OBSERVATION OF GRAVITATIONAL WAVES FROM A BINARY BLACK HOLE MERGER

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for the LIGO Scientific Collaboration
Moriond Meeting, Cosmology and QCD
La Thuile, Italy, March 23, 2016
**ONLINE TRIGGER**

**GraceDB — Gravitational Wave Candidate Event Database**

### Basic Info

<table>
<thead>
<tr>
<th>UID</th>
<th>Labels</th>
<th>Group</th>
<th>Pipeline</th>
<th>Search</th>
<th>Instr</th>
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</thead>
<tbody>
<tr>
<td>G184098</td>
<td>H1OK L1OK</td>
<td>Burst</td>
<td>CWB</td>
<td>AllSky</td>
<td>H1,L1</td>
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</tbody>
</table>

### Analysis-Specific Attributes

<table>
<thead>
<tr>
<th>start_time</th>
<th>1126259461</th>
</tr>
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<tbody>
<tr>
<td>start_time ns</td>
<td>7500000000</td>
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<tr>
<td>duration</td>
<td>2.477e-02</td>
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<td>peak_time</td>
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<tr>
<td>peak_time ns</td>
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</tbody>
</table>

| central_freq   | 123.8285   |
|                |            |
| bandwidth      | 51.8386    |
|                |            |
| false_alarm_rate |          |

| ligo_axis_ra   | 130.9219   |
| ligo_axis_dec  | 4.4808     |
| ligo_angle     | None       |
| ligo_angle_sig | None       |

### Neighbors [-5,+5]

<table>
<thead>
<tr>
<th>UID</th>
<th>Labels</th>
<th>Group</th>
<th>Pipeline</th>
<th>Search</th>
<th>Instruments</th>
<th>GPS Time Event Time</th>
<th>Δgpstime</th>
<th>FAR (Hz)</th>
<th>Links</th>
<th>UTC Submitted</th>
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<tbody>
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<td>LIB</td>
<td>AllSky</td>
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<td>H1,L1</td>
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<td>0.029000</td>
<td>6.338e-09</td>
<td>Data</td>
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<tr>
<td>G184149</td>
<td>Burst</td>
<td>LIB</td>
<td>AllSky</td>
<td>H1,L1</td>
<td>H1,L1</td>
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<td>2015-10-06 13:48:42 UTC</td>
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</tbody>
</table>
THE DISCOVERY

• First direct detection of Gravitational Waves
  
  • first confirmation of their existence from the Hulse-Taylor binary (1975) - Taylor and Weisberg (1982)

• First direct observation of a black hole
  
  • inferred from the characteristic ringdown of the observed signal (and not from the influence on gas surrounding a black hole)

• First observation of a black hole binary
  
  • There is no other way to observe other than via their gravitational wave emission

• The most luminous event ever detected: $3.6 \times 10^{56}$ erg s$^{-1}$
  
  • Total radiated energy ~ 3 solar mass
ITS SIGNIFICANCE

• The only fundamental waves we have so far been able to detect here on Earth are electromagnetic waves
  • light, radio, microwaves, gamma rays, x-rays are all part of the electromagnetic spectrum - Maxwell’s equations

• Gravitational waves are the only other fundamental wave phenomena we know
  • they are described by Einstein’s equations and are waves in the very fabric of spacetime - what does it mean?
CD > AB
Gravitational waves stretch and squeeze spacetime but spacetime is very rigid.
HOW RIGID IS SPACETIME?

• In Einstein equations
  \[ G_{\alpha\beta} = \frac{8\pi G}{c^4} T_{\alpha\beta} \]

• the coupling constant has dimensions of force
  \[ G_F = c^4 / G \sim 10^{44} \text{ N} \]

• Under what circumstance can such a force be felt? Consider force on an orbiting body:
  \[ F = \frac{mv^2}{r} \quad \frac{m}{r} = \frac{v^2}{G} \quad F = \frac{v^4}{G} = \frac{c^4}{G} \left( \frac{v}{c} \right)^4 \]

• Black holes in a binary can experience \( G_F \)
Detector and Sensitivity
LIGO-HANFORD
main noise components

- ground motion: $10^{-8}$ m, $10^{10}$ x bigger
- thermal vibrations: $10^{-12}$ m, $10^6$ x bigger
- gravitational wave strain: $10^{-18}$ m
- laser wave length: $10^{-6}$ m, $10^{12}$ x bigger
The Result - LIGO O1 Sensitivity

Displacement ($\text{m}/\sqrt{\text{Hz}}$)

Frequency (Hz)
Detection and Significance
WHAT DID WE SEARCH FOR?

![Diagram showing Mass 1 vs. Mass 2 with a star indicating GW150914.]
HOW DID WE SEARCH?

MATCHED FILTERING WITH A TEMPLATE BANK

\[ \text{Mass 1} \quad \text{[} M_\odot \text{]} \]

\[ \text{Mass 2} \quad \text{[} M_\odot \text{]} \]

- \[ |\chi_1| < 0.9895, |\chi_2| < 0.05 \]
- \[ |\chi_{1,2}| < 0.05 \]
- \[ |\chi_{1,2}| < 0.9895 \]

arXiv:1602.03839
HOW DID WE SEARCH?

SIGNAL CONSISTENCY CHECK

GW150914
G197392
Background
Simulated signals:
- in software
- in detector

H1

arXiv:1602.03839
WHAT DID WE OBSERVE?
HOW DO WE KNOW GW150914 IS A BLACK HOLE BINARY?

- can measure total mass from the maximum frequency of the system \( \sim 65 \) solar mass

- can measure chirp mass from the chirp (rate at which frequency increases)

if the smallest mass is 3 solar mass then the total mass would be 1000 solar mass

Chirp mass: \( M = \frac{(m_1 m_2)^{3/5}}{M^{1/5}} \approx \frac{c^3}{G} \left[ \frac{5}{96} \pi^{-8/3} f^{-11/3} \dot{f} \right]^{3/5} \)
TIME SERIES, RESIDUE, TIME-FREQUENCY TRACE

Hanford, Washington (H1) vs. Livingston, Louisiana (L1)

- Strain (10⁻²¹)
- Numerical relativity
- Reconstructed (wavelet)
- Reconstructed (template)
- Residual

Frequency (Hz)

Time (s)

Normalized amplitude

LVC, PRL 116, 061102 (2016)
BACKGROUND AND SIGNIFICANCE

• Time slide method
  • time shift data from one detector relative to the other by more than light travel time
  • look for coincidences in time-shifted data
• Triggers from zero time shift correspond to both noise background and real gravitational waves
• Triggers from non-zero time shifts correspond only to noise background
Based on their time-frequency morphology, the events are divided into three mutually exclusive search classes, as shown in the following table:

<table>
<thead>
<tr>
<th>Class</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₁</td>
<td>Events with arbitrary frequency evolution that increase with time.</td>
</tr>
<tr>
<td>C₂</td>
<td>Events with similar frequency evolution to GW150914, not found in the search.</td>
</tr>
<tr>
<td>C₃</td>
<td>Events with frequency that increases with time.</td>
</tr>
</tbody>
</table>

This classification is consistent with the statistical significance of the events, which is defined as the number of standard deviations (σ) above the mean of the background. The significance is calculated for the entire search period and each search class individually.

The significance of GW150914 is found to be greater than 5.1σ, corresponding to a false alarm rate of < 1 in 5 million. This result is further validated by the consistency of the data between the two detectors and the similarity of the reconstructed waveforms.

The selection criteria that define the search class C₃ are as follows:

- The detection statistic $\hat{\rho}_C$ is used to rank the events within each search class.
- The events are ranked according to the detection statistic using a multidetector maximum likelihood method.
- The significance of an event is defined as $\eta_c = \frac{E_c}{E_n}$, where $E_c$ is the residual noise energy after the reconstructed signal is subtracted from the data, and $E_n$ is the residual noise energy after accounting for any coincidences.

In summary, the statistical significance of GW150914 is calculated as $\sqrt{1 + \sigma^2}$, equivalent to $20 \sigma$ for GW150914 against a background of events with arbitrary signal morphology. This corresponds to a probability of observing one or more noise events as strong as GW150914 during one or more years.
Parameters of GW150914
The uncertainty from waveform modelling is less significant than statistical uncertainty; therefore, we are confident that the results are robust against this potential systematic error.

For parameters with bounded ranges, like the spins, these normal distributions are non-truncated distributions. Both provide estimates of the order of magnitude of the potential systematic error.

For parameters with a bounded range, the Bayes factor and the optimal signal-to-noise ratio of the potential systematic error.

The analysis presented here yields an optimal coherent hypothesis divided by that for (Gaussian) noise. At the leading order, the Bayes factor and the optimal signal-to-noise ratio are provided in Table I. For the model evidence, we include different aspects of BBH spin dynamics. The models are based on different analytical approaches and that they assume frequency-independent calibration errors, and that different waveform models. From Table I, we see that the results are robust against this potential systematic error.
The vertical lines mark the 1\% credible interval for the Overall PDF. The distributions we show the Overall (solid), IMRPhenom (blue) and EOBNR (red) PDFs; the dashed vertical lines mark the distributions.

**FIG. 2.** Posterior PDFs for the source luminosity distance. In the two-dimensional plot shows the contours of the 50\% and 90\% credible regions plotted over a two-dimensional plot showing the probability region is 1\% probability (yellow region). The associated ability (blue). The associated ability (blue).

The observed time-delay of GW150914 between the Livingston and Hanford observatories was only the two LIGO instruments in operation, GW150914's location of a GW in the sky, via time-of-arrival, and assuming the inspiral phase to end at about the system is emitted as GWs. Only a fully general relativity of a BBH merger can be estimated at the order of the total energy of a binary system at separation $r$. This area of the sky was targeted by follow-up observations covering radio, optical, near infra-red, X-ray, and gamma-ray wavelengths that are discussed in [101].

We further infer the peak GW luminosity achieved during the merger phase by applying to the posteriors a separate fit to non-precessing NR simulations [94]. The leading to $\sim 5\%$ uncertainties include an estimate for the systematic error of precessing NR simulations, in addition to the dominant statistical contribution. These values are fully consistent with those given in the literature for NR simulations of similar binaries [95, 96]. A Newtonian-order description of the system can accurately describe the majority of precessing NR simulations, in addition to the dominant relativistic treatment of the system. In the literature for NR simulations, in addition to the dominant contribution from general relativistic effects.

Using the inferred distance leads to an estimated luminosity of $\sim 1.3 \times 10^{52}$ ergs. This is the luminosity that corroborates this result. At this order, the flux is provided on the order of magnitude estimate of the luminosity. GW150914 provided an order-of-magnitude estimate of the luminosity of $\sim 10^{52}$ erg s$^{-1}$. Only a fully general relativity of a BBH merger can be estimated at the order of the total energy emitted. GW150914 radiated a total of $\sim 10^{52}$ erg s$^{-1}$. This area of the sky was targeted by follow-up observations covering radio, optical, near infra-red, X-ray, and gamma-ray wavelengths that are discussed in [101].

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FIG. 2. Posterior PDFs for the source luminosity distance $D_L/\text{Mpc}$ and the binary inclination $\theta_{JN}$. The contours of the 2-dimensional marginalised distributions we show the Overall PDF. The credible regions plotted over a colour-coded PDF.

FIG. 3. PDFs for the source-frame mass and spin of the remnant BH produced by the coalescence of the binary. In the 2-dimensional plot shows the contours of the 50%, 90% and 90% credible interval for the Overall PDF. The dashed vertical lines mark the median values of the IMRPhenom (blue) and EOBNR (red) PDFs; the dashed lines are the median values of the Overall PDF.

The observed time-delay of GW150914 between the Livingston and Hanford observatories was $10\pm3\text{ s}$, providing an order-of-magnitude estimate of the luminosity distance $D_L$.

The observed gravitational-wave amplitude and phase consistency across the network [98] indicates that the location of a GW in the sky, via time-of-arrival, and the dipole component of the sky localization are fully consistent with the sky localization from the amplitude of the gravitational waves [99].

The comoving density of Milky Way-like galaxies is $\mathcal{N}(\ln\rho_0) = -10.0\pm0.2$ at the redshift of the GW source [100].

The amplitude of the GW signal from GW150914 is $h_0 = (1.1\pm0.3)\times10^{-22}$, corresponding to a projected luminosity distance of $D_L = (410\pm120)\text{ Mpc}$.

From the time delay between the GW signal and the electromagnetic counterpart, we infer the luminosity distance $D_L = (410\pm120)\text{ Mpc}$, and the peak GW amplitude $h_0 = (1.1\pm0.3)\times10^{-22}$.

Using the inferred distance leads to an estimated luminosity $L = (1.1\pm0.3)\times10^{54}\text{ erg s}^{-1}$, which is in rough agreement with the peak isotropic-equivalent energy $E_{\text{iso}} = (1.1\pm0.3)\times10^{54}\text{ erg}$ of the GRB 110918A.

The peak GW luminosity achieved during the merger portion of GW150914 is $L\approx10^{54}\text{ erg s}^{-1}$.

The physical process during the final strong-field phase of the inspiral can be approximated using a Newtonian treatment of the system. This provides an order-of-magnitude estimate of the luminosity $L\approx10^{54}\text{ erg s}^{-1}$.

The total energy emitted in GWs is estimated to be $E_{\text{GW}}\approx10^{54}\text{ erg}$.

The energy is emitted during the merger phase by applying to the posteriors a separate fit to non-precessing NR simulations [94]. The energy is emitted in the form of GWs, and assuming the inspiral phase to end at about $E_{\text{GW}}\approx10^{54}\text{ erg}$.

The energy is emitted during the final strong-field phase of the inspiral, which is described by the dominant NR simulations, in addition to the dominant precessing NR simulations [95, 96].

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### Parameters of GW150914

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary black hole mass</td>
<td>$36_{-4}^{+5} M_\odot$</td>
</tr>
<tr>
<td>Secondary black hole mass</td>
<td>$29_{-4}^{+4} M_\odot$</td>
</tr>
<tr>
<td>Final black hole mass</td>
<td>$62_{-4}^{+4} M_\odot$</td>
</tr>
<tr>
<td>Final black hole spin</td>
<td>$0.67_{-0.07}^{+0.05}$</td>
</tr>
<tr>
<td>Luminosity distance</td>
<td>$410_{-180}^{+160}$ Mpc</td>
</tr>
<tr>
<td>Source redshift $z$</td>
<td>$0.09_{-0.04}^{+0.03}$</td>
</tr>
</tbody>
</table>
Tests of General Relativity
WAVEFORM CONSISTENCY
Tests of Strong Field GR

\[ p_i \]

\[ \delta \hat{p}_i \]

GW150914 (Single)
GW150914 (Multiple)
J0737 – 3039

arXiv:1602.03841
\begin{align*}
\lambda_g &= \frac{h}{m_g c} \\
\lambda_g &> 10^{13}\text{km}
\end{align*}

\begin{align*}
m_g < 1.2 \times 10^{-22}\text{eV/c}^2
\end{align*}
Astrophysical implications
WHERE WAS GW150914?

6.9ms time delay

~600 deg² (90% confidence)

~10⁹ MWEG
Probability of observing

- $N > 0$ (blue)
- $N > 5$ (green)
- $N > 10$ (red)
- $N > 35$ (purple)

highly significant events, as a function of surveyed time-volume.

arXiv:1602.03842
GW150914 IS JUST THE BEGINNING ...
EXPECTED SENSITIVITY IMPROVEMENT

Gravitational Wave Frequency (Hz)

Strain Amplitude Spectral Density (m / Hz^{1/2})

Initial LIGO
Livingston
Hanford
aLIGO Design
A GW-BRIGHT FUTURE

- O2: 6 months 2016-2017
- O3: 9 months 2017-2018
- 2018: KAGRA operational
- 2019+: LIGO full sensitivity
- 2022+: Virgo full sensitivity and LIGO India operational
ORBITAL PRECESSION

\[ \begin{align*}
&\text{Credit: Mark Hannam} \\
\end{align*} \]
Equal-mass, non-spinning BBH consistent with GW150914

Unequal-mass, precessing BBH consistent with GW150914
SIGNATURE OF PRECESSION

“Face-on” to the source

Non-precessing

Precessing

“Edge-on” to the source

Non-precessing

Precessing

Credit: Mark Hannam
RESOURCES

• LIGO Open Science Center (LOSC): download 30 sec of
data around the event plus more!
http://losc.ligo.org/

• Science summary of detection

• Many videos, images and other resources available from
https://www.ligo.caltech.edu/detection
Observation of Gravitational Waves from a Binary Black Hole Merger


https://papers.ligo.org

1. LIGO-P1500229: Observing gravitational-wave transient GW150914 with minimal assumptions
2. LIGO-P1500269: GW150914: First results from the search for binary black hole coalescence with Advanced LIGO
3. LIGO-P1500218: Properties of the binary black hole merger GW150914
4. LIGO-P1500217: The Rate of Binary Black Hole Mergers Inferred from Advanced LIGO Observations Surrounding GW150914
5. LIGO-P1500262: Astrophysical Implications of the Binary Black-Hole Merger GW150914
6. LIGO-P1500213: Tests of general relativity with GW150914
7. LIGO-P1500222: GW150914: Implications for the stochastic gravitational-wave background from binary black holes
8. LIGO-P1500248: Calibration of the Advanced LIGO detectors for the discovery of the binary black-hole merger GW150914
9. LIGO-P1500238: Characterization of transient noise in Advanced LIGO relevant to gravitational wave signal GW150914
10. LIGO-P1500227: Localization and broadband follow-up of the gravitational-wave transient GW150914
11. LIGO-P1500271: High-energy Neutrino follow-up search of Gravitational Wave Event GW150914 with IceCube and ANTARES
12. LIGO-P1500237: GW150914: The Advanced LIGO Detectors in the Era of First Discoveries
And as any detected binary black hole would tell you, "Thanks for listening!"