order to reach the sensitivity required for the intended scientific payoff, NSF would eventually have to build an Advanced LIGO, an upgrade to the capability of the initial detector––which itself would already have substantially improved sensitivity over existing gravitational radiation detectors. Scientists might get lucky and see unpredicted sources of gravitational radiation with the initial LIGO, but NSF planned from the start for the eventual construction of the needed upgrade in sensitivity to get to secure ("gold-plated") theoretically predicted sources, such as coalescing neutron star binary systems, where relatively reliable calculations of event rate and signal strength were possible. The final strategic element that NSF required before the initiation of the project was provision of open access for an active user community—the facilities would not be exclusively controlled by Caltech and MIT. The NSF Physics Division had lots of experience with the leadership role provided by an active scientific user community in driving improvements to a facility and getting good science out. Moreover, the large number of technical problems outstanding would best be solved by the addition of a great many more talented and experienced scientists and engineers. So creation of such a group would have to be an integral part of LIGO's responsibilities.

How was NSF able to manage the creation of LIGO, the biggest endeavor NSF ever undertook? NSF too was forced to restructure under the complexity and financial stresses of Big Science.

Ed Temple, experienced with the Department of Energy (DOE) style of management, told me privately that DOE staffing levels for a project of this size would likely have been 6 people at headquarters and 30 people in the field. NSF was trying to manage all this with a single half-time theorist, and this would have predictable consequences. Bob Eisenstein, who was the NSF Physics Division Director when the cooperative Agreement was negotiated, improved NSF oversight enormously by bringing on David Berley as a full-time Program Manager for LIGO, and I continued to help half-time. Berley was previously the NSF Program Director for High Energy Physics (1980-1991). He had been in charge of building things elsewhere as well, both at Brookhaven (where he was Head AGS Planning and Support Division, 1970-1974) and at DOE (1977-1980). We were lucky to have him in our office. He began using all of the well-known construction methodology of high energy physics, where you take a big project apart, look at its pieces, and figure out how to build all the modules necessary. David immediately saw the need to reorganize the staff within NSF, and created the LIGO Coordinating Group, a team from across the NSF to expedite the review and processing of the many scientific, legal and contractual issues which would arise during this construction epoch.

With regard to the challenge of financing this new endeavor, despite the anxiety of the Astronomy community, NSF was not working with a fixed funding pie––that is the wrong model. Erich Bloch, the Director at NSF from 1984-1990, played the science funding game very adroitly. (He had been the engineering manager at IBM's STRETCH supercomputer system.) In the annual budget process Bloch was asked by OMB each year to submit a budget for a fixed total amount of money, and so in preparing the FY1992 budget request to Congress (in 1990) Bloch put together a base NSF program without LIGO, despite having previously kept OMB informed that it was under consideration. He told OMB that if they had some extra money left over, LIGO was something else NSF could begin. (This maneuver is well-known in the Capital as "the Washington Monument Ploy," i.e. the Interior Department proposes to close this popular monument when they face a serious budget cut.) OMB played along with this charade, and agreed to add additional funds on top of the NSF science and education base request in order to initiate LIGO construction. So funding for LIGO certainly did not come out of funds available for Astronomy, or indeed out of any other NSF program. Moreover, these funds were to remain in the Foundation's new base budget after the completion of LIGO construction, to be used in a separate new Major Research Equipment budget line for capital construction funds for all future major NSF construction projects as they came along. (This innovation was due to another physicist who served as NSF Director, Neal Lane.) It was agreed internally at NSF (with signed agreements) that the operating funds for LIGO would be included in future budgets to Congress for the project, and not come out of the existing scarce research funds then currently available to the Physics Division. This was all handled very intelligently.

In 1992 the LIGO construction epoch began, and Fig. 2 presents the actual funding profile for each year of construction. The project advanced as expected at first, but just as really big expenditures were about to be initiated there was an obvious glitch. What happened?

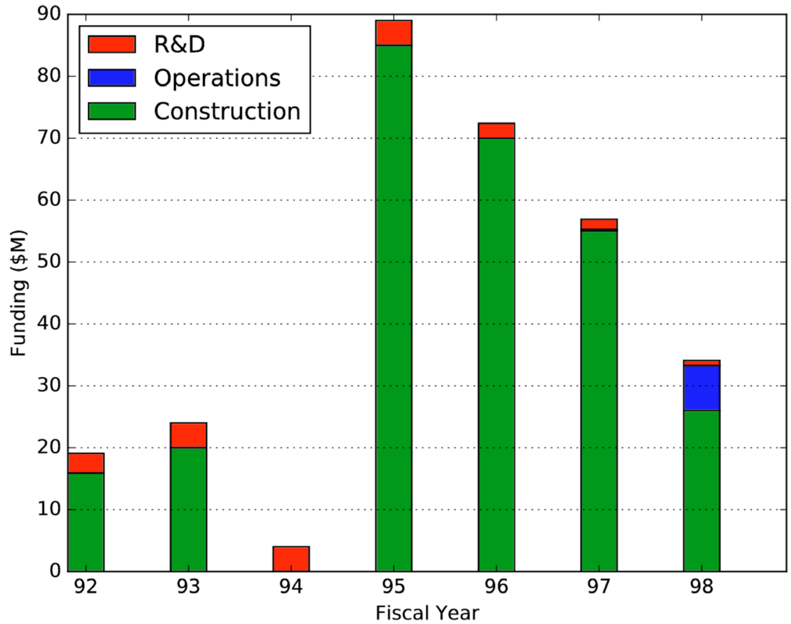


Fig.2

In November 1992, as part of routine NSF oversight, David Berley put together a visiting LIGO "Special Emphasis Panel" review, followed in June 1993 with another "Special Emphasis Panel." Both of these panels were increasingly concerned about the overall progress being made by LIGO management, and identified several key issues which were reported to NSF and Caltech. First of all, the project had not yet produced a written project management plan, showing how it would spend the $272 million construction budget, detailing how LIGO would use money over time, and what it would get at each stage. This required planning for budgets, staff levels, deliverables, schedules and milestones. Writing all these details down on paper just was not happening. The second problem identified was that staffing levels were not adequate to manage all the activities about to begin. Under these circumstances, NSF had no context for evaluation of the effectiveness of individual subcontracts in adding value to the effort, as the project breakdown was not yet defined. Consequently, major spending could not be approved, and the project came to a halt. The third problem noticed by the review committees was that access to the project by the outside scientific community was not happening as desired. This was a very serious obstacle for the project, blocking an important channel for solving all the difficult scientific and technical problems it would face.

NSF arranged a series of meetings with senior management from LIGO, Caltech and MIT to see if we could figure out ways to solve all the identified problems, and these discussions went on for some time.

Eventually the whole process collapsed, and Caltech and MIT representatives went back home for internal discussions. In January 1994 they came back to NSF with the request that Barry Barish be brought in as the new LIGO director. He was at Caltech, and it was LIGO's good fortune that the Superconducting Super Collider (SSC) had closed and he had less to do than usual. He had been working on a billion dollar construction project there. If NSF approved, he would bring along very experienced staff from the SSC. Gary Sanders, one of these people, was also proposed as the LIGO project manager.

Reboot

In February 1994 NSF agreed to these changes, and the new management team moved into place and began to work very, very intensely trying to figure out a plan to fix the problems. They revisited all of the previous plans for the project, set to work developing a needed work breakdown structure in enormous detail, and began new cost and contingency estimates from the ground up. They also added provisions for additional management controls during the construction phase, and additional project management staff to keep activities moving smoothly. When completed, this analysis and a proposed new management strategy would have to be discussed with the National Science Board to decide whether and how to proceed.

Fig.3

11/92, 6/93 Special Emphasis Panel review
Issues identified: written management plan, staffing levels, access by scientific community
8/93 NSF adds full time LIGO Program Manager: David Berley
1/94 Management meeting with NSF, Caltech, MIT, and LIGO representatives
2/94 New PI designated: Barry Barrish
HEP construction methodology
Discussions with NSF management, OMB, Congress.
9/94 Special Emphasis Panel review
11/94 Project Management Plan approved. Risk made routine.
11/94 NSB approves rebaselining of LIGO cost and scope (construction cost increased from $250M to $292)
1/95 - 5/01 Special Emphasis Panel held twice a year to review project. On budget, on time, on scope.

Meanwhile NSF management was busy talking to Congress and the OMB, describing the evolving situation. At the request of NSF, the FY1994 LIGO construction funding request to Congress was put on hold. NSF explained what was happening, and what we were attempting to do to fix it. We said that with the present issues unresolved we could not take any money. We promised to keep them fully informed whenever anything significant happened. We said if we were able to get LIGO management back on track, we would come back to ask for consideration to resume funding. And if we could not fix it we would not come back. Staff at the OMB and the key Congressional Committees were enormously understanding. (For the role of the NSF during this period, see Fig. 3).

While all this was going on, Rai and I continued our occasional walks around Walden Pond, discussing plans for a very uncertain future.

After several months Barish and his team were able to formulate a revised plan to manage the LIGO construction phase, and they produced a very detailed project management plan, with accompanying work breakdown structure, schedules, budgets, milestones and deliverables. In September 1994 the Physics Division assembled a very professional and experienced review panel that David Berley put together, a team possessing all of the necessary skills and experience to evaluate the project's efforts in cost estimation, project management, and controls. They went over the new plans and costs. They reported to NSF that things were now in shape and LIGO was ready to proceed; that LIGO actually had a detailed and credible project management plan which they recommended be approved by NSF. With this accomplished, the project was broken down into a bunch of small tasks that could be monitored by management, and this made project risks routine.

In November 1994, the NSF Physics Division returned to the National Science Board, together with the chairman of the recent review committee, and reported the results of the September review. We asked for the NSB to approve a re-baselining of the construction costs, because Barish put additional people and needed accounting and controlling systems in that had not been part of the original cost basis of the project. Also there were some "marching army" costs necessary to keep things together while the project was being reorganized under the new management team. This led to an increase in total costs for the initial phase of LIGO from 250 to 292 million dollars. After a thorough examination, the National Science Board was satisfied with the changes, approved the additional costs, and agreed that LIGO could go ahead. We returned to Congress and informed the staff of the recent progress, and with their approval were back in business.

From that point on NSF conducted routine oversight reviews with a visiting panel twice a year from 1995 to 2001 and everything went very smoothly. The project was on budget, on time, and on scope, despite the jumping of several orders of magnitude in existing technology, to deliver wonderful performance results. This was not an accident. If you try to put up a conventional office building and do not watch what you are doing, the costs can go up a factor of two over your budget estimate. LIGO was doing something very non-conventional, and management made sure, by force of will, that the project came in as planned. NSF ultimately paid out the remaining annual increments of funds for construction and initial operations (to bring the phase 1 instrument close to its initial design sensitivity), over a period of time on a conventional schedule, as planned. This is shown in Figs. 2 and 4.

Grand challenge computing

In parallel with this major facility construction, NSF made a significant investment in gravitational theory, to improve our understanding of modeling potential strong gravitational radiation sources. In 1992 and 1993, the Foundation, as part of the U.S. High-Performance Computing and Communications (HPCC) program, funded new research by groups pursuing so-called "Grand Challenges." These Grand Challenge projects brought together disciplinary researchers, computer scientists and emerging information technologies to tackle "fundamental problems in science and engineering, with broad economic and scientific impact, whose solution could be advanced by applying high-performance computing techniques and resources." Among the nine new Grand Challenge Application groups initiated in 1993, one was entitled "Black Hole Binaries: Coalescence and Gravitational Radiation". With this effort, the US community of gravitational theorists working on numerical relativity were dragged through their own transition to Big Science, with the usual painful elements of large collaborations and distant centralized facilities. Through this extended effort, theorists worked just as hard as experimentalists. With a significant new budget of over 1 million dollars per year, perhaps the most lasting effect of this investment was the education and training of a new generation of young researchers working on simulations of solutions of the Einstein field equations that were fully nonlinear and 3D, incorporating the full complexities of strong field gravity. Recently, the achievement of their original ambitious scientific goal was recognized by Kip Thorne, who conceded that he had lost his provocative bet, made in Austin in 1995, against their timely success.

The wager was as follows: *Kip Thorne hereby wagers that LIGO will discover convincing gravitational waves from black hole coalescence before the numerical relativity community has a code capable of computing merger waveforms, to 10 per cent accuracy, as determined by internal computational consistency, for coalescences with random spin directions and magnitudes and random mass ratios in the range 1:1 to 10:1. The signatories below wager that Kip is wrong. The loser(s) will supply a bottle or bottles of wine, value not less than $100, to be consumed by the winner(s) and loser(s) together.*

Birth of the LSC

In the middle of LIGO construction, ongoing activities seemed to be proceeding well, but NSF still had a concern about the future development of LIGO with regard to planning for the access to LIGO by the wider scientific community. After discussions with Barry Barish, David Berley felt that the best way to activate this effort was to enable a thoughtful discussion with experienced community leaders and facility directors on how this might be achieved. To this end, Berley organized a panel on the use of LIGO which met in June 1996. What emerged was a non-trivial plan, developed by Barish with input and discussion by this committee and its chairman, that LIGO would be separated into two parts, each with separate governance.

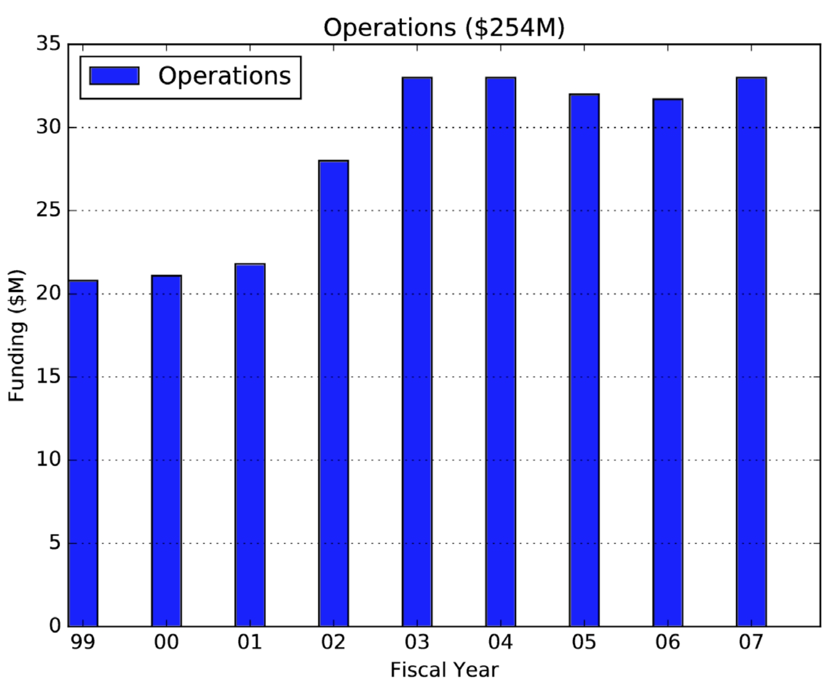


Fig.4

The parts would be:

- The LIGO Laboratory (responsible for constructing and operating the facility)
- The LIGO Scientific Collaboration (LSC) (A User's Group responsible for carrying out the science)

The panel report also provided a first description of the magnitude of the computing facilities required to support users, as well as indicating the need for future software development needed to do the science.

All this has now been implemented and is working extremely well. The recent success of the planning, execution, and installation of Advanced LIGO, the second phase of construction envisioned in the original proposal, has now brought the facility to the level of sensitivity necessary to detect the "gold-plated sources" envisioned in the original construction award in FY 1992.

Coda

LIGO was a project initiated long ago, at a time when the scientific community defined basic research priorities at NSF in a bottom-up fashion. Then, the function of NSF was to help scientists do what they found interesting. NSF believed that basic research belonged at universities, as you could never predict what the outcome would be there. LIGO was the result of investment in long-term research, development, and construction (over four decades—a scientific lifetime) to reach towards a difficult but enormously exciting goal. During that period, the NSF oversight philosophy was to get good people and try to stay out of their way as much as possible, but to stand by and be ready to help with mid-course corrections when needed. During much of this time, Congress was ready to take risks to achieve significant progress, and to show patience when things hit a bump.

LIGO was conceived at a time when scientists, administrators, and politicians showed great vision. We now live in a different era. There is confusion about the value of basic research compared to applied science and engineering. Key Congressional committees are lead by politicians who do not believe in evolution. Short term goals are important, and long term vision is rare. A similar project with such high levels of risk could not be attempted today. It is important that LIGO achieve major successes and solve many cosmic mysteries, to repay the trust and commitment of a public that has invested much and waited patiently for a long time to see it operational. I look forward to the exciting payoffs immediately ahead.

LIGO 2016

A fully locked H1 operates during the early evening in December 2015 under the watchful eye of operations specialist Thomas Shaffer. Postdoctoral scholar Darkhan Tuyenbayev looks at photon calibrator data in the front of the LHO control room.

Going operational: LISA Pathfinder

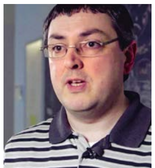
The LISA Pathfinder composite is being mounted on its launch vehicle adapter in the clean room in Kourou.

When I started writing this, we were nearing the end of the launch campaign and LISA Pathfinder (LPF) had just been installed in its launch fairing, never to be seen by human eyes again. Next, accompanied by heavy safety and security it made the 10km journey from the integration building out to the launch site in Kourou before being placed on top of the 30m tall VEGA rocket for the final preparations for launch 13 days later.

From my side, it feels like there is still so much to do to be ready for commissioning and science operations, but that's probably to be expected. As we near launch, I feel a heady mix of excitement and anticipation about what's to come. We have been preparing for science operations for so long, almost 8 years now, that it is difficult to remember a time when we were not saying "Not long to launch now, …" but there was always a little more time to tweak this, change that, write a new algorithm, improve the software, design one more experiment, rework the timeline, and so on. That time has now passed, and we have to get down to the serious business of performing the correct experiments in the optimal order so that we learn all we can about building and operating a gravitational wave observatory in space. No small task.

For other members of the team, those who have been working on the hardware of LISA Pathfinder for even longer than I, this must be a really nail-biting time:

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.

Karsten Danzmann, AEI Hannover:
"After 17 years of working for this, it feels hard to believe that it is real. Anxious excitement is maybe a correct description of my feelings."

Bill Weber, University of Trento:
"I am very excited for the launch and trust that VEGA and the propulsion module will bring us safely into orbit around L1. Then, I am thrilled and somewhat frightened to

think about how much we will learn every day from our orbiting laboratory, as we turn on the instruments and move towards drag-free control of the LPF spacecraft and an interferometric measurement of the relative acceleration of two free-falling test masses."

Eric Plagnol, APC Paris:
"I am certainly excited and maybe a little tense as the fate of LISA Pathfinder is out of our hands in the coming weeks… but confident that ESA's Mission Operation Center will make this first step a success."

Stefano Vitale, University of Trento:
"Quite an exciting moment! I think everybody in the field should keep their fingers crossed!!"

Miquel Nofrarias, IEEC, Barcelona:
"I feel privileged to live this moment. Somehow, it looks to me similar to the 1919 expedition to the island of Principe... it was also a risky and complicated adventure with only one chance to measure. We are just taking a ship that goes a little further!"

Dave Robertson, University of Glasgow:
"After more than a decade involved in designing, building testing and documenting the LISA Pathfinder optical bench it will be both exciting and a huge relief to finally get good data from it in orbit. Until then there is the suppressed terror that something, somewhere, will go wrong. Watching the live feed from the launch site at 4.15am is particularly worrying and may be done from behind a sofa with a small Balvenie whisky in hand."

Nikos Karnesis' tale

How did you get started in LISA Pathfinder?

My journey alongside LISA Pathfinder began when I joined the Institute of Space Sciences of Catalonia (IEEC-CSIC) as a PhD candidate. Even back then I started realising the importance of the mission and the excitement of the team for the upcoming launch. As time passed the launch date was coming closer and closer, while everybody was working and preparing for a smooth mission operations period.

One of LISA Pathfinder's two test masses.

What do you work on, and where do your main interests lie?

My interests cover a range of topics, like gravitational wave astronomy and in particular the science of space-based observatories like LISA. I mostly focus on the data analysis techniques used for such instruments and the relevant statistical tools. I have also been a member of the developers team for the data analysis toolbox for LISA Pathfinder since the start of my PhD studies.

Where are you working now?

After my thesis defence, I moved to the Albert Einstein Institute in Hannover to continue my work as part of the LISA Pathfinder data analysis team. The environment here is ideal for the individuals that want to work on topics relevant to gravitational wave astronomy, instrumentation, and data analysis. The institute is very well manned with experts in interferometer metrology, and theorists that are very experienced in astronomy and detection problems.

What has been the most interesting thing about preparing for science operations?

In science, probably the most interesting part is, surprisingly, the problems that one encounters along the way! During all these years that I have been involved in the project I have participated in many simulations, endless meetings about software development, countless discussions about the operation of LISA Pathfinder, and all with a single final aim: to solve all of the foreseeable problems during the mission. Planning, and attention to the slightest detail of our experiments, is what keeps us going every day. The last part is very important for this type of mission - essentially laboratories in space - because it is not as straightforward to adjust and optimise the instrument as we would do on the ground.

How did you feel when LISA Pathfinder launched?

Watching the VEGA rocket fly in the air was an unforgettable experience. I felt moved and rewarded that the satellite we had been building for so long was finally put into orbit. It was also very satisfactory to see smiles on peoples' faces that have spent half of their career working on this mission. I could only imagine their feelings at this moment. But at the same time, we soon started realising that data is going to be flowing soon, and the work preparing ourselves for operations will have to be intensified. Suddenly time seemed short!

Are you looking forward to science operations?

Definitely! We have been preparing for this for years. Although if we think about the du-

▲ *Preparing for science operations has been a long process involving many technical meetings, training sessions, and reviews. The photograph shows one of the recent reviews which took place in ESOC in July 2015 where the team went through the status of many of the analysis procedures needed for flight.*

ration of the mission, operations will last for only a few months. This immediately puts extra pressure on the online activities of the community and to our instrument experts. But we are all looking forward to an exciting and inspiring year, filled with invigorating activities.

What will you do after LISA Pathfinder?

After the successful conclusions of LISA Pathfinder, we commence the second phase of the plan of the space-oriented gravitational wave community, which is none other than LISA herself. Our experience from LISA Pathfinder will be transferred directly to the design of the three-satellite mission. Laboratories will get busy again and simulations are going to be performed for a mission much more demanding than LISA Pathfinder.

Highlights to come

First light

Around January 14th 2016 we will see first light. The laser and optical metrology system will be switched on. This constitutes two firsts: the first time the entire system will be operated together, and the first time an interferometer will be operated in space. This is a particularly exciting time for me as the Optical Metrology Subsystem was partly designed, prototyped and then tested in Hannover at the AEI, and so its activation and operation are close to our hearts. Some of us will be there to take part in the switch on and work together with the industrial teams to bring the system to an operational state.

LPF goes it alone

Around January 22nd, the LISA Pathfinder science module will be separated from the propulsion module. This is a complex manoeuvre which involves spinning up the composite satellite to provide angular stability before firing the pyros (small explosive devices) to separate it into two. Next the science module has to be de-spun using only the micro-Newton thrusters before it begins its orbit around around L1 (Lagrange Point 1).

Relieving the pressure

With the propulsion module gone and the LISA Pathfinder science module close to L1 the next major milestone will be to release the launch locks that have safely held the test masses in position from the time of integration all the way through the rigours of launch. Around the end of January, as the 8 solid `fingers' are released from each test mass, simultaneously a venting valve is opened, connecting the vacuum around the test mass to the vacuum of deep space, allowing the residual pressure that has built up due to out-gassing in the year or so since integration to begin dissipating. The test masses are now held by the Grabbing-Positioning-and-Release mechanism: two controllable fingers, one on each side of the test mass.

Free at last!

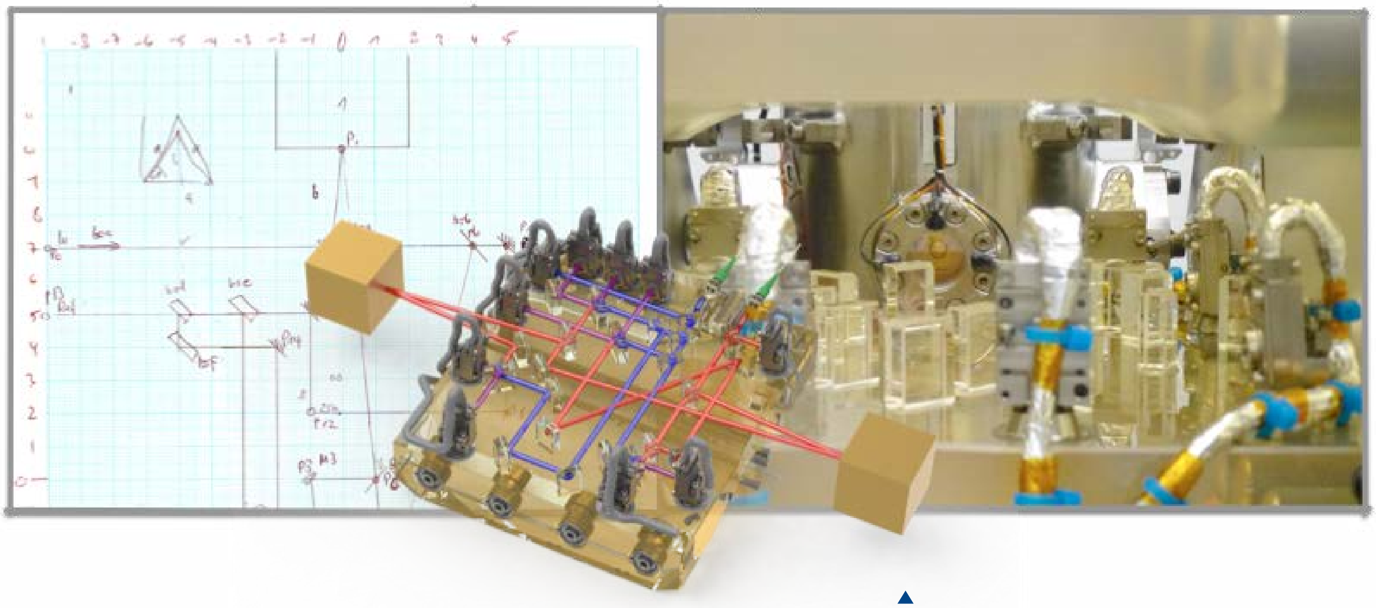
The moment of truth: the test masses will be released from the grip of the retractable fingers. This has to be done in such a way as to leave any residual velocity below a few micro-metres per second so that the relatively weak electrostatic actuation can grab the test masses and control them relative to the spacecraft. We are now in a position to begin drag-free operation of the test masses.

Science Operations: Let the fun begin!

Following the test mass release, the different control modes will be commissioned, allowing the system to climb up to our science mode in which one test mass is drag-free (i.e. the spacecraft will follow it using the micro-Newton thrusters) and the second test mass is weakly controlled to follow the first, all using interferometric readouts. The stable operation of the science mode towards the end of February will mark the end of commissioning and the beginning of science operations.

Launching the future

At 04:15 UTC on Thursday December 3rd 2015, LISA Pathfinder was launched. To say this was a tense moment would be to engage in wild understatement. We had just gone through the emotional rollercoaster of a one day launch delay, and the virus that I had managed to hold off since the



The primary metrology system on LISA Pathfinder is the Optical Metrology System (OMS). A complex configuration of 4 different interferometers, the OMS has undergone a long design and construction process to ensure high performance when in flight. The image shows one of the original sketches of the optical layout, a CAD model of the optical bench, and finally a photograph of the flight optical bench mounted between the two vacuum chambers which house the test masses.

weekend attacked with gusto. Nevertheless after a few feverish hours in bed I was back on the streets at 03:30 am heading for the European Space Operations Centre in Darmstadt where I would meet colleagues and watch the launch before taking part in a press event followed by a very welcome celebratory breakfast. But now it's up there! And about one hour after launch the successful acquisition of signal at ESOC marked the point at which our mission really starts.

Following 2 weeks of orbit raising manoeuvres, a final burn on December 12th pushed LISA Pathfinder out of the grip of the Earth and off towards L1. That journey takes a while, so the team got a well deserved Christmas break to recharge before the main show begins.

On December 3rd 2015 at 01:04 am LISA Pathfinder was launched from Kourou in French Guiana. The photograph shows the lift-off of the VEGA rocket which would bring LISA Pathfinder into its initial orbit around the Earth.

With Pathfinder well underway we are embarking on our first step towards a gravitational wave observatory in space. The experiments we will do on board of LISA Pathfinder will teach us much about what it means to fly and operate such technology, and should allow us to design and then build the best future observatory that we can. And time is short! The science operations phase will last a mere 90 days, during which the team will perform a dense program of experiments to learn all that we can about free falling test masses, laser interferometry in space, micro-Newton control of drag-free spacecraft, and much more besides. So in some sense, after many years of waiting for this moment, now that it's nearly upon us, at the same time the mission is nearly over. But the really interesting and fun measurements lay ahead and we need to focus on those before moving on to the building of LISA and observing the gravitational universe.

December 2015 – The Launch Story

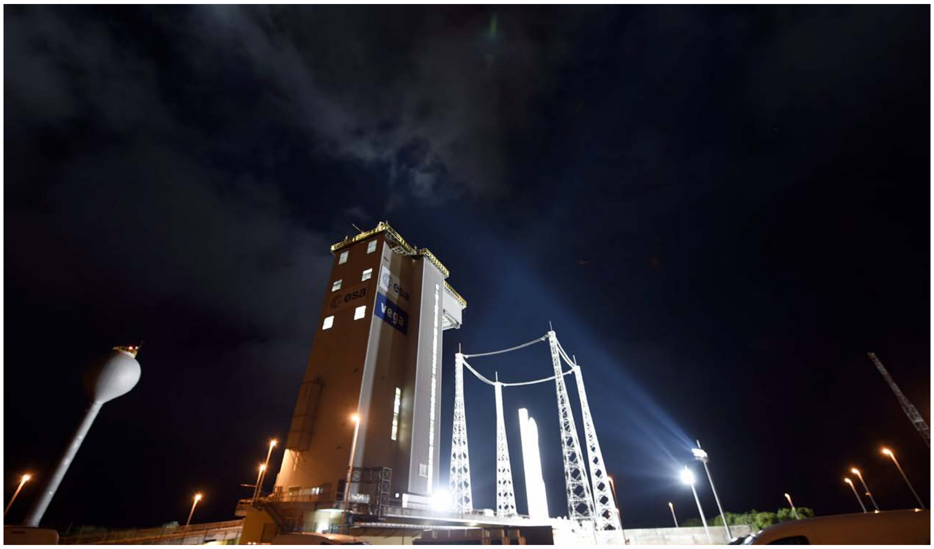
Harry Ward

Harry Ward leads the space gravitational wave work at Glasgow. For LISA Pathfinder the group built, tested and delivered the optical metrology system that lies at its core.

On a bright and crisp 30th November morning, a group of around 80 scientists, engineers, managers, public relations experts and press – all with their different agendas, and emotions – gradually gathered in a virtually deserted Terminal 3 at Charles de Gaulle airport in Paris. Among most of the LISA Pathfinder scientists – for whom launching something they had laboured hard for over a decade to produce was a new experience – there was a slightly nervous air of excited anticipation. But many others were old-hands at the space business and seemed very relaxed, at least for now.

Travelling by private Business Class charter is certainly the way to fly! Extremely well-fed and "watered" throughout the journey, we flew to Cayenne, arriving there around 7.30 pm. Shortly after arrival we were on a bus en-route to Kourou, the town nearest to the Guiana Space Centre, Europe's Spaceport. After a quick check-in to the hotel – in my case the former prison for French criminals that were not quite bad enough to be consigned to the nearby Devil's Island – we all convened for a reception. Launch was due to take place in the early hours of Wednesday morning, so we were looking forward to a Tuesday of spaceport visits before the night-time build-up to the launch. As well as looking forward to that, I was also looking just about everywhere else: I am not an animal or insect fan, and reports had reached me of hotel rooms with various forms of wildlife. Toads, tarantulas, and unrecognised – but large – flying things had all featured in dispatches by those who had travelled out earlier! Fortunately, and probably due in no small way to the almost overwhelming amount of DEET applied daily by the entire group, just about every insect gave us a very wide berth.

Tuesday dawned hot and humid. After breakfast we boarded our buses and headed for the spaceport. A location by the sea and with a jungle-like climate that is essentially constant 24/7 clearly presents a challenge to infrastructure: my overwhelming impression was that everywhere – even the high-tech spaceport buildings – was faintly brown and streaked by rust stains. As we drove along the route from Kourou, a group of buildings stood out: freshly-painted in white and with very trim surroundings, this proved to be the French Foreign Legion barracks. I suspect regular painting must feature in their training…



▲ *The Vega launcher, carrying LISA Pathfinder, is all set for launch after the mobile gantry withdrawal, at Europe's Spaceport in Kourou, French Guiana, on 3 December 2015.*

Our tour was fascinating. Standing at the base of the mobile launch table and looking up at the full height of an Ariane 5 is impressive, as is standing at the edge of the Soyuz launch site blast pit. We also got fairly close to the Pathfinder launch pad, though the launcher itself was hidden by the mobile support building. Then a quick visit to the on-site launch control centre followed – with first sight of a ticking countdown clock – before we headed off-site for lunch.

It was on the bus to lunch that the whispers started. Someone heard about a launcher problem. Was it a failure of a thruster, or a telemetry issue? Or nothing? Brows were tightening, emails were being studied closely on smartphones, routine conversations were quietening so that ears could tune in to the murmurs. At lunch the buzz continued; gradually better information began to trickle down: not a component failure, more a flight analysis issue perhaps? Before long we were summoned to gather to hear the official statement: launch cancelled – at least for tonight; no update until tomorrow lunchtime; problem is a potential one rather than an actual one: the long shadow period for the fourth stage before re-ignition might result in it getting too cold; further analysis to be conducted overnight in various places. Concern and disappointment spread rapidly. Phone reception was almost non-existent in the restaurant so communication back to Europe was almost impossible. A couple of us overheard that reception was possible "in the middle of the Kourou river". So I cancelled the planned Glasgow launch party by texting while leaning off the end of a boat launch pontoon just by the restaurant!

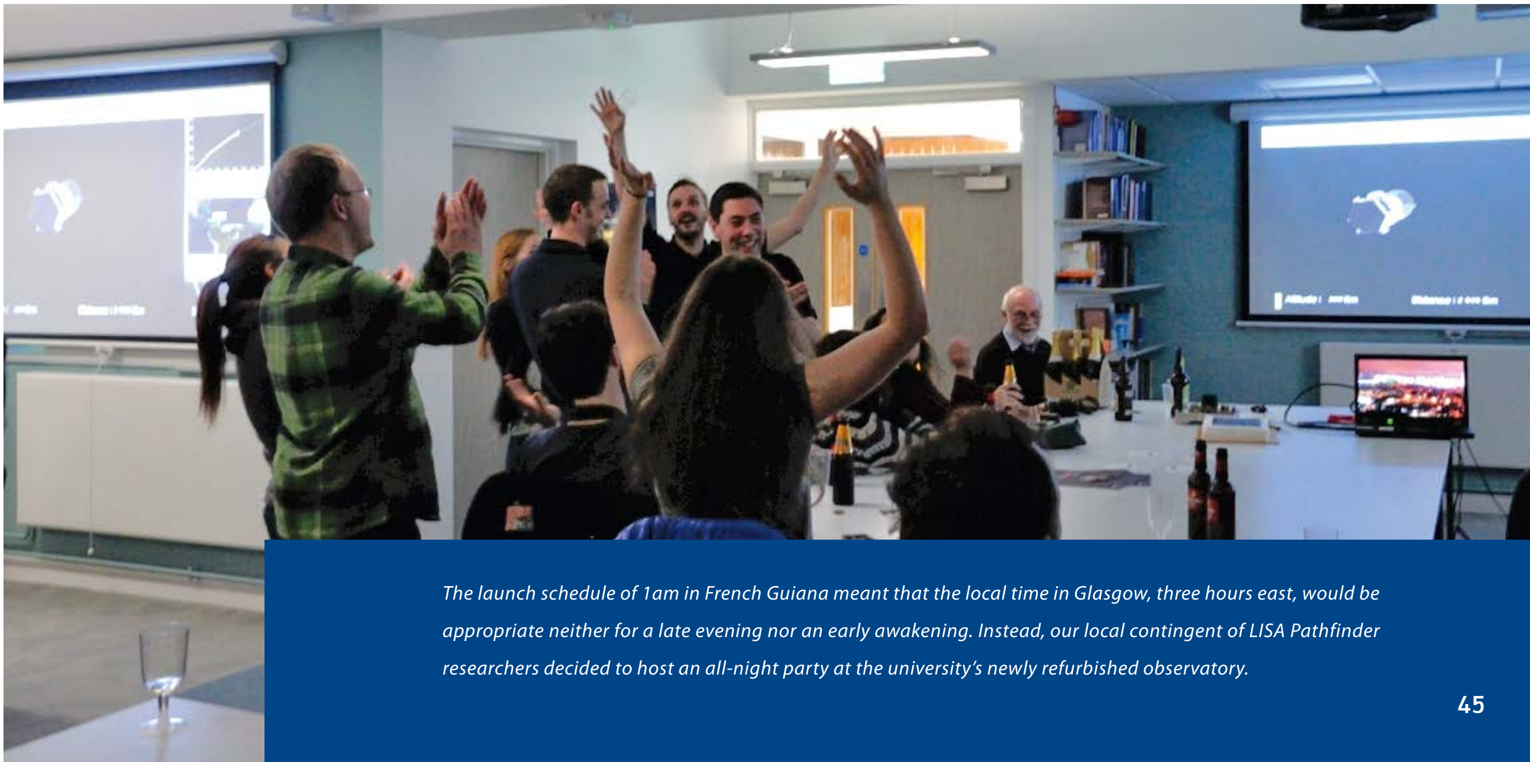
The remainder of Tuesday was fairly subdued. A trip to the Jupiter mission control room showed us where we would be for the actual launch – if it happened. However we were very conscious that our delayed return flight would have to leave Cayenne at 0700 on Wednesday morning, launch or no-launch, so spirits were a bit muted. With time to be filled on Wednesday morning I went on a tour to the zoo. It was hard, however, to stop clock watching: the time till the launch update news dragged on. As we drove to lunch we passed a convoy of Foreign Legion trucks heading in the direction of the Spaceport. We knew they had a role in securing the site for a launch. Did they know something we didn't? It must be a sign...

Again it was at lunch that the news broke. First the whispers from a table of engineers, then the spreading smiles. A phone call to Stefano Vitale at our table brought more details - and the smiles spread further! Should we send messages home? Better not; wait for the official announcement. Another summons to an adjacent room to hear the update: go for launch at 01.04 Kourou time!

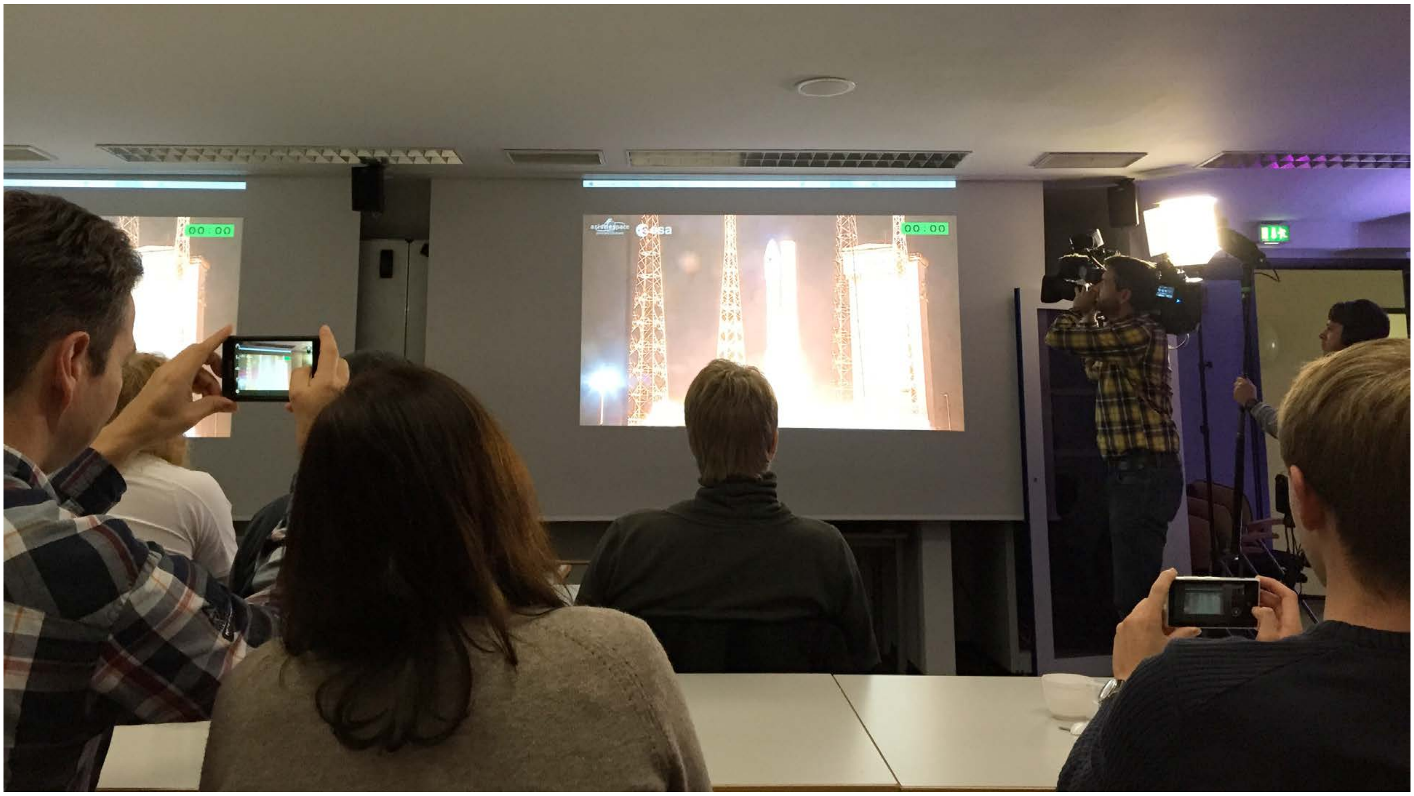
Parties in Europe were hastily reconvened while we had our final dinner at the hotel. Bags were packed in readiness for a hasty post-launch departure, then it was back on the buses to the Jupiter room. In the "fishbowl" – separated from us by huge glass walls – controllers were hard at work. Big screens showed live video of the launcher and countdown timers. Finally everyone took their assigned seat, the room hushed and the live ESA and Arianspace TV presentation began. For me it was a particular pleasure to hear the Project Scientist, Paul McNamara, talk us through the final stages. Paul is a former PhD student of mine at Glasgow, and like many of us, has spent a very long time preparing for this moment.

With just one minute to launch the doors to the viewing platforms were swung open and everyone made a move. Once outside there was just time to (push to) get a good spot, face in the correct direction, try to get a camera turned on, and then hear over the public address "trois, deux, un, top, alloumage".

In the distance the sky lights up. For a fraction of a second time seems to slow down as you mentally evaluate if what you are seeing is more consistent with a launchpad explosion or a successful lift-off! But then all is clear: lift-off – and an extremely fast one. Not like the leisurely Apollo launches of my youth, more like a firework at a New Year's party. The launcher quickly vanished into the clouds, but by good fortune reappeared briefly through a gap in the clouds about half a minute later, at which point we also heard the loud rumble of the launch.



The launch schedule of 1am in French Guiana meant that the local time in Glasgow, three hours east, would be appropriate neither for a late evening nor an early awakening. Instead, our local contingent of LISA Pathfinder researchers decided to host an all-night party at the university's newly refurbished observatory.



Starting 04:30 on the 3rd of December 2015, Hannoverians converged on the Albert Einstein Institute to attend the launch party for LISA Pathfinder. Dr Benjamin Knispel of the Institute ran the event. Local television stations filmed the audience, as an estimated ninety people gathered for breakfast and awaited lift-off. The European Space Agency coverage, re-broadcast from French Guiana into the room, tracked the countdown. At precisely 05:04 Central European Time, the Vega rocket carrying LISA Pathfinder ignited; a second later, the broadcast cut out! To the relief of all at the launch party, coverage returned a moment later, showing that the rocket was headed soundly skyward.

Back inside the control room there was still intense concentration from the controllers: we might be off the ground, but there were still a lot of critical steps to go. One by one we heard of "all nominal conditions", stage shutdown and next stage startup, all leading to a final release of tension when the fourth stage shutdown was confirmed. Then there were lots of congratulations and happy faces. The guests filed out to a reception in the area outside Jupiter. No rest for the controllers, however: the final and critical burn – the one that had caused the launch-delay panic – was still to take place in about an hour. In due course we filed back in – and waited. Fourth stage burn start confirmed, then finally, nominal shutdown: Pathfinder was in its planned initial orbit! Applause broke out all around, together with much hand-shaking, and back slapping. A series of speeches followed and then we had to make a quick dash for the buses to collect our luggage and head for the deserted airport. I think we were in the air not long after the first Champagne corks popped outside the Jupiter room!

I have heard that partying in Kourou went on a long time – in some cases till the Sun was well-up on Thursday! Aboard the plane, the earlier brave talk of extended on-board celebrations faded quite quickly, not because of any sense of anticlimax, simply because of exhaustion! Sleep followed for most, and nine or so hours later, a plane-load of very, very contented guests came back to Earth with a bump.

For Pathfinder, the first frightening part – at least for the payload providers – was over. And by Christmas all the orbit-raising burns and the final escape burn had taken place flawlessly, setting Pathfinder on-course to arrive at L1 around 22nd January. And arrive it did: on schedule and with all tested subsystems performing perfectly. So we can now look forward to the next phase – science operations starting in early March. Watch this space!

Glossary

AGN: active galactic nuclei
BBH: binary black hole
BNS: binary neutron star
CBC: compact binary coalescence
CBR: cosmic background radiation
cWB: coherent wave burst
DARM: differential arm (the gravitational wave channel)
DetChar: detector characterization
DQ: data quality
EM: electromagnetic
ER8: engineering run 8 (in which GW150914 was detected)
ESD: electrostatic drive
EVNT: event logbook
GR: general relativity
GraceDB: gravitational wave event candidate database
GRB: gamma ray burst
GW: gravitational wave
GW150914: the event!
iDQ: interactive data quality
LDVW: LIGO data viewer
LHO / H1: LIGO Hanford Observatory
LLO / L1: LIGO Louisiana Observatory
LSC: LIGO Scientific Collaboration
NSF: National Science Foundation
O1: observing run 1
Omega scan: spectrograms generated using a sine-gaussian basis instead of the sinusoidal basis of a traditional fast-fourier transform
S4/5/6: LIGO science runs 4, 5, 6

The LIGO Magazine

LIGO is funded by the National Science Foundation and operated by the California Institute of Technology and Massachusetts Institute of Technology. This material is based upon work supported, in part, by the National Science Foundation. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

The authors gratefully acknowledge the support of the United States National Science Foundation (NSF) for the construction and operation of the LIGO Laboratory and Advanced LIGO as well as the Science and Technology Facilities Council (STFC) of the United Kingdom, the Max-Planck-Society (MPS), and the State of Niedersachsen/Germany for support of the construction of Advanced LIGO and construction and operation of the GEO600 detector. Additional support for Advanced LIGO was provided by the Australian Research Council. The authors also gratefully acknowledge the support of LSC related research by these agencies as well as by the Council of Scientific and Industrial Research of India, Department of Science and Technology, India, Science & Engineering Research Board (SERB), India, Ministry of Human Resource Development, India, the Istituto Nazionale di Fisica Nucleare of Italy, the Spanish Ministerio de Economía y Competitividad, the Conselleria d'Economia i Competitivitat and Conselleria d'Educació, Cultura i Universitats of the Govern de les Illes Balears, the European Union, the Royal Society, the Scottish Funding Council, the Scottish Universities Physics Alliance, the Hungarian Scientific Research Fund (OTKA), the National Research Foundation of Korea, Industry Canada and the Province of Ontario through the Ministry of Economic Development and Innovation, the Natural Science and Engineering Research Council Canada, Canadian Institute for Advanced Research, the Brazilian Ministry of Science, Technology, and Innovation, Russian Foundation for Basic Research, the Leverhulme Trust, the Research Corporation, Ministry of Science and Technology (MOST), Taiwan and the Kavli Foundation.

Online ISSN: 2169-4443
World Wide Web URL: http://www.ligo.org/magazine
Publisher: LIGO Scientific Collaboration, Pasadena, CA, USA
LIGO DCC: LIGO-P1600010
Contact: magazine@ligo.org

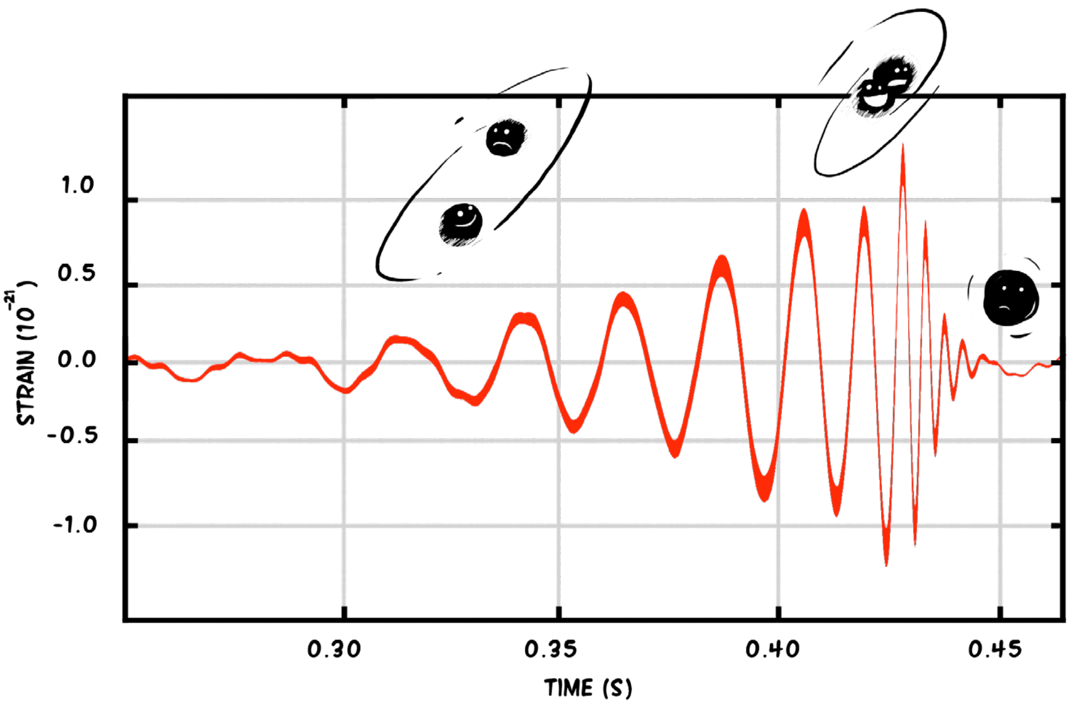
Design & production: Milde Marketing Science Communication + formgeber
Printed by GS Druck und Medien GmbH Potsdam

A signal from two merging black holes

A pair of black holes orbiting each other will create gravitational waves, ripples in space and time. As these waves are emitted, the orbit will shrink. The black holes get closer together and move faster and faster about each other. Eventually they merge together and form a bigger black hole. This emits gravitational waves as it settles down to its final shape.

A billion years ago, such an event happened. On September 14, the gravitational waves reached Earth and the final fraction of a second was detected by LIGO. Gravitational waves are a stretch and squash of space, and by the time the signals reached Earth they are tiny. We measure a minuscule change in the distance between the mirrors in a LIGO instrument. Below we show what such a signal from this event should look like.

Christopher Berry



Information extracted from the signal GW150914

The signal:
Date: 14 September 2015
Time: 09:50:45 UTC
Peak strain: ~10^{-21}
Peak frequency: ~150 Hz
Arrival time difference between Hanford and Livingston: ~7 ms

Where:
Distance: ~1 billion light years
Redshift: ~0.09
Location on sky resolved to ~600 square degrees (most likely southern hemisphere)
Orientation: face-on/off

The source:
Primary black hole
mass: ~36 solar masses
spin: <0.7
Secondary black hole
mass: ~29 solar masses
spin: <0.9

Gravitational wave energy output equivalent to ~3 solar masses

Final black hole:
mass: ~62 solar masses
spin: ~0.7