Axion Haloscopes for Gravitational Wave Searches

International Workshop on Baryon and Lepton Number Violation

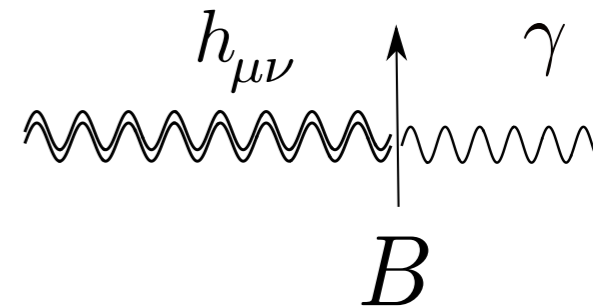**BLV2024**

Karlsruhe, Germany

October 9, 2024

Camilo García Cely

In collaboration with Valerie Domcke, Sungmook Lee, Luca Marsili, Andreas Ringwald, Nicholas Rodd and Aaron Spector
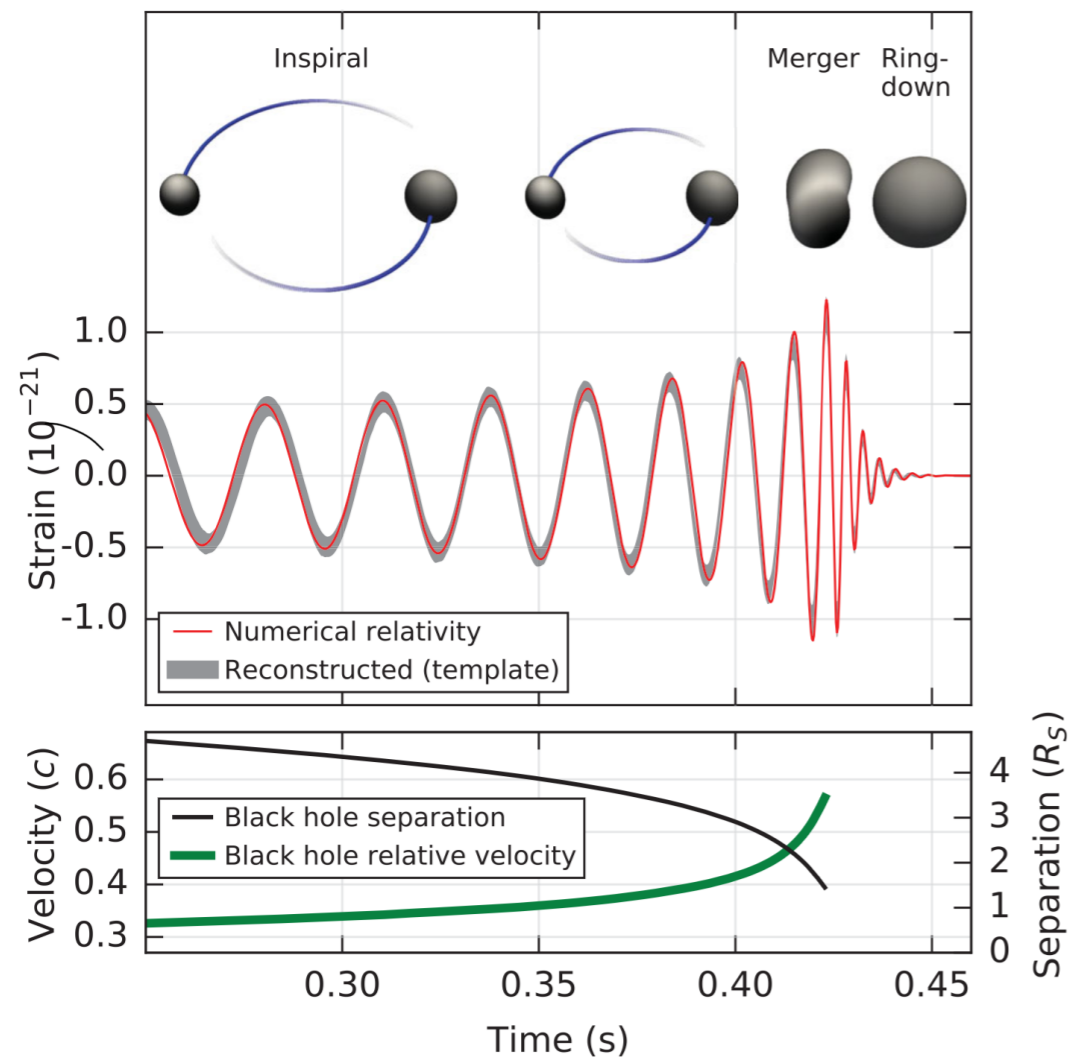
Outline

$h_{\mu\nu}$ γ

B

Part I

The Gertsenhtein effect and high-frequency gravitational waves

Camilo García Cely, University of Valencia

High-frequency gravitational waves

Inspiral — Merger — Ringdown

Strain (10^{-21})

— Numerical relativity
▬ Reconstructed (template)

— Black hole separation
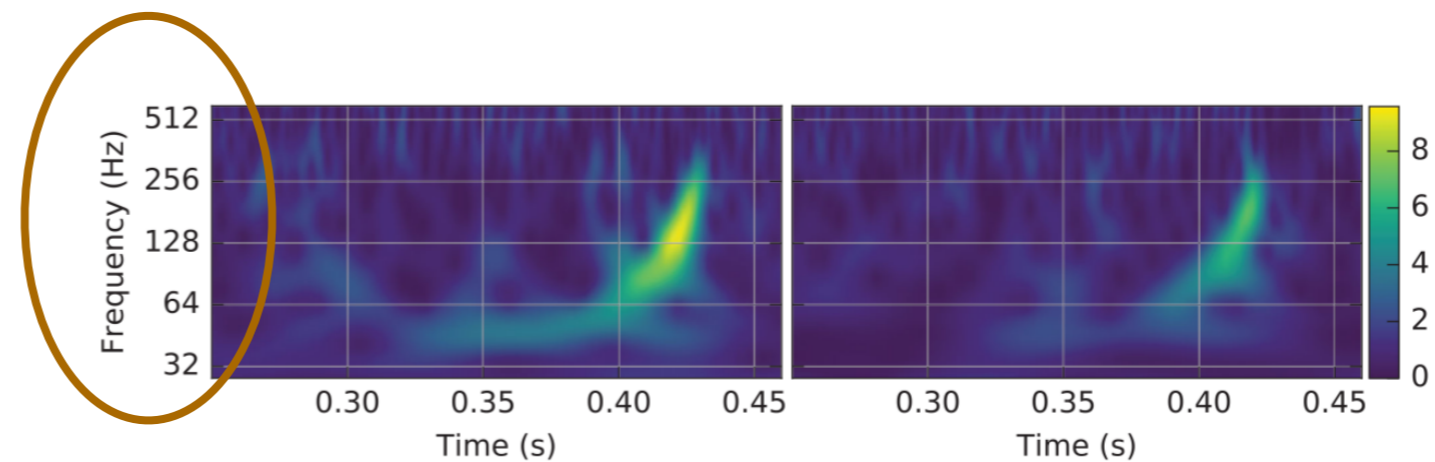▬ Black hole relative velocity

Velocity (c) / Separation (R_S)

Time (s)

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)

Frequency (Hz)

Time (s)

$$ f \approx \frac{1}{2\pi}\sqrt{\frac{GM}{R^3}} \ll 10\,\mathrm{kHz} $$

No known astrophysical objects are small and dense enough to produce gravitational waves beyond 10 kHz

High-frequency gravitational waves

Challenges and opportunities of gravitational-wave searches at MHz to GHz frequencies

Nancy Aggarwal ✉, Odylio D. Aguiar, Andreas Bauswein, Giancarlo Cella, Sebastian Clesse, Adrian Michael Cruise, Valerie Domcke ✉, Daniel G. Figueroa, Andrew Geraci, Maxim Goryachev, Hartmut Grote, Mark Hindmarsh, Francesco Muia ✉, Nikhil Mukund, David Ottaway, Marco Peloso, Fernando Quevedo ✉, Angelo Ricciardone, Jessica Steinlechner ✉, Sebastian Steinlechner ✉, Sichun Sun, Michael E. Tobar, Francisco Torrenti, Caner Ünal & Graham White

A growing community is seriously considering the search of high frequency gravitational waves
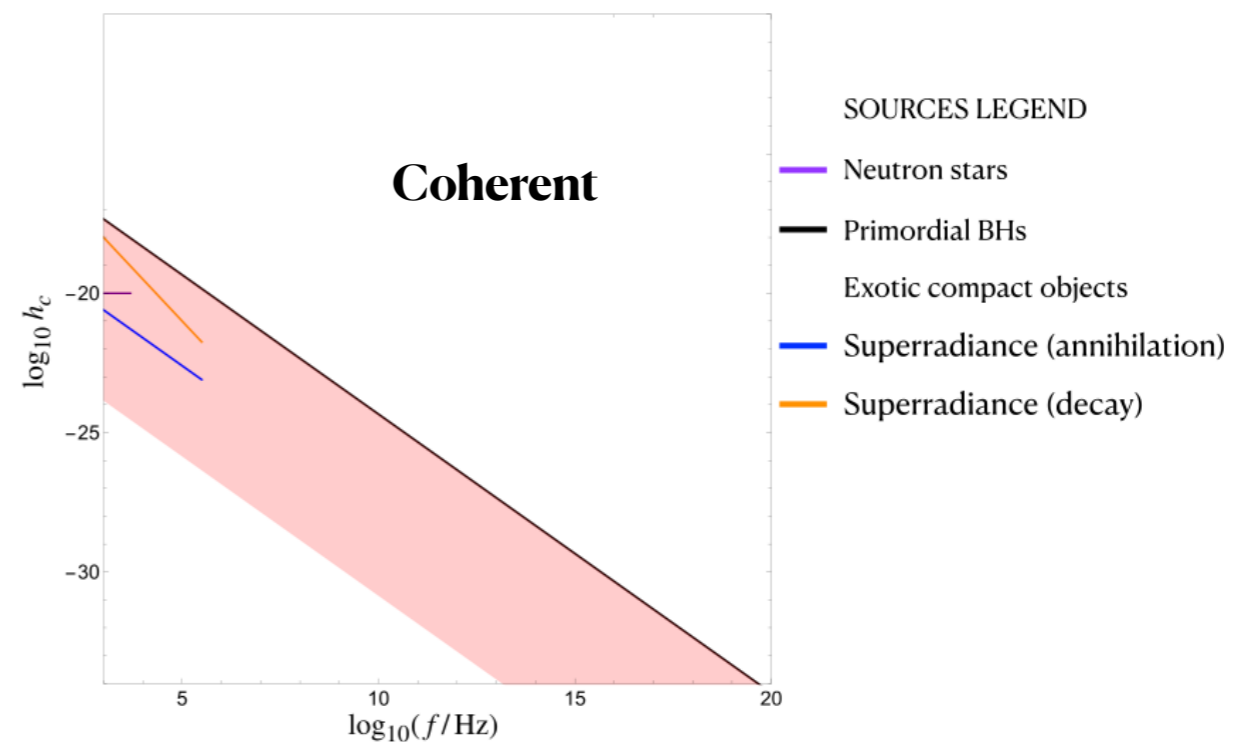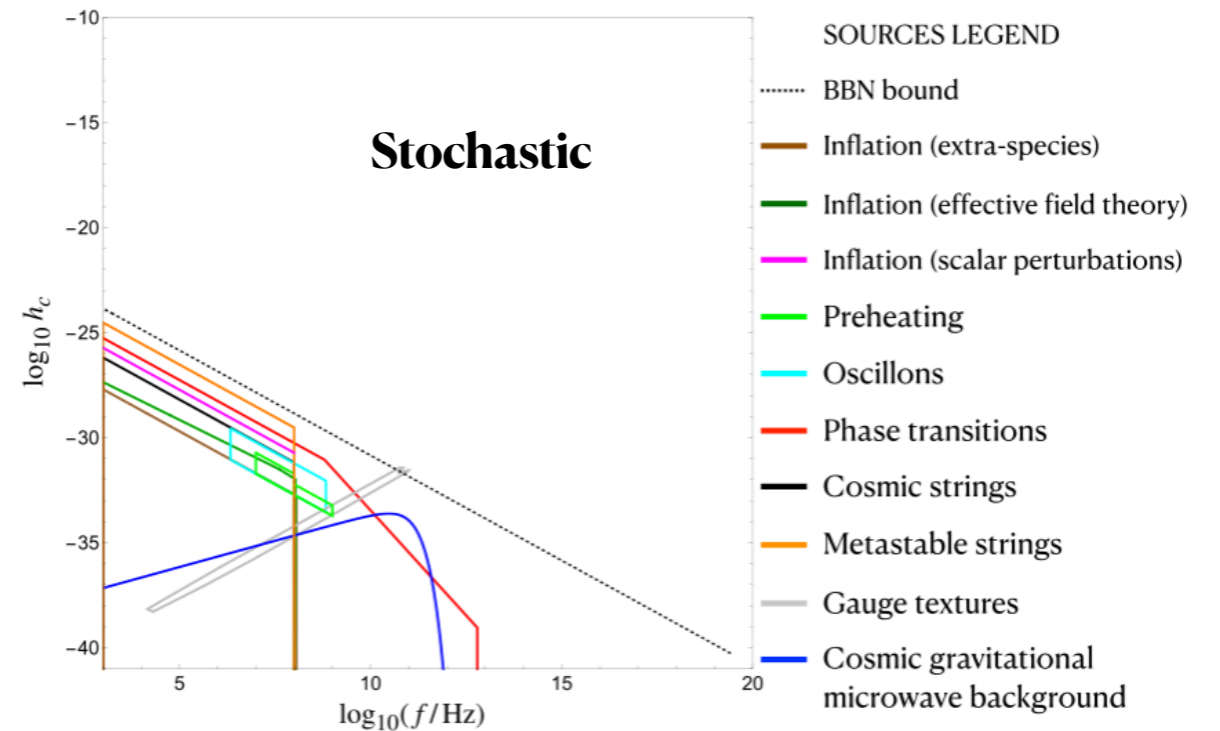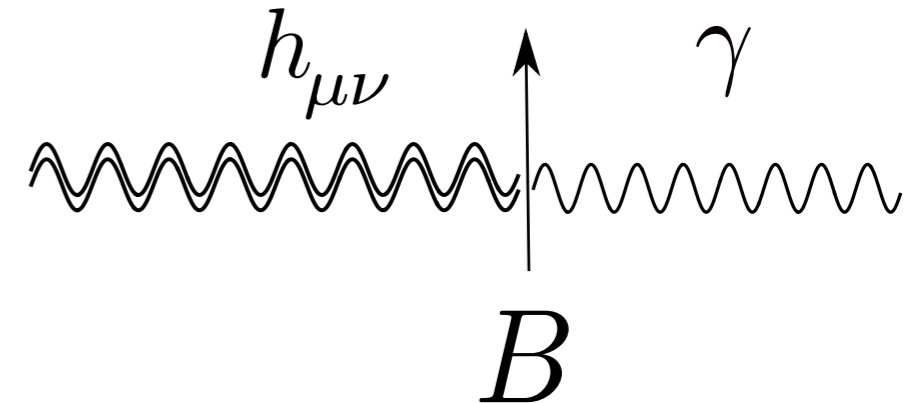
Revisiting Gertsenhstein's ideas

WAVE RESONANCE OF LIGHT AND GRAVITIONAL WAVES

M. E. GERTSENSHTEĬN

Submitted to JETP editor July 29, 1960

J. Exptl. Theoret. Phys. (U.S.S.R.) **41**, 113–114 (July, 1961)

The energy of gravitational waves excited during the propagation of light in a constant magnetic or electric field is estimated.

$h_{\mu\nu}$ γ

B

## ON THE DETECTION OF LOW FREQUENCY GRAVITATIONAL WAVES

M. E. GERTSENSHTEĬN and V. I. PUSTOVOĬT

Submitted to JETP editor March 3, 1962

J. Exptl. Theoret. Phys. (U.S.S.R.) **43**, 605–607 (August, 1962)

It is shown that the sensitivity of the electromechanical experiments for detecting gravitational waves by means of piezocrystals is ten orders of magnitude worse than that estimated by Weber. [1] In the low frequency range it should be possible to detect gravitational waves by the shift of the bands in an optical interferometer. The sensitivity of this method is investigated.

Terrestrial interferometers

6

Camilo García Cely, University of Valencia
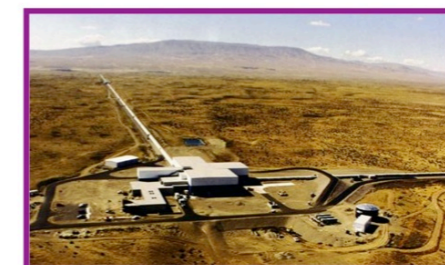
The (inverse) Gertsenhstein Effect

- The conversion of gravitational waves into electromagnetic waves is a classical process. Its rate does not involve $\hbar$

$$P \sim GB^2L^2$$

- Cosmological conversion

Potential of Radio Telescopes as High-Frequency Gravitational Wave Detectors
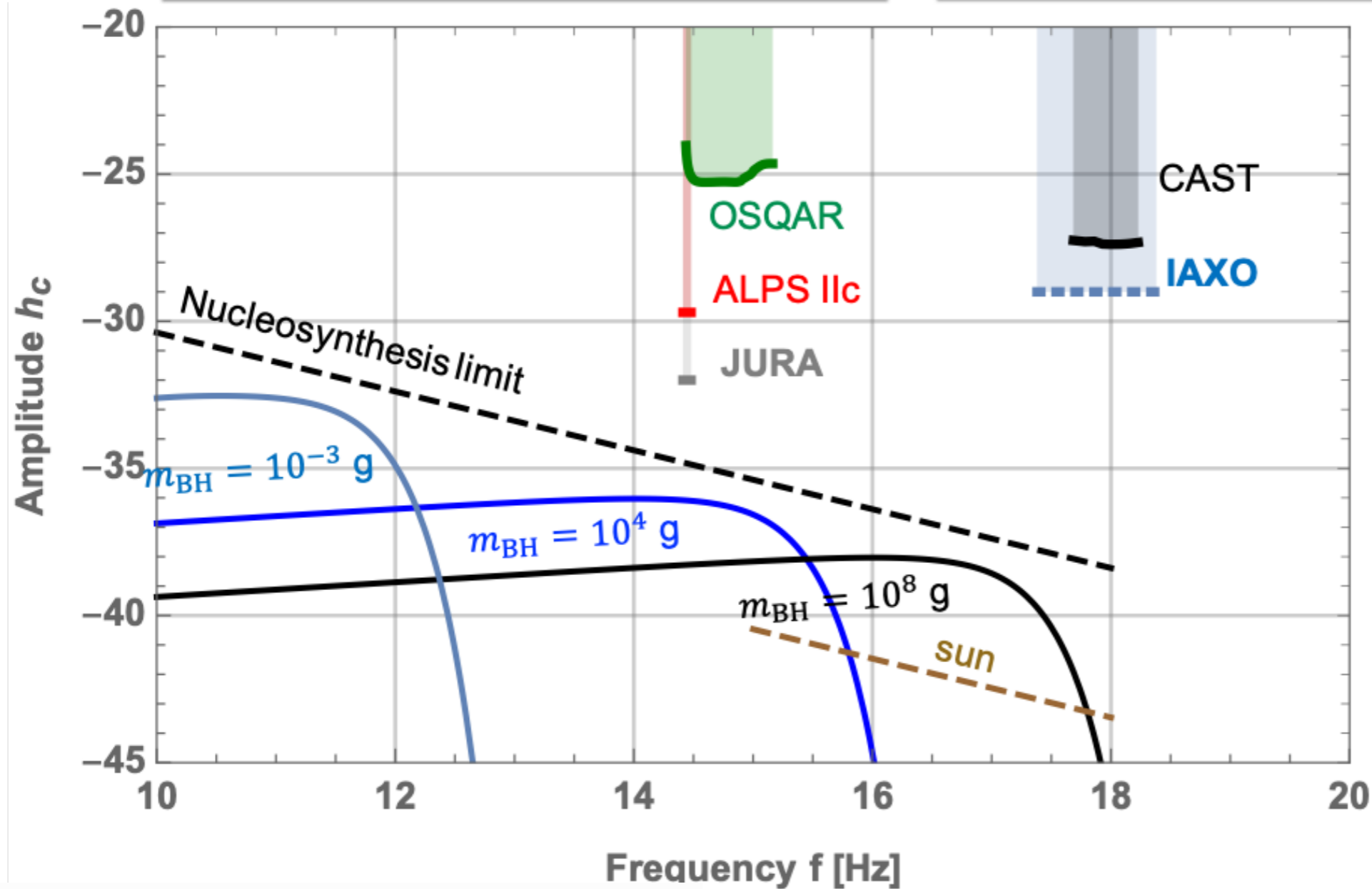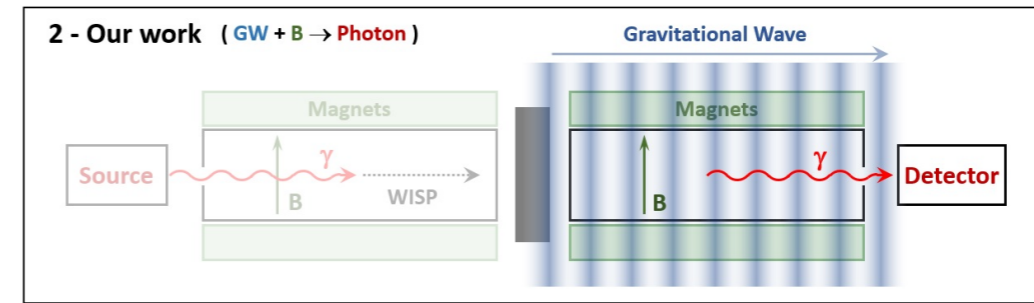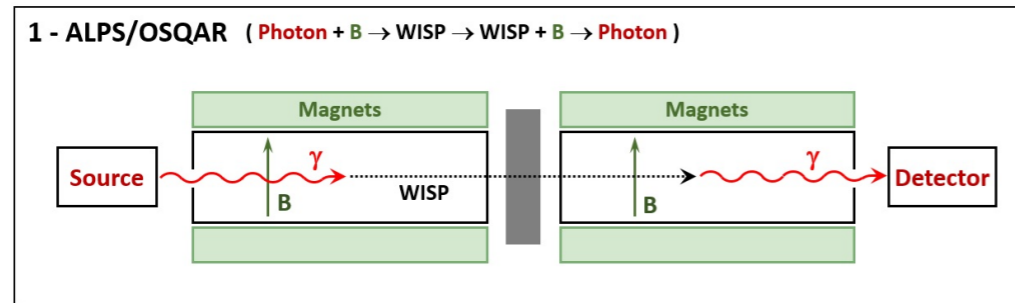
Valerie Domcke and Camilo Garcia-Cely
Phys. Rev. Lett. **126**, 021104 – Published 14 January 2021

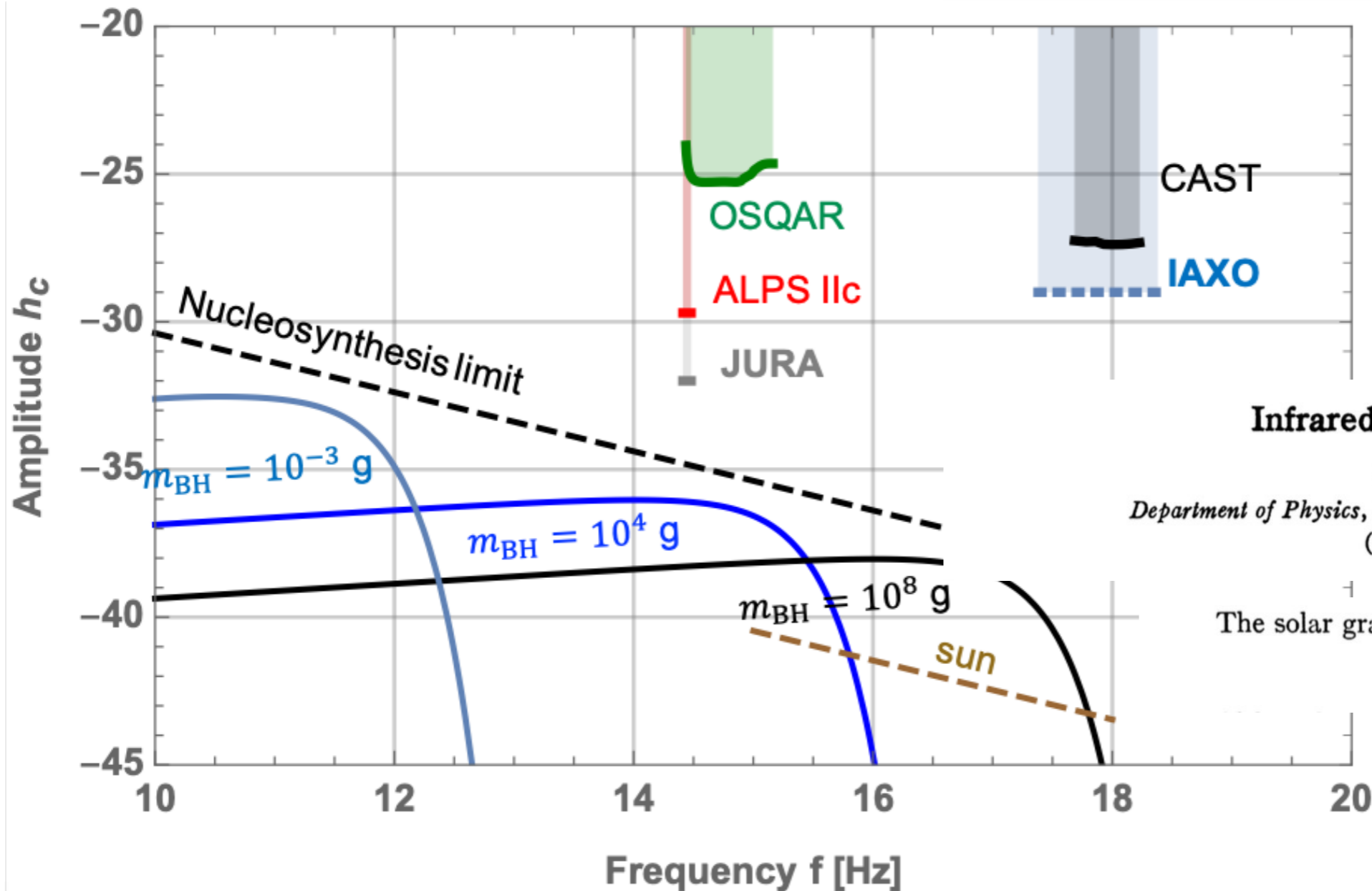- The process is strictly analogous to axion conversion.

Raffelt, Stodolski'89

Camilo García Cely, University of Valencia

The (inverse) Gertsenhstein Effect

A. Ejlli, D. Ejlli, A. M. Cruise, G. Pisano & H. Grote

Camilo García Cely, University of Valencia

The (inverse) Gertsenhstein Effect

A. Ejlli, D. Ejlli, A. M. Cruise, G. Pisano & H. Grote

Camilo García Cely, University of Valencia
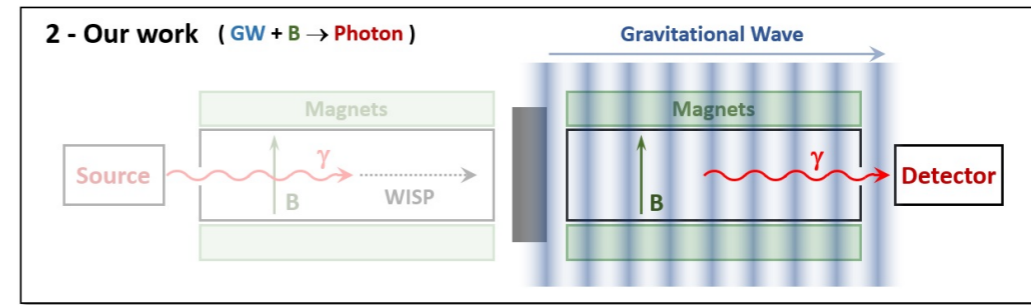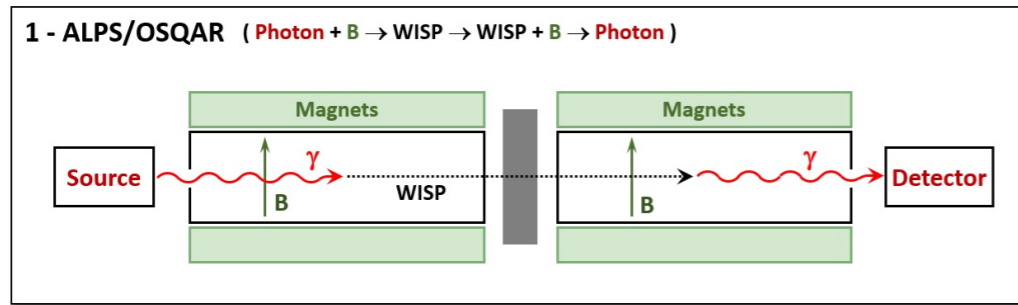
Solar emission of axions

- ## Helioscopes

a γ

B
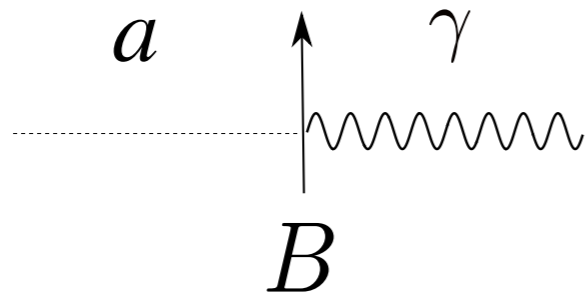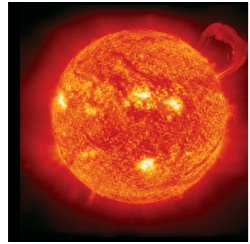
- CAST
- IAXO
- .....

Hoof et al, 2021

Primakoff (P)   plasmon (LP, TP)   Compton (C) e-I bremsstrahlung (ff)

axio-deëxcitation (bb)   axio-recombination (fb) e-e bremsstrahlung (ee)

ABC

P

LP

TP

B16-GS98
GS98
BS05-OP
BP04
BP00
BP98
BS05-AGSOP
AGS05
AGSS09ph
AGSS09
B16-AGSS09

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Solar emission of gravitational waves
Microscopic contribution: graviton emission

$h_{\mu\nu}$
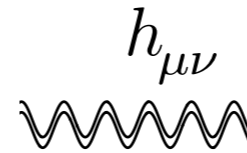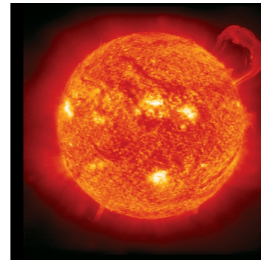
Bremsstrahlung

Photoproduction

GGC, Ringwald, 2024

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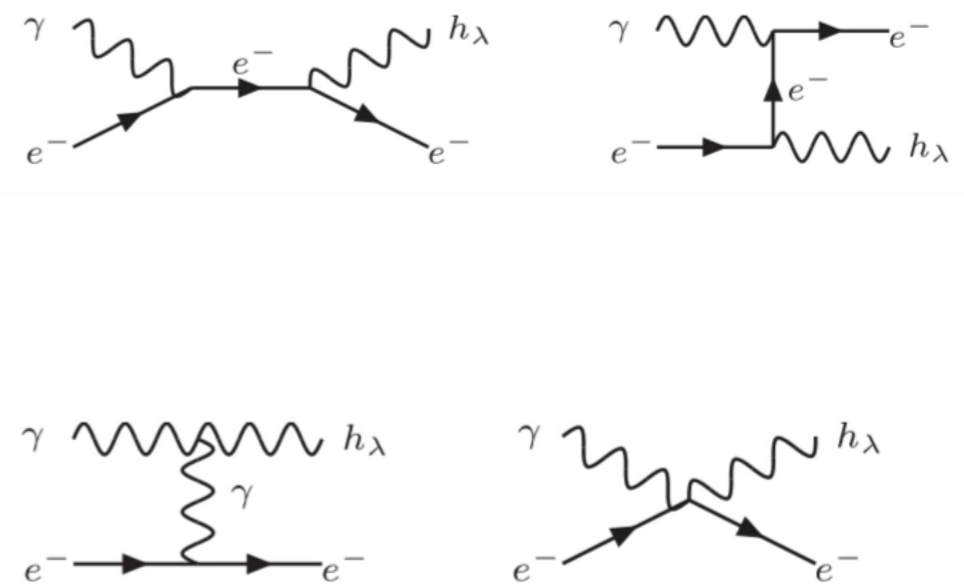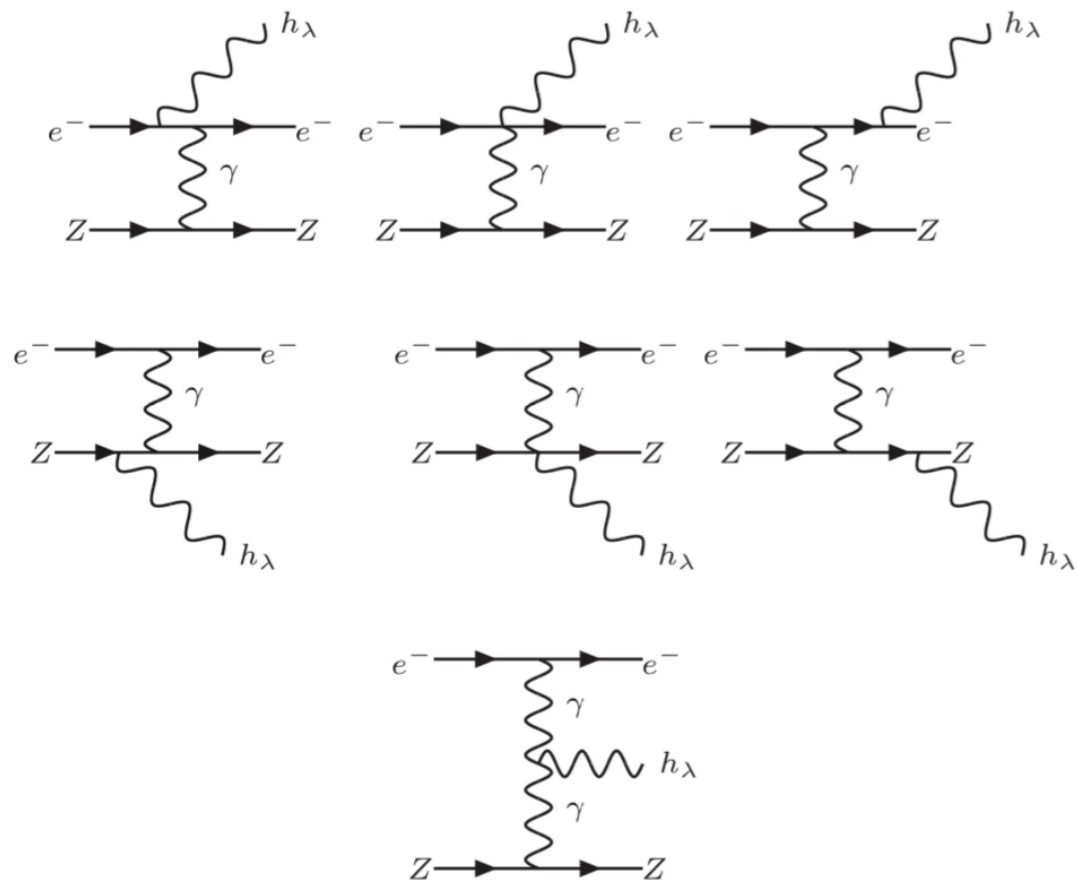
Solar emission of gravitational waves

Macroscopic contribution: Hydrodynamical fluctuations

Gravitational wave background from Standard Model physics: qualitative features

J. Ghiglieri[1] and M. Laine[1]

📄 Article PDF

References ▾

+ Article and author information

Abstract

Because of physical processes ranging from microscopic particle collisions to macroscopic hydrodynamic fluctuations, any plasma in thermal equilibrium emits gravitational waves. For the largest wavelengths the emission rate is proportional to the shear viscosity of the plasma. In the Standard Model at

Solar gravitational waves

$h_{\mu\nu}$

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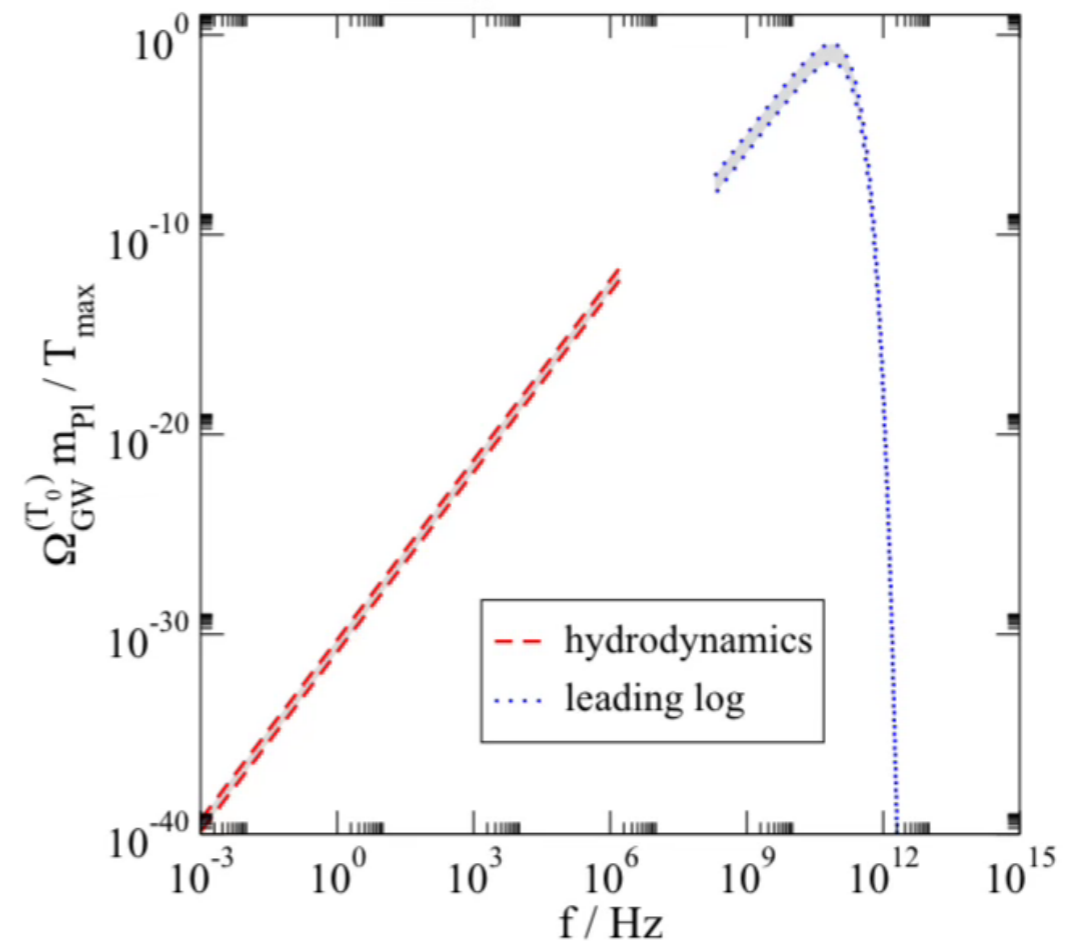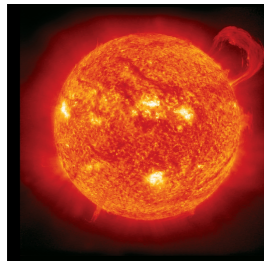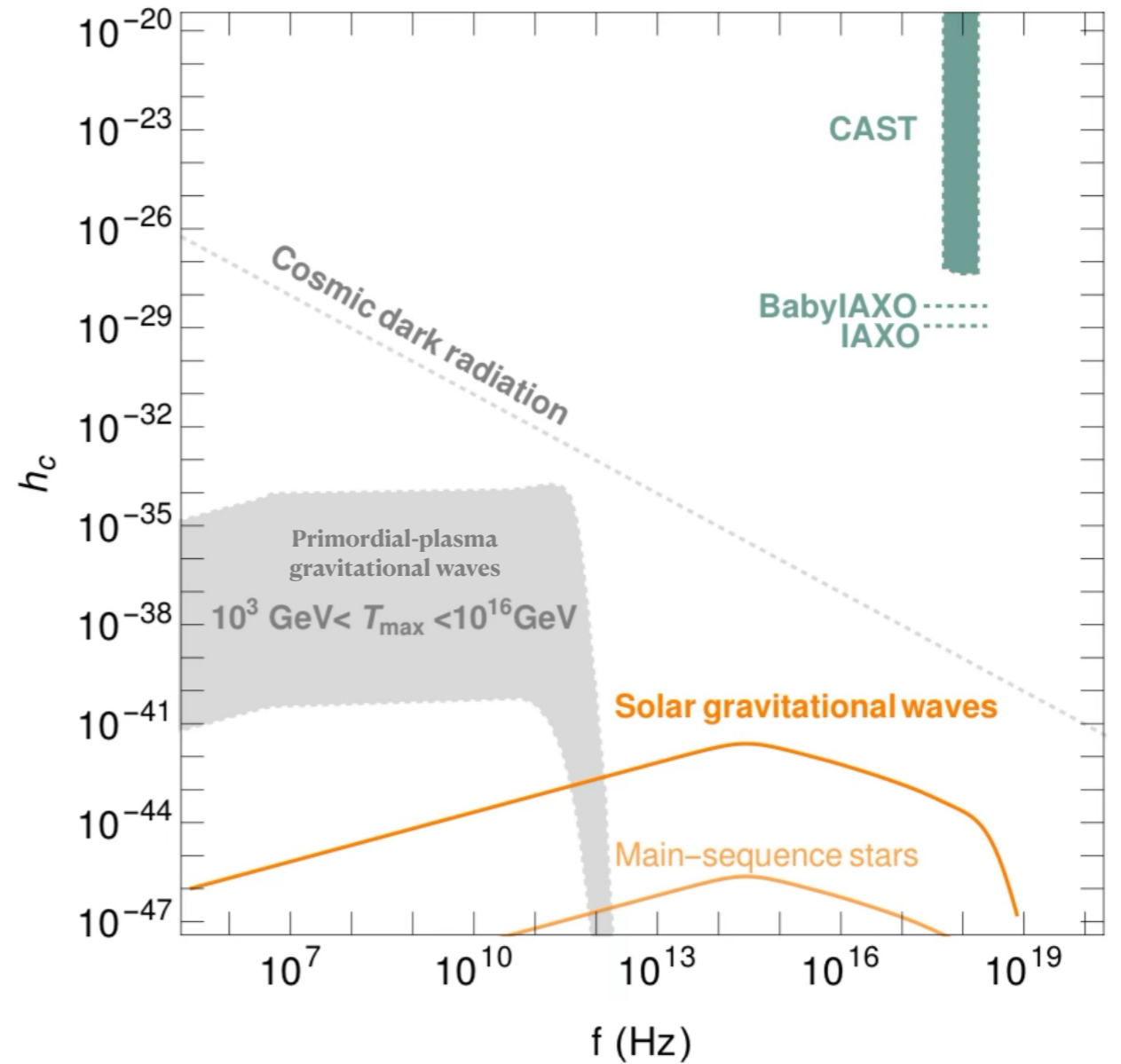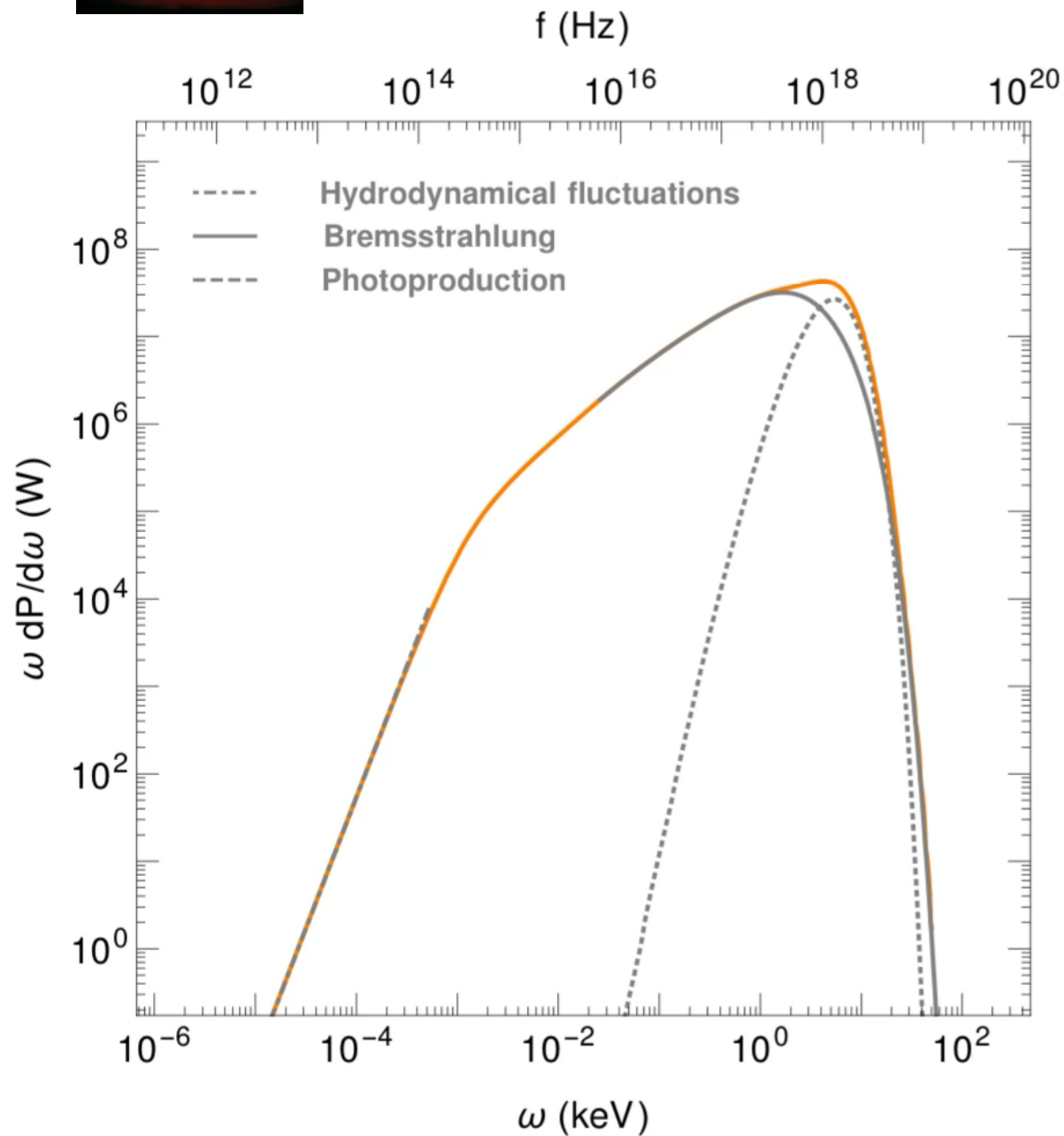
Part II

**Gravitational waves in haloscopes.
Cavities and lumped element detectors**

Camilo García Cely, University of Valencia

Axion electrodynamics

$$\mathscr{L} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

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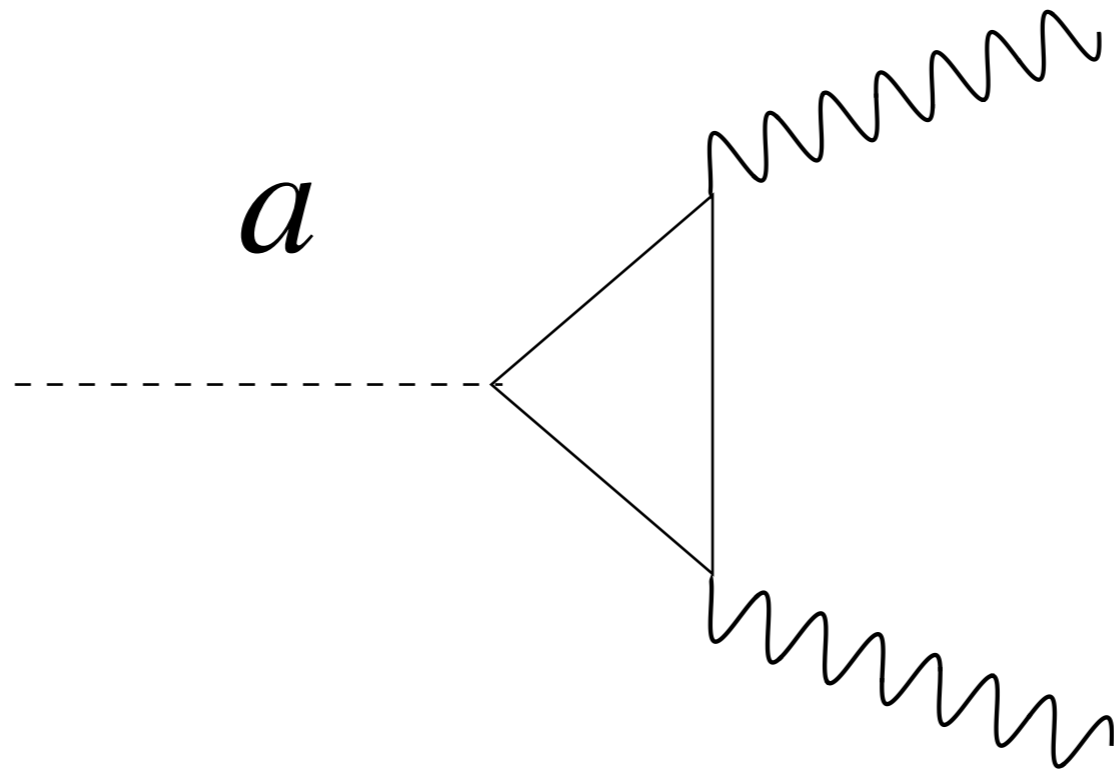
Axion electrodynamics

Axions act as a source term to Maxwell's equations, effectively inducing an electromagnetic current.

$$\nabla \cdot \mathbf{B} = 0$$

Sikivie, 1983

$$\nabla \times \mathbf{E} + \partial_t \mathbf{B} = 0$$

$$\nabla \cdot \mathbf{E} = j^0$$

$$\nabla \times \mathbf{B} - \partial_t \mathbf{E} = \mathbf{j}$$

$$j^0 = - g_{a\gamma\gamma} \nabla a \cdot \mathbf{B} \qquad \mathbf{j} = g_{a\gamma\gamma} \left(\nabla a \times \mathbf{E} + \partial_t a \mathbf{B} \right)$$

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How does it work?

Gravitational waves act as a source term to Maxwell's equations, effectively inducing an electromagnetic current.

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \qquad \left| h_{\mu\nu} \right| \ll 1$$

$$j_{\text{eff}}^{\mu} = \partial_{\nu} \left(-\frac{1}{2} h \, F^{\mu\nu} + F^{\mu\alpha} h^{\nu}{}_{\alpha} - F^{\nu\alpha} h^{\mu}{}_{\alpha} \right)$$

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Haloscopes based on microwave cavities

$$j_{\text{eff}} \sim \omega_a \theta_a B_0$$

$$\vec{B}_0$$
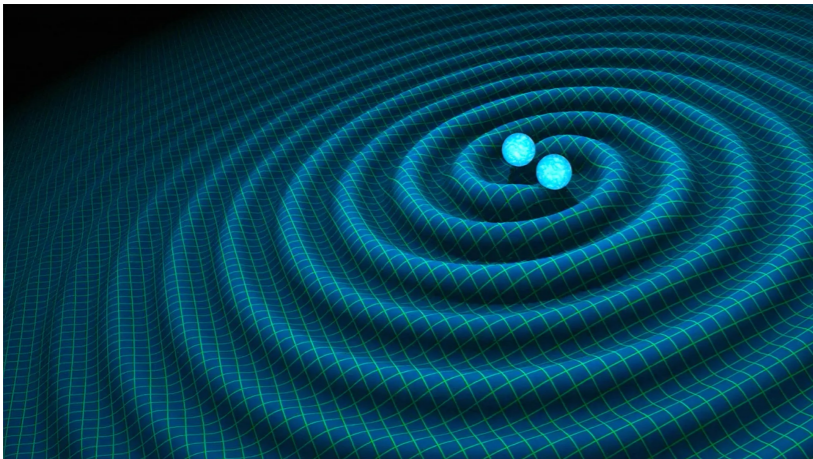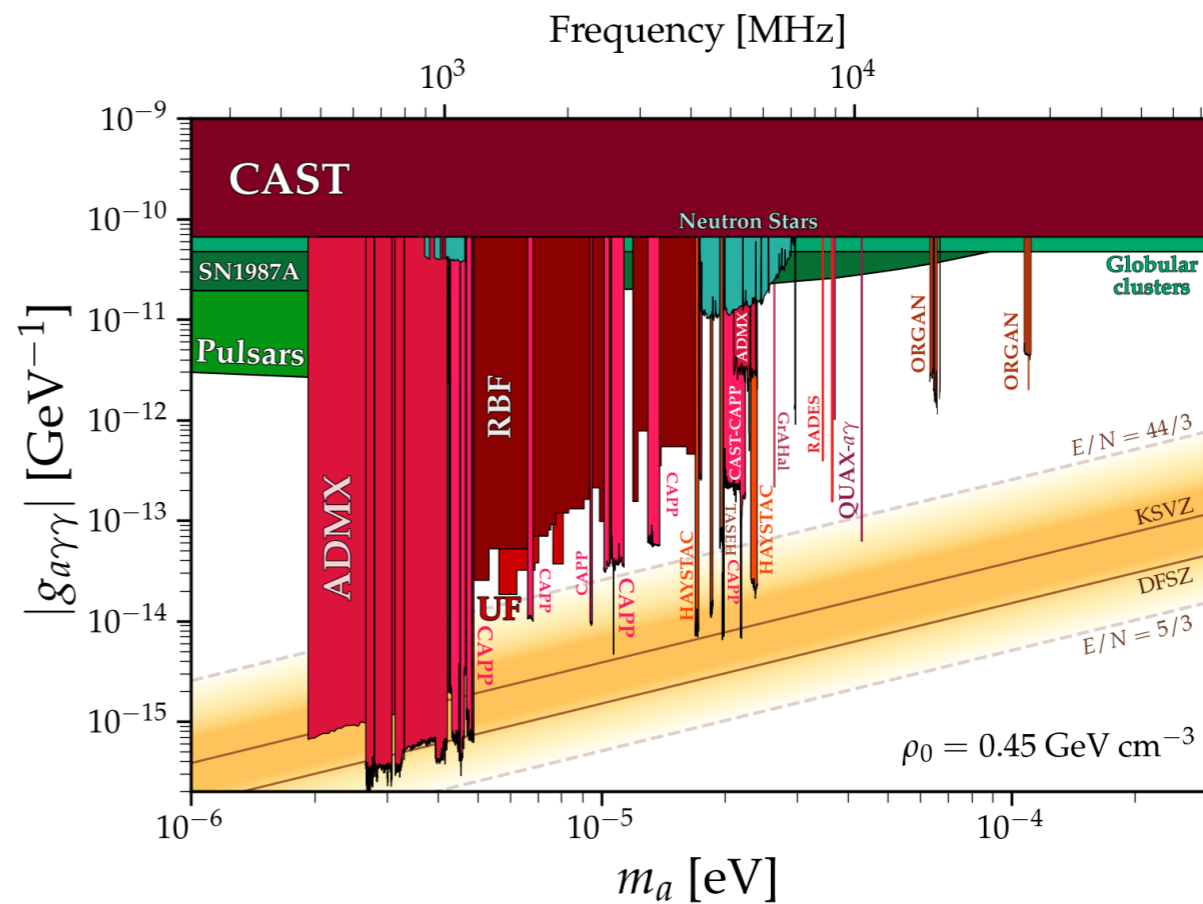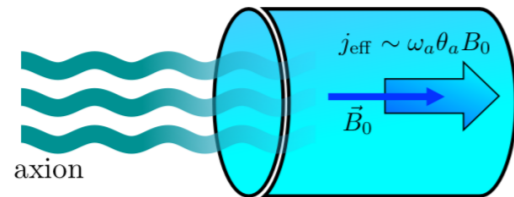
axion

It resonates when the axion frequency matches one of the eigenmode frequencies

$$\left(\partial_t^2 + \frac{\omega_n}{Q_n} \partial_t + \omega_n^2 \right) e_n(t) = - \frac{\int_{V_{\text{cav}}} d^3\mathbf{x} \, \mathbf{E}_n^* \cdot \partial_t \boldsymbol{j}_{\text{eff}}}{\int_{V_{\text{cav}}} d^3\mathbf{x} \, \left| \mathbf{E}_n \right|^2}$$

Eigenmodes $\qquad \mathbf{E}(\mathbf{x}, t) = \sum_n e_n(t) \mathbf{E}_n(\mathbf{x})$

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Haloscopes based on microwave cavities
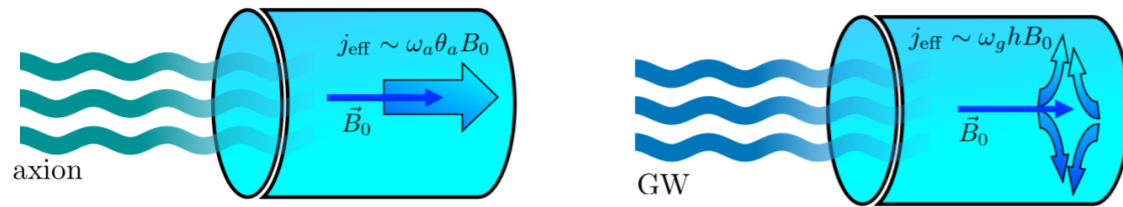
Detecting high-frequency gravitational waves with microwave cavities

Asher Berlin, Diego Blas, Raffaele Tito D'Agnolo, Sebastian A. R. Ellis, Roni Harnik, Yonatan Kahn, and Jan Schütte-Engel

$$j^\mu_{\text{eff}} = \partial_\nu \left(-\frac{1}{2} h\, F^{\mu\nu} + F^{\mu\alpha} h^\nu{}_\alpha - F^{\nu\alpha} h^\mu{}_\alpha \right)$$

It resonates when the GW frequency matches one of the eigenmode frequencies

Projected Sensitivities of Axion Experiments

ADMX
$\omega_g/2\pi \in [0.65, 1.02]$ GHz
$Q \sim 8 \times 10^4$, $B_0 = 7.5$ T
$V_{\text{cav}} = 136$ L, $T_{\text{sys}} \sim 0.6$ K

HAYSTAC
$\omega_g/2\pi \in [5.6, 5.8]$ GHz
$Q \sim 3 \times 10^4$, $B_0 = 9$ T
$V_{\text{cav}} = 2$ L, $T_{\text{sys}} \sim 0.13$ K

CAPP
$\omega_g/2\pi \in [1.6, 1.65]$ GHz
$Q \sim 4 \times 10^4$, $B_0 = 7.3$ T
$V_{\text{cav}} = 3.47$ L, $T_{\text{sys}} \sim 1.2$ K

ORGAN
$\omega_g/2\pi = 26.531$ GHz
$Q \sim 1.3 \times 10^4$, $B_0 = 7$ T
$V_{\text{cav}} \sim 0.0078$ L, $T_{\text{sys}} \sim 4$ K

SQMS params.
$\omega_g/2\pi \in [1, 2]$ GHz
$Q \sim 10^6$, $B_0 = 5$ T
$V_{\text{cav}} = 100$ L, $T_{\text{sys}} \sim 1$ K

Strain Sensitivity h_0

See also 2303.01518

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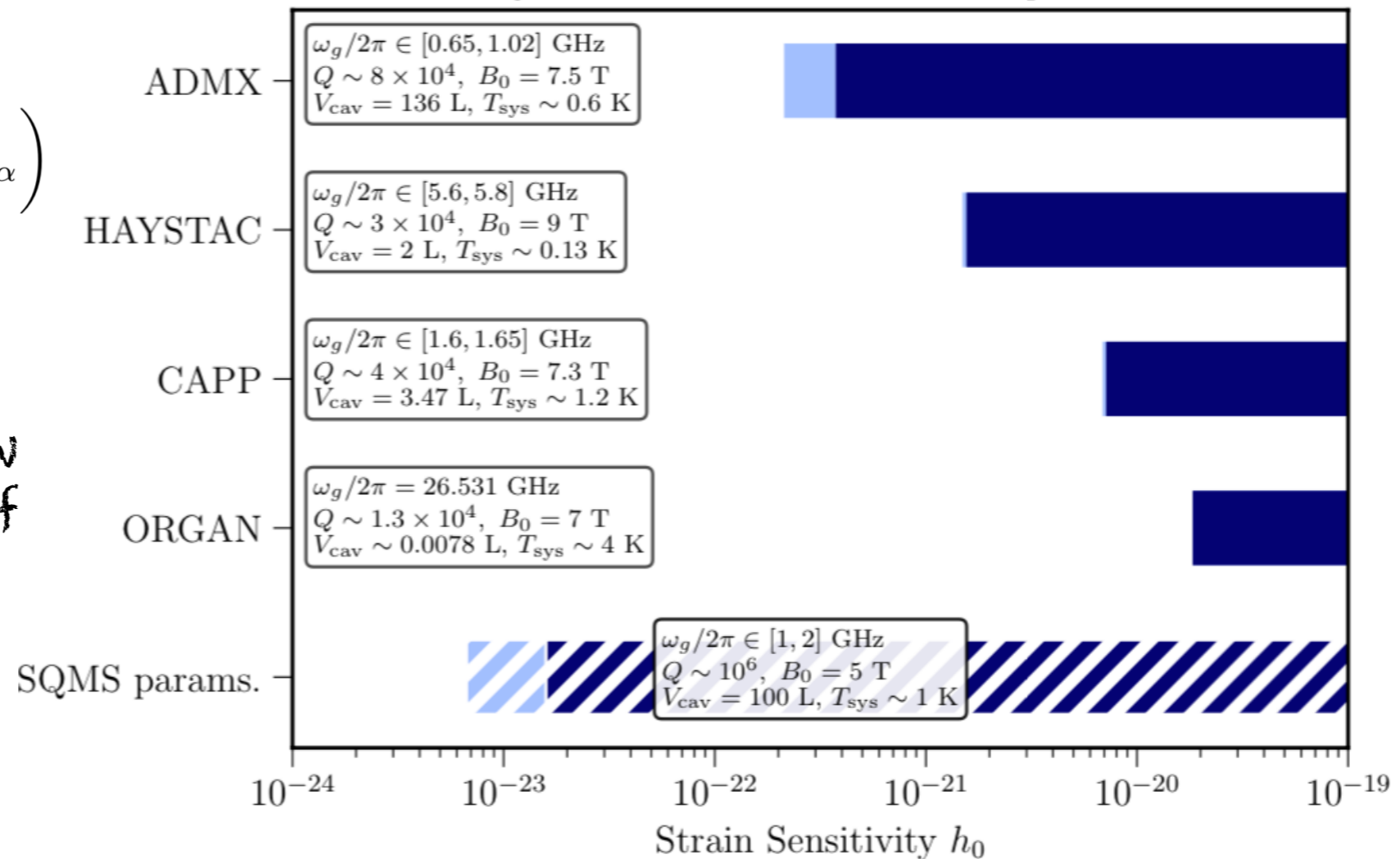
Towards realistic simulations

Study of a cubic cavity resonator for gravitational waves detection in the microwave frequency range

Pablo Navarro, Benito Gimeno, Juan Monzó-Cabrera, Alejandro Díaz-Morcillo, and Diego Blas

$$j^{\mu}_{\text{eff}} = \partial_{\nu} \left(-\frac{1}{2} h\, F^{\mu\nu} + F^{\mu\alpha} h^{\nu}{}_{\alpha} - F^{\nu\alpha} h^{\mu}{}_{\alpha} \right)$$

High-frequency gravitational waves detection with the BabyIAXO haloscopes

José Reina Valero, Jose R. Navarro Madrid, Diego Blas, Alejandro Díaz Morcillo, Igor García Irastorza, Benito Gimeno, Juan Monzó Cabrera

We present the first analysis using RADES-BabyIAXO cavities as detectors of high-frequency gravitational waves (HFGWs). In particular, we discuss two configurations for distinct frequency ranges of HFGWs: Cavity 1, mostly sensitive at a frequency range of 252.8 - 333.2 MHz, and Cavity 2, at 2.504 - 3.402 GHz, which is a scaled down version of Cavity 1. We find that Cavity 1 will reach sensitivity to strains of the HFGWs of order $h_1 \sim 10^{-21}$, while Cavity 2 will reach $h_2 \sim 10^{-20}$. These represent the best estimations of the RADES-BabyIAXO cavities as HFGWs detectors, showing how this set-up can produce groundbreaking results in axion physics and HFGWs simultaneously.
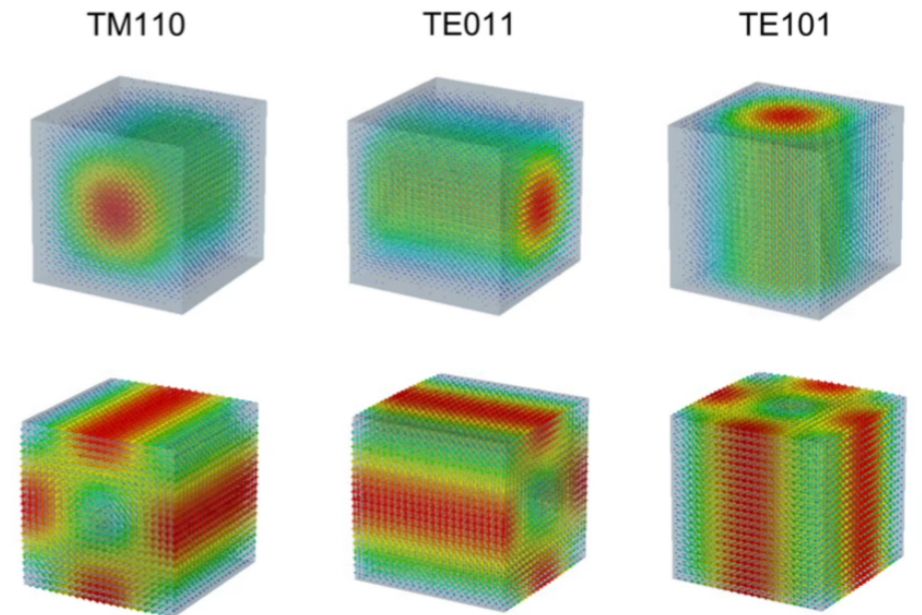
FIG. 3. Electric (up) and magnetic (down) field distributions for the three considered modes TM_{110}, TE_{011} and TE_{101} of cavity C1. The electromagnetic field distributions are identical in the other cavities C2 and C3. The red hue represents the largest values for the modules of electric and magnetic fields, while the blue color represents the lowest values for these modules. The remaining colors in this illustration represent intermediate levels between minima and maxima.

Haloscopes based on lumped-element detectors
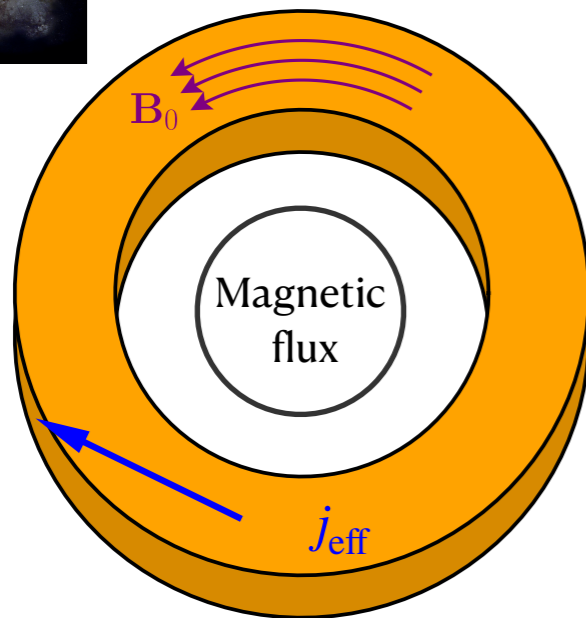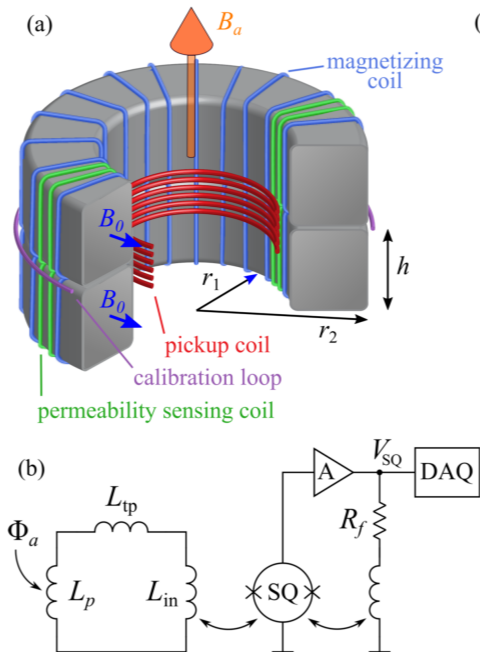
(a)

B_a

magnetizing coil

B_0

B_0

r_1

r_2

h

pickup coil
calibration loop
permeability sensing coil

(b)

L_{tp}

Φ_a

L_p L_{in}

SQ

R_f

A

V_{SQ}

DAQ

(c) SHAFT

$$\nabla \times \mathbf{B} - \partial_t \mathbf{E} = \underbrace{g_{a\gamma\gamma}\, \partial_t a\, \mathbf{B_0}}_{j_{\text{eff}}}$$

Magnetic flux

B_0

j_{eff}

physics   https://doi.org/

Search for axion-like dark matter with ferromagnets

Alexander V. Gramolin[1], Deniz Aybas[1,2], Dorian Johnson[1], Janos Adam[1] and Alexander O. Sushkov[1,2,3]

The electromagnetic fields produced by the axion drive a current through a pickup coil

Camilo García Cely, University of Valencia

Haloscopes based on lumped-element detectors

$h_{\mu\nu}$

$\mathbf{B_0}$

Magnetic flux

j_{eff}

$\mathbf{k}$

$B_z/[B_{\max}h^{\times}(\omega R)^2]$

$\Box h_{\mu\nu} = -16\pi G T_{\mu\nu}$

h_+ $h_{\times}$
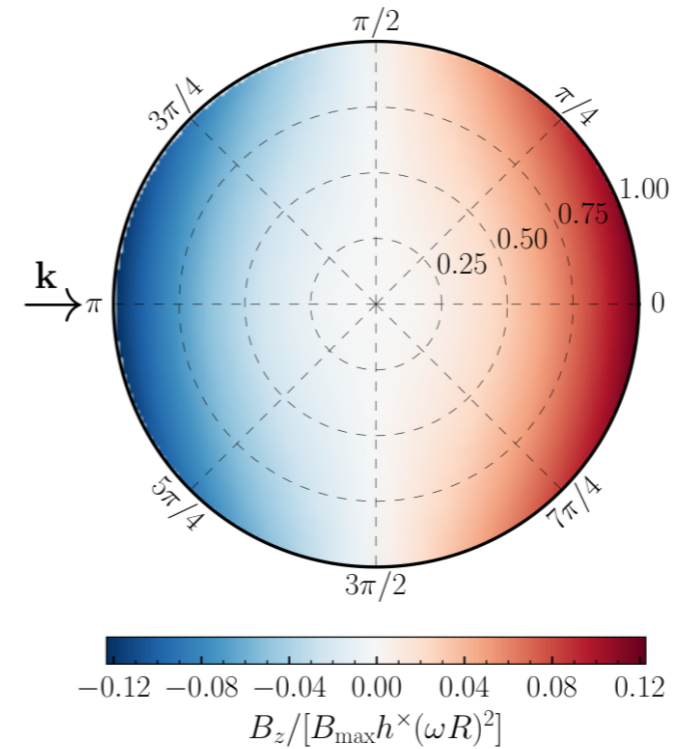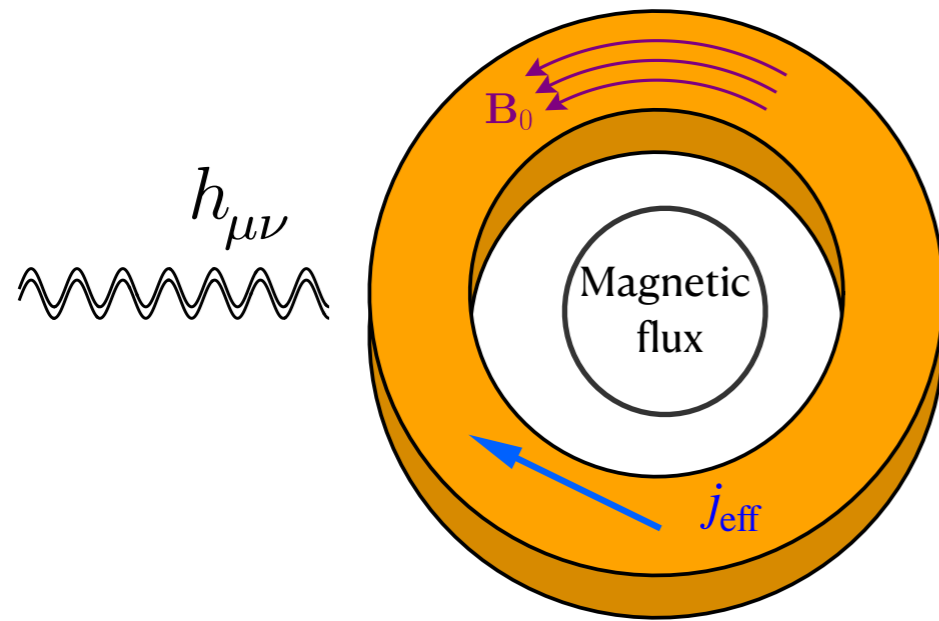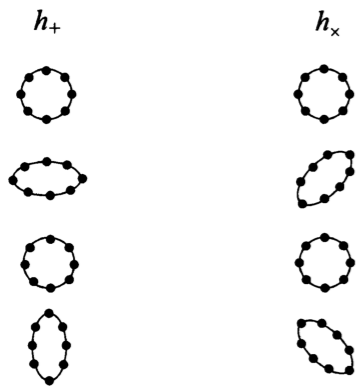
$$\Phi \approx \frac{\mathrm{i}e^{-\mathrm{i}\omega t}}{16\sqrt{2}} h^{\times}\omega^3 B_{\max}\pi r^2 Ra(a+2R)s_{\theta_h}^2$$

$$\Phi_{\mathrm{axions}} \approx e^{-\mathrm{i}\omega t}\, g_{a\gamma\gamma}\sqrt{2\rho_{\mathrm{DM}}}B_{\max}\pi r^2 R$$

Only one polarization

Suppression at small frequencies

The sensitivity scaling with the volume is faster than for axions

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Selection rules

Domcke, CGC, Lee, Rodd, 2023

Geavitational
waves carry two
polarization modes

$$\Box h_{\mu\nu} = -16\pi G T_{\mu\nu}$$

h_+ $h_\times$

Pickup loop orientation

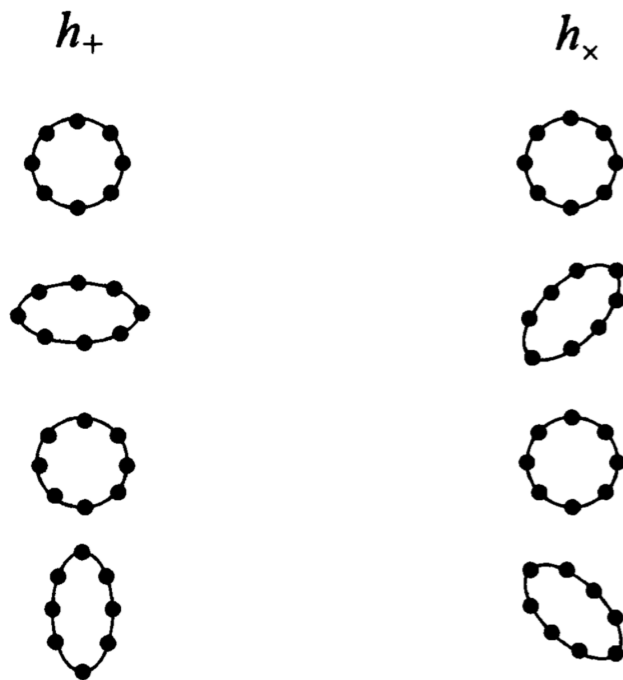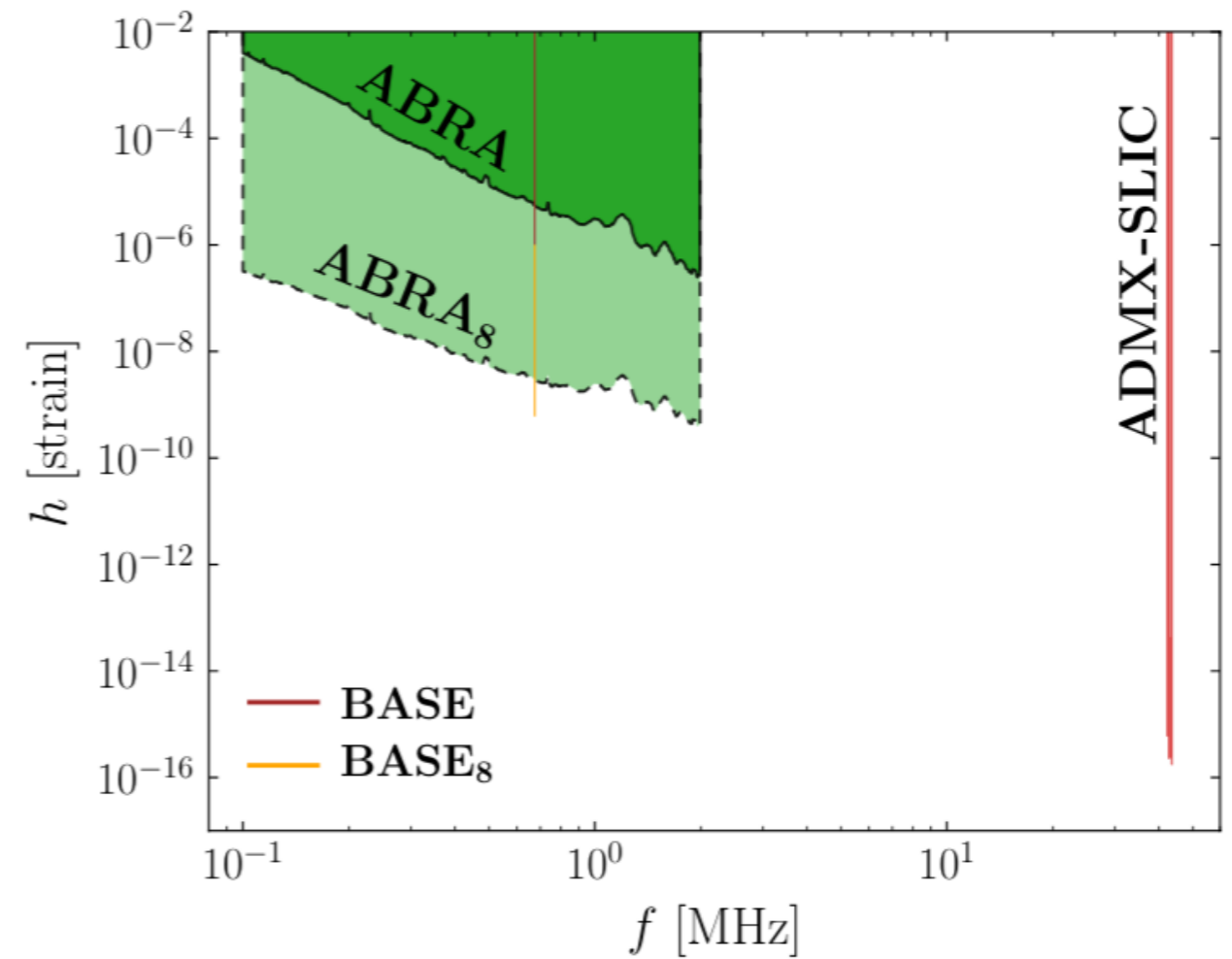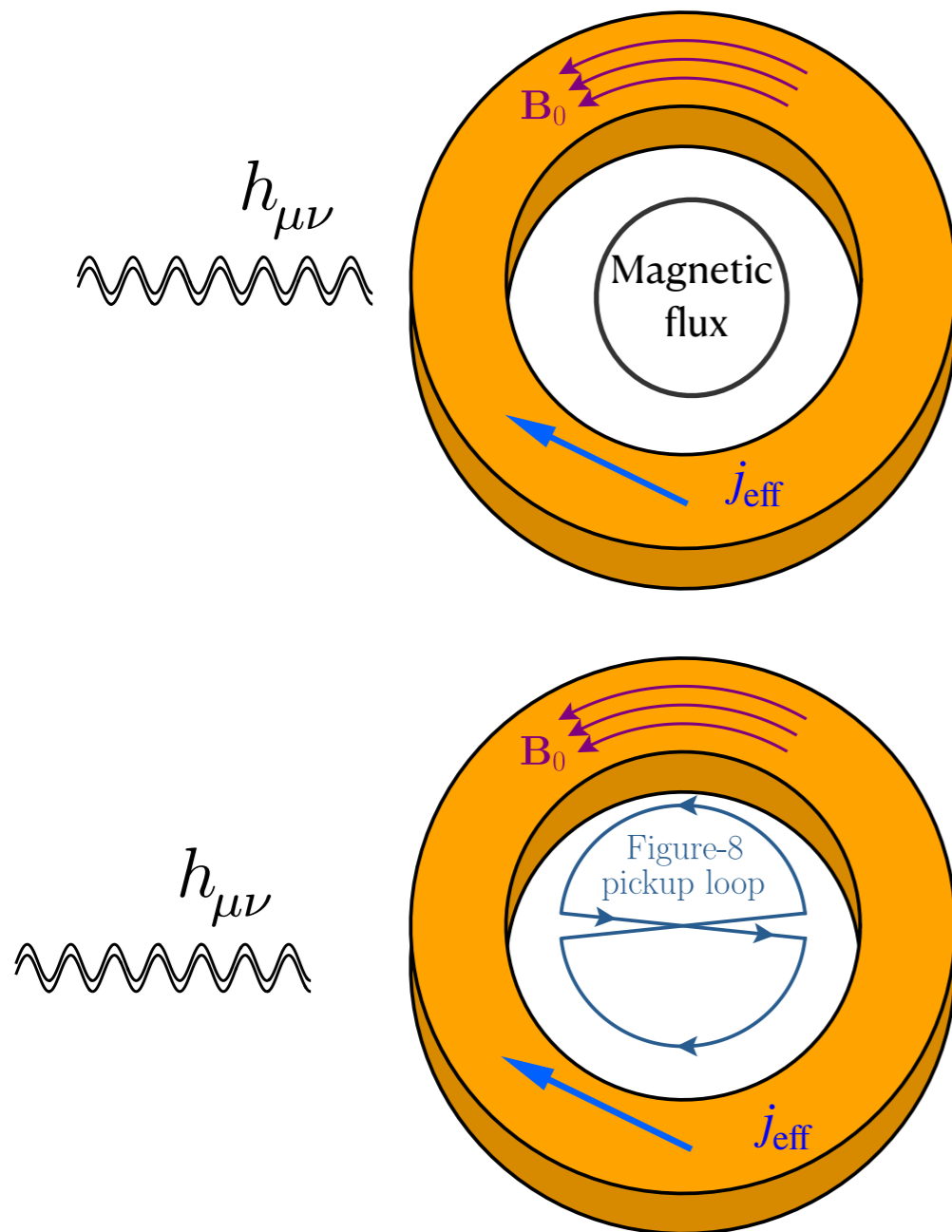|	Solenoid: $\mathbf{B}_0 \propto \hat{\mathbf{e}}_z$	Toroid: $\mathbf{B}_0 \propto \hat{\mathbf{e}}_\phi$
$\hat{n}' \propto \hat{\mathbf{e}}_z$ $(\kappa_y = +1, \kappa = -1)$	h^+, n even $\Rightarrow \mathcal{O}[(\omega L)^2]$ $\Phi_h = \frac{e^{-i\omega t}}{48\sqrt{2}} h^+ \omega^2 B_0 s_{\theta_h}^2 \pi r^2 \left(11r^2 + 14R^2 + 16R^2 \ln \frac{R}{H}\right)$	$h^\times$, n odd $\Rightarrow \mathcal{O}[(\omega L)^3]$ $\Phi_h = \frac{ie^{-i\omega t}}{48\sqrt{2}} h^\times \omega^3 B_{\max} \pi r^2 aR(a+2R) s_{\theta_h}^2$
$\hat{n}' \propto \hat{\mathbf{e}}_\phi$	$h^\times$, n odd $\Rightarrow \mathcal{O}[(\omega L)^3]$ $\Phi_h = \frac{ie^{-i\omega t}}{96\sqrt{2}} h^\times \omega^3 B_0 \pi r^2 l(12R^2 - 5r^2) s_{\theta_h}^2$	h^+, n even $\Rightarrow \mathcal{O}[(\omega L)^2]$ $\Phi_h = \frac{3e^{-i\omega t}}{4\sqrt{2}} h^+ \omega^2 B_{\max} \frac{\pi r^2 aRl(a+2R)}{H^2} s_{\theta_h}^2$
$\hat{n}' \propto \hat{\mathbf{e}}_\rho$ $(\kappa_y = +1, \kappa = +1)$	h^+, n odd $\Rightarrow \mathcal{O}[(\omega L)^3]$ $\Phi_h = \frac{ie^{-i\omega t}}{96\sqrt{2}} h^+ B_0 \omega^3 c_{\theta_h} s_{\theta_h}^2$ $\times \pi r^2 l \left(3l^2 - 22(r^2 + 2R^2) - 36R^2 \ln \frac{R}{H}\right)$	$h^\times$, n even $\Rightarrow \mathcal{O}[(\omega L)^4]$ $\Phi_h = \frac{e^{-i\omega t}}{32\sqrt{2}} h^\times \omega^4 B_{\max} \pi r^2 aRl(a+2R) c_{\theta_h} s_{\theta_h}^2$

Camilo García Cely, University of Valencia

Toroidal magnetic fields

Camilo García Cely, University of Valencia

Haloscopes based on lumped-element detectors

Domcke, CGC, Lee, Rodd, 2023

Camilo García Cely, University of Valencia
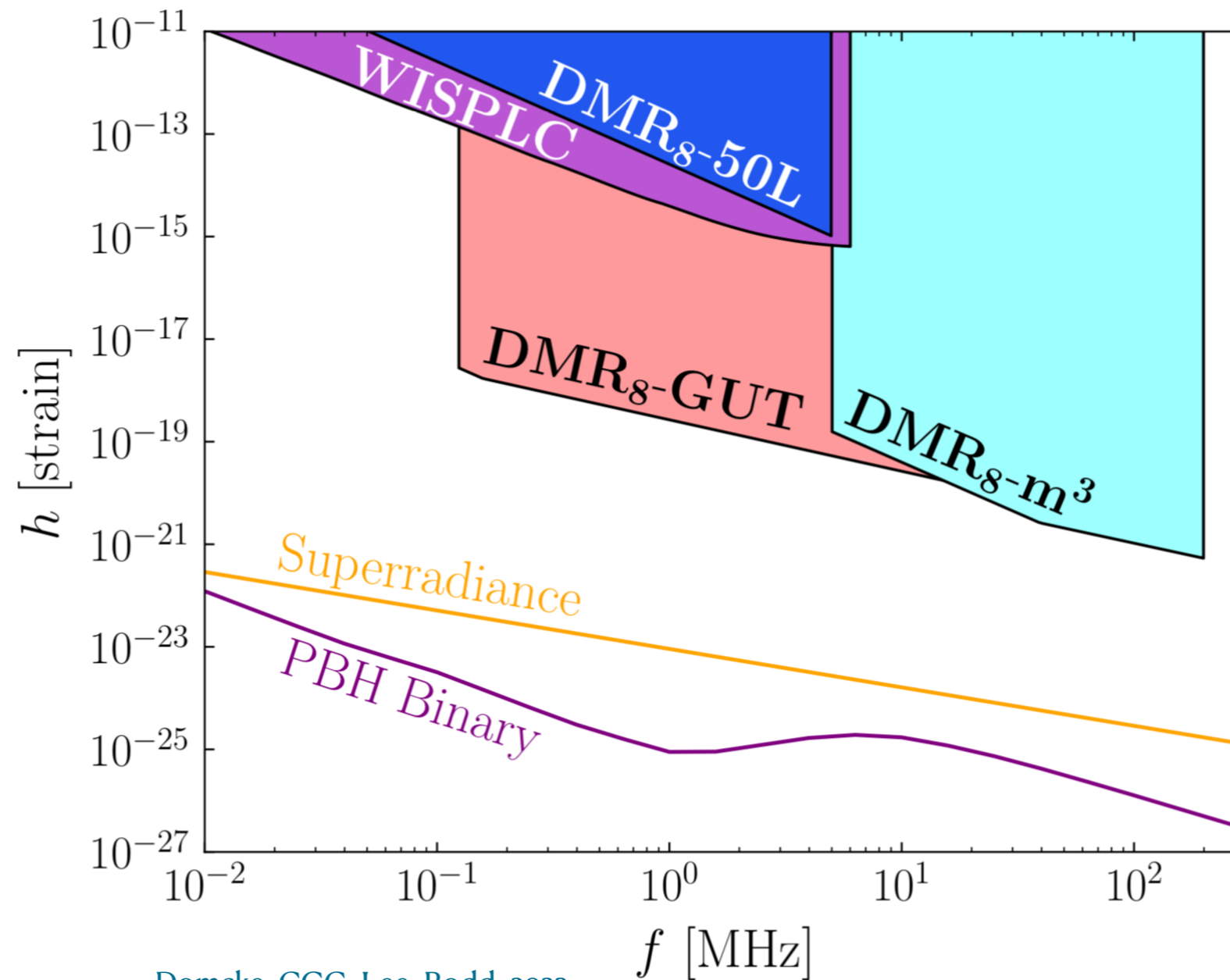
New ideas

Axion birefringence
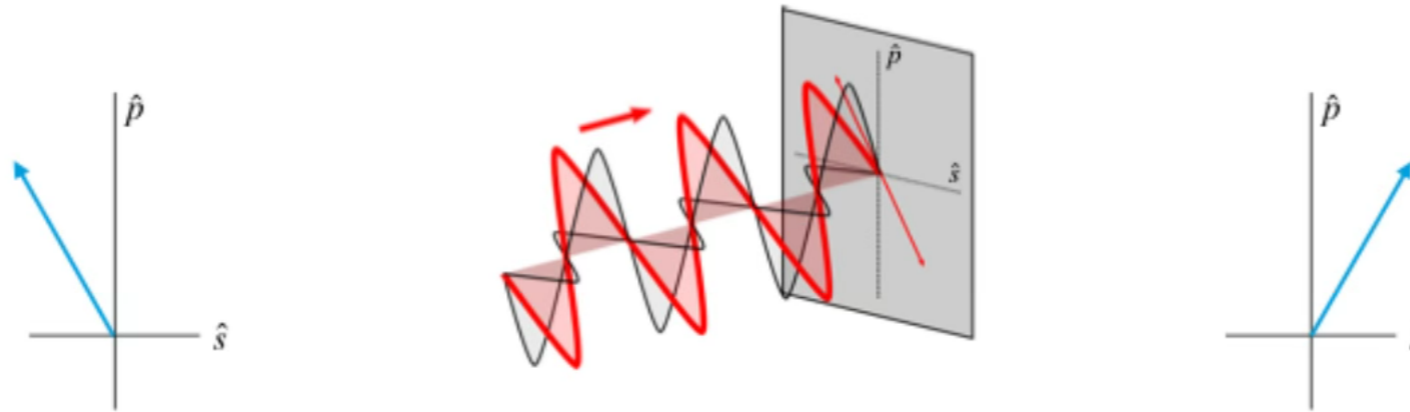
Geometrical optics limit

$$\frac{d\mathbf{e}}{dt} = -\frac{1}{2} g_{a\gamma\gamma} \dot{a}(t)\, \hat{\mathbf{k}} \times \mathbf{e}$$

Camilo García Cely, University of Valencia

New ideas

Axion birefringence

Axion Dark Matter Search with Interferometric Gravitational Wave Detectors

Koji Nagano[1], Tomohiro Fujita,[2,3] Yuta Michimura,[4] and Ippei Obata[1]

Camilo García Cely, University of Valencia
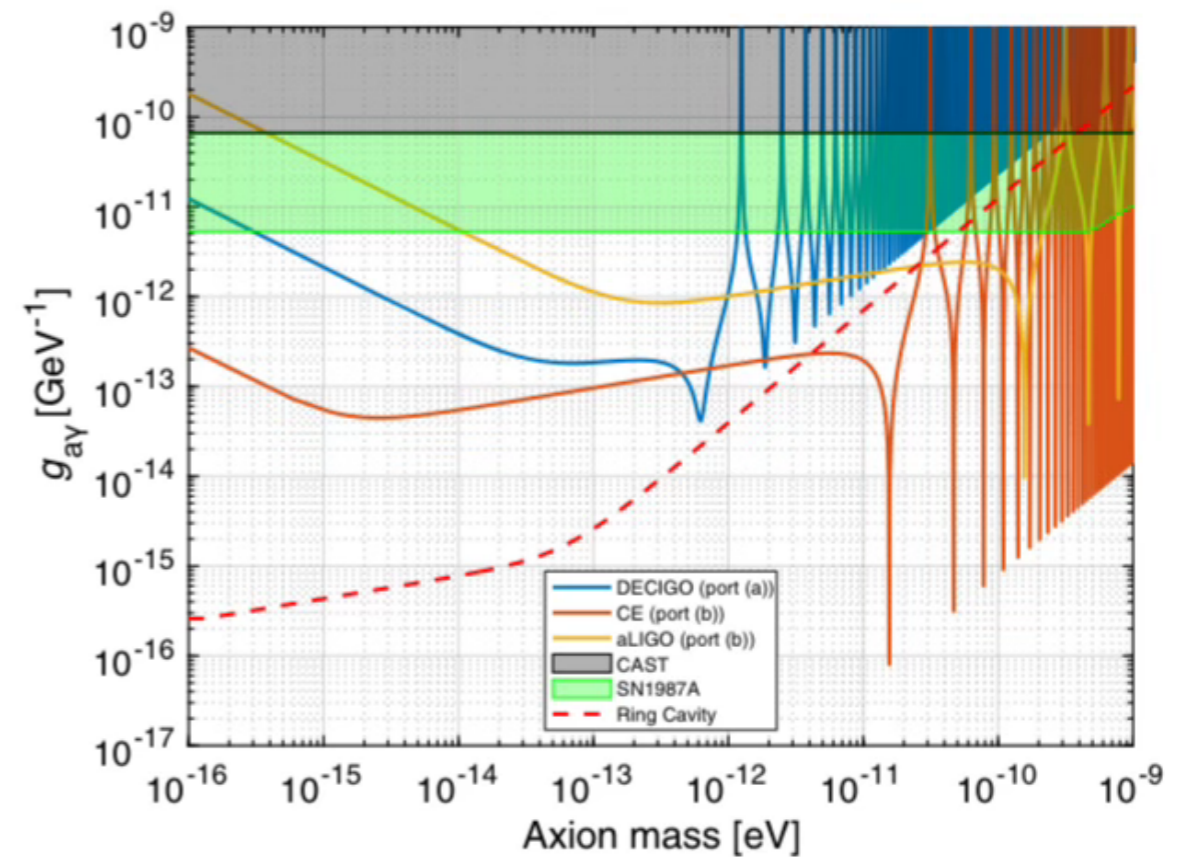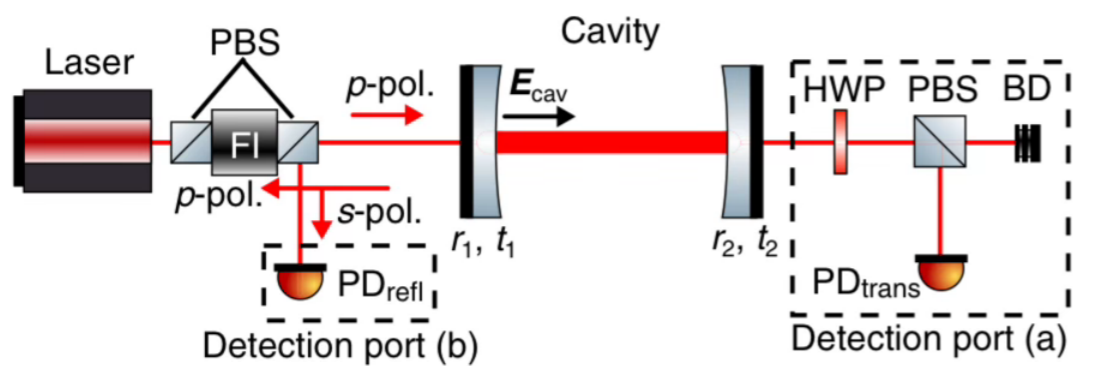
Gravitational Faraday effect

$h_{\mu\nu}$
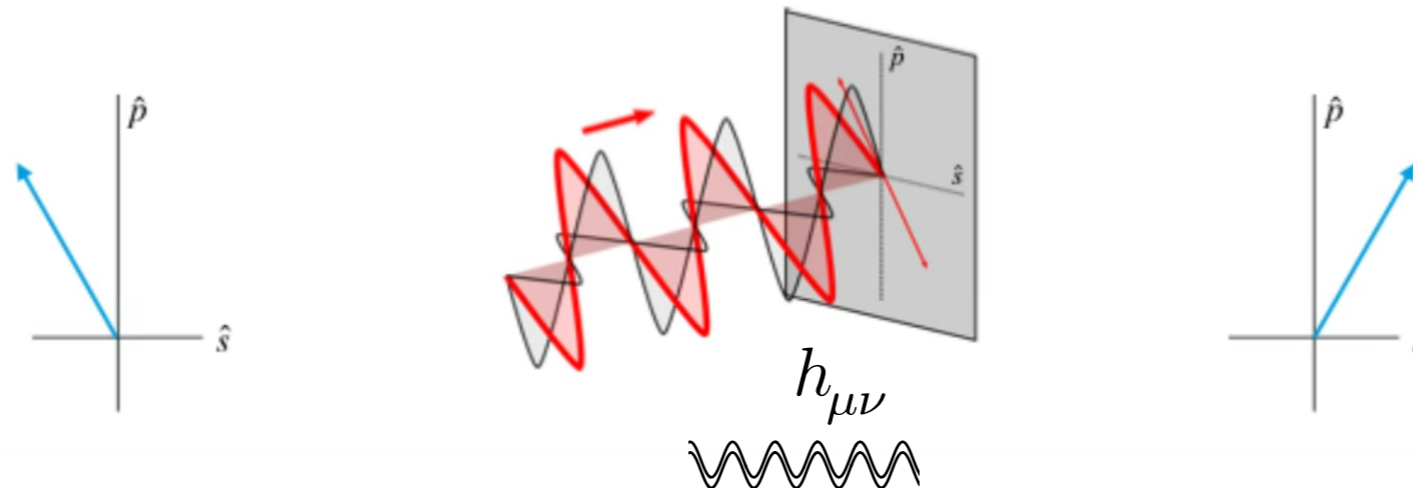
ALPs experiment at DESY

For GWs coming from the zenith

- The cross polarization has the same cavity response function as axions
- The plus polarization decouples

(selection rules)

PRELIMINARY

Competetive bounds at high frequencies

Camilo García Cely, University of Valencia

Conclusions

The techniques developed for detecting axion dark matter could potentially be used to discover new sources of gravitational waves.

Different experimental proposals have coalesced on a strain sensitivity of 10^{-22} for MHz GWs, still orders of magnitude away from signals of the early Universe.

Lots of room for improvement because experiments are not optimized for gravitational wave searches.

Indeed, theoretical studies indicate that selection rules limit the detectability of gravitational waves in highly symmetric detectors.

Simple modifications of readout (such as the figure-8 pickup loop) can overcome this limitation

Selection rules

Domcke, CGC, Lee, Rodd, 2023

Write down the detector response matrix for a wave coming from an arbitrary direction, and impose **cylindrical symmetry** for both external magnetic field and loop:

Selection Rule 1: For an instrument with azimuthal symmetry, $\Phi_h \propto h^+$ at $\mathcal{O}[(\omega L)^2]$

Selection Rule 2: For an instrument with azimuthal symmetry, the flux is proportional to either h^+ or $h^\times$, but not both. This holds to all orders in (ωL).

Selection Rule 3: For an instrument with full cylindrical symmetry, Φ_h will contain only even or odd powers of ω.

Camilo García Cely, University of Valencia

Proper detector frame

The coordinate system closely matches the intuitive description of an Earth-based laboratory

Fermi, 1922
Manasse and Misner, 1963
Ni and Zimmermamn, 1978

- Coordinates given by ideal rigid rulers

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu = \eta_{\mu\nu}dx^\mu dx^\nu \text{ for } dx^\mu = (0, dr\,\hat{\mathbf{r}})$$

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- The gravitational wave acts as a Newtonian force.
  If negligible, the static fields applied in experiments remain static in the presence of GWs.

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- Crucial for haloscopes   Berlin et al 2022

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Excitation of mechanical modes

The proper detector frame closely matches the intuitive description of an Earth-based laboratory

Fermi, 1922
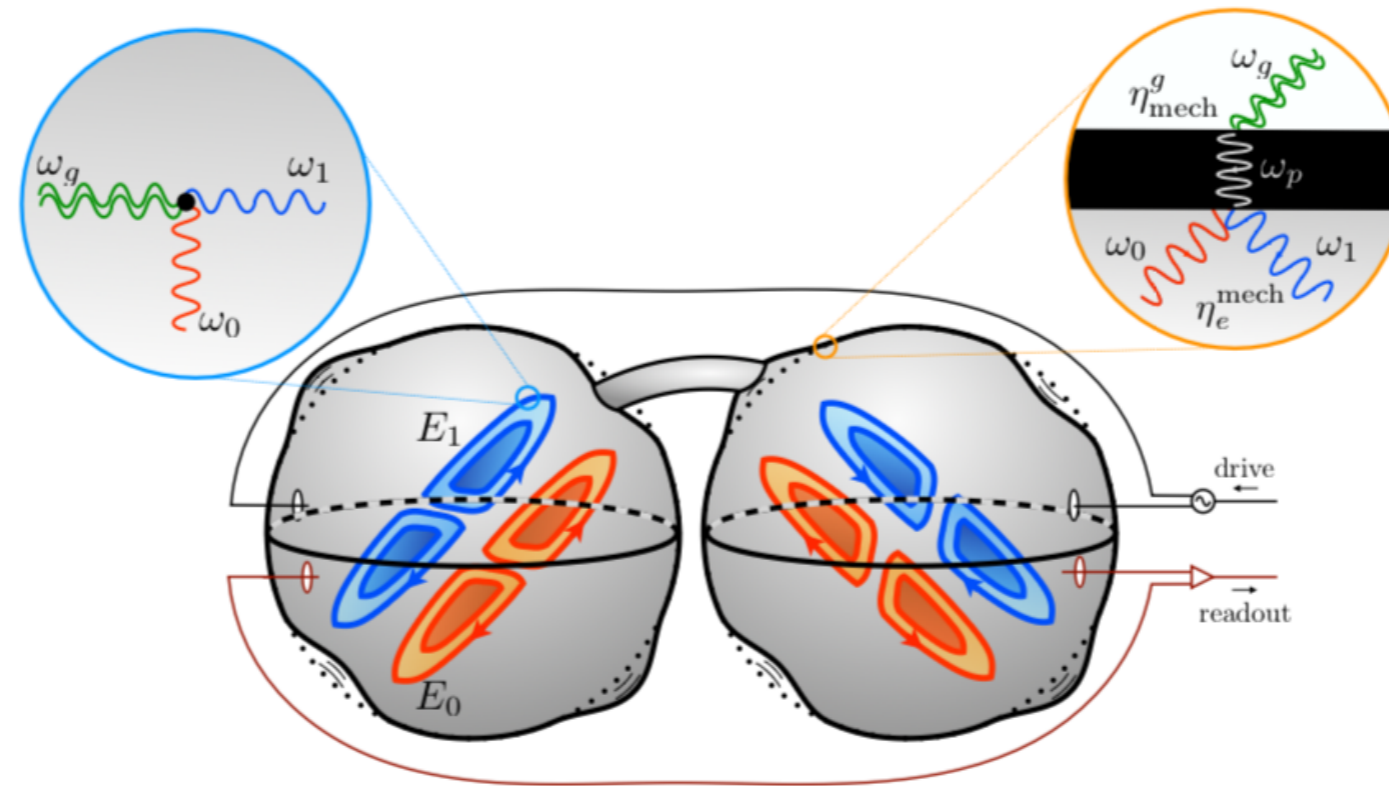Manasse and Misner, 1963
Ni and Zimmermamn, 1978

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Berlin et al 2022

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Excitation of mechanical modes

- The gravitational wave acts as a Newtonian force.
  If not negligible, coupling of the mechanical modes can play
  an important role (this is certainly the case at frequencies
  above the first mechanical resonance)

- This can enhance the sensitivity   Berlin et al 2022

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Novel effects

Effective magnetization and polarization

$$j^\mu_{\text{eff}} = \left(- \nabla \cdot \mathbf{P}, \nabla \times \mathbf{M} + \partial_t \mathbf{P} \right)$$

$$\mathbf{P} = g_{a\gamma\gamma} a \mathbf{B}, \quad \mathbf{M} = g_{a\gamma\gamma} a \mathbf{E}$$

$$P_i = - h_{ij} E_j + \frac{1}{2} h E_i + h_{00} E_i - \epsilon_{ijk} h_{0j} B_k$$

$$M_i = - h_{ij} B_j - \frac{1}{2} h B_i + h_{jj} B_i + \epsilon_{ijk} h_{0j} E_k$$
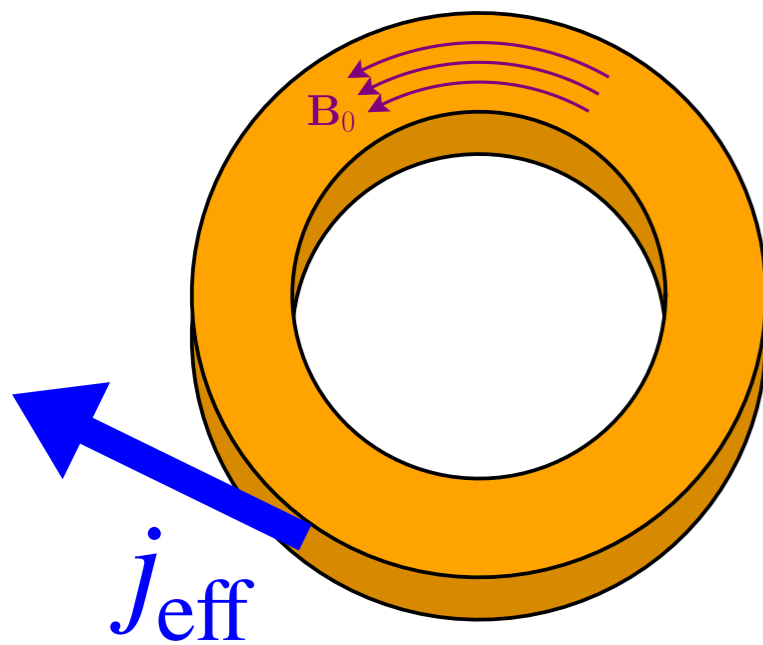
McAllister et al, 1803.07755
Tobar et al, 1809.01654
Ouellet et al, 1809.10709

Domcke, CGC, Rodd, 2202.00695

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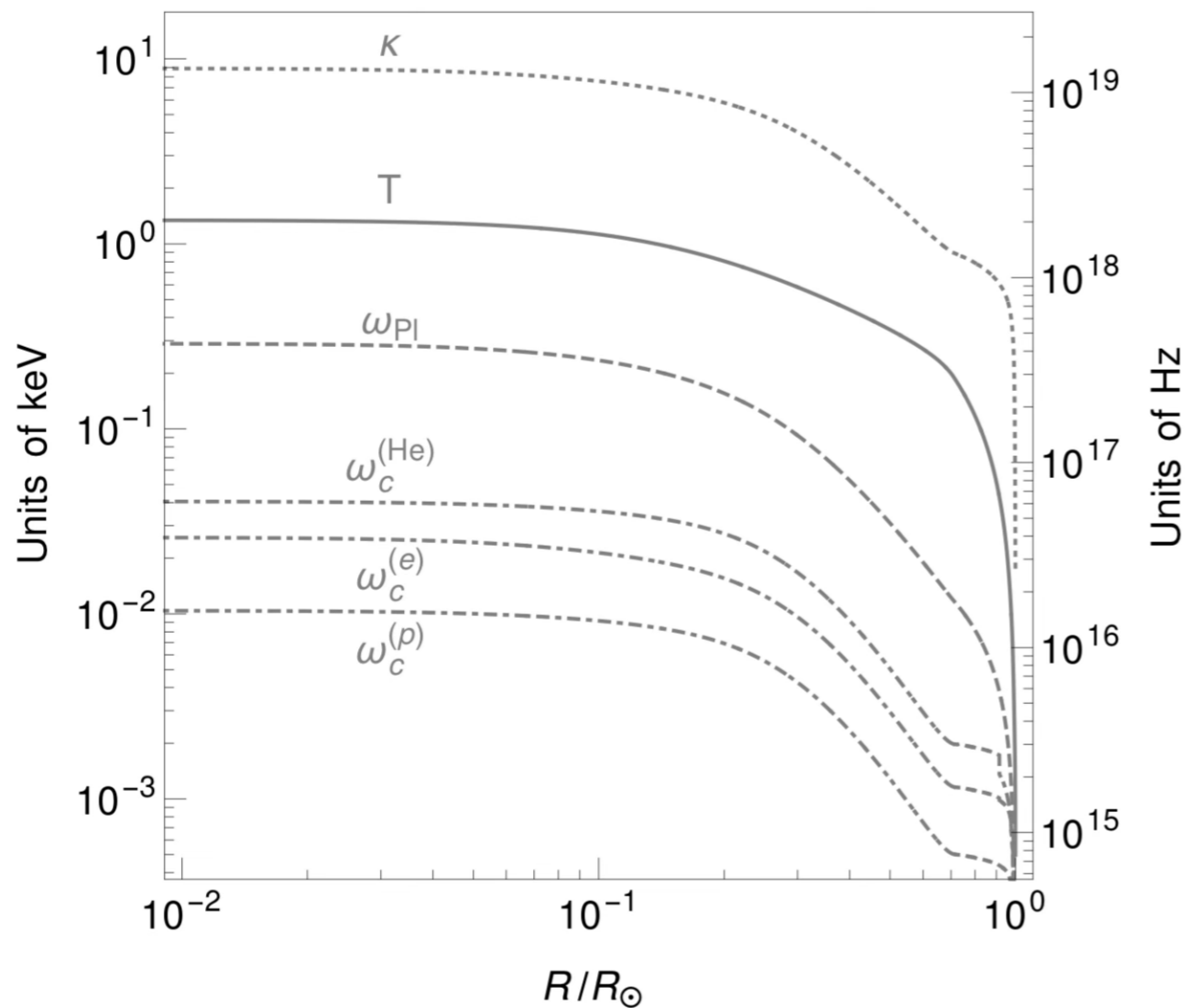
Non-zero *effective* surface currents

B_0

j_{eff}

At the interface of two bodies with different values of the magnetisation vector M, Maxwell's equations predict a surface current proportional to n × ΔM

For axions this happens to vanish, but that is not the case of GWs

Sizeable effects. This should also be relevant for cavities

Camilo García Cely, University of Valencia

The (inverse) Gertsenhstein Effect

García-Cely, Ringwald, 2024