Axion Haloscopes for Gravitational Wave Searches

Workshop on Quantum Sensing for Fundamental Physics

Mainz Institute for Theoretical Physics
Johannes Gutenberg University

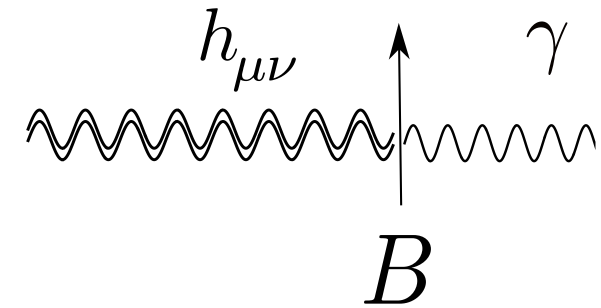
November 19, 2024

Camilo García Cely

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

Outline

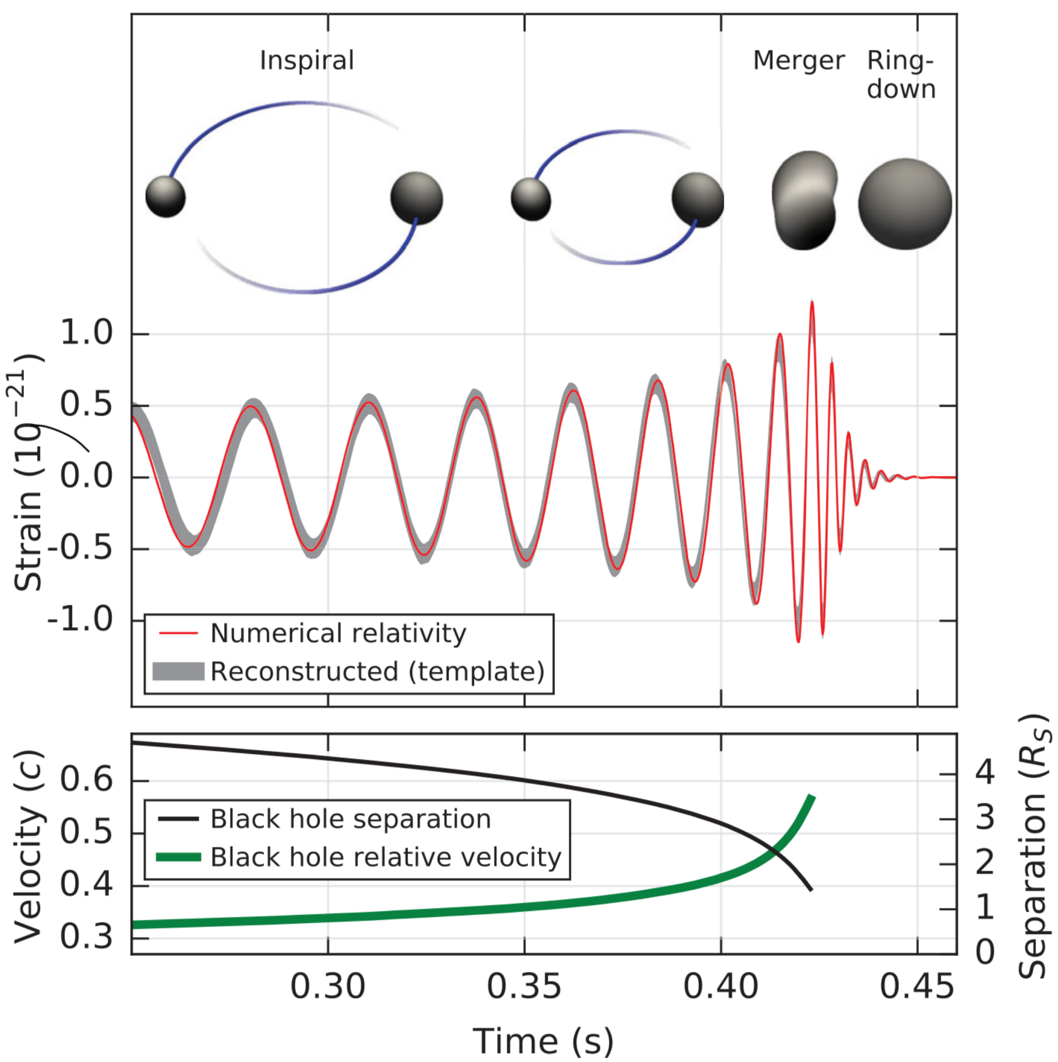
- Part I: The Gertsenhtein effect and high-frequency gravitational waves
- Part II : polarization effects in haloscopes
- Conclusions

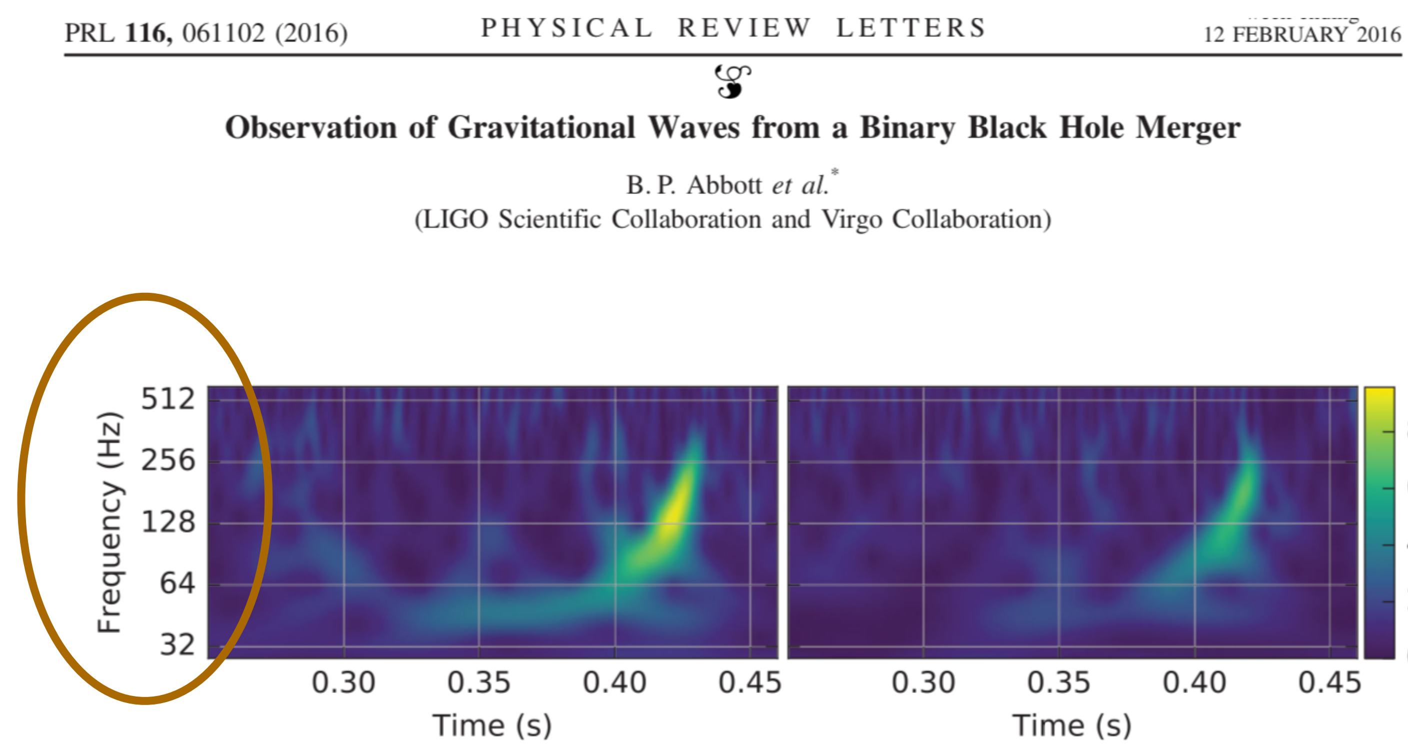


Part I

The Gertsenhtein effect and high-frequency gravitational waves

High-frequency 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

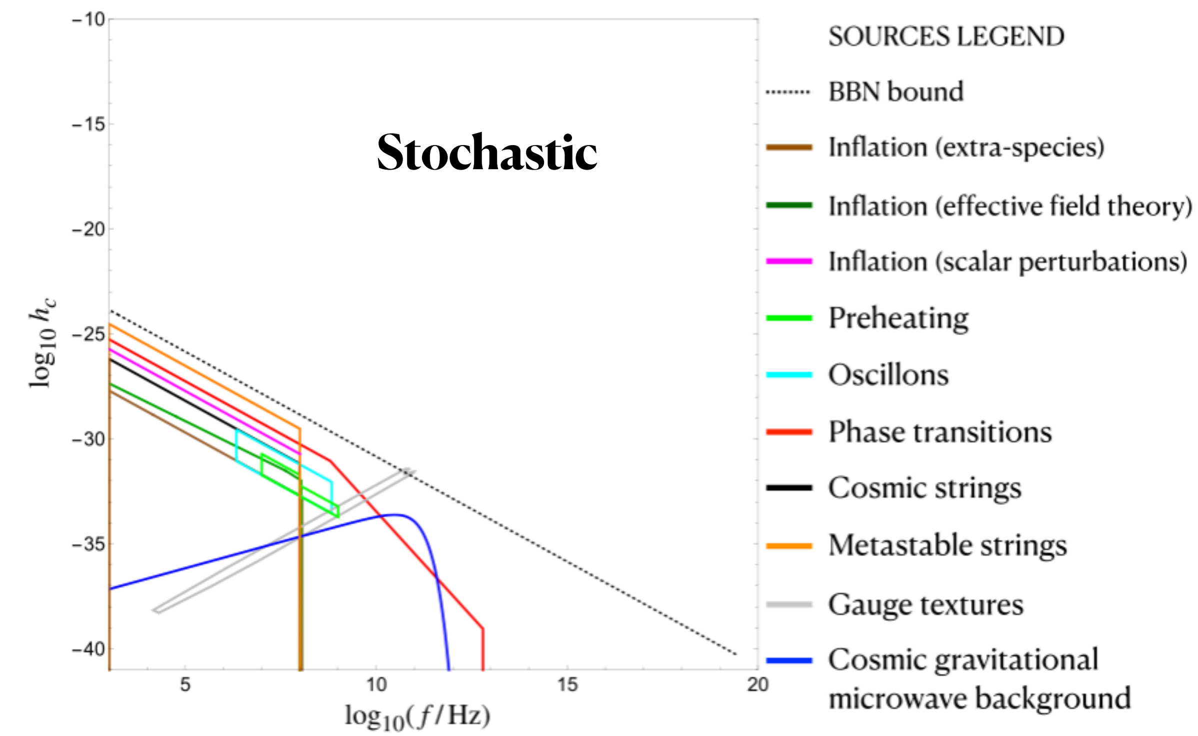
Review Article | Open Access | Published: 06 December 2021

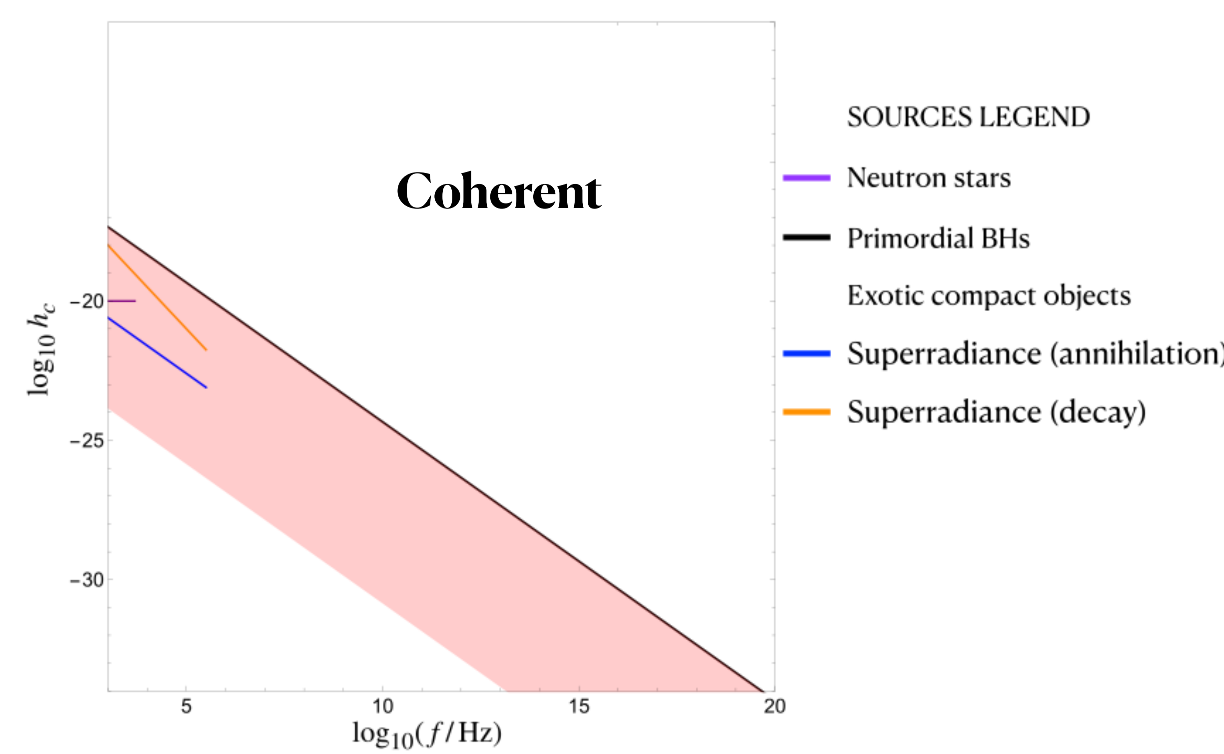
Challenges and opportunities of gravitational-wave searches at MHz to GHz frequencies

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

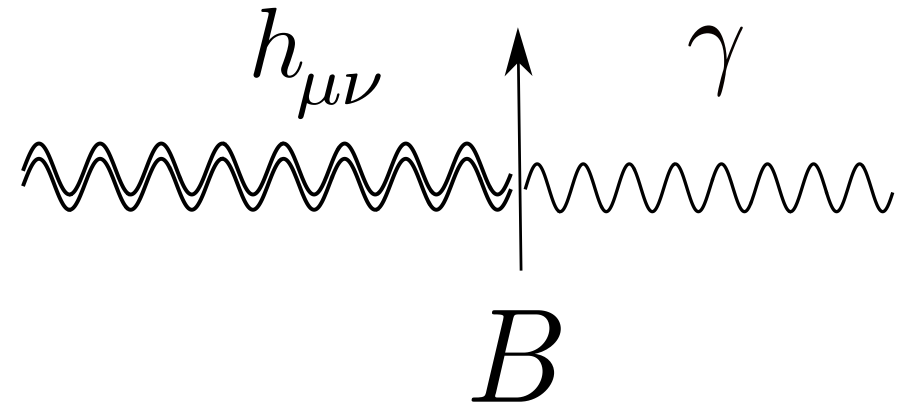
A growing community is seriously considering the search of high frequency gravitational waves





Revisiting Gertsenhstein's ideas

SOVIET PHYSICS JETP VOLUME 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

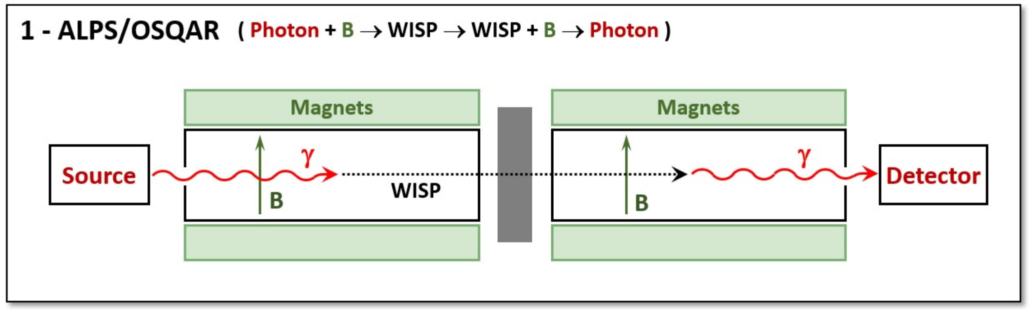
Potential of Radio Telescopes as High-Frequency Gravitational Wave Detectors

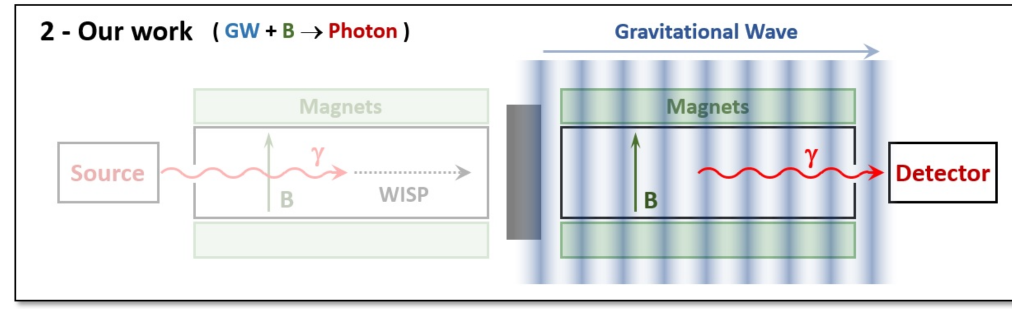
Valerie Domcke and Camilo Garcia-Cely
Phys. Rev. Lett. **126**, 021104 – Published 14 January 2021

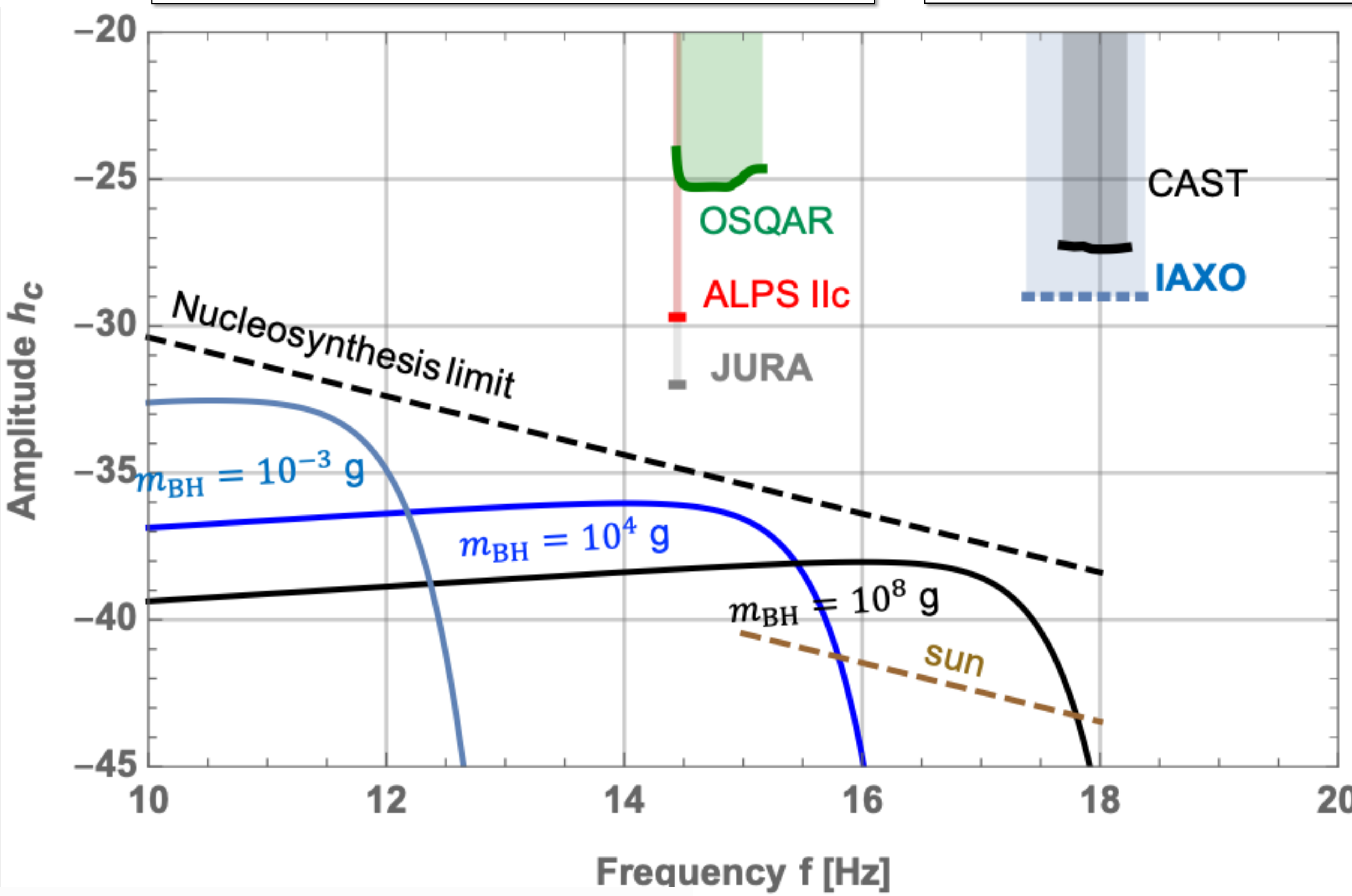
- The process is strictly analogous to axion conversion.

Raffelt, Stodolski'89

The (inverse) Gertsenhstein Effect





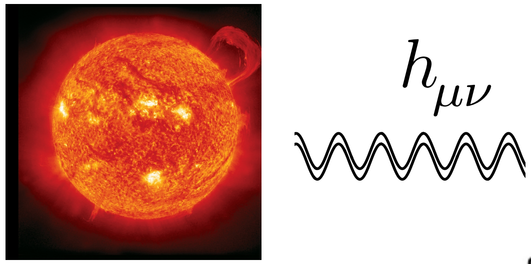


Still far from testing
Early Universe signals

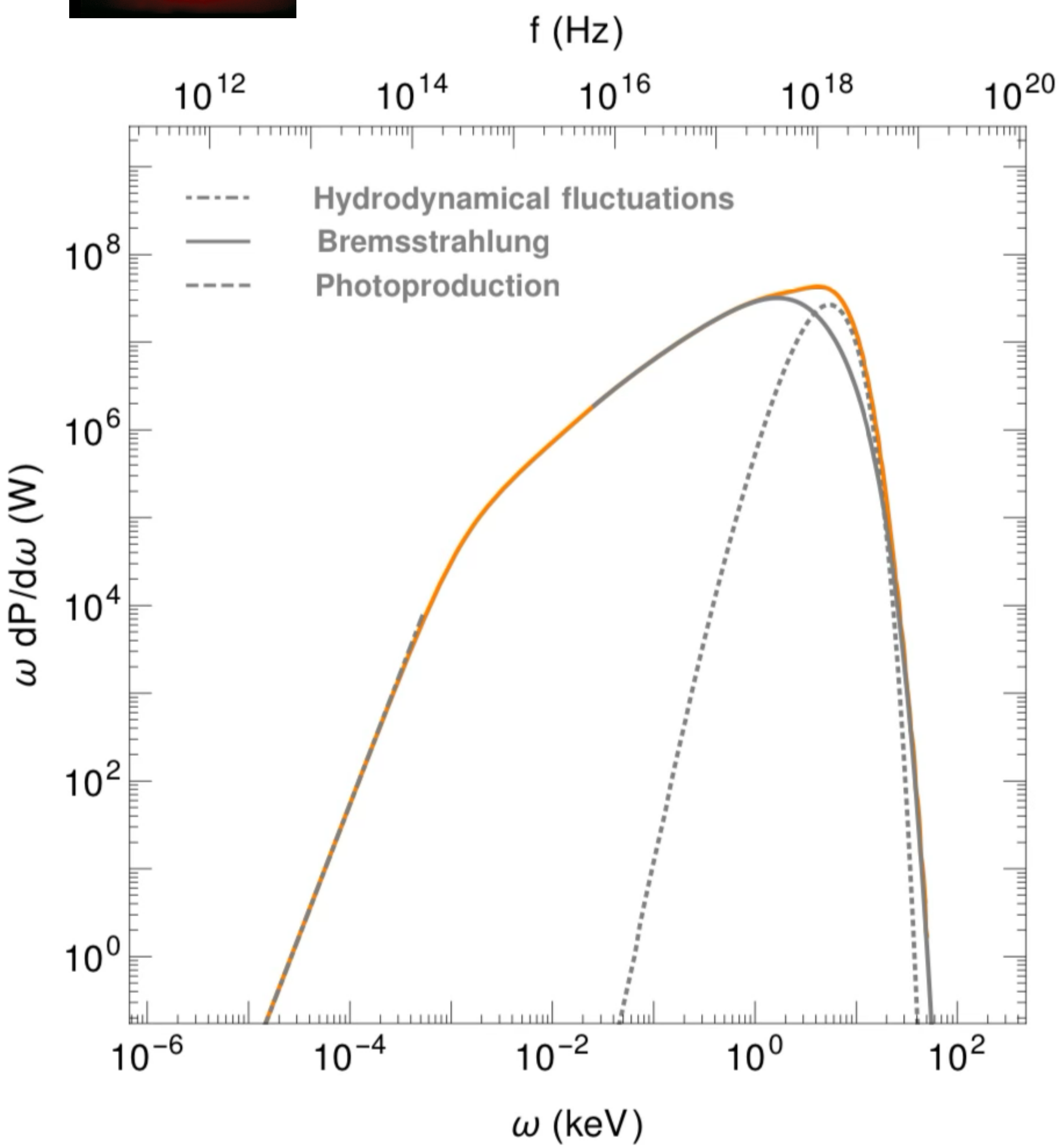
A. Ejlli, D. Ejlli, A. M. Cruise, G. Pisano & H. Grote

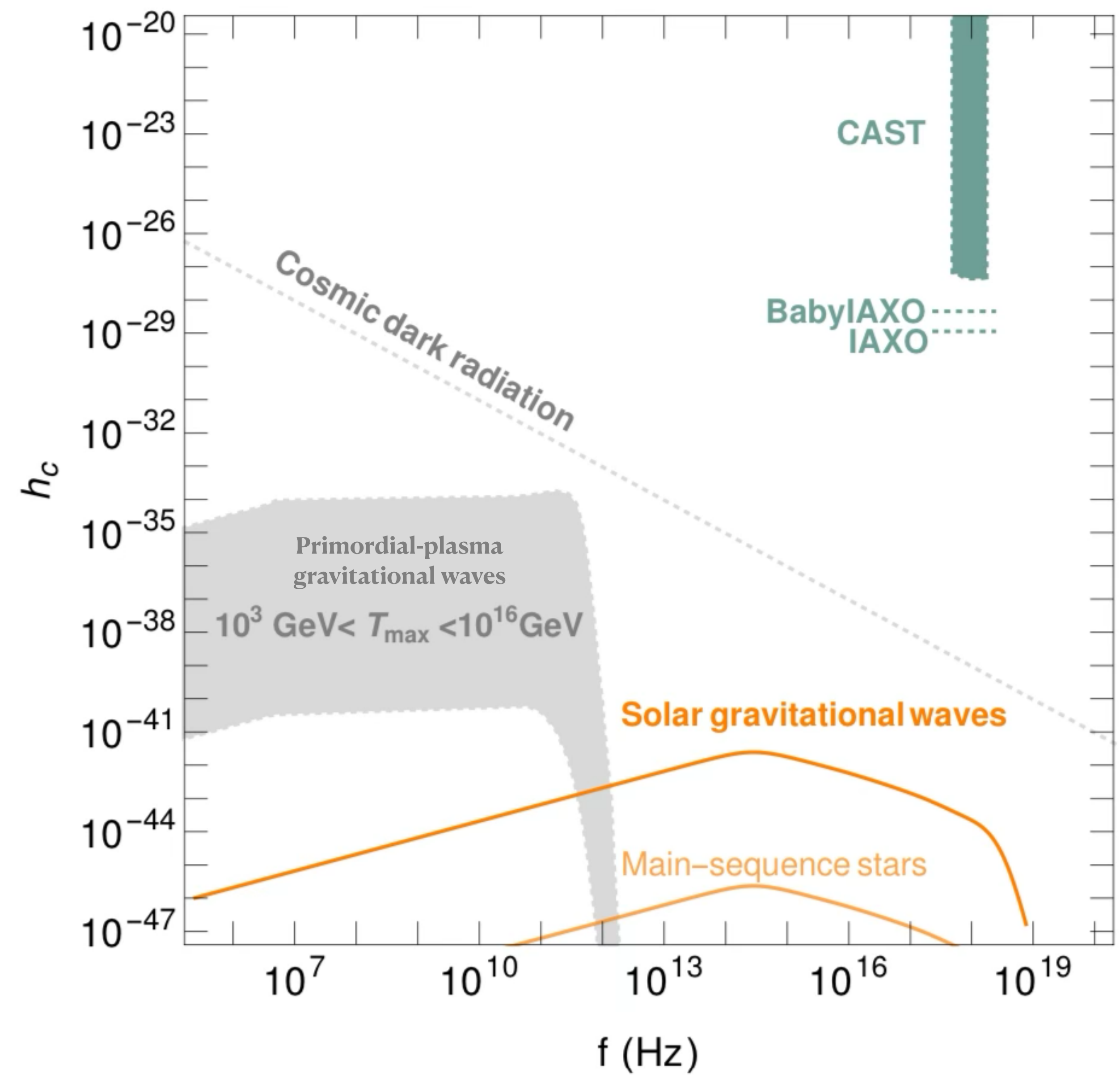
The European Physical Journal C **79**, Article number: 1032 (2019)

Solar gravitational waves



CGC, Ringwald, 2024

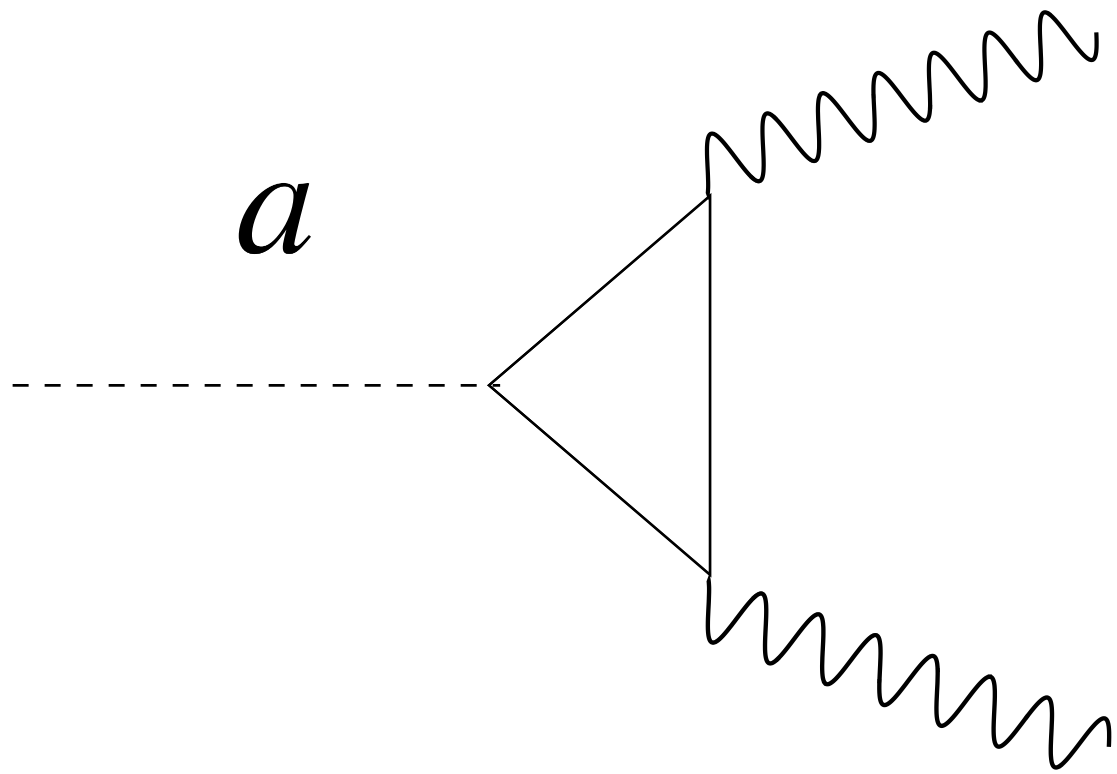




Part II

Polarization effects in haloscopes

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

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

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

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

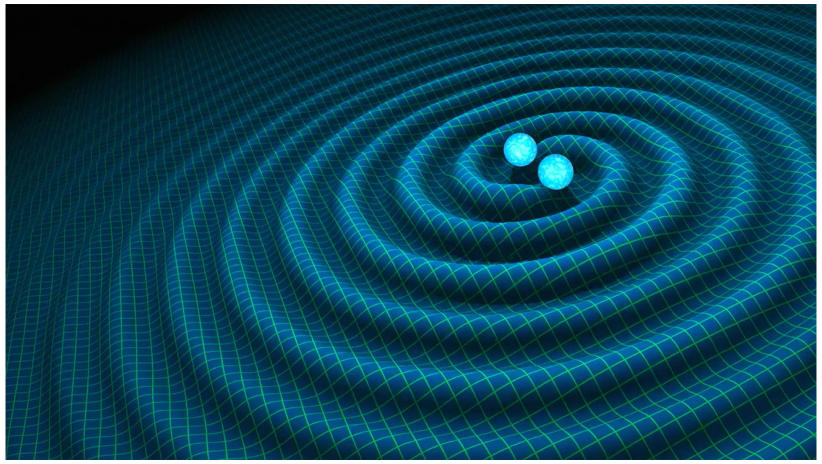
$$j^0 = -\, g_{a\gamma\gamma} \nabla a \cdot \mathbf{B} \qquad \mathbf{j} = g_{a\gamma\gamma} \left(\nabla a \times \mathbf{E} + \partial_t a \mathbf{B} \right)$$

Camilo García Cely, University of Valencia-CSIC

How does it work?

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

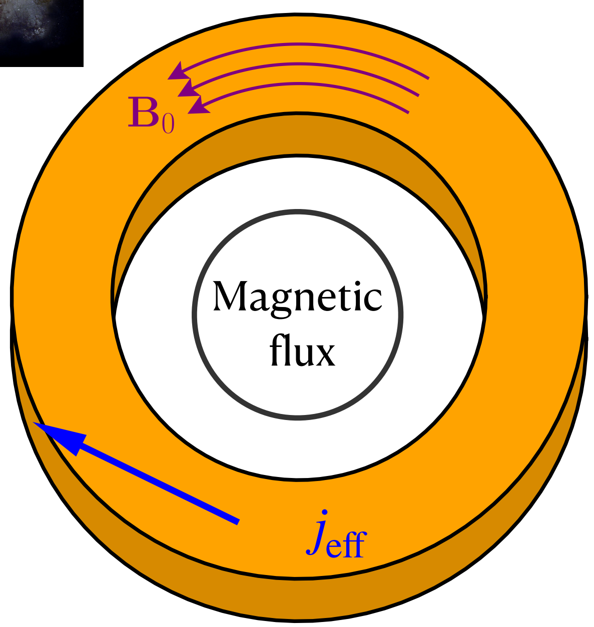
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \qquad \left| h_{\mu\nu} \right| \ll 1$$



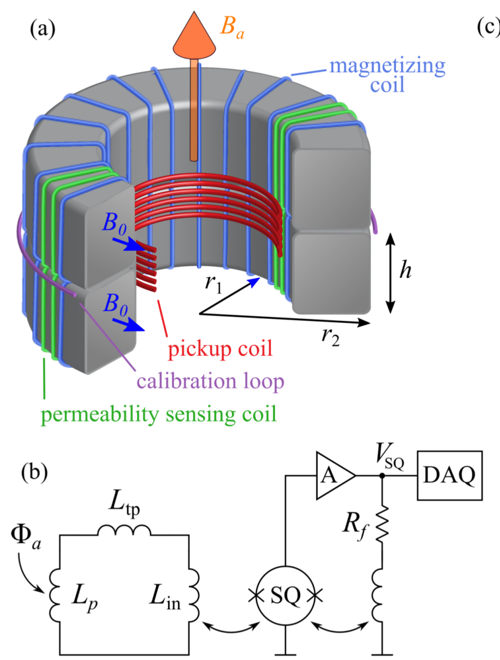
$$j^{\mu}_{\rm eff} = \partial_{\nu} \left(-\frac{1}{2} h \, F^{\mu\nu} + F^{\mu\alpha} h^{\nu}{}_{\alpha} - F^{\nu\alpha} h^{\mu}{}_{\alpha} \right)$$

Camilo García Cely, University of Valencia-CSIC

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]

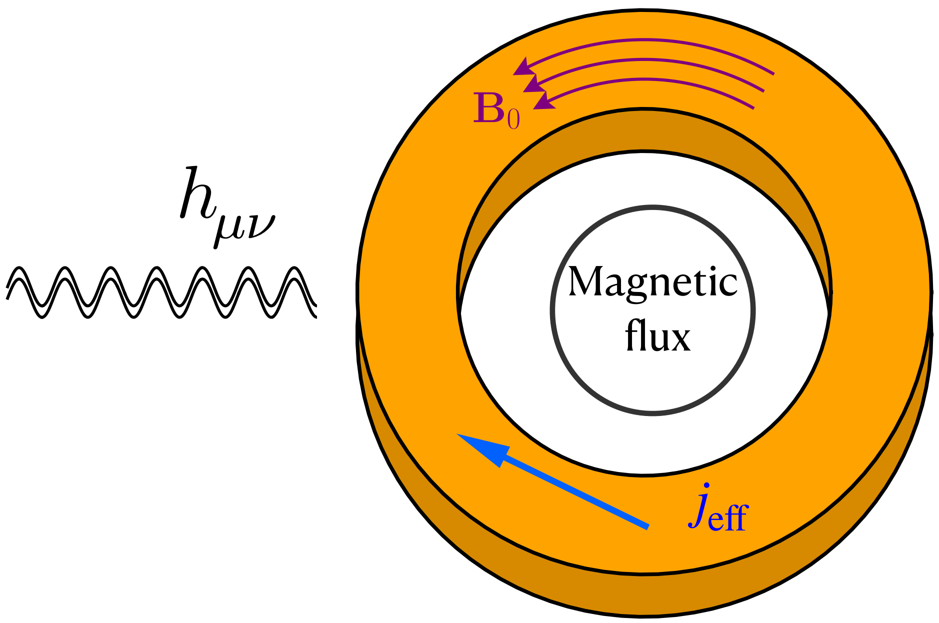
PRL 117, 141801 (2016) PHYSICAL REVIEW LETTERS week ending 30 SEPTEMBER 2016

Broadband and Resonant Approaches to Axion Dark Matter Detection

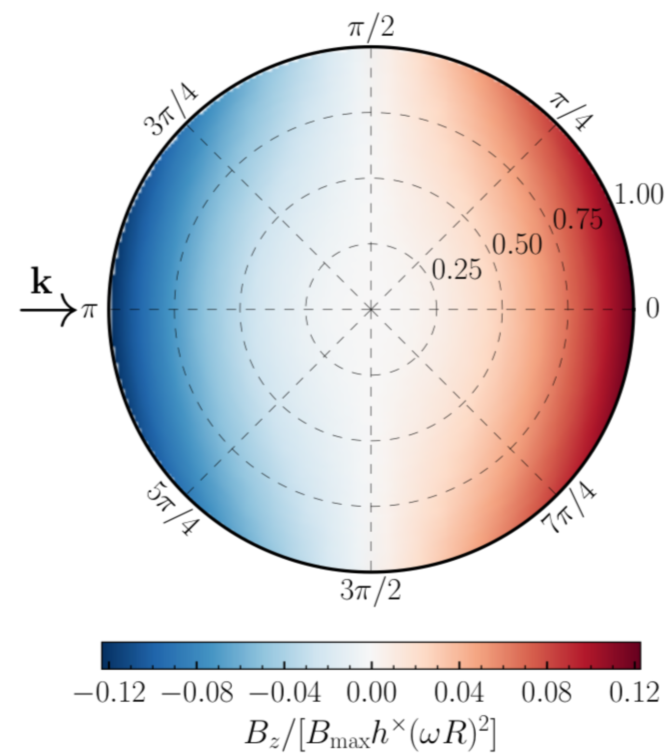
Yonatan Kahn,[1,*] Benjamin R. Safdi,[2,†] and Jesse Thaler[2,‡]
[1]Department of Physics, Princeton University, Princeton, New Jersey 08544, USA
[2]Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
(Received 3 March 2016; published 30 September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

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

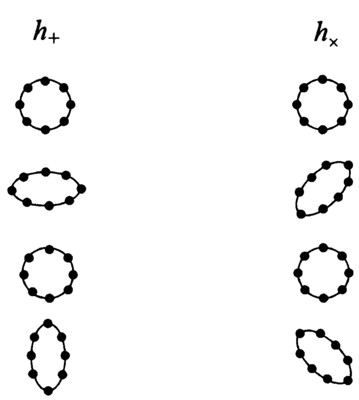
Haloscopes based on lumped-element detectors



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



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



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

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

Only one polarization

Suppression at small frequencies

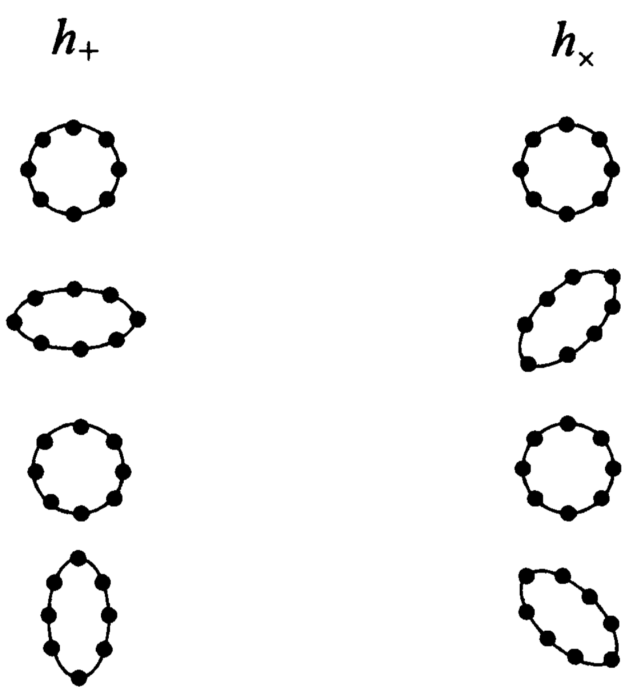
The sensitivity scaling with the volume is faster than for axions

Selection rules

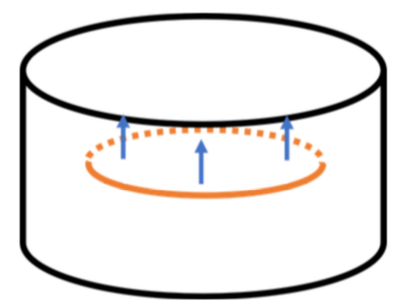
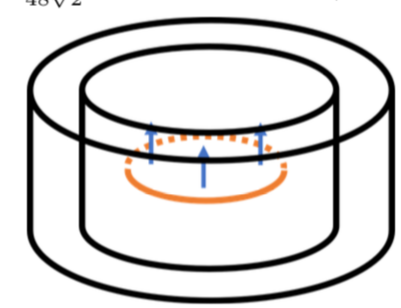
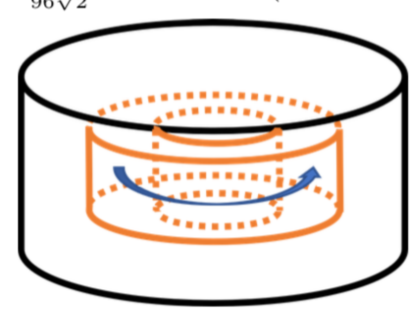
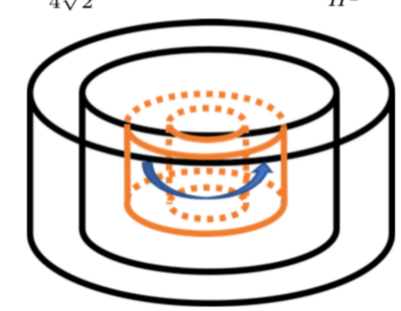
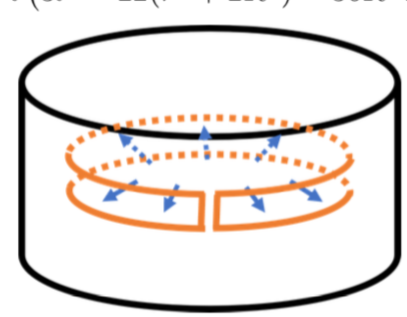
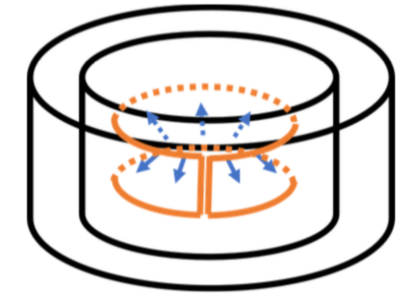
Type of external field Domcke, CGC, Lee, Rodd, 2023

Geavitational waves carry two polarization modes

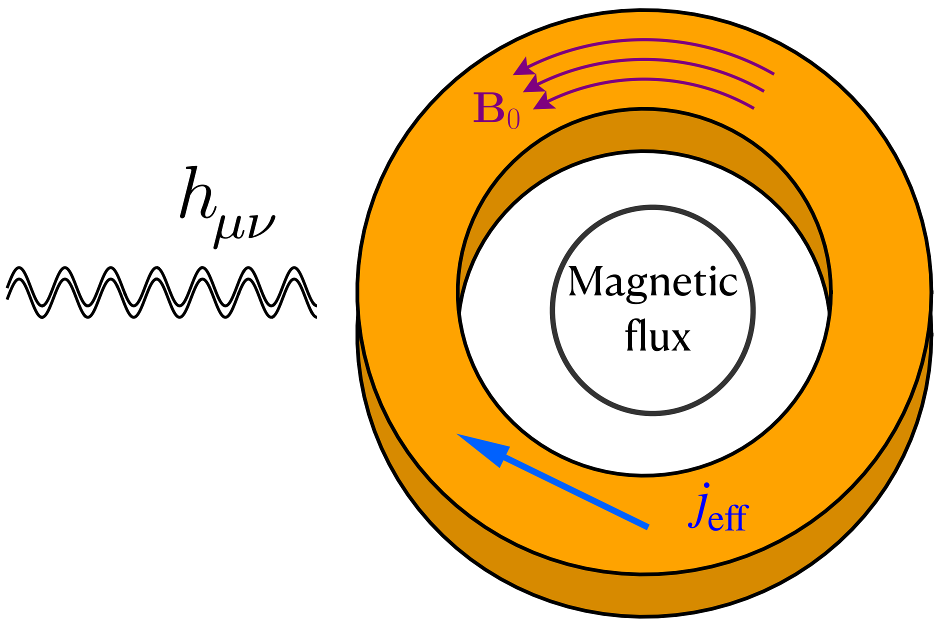
$$\Box h_{\mu\nu} = -16\pi G T_{\mu\nu}$$

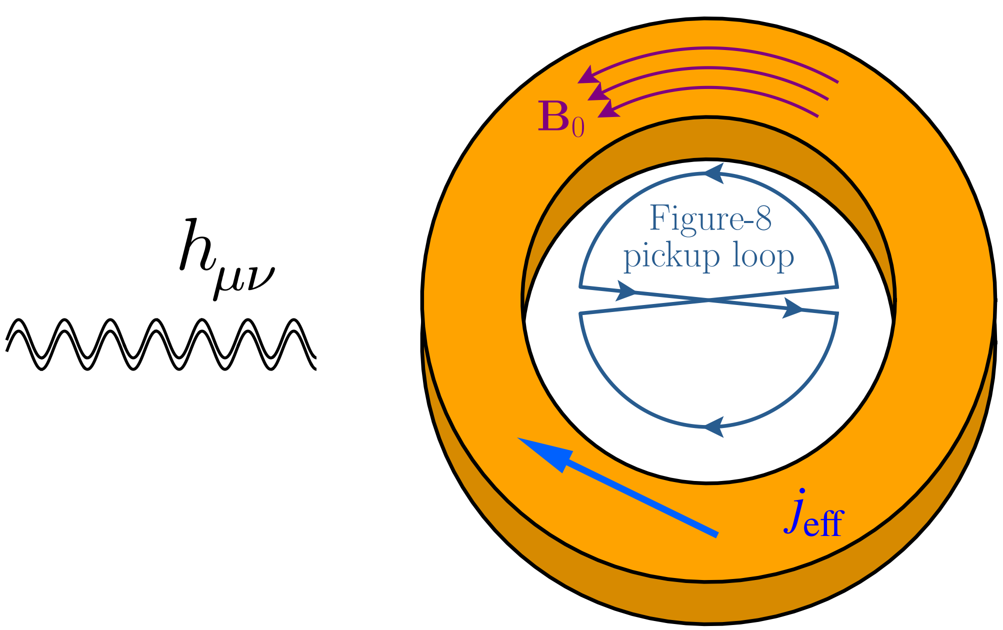


Pickup loop orientation

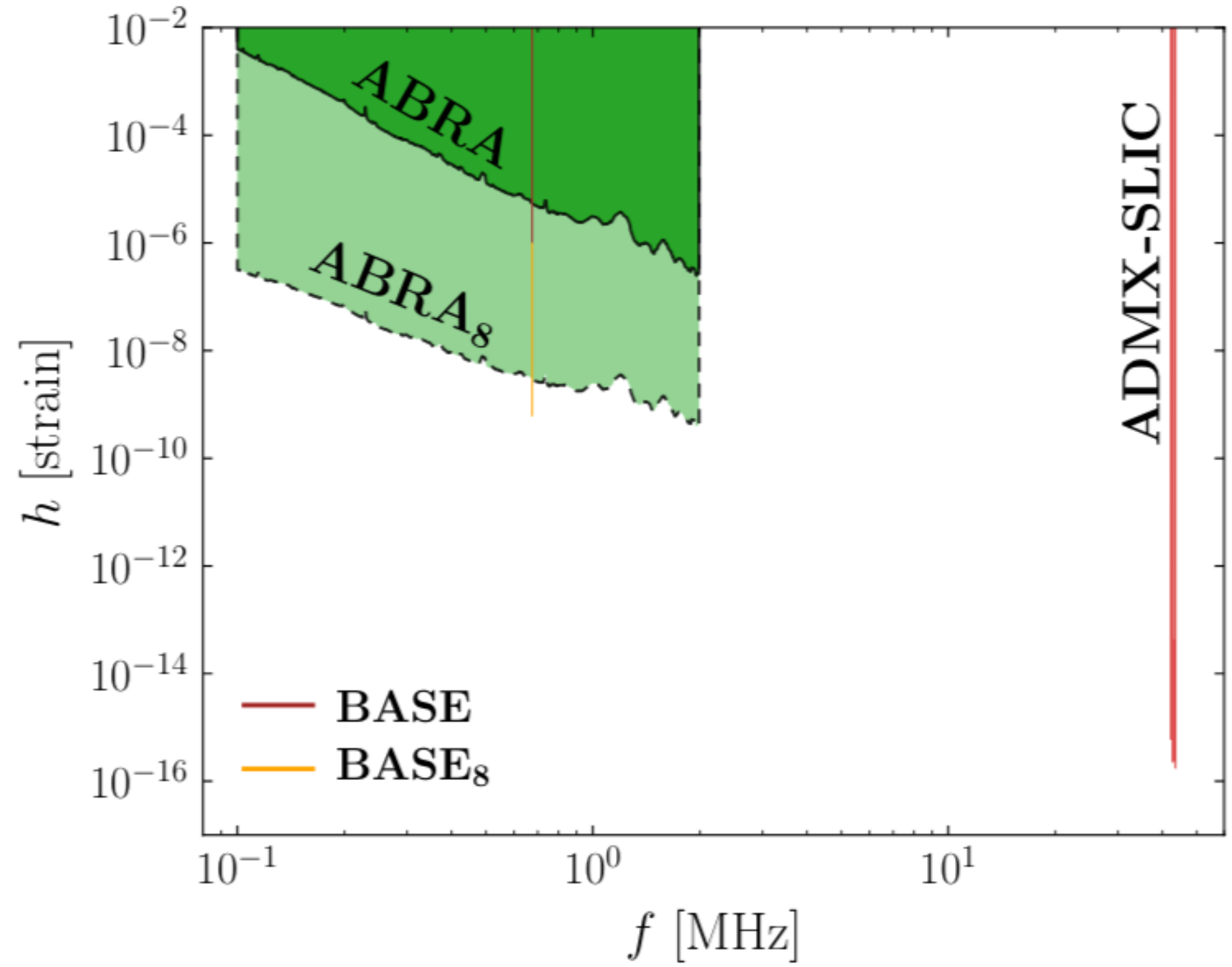
	Solenoid: $\mathbf{B}_0 \propto \hat{\mathbf{e}}_z$	Toroid: $\mathbf{B}_0 \propto \hat{\mathbf{e}}_\phi$
$\hat{\mathbf{n}}' \propto \hat{\mathbf{e}}_z$ $(\kappa_y = +1,\, \kappa = -1)$	h^+, n even $\Rightarrow \mathcal{O}[(\omega L)^2]$ $\Phi_h = \frac{e^{-i\omega t}}{48\sqrt{2}} h^+ \omega^2 B_0 s_{\theta_h}^2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

Toroidal magnetic fields

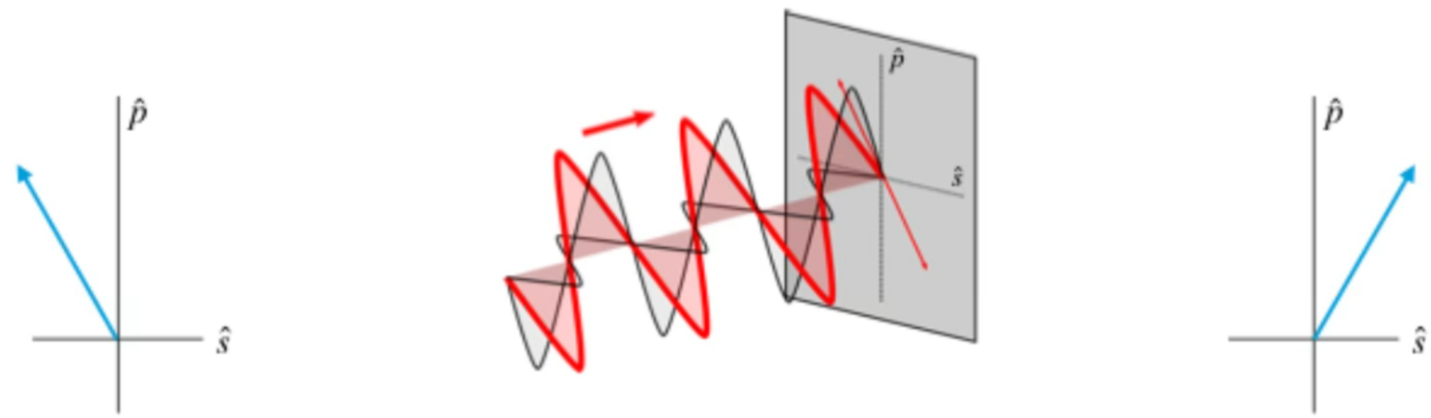




Valerie Domcke, Camilo Garcia-Cely, and Nicholas L. Rodd
Phys. Rev. Lett. **129**, 041101 – Published 20 July 2022



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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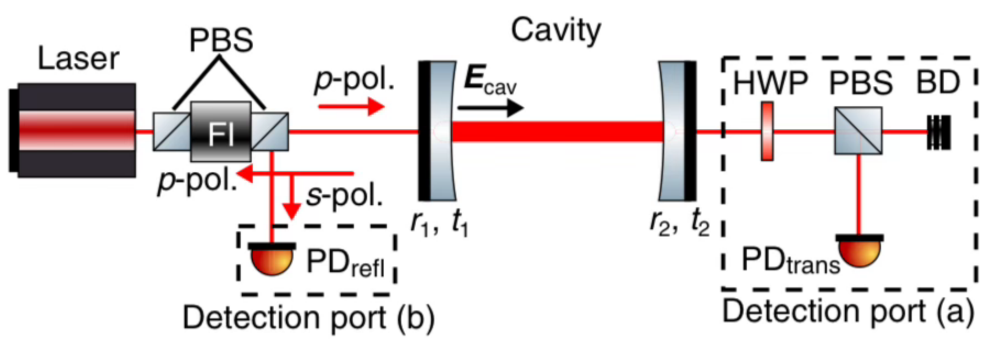
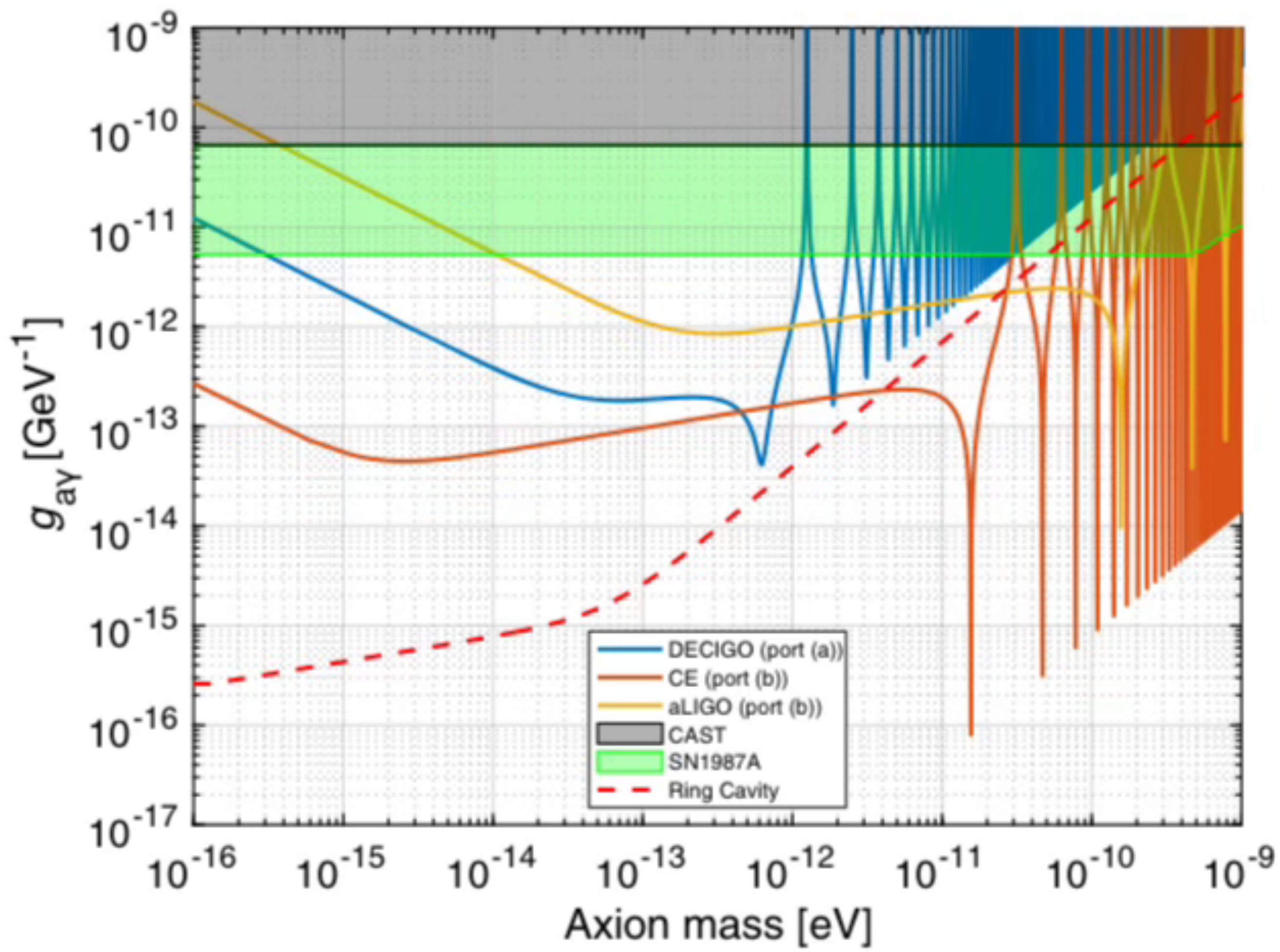
Axion birefringence

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

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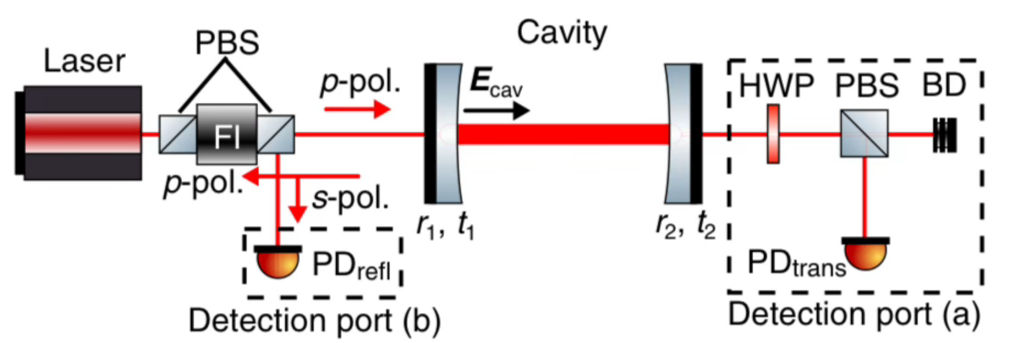
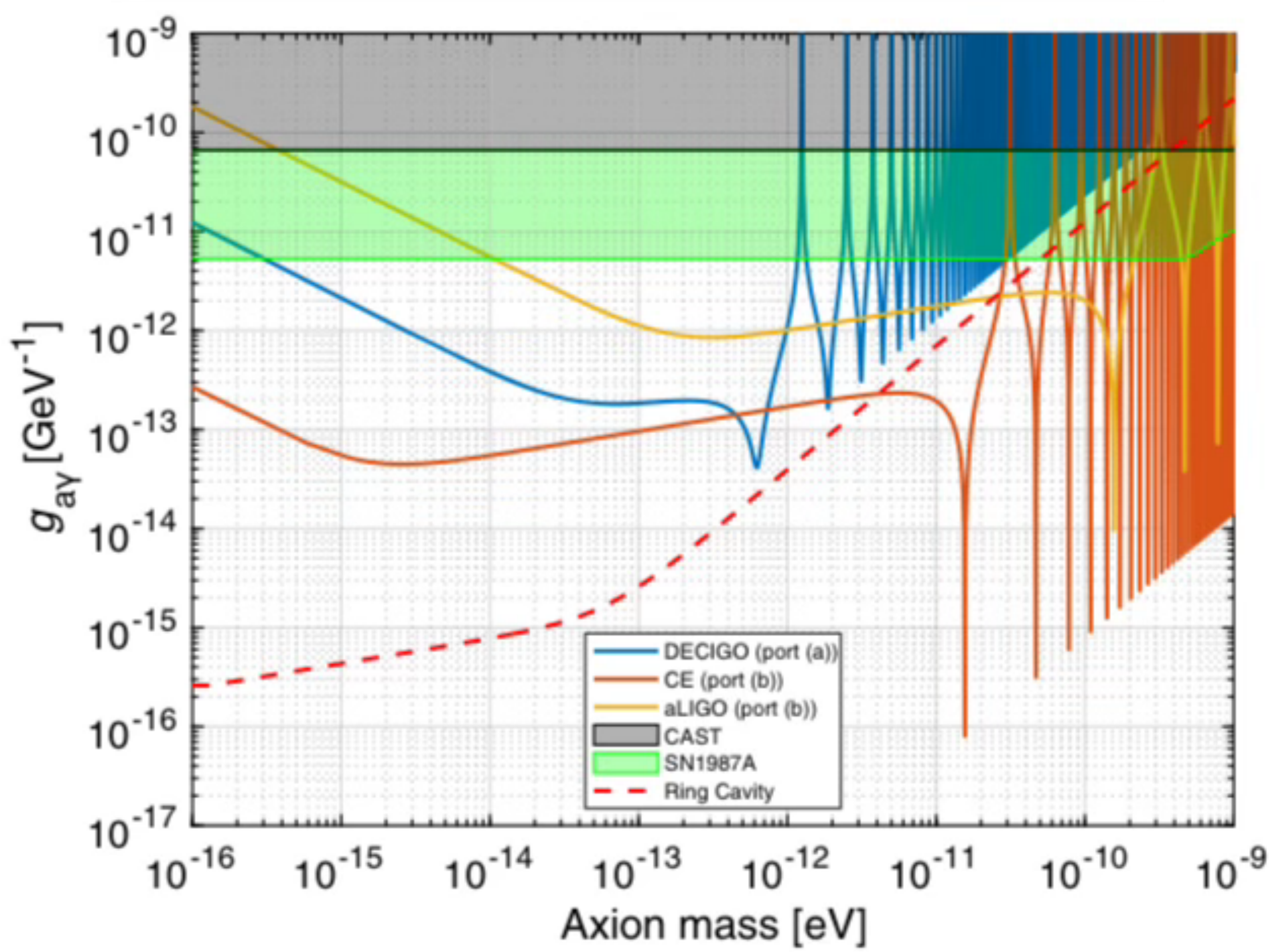


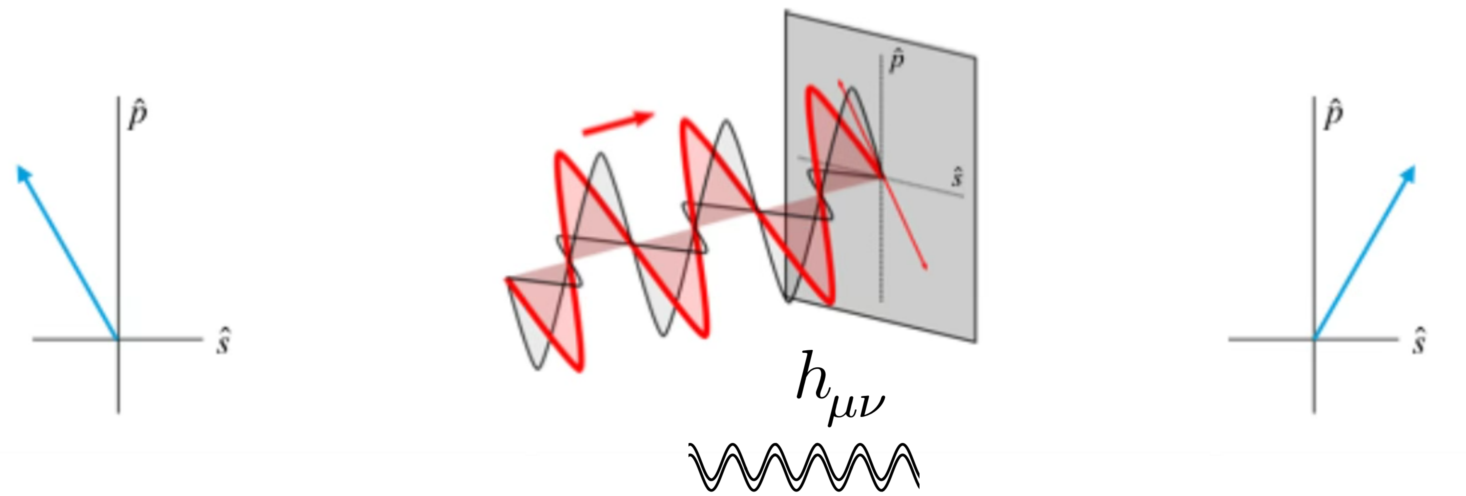


work in progress with Luca Marsili, Aaron Spector and Andreas Ringwald

ALPs experiment at DESY

Birefringence due to a gravitational wave

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



Geometrical
optics limit

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

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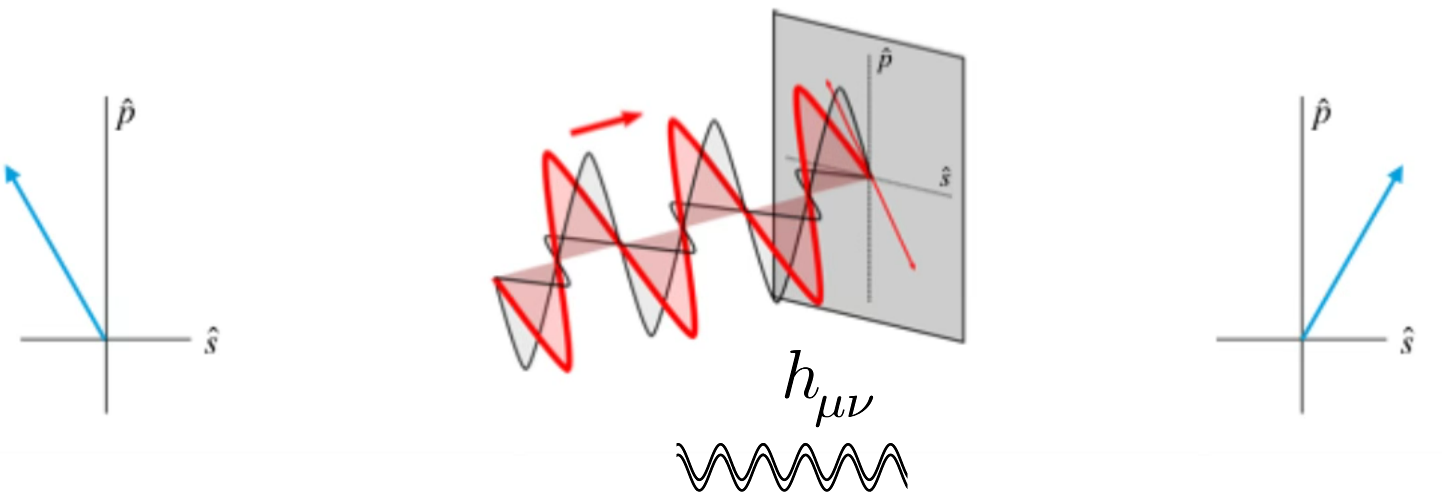
Birefringence due to a gravitational wave

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



ALPs experiment at DESY

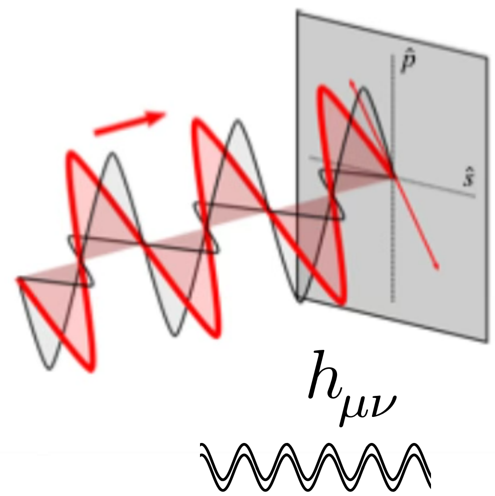
- For GWs coming from the zenith, the cross polarization has the same cavity response function as axions
- The plus polarization decouples (selection rules again)

PRELIMINARY

Camilo García Cely, University of Valencia

Birefringence due to a gravitational wave

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



ALPs experiment at DESY

Response function

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

$h_+ \quad 0$

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

Birefringence due to a gravitational wave

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

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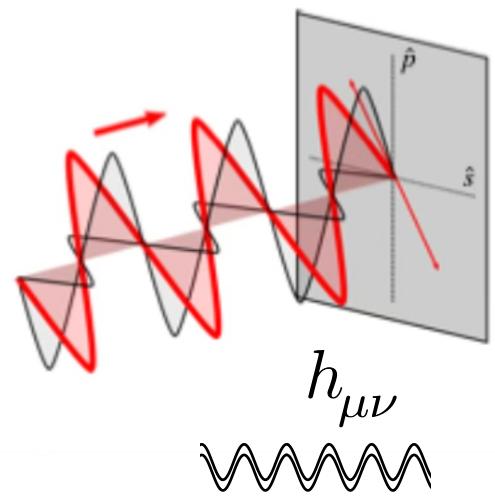

ALPs experiment at DESY

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

Camilo García Cely, University of Valencia

Conclusions

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

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

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

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

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