Detection of high-frequency gravitational waves with high-energy pulsed lasers

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Introduction

• GWs predicted in 1916 by Einstein and detected in 2015 by the LIGO and Virgo.

• Current projects search for GW in the frequency range nHz - kHz. Higher frequency search allows for discovery of new physics

• Detection of GWs is based on the graviton to photon conversion
Overview of the presentation

• Motivations

• Graviton-to-photon conversion

• Detector sensitivity

• Sources of high-frequency GWs
Motivations
Example of a cosmological source:
Evaporating primordial BHs

From left to right, $E_{\text{init}} = 10^{15}, 10^{14}, 10^{13}, 10^{12}$ GeV

Example of an astrophysical source:
Light BH mergers

$f_{\text{ISCO}} \propto m^{-1}$

Searching for high frequency GWs is equivalent to searching for light binaries

Challenge for detection: $h \propto m$

arXiv:0812.0825

arXiv:1610.03567
Graviton-to-photon conversion
Diagram of the experimental setup

Gravitational Wave

Laser

Generated Photons

Mirror

Detector

arXiv: 2301.08163
Equations of motion

\[ g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \quad \Rightarrow \quad S = \int d^4x \sqrt{-g} \left( -\frac{1}{4} g^{\mu\alpha} g^{\nu\beta} F_{\mu\nu} F_{\alpha\beta} \right) \]

\[ \partial_\nu F^{\nu\mu} = \partial_\nu \left( \frac{1}{2} h F^{\mu\nu} + h_\alpha^\nu F^\alpha\mu - h_\alpha^\mu F^{\alpha\nu} \right) \]

\[ E_p = \int_0^\tau dt \ S = \int_0^\tau dt \ \int d\Sigma \ \vec{n} \cdot (\vec{E} \times \vec{B}) \geq \hbar \omega \]
## Results

<table>
<thead>
<tr>
<th>Frequency</th>
<th>$\omega_g \neq 2\omega$</th>
<th>$\omega_g = 2\omega$</th>
</tr>
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<tbody>
<tr>
<td>Energy per pulse going in the detector</td>
<td>$\sim E_{las}(h_+^2 + h_\times^2)$</td>
<td>$4E_{las}(h_+^2 + h_\times^2)L^2\omega^2$</td>
</tr>
<tr>
<td>Minimal strain</td>
<td>$h_{\text{min}} \sim \sqrt{\frac{\omega_g - \omega}{2n_sE_{las}}}$</td>
<td>$h_{\text{min}} = \frac{1}{\sqrt{8n_s\omega^2E_{las}^2}}$</td>
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</table>
Detector sensitivity
• **THz FEL**: Rep. rate of 200 kHz, $\tau = 1 \text{ps}$, $E_{\text{las}} = 100 \mu J$, $1 \text{THz} \leq \omega / 2\pi \leq 30 \text{THz}$

• **NIF laser**: Rep. rate of 4 shots per day, $\tau = 20 \text{ns}$, $E_{\text{las}} = 9.4 \text{kJ}$, $\lambda = 1051,527,351 \text{nm}$

• **Next gen NIF**: Rep. rate of 10 kHz, $\tau = 20 \text{ns}$, $E_{\text{las}} = 1.8 \text{MJ}$, $\lambda = 1051,527,351 \text{nm}$

• **EuXFEL**: Rep. rate of 10 Hz, $5.8 \text{keV} \leq \omega / 2\pi \leq 24 \text{keV}$, $\tau = 0.1 \text{ps}$, $E_{\text{las}} = 2.1,0.5 \text{mJ}$,
Sources of high-frequency GWs
Constraints on cosmological sources: The BBN bound

\[ \rho = \rho_\gamma + \rho_\nu + \rho_{\text{extra}} \]

- BBN predicts correctly the abundance of light elements with \( \rho_{\text{extra}} = 0 \). Adding GWs should not spoil BBN.

- This translates into \( \Omega_{GW} = \frac{4\pi^2}{3H_0^2} f^2 h^2 \lesssim 5 \times 10^{-6} \).

\[ h \lesssim 10^{-36} \left( \frac{10^{15} \text{Hz}}{f} \right) \]
Light BH Binaries

As the objects get closer the frequency changes

$$\omega_g(t) \propto (t_c - t)^{-3/8}$$

To satisfy the resonance condition the change in frequency must be small

$$\frac{\delta\omega_g}{\omega_g} \ll \frac{1}{L\omega} \ll 1$$

$$\Delta t \ll \frac{1}{(Gm)^{5/3}L\omega^{11/3}} \sim 10\text{days} \left(\frac{1\text{ps}}{\tau}\right) \left(\frac{30\text{THz}}{2\omega/2\pi}\right)^{11/3} \left(\frac{10^{-22}\text{M}_\odot}{m}\right)^{5/3}$$

arXiv:1610.03567
Conclusion

• Detectable GWs are those for which $10^{13}$ Hz $\leq \omega_g = 2\omega \leq 10^{19}$ Hz and $h \geq 10^{-11} \left( \frac{1\text{Hz}}{\omega} \right)^{1/2}$.

• Due to the BBN bound, GWs from cosmological sources cannot be detected with today’s lasers.

• GWs from BH mergers can be detected if they are close. Due to the change in frequency of the binary, there is a constraint on the duration of the experiment.

• The paper can be found on arXiv: arXiv:2301.08163
Thank you for your attention!
Any questions?