Discussion on Gravitational Waves

Estefania Coluccio Leskow

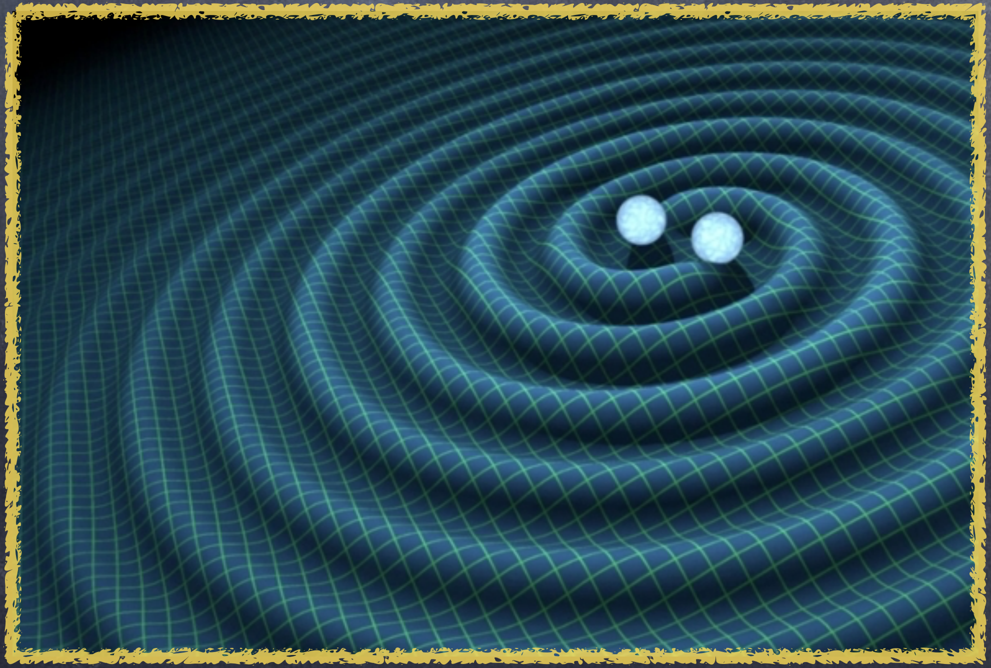
8/03/16

A cataclysmic event, producing the gravitational-wave signal GW150914, took place in a distant galaxy more than one billion light years from the Earth….

Introduction

- 1916: Einstein-> GR-> existence of GW.
- 1916: Schwarzschild -> existence of black holes.
- No direct evidence up to now.
- 1974: Taylor and Hulse -> indirect evidence of GW in neutro stars system.
- Detection is important: 1) new window of obervational astronomy. 2) understanding fundamental laws of physics-> GR proof.

- GWs carry energy and deform the spacetime.
- Propagate through matter with little interaction, so hard to detect.
- Their amplitude decreases as they propagate and are redshifted.
- Emitted in regions of space time where gravity is very strong and velocities close to the speed of light. Usually these areas are sorrounded by matter that absorb EM radiation or do not emit any, so GWs are the only way to study them.



Theory of GW

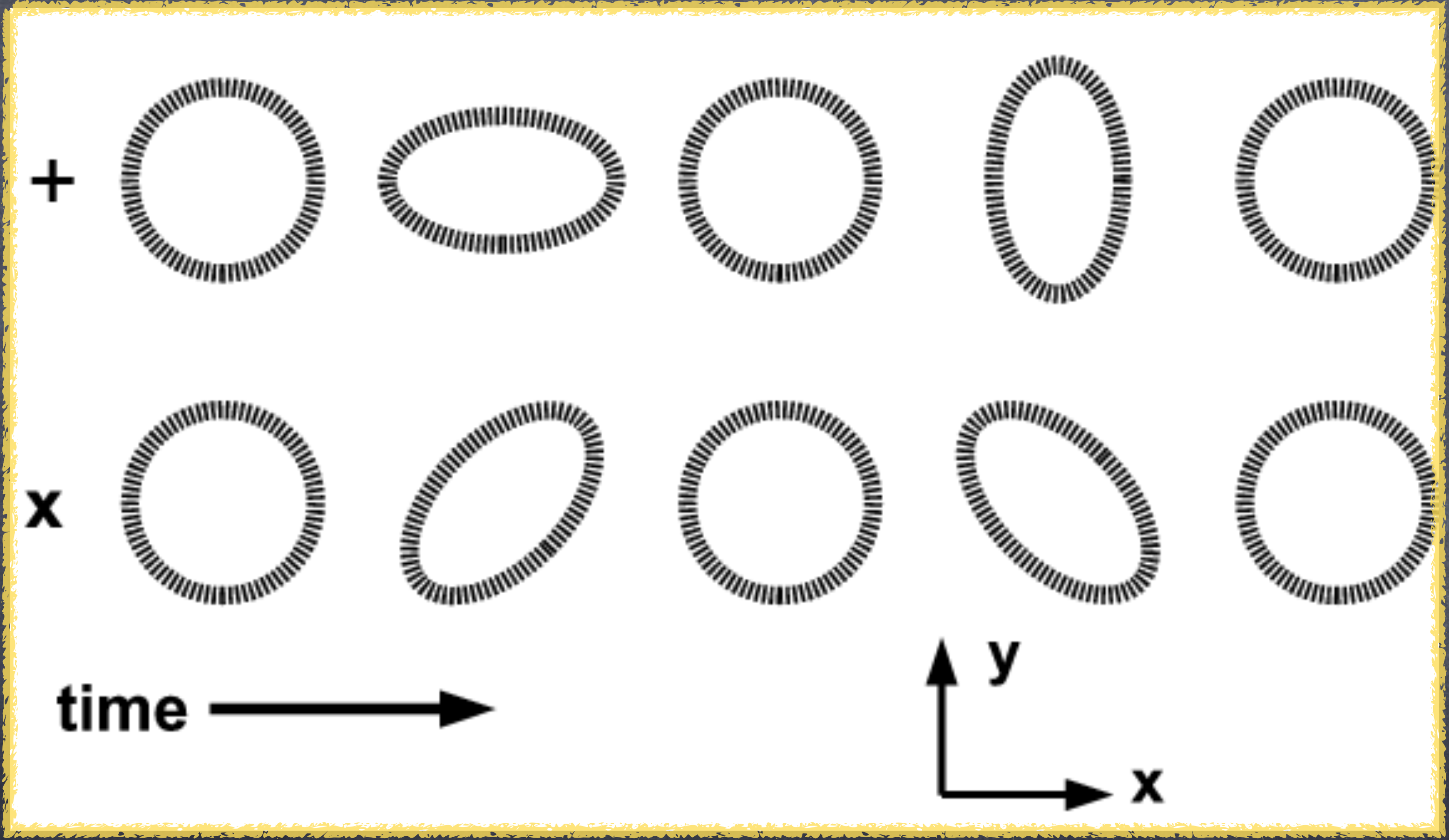
- Accelerating charges -> EM radiation
- Accelerating masses -> GW radiation
- Some equations: $\boxed{ds^2 = g_{\mu\nu} dx^\mu dx^\nu}$ $\boxed{G_{\mu\nu} = 8\pi G T_{\mu\nu}}$
- Any change in T_{ab} -> change in grav. field -> change in g_{ab}:

$$\boxed{g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}}$$

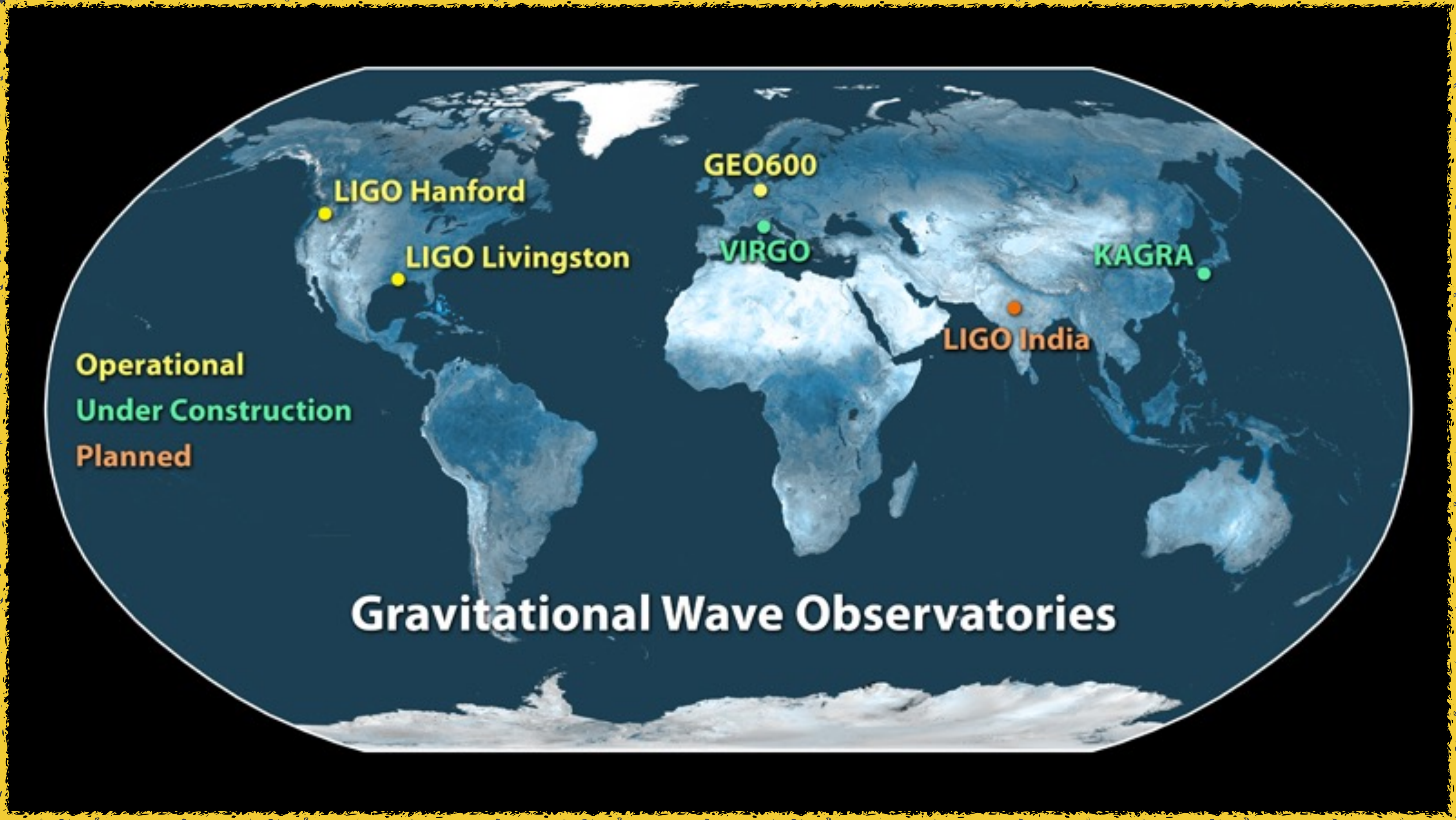
- Perturbations governed by wave equation: $\boxed{\partial_\lambda \partial^\lambda h_{\mu\nu} = 0}$
- Plane wave solution: $\boxed{h_{\mu\nu} = A^{\mu\nu} e^{i k_\alpha x^\alpha}}$

2 independent comp.

- Some properties: $\boxed{A_{\mu\nu}k^{\mu}=0}$ $\boxed{k^{a}k_{a}=0}$ → transverse waves-null vector
- Amplitude: $\boxed{A^{\mu\nu}=h_{+}e^{\mu\nu}{}_{+}+h_{X}e^{\mu\nu}{}_{X}}$ → two polarizations



- GWs: the lowest multipole allowed for radiation is the QUADRUPOLE (l=2).



Gravitational Wave Observatories

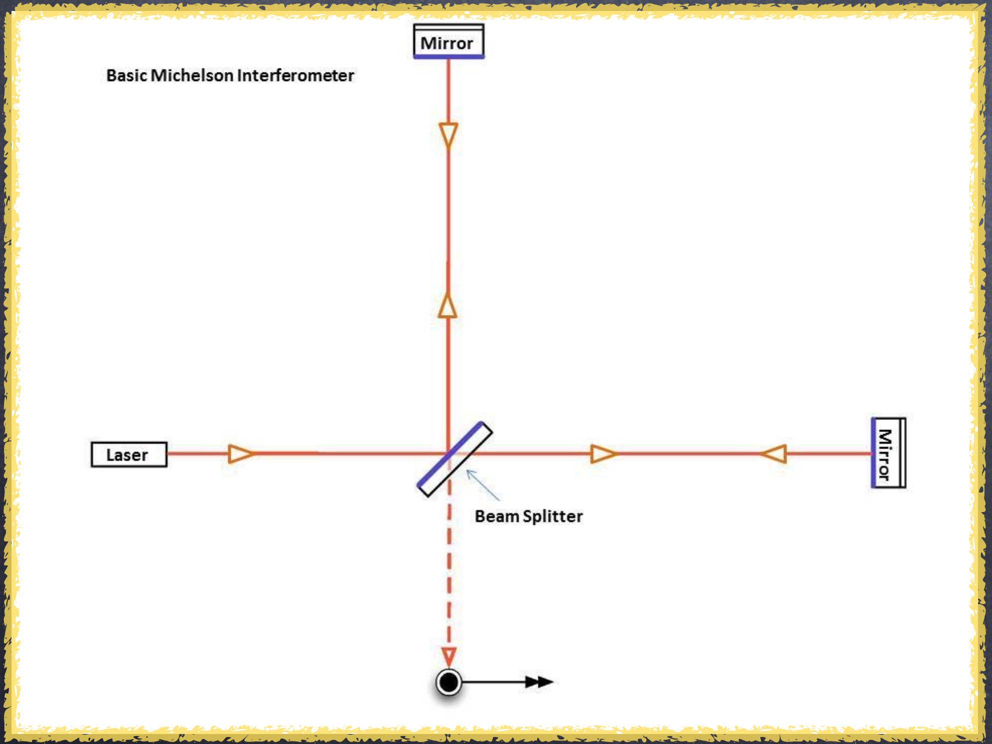
GWs detection by LIGO

(PRL 116, 061102 (2016))

- On September 14, 2015, the two LIGO detectors simultaneously observed a GW signal.

How do LIGO detect GWs?

- A GW has the effect of alternately stretching and squeezing the spatial separation between two points.
- High sensitivity needed -> Interferometers.
- L-shaped interferometer needed -> quadrupolar GW nature!



- When a gravitational wave passes by, the stretching and squashing of space causes the arms of the interferometer alternately to lengthen and shrink. As the interferometers' arms change lengths, the laser beams take a different time to travel through the arms -> interference pattern is produced.

- If the arm lengths are equal (L1 = L2), no light is transmitted to the photodetector.

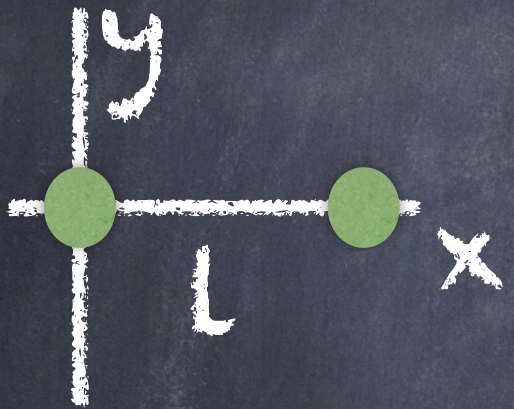
- Distance btw two events:

$$\boxed{ds^2 = g_{\mu\nu} dx^\mu dx^\nu}$$

$$\boxed{g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}}$$

$$\boxed{A^{\mu\nu} = h_+ e^{\mu\nu}{}_+ + h_X e^{\mu\nu}{}_X}$$

$$\boxed{h_{\mu\nu} = A^{\mu\nu} e^{ik_\alpha x^\alpha}}$$



$$\boxed{\begin{aligned} dl^2 &= g_{11} dx^2 \\ dl^2 &= (1 + h_{11}) l^2 = [1 + h_+ \cos(wt)] l^2 \\ dl &\approx [1 + \frac{1}{2} h_+ \cos(wt)] l \end{aligned}}$$

$$\boxed{dl = h(t) l}$$

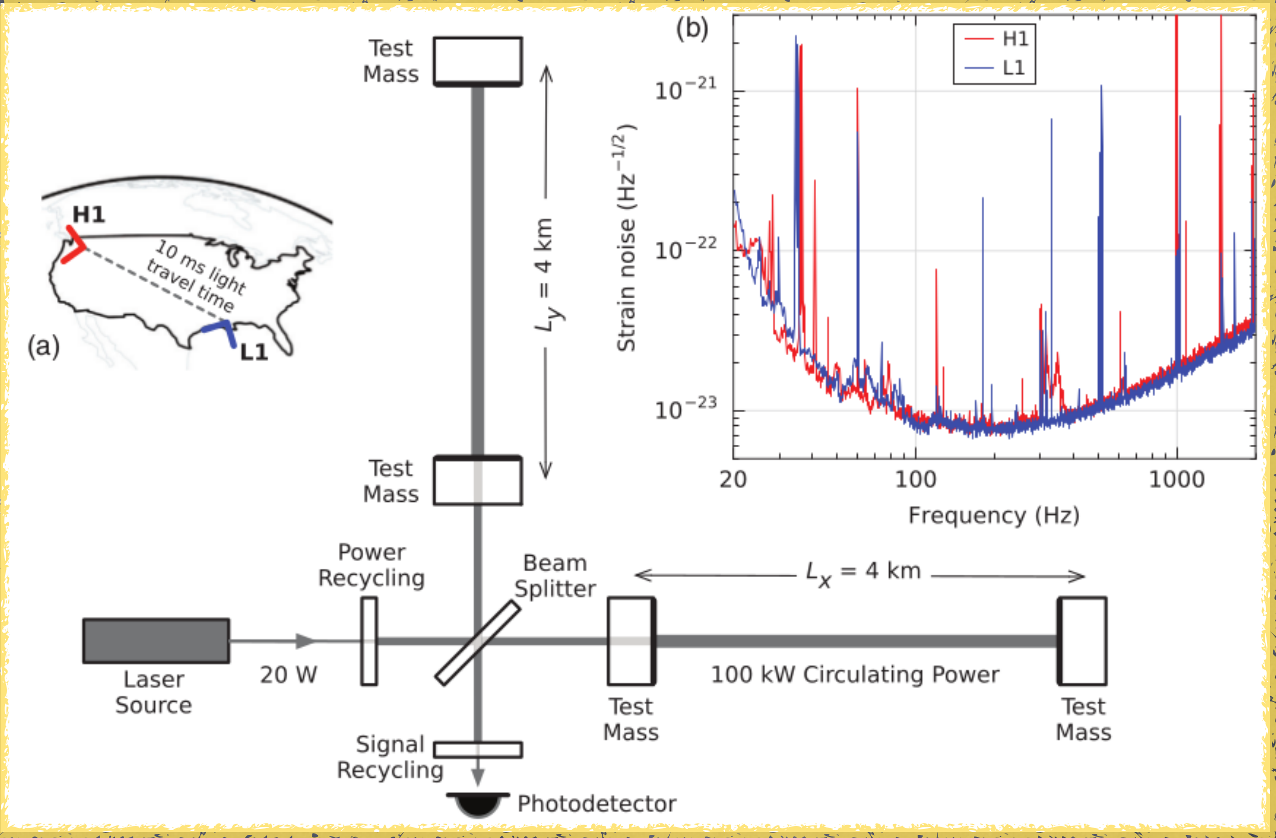
GW strain amplitude

- This differential length variation alters the phase difference between the two light fields returning to the beam splitter, transmitting an optical signal proportional to the gravitational wave strain to the photodetector.

How to obtain high sensitivity

$$\Delta L \approx 10^{-21} \times 4km = 4 \times 10^{-18} m!!$$

- Fabry-Perot resonant arm cavities magnify the phase shift by a factor equal to the average number of bounces (300) -> it's like making the arm longer!
- Power recycling mirror (20 W -> 700 W).



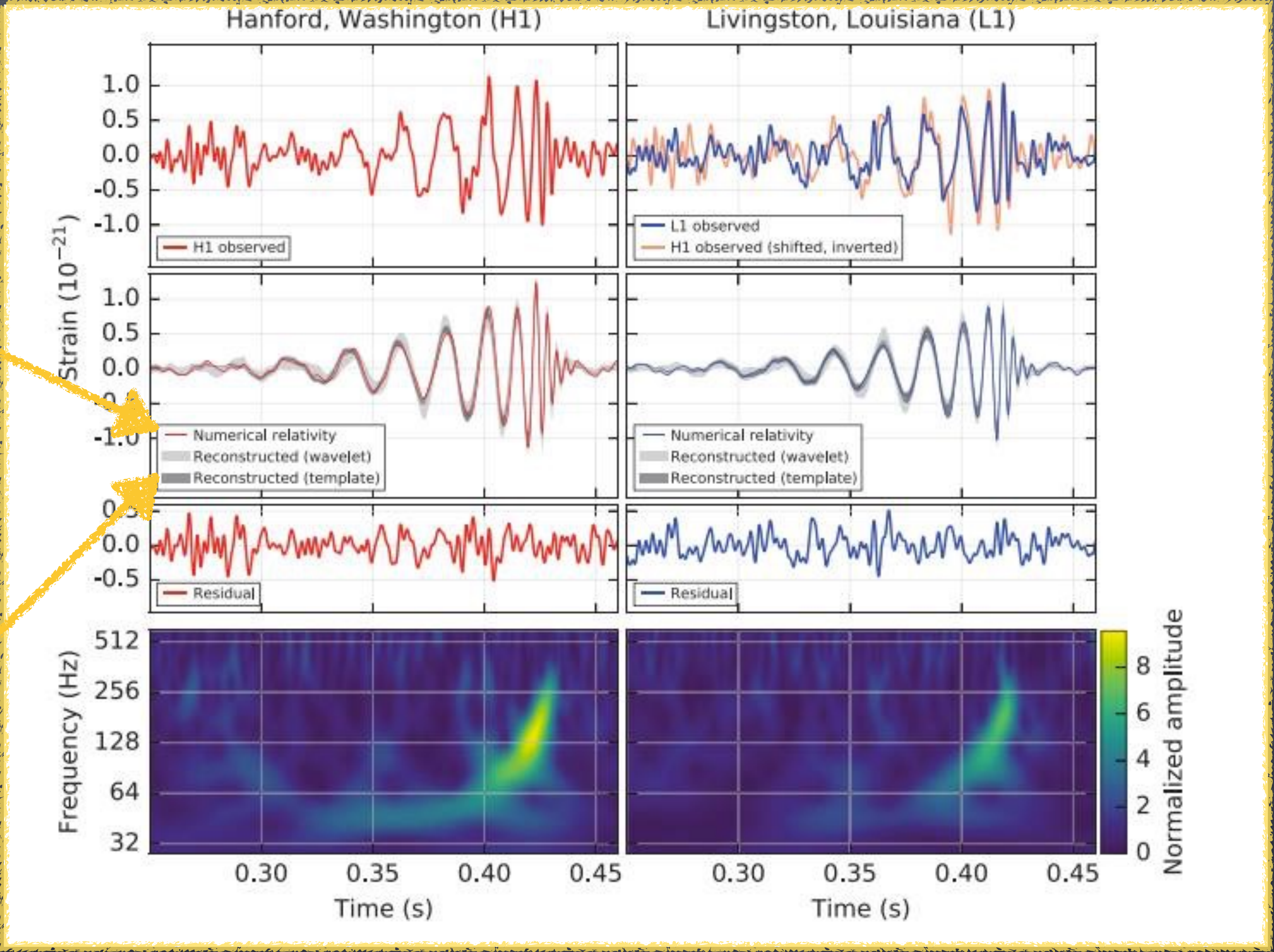
Noise:

- Seismic noise (low frequencies < 60Hz)
- Thermal noise (intermediate freq.)
- Photon shot noise (high freq. > 150 Hz)

Observation of GW150914

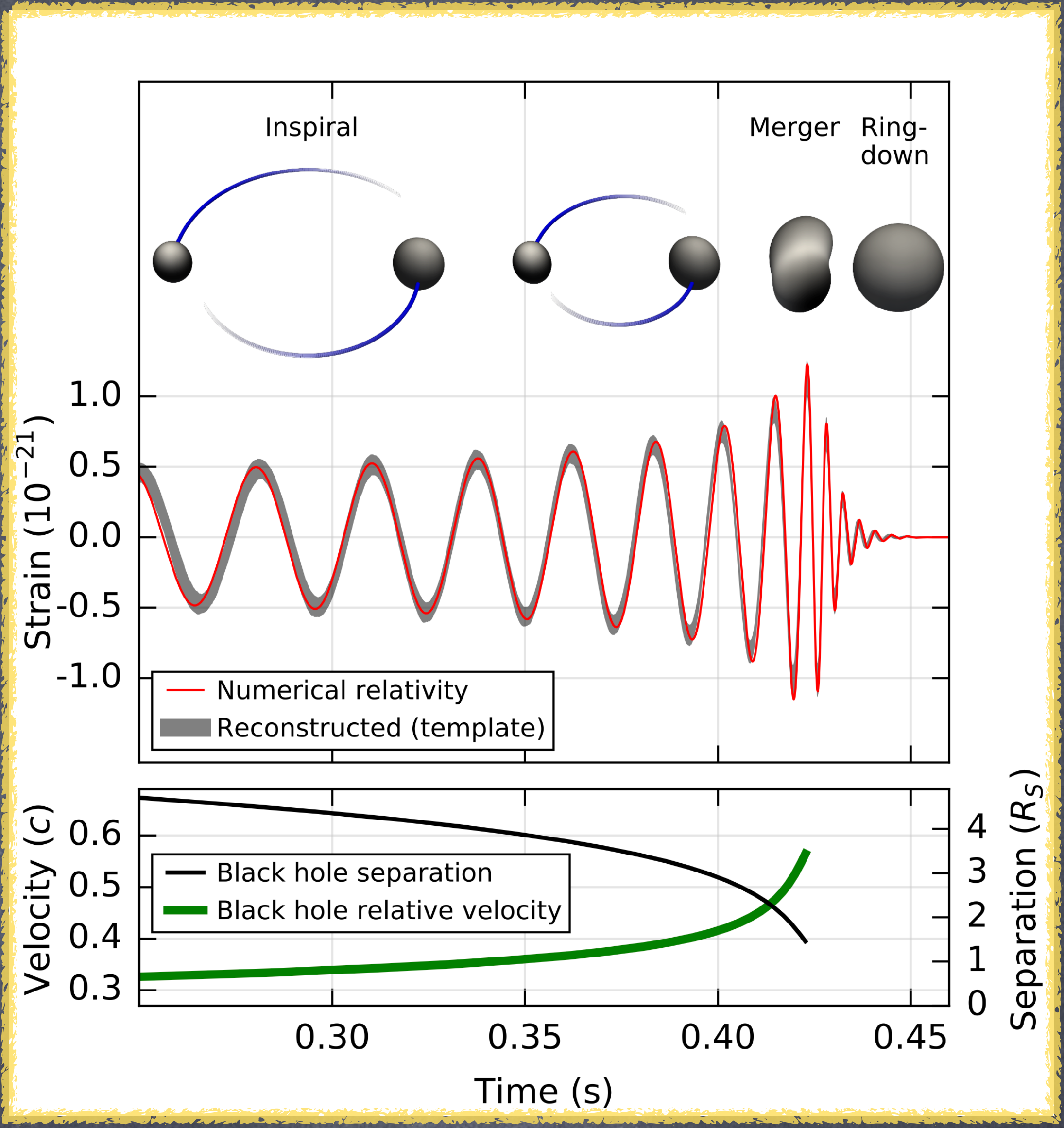
NR waveform for a system with parameters consistent with those recovered from GW150914

90% credible regions for two independent reconstructions



- Coincident signal: 10 ms intersite propagation time.

- The GW strain data acquired by LIGO is compared with lots of theoretically predicted waveforms - a process known as matched filtering - with the goal of finding the waveform that best matched the data.



Two black holes with 36 and 29 solar masses -> one black hole with 62 solar masses

36+29=65 -> 3 solar masses converted in gravitational waves energy!!

Searches

- GW150914 was detected by two different type of searches.

1. One recovers signals from the coalescence of compact objects using waveforms predicted by GR.
2. Targets generic transient signal, with minimal assumptions about the waveforms.

Both searches uses independent methods, with uncorrelated bckgr. events.

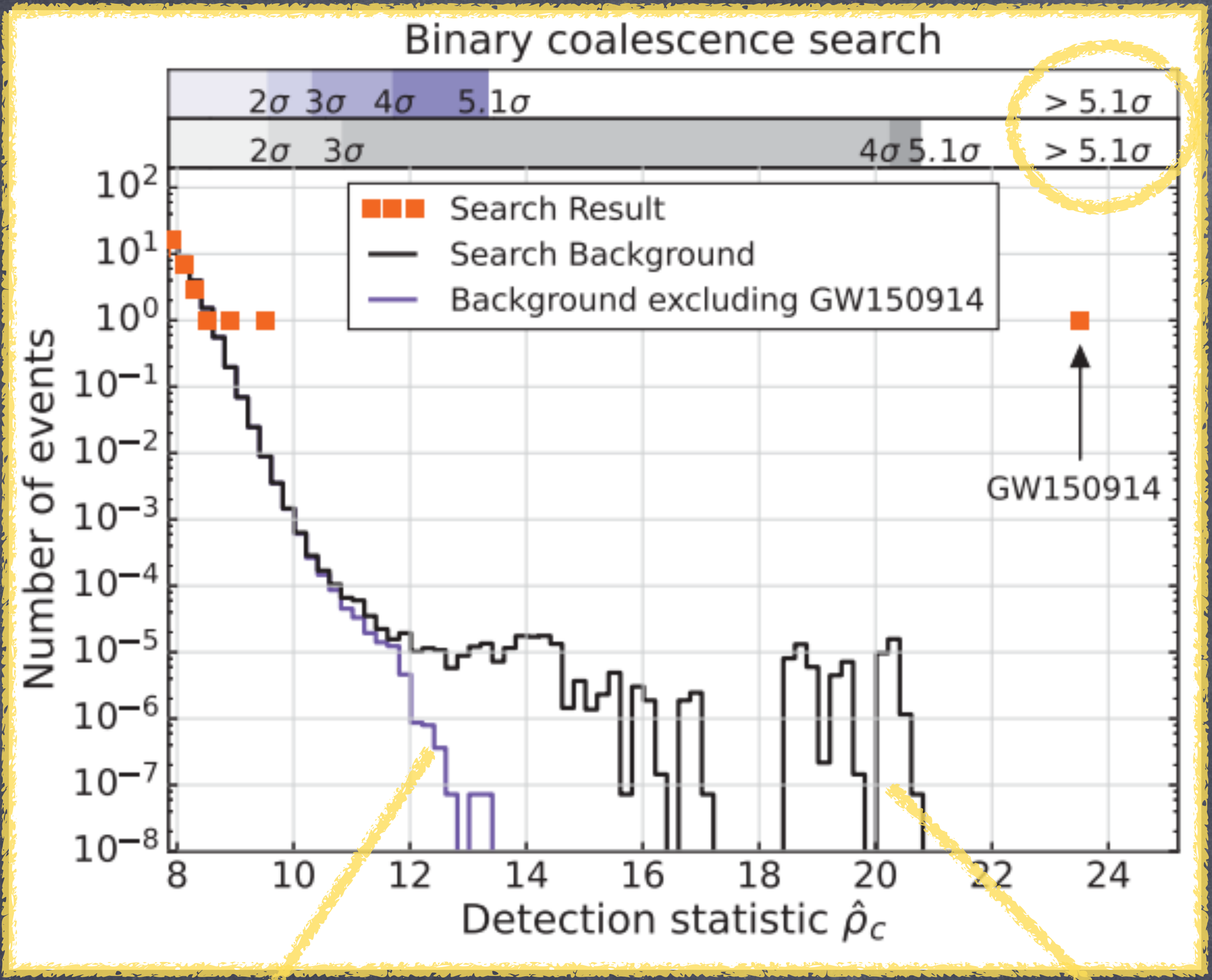
- Events are assigned a detection-statistic value that ranks their likelihood of being a GW signal.
- The significance of a candidate event is determine by the rate at which detector noise produces events with a detection-statistic value >= to the candidate event.

Background

- Estimating bckgr. is very challenging: nonstationary and non-gaussian.

- Introduce a series of artificial time shifts between the H1 and L1 data, creating a much longer data set in which to search for apparent signals that were as strong (or stronger) than GW1590914. By using time shifts greater than 10 milliseconds (the light travel time between the detectors) they ensured that these artificial data sets contained no real signals, but only coincidences in noise. Then they see how often a coincidence mimicking GW150914 appears. This analysis gives the false alarm rate: how often they could expect to measure such a seemingly loud event that was really just a noise fluctuation -> overstimation of the bckgr.

Binary coalescence search



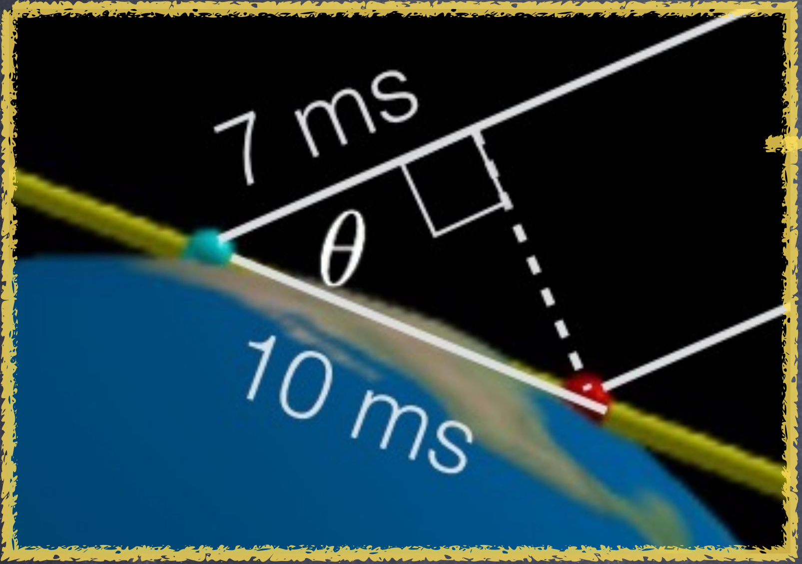
An event as strong as GW150914 is expected to appear by chance only once in about 200,000 years of data!!

Background excluding those coincidences (of the black curve tail)

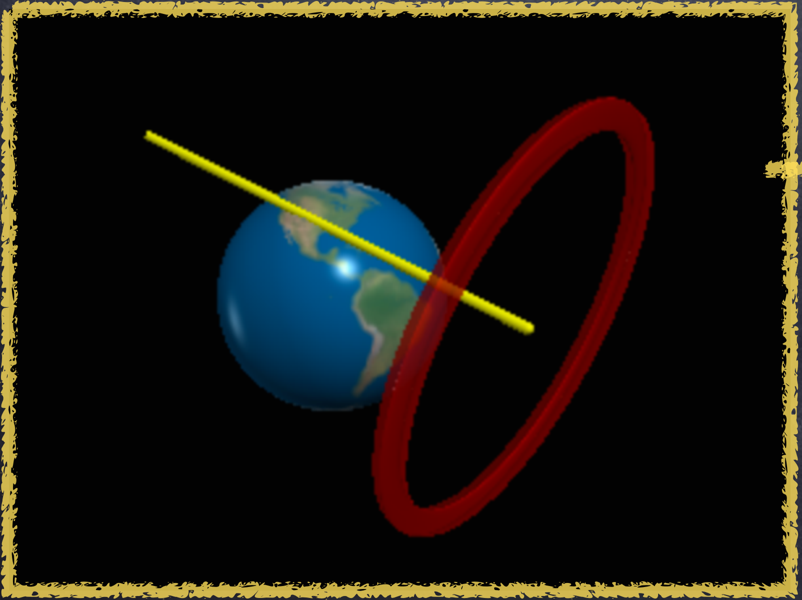
estimated coincidental noise "events". Tail: random coincidences of GW150914 in one detector and noise in the other.

How do they determine the direction of the event?

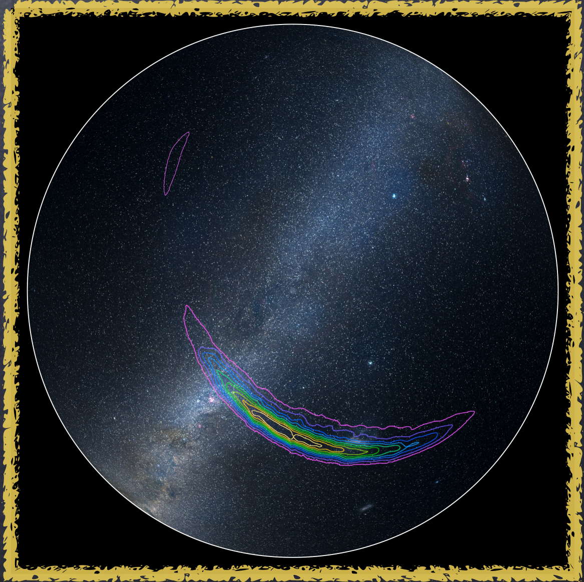
- With two detectors you can make sure they both have a signal.
- Using the difference in times for the two detectors, you can get an idea of what direction the gravitational wave came from.



If a gravitational wave traveled along the yellow line, the difference in time would be 10 ms due to the distance WA-LA. The measured time difference for the detected gravitational wave was about 7 ms.



There are an infinite number of points that would give this time difference. However, those points are confined to a ring with angle tetha.



Conclusions

- Two predictions of Einstein's theory were confirmed:

1. First direct detection of gravitational waves.
2. First observation of a binary black hole merger.

- The detected waveform matches the prediction of general relativity.

Thanks for your attention!