LIGO’s Black Holes

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LIGO is awesome

Abbott+, PRL 116, 131103 (2016)
GW150914 is awesome

Abbott+., PRL 116, 061102 (2016)
O1: First science run

- September 12, 2015 to January 19, 2016
- ~50 days of good quality, coincident data
- Total of 2.87 events:
  - GW150914, GW151226, LVT151012
- >20 collaboration papers
O2: LIGO currently operating*

- Second observing run started November 30, 2016
- Will run until August 25, 2017
- LIGO has issued some alerts to EM partners
- No public announcements yet

*In 3 hours LIGO turns off for a ~2 week commissioning break
O1: 2.9 interesting sources

LIGO's first observing run
September 12, 2015 - January 19, 2016

- September 14, 2015 CONFIRMED
- October 12, 2015 CANDIDATE
- December 26, 2015 CONFIRMED
Does general relativity work?
Are they really black holes? Yes!

- Whitened data
- Wavelet is unmodeled sine-Gaussian (no general relativity)
- BBH template is general relativity
- Agreement between Wavelet and GR!

Abbott+, PRL 116, 241102 (2016)
Does general relativity work? Yes!

- Subtract best-fit waveform from the data
- Search for an “unmodeled” source
- Nothing is left but noise: GR describes the signal!

Inspiral is consistent with merger+ringdown

Weak evidence for rindgown
What have we detected?
LIGO black hole parameters

Abbott+, *PRX* 6, 041015 (2016)
Spins of the three events

Not all BHs in the Universe are extremal Kerr!

Abbott+, *PRX* 6, 041015 (2016)

Not all BHs in the Universe are Schwarzschild!
BBH event rate density

- Combined rate of \( \lesssim 10 \, \text{yr}^{-1} \, \text{Gpc}^{-3} \) is excluded
- Will improve rapidly with additional observations

Abbott+, *PRX* 6, 041015 (2016)
How does the Universe make these black holes?
Was GW150914 a surprise?

ABSTRACT

The unprecedented range of second-generation gravitational-wave (GW) observatories calls for refining the predictions of potential sources and detection rates. The coalescence of double compact objects (DCOs)—i.e., neutron star–neutron star (NS–NS), black hole–neutron star (BH–NS), and black hole–black hole (BH–BH) binary systems—is the most promising source of GWs for these detectors. We compute detection rates of coalescing DCOs in second-generation GW detectors using the latest models for their cosmological evolution, and implementing inspiral-merger-ringdown gravitational waveform models in our signal-to-noise ratio calculations. We find that (1) the inclusion of the merger/ringdown portion of the signal does not significantly affect rates for NS–NS and BH–NS systems, but it boosts rates by a factor of \( \sim 1.5 \) for BH–BH systems; (2) in almost all of our models BH–BH systems yield by far the largest rates, followed by NS–NS and BH–NS systems, respectively; and (3) a majority of the detectable BH–BH systems were formed in the early universe in low-metallicity environments. We make predictions for the distributions of detected binaries and discuss what the first GW detections will teach us about the astrophysics underlying binary formation and evolution.
Was GW150914 a surprise?

COMPACT BINARY MERGER RATES: COMPARISON WITH LIGO/VIRGO UPPER LIMITS

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ABSTRACT

We compare evolutionary predictions of double compact object merger rate densities with initial and forthcoming LIGO/Virgo upper limits. We find that: (i) Due to the cosmological reach of advanced detectors, current conversion methods of population synthesis predictions into merger rate densities are insufficient. (ii) Our optimistic models are a factor of 18 below the initial LIGO/Virgo upper limits for BH–BH systems, indicating that a modest increase in observational sensitivity (by a factor of ~2.5) may bring the first detections or first gravitational wave constraints on binary evolution. (iii) Stellar-origin massive BH–BH mergers should dominate event rates in advanced LIGO/Virgo and can be detected out to redshift z ∼ 2 with templates including inspiral, merger, and ringdown. Normal stars (<150 M⊙) can produce such mergers with total redshifted mass up to M_{tot,z} ∼ 400 M⊙. (iv) High black hole (BH) natal kicks can severely limit the formation of massive BH–BH systems (both in isolated binary and in dynamical dense cluster evolution), and thus would eliminate detection of these systems even at full advanced LIGO/Virgo sensitivity. We find that low and high BH natal kicks are allowed by current observational electromagnetic constraints. (v) The majority of our models yield detections of all types of
Two formation channels

Isolated
- Progenitors stars form in binary
- Mass transfer, supernovae, common-envelope (or homogeneous evolution? Pop III?)

Dynamical
- Black holes segregate towards center
- Dynamical interaction: black holes form binaries, three body interactions harden and (sometimes) eject binaries
How did the Universe make these black holes?

- Example of a binary similar to GW150914, from birth, through evolution, to merger
- Lots of complicated astrophysics!

Can we see these sources?
Looking for counterparts to GW150914

- Alert sent within 48 hours (for first GW event ever, and during engineering run)
- Over 20 EM partners responded
Dark Energy Camera follow-up

- EM follow-up effort led by Edo Berger (Harvard) and Marcelle Soares-Santos (FNAL)
- Wide-field deep instrument: ideal for GW follow-up
- 3 deg² field-of-view on 4 meter telescope
- Existing subtraction pipelines and template data (for supernovae)
DECam follow-up

- Covered ~100 deg$^2$ to ~22 mag (i and z band)
- Covered ~38%/11% of initial/final probability map

Basic problem:
localization areas are too big!!
What happens next?
LIGO’s future

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<tbody>
<tr>
<td>Estimated run duration</td>
<td>4 months</td>
<td>6 months</td>
<td>9 months</td>
<td>(per year)</td>
<td>(per year)</td>
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<tr>
<td>BNS range/Mpc LIGO</td>
<td>40–80</td>
<td>80–120</td>
<td>120–170</td>
<td>200</td>
<td>200</td>
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<tr>
<td>Virgo</td>
<td>—</td>
<td>20–60</td>
<td>60–85</td>
<td>65–115</td>
<td>130</td>
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<tr>
<td>Estimated BNS detections</td>
<td>0.0005–4</td>
<td>0.006–20</td>
<td>0.04–100</td>
<td>0.2–200</td>
<td>0.4–400</td>
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<tr>
<td>90% CR % within 5 deg²</td>
<td>&lt; 1</td>
<td>2</td>
<td>&gt; 1–2</td>
<td>&gt; 3–8</td>
<td>&gt; 20</td>
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<tr>
<td>20 deg²</td>
<td>&lt; 1</td>
<td>14</td>
<td>&gt; 10</td>
<td>&gt; 8–30</td>
<td>&gt; 50</td>
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<tr>
<td>median/deg²</td>
<td>480</td>
<td>230</td>
<td>—</td>
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Abbott+, LRR 2016

Many more events. Much better localization. High SNR events. Neutron star systems? Surprises?
Sky areas will get smaller

- Virgo, and other additional detectors, would dramatically improve localization
Finding the one


Low latency 3D localization: sky location + distance

Some sources are very well localized

Can find unique host galaxy!

- Solid: HLV O3
- Dashed: HLVJl design
- Dotted: HLV design

BBH
- (10/10)

BBH
- (30/30)
Final mass and spin

Final spins are well constrained

Are the LIGO BHs made from smaller BHs?


- Orbital angular momentum dominates
- Universal distribution of final black hole spin, robust to changes in initial spins, mass ratio, number of mergers, etc.

**Probably not**
Where is GW astro headed?

- tens or hundreds of detections
- mass/mass ratio distribution
- spin/spin alignment distribution
- rate/evolution with redshift
- constrain models of BH formation/evolution
- NSs? mass gap? EOS?
- EM counterparts?
- host galaxy properties?
- standard sirens/H₀?
- test gravity with high-SNR golden events
- stochastic background?
- supernovae?
- surprises?!