B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration) (2016). *Observation of Gravitational Waves from a Binary Black Hole Merger.* Physical Review Letters, Vol. 116, No. 061102

Note, we AREN'T going to read this paper in order. We're going to read it the sections in the following order ABSTRACT, INTRODUCTION, DETECTORS, DETECTOR VALIDATION, OBSERVATION, SEARCHES, SOURCE DISCUSSION, OUTLOOK, CONCLUSION

A 16-page paper seems, at first, quite intimidating. But this is no normal paper. Almost half of its pages are dedicated to acknowledging the work of the huge number of scientists from all over the globe that were involved in the research. That being said, the author list for this paper, as seen on page one, seems to be just one person: B. P. Abbott. This is not the case. *Et al.* is an abbreviation of the Latin phrase *et alia* which translates as *and others*. In fields of science where there are a significant number of contributors (such as the Large Hadron Collider or LIGO, for instance), journals save some space at the start of the article by presenting a smaller number of authors. On p.11, after the references, the true author list is presented. Alongside each author is a superscript number and these tally with the long list of academic institutions which follow the author list. There are around 1000 authors on this paper, working at 133 different institutions (with some authors having multiple affiliations), so this is truly a global achievement. You'll also note that three of the authors sadly passed away during the process of researching, analysing, and writing the paper, showing in some way how much time it takes to produce such a significant piece of research. This article highlights that meticulous planning wasn't just a part of the research and data collection, but part of the publishing process too.

After the title and authors, this paper begins with an *abstract*. An *abstract* is a short summary of the work you're about to read, giving the main findings and their implications. When reading a paper, especially if you're looking over a significant quantity of literature at the beginning of a new project, you might use the abstract as a guide to whether or not the piece of research is useful for you to read. This abstract is eight sentences long and we'll look at each one in turn.

Sentence 1: The authors bluntly state what this paper is about: an observation of gravitational waves.

Sentence 2: They discuss the features of the signal that they have measured – a wave which has increasing frequency and they discuss how large the signal becomes.

Sentence 3: They say how it matches predictions from simulations. This is crucial. The whole reason LIGO was created and over $1billion was spent on the project was to test the predictions of the General Theory of Relativity. Here, the authors are stating that their signal matches Albert Einstein's predictions from the early 1900's.

Sentence 4: They discuss how statistically significant their results are. A five sigma (5σ) effect is the benchmark for a discovery in many fields. It means there's only a one in 3.5million chance of such a signal occurring within their data from a source that was *not* a gravitational wave. For a nice blog on the 5σ effect, see this article.

Sentence 5: This gives details about the astronomical event that is believed to be the source of the gravitational waves, two black holes of similar sizes colliding around 410 million Parsecs away (a parsec is 3.26 light years) to form a larger black hole.

Sentence 6: This gives details on the error bars that are presented in the previous sentence.

Sentence 7: This sentence explains why the research is significant within the field of astrophysics, astronomy and cosmology.

Sentence 8: This sentence explains the wider importance of the work.

I. INTRODUCTION (Some of these videos may be useful for this section. A 5min introduction by the scientists involved: https://www.youtube.com/watch?v=B4XzLDM3Py8 A very simple visual explanation of gravitational waves by Amber Stuver: https://www.youtube.com/watch?v=hebGhsNsjG0 A demonstration of gravitational waves by Steve Mould: https://www.youtube.com/watch?v=dw7U3BYMs4U)

(P1, C1) The *'linearized weak-field equations'* are simplified versions of the equations from Einstein's General Theory of Relativity. These equations, amongst other things, describe the working of gravity, space and time. What are some of the solutions (objects or events within the universe) that scientists have found for these equations?	Einstein found solutions that were waves. Schwarzchild found a solution that turned out to be black holes (actually, the Schwarzchild solution is for a non-rotating, spherically symmetric object. It also describes the space time around the Sun, for example. It describes a black hole if all the mass is contained within a region of radius $<2GM/c^2$, the event horizon). Kerr found a solution of rotating black holes (similarly, this is appropriate for a rotating, but otherwise spherically symmetric body, not just a black hole.)
(P1, C1) Why should we strictly refer to Einstein's work as the 'General Theory of Relativity' and not the 'Theory of General Relativity'?	Because it is the theory that is general, not the relativity. Einstein came up with two 'Theories of Relativity' (these are in essence, theories of motion for when one object moves relative to another). He initially came up with the Special Theory of Relativity, which is special because it is limited to the special case of objects at constant velocity. The General Theory of Relativity broadens his previous work and applies also to accelerating objects (and hence objects experiencing a gravitational attraction), and those whose accelerations are also variable.
(P1, C1) What is a black hole? And what is a black hole merger?	A black hole is a region of spacetime where the gravitational field is so strong that neither particles nor light can escape it (hence named 'black' as light cannot get out). It's often thought of as a region of unimaginably compact mass (high density), but this depends on how you consider the size of the black hole. Certainly, at its centre – a region known as the singularity of a black hole – the density is infinite. But if we consider the size of the black hole to be the region enclosed by the event horizon (the boundary within which nothing can escape), then the density is actually comparable to many earthly objects. For example, supermassive black holes have an average density similar to water if we consider their volume to be the volume contained within the event horizon. Black holes can form at the end of the life of stars (so-called Stellar Black Holes and it's hypothesised that some formed in the very early universe (so-called Primordial Black Holes). A black hole merger is when two black holes collide together to form a larger black hole. They don't collide head on, but orbit around their mutual centre of mass, orbiting one another faster and faster until they eventually come together. The important point here is that they only come together because they emit gravitational waves. The gravitational waves carry energy and angular momentum from the orbit and cause the merger.
(P1, C1) Gravitational waves can be described as 'transverse waves of spatial strain' - what does this mean?	The gravitational waves are transverse waves (the oscillation is perpendicular to the direction of travel) and the oscillation is one of a strain (a change in length) in space itself. Space (and time!) is squeezed and stretched with the passing of a gravitational wave.

(P1, C1) How have black holes been detected previously?	Through 'electromagnetic observations' - looking at the radiation (from any part of the electromagnetic spectrum) that is emitted by matter close to the black hole (but not by the black hole itself, as they don't emit radiation by definition). The most solid evidence for stellar mass black holes comes from binary stars where we can use the properties of the orbit of the companion star that feeds the black hole to infer the black hole mass.
(P1, C2) Given that Hulse, Taylor and Weisberg have shown the *existence* of gravitational waves from their analysis of a binary pulsar system (binary means two, a pulsar is a spinning neutron star that emits electromagnetic radiation from its poles), why are the findings of this paper considered to be ground-breaking? (This link gives some detail on the Hulse-Taylor binary that won them a Nobel prize)	This paper is the first direct observation of gravitational waves. Hulse, Taylor and Weisberg could only make sense of their observations of the two pulsars by including energy that was being emitted from the system as gravitational waves, but they didn't actually detect the gravitational waves. The movement of the two stars implied the existence of gravitational waves, in the same way that seeing a boat move up and down on the ocean implies the existence of waves in the ocean. But they didn't actually see the waves themselves.
(P1, C2) What are some of the detectors that have previously hunted for gravitational waves unsuccessfully?	Weber's resonant mass detectors, cryogenic resonant detectors, interferometric detectors (that were suggested in the 1960s and 1970s) before being tested and finally built in the early 2000s (e.g. TAMA 300, GEO 600 and LIGO).
(P1, C2) What characteristic makes Advanced LIGO (which is the improved version of LIGO) the only detector to have directly seen gravitational waves?	It has a much greater sensitivity for detecting variations in length (and hence variations in space itself). Despite the huge mass energy densities involved in the merger, at our distance the amplitude of the wave (as expressed by strain) is incredibly tiny, thus it took a century to actually measure them.
(P1, C2 and P2, C1) Why are *'highly disturbed black holes'* such vital objects for testing the predictions of the General Theory of Relativity?	Because these highly disturbed black holes (e.g. black hole mergers) are events of extremely high gravitational fields and significantly high velocities and accelerations – they are therefore testing the regime of the General Theory of Relativity, which only makes unique predictions that Newton's theory of gravity would not include, at these very high accelerations and gravities. However, there are two factors that make testing the General Theory of Relativity quite hard. First gravity is a very weak force, just think it takes the entire mass of the Earth to cause a book to fall down to the ground, and even a child is strong enough to pick it back up and counter that force. The waves in spacetime caused by gravity are incredibly small for even objects as massive as the Sun. Second, the objects which do have gravity strong enough to test the predictions of the General Theory of Relativity are very far away, millions of light years in this case. This is why only the most massive and gravitationally intense events are going to be strong enough to be detected here on Earth, and even then, we require some of the most sensitive equipment scientists have ever made.

II. DETECTORS (You might find some helpful additional information for this section here)

(P3, C1) Why do they need multiple detectors that are widely separated?	So that they can tell apart gravitational wave signals from other sources of vibration that occur locally. Also having two detectors allows the direction of the wave to be found, in the same way that having two ears allows us to hear the direction of sounds, because there is a slight difference in the time when each detector receives a signal.
(P3, C1) Give an example of the type of environmental noise that can be isolated by having detectors separated by large distances?	Earthquakes, cars, building work, animals digging burrows. Anything that could disturb the ground locally. Particularly concerning are things which happen at the same frequency as the gravitational waves. The detectors operate from ~10-1000 Hz. Seismic noise dominates the low end frequency sensitivity.
(P3, C1&C2) Each Advanced LIGO experiment consists of "a modified Michelson interferometer that measures gravitational-wave strain as a difference in length of its orthogonal arms". Using the diagram in Figure 3, explain this in simple terms.	Advanced LIGO consists of two arms that are at 90 degrees to one another (orthogonal). It operates using the principle of interference – that waves can be combined in a constructive (additive) or destructive (depletive) manner. The two arms of Advanced LIGO work as a Michelson interferometer whereby the light from a laser, which is all in phase with itself at the start, is split by a beam splitter into the two arms. Light travels along each arm and is then reflected by a mirror so that it travels back along each arm. The light recombines to form an interference pattern depending upon the amount of path difference between the two paths. More specifically, LIGO detectors destructively interfere the waves so that the detectors sit in the dark. When the gravitational waves pass through they change the path length so the cancellation is no longer perfect and there are repeating flashes of light from the passage of the gravitational wave. There are a few hundred photons from this particular gravitational wave source. Even a tiny path difference will cause some interference to be seen.
(P3, C2) When a gravitational wave passes through the equipment, what does it do to the arms? How does Advanced LIGO notice such a difference?	Changes the length of one arm relative to the other. As a gravitational wave changes space itself, if the wave hits the arms in the right way then the path that the light has taken will be lengthened or shortened in one of the arms compared to the other. As there is a path difference between the light travelling in each arm if a gravitational wave passes through, then once the light is recombined prior to the detector, the interference pattern will have altered.
(P3, C2) Advanced LIGO gives its measurements in terms of strain (which LIGO give the symbol, h), which is defined as the change in length (ΔL) divided by the total length (L). So the equation is $h=\Delta L \div L$. Why is strain unitless?	Because it is defined as a length divided by another length. Both of these have the same units and so once divided, the result is unitless (or, more formally, dimensionless).
(P3, C2) Using the equation from strain ($h=\Delta L \div L$), if the total length of one of the arms is 4 km, and the maximum strain measured by Advanced LIGO (according to the abstract) is 1.0×10^{-21}, then what is the	If $h= 1.0\text{x}10^{-21}$, and L=4km=4000m, then $\Delta L=h\times L$ so $\Delta L= 1.0\text{x}10^{-21}\times4000=4\text{ x}10^{-18}$m. This is just larger than the purported size of quarks (these sizes aren't confirmed) and are smaller than the sizes of single protons or neutrons.

maximum change in the length of one of the arms?	
(P3, C2) Advanced LIGO is not a basic Michelson interferometer, what have they done to enhance the signal?	By having two mirrors in each arm (one at each end), the light actually traverses the ‘resonant cavity’ that is formed by letting the light bounce between the mirrors 4km apart, 300 times. This increases the distance that the light travels to 1200km. To achieve this number of reflections, you need lots of laser power to counteract the very small losses at the optical (mirror) surfaces.
(P4, C1) The laser that they use is ‘*a 1064-nm wavelength Nd:YAG laser, stabilized in amplitude, frequency, and beam geometry*’. In what region of the electromagnetic spectrum is the laser and why does it need to be stabilised?	1064nm (1.064µm) is in the infrared part of the electromagnetic spectrum. It needs to be stabilised to ensure that, when the light is recombined, any interference is due to gravitational waves causing space to change, not because the light varied a little in its frequency due to the source.
(P4, C1&C2 and P5, C1) What are some of the ways in which the equipment has been built so as to *minimise* vibrations that would alter the positions of the mirrors?	The mirrors are supported in a quadruple pendulum system to damp their movement from the outside world, as well as being put on an active seismic isolation platform. Materials are chosen to reduce mechanical loss throughout. Further vibration isolation stages and ultrahigh vacuums are used. A neat analogy for the “active seismic-isolation platform” is that it works just like noise cancelling headphones, by moving the mirrors in such a way as to cancel the effects of seismic noise.
(P4, C1&C2 and P5, C1) What are some of the ways in which the equipment has been built so as to *monitor* vibrations that would alter the positions of the mirrors?	They monitor the change in position of the mirror caused by the laser itself as the collision between photons and the mirror imparts momentum to the mirror, moving it by a small amount. They monitor this by comparing to a calibration laser. The also use simulated waveforms to check the calibration of the detector. They monitor environmental disturbances with seismometers, accelerometers, microphones, magnetometers, radio receivers, weather sensors, ac-power line monitors, and a cosmic-ray detector.
(P5, C1) One of the key aspects of Advanced LIGO is having the two sites at opposite sides of the United States (see Figure 3a). It takes light 10 ms to travel directly between these sites (and as gravitational waves travel at the speed of light as well, this is true of gravitational waves too). Advanced LIGO is therefore looking for a similar signal at both sites but shifted in time by a small amount. How do they ensure their timings are accurate to	They synchronise their timings to GPS (to better than 10µs). They have an atomic clock and a second GPS receiver to verify timings.

know that any gravitational wave has travelled at the speed of light between the two stations?	
(P4) Figure 3(b) shows a graph of the noise experienced at each of the Advanced LIGO sites around the time of the detection. Discuss what you see in this graph (remember that is uses log scales).	There is a general trend at both sites that the strain noise decreases from around 10^{-22} at 20Hz down to 8×10^{-24} at 200Hz (remember the log scales used). The amount of noise then increases again to around 3×10^{-23} at 2000Hz. The noise at both sites follows this general trend. On top of this, there are peaks in the distribution throughout, that can reach up to around 2×10^{-21}. Some of these are common to both sites, though not all. The sources of some of these features are discussed in the caption.

IV. DETECTOR VALIDATION

(P5, C1&2) This section discusses the checks they performed to ensure their signal wasn't spurious. Given that the answer is "no, we didn't find anything", why is such a section necessary?	To show their scientific integrity. The scientific community want to be sure that this observation is a true observation so it's important for the researches to list all the checks they did complete in case anyone else thinks of something they've missed. Scientists aren't just reading this thinking "I'm sure this is correct", they often spend their time thinking "I wonder if this might be wrong". This section is written to allay some people's fears about the origins of their signal.

We now go backwards in the paper to the section on OBSERVATION

III. OBSERVATION

(P2, Figure 1) Looking at the top left panel of the figure (the *observed* Hanford, Washington signal), describe the signal (you may find it useful to look at the panel beneath it too – a simulation of a gravitational wave event that they believe would match their signal).	We see something that initially looks a like noise from 0.25-0.325s. Around 0.325s a wave seems to appear in the data, oscillating around a strain of 0.0. The wave increases in frequency and amplitude up to around 0.425s where it reaches a maximum strain of around $\pm1\times10^{-21}$ (which is what we knew from the abstract). After 0.425s, the amplitude then rapidly decreases.
(P2, Figure 1) In the top right panel, they show the data from the Livington, Louisiana site with the Hanford, Washington data added to it but shifted and inverted. It is rare in science to simply shift and invert your data to show that they	The data must be shifted in time to account for the distance between the detectors and the fact that it takes time for the gravitational wave to pass from one to the other. The signal must be inverted as the orientations of the L-shaped interferometers are not the same at both sites.

agree. Reading the caption, why is it necessary to perform this shift and inversion (and in fact also an important sanity check on their results)?	
(P2, Figure 1) In the third row of the Figure, we see the residuals. These are the result of subtracting the simulated data (the data in the second row) from the real data (the data in the top row). These residuals seem to show nothing but noise, why is this a good thing?	It means that all of the pertinent features of the measured signal and the simulated signal are in agreement. If the theory and the data did not match, then when they are subtracted, you'd be left with a residual that still had significant features in it. Here, though, the residual seems to be just noise, centred on 0.0 as you would hope.
(P3, C1) Other than to distinguish between signal and noise, why else do they have two detectors on opposite sides of the country?	To be able to tell where in the sky the gravitational wave originates from. Much like triangulation of phone signal data, the time delay between the signal's arrival at the two sites combined with the knowledge that gravitational waves travel at the speed of light allows us to work out a rough area of the sky the gravitational waves originate.
(P3, C1) What general method do researchers use to understand what astronomical objects are the cause of the gravitational waves?	They compare to computer simulated models using the simplified Einstein equations, of all sorts of different astronomical events to see which closely matches the observed signal. In this case, the increase in frequency and amplitude, combined with the sudden 'ring-down' (where the amplitude rapidly decreases) is indicative of two black holes orbiting closer before combining.
(P3, C1) Why does the emission of gravitational waves cause two black holes to orbit closer?	Because the emission of gravitational waves leads to energy loss from the system of the two black holes. As the black holes become less energetic, the strong gravitational attraction between the black holes can bring them closer and closer together.
(P3, C1) Why can the signal not be due to two neutron stars colliding?	Due to the smaller masses of neutron stars (compared to black holes), they orbit one another at significantly higher frequencies than those measured in the lead up to the merger.
(P3, C1) Why can the signal not be due to a neutron star and a black hole colliding?	A black hole and neutron star that could give rise to the correct 'chirp mass' would need very a very large total mass. If this was the case, they'd merge at a lower frequency.
(P3, C1) Why can the signal not be due to other astronomical objects colliding?	Neutron stars and black holes are the astronomical objects which are the densest. To reach the orbital frequency observed (75Hz), the objects must be able to get very close to one another (to complete orbits) prior to merging. This requires the objects to be small. We know that to cause such significant gravitational waves, the objects must have a very large mass. Therefore, the conclusion is that the objects must be very dense, leaving us with just neutron stars and black holes as the possible causes.
(P3, Figure 2) At the top of the panel, there are 4 diagrams. Describe what is happening in these diagrams and how it relates	We have two objects orbiting one another. The inspiral is when the objects get closer and closer together whilst still orbiting one another. As they orbit closer and closer, the frequency of the gravitational waves emitted increases (which we would see as the strain – the change in length seen on earth - changing more rapidly). Just prior to the merger, the

to the numerical simulation of the strain (the red line).	gravitational waves are at their maximum frequency as the objects are orbiting as frequently as possible so the strain changes most rapidly here. The increase in amplitude of the gravitational waves is caused by the objects being closer together, so that the gravitational force is even stronger and so shedding even more energy as gravitational waves. Once merged, the objects now form one single object, whose mass is no longer in a state of great change – this means that the gravitational waves stop very suddenly after the merger.
(P3, C1) Looking at the equation for the chirp mass, validate that units remain kg in each part (the f with a dot above it is the time derivative of frequency and so has units of s^{-2}).	Starting with the second term: $\frac{(m_1 m_2)^{3/5}}{(m_1 + m_3)^{1/5}}$ Substituting each variable with its units first of all, then combining the powers within the brackets, then raising these to the power outside the bracket gives: $\frac{([kg][kg])^{3/5}}{([kg]+[kg])^{1/5}} = \frac{([kg]^2)^{3/5}}{([kg])^{1/5}} = \frac{[kg]^{6/5}}{[kg]^{1/5}} = [kg]$ The final term is a little less friendly, but the same idea applies. The units of c are m/s. The units of G are $m^3/kg/s^2$ $\frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5}$ First substituting the units, then multiplying out the powers, gives $\frac{[ms^{-1}]^3}{[m^3kg^{-1}s^{-2}]}\left[[s^{-1}]^{-11/3}[s^{-2}]\right]^{3/5} = \frac{[m^3s^{-3}]}{[m^3kg^{-1}s^{-2}]}\left[[s^{11/3}][s^{-2}]\right]^{3/5} = \frac{[s^{-1}]}{[kg^{-1}]}\left[s^{5/3}\right]^{3/5} = [kg][s^{-1}][s] = [kg]$

Now we move to section V. SEARCHES

V. SEARCHES

This section of the paper is a little more technical as it provides further evidence to validate the claims made so far. It may be that less of this section makes sense, and that is to be expected. But we can still aim to understand the general idea of this section.

Here, scientists are aiming to present evidence that the detected signal is from a black hole merger (with a strong statistical significance) rather than from the next most probable other cause: experimental noise. Another way of putting it is to say that the researchers want to estimate if such a signal could be spurious/produced by chance – they do this by looking at the LIGO signal at other times and working out how likely it is that the signal is real.

“We present the analysis of 16 days of coincident observations between the two LIGO detectors from September 12 to October 20, 2015.” The gravitational wave detection occurred on September 14th, 2015.

Let’s start by imagining we had just one single Advanced LIGO detector and, for over a month, they’re constantly measuring the strain (the change in length of the arms). They have reams and reams of data, detailing the strain at every instant in time. The measured strain will never be zero, because their measurements are so precise that they pick up changes to the length of the arms that can occur for any random reason (vibrations in the ground due to cars travelling down the road, thermal fluctuations, burrowing animals etc.). They call these background events. So, when searching through all of the data, it would be very difficult to tell apart a strain signal caused by gravitational wave from one caused by the background events.

But, it’s okay, because they actually have two detectors that are separated by a huge distance (a distance which takes light 10ms to travel in a straight line). So, the search is actually for coincident strain events -

events that occurs at the same time (technically, within a 10ms window to account for the travel time) - between the two stations.

But even with this additional requirement of coincidental signals, they have so much data that due to the random nature of *measurements,* and the law of large numbers, you'd always expect to find some coincident data *just by chance.*

These searches, then, are occurring *within the data* collected by LIGO over this period of just over a month in September and October 2015 to ascertain what might be signal, and what is just coincidental noise.

The first paragraph within the **generic transient search** section says: "Designed to operate without a specific waveform model, this search identifies coincident excess power in time- frequency representations of the detector strain data, for signal frequencies up to 1 kHz and durations up to a few seconds."

Splitting this up a bit at a time:

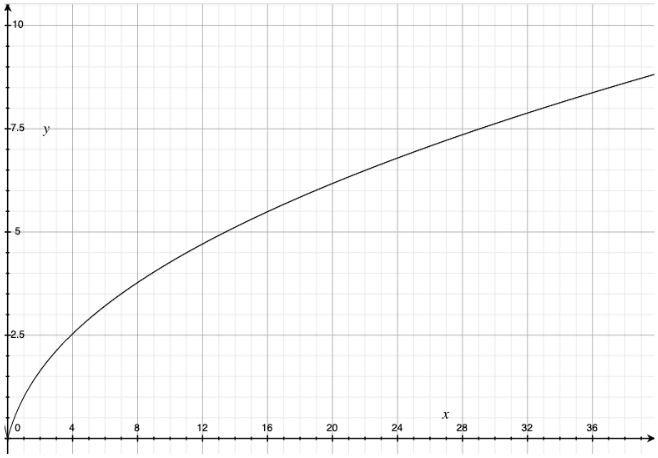
- "Designed to operate without a specific waveform model" - they are searching their data without making assumptions above what shape a gravitational wave signal will have. They know what a signal of two black holes would look like but want to be sure that the data they found on September 14th is significant, regardless of what shape it takes.
- "this search identifies coincident excess power in time- frequency representations of the detector strain data" - they are looking for significant changes in the strain that are *coincident* (in this case meaning within the 10ms travel time) between the two sites.
- "for signal frequencies up to 1 kHz and durations up to a few seconds" - they have some limits within this search to keep the frequency below 1kHz and they're looking for changes in strain that last for a few seconds

They search their data according to a detection statistic given as

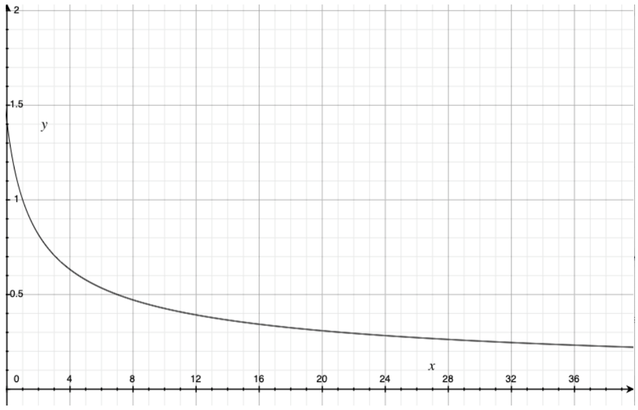
$$\eta_c = \sqrt{2E_c/(1 + E_n/E_c)}$$

E_c is a value that quantifies the strength of a signal and E_n quantifies the amount of noise.

On the following graph, I plot the detection statistic, η_c on the y axis and the signal strength quantifier E_c on the x axis (assuming the noise quantifier E_n is constant). We see that as the signal strength increases, the statistical significance increases, which is what we'd hope.



On the following graph, I plot the detection statistic, η_c on the y axis and the noise strength quantifier E_n on the x axis (assuming the signal quantifier E_c is constant). We see that as the noise strength increases, the statistical significance decreases, which is what we'd hope.



In their search they find that this event is very statistically significant. Using two separate searches they quantify that the chance of seeing a signal like this by chance (the false alarm rate) is lower than 1 in 22 500 years in one search and around 1 in 8 400 years in another.

The **binary coalescence search** is different as it asks, if we *assume* the signal is from a binary merger (binary meaning two, so two objects merging together) then what sort of merger is the most likely? They take simulated models, using the General Theory of Relativity and model what different sized mergers of different objects would look like. They then compare these to the observed data and see how well they match up. They do a statistical test, called a chi-squared test which quantifies how well the modelled data fits the observed data. From this, the best-fit model shows two black holes merging, one around 36 solar masses, and one around 29 solar masses. They merge to form a black hole around 62 solar masses. Their models give error bars to all of these values.

We'll have fewer questions for this section:

(P5-P7) We don't know beforehand when a gravitational wave event is going to happen. How does this affect the way in which we attempt to measure such events?	Scientists have to measure over a long period of time and then analyse all of the data to see if an event occurred at any point in their data. Given that they have so much data, they need ways to search it to isolate what is signal and what is noise. These searches take two forms here, one where they look for any signals whatsoever and quantify how significant it is (taking into account they have two sites and are looking for coincident data). The other search takes theoretical models of what the data could look like in different scenarios and compares it to the measured data to see if it fits and explains where their signal came from.
(P6, Figure) What would you say is the key message to understand from this figure about the event GW150914?	That the GW150914 event stands alone in a very statistically significant portion of the picture. Unlike other events, it is far away from the lines that mark what the random background noise events look like, showing it to be something significant.
(P7, C1) Why is the mass of the merged black hole less than the mass of the two initial black holes combined?	Because, as the two black holes go through the process of merging, they lose energy in the form of gravitational waves. As energy and mass are interchangeable from Einstein's relation ($E=mc^2$), any energy that has been lost to the universe from the two black holes will not be held in the mass of the final, merged black hole.

SUMMARY QUESTIONS

What makes this such a ground-breaking paper?

Without relying on the abstract/conclusion, how would you summarise what you have understood about this paper in one paragraph?

If you had to explain why someone should read this paper in one sentence, what would you say?

Do you have any criticisms of this paper?