GW170817: gravitational waves from the merger of two neutron stars

Dr. Jess McIver for the LIGO-Virgo Collaboration
Caltech/JPL Association for Gravitational-Wave Research Seminar
Oct 24, 2017
Gravitational waves

Ripples in the fabric of spacetime generated by the acceleration of matter

\[ h_{ij}(t) \propto \frac{G}{c^4 r} \frac{d^2 I_{ij}}{dt^2} \]
Indirect evidence of gravitational waves

Hulse-Taylor Binary Pulsar
PSR B1913+16

Weisburg, Nice & Taylor, 2010

Cumulative period shift (s)

GR prediction

Weisburg, Nice & Taylor, 2010
Gravitational wave propagation

\[ h(t) = A e^{i(2\pi ft - \mathbf{k} \cdot \mathbf{r})} \]

Spacetime strain \( h(t) \) measured as \( \frac{\Delta L}{L} \)
Observing GWs with interferometry
How does LIGO detect gravitational waves?
How sensitive is the LIGO experiment?
Where are the LIGO detectors?
Matched Filter Analysis

\[ \chi_{1,2} \propto \vec{S}_{1,2} \cdot \hat{L} \]

Matched filter signal-to-noise ratio

Template Bank

01 results

\[ \rho^2(t) = \left[ \langle s|hc \rangle^2(t) + \langle s|h_s \rangle^2(t) \right] \]

\[ \langle s|h \rangle = 4\text{Re} \int_0^\infty \frac{\hat{s}(f)\hat{h}^*(f)}{S_n(f)} e^{2\pi if t} df \]
Observed black hole mergers to date

GW150914
LVT151012
GW151226
GW170104
GW170814

time observable by LIGO-Virgo

LIGO/Caltech/MIT/LSC
Black Holes of Known Mass

Solar Masses vs. X-Ray Studies

GW150914
LVT151012
GW170104
GW170814
GW151226

LIGO/VIRGO
LIGO/Caltech
Sky localization
Sky localization of BBHs with LIGO
A three interferometer network and EM observer partners
Sky localization with three detectors
Prior to the Advanced LIGO’s second observing run (O2), no BNS mergers were observed.

The first observing run (O1) placed upper limits on the rate of BNS mergers that did not yet rule out any astrophysical predictions (as high as $\sim 10,000 \text{ Gpc}^{-3} \text{ yr}^{-1}$)
130 million years ago, two neutron stars merged
GW170817: Gravitational waves from a binary neutron star merger
A glitch in LIGO-Livingston
GW170817 and GWs from binary black holes

GW150914
LVT151012
GW151226
GW170104
GW170814
GW170817

time observable (seconds)

LIGO/University of Oregon/Ben Farr
From GWs: inferring the component masses

\[ M = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} \]
Masses in the Stellar Graveyard
in Solar Masses

LIGO-Virgo Black Holes

X-ray Binary Black Holes

Known Neutron Stars

LIGO-Virgo Neutron Stars

LIGO-Virgo/Frank Elavsky/Northwestern University
From GWs: constraining NS EoS

Tidal deformability

$$\Lambda = \frac{2}{3} k_2 \left[ \left( \frac{c^2}{G} \right) \left( \frac{R}{m} \right) \right]^5$$

B.P. Abbott et al PRL. (2017)
From GWs: sky localization
Sky localization with GWs and gamma rays
Virgo’s role in localization
Prompt emission: GWs and gamma rays
Prompt emission: GWs and gamma rays
Electromagnetic follow-up

<table>
<thead>
<tr>
<th>GW</th>
<th>LIGO, Virgo</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ-ray</td>
<td>Fermi, INTEGRAL, AstroSat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind</td>
</tr>
<tr>
<td>X-ray</td>
<td>Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL</td>
</tr>
<tr>
<td>UV</td>
<td>Swift, HST</td>
</tr>
<tr>
<td>Optical</td>
<td>Swift, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1, HCT, TAC, LBT, TTT, Gemini-South, NTT, GROSD, SOAR, ESO-VLT, XMM-Newton, ESO VST, VRT, SALT, CHILESCOPE, TOPOSO, ROOTES-5, Zadko, Telescopes: Teli, AAT, SALT, ESO-NTT, SOAR, ESO-VLT, Katama Telescope, HST</td>
</tr>
<tr>
<td>IR</td>
<td>REM-ROS2, VISTA, Gemini-South, 2MASS, Spitzer, NTT, GROSD, SOAR, NOT, ESO-VLT, Katama Telescope, HST</td>
</tr>
<tr>
<td>Radio</td>
<td>ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ACTA, OVRO, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS, BOOTES-5, Zadko, Telescopes: Teli, AAT, SALT, ESO-NTT, SOAR, ESO-VLT, Katama Telescope, HST</td>
</tr>
</tbody>
</table>

 normalized $F_\lambda$

$w$ wavelength (Å)

<table>
<thead>
<tr>
<th>1M2H Swope</th>
<th>DLT40</th>
<th>VISTA</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.86h $i$</td>
<td>11.08h $h$</td>
<td>11.24h $YJK_s$</td>
</tr>
<tr>
<td>MASTER</td>
<td>DECam</td>
<td>Las Cumbres</td>
</tr>
<tr>
<td>11.31h $W$</td>
<td>11.40h $iz$</td>
<td>11.57h $w$</td>
</tr>
</tbody>
</table>

Chandra: 9d X-ray

J VLA: 16.4d Radio
What we’ve learned from GW170817

From gravitational waves:

• Astrophysical rate of BNS mergers $R = 1540^{+3200}_{-1220}$ Gpc$^{-3}$ yr$^{-1}$
• Stochastic background from BNS and BBH mergers should be detectable with current generation of detectors at design sensitivity!
• Limits on dynamical ejecta in the associated kilonova.
• To come: improved constraints on deviations from general relativity using much longer duration waveform.
• To come: insight on the remnant object from the post-merger GW signal.

Companion papers:

2. GW170817: Implications for the Stochastic Gravitational-Wave Background from Compact Binary Coalescences. arXiv 1710.05837
What we’ve learned from GW170817

From multi-messenger observations:

• Confirmation of association between short GRBs and BNS mergers.
• Independent measurement of the Hubble constant consistent with prior measurements.
• Speed of gravity is consistent with speed of light to one part in $10^{15}$.
• Improved Lorentz invariance limits; constrained to one part in $10^{13}$.
• New insights into physics of gamma-ray burst events.
• Constraints on progenitors and the evolution of the BNS pair.
• BNS mergers as producers of heavy elements confirmed.
• More to come - see Kasliwal/Hallinan CaJAGWR seminar on Nov 7!

Companion papers:

5. *Search for High-energy Neutrinos from Binary Neutron Star Merger GW170817 with ANTARES, IceCube, and the Pierre Auger Observatory.* arXiv 1710.05839
Independent measurement of the Hubble constant
Future challenges: targeting transient noise

gravityspy.org
Zevin et al, CQG (2017)
LIGO-Livingston transient noise during the second observing run
Understanding the impact of transient noise on estimation of source properties

Minimum 90% confidence sky area (2 seconds before the scattering noise feature): 300 sq. deg.

Maximum 90% confidence sky area: (During the first 0.5 seconds of the scattering noise): 540 sq. deg.

Parameter estimation produced with the lalinference pipeline: arXiv 1409.7215

McIver et al. (in prep)
The future of gravitational wave astronomy
Roadmap to design sensitivity

Advanced LIGO

Strain noise amplitude/Hz$^{-1/2}$

Frequency/Hz

Advanced Virgo

Strain noise amplitude/Hz$^{-1/2}$

Frequency/Hz

arXiv 1304.0670
Future prospects: the global GW network

Gravitational Wave Observatories

- LIGO Hanford
- LIGO Livingston
- Virgo
- GEO600
- KAGRA
- LIGO India

- Operational
- Under Construction
- Planned
Future prospects for terrestrial gravitational wave astronomy

B. P. Abbott et al. CQG 34 (2017)
Beyond terrestrial detectors
Pulsar Timing Arrays
The International Pulsar Timing Array

Green Bank Telescope, WV, US
Arecibo Observatory, PR, US
Nancay Radio Telescope, Nancay, France
Lovell Telescope, Cheshire, UK
Parkes Observatory, Parkes, Australia
LOFAR, Exloo, Netherlands
GMRT, Pune, India
WSRT, Westerbork, Netherlands
Effelsberg 100-m Radio Telescope, Effelsberg, Germany
The future of gravitational wave astrophysics is bright!