原子电场中的引力子-光子转化和高频引力波探测

Graviton-Photon Conversion in Atomic Electric Field and High Frequency Gravitational Wave Detections

(Based on: https://arxiv.org/abs/2302.07044)

Gui-Rong Liang （梁桂荣）

China University of Mining and Technology
中国矿业大学 · 徐州

河南师范大学
2026.01.07

课题发起者、合作者简介

A brief introduction of the collaborator, who proposed the topic

Jin Dai (戴瑾), born on 1965,
now the chair scientist in a semiconductor company in Beijing.

- Bachelor's Degree: Peking University, Physics;
- Ph.D Degree: Texas University, Physics;
- Ph.D supervisor: Joeseph Polchinski;
- Main contribution: Co-proposer of "D-Brane" in string theory;
- Career experience: More than 20 years in areas of wireless communication, chip and semiconductor industry;
- Popular Science Books: "Chip Story" (《芯片风云》), "Understanding Quantum Mechanics from the first step" (《从零读懂量子力学》).

学术引用与关注

Key citations and endorsement

我们的工作已被 CERN 白皮书引用并将该方案单列一小节

Challenges and Opportunities of Gravitational Wave Searches above 10 kHz #1

Nancy Aggarwal (Northwestern U.), Odylio D. Aguiar (Sao Jose, INPE), Diego Blas (Barcelona, IFAE and ICREA, Barcelona), Andreas Bauswein (Darmstadt, GSI), Giancarlo Cella (INFN, Pisa) et al. (Jan 20, 2025)

e-Print: 2501.11723 [gr-qc]

5.5.2 GW to Electromagnetic-Wave Conversion in a Static Electric Field

Ref. [528] considered the inverse Gertsenshtein effect in a static electric field rather than a static magnetic field.[31] The physics is essentially the same in the two cases but the intensity of electric fields in laboratory settings is limited due to their tendency to pull electrons from any support structure. Consequently, the energy densities reachable in electric fields are about a million times smaller than those of magnetic fields in the several Tesla range.

This limitation can be overcome by focusing on graviton-to-photon conversion in *atomic* electric fields, which can be much stronger [529]. The conversion happens when the wavelength under consideration is shorter than the atomic radius, making the method sensitive at frequencies of 10^{20}–10^{24} Hz, or graviton energies between 100 keV and 1 GeV. [529] proposed to search for the generated photons in current and future neutrino detectors, for instance JUNO. A downside of this technique is the limitation to very high frequencies, at which it seems difficult to envisage sufficiently strong GW sources.

Technology	Operational Frequency
Dielectric Axion Haloscopes, Section 5.4.2, [524]	
Madmax (R&D), [522]	[100 MHz – 10 GHz]*
DALI prototype (R&D), [526]	7, 33 GHz
DALI phase II (proposed), [526]	(6 – 60) GHz
High Energy Pulsed Lasers, Section 5.5.1, [527]	[10^4 – 10^{10}] GHz
Conversion in a Static Electric Field, Section 5.5.2	
Atomic electric field, [529]	(10^{11} – 10^{15}) GHz
Resonant Polarization Rotation, Section 5.5.2, [530]	
Cruise's detector (proposed), [531]	[0.1 – 10^5] GHz
Cruise & Ingley's detector (prototype), [532, 533]	100 MHz
Optical cavities of ALPS II (built), [534]	[0.1 MHz – 0.1 THz]
Superconducting Rings, Section 5.7.1, [561, 585]	10 GHz
Graviton–Magnon Resonance, Section 5.7.2, [565, 569]	[8 – 14] GHz
Atomic Precision Measurement, Section 5.7.3, [571]	[10 kHz – 10 GHz]
One-Electron Quantum Cyclotron, Section 5.7.4, [569]	[20 – 200] GHz
Rydberg Atoms, Section 5.7.5, [577]	[0.3 – 16] GHz

529. J. Dai and G.-R. Liang, "Graviton-Photon Conversion in Atoms and the Detection of Gravitons," arXiv:2302.07044 [gr-qc]. (Sections: 5.5.2, 7)

Outlines

1. Basic formalism and key properties of GRAPH
   (1) Formalism
   (2) Transverse static electric field
   — the simplest example to illustrate key features

2. Photon to graviton transition (P→G): *Gertsenshtein effect*
   — The "gravitational photo-electric effect" to test the energy quantization of the gravitational field

3. Graviton to photon transition (G→P)
   (1) High frequency GW Detections
   (2) A More General framework
   (3) Spherical atomic electric field
   — a possible way to detect high frequency GW

4. Final words and discussions

Clarifications

We will frequently use the word "graviton" as a synonym of "high frequency GW",

or the "energy quantization" of gravitational field.

while we work in classical regime through out the procedure.

(1) Formalism: GRAPH in flat spacetime

— the action and Equations of Motion

GRAPH is fully described by the action:

$$S = S_g + S_{\rm EM} = \int \mathrm{d}^4x\sqrt{-g}\left(\frac{R}{16\pi} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}\right), \quad (1)$$

with R the Ricci scalar, and $F_{\mu\nu}$ the electromagnetic tensor as

$$F_{\mu\nu} = \nabla_\mu A_\nu - \nabla_\nu A_\mu = \partial_\mu A_\nu - \partial_\nu A_\mu. \quad (2)$$

The interaction is solely contained in

$$S_{\rm EM} = -\frac{1}{4}\int \mathrm{d}^4x\sqrt{-g}\; F_{\mu\nu}F^{\mu\nu}, \quad (3)$$

both the metric and EM field are perturbed around a background as

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}, \quad A_\mu \to \overline{A}_\mu + A_\mu \; (F_{\mu\nu} \to \overline{F}_{\mu\nu} + f_{\mu\nu}). \quad (4)$$

Keeping terms containing both $f_{\mu\nu}$ and $h_{\mu\nu}$ up to the 2nd order, the EM action is expanded as

$$\delta S_{\mathrm{EM}} = \int \mathrm{d}^4x \left(-\frac{1}{4} f_{\mu\nu} f^{\mu\nu} + \overline{F}_{\lambda(\mu} f^{\lambda}{}_{\nu)} h^{\mu\nu} - \cancel{\frac{1}{4} h^{\lambda}{}_{\lambda} \overline{F}^{\rho\sigma} f_{\rho\sigma}} \right), \quad (5)$$

the cancellation is due to TT gauge. The rest of the Lagrangian is naturally composed of a free term and an interaction term,

$$\mathcal{L}_{\mathrm{EM}} = \mathcal{L}_f + \mathcal{L}_{\mathrm{int}} = -\frac{1}{4} f_{\mu\nu} f^{\mu\nu} + \frac{1}{2} \mathcal{T}^{\mu\nu} h_{\mu\nu} \quad (6)$$

with the “interactive tensor”, governing the core of GRAPH:

$$\mathcal{T}^{\mu\nu} = \overline{F}^{\mu\lambda} f^{\nu}{}_{\lambda} - \cancel{\frac{1}{4} \eta^{\mu\nu} \overline{F}_{\rho\sigma} f^{\rho\sigma}}. \quad (7)$$

For G→P conversion, $\mathcal{L}_{\mathrm{EM}}$ alone is enough, but in a more explicit form with a current J^μ, extracted as

$$J_\rho = -\partial^\sigma \left[\left(\overline{F}_{\mu\rho}\eta_{\nu\sigma} - \overline{F}_{\mu\sigma}\eta_{\nu\rho} - \cancel{\frac{1}{2}\eta_{\mu\nu}\overline{F}_{\sigma\rho}} \right) h^{\mu\nu} \right]. \tag{8}$$

Therefore, the EOM for G→P conversion is

$$\nabla_\mu f^{\mu\nu} = -J^\mu \tag{9}$$

and the retarded potential is

$$A^\mu(r,t) = \frac{1}{4\pi} \int \frac{J^\mu(r', t - |r - r'|)}{|r - r'|} \, \mathrm{d}V'. \tag{10}$$

For P→G conversion, we perturb the Einstein-Hilbert action

$$S_g = \frac{1}{16\pi} \int \mathrm{d}^4 x \sqrt{-g}\; R \tag{11}$$

around flat spacetime $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$, to get

$$\mathcal{L}_h = \frac{1}{2\kappa^2} \left(\nabla^\mu h^{\lambda\nu} \nabla_\lambda h_{\mu\nu} - \frac{1}{2} \nabla^\lambda h^{\mu\nu} \nabla_\lambda h_{\mu\nu} - \cancel{\nabla^\rho h_{\lambda\rho} \nabla^\lambda h + \frac{1}{2} \nabla^\lambda h \nabla_\lambda h} \right) \tag{12}$$

and then piece it with $\mathcal{L}_{\text{int}}$, giving the source term on the RHS of GW equation:

$$\Box h_{\mu\nu} = -2\kappa^2 \mathcal{T}_{\mu\nu} = -2\kappa^2 \overline{F}_{\lambda(\mu} f^{\lambda}{}_{\nu)} \tag{13}$$

and the retarded solution is thus

$$h_{\mu\nu}(r, t) = \frac{\kappa^2}{2\pi} \int \frac{\mathcal{T}_{\mu\nu}(r', t - |r - r'|)}{|r - r'|} \, \mathrm{d}V'. \tag{14}$$

(2) Transverse static electric field

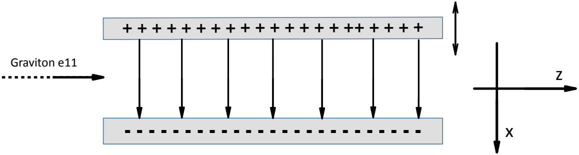
— the simplest example to illustrate key features

3. From Graviton to Photon transition (G→P)

(2) Transverse static electric field

The simplest model to present physical properties of GRAPH: A static electric field by charged parallel plates.

Incident GW $\Longrightarrow$ space distortion $\Longrightarrow$ EMW excitation.



High frequency: almost identical orientation.

$$\mathcal{L}_{\text{int}} = \frac{1}{2}\mathcal{T}^{\mu\nu}h_{\mu\nu} = \frac{1}{2}\overline{F}^{\mu\lambda}f^{\nu}{}_{\lambda}h_{\mu\nu}$$

$$\overline{E} = \overline{F}_{10} = -\overline{F}_{01}, \qquad h_{\mu\nu} = 2\mathrm{Re}\left[e_{\mu\nu}\mathrm{e}^{\mathrm{i}\omega(z-t)}\right]$$

In this case, the Lagrangian is given as

$$\mathcal{L}(h, E) = -2\overline{E}\mathrm{Re}\left[\left(E_1 e_{11} + E_2 e_{12}\right) \mathrm{e}^{\mathrm{i}\omega(z-t)}\right], \tag{15}$$

hence the corresponding electric current is

$$J_i = 2\omega\overline{E}|e_{1i}|\cos\left[\omega(z-t) + \varphi_i - \frac{\pi}{2}\right], \tag{16}$$

where the phase $\varphi_i - \frac{\pi}{2}$ is irrelevant to our problem. We see that only J_x and J_y exist in this case.

We focus on incident e_{11} mode, and follow the standard Green's function procedure:

$$J_i \to A_i \to E_i \to P_{EM} = \frac{\epsilon_0}{2}\int E_{\mathrm{max}}^2 r^2 \,\mathrm{d}\Omega \tag{17}$$

3. From Graviton to Photon transition (G→P)

(2) Transverse static electric field

Under high frequency approximation $\lambda \ll L$, the total power:

$$P_{\rm EM} = \frac{1}{2}\omega^2 \epsilon_0 \overline{E}^2 VL|e_{11}|^2/c, \tag{18}$$

with $V = LWH$ the volume of capacitor.

The incoming gravitational radiation power is

$$P_{\rm GW} = \frac{\omega^2 c^3 |e_{11}|^2}{8\pi G} WH. \tag{19}$$

the probability that a graviton turns into photon (the ratio):

$$\epsilon_{g\to\gamma} = P_{\rm EM}/P_{\rm GW} = 4\pi G \epsilon_0 \bar{E}^2 L^2/c^4 = \frac{8\pi G}{c^4} \varepsilon_{\rm EM} L^2. \tag{20}$$

For a constant magnetic field background,

$$\epsilon_{g\to\gamma} = P_{\rm EM}/P_{\rm GW} = 4\pi G \bar{B}^2 L^2/\mu_0 c^4 = \frac{8\pi G}{c^4} \varepsilon_{\rm EM} L^2. \tag{21}$$

Key features of conversion probability:

- Frequency-independent, but EM field energy density dependent.
- Proportional to the length squared:

  Reason: massless gravitons and photons have equal velocities, the probability amplitudes adds up coherently along the path.

  Results: relation very sensitive to phase changes. Tiny speed difference will break the proportionality to length squared. (e.g. QED effect, light propagating in medium)

四同：同频、同速、同向、同相

2. From Photon to Graviton transition (P→G)

— An experiment to test the energy quantization of gravitational field

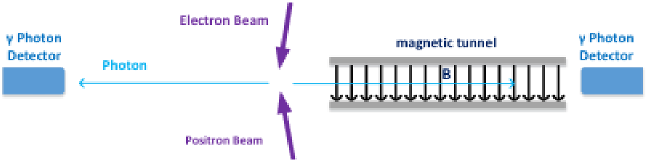
2. From Photon to Graviton transition (P→G)

An experiment to test the energy quantization of gravitational field

A gravitational version of photo-electric effect:

Let pairs of entangled γ-photons travel in the opposite direction, with a single branch going through a magnetic tunnel.

Count the photons on the 2 detectors to find the missing photons.



Criteria for energy quantization of gravitational field:

- If photon numbers on the two sides are equal, but frequency on the RHS is red-shifted — classical;
- If photon number on the RHS is less, but the rest on the two sides have the same frequency — quantized.

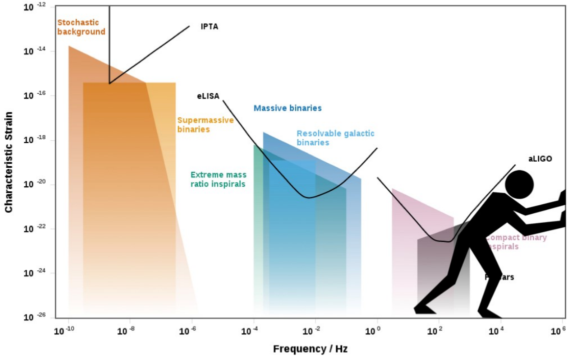
(1) Motivation: Detection of High frequency GWs

— Detection frequency bands and methods

3. Graviton to photon transition (G→P)

(1) Motivation: Detection of High frequency GWs

Detected GW frequencies $\ll$ visible light ($\sim 10^{14}$ Hz).
LIGO: 10Hz $\sim$ 10kHz, PTA: 1nHz



We have to push GW detection to a higher frequency band!

Rough Classifications of High-Frequency GWs:

- Relatively High Frequencies (RHF, 稍高频) — $10^4 \sim 10^6$Hz (Just a little above the LIGO detectability)
- Very High Frequencies (VHF, 甚高频) — $10^6 \sim 10^{12}$Hz (mainly cover MHz and GHz bands)
- Ultra High Frequencies (UHF, 超高频) — $10^{12} \sim 10^{18}$Hz: (mainly cover visible EMW band $\sim 10^{14}$Hz)
- Extremely High Frequencies (EHF, 极高频) — $> 10^{18}$Hz: (atomically detectable, the main focus in this report)

Detection of High-Frequency GWs:

- Optically levitated dielectric sensors —— $10^3 \sim 3 \times 10^5$Hz
- Resonant polarization rotation —— around 10^8Hz
- Bulk acoustic wave devices —— $10^6 \sim 7 \times 10^8$Hz
- GW deformation of microwave cavities —— $10^6 \sim 10^{10}$Hz
- Graviton-Photon conversion —— a wideband, $f \gg c/L$ (equivalently $\lambda \ll L$, L the scale of background EM field)

  Atomically detectable: $f > f_A = c/r_A \simeq 10^{18}$Hz

(2) A More General framework of GRAPH

— Considering QED, plasma effect and back-reaction

3. From Graviton to Photon transition (G→P)

(2) A More General framework of GRAPH

Considering QED, plasma effect and back-reaction

A Schrodinger-type equation:

$$\mathrm{i}\frac{\mathrm{d}}{\mathrm{d}z}\psi(z) = \mathcal{M}\psi(z), \tag{22}$$

with

$$\psi(z) = \begin{pmatrix} h_\lambda(z) \\ A_\lambda(z) \end{pmatrix} \mathrm{e}^{\mathrm{i}\omega z}, \qquad \mathcal{M} = \begin{pmatrix} 0 & \Delta_{g\gamma} \\ \Delta_{g\gamma} & \Delta_\gamma \end{pmatrix}. \tag{23}$$

Notations:

- Polarization — $\lambda = +, \times$
- GRAPH coupling — $\Delta_{g\gamma} = 2\sqrt{\pi}B/M_{\mathrm{pl}}$
- Effective photon mass — $\Delta_\gamma = \Delta_{\mathrm{QED}} + \Delta_{\mathrm{plasma}}$.

Initial condition:
G→P transition: $h_\lambda(0) = 1, A_\lambda(0) = 0$;
P→G transition: $A_\lambda(0) = 1, h_\lambda(0) = 0$.

Conversion probability:

$$\epsilon_{g\leftrightarrow\gamma} = \left(\frac{2\Delta_{g\gamma}}{\Delta_{\mathrm{osc}}}\right)\sin^2(\Delta_{\mathrm{osc}} z/2). \tag{24}$$

Oscillation factor — $\Delta_{\mathrm{osc}} = \sqrt{\Delta_\gamma^2 + (2\Delta_{g\gamma})^2}$.

A complete conversion ($\epsilon_{g\leftrightarrow\gamma} = 1$) requires $\Delta_\gamma = 0$,

$$\epsilon_{g\leftrightarrow\gamma} = \sin^2(\Delta_{g\gamma} z). \tag{25}$$

For the phase to be $\pi/2$, the conversion length is

$$l_{g\leftrightarrow\gamma} = \frac{\pi/2}{\Delta_{g\gamma}} = \frac{\sqrt{\pi} M_{\rm pl}\ c}{4eB} \simeq 1.7 \times 10^{19}\ \mathrm{m} \simeq 1.8 \times 10^{3}\ \mathrm{lys}, \quad (26)$$

$B \sim 1\mathrm{T}$ for man-made magnetic field.

In ground-based experiment, $z \ll l_{g\leftrightarrow\gamma}$,

$$\epsilon_{g\leftrightarrow\gamma} \simeq (\Delta_{g\gamma} z)^2 = 4\pi G B^2 z^2 \xlongequal{\text{SI units}} \frac{8\pi G}{c^4} \varepsilon_{\rm EM} z^2, \qquad (27)$$

which is consistent with equation (21).

To increase the conversion probability, we have to choose a strong EM field to enhance $\varepsilon_{\rm EM}$!

Largest man-made and atomic electric and magnetic fields:

For the same energy density:

$$\frac{1}{2}\epsilon_0 E^2 = \frac{1}{2}B^2/\mu_0 \quad \Longrightarrow \quad E = cB$$

EM Field	E (V/m) / ε_E (J/m^3)	B (T) / ε_B (J/m^3)
Man-made	1.3×10^9 / 7.48×10^6	45.5 / 8.24×10^8
Atomic	5.14×10^{11} / 1.17×10^{12}	12.52 / 6.24×10^7

The atomic electric field has the largest energy density!

(3) Spherical atomic electric field

— a possible way to detect extremely high frequency GW

Strong electric field: inside an atom, particularly near the nuclei.

A simple model for the spherical atomic electric field, $\vec{E}(x) = \overline{E}(r)\hat{r}$,

$$\overline{E}(r) = \frac{Ze}{4\pi r^2}\ q\left(\frac{r}{r_A}\right), \tag{28}$$

with the "fraction function" given as

$$q\left(\frac{r}{r_A}\right) = \begin{cases} 0, & r > r_A \\ 1 - \frac{r^3}{r_A^3}, & r_N < r < r_A \\ \frac{r^3}{r_N^3} - \frac{r^3}{r_A^3}, & r < r_N, \end{cases} \tag{29}$$

it cancels outside the atom when the GW wave length is long, but sensitive to high frequency GW to produce GRAPH.

We consider GW with polarization e_{12}, traveling in z direction, and ignore the atomic magnetic field.

In this case, the interaction term is

$$\mathcal{L}(e_{12}) = -2\mathrm{Re}\left[\left(\overline{E}_x E_y + \overline{E}_y E_x\right) e_{12}\ \mathrm{e}^{\mathrm{i}\omega(z-t)}\right], \tag{30}$$

the effective current spacetime vector to be

$$j_\mu^{\mathrm{eff}} = -2\mathrm{Re}\left[\left(\partial_x \overline{E}_y + \partial_y \overline{E}_x, \mathrm{i}\omega \overline{E}_y, \mathrm{i}\omega \overline{E}_x, 0\right) e_{12} \mathrm{e}^{\mathrm{i}\omega(z-t)}\right] \tag{31}$$

Using Green's function, at a faraway point:

$$A_\mu(r, \hat{k}, t) = \frac{1}{4\pi r} \int \mathrm{d}^3 x'\ j_\mu^{\mathrm{eff}}\left(x', t - n(r - \hat{k} \cdot \vec{x}')\right) \tag{32}$$

where the integration of x' is on the whole atom.

The angular EM radiation power distribution:

$$P(\theta, \varphi) = \frac{Z^2 e^2}{32\pi^2} |e_{12}|^2 \omega^2 \, f^2(\omega, \theta) \; \Omega(\theta, \varphi) \tag{33}$$

Inclination function $f(\omega, \theta)$

$$f(\omega, \theta) = \omega r_A \int_0^1 \mathrm{d}\rho \; q(\rho) \int_0^\pi \mathrm{d}\theta' \sin^2\theta' \cos\left[\omega r_A \rho (1 - n\cos\theta)\cos\theta'\right] J_1(\omega r_A n\rho \sin\theta' \sin\theta),$$

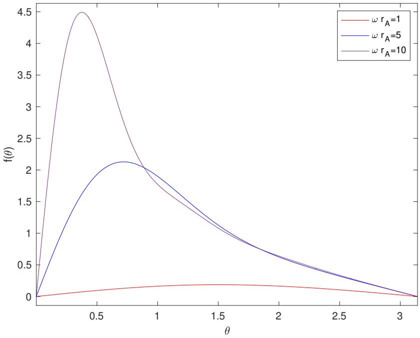
with $\rho \equiv r/r_A$.

Azimuthal distribution $\Omega(\theta, \varphi)$

$$\Omega(\theta, \varphi) = 1 - \sin^2\theta \sin^2 2\varphi$$

Its azimuthal distribution $\Omega(\theta, \varphi)$ is of quadrupole nature, with maximum at 4 directions of $\pm x$ and $\pm y$, and minimum at 4 direction of 45°.

The inclination function $f(\omega, \theta)$ in $0 \leqslant \theta \leqslant \pi$ when $\omega r_A = 1, 5, 10$, with the assumption $n \simeq 1$ for extremely high frequencies.



As ωr_A increases, the peak moves to a smaller angle, shrinking EMW in almost the same direction with incident GW.

Total EM radiation power:

$$P_{\text{EM}} = \int_0^{\pi} \mathrm{d}\theta \int_{-\pi}^{\pi} \mathrm{d}\varphi \; P(\theta, \varphi) = \frac{|e_{12}|^2 (Ze\omega)^2}{16\pi} \beta_A(\omega r_A) \tag{34}$$

with

$$\beta_A(\omega r_A) = \int_0^{\pi} \mathrm{d}\theta \; f^2(\omega, \theta) \left(1 - \frac{1}{2}\sin^2\theta\right). \tag{35}$$

The cross section:

$$\sigma = \frac{P_{\text{EM}}}{P_{\text{GW}}} = \frac{G(Ze)^2}{2\epsilon_0 c^4} \beta_A(\omega r_A) \simeq Z^2 \beta_A(\omega r_A) \times 1.2 \times 10^{-71}\ \text{m}^2. \tag{36}$$

In the interval $100 \leqslant \omega r_A \leqslant 10^6$, numerically $\beta_A(\omega r_A) \approx \frac{1}{2}\omega r_A$, the cross section:

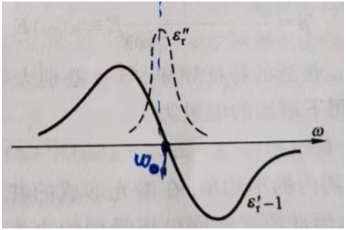
$$\sigma = \omega r_A Z^2 \times 6 \times 10^{-72} \text{m}^2, \tag{37}$$

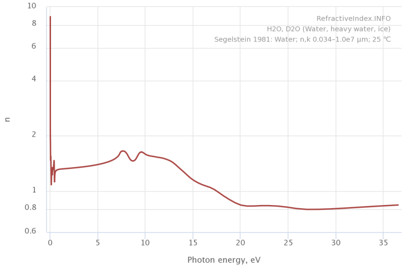
the corresponding graviton energy: 100 keV to 1 GeV.

3. From Graviton to Photon transition (G→P)

(3) Spherical atomic electric field

But, there's one thing we have to take care of...





Refraction index n as a function of frequency(Hz)/photon energy(eV).

Low frequency region: $n > 1 \quad \Longrightarrow \quad c_m = 1/n < 1$

High frequency region: $n < 1 \quad \Longrightarrow \quad c_m = 1/n > 1$.

Internal electron frequency: $\omega_o = E_o/\hbar \simeq 10^{15}\text{Hz}$
Atomically detectable GW frequency: $\omega_A = 2\pi c/r_A \simeq 10^{18}\text{Hz}$

$$\omega_o \ll \omega_A$$

Atomically detectable GW locates at extremely high frequency (EHF) region, with $n < 1$ and $c_m > 1$.

Ultra-high frequency region:
Simple harmonic oscillator model for electrons.

The medium permittivity:

$$\varepsilon = \varepsilon_0 - \frac{n_e e^2}{m_e}\frac{1}{\omega^2 - \omega_0^2}. \tag{38}$$

At extremely high frequency, ω_0 is suppressed, the refraction index is

$$n(\omega) = \sqrt{\varepsilon/\varepsilon_0} \simeq 1 - \frac{1}{2}\frac{\omega_p^2}{\omega^2}, \qquad \text{with} \qquad \omega_p \equiv \sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}}, \tag{39}$$

the phase velocity is

$$\frac{c_m}{c} = \frac{1}{n} \simeq 1 + \frac{\omega_p^2}{2\omega^2}. \tag{40}$$

Coherent length l_c (phase difference less than half of a cycle):

$$l_c = \frac{\pi c}{\frac{2\pi(c_m - c)}{\lambda}} \simeq \frac{2\pi c\omega}{\omega_p^2}. \quad (41)$$

Higher frequency $\Longrightarrow$ smaller velocity difference $\Longrightarrow$ longer coherent length

Datas of H_2O: electron density $n_0 \simeq 3.33 \times 10^{29}\text{m}^{-3}$,
characteristic frequency $\omega_p \simeq 3.25 \times 10^{16}\text{Hz}$.

For a 100 MeV graviton ($\sim 1.52 \times 10^{23}$ Hz):

$$\left.\begin{array}{r} \text{Coherent length: } l_c \simeq 0.27\text{m} \\ \text{Mean free path: } l_m \simeq 0.3\text{m} \end{array}\right\} \Longrightarrow \text{Enhancement length} : l_\uparrow = \min\{l_c, l_m\}$$

$$\sigma_{\text{tot}} = \left[l_\uparrow (n_0/10)^{1/3}\right]^2 \sigma \simeq 10^{18}\ \sigma \simeq 10^{-54}\text{m}^2 \quad (42)$$

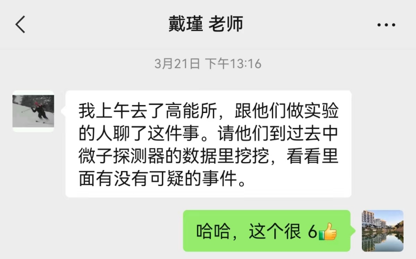
Enhancement of about 18 orders of magnitude.

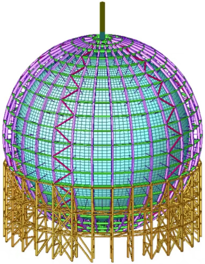
Not so many orders of magnitude from neutrino-atom cross section.

3. From Graviton to Photon transition (G→P)

(3) Spherical atomic electric field

High energy gravitons could be with current/updaded neutrino experiment facilities.
—Deep underground to exclude noises.





Low conversion efficiency: 1. hard to detect; 2. can be detected.

Source of high energy gravitons:

- Primordial Black Hole evaporation — $10^{15} \sim 10^{18}$Hz
- Primordial Black Hole (PBH) binaries — m-dependent f
- Exotic Compact Object (ECO) binaries — m-dependent f
- Supermassive Black Hole (SMBH) photon sphere — 10^{20}Hz
- Magnetars — 10^{20}Hz
- Thermal gravitational noise of the Sun — $10^{12} \sim 10^{18}$Hz

ECO binaries (composed of beyond Standard Model particles):

$$f_{\rm ISCO} \simeq C^{3/2} \left(\frac{6 \times 10^{-3} M_\odot}{M} \right) 10^6 \text{Hz}, \tag{43}$$

$C = GM/R$ the compactness of ECO. ($C_{\rm BH} = 1/2$)

$f > 10^{18}\text{Hz} \implies m_{\rm ECO} < 10^{-15} M_\odot \simeq 10^{15}\text{kg} \quad \text{(sublunar)}$

PBH binaries:
GW frequency from the innermost stable circular orbit (ISCO),

$$f_{\rm ISCO} = \frac{4400{\rm Hz}}{(m_1 + m_2)/M_\odot}, \tag{44}$$

m_1 and m_2 masses of the two PBHs assumed to be equal.

$f > 10^{18}{\rm Hz} \implies m_{\rm PBH} < 10^{-15} M_\odot \simeq 10^{15}{\rm kg}$ (sublunar)

Another bound: $m_{\rm PBH} > 10^{12}{\rm kg}$ to be stable $\implies f < 10^{21}{\rm Hz}$
(Stable: Hawking evaporation time > age of the universe)

GW detection range: $f \simeq 10^{18} \sim 10^{21}{\rm Hz}$

Detailed work to be done:

$$\left.\begin{array}{l}\text{Abundance of PBH}\\ \text{Detection sensitivity}\end{array}\right\} \quad \Longrightarrow \quad \text{Event rate (events per year)}$$

$$\text{Null detection} \quad \Longrightarrow \quad \text{Lower abundance}$$

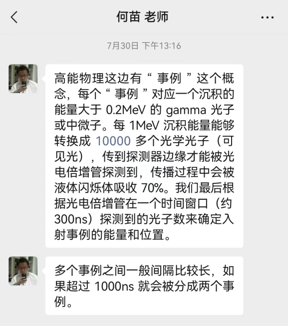
$$\tilde{f}_{\mathrm{PBH}} \lesssim 9.1 \left(\frac{h_{\mathrm{det}}}{10^{-20}}\right)^{3/2} \left(\frac{m_{\mathrm{PBH}}}{M_\odot}\right)^{-1.07} \tag{45}$$

We need to know the detection sensitivity (strain/power) of neutrino facilities.

3. From Graviton to Photon transition (G→P)

(3*) Source of high energy gravitons and some restrictions

We are actively communicating with JUNO members to know the sensitivity.



Basically, if there's a MeV level single photon produced in 300ns, it can be detected.

4. Final words and discussions

A beautiful poem written by Jin Dai，which perfectly describes what we've done

破阵子/*The Sound of Silence*

万众喧嚣闭耳，
一滴水落独听。
梦里高歌音未响，
此意何能言语明？
唯闻寂静声。

五色霓虹刺目，
一条石径独行。
道法阑珊藏陋巷，
觉悟还需心点灯。
得交暗夜朋。

———— 戴瑾

译文/*My Translation*

把所有的噪声信号屏蔽，等待引力子打到原子上激发出一颗光子。

我们预期可以探测到宇宙中的各种高频引力波信号，但现在还没有发生，此时能做的只有静静守候。

各种观测手段五花八门，我们偏偏采用引力子-光子转化的小众途径。

该机制自提出以来似乎关注的人已经不多了，但要重新发掘出它的巨大潜力和作用，必须静心思考感悟，和暗夜交朋友。

———— 梁桂荣

Thank you for listening!

Comments are welcomed!