Galaxy Clusters as Cosmic Lenses for high-frequency gravitational waves

Speaker: Tiziano Zanzarella
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Based on ongoing work by F. Lecce, F. R. Candón, A. Lella, A. Mirizzi, J. K. Vogel, **TZ**

Outline

- Sources of Gravitational-Waves (GWs)
- Background of High-Frequency- Gravitational Waves (HFGWs)
- Detection and constraint of HFGWs
- Graviton-Photon conversions
- Bounds on HFGWs from graviton-photon conversions in the Virgo Cluster

Sources of HFGWs ($f \gtrsim 1\ \mathrm{MHz}$)

Standard astrophysical systems cannot produce GW with frequencies above the kHz range.

HFGW

***Violent* early-Universe events**

- **Inflation**
- **Cosmological phase transitions**
- **Evaporation of PHBs**

***Exotic* late-Universe objects and mechanisms**

- **Coalescenece of exotic objects and PBHs**
- **Black hole superradiance**
- **Hydrodinamic instabilities in stars**

[N. Aggarwal et al., 2025]

HFGW may be the **key** to shed light onto an otherwise inaccessible **dark Universe**.

The Gravitational-Wave Background

Superposition of non-individually resolvable signals

Stochastic, **diffuse**, **unpolarized** background of GWs

[N. Christensen, 2018]

Its intensity is specified by the **characteristic amplitude** $\boldsymbol{h_c}$, tied to the ensemble average of the tensor strain induced by GWs. [M. Maggiore, 2000]

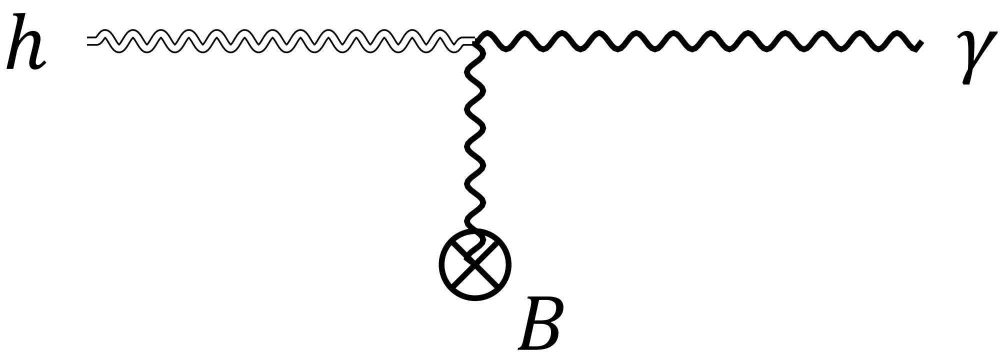
$$\langle h_{ab}(t)h^{ab}(t)\rangle = 2\int_{f=0}^{f=+\infty} d(\log f)\ h_c^2(f)$$

HFGW detection

- At high frequency, GWs show a **particle nature**

Electromagnetism in curved spacetime: $\mathcal{L}_{g\gamma} = -\frac{\sqrt{-g}}{4} F_{\mu\nu} F^{\mu\nu}$

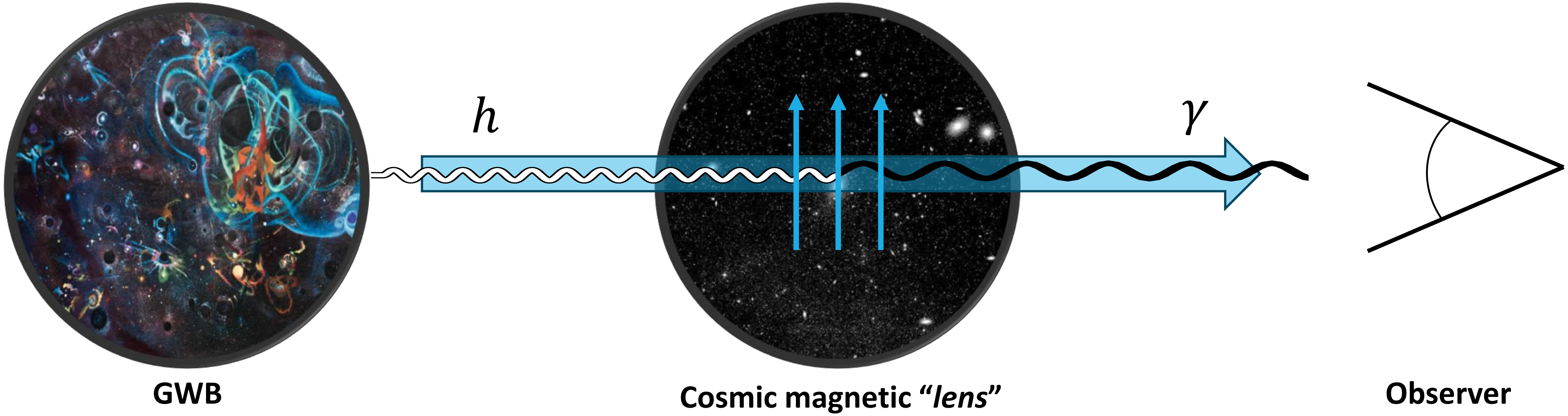
Graviton-photon mixing in external magnetic fields
(inverse Gerstenshtein effect)



[Raffelt-Stodolsky 1988]
[Dolgov-Ejlli, 2012]
[N. Aggarwal et al., 2025]

Indirect constraints: HFGW signatures in astrophysics

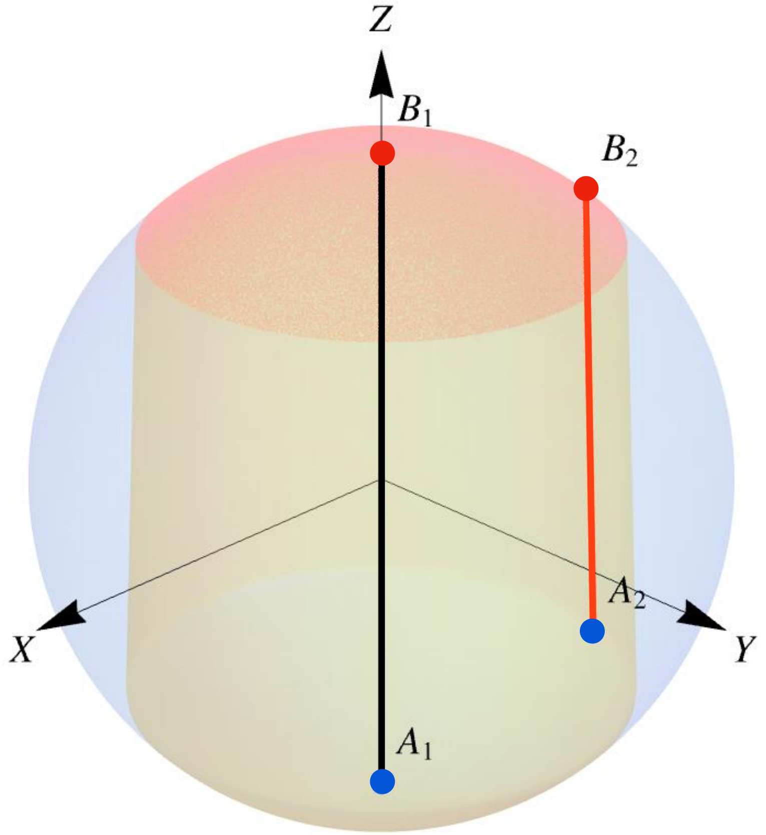
Astrophysical probes for HFGWs

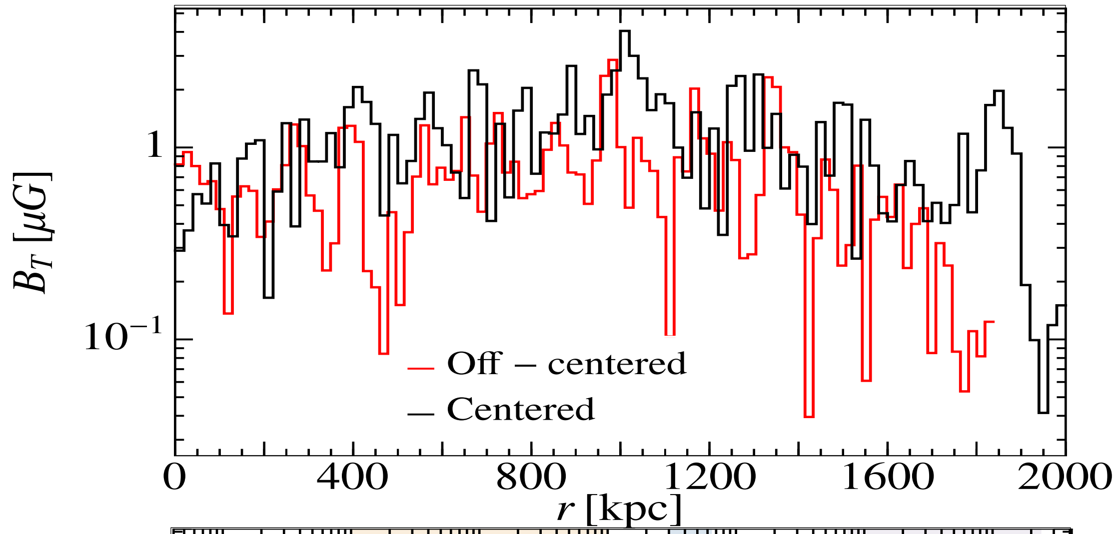


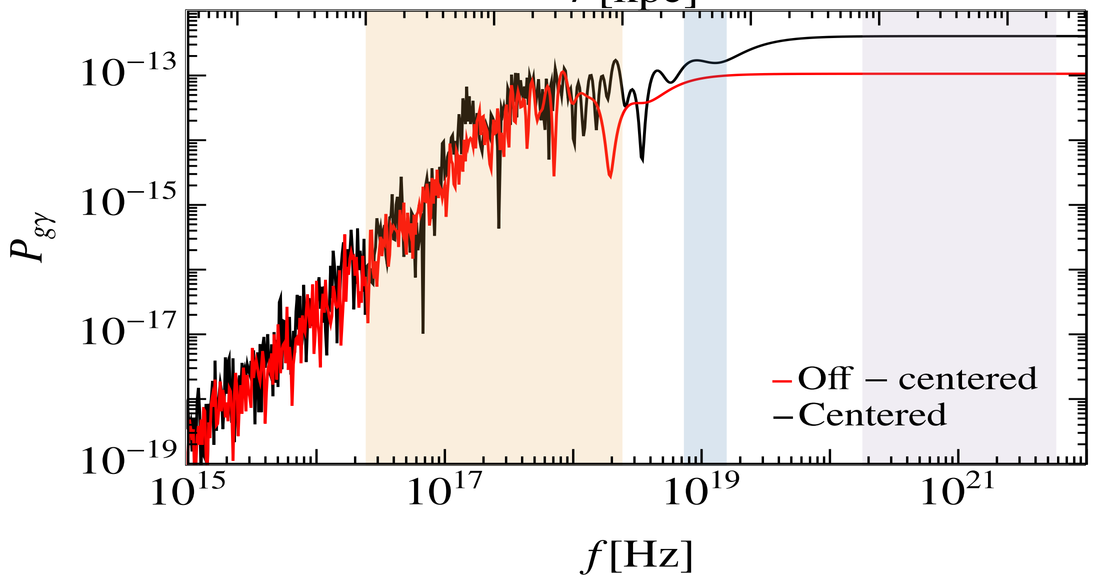
Photon signal from converted gravitons **must not exceed** observed photon signal by telescopes

CONSTRAINT ON GWB

The cosmic magnetic lens: Virgo Cluster



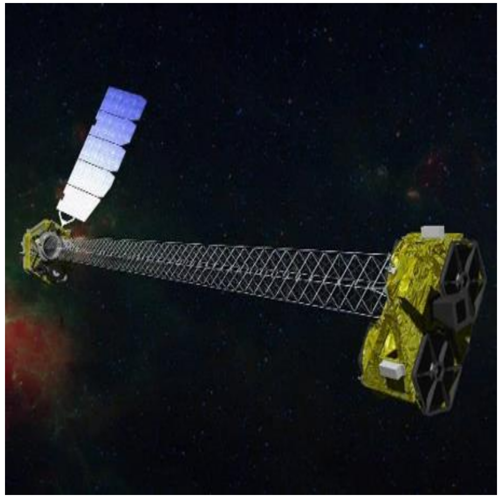




- Modeled as a sphere of $\mathrm{R} = 1\ \mathrm{Mpc}$
- Distance: $\mathrm{d} = 16.5\ \mathrm{Mpc}$
- Magnetic field from hydrodynamical simulations (IllustrisTNG)

Three different observers

eROSITA



NuSTAR

COMPTEL

- Energy range: $0.2 - 10$ keV
- Effective area: 1500 cm^2 at 1.5 keV
- FoV radius: $0.52°$
- Sees entire VC (multiple tiles)

- Energy range: $30 - 70$ keV
- Effective area: 847 cm^2 at 9 keV
- FoV radius: $0.12°$
- Sees small portion of VC

- Energy range: $700 - 30000$ keV
- Effective area: 40 cm^2 at 5 MeV
- FoV radius: $33°$
- Sees entire VC

Bounds on the HFGW spectrum

- Flux of converted gravitons is evaluated as

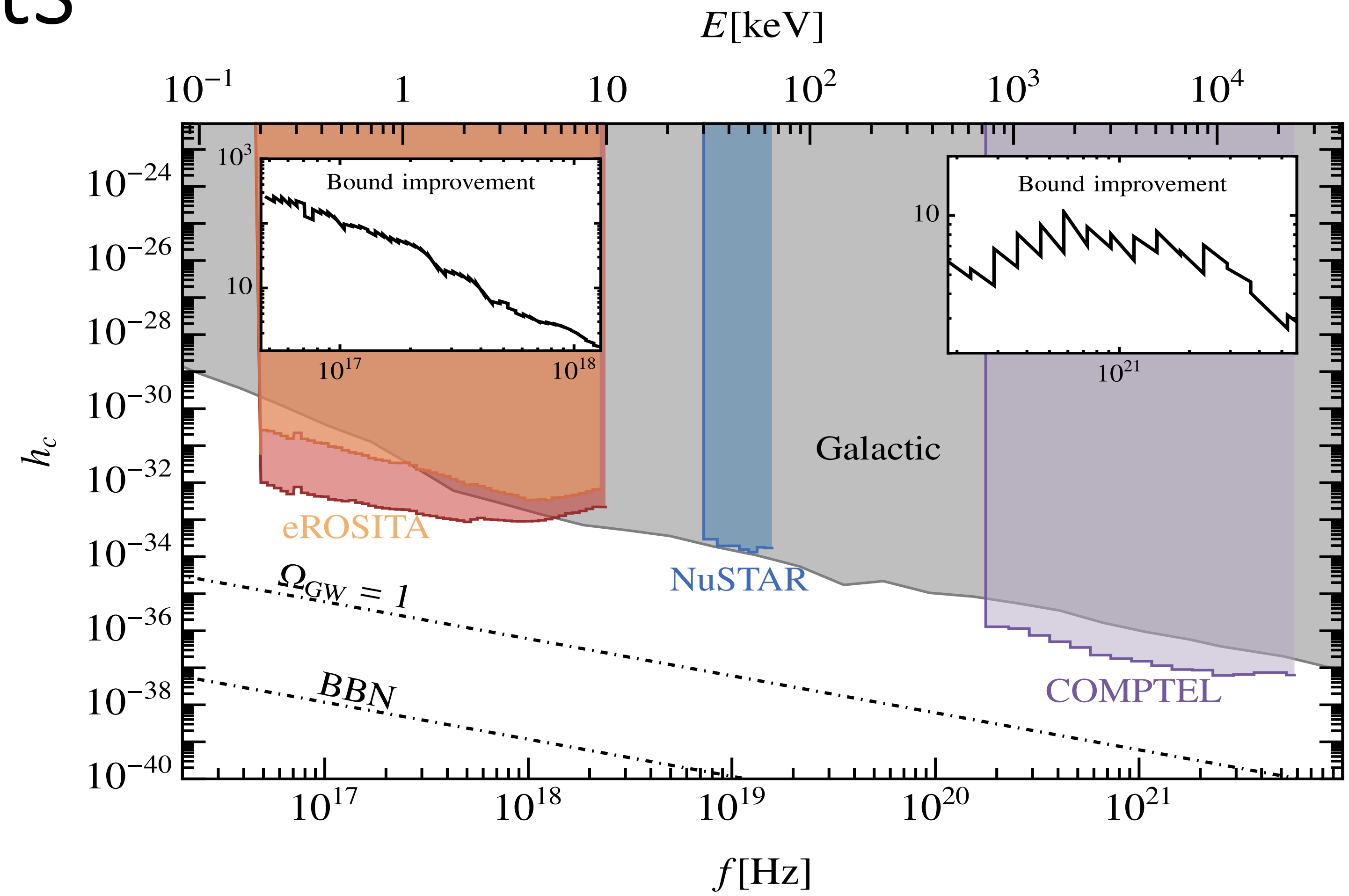
$$R_{bin}^{\text{th}}(f) = \int_{bin} df' \frac{1}{2\pi f'} A_{\text{eff}}(f') \int d\Omega \frac{d^2 F_\gamma}{df'\, d\Omega}(f', \Omega)$$

$$\frac{d^2 F_\gamma}{df'\, d\Omega}(f', \Omega) = \begin{cases} \text{Flux of incoming gravitons} \\ \text{Conversion probability} \end{cases}$$

Flux of incoming gravitons → Scales as h_c^2

Conversion probability → Different LoS, different probability

Results



A. Lella et al., 2024]

- **BBN bound**: Energy density of GWs must not exceed a value that explains the proportion of light nuclei observed today
- $\boldsymbol{\Omega_{GW}}$**= 1 bound**: Energy density of GWs must not saturate the total energy of the Universe

Conclusions

- Galaxy clusters have a great potential as ***cosmic lenses*** for HFGWs

- **Large FoV surveys** are the most suitable observers for HFGW conversions, since they exploit a large portion of the converting volume

- The VC as a cosmic lens **improves significantly current astrophysical bounds**, when observed with the appropriate instrument

Thank you for your attention

QUESTIONS ARE WELCOME!

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Appendix

Graviton – photon conversion probability

- Graviton – photon EoMs

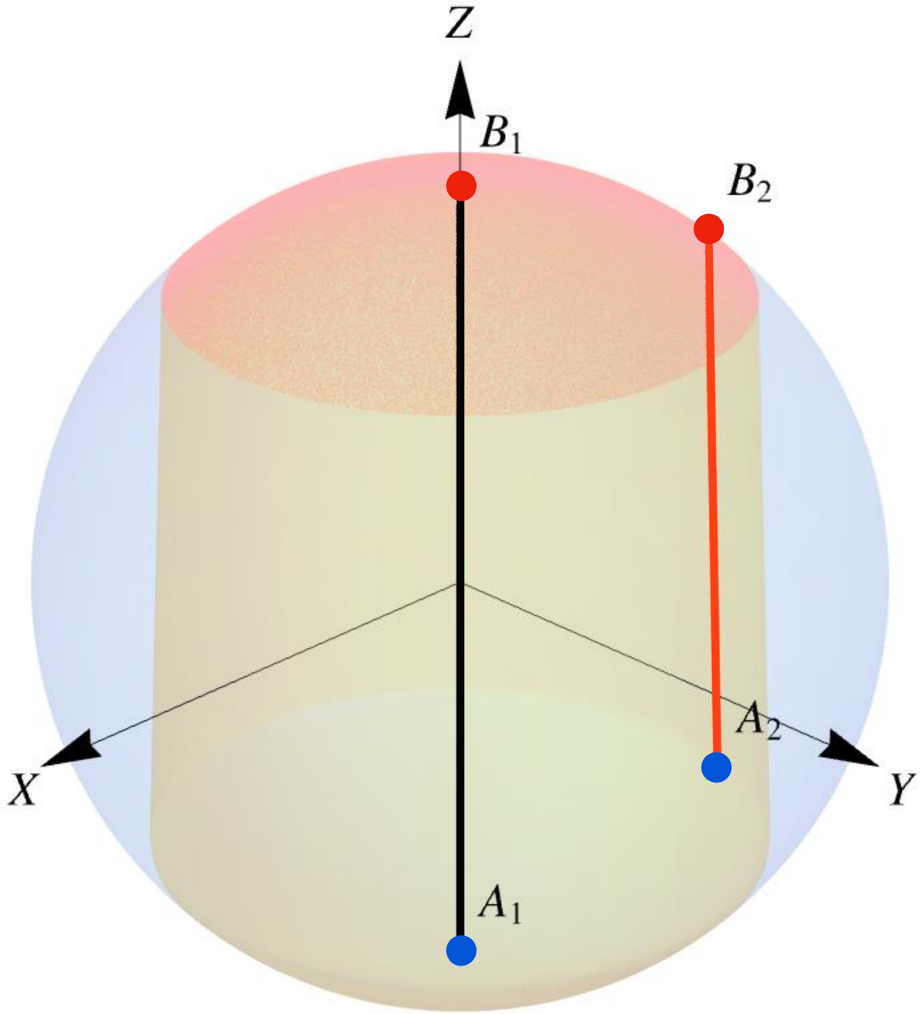
$$\left(i\frac{d}{dz}-\omega\right)\begin{pmatrix}h_+\\h_\times\\A_x\\A_y\end{pmatrix}=\mathcal{H}\begin{pmatrix}h_+\\h_\times\\A_x\\A_y\end{pmatrix}$$

$$\mathcal{H}=\begin{pmatrix}0 & \mathcal{H}_{g\gamma}\\ \mathcal{H}_{g\gamma} & \mathcal{H}_{\gamma\gamma}\end{pmatrix}$$

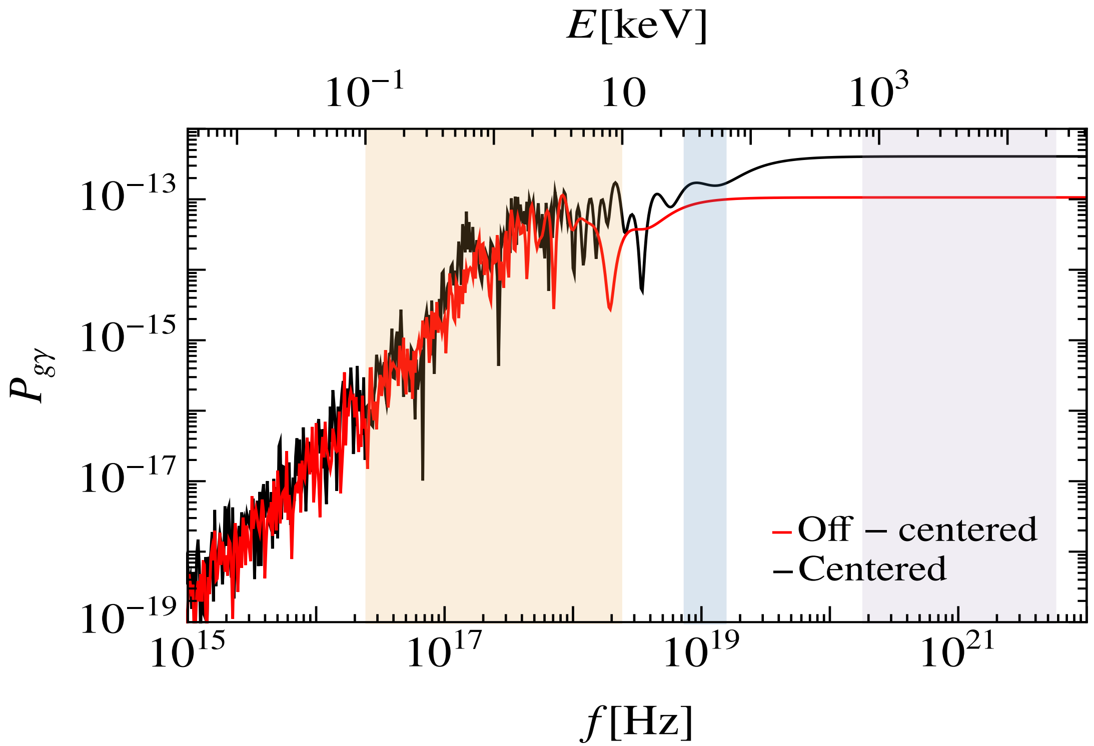
$$\mathcal{H}_{g\gamma}=\frac{B_T}{\sqrt{2}M_P}\begin{pmatrix}sin\phi & cos\phi\\ cos\phi & -sin\phi\end{pmatrix},\qquad \mathcal{H}_{\gamma\gamma}=\begin{pmatrix}\Delta_{pl} & 0\\ 0 & \Delta_{pl}\end{pmatrix}$$

$$P_{g\gamma}=|A_x|^2+\left|A_y\right|^2$$

Graviton-photon conversion probability



- A generic instrument observes only a portion of the VC
- Probability is evaluated along multiple LoSs
- Exiting points in the observed cap, entering points on the other side

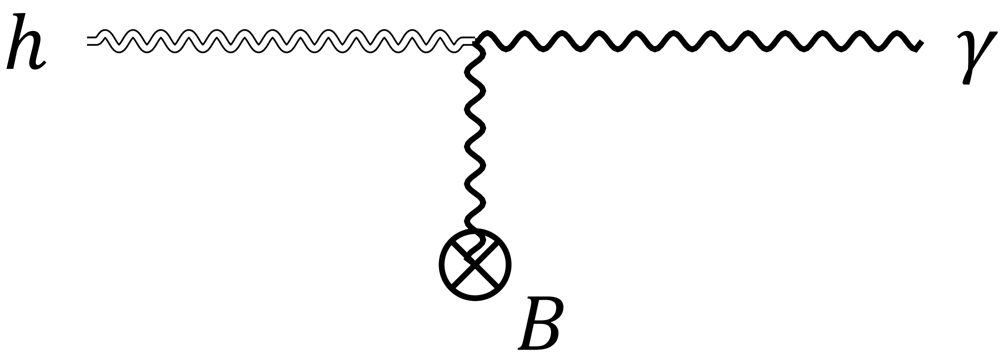


HFGW detection

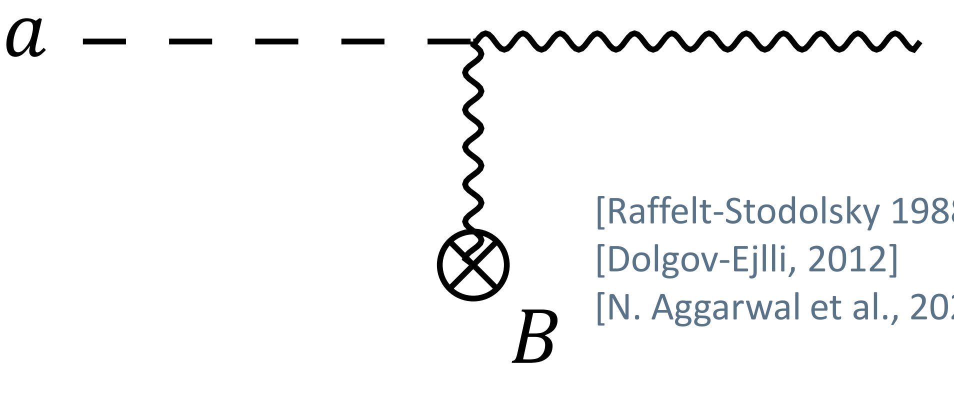
- At high frequency, GWs show a **particle nature**

Electromagnetism in curved spacetime: $\mathcal{L}_{g\gamma} = -\frac{\sqrt{-g}}{4} F_{\mu\nu} F^{\mu\nu}$

Graviton-photon mixing in external magnetic fields ***(inverse Gerstenshtein effect)***



- Also axions mix with photons: $\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a$
- Axion **magnetic detectors** can be adapted to **gravitons** (CAST, IAXO, ALPS II)
- **Indirect constraints**: HFGW signatures in astrophysics



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