Lessons from Axion Dark Matter for Gravitational-Wave Physics

PRISMA+ Colloquium

Mainz, Germany
December 18, 2024

IFIC INSTITUT DE FÍSICA CORPUSCULAR

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

VNIVERSITAT DE VALÈNCIA

Camilo García Cely

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

DESY
10.2017 - 02.2022
Hamburg, Germany

Université Libre de Bruxelles
10.2014 - 09.2017
Brussels, Belgium

Ph.D. in Physics.
Technische Universität München
09.2011 - 09.2014
Munich, Germany

M.Sc. in Physics.
University of Wisconsin
09.2008 - 12.2010
Madison, Wisconsin

B.Sc. in Physics.
Universidad del Valle
09.2003 - 10.2007
Cali, Colombia

Camilo A. Garcia Cely

Research interests

- Dark Matter
- Gravitational waves
- (Astro-)particle physics
- Cosmology

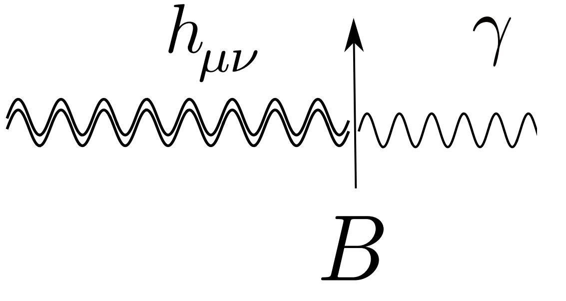
Outline

- Motivation: the Gertsenhstein effect

    Axions versus high-frequency gravitational waves

- Standard model backgrounds:

    Solar gravitational waves

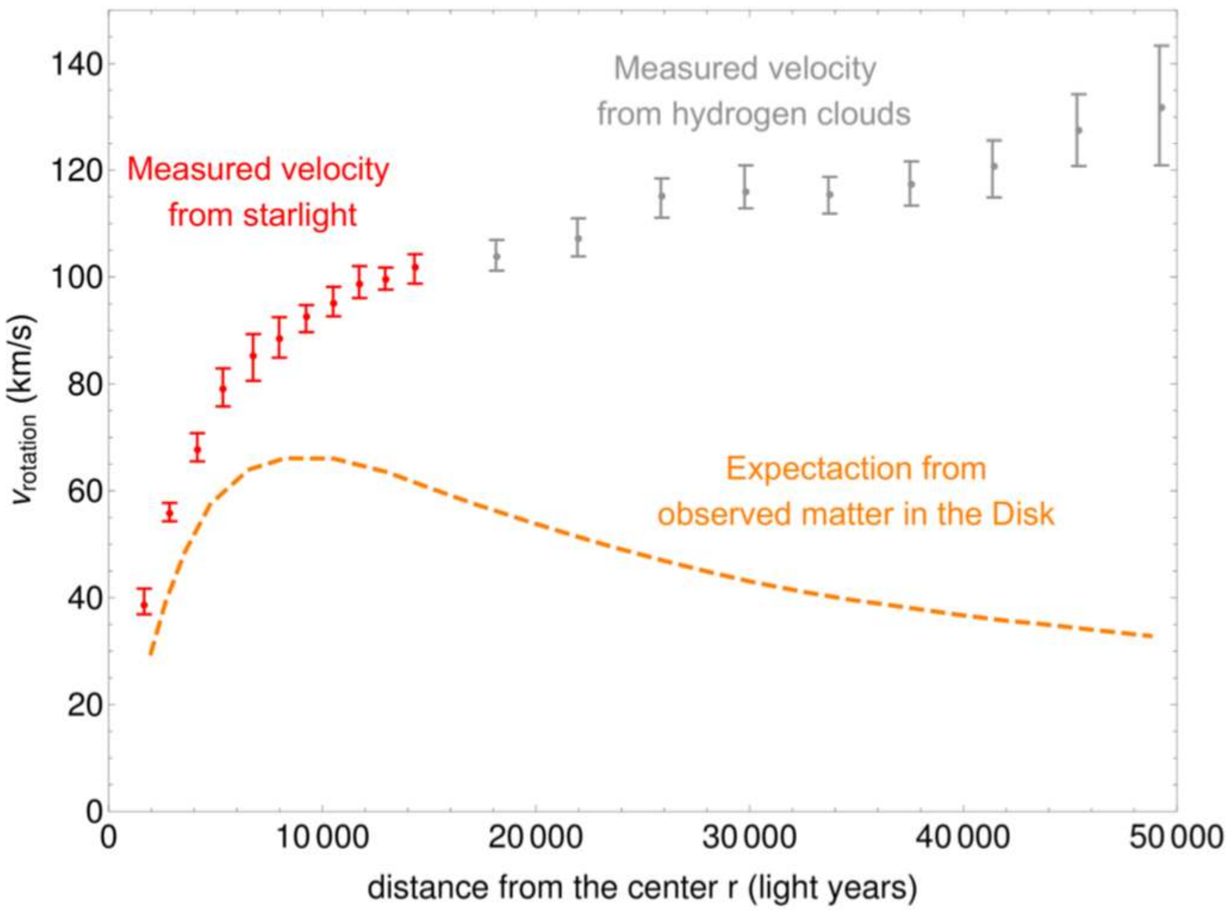


- Novel experimental approaches:

    Axion haloscopes and polarimetry techniques

- Conclusions

Dark Matter



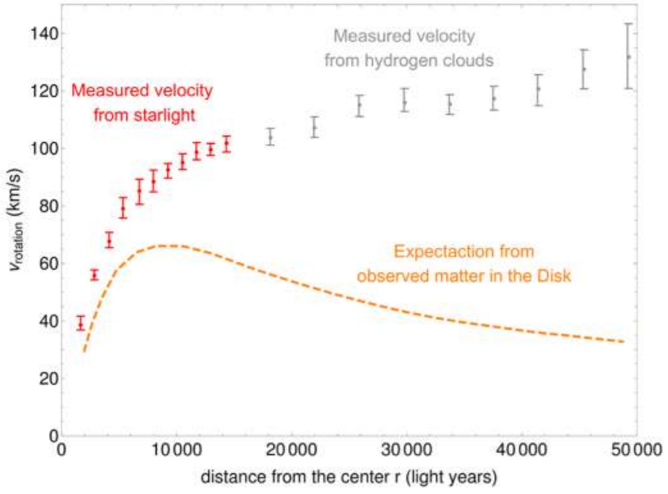
Triangulum Galaxy (M33)

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

Vera Rubin

Collisionless Cold Dark Matter

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



kpc

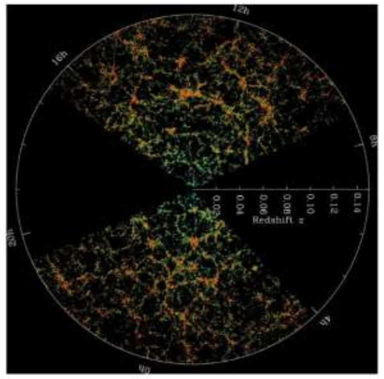
Velocity measurements

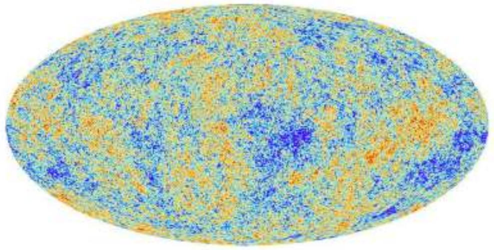
- Flat rotation curves of spiral galaxies
- Velocity dispersion of stars in giant elliptical and dwarf spheroidal galaxies
- Velocity dispersion of galaxies in clusters

Mpc

Lensing

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





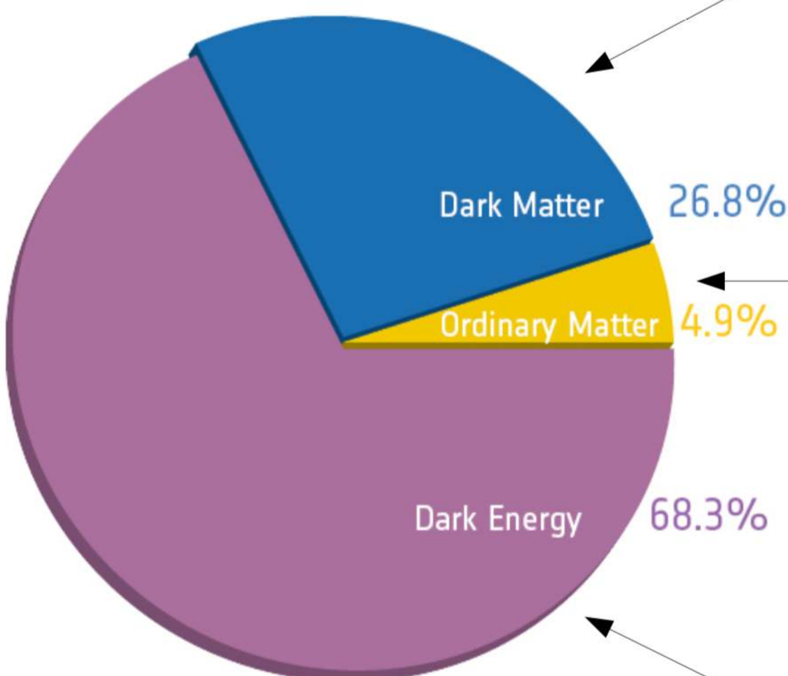
Gpc

Universe at large scales

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

Collisionless Cold
Dark Matter

?



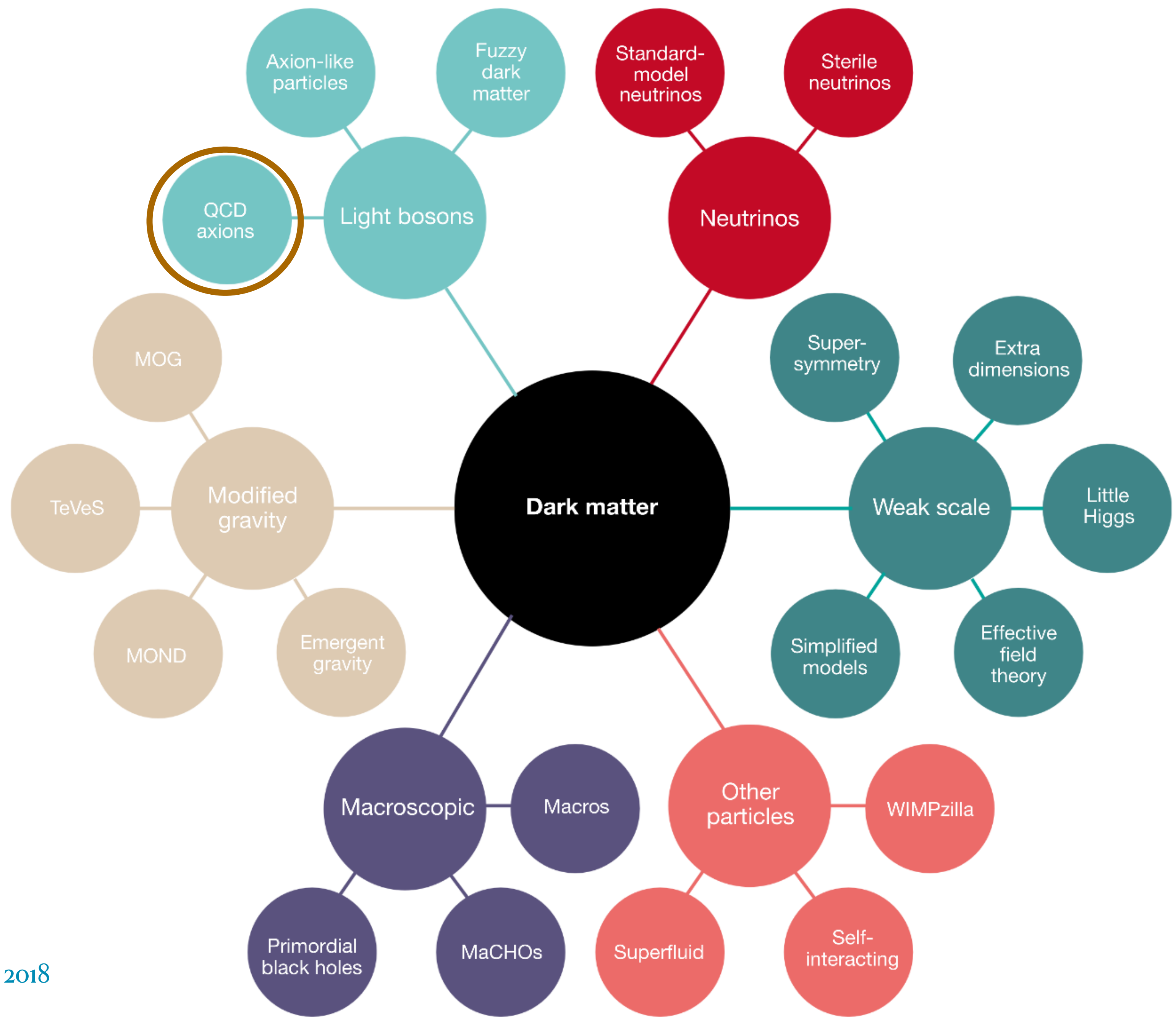
Standard Model stable particles:

Mostly protons, electrons,
neutrinos and photons

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

?

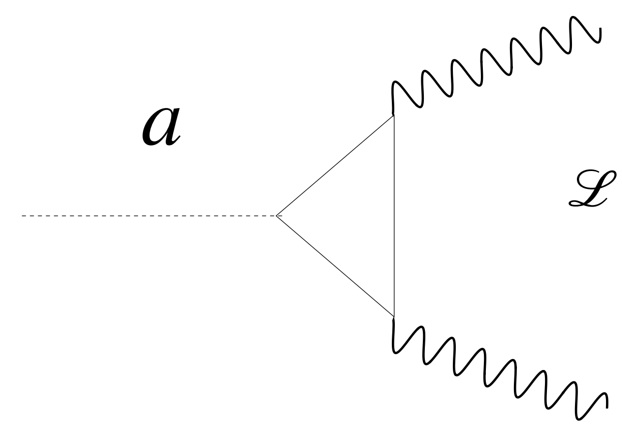
Collisionless Cold
Dark Matter



Bertone Tait, 2018

QCD axion as dark matter

- Pseudoscalar field



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

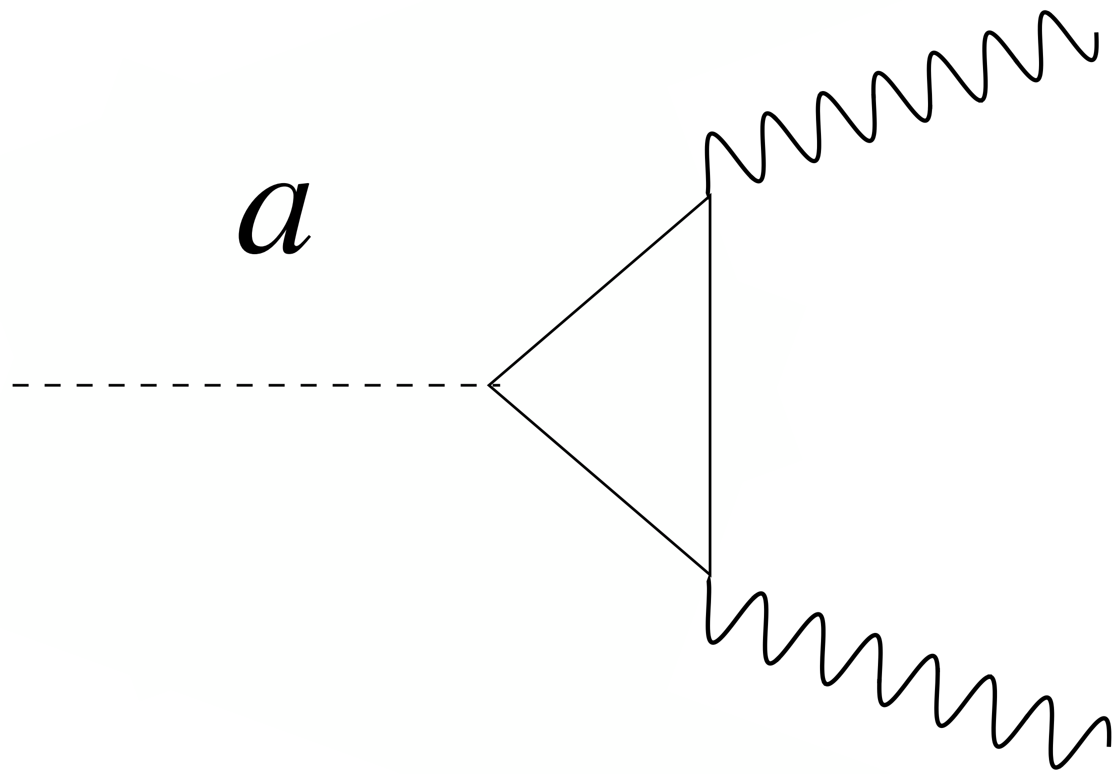
- Solution to the strong CP problem

Peccei, Quinn 1977

- Excellent dark matter candidate

Weinberg, Wilczek 1978

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

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

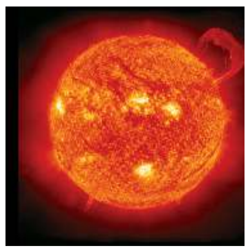
$$\nabla \cdot \mathbf{E} = j^0$$

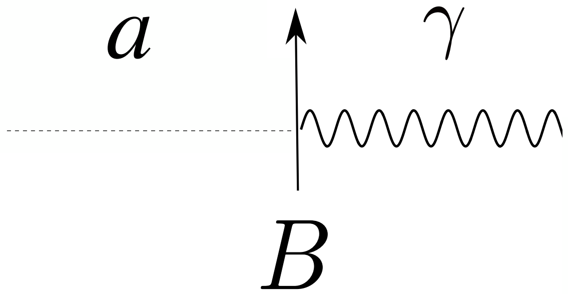
$$\nabla \times \mathbf{B} - \partial_t \mathbf{E} = \mathbf{j}$$

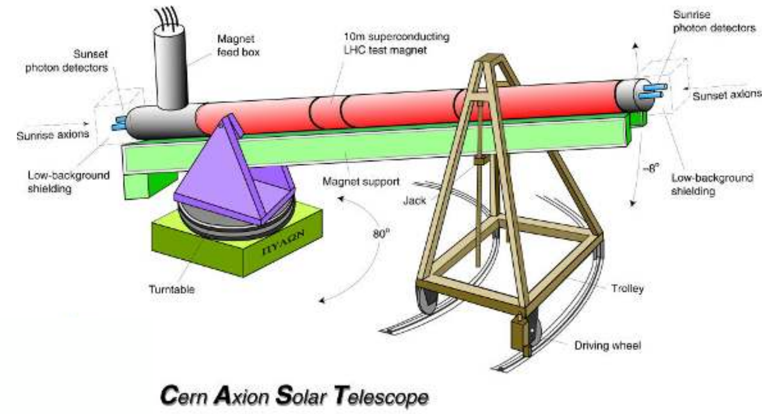
$$j^0 = - g_{a\gamma\gamma} \nabla a \cdot \mathbf{B} \qquad \mathbf{j} = g_{a\gamma\gamma} \left(\nabla a \times \mathbf{E} + \partial_t a \mathbf{B} \right)$$

Axion electrodynamics

- Helioscopes (X rays)

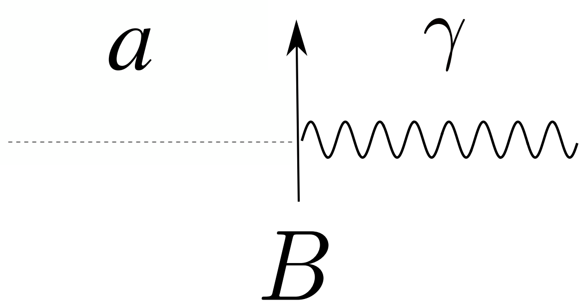






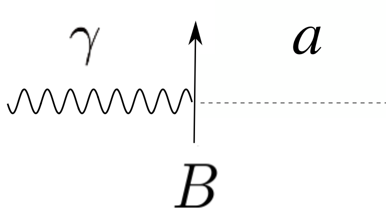
- CAST
- IAXO
- .....

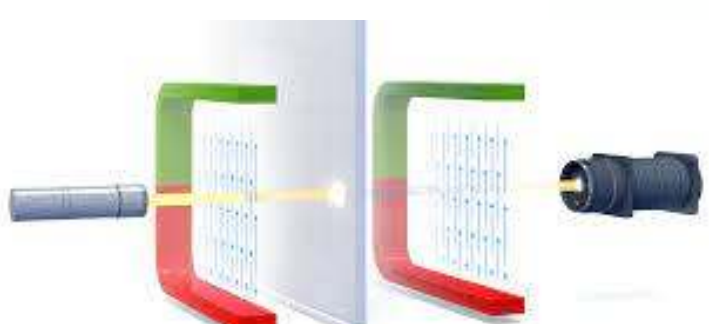
- Haloscopes (radio frequencies)

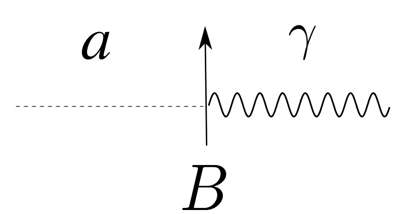


- microwave cavities
- MADMAX
- ADMX
- HAYSTAC
- ABRACADABRA
- Lumped element detectors
- ...

- Purely lab experiments







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

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

Camilo García Cely, University of Valencia-CSIC

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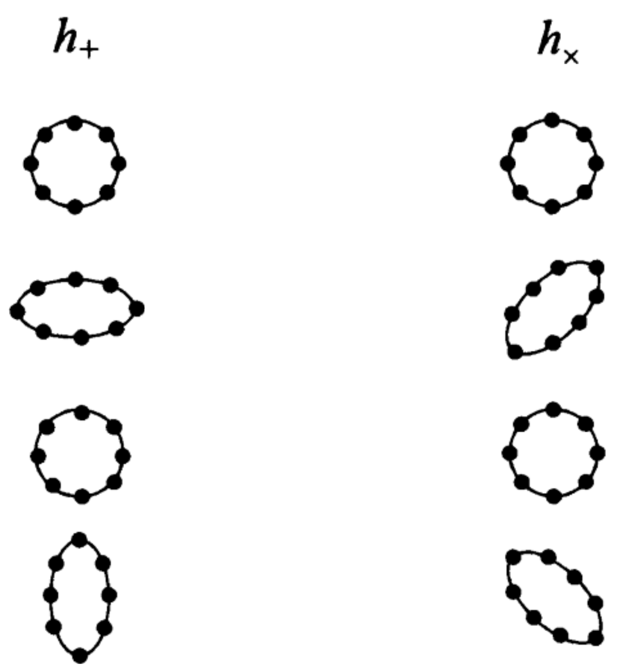

The deformation of a ring of test masses due to the different polarization

Camilo García Cely, University of Valencia-CSIC

Gravitational waves

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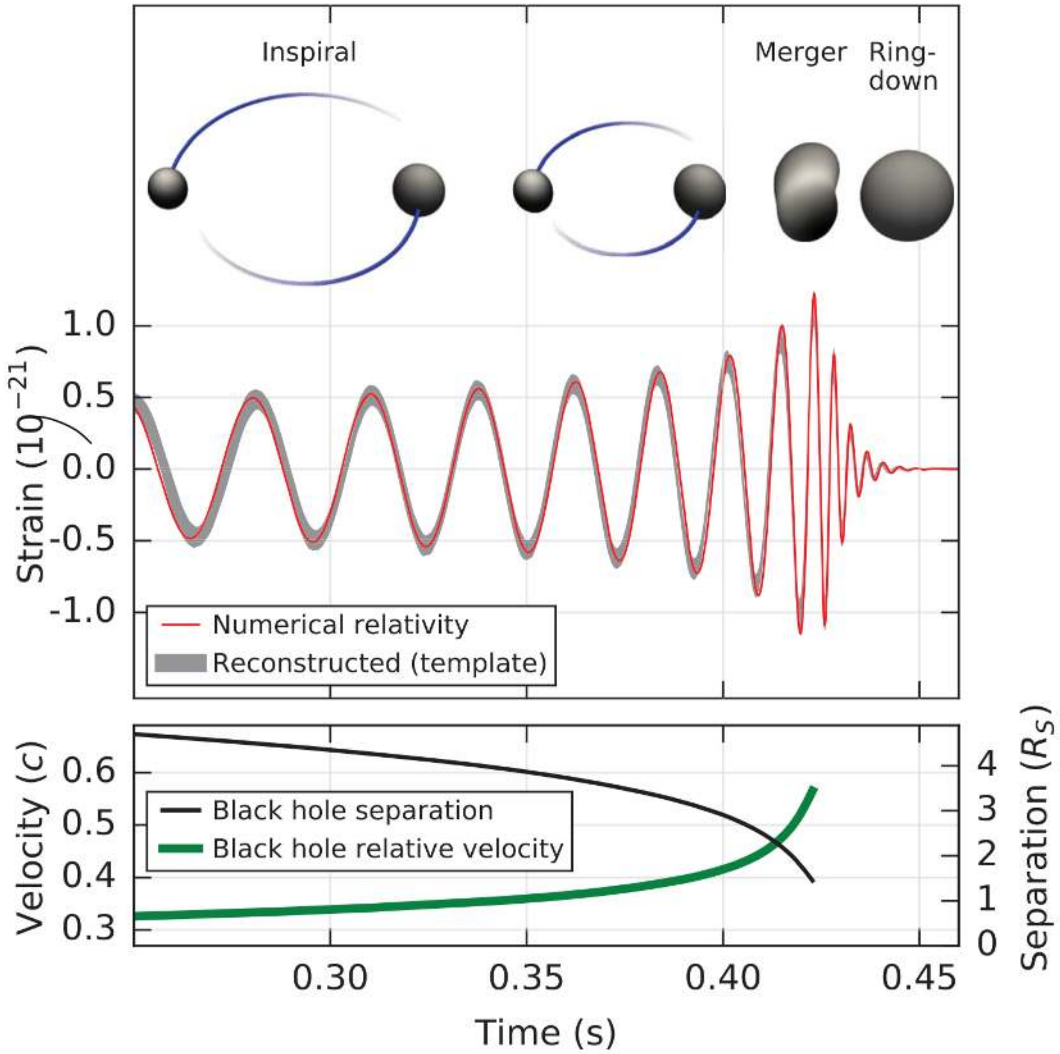
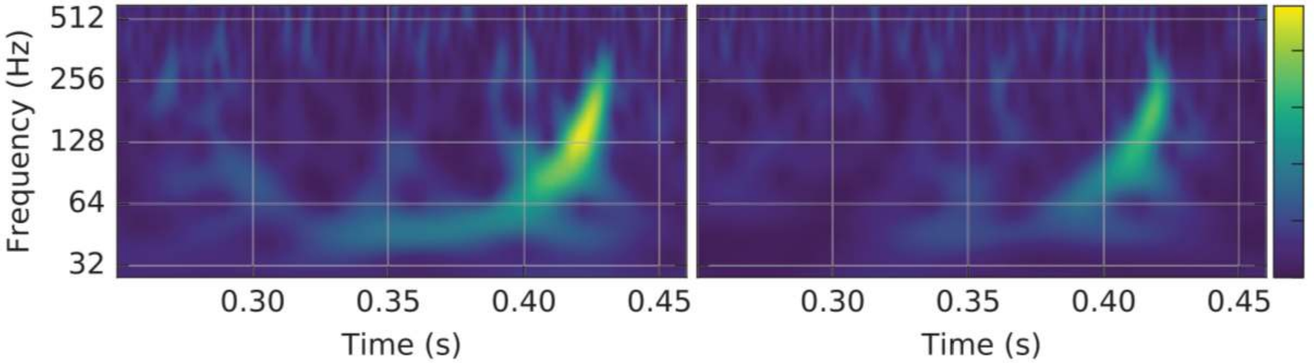
PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

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

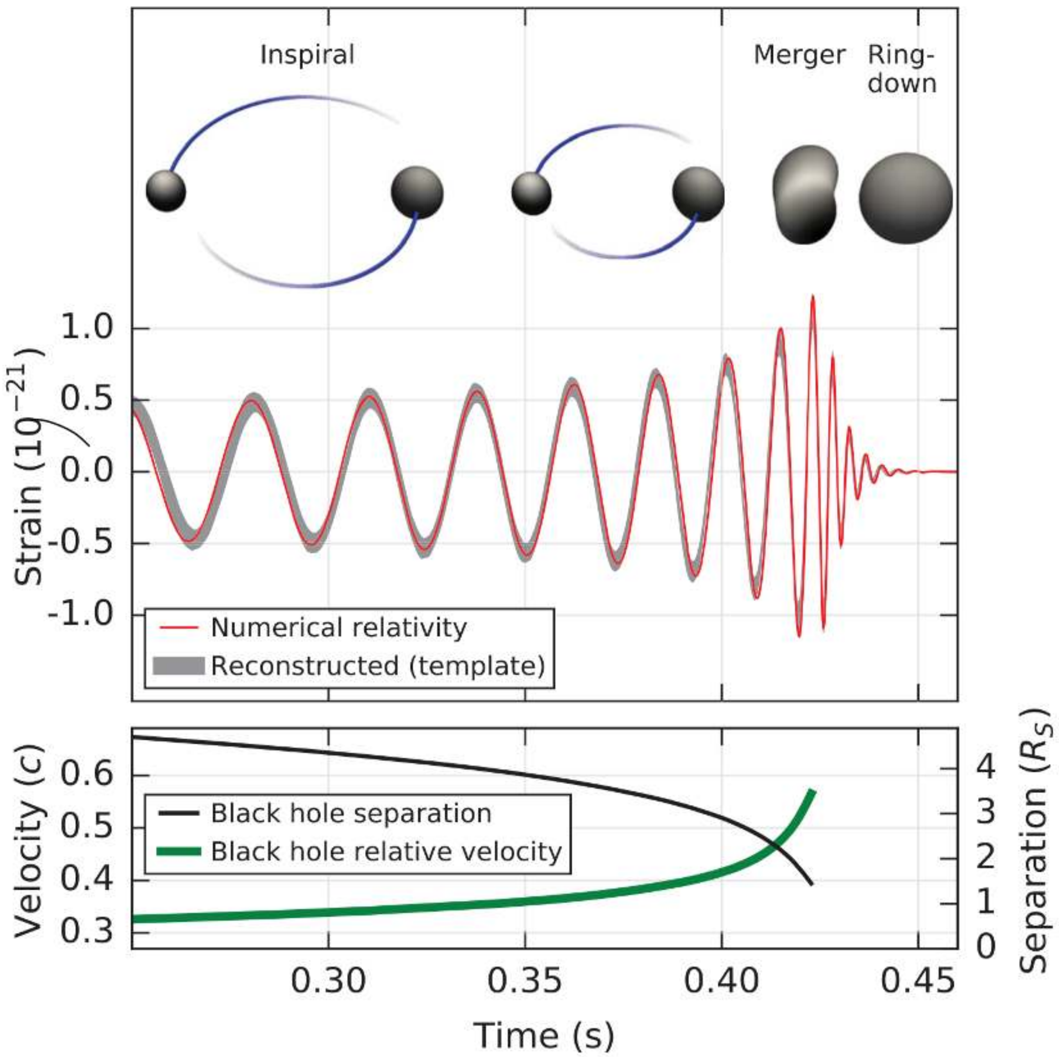




interferometers

Camilo García Cely, University of Valencia-CSIC

Gravitational waves




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

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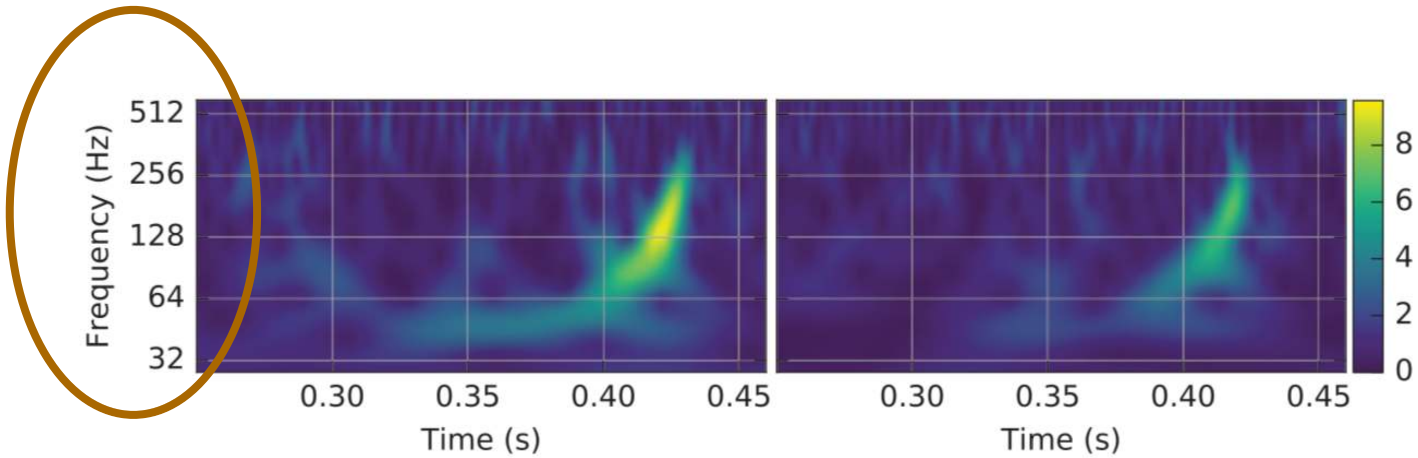


$$f \approx \frac{1}{2\pi}\sqrt{\frac{GM}{R^3}} \ll 10\,\mathrm{kHz}$$

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

High-frequency gravitational waves

Part of a collection:

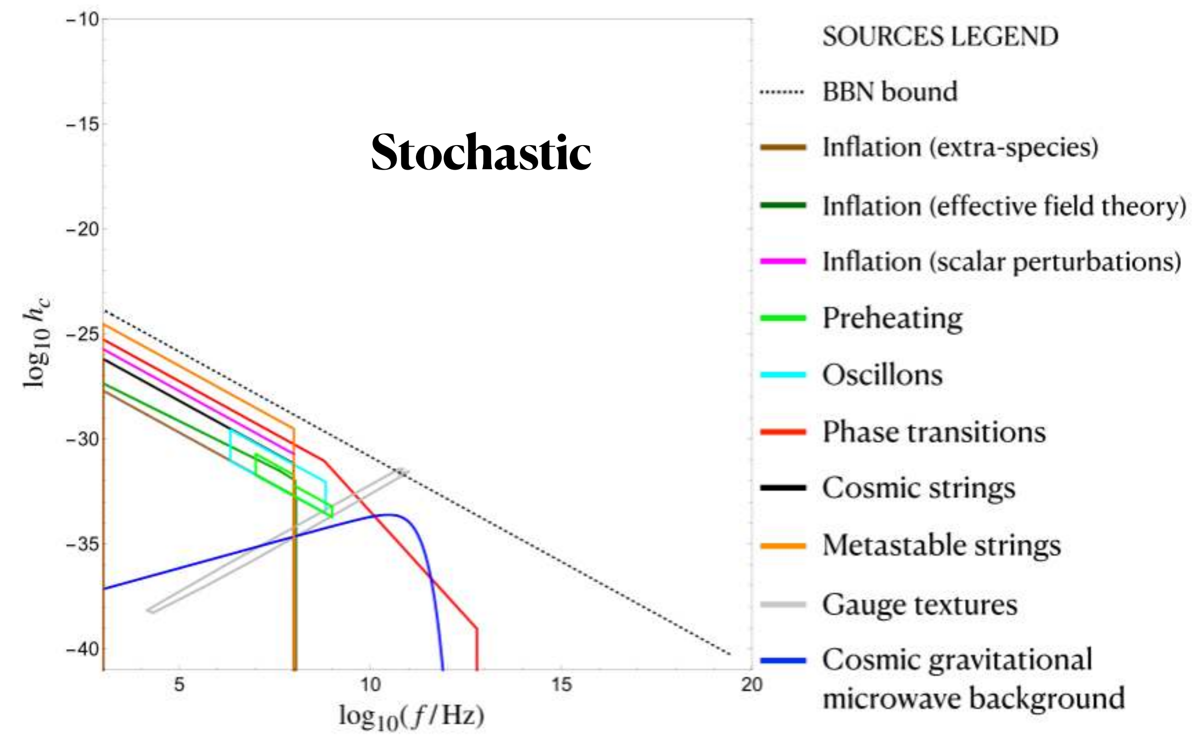
Gravitational Waves

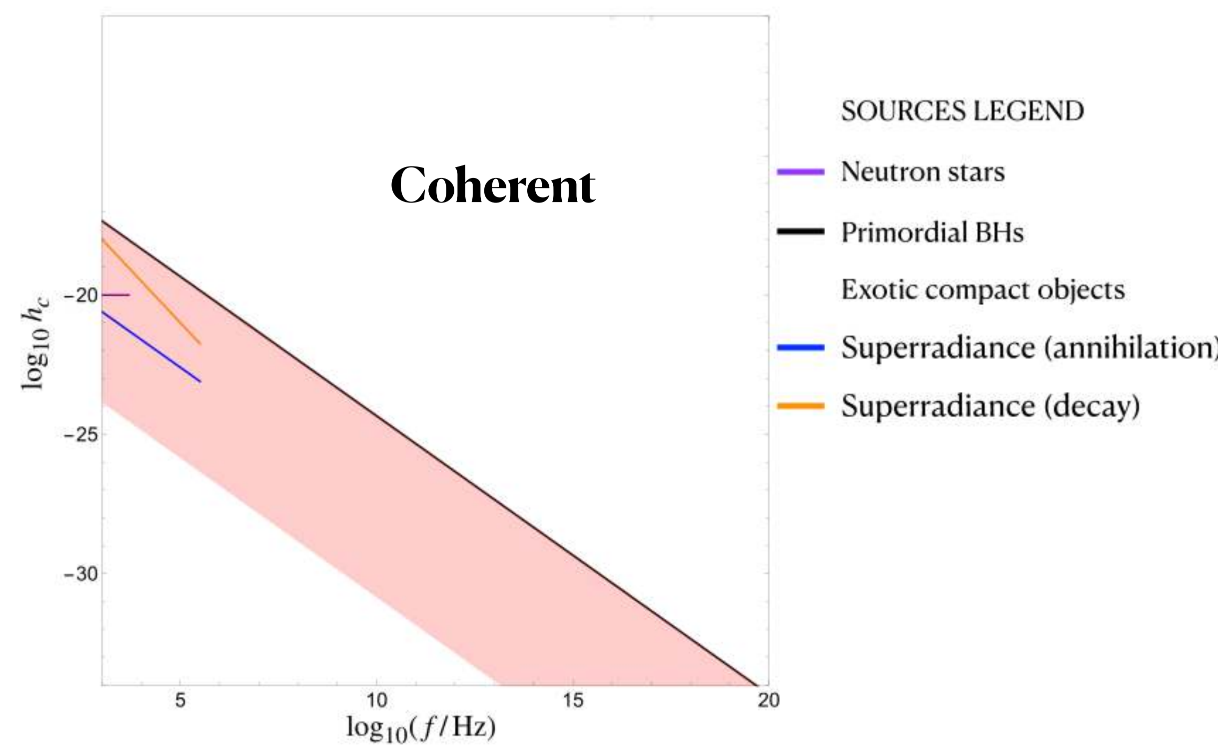
Review Article | Open Access | Published: 06 December 2021

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

Motivation

The Gertsenhstein effect

Axions versus high-frequency gravitational waves

Revisiting Gertsenhstein's ideas

SOVIET PHYSICS JETP VOLUME 14, NUMBER 1 JANUARY, 1962

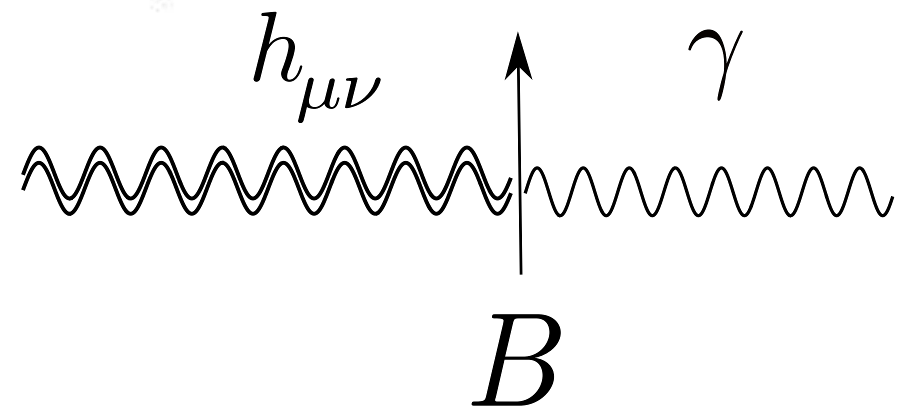
WAVE RESONANCE OF LIGHT AND GRAVITIONAL WAVES

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

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

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

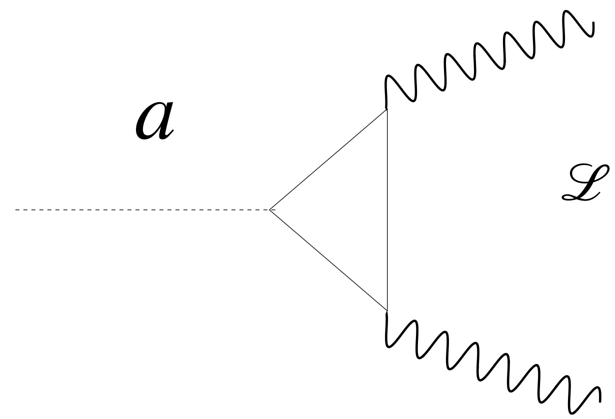
Valerie Domcke and Camilo Garcia-Cely
Phys. Rev. Lett. **126**, 021104 – Published 14 January 2021

- The process is strictly analogous to axion conversion.

Raffelt, Stodolski'89

QCD axion as dark matter

- Pseudoscalar field



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- Excellent dark matter candidate

Weinberg, Wilczek 1978

Collisionless Cold
Dark Matter

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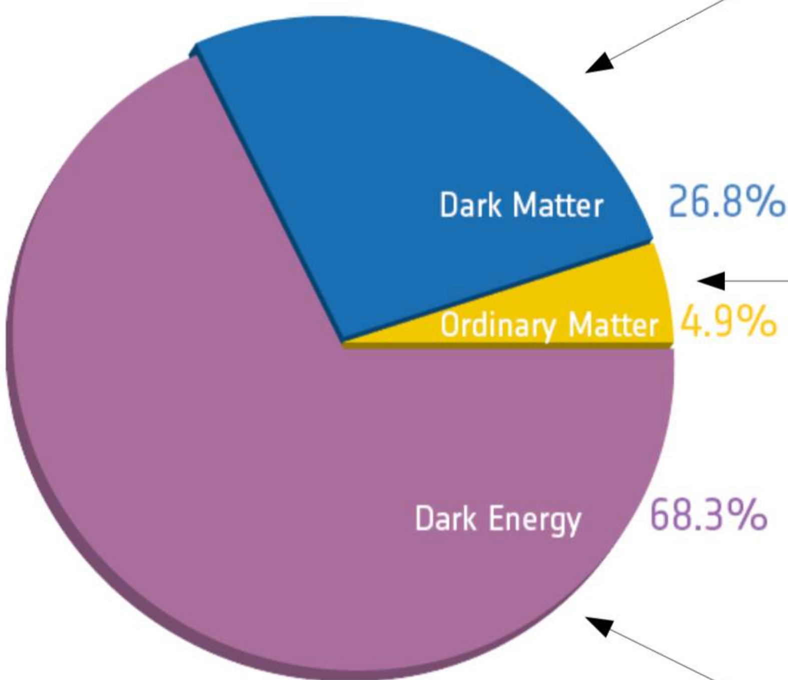

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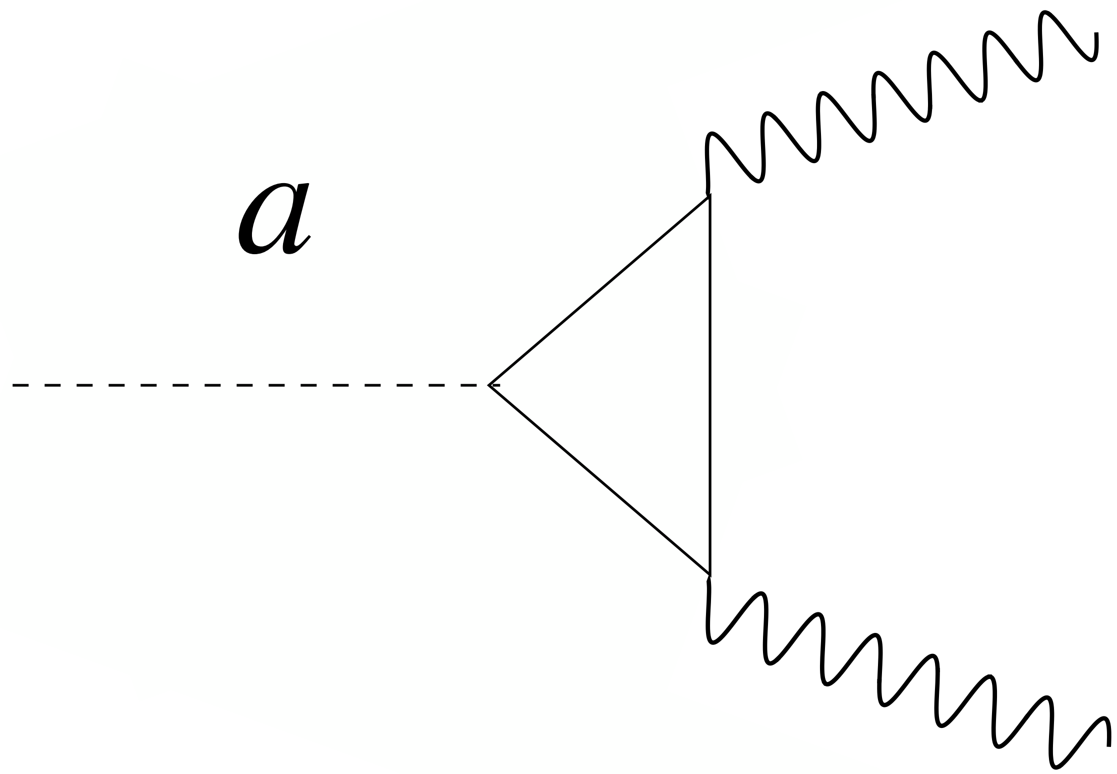
?

Axion electrodynamics



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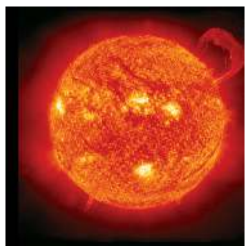
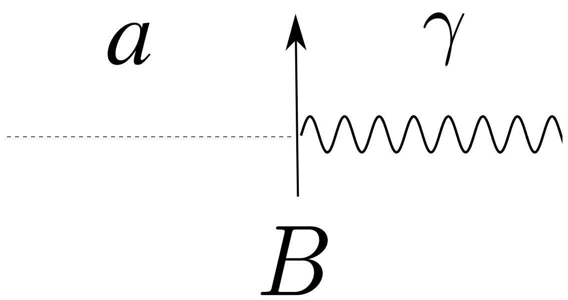
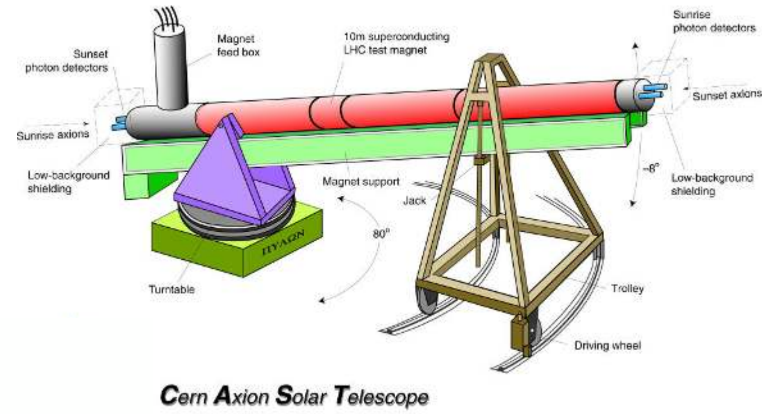
Axion electrodynamics

- Helioscopes (X rays)

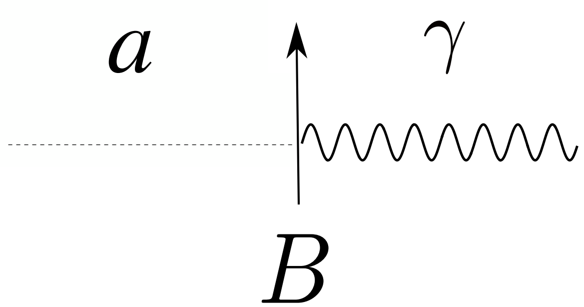






- CAST
- IAXO
- .....

- Haloscopes (radio frequencies)



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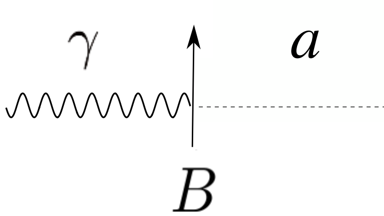
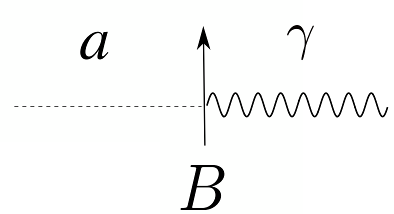
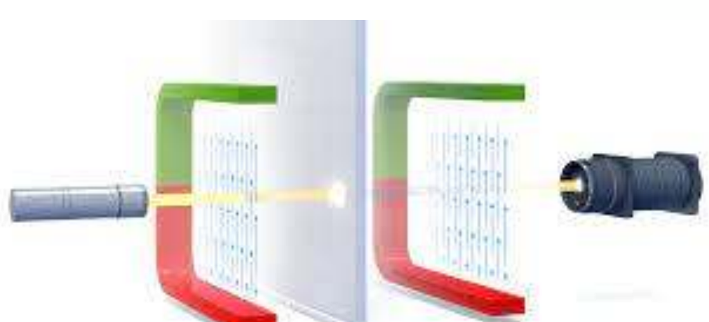
- Purely lab experiments







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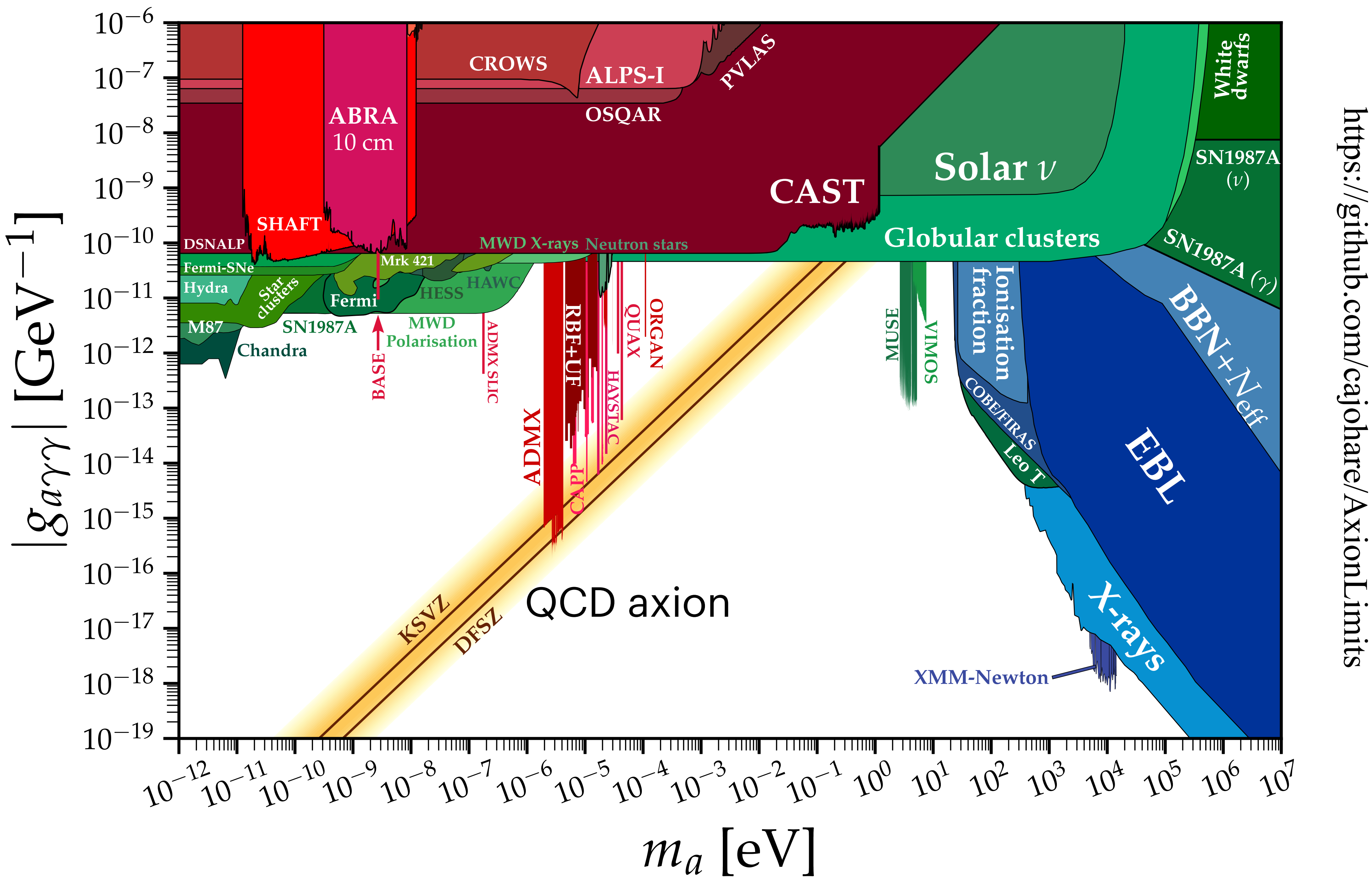
Axion electrodynamics



$$g_{a\gamma\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$$

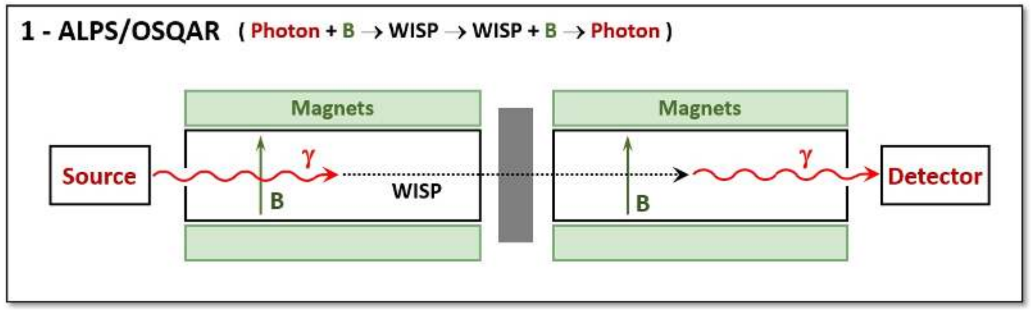
DFSZ (Dine, Fischler, Srednicki, Zhitniskii)

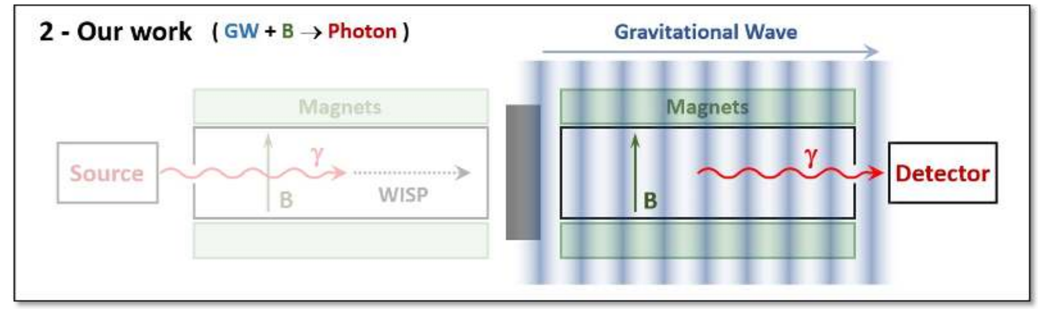
axions couple to fermions $E/N = 8/3$

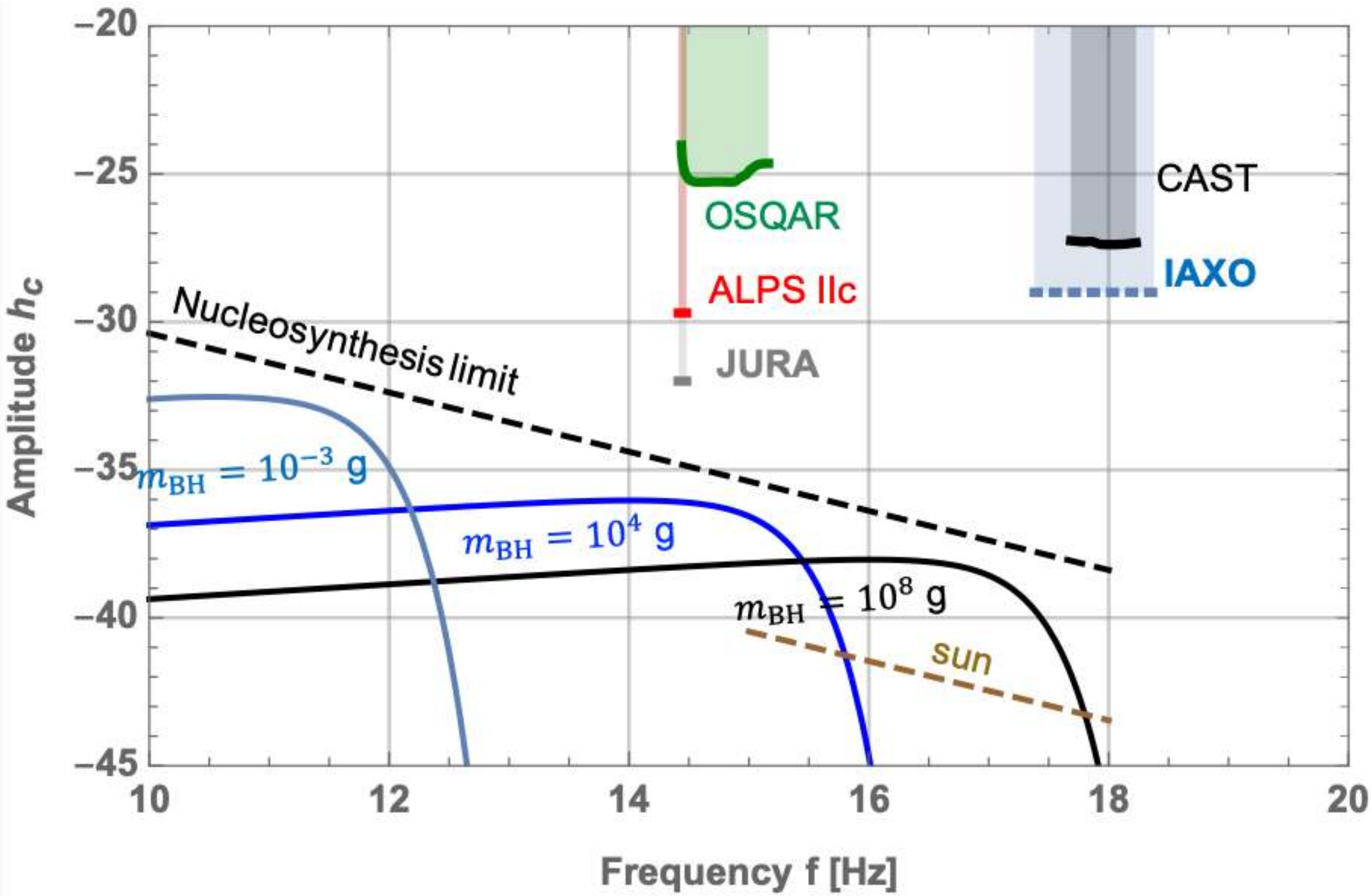
KSVZ (Kim, Shifman, Vainshetein, Zakharov)

axions couple to exotic heavy quarks only. $E/N = 0$

The (inverse) Gertsenhstein Effect







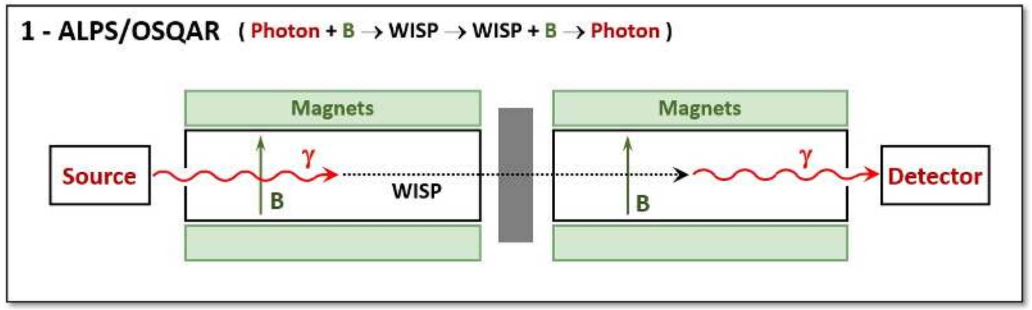
A. Ejlli, D. Ejlli, A. M. Cruise, G. Pisano & H. Grote

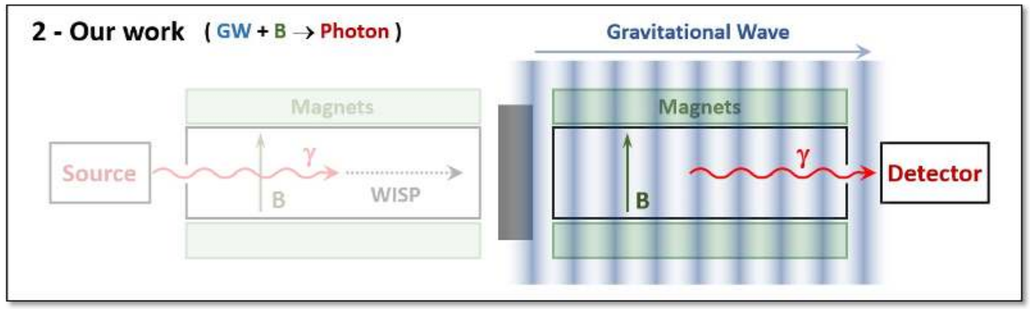
The European Physical Journal C **79**, Article number: 1032 (2019)

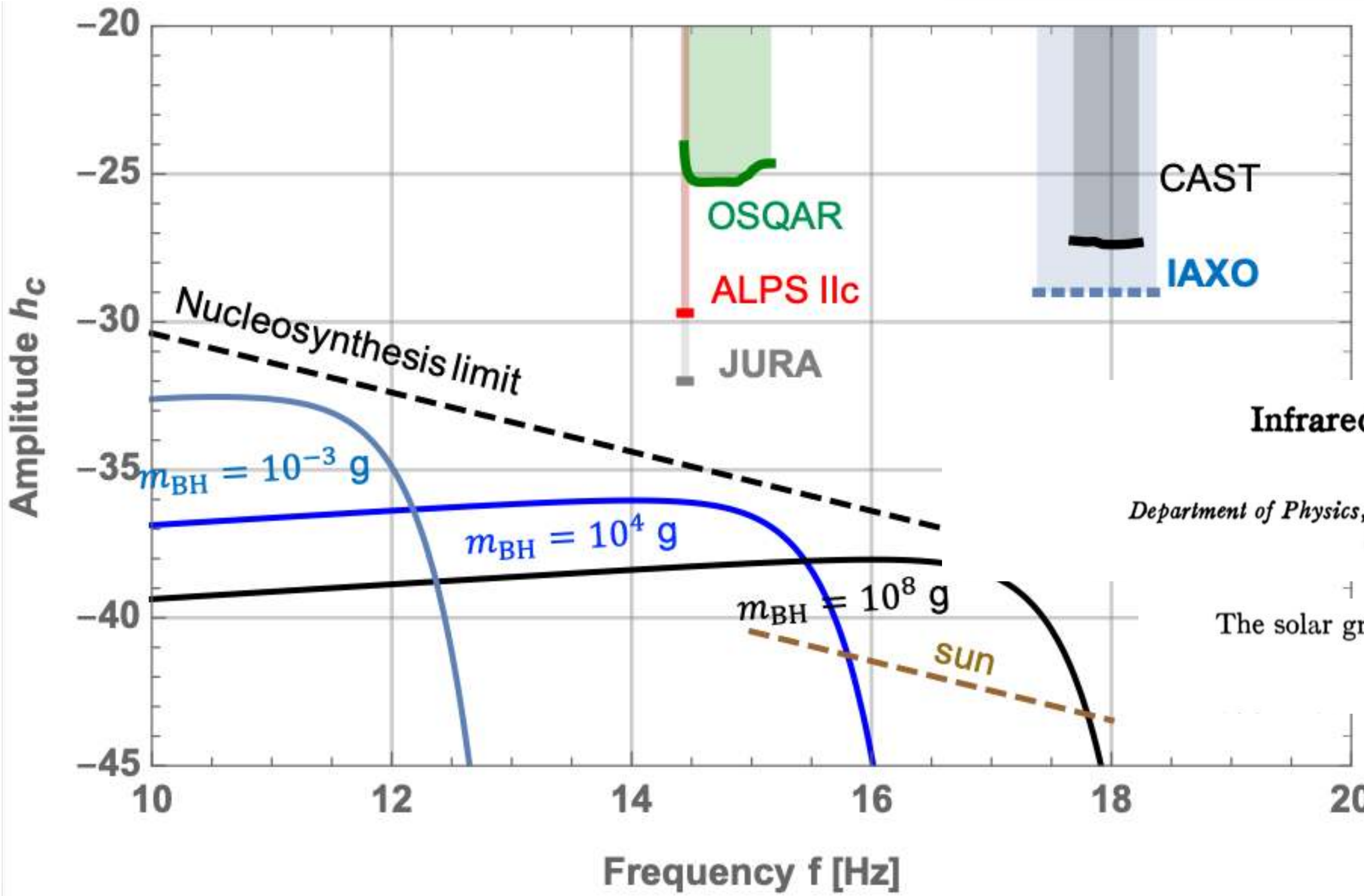
Standard model backgrounds

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

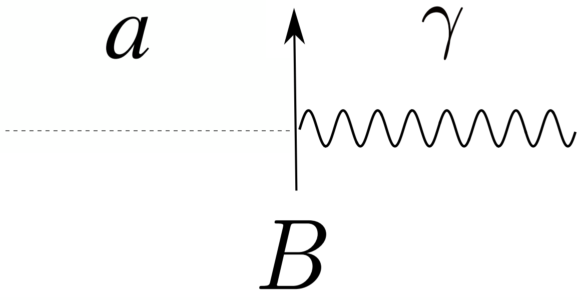
$$P_{\odot} \simeq 6 \times 10^{14} \text{ erg/sec}. \quad (4.24)$$

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

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

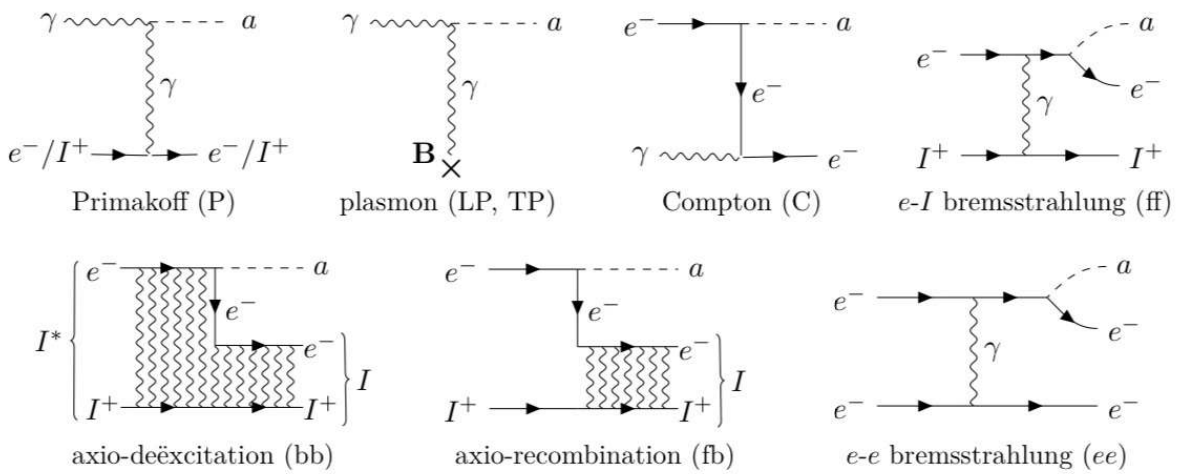
Solar emission of axions

- 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

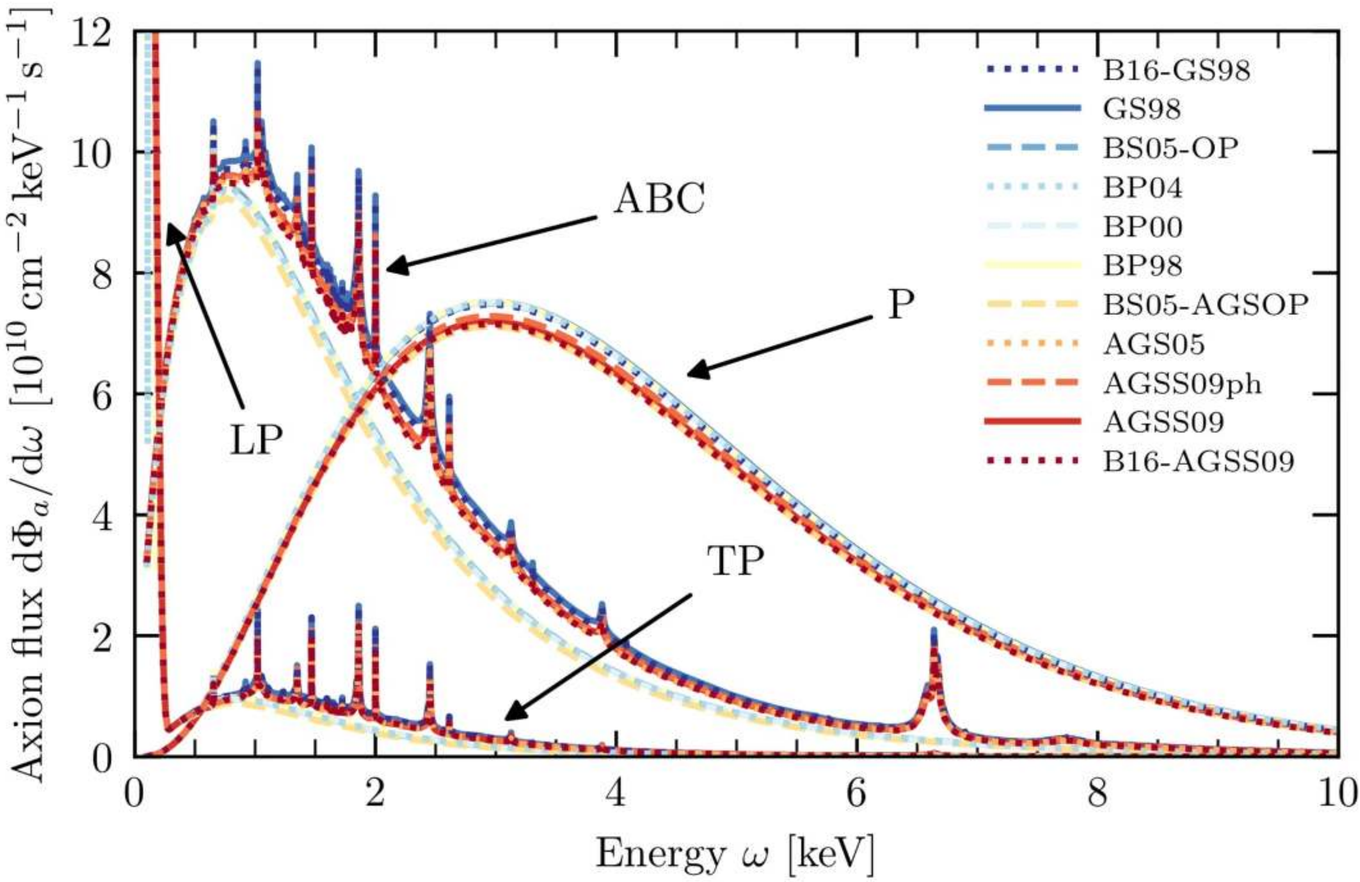
N. V. Mikheev
Department of Theoretical Physics, Yaroslavl State University, Sovietskaya 14, Yaroslavl 150000, Russia

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

L. A. Vassilevskaya

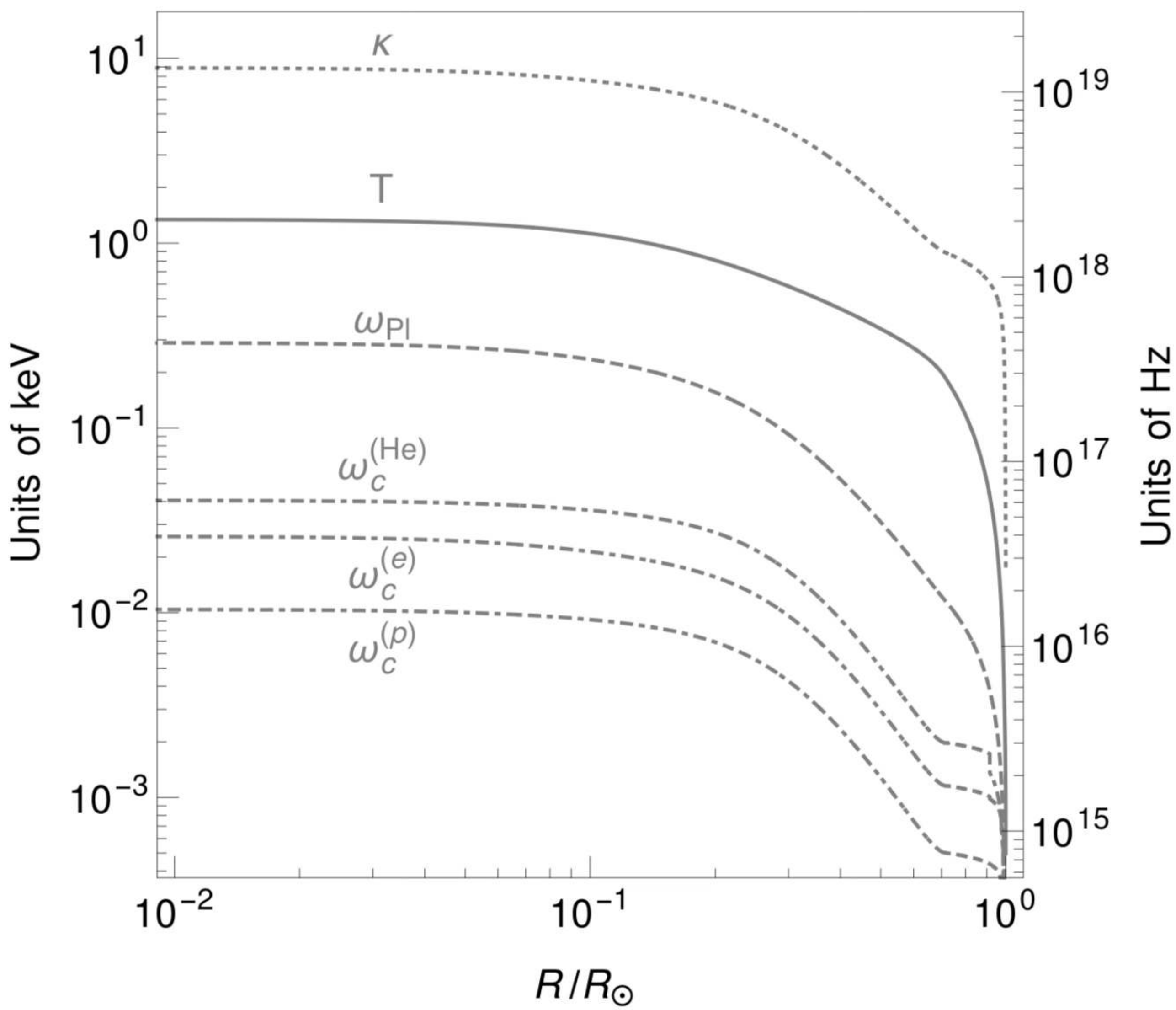
Solar axion flux from the axion-electron coupling

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



The (inverse) Gertsenhstein Effect

García-Cely, Ringwald, 2024



Infrared Photons and Gravitons*

Steven Weinberg†

Department of Physics, University of California, Berkeley, California

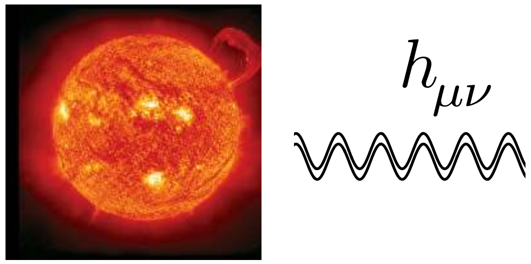
(Received 1 June 1965)

The solar gravitational radiation power is then

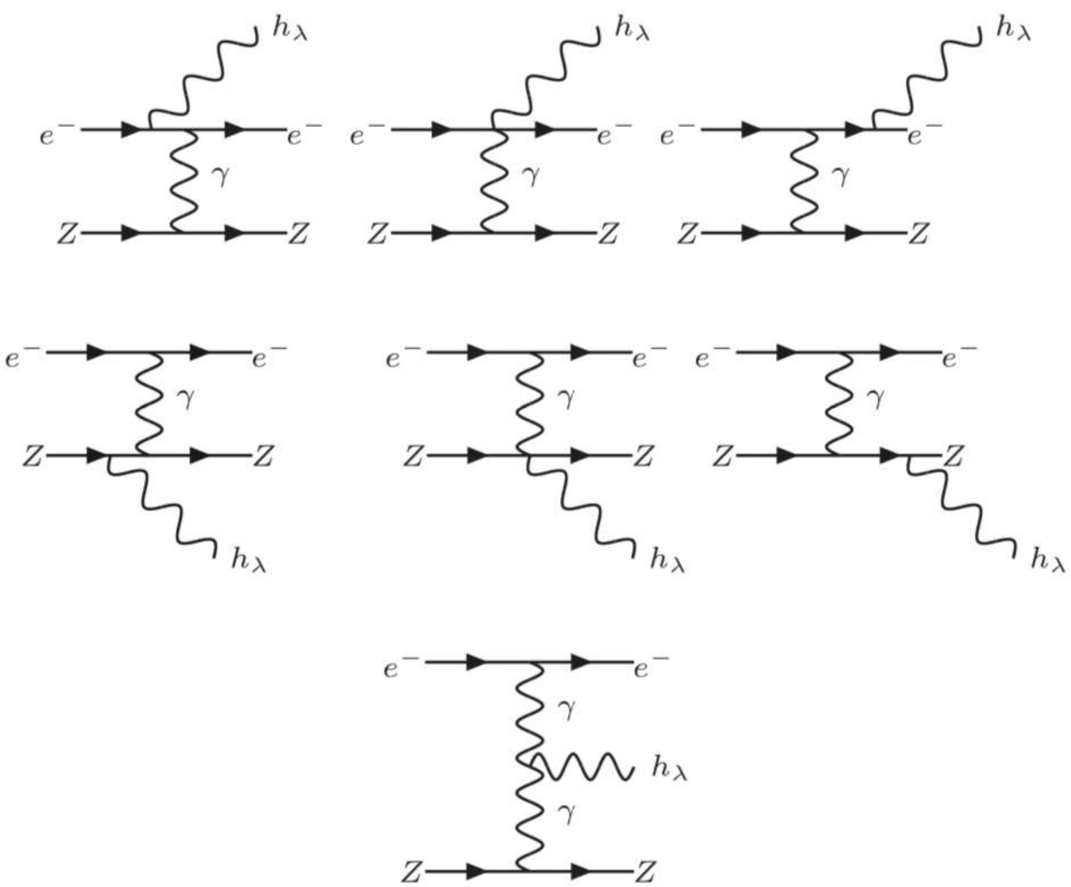
$$P_\odot \simeq 6\times 10^{14}\ \text{erg/sec}. \quad (4.24)$$

Solar emission of gravitational waves

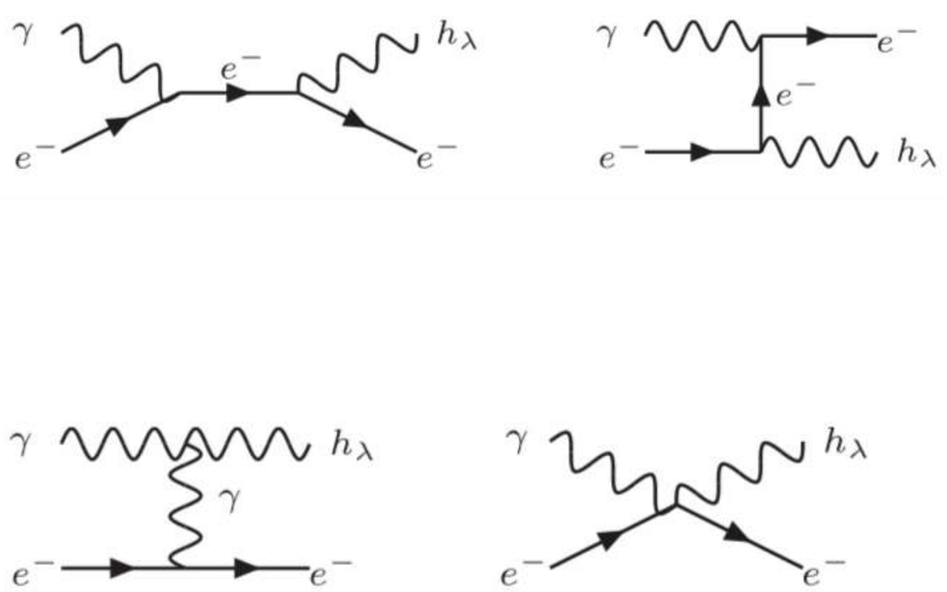
Microscopic contribution: graviton emission



Bremsstrahlung



Photoproduction



García-Cely, Ringwald, 2024

Solar emission of gravitational waves

Macroscopic contribution: Hydrodynamical fluctuations

García-Cely, Ringwald, 2024

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

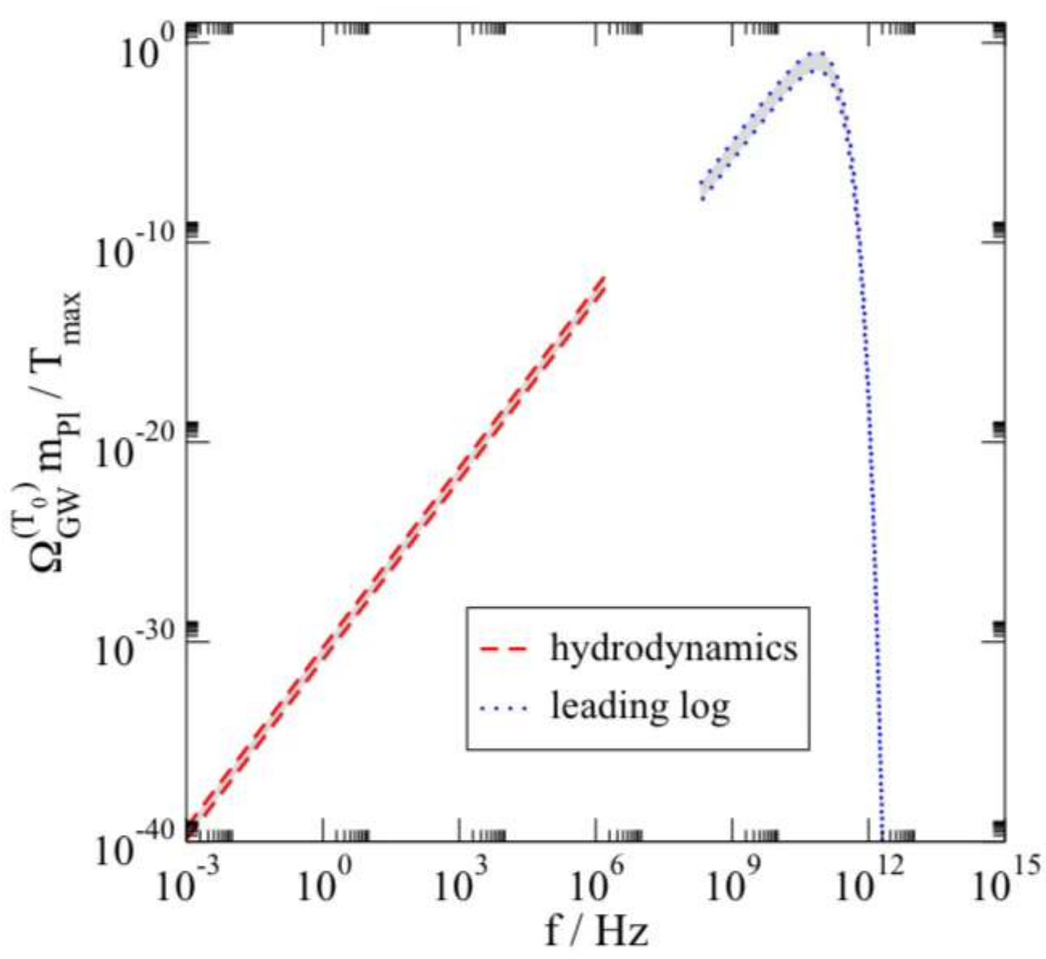
Article PDF

References

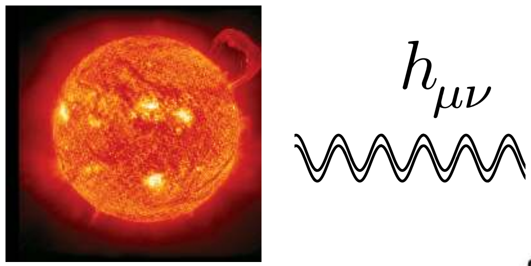
+ Article and author information

Abstract

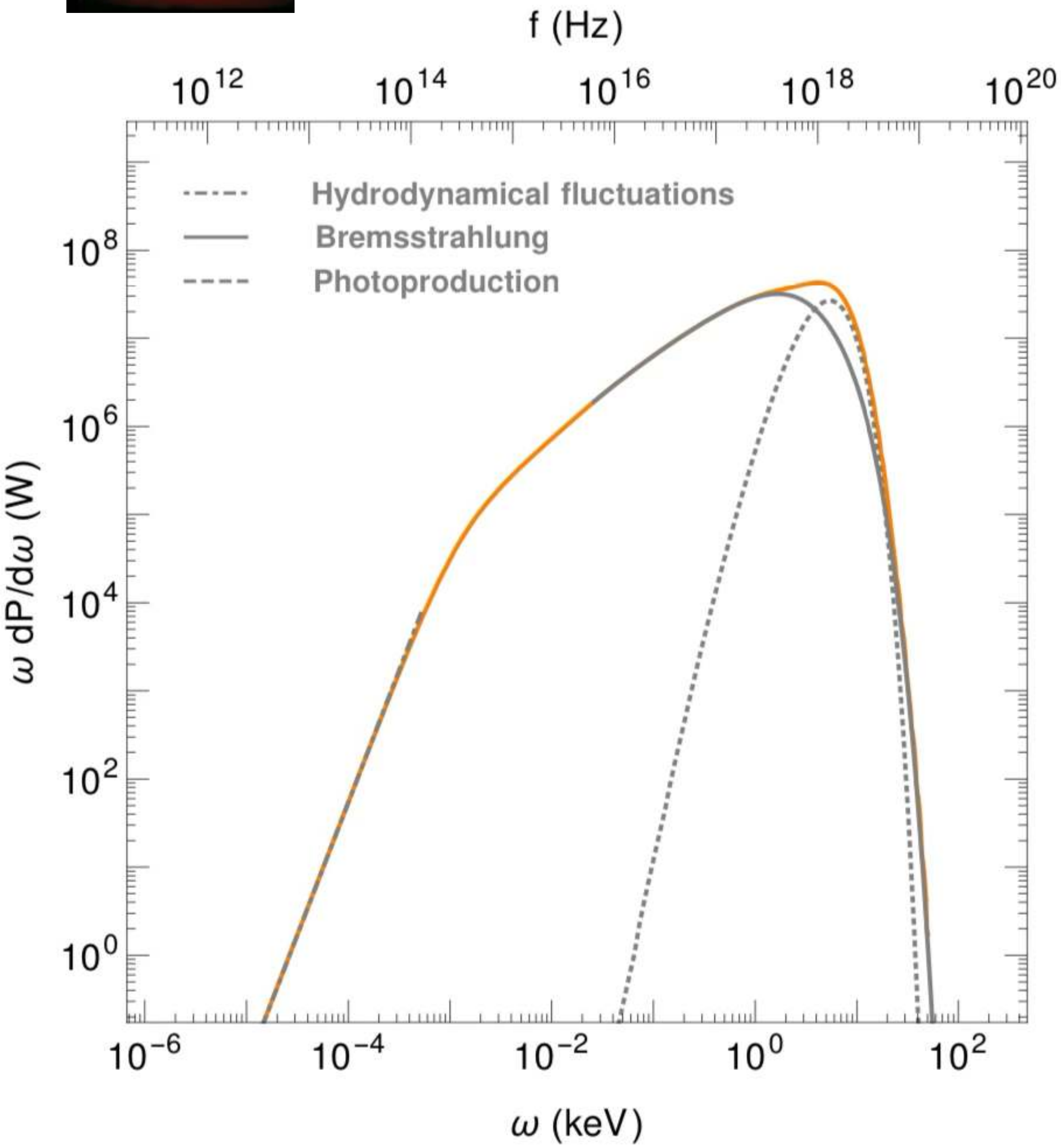
Because of physical processes ranging from microscopic particle collisions to macroscopic hydrodynamic fluctuations, any plasma in thermal equilibrium emits gravitational waves. For the largest wavelengths the emission rate is proportional to the shear viscosity of the plasma. In the Standard Model at



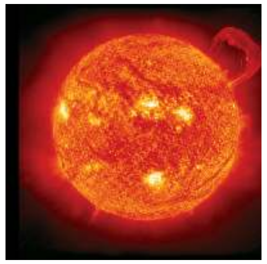
Solar gravitational waves



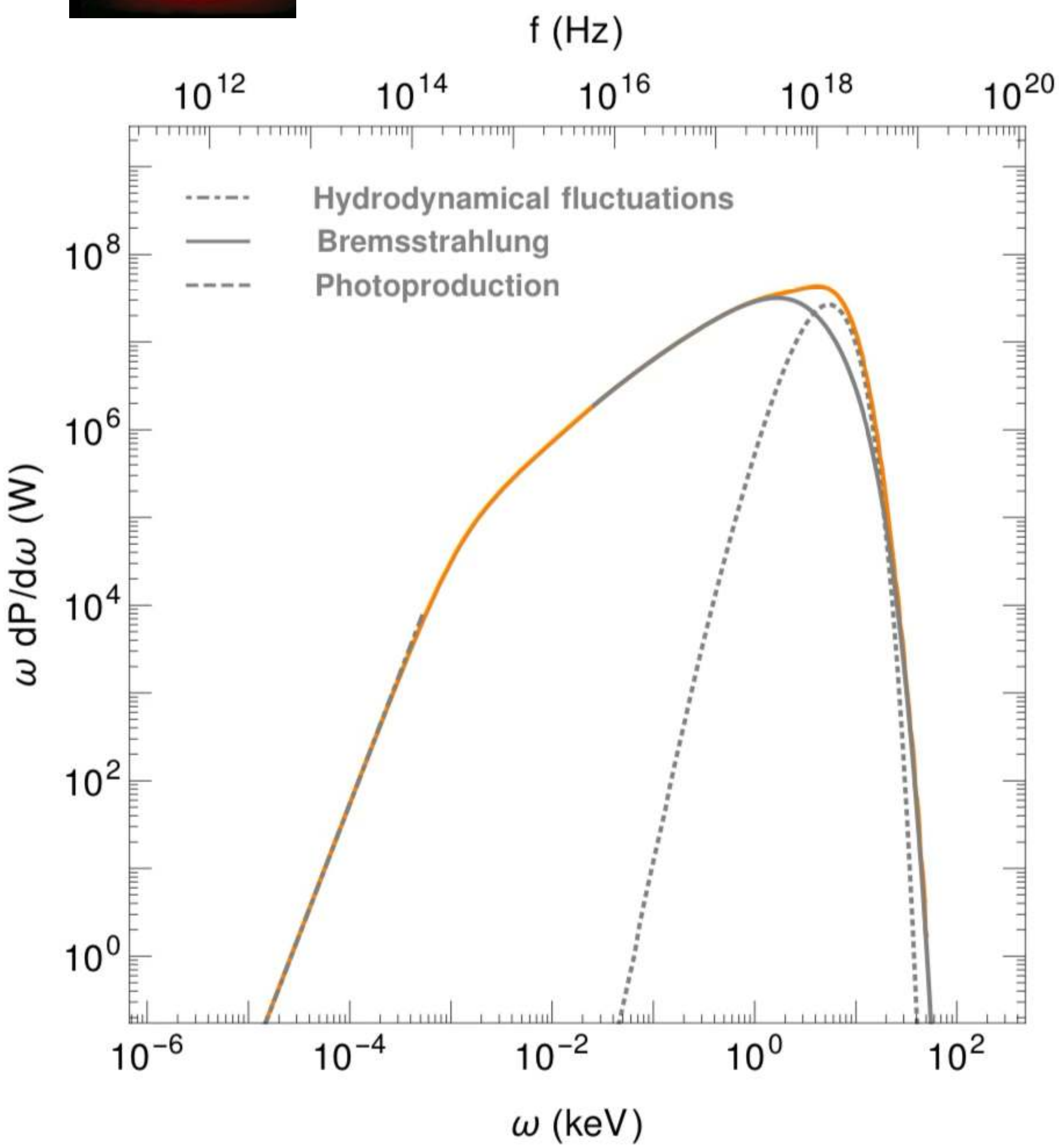
García-Cely, Ringwald, 2024

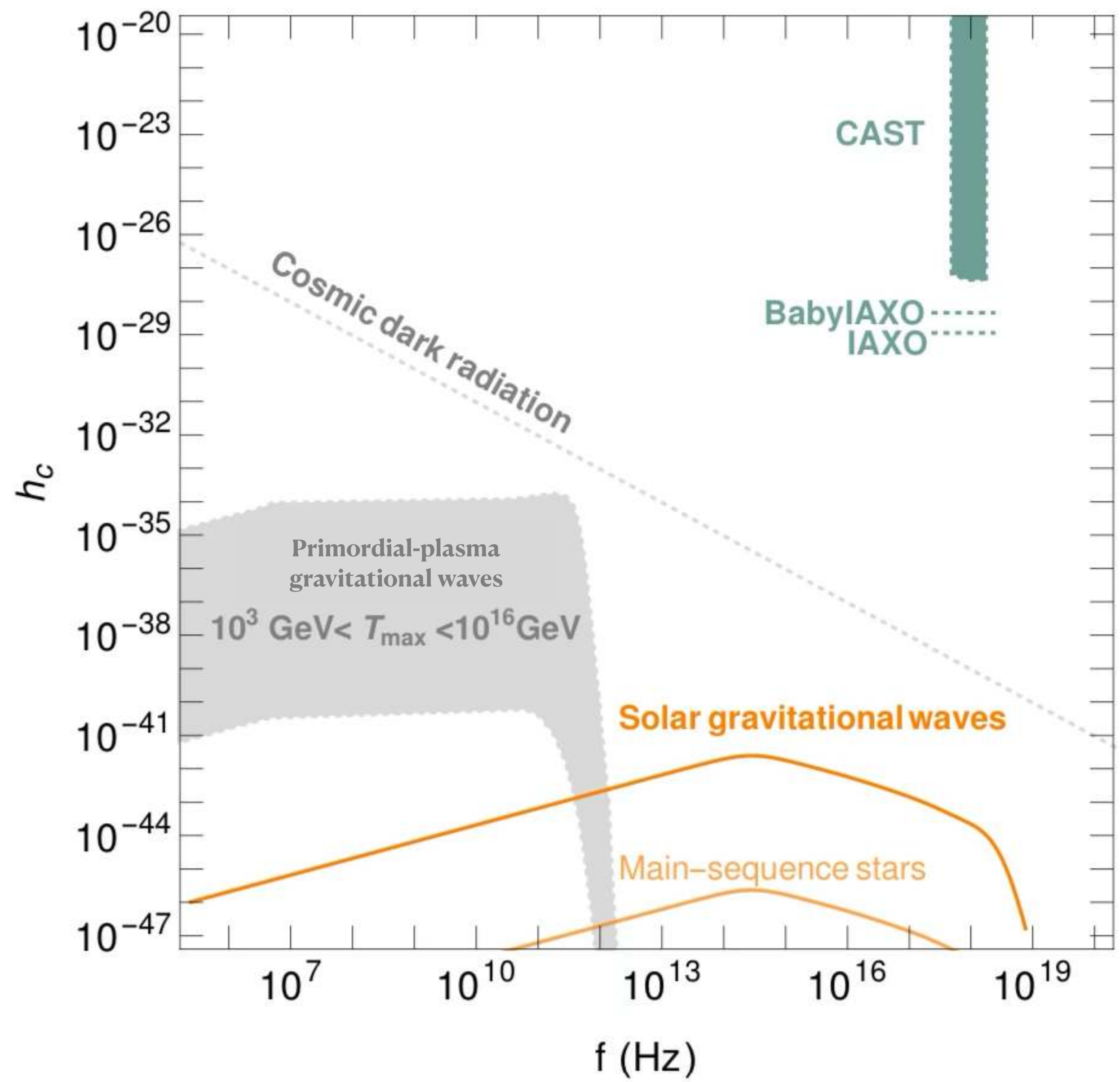


Solar gravitational waves

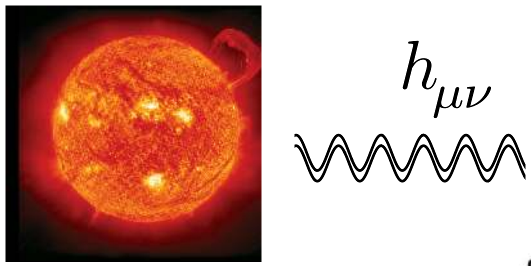


García-Cely, Ringwald, 2024

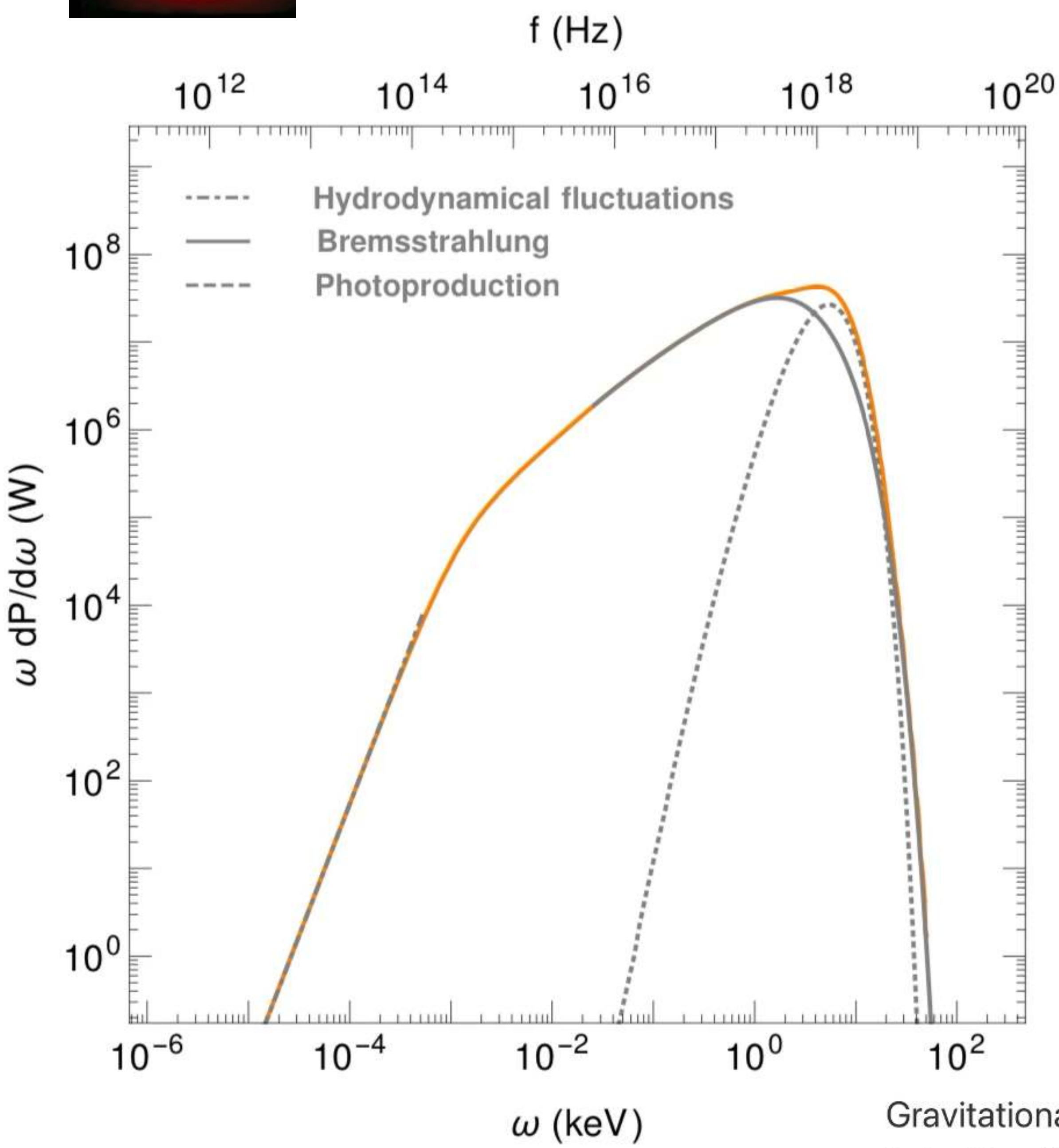


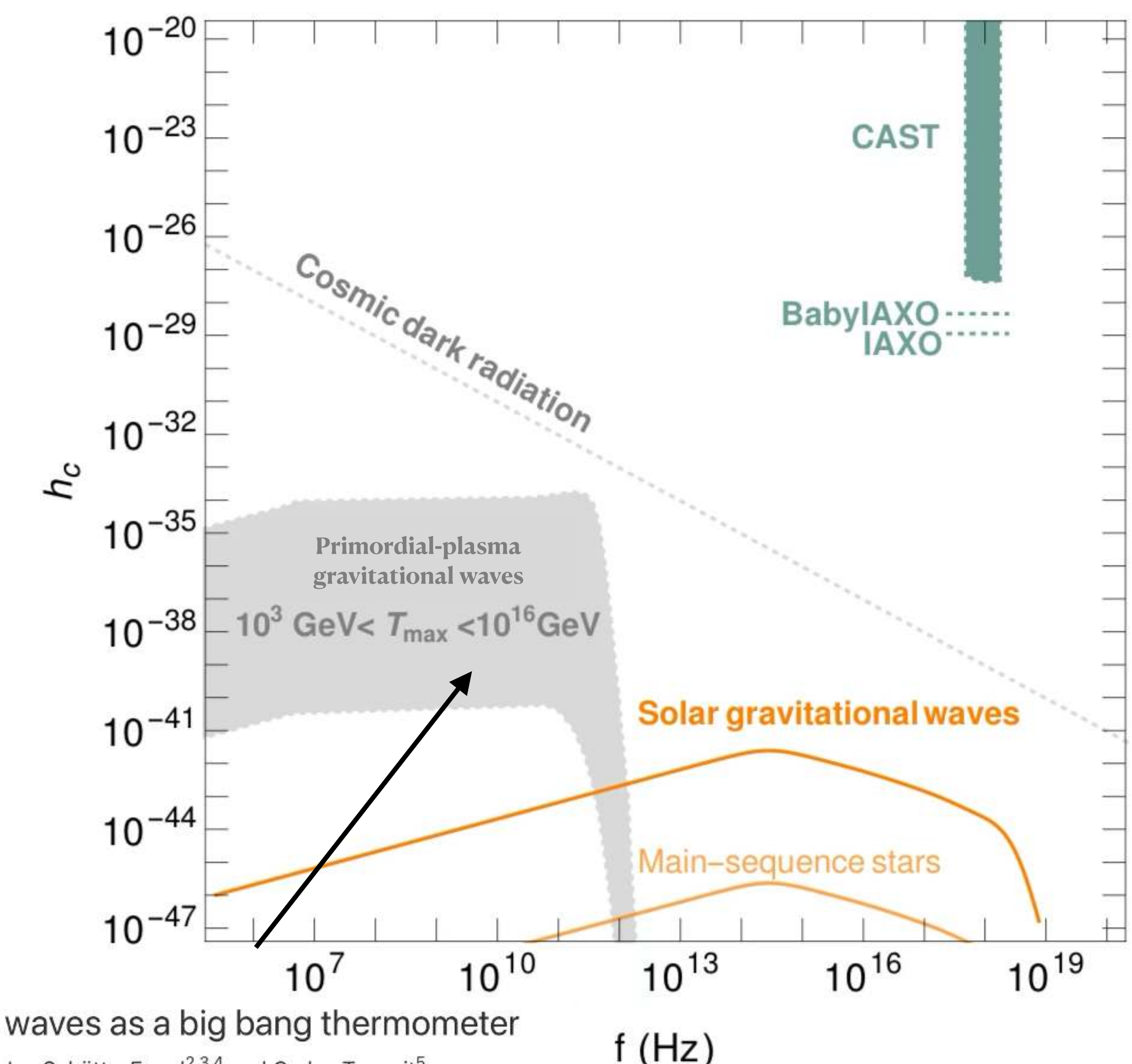


Solar gravitational waves



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

Novel experimental approaches

Axion haloscopes and polarimetry techniques

How does it work?

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

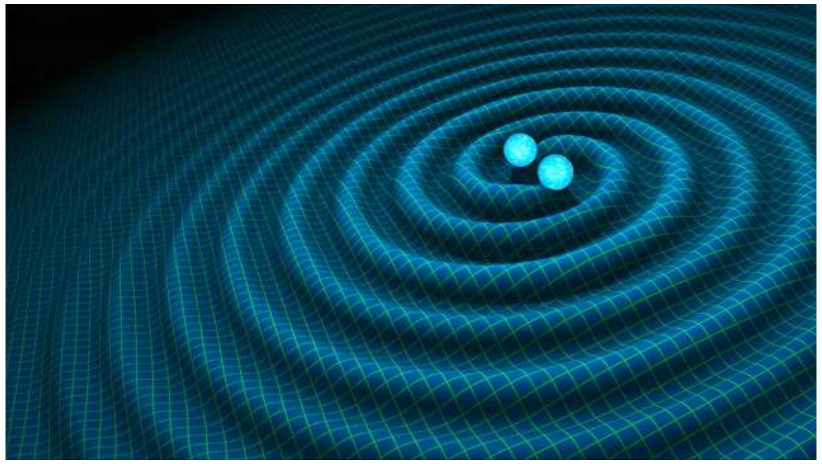
Sikivie, 1983

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

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

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

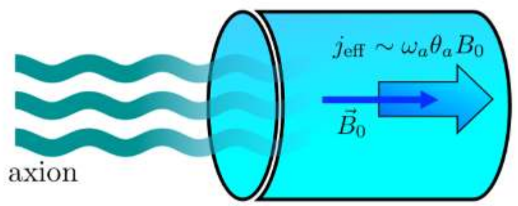
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \qquad \left| h_{\mu\nu} \right| \ll 1$$

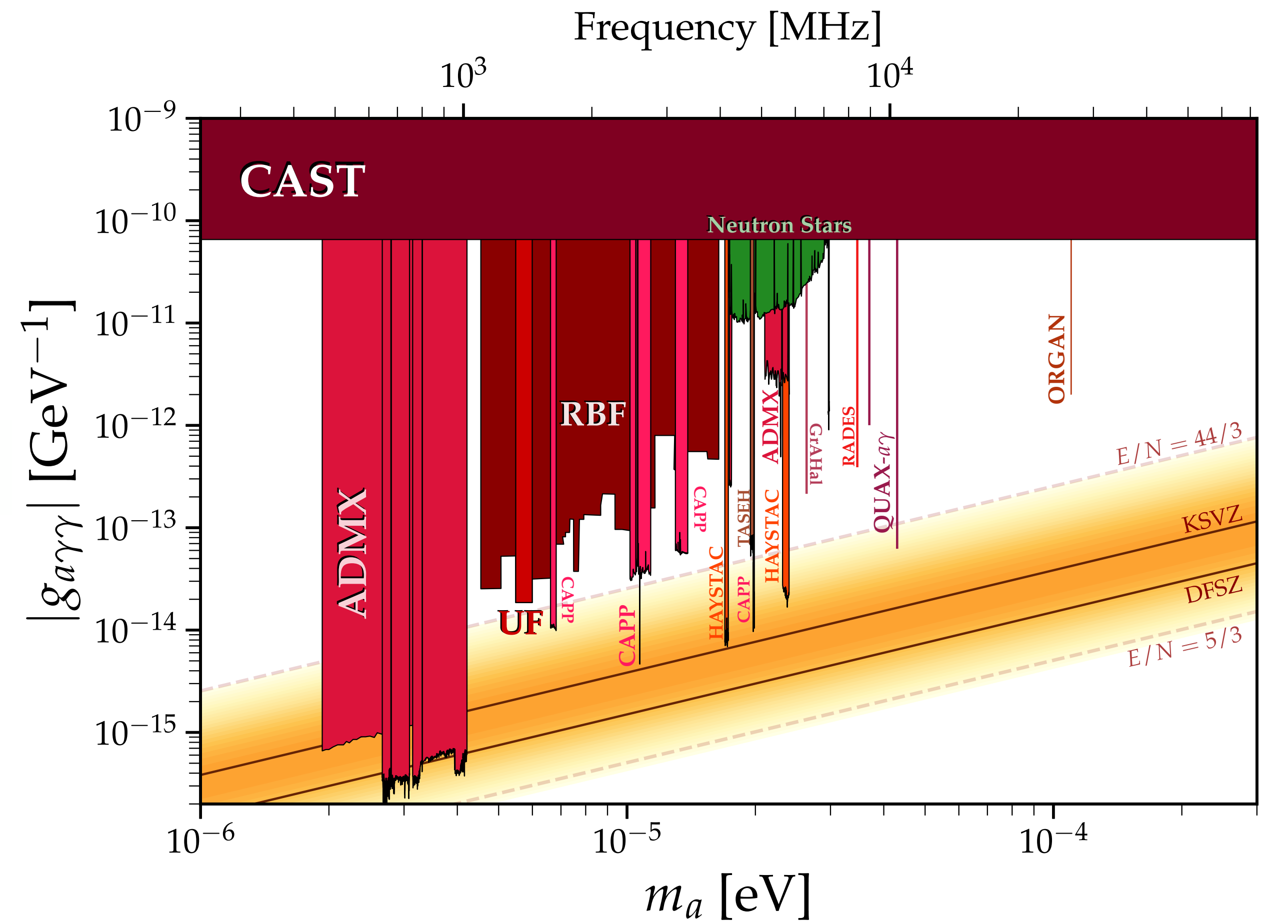


$$j^{\mu}_{\text{eff}} = \partial_\nu \left(-\frac{1}{2} h\, F^{\mu\nu} + F^{\mu\alpha} h^{\nu}{}_{\alpha} - F^{\nu\alpha} h^{\mu}{}_{\alpha} \right)$$

Camilo García Cely, University of Valencia-CSIC

Haloscopes based on microwave cavities





https://github.com/cajohare/AxionLimits

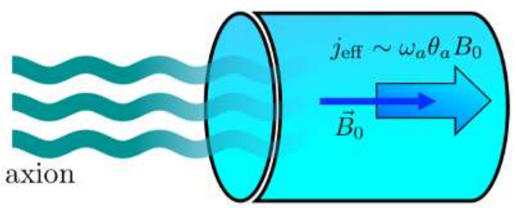
It resonates when the axion frequency matches one of the eigenmode frequencies

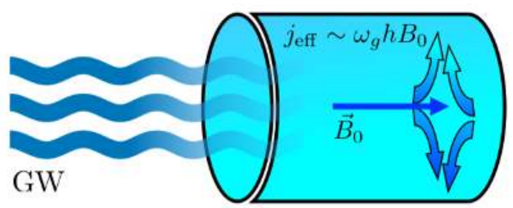
$$\left(\partial_t^2 + \frac{\omega_n}{Q_n}\partial_t + \omega_n^2\right) e_n(t) = -\frac{\int_{V_{\rm cav}} d^3\mathbf{x}\,\mathbf{E}_n^* \cdot \partial_t \boldsymbol{j}_{\rm eff}}{\int_{V_{\rm cav}} d^3\mathbf{x}\,\left|\mathbf{E}_n\right|^2}$$

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

Camilo García Cely, University of Valencia-CSIC

Haloscopes based on microwave cavities





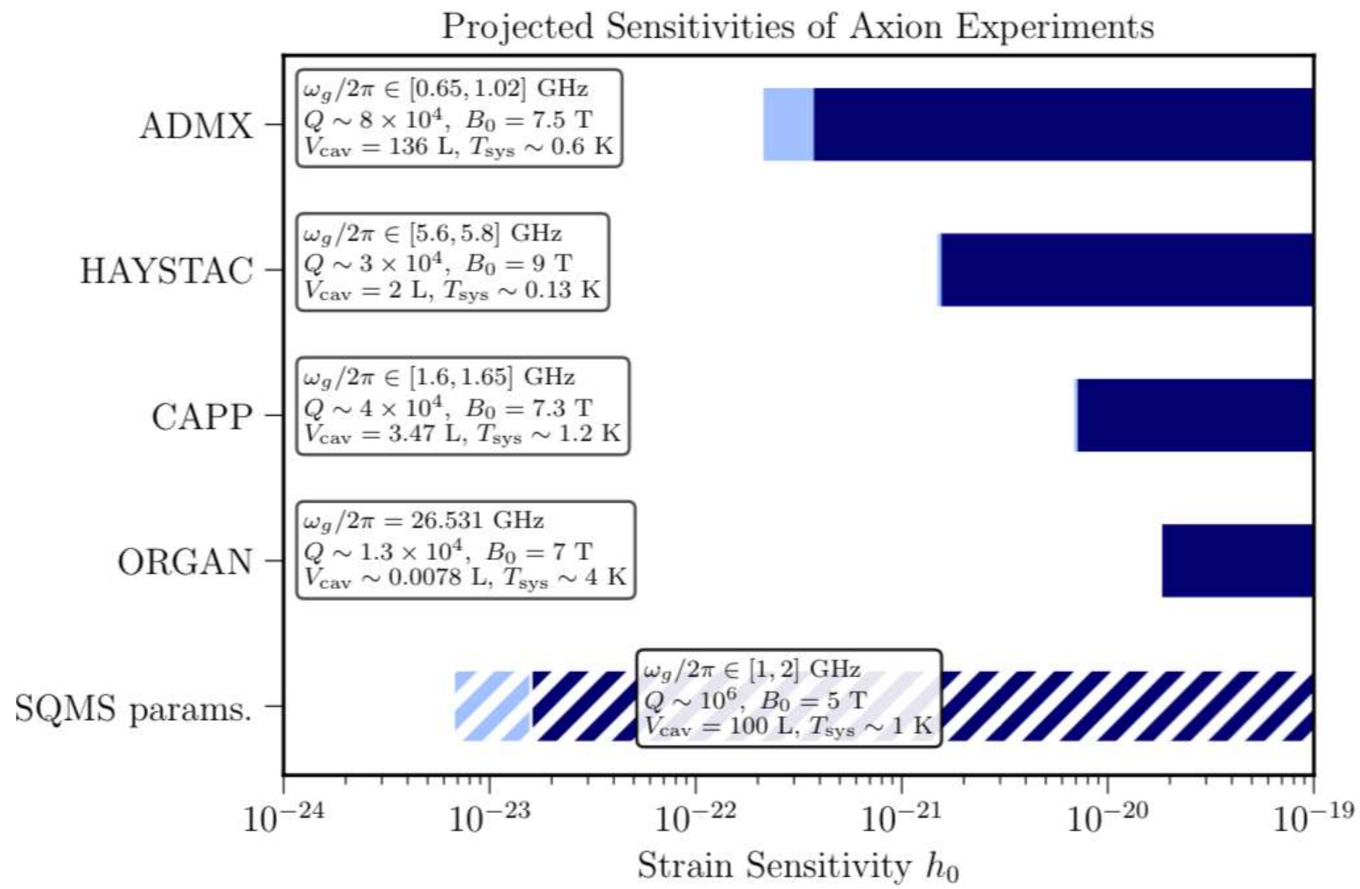
It resonates when the GW frequency matches one of the eigenmode frequencies

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



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

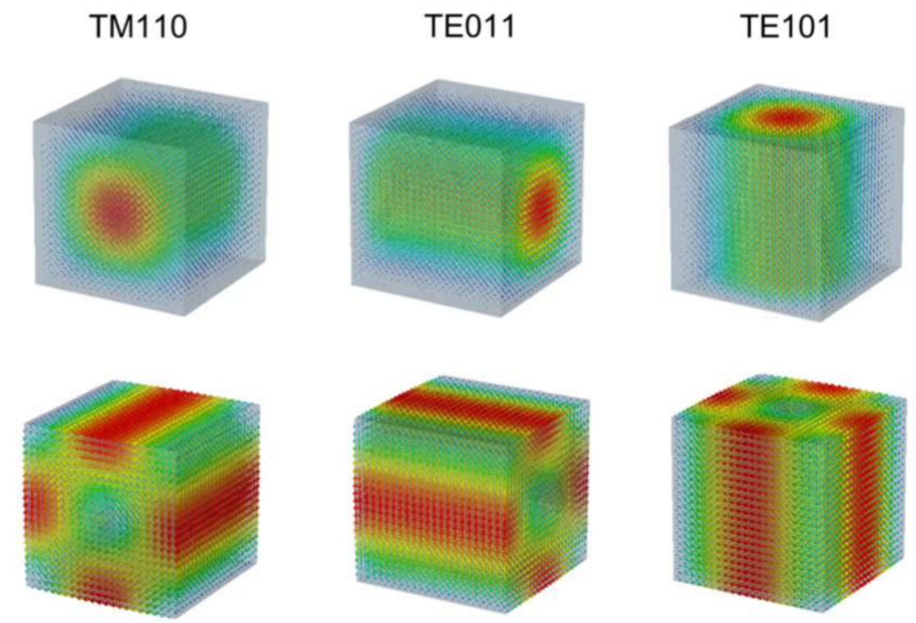


FIG. 3. Electric (up) and magnetic (down) field distributions for the three considered modes TM_{110}, TE_{011} and TE_{101} of cavity C1. The electromagnetic field distributions are identical in the other cavities C2 and C3. The red hue represents the largest values for the modules of electric and magnetic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

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

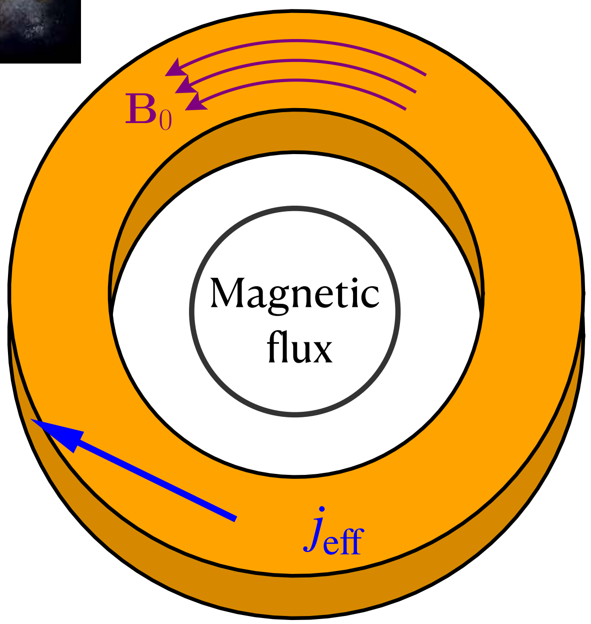
[Submitted on 30 Jul 2024 (v1), last revised 14 Aug 2024 (this version, v2)]

High-frequency gravitational waves detection with the BabyIAXO haloscopes

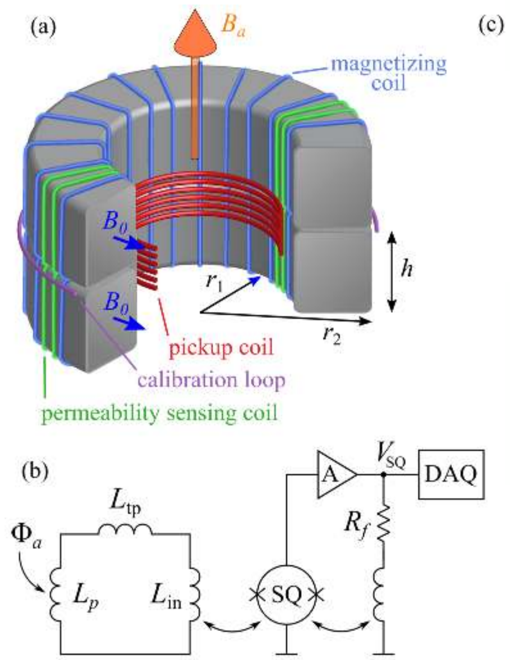
José Reina Valero, Jose R. Navarro Madrid, Diego Blas, Alejandro Díaz Morcillo, Igor García Irastorza, Benito Gimeno, Juan Monzó Cabrera

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.

Haloscopes based on lumped-element detectors



$$\nabla \times \mathbf{B} - \partial_t \mathbf{E} = \underbrace{g_{a\gamma\gamma}\, \partial_t a\, \mathbf{B}_0}_{j_{\rm eff}}$$



(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]

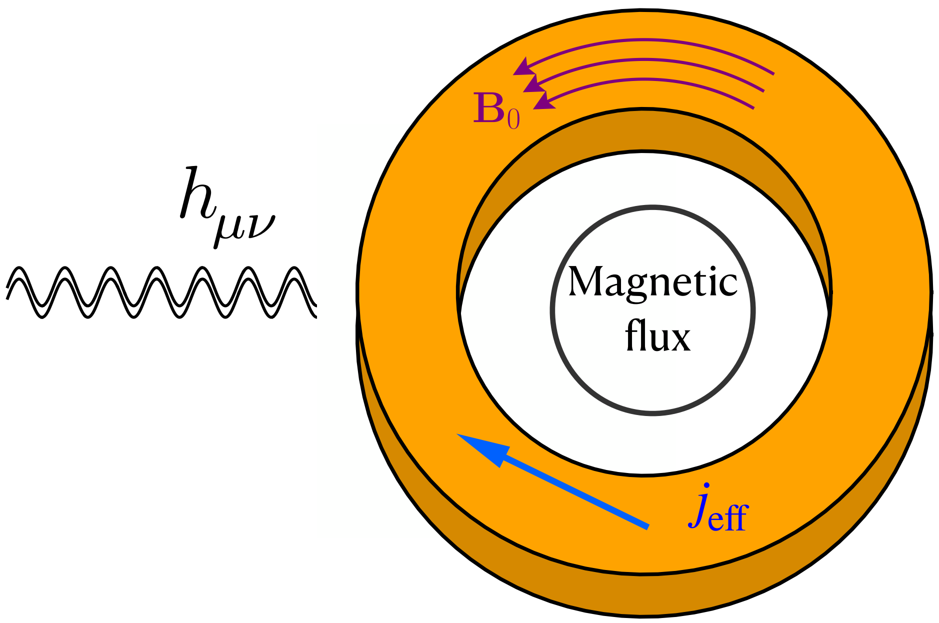
PRL 117, 141801 (2016) PHYSICAL REVIEW LETTERS week ending 30 SEPTEMBER 2016

Broadband and Resonant Approaches to Axion Dark Matter Detection

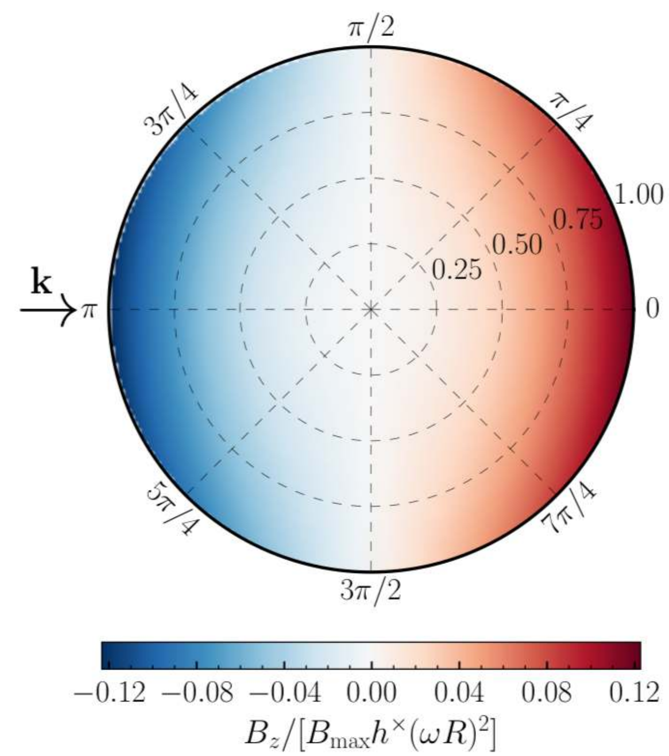
Yonatan Kahn,[1,*] Benjamin R. Safdi,[2,†] and Jesse Thaler[2,‡]
[1]Department of Physics, Princeton University, Princeton, New Jersey 08544, USA
[2]Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
(Received 3 March 2016; published 30 September 2016)

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

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

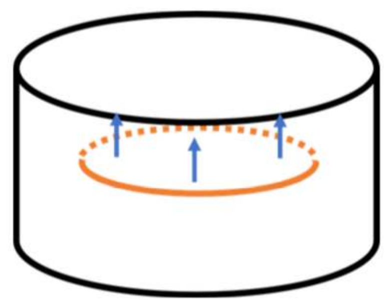
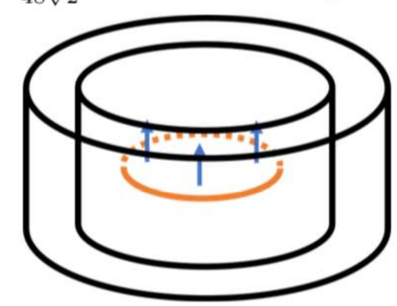
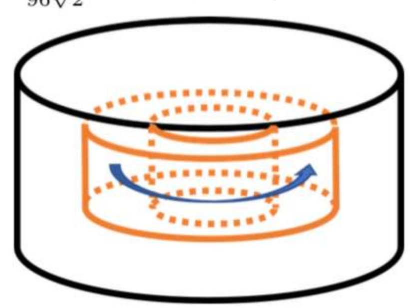
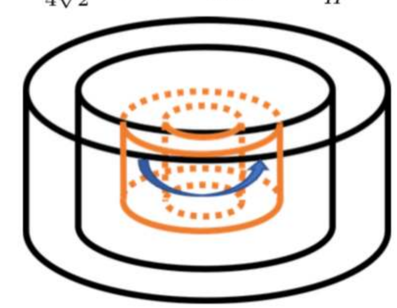
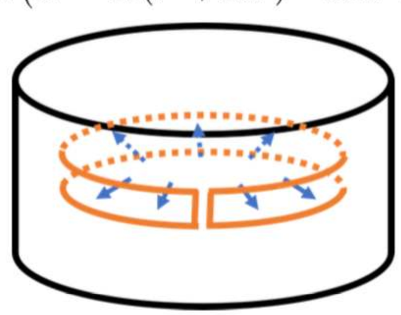
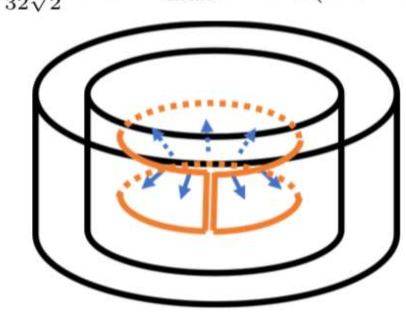
(selection rules)

Selection rules

Domcke, CGC, Lee, Rodd, 2023

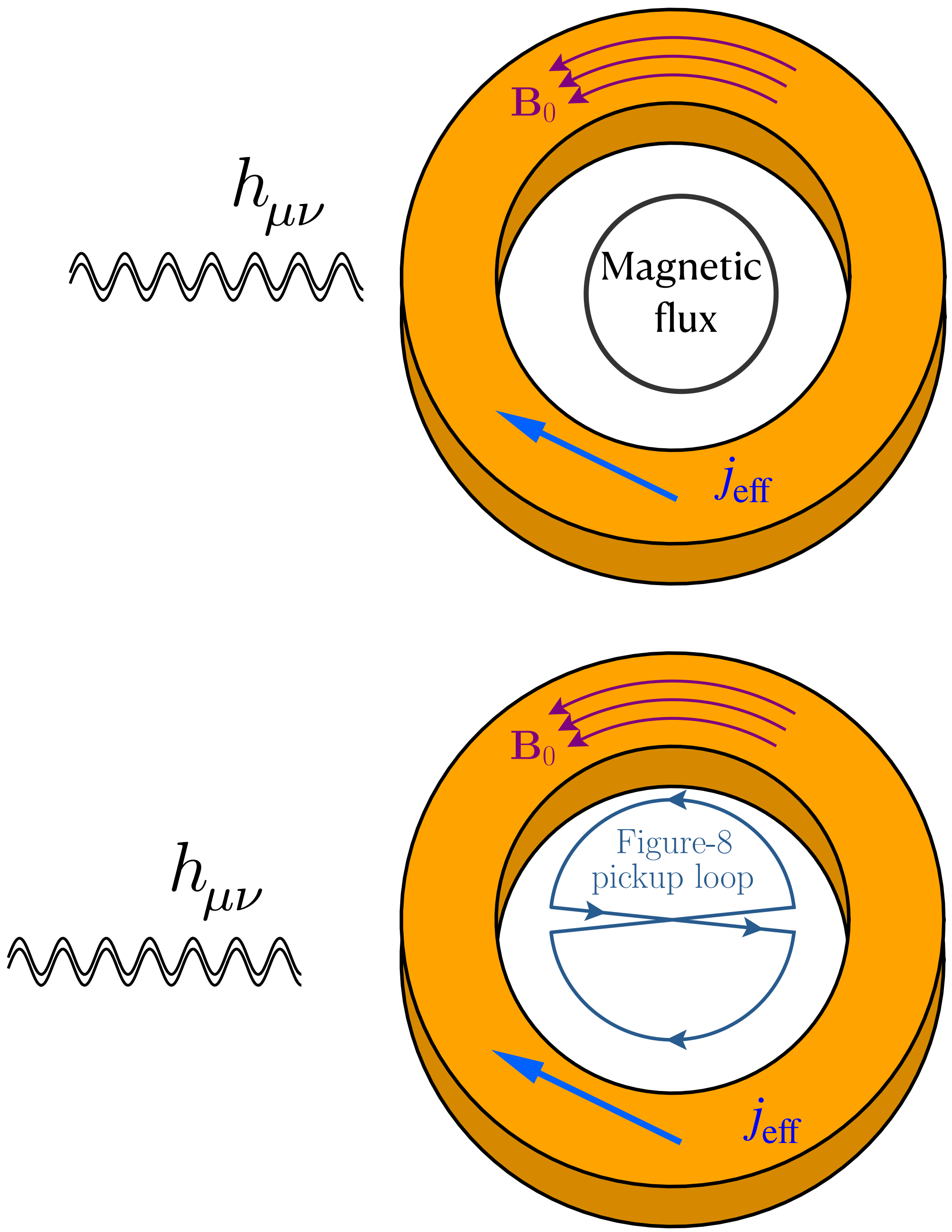
Type of external field

Pickup loop orientation

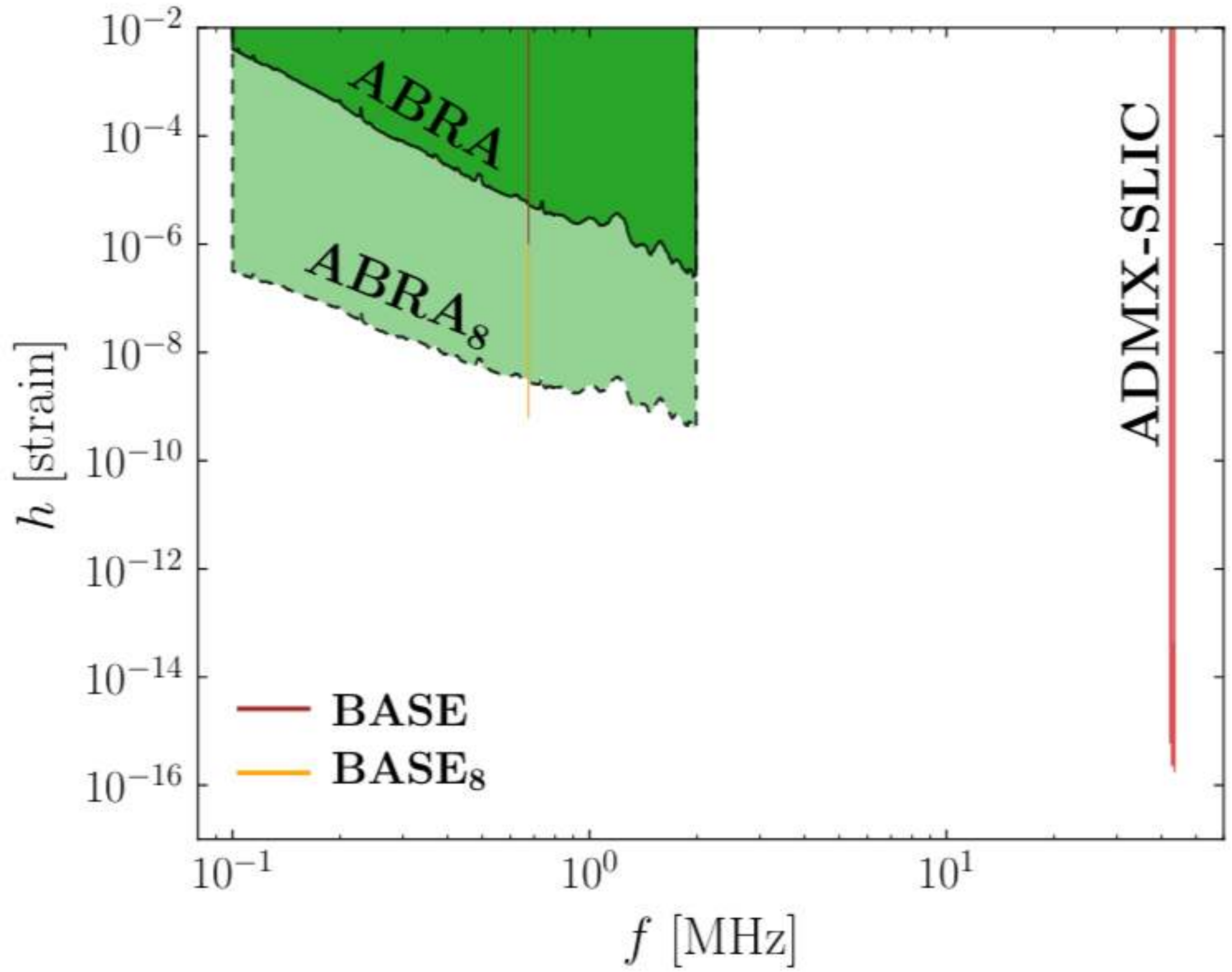
	Solenoid: $\mathbf{B}_0 \propto \hat{\mathbf{e}}_z$	Toroid: $\mathbf{B}_0 \propto \hat{\mathbf{e}}_\phi$
$\hat{\mathbf{n}}' \propto \hat{\mathbf{e}}_z$	h^+, n even $\Rightarrow \mathcal{O}[(\omega L)^2]$ $\Phi_h = \frac{e^{-i\omega t}}{48\sqrt{2}} h^+ \omega^2 B_0 s_{\theta_h}^2 \pi r^2 \left(11r^2 +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

Selection rules



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



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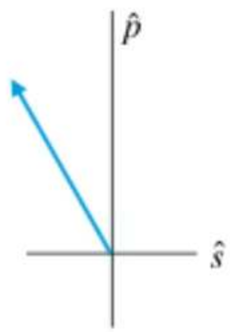
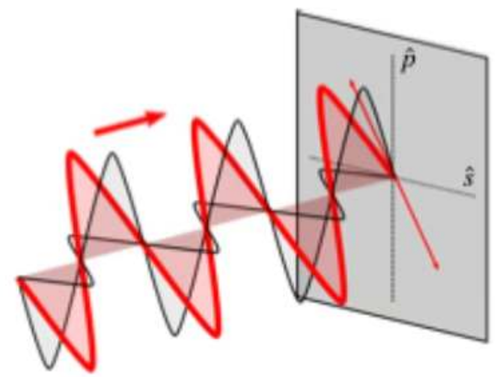
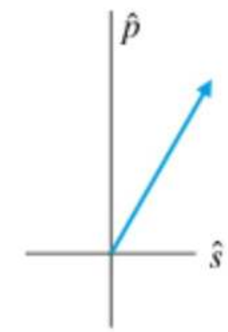
Axion birefringence







Geometrical optics limit

↓

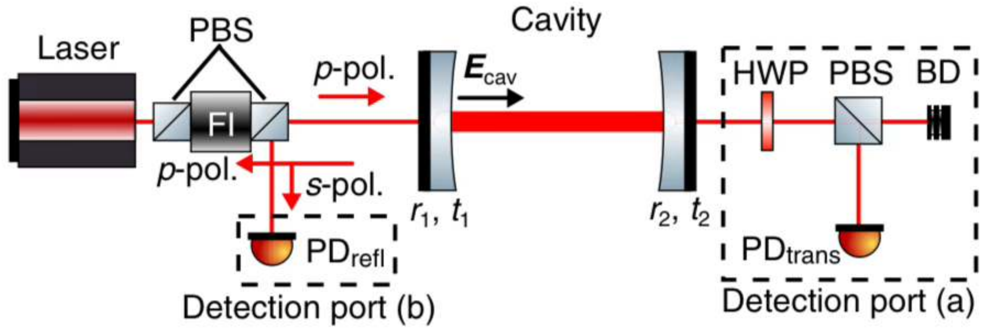
$$\frac{d\mathbf{e}}{dt} = -\frac{1}{2} g_{a\gamma\gamma} \dot{a}(t)\, \hat{\mathbf{k}} \times \mathbf{e}$$

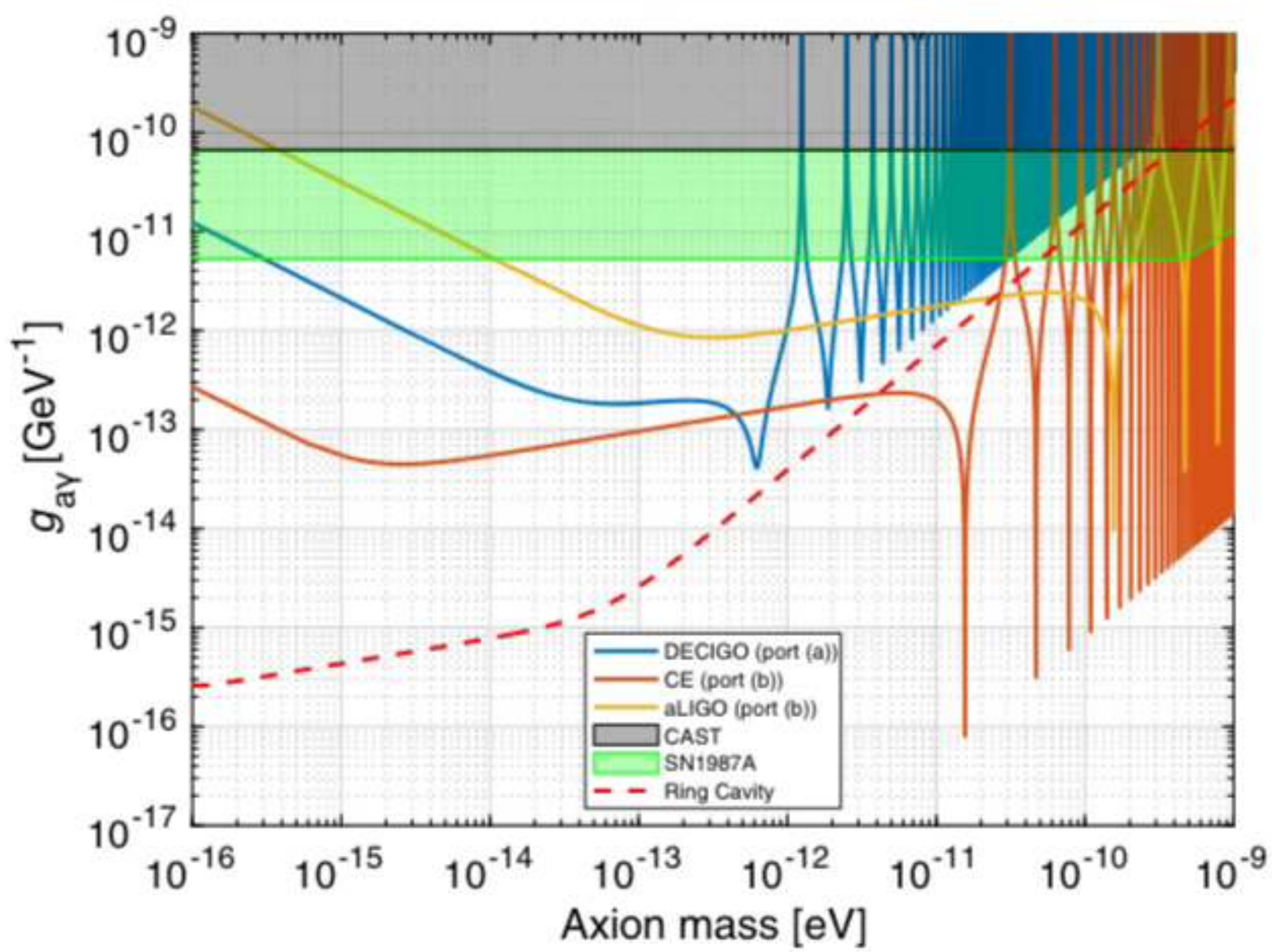
Axion birefringence

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]



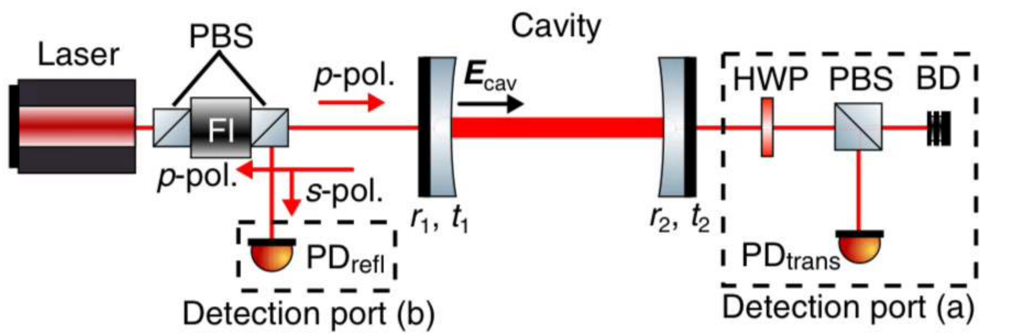


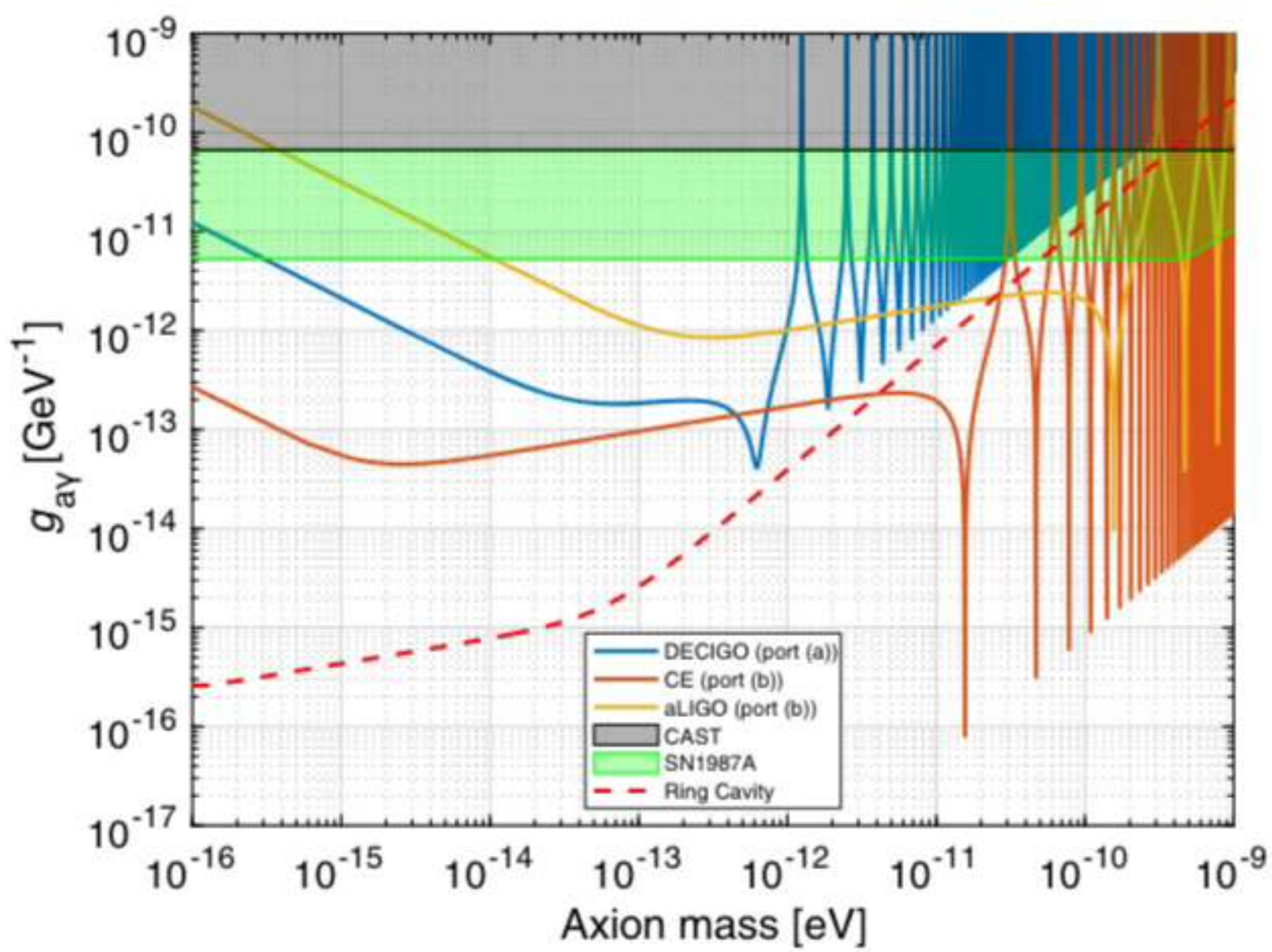
Axion birefringence

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]





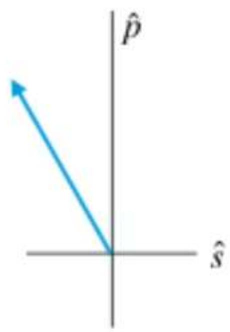
work in progress with Luca Marsili, Aaron Spector and Andreas Ringwald

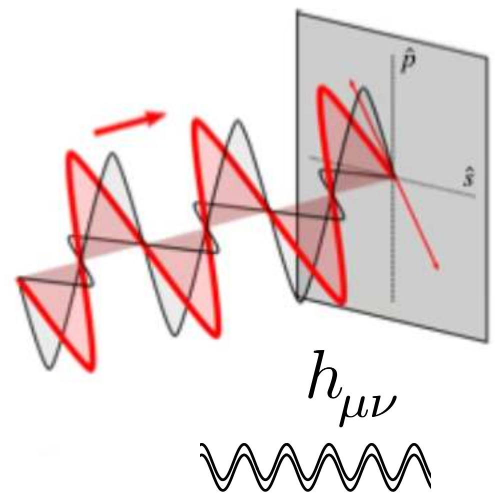
ALPs experiment at DESY

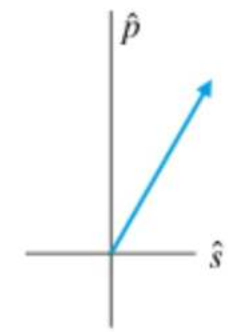
Camilo García Cely, University of Valencia-CSIC

Birefringence due to a gravitational wave

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





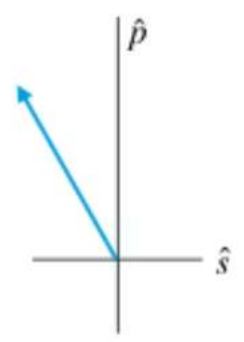


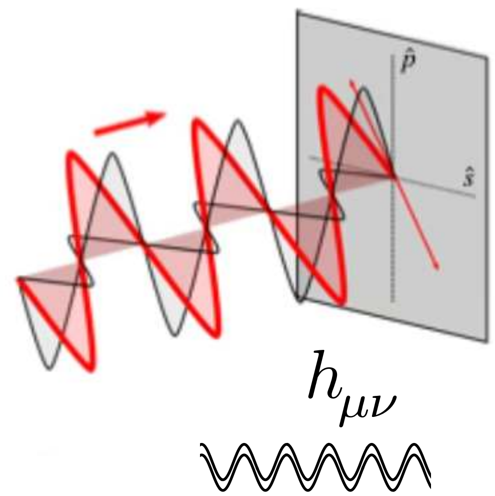
Geometrical optics limit

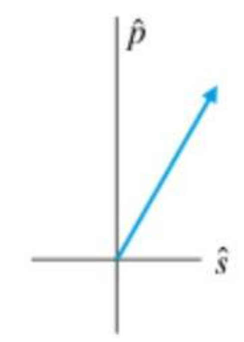
$$\frac{de^i}{dt} = \left(\Gamma^0_{\rho\lambda} \frac{dx^i}{dt} - \Gamma^i_{\rho\lambda} \right) \frac{dx^\rho}{dt} e^\lambda$$

Birefringence due to a gravitational wave

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







ALPs experiment at DESY

For GWs coming from the zenith

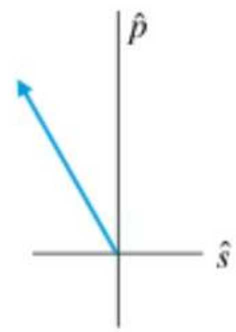
- The cross polarization has the same cavity response function as axions
- The plus polarization decouples (selection rules)

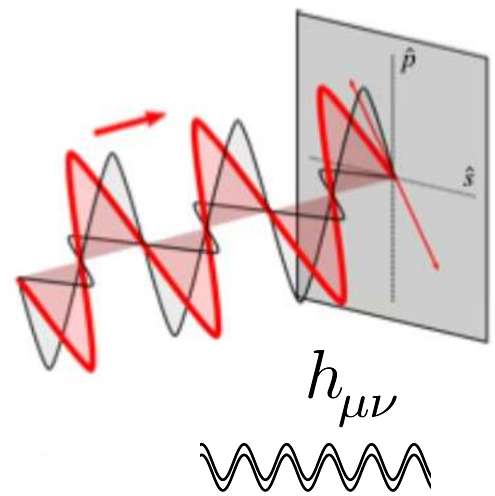
PRELIMINARY

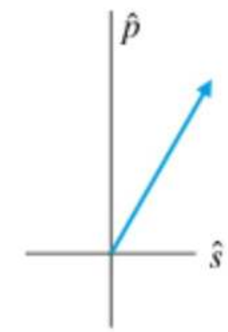
Camilo García Cely, University of Valencia-CSIC

Birefringence due to a gravitational wave

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







ALPs experiment at DESY

Response function

Axions $\dfrac{4r^2}{(1-r^2)^2}$

h_+ 0

$h_\times$ $\dfrac{r^2\left(1+e^{i\pi\cos\theta_h}\right)}{\sqrt{2}(1-r^2)^2}$

Birefringence due to a gravitational wave

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

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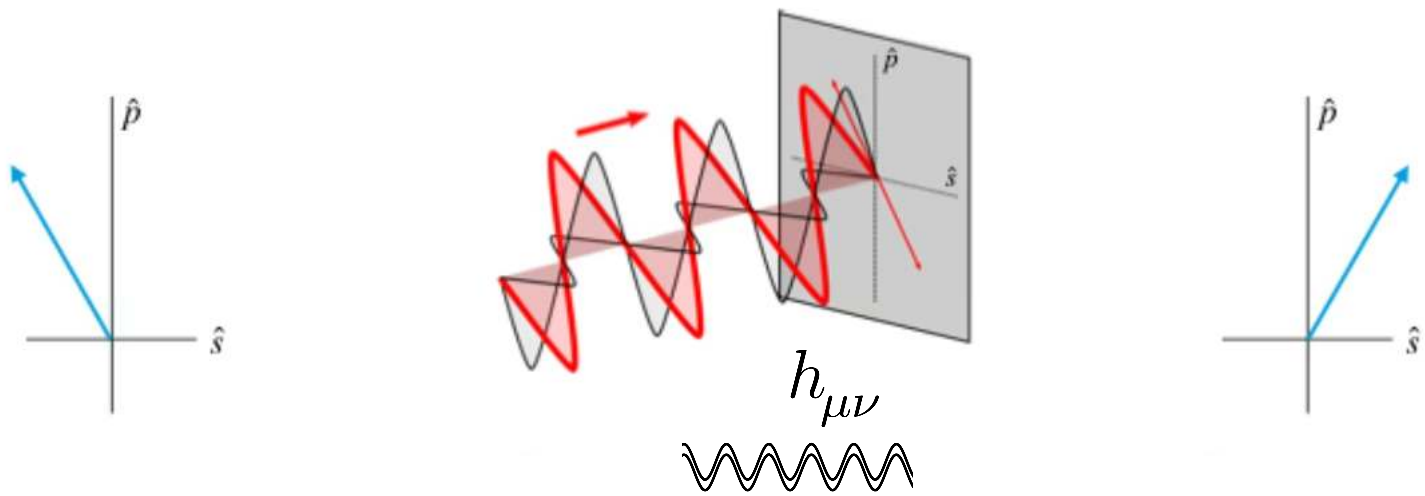


ALPs experiment at DESY

	Response function	QWP
Axions	$\frac{4r^2}{(1-r^2)^2}$	0
h_+	0	$\frac{r^2\left(1-e^{i\pi(\cos\theta_h+1)}\right)(\cos 2\theta_h+3)\sin 2\phi_h}{4\sqrt{2}(1-r^2)^2}$
$h_\times$	$\frac{r^2\left(1+e^{i\pi\cos\theta_h}\right)}{\sqrt{2}(1-r^2)^2}$	$\frac{\sqrt{2}r^2\left(1+e^{i\pi\cos\theta_h}\right)\cos\theta_h\cos^2\phi_h}{(1-r^2)^2}$

Conclusions

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

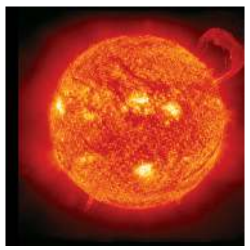
Different experimental proposals have coalesced on a strain sensitivity of 10^{-22} for MHz GWs, still orders of magnitude away from signals of the early Universe.

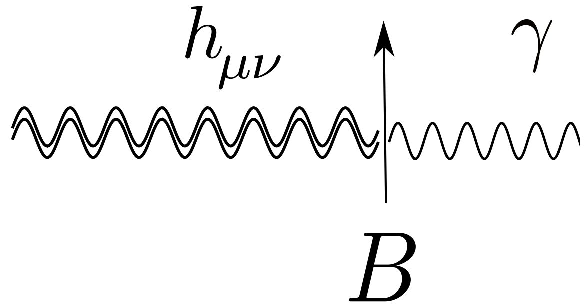
Lots of room for improvement because experiments are not optimized for gravitational wave searches.

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

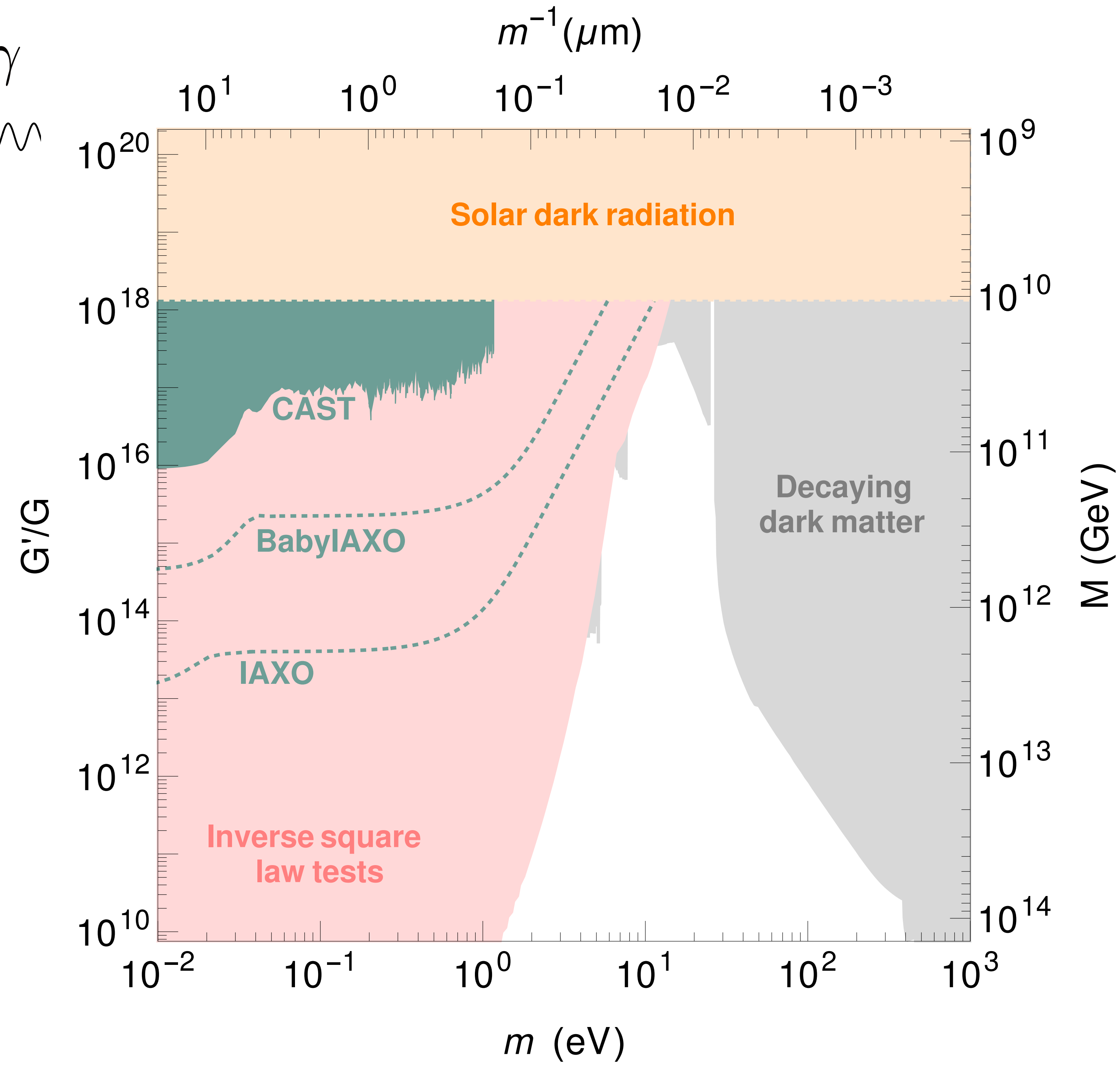
Simple modifications of readout (such as the figura-8 pickup loop or a quarter wave plate) can overcome this limitation

Solar emission of light spin-2 particles





CGC, Ringwald **PRELIMINARY**

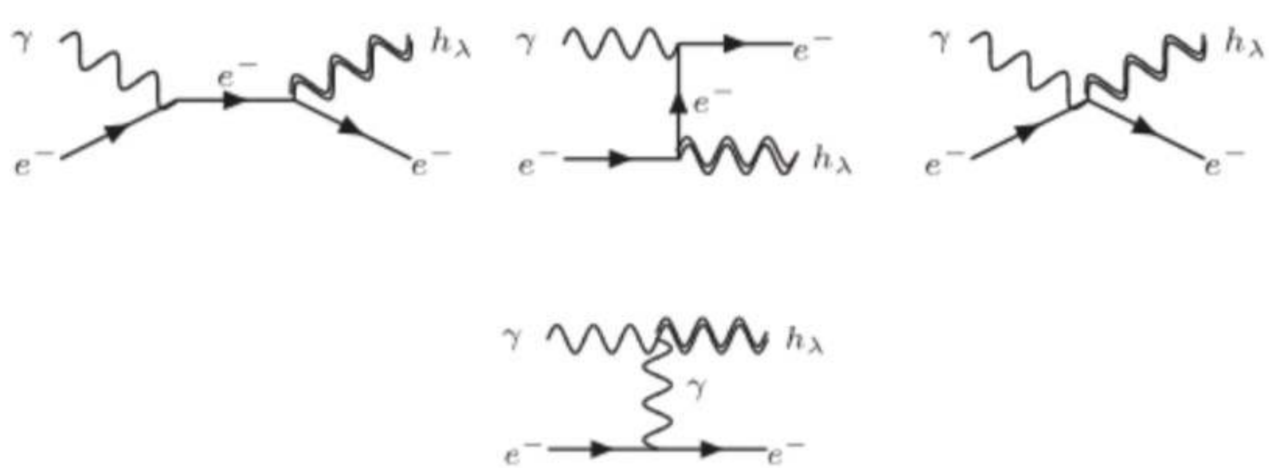


Solar emission of light spin-2 particles

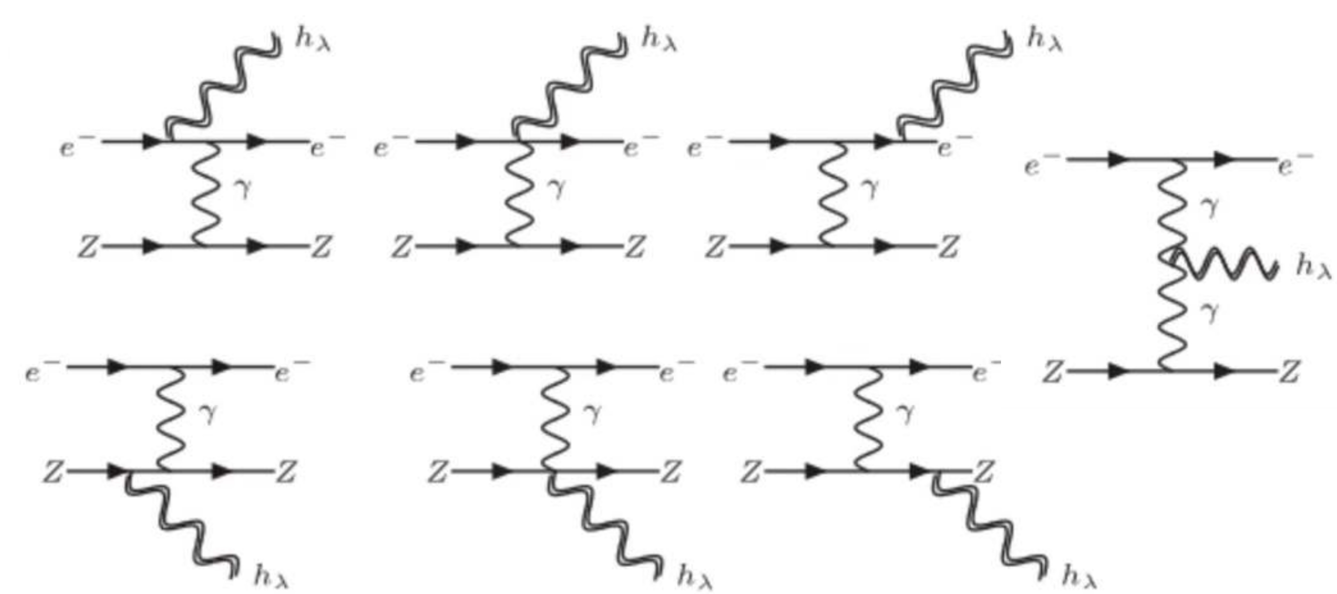
CGC, Ringwald **PRELIMINARY**

Collision	λ	$\frac{d\Gamma}{d\omega dV}$	
Photo-production $\gamma Z \to Z\, h_\lambda$	± 2	$n_\gamma n_Z G' Z^2 \alpha\pi\, \delta(\omega - p_i) \int d\cos\theta \cot^2\frac{\theta}{2}[1+\cos^2\theta]F(\theta)$	$F(\theta) = \frac{\left(2\omega\sin\frac{\theta}{2}\right)^2}{\kappa^2 + \left(2\omega\sin\frac{\theta}{2}\right)^2}$
	± 1	0	
	0	$\frac{4}{3} n_\gamma n_Z G' Z^2 \alpha\pi\, \delta(\omega - p_i) \int d\cos\theta \cot^2\frac{\theta}{2}\sin^4\frac{\theta}{2} F(\theta)$	
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-CSIC

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.

Proper detector frame

The coordinate system 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

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

- 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

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Excitation of mechanical modes

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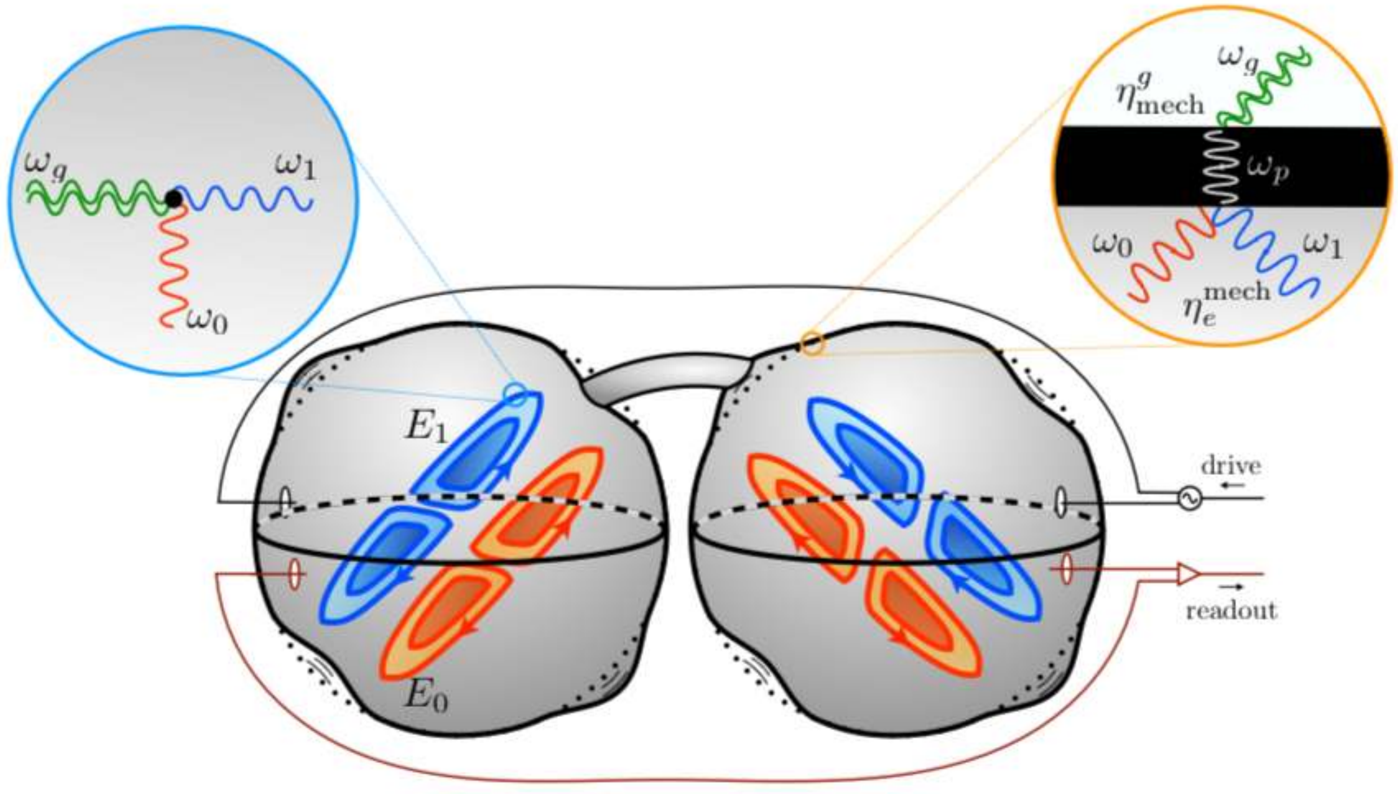
Excitation of mechanical modes



- 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