Gravitationally induced gamma ray background

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based on:

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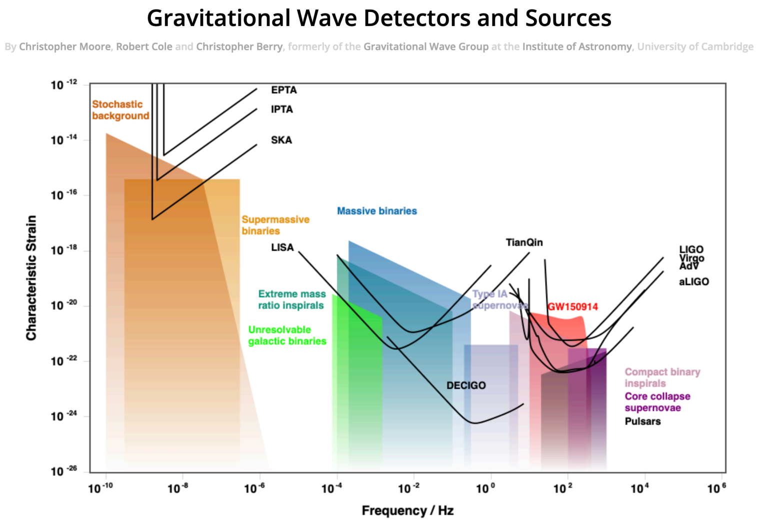

gwplotter.com

Moore, Cole, and Berry

What about frequencies $f \gg 10$ kHz?!

Already many efforts in this direction: Aggarwal et al'2020

"Challenges and Opportunities of Gravitational Wave Searches at MHz to GHz Frequencies"

Extension to 10^{18} Hz Dolgov&Ejlli'13
and even to 10^{27} Hz Ito, Kohri, and Nakayama'23

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2 questions to be addressed in this talk

- What are the largest energies of gravitons to be observed?
- Are there physical mechanisms capable of producing such high energy gravitons?

How to measure extremely high frequency GWs? Gertsenshtein effect

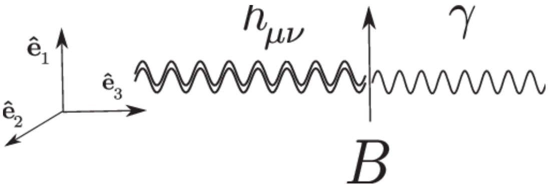
$$\mathcal{L}_{em} = -\frac{1}{4} g^{\mu\lambda} g^{\nu\rho} F_{\mu\nu} F_{\lambda\rho} \qquad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

Consider $F_{\mu\nu}$ as a superposition of an external static (electro)magnetic field and a photon field:

$\Longrightarrow$ oscillations $\boxed{h \leftrightarrow \gamma}$ in the presence of A^{ext}

$$\propto \frac{1}{M_{Pl}}$$



- Gertsenshtein effect: $\gamma \to h$
- Inverse Gertsenshtein effect: $h \to \gamma$

Close relative of axion-to-photon conversion: $\frac{a}{f} F_{\mu\nu}\tilde{F}^{\mu\nu}$

Ignore photon interactions.

Conversion probability: $$\boxed{P_{h\to\gamma}(L) = \frac{\mathbf{B}^2 L^2}{2M_{Pl}^2}}$$

- Good: magnetic fields are present everywhere, — galaxies, planets, stars etc.
  $B(\text{Milky Way}) \sim 10^{-6}$ Gauss $\sim 10^{-26}$ GeV^2
  $B(\text{Earth}) \sim 1$ Gauss $\sim 10^{-20}$ GeV^2
  $B(\text{neutron star}) \sim 10^{8}$ Gauss $\sim 10^{-12}$ GeV^2
- Bad: magnetic fields are very weak, while the effect is Planck suppressed!
- Good: magnetic fields are spread over large scales, e.g.,

$$L(\text{Milky Way}) \sim 10 \text{ kpc} \Longrightarrow P_{h\to\gamma} \sim 10^{-15}$$

$$A_i(\vec{x},t) = \sum_{\lambda=\parallel,\perp} A_\lambda(\vec{x})\epsilon_i^\lambda e^{-i\omega t} \qquad h_{ij}(\vec{x},t) = \sum_{\lambda=\times,+} h_\lambda(\vec{x})e_{ij}^\lambda e^{-i\omega t} \ ,$$

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$$\left(i\frac{d}{dz} + \omega\right)\begin{pmatrix} h_+ \\ h_\times \\ A_\parallel \\ A_\perp \end{pmatrix} = \begin{pmatrix} 0 & C_{\mathrm{h}\gamma} \\ C_{\mathrm{h}\gamma}^\dagger & 0 \end{pmatrix} \begin{pmatrix} h_+ \\ h_\times \\ A_\parallel \\ A_\perp \end{pmatrix}$$

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$$C_{\mathrm{h}\gamma} = \frac{i}{\sqrt{2}M_{\mathrm{Pl}}}\begin{pmatrix} \vec{B}\cdot\vec{\epsilon}_\perp & \vec{B}\cdot\vec{\epsilon}_\| \\ -\vec{B}\cdot\vec{\epsilon}_\| & \vec{B}\cdot\vec{\epsilon}_\perp \end{pmatrix}$$

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$$P_{h\to\gamma}(L) \equiv \sum_{\lambda=\parallel,\perp} |\langle A_\lambda(L)|h_{\times,+}(0)\rangle|^2 = \frac{1}{2M_{Pl}^2}\cdot\left|\int_0^L \vec{B}_T dz\right|^2$$

$$\vec{B}_\mathrm{T} \equiv \left(\vec{B}\cdot\vec{\epsilon}_\parallel\right)\vec{\epsilon}_\parallel + \left(\vec{B}\cdot\vec{\epsilon}_\perp\right)\vec{\epsilon}_\perp$$

Include photon interactions with electrons

$$\mathcal{L}_{int} = e\bar{\Psi}\gamma^{\mu}\Psi A_{\mu}$$

Or Euler-Heisenberg interaction after integrating out fermions:

$$\mathcal{L}_{EH} = \frac{\alpha^2}{90 m_e^4} \cdot \left[(F_{\mu\nu}F^{\mu\nu})^2 + \frac{7}{4} \cdot \left(F_{\mu\nu}\tilde{F}^{\mu\nu} \right)^2 \right]$$

$$\left(i\frac{d}{dz}+\omega\right)\begin{pmatrix}h_+\\h_\times\\A_\parallel\\A_\perp\end{pmatrix}=\begin{pmatrix}0 & C_{\mathrm{h}\gamma}\\C^\dagger_{\mathrm{h}\gamma} & \omega(n-1)\end{pmatrix}\begin{pmatrix}h_+\\h_\times\\A_\parallel\\A_\perp\end{pmatrix}.$$

$$C_{\mathrm{h}\gamma}=\frac{i}{\sqrt{2}M_{\mathrm{Pl}}}\begin{pmatrix}\vec{B}\cdot\vec{\epsilon}_\perp & \vec{B}\cdot\vec{\epsilon}_\parallel\\-\vec{B}\cdot\vec{\epsilon}_\parallel & \vec{B}\cdot\vec{\epsilon}_\perp\end{pmatrix}$$

n is a refraction index

No photon interactions $\Longrightarrow n=1\Longrightarrow P_{h\to\gamma}(L)=\frac{B^2L^2}{2M_{Pl}^2}$

Photon interactions $\Longrightarrow n\neq 1$

$$n - 1 = (n-1)_{pl} + \frac{11}{4}(n-1)_{QED} + (n-1)_{CMB}$$

- $(n-1)_{pl} = -\frac{\omega_{\text{pl}}^2}{2\omega^2}$ negligible in our case $\omega \gg \omega_{pl}$
- $(n-1)_{CMB} = \frac{44\pi^2\alpha^2}{2025} \frac{T_{\text{CMB}}^4}{m_{\text{e}}^4} \Longleftarrow$ Euler-Heisenberg
- $(n-1)_{QED} = \frac{4\alpha^2}{45}\frac{B_T^2}{m_e^4} \Longleftarrow$ Euler-Heisenberg

Refraction index is a purely quantum phenomenon in our case!

Graviton-to-photon conversion probability is changing in the presence of non-trivial refraction index $n \neq 1$

$$P_{h\to\gamma}(L) \approx \frac{\left|\int_0^L dz' \; e^{i\omega(n-1)z'} \vec{B}_T\right|^2}{2M_P^2} \, .$$

Oscillations due to $n \neq 1$ may suppress conversion

$$\omega(n-1)L_{corr} \simeq \pi \Longrightarrow \boxed{\omega_{max} \lesssim 1 \text{ PeV} \left(\frac{10 \text{ kpc}}{L_{corr}}\right) \cdot \left(\frac{6\ \mu\text{G}}{B_T}\right)^2}$$

For $\omega \ll \omega_{max} \Longrightarrow P_{h\to\gamma}(L) = \text{const}$ For $\omega \gg \omega_{max} \Longrightarrow P_{h\to\gamma}(L) \propto \frac{1}{\omega^2}$

$$1 \text{ PeV} = 1000 \text{ TeV}$$

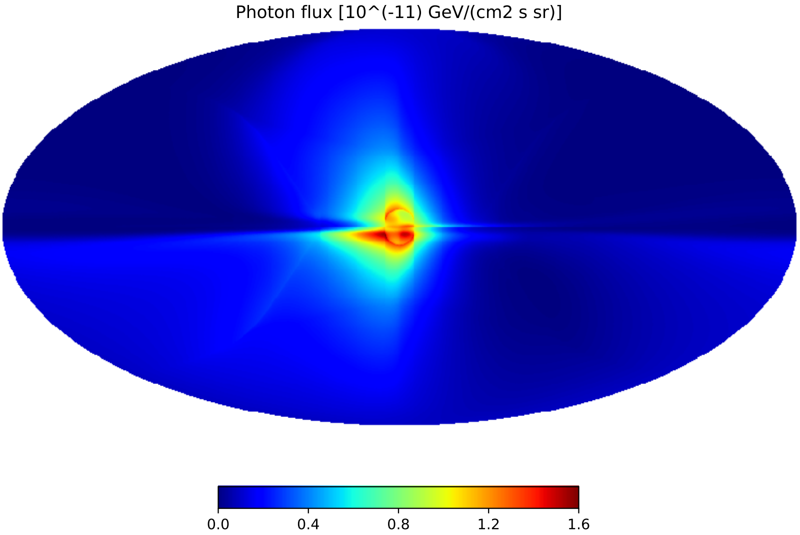
Gravitationally induced gamma ray background

Assume non-zero cosmological energy density of gravitons with $\rho_{gw} \Longrightarrow$ the flux of gravitons

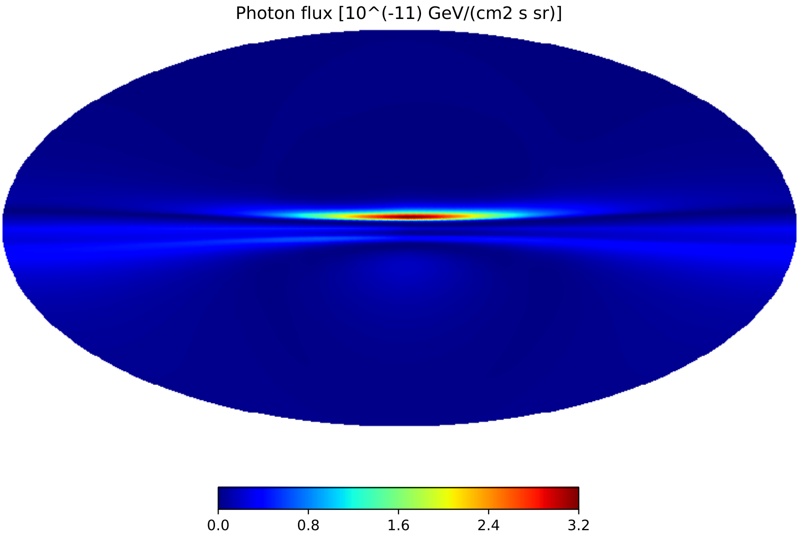
$$\Phi_{\mathrm{gw}}(\omega) = \frac{1}{4\pi} \cdot \frac{d\rho_{\mathrm{gw}}}{d \ln \omega} = \frac{\Omega_{gw}\rho_{tot}}{4\pi}$$

On the way to Earth, a small fraction of gravitons is converted into photons in the Milky Way magnetic field through the inverse Gertsenshtein effect:

$$\Phi_{\gamma}(\omega, \vec{n}) = \Phi_{\mathrm{gw}}(\omega) \cdot P_{\mathrm{h}\to\gamma}(\omega, \vec{n})$$

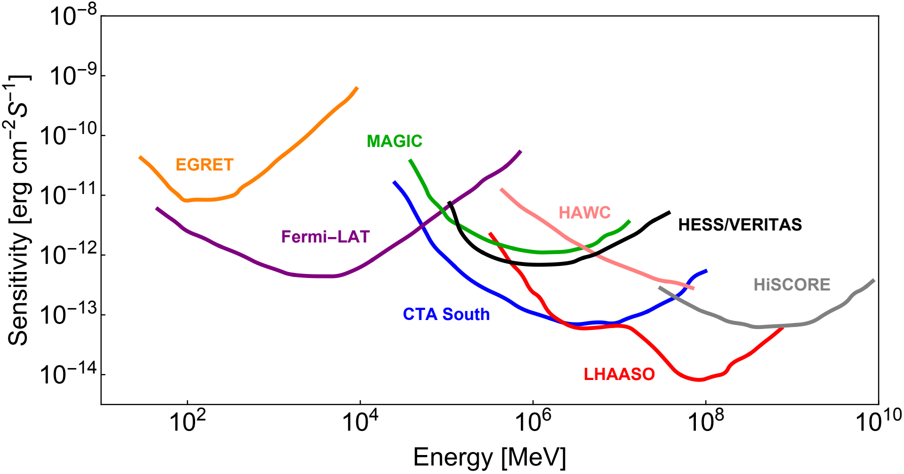


$\Omega_{gw} h_0^2 = 1$ Magnetic field model by Jansson&Farrar'12



Magnetic field model by Pshirkov, Tinyakov, Kronberg, Newton-McGee'11

Some gamma-ray observatories and their sensitivities



What to compare the gravitationally induced flux $\Phi_\gamma = (\text{a few}) \times 10^{-11}\ \text{GeV}/(\text{cm}^2 \cdot \text{sec} \cdot \text{sr}) \cdot \Omega_{gw} h_0^2$ with?

Sensitivity of LHAASO observatory after 1-year towards diffuse gamma-ray background has been estimated in Neronov&Semikoz'20:

$$\Phi_\gamma \sim 10^{-10}\ \ \text{GeV}/(\text{cm}^2 \cdot \text{sec} \cdot \text{sr})$$

One can probably test $\Omega_{gw} h_0^2 \sim 1$, but this is too much!

We failed, but not miserably! In the future, one can probably test $\Omega_{gw} h_0^2 \sim 0.1,\ 0.01, \ldots$

How to produce gravitons with sub-PeV energies?

How to produce gravitons with a significant cosmological abundance?

- Pre-recombination production of gravitons:

  $\Omega_{gw} h_0^2 \lesssim 10^{-6}$ from Planck+BAO'18

  $\Longrightarrow$ no observable signatures

- Post-recombination production of gravitons:
  $\Omega_{gw} h_0^2 \ll 1$ but can be $\Omega_{gw} h_0^2 \gg 10^{-6}$

Superheavy dark matter decay

Assume superheavy field S with the mass $M_S \gtrsim 100$ TeV with the only decay channel into a couple of gravitons:

$$S \to h + h$$

- The field S completely decays by present (but after recombination), in which case it can constitute only a small fraction f of dark matter $\Longrightarrow$

$$\Omega_{\rm gw} h_0^2 \simeq \frac{f \Omega_{\rm dm} h_0^2}{1 + z_{\rm dec}} \lesssim \frac{0.01}{1 + z_{\rm dec}}$$

- The field S decays has a life expectancy exceeding the age of the Universe $\tau_S \gtrsim 10\tau_U$, in which case it can play the role of dark matter

$$\Omega_{\rm gw} h_0^2 \lesssim 0.01$$

Audren et al'14, Chudaykin et al'17, Bucko et al'22

The two-body decay into gravitons can be triggered by the following effective interactions:

$$S \cdot \frac{R^2}{\Lambda} \qquad S \cdot \frac{R_{\mu\nu} R^{\mu\nu}}{\Lambda} \qquad S \cdot \frac{R_{\mu\nu\lambda\rho} R^{\mu\nu\lambda\rho}}{\Lambda}$$

Ema, Mukaida, and Nakayama'21

$$\Gamma\left(S \to h + h\right) \simeq \frac{M_S^7}{4\pi \Lambda^2 M_{Pl}^4}$$

$$\Lambda \sim M_S \quad , \quad \tau_S \gtrsim 10\tau_U \Longrightarrow M_S \sim 1 \text{ PeV} \Longrightarrow$$

sub-PeV gravitons

Summary

- Sub-PeV gravitons with $\Omega_{gw} h_0^2 \sim 1$ are accessible with LHAASO.
- Probing $\Omega_{gw} h_0^2 \sim 0.01$ may be possible with future improvements of Cherenkov arrays.
- It is possible to generate $\Omega_{gw} h_0^2 \sim 0.01$ through 2-graviton decays of superheavy dark matter.
- Above ~ 1 PeV, the graviton-to-photon conversion becomes suppressed with the graviton energy $P \sim 1/\omega^2$ because of the QED birefringence effect.

Thank you!