Results from the 1st Advanced LIGO observing run and their astrophysical implications

Tyson B. Littenberg
NASA Marshall Space Flight Center

for the LIGO Scientific Collaboration & Virgo Collaboration
LIGO-G1602091
The chirp heard ‘round the world

[Graph showing strain over time for Hanford, Washington (H1) and Livingston, Louisiana (L1).]
LIGO’s First Observing Run (O1)

- **September 14, 2015** confirmed
- **October 12, 2015** candidate
- **December 26, 2015** confirmed

LIGO’s first observing run

September 12, 2015 - January 19, 2016

- September 2015
- October 2015
- November 2015
- December 2015
- January 2016
Binary black holes in O1

Naming GW events:

XXYYMMDD

LVT=candidate
GW=confirmed

Date of detection

Finding BBHs in the data

- GW150914 and GW151226 were both > 5-sigma detections
BBH Characterization

Mass & Spin

\[ m_1 \quad m_2 \]

\[ S_1 \quad S_2 \]
BBH Characterization — Masses

component masses [measured]

remnant mass & spin [~predicted]
BBH Characterization — Spins

- Primary
- Secondary
- Magnitude
- Misalignment
BBH Characterization — Spins

- Spin will typically be difficult to pin down precisely except for ideally oriented systems (edge-on)

GW150914  
LVT151012  
GW151226

- GW151226 shows evidence for non-negligible spin of $m_1$, not anti-aligned with $L$
Why is spin so important?
Creating binary black holes

“Field”

“Cluster”

$S_1$ $L$ $S_2$

$S_1$ $S_2$
Creating binary black holes
Why is spin so important?

Spin alignment is a window into the BBH formation channel.
BBH Localization
BBH Localization

- Position reconstruction is a challenge for 2-detector networks.

- This will improve as Virgo and others join the network at comparable sensitivity [see Living Rev. Relativity 19 (2016), 1].
Testing GR

Image credit: NASA/GSFC
Testing GR — consistency tests

- **GW150914** signal was dominated by merger which facilitated some interesting tests:
  - Detectable by excess power searches, enabling analysis of *residuals* after GR model was removed from data.
  - Consistency tests for final mass and spin of remnant black hole
Testing GR — parameterized tests

- Inspiral waveforms computed using post-Newtonian (PN) expansion. Analyses search for departures from the GR values of PN coefficients.

- Additional modification parameters included for late-inspiral, merger, and ringdown stage of the signal.

- So far, measurements are consistent with GR
Inferred rates for BBH


Upper limits on BNS (left)
NSBH (right)

In Summary

What did we learn about the Universe from O1?

- O1 significantly added to the zoo of known stellar-mass black holes

- GW150914 contained the largest stellar-mass black holes ever detected.

- So far, the observed gravitational waves are consistent with Einstein’s general theory of relativity.
What to expect from O2

What we will be asking about black hole mergers:

- How & where are the black holes formed?
- How large can black holes be? How small?
- Are the waves consistent with Einstein’s theory?
- Do they produce any electromagnetic signals?

Space-time volume observed [relative to O1]

Probability of detecting $N$ highly significant events

$N > 10$

$N > 35$

$N > 70$
What to expect from O2

What we will be asking about other transient sources:

- What is the rate of binary neutron star mergers? NSBH?
- Do binary neutron star mergers create GRBs?
- What other sources of GW transients are out there?
Gravitational wave detectors