Ground-based Gravitational Wave Astronomy

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Contents

• Gravitational waves and GW observatories
• GW sources and searches
• Detection problems
  • Data Quality and glitches
  • Optimisation for sensitivity
• Future outlook
GW observatories: Current Status
Gravitational Waves

- Predicted by Einstein (1915)
- Perturbation on Minkowski metric $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$
- (in GR) Quadrupolar with two polarisations: “+” and “x”
- Sourced by large, rapidly changing quadrupoles: astrophysical events!
- Transverse waves:
  - differentially stretch and squash space in quadrupolar pattern

\[ L_{GW} = \frac{1G}{5c^5} \frac{\sqrt{\ddot{r}^2}}{r^2} \approx 10^{46} \text{W} \]

\[ M_8 = 2 \rightarrow 10^{50} \text{kg} \]

\[ h_{jk} = \frac{2G}{c^4 r} \dddot{I}_{jk} \approx 10^{-22} \]

\[ r \sim 100 \text{Mpc} \quad (\sim 10^{15} \text{m}) \]
GW spectrum

http://rhcole.com/apps/GWplotter/

ground based
Signal power amplified by ~60 orders of magnitude!
Worldwide net work

LIGO Hanford

L = 4 km

LIGO Livingston

L = 4 km

Virgo

L = 3 km

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)

Strain noise amplitude (Hz−1/2)

Frequency (Hz)

BBH @ 400 Mpc

BNS @ 150 Mpc
Advanced Detectors

Initial detectors operated until 2010
First Advanced LIGO run Sept 2015
L1 Strain Sensitivity changes over time

- Jun 1 2014, 0.7 W, ES drive, 0. Mpc
- Jun 12 2014, 0.7 W, ES drive, 3. Mpc
- Jun 28 2014, 2 W, ES drive, 5. Mpc
- Jul 24 2014, 2 W, ES drive, 15 Mpc
- Jul 31 2014, 6 W, L2 drive, 20 Mpc
- Nov 27 2014, 25 W, L2 drive, 46 Mpc
- Mar 03 2015, 25 W, L2 drive, 67 Mpc

lower is better
1st Observing Run

- “O1” data taking: Sept 12th - Jan 19th
- LIGO Hanford (H1) and Livingston (L1) only
- ~40% coincident duty cycle
- 51 days coincident, good quality data
- BNS range H1:~80Mpc, L1:~60 Mpc
Advanced Detectors

aLIGO Hanford O1
$r \sim 80 \text{Mpc}$
Noise budget

Displacement (m/√Hz)

Frequency (Hz)

Standing
Squatting
Again
Waiting
Measuring gravitational field of grad students!
Searching and Detection
GW Sources

Modelled

Binary Mergers

Unmodelled

Supernovae

Transients

Continuous

Spinning Neutron Stars

Stochastic Background
GW150914

- Sept 14 09:50:45 UTC
- SNR ~24, duration ~0.2s
- Detected by burst search
- Internal alerts triggered
- Clear chirping signal
  - Low frequency: BBH
- 13 followup papers!
  - http://papers.ligo.org

"Observation of gravitational waves from a binary black hole merger", LVC, Phys. Rev. Lett. 116, 061102
GW strain

Trigger generation

Data Quality, validation

Source characterisation

Significance

Population inference

Astrophysical interpretation

Environment monitoring

Basic parameters
Unmodelled Bursts

- Eyes-wide-open search
- Supernovae, cosmic strings, heavy BBHs, ... unknown sources
- No template waveform to look for
- Find periods of excess power
- Exploit multiple detectors: require signal to appear coherently in network
- GW150914 easily detected by burst search

LVC. “Observing ... GW150914 with minimal assumptions”, arXiv:1602.03843
Coherent Burst searches

- Use knowledge of detector response functions ($F_+$ and $F_x$) and light travel time select coherent signals
- Coherent WaveBurst: Apply cuts to select elliptical polarisation, linear pol. etc
- LALInference Burst / BayesWave: Automatic via Bayes factor coherent vs incoherent signals
- Relatively computationally expensive

Klimenko+ arXiv:1511.05999
Compact Binary Mergers

- Black holes + neutron stars
- Ideal source for GW radiation (quadrupole)
- Inspiral well modelled by Post-Newtonian expansion
- Ringdown: Perturbation theory
- Merger: Numerical relativity
- Phase given by masses, spins
GW151226

- Dec 26th 03:38:53 UTC
- SNR \(\sim 12\), duration \(\sim 1\) s
- Lighter mass
- Required matched filtering to detect
- Barely visible in periodogram
- More info and papers
  - http://papers.ligo.org
Searching for a known signal

- How to find signal?
  - For Gaussian noise, likelihood is
    \[ L / \exp \left( - \sum_{i} \frac{|h(f_i) - d_i|^2}{2a_i^2} \right) \]
  - \( h(f) \) is waveform in frequency domain
  - \( d_i \) is Fourier transformed data
  - \( \sigma_i \) is standard deviation of noise at each frequency, given by spectrum of the noise
GW Searches

• Expanding the likelihood ratio:

\[ \log L = -\frac{1}{2} < d - h | d - h > \]
\[ = < d|h > - \frac{1}{2} < h|h > - \frac{1}{2} < d|d > \]

• \(<a|b>\) is the noise-weighted inner product

\[ <a|b> = 4! \sum_{i,j} a_i b_i^* S_i \]

• \(<d|h>\) is the optimal detection statistic for a known signal \( h \) in Gaussian noise \( d \).

• To search over time use FFT

\[ \sum_{j} \frac{d_j h_j^* (\times)}{S_j} = \sum_{j} \frac{d_j h_j^*}{S_j} \exp(-2 \uparrow i f_j \times) \]
Matched filter each time sample → convolution!