Gravitational wave cosmology

Lecture 2

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Thus far we’ve only seen the Universe (and 95% of it is dark: dark matter and dark energy). In the next few years we will finally be able to listen to the Universe. This will be revolutionary!
Outline

- Lecture 1: introduction to gravitational waves
- Lecture 2: detecting gravitational waves
- Lecture 3: what we might learn from gravitational waves
What do gravitational waves do?

- Alternatively stretch and shrink the distance between points
Detecting gravitational waves

- Gravitational waves are very very very weak
- Fractional strain at Earth due to strong GWs:

\[ h = \frac{\Delta L}{L} \sim 10^{-22} \]
Bar detectors

- Invented by Joe Weber
- Strain from GWs excites resonant modes of bar
- Cryogenically cooled, SQUID sensors
- Narrow band. Surpassed by LIGO
Bar detectors

FIG. 2. Argonne National Laboratory and University of Maryland detector coincidence.
Pulsar timing arrays

- A millisecond pulsar is an exceedingly stable clock (better than best atomic clock)
- Observe many pulsars, and look for timing residuals (20 ns over a year)
- These come from GWs at source (uncorrelated) and at Earth (correlated)
- Can detect GW periods of ~year
- Band: $10^{-9}$–$10^{-6}$ Hz
Pulsar timing arrays

- Sensitive to supermassive binary black holes with orbital periods of months
- First detection possible in coming years
- Improve network by finding additional pulsars
Atom interferometry

- Use a cloud of cold atoms as an interferometer
- Use two separated clouds: each one measures phase
- Probe both clouds with a single laser
- Measurement of phase differences detects GWs
Atom interferometry
Laser interferometer

- Measures exactly what you want

- Lots of sources of noise:
  - thermal
  - seismic
  - shotnoise
  - quantum

- Need a very very fancy interferometer!
Laser interferometer

- Mirrors are “freely falling” test masses
- Interferometer is a transducer: GWs are turned into photocurrent
Michelson interferometer:
- quadruple pendulum; 40 kg end masses
- dual-recycled Fabry-Perot; 4 km arms
- 180 W laser (>700 kW per arm)
- active isolation ($f_{\text{low}} \sim 12$ Hz)
We will detect gravitational waves soon!

- Detectors are currently being significantly upgraded
- Coming generation of instruments expected to make the first detections!
- Will be operating at advanced sensitivity in about 3 years

LIGO (Hanford, WA)
LIGO (Livingston, LA)
Virgo (Pisa, Italy)
LIGO sensitivity

Best sensitivity achieved in each LIGO science run

![Graph showing LIGO sensitivity across different science runs and frequency ranges. Each science run is represented by a different color and line style, with the 2 km reference shown in dashed black and the 4 km reference in solid black. The x-axis represents frequency in Hz, and the y-axis represents strain spectral density in strain Hz$^{-1/2}$.]

- 1st science run
- 2nd science run
- 3rd science run
- 4th science run
- 5th science run
- 2 km reference
- 4 km reference
LIGO should blow your mind!

Sensing changes over 4 km to a thousandth the size of a proton
LIGO measures noise

- Seismic noise
- Thermal noise
- Photon shot noise
What is advanced?

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Initial LIGO</th>
<th>Advanced LIGO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Laser Power</td>
<td>10 W (10 kW arm)</td>
<td>180 W (&gt;700 kW arm)</td>
</tr>
<tr>
<td>Mirror Mass</td>
<td>10 kg</td>
<td>40 kg</td>
</tr>
<tr>
<td>Interferometer Topology</td>
<td>Power-recycled Fabry-Perot arm cavity Michelson</td>
<td>Dual-recycled Fabry-Perot arm cavity Michelson (stable RC)</td>
</tr>
<tr>
<td>GW Readout Method</td>
<td>RF heterodyne</td>
<td>DC homodyne</td>
</tr>
<tr>
<td>Optimal Strain Sensitivity</td>
<td>$3 \times 10^{-23} / \text{rHz}$</td>
<td>Tunable, better than $5 \times 10^{-24} / \text{rHz in broadband}$</td>
</tr>
<tr>
<td>Seismic Isolation Performance</td>
<td>$f_{\text{low}} \sim 50 \text{ Hz}$</td>
<td>$f_{\text{low}} \sim 12 \text{ Hz}$</td>
</tr>
<tr>
<td>Mirror Suspensions</td>
<td>Single Pendulum</td>
<td>Quadruple pendulum</td>
</tr>
</tbody>
</table>
Advanced LIGO sensitivity

The diagram shows the sensitivity of Advanced LIGO at different frequencies. The parameters include:

- Hanford 4 km S6
- Livingston 4 km S6
- Initial LIGO Science Design Goal

The graph plots strain ($1/\sqrt{\text{Hz}}$) against frequency (Hz). Key lines and curves indicate:

- aLIGO Binary Black Hole Optimized
- aLIGO Zero Detuned (Low Power)
- aLIGO Zero Detuned (High Power)
- aLIGO Tuned (High Frequency)
How well does LIGO do?

- Encapsulated in the signal-to-noise ratio (SNR)
- SNR in a detector is a function of the noise curve of the detector as well as the waveform (amplitude and frequency) of the source

\[
\text{SNR} = 4 \int_{f_{\text{min}}}^{f_{\text{max}}} df' \frac{\left| \tilde{h}(f') \right|^2}{S_n(f')}
\]

- \( \tilde{h}(f') \) is the source GW waveform (Fourier)
- \( S_n(f') \) is the spectral strain noise density
LIGO detects noise!
Can extract signal from noise

- Red: binary black hole merger at 100 Mpc
- Data analysis challenge
Only find what you look for

- Matched filter search has greatest reach
- Need excellent waveform templates to analyze data
- Huge numerical and analytic effort to determine waveforms from supernovae and compact object binaries
- Problem is solved for equal-mass, circular, slowly spinning binaries
- Problem is not yet solved for larger mass ratio or highly spinning/eccentric binaries
GWs from binary black holes

• Assume GW emission plus Kepler’s laws:

\[
\frac{dP}{dt} = -\frac{96}{5} \pi^{41/3} \left( \frac{2\pi M}{P} \right)^{5/3}
\]

\[
= -3.4 \times 10^{-12} \left( \frac{M}{M_\odot} \frac{1 \text{ hour}}{P} \right)^{5/3}
\]

• This gives the full time evolution/waveform
Three phases of binary evolution
Only find what you look for

- Analytic methods:
  - post-Newtonian expansions
  - effective one-body formalism
- Gold standard: numerical relativity
Only find what you look for

- **Analytic methods:**
  - post-Newtonian expansions
  - effective one-body formalism
- **Gold standard:** numerical relativity
LIGO/Virgo finds something!
LIGO/Virgo finds nothing

BLIND HARDWARE SIGNAL INJECTION
Sky sensitivity

- Sensitivity of a single interferometer
- Livingston and Hanford are closely aligned, so as to see same polarization
- LIGO sees a peanut on the sky
- Need a network to see the full sky
Sky localization

- Localization comes primarily from timing
- Two detectors produces an annulus on the sky
More detectors is better

A detector in India is essential to cover the sky
Advanced LIGO timetable

- 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)
## Advanced LIGO/Virgo timetable

<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>
<th>% BNS Localized within 5 deg$^2$</th>
<th>% BNS Localized within 20 deg$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>LIGO</td>
<td>Virgo</td>
<td>LIGO</td>
<td>Virgo</td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td>3 months</td>
<td>40 – 60</td>
<td>–</td>
<td>40 – 80</td>
<td>–</td>
<td>0.0004 – 3</td>
</tr>
<tr>
<td>2016–17</td>
<td>6 months</td>
<td>60 – 75</td>
<td>20 – 40</td>
<td>80 – 120</td>
<td>20 – 60</td>
<td>0.006 – 20</td>
</tr>
<tr>
<td>2017–18</td>
<td>9 months</td>
<td>75 – 90</td>
<td>40 – 50</td>
<td>120 – 170</td>
<td>60 – 85</td>
<td>0.04 – 100</td>
</tr>
<tr>
<td>2019+</td>
<td>(per year)</td>
<td>105</td>
<td>40 – 80</td>
<td>200</td>
<td>65 – 130</td>
<td>0.2 – 200</td>
</tr>
<tr>
<td>2022+</td>
<td>(India) (per year)</td>
<td>105</td>
<td>80</td>
<td>200</td>
<td>130</td>
<td>0.4 – 400</td>
</tr>
</tbody>
</table>
Worldwide GW network
Detecting gravitational waves in space!

CANCELED DUE TO FUNDING ISSUES

Laser Interferometer Space Antenna (LISA)

Detects supermassive black hole mergers anywhere in the Universe
Also Space!

Laser Interferometer Space Antenna

eLISA  ➔  2034
DECIGO

Big Bang Observer
Far, far away

- Big Bang Observer (BBO)
Far, far away

- DeciHertz Gravitational wave observatory (DECIGO)
GW science reach