Gravitational Wave Astronomy

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(Results presented on behalf of the LIGO Scientific Collaboration and the Virgo Collaboration)
Gravitational waves are quadrupolar distortions of distances between freely falling masses. They are produced by time-varying mass quadrupoles.

\[ G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \quad (= 0 \text{ in vacuum}) \]

\[ g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \quad h = \frac{\Delta L}{L} \]

The first gravitational wave detected on September 14, 2015, produced by merging black holes 400 Mpc away had a peak amplitude \( h \sim 10^{-21} \).
Advanced LIGO: complicated instruments!
Sept 14 2015
Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott et al.^

(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)
Not just one signal

Where do GWs come from?
A kilonova rainbow


Credit: NSF/LIGO/Sonoma State University/A. Simonnet
Testing General Relativity


<table>
<thead>
<tr>
<th>Event</th>
<th>Properties</th>
<th>SNR</th>
<th>GR tests performed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$D_L$ [Mpc]</td>
<td>$M_{\text{tot}}$ [$M_\odot$]</td>
<td>$M_\ell$ [$M_\odot$]</td>
</tr>
<tr>
<td>GW150914$^b$</td>
<td>430$^{+150}_{-170}$</td>
<td>66.2$^{+3.7}_{-3.3}$</td>
<td>63.1$^{+3.3}_{-3.0}$</td>
</tr>
<tr>
<td>GW151012$^b$</td>
<td>1060$^{+550}_{-480}$</td>
<td>37.3$^{+10.6}_{-3.9}$</td>
<td>35.7$^{+10.7}_{-3.8}$</td>
</tr>
<tr>
<td>GW151226$^{b,c}$</td>
<td>440$^{+180}_{-190}$</td>
<td>21.5$^{+6.2}_{-1.5}$</td>
<td>20.5$^{+6.4}_{-1.5}$</td>
</tr>
<tr>
<td>GW170104</td>
<td>960$^{+440}_{-420}$</td>
<td>51.3$^{+5.3}_{-4.2}$</td>
<td>49.1$^{+5.2}_{-4.0}$</td>
</tr>
<tr>
<td>GW170608</td>
<td>320$^{+120}_{-110}$</td>
<td>18.6$^{+3.1}_{-0.7}$</td>
<td>17.8$^{+3.2}_{-0.7}$</td>
</tr>
<tr>
<td>GW170729$^d$</td>
<td>2760$^{+1380}_{-1340}$</td>
<td>85.2$^{+15.6}_{-11.1}$</td>
<td>80.3$^{+14.6}_{-10.2}$</td>
</tr>
<tr>
<td>GW170809</td>
<td>990$^{+320}_{-380}$</td>
<td>59.2$^{+5.4}_{-3.9}$</td>
<td>56.4$^{+5.2}_{-3.7}$</td>
</tr>
<tr>
<td>GW170814</td>
<td>580$^{+160}_{-210}$</td>
<td>56.1$^{+3.4}_{-2.7}$</td>
<td>53.4$^{+3.2}_{-2.4}$</td>
</tr>
<tr>
<td>GW170818</td>
<td>1020$^{+430}_{-360}$</td>
<td>62.5$^{+5.1}_{-4.0}$</td>
<td>59.8$^{+4.8}_{-3.8}$</td>
</tr>
<tr>
<td>GW170823</td>
<td>1850$^{+540}_{-840}$</td>
<td>68.9$^{+9.9}_{-7.1}$</td>
<td>65.6$^{+9.4}_{-6.6}$</td>
</tr>
</tbody>
</table>

- RT: If we subtract the best fit from data, are residuals inconsistent with instrumental noise?
- IMR: Are parameters obtained when fitting the inspiral phase different than those fitting the merger-ringdown phase?
- PI/PPI: If we parameterize the inspiral/post-inspiral phase, do we find deviations from the GR parameters?
- MDR: Do we have evidence of a modified dispersion relation (a.k.a. as graviton mass)?

Ans: $m_g < 10^{-23}$ eV/c²
Nuclear physics with GWs

\[ \Lambda = \frac{2}{3} k_2 \left( \frac{R}{m} \right)^5 \]
Cosmology with GWs

GW-GRB observation: Fundamental physics

$$-3 \times 10^{-15} \leq \frac{\Delta v}{v_{EM}} \leq +7 \times 10^{-16}.$$ 

$$-2.6 \times 10^{-7} \leq \gamma_{GW} - \gamma_{EM} \leq 1.2 \times 10^{-6}.$$ (4)

The best absolute bound on $\gamma_{EM}$ is $\gamma_{EM} - 1 = (2.1 \pm 2.3) \times 10^{-5}$, from the measurement of the Shapiro delay (at radio wavelengths) with the Cassini spacecraft (Bertotti et al. 2003).

ApJL, 848:L13, 2017
More discoveries

Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA

Living Reviews in Relativity 23, 3 (2020)
Masses in the Stellar Graveyard

in Solar Masses

GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern
Masses in the Stellar Graveyard

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LIGO-Virgo Black Holes

EM Black Holes

EM Neutron Stars

LIGO-Virgo Neutron Stars

GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern
GWTC-2 catalog (O3a): 39 events

https://www.gw-openscience.org
https://pnp.ligo.org/ppcomm/Papers.html
GW190425: Another BNS merger

GW190412: Asymmetric masses

Phys. Rev. D 102, 043015 (2020)
GW190814: Even more asymmetric masses

GW190521: Largest black hole masses

GW190924_021846: Smallest black hole masses

https://pnp.ligo.org/ppcomm/Papers.html
Effective Aligned Spin

Credit: Carl Rodriguez
Effective Precession Spin

Credit: LIGO/Caltech/MIT/Sonoma State (Aurore Simmonnet)
Sources of gravitational waves: not just binary systems!

Coalescing Binary Systems
Neutron Stars, Black Holes

'Bursts'
asymmetric core collapse supernovae cosmic strings

Continuous Sources
Spinning neutron stars crustal deformations, accretion

Astrophysical or Cosmic GW background
stochastic, incoherent background

Credit: AEI, CCT, LSU
Credit: Chandra X-ray Observatory
Casey Reed, Penn State
NASA/WMAP Science Team
Reducing the noise, increasing the rate of detections

LIGO Livingston Detector

The next few years
Third Generation Detectors (Ground based)
Different wavelengths need different instruments
The era of GW astronomy is here!

Image credit: LIGO/T. Pyle

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