Exploring a stochastic background of gravitational waves with LIGO

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Stochastic GW Background

superposition of signals too weak or numerous to be resolved individually

Cosmological:
- Vacuum fluctuation
- inflationary models
- phase transitions and cosmic strings
- String cosmology

Astrophysical:
- compact binary coalescences
- core-collapse supernovae
- rotating neutron stars
Energy density spectrum

$$\Omega_{GW}(f) \equiv \frac{f}{\rho_c} \frac{d\rho_{GW}}{df}$$

GW energy density contained in the frequency range $f$ and $f + df$

Critical energy density to close the universe
$$\rho_c = \frac{3c^2H_0^2}{8\pi G}$$

Theoretical models of stochastic backgrounds in the LIGO band are characterized by a power-law spectrum. We can therefore assume:

$$\Omega(f, \Phi) = \Omega_\alpha(\Phi) \left( \frac{f}{f_{ref}} \right)'^\alpha, \quad \Omega_\alpha(\Phi) = \frac{2\pi^2}{3H_0^2} f_{ref}^3 P(\Phi)$$

### Spectral index

- $\alpha = 0$ constant energy density, representative of many cosmological models
- $\alpha = 3$ constant strain, characteristic of many astrophysical models
- $\alpha = 2/3$ background dominated by compact binary (eg BBH) inspirals
**Detection strategy**

- Cross correlate data stream from multiple detectors over extended observation times $T$
  - look for (correlated) GW background signal
- Signal contribution grows linearly with $T$, noise contribution grows like $\sqrt{T}$, hence $\text{SNR} \propto \sqrt{T}$
  - improves sensitivity, assuming uncorrelated detector noise

\[
D \approx 3000 \text{ km}
\]
\[
\frac{D}{c} \approx 10 \text{ ms}
\]

\[
\text{SNR} = \frac{3H_0^2}{10\pi^2} \sqrt{2T} \left[ \int_0^\infty df \sum_{i=1}^n \sum_{j>i} \frac{\gamma^2_{ij}(f)\Omega_{GW}^2(f)}{f^6 P_i(f) P_j(f)} \right]^{1/2}
\]
• First observing run of Advanced LIGO (O1)
  – 4 months of data from September 18, 2015 to January 12, 2016
• Search for GW stochastic background recently finalised
  (no detection)
• Confirmed detections of 2 significant black hole merger events
  (+ one candidate)
O1 Detections

\[ D \approx 3000 \text{ km} \]
\[ \frac{D}{c} \approx 10 \text{ ms} \]

Abbott, et al., PRX, 6, 041015 (2016)
Implications

\[ D \approx 3000 \text{ km} \]
\[ \frac{D}{c} \approx 10 \text{ ms} \]

CMB analogy

https://map.gsfc.nasa.gov/media/060913/index.html
CMB analogy

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Assumes background is:
• isotropic
• unpolarised
• Stationary
• Gaussian
• and well represented by a power-law

No significant signal detected.
Isotropic Search

<table>
<thead>
<tr>
<th>Spectral index $\alpha$</th>
<th>Frequency band with 99% sensitivity</th>
<th>Amplitude $\Omega_{\alpha}$</th>
<th>95% CL upper limit</th>
<th>Previous limits [33]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>20 − 85.8 Hz</td>
<td>$(4.4 \pm 5.9) \times 10^{-8}$</td>
<td>$1.7 \times 10^{-7}$</td>
<td>$5.6 \times 10^{-6}$</td>
</tr>
<tr>
<td>2/3</td>
<td>20 − 98.2 Hz</td>
<td>$(3.5 \pm 4.4) \times 10^{-8}$</td>
<td>$1.3 \times 10^{-7}$</td>
<td>–</td>
</tr>
<tr>
<td>3</td>
<td>20 − 305 Hz</td>
<td>$(3.7 \pm 6.5) \times 10^{-9}$</td>
<td>$1.7 \times 10^{-8}$</td>
<td>$7.6 \times 10^{-8}$</td>
</tr>
</tbody>
</table>
Arbitrary angular distribution

- Spherical harmonic decomposition looks for point sources
- No significant signal detected
- Upper limit maps of fractional energy density per solid angle $[\Omega \text{ sr}^{-1}]$

\[
\alpha = 0 \quad \alpha = 2/3 \quad \alpha = 3
\]
Point sources

- Radiometer search optimised for point sources
- No significant signal detected
- Upper limit maps of energy flux [erg cm$^2$ s$^{-1}$ Hz$^{-1}$]

\[ \alpha = 0 \quad \alpha = 2/3 \quad \alpha = 3 \]
Interactive maps

Mapping the Gravitational Wave Stochastic Background
Observing Run 1 (GPS 1126823617-1136849617, 20-500 Hz)

https://ldas-jobs.ligo.caltech.edu/~will.campbell/
Angular power spectra (SHD)

- Upper limits on GW background anisotropy

\[ \hat{C}_l = \frac{1}{2l+1} \sum_m \left[ |\hat{P}_{lm}|^2 - (\Gamma^{-1}_R)_{lm,lm} \right] \]
Conclusions

• SGWB searches can constrain important cosmological and astrophysical background models
  – probe physics at energy scales inaccessible by other means
  – constrain models of conjectural objects such as cosmic strings

• More detectors with better sensitivity will continue to improve the effectiveness of our searches

• Reasonable chance of detecting binary black hole background as advanced detectors reach design sensitivity
THANK YOU