Observation of Gravitational Waves from a Binary Black Hole Merger

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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 Curvature Tensor  \quad \text{Ricci Scalar}  \quad \text{Metric Tensor}  \quad \text{Stress-Energy-Momentum Tensor}

Cosmological Constant
Brief Description of Tensor Terms in the Field Equations

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

**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.

\[ \eta_{\mu\nu} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \]
Ricci Curvature Tensor

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

Ricci Curvature Scalar

- Scalar that describes curvature.
- Contract the Ricci Tensor

\[
R_{\mu\nu} = g^{\mu\lambda} R_{\lambda\sigma\nu} = R_{\beta\nu \alpha\mu}
\]

\[
R = g_{\mu\nu} R_{\mu\nu} = R^\mu_{\mu} = R
\]
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.

\[ g_{\mu\nu} = \eta_{\mu\nu} + \epsilon h_{\mu\nu} \]
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

Laser Wavelength ~ 1 µm
Previous Discoveries

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

- Indirect evidences
  - observation of binary pulsar system PSR B1913+16 by Hulse and Taylor [3].
  - Subsequent observations of energy loss[4].

- Black hole mergers had not been observed before

Initial Observation of Gravitational Waves

- 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

By B. P. Abbott et al., 2016, Phys. Rev. Lett. 116, 061102
Processing and Validation of Signal GW150914

- 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

- Coincident chirp inspiral merger ring down signal.
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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 time-derivative

$$
\mathcal{M} = \frac{(m_1m_2)^{3/5}}{(m_1 + m_2)^{1/5}} = \frac{c^3}{G} \left[ \frac{5}{96} \pi^{8/3} f^{-11/3} \right]^{3/5}
$$

- Chirp mass $M \approx 30\,M_\odot$, Total mass $\gtrsim 70\,M_\odot$
- 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
  - $\eta_c = \sqrt{2E_c/(1 + E_n/E_c)}$ 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 $\sigma$
- 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 \( \chi^2 \) statistic
  - Compares events pairs in a 15ms range
Binary Coalescence Results GW150914

- $5.1\sigma$
- Signal to noise ratio
  $P_c = 23.6$
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
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

- 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](https://doi.org/10.1103/PhysRevLett.119.161101)
Impact in Particle Physics

- 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

- 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!