Detection of gravitational waves in axion haloscopes

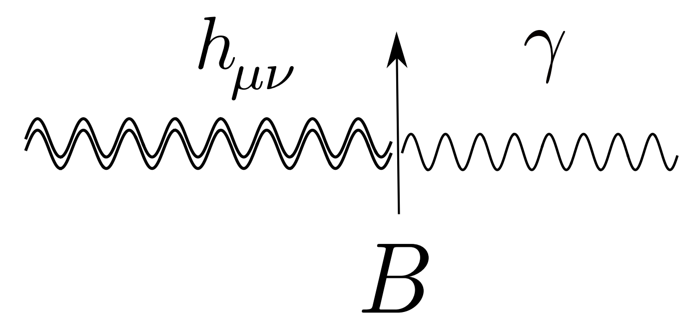
18th IAXO Collaboration Meeting
Teruel, Spain
September 11, 2023

Camilo García Cely

Based on **PRL 129, 041101** and **hep-ph/2306.03125.** In collaboration with Valerie Domcke, Sung Mook Lee and Nicholas L. Rodd.

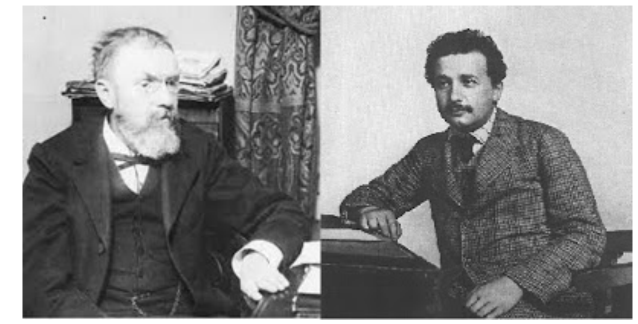
Outline

- Motivation
- Gravitational waves in axion haloscopes
- Recent developments
- Conclusions



Motivation

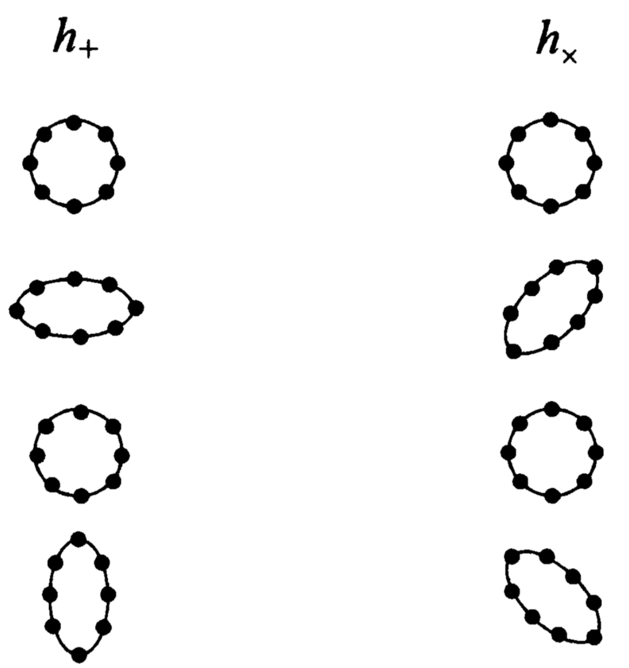
Gravitational waves



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

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

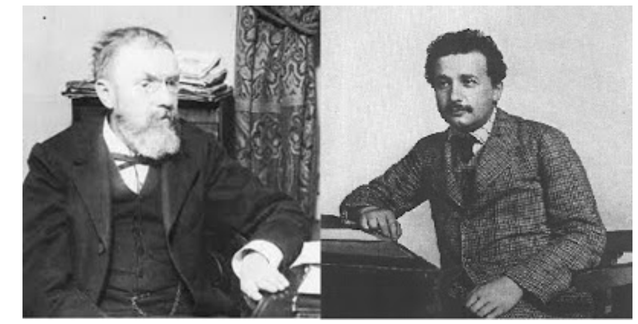
wave equation describing two polarization modes

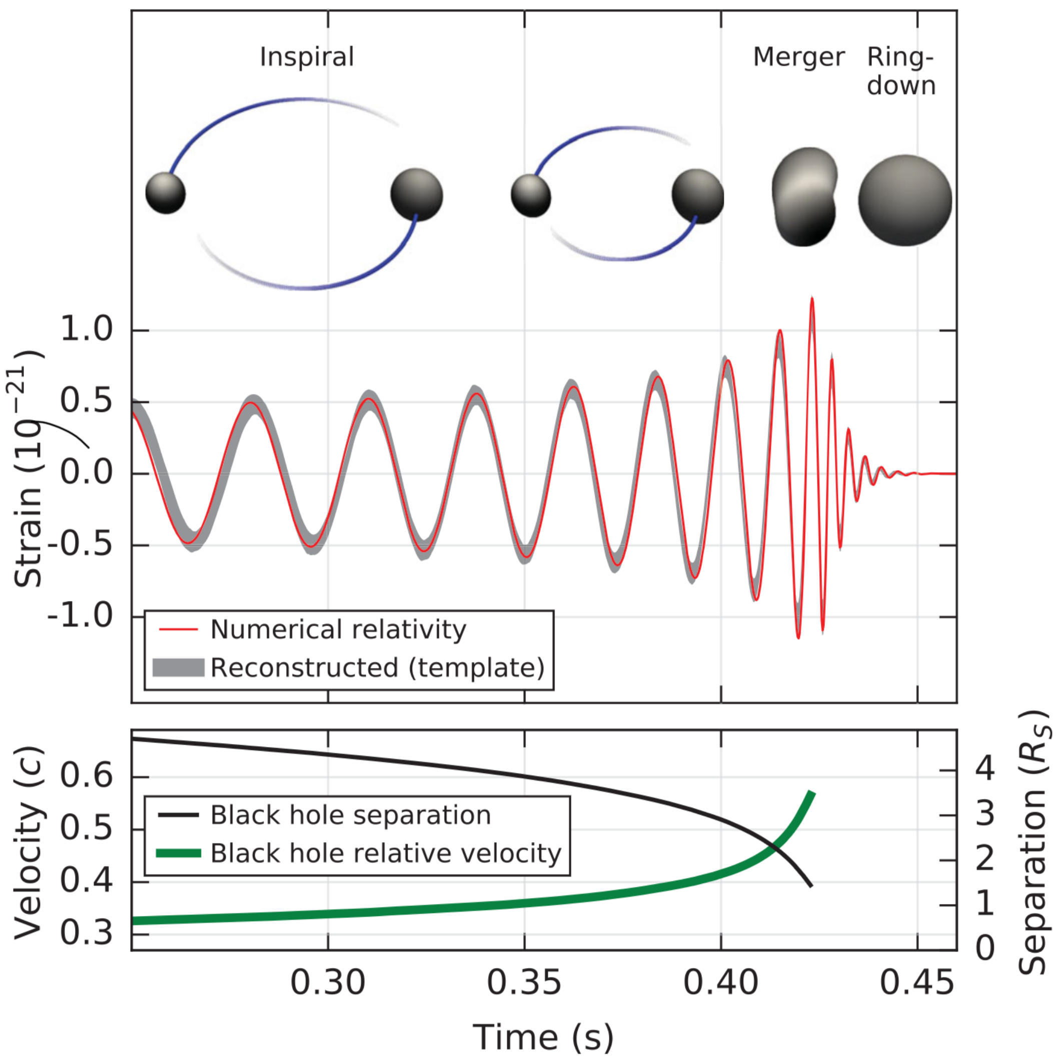


The deformation of a ring of test masses due to the different polarization

Gravitational waves

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



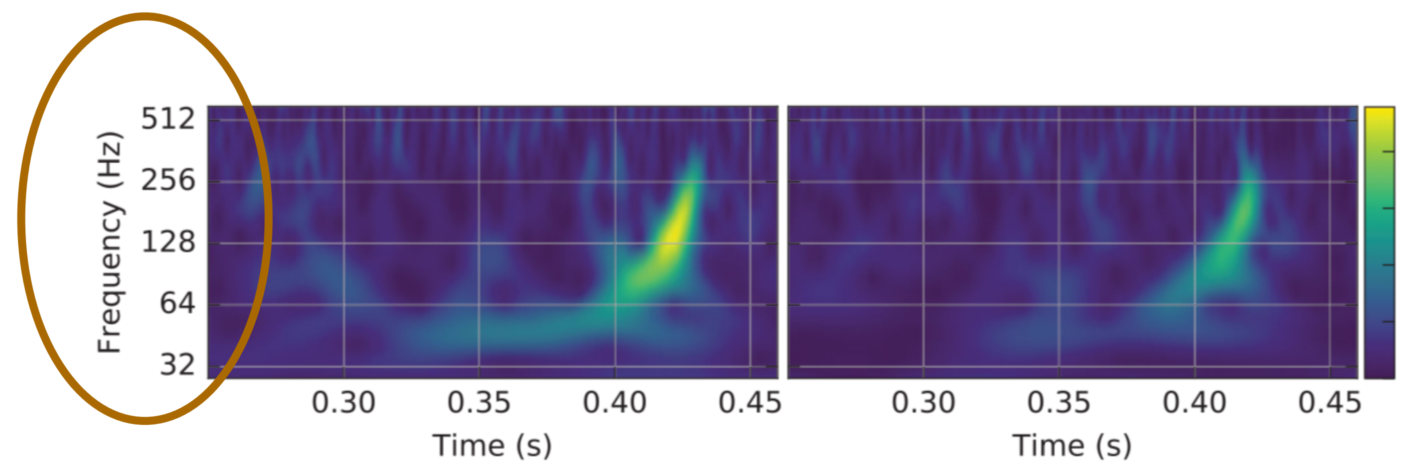


PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]

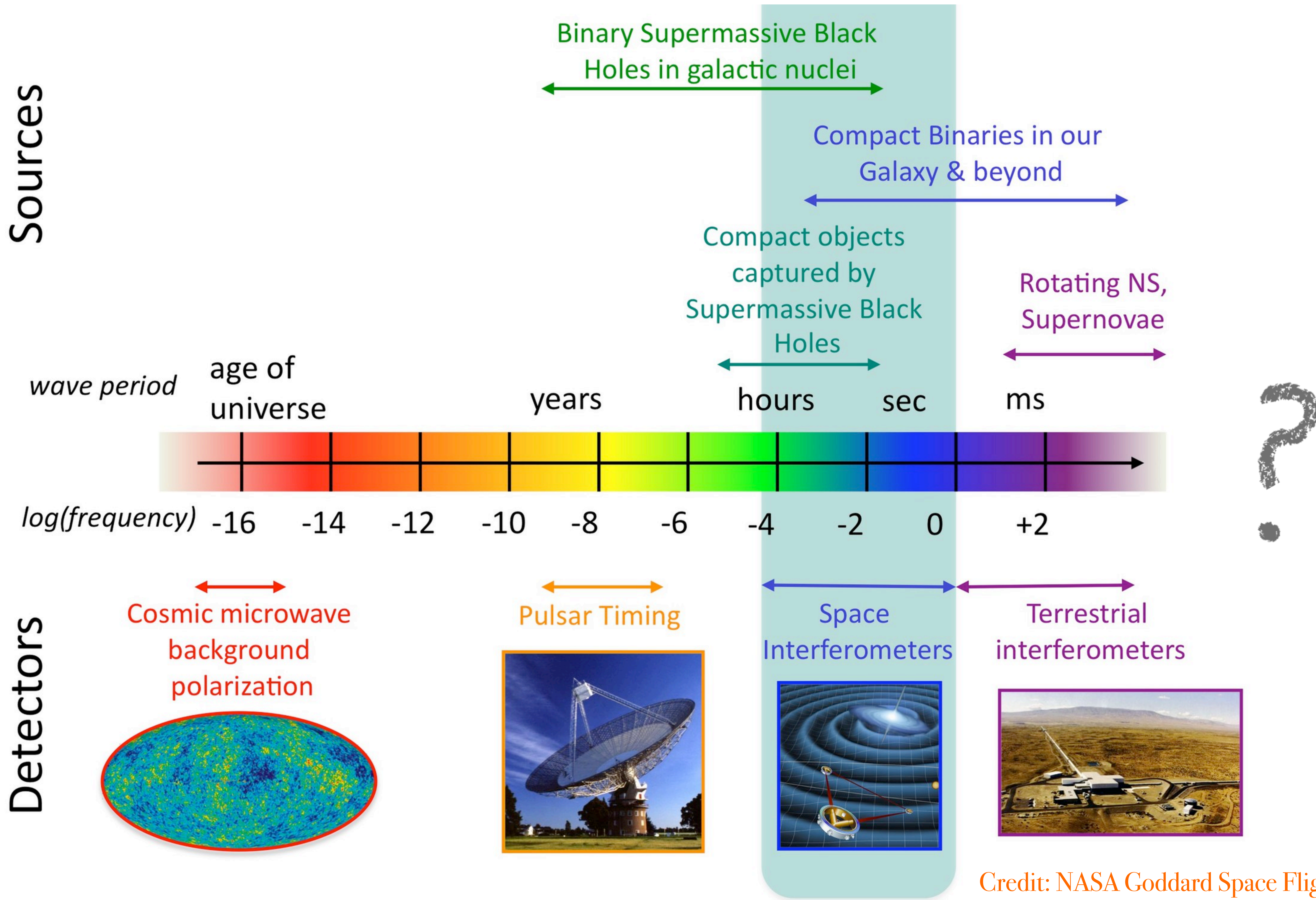
(LIGO Scientific Collaboration and Virgo Collaboration)



interferometers

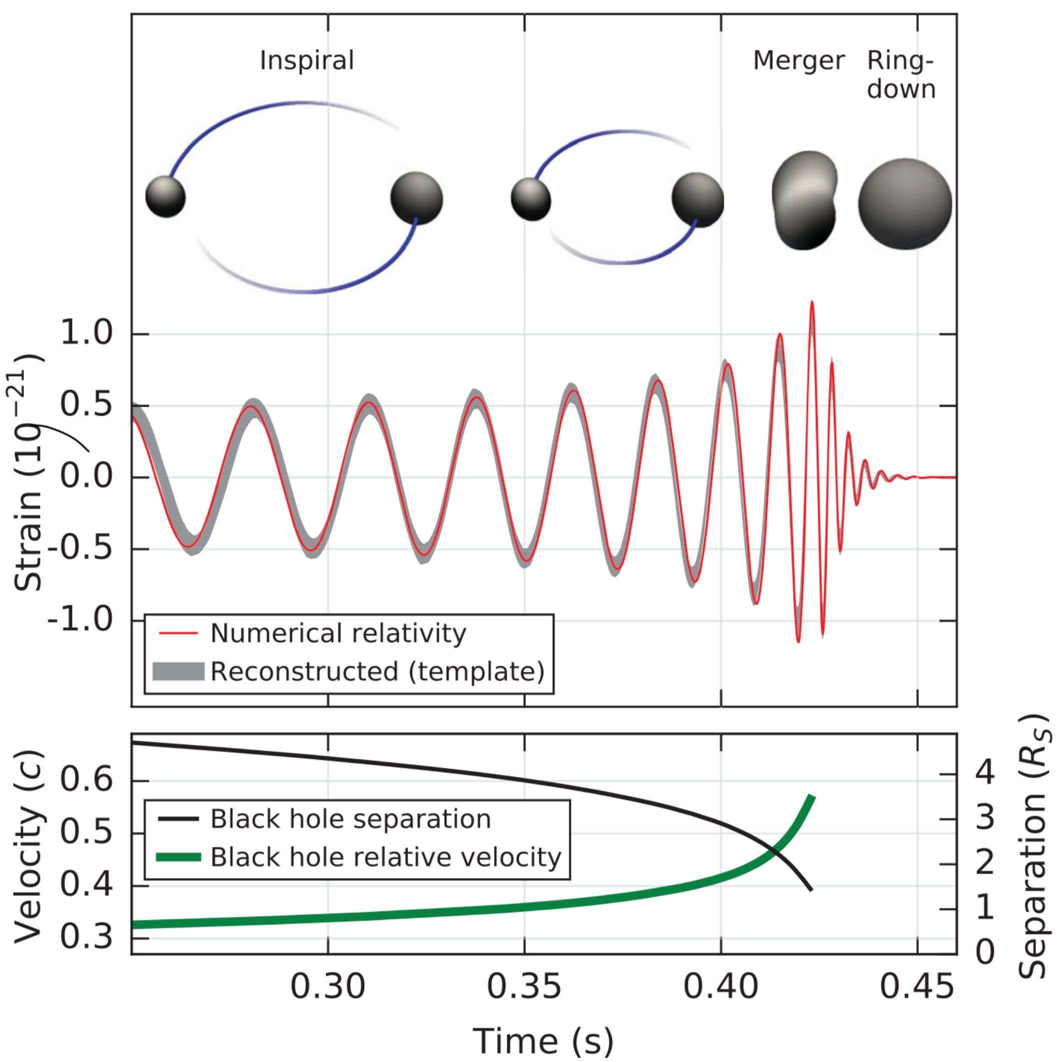
Camilo García Cely, University of Valencia

GW spectrum



Credit: NASA Goddard Space Flight Center

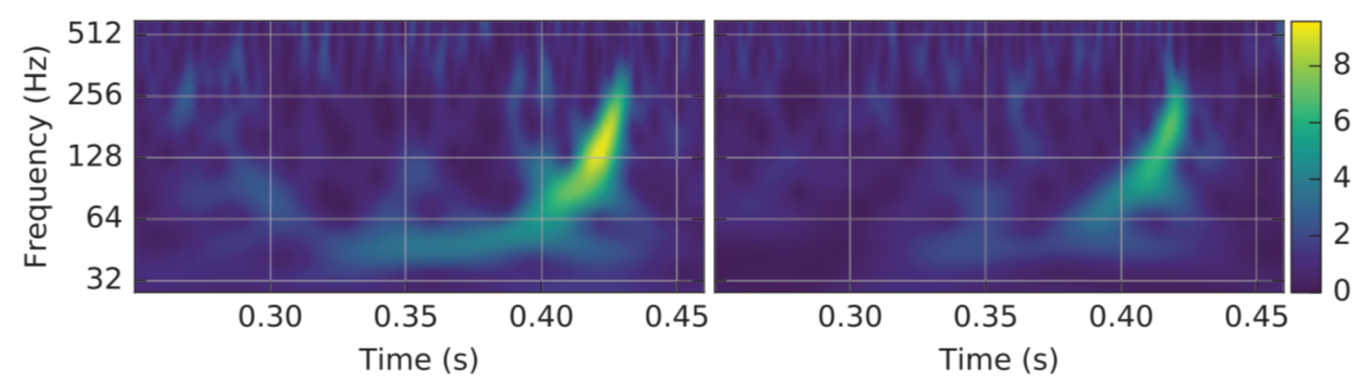
GW spectrum



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)



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

High-frequency gravitational waves

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

Part of a collection:

Gravitational Waves

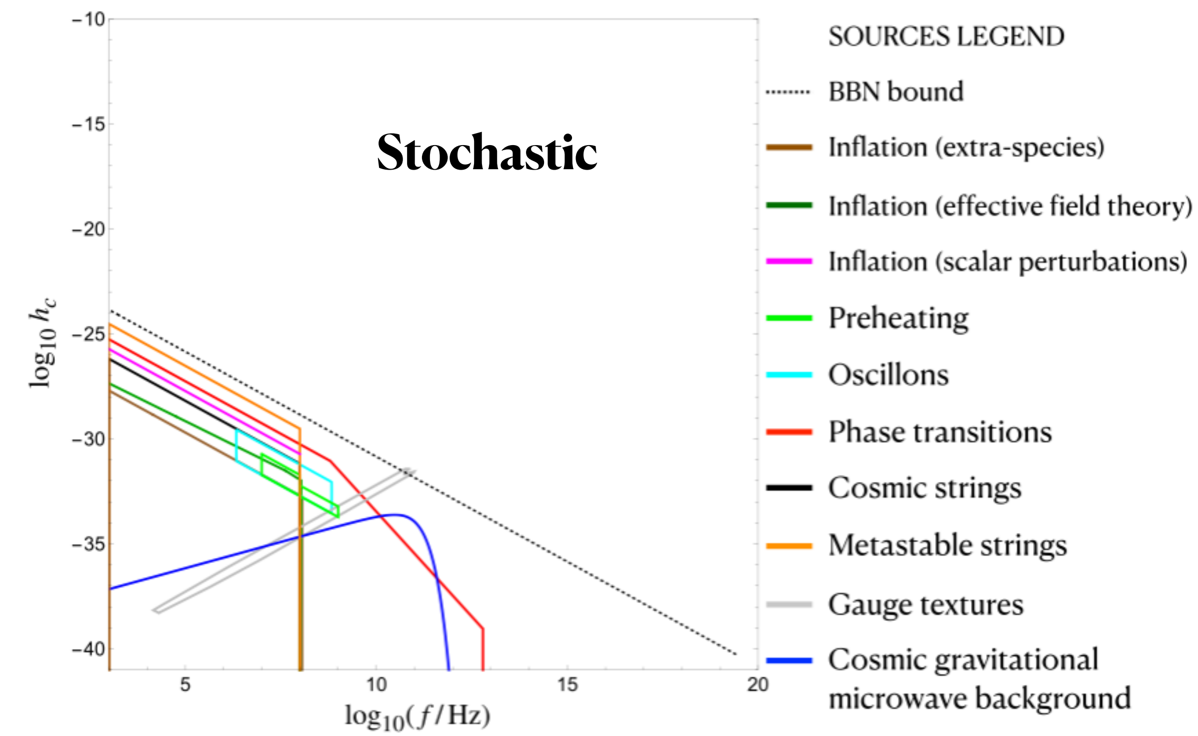
Review Article | Open Access | Published: 06 December 2021

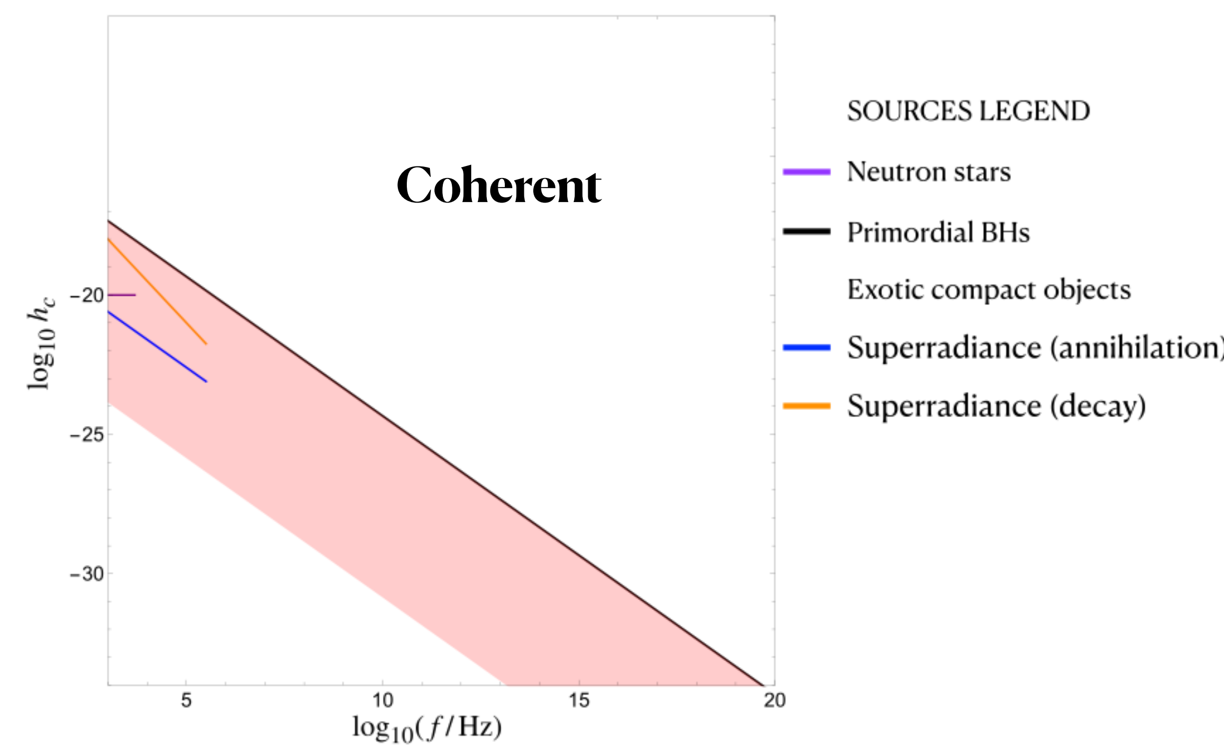
Challenges and opportunities of gravitational-wave searches at MHz to GHz frequencies

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

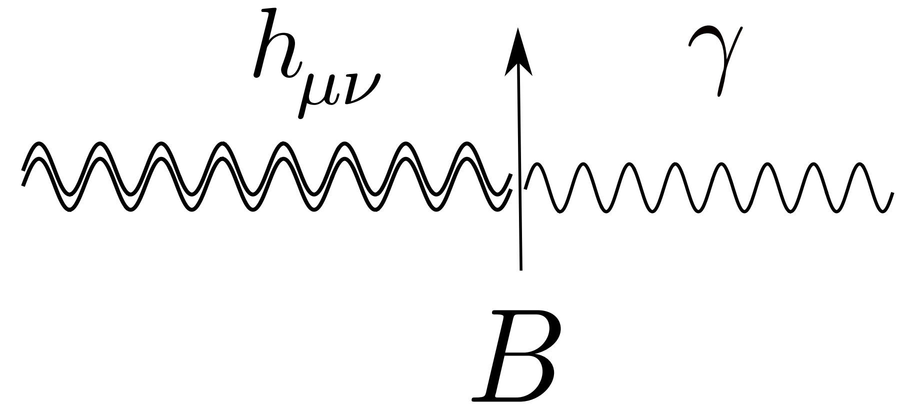
A growing community is seriously considering the search of high frequency gravitational waves





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

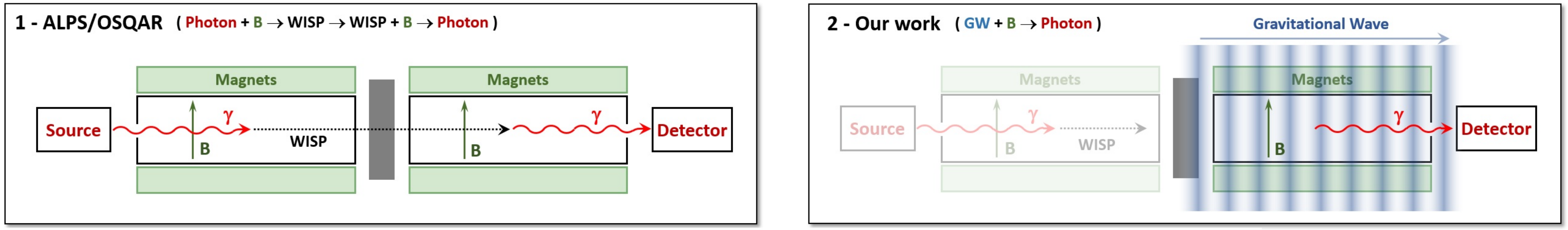
Submitted to JETP editor March 3, 1962

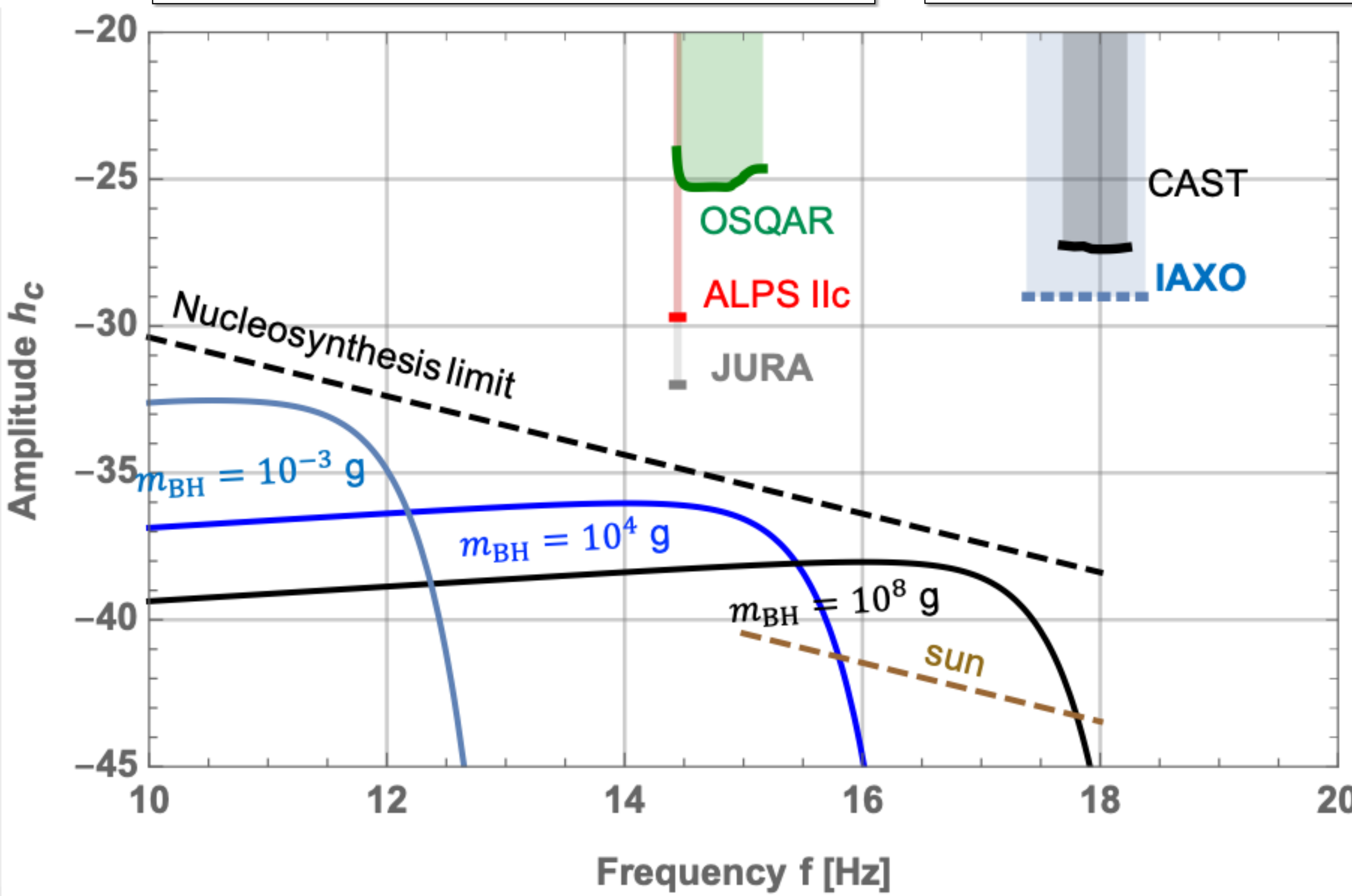
J. Exptl. Theoret. Phys. (U.S.S.R.) **43**, 605-607 (August, 1962)

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

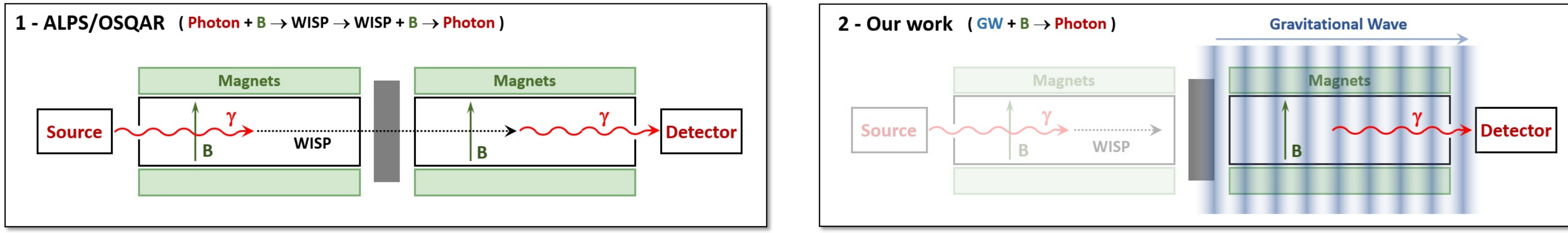


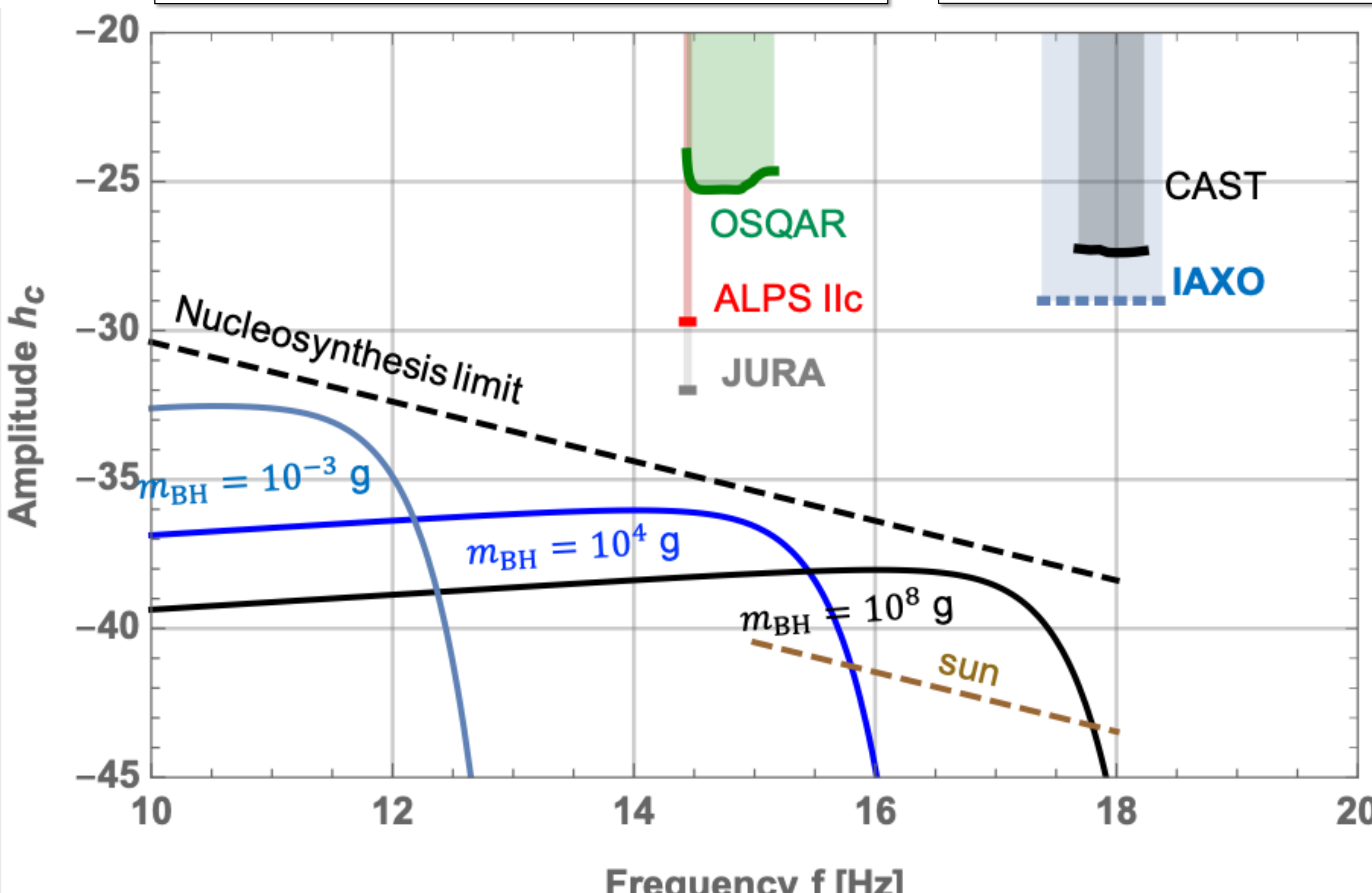


A. Ejlli, D. Ejlli, A. M. Cruise, G. Pisano & H. Grote

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

The (inverse) Gertsenhstein Effect





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)

The (inverse) Gertsenhstein Effect

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

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

- Involving gravity the conversion probabilities are small. It may be compensated by a 'detector' of cosmological size.

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 dark matter conversion.

Raffelt, Stodolski'89

Gravitational waves in axion haloscopes

PHYSICAL REVIEW LETTERS **129,** 041101 (2022)

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

Valerie Domcke,[1,2] Camilo Garcia-Cely,[3] and Nicholas L. Rodd[1]

Symmetries and Selection Rules: Optimising Axion Haloscopes for Gravitational Wave Searches

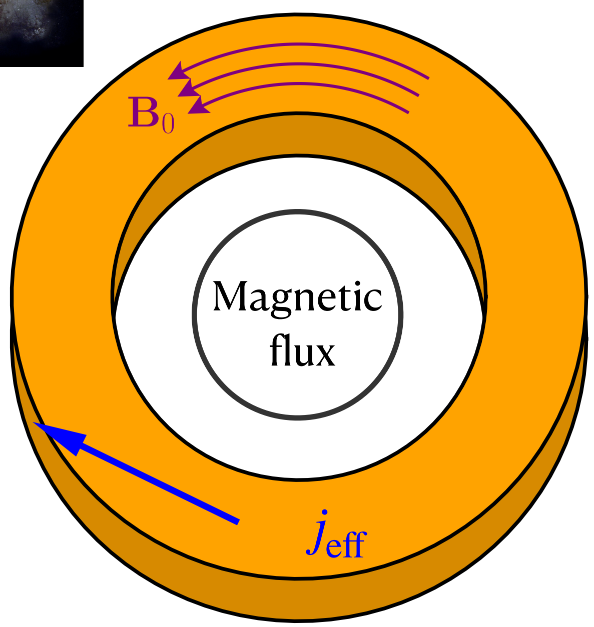
Valerie Domcke (CERN), Camilo Garcia-Cely (Valencia U., IFIC), Sung Mook Lee (CERN and IPAP, Seoul), Nicholas L. Rodd (CERN)

Jun 5, 2023

	Axion electrodynamics	**Gravitational wave electrodynamics**
For example	Axion-Photon conversion	Gertsenshtein effect
Effective current $j^\mu_{\rm eff} = \left(-\nabla\cdot\mathbf{P}, \nabla\times\mathbf{M} + \partial_t\mathbf{P}\right)$	$\mathbf{P} = g_{a\gamma\gamma} a \mathbf{B}, \quad \mathbf{M} = g_{a\gamma\gamma} a \mathbf{E}$ 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
Benchmark	QCD axion $g_{a\gamma\gamma}a \sim \frac{\alpha\sqrt{\rho_{\rm DM}}}{2\pi m_a f_a} \sim \frac{\alpha\sqrt{\rho_{\rm DM}}}{2\pi m_\pi f_\pi} \sim 10^{-22}$	$h \sim 10^{-22}$

Camilo García Cely, University of Valencia

Haloscopes based on lumped-element detectors

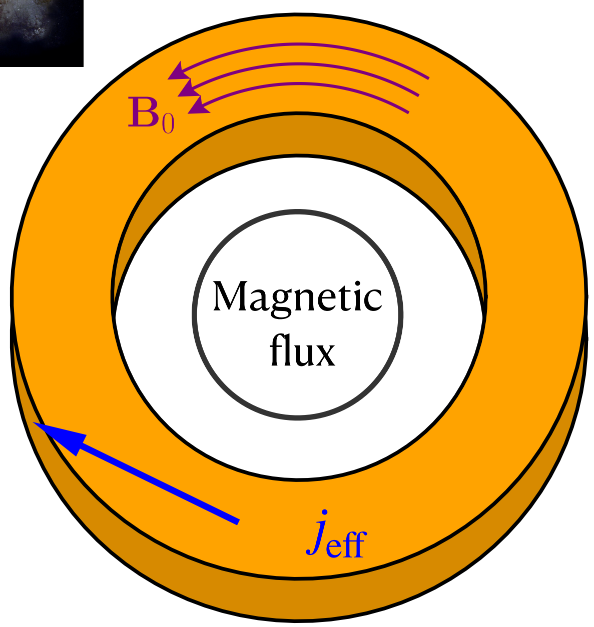


$$\nabla \times \mathbf{B} - \partial_t \mathbf{E} = \underbrace{g_{a\gamma\gamma}\, \partial_t a\, \mathbf{B_0}}_{j_{\text{eff}}}$$

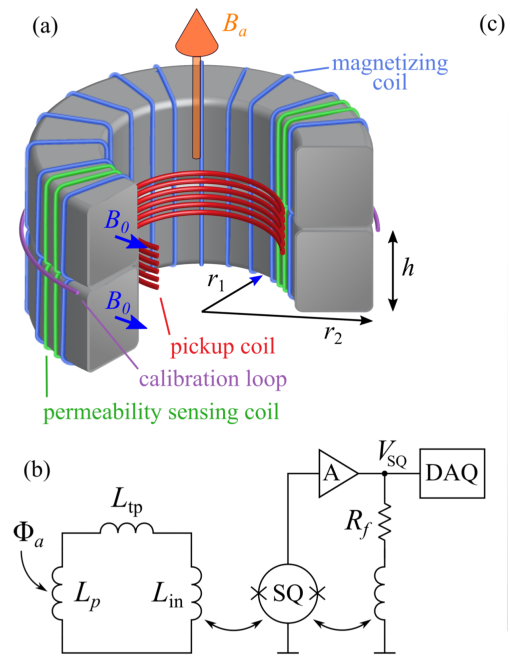
The electromagnetic fields produced by the axion drive a current through a pickup coil

Camilo García Cely, University of Valencia

Haloscopes based on lumped-element detectors



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



(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]

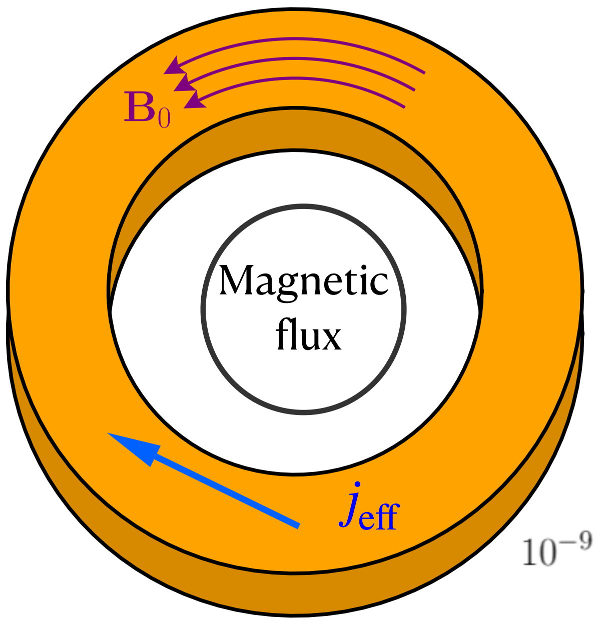
PRL 117, 141801 (2016) PHYSICAL REVIEW LETTERS week ending 30 SEPTEMBER 2016

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)

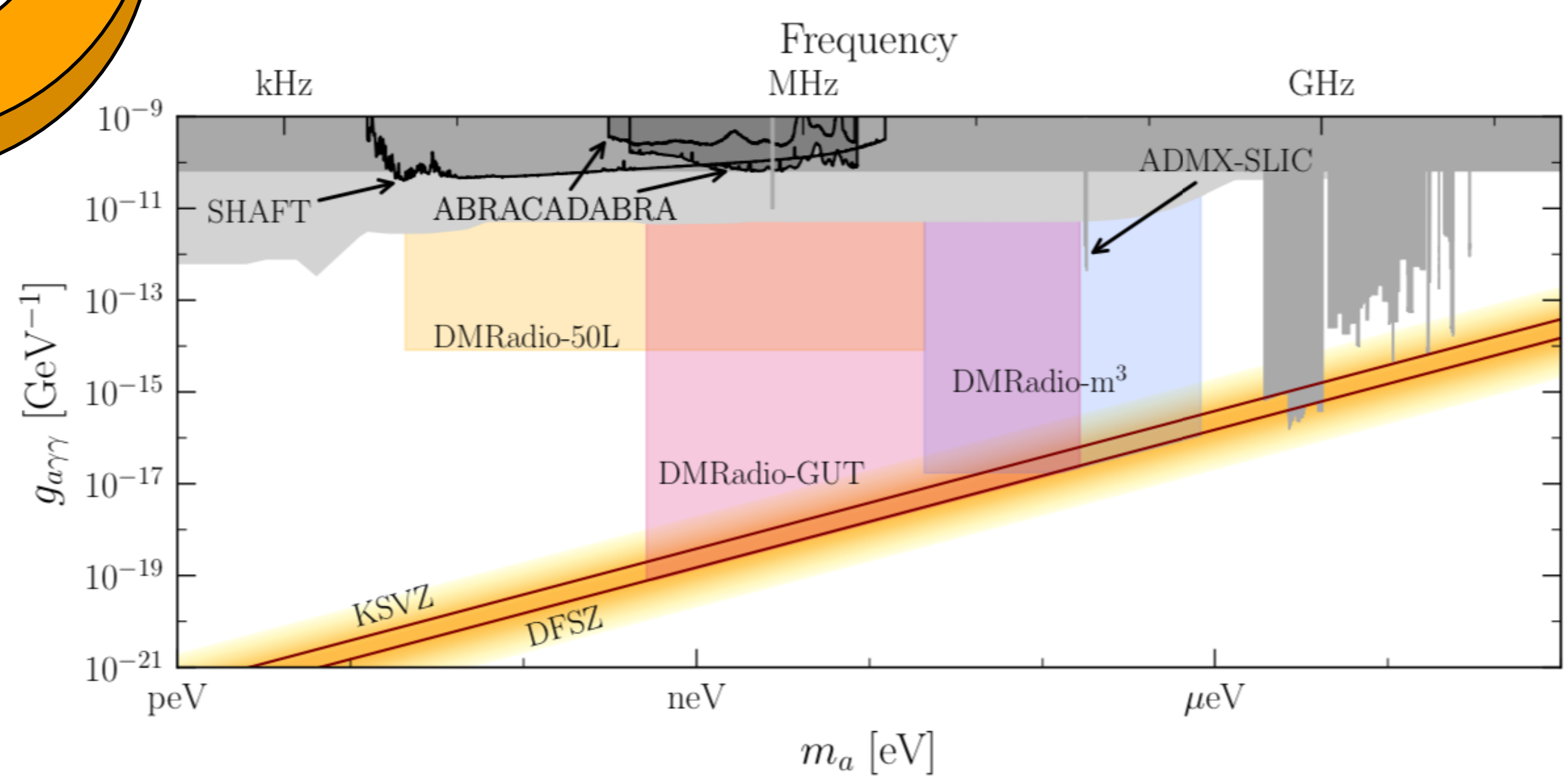
The electromagnetic fields produced by the axion drive a current through a pickup coil

Haloscopes based on lumped-element detectors



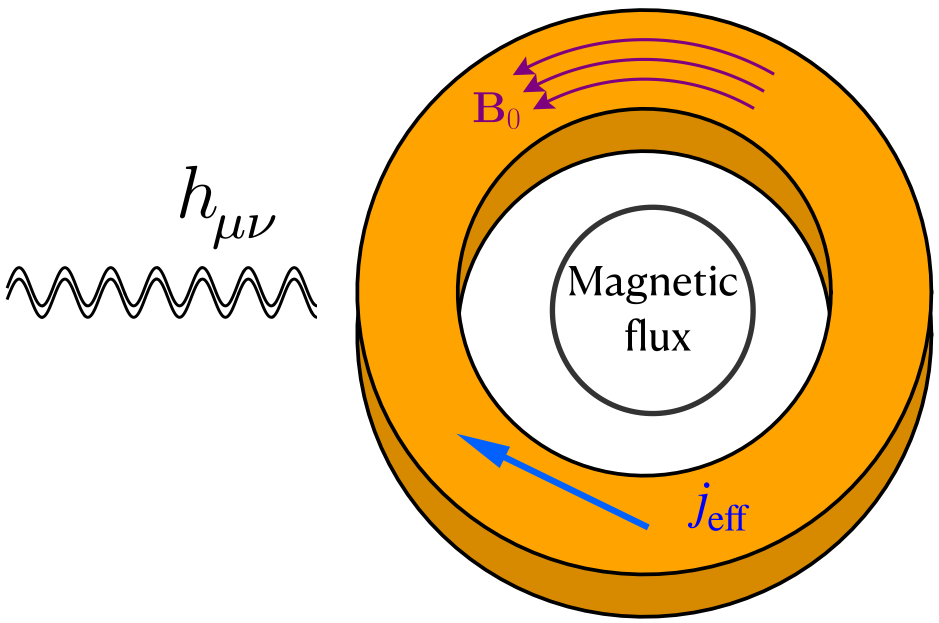
Proposal for a definitive search for GUT-scale QCD axions

L. Brouwer *et al.* (DMRadio Collaboration)
Phys. Rev. D **106**, 112003 – Published 12 December 2022

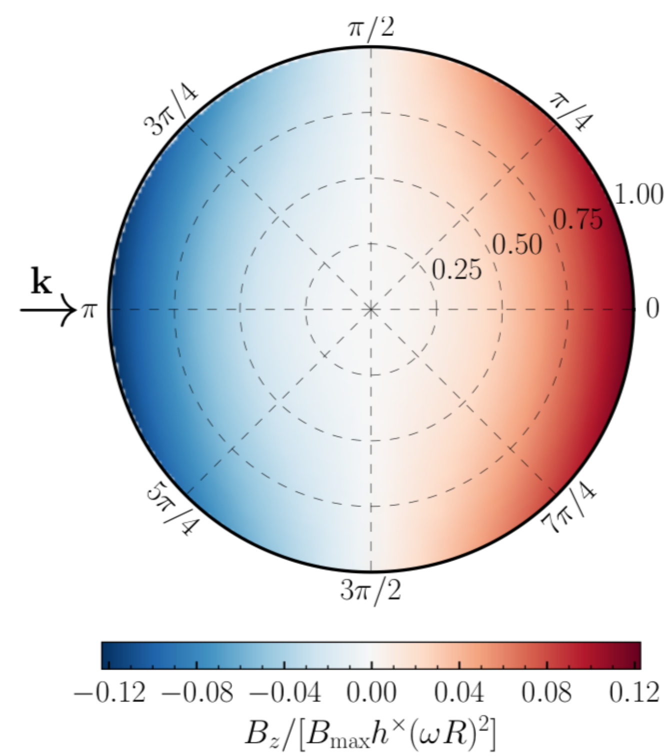


Camilo García Cely, University of Valencia

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

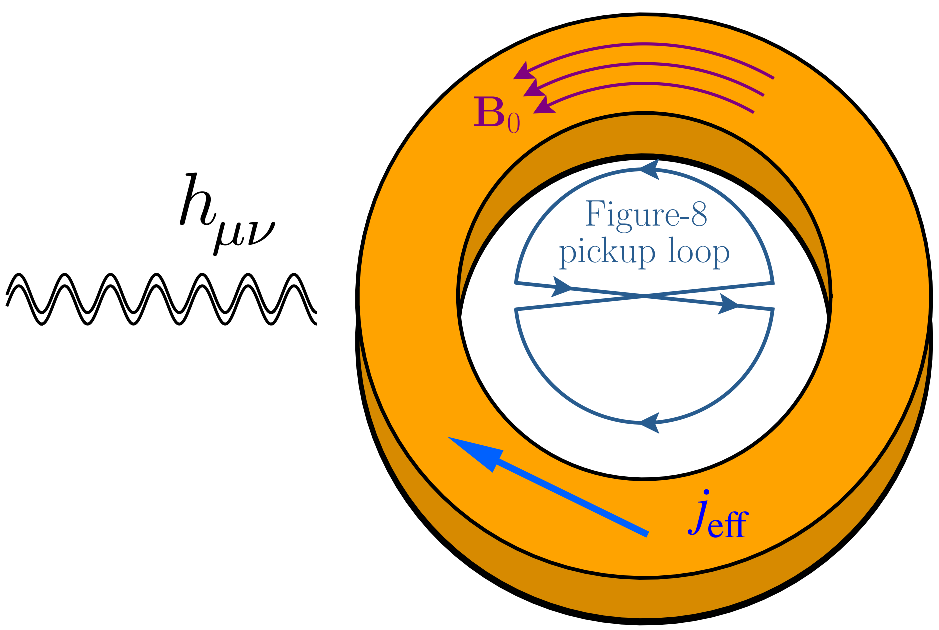
Suppression at small frequencies

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

The sensitivity scaling with the volume is faster than for axions

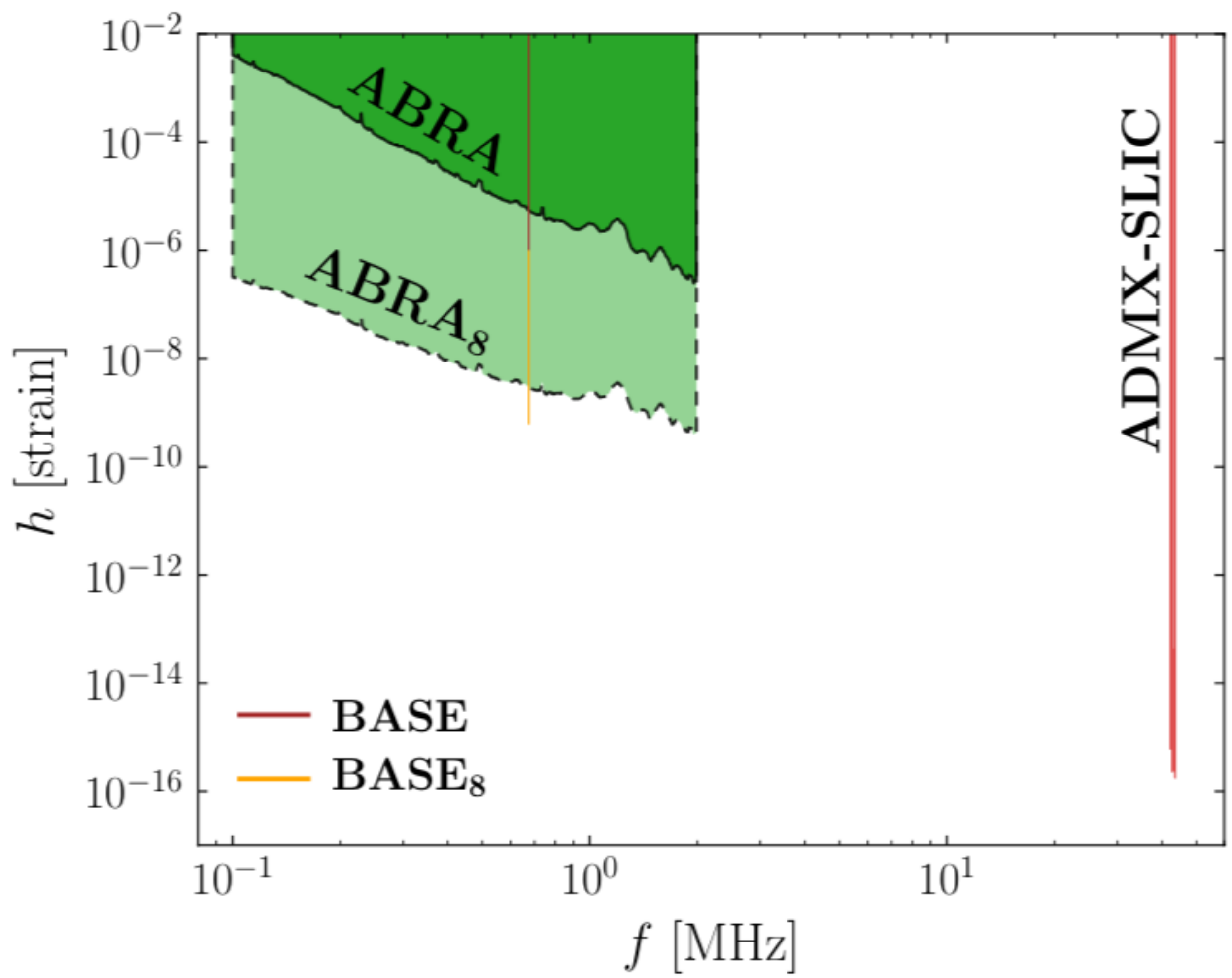
Haloscopes based on lumped-element detectors

Break cylindrical symmetry



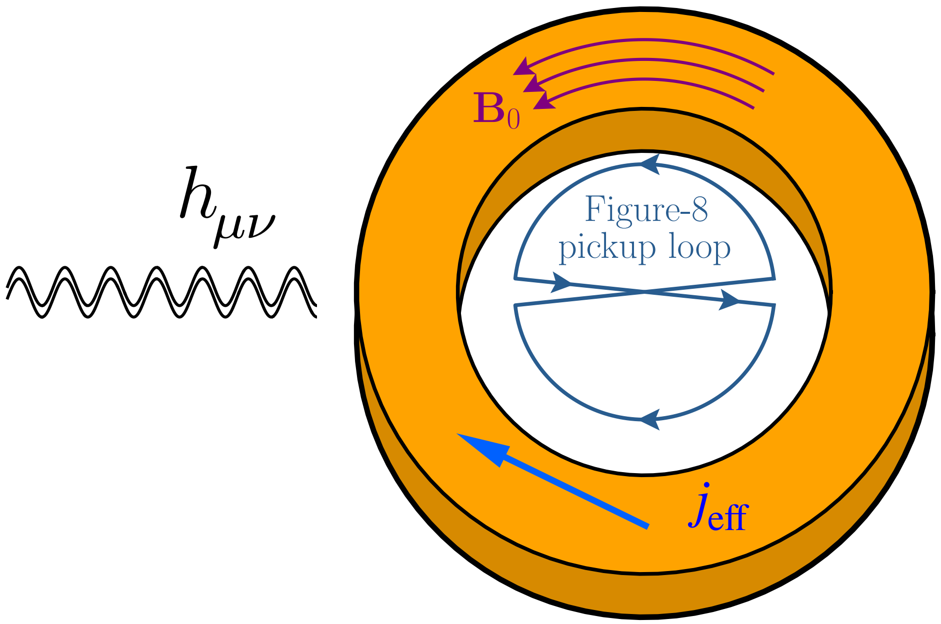
Valerie Domcke, Camilo Garcia-Cely, and Nicholas L. Rodd
Phys. Rev. Lett. **129**, 041101 – Published 20 July 2022

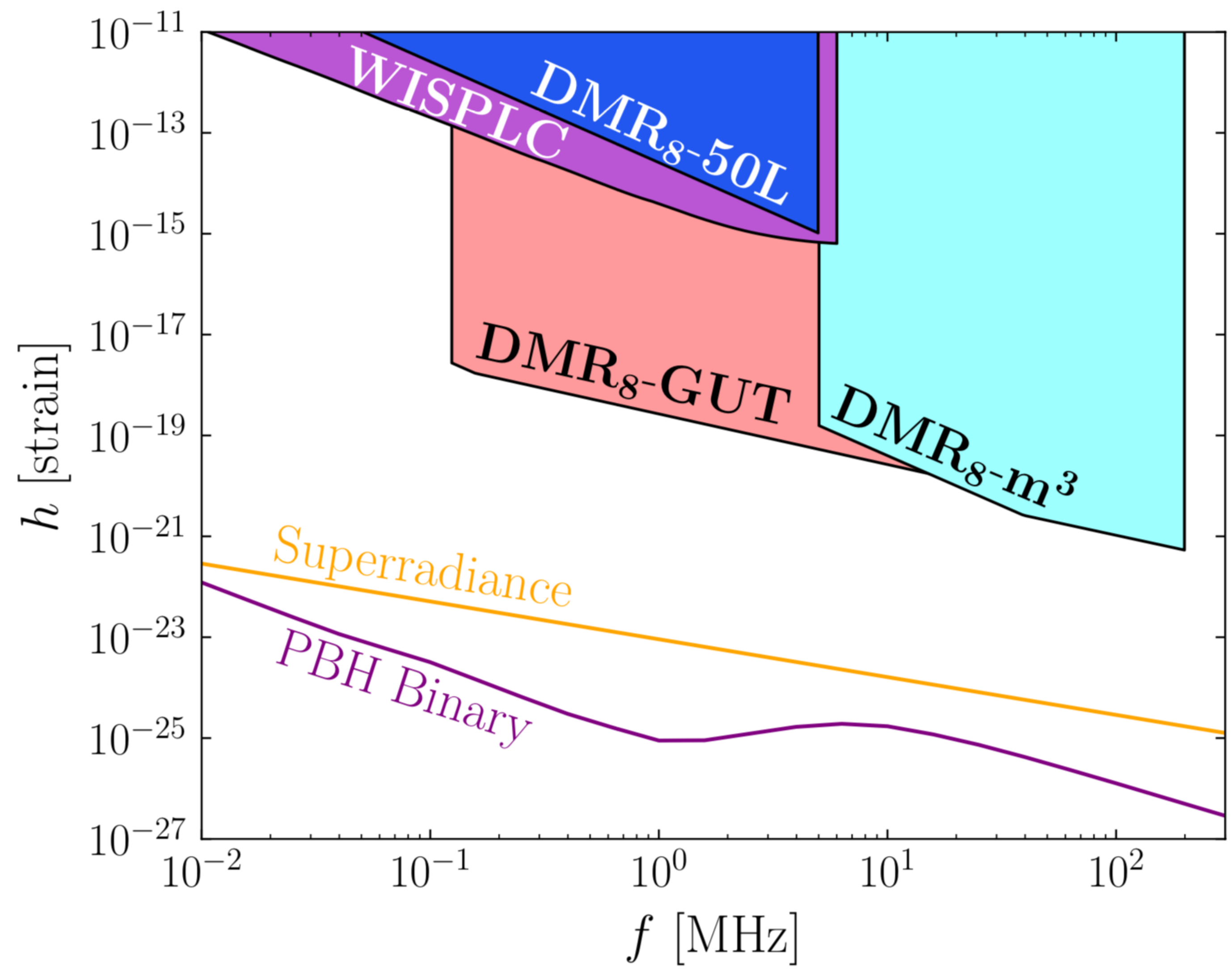
Domcke, CGC, Lee, Rodd, 2023



Haloscopes based on lumped-element detectors

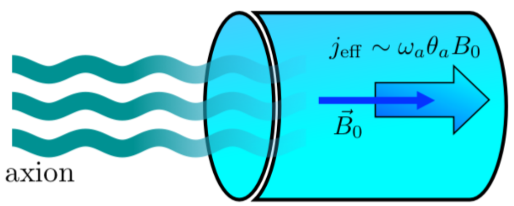
Domcke, CGC, Lee, Rodd, 2023

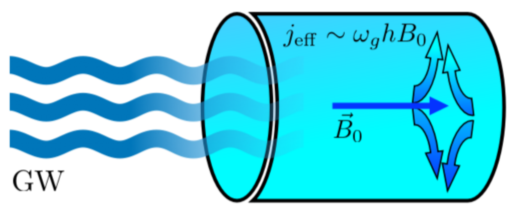




Recast of axion searches to establish GW sensitivity, taking into account the different time scales involved in the signals and detectors.

Haloscopes based on microwave cavities





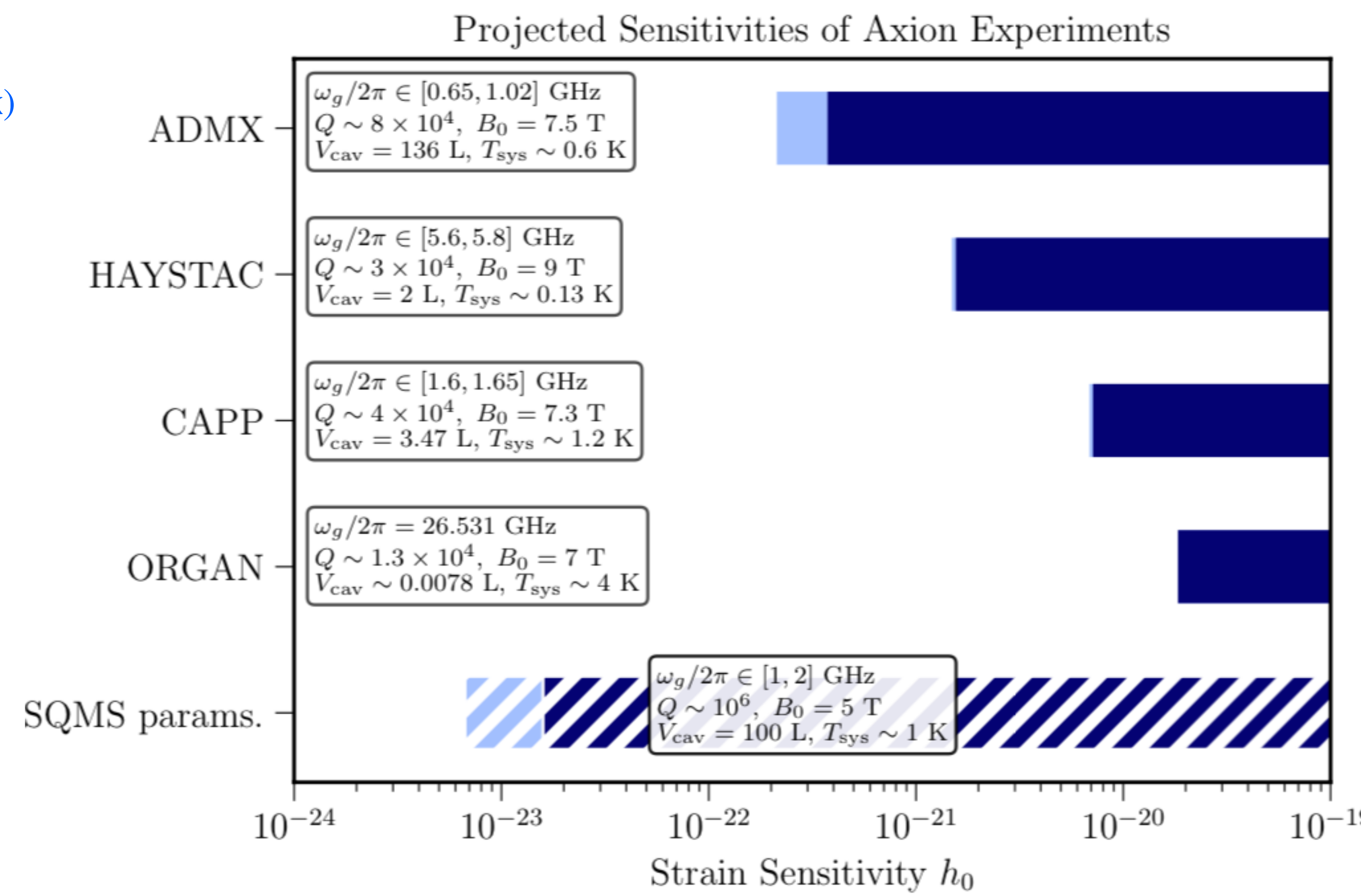
Detecting high-frequency gravitational waves with microwave cavities

Asher Berlin, Diego Blas, Raffaele Tito D'Agnolo, Sebastian A. R. Ellis, Roni Harnik, Yonatan Kahn, and Jan Schütte-Engel
Phys. Rev. D **105**, 116011 – Published 17 June 2022

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

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

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



Recent Developments

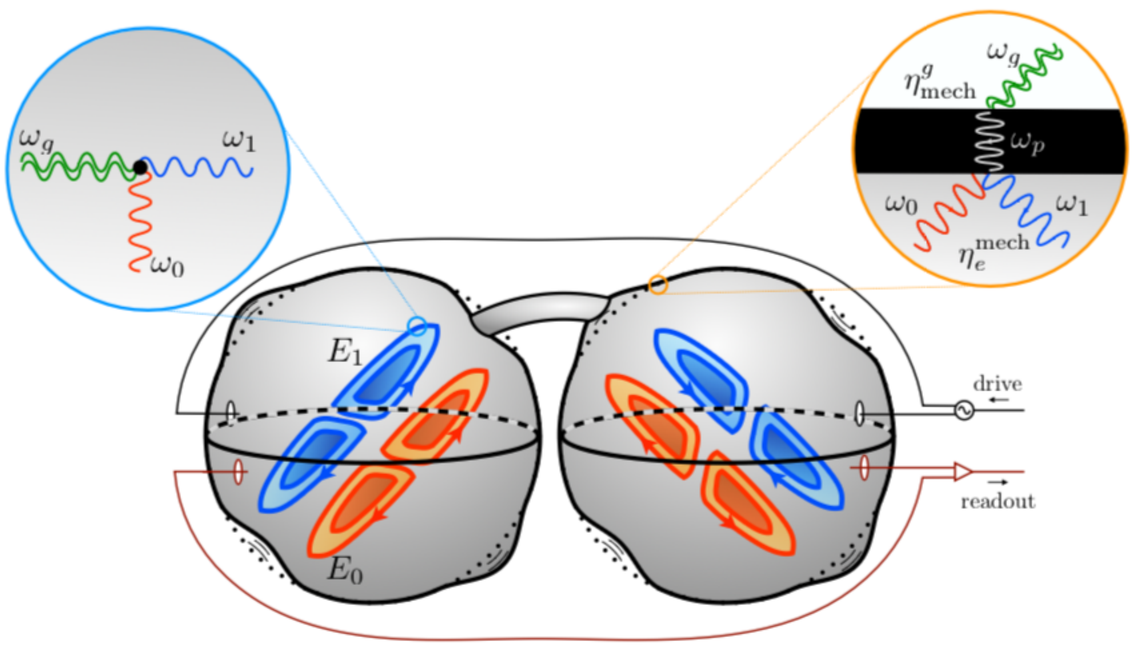
The coupling of the mechanical modes can play an important role

[Submitted on 2 Mar 2023]

MAGO 2.0: Electromagnetic Cavities as Mechanical Bars for Gravitational Waves

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

Superconducting cavities can operate analogously to Weber bar detectors of gravitational waves, converting mechanical to electromagnetic energy. The significantly reduced electromagnetic noise results in increased sensitivity to high-frequency signals well outside the bandwidth of the lowest mechanical resonance. In this work, we revisit such signals of gravitational waves and demonstrate that a setup similar to the existing "MAGO" prototype, operating in a scanning or broadband manner, could have sensitivity to strains of $\sim 10^{-22} - 10^{-18}$ for frequencies of $\sim 10\ \mathrm{kHz} - 1\ \mathrm{GHz}$.



Selection rules for low-mass haloscopes

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:

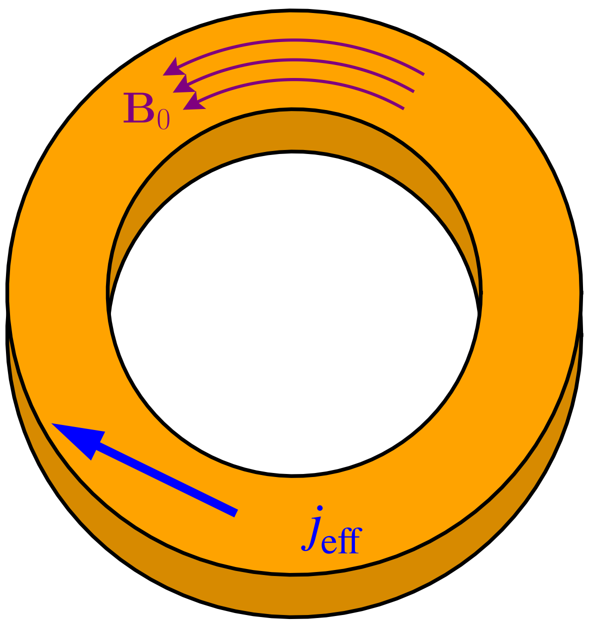
Selection Rule 1: For an instrument with azimuthal symmetry, $\Phi_h \propto h^+$ at $\mathcal{O}[(\omega L)^2]$

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.

Surface currents

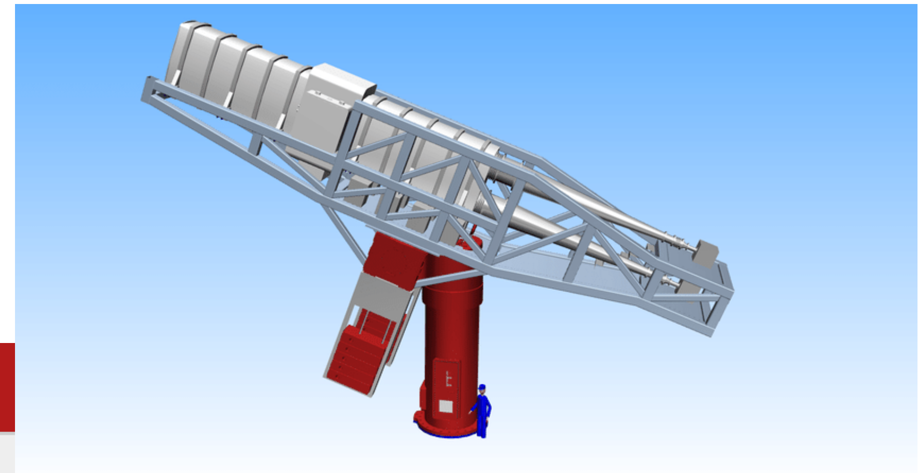
Domcke, CGC, Lee, Rodd, 2023



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 GW

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

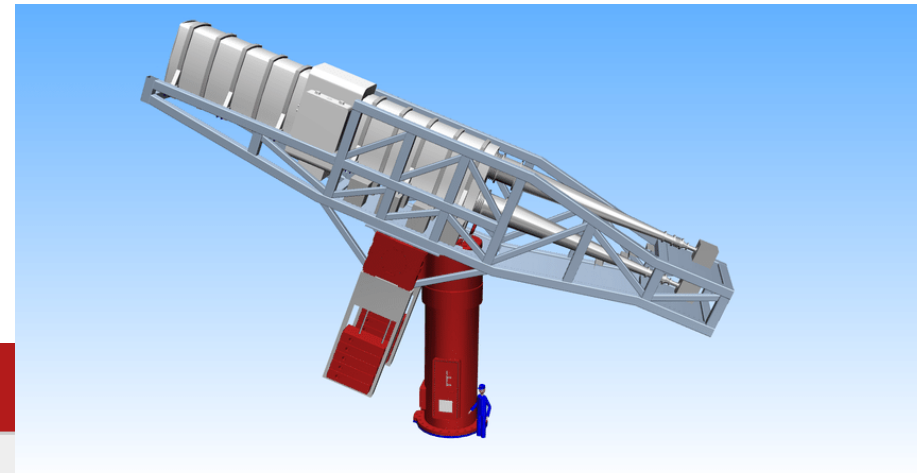
With adaptions to the coupling structures, the BabyIAXO RADES cavities also have sensitivity to hypothesized high-frequency gravitational waves (HFGWs), see, e.g. [55–57].

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.

Camilo García Cely, University of Valencia

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

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 no experiment as of today has been 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