LIGO-Virgo Gravitational-Wave Findings So Far, and Current Events

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February 19, 2020
LIGO = Laser Interferometer Gravitational-wave Observatory

LIGO Hanford Observatory
Two LIGO Observatories

LIGO Hanford

LIGO Livingston Observatory
Plus the Virgo Observatory in Italy

Having three detectors significantly improves our ability to confidently detect weak sources and to locate them in the sky.
Improving detectors over time to reduce the noise level

Initial LIGO (2002-2010)

Advanced LIGO (as of 2015)

$10^{-23}$ amplitude spectral density!
Advanced Detector Observing Runs

**O1** — *September 12, 2015 to January 19, 2016*

LIGO Hanford and Livingston

**O2** — *November 30, 2016 to August 25, 2017*

Initially, just the two LIGO observatories
Virgo joined on August 1, 2017

**O3** — *Began April 1, 2019*

Both LIGO observatories plus Virgo
Ten binary black hole mergers detected in O1+O2!

Masses in the Stellar Graveyard
in Solar Masses

LIGO-Virgo Black Holes

EM Black Holes

LIGO-Virgo | Frank Elavsky | Northwestern

Browse events at https://ligo.northwestern.edu/media/mass-plot/index.html
Highlights: Binary Black Hole Mergers
Exploring the Properties of GW Events

Bayesian parameter estimation: Adjust physical parameters of waveform model to see what fits the data from all detectors well

- Get ranges of likely ("credible") parameter values

Illustration by N. Cornish and T. Littenberg
Mass ratio \( (q) \) consistent with 1 for all these events, but with significant uncertainty.

The data determines “chirp mass” best for low-mass BBHs, and total mass best for high-mass BBHs.

[Abbott et al. 2019, PRX 9, 031040]
Want to infer true population of merging BBH systems from observed events

Simulating detectable range, which depends strongly on masses

Different models can fit the data, but they tend to drop off around $45 \ M_{\odot}$ for $m_1$

Caution: model-dependent, including assumptions about $q$ and spin distribution (not shown here)

Stellar evolution models suggest that remnant BHs only span a certain mass range. Above \( \sim 125 \, M_\odot \), stars are disrupted in pair instability or pulsational pair instability supernova.
A key parameter that could help distinguish among different formation pathways:

- A massive binary star system with sequential core-collapses
- Chemically homogeneous evolution of a pair of massive stars in close orbit
- Dynamical formation of binary from two BHs in a dense star cluster
- Binaries formed from a population of primordial black holes

The data determines an “effective spin” parameter $\chi_{\text{eff}}$ the best

$$\chi_{\text{eff}} = \frac{c}{G} \left( \frac{S_1}{m_1} + \frac{S_2}{m_2} \right) \cdot \frac{\hat{L}}{M}$$

Most of our BBH have $\chi_{\text{eff}}$ consistent with 0, though two (GW151226 and GW170729) evidently have nonzero values

[Abbott et al. 2019, PRX 9, 031040]
Highlights: Binary Neutron Star Merger
August 17, 2017: a binary neutron star merger!

GW170817

Initially found using a template with typical neutron star masses

And coincident (within ~2 sec) with a short gamma-ray burst (GRB) detected by the GBM instrument on the Fermi satellite!

Visible in LIGO spectrograms!

We located it in the sky it pretty well

To an area of ~31 deg$^2$ (after working around a glitch in the LIGO-Livingston data), ultimately to ~16 deg$^2$

[Abbott et al. 2017, PRL 119, 161101]
Astronomers found the optical counterpart!

Independently found by 6 teams, within a span of \(~45\) minutes, in the galaxy NGC 4993

GRB 170817A / AT2017gfo Electromagnetic Signatures

**Gamma-Ray Burst**

Pretty typical observed properties, but very dim (i.e., low $E_{iso}$) considering how close it was

**Kilonova**

Thermal emission from ejected material, heated by decay of $r$-process elements formed in event

**Afterglow**

Slow onset and rise, constant spectral index completes picture of a successful off-axis jet
Implication for heavy elements

In the past few years, it has become clear that neutron star mergers—not supernovae—produce most of the very heavy elements

“r-process nucleosynthesis” from rapid neutron capture

[Figure from Wikipedia “r-process” article]
GR relates absolute GW signal amplitude to luminosity distance

... assuming that other source parameters are known: masses, orbit inclination angle, etc.

→ A binary merger is a “standard siren”, measuring distance
  (but with uncertainty if other source parameter aren’t known precisely)

Using GW170817, combining the GW distance estimate with measured redshift of its host galaxy NGC 4993, we measured the Hubble constant:

→ $H_0 = 70^{+12}_{-8}$ km/s per megaparsec

The uncertainty here is dominated by the unknown inclination of the binary orbit; using radio VLBI or kilonova observations allows one to constrain it further

Using statistical association of GW170814 with galaxies cataloged by the Dark Energy Survey

Using statistical method with 5 BBH mergers and galaxy catalogs, combined with GW170817

The BBH sample is pretty weak at this point…


[Abbott et al., arXiv:1908.06060]
Other Analyses and GW Signal Searches
Tests of GR

Speed of gravitational waves vs. light

Upper limit on the mass of the graviton (if it exists): \( 4.7 \times 10^{23} \text{ eV/c}^2 \) (combined analysis)

Inspiral waveform deviations due to dipole gravitational radiation, or as arbitrary deviations from post-Newtonian expansion coefficients

Limits on alternate polarizations in GW signal

[Abbott et al. 2019, PRL 123, 011102]

Searches for Other Transient GW Signals

Multi-messenger searches for GW signals associated with:
- GRBs (other than GRB 170817A)
- Magnetar flares
- Nearby core-collapse supernovae

Search for sub-solar-mass binary mergers
- Dark matter could be primordial BBH systems?

Searches for more general GW burst signals
- Short-duration (less than a few seconds)
- Long-duration
- Intermediate-mass binary black holes
- Eccentric binary black holes
  [Abbott et al. PRD 100, 024017; PRD 99, 104033; PRD 100, 064064; ApJ 883, 149]
Searches for Continuous GW Signals

Quasiperiodic GW signals from rotating neutron stars

GW emission requires a small deviation from axisymmetry

Search for GWs from known radio pulsars at the pulsar’s rotation frequency, at twice the rotation frequency, and in a narrow frequency band \[\text{[Abbott et al., PRD 100, 024004; PRD 99, 122002]}\]

Search over a wide parameter space for quasiperiodic GWs coming from Sco X-1, which is the brightest low-mass X-ray binary (LMXB) \[\text{[Abbott et al., arXiv:1906.12040]}\]

All-sky isotropic and directional searches for a stochastic GW background

Constrain energy density of background GWs: \(\Omega_{GW} < 6.0 \times 10^{-8}\) (assuming flat in frequency)

Directional: (for different power-law indices) \[\text{[Abbott et al. 2019, PRD 100, 061101(R); PRD 100, 062001]}\]
Current and Future Observations
The detectors were down for ~1.5 years for lots of work:

- Test mass and reaction mass replacements
- Test mass “acoustic mode” dampers
- Better control of scattered light
- Laser upgrade
- **Squeezed light** source installation
- Large gate valve repair
- etc.

The O3 observing run began on April 1, 2019 and will run through April 30, 2020
How detection rate scales with range

O3 has ~30% greater range than O1/O2

\[ (1.3)^3 = 2.2 \text{ times the volume} \]
How have we done in O3 so far?

You can find detector status pages, public (O1+O2) data and analysis tutorials at www.gw-openscience.org
LIGO/Virgo O3 Public Alerts

Detection candidates: 52

as of today


<table>
<thead>
<tr>
<th>Event ID</th>
<th>Possible Source (Probability)</th>
<th>UTC</th>
<th>GCN</th>
<th>Location</th>
<th>FAR</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>S200219ae</td>
<td>BBH (96%), Terrestrial (4%)</td>
<td>Feb. 19, 2020</td>
<td>UTC</td>
<td></td>
<td>1 per 2.3819 years</td>
<td></td>
</tr>
<tr>
<td>S200213r</td>
<td>BNS (63%), Terrestrial (37%)</td>
<td>Feb. 13, 2020</td>
<td>UTC</td>
<td></td>
<td>1 per 1.7934 years</td>
<td></td>
</tr>
<tr>
<td>S200208q</td>
<td>BBH (90%)</td>
<td>Feb. 8, 2020</td>
<td>UTC</td>
<td></td>
<td>1 per 12.587 years</td>
<td></td>
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<tr>
<td>S200129m</td>
<td>BBH (&gt;99%)</td>
<td>Jan. 29, 2020</td>
<td>UTC</td>
<td></td>
<td>1 per 4.7313e+23 years</td>
<td></td>
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<tr>
<td>S200128d</td>
<td>BBH (97%), Terrestrial (3%)</td>
<td>Jan. 25, 2020</td>
<td>UTC</td>
<td></td>
<td>1 per 1.0238 years</td>
<td></td>
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<tr>
<td>S200116ah</td>
<td>NSBH (&gt;99%)</td>
<td>Jan. 16, 2020</td>
<td>UTC</td>
<td></td>
<td>1 per 15618 years</td>
<td>RETRACTED</td>
</tr>
</tbody>
</table>
Out of the 51 (non-retracted) candidates shared in public alerts so far:

- 34 BBH candidates (mostly strong detections)
- 5 BNS candidates
- 6 NS-BH candidates
- 3 “mass gap” candidates
- 3 most likely terrestrial

But note that the majority of BNS and NS-BH candidates are fairly marginal
Best O3 binary neutron star candidate so far: S190425z

Binary neutron star merger detected strongly by LIGO Livingston, and weakly (sub-threshold) by Virgo. (LIGO Hanford was off 😞)
Confirmed! GW190425, our first published detection of O3

Not as strong an event as GW170817, but clearly separated from background (noise)

Total mass $\sim 3.4 M_\odot$!
(Larger than any other known BNS system)

S190814bv: Likely neutron star–black hole mixed binary!

Detected rather confidently by both LIGO detectors and Virgo

Astronomers looked for and followed up potential counterparts, but nothing convincing...
Over 100 “circulars” (rapid communications) about this event were issued
Expanding the network of Advanced GW detectors

2015
LIGO Hanford

2015
LIGO Livingston

2011
GEO-HF

2017
Virgo

~2025
KACRA

~2025
LIGO India

3 separate collaborations working together
Further Advanced LIGO / Virgo commissioning and upgrades are in progress

Including the **A+ Project** and Advanced Virgo Plus

The KAGRA detector in Japan is currently being commissioned

A site has been selected for the LIGO-India observatory, and ground will be broken soon

→ By the mid-2020s, will have five highly sensitive detectors distributed around the Earth

Third-Generation GW Detectors

Being pursued as a globally coordinated effort under the auspices of a subcommittee of the Gravitational Wave International Committee, **GWIC 3G**

- **Einstein Telescope** (European project)
  - Underground triangular array of detectors
- **Cosmic Explorer** (U.S. project)
  - Surface detector with arms up to 40 km long

Could begin operating around 2030
After decades of patient work, we’ve confirmed another major prediction of GR and launched a new kind of astronomy!

So far, we have detected a few dozen binary black hole mergers, at least two binary neutron stars, and at least one likely BH-NS

- We have tested detailed predictions from General Relativity
- We’re getting a picture of the population of merging black holes
- Our very first binary neutron star merger was accompanied by a spectacular counterpart observed at all electromagnetic wavelengths

The O3 run continues to give us about one event per week

… and the international GW detector network is on track to grow

Learn more at www.ligo.org
Extra slides
# The Wide Spectrum of Gravitational Waves

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>Likely Sources</th>
<th>Detection Method</th>
<th>Projects</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sim 10^{-17}$ Hz</td>
<td>Primordial GWs from inflation era</td>
<td>B-mode polarization patterns in cosmic microwave background</td>
<td>BICEP2/Keck, ACT, EBEX, POLARBEAR, SPTpol, SPIDER, ...</td>
</tr>
<tr>
<td>$\sim 10^{-8}$ Hz</td>
<td>Cosmic strings?</td>
<td>Pulsar Timing Array (PTA) campaigns</td>
<td>NANOGrav, European PTA, Parkes PTA</td>
</tr>
<tr>
<td>$\sim 10^{-2}$ Hz</td>
<td>Ultra-compact Galactic binaries</td>
<td>Interferometry between spacecraft</td>
<td>AEI/MM/exozet</td>
</tr>
<tr>
<td>$\sim 100$ Hz</td>
<td>Spinning NSs, Stellar core collapse</td>
<td>Ground-based interferometry</td>
<td>LIGO, GEO 600, Virgo, KAGRA</td>
</tr>
</tbody>
</table>

**Gravitational radiation driven Binary Inspiral + Merger**
- Supermassive BHs
- Massive BHs, extreme mass ratios
- Neutron stars, stellar-mass BHs
Gravitational wave detection with spacecraft: LISA

Use laser interferometry to measure changes in the distances among a trio of spacecraft in orbit around the Sun

Forms two independent Michelson interferometers plus a Sagnac null channel

~milliHertz sources:

- Supermassive black hole binaries
- Intermediate mass BH binaries
- Extreme mass ratio inspirals (maps spacetime near BH)
- Galactic compact binaries
- Stochastic GW background?

[Danzmann et al. 2017, LISA Proposal to ESA]