Detection Prospects of Gravitational Waves in Axion Cavity Experiments

Cosmic WISPers 2024
Istanbul, Turkey
September 3, 2024

IFIC INSTITUT DE FÍSICA CORPUSCULAR

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

VNIVERSITAT DE VALÈNCIA

Camilo García Cely

Based on

Novel Search for High-Frequency Gravitational Waves with Low-Mass Axion Haloscopes

Valerie Domcke, Camilo Garcia-Cely, and Nicholas L. Rodd
Phys. Rev. Lett. **129**, 041101 – Published 20 July 2022

JHEP — PUBLISHED FOR SISSA BY SPRINGER
PUBLISHED: *March 21, 2024*

Symmetries and selection rules: optimising axion haloscopes for Gravitational Wave searches

Valerie Domcke,[a] Camilo Garcia-Cely,[b] Sung Mook Lee[a,c] and Nicholas L. Rodd[a]

arXiv > hep-ph > arXiv:2407.18297

High Energy Physics - Phenomenology

[Submitted on 25 Jul 2024]

Complete Gravitational-Wave Spectrum of the Sun

Camilo García-Cely, Andreas Ringwald

and work in progress with Luca Marsili, Aaron Spector and Andreas Ringwald

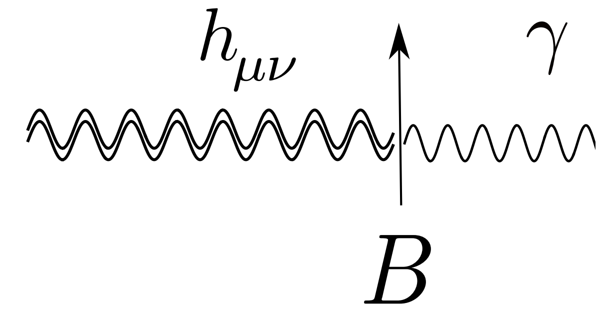
Outline

- Part I: The Gertsenhtein effect and high-frequency gravitational waves

- Part II: gravitational waves in haloscopes. Cavities and lumped element detectors.

- Part III: new ideas for the detection in cavities

- Conclusions



Part I

The Gertsenhtein effect and high-frequency gravitational waves

Revisiting Gertsenhstein's ideas

SOVIET PHYSICS JETP VOLUME 16, NUMBER 2 FEBRUARY, 1963

ON THE DETECTION OF LOW FREQUENCY GRAVITATIONAL WAVES

M. E. GERTSENSHTEĬN and V. I. PUSTOVOĬT

Submitted to JETP editor March 3, 1962

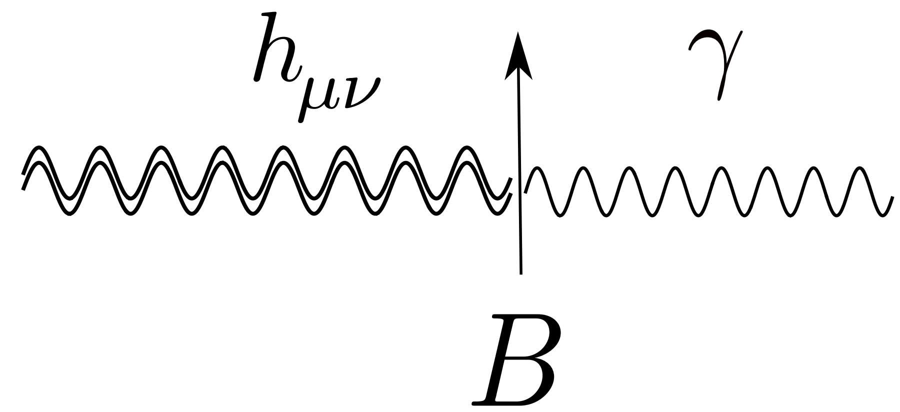
J. Exptl. Theoret. Phys. (U.S.S.R.) **43**, 605-607 (August, 1962)

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

Revisiting Gertsenhstein's ideas

SOVIET PHYSICS JETP VOLUME 14, NUMBER 1 JANUARY, 1962



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.

SOVIET PHYSICS JETP VOLUME 16, NUMBER 2 FEBRUARY, 1963

ON THE DETECTION OF LOW FREQUENCY GRAVITATIONAL WAVES

M. E. GERTSENSHTEĬN and V. I. PUSTOVOĬT

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Terrestrial interferometers

The (inverse) Gertsenhstein Effect

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

$$P \sim G B^2 L^2$$

- 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

High-frequency gravitational waves

Part of a collection:

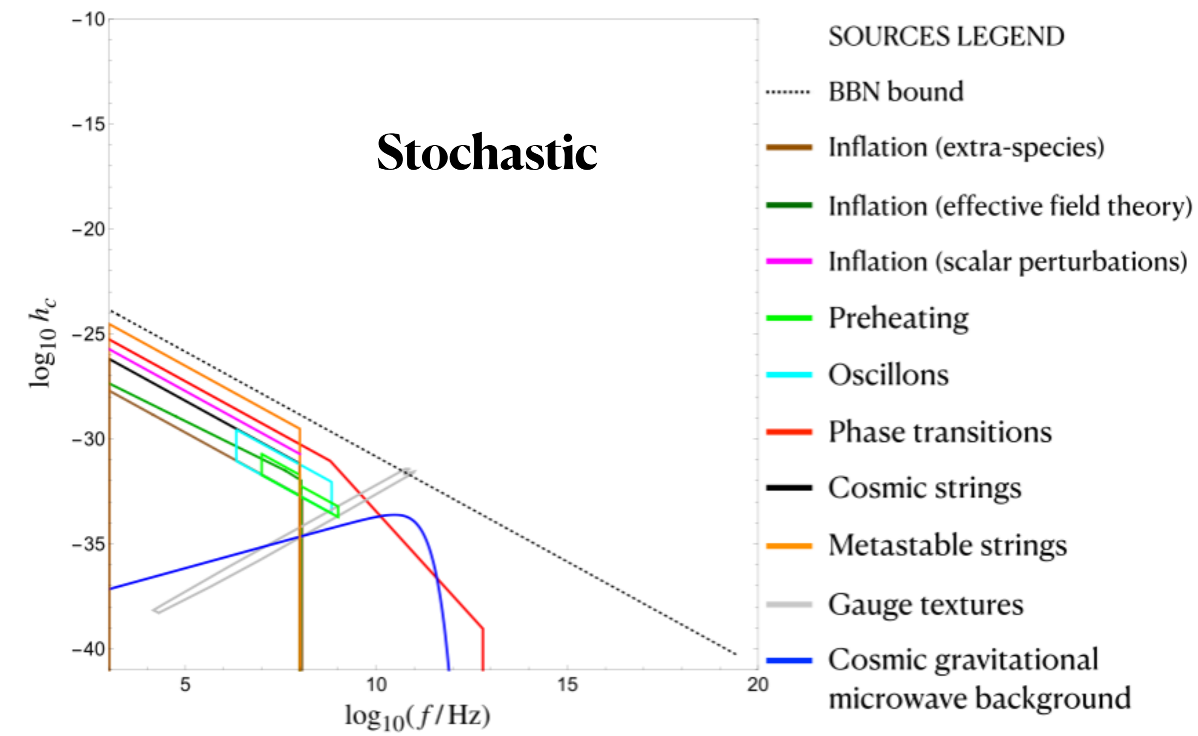
Gravitational Waves

Review Article | Open Access | Published: 06 December 2021

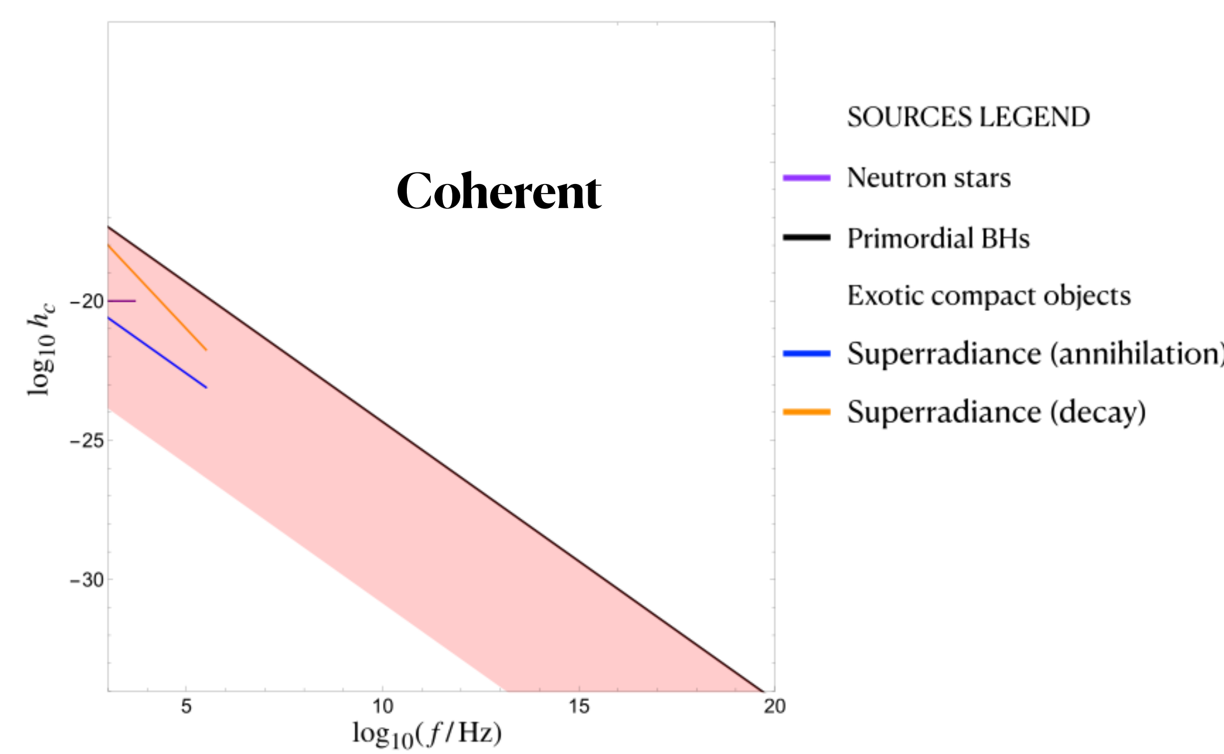
Challenges and opportunities of gravitational-wave searches at MHz to GHz frequencies

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

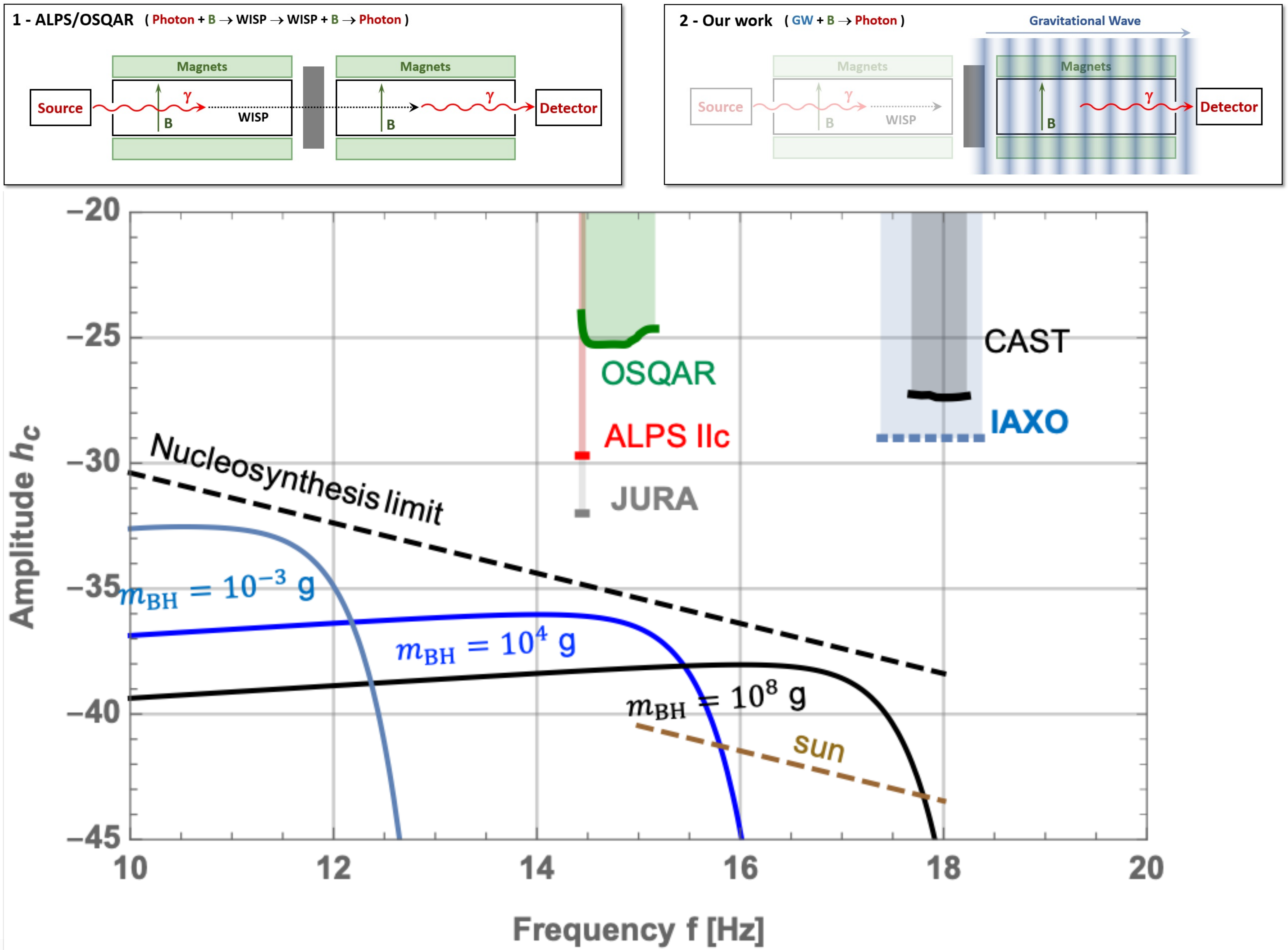
Living Reviews in Relativity **24**, Article number: 4 (2021) | Cite this article



A growing community is seriously considering the search of high frequency gravitational waves



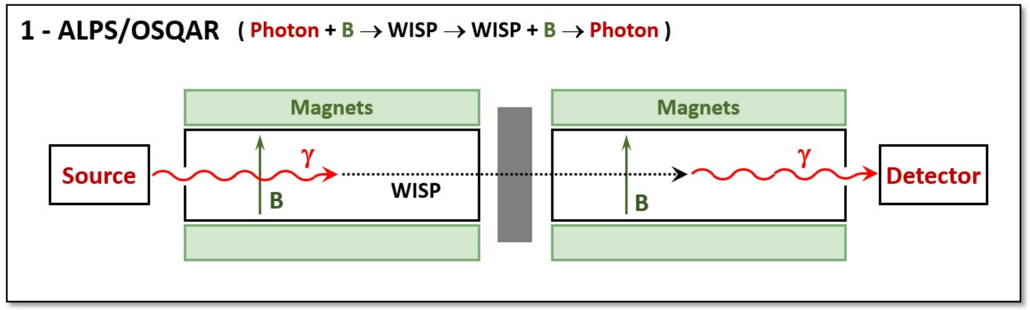
The (inverse) Gertsenhstein Effect

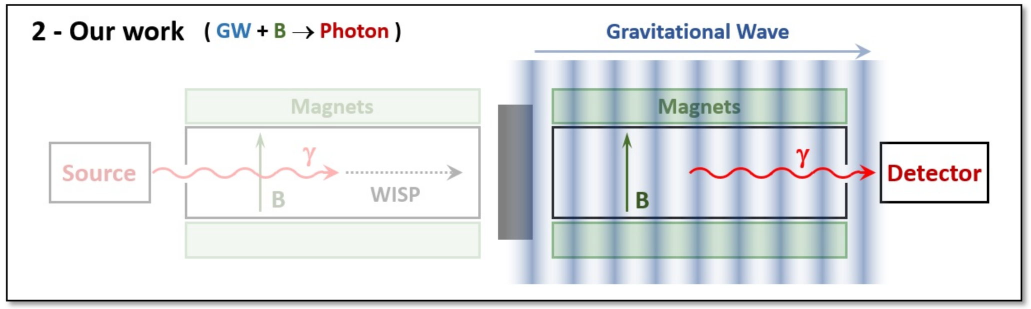


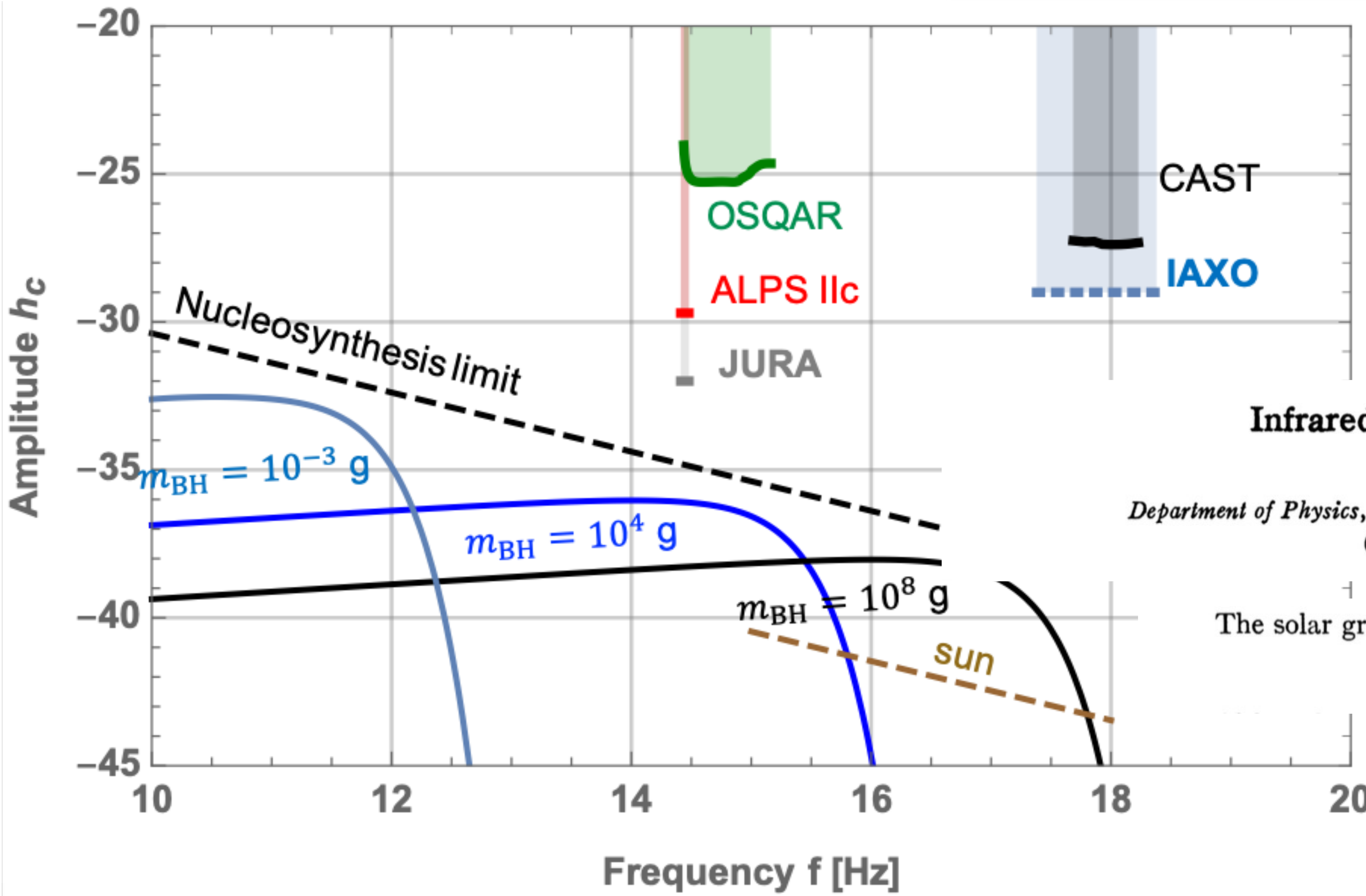
A. Ejlli, D. Ejlli, A. M. Cruise, G. Pisano & H. Grote

The European Physical Journal C **79**, Article number: 1032 (2019)

The (inverse) Gertsenhstein Effect







Infrared Photons and Gravitons*

STEVEN WEINBERG†

Department of Physics, University of California, Berkeley, California

(Received 1 June 1965)

The solar gravitational radiation power is then

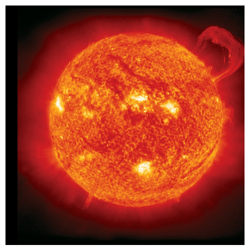
$$P_{\odot} \simeq 6\times10^{14}\ \text{erg/sec}. \qquad (4.24)$$

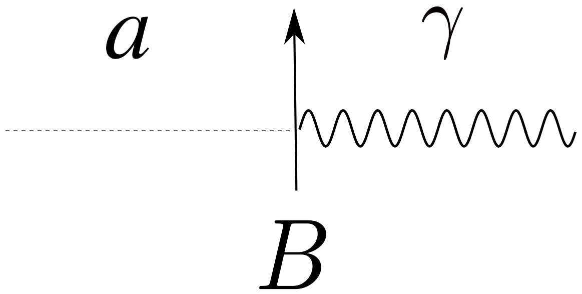
A. Ejlli, D. Ejlli, A. M. Cruise, G. Pisano & H. Grote

The European Physical Journal C **79**, Article number: 1032 (2019)

Solar emission of axions

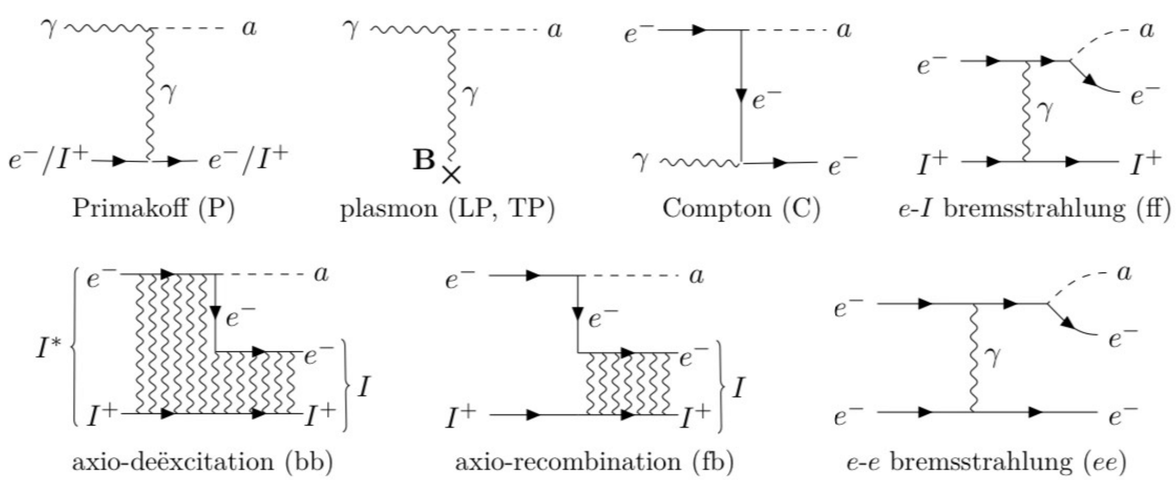
- Helioscopes

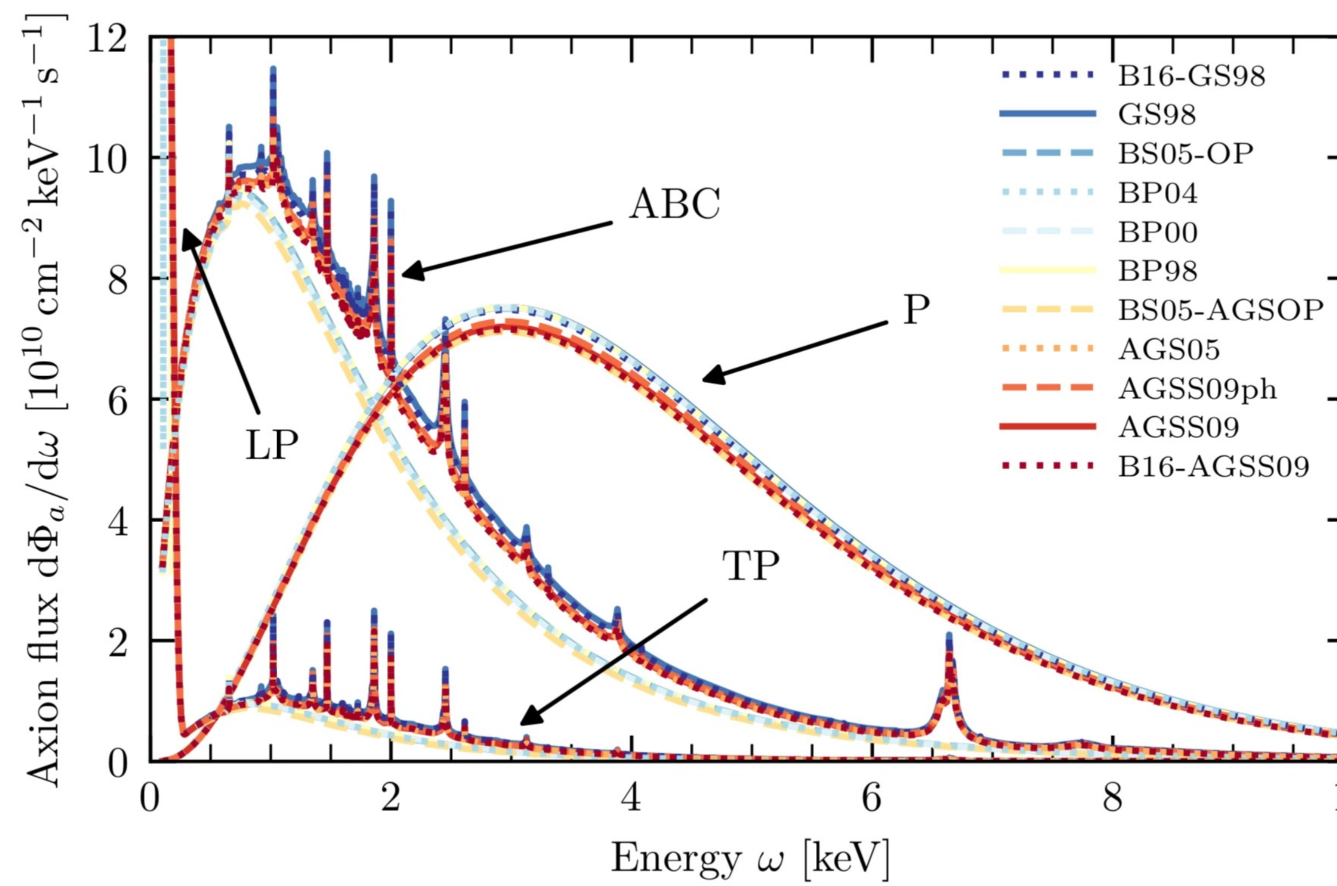




- CAST
- IAXO
- .....

Hoof et al, 2021





PHYSICAL REVIEW D VOLUME 33, NUMBER 4 15 FEBRUARY 1986

Astrophysical axion bounds diminished by screening effects

Georg G. Raffelt

PHYSICAL REVIEW D VOLUME 37, NUMBER 6 15 MARCH 1988

Plasmon decay into low-mass bosons in stars

Georg G. Raffelt

PHYSICAL REVIEW D **102,** 043019 (2020)

Axion helioscopes as solar magnetometers

Ciaran A. J. O'Hare,[1,*] Andrea Caputo,[2,†] Alexander J. Millar,[3,4,‡] and Edoardo Vitagliano[5,§]

PHYSICAL REVIEW D **101,** 123004 (2020)

Revisiting longitudinal plasmon-axion conversion in external magnetic fields

Andrea Caputo,[1,*] Alexander J. Millar,[2,3,†] and Edoardo Vitagliano[4,‡]

PHYSICAL REVIEW D **102,** 123024 (2020)

Production of axionlike particles from photon conversions in large-scale solar magnetic fields

Ersilia Guarini,[1] Pierluca Carenza,[1,2] Javier Galán,[3] Maurizio Giannotti,[4] and Alessandro Mirizzi[1,2]

Axion emission by magnetic-field induced conversion of longitudinal plasmons

N. V. Mikheev
Department of Theoretical Physics, Yaroslavl State University, Sovietskaya 14, Yaroslavl 150000, Russia

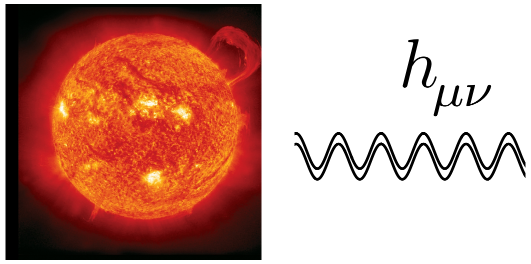
G. Raffelt
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Föhringer Ring 6, 80805 München, Germany

L. A. Vassilevskaya

Solar axion flux from the axion-electron coupling

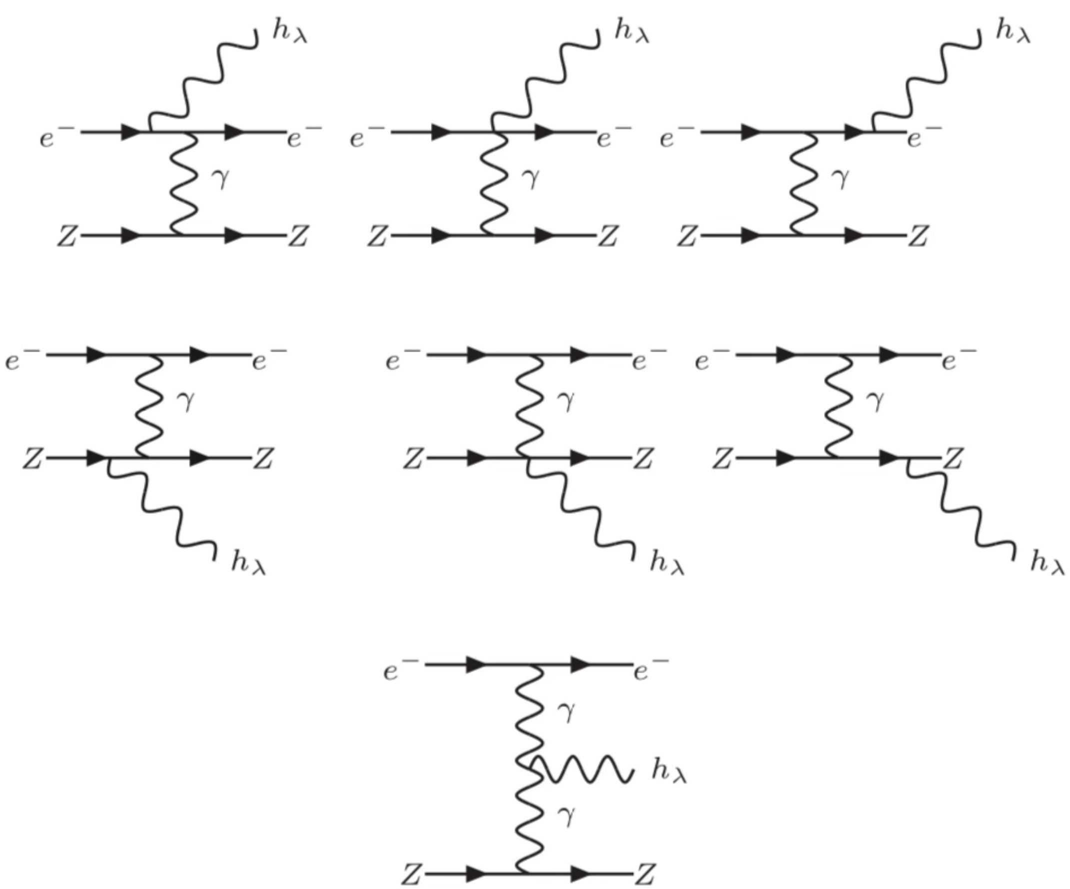
Javier Redondo (Munich U., ASC and Munich, Max Planck Inst.)
Oct 2, 2013

Solar emission of gravitational waves



García-Cely, Ringwald, 2024

Bremsstrahlung



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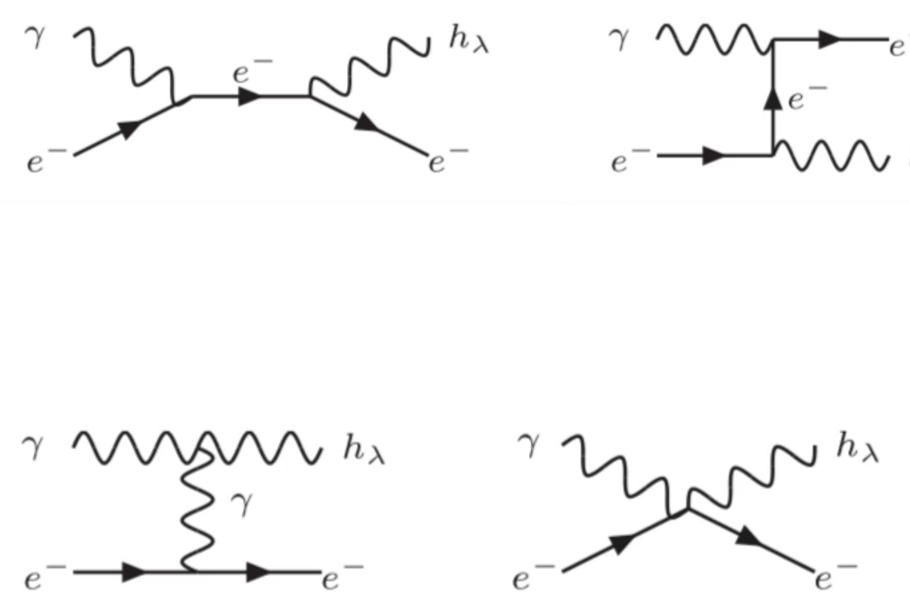


Camilo García Cely, University of Valencia

Hydrodynamical contribution

Gravitational wave background from Standard Model physics: qualitative features

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

Published 16 July 2015 • Journal of Cosmology and Astroparticle Physics, Volume 2015, July 2015

Citation J. Ghiglieri and M. Laine JCAP07(2015)022

DOI 10.1088/1475-7516/2015/07/022

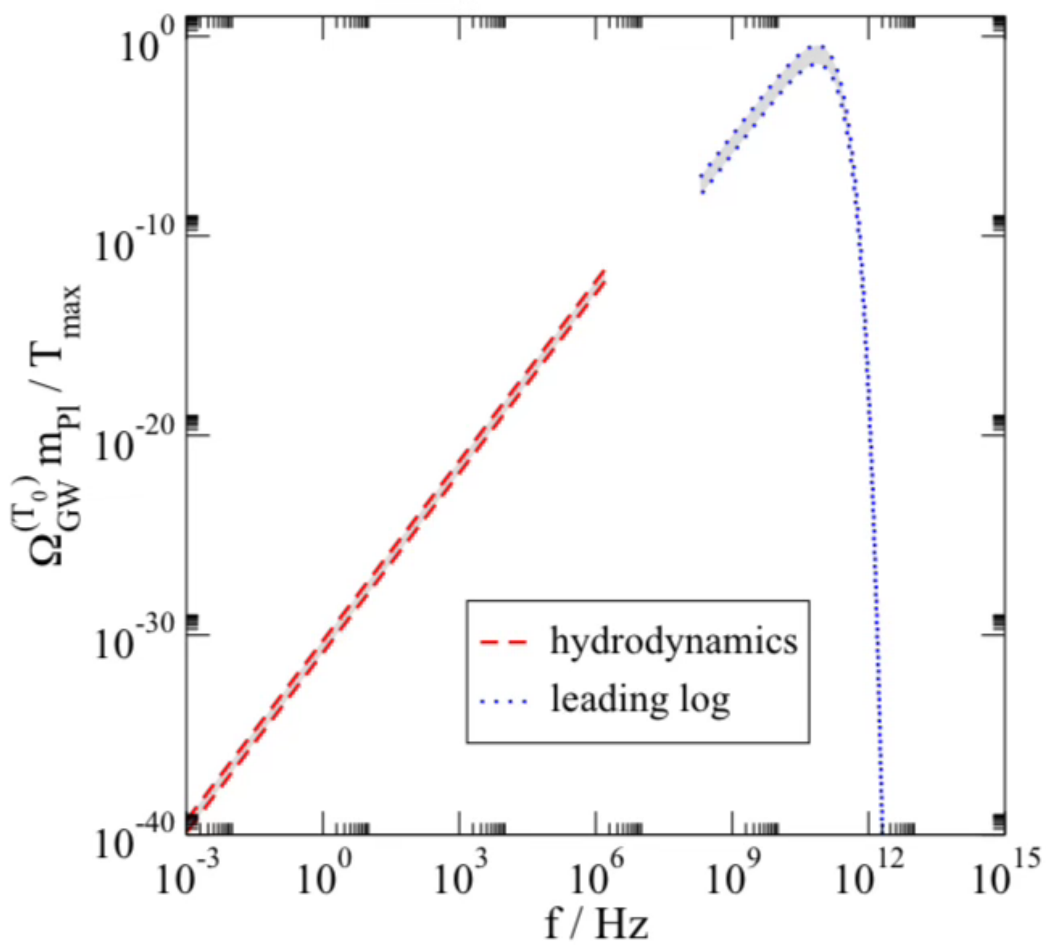
Article PDF

References ▾

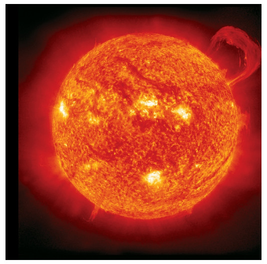
+ Article and author information

Abstract

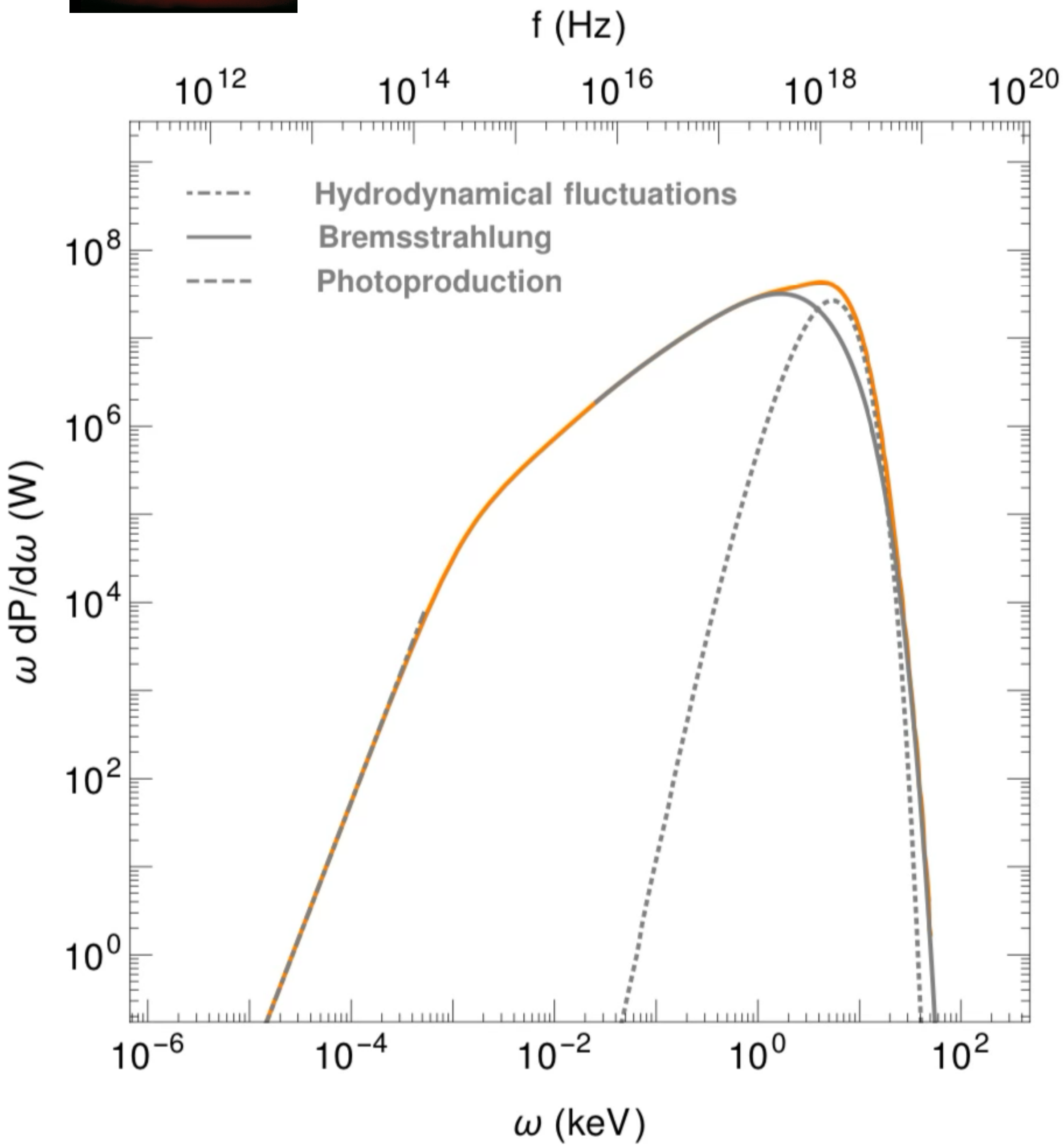
Because of physical processes ranging from microscopic particle collisions to macroscopic hydrodynamic fluctuations, any plasma in thermal equilibrium emits gravitational waves. For the largest wavelengths the emission rate is proportional to the shear viscosity of the plasma. In the Standard Model at

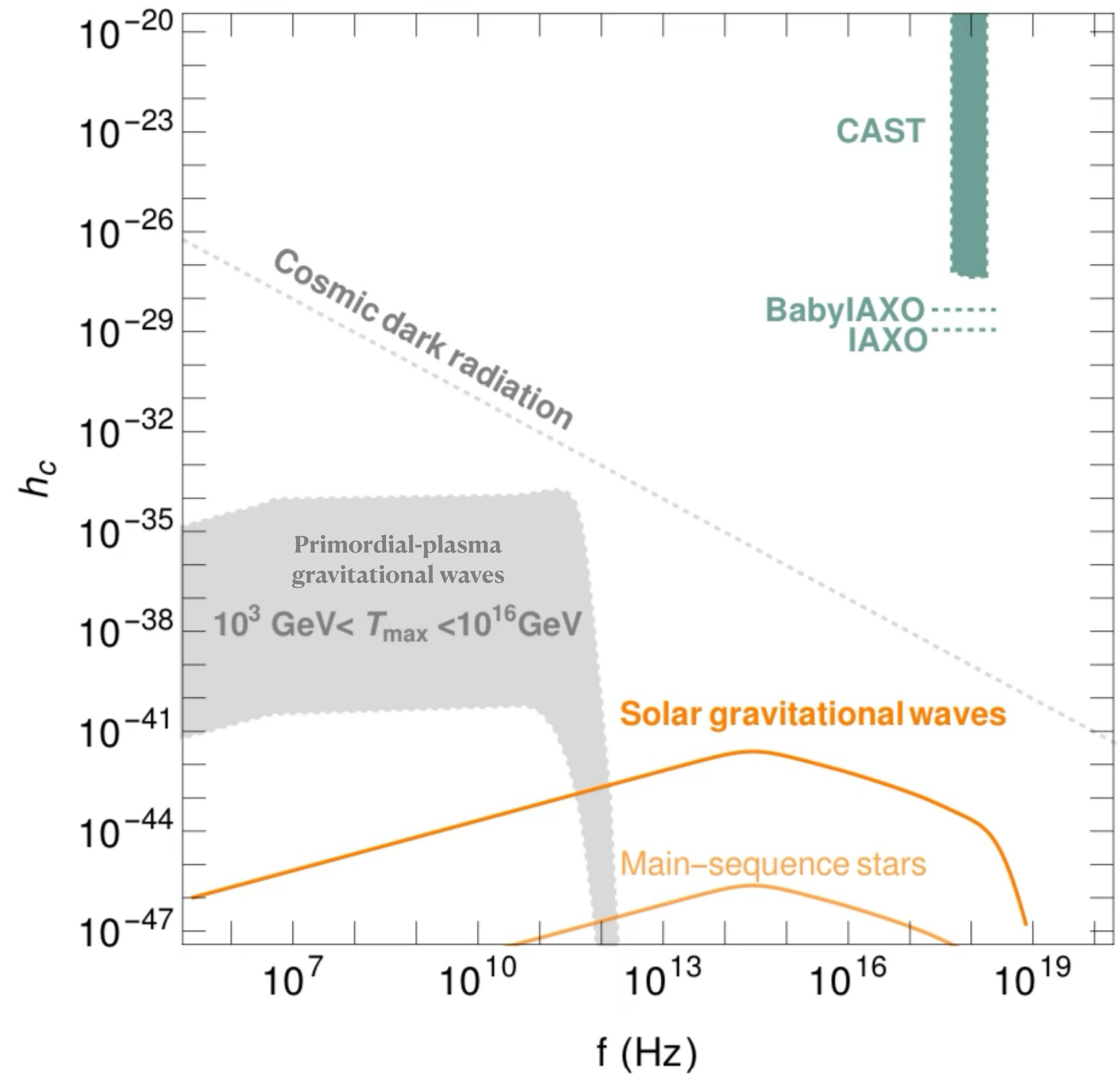


Solar gravitational waves



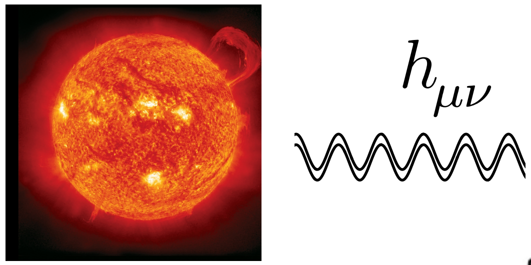
García-Cely, Ringwald, 2024



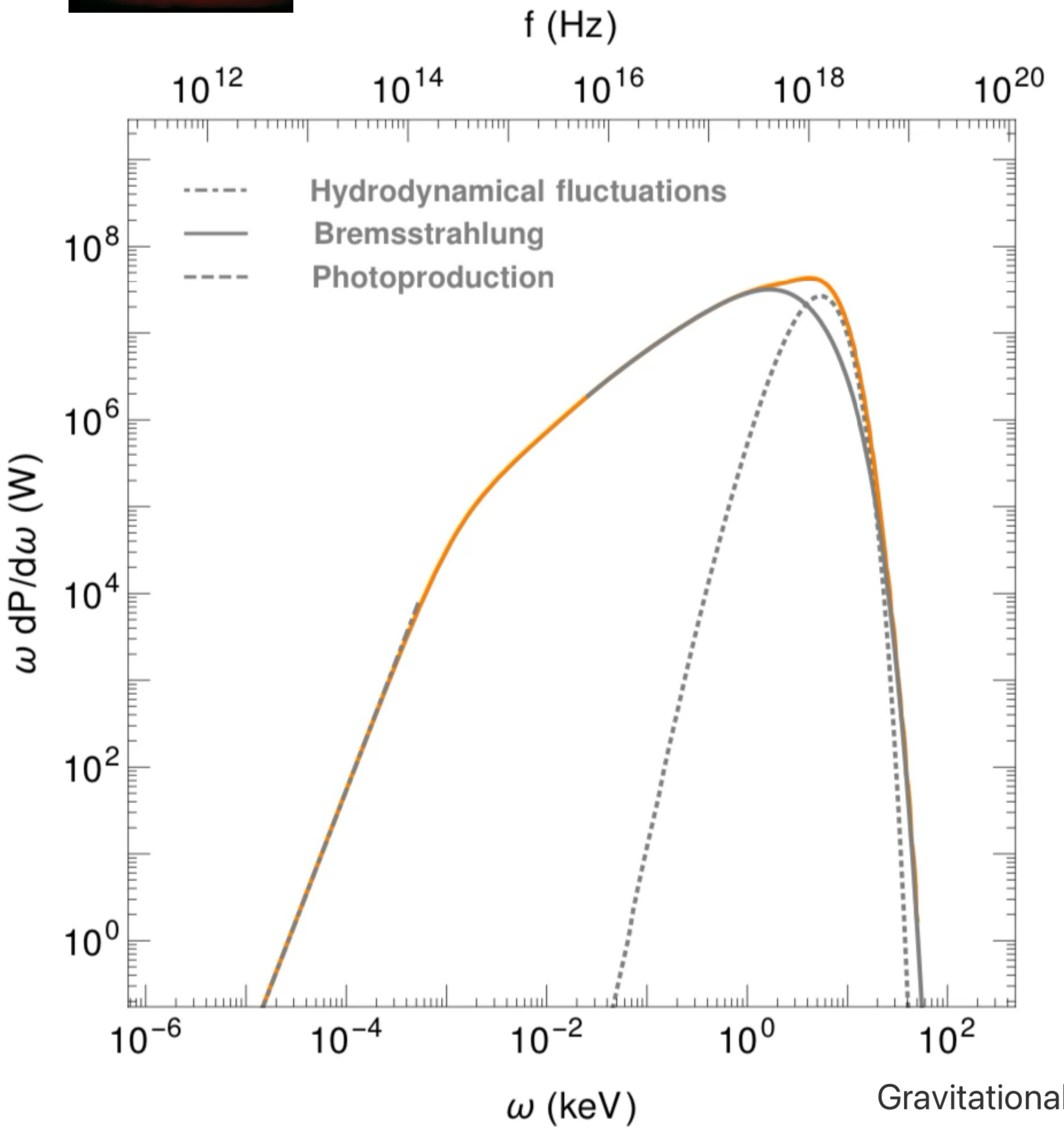


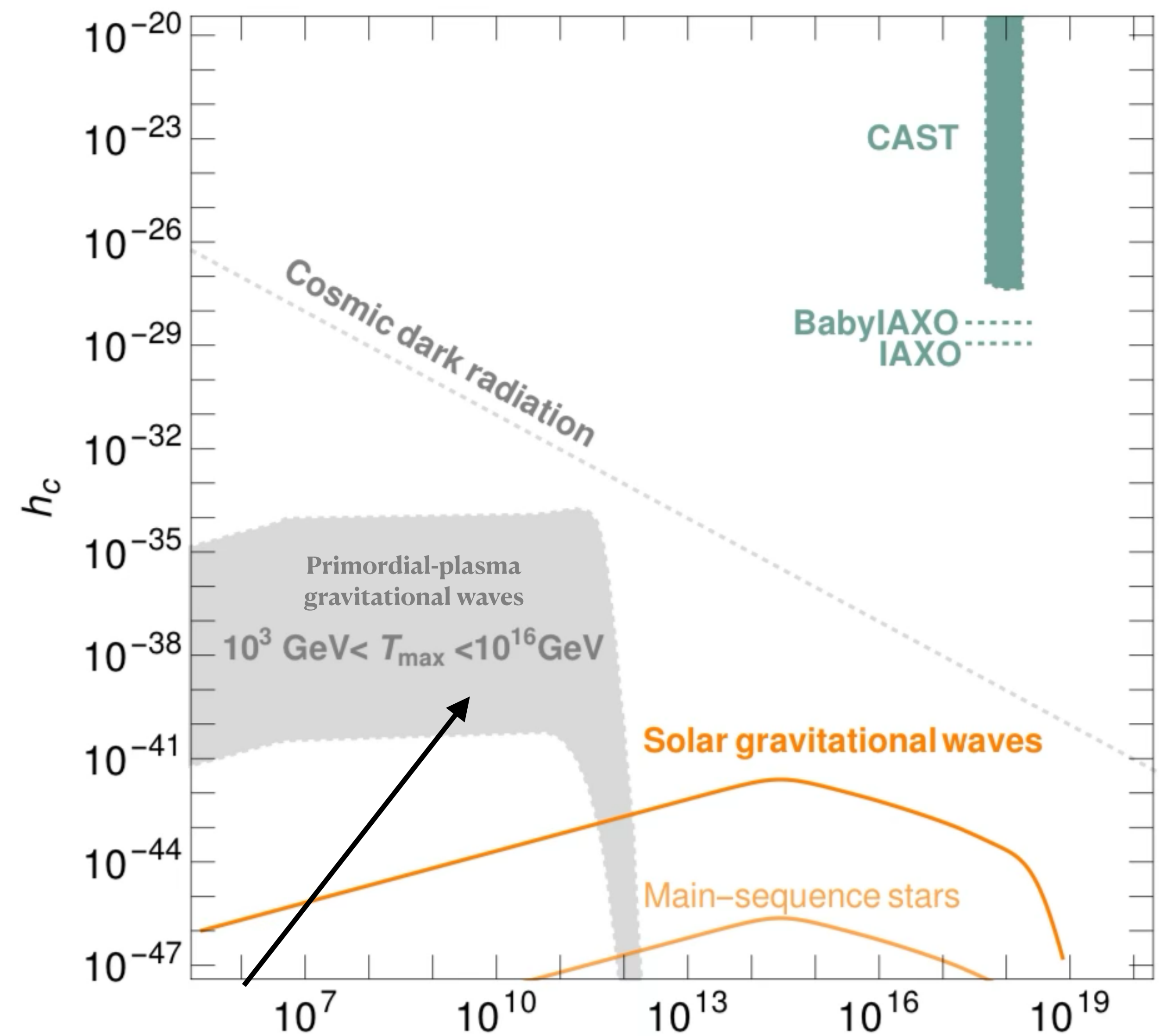
Camilo García Cely, University of Valencia

Solar gravitational waves



García-Cely, Ringwald, 2024





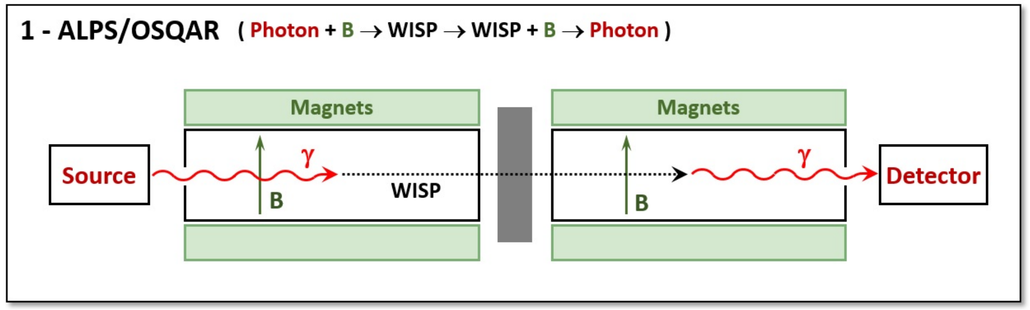
Gravitational waves as a big bang thermometer

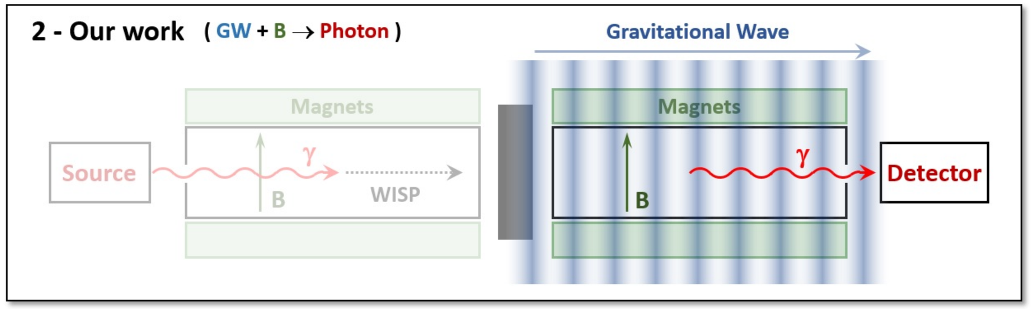
Andreas Ringwald[1], Jan Schütte-Engel[2,3,4] and Carlos Tamarit[5]

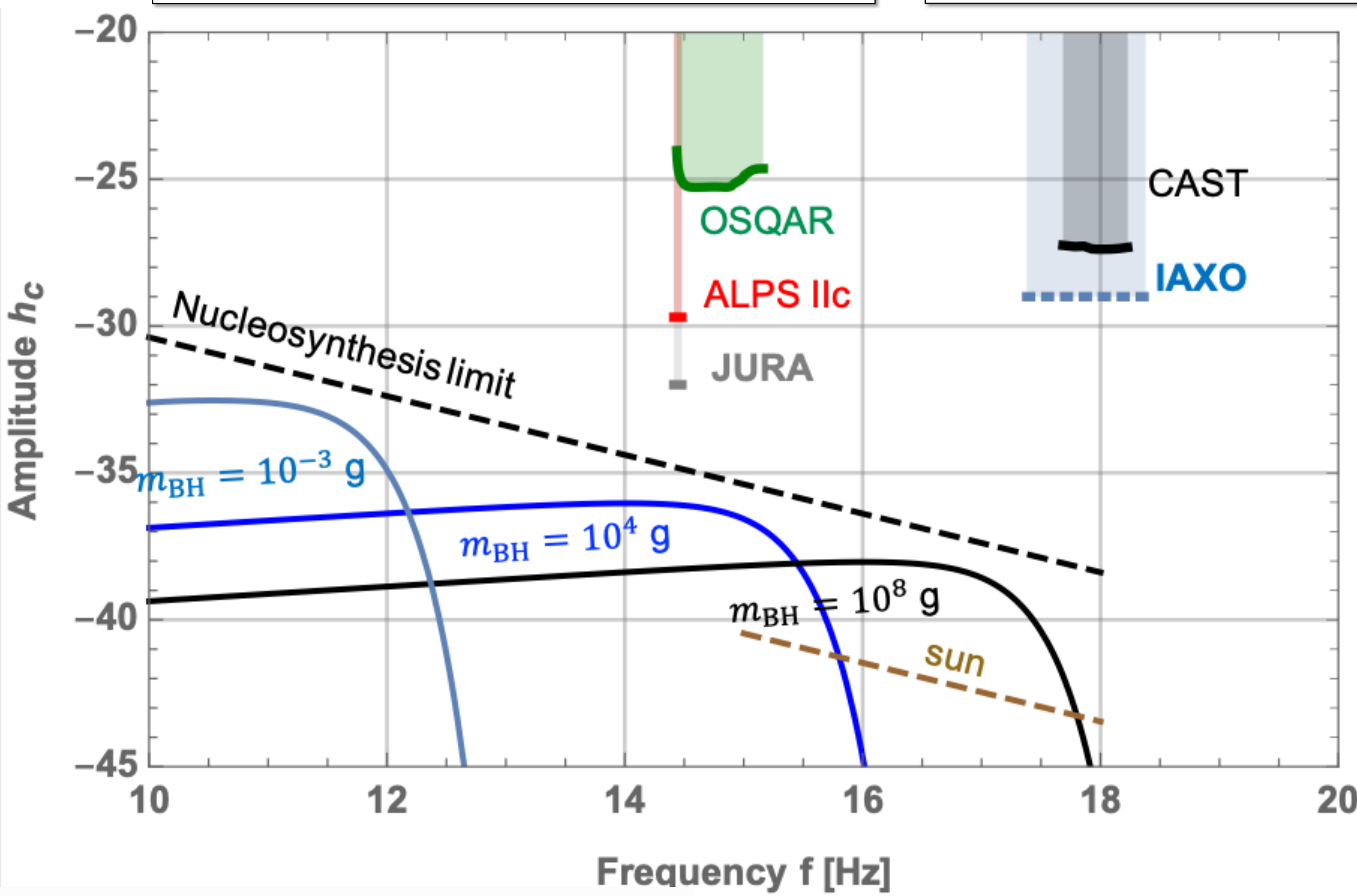
Published 17 March 2021 • © 2021 IOP Publishing Ltd and Sissa Medialab

Journal of Cosmology and Astroparticle Physics, Volume 2021, March 2021

The (inverse) Gertsenhstein Effect







Still far from testing
Early Universe signals

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

The European Physical Journal C **79**, Article number: 1032 (2019)

Part II

Gravitational waves in haloscopes. Cavities and lumped element detectors

How does it work?

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

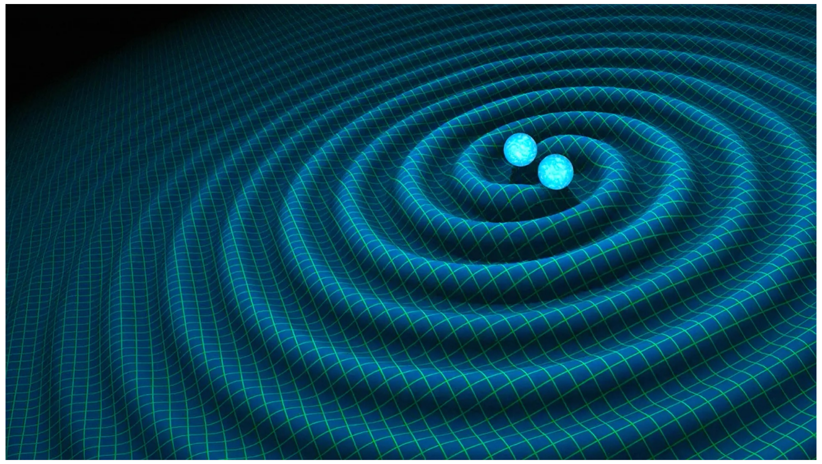
$$j^0 = -\, g_{a\gamma\gamma} \nabla a \cdot \mathbf{B}$$

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

Sikivie, 1983

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

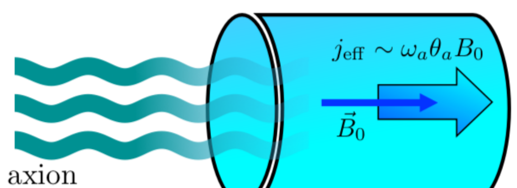
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \qquad \left| h_{\mu\nu} \right| \ll 1$$

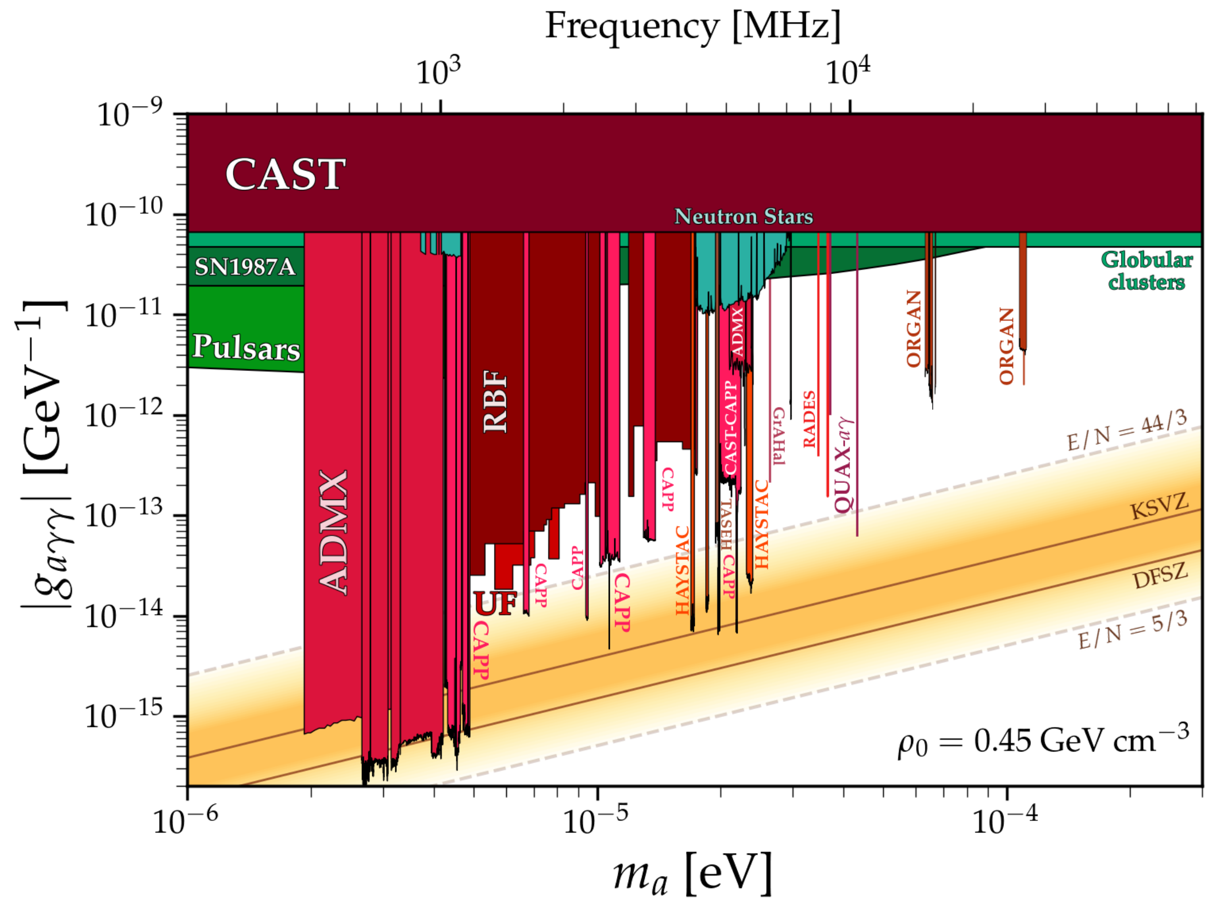


$$j^{\mu}_{\text{eff}} = \partial_\nu \left(-\frac{1}{2} h\, F^{\mu\nu} + F^{\mu\alpha} h^{\nu}{}_{\alpha} - F^{\nu\alpha} h^{\mu}{}_{\alpha} \right)$$

Camilo García Cely, University of Valencia

Haloscopes based on microwave cavities





https://github.com/cajohare/AxionLimits

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

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

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

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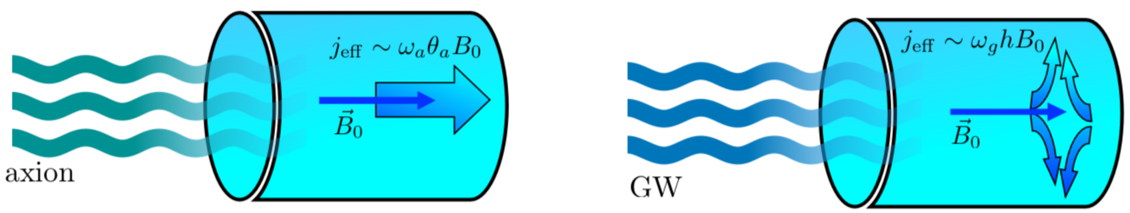
Haloscopes based on microwave cavities



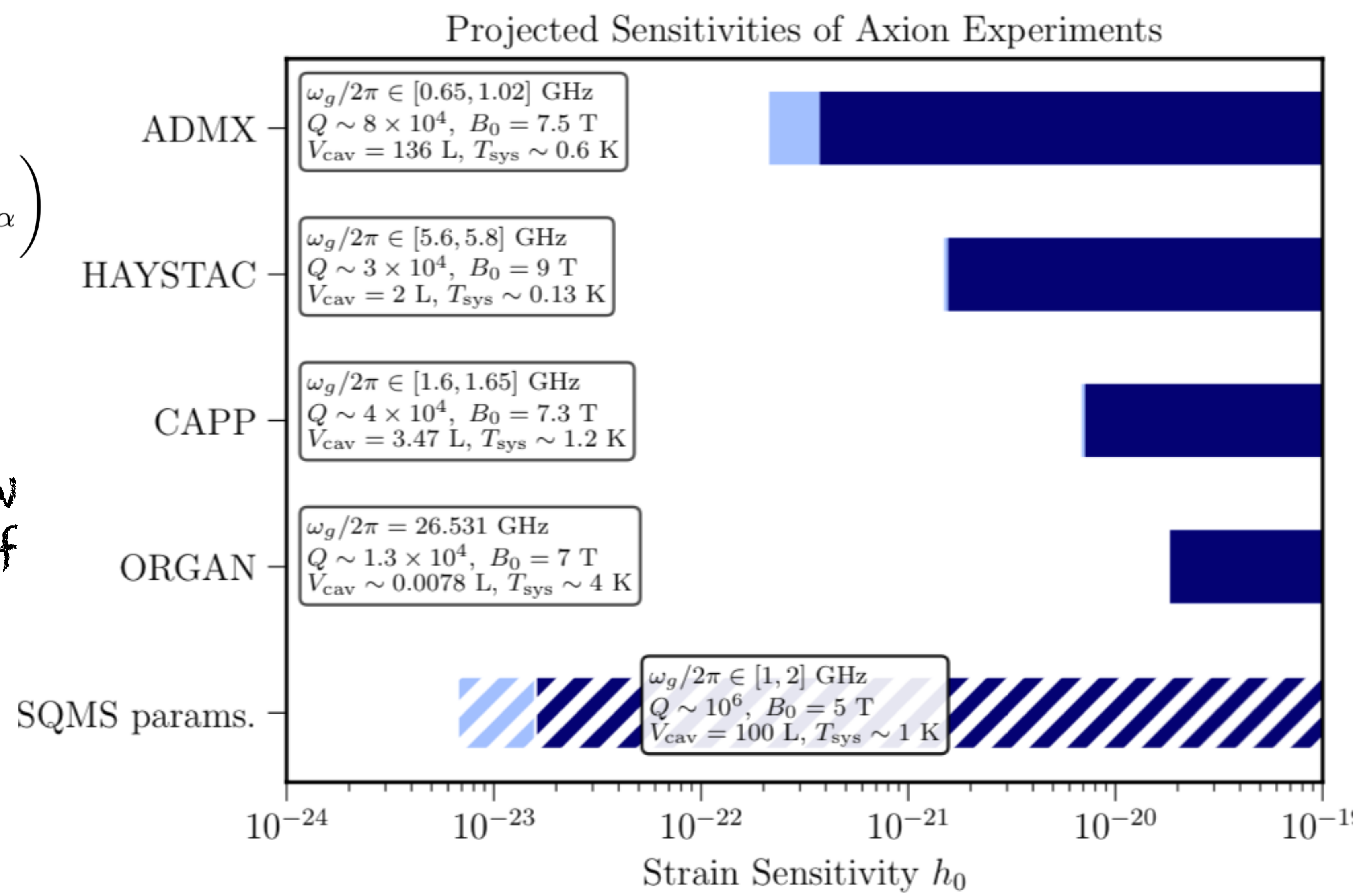
Detecting high-frequency gravitational waves with microwave cavities

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

Phys. Rev. D **105**, 116011 – Published 17 June 2022

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

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



See also 2303.01518

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
Phys. Rev. D **109**, 104048 – Published 14 May 2024

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

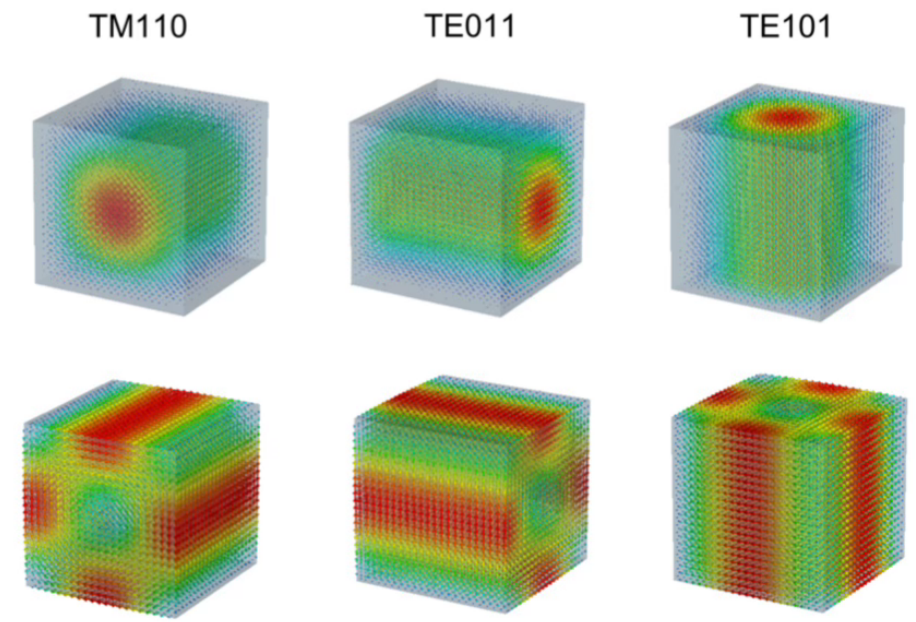


FIG. 3. Electric (up) and magnetic (down) field distributions for the three considered modes TM_{110}, TE_{011} and TE_{101} of cavity C1. The electromagnetic field distributions are identical in the other cavities C2 and C3. The red hue represents the largest values for the modules of electric and magnetic 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.

[Submitted on 30 Jul 2024 (v1), last revised 14 Aug 2024 (this version, v2)]

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.

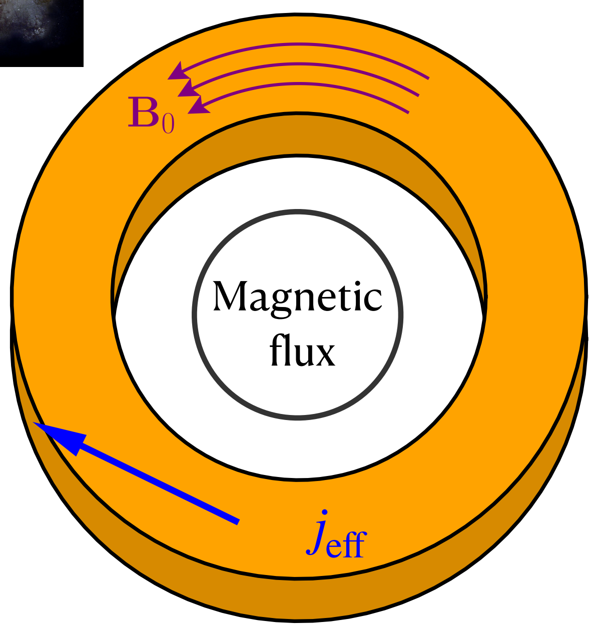
arXiv:2403.18610 (gr-qc)

[Submitted on 27 Mar 2024]

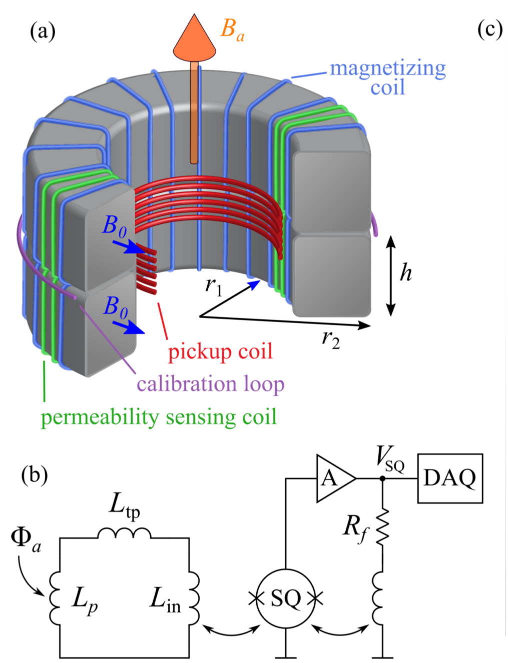
Cavity Detection of Gravitational Waves: Where Do We Stand?

Claudio Gatti, Luca Visinelli, Michael Zantedeschi

Haloscopes based on lumped-element detectors



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



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]

PRL 117, 141801 (2016) PHYSICAL REVIEW LETTERS week ending 30 SEPTEMBER 2016

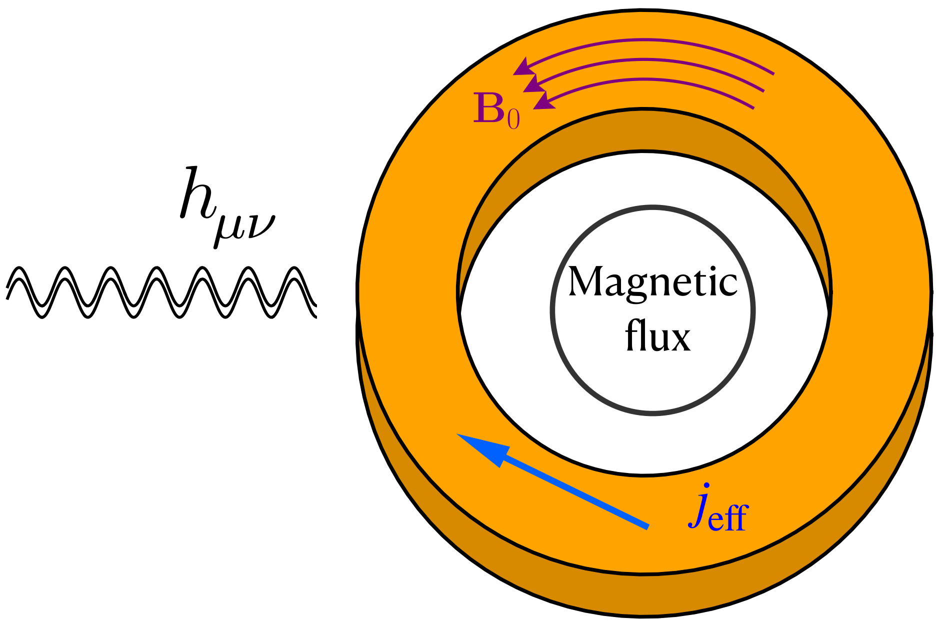
Broadband and Resonant Approaches to Axion Dark Matter Detection

Yonatan Kahn,[1,*] Benjamin R. Safdi,[2,†] and Jesse Thaler[2,‡]
[1]*Department of Physics, Princeton University, Princeton, New Jersey 08544, USA*
[2]*Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

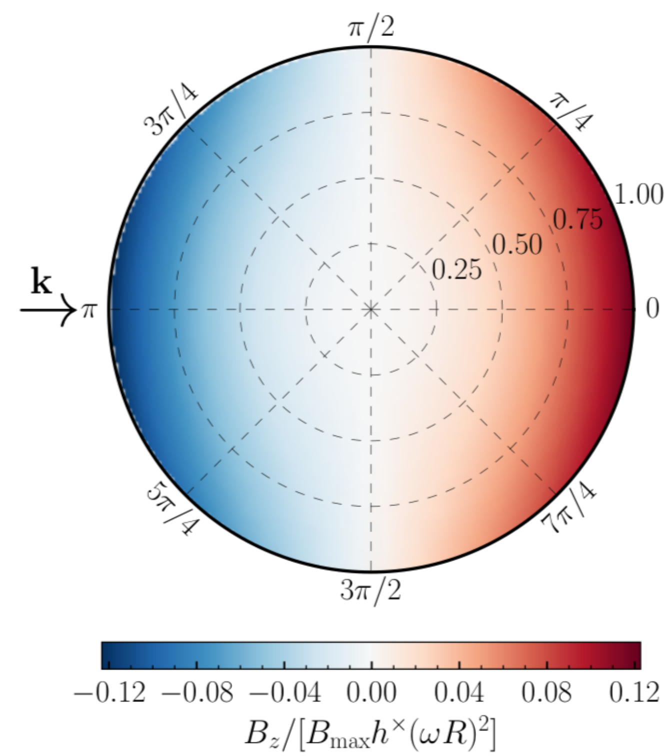
(Received 3 March 2016; published 30 September 2016)

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

Haloscopes based on lumped-element detectors



Valerie Domcke, Camilo Garcia-Cely, and Nicholas L. Rodd
Phys. Rev. Lett. **129**, 041101 – Published 20 July 2022



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

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

Only one polarization

Suppression at small frequencies

The sensitivity scaling with the volume is faster than for axions

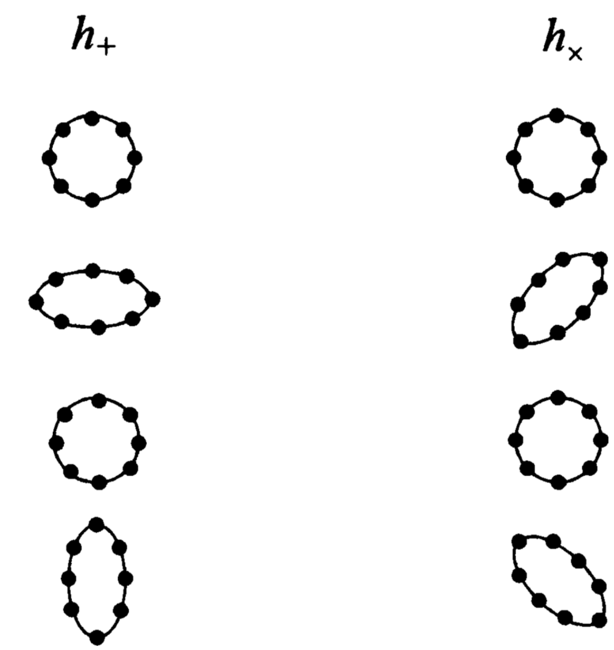
Camilo García Cely, University of Valencia

Gravitational waves

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

wave equation describing two polarization modes

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

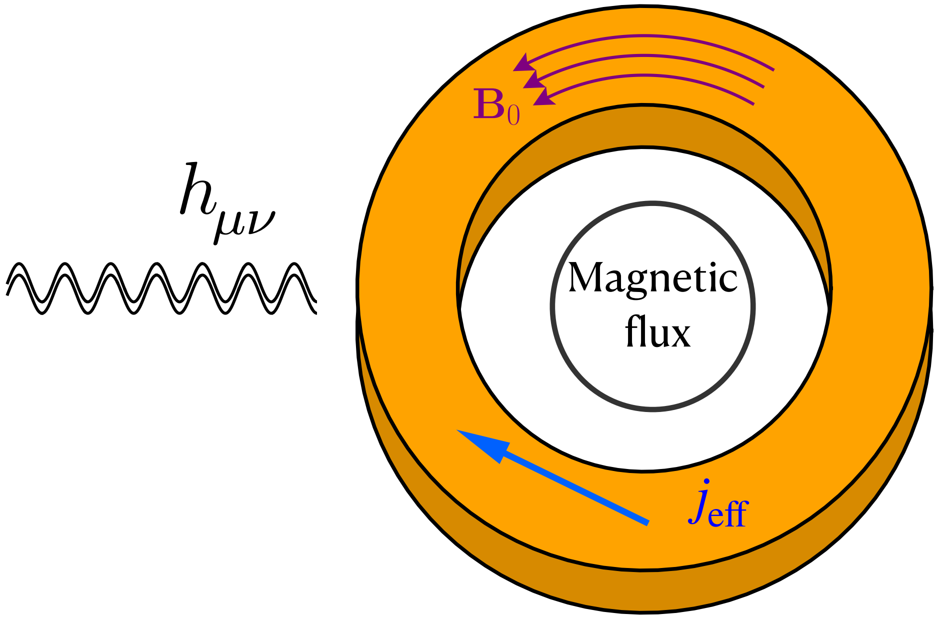


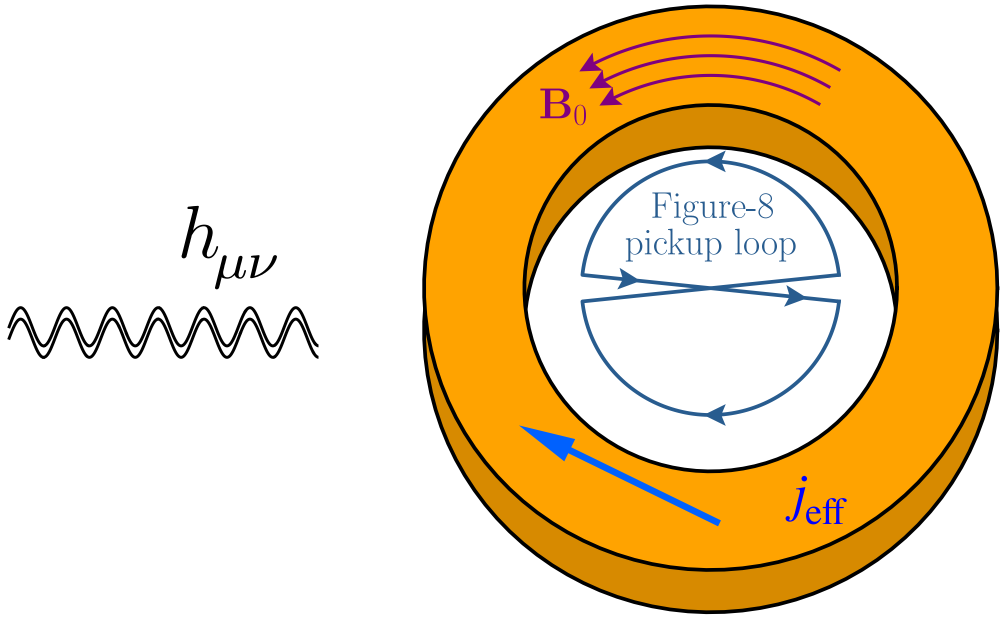
The deformation of a ring of test masses due to the different polarization

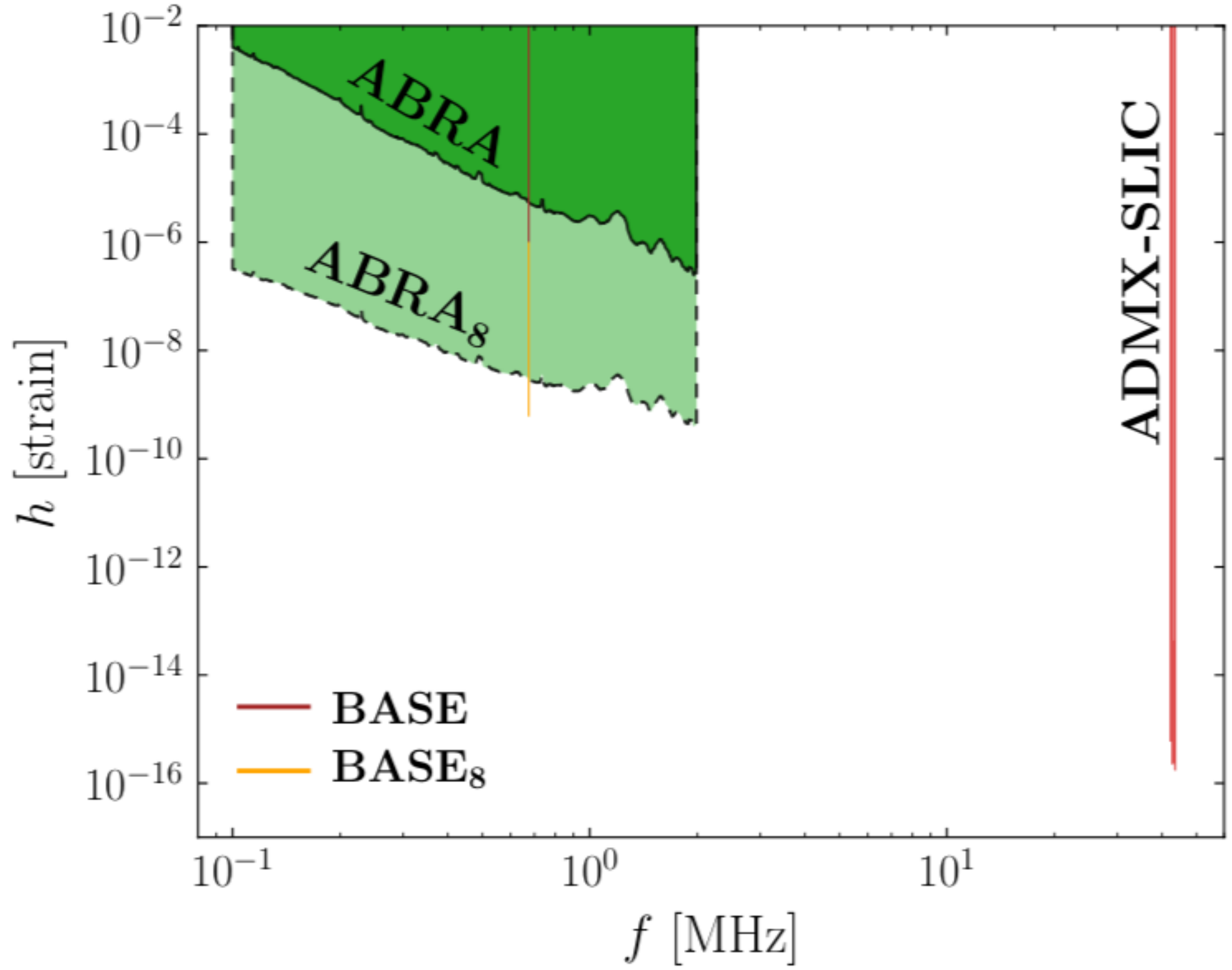
Camilo García Cely, University of Valencia

Toroidal magnetic fields

Valerie Domcke, Camilo Garcia-Cely, and Nicholas L. Rodd
Phys. Rev. Lett. **129**, 041101 – Published 20 July 2022





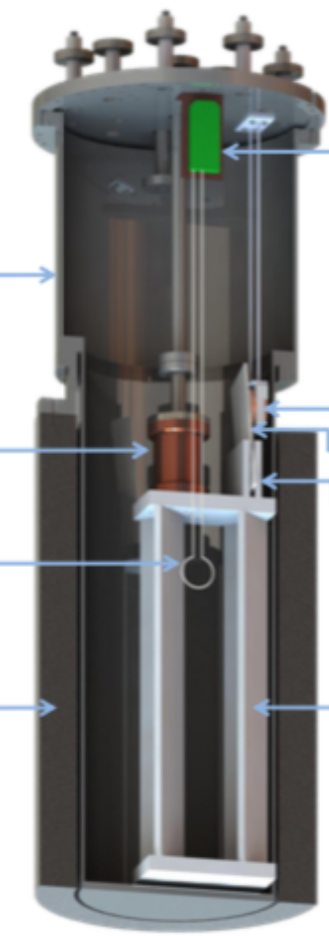


Solenoidal configurations

Domcke, CGC, Lee, Rodd, 2023

ADMX SLIC: Results from a Superconducting *LC* Circuit Investigating Cold Axions

N. Crisosto, P. Sikivie, N. S. Sullivan, D. B. Tanner, J. Yang, and G. Rybka
Phys. Rev. Lett. **124**, 241101 – Published 17 June 2020



BASE

Constraints on the Coupling between Axionlike Dark Matter and Photons Using an Antiproton Superconducting Tuned Detection Circuit in a Cryogenic Penning Trap

Jack A. Devlin, Matthias J. Borchert, Stefan Erlewein, Markus Fleck, James A. Harrington, Barbara Latacz, Jan Warncke, Elise Wursten, Matthew A. Bohman, Andreas H. Mooser, Christian Smorra, Markus Wiesinger, Christian Will, Klaus Blaum, Yasuyuki Matsuda, Christian Ospelkaus, Wolfgang Quint, Jochen Walz, Yasunori Yamazaki, and Stefan Ulmer
Phys. Rev. Lett. **126**, 041301 – Published 25 January 2021

WISPLC

Search for dark matter with an *LC* circuit

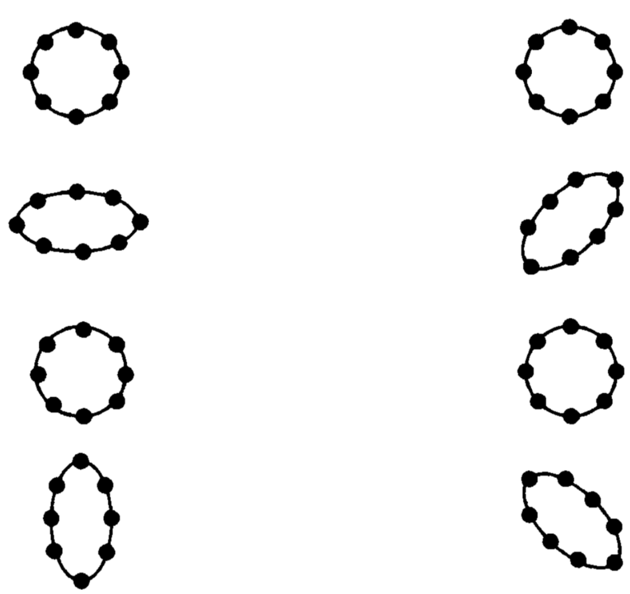
Zhongyue Zhang (张钟月), Dieter Horns, and Oindrila Ghosh
Phys. Rev. D **106**, 023003 – Published 5 July 2022

Selection rules

Geavitational waves carry two polarization modes

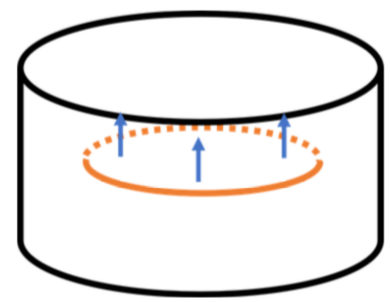
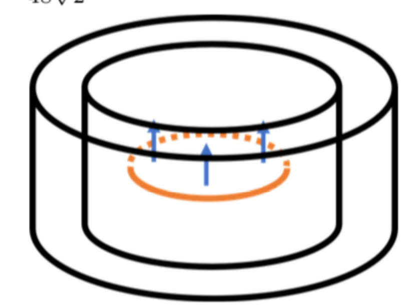
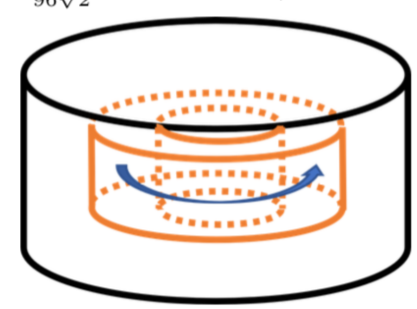
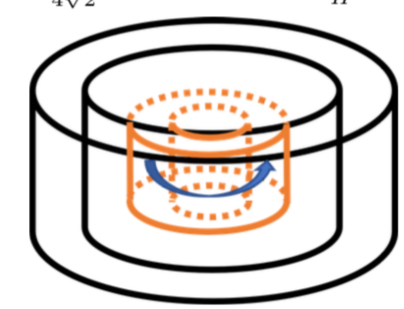
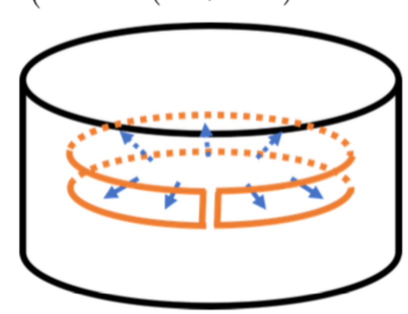
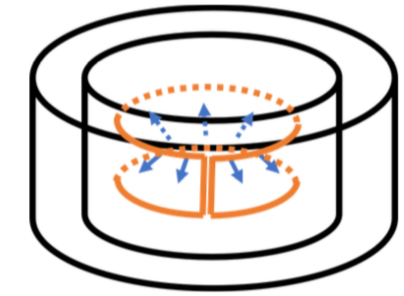
$$\Box h_{\mu\nu} = -16\pi G T_{\mu\nu}$$

h_+ $h_\times$



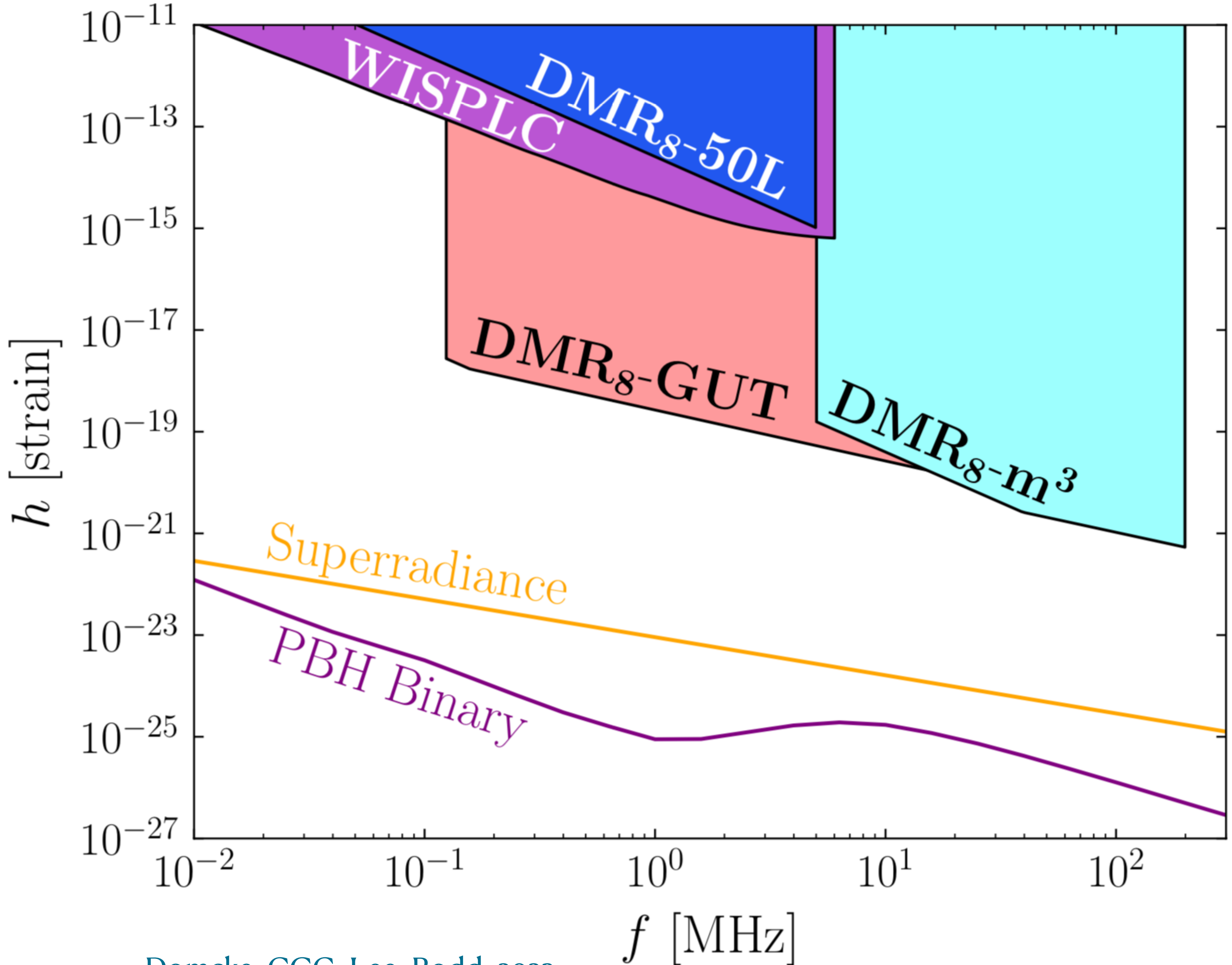
Type of external field Domcke, CGC, Lee, Rodd, 2023

Pickup loop orientation

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

Camilo García Cely, University of Valencia

Haloscopes based on lumped-element detectors



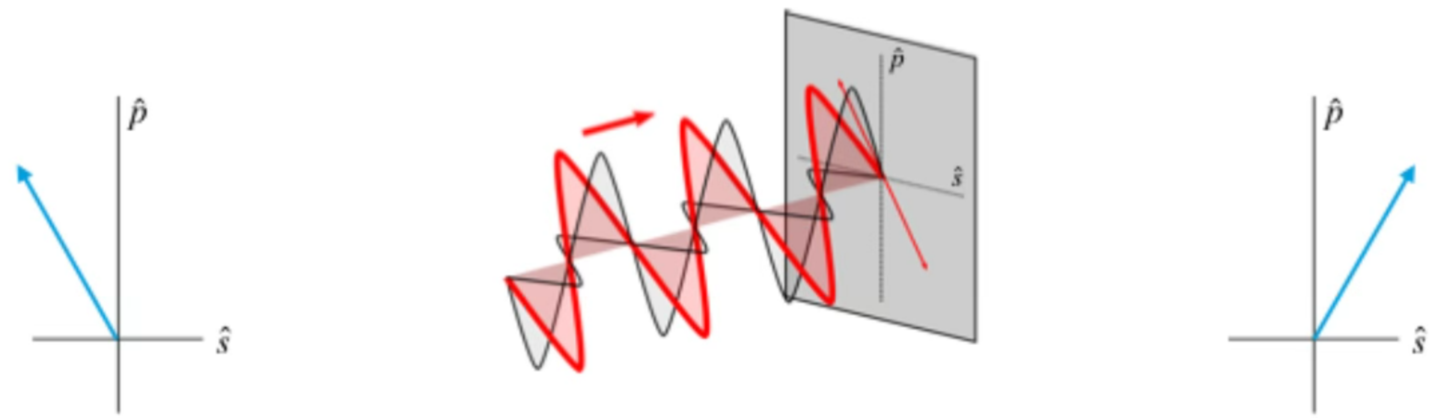
Domcke, CGC, Lee, Rodd, 2023

Camilo García Cely, University of Valencia

Part III

New ideas in cavities

Axion birefringence



Geometrical optics limit

↓

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

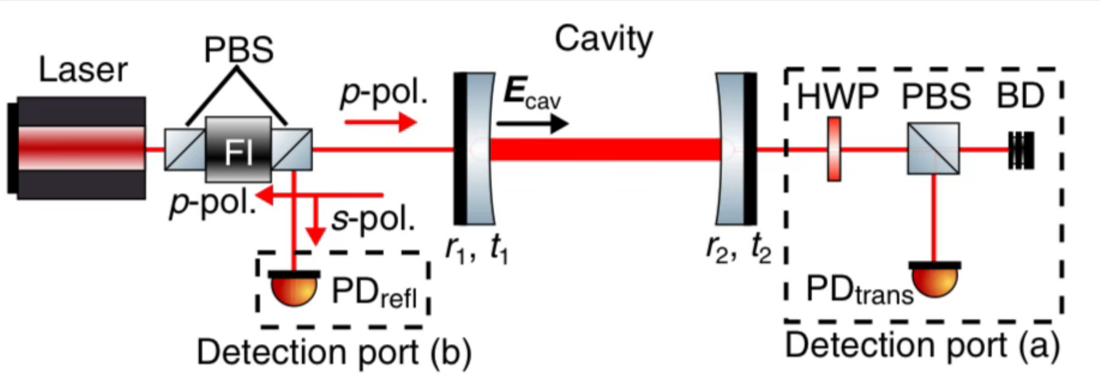
Camilo García Cely, University of Valencia

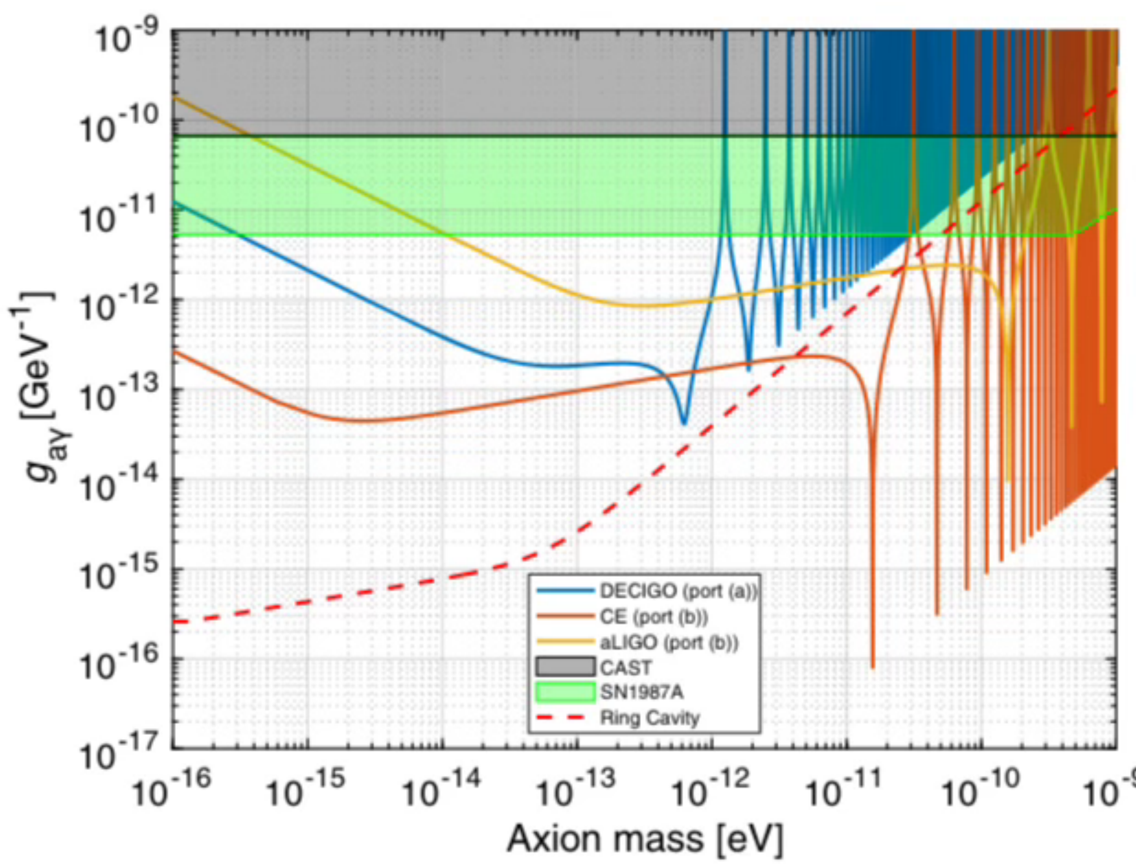
Axion birefringence

PHYSICAL REVIEW LETTERS **123**, 111301 (2019)

Axion Dark Matter Search with Interferometric Gravitational Wave Detectors

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





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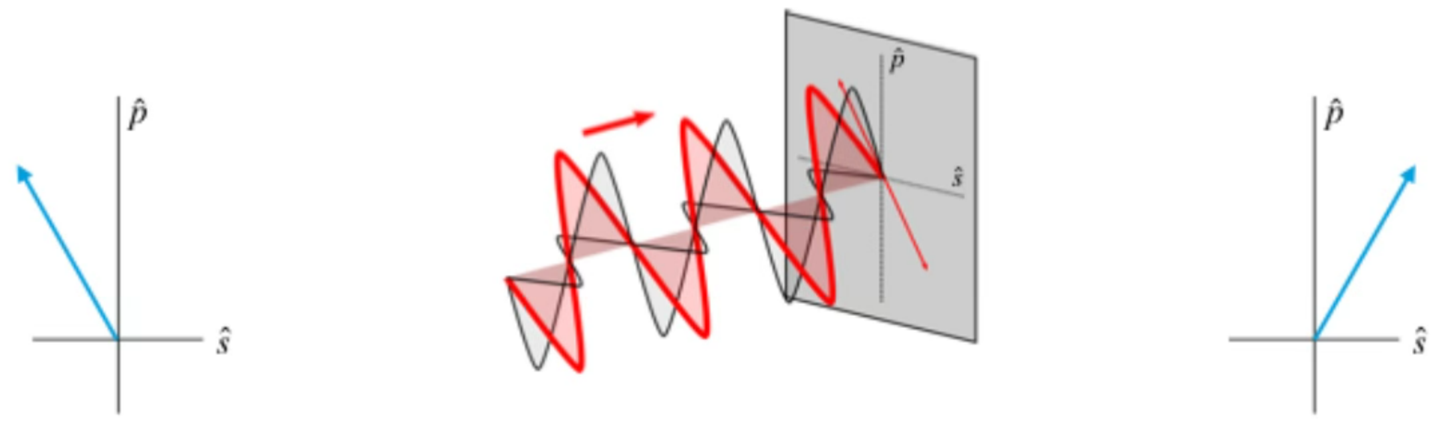
Axion birefringence



Geometrical optics limit

↓

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

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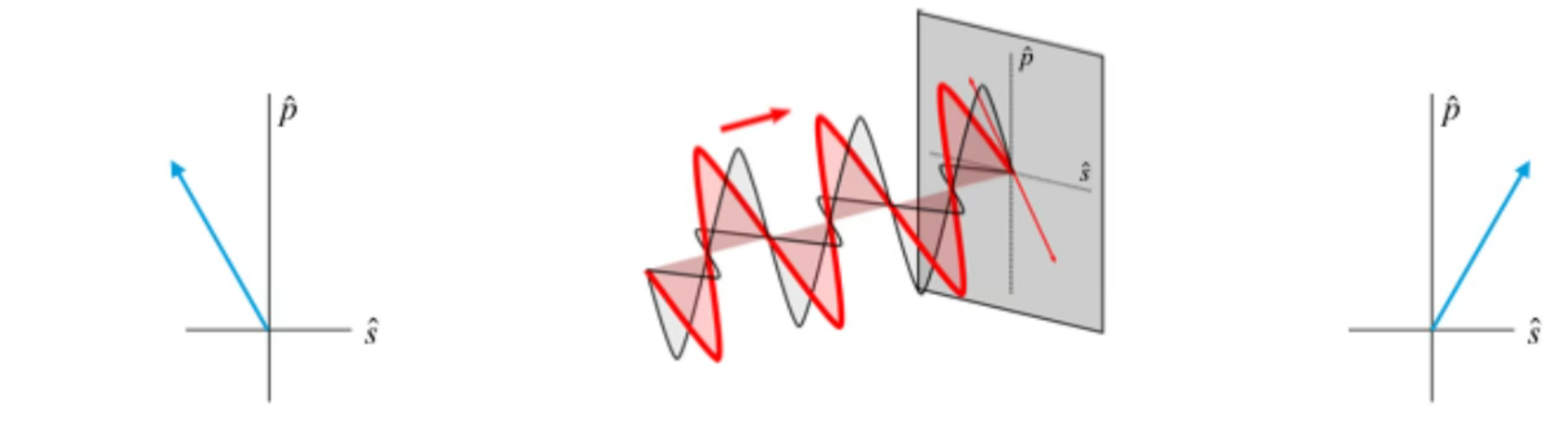
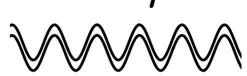
Gravitational Faraday effect

Work in progress



$h_{\mu\nu}$



Geometrical optics limit

↓

$$\frac{de^i}{dt} = \left(\Gamma^0_{\rho\lambda}\frac{dx^i}{dt} - \Gamma^i_{\rho\lambda}\right)\frac{dx^\rho}{dt}e^\lambda$$

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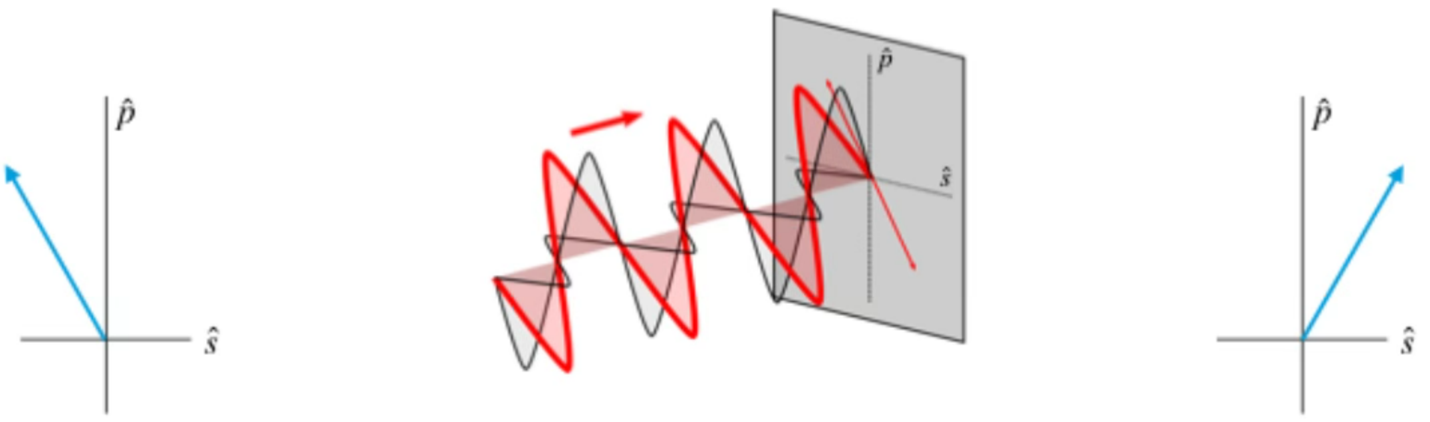
Gravitational Faraday effect

Work in progress



Searching for axions and gravitational waves at ALPS through the Faraday Effect

Camilo García-Cely, [a] Luca Marsili,[a] Andreas Ringwald, [b] Aaron D. Spector[b]

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.

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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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- The gravitational wave acts as a Newtonian force.

  If negligible, the static fields applied in experiments remain static in the presence of GWs.

- Crucial for haloscopes

Berlin et al 2022

Camilo García Cely, University of Valencia

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 Zimmermann, 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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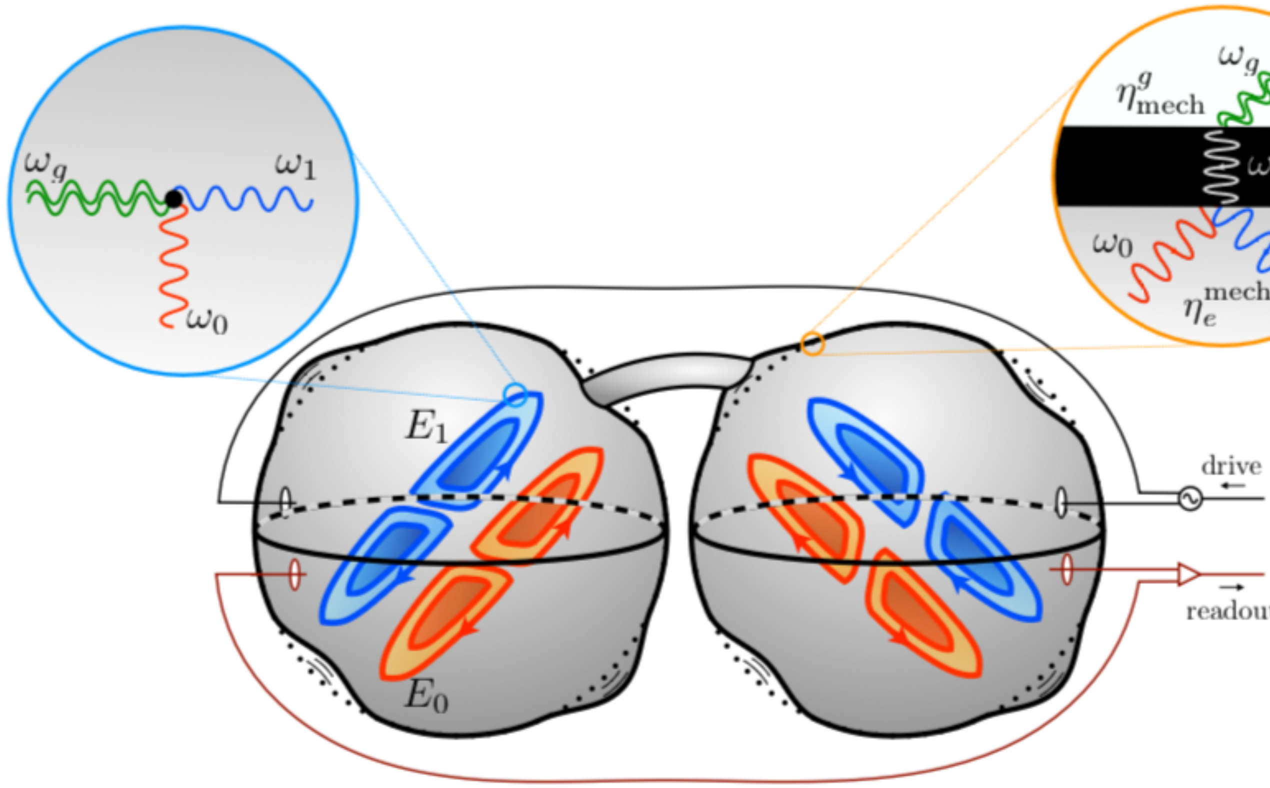
  If negligible, the static fields applied in experiments remain static in the presence of GWs.

Berlin et al 2022

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

Novel effects

Effective magnetization and polarization

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

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

McAllister et al, 1803.07755
Tobar et al, 1809.01654
Ouellet et al, 1809.10709

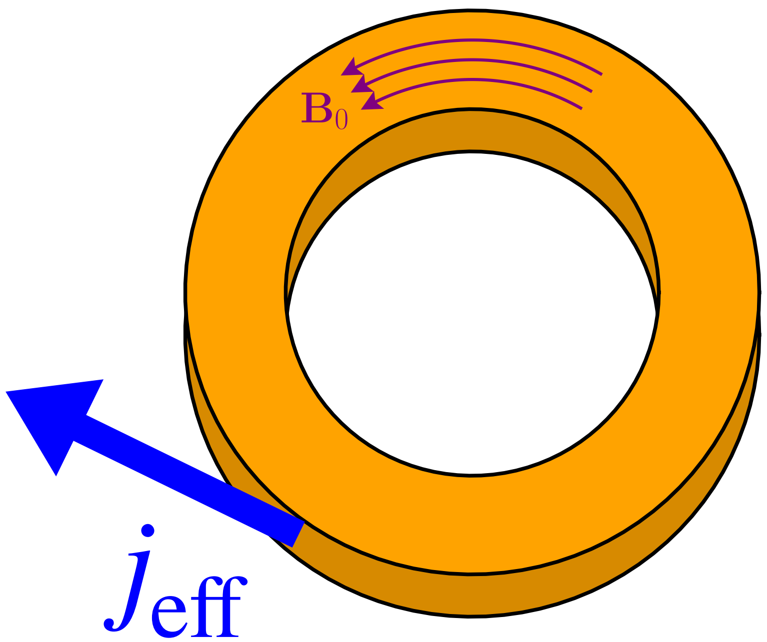
$$P_i = -h_{ij}E_j + \frac{1}{2}hE_i + h_{00}E_i - \epsilon_{ijk}h_{0j}B_k$$

$$M_i = -h_{ij}B_j - \frac{1}{2}hB_i + h_{jj}B_i + \epsilon_{ijk}h_{0j}E_k$$

Domcke, CGC, Rodd, 2202.00695

Non-zero *effective* surface currents

Domcke, CGC, Lee, Rodd, 2023



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

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

Sizeable effects. This should also be relevant for cavities