Observing gravitational waves with Advanced detectors

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on behalf of the LIGO Scientific Collaboration and Virgo
Outline

• Very brief introduction to gravitational waves

• Overview of first generation gravitational wave detectors and science highlights

• Advanced LIGO and Advanced Virgo
  ➢ Progress towards Advanced detector era

• Science with Advanced detectors
  ➢ Gravitational wave astronomy
  ➢ Multi-messenger astronomy
Gravitational waves are generated by moving masses that possess a quadrupole moment of inertia:

$$h \approx \frac{G}{c^2} \frac{M}{d} \left(\frac{v}{c}\right)^2$$

$h \sim 10^{-47}$ @1m

$h \sim 10^{-21}$ @ 100 Mpc

- Need very large mass, moving at relativistic velocities
  - gravity interacts very weakly with matter
What are we trying to measure?

- Gravitational waves have two polarisations
- acts as a strain force
  - squeezes and stretches a ring of test masses
## Gravitational wave sources types

<table>
<thead>
<tr>
<th>Modelled</th>
<th>Unmodelled</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Compact Binary Coalescence</strong></td>
<td><strong>Burst</strong></td>
</tr>
<tr>
<td>Short</td>
<td></td>
</tr>
<tr>
<td>Continuous</td>
<td></td>
</tr>
<tr>
<td>Long</td>
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</tbody>
</table>

- **Compact Binary Coalescence**
  - Modelled: Short
  - Unmodelled: Short

- **Continuous**
  - Modelled: Long
  - Unmodelled: Long

- **Burst**

- **Stochastic**
Gravitational wave spectrum

10^{-16} \text{ Hz} \hspace{2cm} 10^{-9} \text{ Hz} \hspace{2cm} 10^{-4} \text{ Hz} \hspace{2cm} 10^{0} \text{ Hz} \hspace{2cm} 10^{3} \text{ Hz}

- Inflation Probe
- Pulsar timing
- Space detectors
- Ground interferometers

Slide Credit: Matt Evans (MIT)
Gravitational wave spectrum

Relic radiation

Cosmic Strings

Extreme Mass Ratio Inspirals

BH and NS Binaries

Supermassive BH Binaries

Binaries coalescences

Supernovae

Spinning NS

$10^{-16}$ Hz

Inflation Probe

$10^{-9}$ Hz

Pulsar timing

$10^{-4}$ Hz

Space detectors

$10^0$ Hz

$10^3$ Hz

Ground interferometers

Slide Credit: Matt Evans (MIT)
Laser interferometer GW detectors

\[ h \sim \frac{\Delta L}{L} \]
First generation sensitivities

- Strain (1/√Hz)
- Seismic noise
- Suspension thermal noise
- Shot noise

Graph showing sensitivities for different types of noise with frequency axis ranging from 2 Hz to 10^4 Hz.
First generation sensitivities

![Graph showing strain sensitivity vs. frequency for different detectors: LIGO H1 S6, LIGO L1 S6, Virgo (Jul. 2009), and Virgo design (10 W).]
Highlights from the first generation

- Constraints on stochastic gravitational wave background
  - energy density in GW is constrained to be less than $6.7 \times 10^{-6}$ which is better than nucleosynthesis limit, Abbott et al, Nature 2009
- Upper limits on gravitational radiation from pulsars
  - no more than 1% of rotational energy form Crab (10% from Vela) is emitted as gravitational waves, Aasi et al, ApJ 2014
- Absence of gravitational waves in LIGO-Virgo data associated with short GRBs 070201 and 051103
- Constrain rate of compact binary coalesences to within a factor of ~100 of nominal rate
- Demonstrated improved sensitivity from squeezing in large scale interferometers Nature Physics 2011
Science summaries


Example:

SEARCHING FOR THE YOUNGEST NEUTRON STARS IN THE GALAXY

Black holes may be getting all the press these days, but neutron stars are even more complicated and involve more physics. These collapsed stars are almost as compact and therefore as relativistic as black holes, but unlike black holes the matter in them is still visible to the outside universe. The matter in the interior of a neutron star is a hundred trillion times denser than rock, can have magnetic fields a quadrillion times stronger than the Earth does, and may be made of stranger particles than any we see except as brief flashes in particle accelerators. Gravitational waves carry information about that matter more directly than electromagnetic waves (light, x-rays and so on) that only reach us from the surface of the star. Continuous waves in particular could tell us some of the properties of that matter that are hard to get even from other types of gravitational-wave signal.

Young neutron stars may be the most likely to emit continuous gravitational waves, since the supernovae that form them are violent, asymmetric events that might leave the stars “roughed up” for some time. That is, the solid crust which neutron stars certainly have may not be smooth, and as a star rotates the roughness in the high density matter will emit gravitational waves. Also, electromagnetic observations of pulsars - neutron stars that appear as flashing dots in radio, x-rays, visible light, etc - tell us that the old ones are spinning down slowly, and thus cannot be emitting strong gravitational waves. The youngest neutron stars (up to a few thousand years old) might also still have active remdes, a type of wave in the fluid that makes up most of the star that can keep itself going through gravitational-wave emission.
**Advanced LIGO and Advanced Virgo**

Advanced detectors aim to improve sensitivity by a factor of 10, leading to a factor of 1000 increase in search volume and, thus, expected event rate.
Probing further with Advanced detectors

- Advanced detectors aim to improve sensitivity by a factor of 10, leading to a factor of 1000 increase in search volume and, thus, expected event rate.

Initial Reach

Advanced Reach

image credit: Matt Evans (MIT)
Upgrading to Advanced detectors

- Lasers become more powerful: use 200 W lasers
- Improvements to suspensions
  - Advanced LIGO: Test masses (previously 10 kg simple pendulums) become 40 kg monolithic suspensions in quadruple pendulums
  - Advanced Virgo: already has super attenuator, upgrade to 42 kg test mass plus install thermal compensation and scattered light mitigation
  - Both: implement better quality optics
- Advanced LIGO: Seismic isolation goes from passive to active
Towards Advanced detectors

LIGO Livingston can now see compact binary coalescences within ~60 Mpc!

Regular locks at Hanford with good progress towards target sensitivity

https://dcc.ligo.org/LIGO-G1401390/public
Towards Advanced detectors

- LIGO Hanford and Livingston have been installed on time and on budget
  - Livingston has achieved continuous operation for periods up to 10 hours in duration
  - Hanford, installed more recently, has achieved continuous operation for periods up to 3 hours in duration
  - Livingston has achieved a sensitivity that allows binary neutron star coalescences to be observed up to $\sim 60$ Mpc; Hanford is progressing steadily towards a similar sensitivity

- Intense installation effort currently underway at Advanced Virgo and it is on target to be online at a competitive sensitivity for Observing Run 2
Upcoming Observing runs

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Estimated Run Duration</th>
<th>$E_{GW} = 10^{-2}M_\odot c^2$ Burst Range (Mpc)</th>
<th>BNS Range (Mpc)</th>
<th>Number of BNS Detections</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>LIGO</td>
<td>Virgo</td>
<td>LIGO</td>
</tr>
<tr>
<td>2015</td>
<td>3 months</td>
<td>40 – 60</td>
<td>–</td>
<td>40 – 80</td>
</tr>
<tr>
<td>2016–17</td>
<td>6 months</td>
<td>60 – 75</td>
<td>20 – 40</td>
<td>80 – 120</td>
</tr>
<tr>
<td>2017–18</td>
<td>9 months</td>
<td>75 – 90</td>
<td>40 – 50</td>
<td>120 – 170</td>
</tr>
</tbody>
</table>

![Graph showing strain noise amplitude vs frequency for Advanced LIGO and Advanced Virgo with different epochs and run durations.](image)

Graph legend:
- Early (2015, 40 – 80 Mpc)
- Mid (2016–17, 80 – 120 Mpc)
- Late (2017–18, 120 – 170 Mpc)
- Design (2019, 200 Mpc)
- BNS-optimized (215 Mpc)

Graph legend:
- Early (2016–17, 20 – 60 Mpc)
- Mid (2017–18, 60 – 85 Mpc)
- Late (2018–20, 65 – 115 Mpc)
- Design (2021, 130 Mpc)
- BNS-optimized (145 Mpc)

arXiv:1304.0670
Examples of gravitational wave astronomy

- Measure the neutron star equation of state
  - tidal effects in binary neutron star inspiral leave an imprint on detected gravitational waves which, in principle, allow equation of state to be identified, *del Pozzo et al, PRL 2013*

- Compact binary coalescences as standard sirens
  - *Schutz, Nature 1989*
  - strain amplitude gives the apparent luminosity
  - rate of change of signal frequency provides an intrinsic luminosity
  - mass-redshift degeneracy can be broke by EM observations, *del Pozzo, PRD 2012*
  - observing tidal effects in NS inspirals can also break degeneracy, *Messenger and Read, PRL 2012*

- Hypermassive neutron star “spectroscopy”
  - characteristic frequencies of post-merger hypermassive neutron stars provide an additional means to break mass-redshift degeneracy *Messenger et al PRX 2014*
Multi-messenger astronomy

- Prompt follow-up of observed gravitational waves to search for counterpart signals
- Previously: Gravitational wave triggers were passed on to 10 EM partners with 30 min latency in first tests

- Now: The LSC and Virgo will partner with astronomers to carry out an inclusive observing campaign for potentially interesting gravitational wave triggers with MoUs to ensure coordination and confidentiality; open to all requests from astronomers and astronomy projects
  ➢ have ~75 partner MoUs
Multi-messenger astronomy

- Later: After the published discovery of gravitational waves with data from LSC and/or Virgo, both the LSC and Virgo will begin releasing especially significant triggers promptly to the entire scientific community to enable a wider range of follow-up observations.

  dcc.ligo.org, LIGO-M1200055
Gravitational wave detector network ~2020
Sky localisation with 3 detector sites

S. Fairhurst, “Improved source localization with LIGO India”, arXiv:1205.6611v1
Sky localisation with 5 detector sites

S. Fairhurst, “Improved source localization with LIGO India”, arXiv:1205.6611v1
Science questions to be answered

• Fundamental Physics
  ➢ Is the nature of gravitational radiation as predicted by Einstein?
  ➢ Are nature’s black holes the black holes of general relativity?
  ➢ What is the equation of state of ultra dense matter in neutron stars?

• Astrophysics
  ➢ What is the central engine behind gamma-ray bursts?
  ➢ What happens when a massive star collapses?
  ➢ How abundant are stellar mass black holes?
  ➢ How massive can neutron stars be?

• Cosmology
  ➢ What is the history of the accelerating expansion of the Universe?

.....and more!