Lessons from Axion Dark Matter for the Field of Gravitational Wave Physics

Colloquium at the Max Planck Institute for Physics

Munich, Germany
April 16, 2024

IFIC INSTITUT DE FÍSICA CORPUSCULAR

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

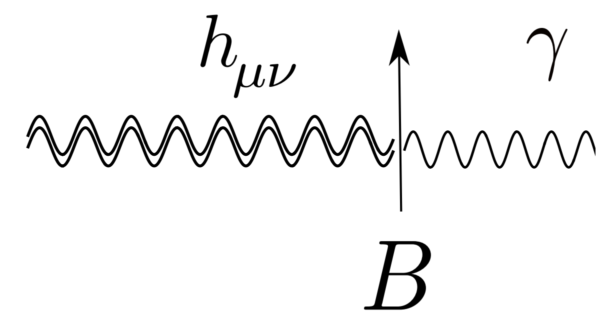
VNIVERSITAT DE VALÈNCIA

Camilo García Cely

Based on PRL 129, 041101, JHEP 03 (2024) 128 and hep-ph/2404.xxxxx
In collaboration with Valerie Domcke, Sung Mook Lee, Nicholas L. Rodd, and Andreas Ringwald

Outline

- Motivation: axions vs. gravitational waves
- Detecting gravitational waves with axion haloscopes
- Recent developments
- Solar gravitational waves
- Conclusions



Axion dark matter versus gravitational waves

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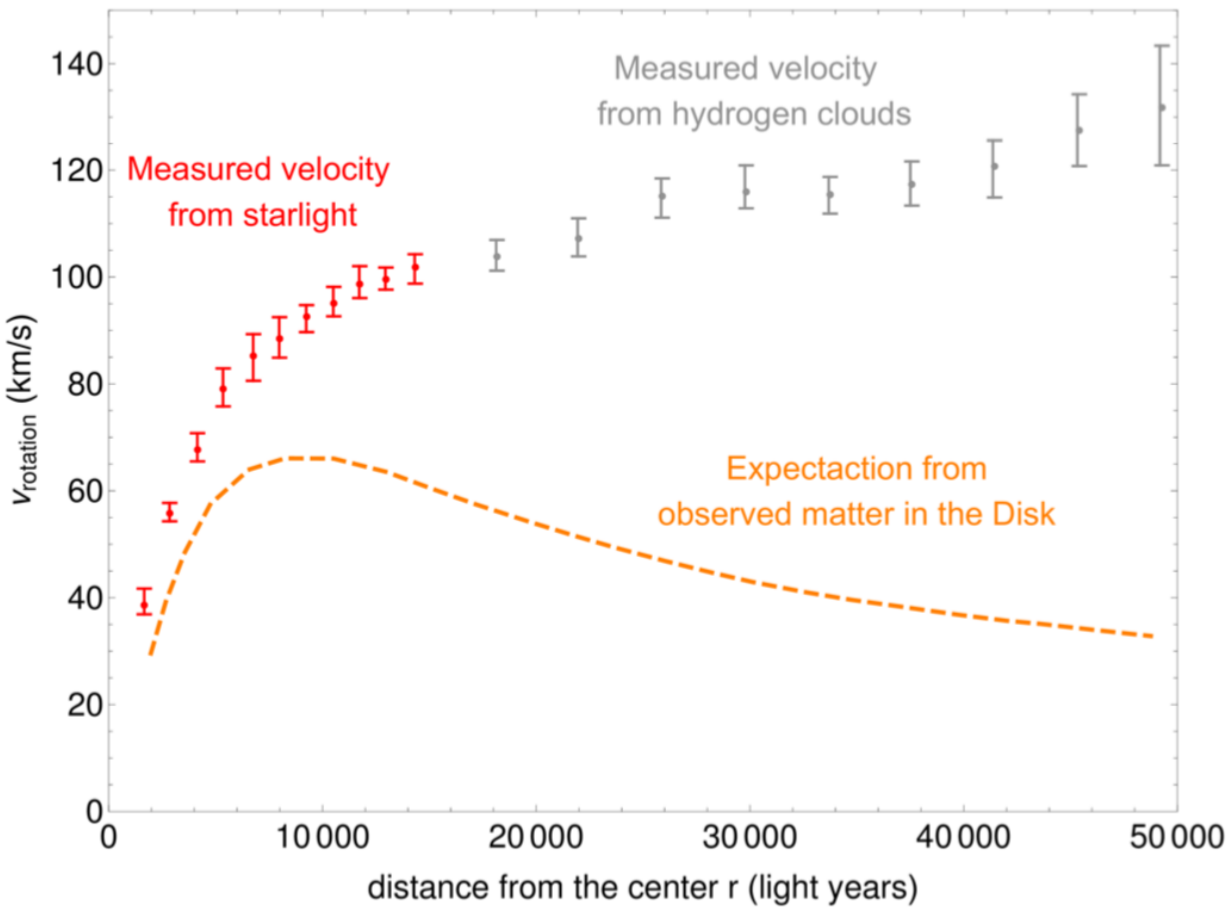
Dark Matter



Triangulum Galaxy (M33)

There must be some ***matter that we don't see***
or Newton's Laws don't work in galaxies

Vera Rubin

Camilo García Cely, University of Valencia

Collisionless Cold
Dark Matter

The dark matter hypothesis is remarkably simple and explain observations at many other scales

Velocity measurements

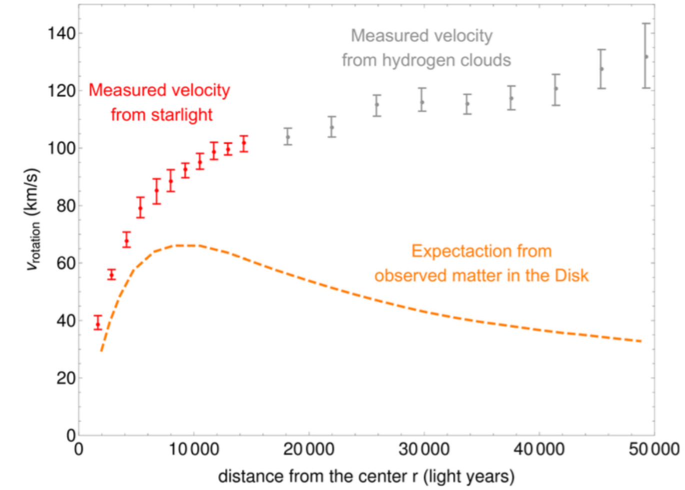
- Flat rotation curves of spiral galaxies
- Velocity dispersion of stars in giant elliptical and dwarf spheroidal galaxies
- Velocity dispersion of galaxies in clusters

Lensing

- Weak lensing by large-scale structure and cluster mergers
- Strong lensing by individual galaxies and clusters

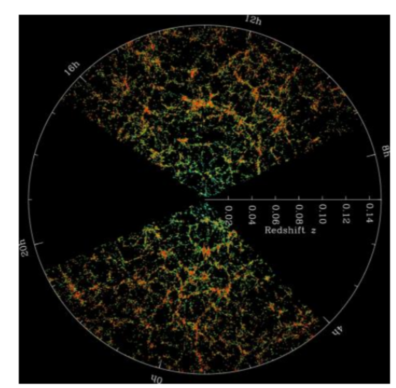
Universe at large scales

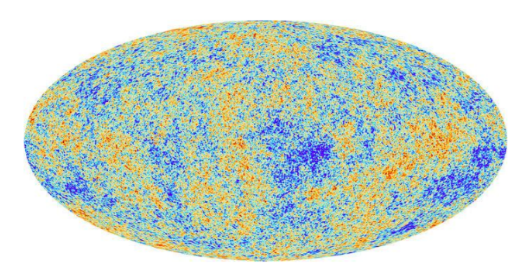
- Abundance of clusters
- Large-scale distribution of galaxies
- Power spectrum of CMB anisotropies



kpc

Mpc





Gpc

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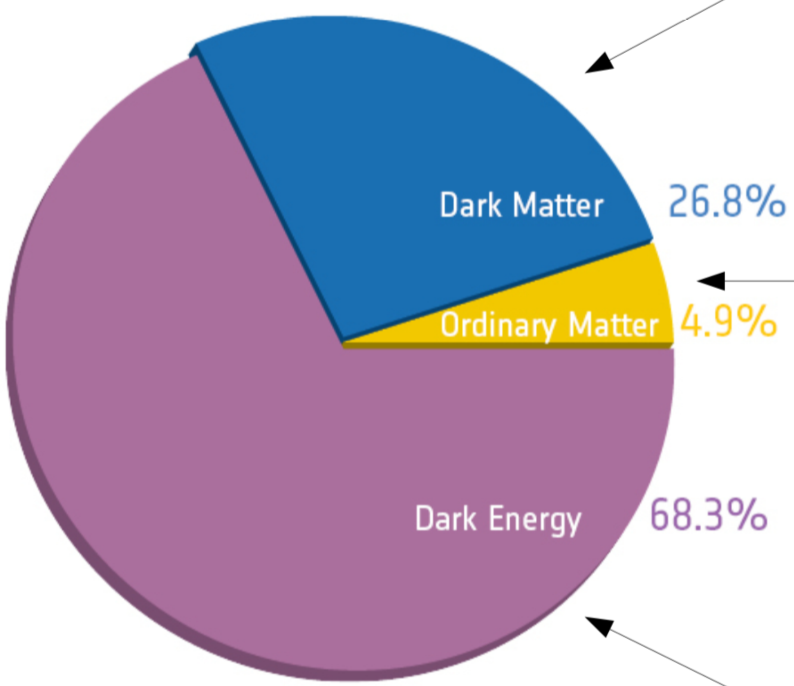
Collisionless Cold
Dark Matter

?



Standard Model stable particles:

Mostly protons, electrons,
neutrinos and photons

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

?

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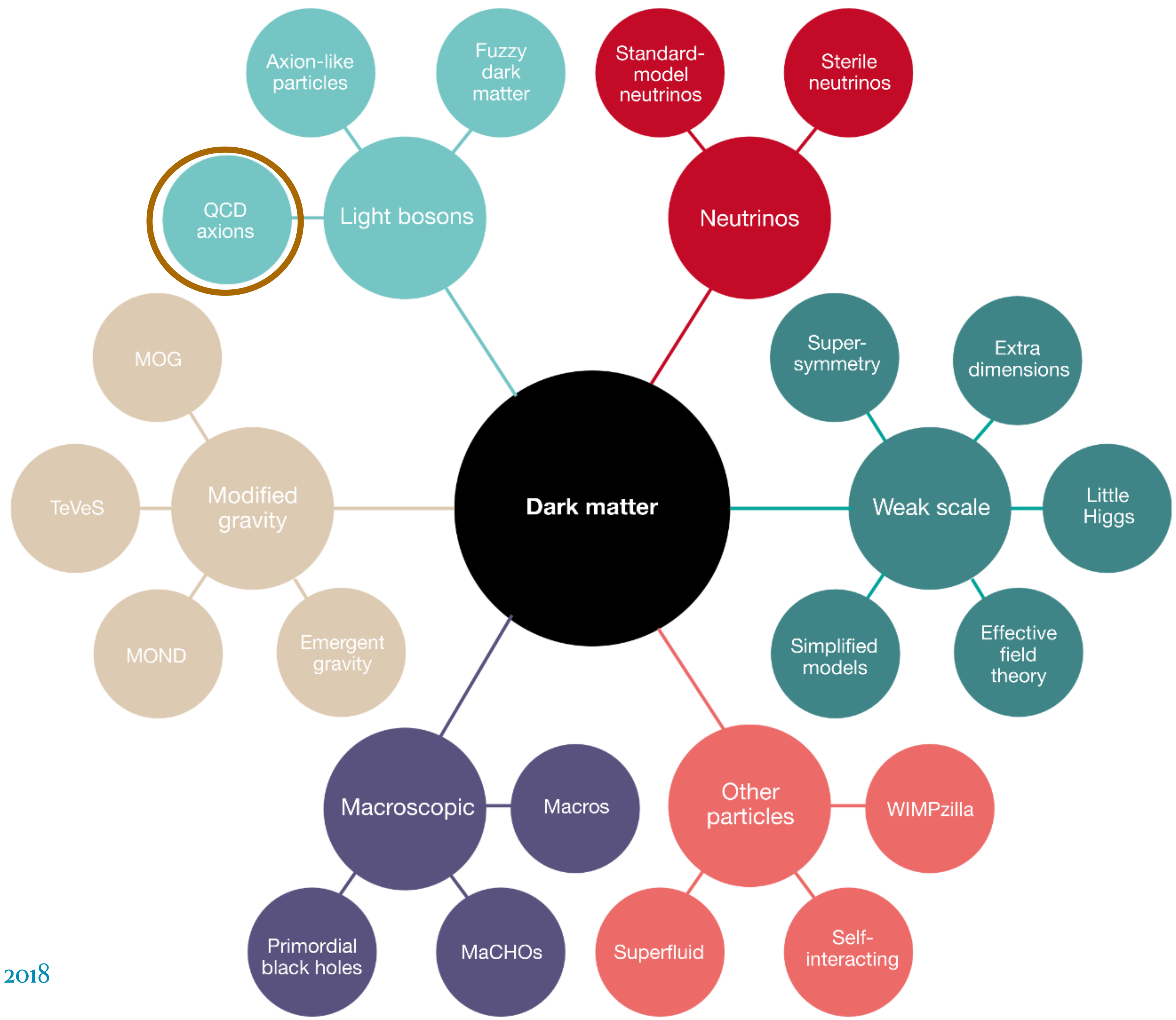
Collisionless Cold
Dark Matter



Bertone Tait, 2018

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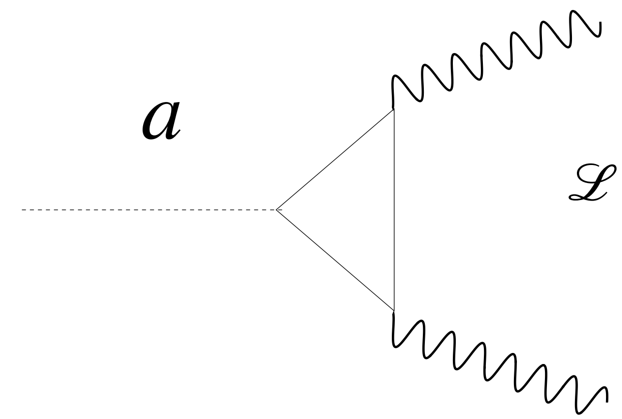
QCD axion as dark matter

- Pseudoscalar field



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

- Solution to the strong CP problem

Peccei, Quinn 1977

- Excellent dark matter candidate

Weinberg, Wilczek 1978

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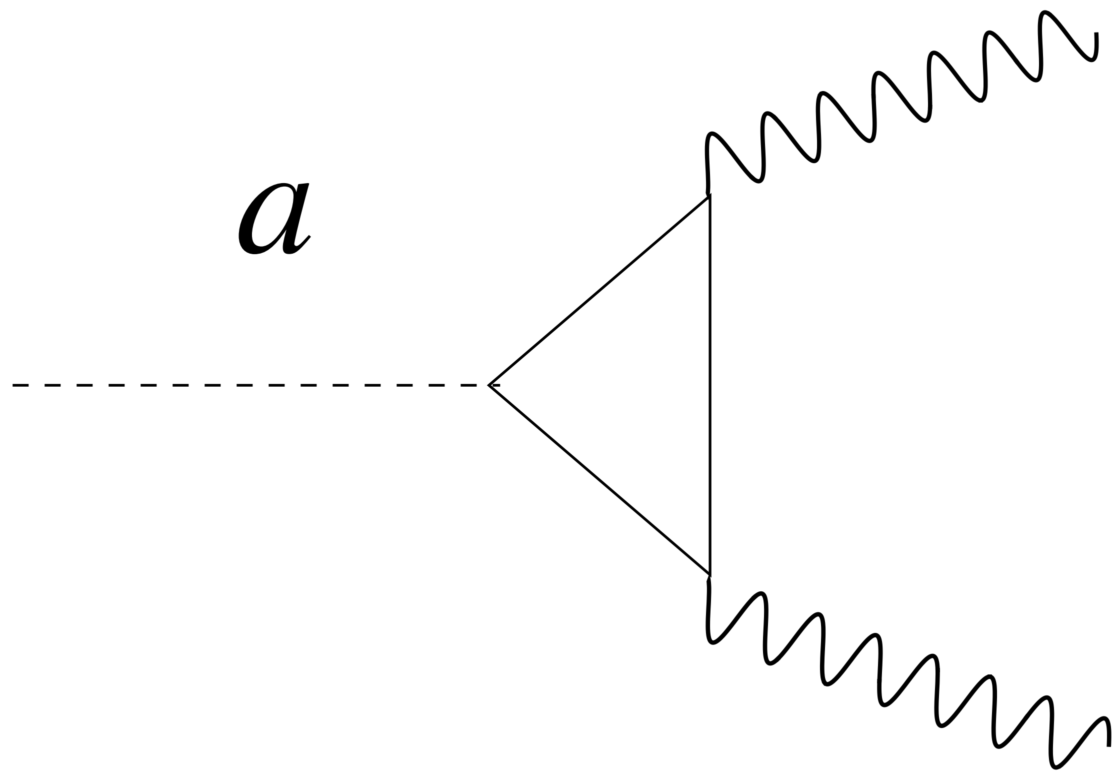
Axion electrodynamics



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

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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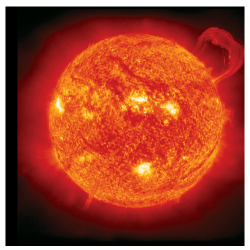
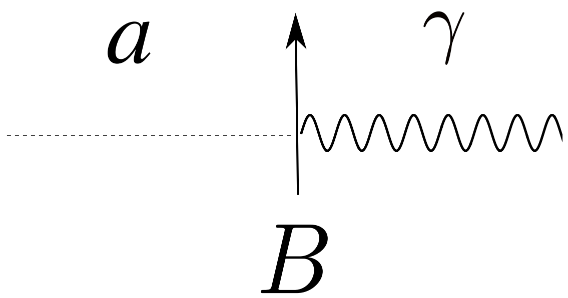
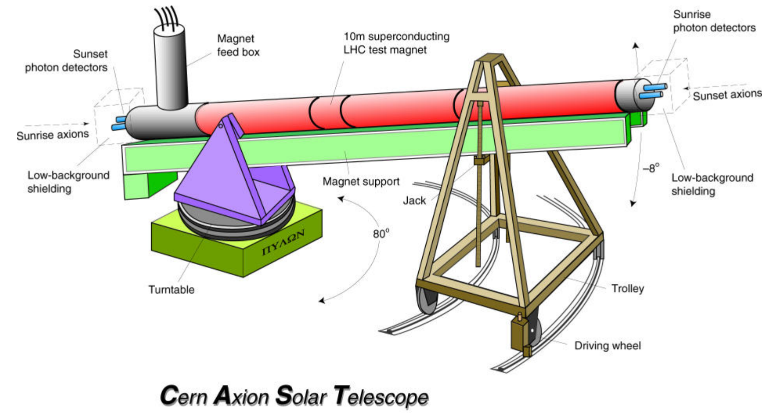
Axion electrodynamics

- Helioscopes (X rays)

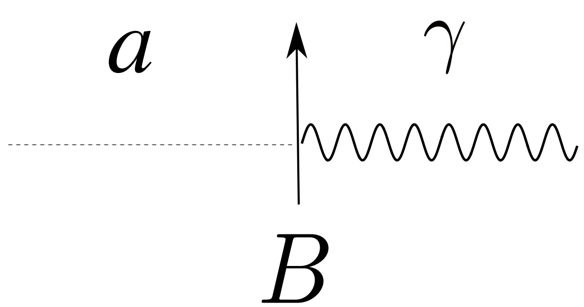


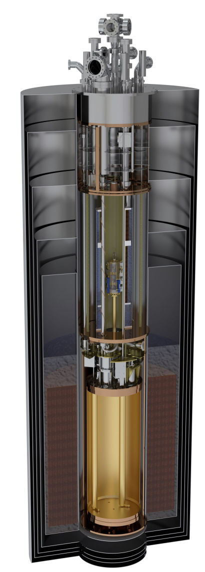




- CAST
- IAXO
- .....

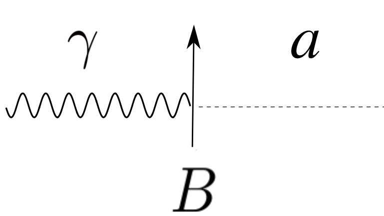
- Haloscopes (radio frequencies)

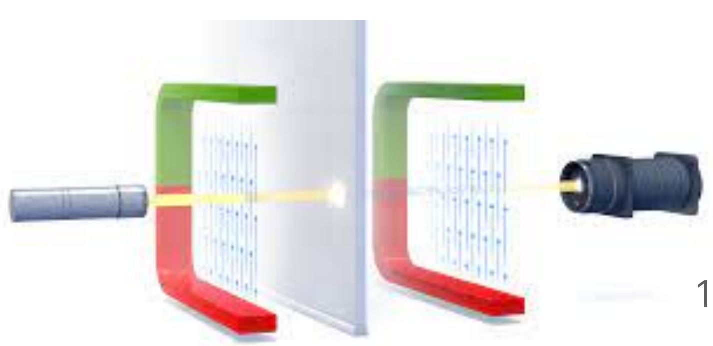


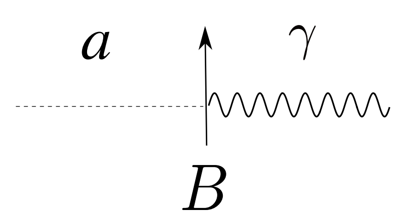


- microwave cavities
- MADMAX
- ADMX
- HAYSTAC
- ABRACADABRA
- Lumped element detectors
- ...

- Purely lab experiments







- Light shining through the walls
- OSCAR
- ALPS II
- ...

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Gravitational waves

- Speculation by Poincaré (1905)
- Einstein provided a firm theoretical background for them (1916)

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

wave equation describing two polarization modes

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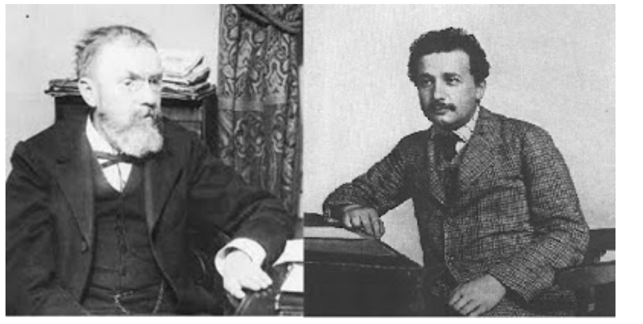

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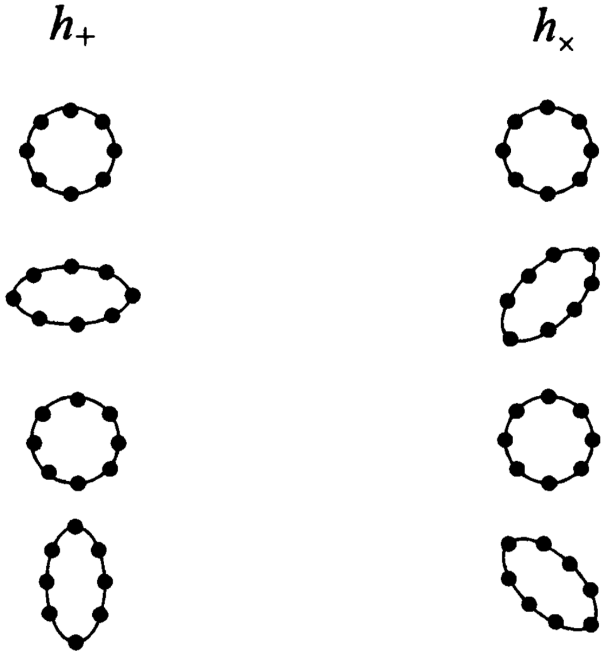

The deformation of a ring of test masses due to the different polarization

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Gravitational waves

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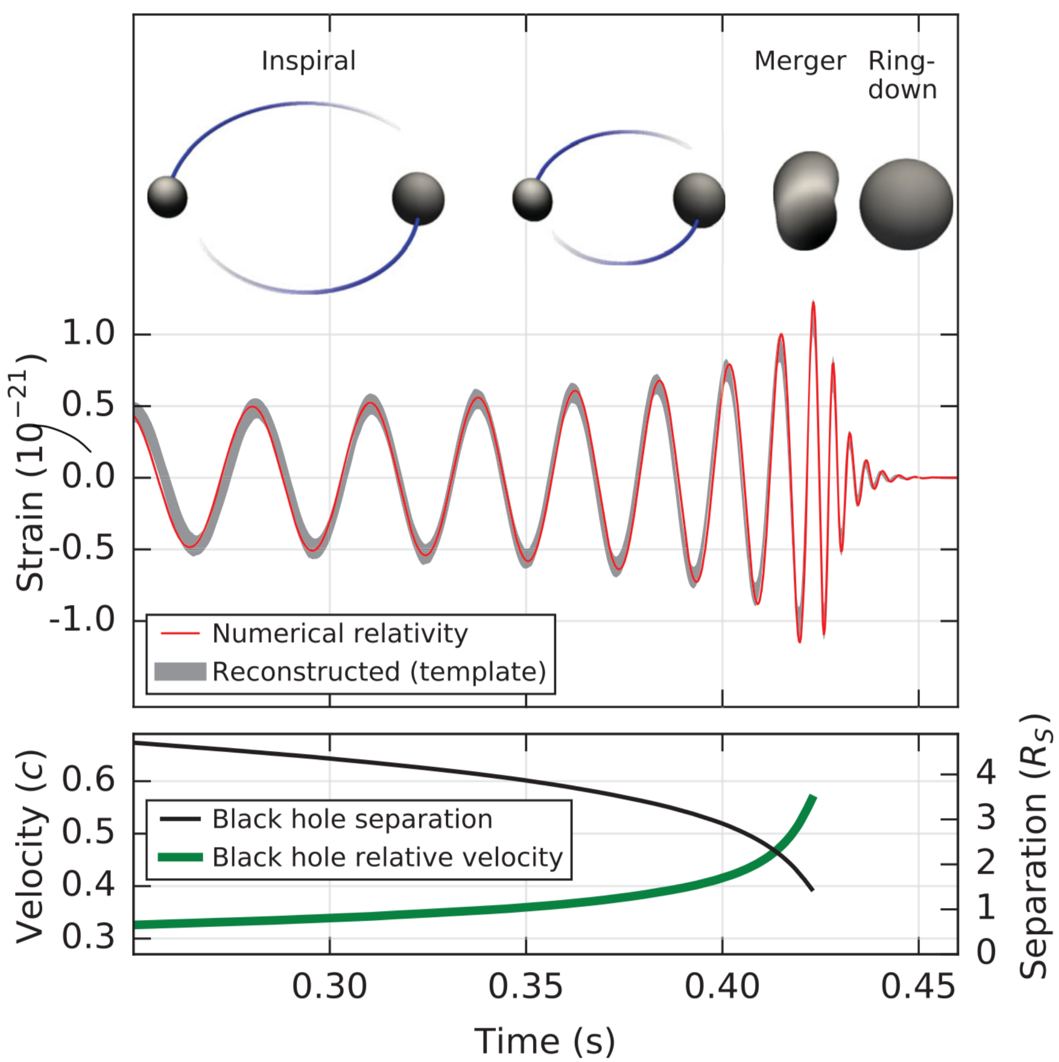
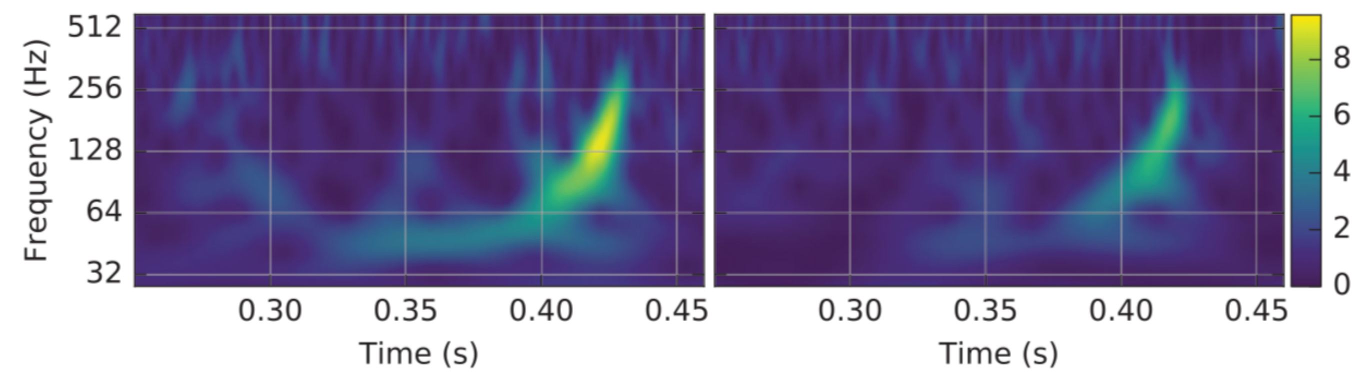
PRL 116, 061102 (2016) PHYSICAL REVIEW LETTERS 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

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





interferometers

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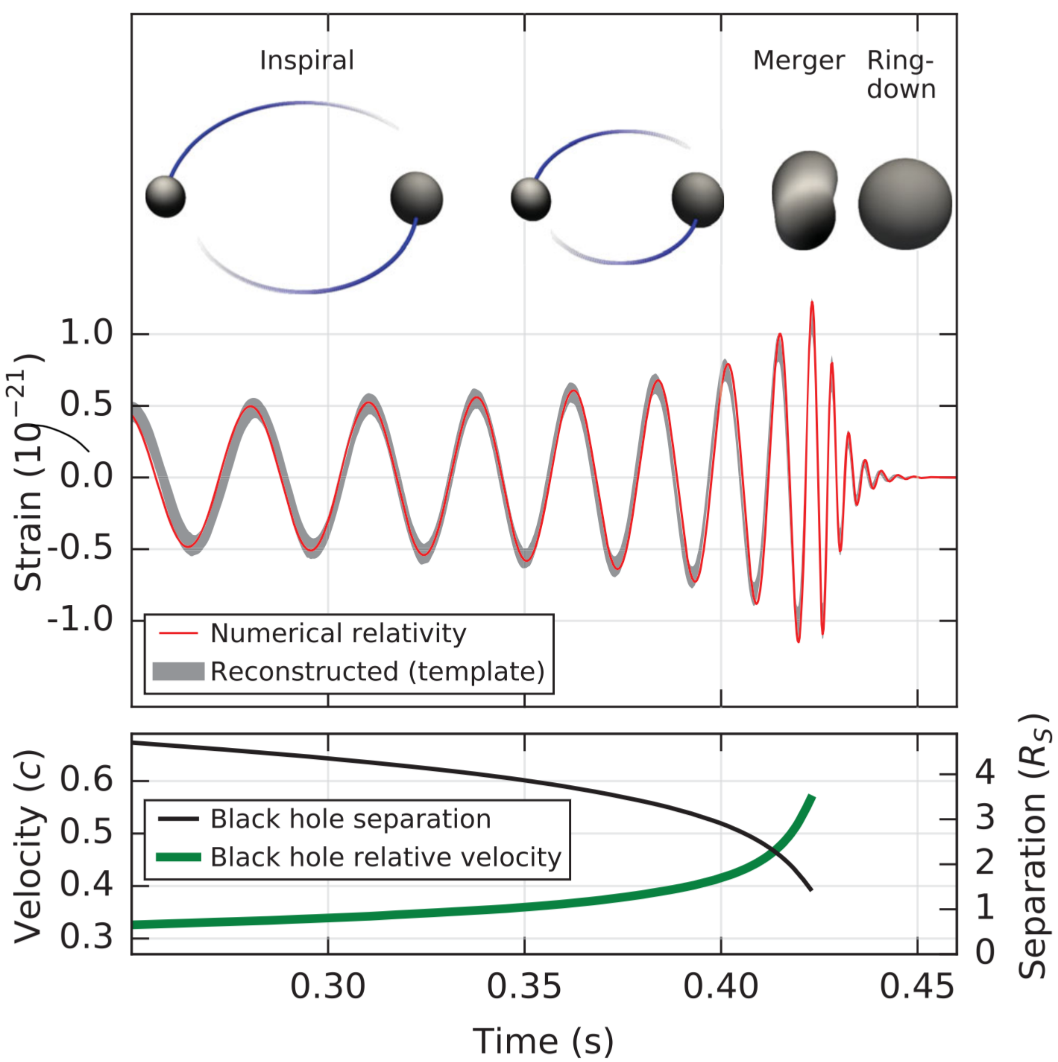
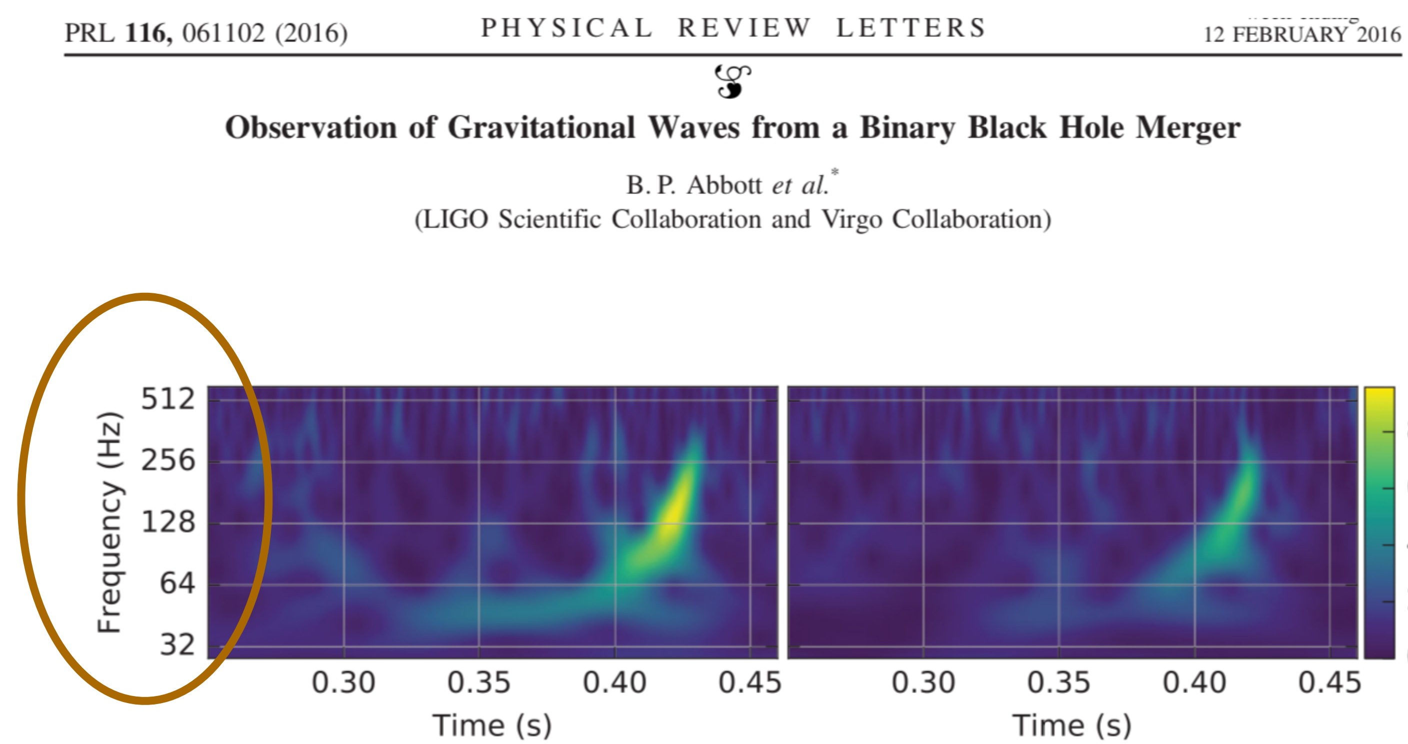
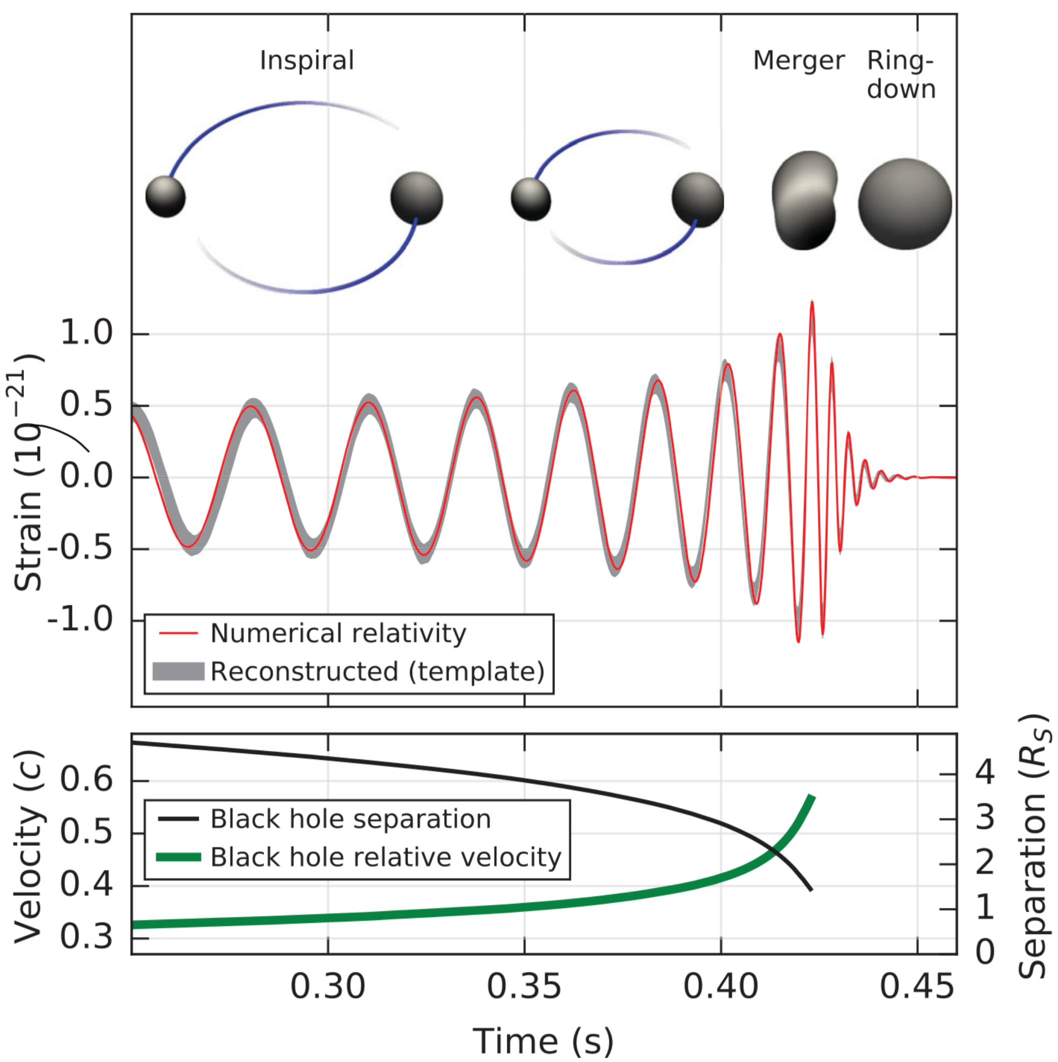
Gravitational waves

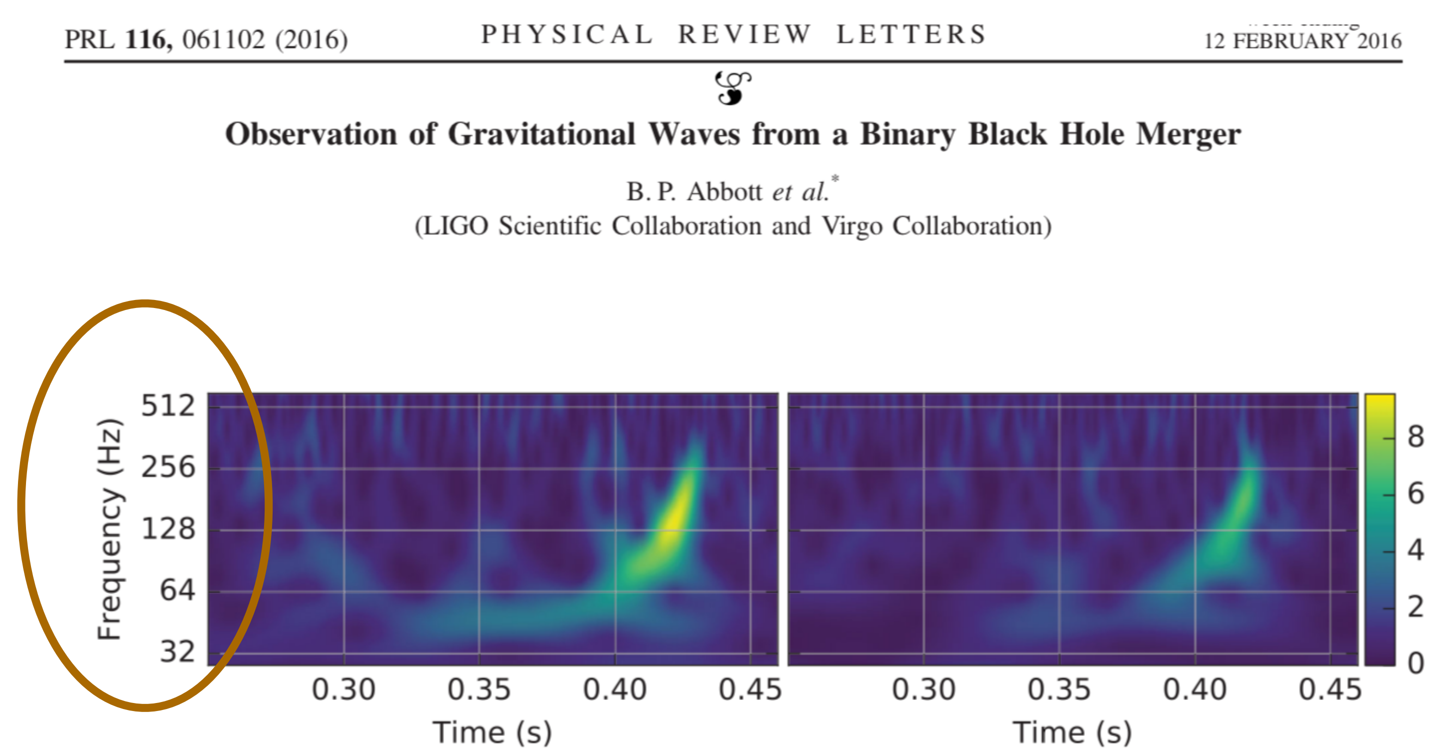




$$f \approx \frac{1}{2\pi}\sqrt{\frac{GM}{R^3}}$$

Gravitational waves





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

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

High-frequency gravitational waves

Part of a collection:

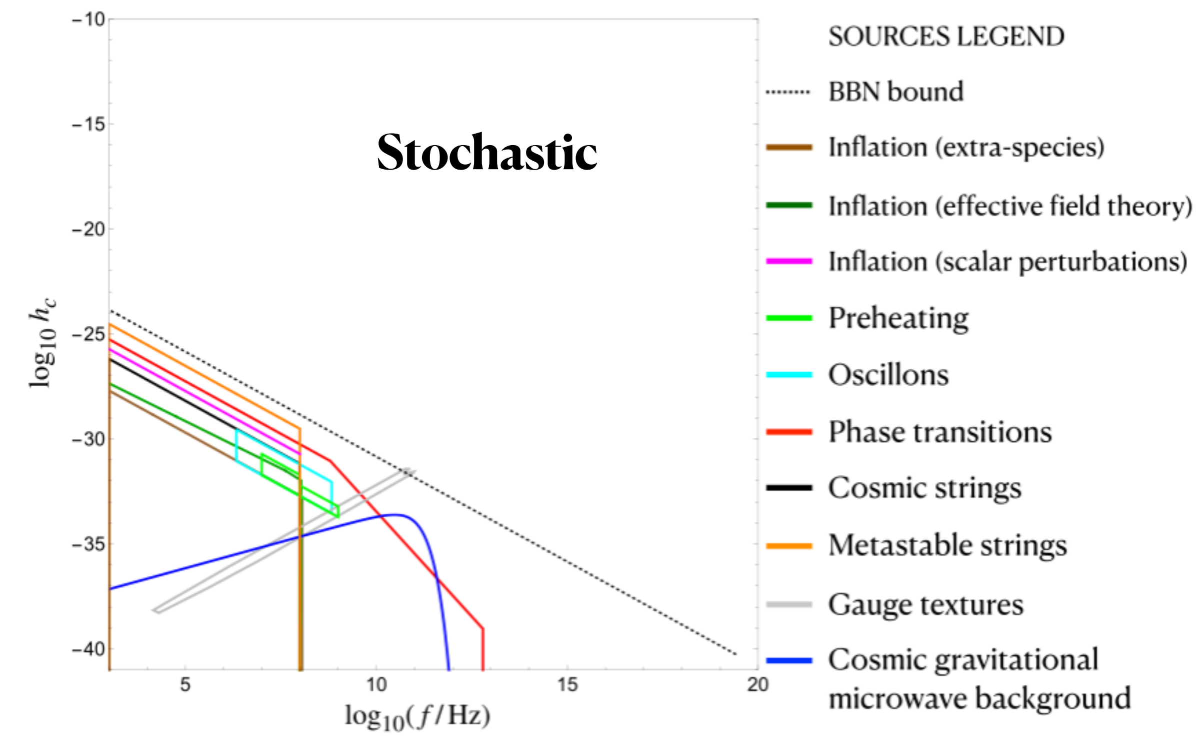
Gravitational Waves

Review Article | Open Access | Published: 06 December 2021

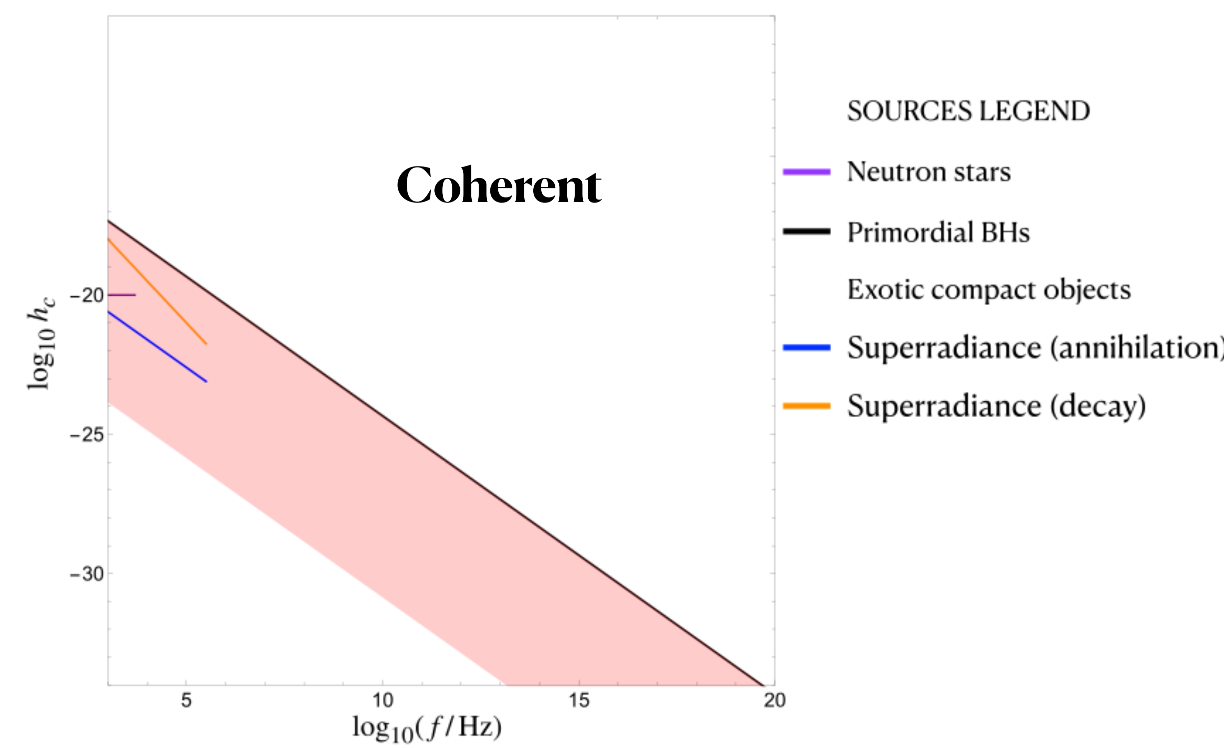
Challenges and opportunities of gravitational-wave searches at MHz to GHz frequencies

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



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

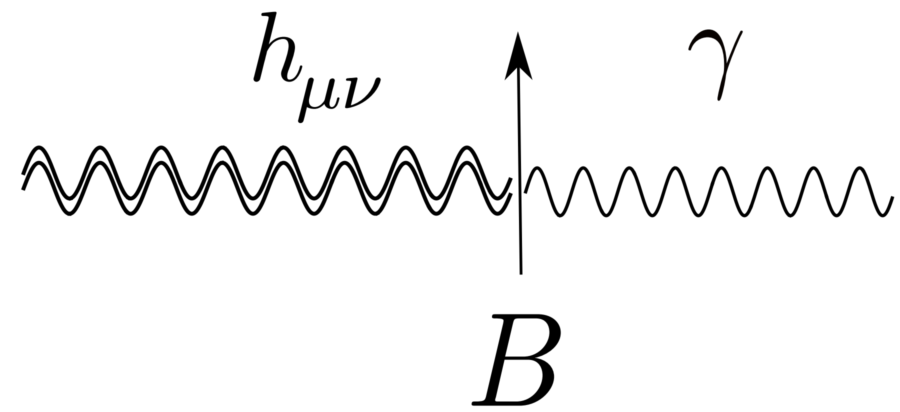
J. Exptl. Theoret. Phys. (U.S.S.R.) 43, 605-607 (August, 1962)

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

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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

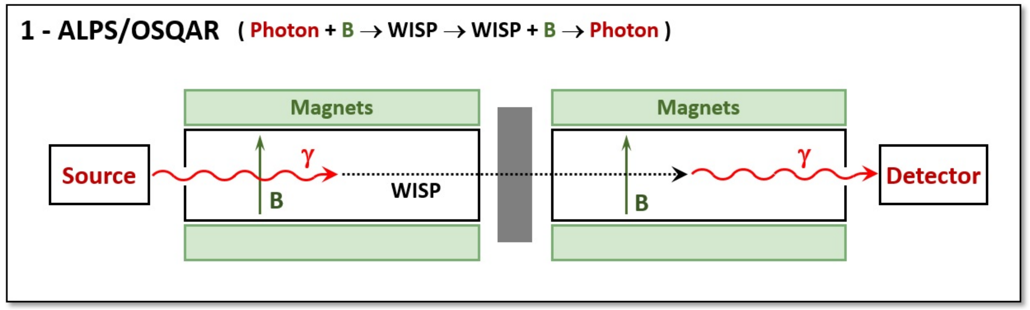
Potential of Radio Telescopes as High-Frequency Gravitational Wave Detectors

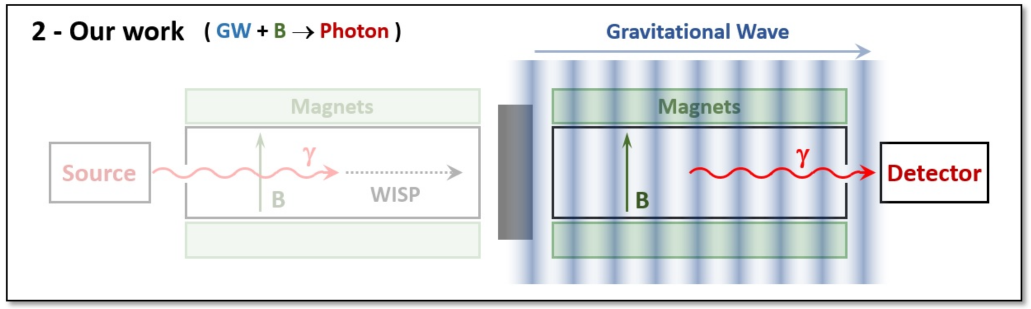
Valerie Domcke and Camilo Garcia-Cely
Phys. Rev. Lett. **126**, 021104 – Published 14 January 2021

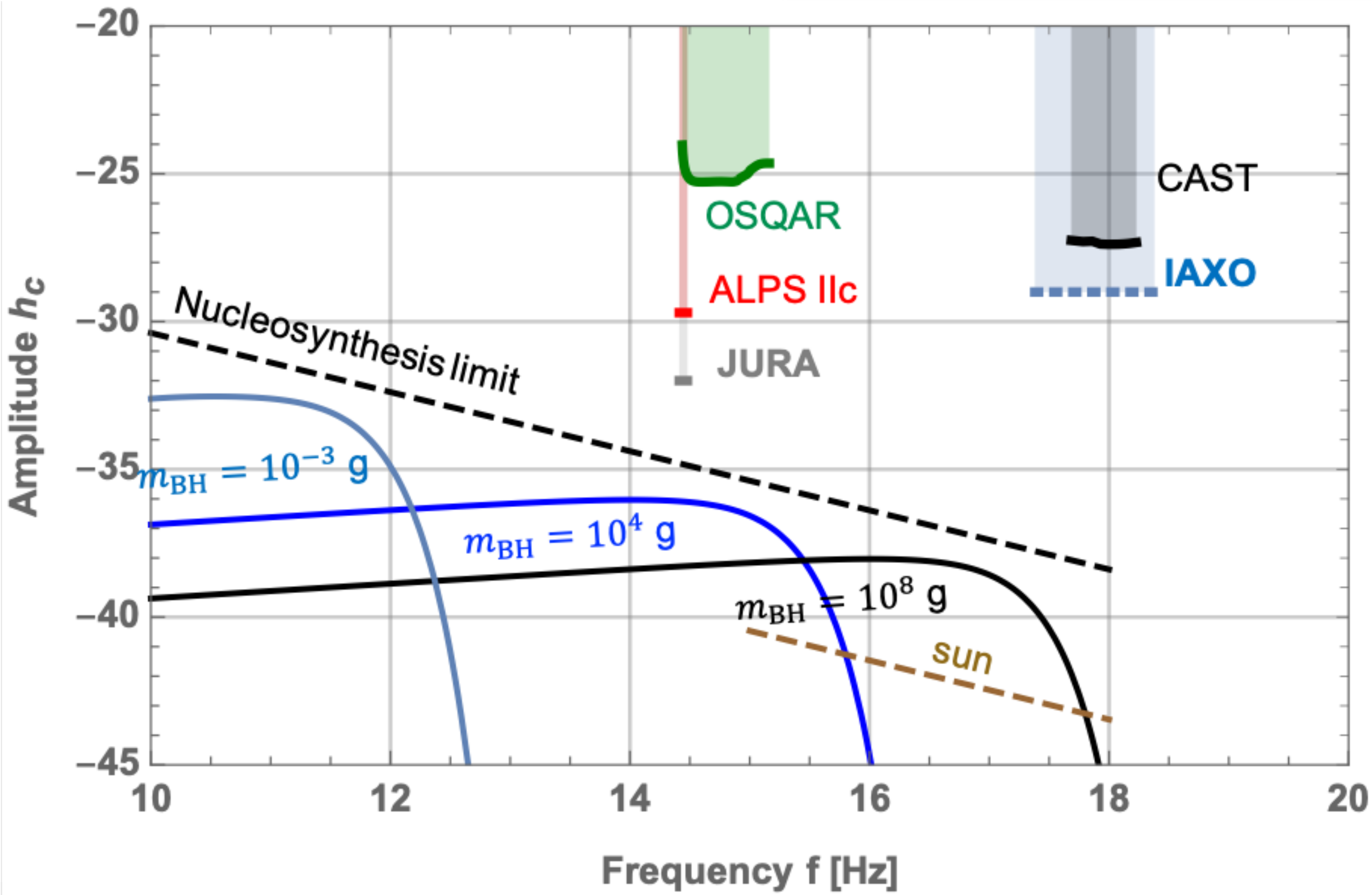
- The process is strictly analogous to axion conversion.

Raffelt, Stodolski'89

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)

Detecting gravitational waves with axion haloscopes

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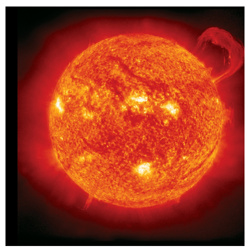
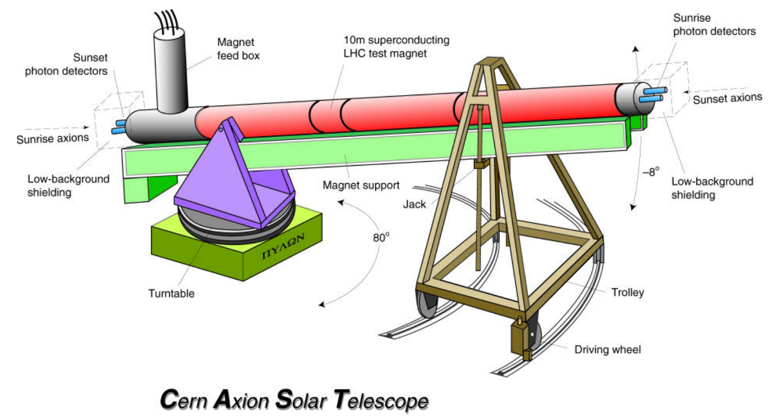
Many possibilities

- Helioscopes (X rays)





- CAST
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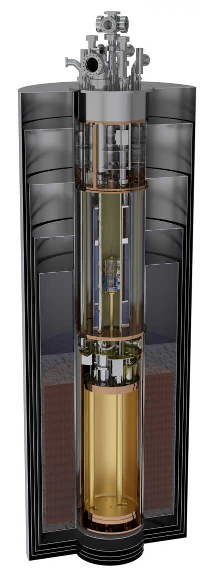
- .....

- Haloscopes (radio frequencies)



- microwave cavities
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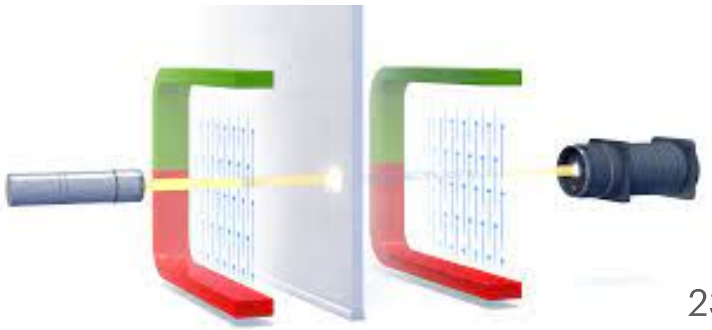
- Purely lab experiments



- Light shining through the walls
- OSCAR
- ALPS II
- ...

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How does it work?

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

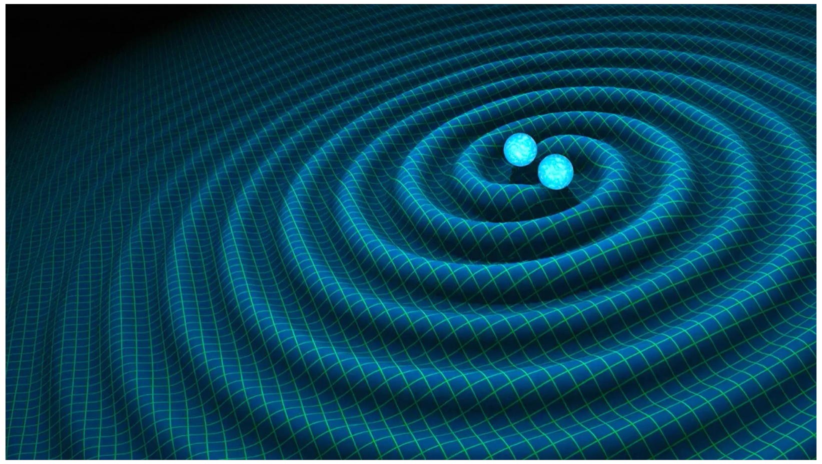
Sikivie, 1983

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

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

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

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



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

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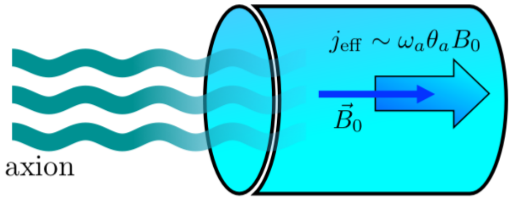
Haloscopes based on microwave cavities



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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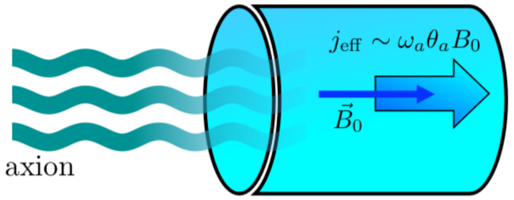
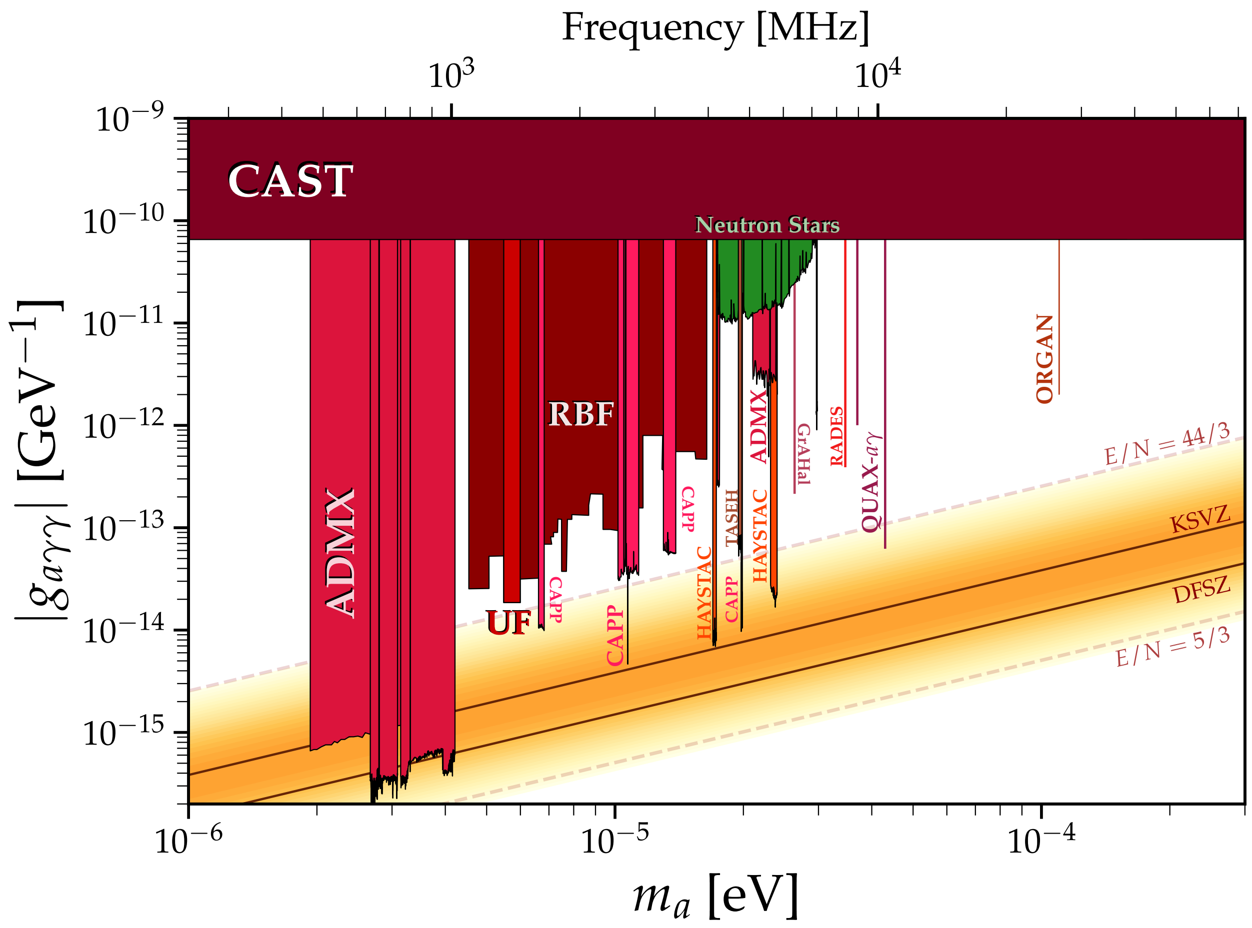
Haloscopes based on microwave cavities





https://github.com/cajohare/AxionLimits

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

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

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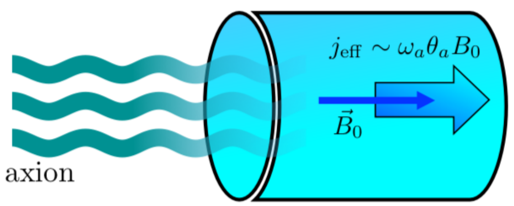
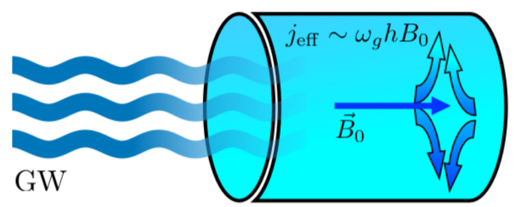
Haloscopes based on microwave cavities





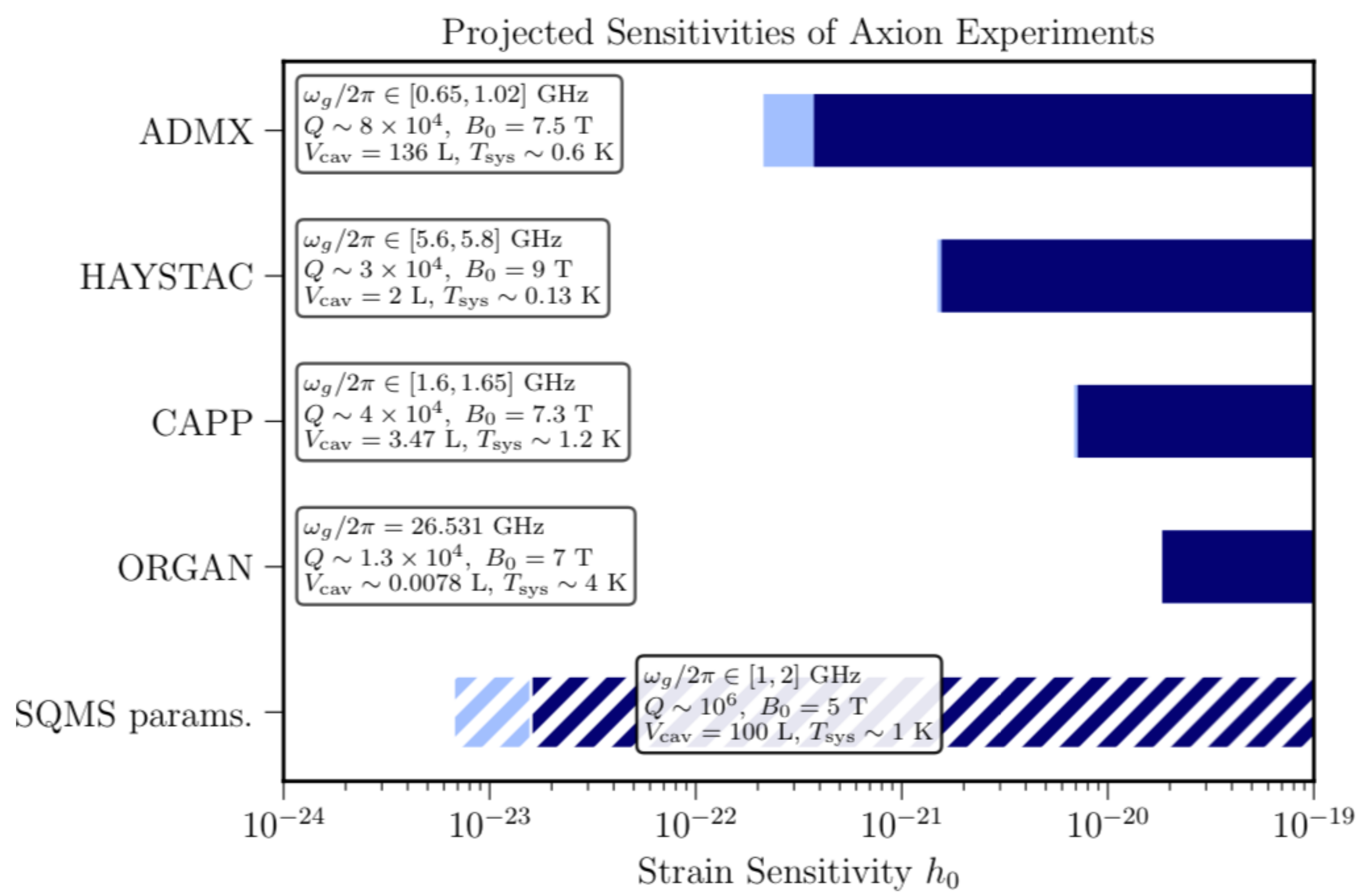
It resonates when the GW frequency matches one of the eigenmode frequencies

Detecting planetary-mass primordial black holes with resonant electromagnetic gravitational-wave detectors

Nicolas Herman, André Fűzfa, Léonard Lehoucq, and Sébastien Clesse
Phys. Rev. D **104**, 023524 – Published 19 July 2021

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



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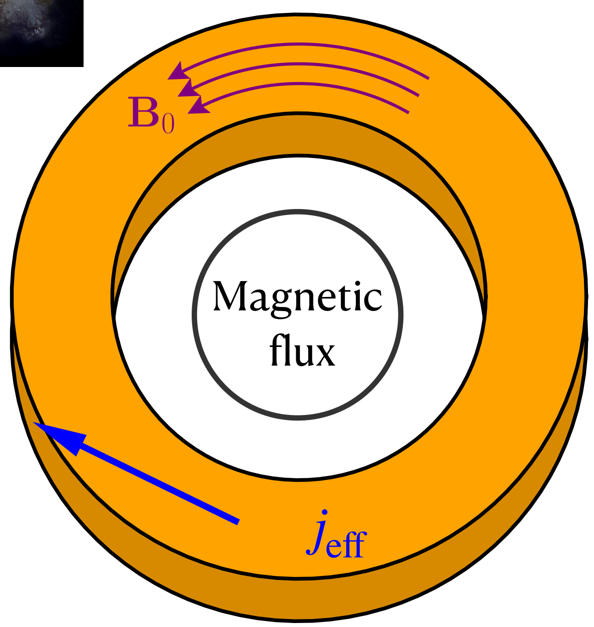
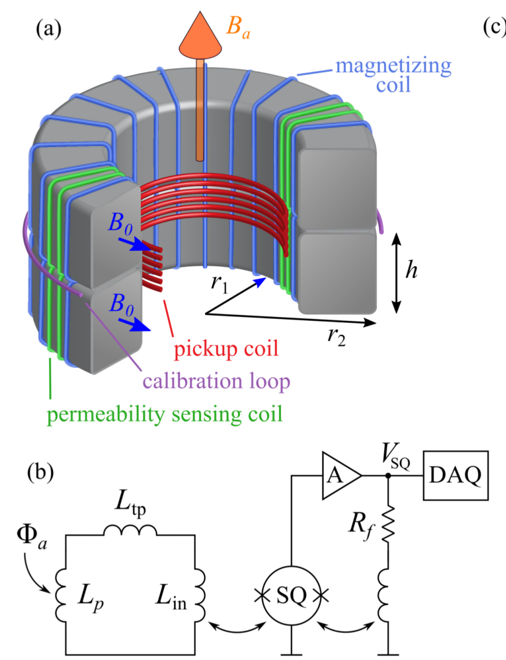
Haloscopes based on lumped-element detectors



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



(c) SHAFT

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)

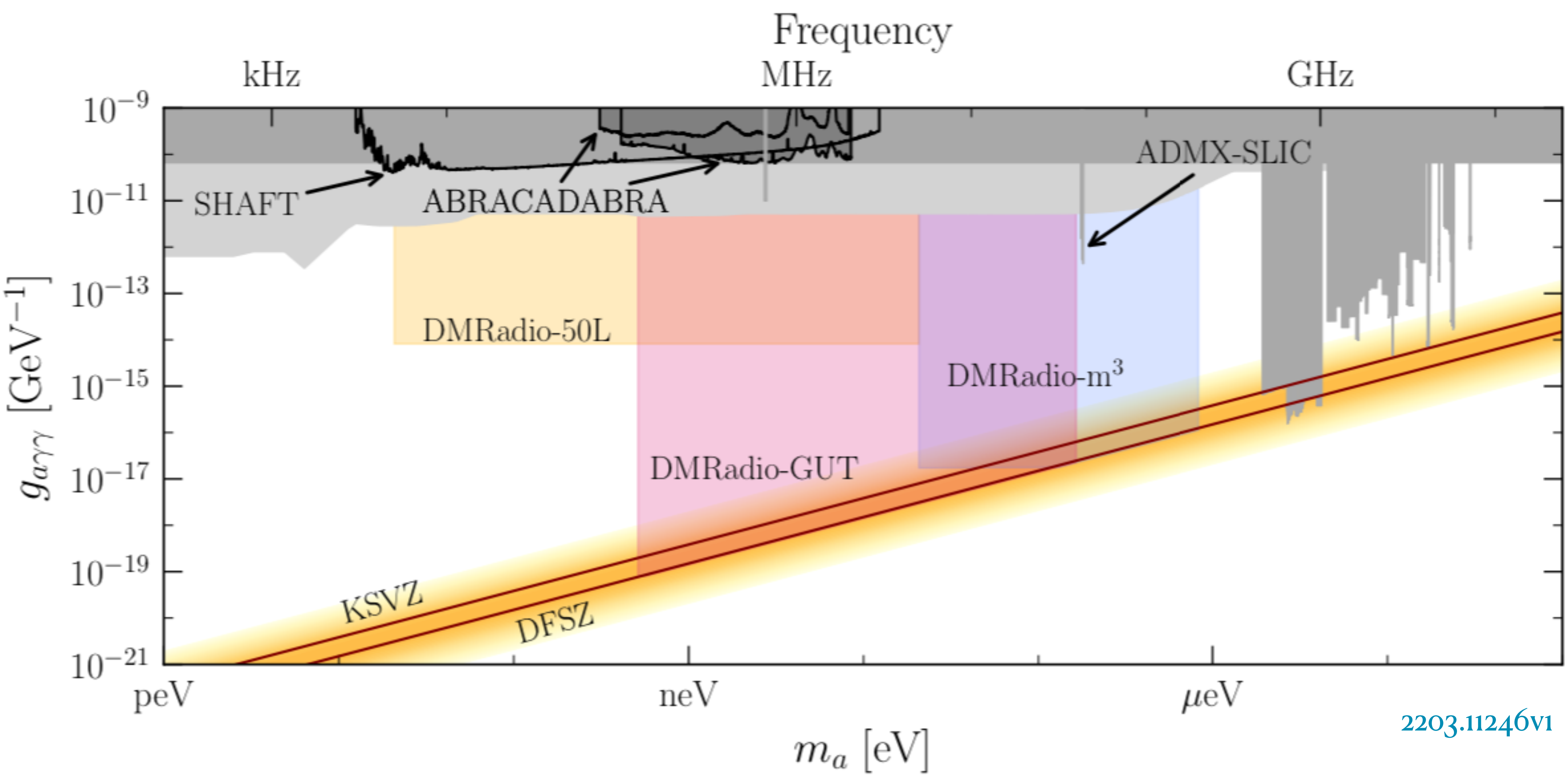
The electromagnetic fields produced by the axion drive a current through a pickup coil

Camilo García Cely, University of Valencia

Haloscopes based on lumped-element detectors

DMRadio program

Searches at frequencies lower than those achieved with conventional cavity haloscopes.



2203.11246v1

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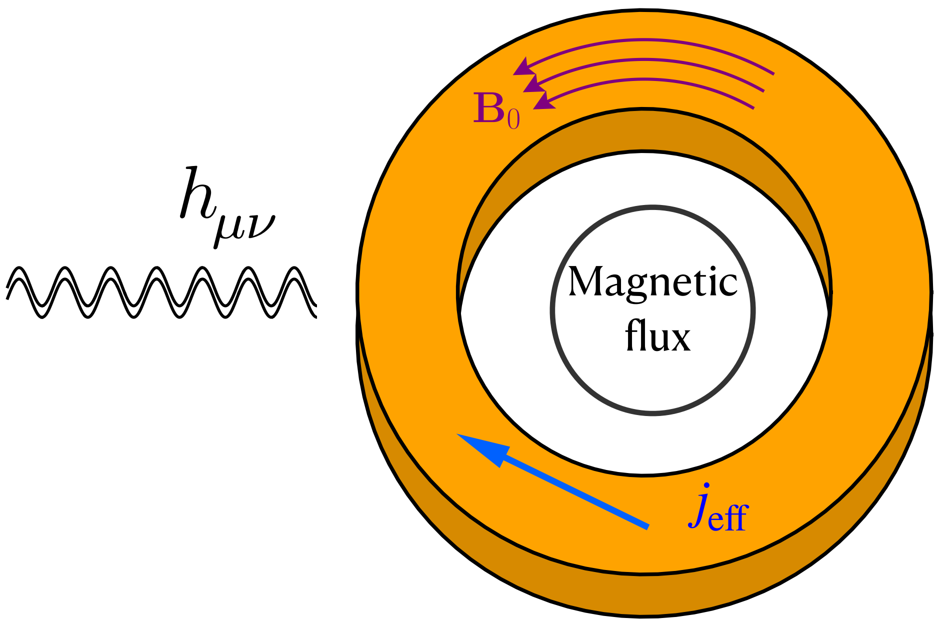
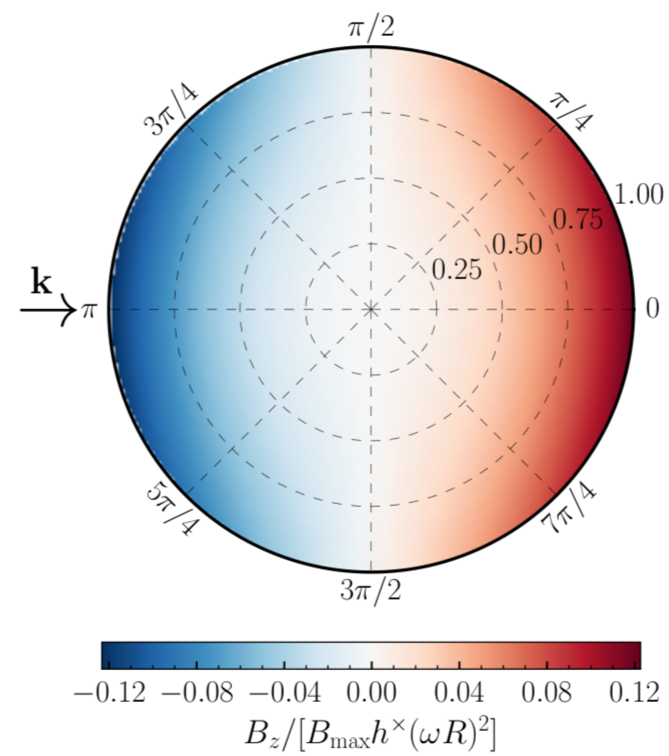
Haloscopes based on lumped-element detectors



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



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

Only one polarization

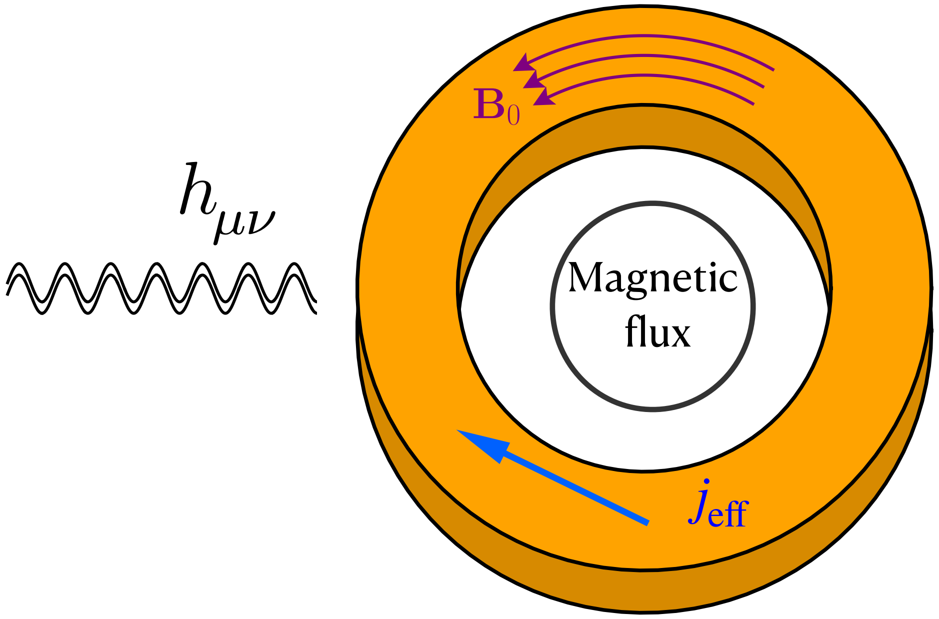
Suppression at small frequencies

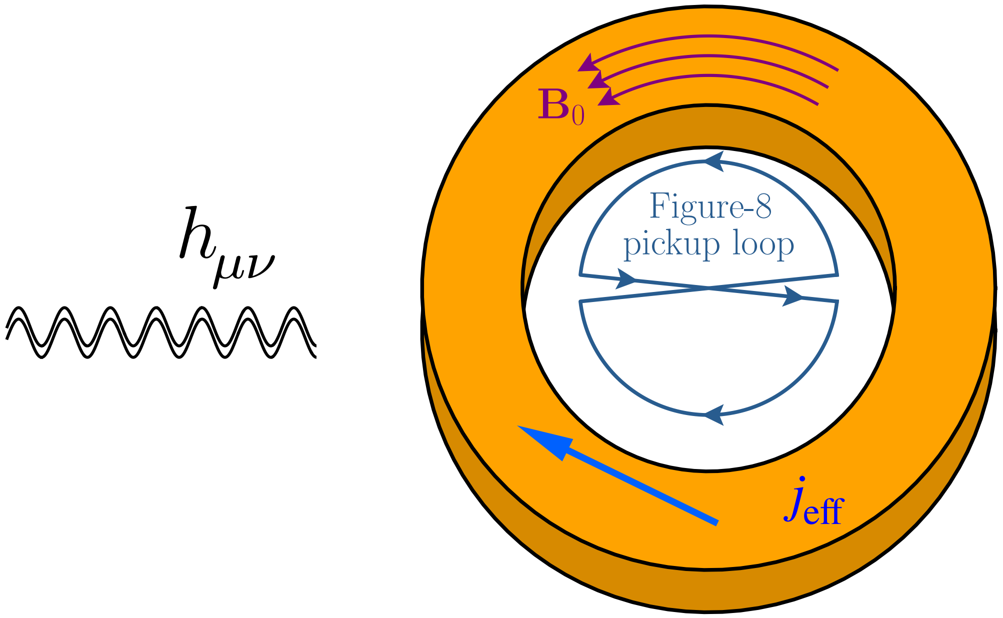
$$\Phi_{\text{axions}} \approx e^{-\mathrm{i}\omega t} g_{a\gamma\gamma}\sqrt{2\rho_{\text{DM}}} B_{\max}\pi r^2 R$$

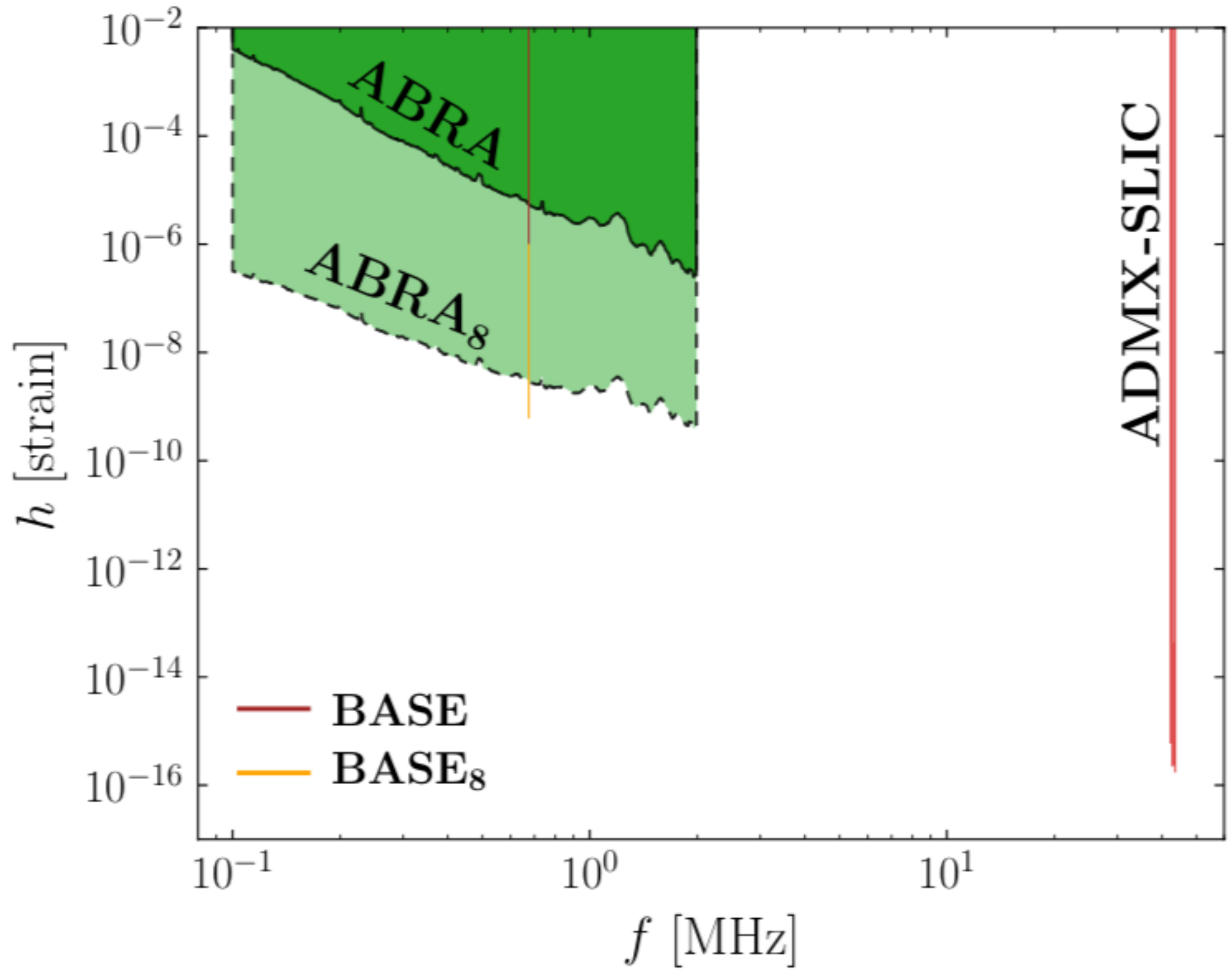
The sensitivity scaling with the volume is faster than for axions

Toroidal magnetic fields

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





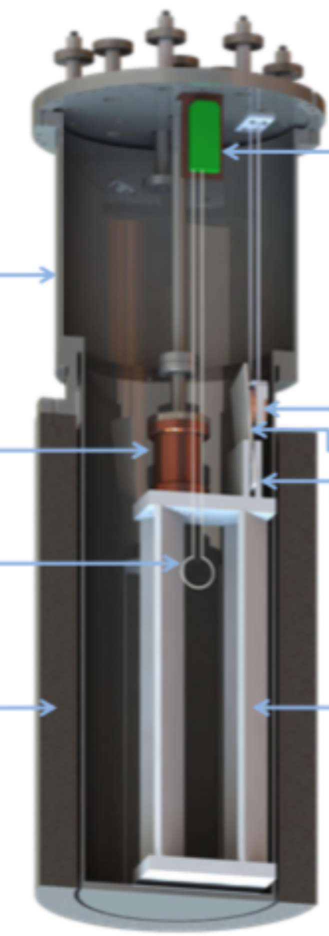


Solenoidal configurations

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

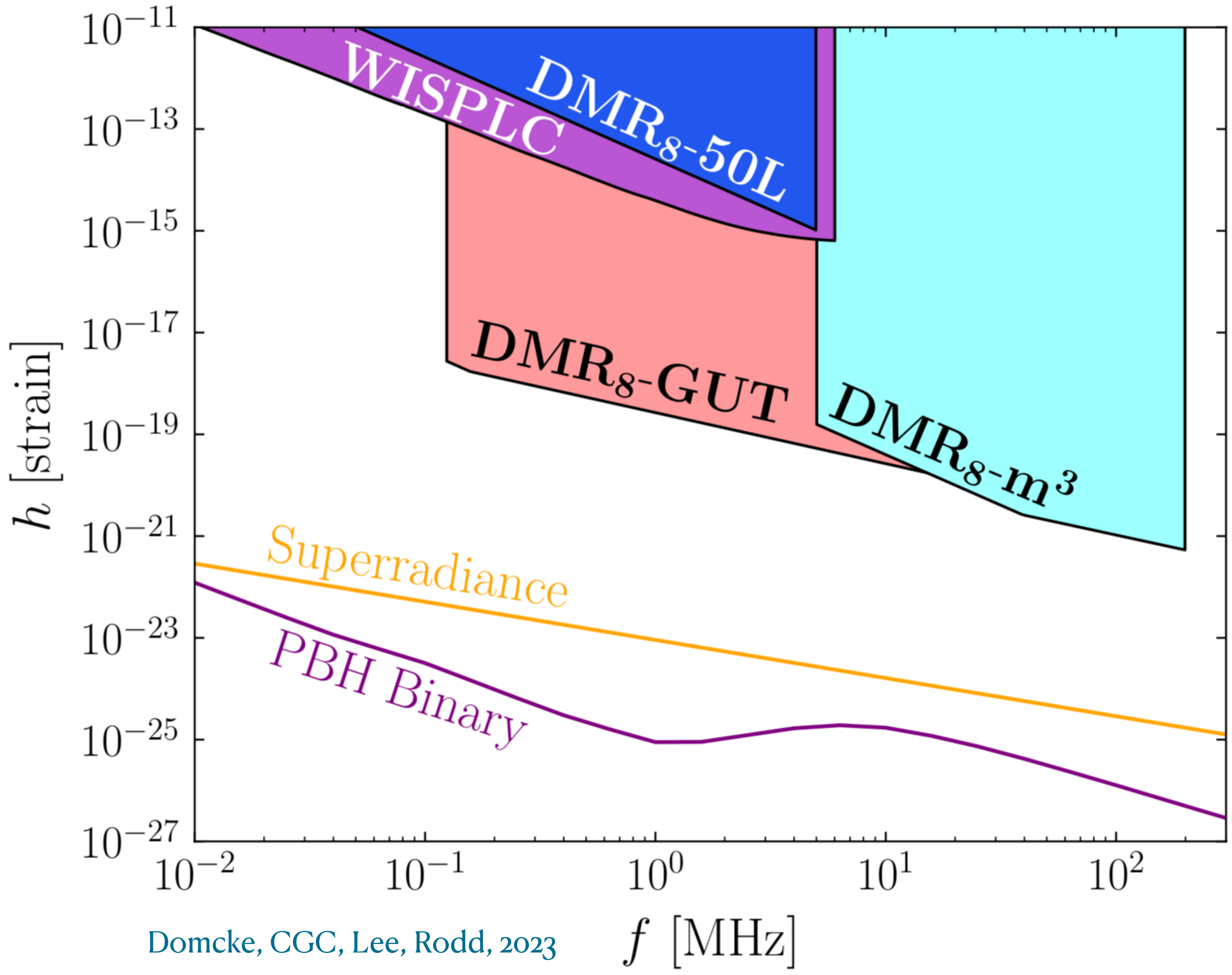
WISPLC

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

Camilo García Cely, University of Valencia

Haloscopes based on lumped-element detectors



Domcke, CGC, Lee, Rodd, 2023

Camilo García Cely, University of Valencia

Recent developments

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

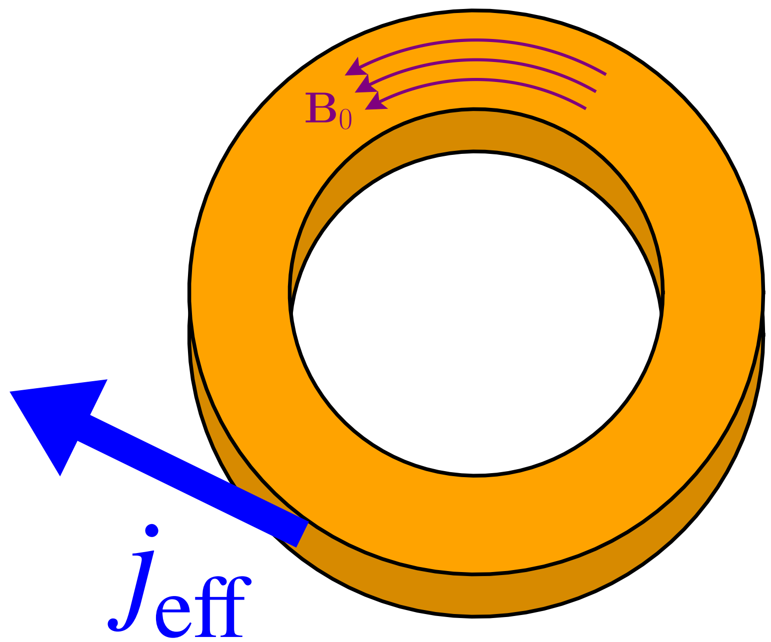
$$P_i = -h_{ij}E_j + \frac{1}{2}hE_i + h_{00}E_i - \epsilon_{ijk}h_{0j}B_k$$

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

Domcke, CGC, Rodd, 2202.00695

Non-zero *effective* surface currents

Domcke, CGC, Lee, Rodd, 2023

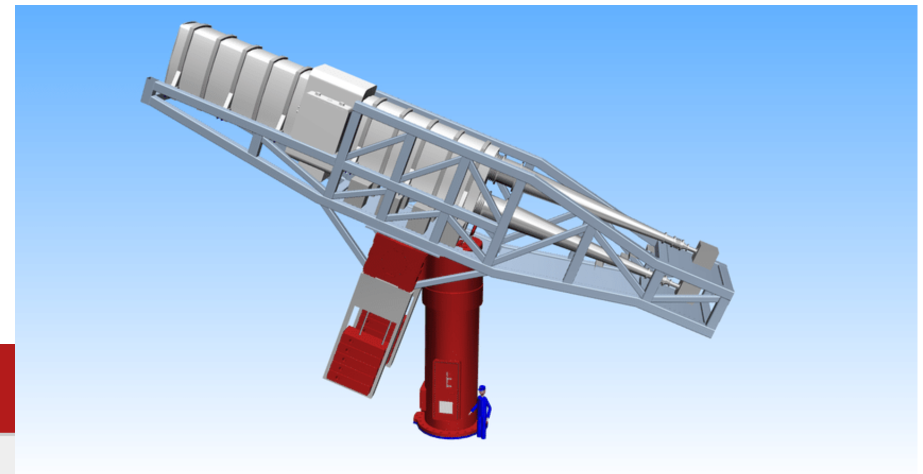


At the interface of two bodies with different values of the magnetisation vector M, Maxwell's equations predict a surface current proportional to $n \times \Delta M$

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

Sizeable effects. This should also be relevant for cavities

Estimates for BabyIAXO RADES



arXiv > physics > arXiv:2306.17243

Physics > Instrumentation and Detectors

[Submitted on 29 Jun 2023]

A proposal for a low-frequency axion search in the 1-2 μeV range and below with the BabyIAXO magnet

S. Ahyoune, A. Álvarez Melcón, S. Arguedas Cuendis, S. Calatroni, C. Cogollos, J. Devlin, A. Díaz-Morcillo, D. Díez Ibáñez, B. Döbrich, J. Galindo, J.D. Gallego, J.M. García-Barceló, B. Gimeno, J. Golm, Y. Gu, L. Herwig, I.G. Irastorza, A.J. Lozano-Guerrero, C. Malbrunot, J. Miralda-Escudé, J. Monzó-Cabrera, P. Navarro, J.R. Navarro-Madrid, J. Redondo, J. Reina-Valero, K. Schmieden, T. Schneemann, M. Siodlaczek, S. Ulmer, W. Wuensch

5.3 Prospect sensitivity for HFGWs

With adaptions to the coupling structures, the BabyIAXO RADES cavities also have sensitivity to hypothesized high-frequency gravitational waves (HFGWs), see, e.g. [55–57].

We follow the qualitative estimate for the sensitivity to the induced strain h_0 of a plane high-frequency gravitational wave of ~ 2 min duration in Eq. 29 of [55], with similar benchmark values for the field integral. BabyIAXO RADES achieves in principle sensitivities to strains of $h_0 \sim 10^{-21}$, comparable to ADMX. Note that accounting for the effect of mechanical deformations (mechanical bars) can lead to an even higher sensitivity [57].

More detailed studies in this direction are currently ongoing in our group.

Lots of room for improvement

Towards realistic simulations

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

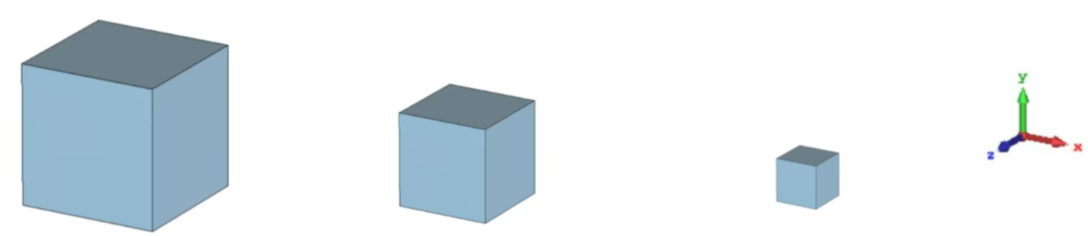
Dec 4, 2023

26 pages
e-Print: 2312.02270 [hep-ph]

Pablo Navarro,[a] **Benito Gimeno,**[b] **Juan Monzón-Cabrera,**[a] **Alejandro Díaz-Morcillo,**[a] **Diego Blas**[c,d]

[a]Departamento de Tecnologías de la Información y las Comunicaciones, Universidad Politécnica de Cartagena, Plaza del Hospital 1, 30302 Cartagena, Spain,
[b]Instituto de Física Corpuscular (IFIC), CSIC-University of Valencia, Calle Catedrático José Beltrán Martínez, 2, 46980 Paterna (Valencia), Spain,
[c]Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Campus UAB, 08193 Bellaterra (Barcelona), Spain
[d]Institució Catalana de Recerca i Estudis Avançats (ICREA), Passeig Lluís Companys 23, 08010 Barcelona, Spain

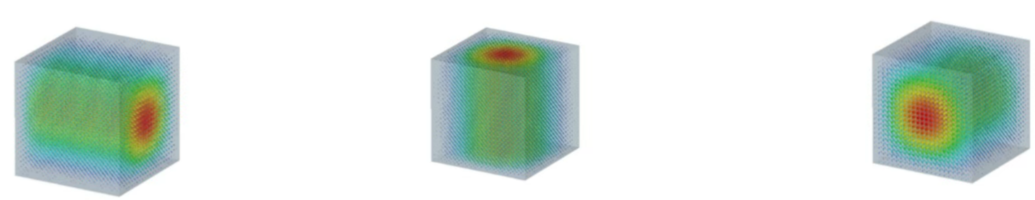
- Objective: study of a microwave cubic cavity for Gravitational Waves (GWs) detection based on the inverse Gertsenhstein effect.
- The magnetostatic field B is oriented in the z axis.



CAVITY 100 MHz　　CAVITY 1 GHz　　CAVITY 10 GHz

- 3 coaxial probes (antennas) in orthogonal directions.

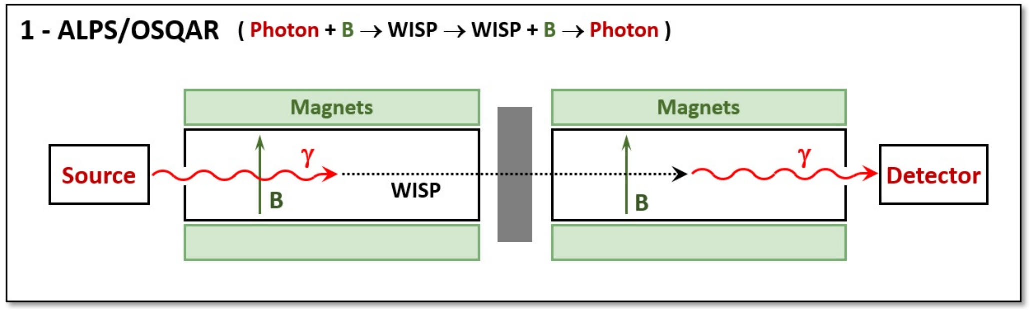
(courtesy of B. Gimeno)

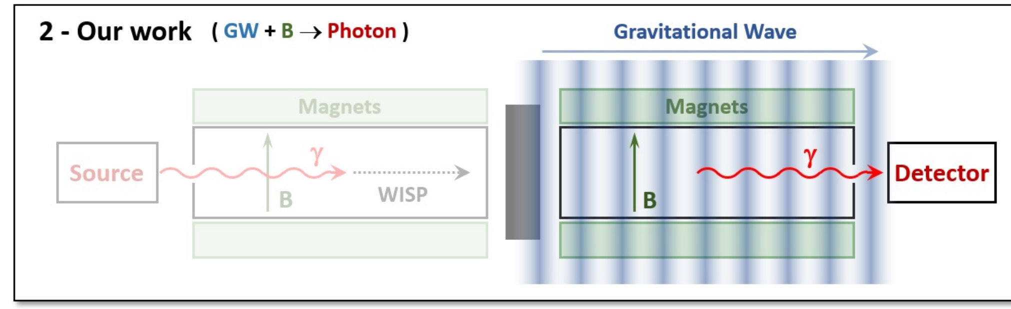


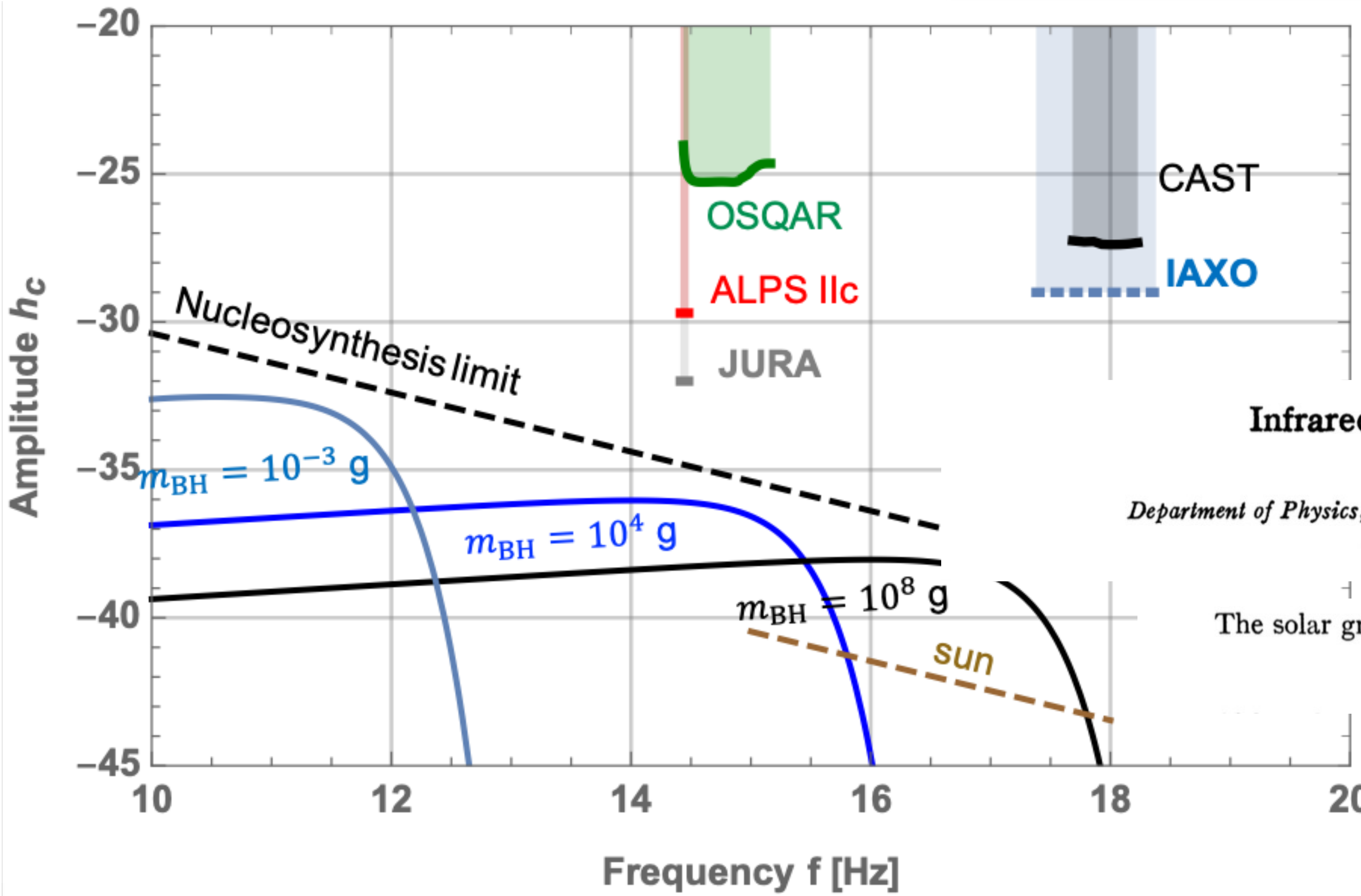
TE 011　　TE 101　　TM 110

Solar gravitational waves

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

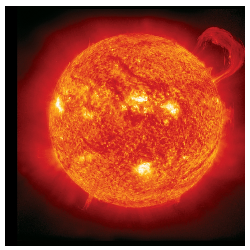
$$P_\odot \simeq 6 \times 10^{14} \text{ erg/sec}. \qquad (4.24)$$

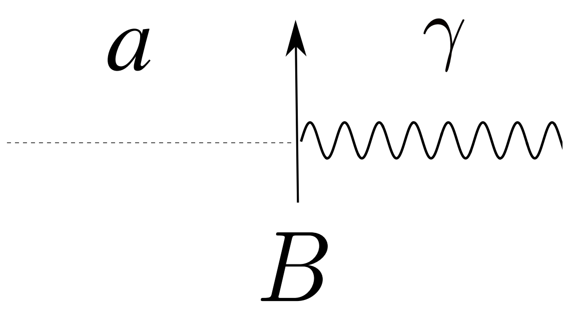
A. Ejlli, D. Ejlli, A. M. Cruise, G. Pisano & H. Grote

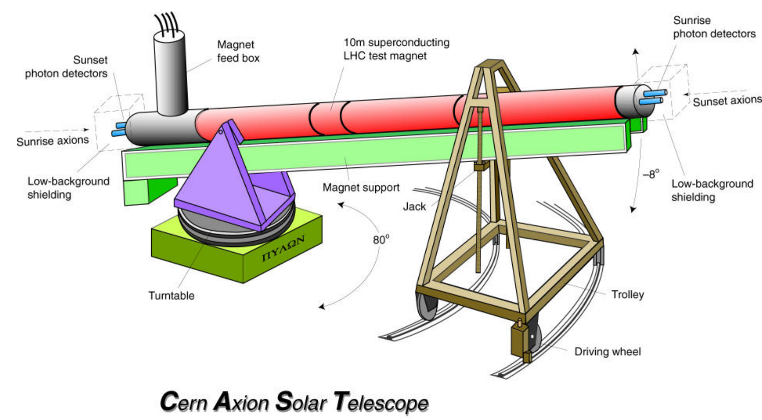
The European Physical Journal C **79**, Article number: 1032 (2019)

Solar emission of axions

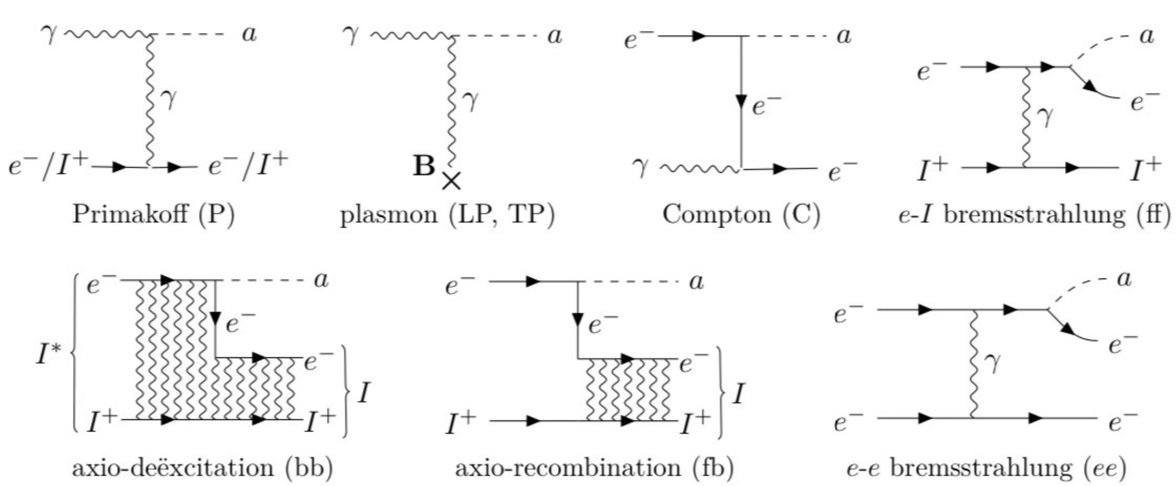
- Helioscopes (X rays)







- CAST
- IAXO
- .....



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, Andrea Caputo, Alexander J. Millar, and Edoardo Vitagliano

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

Revisiting longitudinal plasmon-axion conversion in external magnetic fields

Andrea Caputo, Alexander J. Millar, and Edoardo Vitagliano

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

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

Ersilia Guarini, Pierluca Carenza, Javier Galán, Maurizio Giannotti, and Alessandro Mirizzi

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

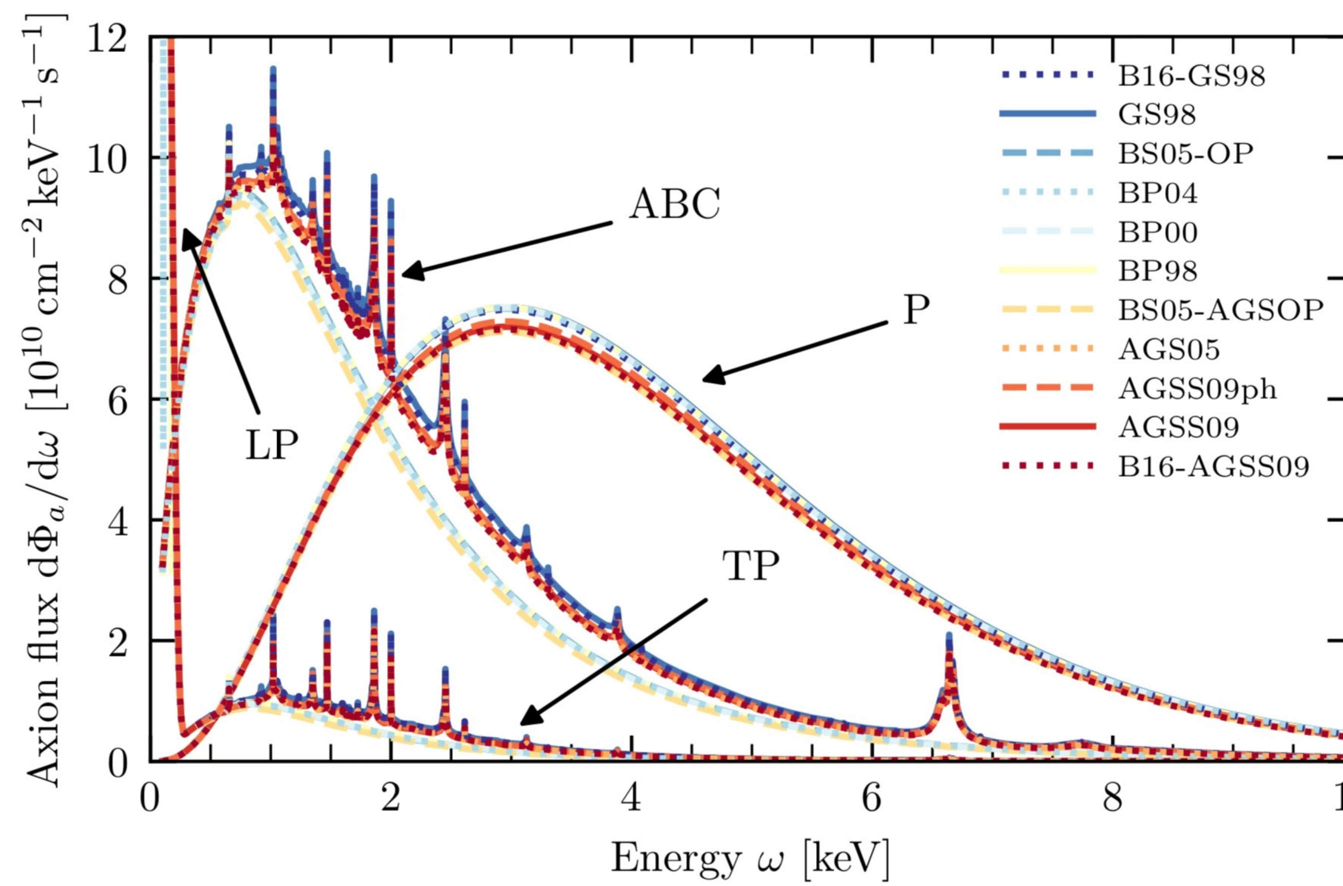
L. A. Vassilevskaya

Solar axion flux from the axion-electron coupling

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

Oct 2, 2013

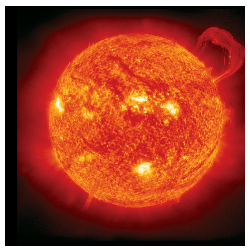
Hoof et al, 2021

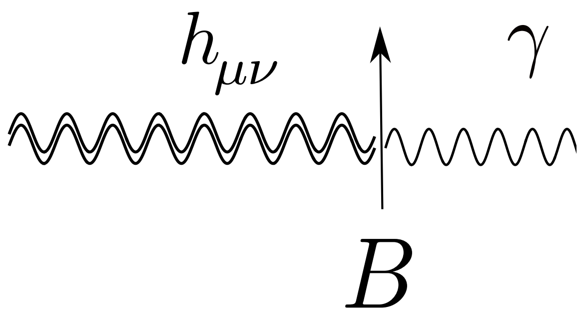


Solar emission of light spin-2 particles

- Helioscopes (X rays)

CGC, Ringwald **PRELIMINARY**





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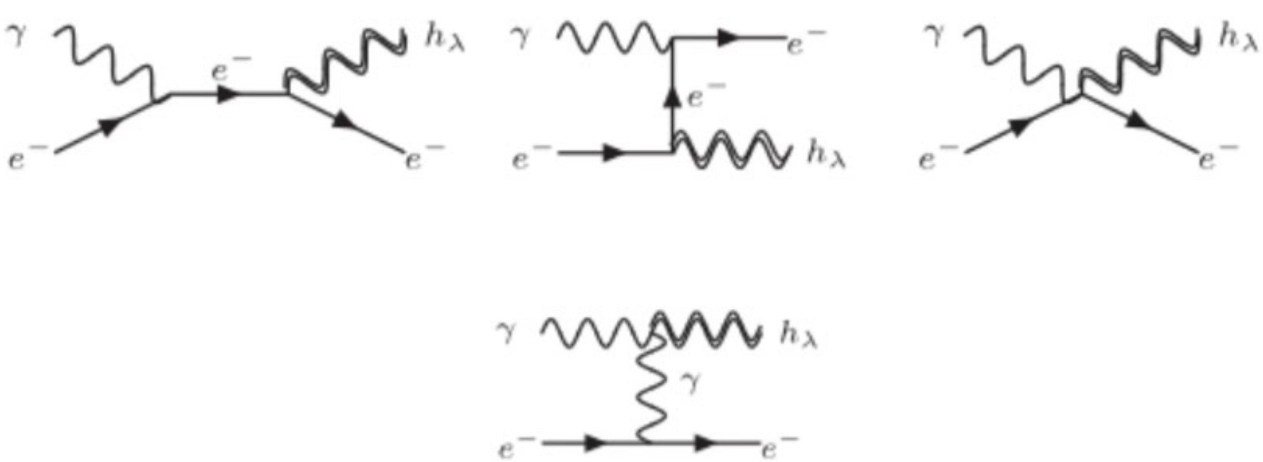
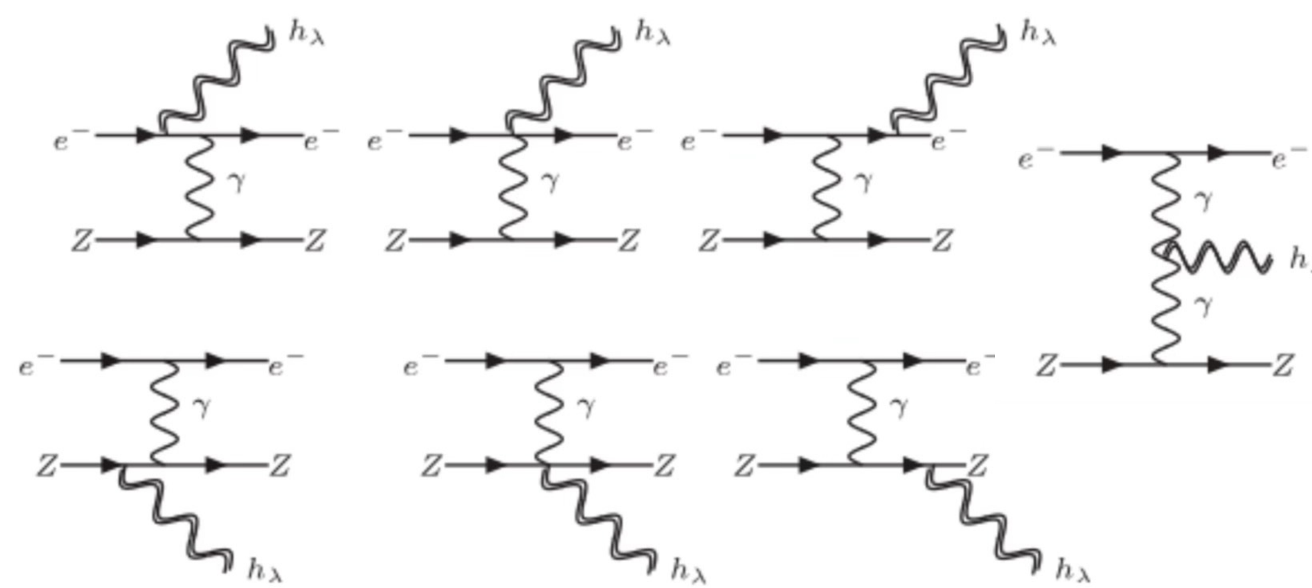
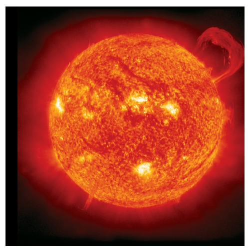
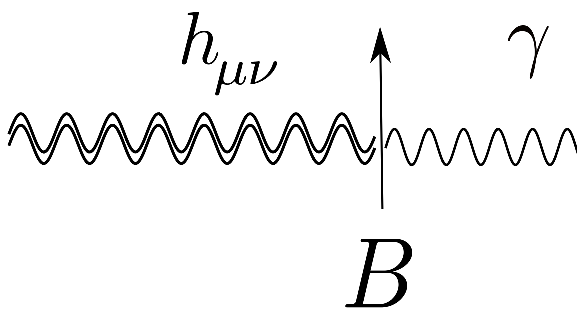


2. *Bremsstrahlung*

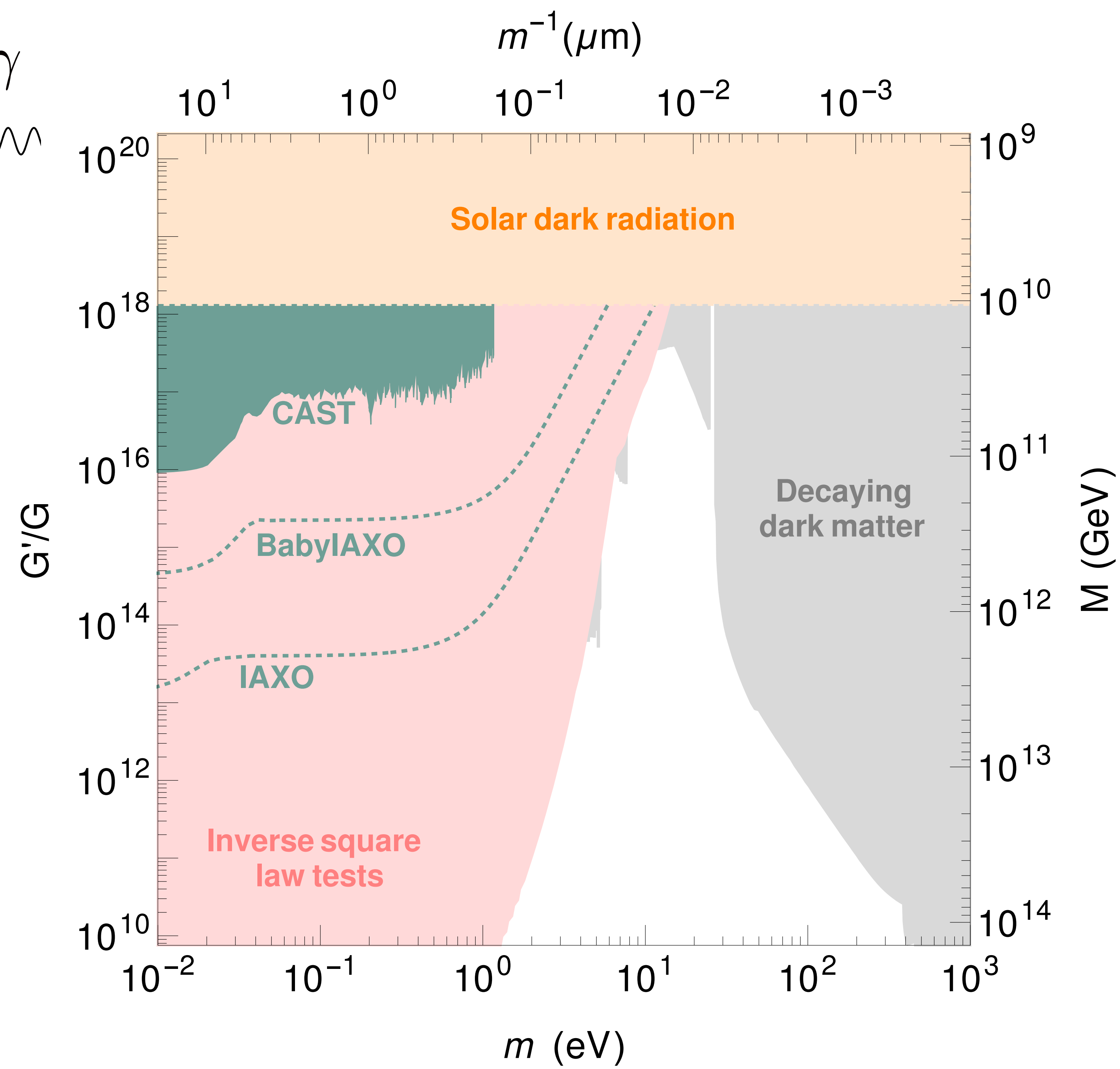


Solar emission of light spin-2 particles





CGC, Ringwald **PRELIMINARY**



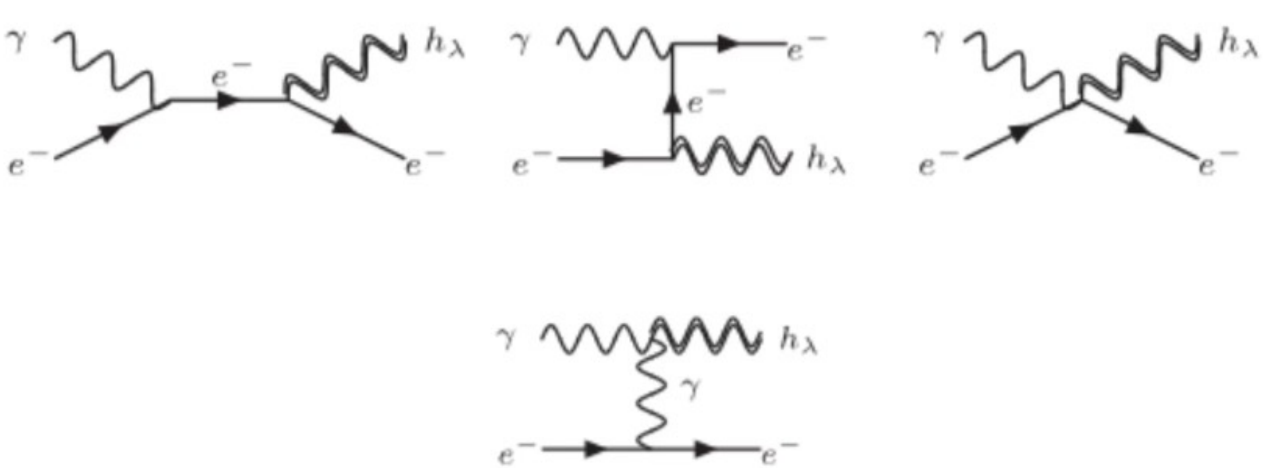
Camilo García Cely, University of Valencia

Solar emission of light spin-2 particles

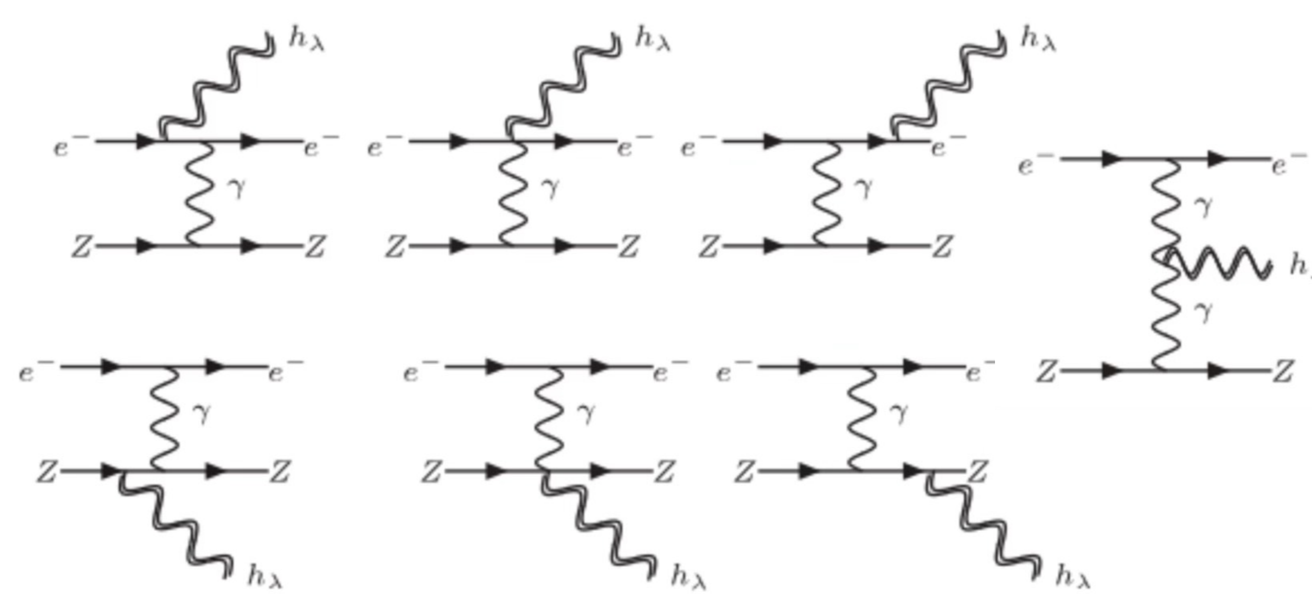
CGC, Ringwald **PRELIMINARY**

Collision	λ	$\frac{\mathrm{d}\Gamma}{\mathrm{d}\omega \mathrm{d}V}$	
Photo-production $\gamma Z \to Z\, h_\lambda$	± 2	$n_\gamma n_Z G' Z^2 \alpha\pi\, \delta(\omega - p_i) \int \mathrm{d}\cos\theta \cot^2\frac{\theta}{2}[1+\cos^2\theta]F(\theta)$	$F(\theta) = \frac{\left(2\omega\sin\frac{\theta}{2}\right)^2}{\kappa^2+\left(2\omega\sin\frac{\theta}{2}\right)^2}$
	± 1	0	
	0	$\frac{4}{3} n_\gamma n_Z G' Z^2 \alpha\pi\, \delta(\omega - p_i) \int \mathrm{d}\cos\theta \cot^2\frac{\theta}{2} \sin^4\frac{\theta}{2} F(\theta)$	
Bremsstrahlung $eZ \to eZ\, h_\lambda$	± 2	$\frac{32 n_e n_Z G' Z^2 \alpha^2 p_i}{15\omega}\left(\frac{1}{m_e}+\frac{1}{m_Z}\right)\left(3(1+\xi^2)L + 10\xi + \mathcal{O}(\xi_s^2)\right)$	$\xi = \frac{p_f}{p_i}, \quad \xi_s = \frac{\kappa}{p_i}$
	± 1	0	
	0	$\frac{16 n_e n_Z G' Z^2 \alpha^2 p_i}{45\omega}\left(\frac{1}{m_e}+\frac{1}{m_Z}\right)\left((1+\xi^2)L + 30\xi + \mathcal{O}(\xi_s^2)\right)$	$\omega = E_i(1-\xi^2)$
Bremsstrahlung $ee \to ee\, h_\lambda$	± 2	$\frac{16 n_e^2 G' \alpha^2 p_i}{15\omega m_e}\left(\left(6(1+\xi^2) - \frac{3(1-\xi^2)^4+7(1-\xi^4)^2}{2(1+\xi^2)^3}\right)L + 20\xi - \frac{6\xi(1+\xi^4)}{(1+\xi^2)^2} + \mathcal{O}(\xi_s^2)\right)$	$L = \log\sqrt{\frac{(1+\xi)^2+\xi_s^2}{(1-\xi)^2+\xi_s^2}}$
	± 1	0	
	0	$\frac{16 n_e^2 G' \alpha^2 p_i}{15\omega m_e}\left(\left(\frac{1}{3}(1+\xi^2) - \frac{(1-\xi^2)^4+29(1-\xi^4)^2}{12(1+\xi^2)^3}\right)L + \frac{29\xi}{3} + \frac{2\xi^3}{3(1+\xi^2)^2} + \mathcal{O}(\xi_s^2)\right)$	

1. *Photoproduction*



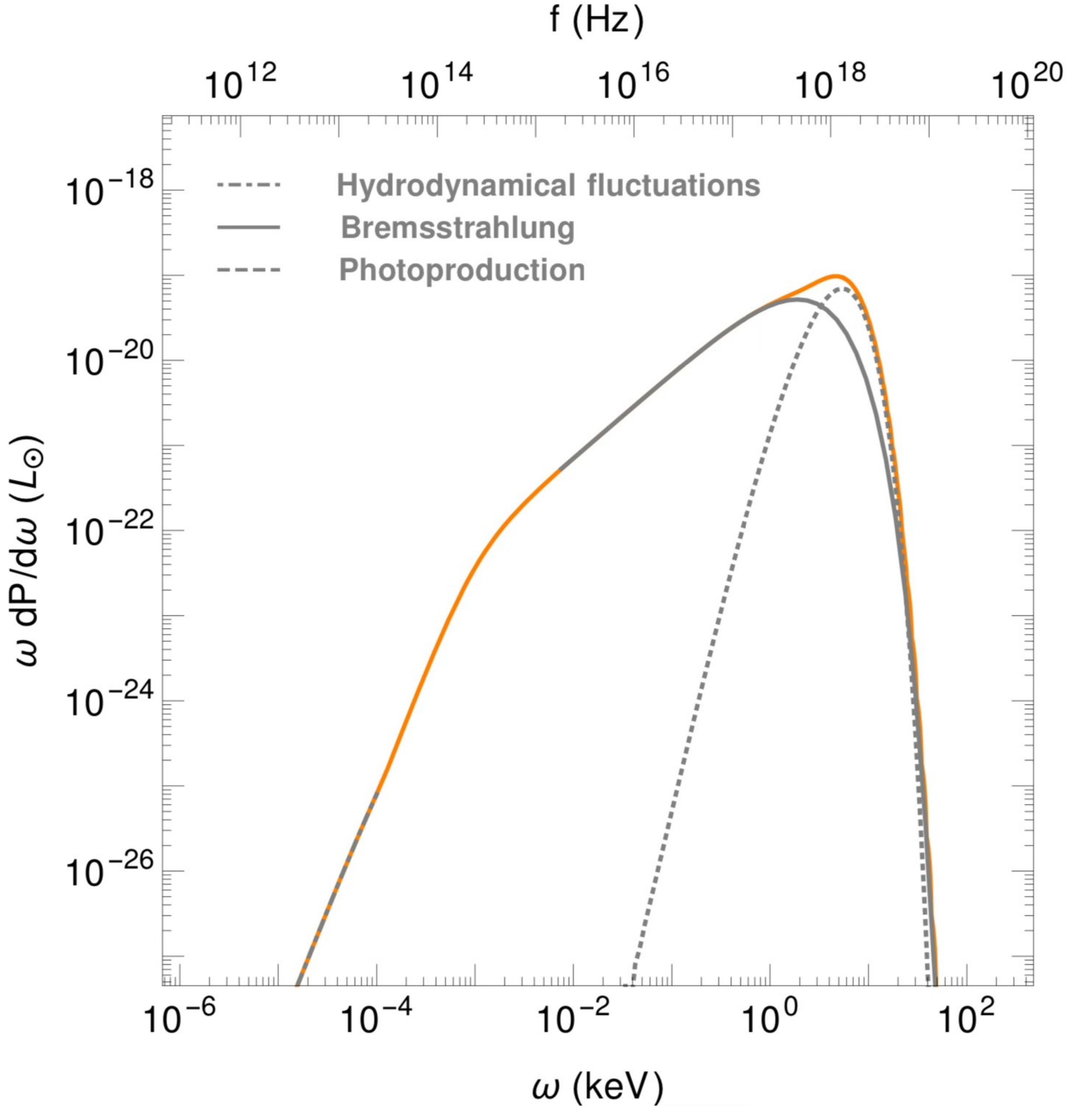
2. *Bremsstrahlung*



Camilo García Cely, University of Valencia

Solar gravitational waves

CGC, Ringwald **PRELIMINARY**



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

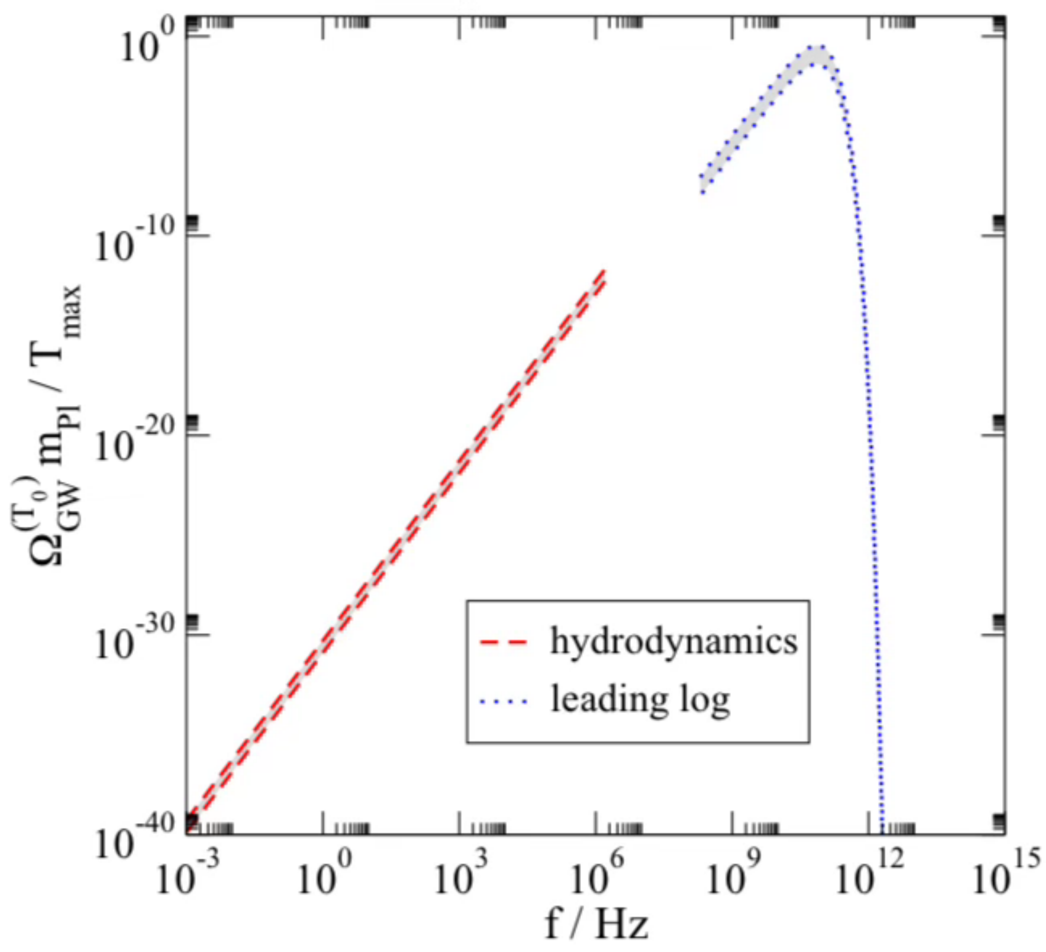
Article PDF

References ▾

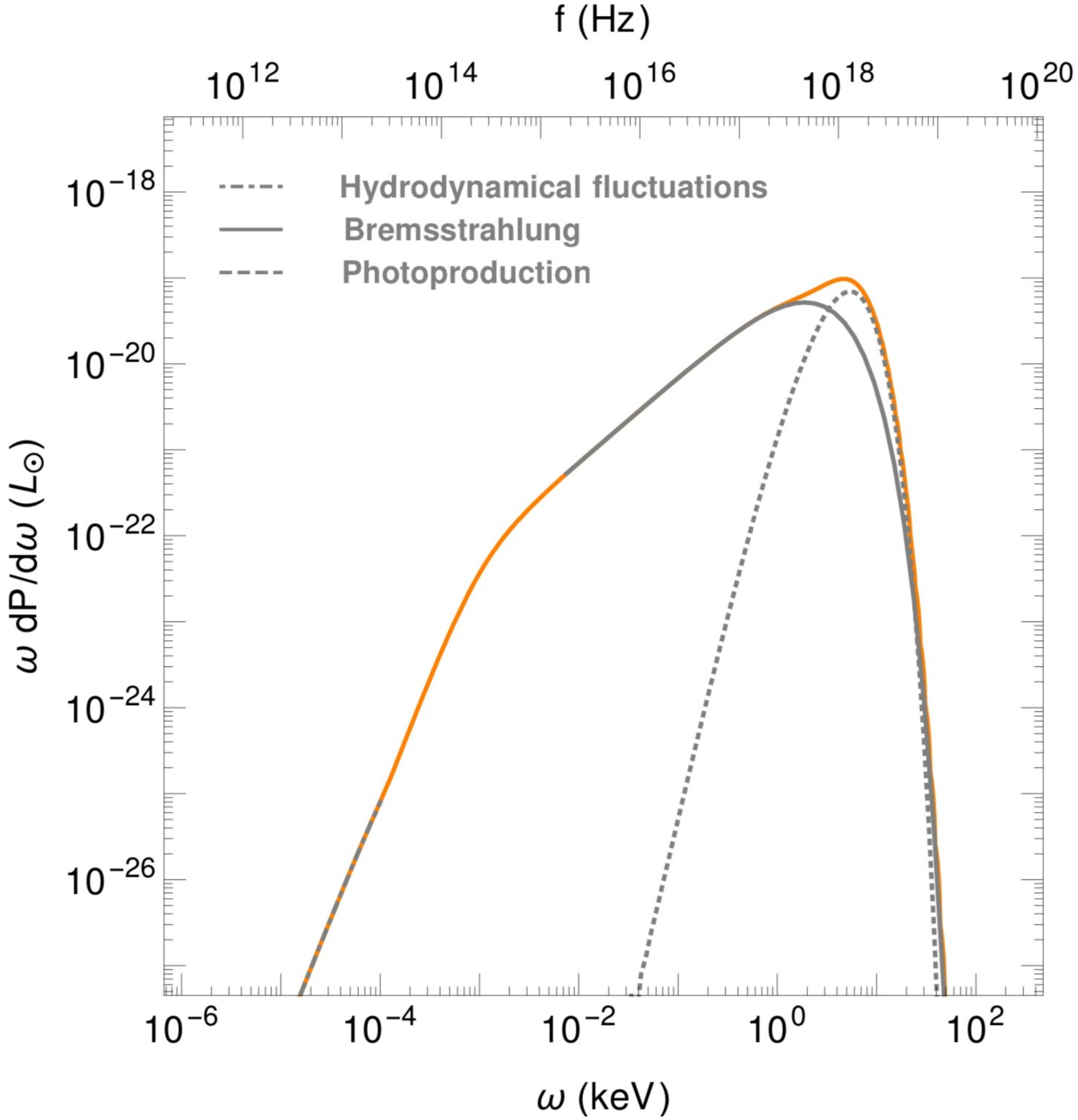
+ Article and author information

Abstract

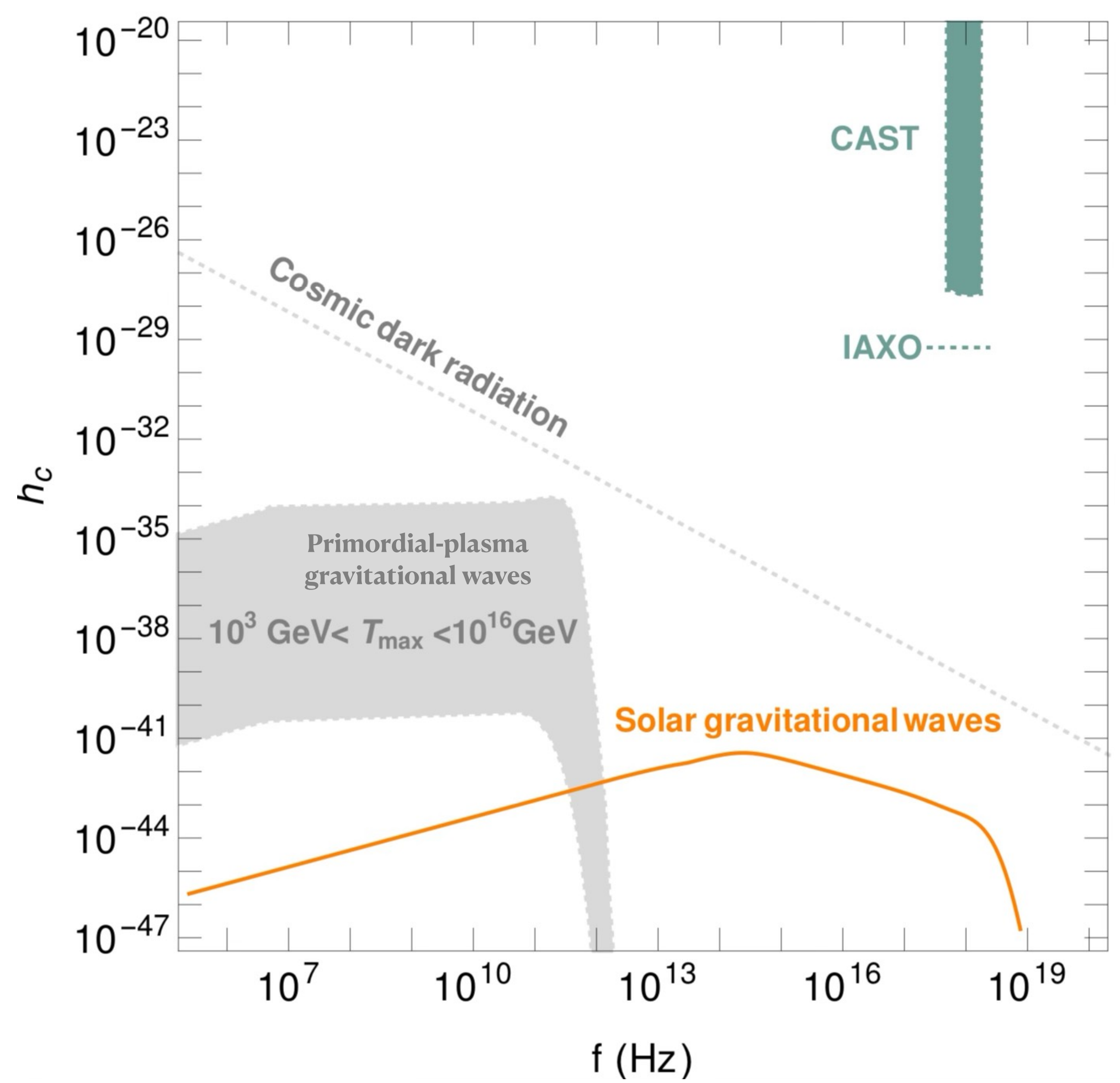
Because of physical processes ranging from microscopic particle collisions to macroscopic hydrodynamic fluctuations, any plasma in thermal equilibrium emits gravitational waves. For the largest wavelengths the emission rate is proportional to the shear viscosity of the plasma. In the Standard Model at



Solar gravitational waves

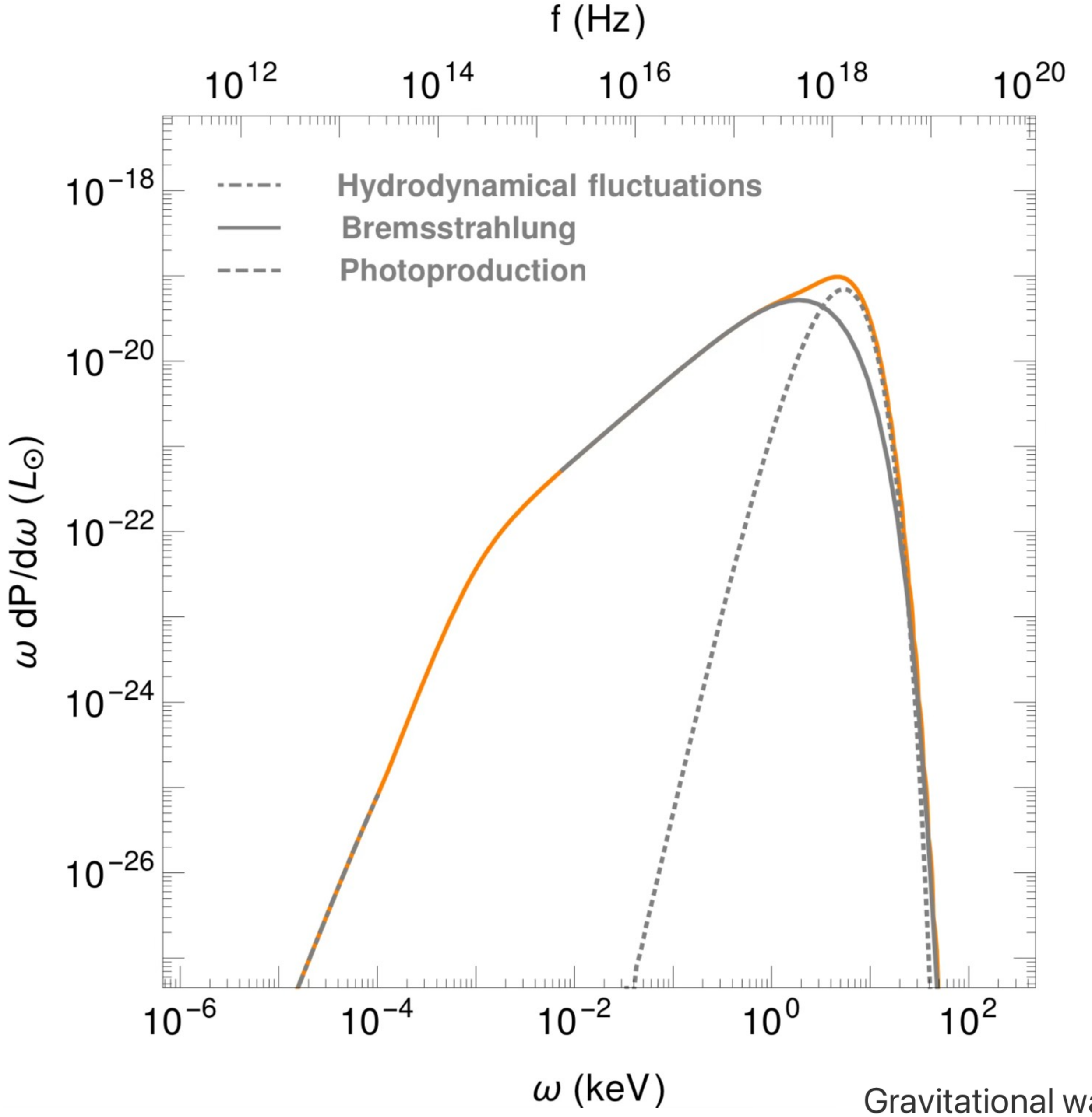


CGC, Ringwald **PRELIMINARY**

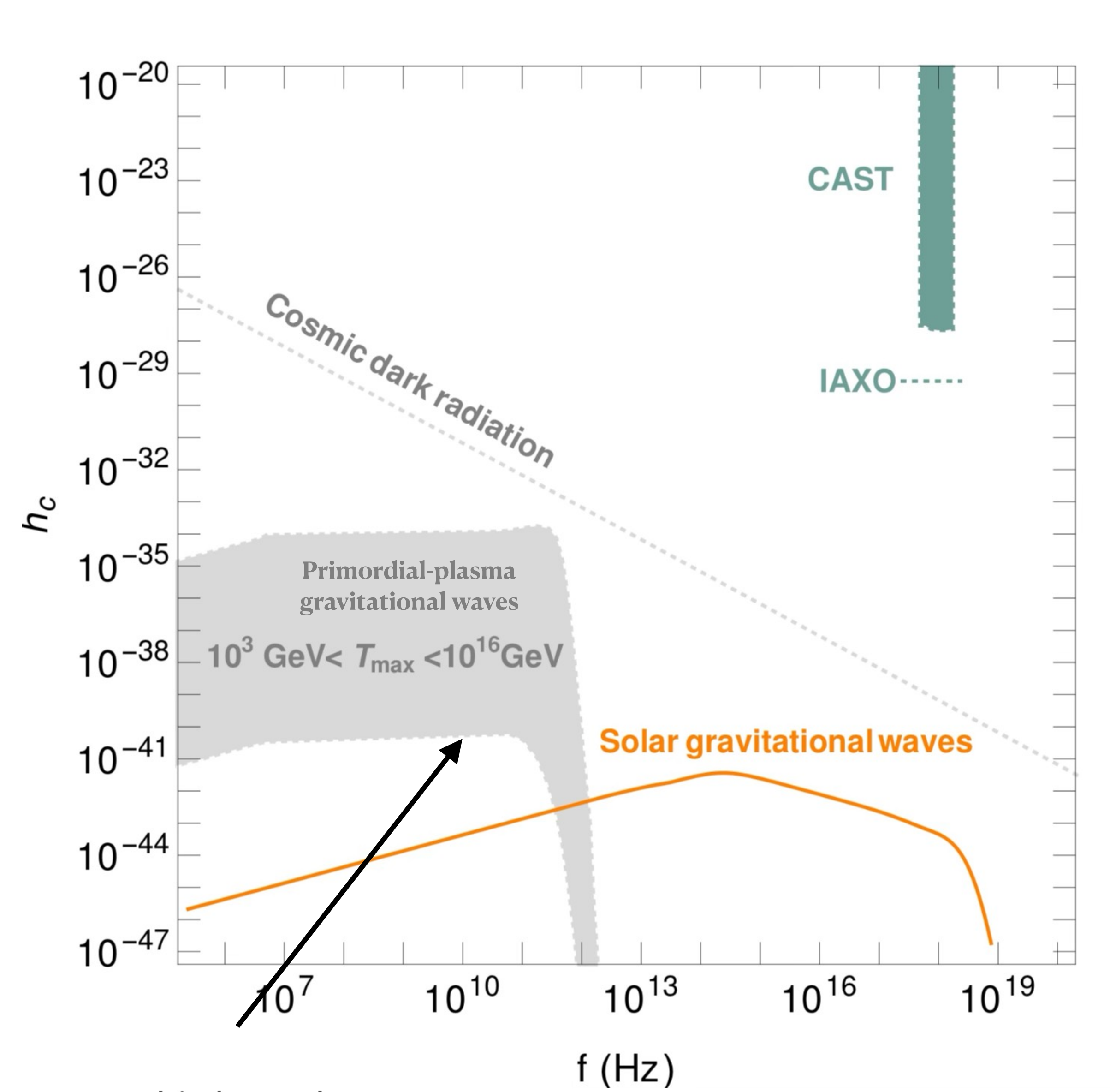


Camilo García Cely, University of Valencia

Solar gravitational waves



CGC, Ringwald **PRELIMINARY**



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

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.

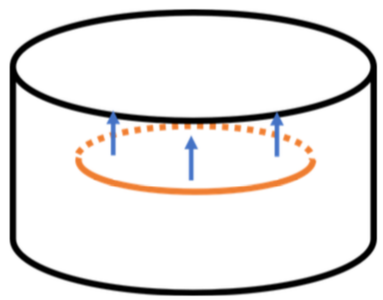
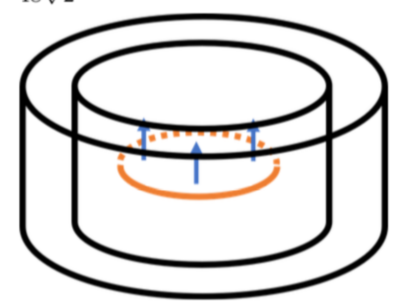
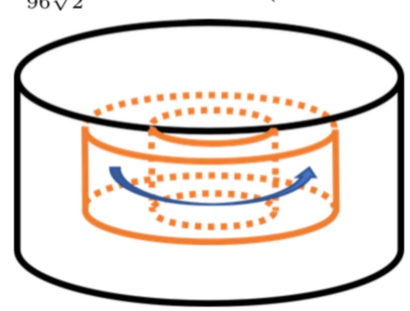
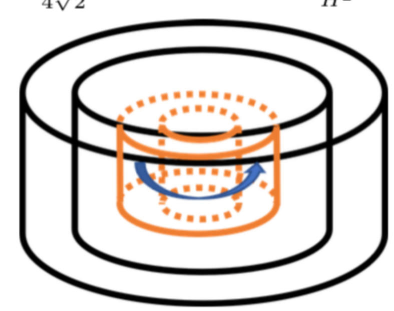
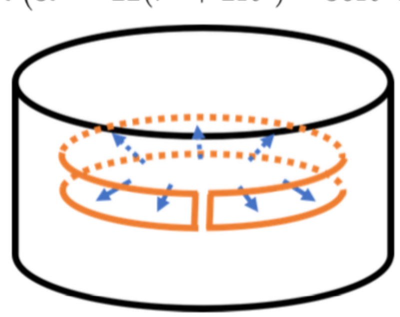
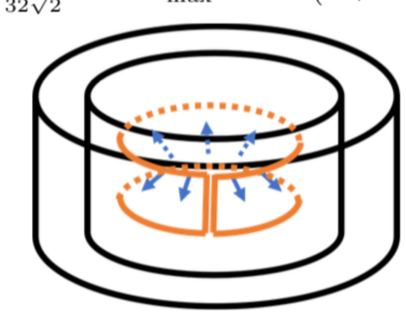
Simple modifications of readout (such as the figure-8 pickup loop) can overcome this limitation

Impact of the geometry

Type of external field

Domcke, CGC, Lee, Rodd, 2023

Pickup loop orientation

	Solenoid: $\mathbf{B}_0 \propto \hat{\mathbf{e}}_z$	Toroid: $\mathbf{B}_0 \propto \hat{\mathbf{e}}_\phi$
$\hat{\mathbf{n}}' \propto \hat{\mathbf{e}}_z$	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 $\Rightarrow \mathcal{O}[(\omega L)^2]$ $\Phi_h = \frac{3e^{-i\omega t}}{4\sqrt{2}} h^+ \omega^2 B_{\max} \frac{\pi r^2 aRl(a+2R)}{H^2} s^2_{\theta_h}$ 
$\hat{\mathbf{n}}' \propto \hat{\mathbf{e}}_\rho$	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 $\Rightarrow \mathcal{O}[(\omega L)^4]$ $\Phi_h = \frac{e^{-i\omega t}}{32\sqrt{2}} h^\times \omega^4 B_{\max} \pi r^2 aRl(a+2R) c_{\theta_h} s^2_{\theta_h}$ 

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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

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

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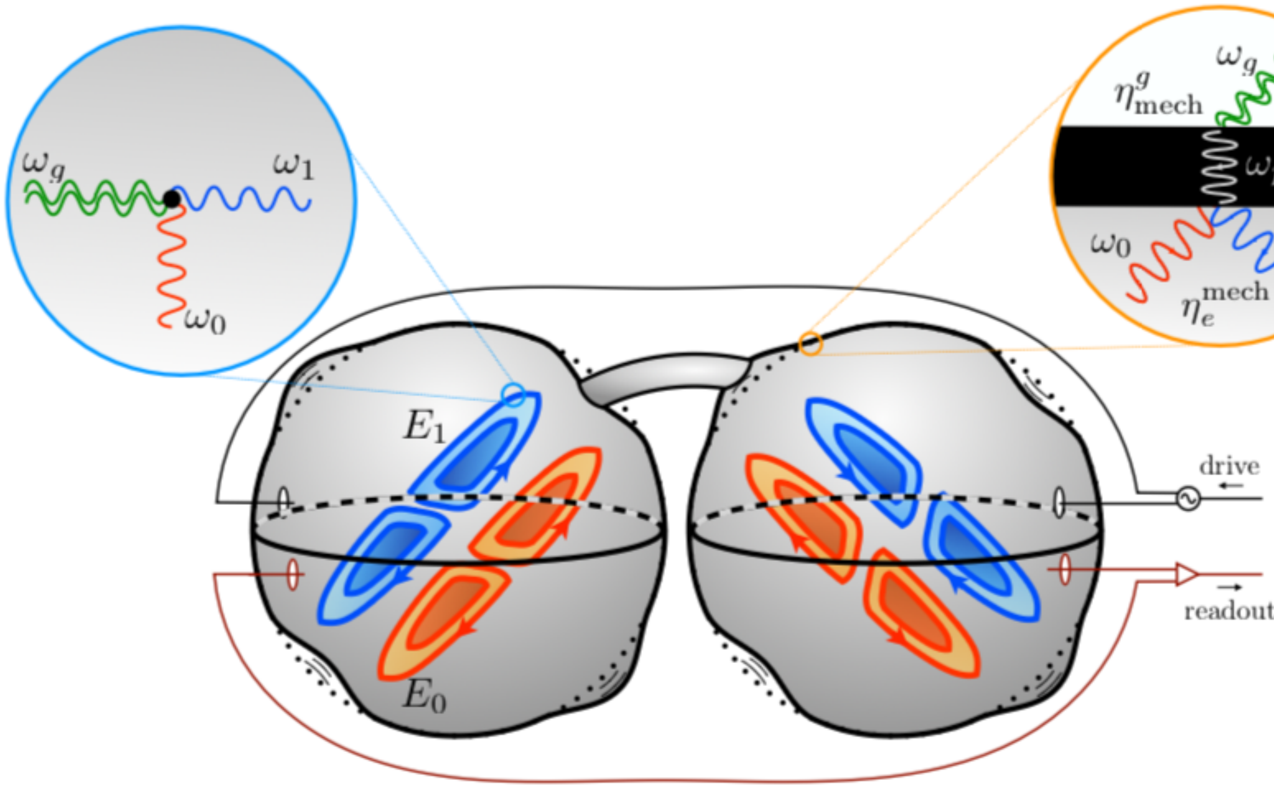
  If negligible, the static fields applied in experiments remain static in the presence of GWs.

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

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