Observation of Gravitational Waves from a Binary Black Hole Merger

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(LIGO Scientific Collaboration and Virgo Collaboration)
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On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of $1.0 \times 10^{-21}$. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of $4.10^{+1.60}_{-1.80}$ Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$.

Detection Paper Factoids

"the stat that really struck me was that in the first 24 hrs., not only was the page for your PRL abstract hit 380K times, but the PDF of the paper was downloaded from that page 230K times. This is far more hits than any PRL ever, and the fraction of times that it resulted in a download was unusually high. Hundreds of thousands of people actually wanted to read the whole paper! That is just remarkable." Robert Garistro (PRL editor)
Detection-Companion-Papers
https://www.ligo.caltech.edu/page/detection-companion-papers

Discovery Paper

- "Observation of Gravitational Waves from a Binary Black Hole Merger" Published in *PRL* 116, 061102 (2016).

Related papers

- "Observing gravitational-wave transient GW150914 with minimal assumptions"
- "GW150914: First results from the search for binary black hole coalescence with Advanced LIGO4"
- "Properties of the binary black hole merger GW150914"
- "The Rate of Binary Black Hole Mergers Inferred from Advanced LIGO Observations Surrounding GW150914"
- "Astrophysical Implications of the Binary Black-Hole Merger GW150914"
- "Tests of general relativity with GW150914"
"GW150914: Implications for the stochastic gravitational-wave background from binary black holes"

"Calibration of the Advanced LIGO detectors for the discovery of the binary black-hole merger GW150914"

"Characterization of transient noise in Advanced LIGO relevant to gravitational wave signal GW150914"

"High-energy Neutrino follow-up search of Gravitational Wave Event GW150914 with IceCube and ANTARES"

"GW150914: The Advanced LIGO Detectors in the Era of First Discoveries"

"Localization and broadband follow-up of the gravitational-wave transient GW150914"

GW150914 Data Release

Data release at LIGO Open Science Center (LOSC) website.
- **Newtonian gravity**: force depends on distance between massive objects and there is instantaneous action at a distance.

- **Einstein’s gravity**: time dependent gravitational fields propagate like light waves, proportional to quadrupole moment and at speed of light.
Einstein’s Theory of Gravitation

Gravitational Waves

- Using Minkowski metric, the information about space-time curvature is contained in the metric as an added term, $h_{\mu\nu}$. In the weak field limit, the equation can be described with linear equations. If the choice of gauge is the *transverse traceless gauge* the formulation becomes a familiar wave equation:

$$\left( \nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) h_{\mu\nu} = 0$$

- The strain $h_{\mu\nu}$ takes the form of a plane wave propagating at the speed of light ($c$).

- Since gravity is spin 2, the waves have two components, but rotated by 45° instead of 90° from each other.

$h_{\mu\nu} = h_+ (t - z/c) + h_x (t - z/c)$
“Direct Detection”
Suspended Mass Interferometers

Diagram showing a test mass suspended from a laser beam and a sensor.
Compact binary collisions

» Neutron Star – Neutron Star
  – waveforms are well described
» Black Hole – Black Hole
  – Numerical Relativity waveforms
» Search: *matched templates*

“chirps”
LIGO Interferometer Concept

- Laser used to measure relative lengths of two orthogonal arms
  - Arms in LIGO are 4km
  - Measure difference in length to one part in $10^{21}$ or $10^{-18}$ meters

...causing the interference pattern to change at the photodiode

Suspended Masses
change in different ways....
Interferometer Noise Limits

- Seismic Noise
- Test mass (mirror)
- Residual gas scattering
- Beam splitter
- Photodiode
- Quantum Noise
- "Shot" noise
- Radiation pressure
- Laser (LASER)
- Wavelength & amplitude fluctuations
- Thermal (Brownian) Noise
What Limits LIGO Sensitivity?

- Seismic noise limits low frequencies
- Thermal Noise limits middle frequencies
- Quantum nature of light (Shot Noise) limits high frequencies
- Technical issues - alignment, electronics, acoustics, etc limit us before we reach these design goals
LIGO
beam tube
LIGO vacuum equipment
Advanced LIGO

Better seismic isolation
Higher power laser
Better test masses and suspension

Strain (1/√Hz)

Frequency (Hz)
Achieving x10 sensitivity improvement?

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Initial LIGO</th>
<th>Advanced LIGO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Laser Power</td>
<td>10 W (10 kW arm)</td>
<td>180 W (&gt;700 kW arm)</td>
</tr>
<tr>
<td>Mirror Mass</td>
<td>10 kg</td>
<td>40 kg</td>
</tr>
<tr>
<td>Interferometer Topology</td>
<td>Power-recycled Fabry-Perot arm cavity Michelson</td>
<td>Dual-recycled Fabry-Perot arm cavity Michelson (stable recycling cavities)</td>
</tr>
<tr>
<td>GW Readout Method</td>
<td>RF heterodyne</td>
<td>DC homodyne</td>
</tr>
<tr>
<td>Optimal Strain Sensitivity</td>
<td>$3 \times 10^{-23}$ / rHz</td>
<td>Tunable, better than $5 \times 10^{-24}$ / rHz in broadband</td>
</tr>
<tr>
<td>Seismic Isolation Performance</td>
<td>$f_{\text{low}} \sim 50$ Hz</td>
<td>$f_{\text{low}} \sim 13$ Hz</td>
</tr>
<tr>
<td>Mirror Suspensions</td>
<td>Single Pendulum</td>
<td>Quadruple pendulum</td>
</tr>
</tbody>
</table>

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HEPAP
200W Nd:YAG laser

Designed and contributed by Max Planck Albert Einstein Institute

- Stabilized in power and frequency
- Uses a monolithic master oscillator followed by injection-locked rod amplifier
Test Masses

Test Masses:
34cm $\phi$ x 20cm
40kg

Compensation plates:
34cm $\phi$ x 10cm
40kg

BS:
37cm $\phi$ x 6cm

Round-trip optical loss: 75 ppm max

ITM
$T = 1.4\%$

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LIGO-G1600214
Test Mass

Quadruple Pendulum suspension

Optics Table Interface (Seismic Isolation System)

Damping Controls

Hierarchical Global Controls

Electrostatic Actuation

Final elements
All Fused silica
Seismic Isolation: Multi-Stage Solution

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LIGO
Simultaneous Detection
September 14, 2015

LIGO Livingston Data

Strain ($10^{-21}$)

Time (sec)

LIGO Hanford Data

Time (sec)
September 14, 2015

Strain ($10^{-21}$)

**LIGO Livingston Data**

**Predicted**

**LIGO Hanford Data**

**Predicted**

Time (sec)

0.30  0.35  0.40  0.45

0.30  0.35  0.40  0.45
Gravitational Wave Event
GW150914

Data bandpass filtered between 35 Hz and 350 Hz
Time difference 6.9 ms with Livingston first

Second row – calculated GW strain using Numerical Relativity Waveforms for quoted parameters compared to reconstructed waveforms (Shaded)

Third Row – residuals

bottom row – time frequency plot showing frequency increases with time (chirp)
Full bandwidth waveforms without filtering. Numerical relativity models of black hole horizons during coalescence.

Effective black hole separation in units of Schwarzschild radius ($R_s = 2GM_f/c^2$); and effective relative velocities given by post-Newtonian parameter $v/c = (GM_f \pi f/c^3)^{1/3}$
Statistical Significance of GW150914

Binary Coalescence Search

- Search Result
- Search Background
- Background excluding GW150914

GW150914
Measuring the parameters

- Orbits decay due to emission of gravitational waves
  - **Leading order** determined by “chirp mass”
    \[
    \mathcal{M} = \frac{(m_1 m_2)^{3/5}}{M^{1/5}} \simeq \frac{c^3}{G} \left[ \frac{5}{96} \pi^{-8/3} f^{-11/3} \right]^{3/5}
    \]
  - Next orders allow for measurement of mass ratio and spins
  - We directly measure the red-shifted masses (1+z) m
  - Amplitude inversely proportional to luminosity distance

- Orbital precession occurs when spins are misaligned with orbital angular momentum – no evidence for precession.

- Sky location, distance, binary orientation information extracted from time-delays and differences in observed amplitude and phase in the detectors
Use numerical simulations fits of black hole merger to determine parameters, we determine total energy radiated in gravitational waves is $3.0 \pm 0.5 \, M_\odot c^2$. The system reached a peak $\sim 3.6 \times 10^{56}$ ergs, and the spin of the final black hole < 0.7 (not maximal spin).

<table>
<thead>
<tr>
<th>Source Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary black hole mass</td>
<td>$36^{+5}<em>{-4} , M</em>\odot$</td>
</tr>
<tr>
<td>Secondary black hole mass</td>
<td>$29^{+4}<em>{-4} , M</em>\odot$</td>
</tr>
<tr>
<td>Final black hole mass</td>
<td>$62^{+4}<em>{-4} , M</em>\odot$</td>
</tr>
<tr>
<td>Final black hole spin</td>
<td>$0.67^{+0.05}_{-0.07}$</td>
</tr>
<tr>
<td>Luminosity distance</td>
<td>$410^{+160}_{-180} , \text{Mpc}$</td>
</tr>
<tr>
<td>Source redshift, $z$</td>
<td>$0.09^{+0.03}_{-0.04}$</td>
</tr>
</tbody>
</table>
Results

Heavy stellar black holes

- Stellar binary black holes do exist!
  - Form and merge in time scales accessible to us
  - Predictions previously encompassed \([0 – 10^3] / \text{Gpc}^3 / \text{yr}\)
  - Now we exclude lowest end: rate > 1 Gpc\(^3\) / yr

- Masses \((M > 20 M_\odot)\) are large compared with known stellar mass BHs

- Progenitors are
  - Likely heavy, \(M > 60 M_\odot\)
  - Likely with a low metallicity, \(Z < 0.25 Z_\odot\)

- Measured redshift \(z \sim 0.1\)

- Low metallicity models can produce low-z mergers at rates consistent with our observation
Upper bound on the graviton mass

If \( c_{GW} < c \)

\( \iff \) gravitational waves have a modified dispersion relation

Findings: at 90% confidence, \( \lambda_g > 10^{13} \text{ km} \)

or equivalently

\( m_g < 1.2 \times 10^{-22} \text{ eV/c}^2 \)
Localization
LIGO: Lesson’s Learned

LIGO Project Approved / Funded by NSF in 1994

» High risk; high scientific payoff !!
» Unwavering NSF support for 22 years!
» Total NSF Investment to date ~1.2 B$, construction + research
» One major project upgrade (MREFC)

Lessons

» NSF can successfully manage large scientific projects
» Scientists management successful --- on budget, schedule and performance.
» Key strategy: forward looking infrastructure, ongoing R&D and evolving capability

“Open” Scientific Collaboration

» Open access data – discovery data released on Feb 11
» General policy; all data after 2 years (will shorten).
LIGO Scientific Collaboration
Sensitivity for first Observing run

At ~40 Hz, Factor ~100 improvement

Broadband, Factor ~3 improvement

Initial LIGO

O1 aLIGO

Design aLIGO

Strain noise, 1/(Hz^{1/2})

Frequency, Hz
Prospects for Observing and Localizing Gravitational Wave Transients with Advanced LIGO and Advanced Virgo

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Observing scenario
Rate expectations

future running

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.
Astrophysical targets for ground-based detectors

Coalescing Binary Systems
- Neutron stars, low mass black holes, and NS/BS systems

'Bursts'
- galactic asymmetric core collapse supernovae
- cosmic strings
- ???

Stochastic GWs
- Incoherent background from primordial GWs or an ensemble of unphased sources
- primordial GWs unlikely to detect, but can bound in the 10-10000 Hz range

Continuous Sources
- Spinning neutron stars
- probe crustal deformations, ‘EOS, quarkiness’
The advanced GW detector network: 2015-2025

- Advanced LIGO Hanford 2015
- Advanced LIGO Livingston 2015
- GEO600 (HF) 2011
- Advanced Virgo 2016
- LIGO-India 2022
- KAGRA 2017

31 March 2016
Localization of the Source

future: more precise

- Adding Virgo will break the annulus
- As sensitivity progresses, so does the localization. In the design LIGO-Virgo network, GW150914 could have been localized to less than 20 deg^2
- LIGO India will lead to a further impressive improvement

31-March-2016
LIGO-G1600214
Voyager Noise Curve: $P_{\text{in}} = 300.0 \ \text{W}$

- Quantum
- Seismic
- Newtonian
- Suspension Thermal
- Coating Brownian
- Coating Thermo-optic
- Substrate Brownian
- Excess Gas
- Total noise
Technologies crucial for next-generation detectors; KAGRA can be regarded as a 2.5-generation detector.
The Einstein Telescope: x10 aLIGO

- Deep Underground;
- 10 km arms
- Triangle (polarization)
- Cryogenic
- Low frequency configuration
- High frequency configuration
Einstein Telescope (Europe)

ET High Frequency

ET Low Frequency
The Gravitational Wave Spectrum

- Relic radiation
- Cosmic Strings
- Extreme Mass Ratio Inspirals
- Supermassive BH Binaries
- Binaries coalescences
- Spinning NS
- Supernovae

Frequency bands:
- $10^{-16}$ Hz: Inflation Probe
- $10^{-9}$ Hz: Pulsar timing
- $10^{-4}$ Hz: Space detectors
- $10^{0}$ Hz: Ground interferometers
- $10^{3}$ Hz

Slide Credit: Matt Evans (MIT)
End