Gravitational Waves from the First Observing Run of the advanced LIGO

Hyung Mok Lee
Seoul National University

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Outline

• The Observing Runs of the advanced LIGO

• Two GW events and one candidate
  • GW 150914/GW151226
  • LVT151012

• Implications
  • Binary Black Holes
  • Background Gravitational Waves

• Prospects
O1 Sensitivity

![Graph showing O1 Sensitivity](image-url)
The 1st Observing Run

- September 12, 2015 - January 19, 2016
- Total coincidence analysis time: 51.5 days
- Total coincidence analysis time after removing noisy data: 48.6 days (~38%)
- Two analysis pipelines: PyCBC and GstLAL
  - PyCBC analysis: 46.1 days
  - GstLAL analysis: 48.3 days
GW Events from O1
(arXiv1606.0485)

- GW150914 (>5.3σ)
- LVT151012 (Candidate, 1.7σ)
- GW151226 (>5.3σ)
Significance of the events
Abbott et al., arXiv:1606.04856v1

[Diagrams showing the detection statistics for PyCBC and GstLAL
for different events GW150914 and GW151226.
Graphs compare search results with background models.
]
Derived parameters of the events

Abbott et al., arXiv:1606.04856v1

<table>
<thead>
<tr>
<th>Event</th>
<th>GW150914</th>
<th>GW151226</th>
<th>LVT151012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal-to-noise ratio $\rho$</td>
<td>23.7</td>
<td>13.0</td>
<td>9.7</td>
</tr>
<tr>
<td>False alarm rate FAR/yr$^{-1}$</td>
<td>$&lt; 6.0 \times 10^{-7}$</td>
<td>$&lt; 6.0 \times 10^{-7}$</td>
<td>0.37</td>
</tr>
<tr>
<td>p-value</td>
<td>$7.5 \times 10^{-8}$</td>
<td>$7.5 \times 10^{-8}$</td>
<td>0.045</td>
</tr>
<tr>
<td>Significance</td>
<td>$&gt; 5.3\sigma$</td>
<td>$&gt; 5.3\sigma$</td>
<td>$1.7\sigma$</td>
</tr>
<tr>
<td>Primary mass $m_1$/$M_\odot$</td>
<td>$36.2^{+5.2}_{-3.8}$</td>
<td>$14.2^{+8.3}_{-3.7}$</td>
<td>$23^{+18}_{-6}$</td>
</tr>
<tr>
<td>Secondary mass $m_2$/$M_\odot$</td>
<td>$29.1^{+3.7}_{-4.4}$</td>
<td>$7.5^{+2.3}_{-2.3}$</td>
<td>$13^{+4}_{-5}$</td>
</tr>
<tr>
<td>Chirp mass $\mathcal{M}$/$M_\odot$</td>
<td>$28.1^{+1.8}_{-1.5}$</td>
<td>$8.9^{+0.3}_{-0.3}$</td>
<td>$15.1^{+1.4}_{-1.1}$</td>
</tr>
<tr>
<td>Total mass $M$/$M_\odot$</td>
<td>$65.3^{+4.1}_{-3.4}$</td>
<td>$21.8^{+5.9}_{-1.7}$</td>
<td>$37^{+13}_{-4}$</td>
</tr>
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<td>---------------</td>
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<td>-----------</td>
</tr>
<tr>
<td>Effective inspiral spin $\chi_{\text{eff}}$</td>
<td>$-0.06^{+0.14}_{-0.14}$</td>
<td>$0.21^{+0.20}_{-0.10}$</td>
<td>$0.0^{+0.3}_{-0.2}$</td>
</tr>
<tr>
<td>Final mass $M_f^{\text{source}}/M_\odot$</td>
<td>$62.3^{+3.7}_{-3.1}$</td>
<td>$20.8^{+6.1}_{-1.7}$</td>
<td>$35^{+14}_{-4}$</td>
</tr>
<tr>
<td>Final spin $a_f$</td>
<td>$0.68^{+0.05}_{-0.06}$</td>
<td>$0.74^{+0.06}_{-0.06}$</td>
<td>$0.66^{+0.09}_{-0.10}$</td>
</tr>
<tr>
<td>Radiated energy $E_{\text{rad}}/(M_\odot c^2)$</td>
<td>$3.0^{+0.5}_{-0.4}$</td>
<td>$1.0^{+0.1}_{-0.2}$</td>
<td>$1.5^{+0.3}_{-0.4}$</td>
</tr>
<tr>
<td>Peak luminosity $\ell_{\text{peak}}/(\text{erg s}^{-1})$</td>
<td>$3.6^{+0.5}_{-0.4} \times 10^{56}$</td>
<td>$3.3^{+0.8}_{-1.6} \times 10^{56}$</td>
<td>$3.1^{+0.8}_{-1.8} \times 10^{56}$</td>
</tr>
<tr>
<td>Luminosity distance $D_L/\text{Mpc}$</td>
<td>$420^{+150}_{-180}$</td>
<td>$440^{+180}_{-190}$</td>
<td>$1000^{+500}_{-500}$</td>
</tr>
<tr>
<td>Source redshift $z$</td>
<td>$0.09^{+0.03}_{-0.04}$</td>
<td>$0.09^{+0.03}_{-0.04}$</td>
<td>$0.20^{+0.09}_{-0.09}$</td>
</tr>
<tr>
<td>Sky localization $\Delta\Omega/\text{deg}^2$</td>
<td>230</td>
<td>850</td>
<td>1600</td>
</tr>
</tbody>
</table>
Posterior probability densities

Abbott et al., arXiv:1606.04856v1

LIGO Scientific Collaboration

VIRGO
What O1 results tell us?

- Existence of stellar mass black holes in binaries
- Individual masses in wide range (7-35 Msun)
- How often BH merger takes place?
  - 9-240 yr^{-1} Gpc^{-1}
Black Hole Masses

- BH mass depends on metallicity
- Maximum mass of BH ~ 40 $M_\odot$ for $Z<0.1 \ Z_\odot$.
- GW150914 could have been formed when the universe was young or in low metallicity galaxies
- Origin:
  - Dynamical (e.g., Bae et al. 2014)
  - Coevolved (e.g., Belczynski et al. 2015, 2016)

Data provided by Belczynski
Effects of BH Mass Function on Mass Ratios of Dynamical BBH (Park et al. in preparation)

- Preliminary results with Belczinski’s BH mass function
  - Massive BHs sink toward the core first, and form binaries
  - Less massive ones follow sequentially
  - BH mass ratio remain close to 1: most binaries have mass ratio less than 2

\[ Z = 0.1 Z_\odot \]

GW151226 Preliminary!
GW background

• Incoherent superposition of merging BH could generate stochastic GW background

\[ \Omega_{GW}(f) \equiv \frac{f}{\rho_c} \frac{d\rho_{GW}}{df} \]

• Consider a BBH of class \( k \) with parameters \( \theta_k \) merge at a rate \( R_m(z; \theta_k) \) per unit comoving volume, then \( \Omega_{GW} \) can be obtained by

\[ \Omega_{GW}(f) \equiv \frac{f}{\rho_c H_0} \int_0^{\infty} dz \frac{R_m(z, \theta_k) dE_{GW}}{df_s}(f_s, \theta_k) \frac{(1 + z) E(\Omega_M, \Omega_\Lambda, z)}{(1 + z) E(\Omega_M, \Omega_\Lambda, z)} \]

• \( E(\Omega_M, \Omega_\Lambda, z) \) captures the dependence of comoving volume on \( z \).

• Fiducial model based on GW150914: mass, rates, spin, etc. and

\[ R = 16 \text{Gpc}^{-3} \text{yr}^{-1} \]
Detectability

• Expected sensitivity of LIGO and Virgo detectors to the fiducial model based on GW150914 mass
  • 33% coincidence for O1 and 50% for all other runs
• The estimation of $\Omega_{GW}$ does not change significantly with GW151226.

Abbott et al. 2016, PRL, 116, 131102, GW150914 only
Prospects

- O2 (from November 2016) ~ 6 months
- O3: 2017, ~9 Months
- More detections will follow in the upcoming runs
- Accumulation of BBH events will enable us to constrain formation models, etc.
- We may be able to detect GW background in the near future.

Abbott et al., arXiv:1606.04856v1
LIGO Upgrade Plan (LIGO-T1400316)

- LIGO sensitivity can increase x 1.5 with moderate upgrade (A+)
- Factor of 3 increase will require major upgrade (Voyager)
- Order of magnitude upgrade will require a new detector (Cosmic explorer)
- Recently a new detector with 8km in Australia with existing technologies was proposed (Blair et al. 2015, Hopewell et al. 2016)
With 8 km detector

- Horizon distance will increase $\sim x 4$
- Detection rate will increase $x 64$: $\sim$ a few 1000 per year

Figures from Hopewell et al., in prep.
Cosmology with GW

- Luminosity distance can be determined with GW data alone.
- If host galaxy is identified, we can derive $z-d_L$ relation.
- Within $d_L \sim 0.4$ Gpc ($z \sim 0.09$), more than 20% source can be localized within 0.1 sq. deg.
  - There would be $\sim 3$ Milky-like galaxies within the error circle.
  - Number of galaxies grows with $z^4$ within error circle: distant GW sources are increasingly difficult to localize.
- How about Neutron star mergers?
  - EM followup will enable us to identify host galaxies more easily
  - Horizon would be $\sim 1$ Gpc with 8km detector

Assuming 8km detector in Australia, GW150914-like source (Hopewell et al. in preparation)
Superconducting tensor GW Detector

Superconducting Omni-directional Gravitational Radiation Observatory (SOGRO)

By detecting all six components of the Riemann tensor, the source direction and the polarization can be determined.

\[
h_{ij}(t) = \frac{1}{L} \left[ x + ij(t) x_{ij}(t) \right] \left[ x + ji(t) x_{ji}(t) \right]
\]

Detectors and Sources at other frequency bands

http://rhcole.com/apps/GWplotter/
Low-frequency detector and GW150914

~1 week before September 14, 2015

Paik et al. 2016, CQG, 33, 075003
Summary

• GW150914:
  • First Unambiguous detection of stellar mass black holes and a BH binary
  • Accurate measurement of black hole masses (within ~10%)
  • Higher mass of stellar mass BH than previously thought: low metallicity environment?
• GW151226:
  • Lower masses than GW150914, similar to the X-ray binary BH mass
  • Lower mass progenitor or high metallicity environment?
• Origin
  • Coevolved or dynamical?: Cannot be constrained yet
• Prospects
  • Frequent detections are expected with forthcoming observing runs
  • Sensitive detectors in the near future will enable us to observe more distant sources
  • Low frequency GW detectors will enable us to observe more massive black holes