BACKGROUND RESOUCE MATERIAL
on the
LIGO DETECTION EVENT (GW 150914)

At 7.30 am on Feb 11th 2016, Pacific Standard time, the LIGO/VIRGO collaboration announced the observation of a remakable event by the LIGO detector. The observation at actually been made several months earlier, at 09 hrs, 50 mins, 45 secs Universal Time on Sept 14th 2015, but kept completely under wraps until the public announcement, while the team analyzed and modeled the data, using models for black hole merge events,and performed numerous checks to make sure that that everything was correct.

The LIGO detector has 2 parts, one in Louisiana and the other in Hanford, Washington state. The figure shows what they saw over a period of roughly 0.2 secs in time. A gravitational wave swept first past the Louisiana detector, and then 6.9 millisconds later past the Hanford detector – the time lag because the wave was moving at the velocity of light. The graph shows the miniscule deflection in each detector, caused by a tiny distortion in spacetime as the wave passed.

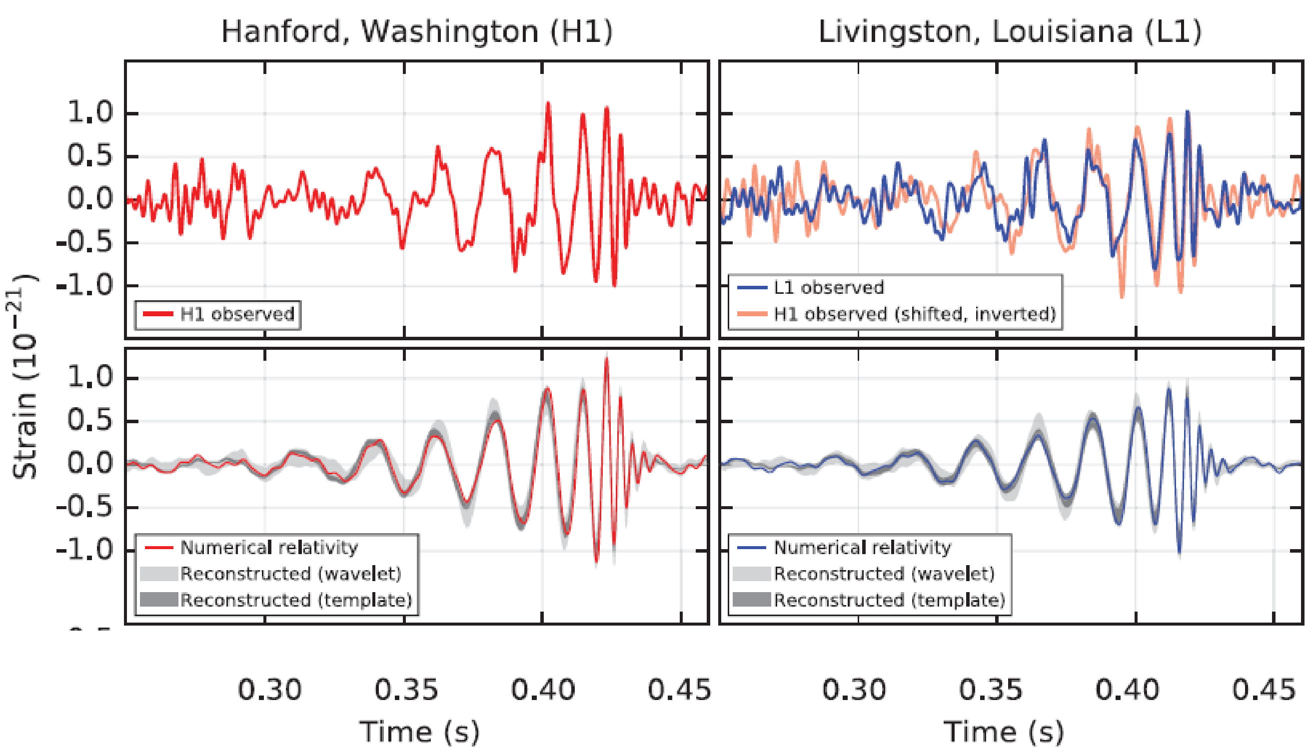


Fig 1. TOP: the signals observed at the 2 detectors; BOTTOM: comparison with the signals calculated for an inspiraling pair of black holes.

This was a discovery of enormous significance, the 1st ever observation of gravitational waves (and it has been advertised as such on TV, the internet, and in many newspapers). It will surely have a huge impact on our future understanding of the universe, for reasons described below. It is also a discovery with a 100-year long history, which is well worth beginning with.

Gravitational waves – wavelike distortions of spacetime, travalling at the velocity of light - were first discussed by Einstein in a paper in 1916, a century ago, using his brand new General Theory of Relativity. However the story after then becomes confused, because it turned out that the theory of these waves was very subtle, to the point where in 1937 Einstein and Rosen even tried to argue that gravitational waves did not exist in General Relativity! The situation was not cleared up until the period from 1957-62, with the work of Pirani and Bondi (in the UK), Trautmann (in Poland) and Sachs (in the US). One complication is that a gravitational wave, having energy, can cause a curvature of the spacetime through which it moves, and can therefore ‘self-focus’.

None of this debate was of any practical importance at that time, since gravitational waves hardly interact with matter unless the gravitational fields are extremely strong; this meant that it was hard to see how they could ever be emitted in large quantities by any object, or how we could possibly ever detect them, even if they were.

The situation changed from the early 1960’s onwards, with (i) the discovery by Penrose in 1963 that black holes must exist under reasonable conditions in the universe, and his invention of mathematical methods to treat their properties (ii) the discovery in 1963 by Kerr of the mathematical description of a rotating black hole, and (iii) the discovery of pulsars and quasars by astronomers, and the gradual realization, in the period from 1967-1990’s, that pulsars were extremely compact supernova remnants with huge gravitational fields, while the ultra-luminous quasars were actually supermassive black holes in galactic centres, emitting massive ‘jets’ of radiation along their rotational axes (which have devastating effects on their home galaxies).

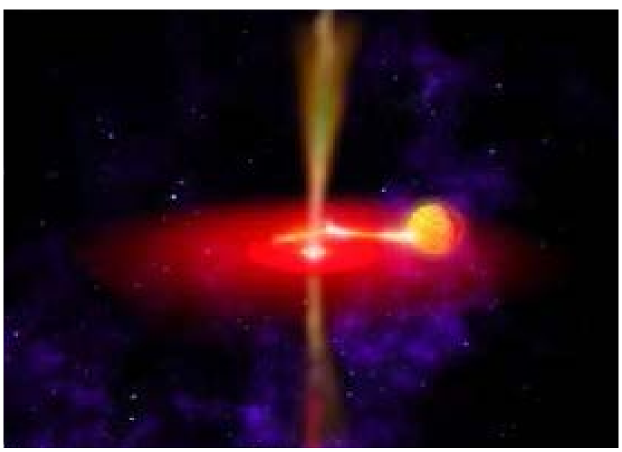


Fig 2(a) Painting of the X-ray binary Cygnus X-1: a supergiant star orbiting a black hole, of mass ~ 15 suns.

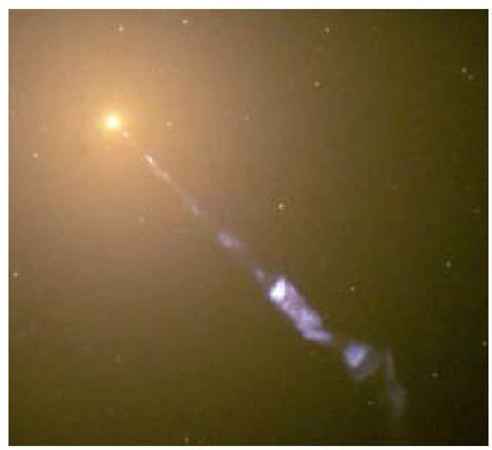


Fig 2(b) A jet from a supermassive black hole in M87. Such jets can stretch to over a milion light-years

We now know that it the universe is a terribly violent place, with supernovae creating many neutron stars, or even black holes of typical mass 5-25 suns. Such monstrous explosions can of course cause large gravitational wave emission – just as a sudden shift or other motion in the earth’s crust creates strong wave-like motion in the earth or in the sea (eathquakes and tsunamis), a violent upheaval in spacetime will create gravitational waves. Thus, a search for gravitational waves is essentially a search for traces or records of such violent events in the universe.

Such searches began in the 1960's with the work of J Weber, who used giant aluminium bars, weighing tons, as detectors, expecting them to "ring" as the wave passed by. But here a fundamental problem emerged. Even a very energetic perturbation of spacetime created at a distance of thousands of light-years will cause a quite undetectably small distortion of the aluminium bar. Gravitational waves are not like light, or other electromagnetic waves, which we can observe over distances of billions of light years – the spacetime distortion caused by a gravity wave of even very large energy is extremely small.

So a new idea, and new technology, were needed. The idea was an interferometric detector, in which spacetime distortions over distances of several km were observed by bouncing laser light back and forth between massive mirrors. The distance between the mirrors is monitored using interference between the light beams, which allows for very sensitive length measurements. The LIGO detectors are of this kind – see Fig. 3 below - and, crucially, there are two of them in different locations.

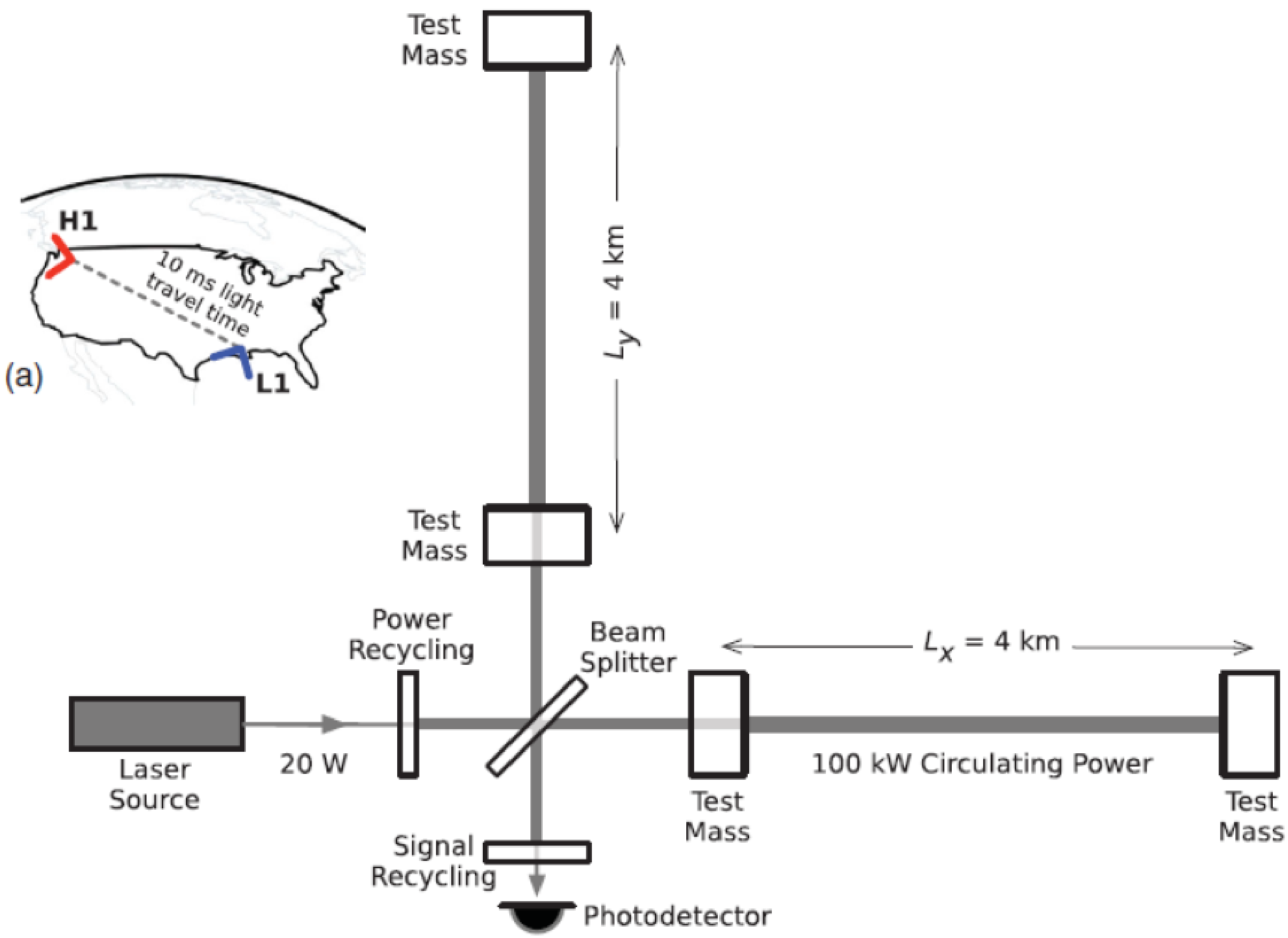


Fig 3: Diagram of a LIGO detector: Photons from a laser are fed into a set of 2 pairs of mirrors (the "test masses") using a beam splitter. A pasing gravitaional wave will cause a 'quadrupolar' distortion of spacetime, so that if the path between one set of mirrors contracts, the other will lengthen, and vice-versa. This is measured by looking at interference between the 2 beams. The 2 detectors are separated by 3,000 km (light takes 10 milliseconds to travel this distance).

The huge problem in any system like this is noise. Without sophisticated isolation from vibrations and electromagnetic noise, the situation is hopeless – the vibrations caused by cars within a few km of the detectors will cause large oscillations in the distance between the mirrrors, thousands or millions of times larger than the effect being looked for. Even with vibration isolation, one has to be sure that no signal is caused by some extraneous perturbation. So two detectors are built, thousands of km apart. If both see the same signal, with a small time delay required for the gravity wave to travel between the 2 detectors, then one can be sure that one is not seeing an earth-based perturbation.

And this is exactly what was seen – only a few months after the new upgraded LIGO detectors were brought on line. The 6.9 millisecond time lag between the arrival of the wave at the Louisisan detector and its arrival in Washington can be entirely understood if one takes account of the direction from which the wave came - indeed, from the delay, one can can fix a region from the sky from where it must have come, shown in the figure. As we will see, we can also determine the distance of the source.

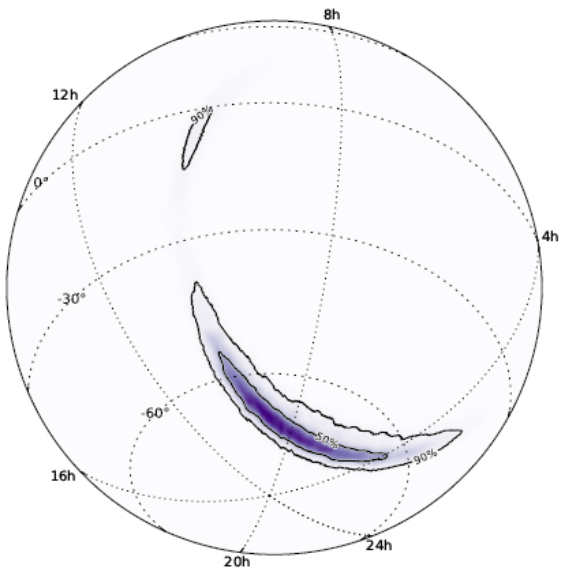


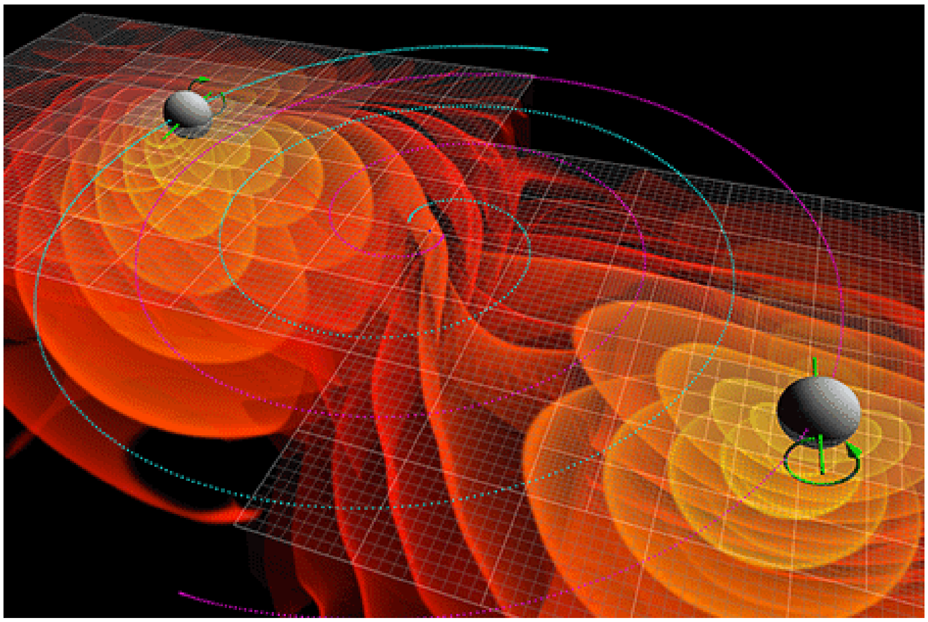
Fig 4: The region of sky from which the gravitational waves came is fixed if one knows the time lag between the arrival of the signal at each detector. The uncertainty in the arrival time means that the area is fixed with very low resolution. From the amplitude of the signal, & knowing the black hole masses, one can find the distance of the source.

The waveform seen by LIGO lasted for a very short time – less than 2/10ths of a second. And it had a characteristic shape – the frequency and amplitude increase sharply, and then suddenly, with a few more ‘rings’, the signal rapidly decays and is gone. This is a very distinctive signal – so what caused it?

BLACK HOLE COLLISIONS

Most stars are formed as part of a multiple system – usually binaries, but triplets are common, and even quite a few sextuplets are known. Thus the sun, a solitary star, is not amongst the most common cases. Consider now what happens if one has a binary system with 2 massive supergiant stars. In only a few million yrs these will burn up their fuel, and explode as supernovae, leaving behind either a pair of neutron stars or of black holes (or one of each).

Now a pair of black holes may continue orbiting each other for a very long time, quite invisible even at close range unless they succeed in accreting gas, dust, or other objects from their surroundings (which will cause a flare of radiation, sometimes emitted as a jet). However the orbits of the 2 black holes around each other will slowly decay, because small amounts of gravitational radiation will be emitted – the orbital motion of the 2 black holes causes a periodic distortion of the surrounding spacetime. Because of this decay, the 2 black holes will very slowly spiral in towards each other.



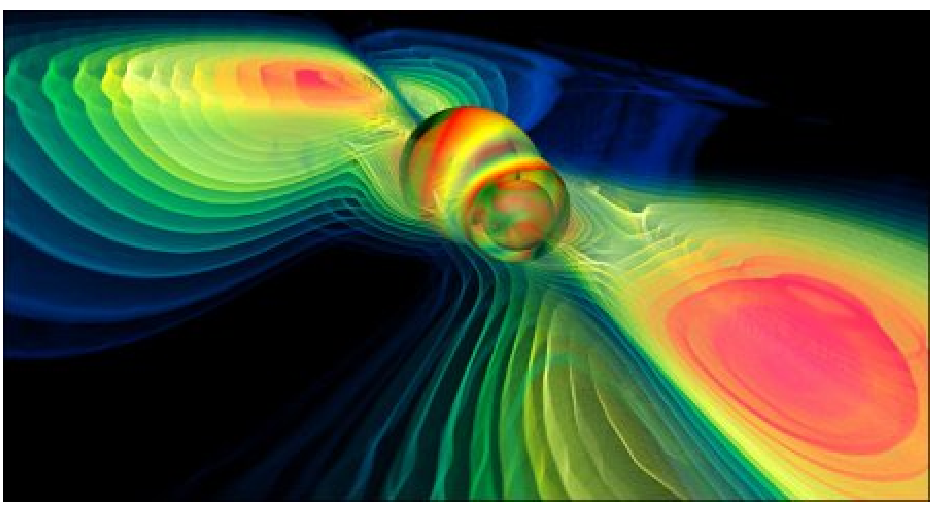


Fig 5: The final stages of the inspiral process. The colours show The energy density locked up in the specetime distortions – the emitted gravitational waves are focussed in certain directions.

This 'inspiral' process can go on for many millions of years. But eventually, as the 2 massive objects approach each other, things begin to speed up – and as they do, the rate of gravitational wave emission also speeds up, very quickly. As the 2 masses spiral ever closer, the periodic distortions of spacetime become huge, and enormous power goes into creating them – this power is sucked from the orbital motion of the black holes, and one gets a runaway process in which the 2 enormous masses accelerate to nearly half the velocity of light in ever tighter decaying orbits – the final stages of this, even with such enormous masses, last only a fraction of a second (see figure below).

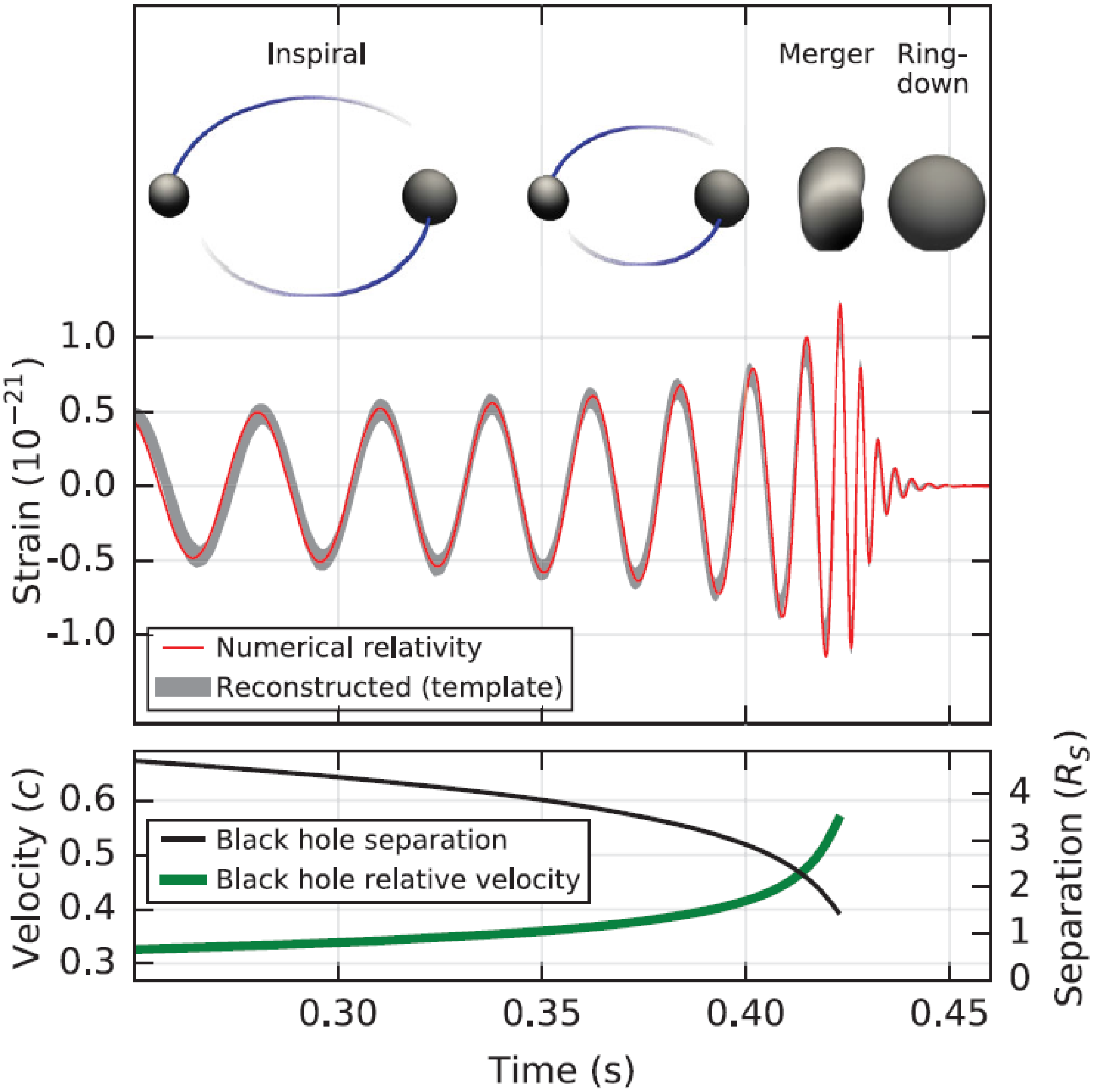


Fig 6: Calculations of the inspiral for the 2 black holes observed in the GW150914 event. In the lower figure, the separation is measured in units of the Schwarzchild radius for the combined mass of the black holes (here R_S > 210 km).

The energy emitted in these final stages as gravitational waves is truly colossal. In this particular event, the equivalent of roughly 3 solar masses of energy was converted to gravitational waves in the last 0.2 secs. This equivalent is defined by Einstein's famous relation $\mathbf{E = mc^2}$, with **m** representing the mass and **c** the velocity of light; since **c** is very large, and **m** here is 3 solar masses, this means the energy **E** is huge. To give an idea of how huge – it is roughly equivalent to the energy emitted by <u>all the stars in the visible universe</u> (and there are roughly 10^{21} of these!), during the same time period.

How do we know that this is what happened? It is because, using Einstein's theory, we can calculate what would happen in such an inspiral event – and the results look almost exactly the same as what was seen in the observation, provided we fix the masses of the 2 black holes as roughly 29 and 36 solar masses respectively. This also allows us to fix the distance of the black hole pair: knowing the power emitted and that observed here, we can say it is roughly 1.3 billion light years. This is very large indeed – only the enormous energy in the event allows us to detect it at such a huge distance. Notice also that it must have occurred 1.3 billion yrs ago, ie., 700 million yrs before multi-celled organisms appeared on earth – an almost unimaginable stretch of time, one tenth the age of the universe.

WHAT IS NEXT ?

Apart from the interest in the particular event seen by LIGO (which is quite fascinating in its own right), one can ask – why is this such a big deal? The key point is that we have found a new window on the universe. From ancient times until the 20th century, our only access to the world around us was visual, ie., via light transmitted to us from other objects (or, if we could actually handle the objects on earth, by measuring forces). In the 20th century this was extended to other forms of electromagnetic radiation apart from light (Ultraviolet, infrared, radio, X-ray, gamma ray), and also to observations of atomic and nuclear particles. But, as we have seen above, we can now detect a quite different kind of signal, gravitational in nature, giving us access to very different phenomena from those we have been able to observe and examine during the long course of human history. Thus we are entering a new scientific era.

Current LIGO plans, for the next year or so, involve continuing to observe the same kind of events as those already seen – collisions of compact objects with masses a few times larger than the sun. But in the same way as happened with the development of telescopes and particle detectors, we may expect to see very rapid technological advances, designed to enormously increase the sensitivity and frequency range of gravitational wave detectors. At this point we should be able to observe all sorts of other highly energetic events and processes that have hitherto been quite unobservable – involving everything from supermassive black hole dynamics in recent times to highly energetic events and processes in the early universe. With multiple detectors we will be able to fix their direction much more accurately, and in some cases, tie the results to visual and other observations.

But the most important thing of all is that we will be entering the unknown – and the entire previous history of scientific endeavor must then lead us to expect the unexpected, in the form of physical phenomena that we can hardly imagine now. And this, ultimately, will be the justification for all the effort that has gone in to the long search for ways to see gravitational waves, and for the great interest in this discovery.

FURTHER READING

(i) You can go to some of the other resource pages on the PITP website for simple introductions to gravity and curved spacetime, to black holes, to the life and work of Einstein, and to other related topics. These are written at an introductory level.

(ii) You can look at the background resource information provided by the LIGO project to the public, along with much else – the best way to get to these is via the very recent Wikipedia article, at

https://en.wikipedia.org/wiki/First_observation_of_gravitational_waves

(iii) You can, if you have scientific training, look at the original papers published by the LIGO group. These can start with the original letter, at

doi:10.1103/PhysRevLett.116.061102