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AGENCIA ESTATAL DE INVESTIGACIÓN

Search for high frequency gravitational waves in electromagnetic cavities

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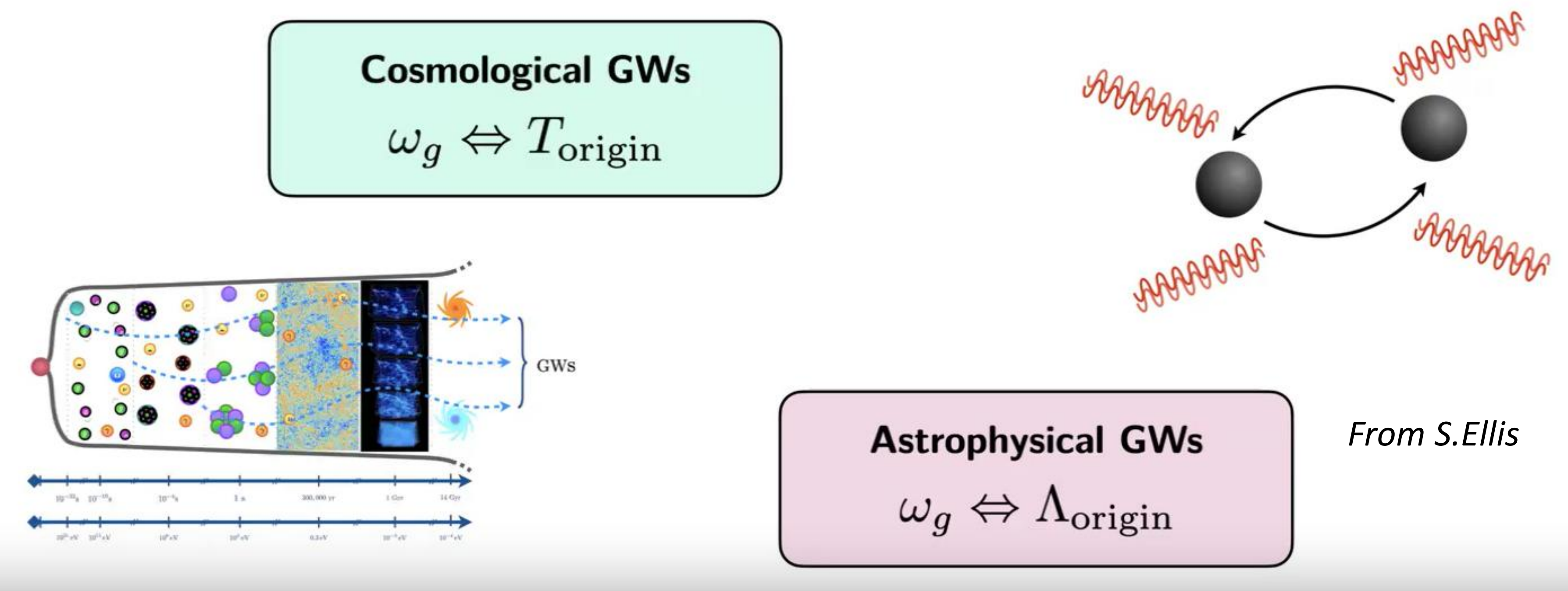
Théorie Univers et Gravitation 2025

Institut de Física d'Altes Energies

HFGW astro/cosmo signals



From S.Ellis

→ Higher GW frequency ⇔ Higher energy scale/Lower length scale we can probe

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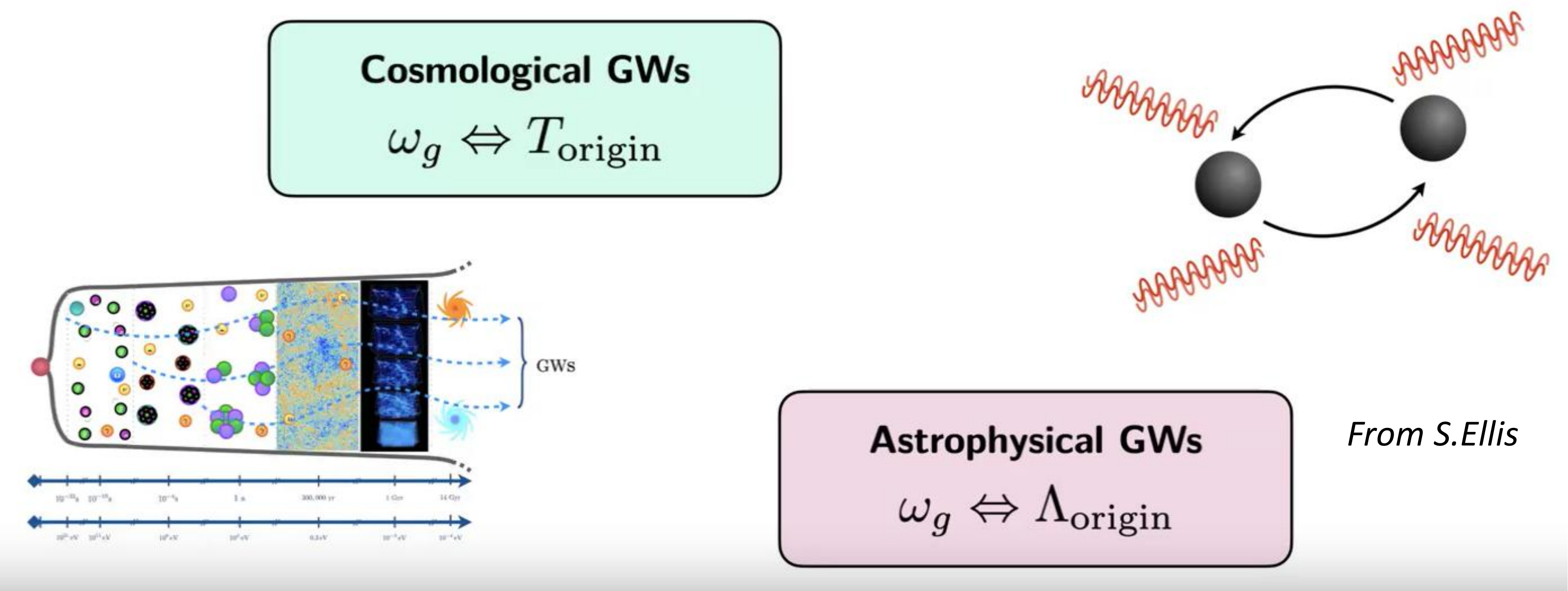

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Some astrophysical sources :

- Mergers of PBH
- Mergers of ECO (boson stars,…)

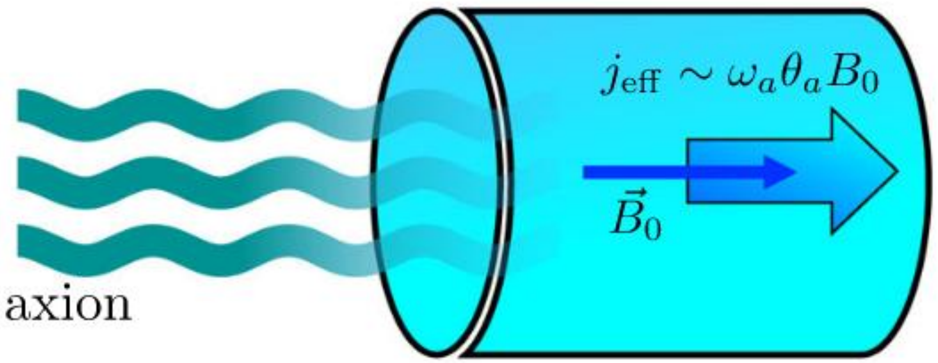
…

- First order phase transition in neutron stars
- Superradiant boson clouds orbiting SMBH (**monochromatic**)

See N. Aggarwal et al, arXiv 2501.11723

→ Many of those sources are BSM

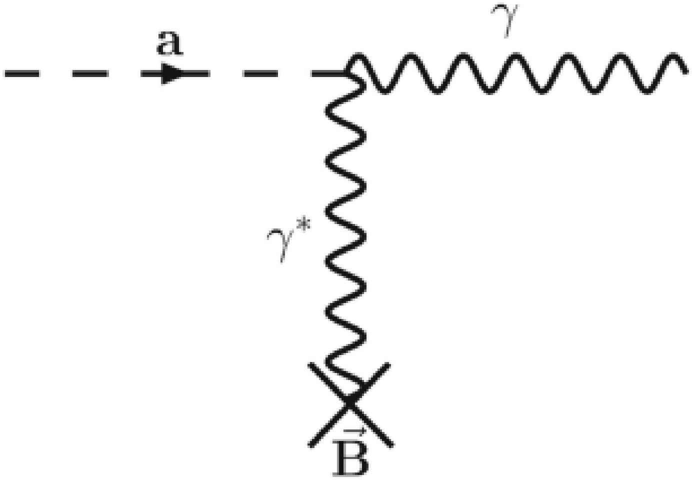
Analogies with axion dark matter



*A. Berlin et al, PRD **105** (2022)*

- Simple way of looking for axions coupled to EM is through inverse Primakoff effect

→Use of microwave cavities to search for GHz axions



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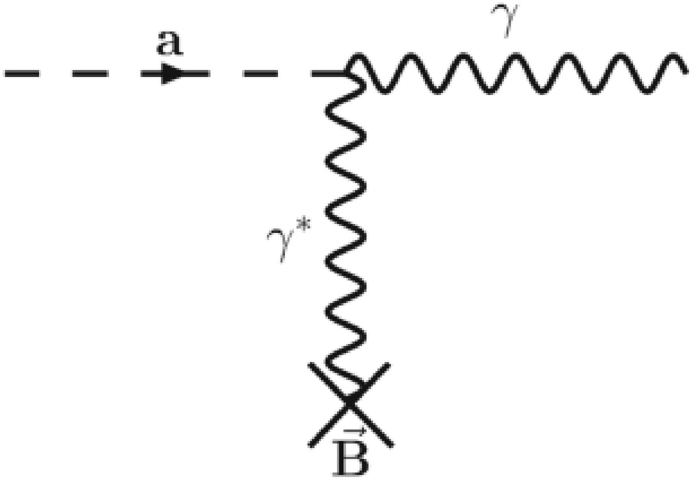
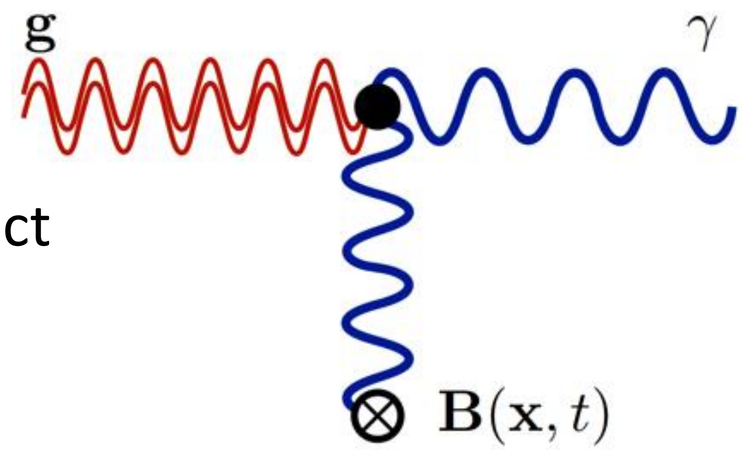


JK Vogel et al (2023)

- GW analog : inverse Gertsenshtein effect

→ Same apparatus is sensitive to HFGW



Credit : S. Ellis

Expected GW signals

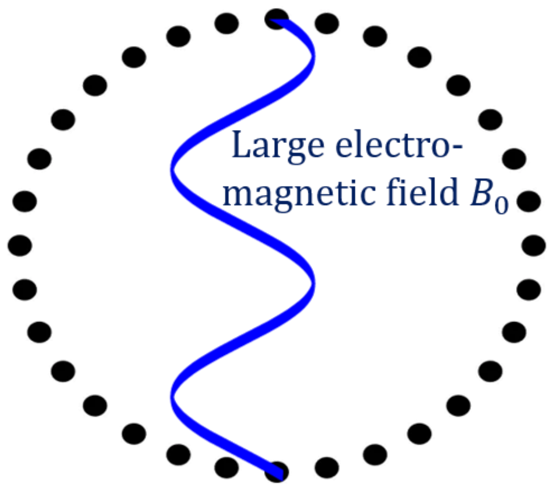
*A. Berlin et al, PRD **105** (2022)*
*V. Domcke et al, PRL **129** (2022)*

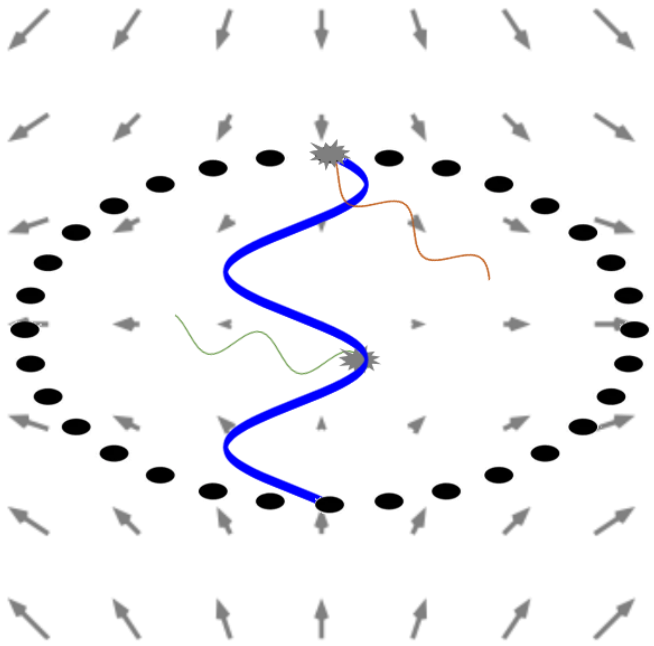
- $S = \int d^4x\sqrt{-g}\left(-\frac{1}{4}g^{\mu\alpha}g^{\nu\beta}F_{\mu\nu}F_{\alpha\beta}\right) \rightarrow \partial_\nu \delta F^{\mu\nu} \equiv j^\mu_{\text{eff}} \propto \omega_g h B_0$

→ GW couples to EM energy

- $\delta \ddot{x}_i - \partial_j \sigma_{ij} = F_i^h$ *M. Hudelist et al, CQG **40** (2023)*

→ GW couples to mechanical energy





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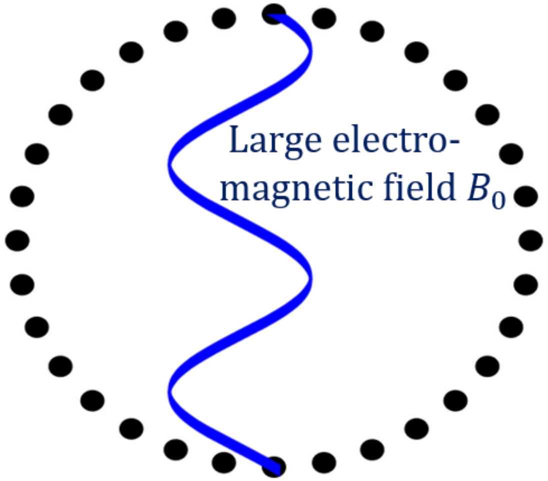

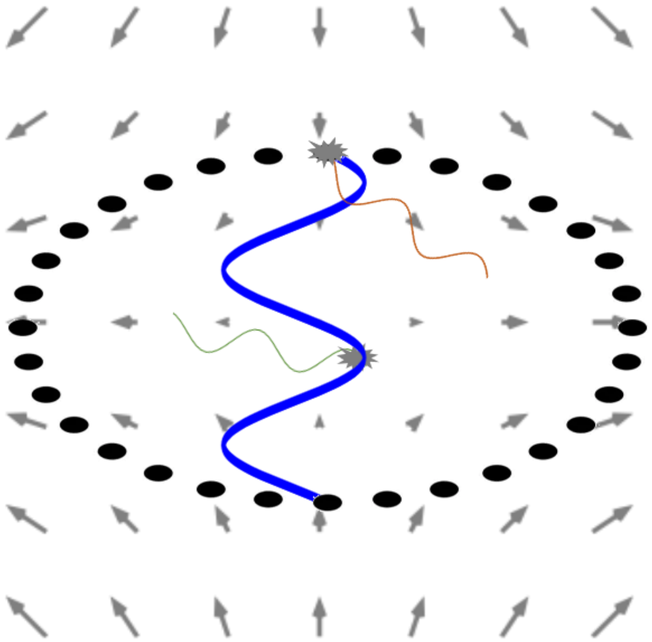

From T. Krokotsch

How do these quantities enter the observable electric field ?

$$E_{\underline{a}} = F_{\mu\nu}e^\mu_{\underline{a}}u^\nu \rightarrow \delta E_{\underline{a}} = \delta F_{\mu\nu}e^\mu_{\underline{a}}u^\nu + F_{\mu\nu}\delta e^\mu_{\underline{a}}u^\nu + F_{\mu\nu}e^\mu_{\underline{a}}\delta u^\nu + \delta x^\rho(\partial_\rho F_{\mu\nu})e^\mu_{\underline{a}}u^\nu$$

W. Ratzinger et al, JHEP ***2024*** *(2024)*

Observer infinitesimal coord. System = Tetrad
$g_{\mu\nu}e^\mu_{\underline{a}}e^\nu_{\underline{b}} = \eta_{\underline{ab}}\ ;\ e^\nu_{\underline{0}} = u^\nu$

→ δF^{0a} is **not** the observed field when dealing with GW

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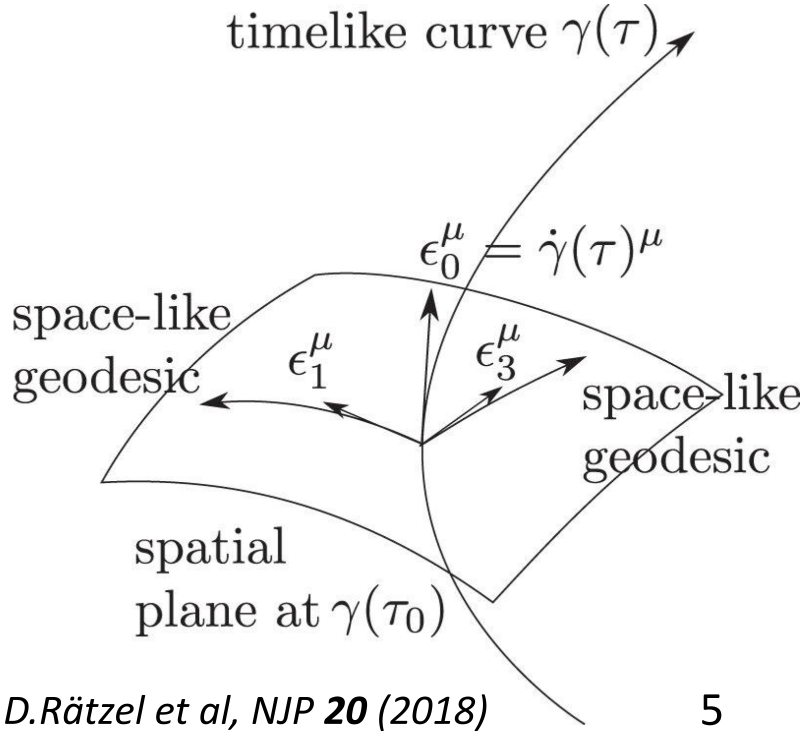
- Proper Detector (PD) Frame : coordinate system built by extending observer's tetrads into geodesics

→ More intuitive : GW acts as a Newtonian force on rigid bodies

→ Metric perturbation more involved



*From D.Rätzel et al, NJP **20** (2018)*

Which frame should we use ?

Freely falling limit : $\omega_g \gg v_s/L$

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What about haloscopes ?

In conductor, $v_s \sim 10^{-5}$, i.e for a cavity with $L \sim 0.1$ m, and $\omega_g \sim$ GHz, $\omega_g L/v_s \gg 1$

→ TT more convenient

$$\delta E_{\underline{a}}^{TT,FF} = \delta F_{a0} + \cancel{F_{\mu 0}\delta e_{\underline{a}}^{\mu}} + \cancel{F_{a\nu}\delta u^{\nu}} + \cancel{\delta x^{\rho}(\partial_{\rho}F_{a0})} = \delta F_{a0}$$

Signal power

In TT, at high frequency, one can solve $\partial_\nu \delta F^{\mu\nu} = j^\mu_{\text{eff}}$ by expanding δF_{a0} in cavity eigenmodes.

On resonance, the signal power in a mode $\vec{E}_n$ is given by

$$P_{sig} = \frac{1}{2} Q \omega_g V \eta_g^2 h^2 \left|\vec{B}\right|^2$$

A. Berlin et al, PRD ***105*** *(2022)*

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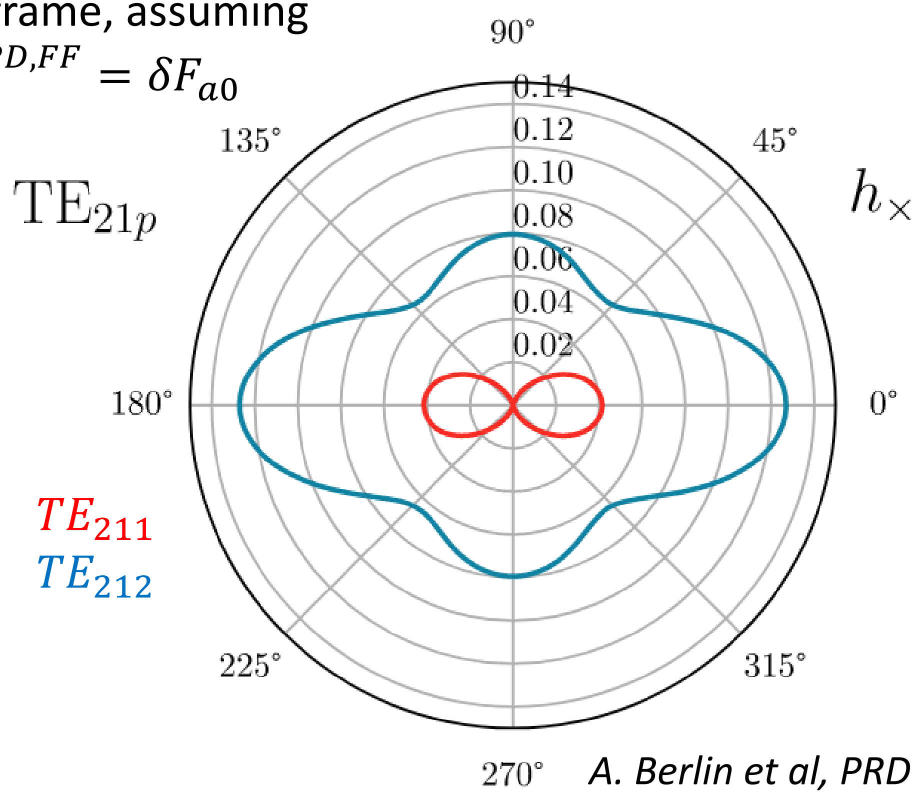
The signal power from axion DM is $P^a_{sig} = \frac{1}{2} g^2_{a\gamma} Q\omega_a V \eta_a^2 a^2 \left|\vec{B}\right|^2$ with $\eta_a = \frac{\left|\int dV \vec{E}_n . \hat{B}\right|}{\sqrt{V \int dV \left|\vec{E}_n\right|^2}}$

*P. Sikivie, RMP **93** (2021)*

→Up to $\mathcal{O}(0.1)$ couplings, we have $h = a g_{a\gamma} \sim 10^{-22}$

Gauge invariance

PD frame, assuming
$\delta E_{\underline{a}}^{PD,FF} = \delta F_{a0}$



*A. Berlin et al, PRD **105** (2022)*

$\eta_\times(\beta)$

Incoming GW
latitude

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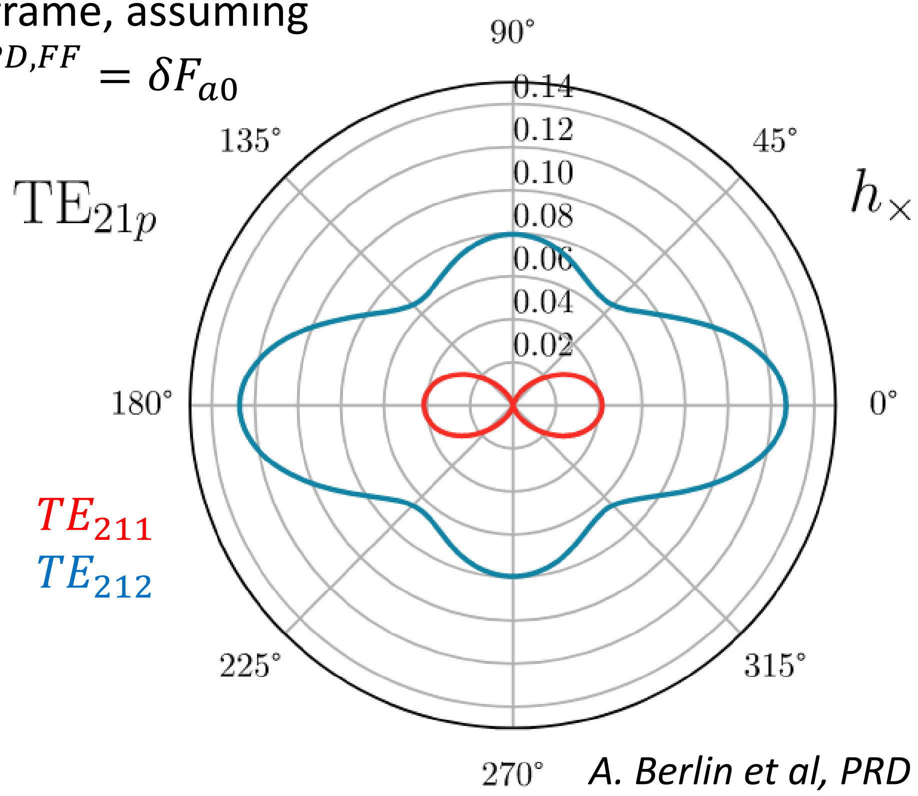

TE_{211}
TE_{212}

A. Berlin et al, PRD **105** (2022)

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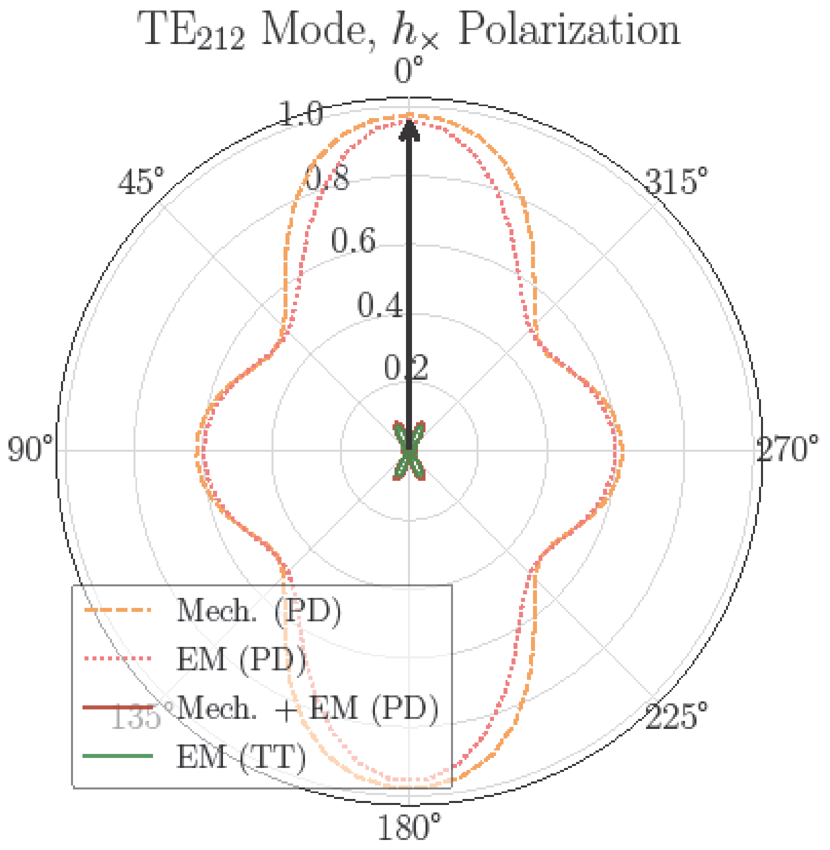

T. Krokotsch, JG, in preparation

To get correct result in PD, need to take into account $F_{aj}\delta u^j$ as a boundary term

→ Signal is gauge invariant as expected.

What is going on now ?

Build covariant framework to compute the full signal in PD/TT at any frequency

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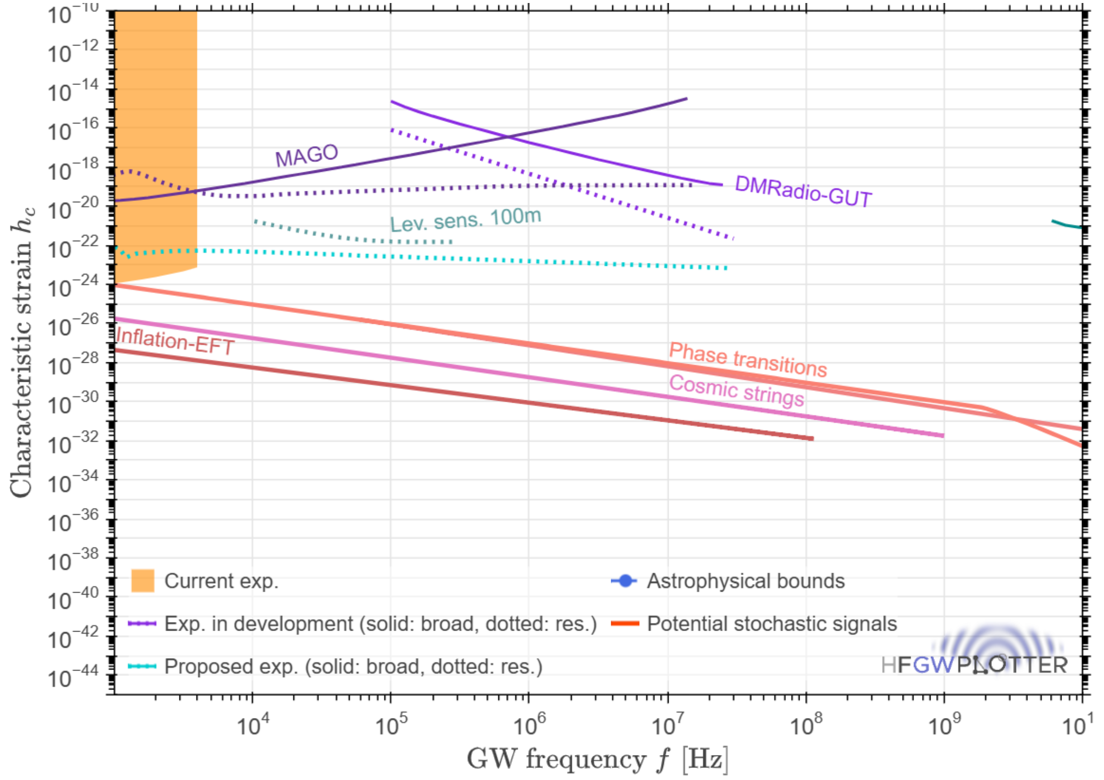
- Heterodyne/Homodyne setups

Conclusion

- Microwave cavities are powerful probes of monochromatic HFGW ($h \sim 10^{-22}$)



- GW couples to all types of energy, care must be taken to model all effects
- With current quantum technology, this is not enough to probe cosmological GW

→ Cross correlate multiple cavities : GravNet ERC

→ Use of Earth modulation for persistent signals

→ Quantum enhancement techniques (e.g. squeezing)