Gravitational wave detection with haloscopes

Galileo Galilei Institute

Axions across boundaries between Particle Physics, Astrophysics, Cosmology and forefront Detection Technologies

June 6, 2023

Camilo García Cely

Ramón y Cajal Researcher

IFIC INSTITUT DE FÍSICA CORPUSCULAR

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

VNIVERSITAT DE VALÈNCIA

Based on

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

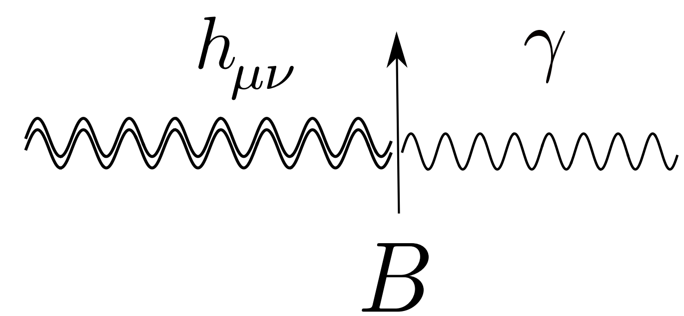
Valerie Domcke, Camilo Garcia-Cely, and Nicholas L. Rodd
Phys. Rev. Lett. **129**, 041101 – Published 20 July 2022

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

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

Outline

- Why high-frequency gravitational waves and ideas to detect them
- Detection in haloscopes
- Selection rules
- Conclusions

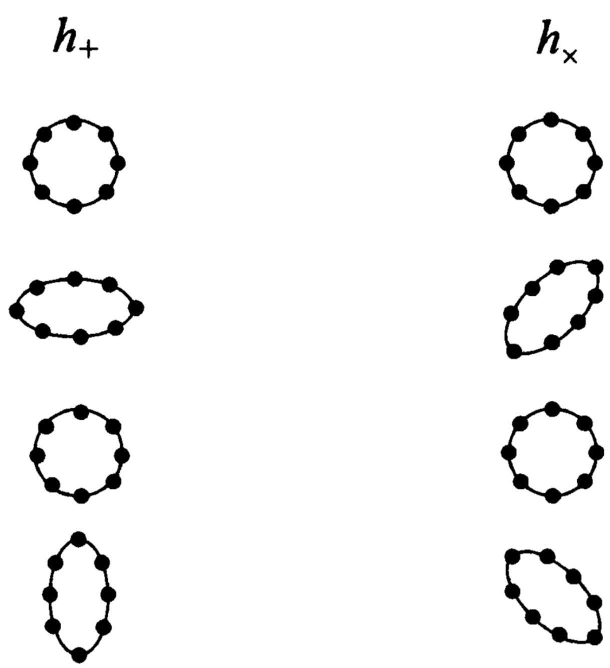



Gravitational waves

- 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

Camilo García Cely, University of Valencia

Gravitational waves

- Speculation by Poincaré (1905)
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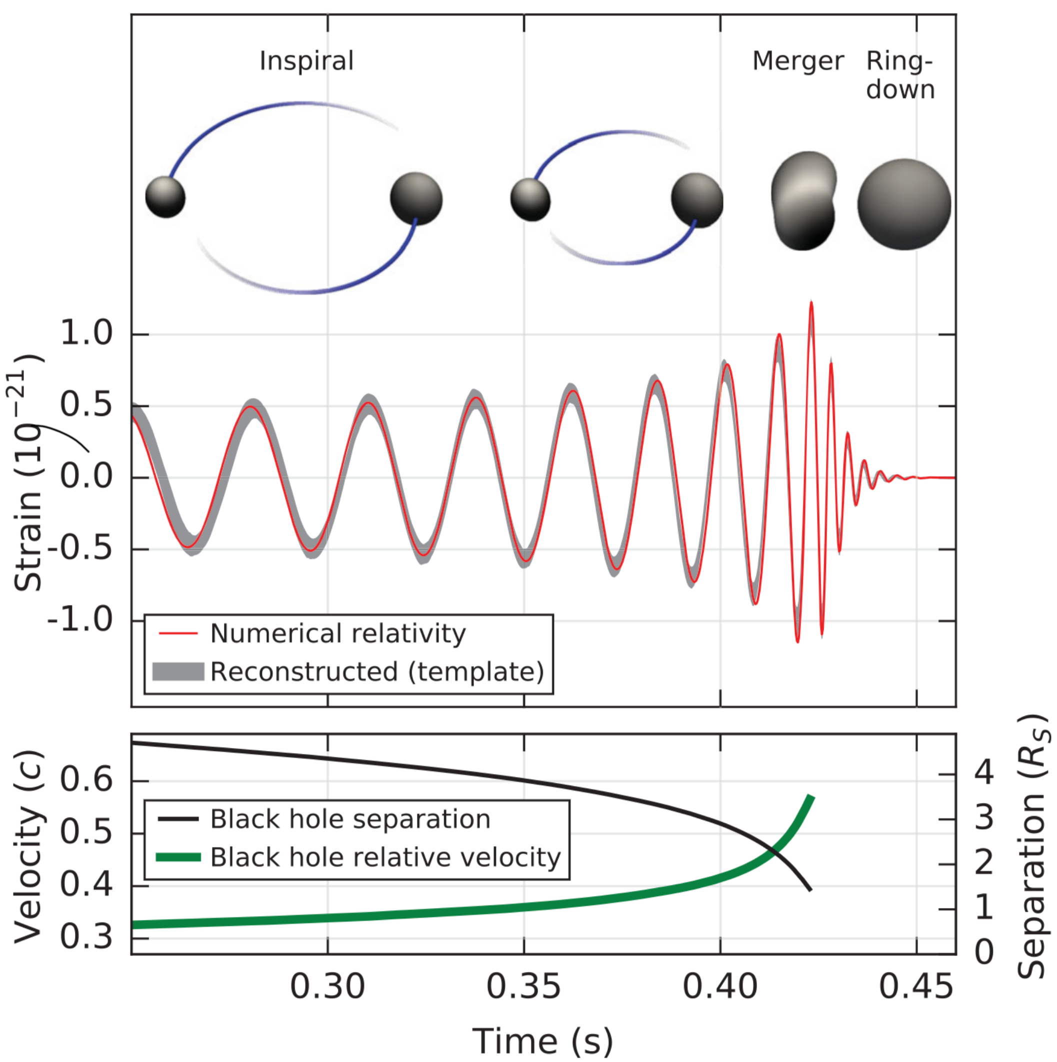
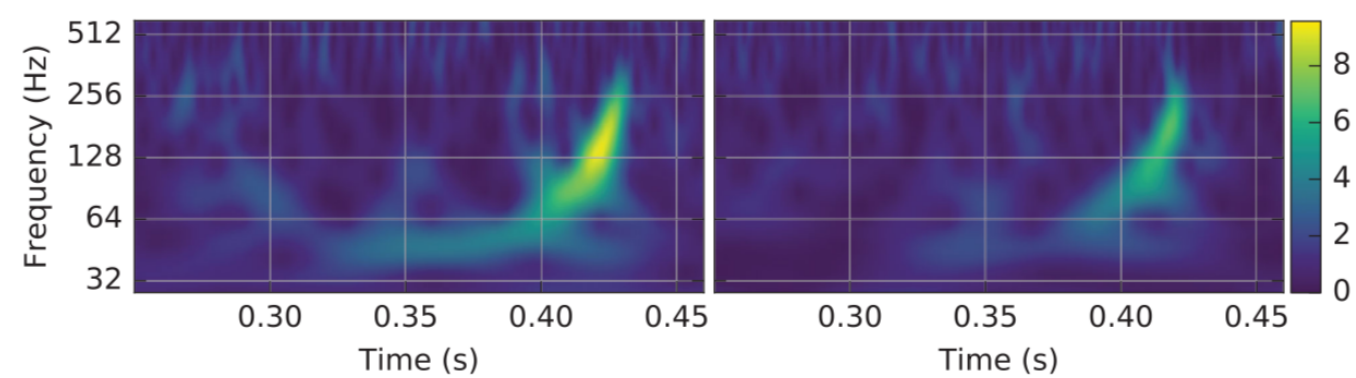
PRL 116, 061102 (2016) PHYSICAL REVIEW LETTERS 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

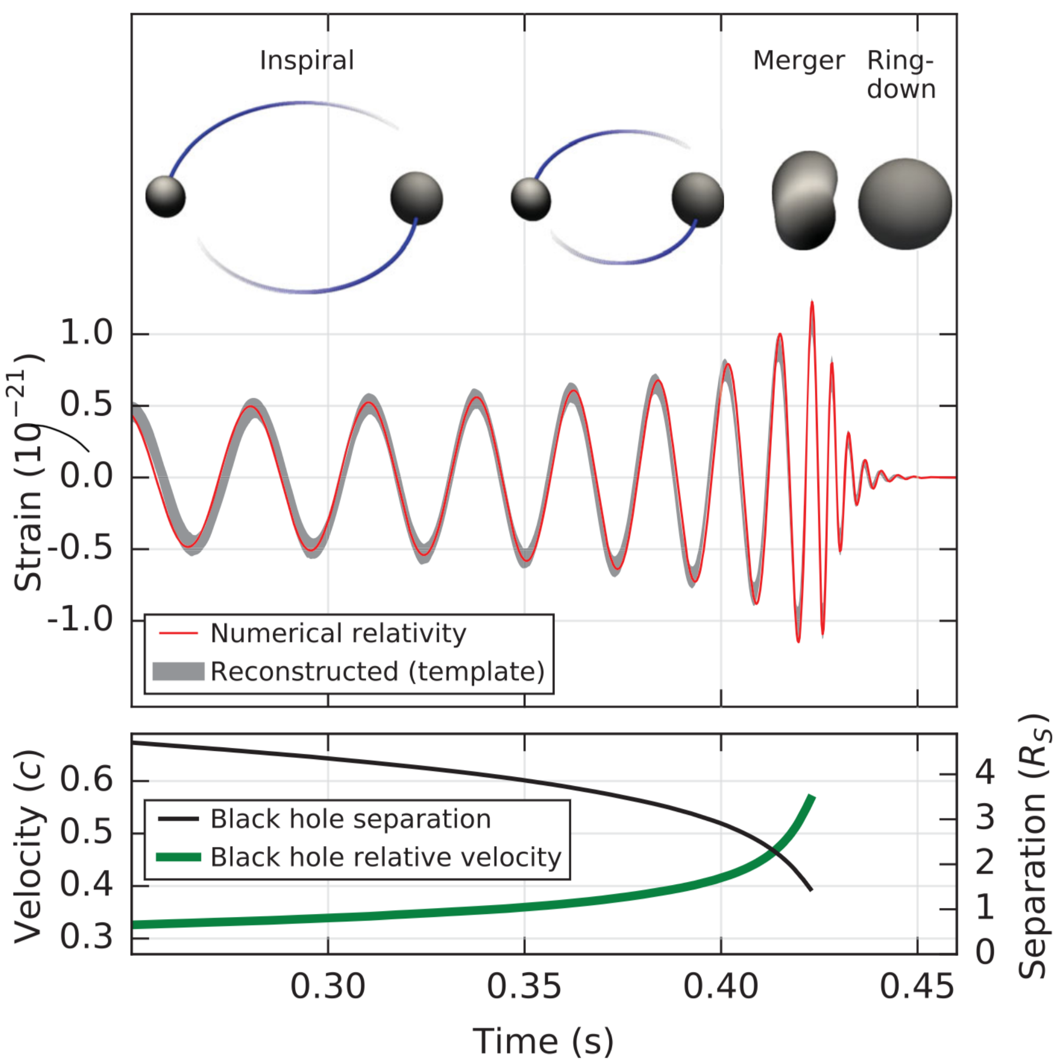
B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)





interferometers

High-frequency gravitational waves



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

Observation of Gravitational Waves from a Binary Black Hole Merger

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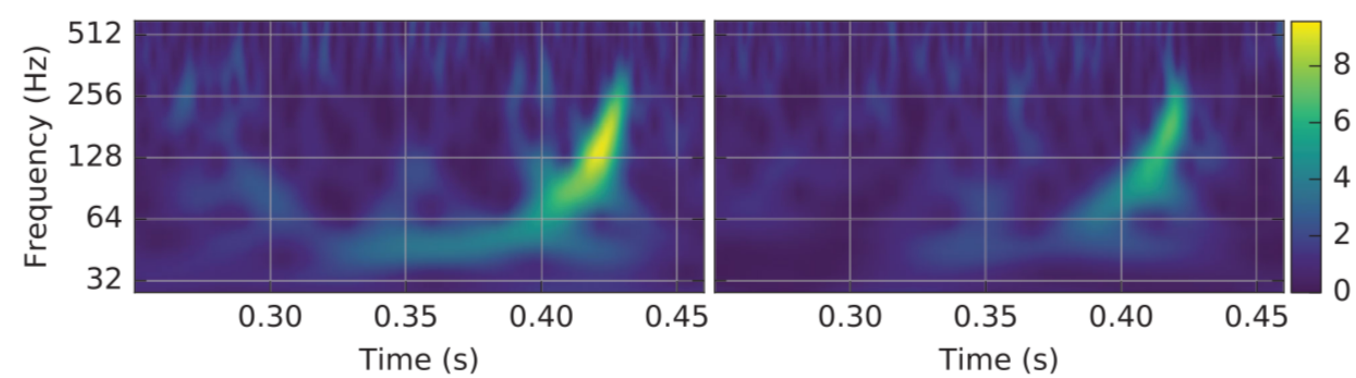


$$f \approx \frac{1}{2\pi}\sqrt{\frac{GM}{R^3}} \ll 10\,\mathrm{kHz}$$

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

High-frequency gravitational waves

Part of a collection:

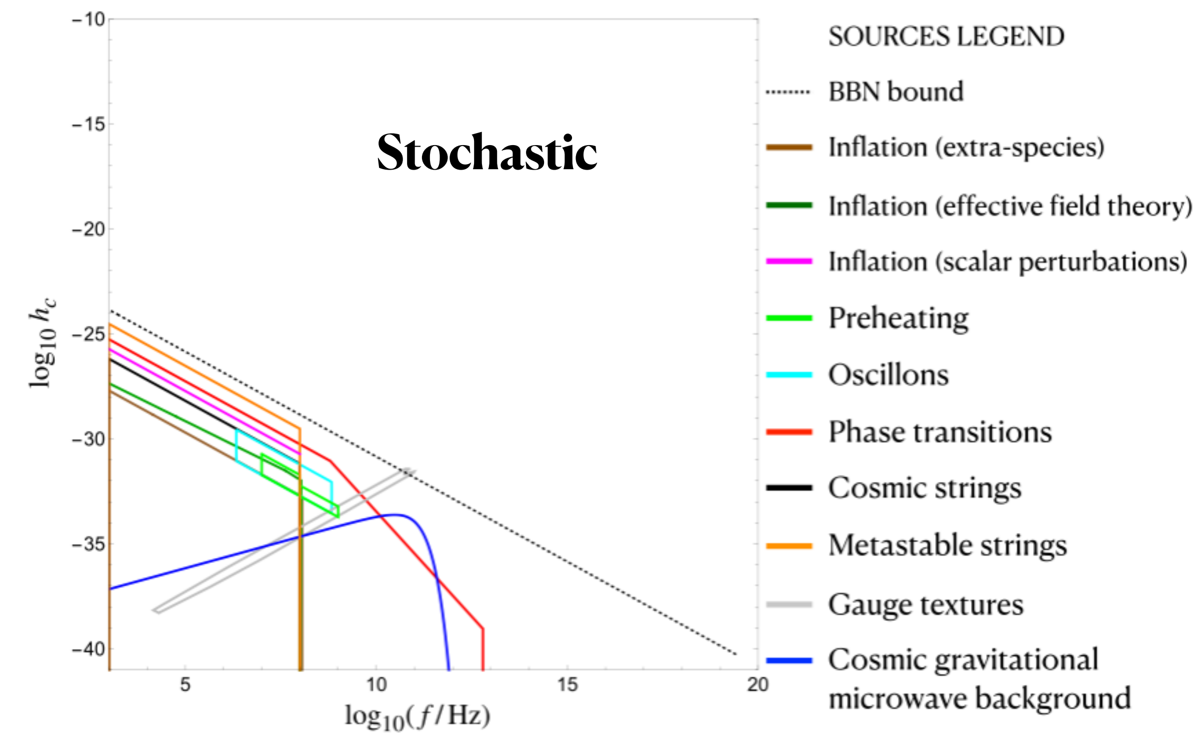
Gravitational Waves

Review Article | Open Access | Published: 06 December 2021

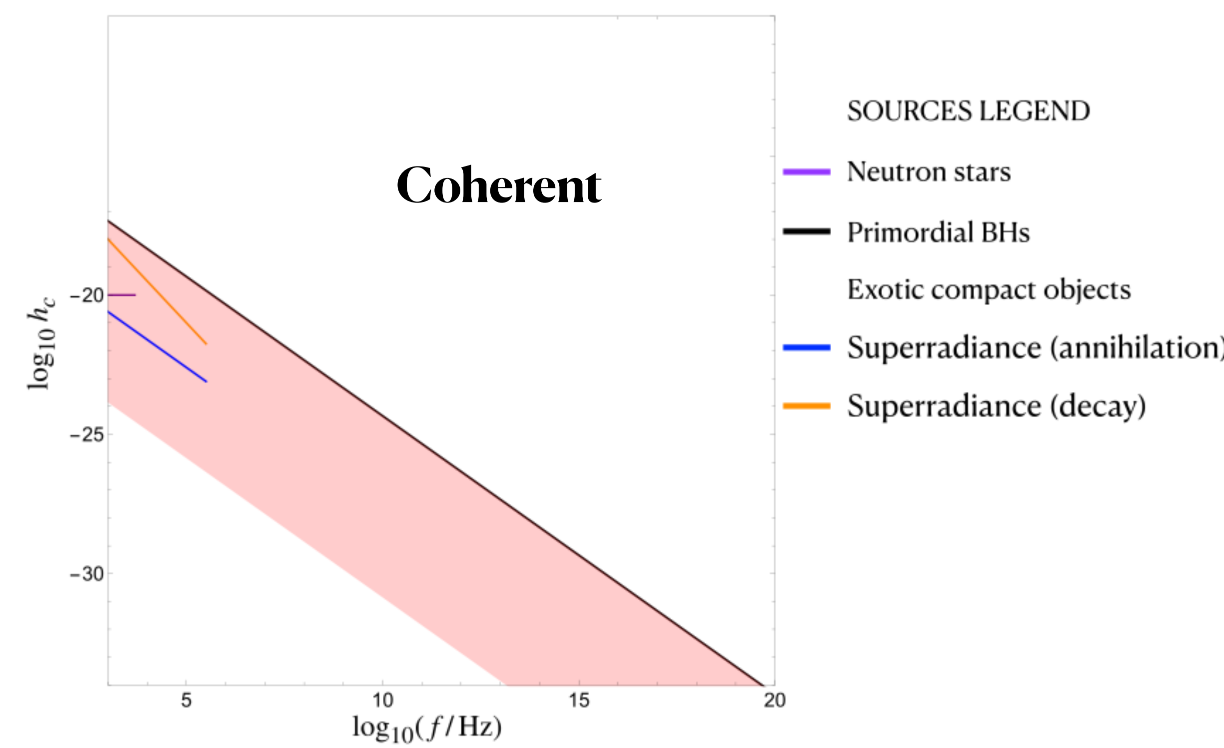
Challenges and opportunities of gravitational-wave searches at MHz to GHz frequencies

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

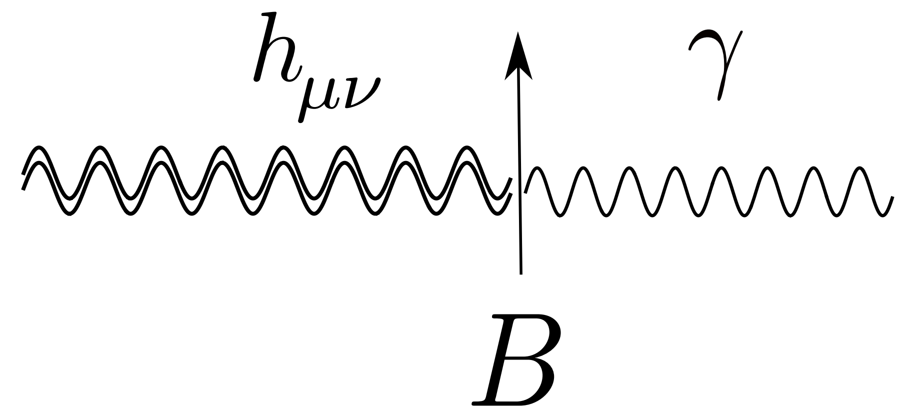


A growing community is seriously considering the search of high frequency gravitational waves



The (inverse) Gertsenhstein Effect

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 $\hbar$

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

- Cosmological conversion

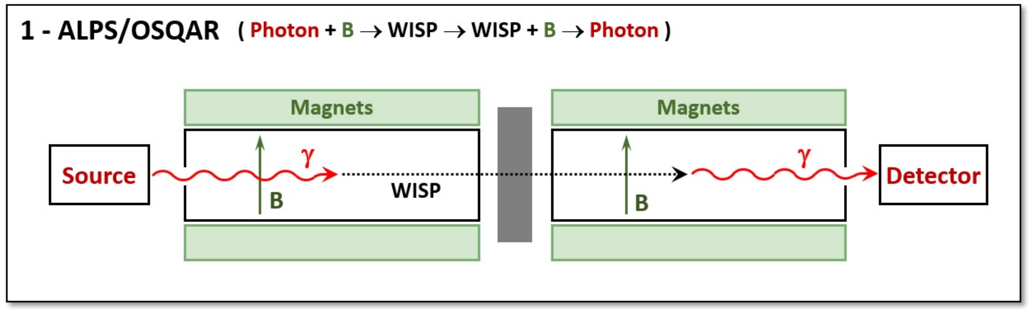
Potential of Radio Telescopes as High-Frequency Gravitational Wave Detectors

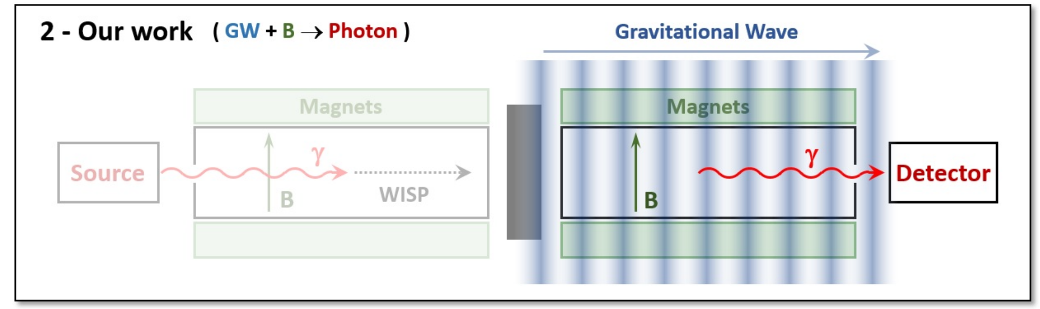
Valerie Domcke and Camilo Garcia-Cely
Phys. Rev. Lett. **126**, 021104 – Published 14 January 2021

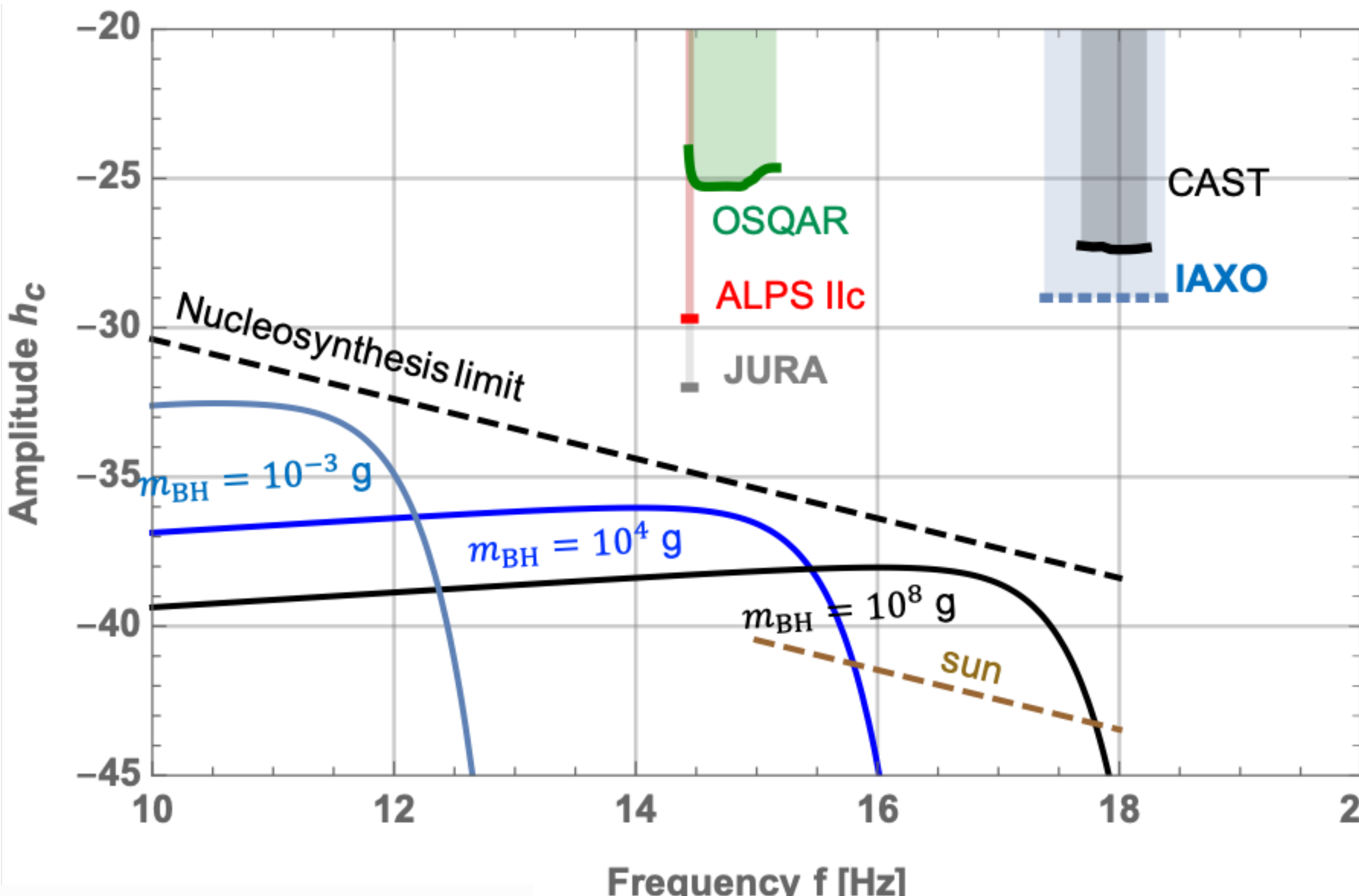
- The process is strictly analogous to axion dark matter conversion.

Raffelt, Stodolski'89

The (inverse) Gertsenhstein Effect



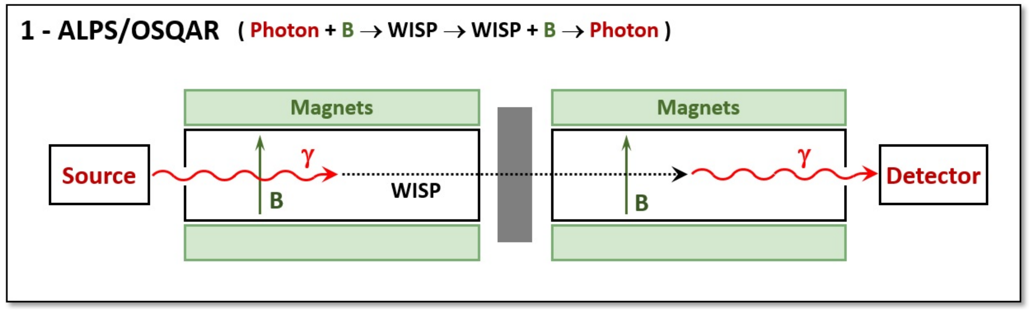


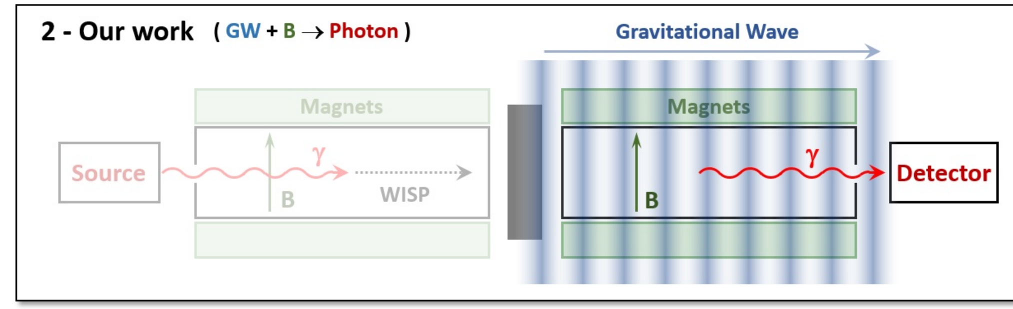


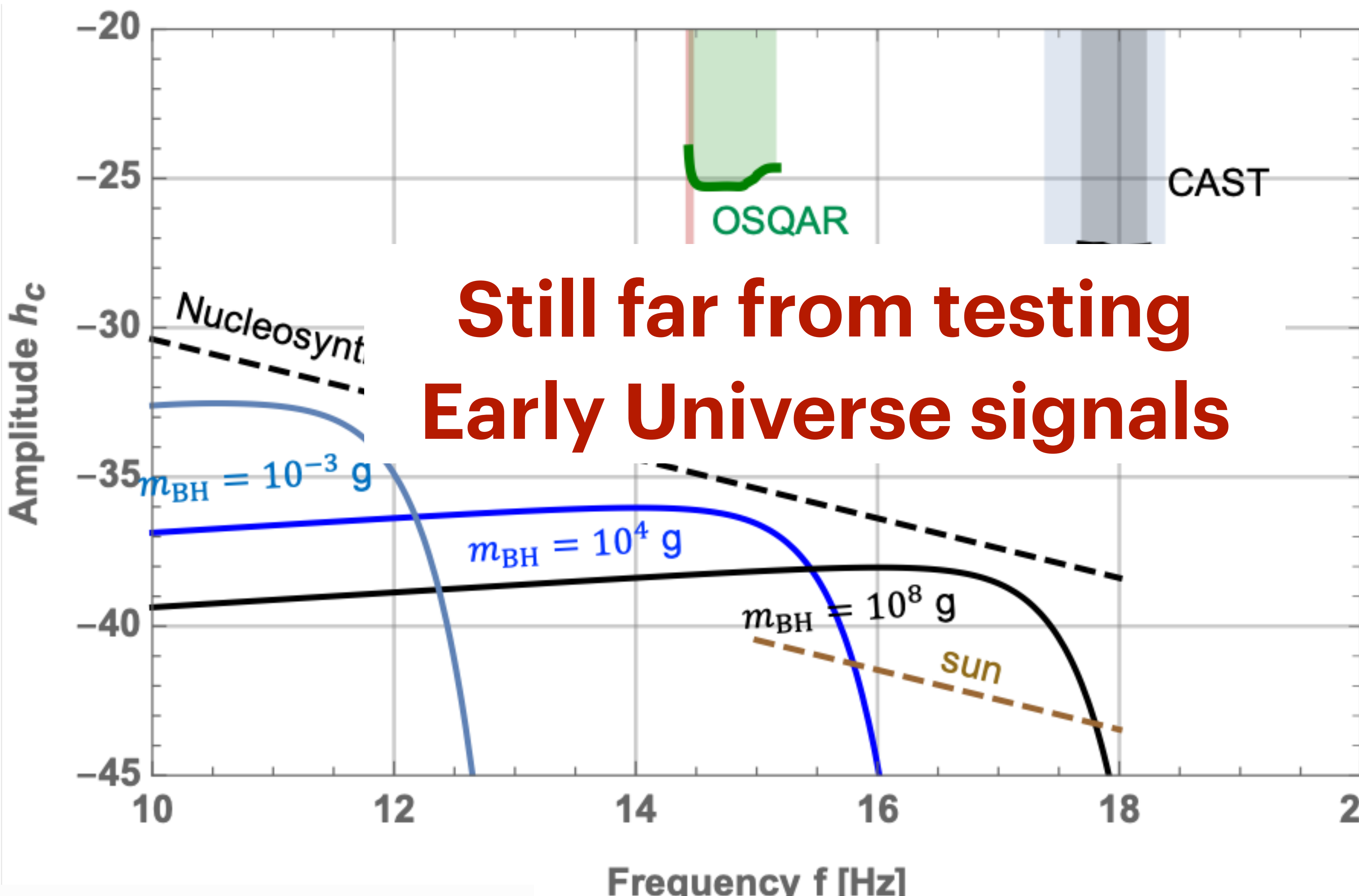
A. Ejlli, D. Ejlli, A. M. Cruise, G. Pisano & H. Grote

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

The (inverse) Gertsenhstein Effect







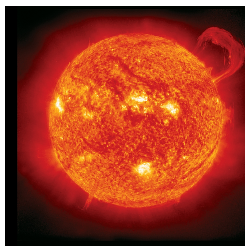
Still far from testing Early Universe signals

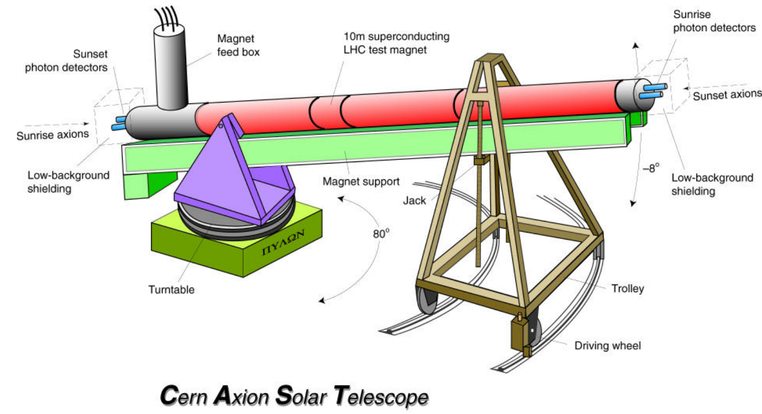
A. Ejlli, D. Ejlli, A. M. Cruise, G. Pisano & H. Grote

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

More possibilities

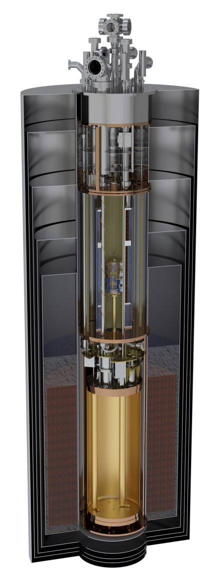
- Helioscopes (X rays)





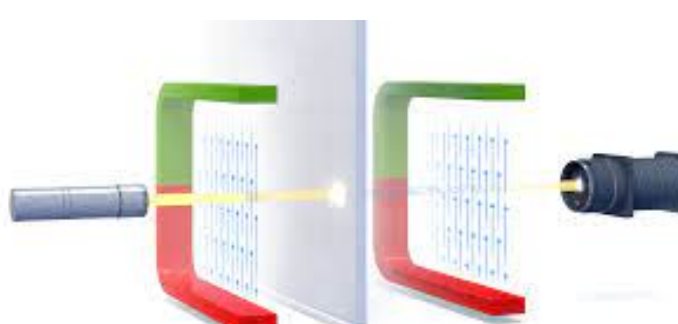
- CAST
- IAXO
- .....

- Haloscopes (radio frequencies)



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

- Purely lab experiments



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

Detection in haloscopes

Effective current

Axions act as a source term to Maxwell's equations, effectively inducing an electromagnetic current. Sikivie, 1983

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

Camilo García Cely, University of Valencia

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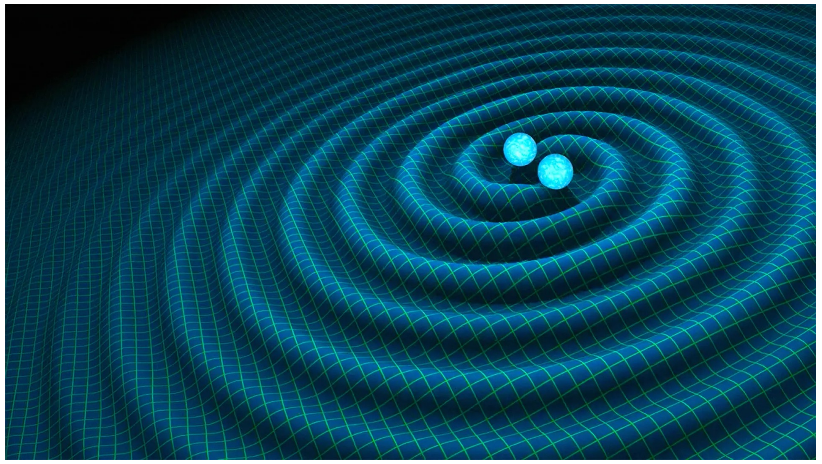
Effectively, the same is true for gravitational waves in haloscopes



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Proper detector frame

In the 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

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Fermi, 1922
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Ni and Zimmermamn, 1978

- Coordinate distances to the origin match the proper distance
  They coincide with those measured 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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  When they are negligible, the static fields applied in experiments remain static in the presence of GWs.

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  When they are negligible, the static fields applied in experiments remain static in the presence of GWs.

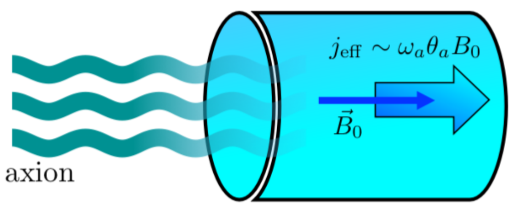
- Crucial for haloscopes

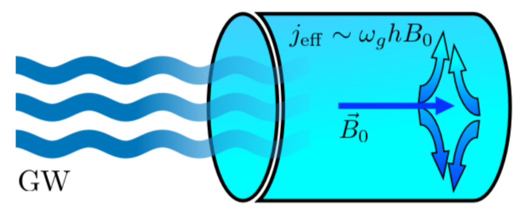
Berlin et al 2022

Camilo García Cely, University of Valencia

	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 $g_{a\gamma\gamma}a \sim \frac{\alpha\sqrt{\rho_{\rm DM}}}{2\pi m_a f_a} \sim \frac{\alpha\sqrt{\rho_{\rm DM}}}{2\pi m_\pi f_\pi} \sim 10^{-22}$	$h \sim 10^{-22}$

Haloscopes based on microwave cavities





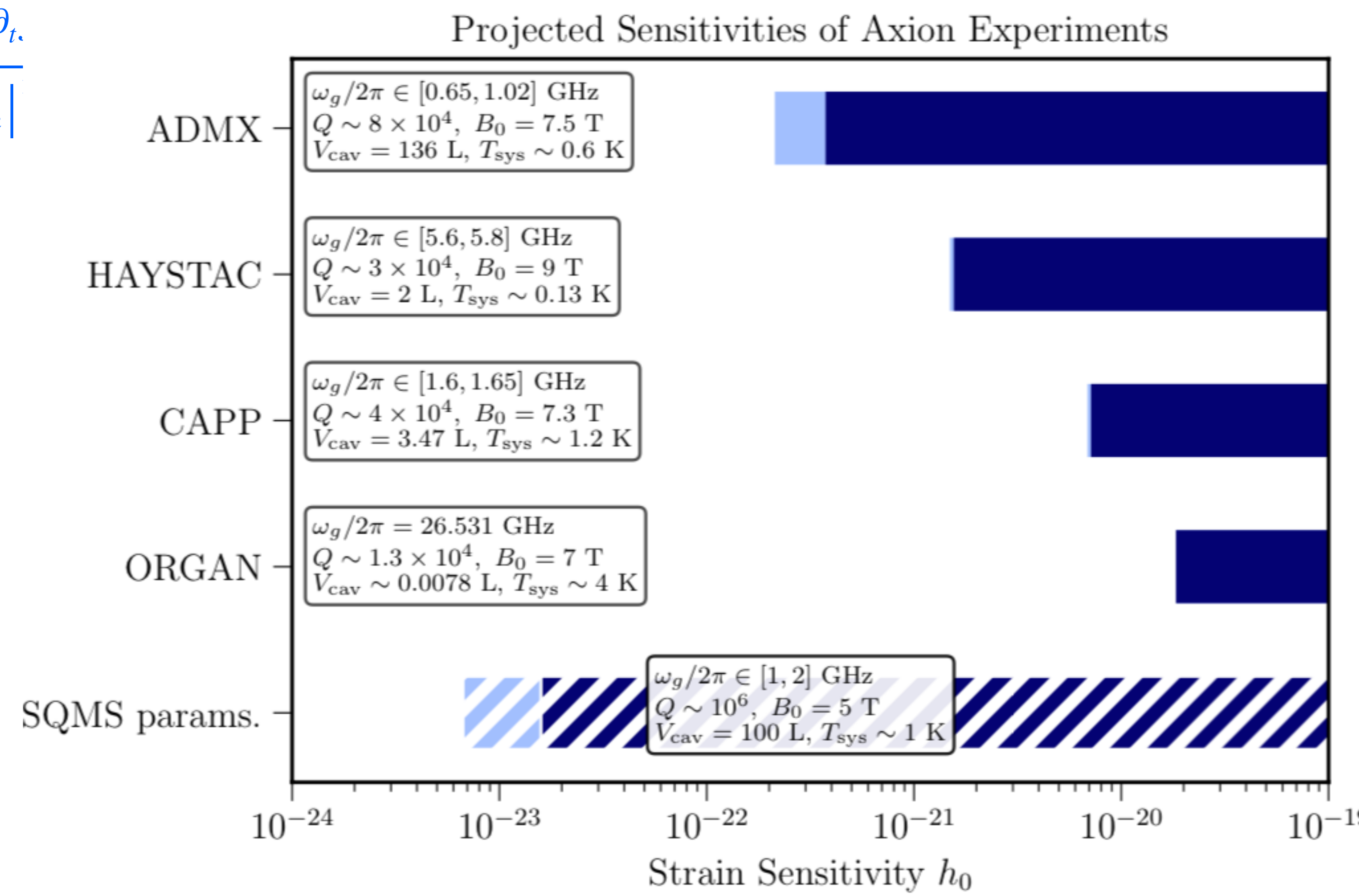
Detecting high-frequency gravitational waves with microwave cavities

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

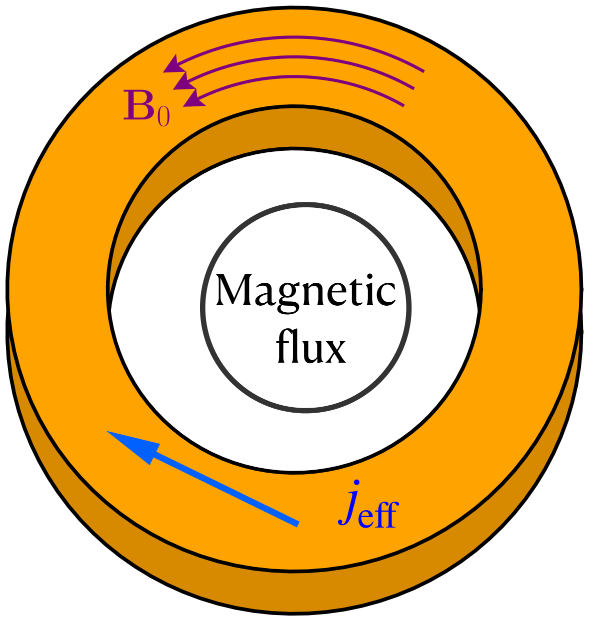
$$\left(\partial_t^2 + \frac{\omega_n}{Q_n}\partial_t + \omega_n^2\right) e_n(t) = -\frac{\int_{V_{\rm cav}} d^3\mathbf{x}\mathbf{E}_n^* \cdot \partial_t.}{\int_{V_{\rm cav}} d^3\mathbf{x}\,\left|\mathbf{E}_n\right|}$$

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



Haloscopes based on lumped-element detectors

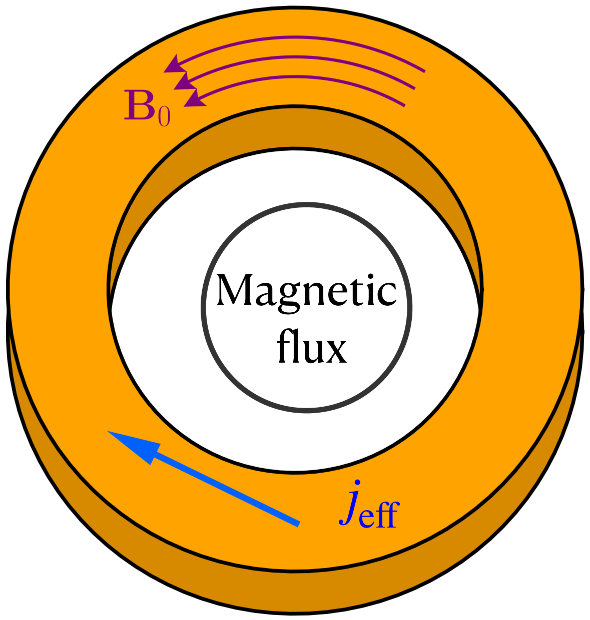


Haloscopes based on lumped-element detectors

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,‡]



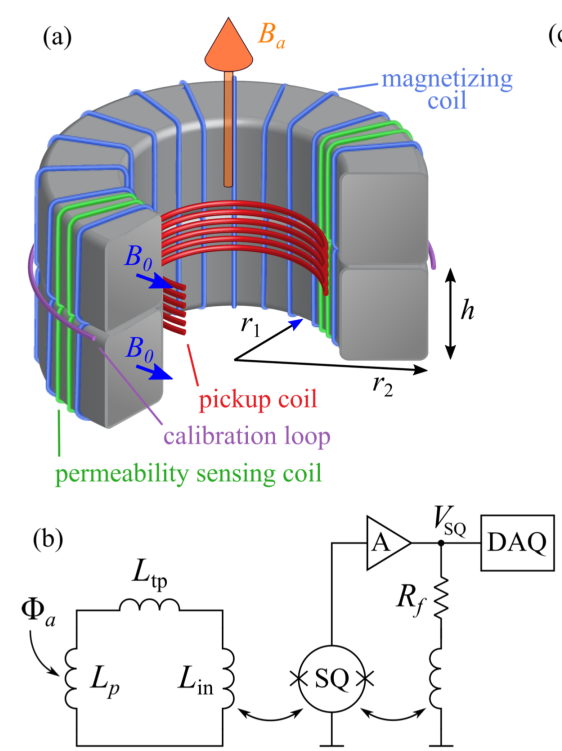
nature physics

SHAFT

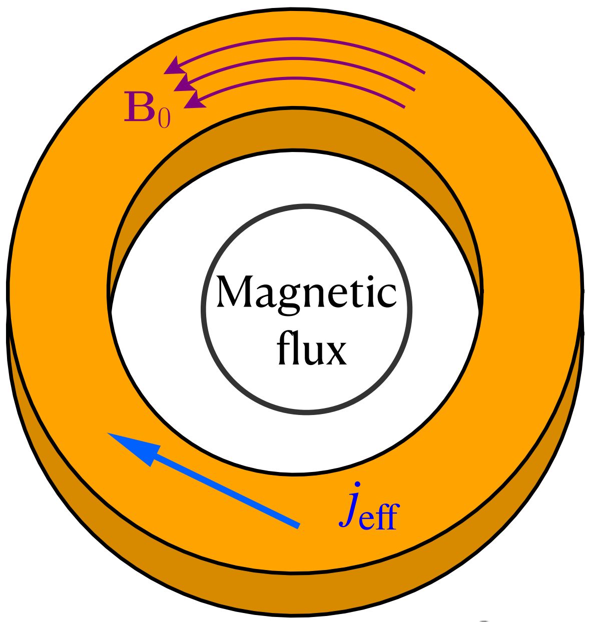
Article | Published: 17 August 2020

Search for axion-like dark matter with ferromagnets

Alexander V. Gramolin, Deniz Aybas, Dorian Johnson, Janos Adam & Alexander O. Sushkov

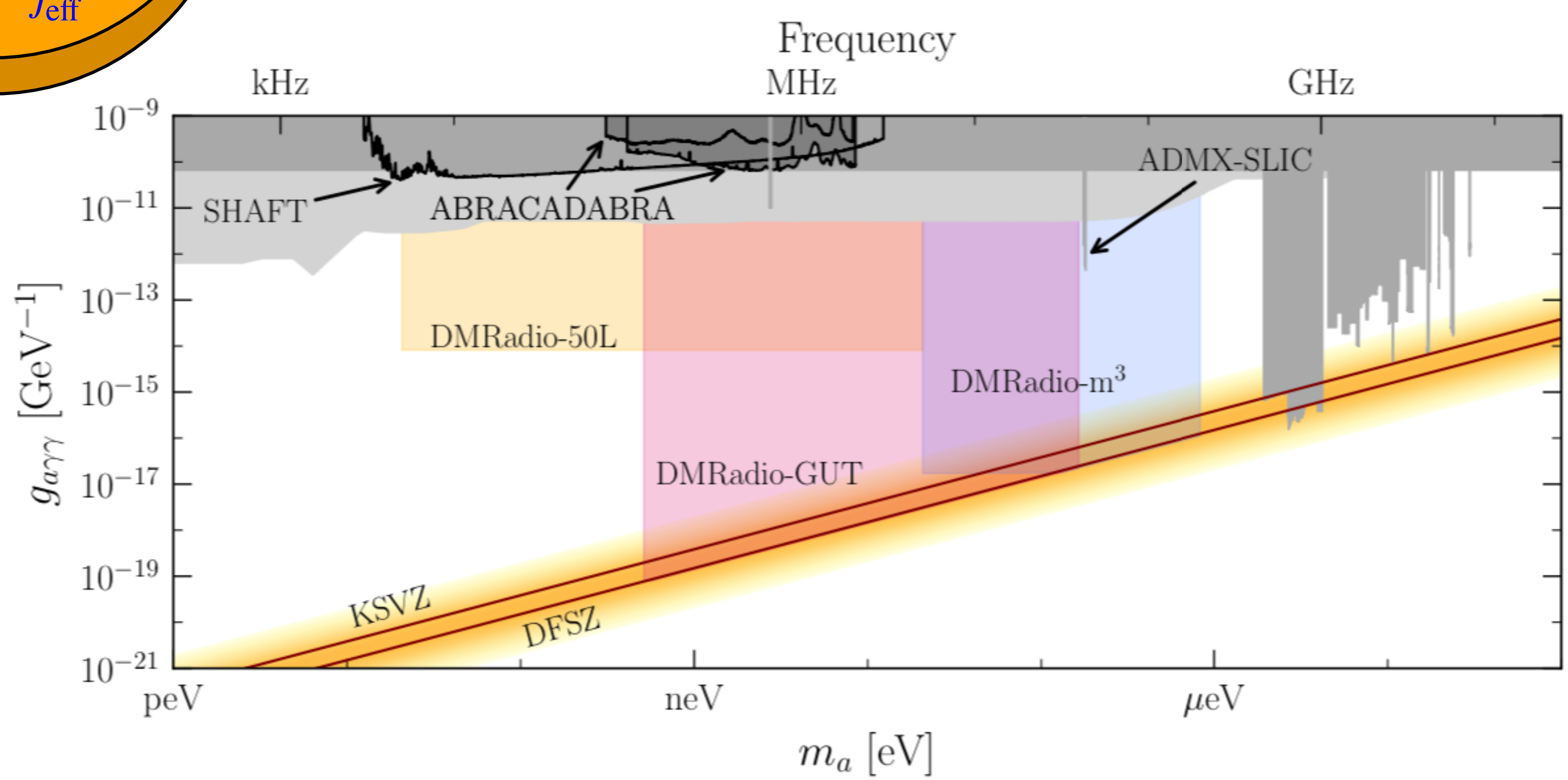


Haloscopes based on lumped-element detectors



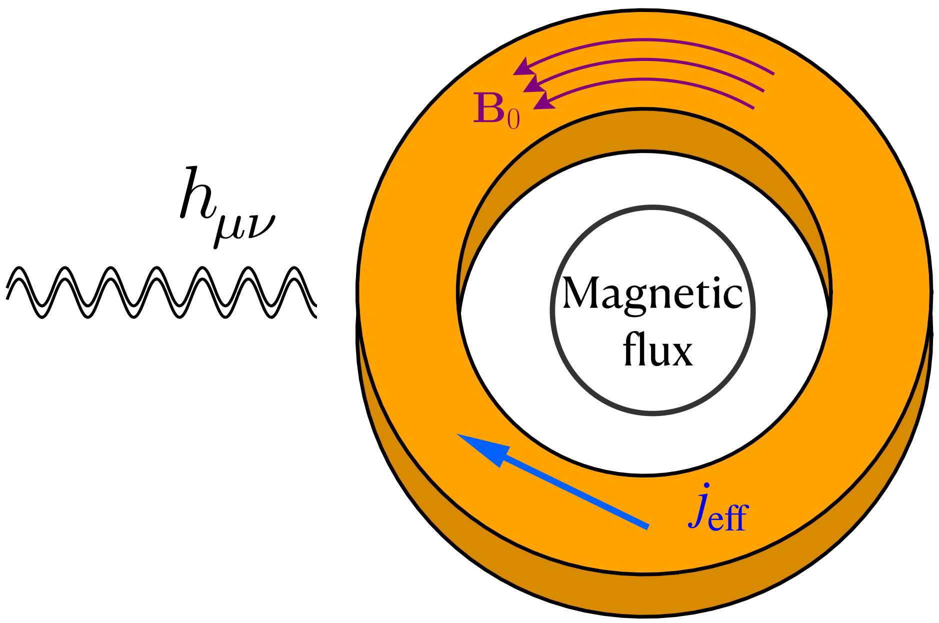
Proposal for a definitive search for GUT-scale QCD axions

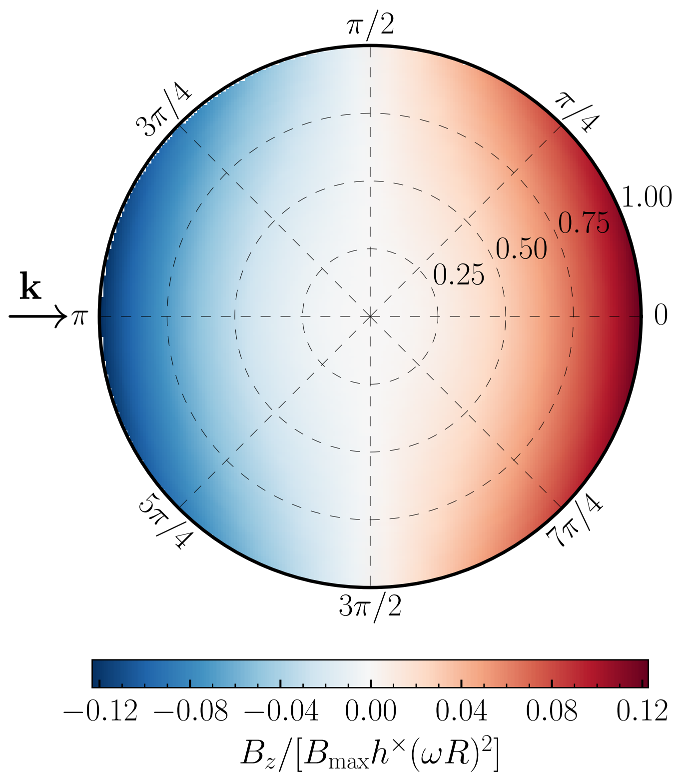
L. Brouwer *et al.* (DMRadio Collaboration)
Phys. Rev. D **106**, 112003 – Published 12 December 2022



Toroidal magnetic fields

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





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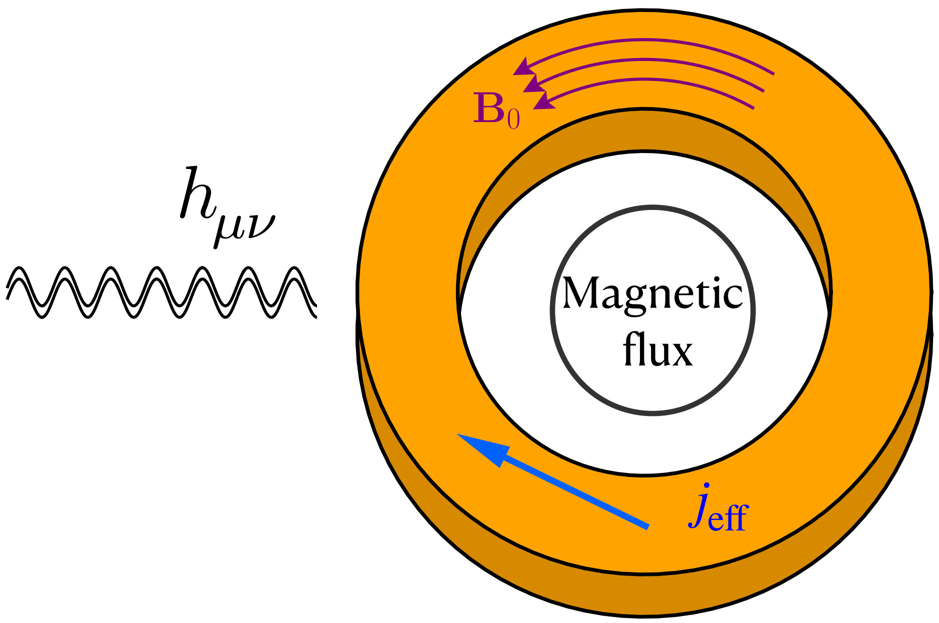
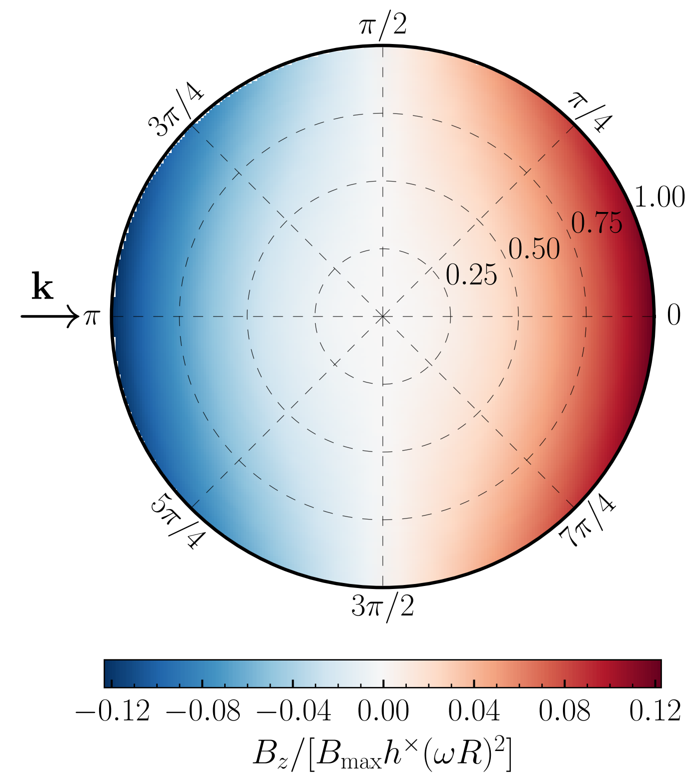
Phys. Rev. Lett. **129**, 041101 – Published 20 July 2022



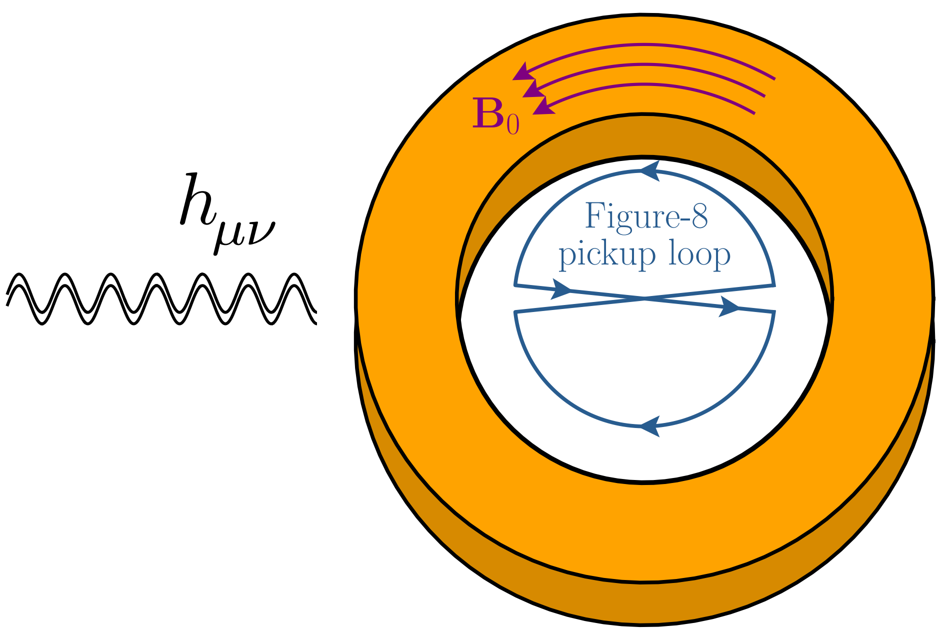


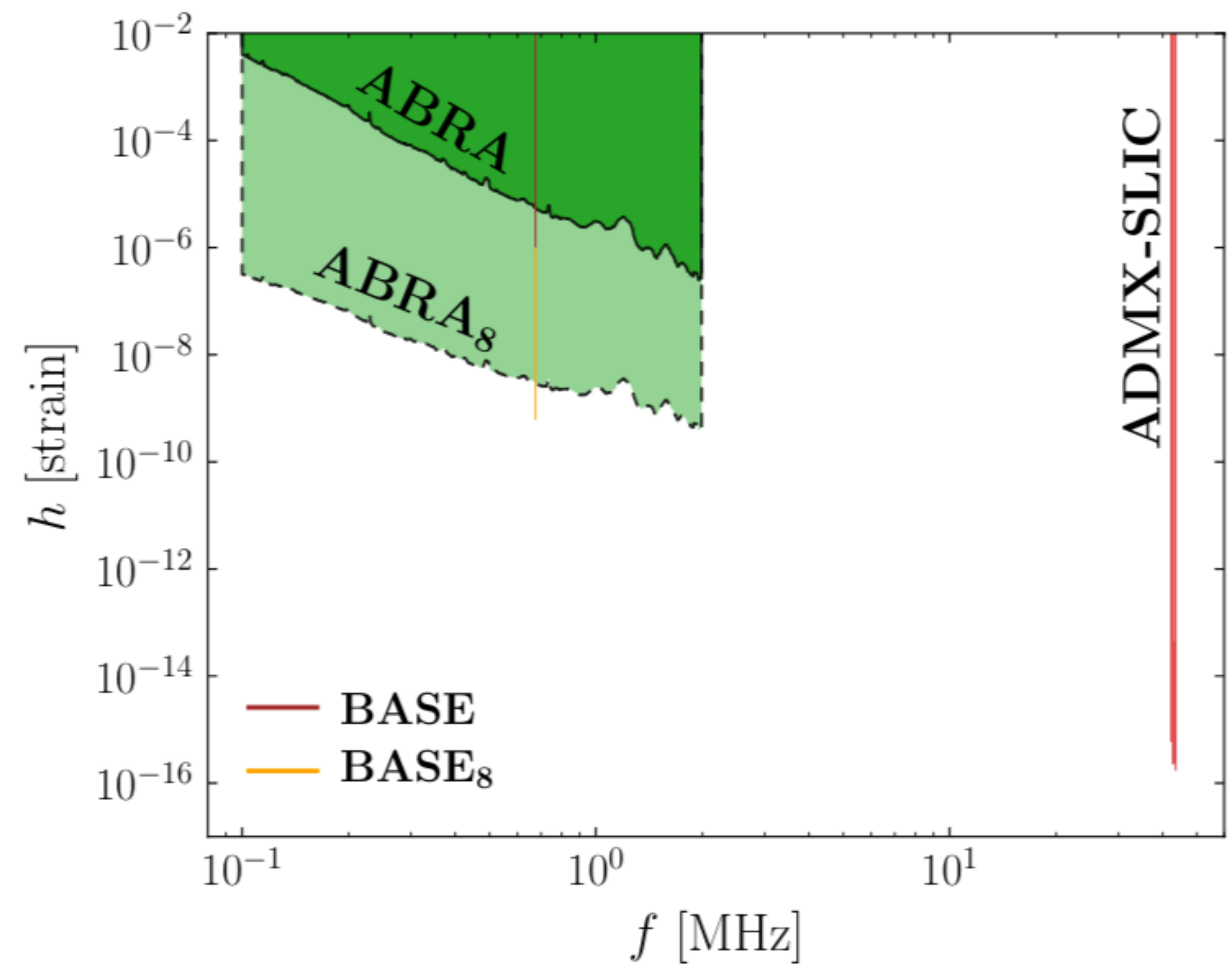
- Only one polarization
- Suppression at small frequencies $\omega R \ll 1$
- The sensitivity scaling with the volume is faster than for axions

Toroidal magnetic fields

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

Domcke, CGC, Lee, Rodd, 2023



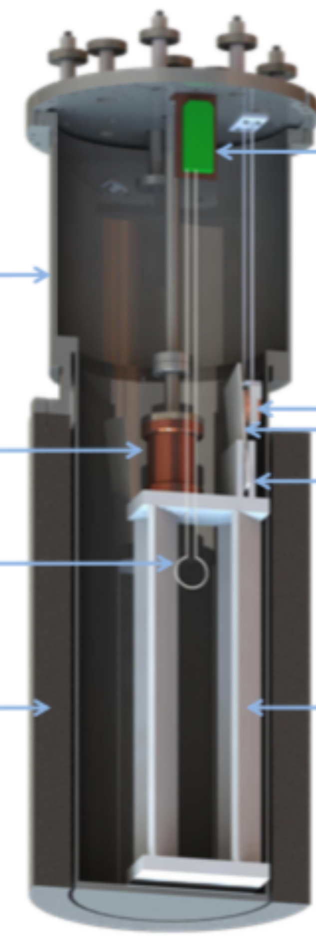


Solenoidal configurations

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

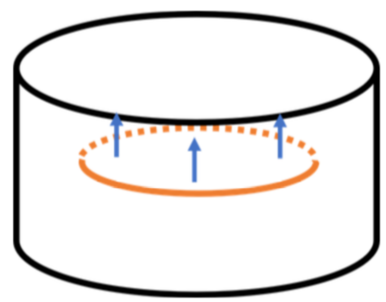
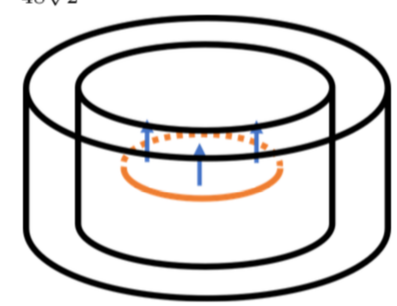
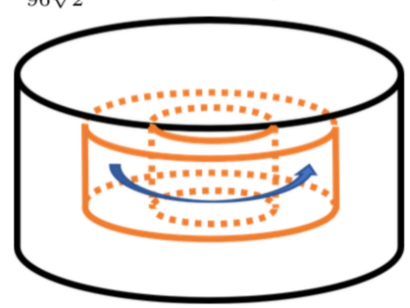
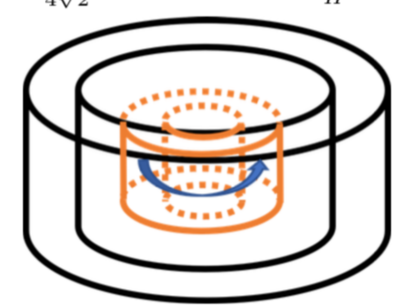
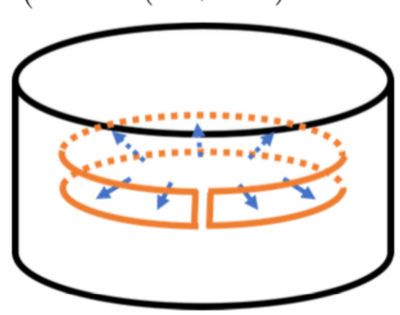
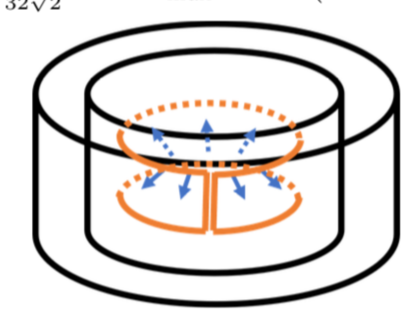
Zhongyue Zhang (张钟月), Dieter Horns, and Oindrila Ghosh
Phys. Rev. D **106**, 023003 – Published 5 July 2022

Beyond toroidal configurations

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 $\Rightarrow \mathcal{O}[(\omega L)^2]$ $\Phi_h = \frac{e^{-i\omega t}}{48\sqrt{2}} h^+ \omega^2 B_0 s^2_{\theta_h} \pi r^2 \left(11r^2 + 14R^2 + 16R^2 \ln \frac{R}{H}\right)$ 	$h^\times$, 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

Selection rules

In the proper detector frame the coordinate system closely matches the intuitive description of an Earth-based laboratory

$$h_{00} = \omega^2 e^{-i\omega t} f(\mathbf{k}\cdot\mathbf{r})\, r_m r_n \sum_{A=+,\times} h_A e^A_{mn}(\hat{\mathbf{k}}),$$

$$h_{0i} = \frac{1}{2}\omega^2 e^{-i\omega t}[f(\mathbf{k}\cdot\mathbf{r}) - i f'(\mathbf{k}\cdot\mathbf{r})][\hat{\mathbf{k}}\cdot\mathbf{r}\; r_m\delta_{ni} - r_m r_n \hat{k}_i] \sum_{A=+,\times} h_A e^A_{mn}(\hat{\mathbf{k}}),$$

$$h_{ij} = -i\omega^2 e^{-i\omega t} f'(\mathbf{k}\cdot\mathbf{r})[|\mathbf{r}|^2\delta_{im}\delta_{jn} + r_m r_n \delta_{ij} - r_n r_j \delta_{im} - r_m r_j \delta_{in}] \sum_{A=+,\times} h^A e^A_{mn}(\hat{\mathbf{k}}),$$

$$f(\xi) = [e^{i\xi} - 1 - i\xi]/\xi^2$$

Domcke, CGC, Rodd, 2023
Berlin et al, 2023

The ω^2 dependence is unavoidable

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 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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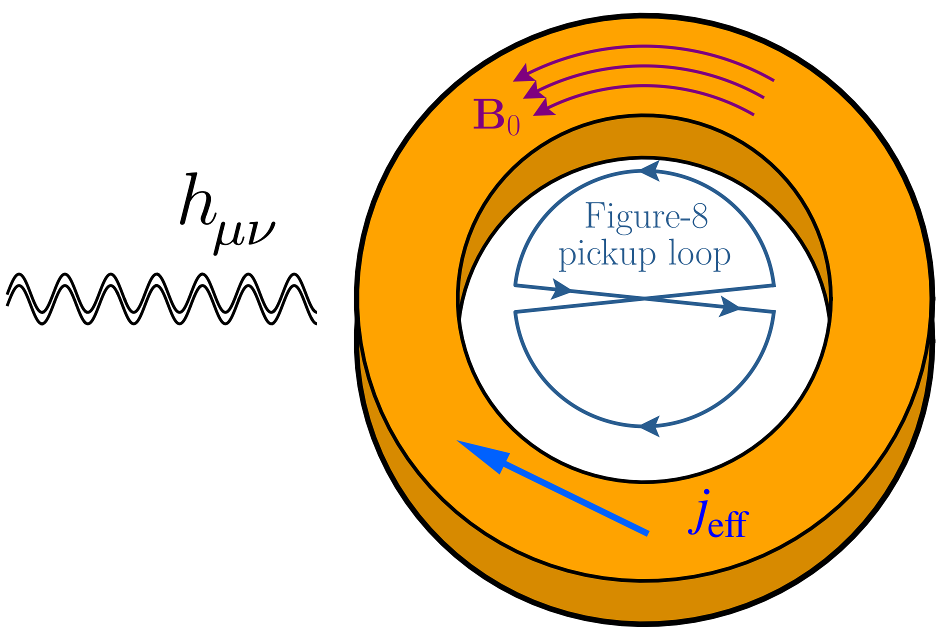
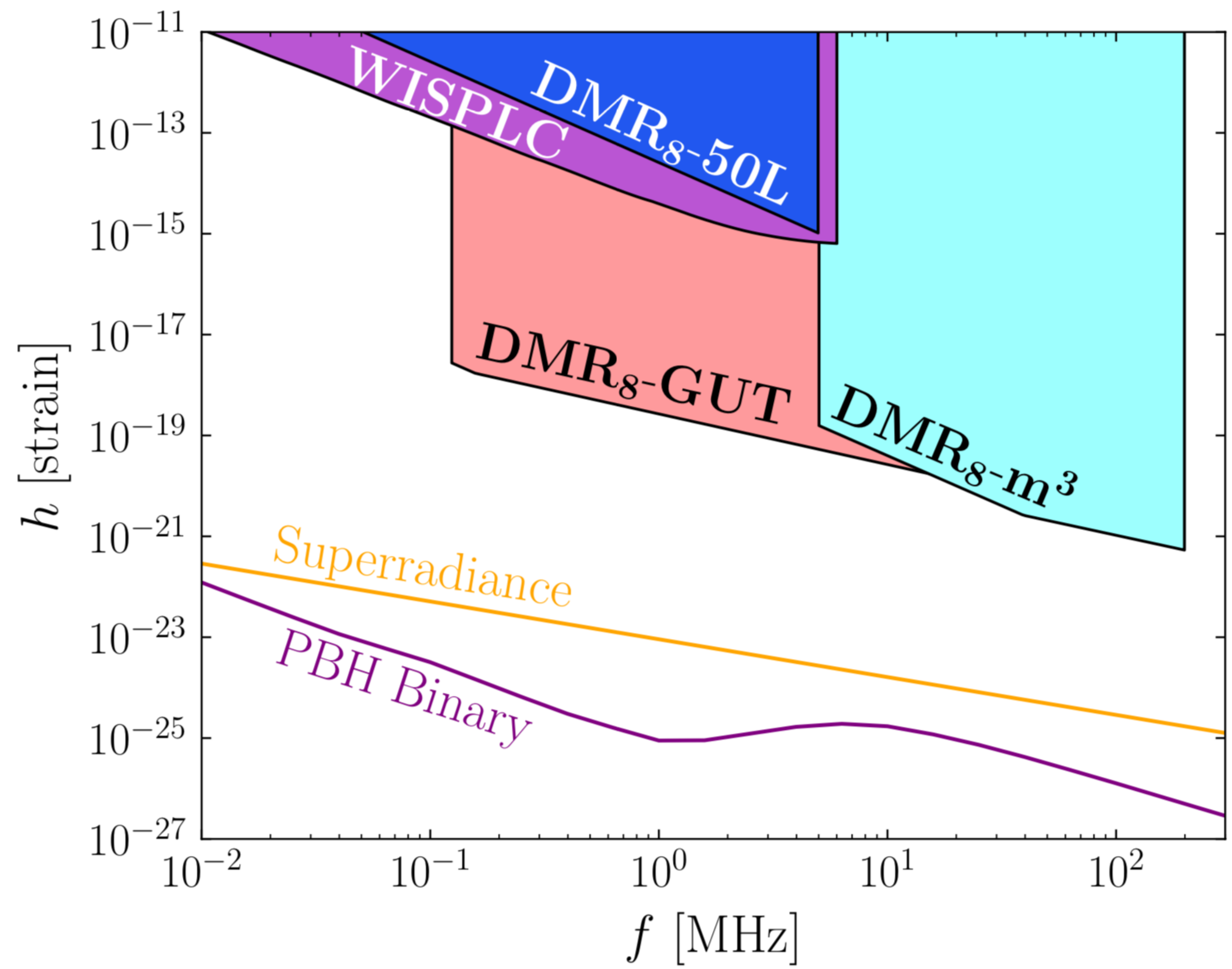
Gravitational waves in low mass axion haloscopes

Domcke, CGC, Lee, Rodd, 2023

Break cylindrical symmetry



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



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Conclusions

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

Selection rules in detectors exhibiting cylindrical symmetry enforce cancellations in the flux associated to gravitational waves.

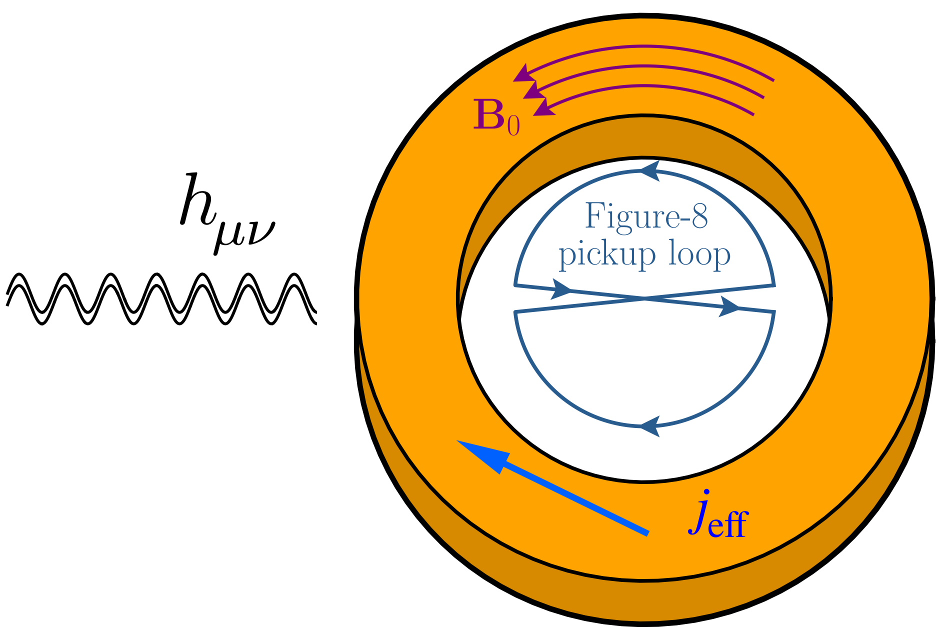
These cancellations can be avoided by changing the geometry of the pickup loop. We demonstrate this for different detector geometries, obtaining a parametric increase of sensitivity.

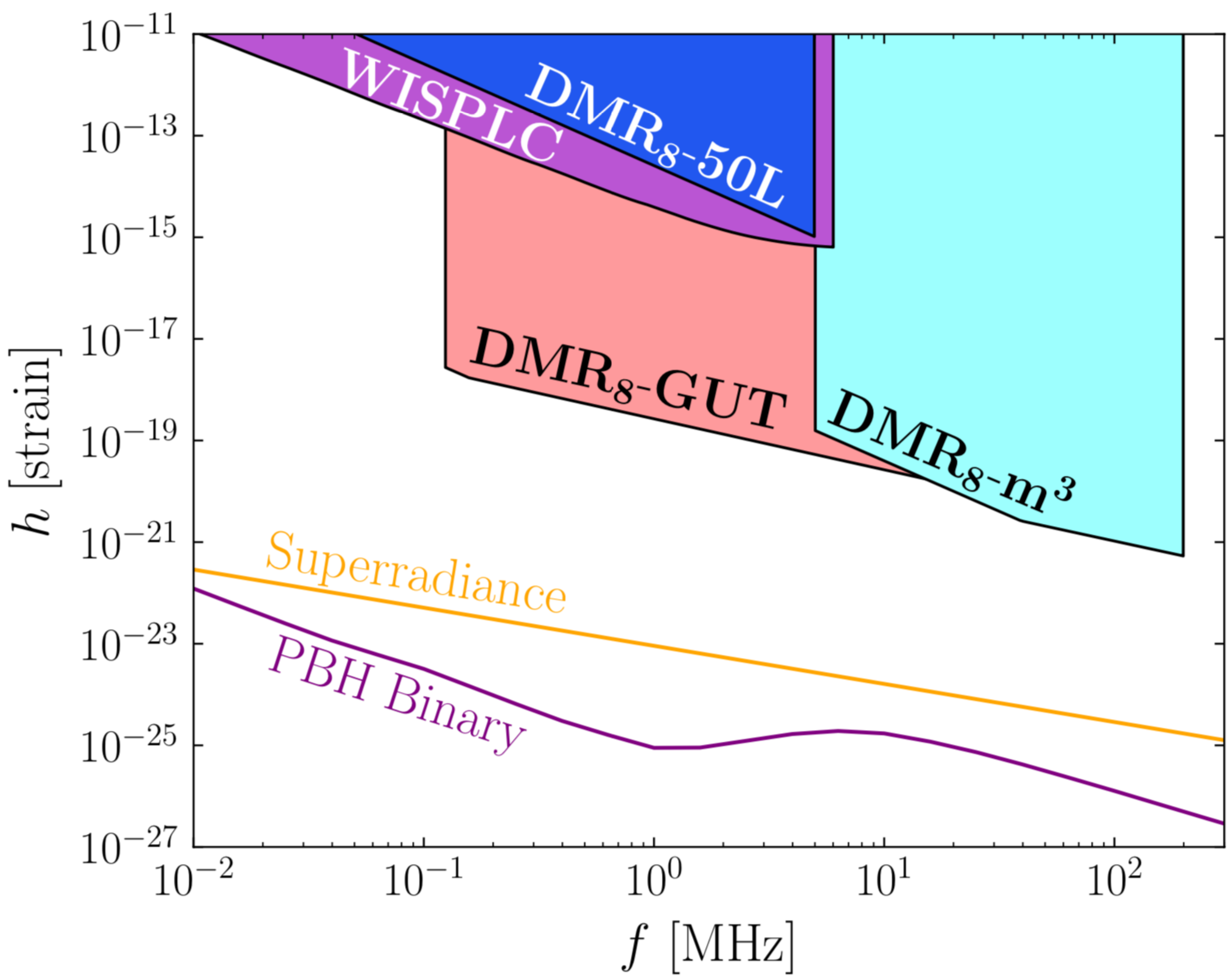
Different experimental proposals have coalesced on a strain sensitivity of 10^{-22} for MHz GWs, still orders of magnitude away from signals of the early Universe. Whether we can hope to probe such strain sensitivities remains to be determined.

Gravitational waves in low mass axion haloscopes

Domcke, CGC, Lee, Rodd, 2023

Break cylindrical symmetry





$$\Phi_h(h^+, h^\times;\, \phi_h, \theta_h) = \mathcal{R}_c\, \Phi_a(g_{a\gamma\gamma}),$$

$$\mathcal{R}_c = \left(\frac{T_m}{\tau_h}\right)^{1/4} \left(\frac{Q_a}{Q_h}\right)^{1/4} \begin{cases} 1 & Q_r < Q_a,\, Q_h, \\ (Q_a/Q_r)^{1/4} & Q_a < Q_r < Q_h, \\ Q_r/Q_h & Q_h < Q_r < Q_a, \\ (Q_a/Q_r)^{1/4} Q_r/Q_h & \text{otherwise.} \end{cases}$$

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