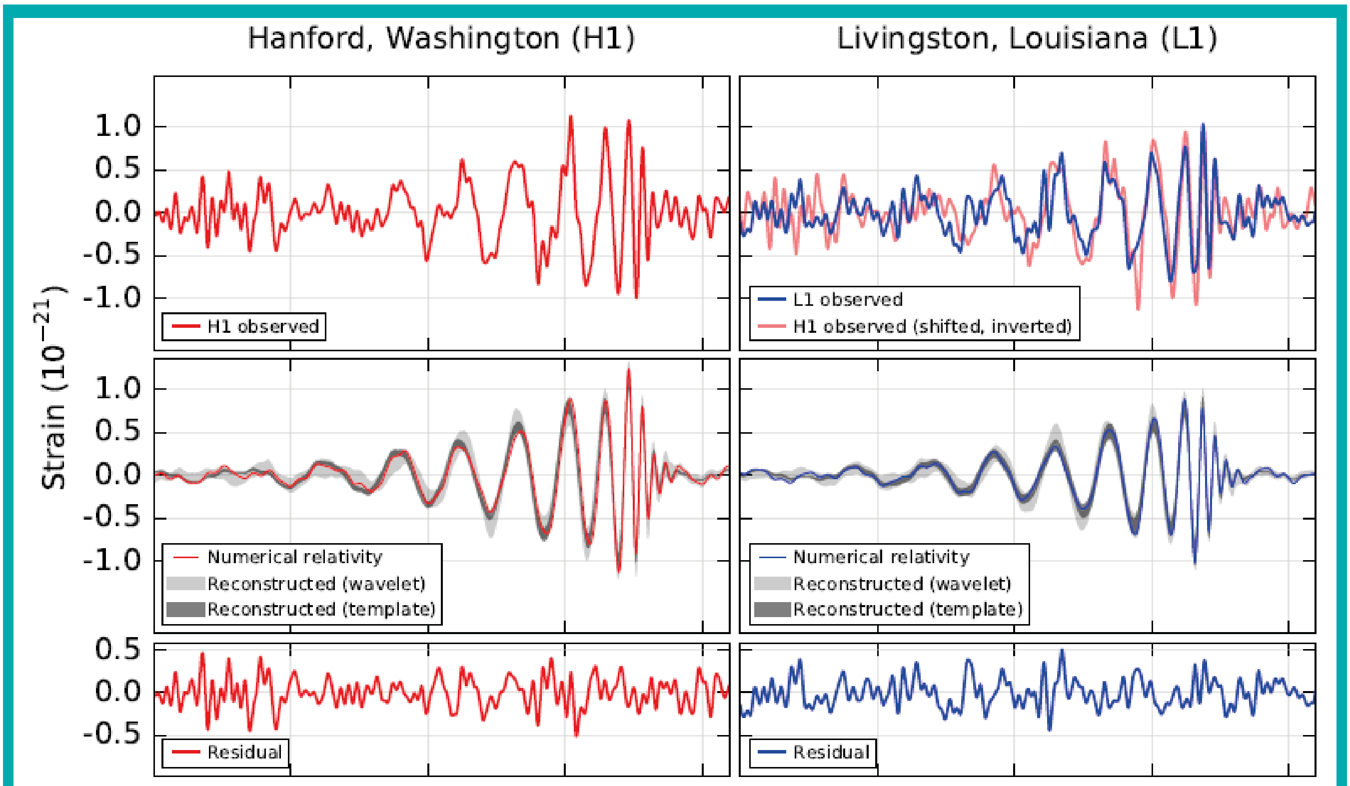
# h ISTORICAL DETECTION !

THE GRAVITATIONAL VOICE

SPECIAL EDITION




The gravitational wave detected at Hanford and Livingston compared with the general relativity prediction

News from EGO and VIRGO

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The content of this newsletter does not necessarily represent the opinion of the management.

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"The gravitational wave detected at Hanford and Livingston"



# EDITORIAL

With this special 30th issue of "h – the gravitational voice", we intend to celebrate the discovery of gravitational waves. We have asked many friends of our world to tell us about their feelings at the achievement of this fantastic goal by the LIGO interferometers and by our whole community. The aim is not to provide a systematic report, but rather a collection of impressions from as many points of view as possible. There is a bit of history, a bit of technical information, some not widely known details and some plans and wishes for the future, near and far. Some things are repeated, but with different voices; which is also, in itself, interesting. We conclude this editorial of the Virgo and EGO newsletter with the warmest wish to soon join our LIGO colleagues and to detect many more events and their sources.
A tutorial on gravitational waves can be found at the end of this issue.

*C.Bradaschia*
*Chief Editor*

## The detection of gravitational waves

This has been a truly fantastic few weeks for gravitational wave science.

This is a field with a long history, a history of perseverance and commitment to essential research across a huge range of disciplines – from theoretical modelling of astrophysical sources of gravitational waves, through signal analysis techniques, to applied physics and control engineering. This has required facing some of the most challenging technological developments in precision measurement science.

The announcement of the first direct detection of gravitational waves is built on a foundation of decades of work by many hundreds of scientists – most importantly, working together, towards the goal of giving us a new tool to explore the limits of our knowledge of the workings of the Universe.

Along with the fabulous news by the LIGO and Virgo collaborations of the first direct detection of gravitational waves, has come the successful operation – still ongoing – of the LISA Pathfinder mission, testing technologies to pave the way for the eLISA space-based gravitational wave detector. On top of that is the news that in India, formal approval has been granted by the government of India of 'LIGO-India' as a Mega-Science project – a critical step towards enhancing the global detector network to maximise the multi-messenger capabilities of our field, working closely with our colleagues in electromagnetic astronomy.

For many years we have promised to 'open a new window on the Universe' and that is a promise on which we have delivered. Now, to look through that open window and realise the full potential of gravitational wave astronomy, we look forward to the new discoveries that will be enabled by accessing the full spectrum of gravitational wave signals – from pulsar timing arrays and space-based detectors as well as even more sensitive detectors on the ground.

What is clear is that this is just the start – our first detected sources are not just 'dark' but black, however right now, the future for gravitational wave astronomy most certainly looks bright.

*S. Rowan*
***Chair of the GWIC***

## We did it !

We did it! These were the decisive words of David Reitze when he announced the first direct detection of gravitational waves. On February 11th, the LIGO Scientific and Virgo collaborations published the paper which ushered in the era of Gravitodynamics and Gravitational wave astronomy.

We are proud of this result and we are glad to see the announcement of this discovery being echoed in communication media all over the world.

As I said during the Cascina press conference, this is the end of a long path, which started in the 1960s, when Jo Weber bravely decided to start the scientific endeavour of detecting gravitational waves.

It was the time of the resonant detectors, first at room temperature, then cooled down to the boiling point of liquid helium. We started a long and painful path, to develop techniques for beating noise, to implement new algorithms for extracting the signals embedded in the noise and to increase sensitivity.

At that time, it was already clear that a coordinated network of detectors, distributed across different locations around the Earth, was needed. The first international effort was in 1986, with the data collected in coincidence by detectors at the three universities of Baton Rouge, Stanford and Rome (the Rome detector was Explorer, the antenna installed at CERN). The modern network of interferometer detectors is the offspring of this first attempt.

The interferometric approach to detection was developed later, after a necessary boost in terms of organization and financial support. These giant machines were built after a long phase of research and development.

The road was long and was characterized by fights against enemies similar to those encountered using resonant bars; for example, seismic and thermal noise.

At the beginning of the 1980s, I visited Caltech, where they were developing a prototype of a GW interferometer using an Argon laser. At that time, they were trying to stabilize it better and were fighting against laser noise.
I also had the occasion to look at the first ingenious attempt, in Japan, to study the laser approach: a set-up installed at the Institute of Space and Astronautical Science. It was a 100m-long Michelson interferometer, in which the unprotected vacuum tubes were installed at the end of one of the institute's parking areas. This detector used an Argon laser and

its sensitivity was limited by one of the main enemies of this technique, against which we are still fighting: diffused light.

New lasers, new suspensions, ultra-high vacuums, new detection strategies and algorithms to detect different categories of signals, have been developed over more than thirty years.

The first detection is the result of this huge improvement, accompanied by a deeper understanding of method limitations.

Many scientists contributed from many different domains; today we have to express our warm thanks to all of them.

*F. Ricci*
***Virgo Spokesperson***

# Behind the scenes of a discovery

The gravitational-wave h(t) signals received by LIGO on 14 September 2015, have very small amplitude compared to instrument noise. Filtering is required to see those signals.

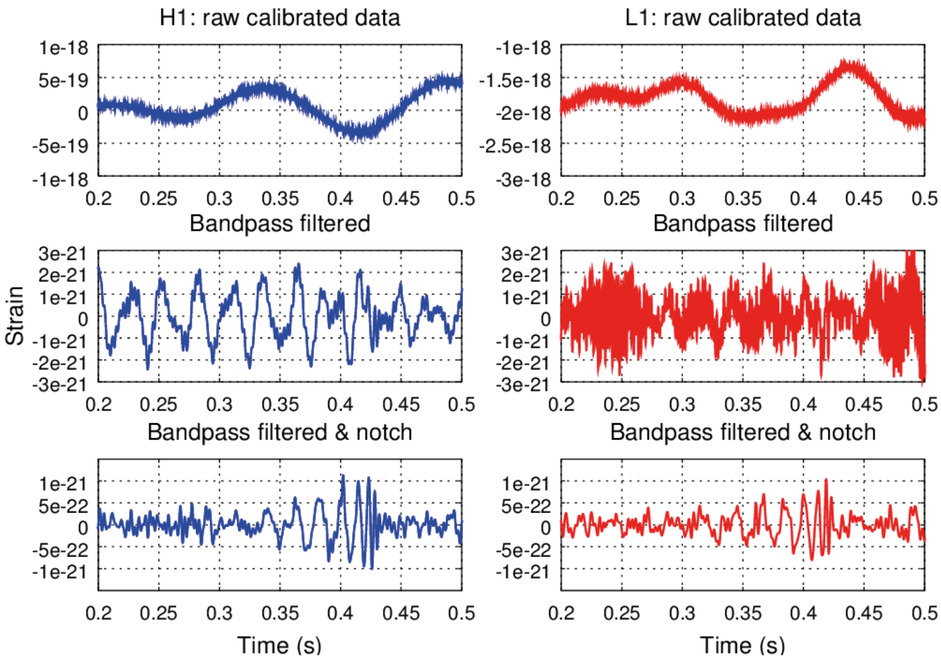
The data have to be processed using a 35–350 Hz bandpass filter to suppress large fluctuations outside the detectors most sensitive frequency band, and band-reject filters (also called notch filters) must be used to remove the strong instrumental spectral lines.

The two stages of this filtering are shown in the attached figure. The raw h(t) data are displayed in the top row. In the middle row, the bandpass filtered data are shown. The data in the bottom row are obtained after bandpass and notch filtering combined. This filtering is close (but not exactly identical) to the so-called whitening filter used to search for gravitational wave signals.

It is interesting to notice that the raw h(t) signal varies in the range $\pm 5x10^{-19}$
The noise is decreased by nearly 1000 after filtering out the noise outside the most sensitive band.

After cutting out the large frequency lines the gravitational wave signal is finally visible with its real tiny amplitude of $\pm 1x10^{-21}$ and its characteristic time behaviour.

*E. Chassande-Mottin*




*An interesting tutorial, entirely written in Python, on the processing required to obtain the detection signals is available at https://losc.ligo.org/s/events/GW150914/GW150914_tutorial.html*

# Before Virgo

Our LIGO friends have made the first direct detection of gravitational waves!

We have good reasons to be both frustrated and satisfied; frustrated because we were hoping to do it together, but we are a bit late, and satisfied because we are co-signing the paper, and, above all, in my opinion, because this first detection is not the most important event. More important is the fact that, together with the LSC, we have opened this 'new window on the Universe', which will provide direct information about dark objects such as neutron stars and black holes.

The timing is also very good, just about 100 years after Einstein discovered gravitational waves, and, incidentally, just when I am retiring. Furthermore, it looks like mid-size black holes could be more frequent than expected: a first important result for astrophysics.

I would like here to remember some facts and express opinions concerning the early times of Virgo from the French side, that some of you may not know.

At the end of the 1970s, when I became interested in the field, the direct detection of gravitational waves was not very popular, after some false discoveries by Jo Weber.

Earlier work by Rai Weiss (1972) to compute the possible noise sources in a large interferometric detector was showing the possibility of improving sensitivity to above that of Weber bars, although the technology was still very far from available, mainly in terms of laser power and stability, quality of optical components, seismic isolation, and thermal noise. Peter Bender's space experiment project was still very preliminary. It promised to be extremely expensive, but appeared to give better opportunities because of the possibility to observe lower frequency signals, originating from more massive and more efficient sources, maybe even from the Big Bang.

For ground detectors, the main target was therefore the detection of supernovae. They are not frequent enough in our galaxy, so the goal was to be sensitive enough to detect them as far away as the Virgo cluster, which seemed to be possible for future cryogenic resonant detectors and for interferometers. The expected signals would have been in the kHz frequency range, so the seismic isolation did not look extremely difficult, and in Orsay, we focused on optical problems, while in Pisa, Adalberto decided to develop a low-fequency seismic isolator (initially for suspending resonant detectors, since INFN groups were leaders in that field and had started considering cryogenic bars). In France, there was no experimental research on gravitation.

It was a field for theoreticians only, and the physics departments of CNRS, although they may have been interested, were not ready to invest big money or any staff in the field. From 1982 to 1985 our small Orsay group (Jean Yves Vinet, Nary Man, myself and two engineers) had difficulties surviving.

We had to join the theoretical laboratory at Institut Henri Poincaré, led by Philippe Tourrenc, in order to be recognised administratively, we had to find empty space in a nuclear physics lab., and to accumulate small grants (up to 12 in parallel, from CNRS, the Ministry of Defence, and private companies) in order to buy some equipment and to attend conferences.

By 1985, the lanscape had changed: Hulse and Taylor (and Thibault Damour) had demonstrated the existence of gravitational radiation, and since the modelling of the efficiency of supernovae (by Bonazzola et al.) was rather pessimistic as concerns their efficiency, the coalescence of binary neutron stars had become the preferred source, although we did not know what the rate of events might be. Therefore, it was important to look for lower-frequency signals, down to 100 Hz. At still lower frequencies, black holes, moreover binary-black holes were not yet very popular, but could be considered.

This is when we met with Adalberto at the Marcel Grossmann meeting in Rome, where he presented ideas and first results concerning his superattenuators, and Jean Yves Vinet presented his theory of recycling, the technique invented by Ron Drever in order to decrease by a large factor the requested laser power. Adalberto and I quickly understood the complementarity of our R&D activities, and decided to work together.

There were additional circumstances: our team had collaborated with the R&D of German and Scottish teams, hoping that we could join together for a full-size European detector, but the German project (GEO 3000) was 'close to being funded' and the staff of the Max Planck Institute did not accept the idea of establishing an international collaboration because 'it would delay the approval of the project[1].

In addition, after Adalberto's talk, they considered that the superattenuator was too complicated and would be noisy. This is when and why Virgo (initially the 'Very Improbable Radio-Gravitational Observatory' in addition to the reference to the galaxy cluster) started.

At that time, we were told that CNRS would not be able to fund its construction because the priority on the list of large projects (TGE, or *Très Grands Equipements*) was the Very Large Telescope in Chile, and although INFN was rather wealthy, Virgo would be expensive and in competition with the development of an array of cryogenic bars.

***NOTES to Alain's article***

*1. It is important for me to say that my decision to get involved in the field is due to the excellent contacts I had as a post-doc in Boulder with Peter Bender, when he was starting to design LISA, and with Rai Weiss when I visited him at MIT in 1980-1981.*
*Afterwards, we kept collaborating informally by exchanging students and post-docs. For instance, David Shoemaker got his PhD on Nd-YAG lasers and recycling with us in Orsay before joining LIGO; Peter Fritschel and Tania Regimbau were exchanged as post-docs. Also Nary, Jean Yves, and I worked on LISA, when ESA became interested from the end of the 1980s, until Virgo was approved, and then again more recently.*

*2. This was a critical point. The specifications were very severe, and could be met by only a few companies, on a small area of a few square millimeters, but we needed much more, and no company was interested in investing equipment and engineers for a market as small as GW detectors.*

So, in parallel with our Italian-French activities, we organised a few international meetings, attended by physicists from the USA and Europe, as well as Marcel Bardon (then leader of Physics at NSF, and who had created its Gravitation department) and Ian Corbett from the British research agency, but unfortunately no representatives of French, Italian or German agencies. So we were unable to reach any formal agreement concerning a common array of detectors.

By 1989, we had been joined by INFN groups from Frascati and Napoli, and we presented the Virgo project document to CNRS and INFN. The document was signed by about 40 physicists (most of them theoreticians) and engineers. CNRS decided quickly to evaluate it, and by the beginning of 1990, the report by Patrick Fleury (a high-energy physicist) was rather positive, although noticing that the experimental staff was largely insufficient.

Then, on the French side, we were rather lucky:

• first, the director of IN2P3, Pierre Lehmann became very interested: he supported LAL and LAPP joining Virgo, and progressively accepted the idea that Jean Marie Mackowski and his team would be offered a new, high-tech laboratory (LMA, Laboratoire des Matériaux Avancés) to create the coatings for the Virgo optics[2],

• at CERN, the LEP had nearly finished its work and new physicists and engineers from INFN and IN2P3 became involved in Virgo.

The absence of a reasonably large prototype could have delayed the starting of Virgo, but Adalberto and I were able to convince our institutions that it would be faster to solve full-size problems directly, rather than spend years on a smaller prototype and have to later meet the real difficulties; it had become clear to us that the 30m German prototype and the 40m Caltech prototype, after 10 years of efforts, were not strongly contributing to solving the problems to be encountered in a full-size detector.

In the meantime, VLT was funded and so Virgo could be considered.

Mid-1992, our Minister of Research, Hubert Curien, decided that Virgo would be funded. This was a big surprise, and may have been a political mistake, since INFN had not yet taken its decision, but it accelerated the process.

construction of Virgo from 1996 to 1999, Daniel Enard (our technical manager) and myself, pushed the management of CNRS to create EGO. This happened at the end of 1999, with the agreement of INFN. This was not unanimously approved, an opinion that I cannot understand. What would a CERN experiment be without CERN, or what would the VLT be without its local staff?

• an important point was the formal agreement between Virgo and the LSC to exchange data, analyse them together, and to sign together the relevant publications, otherwise the name Virgo would not appear in this historical paper.

*C.Nary Man, A. Marraud, A. Brillet, D.Shoemaker*

The CNRS-INFN agreement was signed in 1994, and the construction was able to begin in 1996, after a difficult period for INFN while it acquired the site, which originally belonged to more than 100 private owners. We were also very lucky that Catherine Brechignac, the head of CNRS, continued to support Virgo, while the new research minister did not.

Most of you know the more recent events, which I will not recall, except for the, in my opinion, most important ones:

• after some management difficulties encountered during the

Why did this happen? The main reasons are the following:

1. we proved that low-frequency seismic isolation is effective, although they did not exactly copy the superattenuator;

2. we demonstrated competence in data analysis and source modeling;

3. in optics, we made them understand:

• that Nd lasers and infrared radiation were more appropriate than Argon lasers and green light, because of scattering losses;

• that our simulation program was necessary to specify optical components (Vinet gave them his code in 1990), although they adapted it for their own needs;
• that it was possible to get very-low-absorption silica from Hereaus, after we had collaborated with Heraeus for a few years;
• that LMA was the only place in the world to improve and create adequate optical coatings.

4. we did not accept to become part of the LSC as long as it did not make reference to Virgo.

Now, let me explain why I think our little bit of frustration could have been avoided. First, we should be very grateful to INFN and CNRS to have decided to build Virgo, about 2 years after LIGO had started; this was expensive and risky, and, with its two detectors, LIGO already had the possibility to make a first detection alone, while Virgo did not.

Then, once Virgo and LIGO had started getting close to their nominal sensitivity, I thought that the next step was to uniformise the design of the Advanced Detectors, and to synchronise their construction in order to build a worldwide observatory. But clearly, astrophysicists were not yet very interested, and high-energy physicists are used to thinking in terms of CERN-like experiments and first detection, rather than in terms of observatories, so nothing happened in that direction. This was a mistake, in my opinion, from our French-Italian side.

But let's forget it and remain positive; gravitational waves have been detected, we deserved to co-sign the paper for having been creative and having collaborated on many topics. And now it must be obvious for everybody that the operation of Advanced Virgo is a necessity, that LISA must fly, and that E.T., or rather a worldwide array of large underground detectors should be built in the future, and that the possibility of observing electromagnetic waves in coincidence must also be tested. No unemployment for the years to come!

Thanks to all of you, and good work!

*A. Brillet*

## The discovery as I feel it

Adalberto preferred to provide his feelings from the perspective of an interview. Below are his thoughts on the discovery.

**h.** What was your first thought on learning of the GW150914 candidate?
**A.G.** No comment.

**h.** And when you saw the preliminary version of figure 1 in “the paper”?
**A.G.** Astonished.

**h.** How reliable do you consider the discovery to be? Were you surprised by the type of the first detected event (BHBH inspiral)?
**A.G.** Competely reliable; and yes, I was very surprised by the coalescence.

**h.** How do you feel about the fact that LIGO made the discovery while Virgo was still upgrading?
**A.G.** Simply devastated.

**h.** What do you think will be the consequence of the American discovery for Virgo and the European GW community?
**A.G.** Certainly a strong impulse forward, and Virgo should learn to be more aggressive, considering that LIGO India has just started.

**h.** What would you like to say to the Virgo Collaboration?
**A.G.** Please find deeply-stronger motivations, as the beginning of astrophysical GW observation will be our victory.

**h.** And to LIGO?
**A.G.** They have my unconditional admiration; how clever they have been. They deserved everything.

**h.** And to the public?
**A.G.** Our merit is to have been the first, alone, to propose to build such a special detector with a low-frequency band and to have a successfully operating detector.

**h.** If you were building Virgo today, what would you do differently?
**A.G.** I would certainly play with inertial platforms and I would compare them with Superattenuators.

**h.** Do you have any additional comments you would like to make?
**A.G.** Let’s hope that we are luckier from now on.

*J-M Mackowski, G.Sanders, A.Scribano, A.Brillet, A. Giazotto*

*Worldwide press front pages gathered by our colleagues at Caltech*


## Impressions

Personally, the discovery is clearly one of the most important events of my life. I have been working in this field since 1979, and while it was clear from the beginning that the defining goal for my focus was the first detection, it was both easy and comfortable to lose sight of the goal – there were so many fascinating problems to solve and small and large satisfactions on the path. That, and the very long time scale we all recognized from the beginning, made the pursuit feel more like a lifestyle than a goal-oriented endeavor.

When first seeing on the early morning of 14 September 2015 that we had a signal, and knowing from my work on the instrument and injections that it was likely to be a real signal, I was surprised, pleased, but not overjoyed – because I could not, in a matter of minutes or hours or even days realize the importance of the event for me. Clearly as we worked through the checks to ensure that it was not instrumental and the greater team pursued questions of accidental injections, signal consistency, and the like, I became more intellectually confident that the signal was from gravitational waves. But it was not until I saw the first draft of the discovery paper that it really sunk home. There is something about seeing the simple stated fact of the detection in print (these days on a screen, but the effect is the same) that makes it tangible and caused my worldview to pivot to a 'post-detection' perspective.

LIGO's path is influenced in many ways by the discovery, of course. In the near term, we already feel a responsibility – and pressure from a new and larger community of scientists and those responsible for overseeing science – to observe.

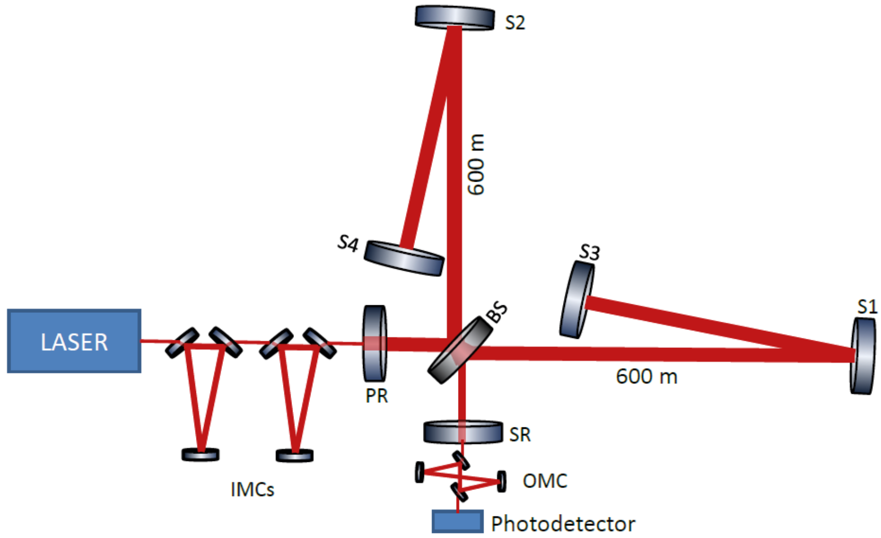
The tantalizing fact that making improvements in sensitivity through commissioning requires us to stop observing, but can lead to more observations than continuing to observe at a limited sensitivity, provides a tension that we previously could manage within the Collaborations. That is no longer the case, and from now forward these new constraints (and 'customers') must have a role in making those decisions to observe or to commission.

On the longer term, from the perspective of the evolution of the instruments, it is now clearer than ever that we need urgently to map the growth of the field and the instruments we plan, and understand how they fit into the larger group of scientists interested in our results. It is a wonderful problem to have!

The change for my daily LIGO-related attention is that I am much more interested in learning about the astrophysics we can do with the signals, and how we get from a time series to an astrophysical conclusion. This new 'sandbox' clearly will be fun for many years to come.

*D.Shoemaker*

# The contribution of GEO600




*A simplified sketch of the optical layout of GEO600. IMC = Input Mode Cleaners , PR = Power Recycling mirror, BS = Beam Splitter , main interferometer mirrors = S1 – S4. SR = Signal Recycling mirror , OMC = Output Mode Cleaner.*

GEO 600 is a German/UK detector with 600m long arms located at Ruthe near Hannover in Germany. The project came about from a collaboration of two of the original bar gravitational wave groups - at the University of Glasgow and at the Max Planck Institute for Physics in Munich. Both groups had their own plans for building large interferometers in the mid 1980s and then came together to propose a joint project for an interferometer with 3-km arms in 1989. However funding crises in both countries led to the project being put on ice.

By then both groups had gathered more than a decade of experience from prototype instruments, the Glasgow one having an arm length of 10 m and the one of the Munich group (by then located between the MPA and the MPQ in Garching) having an arm length of 30 m.
These prototypes were showing such excellent performance in terms of displacement sensitivity that a way forward had to be found. The importance of paying attention to having low loss suspensions for the mirrors was attended to in both prototypes and optical scattering and the need for input mode-cleaners to reduce beam geometry fluctuations were already demonstrated on the Garching prototype. Even during this early development phase the possibility of incorporating squeezing of the vacuum was already under consideration at MPQ.

The solution was found by moving the joint project to the University of Hannover, under the German Leadership of Karsten Danzmann. Jim Hough led the UK input to the project and Bernard Schutz the data analysis effort. Funding was found in 1994 from the Max-Planck Society, the state of Niedersachsen, the Volkswagen Foundation, the BMBF and the newly-formed PPARC Research Council in the UK. A site at Ruthe, near Hannover in Germany, was available mainly on University land, and the geometry of the site combined with the funding envelope restricted the arm length to 600 m.

Experience in Germany had been with multi-beam delay lines in the arms and that at Glasgow with resonant cavities in the arms and the design chosen for the GEO 600 detector was a combination - a folded Michelson interferometer as shown in the figure below. Both power recycling and signal recycling were installed from the beginning, signal recycling and its variant resonant sideband extraction having been invented by Brian Meers in Glasgow and Jun Mizuno in Garching.

The folded Michelson scheme also appeared to us to have the advantage of simpler control systems requirements.

*The GEO600 site in Ruthe 20km south of Hannover, Germany.*

Because of its short arm length compared with LIGO and Virgo a number of innovative technologies were introduced in the GEO 600 interferometer to help reduce the effects of both displacement noise and readout noise. Among these were the adoption of multi-stage pendulums with quasi-monolithic lowest stages using silica fibres, electrostatic rather than magnetic drives for direct test mass control, thermal compensation to change the curvature of the test masses, high power very stable lasers, stray light suppression, and output as well as input mode cleaners.

All these technologies, pioneered on GEO 600, and in some cases further developed, have been incorporated in Advanced LIGO. In particular Germany has funded the provision of lasers for Advanced LIGO and the UK has funded the main suspensions and the silica blanks for one full set of cavity mirrors.

The latest development in GEO600 is the introduction of squeezing.

A reduction in shot noise from approximately 300 Hz upwards, reaching 3.5 dB at frequencies of a few kHz has been demonstrated to date and squeezing is now routinely used as a robust noise reduction tool in GEO600 – another technique pioneered in the GEO collaboration and now ready to be implemented in the advanced LIGO and Virgo detectors.

GEO researchers are also very active in data analysis – in particular the CBC, CW and Transient search groups with past and present leadership in all three.

In addition to the founding members – the Albert Einstein Institute (the Max Planck Institute for Gravitational Physics, Karsten Danzmann, Bernard Schutz et al) and the Leibniz Universität Hannover (Karsten Danzmann et al), the University of Glasgow (Jim Hough, now Sheila Rowan et al), and the University of Cardiff (Sathyaprakash et al) - the GEO consortium has been strengthened by the addition of the University of the Balearics (Alicia Sintes et al), the University of Birmingham (Alberto Vecchio et al), the University of Sheffield (Ed Daw et al), the University of Strathclyde (Nick Lockerbie et al), the University of the West of Scotland (Stuart Reid et al), the University of Cambridge (Tony Lazenby et al), the University of Edinburgh (Jonathan Gair et al), the University of Hamburg (Roman Schnabel et al) and Kings College, London (Mairi Sakellariadou et al).

*J. Hough, H. Lück*

*Impressive numbers on Facebook !*


## Ce n'est qu'un début

Five months have now passed since the first time I saw the event, and still every day I look at that waveform and remain astonished.

For years we have given talks and seminars in front of sceptical colleagues saying, "We are going to open a new window on the universe". And today we offer mankind the sound of what happened 1.3 billion years ago at a distance of $10^{22}$ km on a scale of a few hundred kilometres.

We are astonished, thinking back on all the work done and seeing how well the LIGO detectors have performed, because we know how challenging it was.

*Ce n'est qu'un début:* the excitement after the discovery is not fading. We are aware that we are starting to write a new book. I imagine that the way I feel now is somewhat similar to how Galileo felt when he discovered Jupiter's satellites and I wish every scientist in whatever field could feel like this once in their lifetime.

The entire field of GW research has suddenly changed its status. For decades we have been looked upon as "weirdoes" by the wider physics and astronomy community and now, suddenly, this has turned into something completely different and we appear as a collaboration of serious and rigorous scientists, capable of pursuing and realizing a measurement of unthinkable precision and difficulty.

Now, we are aware that the entire community is waiting for Advanced Virgo to come online, because this will allow us to "pinpoint" with a worldwide network. Our responsibility has further increased. We feel it all, together with the pride and joy of being part of this memorable discovery.

*G. Losurdo*

## An EGOcentric view of the near future

11 February 2016: the first emblematic date in the gravitational wave study of the Universe.

And now?

A series of objectives, in the near future and in the longer term, are on the agenda of the Boards of Direction of the major laboratories involved in the game.

I will provide, in the next few lines, my personal point of view, not necessarily coincident with the vision of the Virgo Collaboration or of the funding Agencies, but dictated by my experience and my vision of the future, starting from the perspective of EGO.

Well, the first objective is obviously to bring Advanced Virgo into operation at a sensitivity comparable with that of the LIGO interferometers, in order to play its fundamental role of third leg in the network table.

The next six months will be totally dominated by activities in this direction. This will not conclude the actions around the interferometer: a plan for completion of upgrades, necessarily postponed, plus further developments (in the first place the squeezer) are on the table, need to be programmed and human and financial resources have to be attributed coherently, foreseeing a series of activities that will last for a few years.

In parallel with the plans for exploitation of the second-generation interferometer, visions of the third generation cannot be stopped. Many good reasons are suggesting both to prepare EGO for the global challenges and to organise the EGO contribution to global efforts.

The well consolidated know-how, the reinforcement and enlargement of the laboratories and the transformation into the status of European Research Infrastructure Consortium, ERIC, are objectives to achieve before the end of 2017.

The road toward the third generation is going to be paved by the blocks of R&D, jointly developed by scientists and engineers, whichever their present label; all of the competencies distributed in the LIGO and VIRGO (and KAGRA) teams are required for the drawing and engineering of the new machine(s).

EGO will put its aces on the table, ready to develop sub-programs or to lead items. The next few years will be exciting for that.

From what I enunciated above, it is evident that further resources, both financial and human, are necessary to allow EGO to play

*A selection of European press website front pages*


*credit Federico Nenci, EGO*

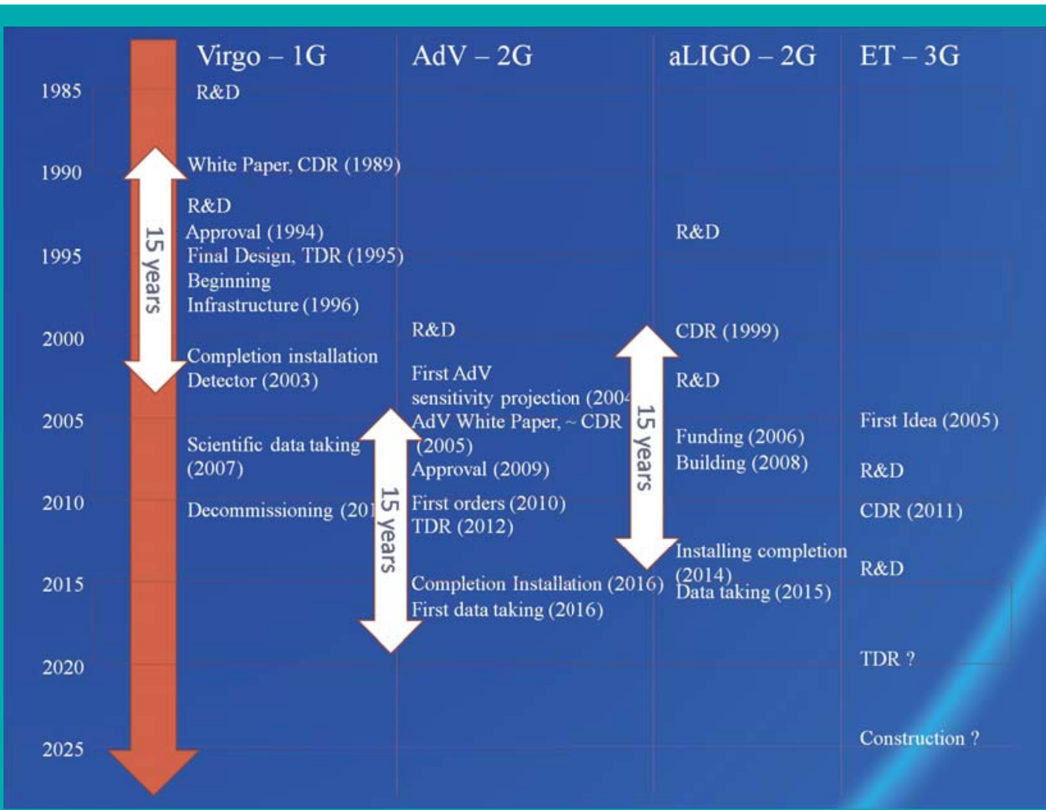



*Figure 1- Time evolution of the past, present and future GW detectors. About 15 years separate the Conceptual Design Report (CDR) and the completion of the installation.*

its role, as is appropriate after so many years of investments in the infrastructure and in the on-site staff. The creation of a Gravitational Waves ERIC, with the participation of various European Countries, hopefully all of those hosting laboratories active in the field, the search for external funds, for example via agreements with the Regione Toscana and by participating in European calls, the opening of new fellowships, will be the basic ingredients for the strategy that the present management is engaged in pursuing, during the remaining time of the mandate.

Scientific targets and strategic progression will characterise the future; the EGO staff is called to play a major role.

*F.Ferrini*
**Director of EGO**

## The discovery and the future of ground interferometers

GW150914, the detection of the gravitational wave (GW) emitted by the coalescence of two black holes, allowed us to fully open a door which until now has only been ajar: future GW observatories.

New observatories will be needed to implement the future of GW research: precision gravitational wave astronomy, astrophysics and cosmology.

GW detectors are giant infrastructures and complex machines and they surely belong in the category referred to as “big science”. For this reason it is crucial to plan future evolutions decades in advance. For the present and past GW detectors we can apply the empirical “15-year rule”: the time between the so-called Conceptual Design Report (CDR) and the completion of the installations is about 15 years (See Figure 1). Future machines will be even more complex, so there is no reason to believe that a shorter period of time will be necessary.

Meanwhile, advanced detectors will progress toward their nominal sensitivity. The plans to update them and the activities to design future observatories are progressing. In this particular sector Europe started first, thanks to the conceptual design of the Einstein Telescope (ET), funded by the European Commission under the seventh Framework Programme. This involved participation from institutions in Italy, France, Germany, the Netherlands and the UK. The CDR of ET was delivered in 2011, allowing speculation that its creation is possible before the end of the next decade.

But, what is the key ingredient of ET and how is it different from current detectors? ET is based on a key concept: “Research Infrastructure”. ET is an observatory, a facility that can host a detector and the future evolutions of the hosted detector (when technological progress allows it).

To be an observatory, ET should be able to resolve both the polarisations of the detected GW, permit observation of many events with high signal-to-noise ratio (SNR) and have the widest frequency bandwidth and highest duty cycle.

All of these requirements constrained the CDR. ET should have a triangular shape, in order to host more than one detector and reconstruct the two GW polarisations.

Each detector is wideband, probably realised by two interferometers, using the so-called Xylophone technique, and will have 10km-long arms. ET should be built underground, in order to minimise external disturbances, such as seismic noise and Newtonian noise. Cryogenic technologies will probably be used to minimise low-frequency thermal noise.

ET is the most advanced and complete idea for a 3G observatory, but it is not the only one. Recently, a plan for the evolution of the LIGO detectors toward a new facility was discussed. The plan still needs to be consolidated but it foresees the upgrade of the LIGO detectors, the introduction of cryogenic infrastructures (the so-called “Voyager” phase) and then the realisation of a new 3G facility (“Cosmic Explorer” or CE). For the CE facility a brute force approach, creating a 40km-arm interferometer, is currently being debated.

Obviously, the 3G design still needs to be decided, but the positive news is the fact that the GW community is beginning a collaborative process in order to produce a coherent global scenario. On the 2nd and 3rd of February this year, a good fraction of the GW scientific community met in Florence for the 7th ET symposium; the first dedicated to ET and LIGO3G. This cornerstone meeting covered many topics: we discussed 3G science, technology and organisation.

The meeting was very successful, sowing the seeds for a future global collaboration on 3G GW observatories. The next milestone is the GWADW meeting, in May, where the technological aspects will be discussed.

*M. Punturo*

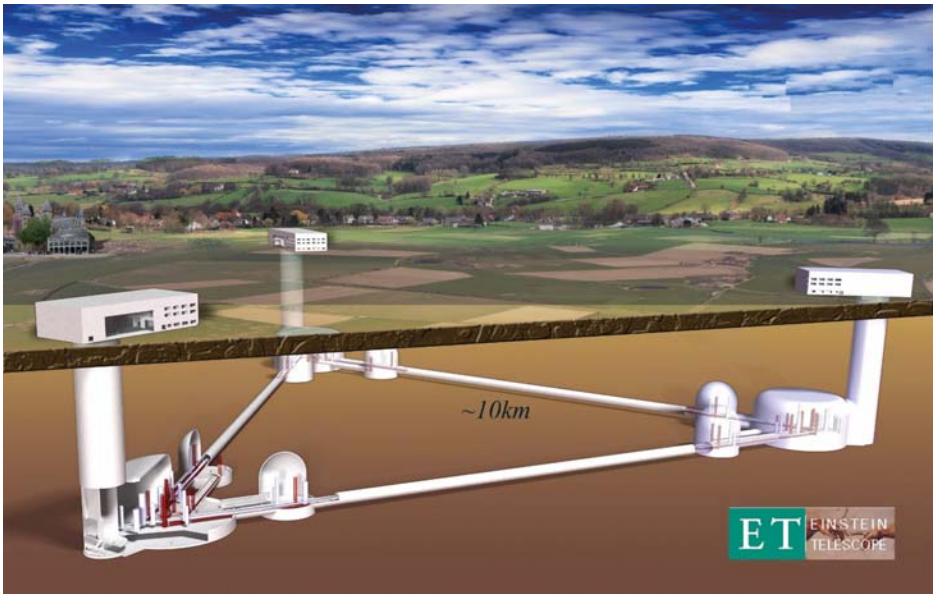



*Figure 2- Artistic view of the ET infrastructure*

*Figure 3- Some of the participants to the 7th ET symposium, Florence, 2-3 February 2016*

## The discovery and space interferometers

On 14 September 2015, we made the first direct observation of gravitational waves. This signal has been given the name GW150914, GW standing for Gravitational Waves, followed by the date when it was observed. Before this discovery, the only fundamental waves we knew were light, radio waves, x-rays and gamma-rays; all part of the electromagnetic spectrum, whose theory was worked out by James Clark Maxwell 150 years ago and their existence confirmed 22 years later by Heinrich Hertz.

In 1916, Einstein showed that similar to the electromagnetic waves of Maxwell's theory, gravitational waves existed in his theory of gravity. By now, everyone knows the buzz phrase: gravitational waves are ripples in the fabric of spacetime. But what does it mean? The curvature of space is defined by the distance between fixed points in space. In the absence of gravitational waves this distance, as measured by, say, how long it takes for a ray of light to get from one point to another, remains fixed. In the presence of gravitational waves, the distance changes and the time of flight of light between the fixed points varies by a tiny amount.

That is what LIGO detectors have measured.

GW150914 caused a change in distance one-thousandth the diameter of proton and so we had to make sure that myriad other causes did not make this change. This was helped greatly by having two LIGO detectors that were separated roughly by 3,000 km and by a theoretical understanding of what gravitational waves from a pair of colliding black holes look like.

The signal lasted for a mere fifth of a second in our detectors, taking 7 milliseconds to pass from the LIGO Livingston detector in Louisiana to the LIGO Hanford detector in Washington. With two detectors we cannot tell the sky position of the source but the fact the signal arrived first in Livingston and then in Hanford tells us that the source is in a patch in the Southern sky.

At the beginning of our observation the frequency was 30 Hz, or the black holes were orbiting 15 times per second around each other. At the end of 200 milliseconds, the frequency was 250 Hz and they were orbiting 125 times around each other. In the end, the horizons of the two black holes collided travelling at half the speed of light.

Secondly, this is the first time anyone has directly observed a pair of black holes (see below for arguments why we think these should be black holes) in orbit around each other.

From the observed gravitational waves we are able to deduce the masses of the black holes just before they merged and we found them to be 29 and 36 times the mass of the Sun, give or take a few. Although astronomers had speculated that such binaries should exist no-one had observed them before. This is not surprising, because binary black holes of this type are not expected to emit any light, x-rays or radio waves and the only way of observing them is via gravitational radiation they emit. From the strength of the signal, we were also able to determine the distance to the source and we estimate it to be roughly 1.3 billion light years away, give or take a few hundred million light years.

Thirdly, we have for the first time observed the formation of a black hole. The signal that we observed was ramping up in amplitude and frequency from 30 Hz, but died almost completely after reaching 250 Hz in less than one-fiftieth of a second.

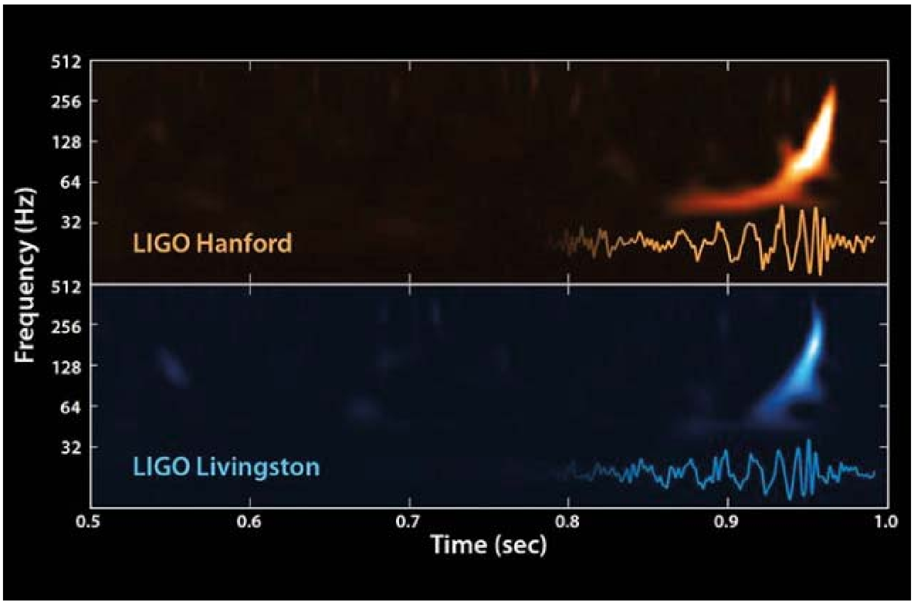



*Figure 1 Time-frequency and time-series plots around the time of the event as seen in the two LIGO detectors.*

So here was a signal that was going up and up, rose to a crescendo, and completely died in an instant.

Given the masses we have measured, the only interpretation that is possible is that we have a pair of black holes that were in orbit. When they came together and merged the signal stopped completely. As far as we can tell, the signal we have detected has all the characteristics of the death of two black holes and the birth of a new one. This has allowed us to test Einstein's general relativity in ways that were not possible before.

It turns out that the final black hole has a mass of about 62 solar masses, implying that about 3 solar masses were converted in the process of inspiral and merger of the two progenitor black holes. That is a colossal amount of energy, but most of it was released during the last few cycles with the luminosity in gravitational waves reaching 50 times that of the entire Universe in light for a brief moment.

What is the significance of our discovery? Improvement in LIGO's sensitivity over the next 3 years and addition of new detectors in Europe (Virgo), Japan (KAGRA) and India (LIGO-India) will allow us to survey a volume of the Universe that is 30 to 100 times more than the current setup does.

The improved gravitational wave detector network should detect one such merger every day. But we also expect to observe colliding neutron stars, supernovae, and other sources, which will help us gain deeper insight into matter under extreme conditions of density and gravity and help deduce the equation of state of dense nuclear matter. In essence, gravitational waves will be a new tool for fundamental physics, astrophysics and cosmology.

This discovery also opens up the possibility of observing sources at other frequencies.

The Laser Interferometer Space Antenna (LISA) is designed to work at frequencies of hundred micro-Hertz to 1 Hz. This is the window in which we could observe coalescences of supermassive black hole binaries in the range of tens of thousands to millions of solar masses.

LISA uses a different technology, but the same fundamental principle of detection. The LISA Pathfinder mission will test the technology during the course of 2016 and its success should pave the way for observation of gravitational waves from space.

The scientific questions addressed by LISA are complementary to those by a ground-based network: LISA is aimed at answering the origin and evolution of massive black holes throughout the Universe by principally observing their growth via binary mergers. We now know that such mergers could involve a heavy black hole of 70 solar masses falling into a supermassive black hole of millions of solar masses.

Such events will not only help us understand merger history of black holes in galactic nuclei but they also give us a map of the spacetime geometry in the vicinity of rotating black holes. This will be a whole new way to test dynamical spacetime in strong gravitational fields.

LISA will enable a new era in astrophysics and cosmology by allowing measurements of black hole masses and spins to exquisite precision.

Black hole masses could be measured to fractional accuracies of one in 100 and their spins to accuracies of 10% in the case of binary black holes of comparable masses. These accuracies are several orders of magnitude better when one of the companions is a stellar mass black hole like GW150914 falling into a supermassive black hole. In the latter case we will also be able to measure the eccentricity of the orbit at some initial time, which should help us understand the environments of massive black holes at galactic nuclei.

LISA can also probe stochastic background, but to do so it will need to be flown in its original configuration that allows the construction of three independent V-shaped detectors. This configuration will also help us infer the polarisation of the radiation, which would not be possible with a single detector configuration of eLISA (or evolved LISA).

In summary, with the detection of GW150914 we have opened a new window for observational astronomy. We can only speculate about the rich physics this window will help us uncover but there are likely to be sources and phenomena that we are not aware of. That is precisely what will be the most exciting discoveries we can expect in this new window.

*B.S. Sathyaprakash*

## The discovery seen from Australia

Today, gravitational wave detection has opened a new window to the universe. Like a message in a bottle, cast into the ocean and recovered on a distant seashore, the first gravitational wave signal has given us a direct link to the era of the first stars, to a time 13 billion years ago, when violent star formation created a prolific quantity of black holes tens of times more massive than our Sun.

The earliest ancestors of our Sun were Population III stars. They are thought to have formed from primordial hydrogen and helium when the universe was less than 1 billion years old. Star formation theory tells us that they were very massive.

These ancestral stars left us time capsules in the form of binary black holes. The black holes may have formed together from huge binary stars, or they may be the result of chance encounters of individual black holes that created tightly bound pairs sometime after their birth.

Each time capsule is a gravitational time bomb! The time clock is set by the spacing of the black holes. If it is too large, the merger will take longer than the age of the universe and we will never see the signal. If it is too small, the merger will have already taken place. Only those within the correct timing range will be detectable.

Before 14 September 2015, we could not be sure that there would be enough such binaries that we would be able to detect them.

On 14 September 2015, gravitational wave astronomy received the first time capsule. The signal was a cosmic spacequake.

The coalescence of a 29 solar mass black hole with a 36 solar mass black hole released 2.6 solar masses of gravitational energy in 100 milliseconds.

It was the largest explosion of energy ever detected by astronomy, but as pure gravitational energy it has been undetectable until we created sufficiently sensitive detectors.

The universe spoke, and for the first time we heard the message and understood it!

The message from the Sun's most distant ancestors tells us that gravitational wave astronomy will soon be able to unravel the early history of the stars that began the 13 billion year process that ended with intelligent life, and detectors like LIGO and Virgo able to listen to these messages from the universe.

The sound detected by LIGO started two octaves below middle-C, and rose up to middle-C in one tenth of a second.

The signal was a vibration of mirrors 4km apart that changed their spacing by about a billionth of the diameter of an atom.

This is the smallest signal ever detected, 100 million times smaller than signals detected by radio telescopes. Even so tiny, the signal stood well above the noise, and arrived at the two LIGO detectors, which are 3002km apart, just 6.9 milliseconds apart, characteristic of a wave travelling at the speed of light and coming in at an angle of about 45 degrees.

Black hole binary merger signals encode their distance, their masses and the spin of the final black hole. The estimated distance of the event was more than one billion light years.

The total power output in GW over the event duration was about ~2 x $10^{22}$ times the luminosity of the sun, or ~$10^{49}$ Watts, peaking to $10^{50}$W in the last millisecond. The total energy output was almost $10^{48}$ Joules. The Sun would have to emit steadily for ten thousand times the age of the universe to give out that much energy - which is impossible because the energy in that burst greatly exceeded the total rest mass energy of the Sun!

Like human ears, gravitational wave detectors have poor directional sensitivity. Directional sensitivity comes from spacing detectors far apart. The best directional sensitivity needs a 3D array, and particularly needs a detector in the southern hemisphere.

From the positions of LIGO. Virgo and KAGRA, Australia is the best location for a southern detector.

This has always been the motivation for Australia to play a major role in gravitational astronomy. In the 1990s the detector NIOBE in Perth worked with the Italian detectors Auriga and Nautilus and Allegro in Louisiana to set limits on gravitational wave bursts from our galaxy.

Australian physicists played a major role in the first detection. Fifty-six Australian scientists were authors on the discovery paper. Australian students Eleanor King and Carl Blair were at Hanford and Livingston at the time of detection. Carl had been implementing parametric instability tuning and a parametric instability monitor for the control rooms. These are needed to bring the laser power up to the 100kW level used during the first observation run.

Without these suppression systems, 15kHz test mass resonances slowly ring up to a large amplitude until the interferometer loses lock, after which it may take hours to get back into operation.

Lock acquisition in LIGO is aided by the green laser locking system installed by Australian National University. This makes use of the wide locking range of a low finesse green laser cavity to take initial control of the interferometer before handing over to the higher sensitivity infrared systems. When laser power levels are increased in the future, further parametric instability control systems will be required at LIGO (and Virgo) as well as precision sensors, such as those developed for LIGO by the University of Adelaide for monitoring thermal distortions of the test masses.


*The numbers on Twitter were also impressive*

The Australian teams are looking to the future. Currently ANU is developing high performance squeezers for future detector upgrades. UWA is developing opto-mechanical white light signal recycling cavities.

These remarkable devices break the inverse relationship between bandwidth and resonant gain that normally places limits on cavity enhancement. Our new technology will allow white light signal recycling to create broadband enhancement.

The two technologies combined could give detectors a sensitivity boost by factors of 3-30 across the frequency band.

We estimate that the Australian technologies currently under development, when implemented, could allow black hole binary coalescence events like the first detected event to be monitored throughout the observable universe, and that event rates of 600 per day are likely.

The Australian teams are also closely involved with data analysis. The UWA data analysis group developed the intrinsically real time SPIIR filter pipeline for binary coalescence events. The pipeline mimics the operation of the human ear.

It uses graphics cards on small clusters, and can provide a trigger even before final coalescence. It independently confirmed the first detection event and has been running throughout much of the first observation run.

The Monash team in Australia is closely involved in stochastic background searches and the Melbourne group is focused on continuous waves from spinning neutron stars.

The case for an Australian detector is still very strong. Even when LIGO-India is operational, an Australian detector doubles the angular resolution of the world array as well as impacting very strongly on the array duty cycle and polarization resolution. Australia has a high level of expertise and hopes that the new discovery will trigger opportunities for building AIGO.

I began searching for gravitational waves in 1972 as a young postdoc in Louisiana. I thought we would detect gravitational waves in a couple of years and then go on to a new challenge. Forty four years later, we succeeded at last, the science is exhilarating, and the opportunities are enormous. We have exposed the tip of the iceberg. The next years will be very exciting.

*D. Blair*

## The ABC of gravitational waves

*Let's start with electromagnetic waves*

Everybody knows that a variable electric current flowing in a metallic wire (an antenna) generates radio waves; this was proven by Guglielmo Marconi in the last years of the 19th century and successfully exploited in the following decades.

As described by Maxwell, a more general way of putting this is that an "electric charge moving with acceleration generates electromagnetic waves"; the strength (amplitude) and frequency of these waves depend on the charge strength and the direction of movement.

In other words, electromagnetic waves are oscillations of the electromagnetic field propagating at the speed of light (which is electromagnetic radiation too!). Electric charges or electric conductors enveloped by these waves are forced to move.

These facts are well known and unsurprising.

*Gravitational waves*

Gravitational waves have a completely different nature, but are generated with a very similar mechanism. It is sufficient to replace electric charges with masses and the electromagnetic field with a gravitational field.

As described by Einstein: "If a mass moves with acceleration, it generates oscillations of the gravitational field" (gravitational waves) propagating at the speed of light. Masses enveloped by gravitational waves are forced to move by this variable gravitational field.

There are also differences between electromagnetism and gravitation: e.g. electric charges are positive and negative, while masses are all of the same sign; this is well known.

But gravity is different from anything else and we must take in to account "special" and "general" relativity. Mass and energy are "the same thing" and the presence of mass warps space-time, the same space-time where we live (this is hard to believe!). Free bodies move along curved trajectories and time flows at a variable rate! This is expressed in a general and rigorous way, "a la Einstein"; it is what Newton referred to as "gravitational field and gravitational force".

*Do gravitational waves really exist?*

Yes! They were detected for the first time, in September 2015, by the LIGO interferometers. This is what we are celebrating with this special issue of the Virgo-EGO newsletter.

The detected signal was generated by the merger of two black holes of about 30 solar masses each, which happened 1.3 billion years ago at a distance of 1.3 billion light-years from us. All this can be inferred by a careful analysis of the signals detected by the two LIGO interferometers.

This discovery fully overcomes our previous indirect knowledge of gravitational wave existence, which was founded on the fact that all the known binary systems composed of two compact stars have a revolutionary period which decreases exactly in accordance with the energy loss due to the emission of gravitational waves (which agrees with general relativity).

But let's now try to understand intuitively the existence of gravitational waves. We start with a classical example: two boys pulling on the ends of a long rope.

If one of the boys suddenly jerked the rope at his end we would see a deformation (wave) travelling along the rope eventually reaching the other end.

Let us now suppose that a big asteroid hits the earth, which is suddenly displaced.

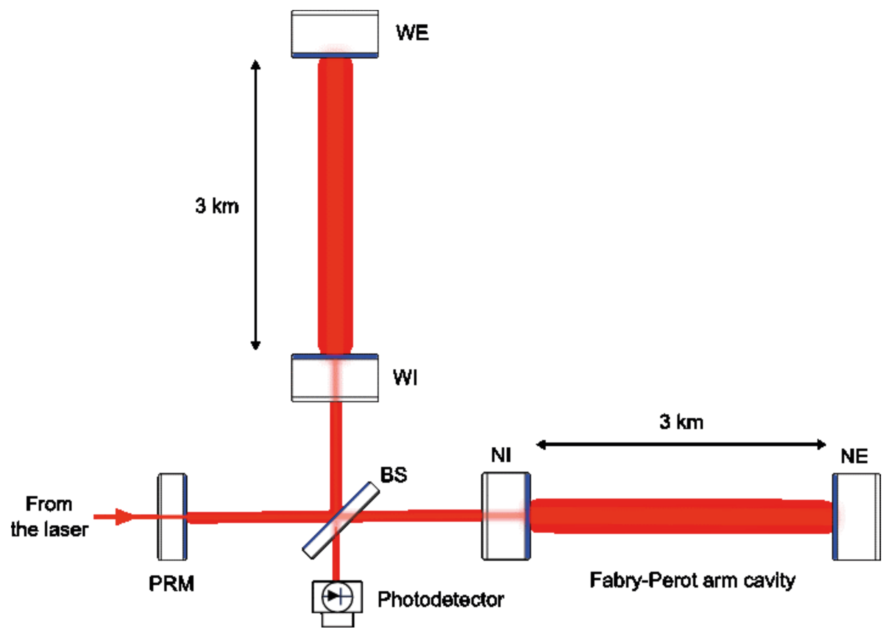
The moon would not feel it immediately; it is not reasonable to imagine the Earth's gravitational field extending rigidly for any distance, and anyway, special relativity prescribes that no effect can propagate with a speed greater than light (Newton suffered when he was forced to admit that).

It is much more logical to think that the information of the Earth's displacement propagates to the moon (which is about 400,000 km from us) in a short, but nonzero time: that is a gravitational field deformation propagating to the moon, that is a gravitational wave - which is exactly what is derived from Einstein's equations.

As with any massless entity, gravitational waves travel in vacuum at the speed of light. After 1.28 seconds the moon would feel the Earth's displacement and would move accordingly.

*A gravitational wave goes by*

Now we are ready to understand the effect of a passing gravitational wave. With Newton we would say that the gravitational field will fluctuate. With Einstein we will say that the space-time fabric will be warped in a variable way. The practical result is that free bodies (masses) present in this region of space will change their mutual distances in a peculiar way.



Distances will first increase in one direction and decrease in the orthogonal direction, then vice-versa, several times.

*Detecting gravitational waves*

A Michelson interferometer (such as Virgo and LIGO) is the ideal instrument to detect such behaviour; it emits two laser beams in orthogonal directions and monitors the interference pattern of the beams reflected from the end mirrors (WE and NE in the figure). Changes in the interference pattern are due to arm length variations produced by gravitational waves or instrument noise. Disentangling the origin of the signals and selecting genuine gravitational wave signals is the duty of data analysis. These instruments may be sensitive to changes of the arm lengths, which are much smaller than the diameter of an atomic nucleus.

The enormous interest in detecting gravitational waves generated by violent events in the cosmos and the incredible difficulty of achieving this result are described elsewhere in this special h issue.

*C.Bradaschia*