Black hole observations with Advanced LIGO: status and future plans for the Advanced detector network

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For the LIGO Scientific Collaboration

IAU Symposium, Slovenia
Sept 2016
LIGO’s first observing run
September 12, 2015 - January 19, 2016
Operation of Interferometric Gravitational Wave Detectors

For Typical Astronomical sources

Gravitational wave amplitude

\[ h = \frac{2 \delta l}{l} \leq 10^{-22} \]
Advanced LIGO sensitivity in 1st Observing run

Range ~ 70 Mpc for NS-NS inspiral, averaged over orbital inclination & sky position (~100 Mpc for face-on NS-NS mergers)
Three events compared

PhysRevLett.116.241103,
arxiv.org/abs/1606.04856 (accepted to PRX)
Advanced LIGO Sensitivity: Observing Run 1 vs design sensitivity

Credit: LIGO Laboratory
Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO and Advanced Virgo

Abbott, B. P. et al.
The LIGO Scientific Collaboration and the Virgo Collaboration
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**Figure 1:** aLIGO (left) and AdV (right) target strain sensitivity as a function of frequency. The binary neutron-star (BNS) range, the average distance to which these signals could be detected, is given in megaparsec. Current notions of the progression of sensitivity are given for early, mid and late commissioning phases, as well as the final design sensitivity target and the BNS-optimized sensitivity. While both dates and sensitivity curves are subject to change, the overall progression represents our best current estimates.

2015 – 2016 (O1) A four-month run (beginning 18 September 2015 and ending 12 January 2016) with the two-detector H1L1 network at early aLIGO sensitivity (40 – 80 Mpc BNS range).

2016 – 2017 (O2) A six-month run with H1L1 at 80 – 120 Mpc and V1 at 20 – 60 Mpc.

2017 – 2018 (O3) A nine-month run with H1L1 at 120 – 170 Mpc and V1 at 60 – 85 Mpc.

2019+ Three-detector network with H1L1 at full sensitivity of 200 Mpc and V1 at 65 – 115 Mpc.
The real instrument is far more complex…
» Commissioning ongoing.....
Future BBH observations

Improve the sensitivity of the Advanced LIGO detectors and operate for longer

2nd scientific run “O2” starts in next couple of months

Advanced Virgo should join the observing network soon
Multi-detector network needed for localisation

Projected ranges and detection rates for binary neutron star inspirals - (arXiv:1304.0670)

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Estimated Run Duration</th>
<th>BNS Range (Mpc)</th>
<th>Number of BNS Detections</th>
<th>% BNS Localized within 5 deg²</th>
<th>% BNS Localized within 20 deg²</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>LIGO</td>
<td>Virgo</td>
<td></td>
<td></td>
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<tr>
<td>2015</td>
<td>3 months</td>
<td>40 – 80</td>
<td>–</td>
<td>0.0004 – 3</td>
<td>–</td>
</tr>
<tr>
<td>2016–17</td>
<td>6 months</td>
<td>80 – 120</td>
<td>20 – 60</td>
<td>0.006 – 20</td>
<td>2</td>
</tr>
<tr>
<td>2017–18</td>
<td>9 months</td>
<td>120 – 170</td>
<td>60 – 85</td>
<td>0.04 – 100</td>
<td>1 – 2</td>
</tr>
<tr>
<td>2019+</td>
<td>(per year)</td>
<td>200</td>
<td>65 – 130</td>
<td>0.2 – 200</td>
<td>3 – 8</td>
</tr>
<tr>
<td>2022+ (India)</td>
<td>(per year)</td>
<td>200</td>
<td>130</td>
<td>0.4 – 400</td>
<td>17</td>
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<td>48</td>
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</table>

using “low” rate, worst noise curve

using “high” rate, best noise curve

Wide range of estimates from observed binary pulsars and population synthesis simulations – begs for observational truth!
Sky localization with 3 sites …

Typical 90% error box areas for Neutron Star-Neutron Star binaries

» median > 20 sq deg

Fairhurst, CQG 28 105021 (2011)
What more do we need soon?

Need a network of detectors for good source location and to improve overall sensitivity

‘KAGRA’ New 3km detector in Japan (cryogenic, underground interferometer in Kamioka mine)

Installation of a 3rd Advanced LIGO detector India

Thus Second Generation Network is developing: Advanced LIGO/Advanced Virgo/Geo-HF/KAGRA/LIGO India
Advanced GW Detector Network: Under Construction → Operating

3 separate collaborations working together
The Global Network c. 2020+

- LIGO-H (USA)
- KAGRA (Japan)
- LIGO-L (USA)
- Virgo (Italy)
- LIGO-India
... and with 5 sites

Fairhurst (2011)
Plans for the era of gravitational wave astronomy

- We expect soon to be making regular detections...
- When we do, it is inevitable we will want to see further into the Universe.....see new sources......with better signal-to-noise .....driven by maximising the astronomy and astrophysics we can do

- Planning has started for the next steps.
The global Gravitational Waves roadmap

From the Gravitational Wave International Committee (GWIC roadmap - available at: http://gwic.ligo.org/roadmap/)
Two ‘Dawn’ meetings in May 2015, Maryland, July 2016, Atlanta – consider in various detection scenarios what directions the field should take.

Considered:

- Likelihood of detecting different sources
- Payoffs of improving sensitivity in different frequency bands
- Technological readiness of instrumentation improvements

(....and of course $$/££)
‘Immediate’ targets:

- Mitigation of Newtonian Noise
- Addition of squeezed light
- Improved coating thermal noise
- (and possible suspension upgrades)

For sensitivity gains of up to ~ 5 in event rate over baseline design.

https://dcc.ligo.org/public/0121/P1500147/001/WhatComesNextForLIGO.pdf
Maximising the potential of the field

From the Gravitational Wave International Committee (GWIC roadmap - available at: http://gwic.ligo.org/roadmap/ )
ET should detect of order $10^5$ compact binary coalescences per year: neutron star binaries to $z \sim 2-4$, stellar mass black hole binaries to $z \sim 8-20$, and intermediate mass black holes (up to $10^4$ solar masses) to $z \sim 5-15$.

http://www.stfc.ac.uk/files/2016-draft-roadmap-for-particle-astrophysics/

ET/Cosmic Explorer will take a census of black holes when the Universe was a mere 650 million years old

B. Sathyaprakash, GWADW 2016
Future detector network evolution

- Low temperature operation
- High laser power
What new technologies are needed?

- Longer arms
- Underground site?
- Higher laser powers
- Cryogenic optics for low thermal noise
- Improved mirror coarings
- Larger, heavier optics; non-Gaussian laser beams;
- Laser wavelength (Silicon: 1550nm; fused Silica: 1064nm)
- Frequency dependent 10 dB 'squeezing'
The future

- The field of gravitational-wave astronomy has begun!
- 100s of black hole observations expected in next 5 years

- 2017: Virgo will improve sky sensitivity
- 2020+: LIGO India, Einstein Telescope, LIGO Voyager
- 2030+: Space-based detectors