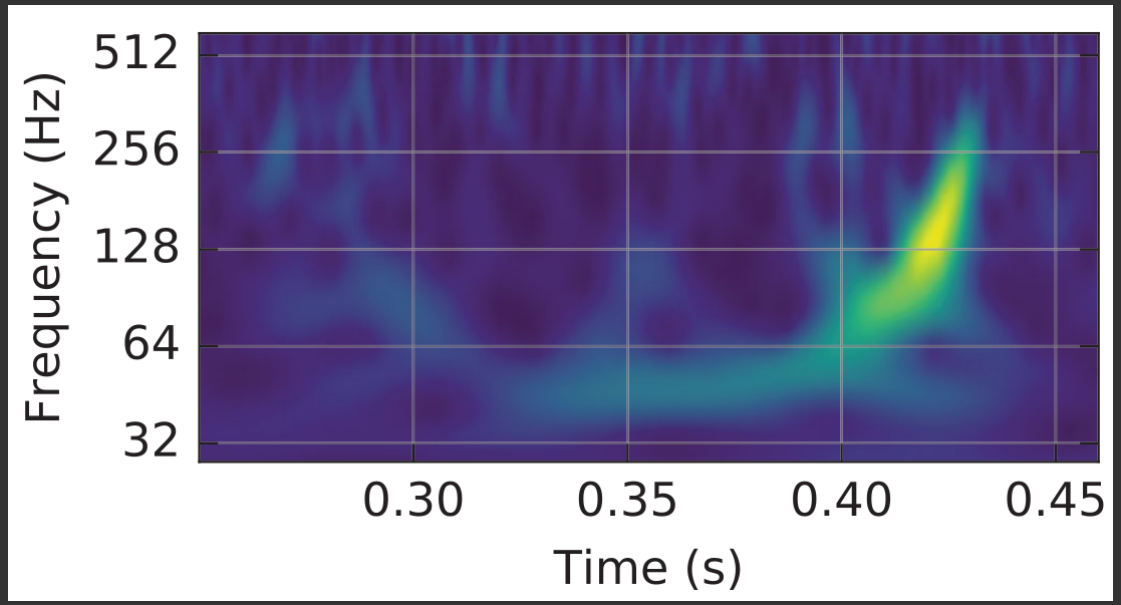
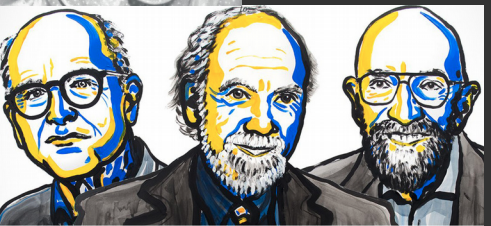
The 100 Year Journey to GW170817





Mohammed Chamma
Nov 2nd 2017

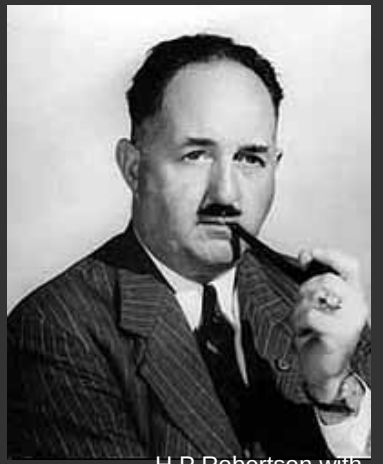
Outline

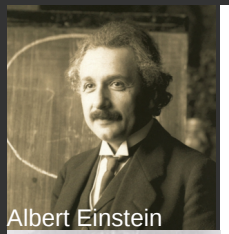
- Are gravitational waves measurable? (1916-1974)
  - Einstein+Rosen
  - Chapel Conference
  - Hulse-Taylor Binary
- The LIGO Project
- Design, Sensitivity, Calibration and Validation of LIGO
- First Direct Detection of Gravitational Waves: GW150914
  - Chirp Mass
  - Search Algorithms
- Summary+References

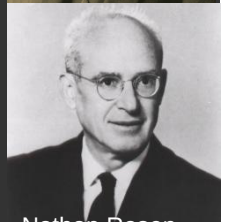
Einsten and Rosen (1916-1936)

- Einstein predicted gravitational waves, then unpredicted them with Nathan Rosen: gravitational waves are mathematical artifacts and carry no energy (1936)
- Submitted to a smaller journal when Einstein was hit with referee comments and never submitted to *Physical Review* again. Peer review was new to Einstein.
- H.P. Robertson was the anonymous reviewer and ultimately correct.
- Einstein eventually changed the conclusions of the paper, Rosen did not agree even into the 1970s.

"Together with a young collaborator, I arrived at the interesting result that gravitational waves do not exist, though they had been assumed a certainty to the first approximation. This shows that the nonlinear field equations can show us more, or rather limit us more, than we have believed up till now."
- Albert Einstein to Max Born


H.P Robertson with his magnificent pipe


Albert Einstein


Nathan Rosen

Dear Sir,

We (Mr. Rosen and I) had sent you our manuscript for publication and had not authorized you to show it to specialists before it is printed. I see no reason to address the—in any case erroneous—comments of your anonymous expert. On the basis of this incident I prefer to publish the paper elsewhere.

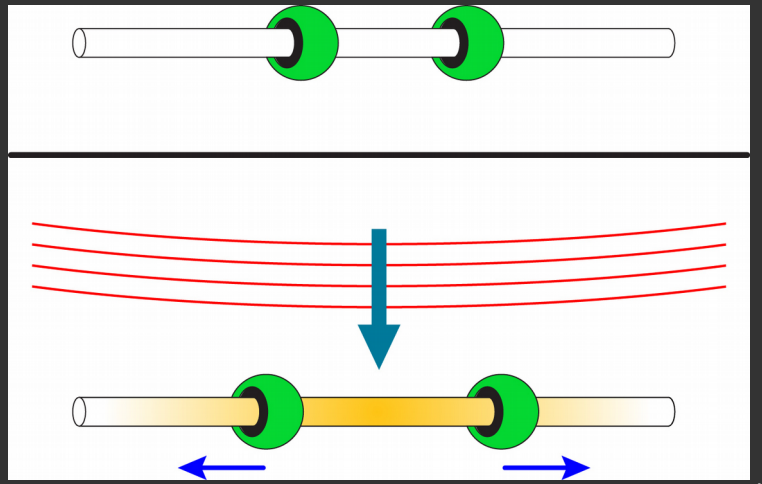
Respectfully,

P.S. Mr. Rosen, who has left for the Soviet Union, has authorized me to represent him in this matter.

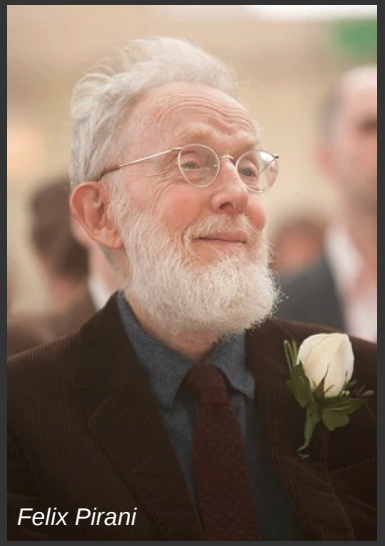
The Chapel Hill Conference (1957)

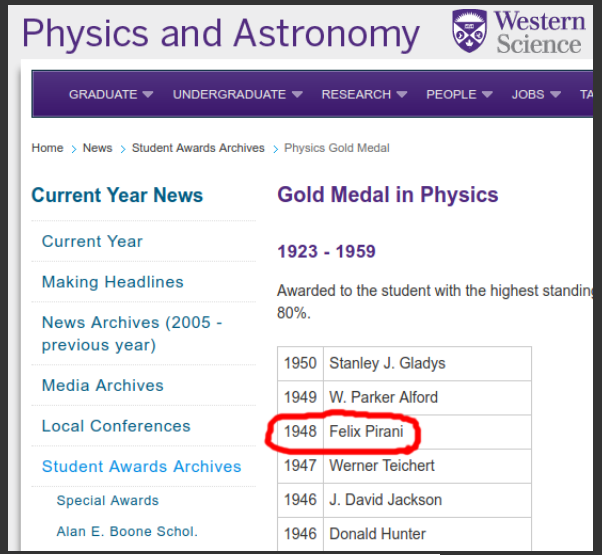
- **First Conference on Gravitation:** *The Role of Gravitation in Physics* – arranged by Cécile DeWitt
  - Invite-only: attendees included J. Wheeler, R. Feynman, F. Pirani, H. Bondi, N. Rosen
  - Transcripts and proceedings available online
  - Largely concerned with quantizing gravity: gravitational waves could mean gravitons
- **Sticky Bead Argument:**
  - Thought experiment mentioned by Richard Feynman, expressed mathematically by Felix Pirani's work
  - A wave passing through a rod with beads on it will move the beads, heating the rod. So the gravitational wave must have energy.
  - Atomic forces in the rod resist the influence of the wave


Chapel Hill, North Carolina



The Chapel Hill Conference (1957): Impact


Felix Pirani



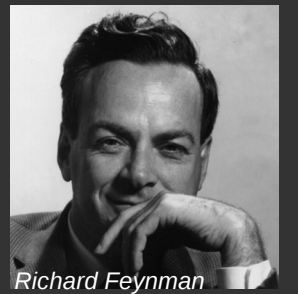
- **Several papers immediately published :**

Gravitational waves in general relativity
III. Exact plane waves

By H. Bondi* and F. A. E. Pirani†
King's College, London
and I. Robinson
Lately of University College of Wales, Aberystwyth

Reality of the Cylindrical Gravitational Waves of Einstein and Rosen

Joseph Weber, *Lorentz Institute, University of Leiden, Leiden, Netherlands, and University of Maryland, College Park, Maryland*
and
John A. Wheeler, *Lorentz Institute, University of Leiden, Leiden, Netherlands, and Palmer Physical Laboratory, Princeton University, Princeton, New Jersey*


Richard Feynman


John Wheeler
Kip Thorne

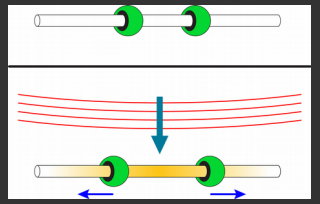
The question of the absorption and production of gravitational waves was raised again. FEYNMAN discussed a device which would absorb gravitational energy, provided one assumes the existence of gravitational radiation (but as he pointed out, "My instincts are that if you can feel it, you can make it."). For this purpose one can use a result already presented at an earlier session that the displacement η of a particle in the path of a gravitational wave satisfies the differential equation

$$\frac{d^2\eta}{dt^2} = R^a_{0ba}\eta.$$

A particle situated initially near a long light rod, oriented parallel to the propagation direction, could be made to scrape against the rod by the transverse-transverse wave amplitudes.

Report from the 1957 Chapel Hill Conference

- The sticky bead argument and ensuing literature convince physicists – except for N. Rosen
- John A. Wheeler was the doctoral advisor of **Kip Thorne** who would later co-found the LIGO Project

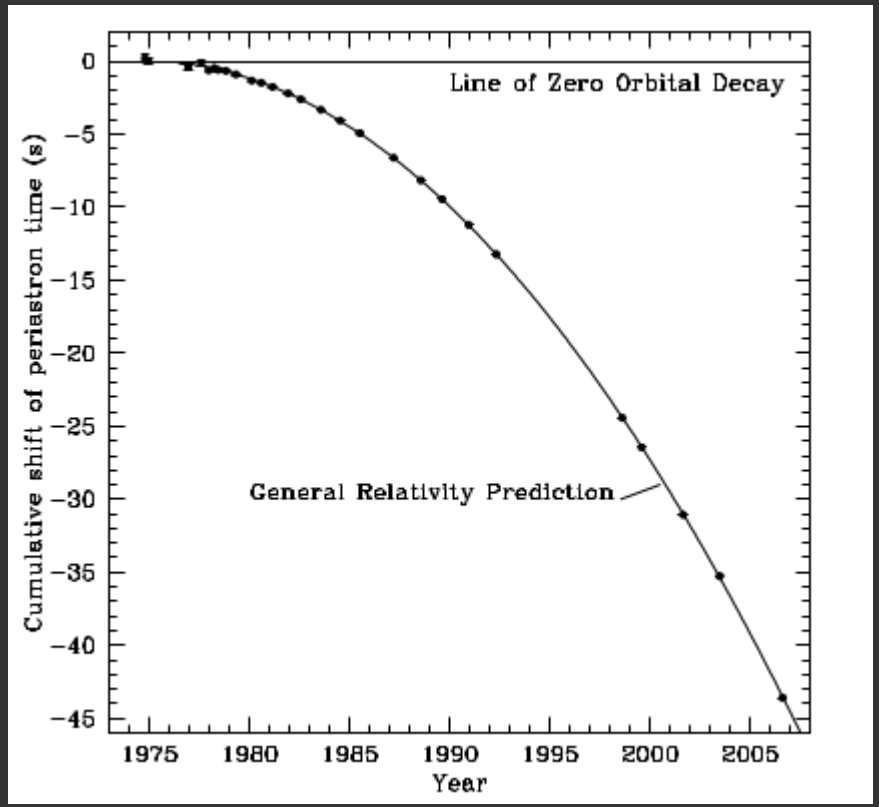



Cécile M. DeWitt

First Indirect Evidence: Hulse-Taylor Binary (1974)

- **Pulsar orbitting another Neutron Star**
  - Pulses every 59ms, with a systematic variation that repeated evs every 7.75 hours
  - The 7.75hr period decreases slightly over time
  - This is explained as orbital energy being emitted by gravitational waves
  - Will collide in 300 million years
  - Nobel Prize 1993

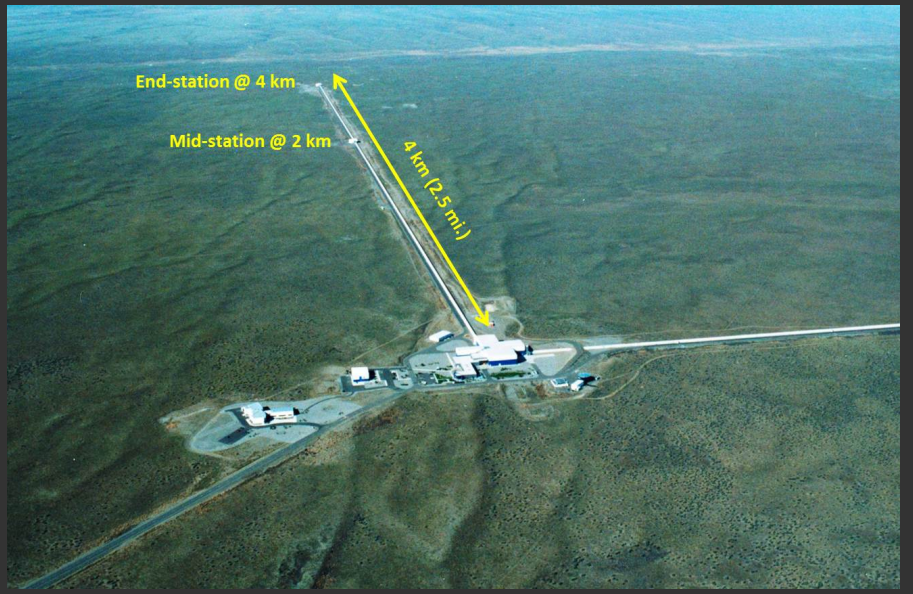
Arecibo: 305m radio dish in Puerto Rico used to make the observations



The LIGO Project

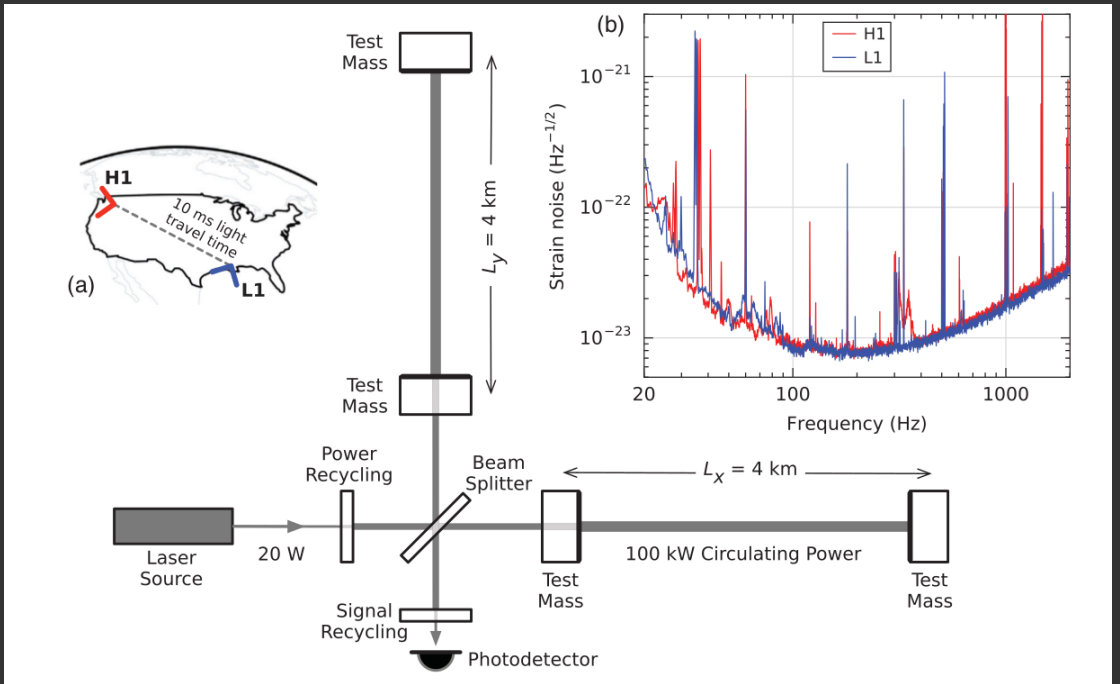
- **Founded in 1984**
  - Based on theoretical work and designs by Kip Thorne and Rainer Weiss
  - Plagued by no progress. NSF threatens to pull funding. Lab directors fired and replaced by Barry Barish in 1994
  - Full design sensitivity in 2020
- **Detections**
  - All detections have been mergers of compact objects (black holes, neutron stars)
  - The most recent detection was the first to have follow-up in other wavelengths: a huge amount of new information

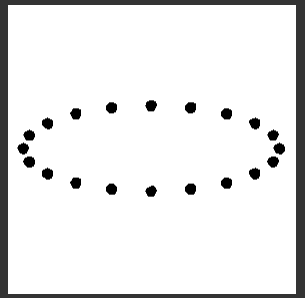
Detections (GWYYMMDD)	**Type**
GW150914	Black Hole Merger
GW151226	Black Hole Merger
GW170104	Black Hole Merger
GW170814 w/ Virgo	Black Hole Merger
GW170817 w/ *everything*	Neutron Star Merger



LIGO Design

- **Michelson Interferometer with extra steps:**
  - If the path length of the laser light changes, a dimming/brightening is observed at the photodetector
  - Huge suspended mirrors are nudged by gravitational waves
  - Problem: Huge suspended mirrors are nudged by pretty much everything else too





Effect of transverse-transverse waves on a ring of test particls

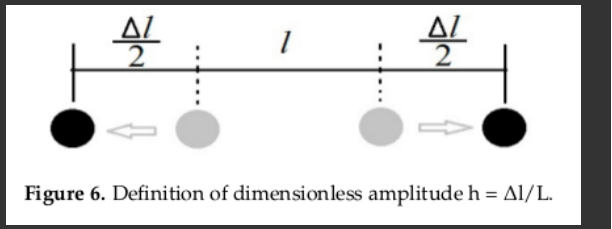
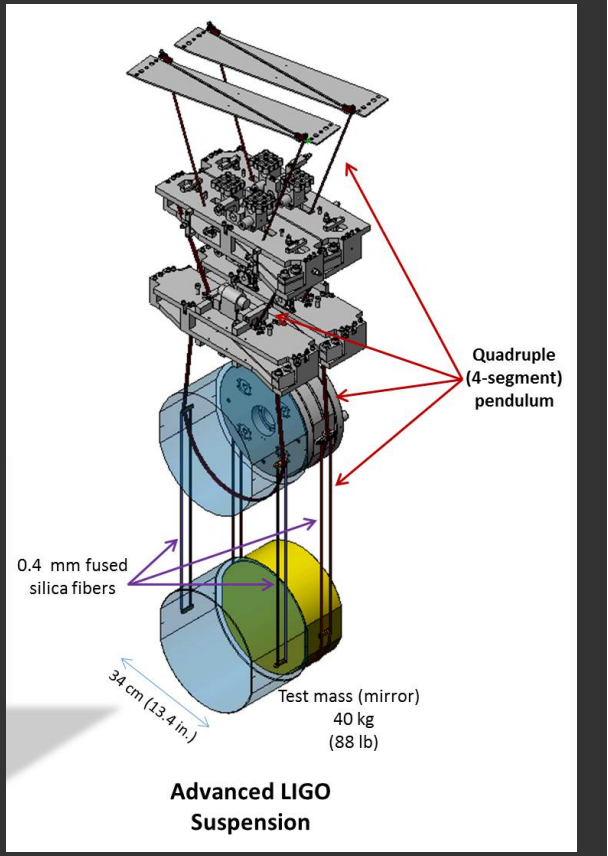
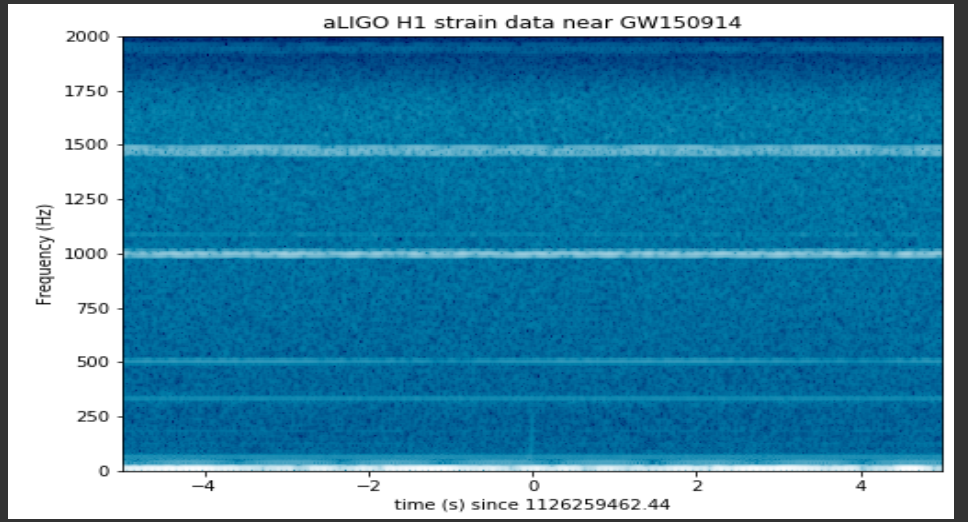


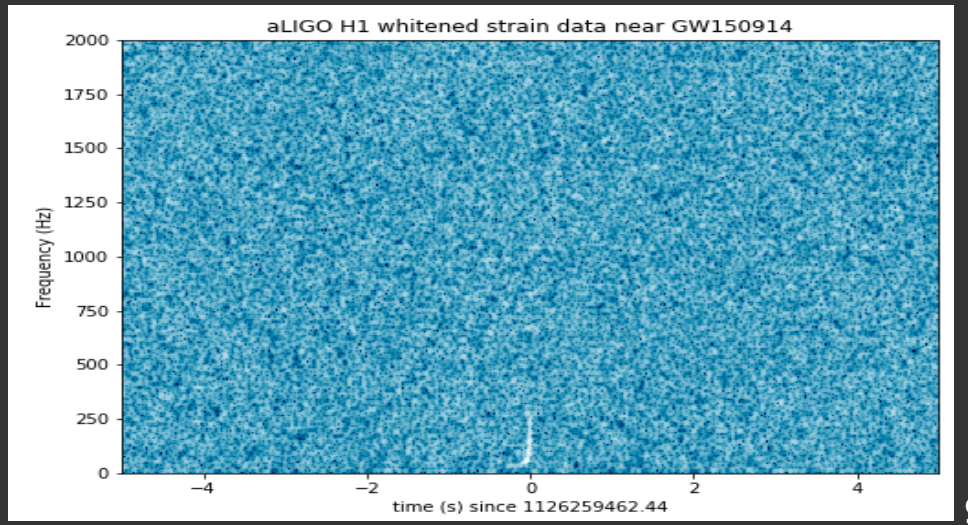
Figure 6. Definition of dimensionless amplitude h = Δl/L.



LIGO Sensitivity

- **Crazy:**
  - Can measure changes in length equivalent to 1/10000th the width of a proton
  - As sensitive as if the distance from the sun to Proxima Centauri changed by the width of a hair!
- Source of Noise:
  - Weather, traffic, sound, AC power lines, cosmic rays, literally anything
  - Detectors are equipped with seismometers, accelerometers, microphones, magnetometers, radio receivers, weather sensors, AC-power line monitors and cosmic-ray detectors.
  - These detectors feed into the stability pendulum to actively reduce noise





LIGO Calibration and Validation

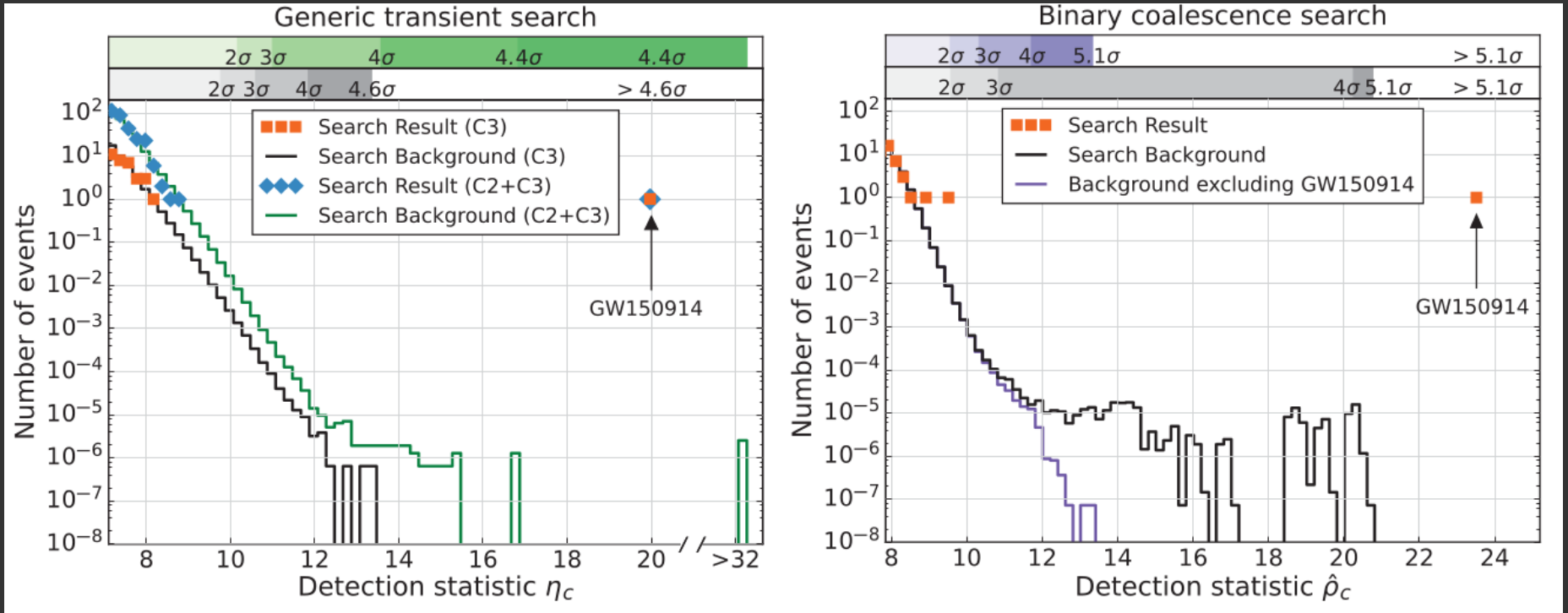
- An “event” is a signal detected at both detectors within 10ms –the intersite propagation time
  - Data from both sites are timestamped using GPS and atomic clocks
- The photodetector response to strain is calibrated by injecting a known laser pulse: the radiation pressure is enough to move the mirrors
- Impossible to measure true background since no way to shield from GWs
  - Instead background is estimated by time-shifting (by >10ms) the data from both detectors and counting the number of fake events
  - The count of fake events in time-shifted data is an estimate of false events in data that is correctly lined up.
- Events are ranked based on how strongly the waveforms correlate:

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

Ec: Energy of cross-correlated waveforms
En: Noise energy

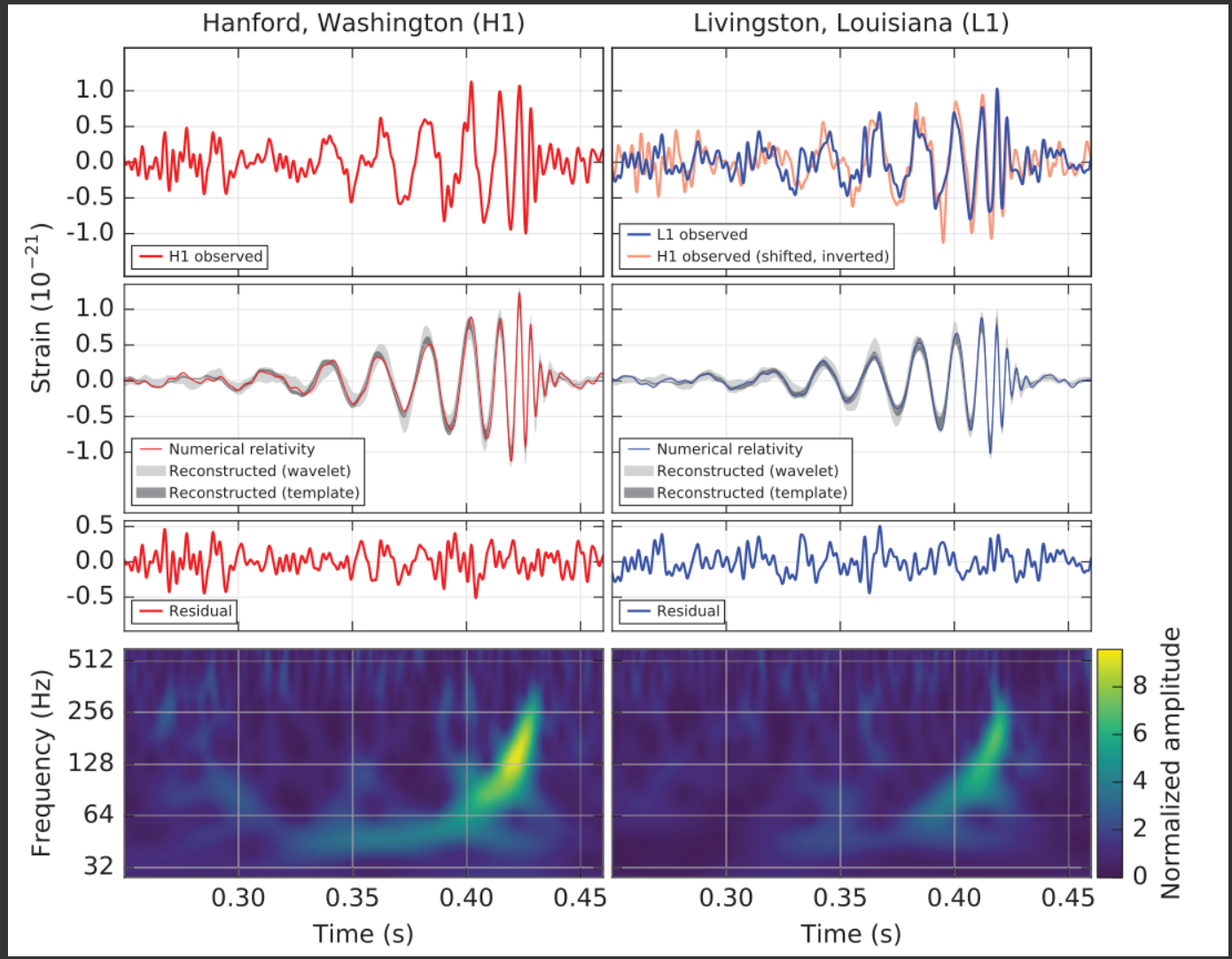
LIGO: Searching for Events

- **Generic Transient Search:**
  - Ignorant of waveforms, searches for short signal spikes of any kind
- **Binary Coalescence Search:**
  - Events are matched against 250,000 waveform templates from numerical general relativity



GW150914

- First announced detection
- Black Hole Merger:
  - Primary: 36 M⊙
  - Seconday: 29 M⊙
  - Final Mass: 62 M⊙
  - GW Energy: 3 M⊙
- Arrived at Hanford 6.9ms after Livingston



Chirp Mass: GW150914

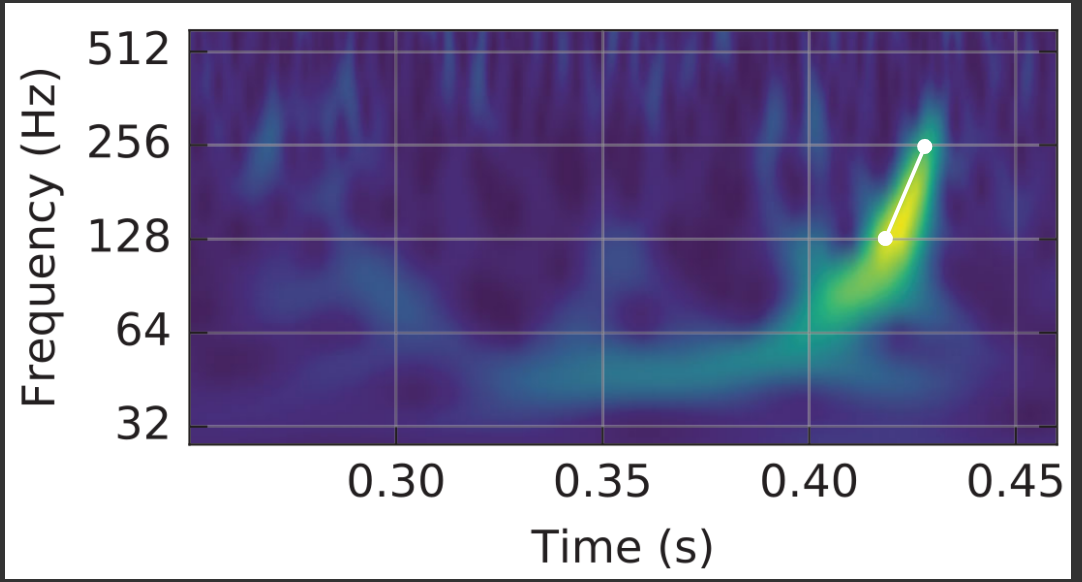
- The gravitational wave depends on the mass of the two components. Measuring frequency and the change in frequency of the wave gives an estimate of the total mass: **chirp mass**

$$M_{ch} = \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5}$$

- GW150914 had a chirp mass of 30 M⊙

$$M_T \geq 4^{3/5} M_{ch} \approx 2.3 M_{ch}$$

- Eyeball:
  - f = 150Hz
  - df/dt = 128Hz / 0.01s
  - Gives total mass of 63 M⊙ –not bad!



To get mass of components you need to model the waveform

Summary

- After general relativity there was much debate about the existence of gravitational waves – debate that was resolved by the Chapel Hill Conference and the Hulse+Taylor discovery
- LIGO is insane: extremely sensitive, robust suite of enviromental sensors and algorithms for validating events
- The first multi-wavelength observation (GW170817) of a gravitational wave event gives a huge amount of information for study
- When full design sensitivity is reached in 2020 LIGO will be sensitive enough to study deviations in waveforms from general relativity: new theory of gravity?

References

- These slides: https://github.com/mef51/LIGOSeminar/raw/master/ligo_talk.pdf
- Chirp Mass: http://theoretical-physics-digest.wikia.com/wiki/Chirp_Mass
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- J.L. Cervantes-Cota et al. A Brief History of Gravitational Waves. Universe 2016, 2(3), 22. http://www.mdpi.com/2218-1997/2/3/22