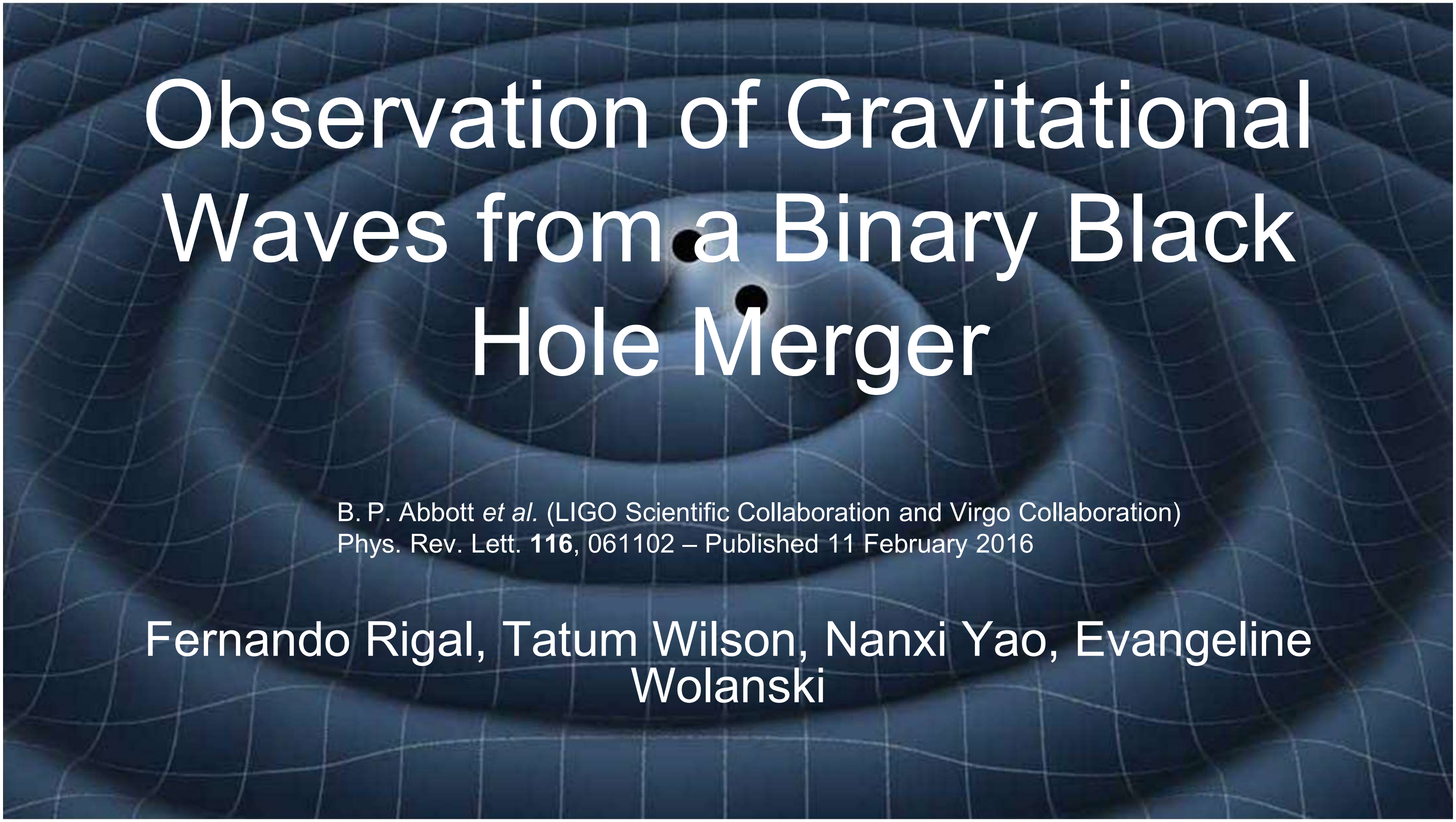

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration)
Phys. Rev. Lett. **116**, 061102 – Published 11 February 2016

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Outline

- Background
  - Einstein Field Equations
  - LIGO/VIRGO Detector
- Results
- Result Analysis
- Citation Analysis

Black Hole Merger

Einstein’s Field Equation Describes How The Curvature of Spacetime Affects Mass and Energy

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} - g_{\mu\nu}\Lambda = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Ricci Scalar

Metric Tensor

Stress-Energy-Momentum Tensor

Ricci Curvature Tensor

Cosmological Constant

[1] A. Einstein, Sitzungsber. K. Preuss. Akad. Wiss. 1, 688 (1916).

Brief Description of Tensor Terms in the Field Equations

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} - g_{\mu\nu}\Lambda = \frac{8\pi G}{c^4}T_{\mu\nu}$$

Metric Tensor

- Matrix that encodes all the information regarding distances between points within a specific manifold.

- **Example:** For Euclidean spacetime, the minkowski tensor is given.

$$\eta_{\mu\nu} = \begin{bmatrix} -c^2 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$R_{\alpha\mu\beta\nu} = R_{\beta\nu\alpha\mu}$$

$$g^{\alpha\lambda} R_{\alpha\mu\beta\nu} = g^{\alpha\lambda} R_{\beta\nu\alpha\mu}$$

$$R^{\lambda}{}_{\mu\beta\nu} = R_{\beta\nu}{}^{\lambda}{}_{\mu}$$

$$\boxed{R_{\mu\nu} = R_{\nu\mu}}$$

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} - g_{\mu\nu}\Lambda = \frac{8\pi G}{c^4} T_{\mu\nu}$$

<u>Ricci Curvature Tensor</u>

- Physically, it measures how much a volume changes in curved space compared to flat space.

<u>Ricci Curvature Scalar</u>

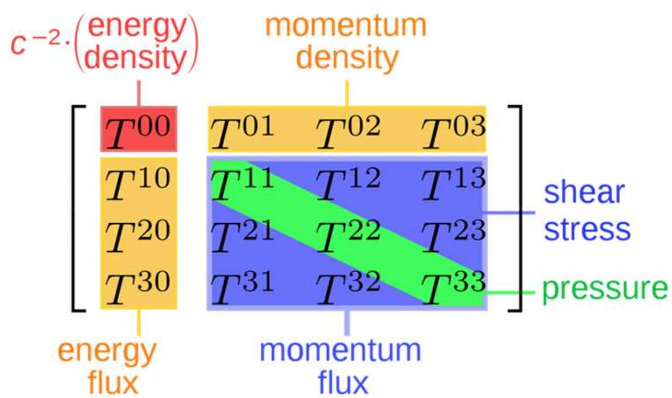
- Scalar that describes curvature.
- Contract the Ricci Tensor

$$R = g^{\mu\nu} R_{\mu\nu} = R^{\mu}{}_{\mu} = R$$

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} - g_{\mu\nu}\Lambda = \frac{8\pi G}{c^4}T_{\mu\nu}$$

Stress-Energy Tensor

- Describes the density and flux of energy and momentum in spacetime.

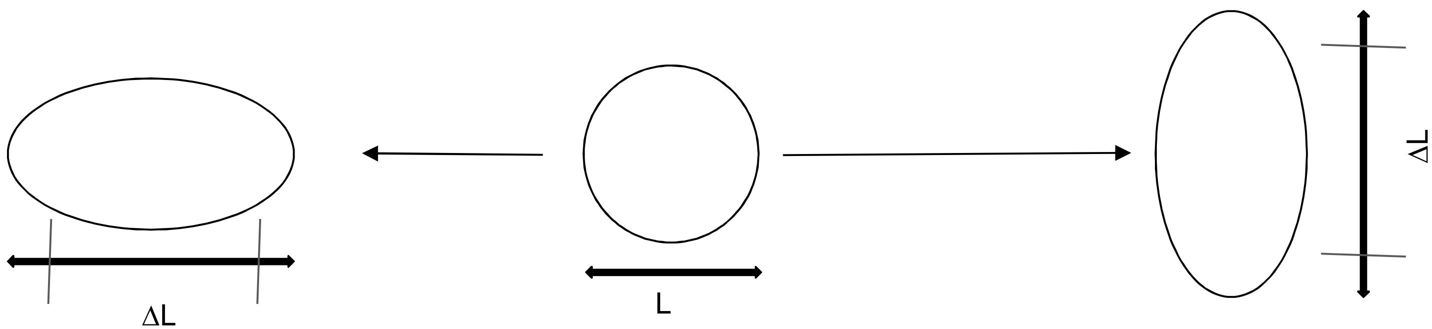


How to get gravitational waves?

- Linearize the field equation using a minkowski-like metric.

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

Gravitational Waves Stretch and Squeeze The Distance Between Objects.



- Strain is defined as the change in length over the length and it is a measure of the strength of the gravitational wave.

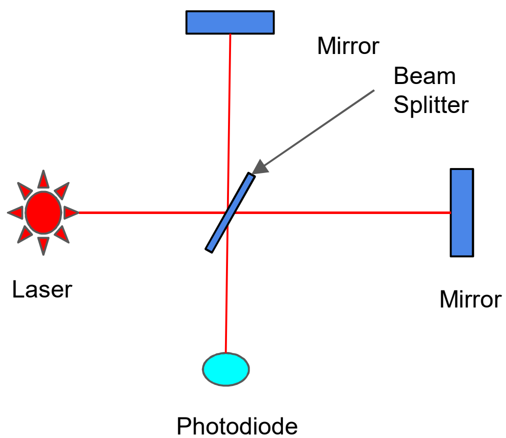
$$h(t) = \frac{\Delta L}{L}$$

- Typical strain value for astrophysical events is of the order 10^-21.

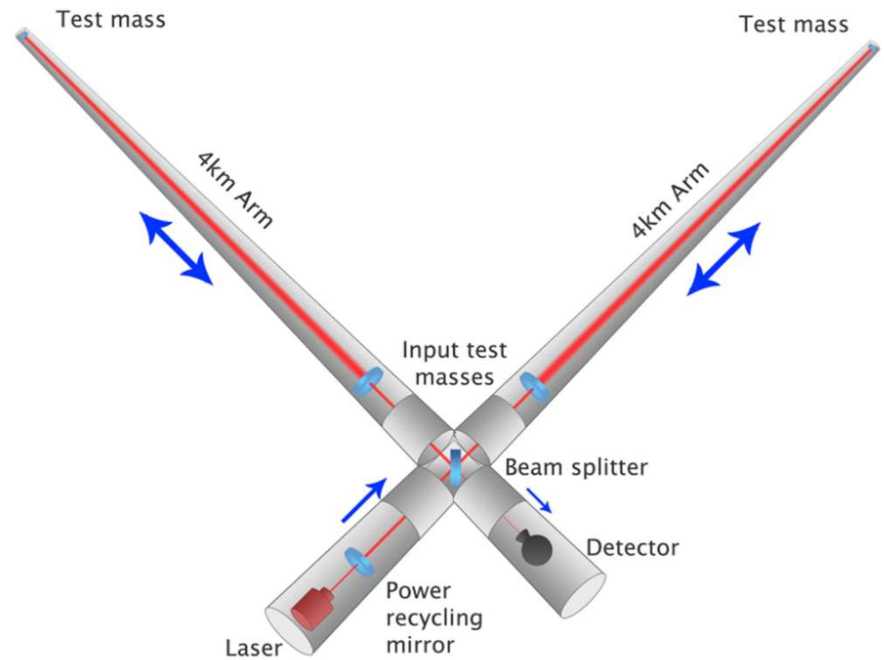
$$h \sim 10^{-21}$$

LIGO/VIRGO Detector

Michelson Interferometer



Scale it up!



Laser Wavelength ~ 1 μm

Previous Discoveries

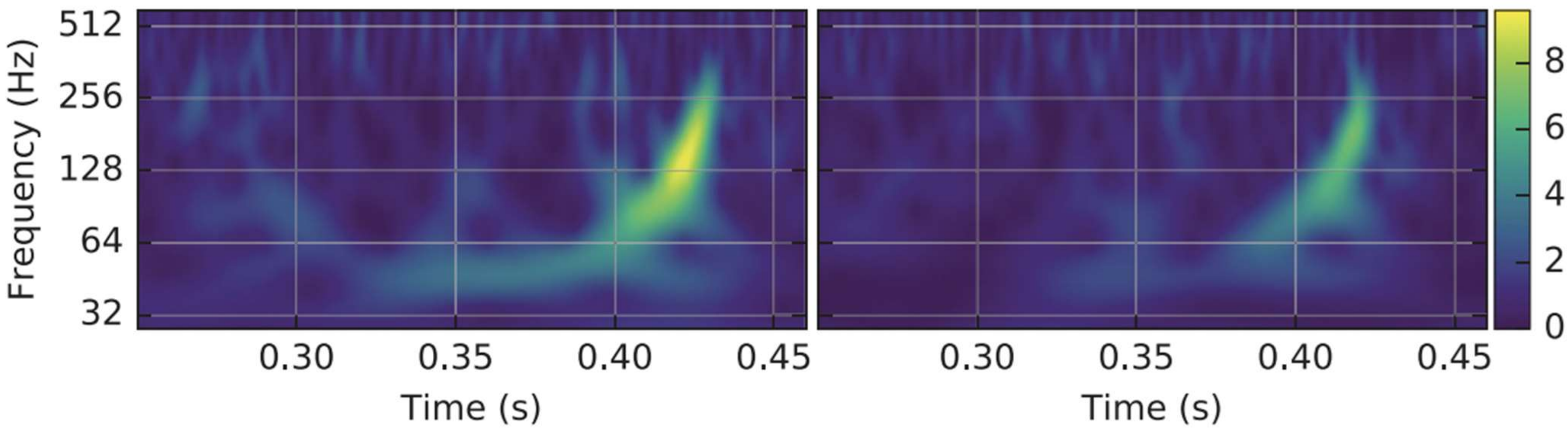
- Theoretical predictions of gravitational waves and black holes ([1],[2])

- Indirect evidences
  - observation of binary pulsar system PSR B1913þ16 by Hulse and Taylor [3].
  - Subsequent observations of energy loss[4].

- Black hole mergers had not been observed before

[1] A. Einstein, Sitzungsber. K. Preuss. Akad. Wiss. 1, 688 (1916).
[2] A. Einstein, Sitzungsber. K. Preuss. Akad. Wiss. 1, 154 (1918).
[3] K. Schwarzschild, Sitzungsber. K. Preuss. Akad. Wiss. 1, 189 (1916)
[4]J. H. Taylor and J. M. Weisberg, Astrophys. J. 253, 908 (1982).

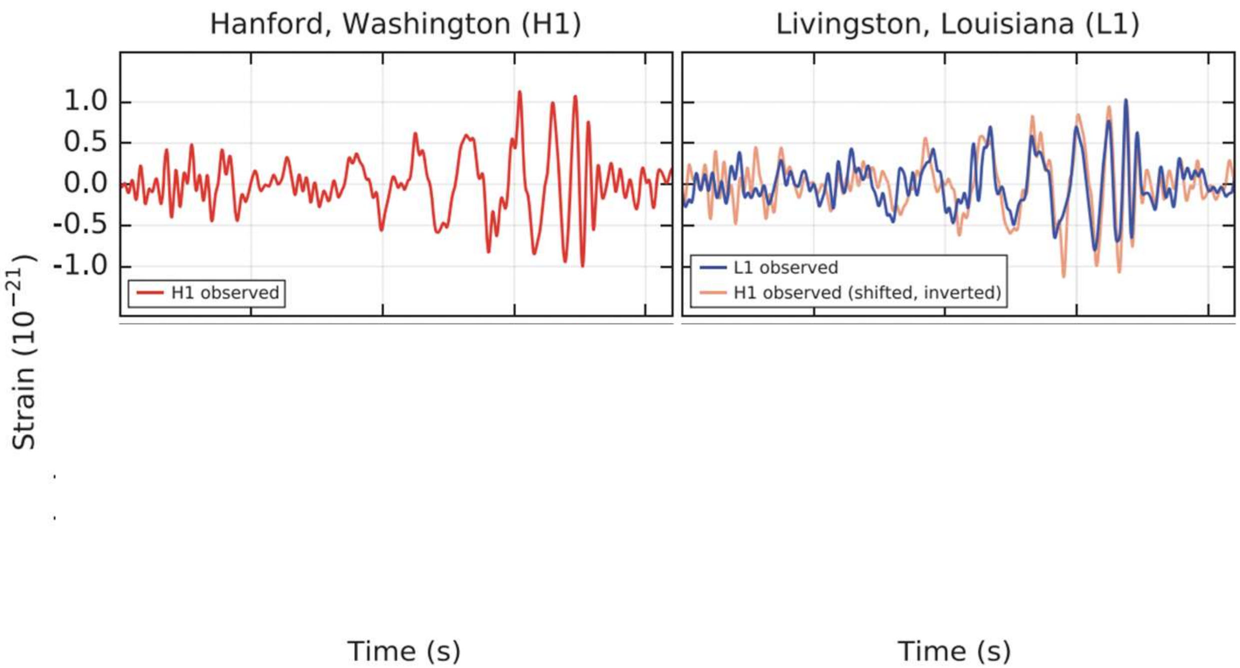
Initial Observation of Gravitational Waves



By B. P. Abbott et al.,2016,Phys. Rev. Lett.116.0611

- Confirms the propagation speed of gravitational waves - speed of light
- Only run through a digital filter - very minimal
- Both frequency and amplitude increase - chirp signal of two compact objects and then ring down to a final object at the end

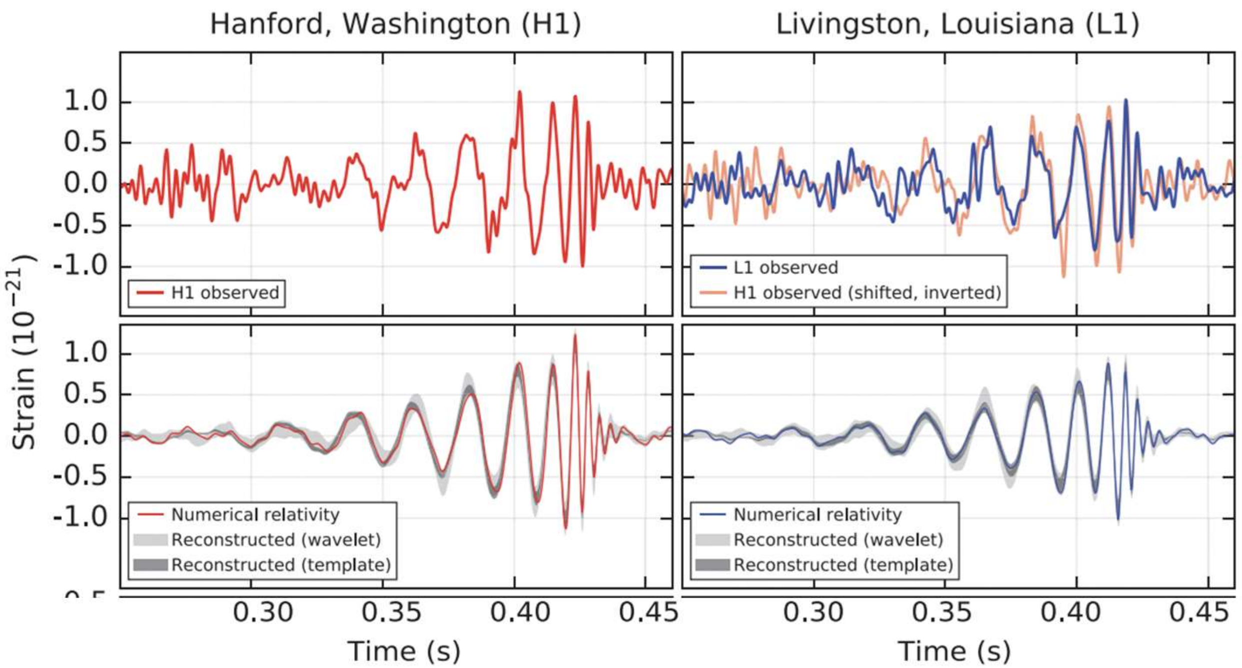
Processing and Validation of Signal GW150914



By B. P. Abbott et al.,2016,Phys. Rev. Lett.116.061102

- Coincident chirp inspiral merger ring down signal.
- Second row: Gravitational-wave strain projected onto each detector in the 35–350 Hz band.

Processing and Validation of Signal GW150914



By B. P. Abbott et al.,2016,Phys. Rev. Lett.116.061102

- Coincident chirp inspiral merger ring down signal.
- Second row: Gravitational-wave strain projected onto each detector in the 35–350 Hz band.

What does the signal tell us?

- Over 2 secs, frequency increases in 8 cycles from 35 Hz to 150 HZ.
- Then we can measure Chirp mass from f, observed frequency, and its timederivative

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} = \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5}$$

  - Chirp mass M $\simeq$ 30M$\odot$, Total mass $\gtrsim$70M$\odot$
  - To obtain an orbital frequency of 75 Hz, the two objects must be very close and compact
  - Only black holes compact enough to reach this frequency

Analysis Overview

- Two different searches
  - Generic transient search
  - Binary coalescence search

- 16 days of data
  - September 12 to October 20, 2015
  - GW150914

- Background is estimated
  - Time-shifted data for each method
  - Determines likelihood of event

Generic Transient Search

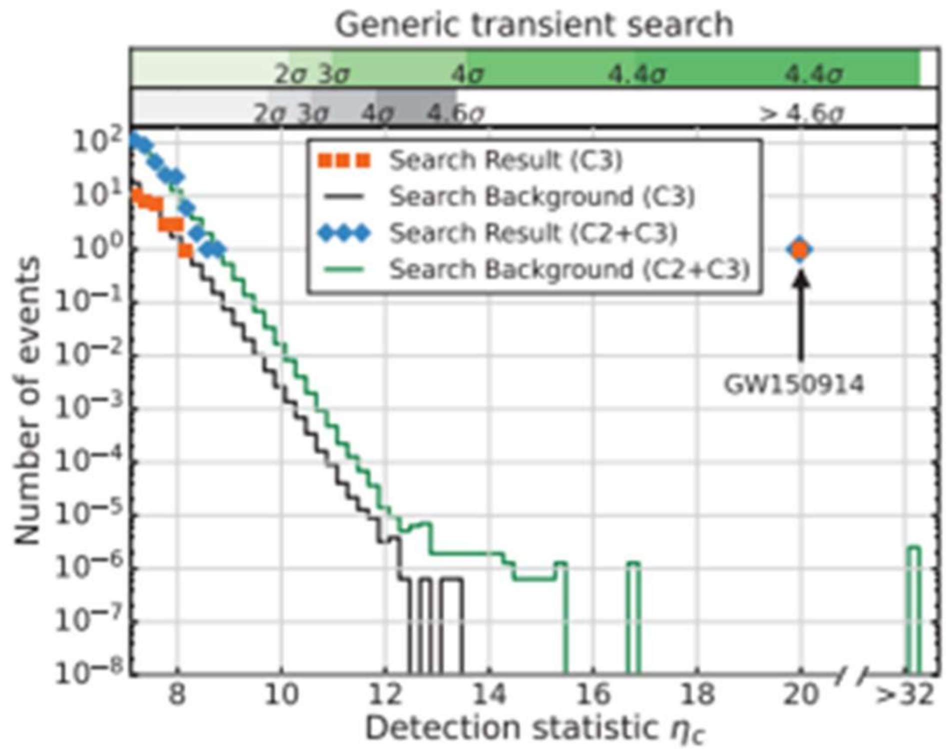
- No waveform model is used to compare events

- Excess power
  - Time frequency data of the detector strain data
  - η_c = sqrt($2E_c/(1 + E_n/E_c)$) where E_c = cross-correlation and E_n = residual noise

- Morphology of data is used to class possible events
  - C1: Known events with morphology of noise transients
  - C2: Remaining events
  - C3: Events with increasing frequency

Generic Transient Search Results GW150914

- $\eta_c = 20$
- 4.6 σ
- Search was between C1 and a combined (C2 and C3)



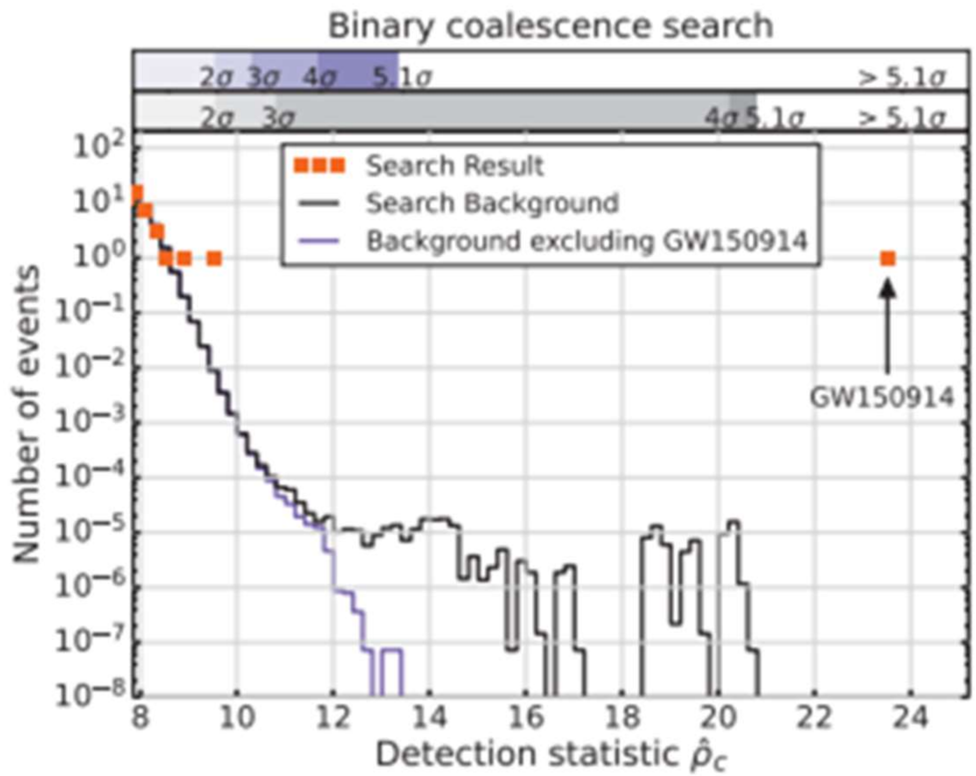
Binary Coalescence Search

- Model of systems used

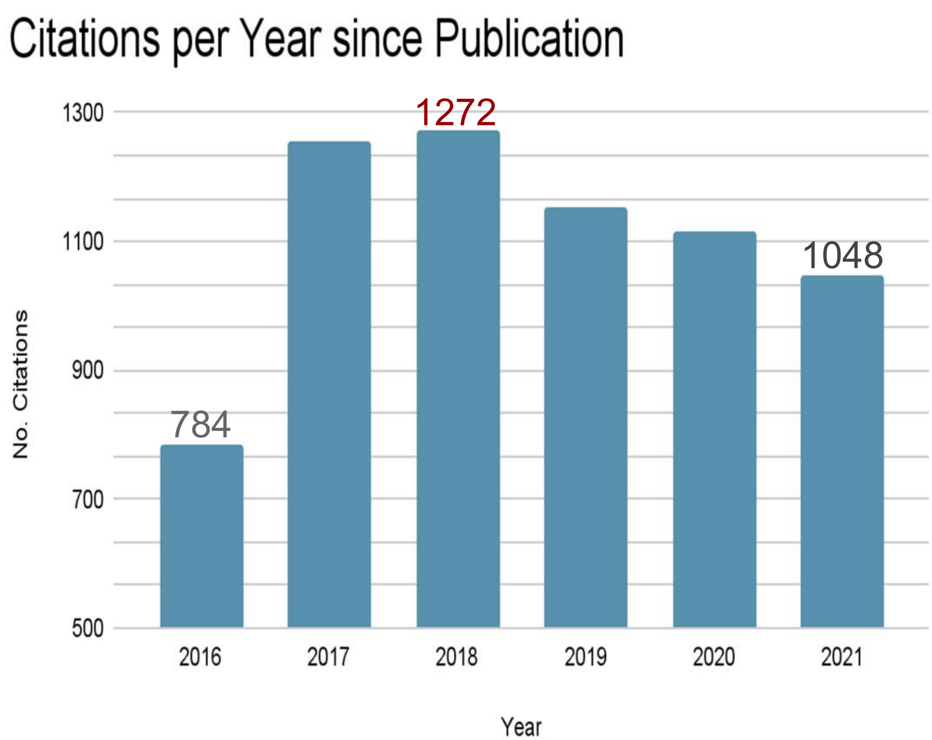
- Signal to noise ratio for each model p(t)
  - Compared using a χ^2 statistic
  - Compares events pairs in a 15ms range

Binary Coalescence Results GW150914

- 5.1σ
- Signal to noise ratio Pc = 23.6

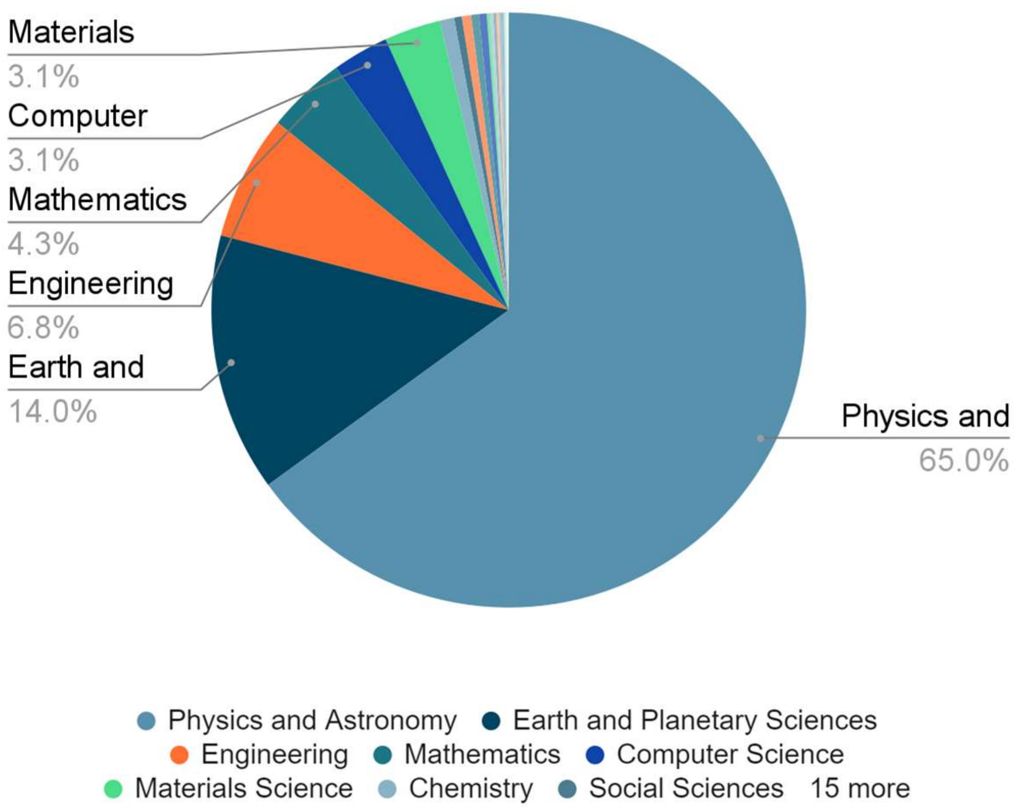


Citation Analysis



- As of 11/25/2021,
  Cited by 6629 documents since publication in 2016
- Least cited in 2016, 784 times
- Cited most in 2018, 1272 times
- This year (2021), cited 1048 times

Categories of Works that Cited



- A vast majority of documents that cite this paper are STEM related (~99%)
- ~0.45% are Arts and Humanities and Social Sciences

*NOTE: this pie chart doesn't account for genre overlap

Impact in Astrophysics

Document title	Authors	Year	Source
GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral *Open Access*	Abbott, B.P., Abbott, R., Abbott, T.D., (...), Zucker, M.E., Zweizig, J.	2017	Physical Review Letters 119(16),161101

- Observation of gravitational waves on 08/17/2017 from Binary Neutron Star Merger
- Used an additional detector (Fermi-GBM) to record Gamma burst data -> Neutron Star
- Were able to locate the sky region of the event with a 90% probability!

DOI: https://doi.org/10.1103/PhysRevLett.119.161101

Impact in Particle Physics

Document title	Authors	Year	Source
Primordial black holes as a dark matter candidate *Open Access*	Green, A.M., Kavanagh, B.J.	2021	Journal of Physics G: Nuclear and Particle Physics 48(4),043001

- What if dark matter was just less-massive black holes formed just after the Big Bang?
  - Primordial black hole, PBH
- This paper goes into detail on current criteria for PBHs to be a dark matter candidate
- Proposition that the black holes involved in GW150914 merger were PBH
- Merging rate of the black holes consistent with scenario of all dark matter being made of PBHs

DOI: 10.1088/1361-6471/abc534

Impact in Biomedical Engineering

Document title	Authors	Year	Source
Stimulation of 3D osteogenesis by mesenchymal stem cells using a nanovibrational bioreactor *Open Access*	Tsimbouri, P.M., Childs, P.G., Pemberton, G.D., (...), Reid, S., Dalby, M.J.	2017	Nature Biomedical Engineering 1(9), pp. 758-770

- Aim is to develop a way to grow bones in 3D that can be used in grafting procedures
- Similar laser interferometry techniques were used to measure the vibrational amplitude in their bioreactor!

DOI: 10.1038/s41551-017-0127-4

Citation Analysis, Summary

- Important enough to be included in review papers
- Techniques described in the paper have use outside the field of physics
- Within the Physics community, has inspired scientists to take more and better data of gravitational waves
  - increase in number of detectors, detector quality, analysis techniques
- Has introduced new questions into the fields of astrophysics and particle physics


Thank you!