QUT

Approaches and Strategies for
Bringing Recent Scientific Discoveries
into the Classroom

with Dr Michael Cowley

Gravitational Waves

Gravitational Waves

- Gravitational waves are disturbances or “ripples” in spacetime
- They are generated by massive accelerating objects
- These ripples travel at the speed of light ($3{\times}10^{8}$ m s^{-1})

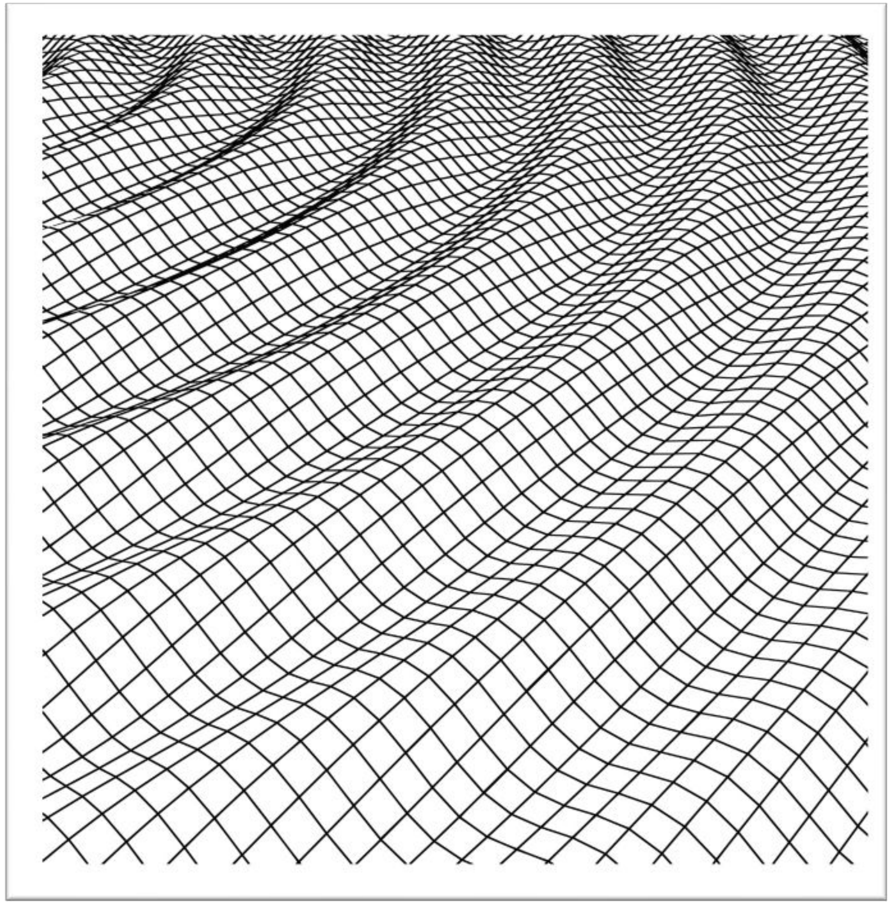


Figure: Ripples

Gravitational Waves vs Gravity Waves

- Gravitational Waves are waves in spacetime, which are a change in gravitational potential generated by accelerated masses
- Gravity Waves are waves in a fluid (e.g., ocean or atmosphere), which are generated by the restoring force of gravity (e.g., wind wave)

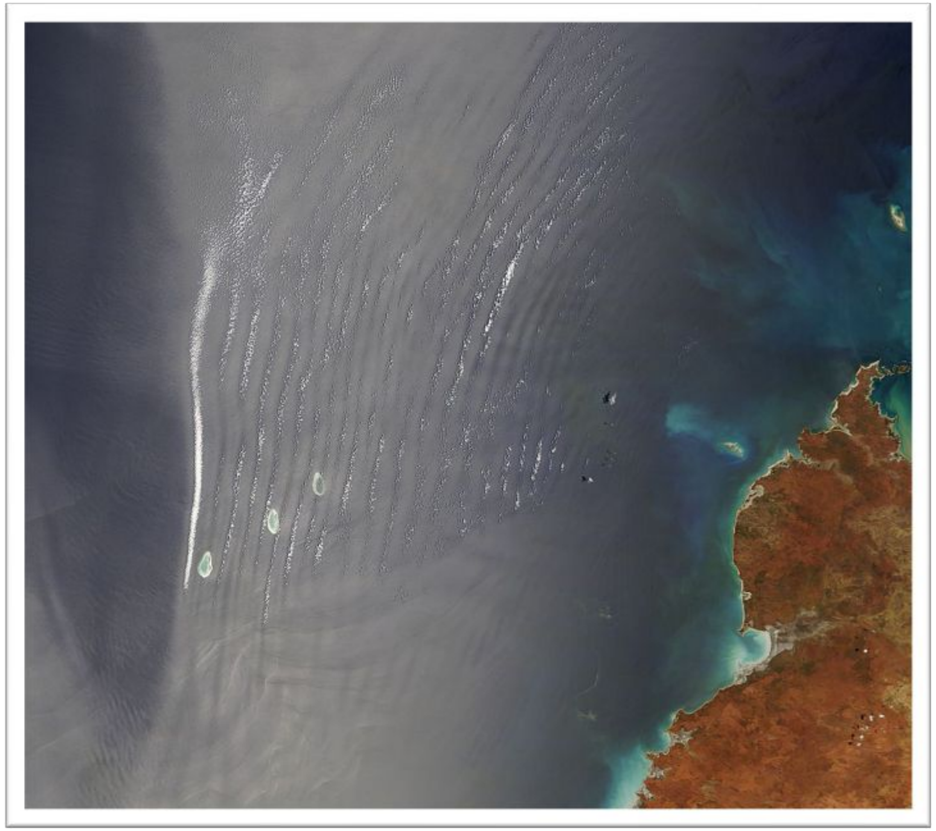
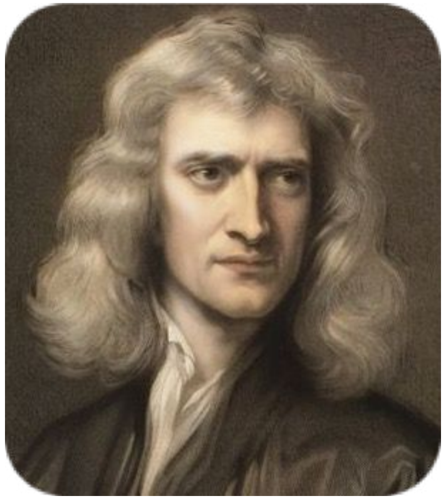


Figure: Gravity waves at Shark Bay, Australia

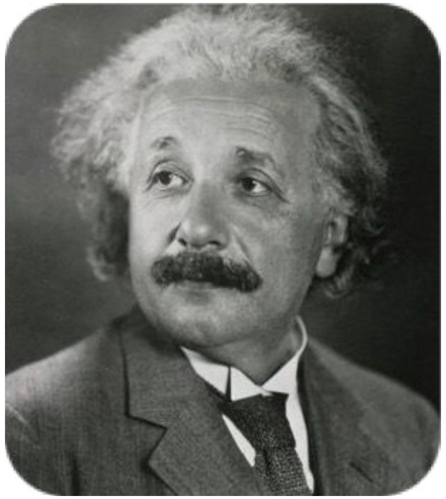
The Nature of Gravity



- **Newton**: an object can be moved via a force without being physically touched by another object, aka "action at a distance"
- This force is proportional to the product of the two masses, and inversely proportional to the square of their distance
- Newton's Law offered no prospect of identifying any mediator of gravitational interaction

$$F = G\frac{m_1 m_2}{r^2}$$

G: Gravitational proportionality constant



- **Einstein**: Gravitational interaction is mediated by the deformation of space-time geometry
- From the general relativity, Einstein's field equations (EFE) show us matter acts upon space-time deforming it, while space-time acts upon matter

$$G_{\alpha\beta} = \frac{8\pi G}{c^4} T_{\alpha\beta}$$

$G_{\alpha\beta}$: Einstein Tensor How spacetime is curved

$T_{\alpha\beta}$: Stress-energy Tensor: How matter and energy is distributed

Einstein Field Equations (EFE)

- Below, I show the Einstein Field Equations in compact form
- The are actually 16 coupled hyperbolic-elliptic nonlinear partial differential equations that describe the gravitational effects produced by a given mass
- The 16 different equations result from the tensors, where we get one for each combination of α and β, which can both be either 0,1,2 or 3 (for 4D spacetime)

$$G_{\alpha\beta} = \frac{8\pi G}{c^4} T_{\alpha\beta}$$

Tensors based on 4D spacetime:

$$a_{\alpha\beta} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix}$$

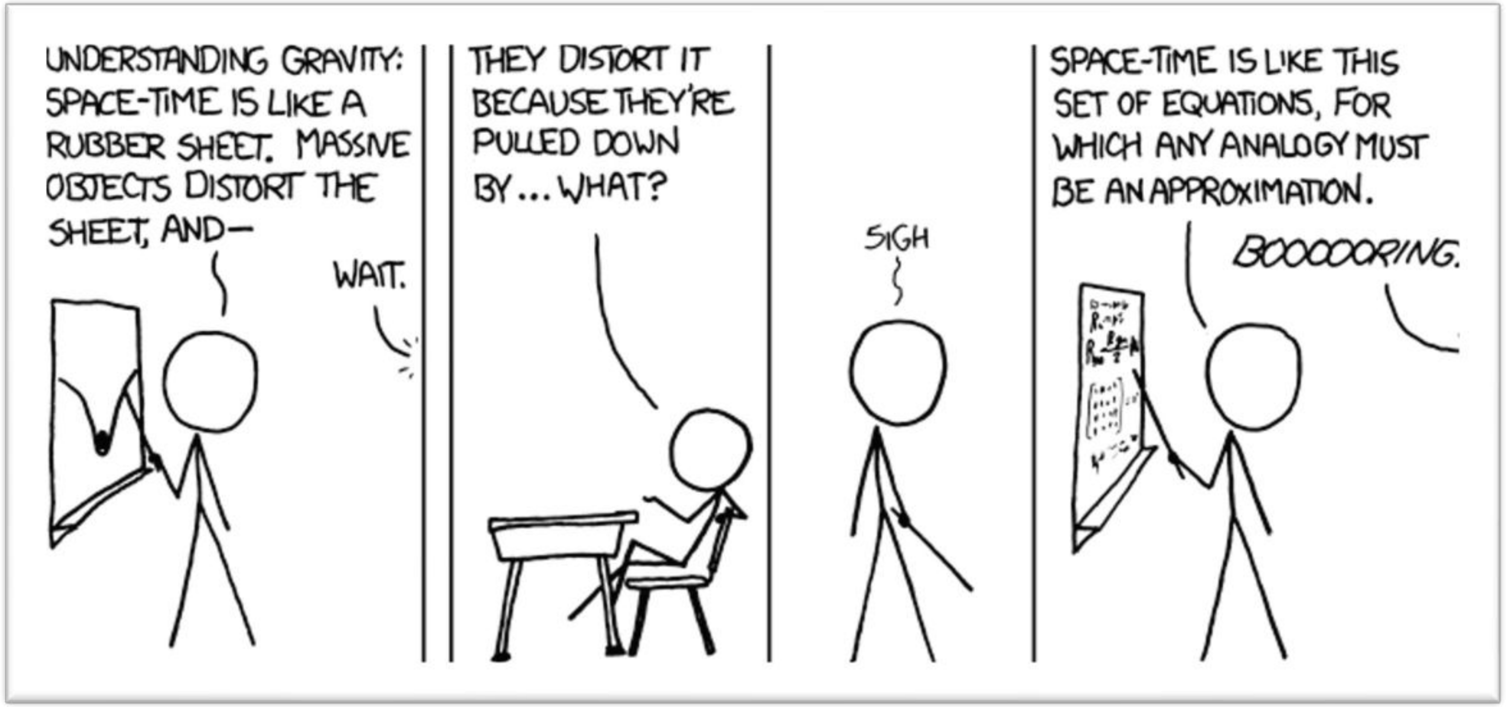
Exanded view of EFE:

$$\frac{1}{2}\sum_{\alpha=0}^{3}\sum_{\beta=0}^{3} g^{\alpha\beta}\partial_\alpha\partial_\mu g_{\beta\nu} + \frac{1}{2}\sum_{\alpha=0}^{3}\sum_{\beta=0}^{3} g^{\alpha\beta}\partial_\alpha\partial_\nu g_{\mu\beta} - \frac{1}{2}\sum_{\alpha=0}^{3}\sum_{\beta=0}^{3} g^{\alpha\beta}\partial_\alpha\partial_\beta g_{\mu\nu} - \frac{3}{2}\sum_{\alpha=0}^{3}\sum_{\beta=0}^{3} g^{\alpha\beta}\partial_\mu\partial_\nu g_{\alpha\beta} - \frac{1}{2}$$
$$\sum_{\alpha=0}^{3}\sum_{\beta=0}^{3}\sum_{\rho=0}^{3}\sum_{\lambda=0}^{3} g^{\beta\lambda} g^{\alpha\rho}\partial_\alpha g_{\rho\lambda}\partial_\mu g_{\beta\nu} - \frac{1}{2}\sum_{\alpha=0}^{3}\sum_{\beta=0}^{3}\sum_{\rho=0}^{3}\sum_{\lambda=0}^{3} g^{\beta\lambda} g^{\alpha\rho}\partial_\alpha g_{\rho\lambda}\partial_\nu g_{\mu\beta} + \frac{1}{4}\sum_{\alpha=0}^{3}\sum_{\beta=0}^{3}\sum_{\rho=0}^{3}$$
$$\sum_{\lambda=0}^{3} g^{\beta\lambda} g^{\alpha\rho}\partial_\nu g_{\alpha\lambda}\partial_\mu g_{\rho\beta} + \frac{1}{4\,|g|}\sum_{\alpha=0}^{3}\sum_{\beta=0}^{3} g^{\alpha\beta}\partial_\beta\,|g|\,\partial_\nu g_{\mu\alpha} - \frac{1}{4\,|g|}\sum_{\alpha=0}^{3}\sum_{\beta=0}^{3} g^{\alpha\beta}\partial_\beta\,|g|\,\partial_\alpha g_{\mu\nu} - \frac{1}{4\,|g|}\sum_{\alpha=0}^{3}$$
$$\sum_{\beta=0}^{3} g^{\alpha\beta}\partial_\beta\,|g|\,\partial_\mu g_{\alpha\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Video Source: Steve Mould (https://youtu.be/dw7U3BYMs4U)

General Relativity in a Nutshell

Matter causes the space-time around it to curve; the curvature of space-time determines how matter moves; insofar as objects, when not being acted upon by a force, follow geodesics - the equivalent to straight lines on a curved surface



Metaphors: friends or foe?

Positive: Metaphors allow a student to build on existing knowledge and help them understand something quickly and intuitively

Negative: This intuition can be misleading and hinder the development of a deeper understanding in the future

General Relativity in a Nutshell

Matter causes the space-time around it to curve; the curvature of space-time determines how matter moves; insofar as objects, when not being acted upon by a force, follow geodesics - the equivalent to straight lines on a curved surface

A Metaphor Too Far
by Philip Ball

In Defence of Metaphors
by Caleb A. Scharf

Metaphors: friends or foe?

Positive: Metaphors allow a student to build on existing knowledge and help them understand something quickly and intuitively

Negative: This intuition can be misleading and hinder the development of a deeper understanding in the future

EFE Solution: Schwarzschild Radius

- The first nontrivial solution of the Einstein Field Equations was found by Karl Schwarzschild in 1916
- From Schwarzschild's solution arises a critical radius, called the Schwarzschild Radius, R_S:

$$R_S = \frac{2GM}{c^2}$$

- G is the Gravitational constant, M is the body's mass, and c is the speed of light

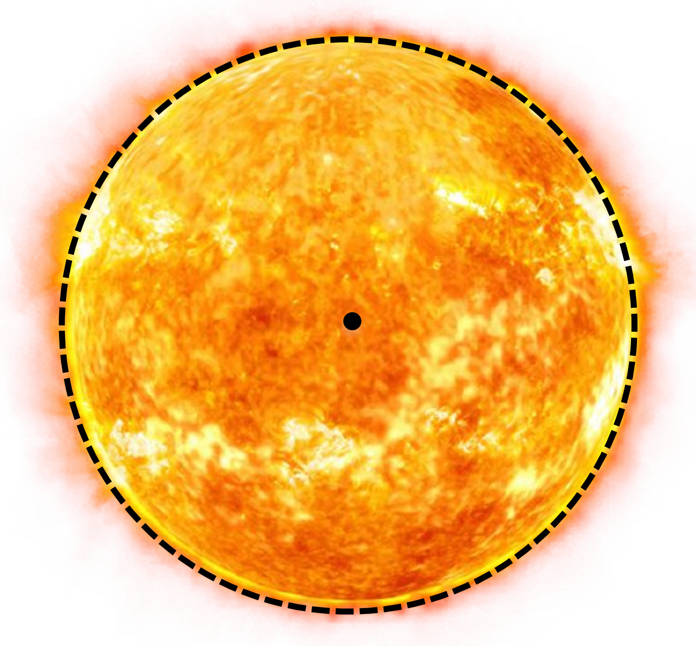
Worked Example: Schwarzschild Radius

Estimate the Schwarzschild radius of the Sun.

$$R_S = \frac{2GM}{c^2}$$

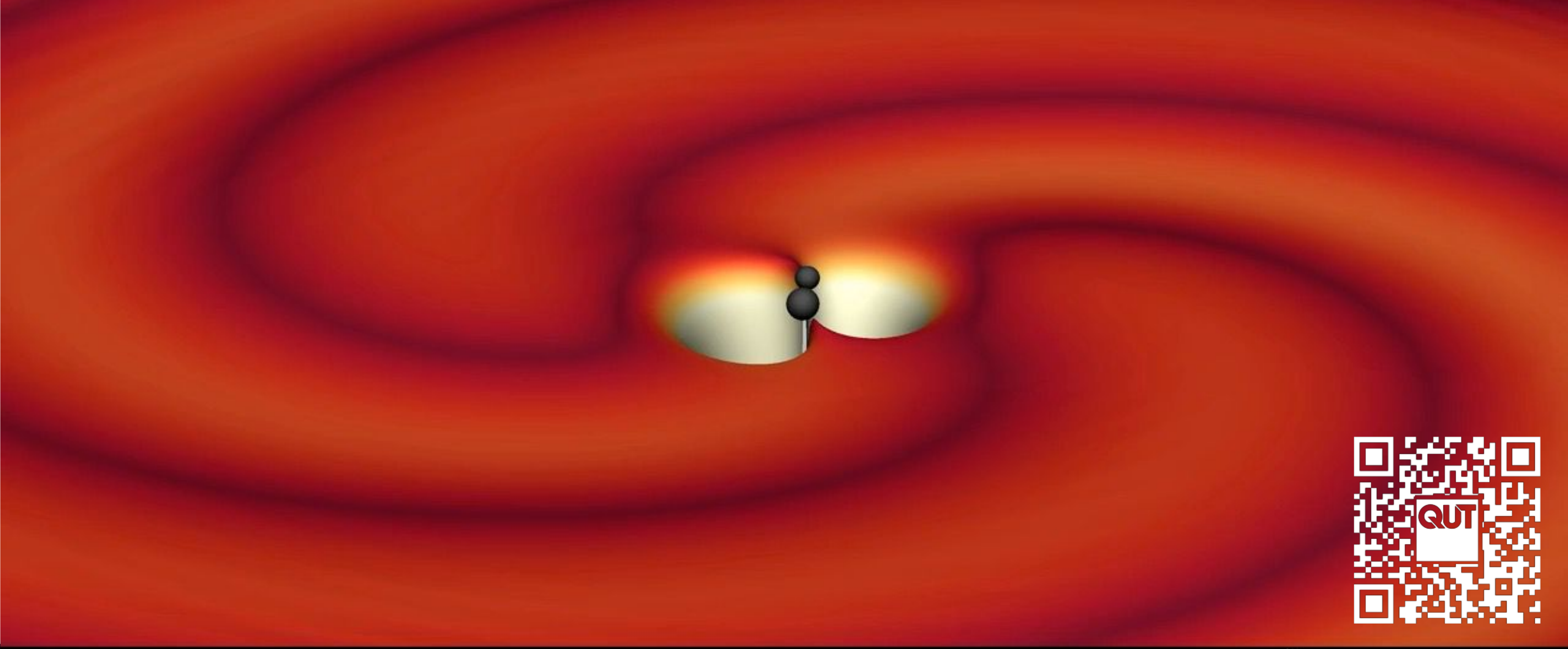
$$R_S = \frac{2(6.7\times10^{-11}\text{m}^3\text{kg}^{-1}\text{s}^{-2})(2.0\times10^{30}\text{kg})}{9.0\times10^{16}\text{m}^2\text{s}^2}$$

$$R_S \approx 3{,}000\ \text{m}$$



Any object whose radius is smaller than its Schwarzschild radius is called a black hole (BH), and the surface at the Schwarzschild radius acts as an event horizon.

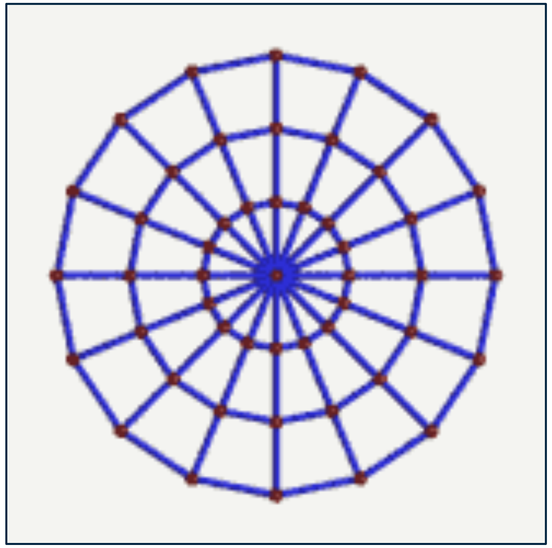
EFE Solution: Ripples in Space-time

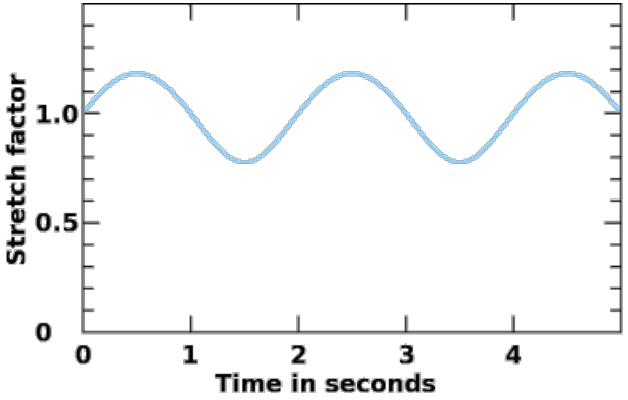


Max Planck Institute
for Gravitational Physics

The Wave Nature of the Ripples (2D)

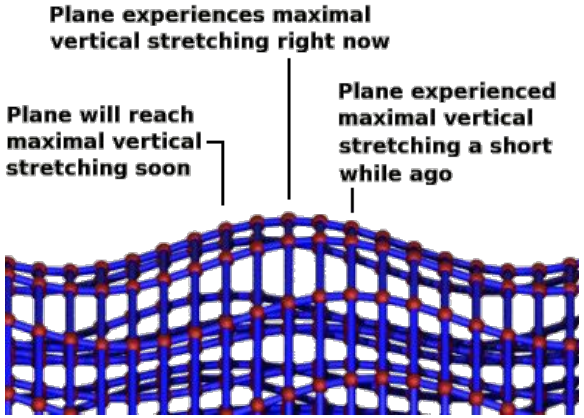
- The main mechanism by which gravitational waves act on spacetime is they rhythmically distort distances between freely falling objects
- For the simplest case of a gravitational wave, the consequences are shown in the animation here – the wave moves from behind the wall towards you
- The free particles (shown in red) are influenced by the wave – stretching in one direction, while shrinking in the perpendicular direction
- The 1D representation is given below (as with the previous slide)

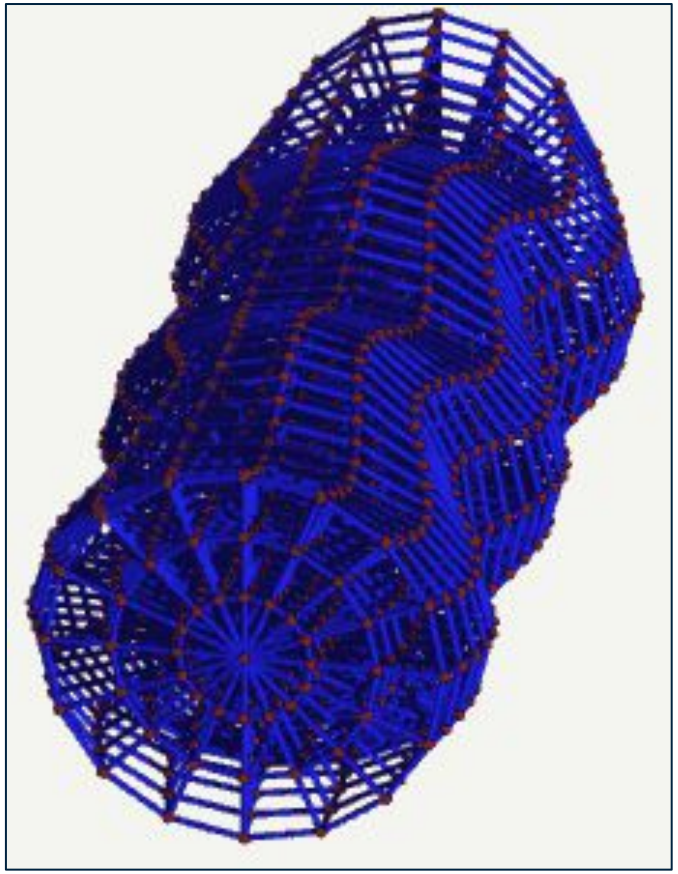




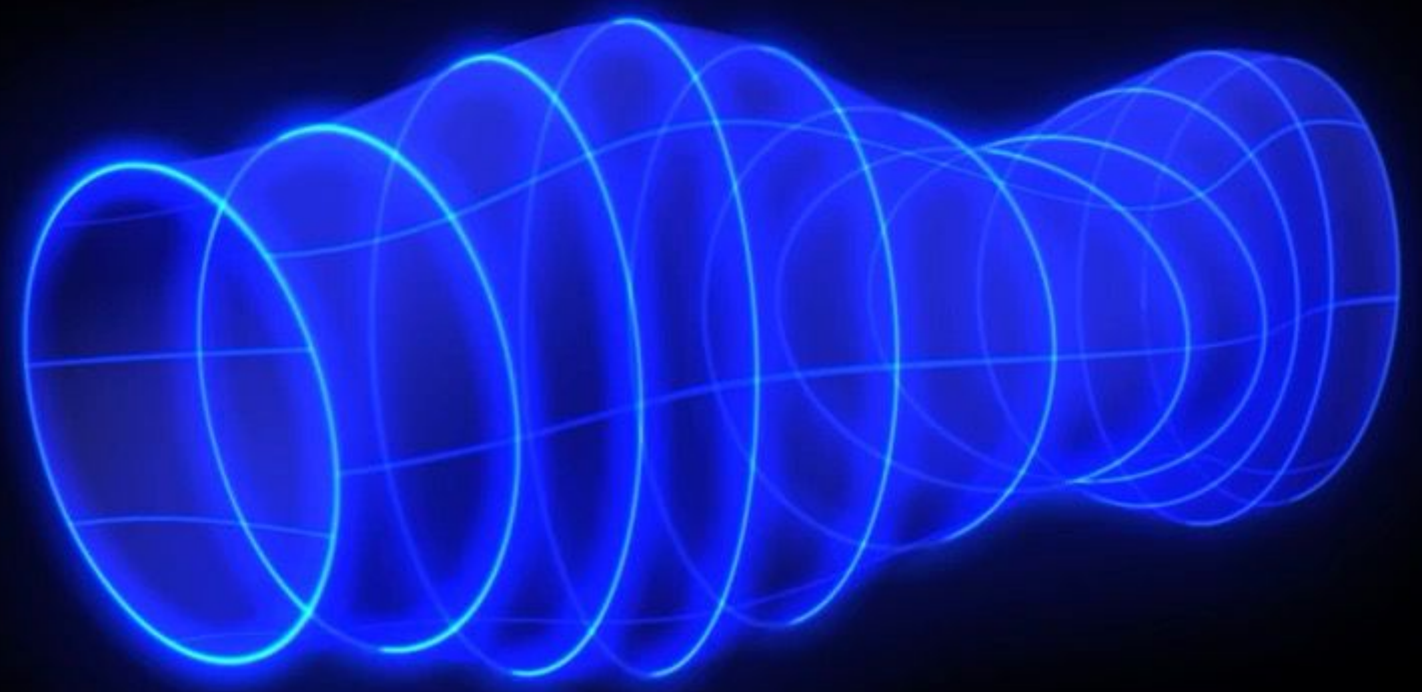
The Wave Nature of the Ripples (3D)

- Let's now extend this view to three dimensions, as shown in this animation
- Here, we have the same free particles, which continue to stretch and shrink, but we now have multiple planes
- If plane A is located in front of plane B, plane A lags behind plane B as it goes through the oscillation
- This time-lag between one plane and the next is what generates a traveling wave pattern
- As a gravitational wave passes an object, that object will find spacetime distorted by the effects of strain





esa The Wave Nature of the Ripples



Sources of Gravitational Waves

Gravitational waves are generated by any object where its acceleration is:

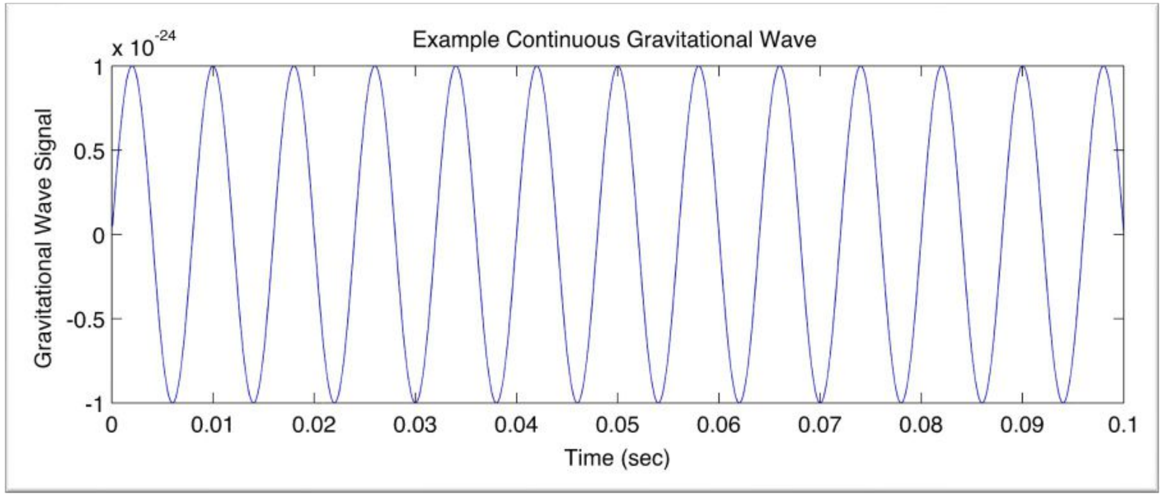
1. not spherically symmetric (like an expanding or contracting sphere) and
2. not cylindrically symmetric (like a spinning sphere)

Video Source: Steve Mould (https://youtu.be/dw7U3BYMs4U)

Continuous Gravitational Waves

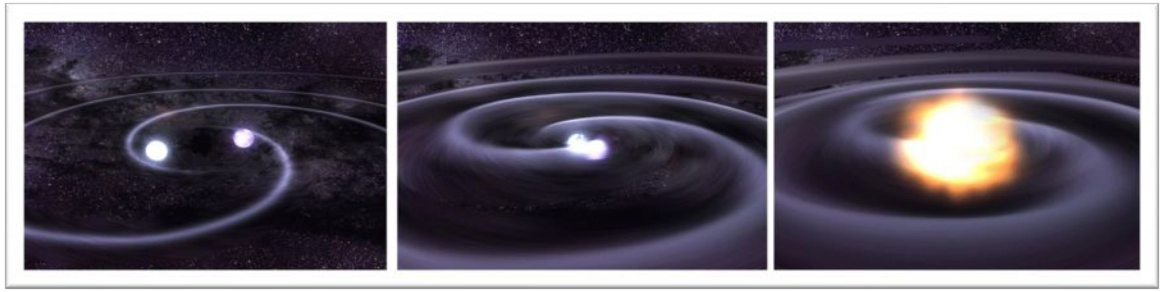
- Continuous gravitational waves are thought to be produced by a single spinning massive object (e.g., like a rotating neutron star)

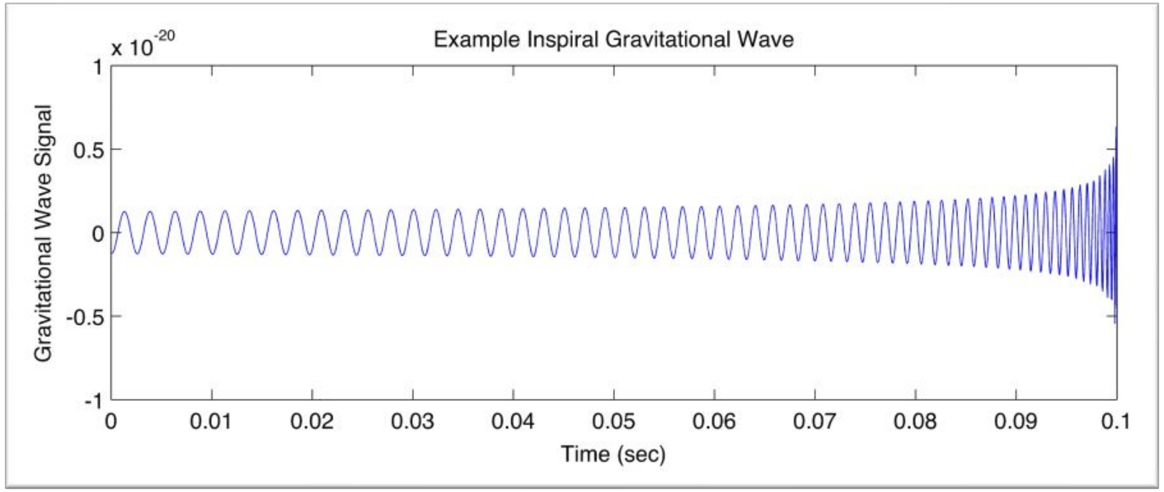
- Any bumps or imperfections on the spherical massive object will generate gravitational waves as it performs its rotation



Inspiral Gravitational Waves

- Inspiral gravitational waves are generated during the end-of-life stage of binary systems where the two objects merge into one
- Such objects include two neutron stars, two black holes, or a neutron star and a black hole whose orbits have degraded

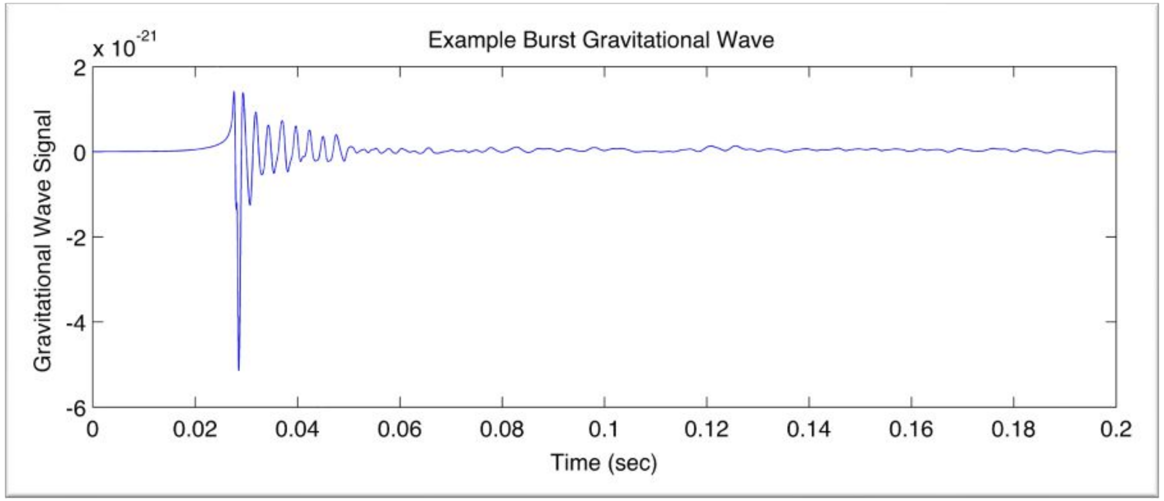




SCAN ME TO LISTEN

Burst Gravitational Waves

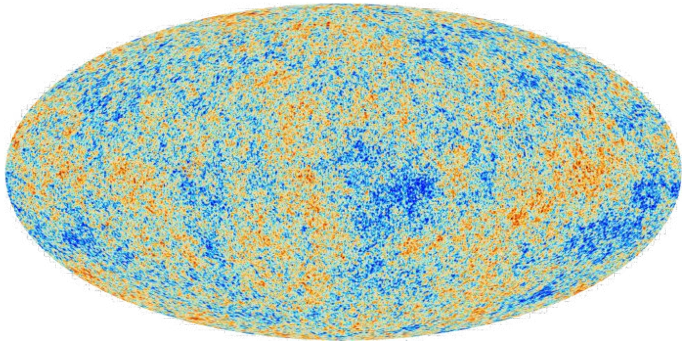
- Burst gravitational waves come from short-duration unknown or unanticipated sources
- There are hypotheses that systems such as supernovae or gamma ray bursts may produce burst gravitational waves

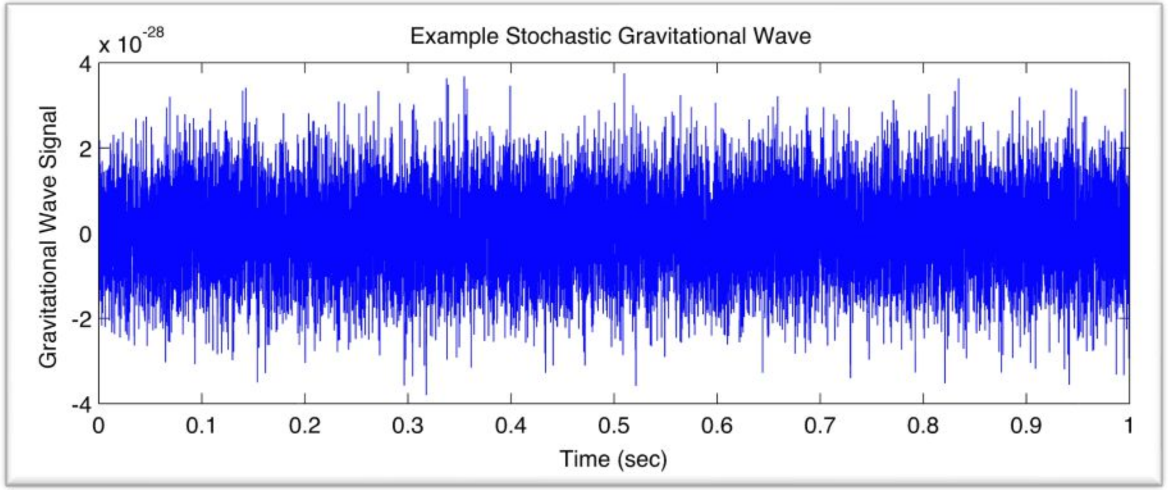


SCAN ME TO LISTEN

Stochastic Gravitational Waves

- Stochastic gravitational waves are the relic waves from the early evolution of the universe
- Analogous to the cosmic microwave background radiation, these gravitational waves arise from a large number of random, independent events combining to create a cosmic gravitational wave background





Measuring the Gravitational Wave Strain

- A gravitational wave's strain (h) is a measure of its effect on space
- Specifically h, which is a dimensionless number, is the ratio by which lengths are stretched or compressed

$$h \approx \Delta L / L$$

Worked Example: Surfing a Tsunami?

Assume identical two black holes, located $340\ \mathrm{Mpc}\ (1\times10^{25}\ \mathrm{m})$ away, with a combined mass of $20M_\odot$, are orbiting very close to each other. What's the strain of the continuous gravitational wave observed at Earth?

$$\text{strain } h \approx \frac{GM}{c^2}\frac{1}{D}\left(\frac{v}{c}\right)^2$$

$$M_\odot = 2\times10^{30}\ \mathrm{kg}$$

$$G = 6.7\times10^{-11}\mathrm{m^3kg^{-1}s^{-2}}$$

$$c = 3\times10^{8}\ \mathrm{m\ s^{-1}}$$

$$v = ?$$

- To derive a simple equation for orbital velocity, we will assume uniform circular motion.
- In the case of an orbiting object, the centripetal force is actually the gravitational force (i.e., $F_g = F_c$)
- Recall $F_g = \frac{GMm}{R^2}$, where big M is the mass of the object applying the gravitational force, little m is the mass of the orbiting object, and R is the distance between them.
- Recall $F_c = ma_c = \frac{mv^2}{R}$ or mass times centripetal acceleration, which is inversely proportional to the radius R, and increases at the square of the velocity

Worked Example: Surfing a Tsunami?

Assume identical two black holes, located $340\ \mathrm{Mpc}\,(1\times10^{25}\ \mathrm{m})$ away, with a combined mass of $20M_{\odot}$, are orbiting very close to each other. What's the strain of the continuous gravitational wave observed at Earth?

strain $h \approx \frac{GM}{c^2}\frac{1}{D}\left(\frac{v}{c}\right)^2$

$M_{\odot} = 2\times10^{30}\ \mathrm{kg}$

$G = 6.7\times10^{-11}\mathrm{m^3kg^{-1}s^{-2}}$

$c = 3\times10^{8}\ \mathrm{m\ s^{-1}}$

$v = ?$

- Since $F_g = F_c \rightarrow \frac{GMm}{R^2} = \frac{mv^2}{R}$
- Now we solve for v
- $\frac{GMm}{R^2} = \frac{mv^2}{R} \rightarrow \frac{GM}{R} = v^2 \rightarrow v = \sqrt{\frac{GM}{R}}$
- We know G (gravitational constant) and the mass is $20M_{\odot}$ (two black holes), but what about the distance between them (i.e., "very close").
- Let's assume they are just touching (i.e., two times their Schwarzschild Radius
- Earlier, we saw $R_S = 3{,}000\ \mathrm{m}$ for $1M_{\odot}$. Therefore, here we have $R = 20 \times 3{,}000\ \mathrm{m} = 60{,}000\ \mathrm{m}$

Worked Example: Surfing a Tsunami?

Assume identical two black holes, located $340\ \mathrm{Mpc}$ $(1\times10^{25}\ \mathrm{m})$ away, with a combined mass of $20M_{\odot}$, are orbiting <u>very</u> close to each other. What's the strain of the continuous gravitational wave observed at Earth?

$$\text{strain } h \approx \frac{GM}{c^2}\frac{1}{D}\left(\frac{v}{c}\right)^2$$

$$M_{\odot} = 2\times10^{30}\ \mathrm{kg}$$

$$G = 6.7\times10^{-11}\mathrm{m^3kg^{-1}s^{-2}}$$

$$c = 3\times10^{8}\ \mathrm{m\ s^{-1}}$$

$$v = 2\times10^{8}\ \mathrm{m\ s^{-1}}$$

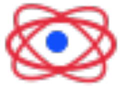
- $v = \sqrt{\frac{GM}{R}}$
- We now know G (gravitational constant) and the mass is $20M_{\odot}$ (two black holes), and R is 60,000 m
- $v = \sqrt{\frac{(6.7\times10^{-11}\mathrm{m^3kg^{-1}s^{-2}})20(2\times10^{30}\ \mathrm{kg})}{60{,}000\ \mathrm{m}}} = 2\times10^{8}\ \mathrm{m\ s^{-1}}$
- Finally, we can solve for strain h
- $h \approx \frac{GM}{c^2}\frac{1}{D}\left(\frac{v}{c}\right)^2 = \frac{(6.7\times10^{-11}\mathrm{m^3kg^{-1}s^{-2}})20(2\times10^{30}\ \mathrm{kg})}{(3\times10^{8}\ \mathrm{m\ s^{-1}})^2}\frac{1}{1\times10^{25}\ \mathrm{m}}\left(\frac{2\times10^{8}\ \mathrm{m\ s^{-1}}}{(3\times10^{8}\ \mathrm{m\ s^{-1}})}\right)^2$
- $h \approx 10^{-21}$

Surfing a Tsunami? …not quite!

One meter

÷ 10,000  Human hair ~100μm

÷ 100  Wavelength of light ~ 1μm

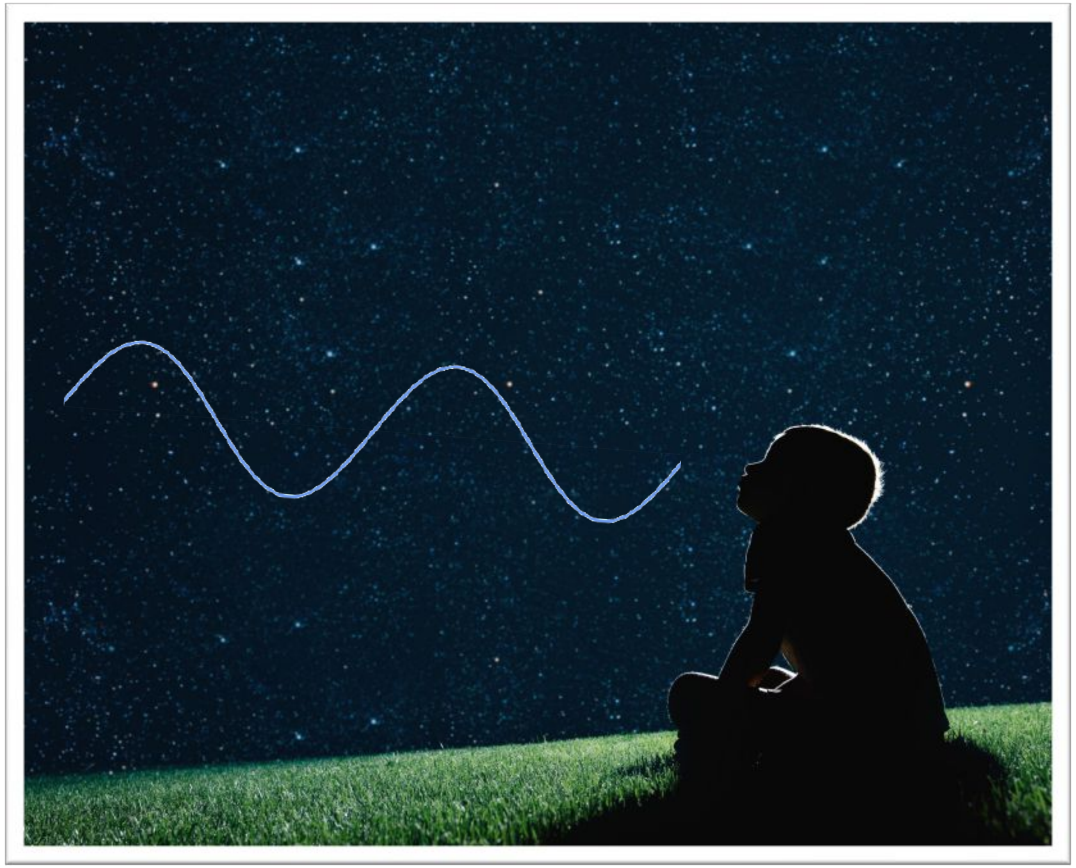
÷ 10,000  Atomic diameter ~ 10^{-10} m

÷ 100,000  Nuclear diameter ~ 10^{-15} m

÷ 1 million $h \sim 10^{-21}$ m

How Do We Detect Gravitational Waves?

- So when a gravitational wave passes by Earth, it squeezes and stretches space by $h \sim 10^{-21}$ m
- This is considerably smaller than subatomic particles, which are too small to be seen by even the most powerful microscopes
- Einstein and his contemporaries debated the existence of gravitational waves for decades and ultimately concluded they'd be too small to even detect
- Others still tried…



Weber Bar: First Detection?

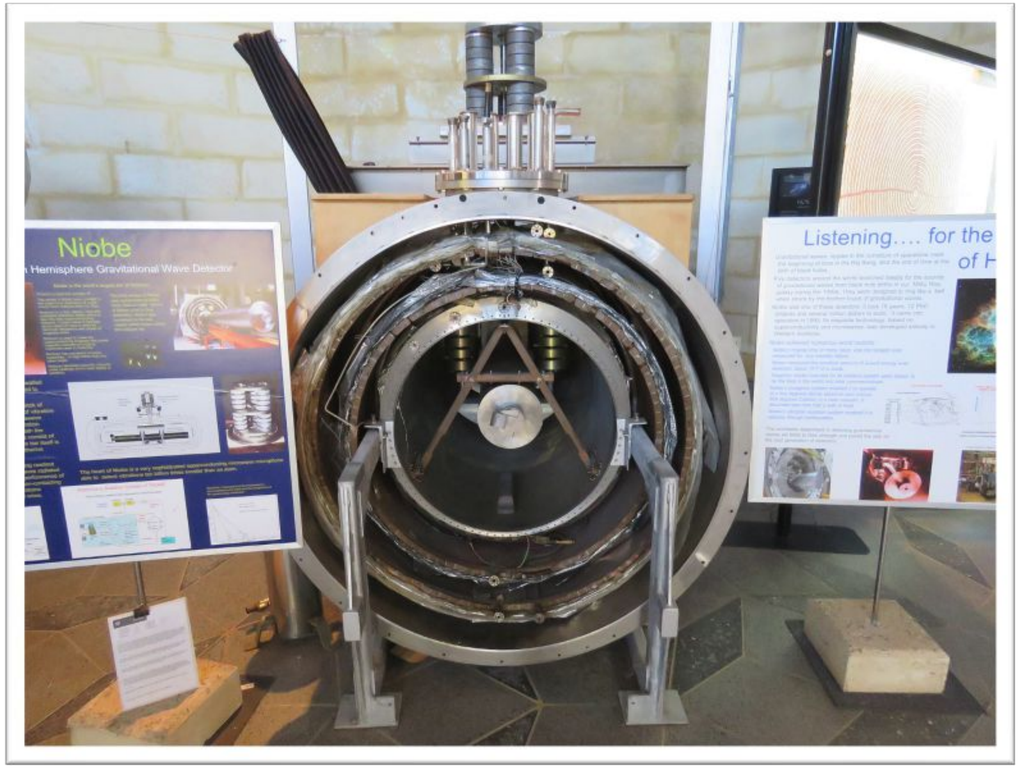
- In 1957, Joseph Weber at the University of Maryland began the first serious hunt for gravitational waves
- He focused on the fact that if gravitational waves change the distance between any two points in spacetime, it should stretch a physical object as they pass through it
- Weber's physical object was the Weber Bar – a 0.61 meter diameter, 1.5 meter long cylinder of aluminium
- The expectation was the Weber Bar would generate detectable acoustic (sound) waves
- By the 1960's, Weber's analysis of his bar data convinced him he was detecting gravitational waves, which he dutifully reported to the scientific community

The Weber Bar

First Detection? ...no

Gravity's Shadow: The Search for Gravitational Waves by Harry Collins

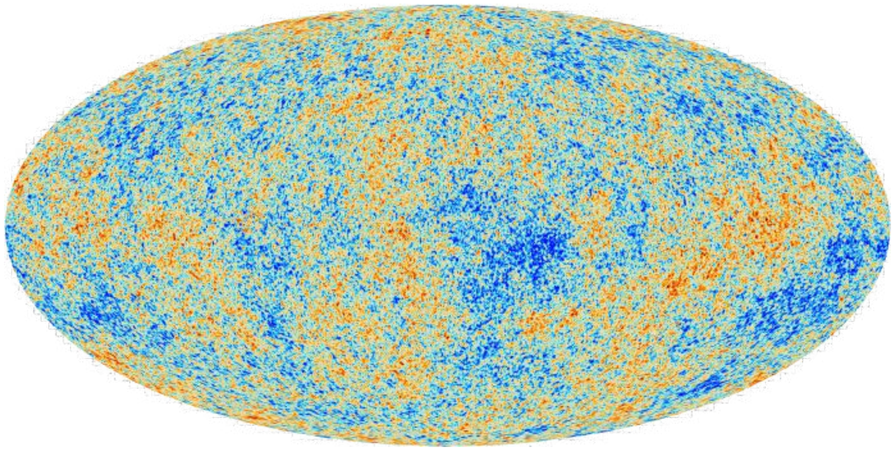
- In the years following the construction of the Weber Bar experiment, many variations were built around the world
- Close to home, the Niobe was constructed by David Blair at University of Western Australia in Perth
- Unfortunately, despite all these extra efforts to duplicate Weber's results, they always returned a null result



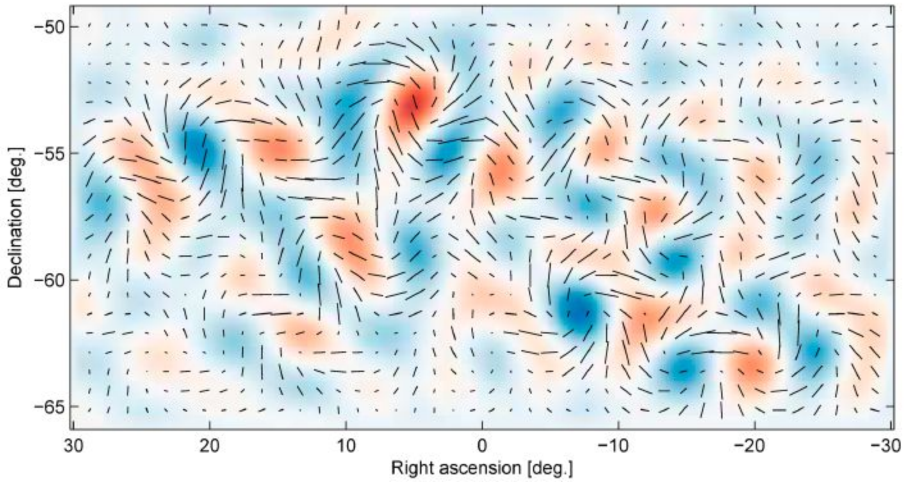
The Gravitational—wave detector NIOBE on display at the Gravity Discovery Centre, Western Australia.

First Detection?

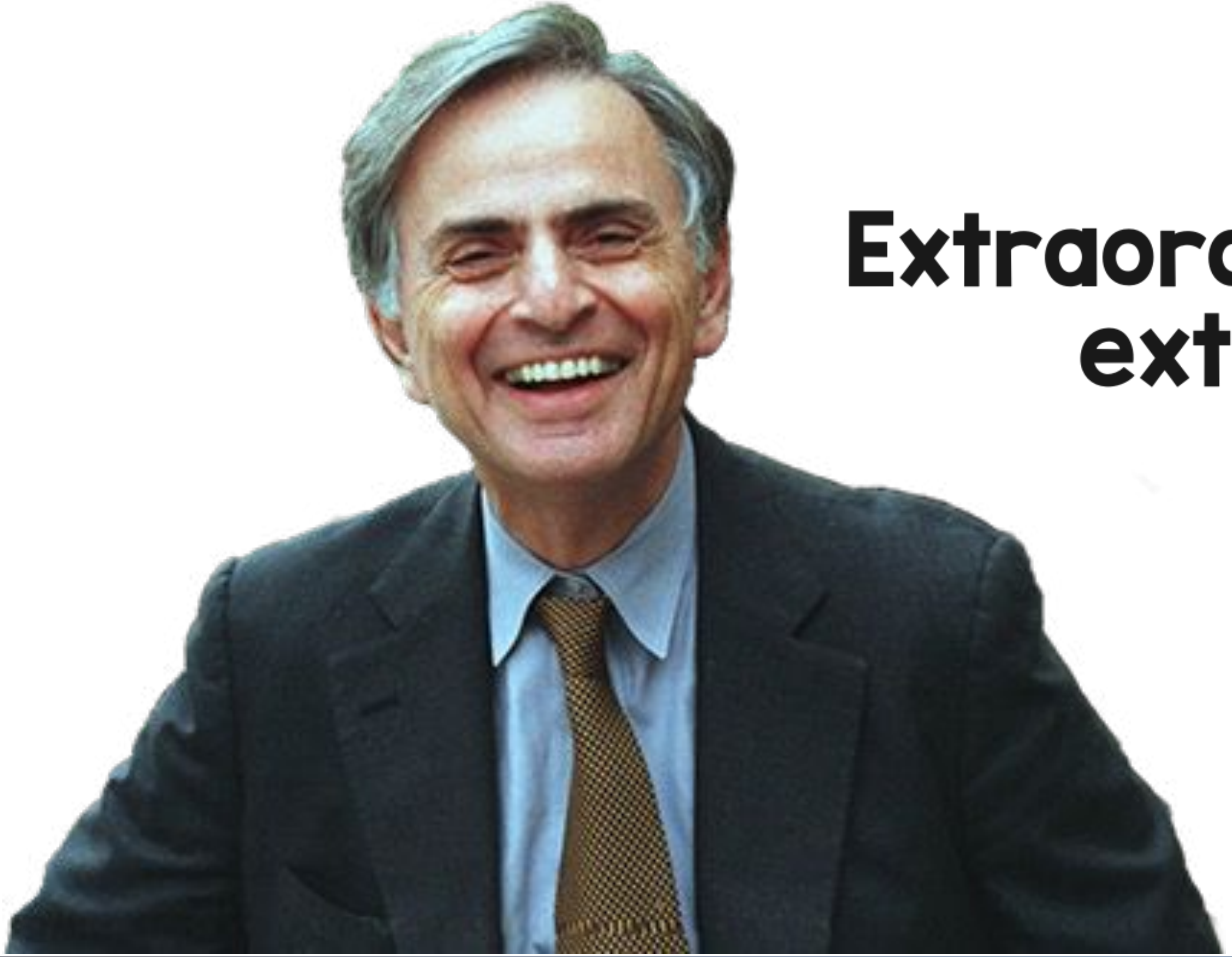
- In 2014, the BICEP2 program, using a telescope located near the South Pole, announced the detection of gravitational waves
- Identified as a faint but distinctive twisting pattern in the polarisation of the radiation from the cosmic microwave background



The Cosmic Microwave Background (CMB)



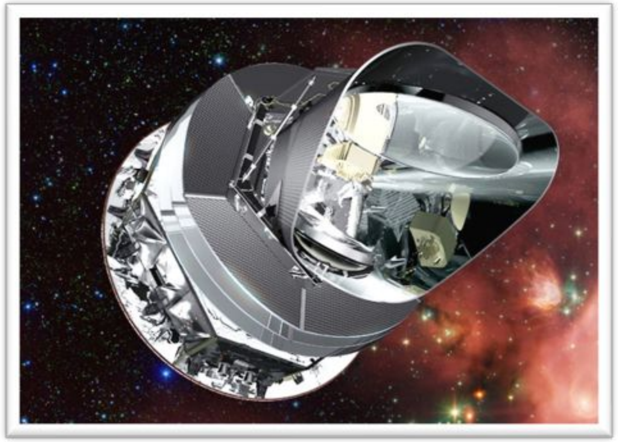
BICEP2 Polarisation Signal



Extraordinary claims require extraordinary evidence

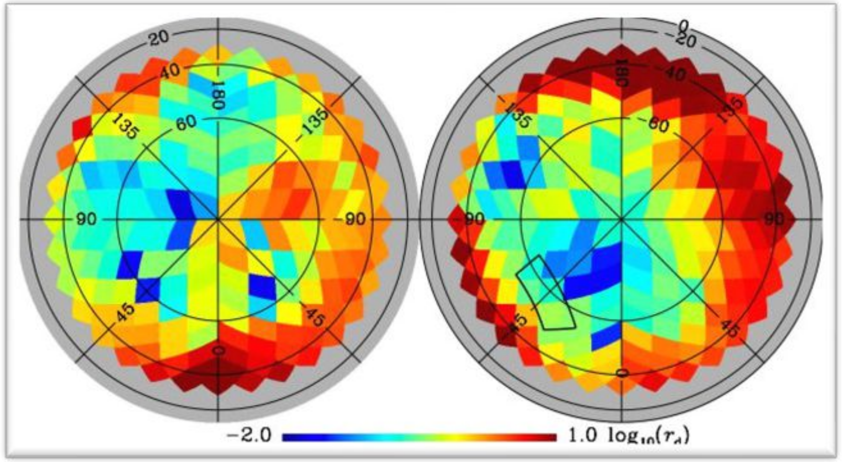
\- Carl Sagan

BICEP 2: First Detection? ...no



In addition to gravitational waves, interstellar dust is believed to produce the same twisting pattern in the polarization map seen by BICEP2.

Along with the original BICEP2 team, physicists using the Planck space observatory produced new dust maps and found more than first predicted.



BICEP 2: First Detection? …no

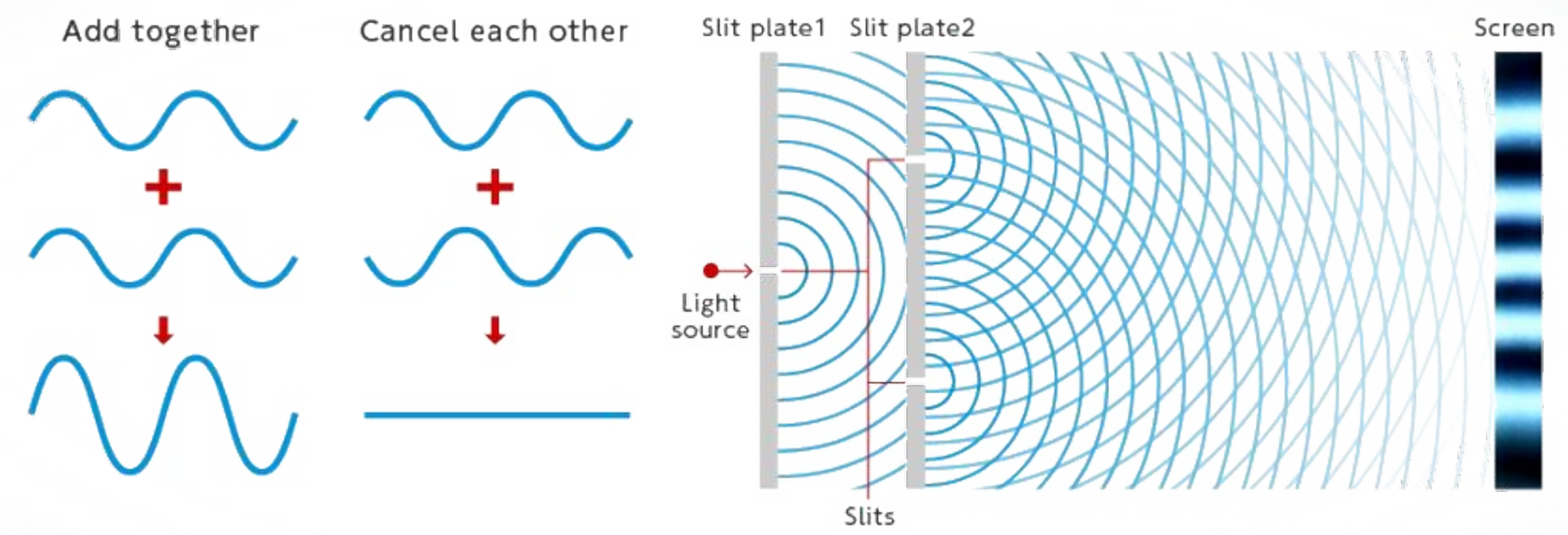
THE CONVERSATION

Academic rigour, journalistic flair

Failure in real science is good – and different from phony controversies

Wave-Nature of Light & Luminiferous Ether

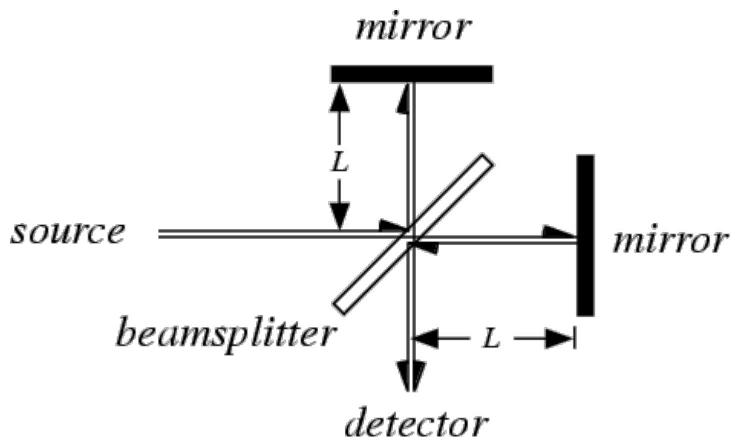
- In 1802, Thomas Young used double-slit interference to confirm the wave nature of light leading many to assume it required a medium to propagate, just like sound travels through air

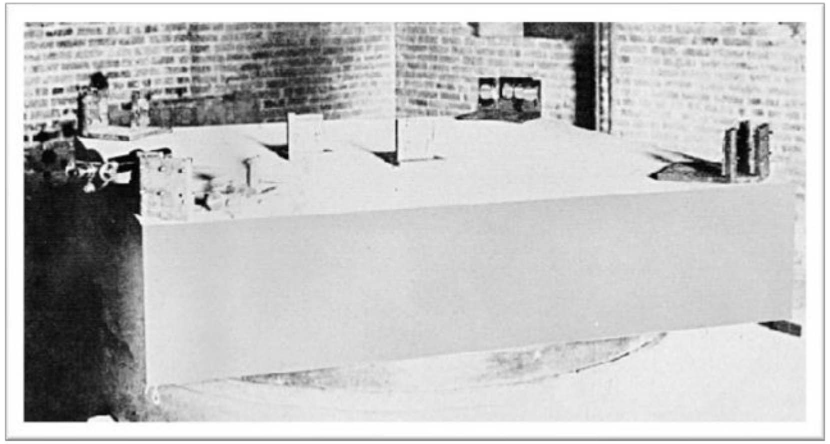


- In 1887, Albert Michelson and Edward Morley used an interferometer in an attempt to measure this medium, dubbed "ether"

Michelson Morley Experiment

- Variations to the velocity of light, caused by an ether, was expected to produce shifting interference patterns
- However, Michelson and Morley found no such shifts in the interference patterns
- The result was negative and ether does not seem to exist
- The experiment has been repeated many times with increasing sensitivity, but a null result returns in all cases

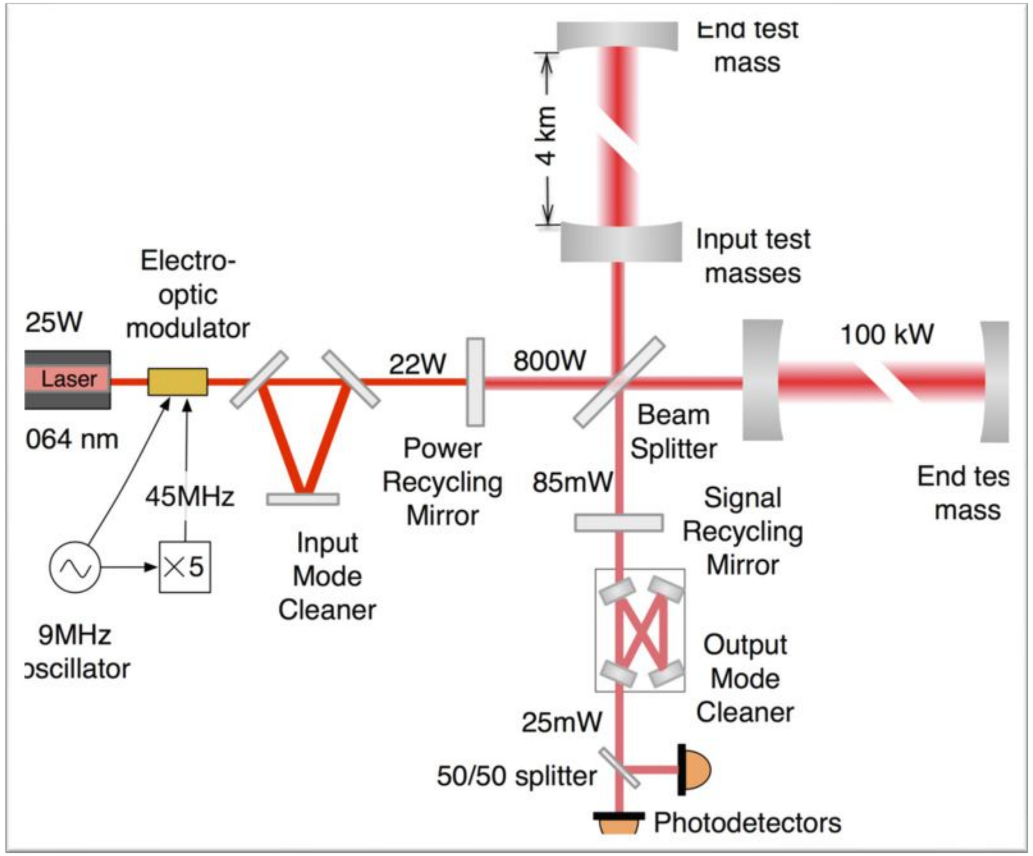




Michelson Morley Experiment

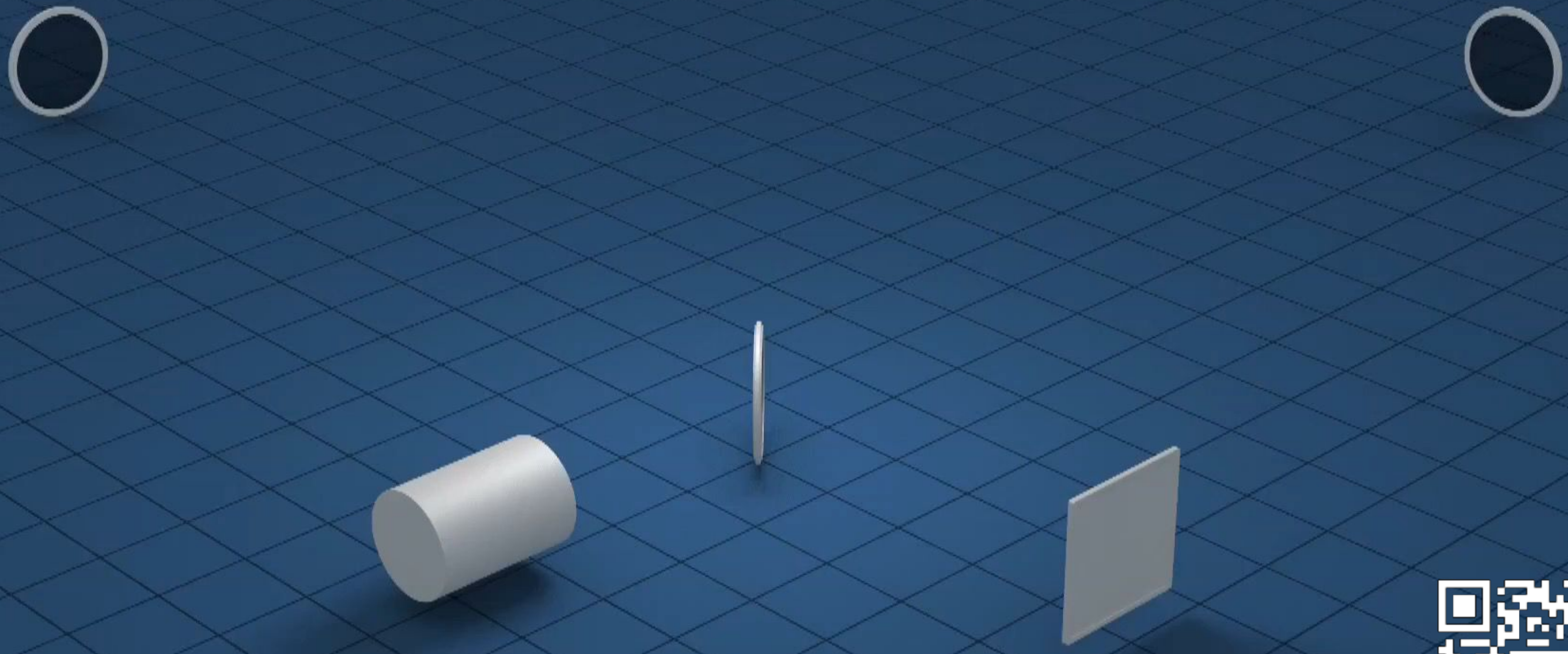
First Detection?

- In 2002, the Laser Interferometer Gravitational-Wave Observatories (LIGO) began operation
- The two large observatories, built in the United States, aimed to detect the strain of gravitational waves by way of laser interferometry
- These observatories use mirrors spaced four kilometres apart!



Slightly more complex than the Michelson Morley Experiment

Interferometer Animation



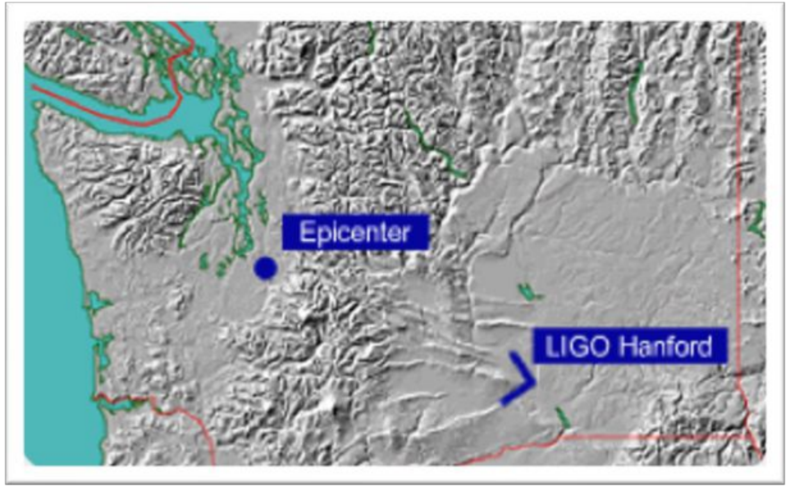
LIGO

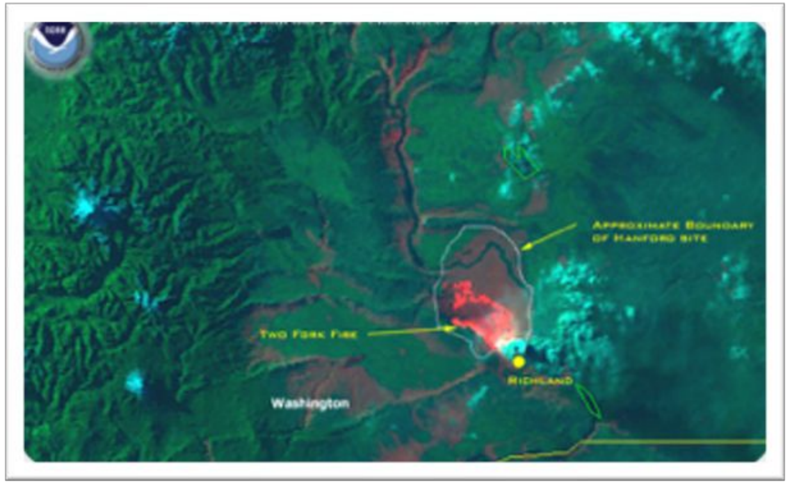
LIGO Louisiana

LIGO Washington

Why in the middle of nowhere?

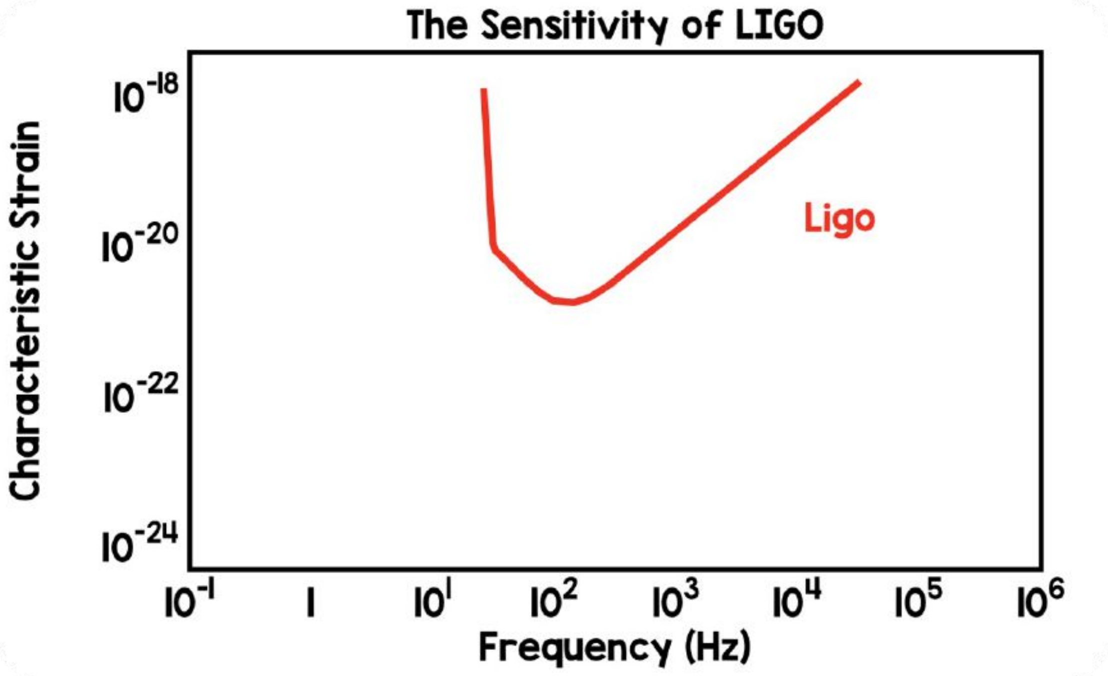
Sensitivity vs. Noise





First Detection? ...no

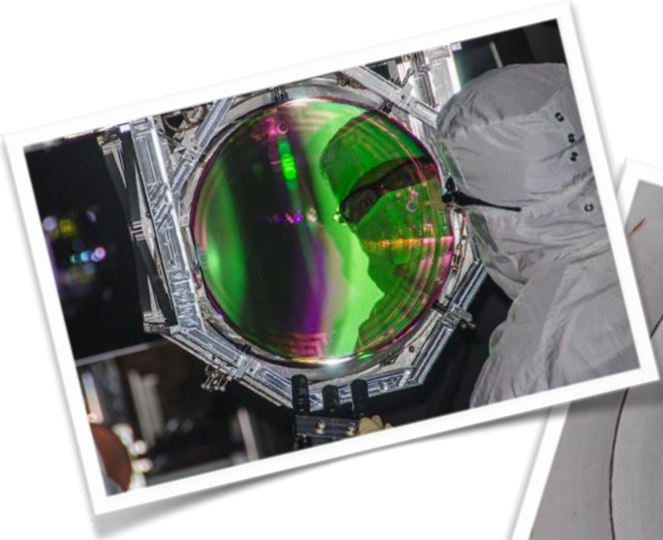
- First generation of LIGO was built from 1994 to 2002
- The program ran from 2002 to 2010
- Nil detections were made
- It was estimated that every year, there would be between 1 and 1/10,000 detection
- Therefore, best case is 8 in total, worse case is to wait 10,000 years for 1 detection!

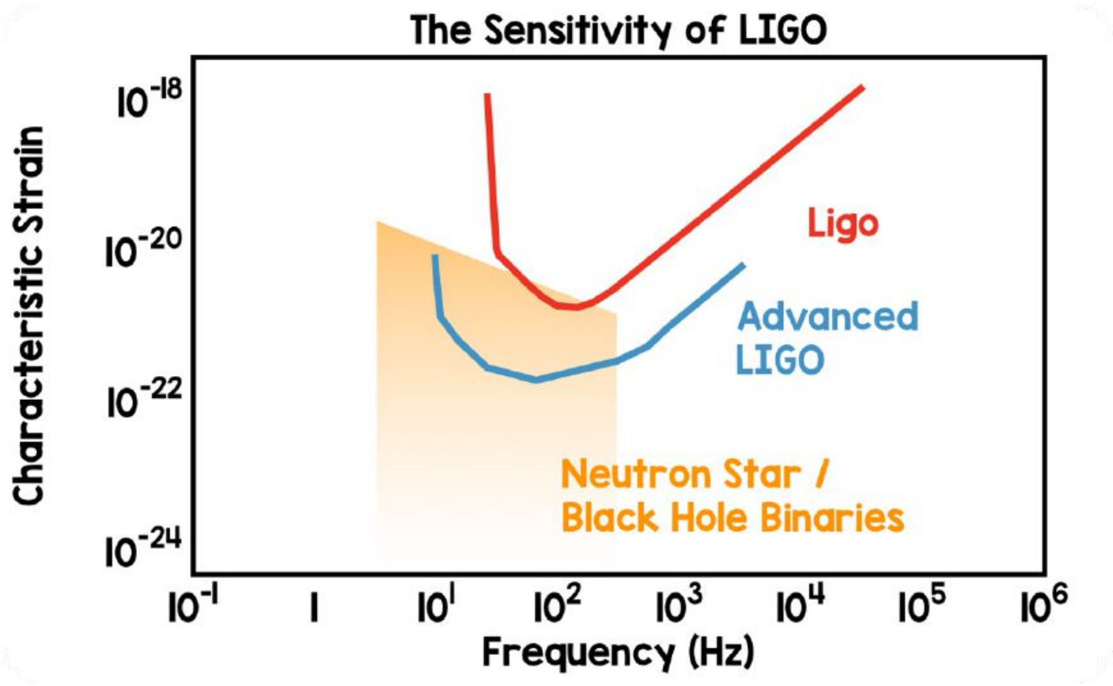


CRICOS No.00213J

Advanced LIGO

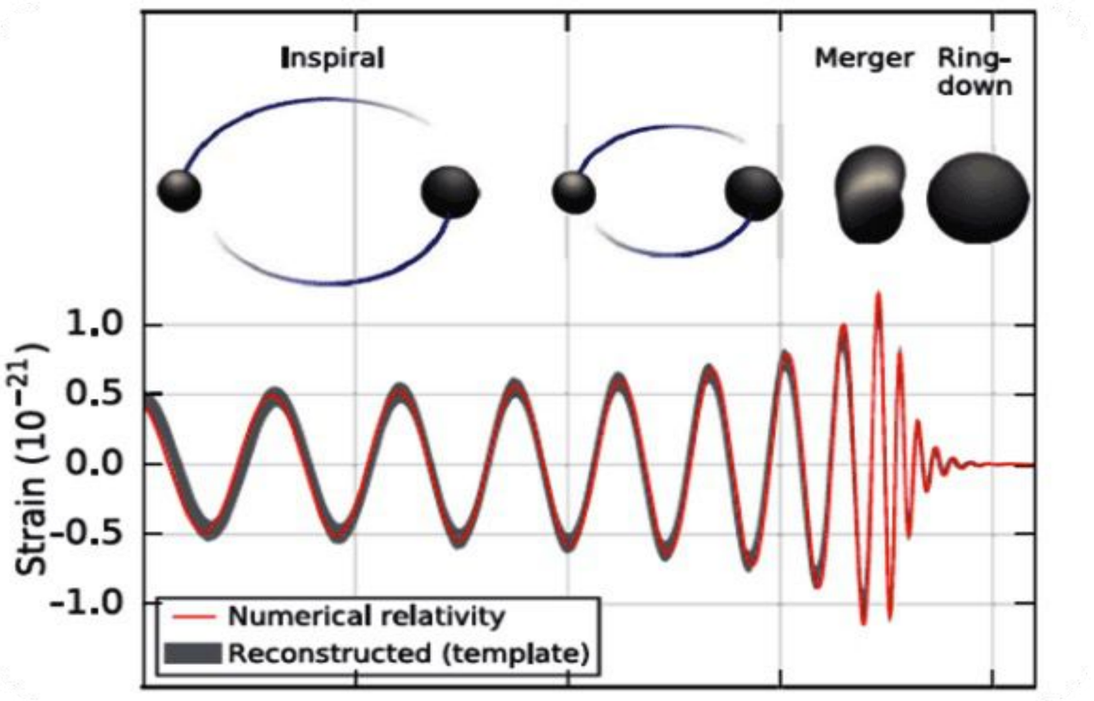
- From 2010 - 2015, LIGO received a $205 million upgrade!



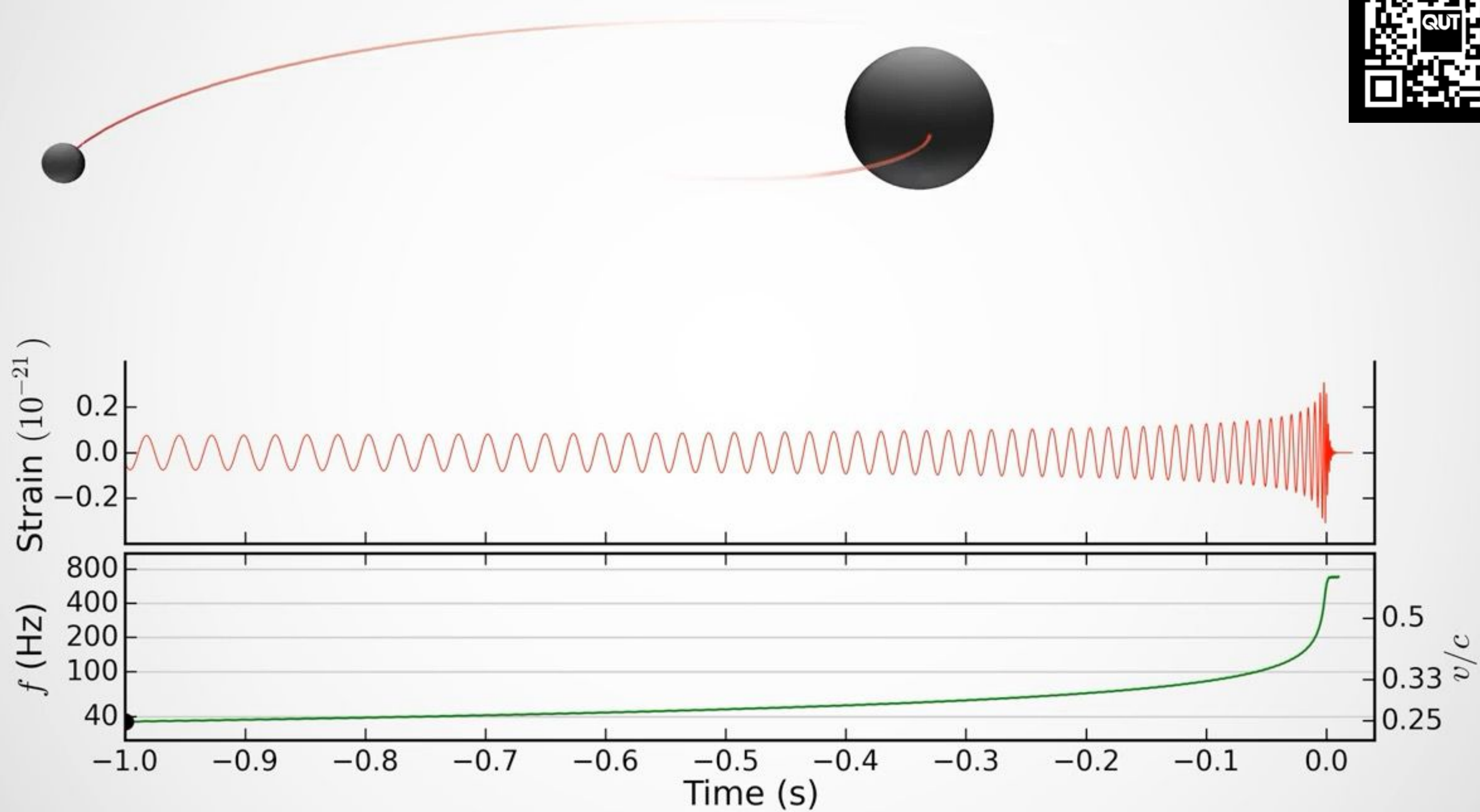


First Detection? ...YES

- On September 14, 2015, the LIGO received the first confirmed gravitational wave signals
- Now known as GW150914 (for the date on which the signals were received in 2015, 9th month, day 14), the event represents the coalescence of two black holes that were previously in mutual orbit
- LIGO's exciting discovery provides direct evidence of what is arguably the last major unconfirmed prediction of Einstein's General Theory of Relativity



GW 150914


Strain (10^{-21})
0.2
0.0
−0.2
f (Hz)
800
400
200
100
40
0.5
0.33
0.25
v/c
−1.0
−0.9
−0.8
−0.7
−0.6
−0.5
−0.4
−0.3
−0.2
−0.1
0.0
Time (s)

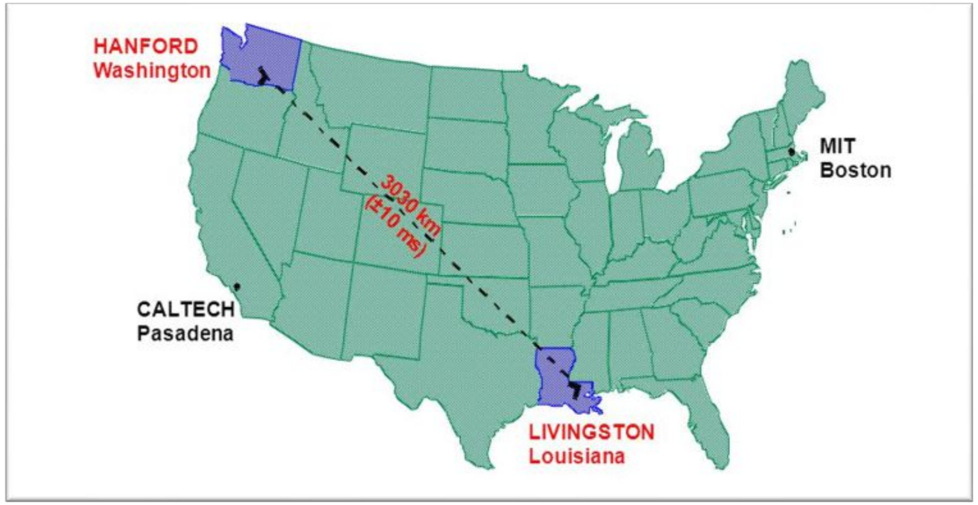
GW 150914

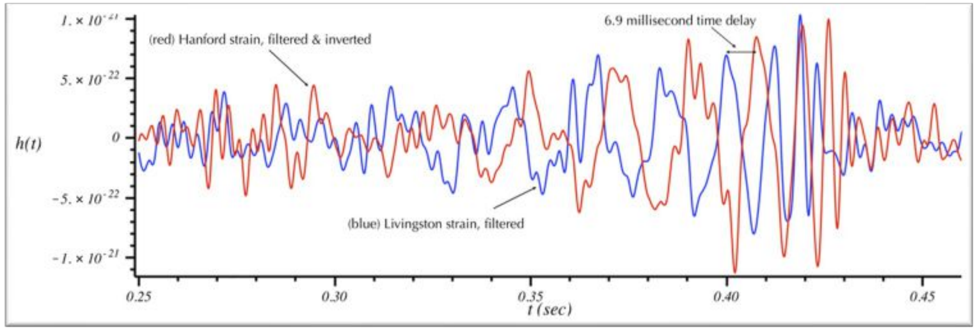
- Two massive black holes merging ($36M_{\odot}$ & $31M_{\odot}$)
- Combined mass of the final black hole was $63M_{\odot}$
- An energy equivalent to the mass of four suns ($4M_{\odot}$) was released by the merger
- Estimated 1.3 billion light years away
- That black hole remnant spins at a rate of 100 rotations per second
- The signal is completely consistent with the predictions of general relativity and agrees well with the predictions of numerical calculations that model the merger of two black holes
- The event was seen in both LIGO detectors with a time offset of 7 milliseconds … why?

2.4	Topic: Ionising radiation and nuclear reactions	Subject Matter: Energy and mass defect	5.3	Topic: Special relativity	Subject Matter: Special relativity/SHE	5.4	Topic: Quantum theory	Subject Matter: Quantum theory

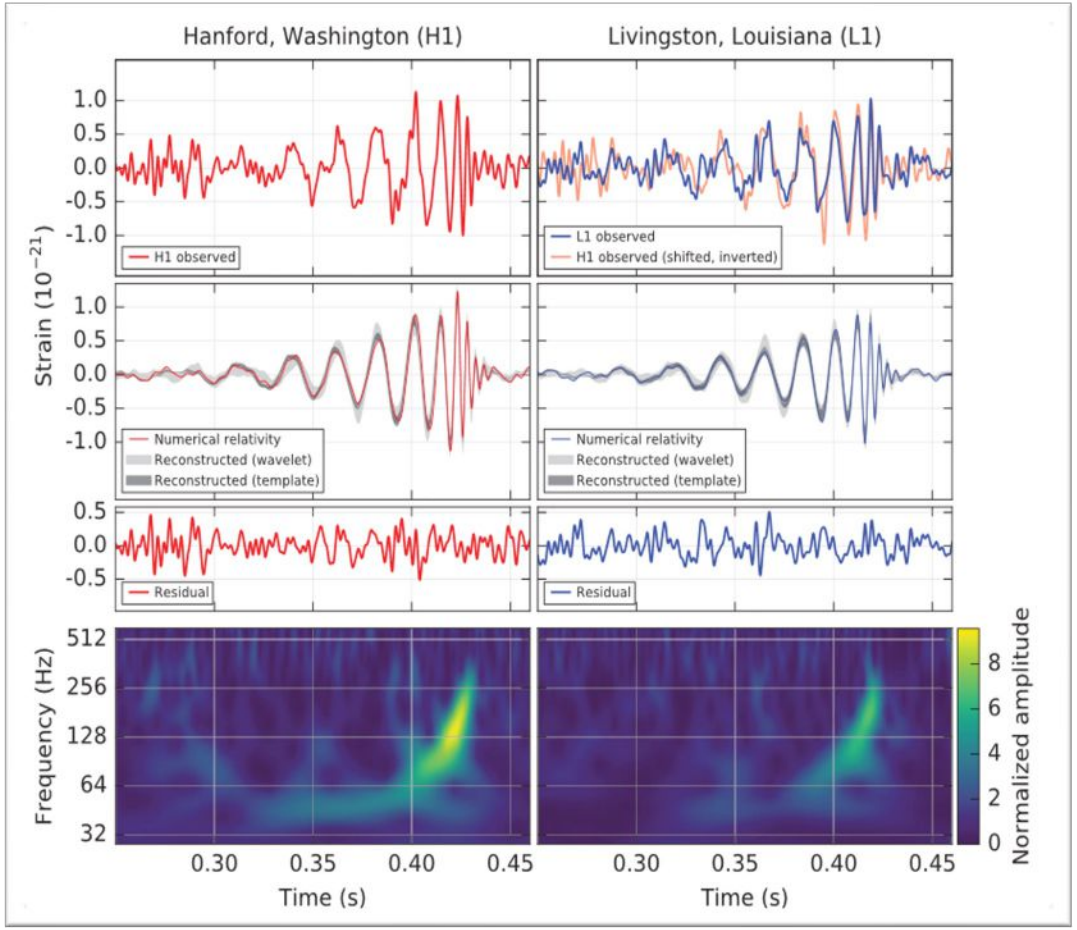
GW 150914 Time Delay

- Given the gravitational waves travel at the speed of light, it takes time to propagate
- A separation of **10 milliseconds** occurs if the waves are traveling parallel to a line connecting the two detectors
- If the waves are traveling perpendicular to this line, the time difference would be **zero milliseconds**
- For GW 150914, we had **7 milliseconds**!

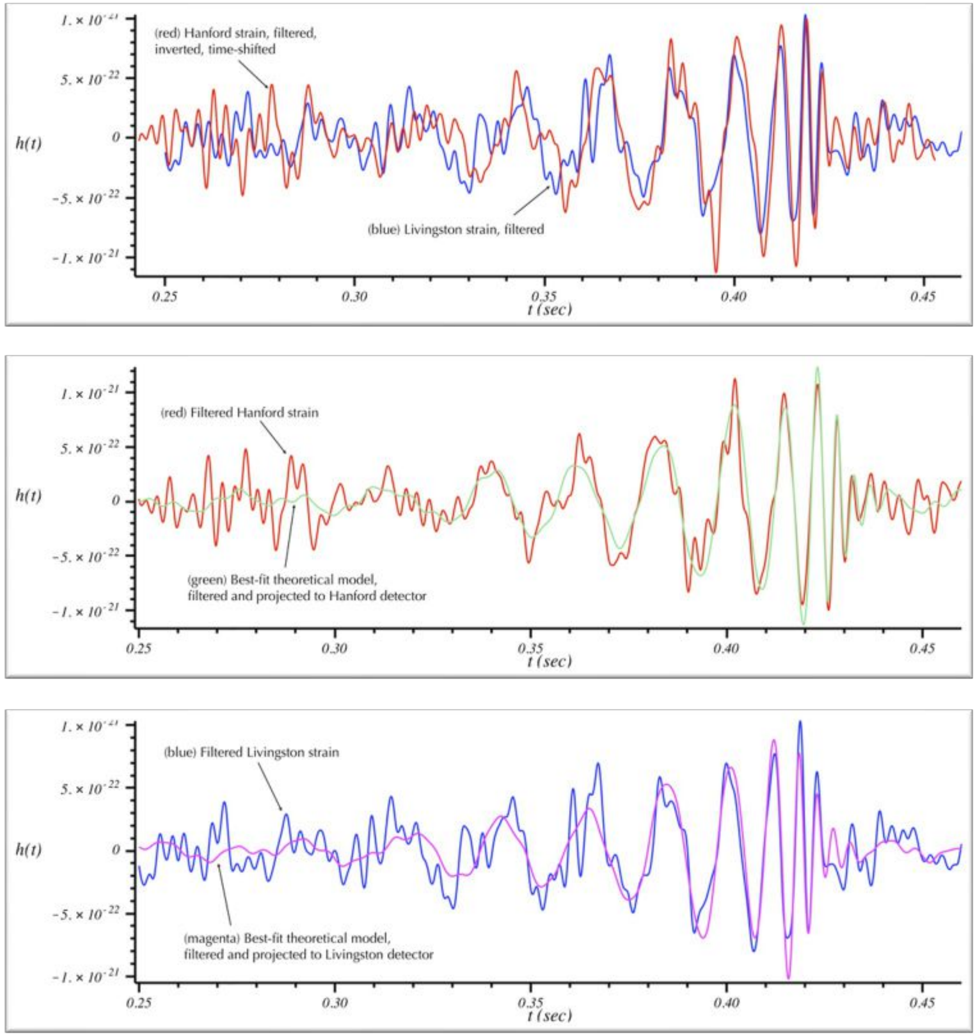




GW 150914



Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
Normalized amplitude
Time (s)



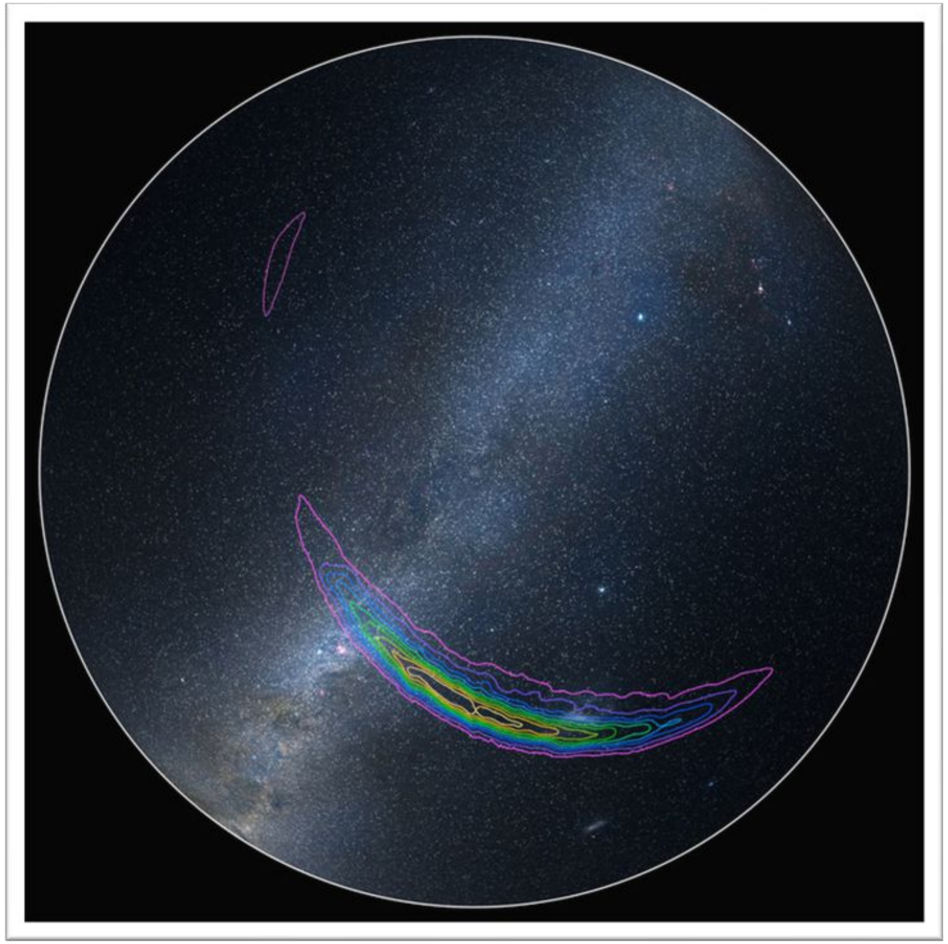
(red) Hanford strain, filtered, inverted, time-shifted
(blue) Livingston strain, filtered
(red) Filtered Hanford strain
(green) Best-fit theoretical model, filtered and projected to Hanford detector
(blue) Filtered Livingston strain
(magenta) Best-fit theoretical model, filtered and projected to Livingston detector
h(t)
t (sec)

Stereo "Sound" of GW 150914

- Unlike an optical telescope, a single gravitational wave detector can say very little about where on the sky a gravitational wave originates
- This is analogous to the relationship between our own hearing – a single ear is not good at finding the direction of a short, sharp sound
- With two ears, we listen in stereo and with crude accuracy (of order 1 to 15° depending on the direction of the sound) we can locate a source
- One of the ways we are able to determine sound direction is via the time difference between the sound recorded by our left and right ears

Stereo “Sound” of GW 150914

- The two LIGO detectors are separated by 3000 km, which means it takes gravitational waves a maximum of 10 milliseconds to propagate from one detector to the other
- Using a process similar to triangulation, we can narrow down GW 150914’s origins



The Big Picture

- This was first time gravitational waves had been directly detected
- This was the first time we observed two black holes collide and merge, forming a single black hole
- This was also the first time we have observed stellar mass black holes with such large masses; it was the first stellar-mass black hole binary to be discovered
- This discovery is important because it represents the birth of a new field of astronomy
- We will now be able to observe and "listen" to a class of celestial phenomena that were previously inaccessible to us with electromagnetic astronomy

Future Directions

Gravitational Wave astronomy is a new way to look at the universe. It has the potential to allow us to explore fundamental physics, examine the weirdest objects in the universe and peer back to the universe's earliest moments.