The Advanced LIGO detectors at the beginning of the new gravitational wave era

Lisa Barsotti
MIT Kavli Institute – LIGO Laboratory
on behalf of the
LIGO Scientific Collaboration

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In this talk

• The Advanced LIGO detectors
• Plans towards the next observing run
• Growing the gravitational wave network
• What’s next – going beyond Advanced LIGO
Gravitational waves cause strain distortion of space-time, Michelson interferometer can measure it.

Gravitational wave (GW) Amplitude

\[ h \sim 10^{-21} \]

Strain over distance \( L \)

\[ L = h \times L = 10^{-21} \times 4000 = 4 \times 10^{18} \text{ m} \]

\[ \frac{L_x}{L} \frac{L_y}{L} = h \]
Advanced LIGO: 2 twins 4 km laser interferometers

LIGO Hanford Observatory (Washington State)
H1 detector

LIGO Livingston Observatory (Louisiana)
L1 detector

Photo Credit: R. Ward, S. Ballmer
The Advanced LIGO detectors

NPRO CW Laser
Nd:YAG @ 1064nm
up to 200W

40 kg fused silica optics
very high optical quality

Up to nearly 1 MW in each arm at full power
to reduce quantum noise
→ about 100 kW during O1

Photo-detector
Test mass suspended by a quadruple pendulum, attached to two stages of active isolation to reduce seismic noise.

Final stage of test mass suspension all fused silica, very high quality factor, designed to reduce thermal noise.

Test masses have dielectric coating material with low mechanical loss to reduce thermal noise.
The Advanced LIGO detectors

More than 300 control loops needed to keep the interferometer optimally running

Interferometer noise + gravitational wave signal
GW 150914

![Graph showing LIGO Hanford and LIGO Livingston frequencies over time.](image_url)
Many noise sources in the 10-100 Hz band

Strain noise during O1: better than ever, not at design sensitivity yet

“Strain Noise” = Detector noise expressed as equivalent GW strain

Sensitivity of the Advanced LIGO detectors at the beginning of gravitational wave astronomy  D. V. Martynov et al. Phys. Rev. D 93, 112004
Observing Run O1
(from mid-September 2015 to mid-January 2016)

- During O1: H1 and L1 operational for ~4 calendar months
- Duty cycle: H1 = 62%, L1 = 55% ➔ H1&L1 = 43%
- 51.5 days of coincident time, 48.6 days after data quality process

The product of observable volume and measurement time exceeded that of all previous runs within the first 16 days of coincident observation.
VIRGO expected to join the network soon

3 km advanced detector
Installation nearly completed

Gravitational Wave Observatories
LIGO-Virgo Observing Plan Overview


Binary Neutron Star ranges

- 65-80 Mpc
- 80-120 Mpc
- 120-170 Mpc
- 200 Mpc

2015 - 2019
Since the end of the first Observing Run O1

- Work to improve the sensitivity:
  - Noise “hunting”: understand and reduce the noise at low frequency
  - Increase the circulating power to reduce quantum noise (several challenges associated with that)

- Data quality improvements

- Interferometer robustness
(Some of) the challenges with high circulating laser power

- Thermal lens in the interferometer mirrors induced by high circulating power require active thermal compensation
- Mirror alignment control
- “Parametric” instabilities: acoustic modes of the mirrors get excited and pump light in high order optical modes, that become resonant in the arms

Observation of Parametric Instability in Advanced LIGO
Projected sensitivity for O2 (this Fall)

PROJECTION!!

15-20% improvement
Binary Black Holes Rates

https://arxiv.org/abs/1606.04856

- O2: projected time volume at least 2/2.5 larger wrt O1
- Expect to see (at least) a few significant events by the end of O2
- Ten(s) of events by the end of O3
The upcoming world-wide network of advanced detectors

LIGO Hanford
LIGO Livingston
GEO600
VIRGO
KAGRA

Gravitational Wave Observatory

LIGO-INDIA approved!

3 km underground test-bed Michelson successfully locked!

3 km advanced detector installation nearly completed

LIGO-India project will establish a state-of-the-art gravitational wave observatory in collaboration with LIGO Laboratory run by Caltech & MIT
Can we do better than advanced detectors?

![Graph showing strain vs. frequency for various noise contributions: LIGO 2010, O1 (2015), Advanced LIGO Design (2019).](image)

- Quantum noise
- Seismic noise
- Gravity Gradients
- Suspension thermal noise
- Coating Brownian noise
- Coating Thermo-optic noise
- Substrate Brownian noise
- Excess Gas
- Total noise
Beyond advanced detectors

- Two complementary strategies: better technologies and longer interferometer arms
- Up to a factor of 2-4 better sensitivity than design in current facility
- Ultimately need new facility with longer baseline for factor of 10+ improvements

European design study: Einstein telescope
Triangular shape, underground
Conclusions

• Advanced LIGO works, and there are gravitational wave signals out there to detect!
• Progression of sensitivity improvements interleaved with observing runs in the near future
• Network of advanced detectors coming on-line in the upcoming years (Virgo, Kagra, LIGO-India)
• World-wide gravitational wave community working to further extend the reach of ground based detectors, for many events and very high SNR
It is just the beginning:
the Gravitational Wave Spectrum

- Relic radiation
- Cosmic Strings
- Supermassive BH Binaries
- BH and NS Binaries
- Binaries coalescences
- Extreme Mass Ratio Inspirals
- Supernovae
- Spinning NS
- Pulsar timing
- Space detectors
- Ground interferometers

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L. Barsotti
GW150914, a discovery in one slide...

- Primary black hole mass: $36^{+5}_{-4} M_\odot$
- Secondary black hole mass: $29^{+4}_{-4} M_\odot$
- Final black hole mass: $62^{+4}_{-4} M_\odot$
- Final black hole spin: $0.67^{+0.05}_{-0.07}$
- Luminosity distance: $410^{+160}_{-180}$ Mpc
- Source redshift, $z$: $0.09^{+0.03}_{-0.04}$
Advanced LIGO Sensitive Volume

- Rate roughly 50 BBH mergers each year in a volume of $1 \text{ Gpc}^3$
- About 10 million galaxies per $\text{Gpc}^3$
- Advanced LIGO range now $\sim 0.1$ to $1 \text{ Gpc}$, depending on system mass

We can expect 5 or more BBH events in the next observing run

Initial Range

Advanced Range
A+: a factor of 2 sensitivity improvement over Advanced LIGO

- Mature technologies available to reduce quantum noise and improve aLIGO sensitivity by ~35% beyond design $\Rightarrow x^{1.35^3} = 2.5$ in rate
  - Squeezed light for gravitational wave detectors:

- Need to reduce thermal noise for maximal benefit:
  - Reducing coating thermal noise as well can lead to a reduction in the noise by a factor of 2
  - Remember: detection rate scales with cube...
  $\Rightarrow x^{2^3} = 8$ in rate!