Adapting axion dark matter concepts for high-frequency wave detection

Université Libre de Bruxelles

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IFIC INSTITUT DE FÍSICA CORPUSCULAR

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

VNIVERSITAT DE VALÈNCIA

Camilo García Cely

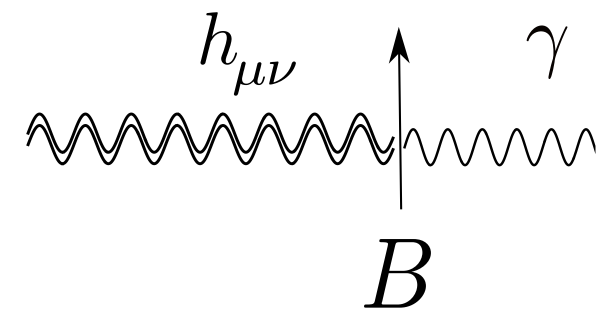
Based on PRL 129, 041101 and hep-ph/2306.03125

In collaboration with Valerie Domcke, Sung Mook Lee and Nicholas L. Rodd.

Adapting axion dark matter concepts for high-frequency wave detection

Outline

- Axion electrodynamics
- Haloscopes based on lumped-element detectors
- Impact of the geometry and selection rules
- Novel effects
- Conclusions



Axion electrodynamics

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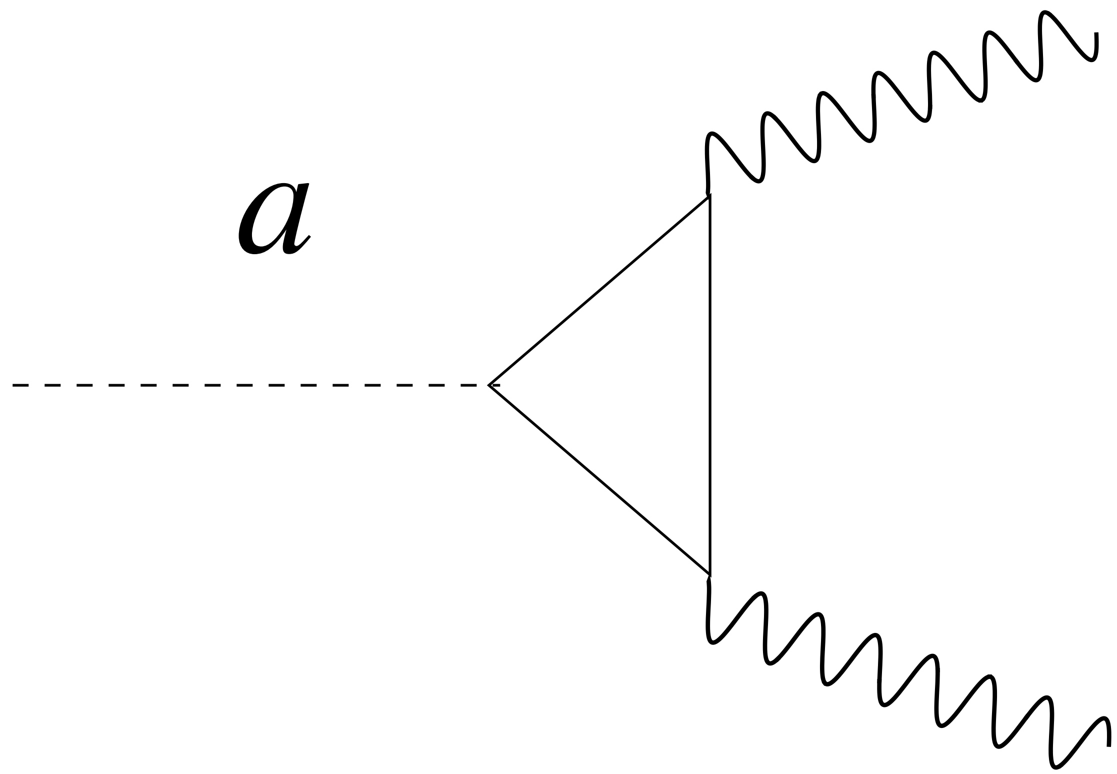
Axion electrodynamics



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

Axion electrodynamics

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

$$\nabla \cdot \mathbf{B} = 0$$

Sikivie, 1983

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

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

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

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

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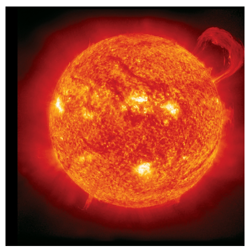
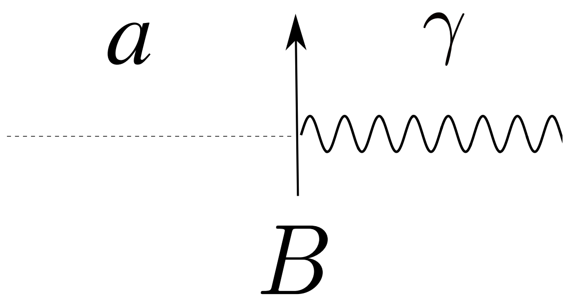
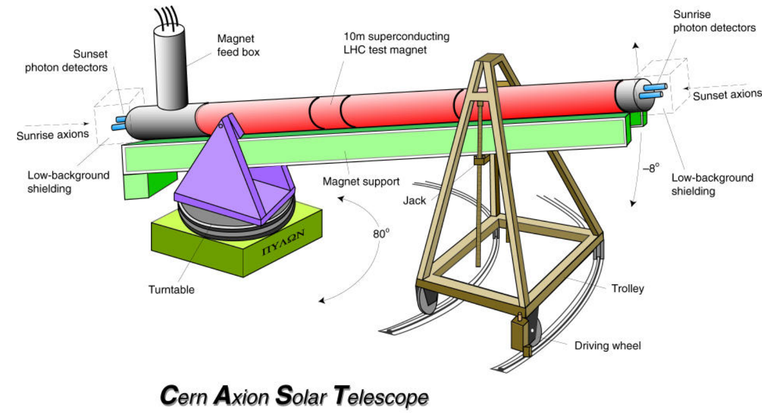
Axion electrodynamics

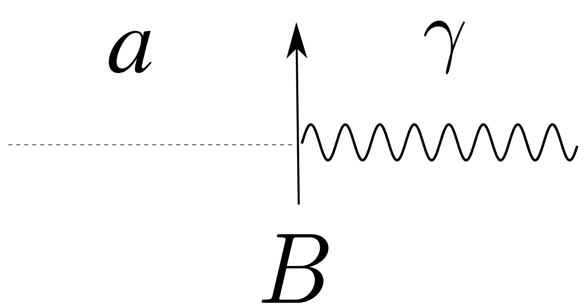
- Helioscopes (X rays)

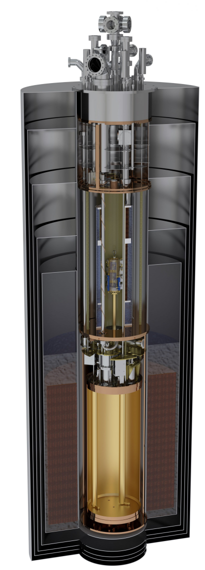





- CAST
- IAXO
- .....

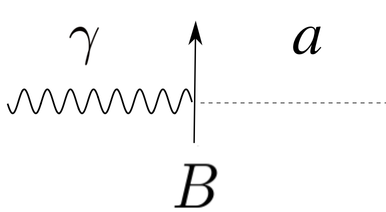
- Haloscopes (radio frequencies)

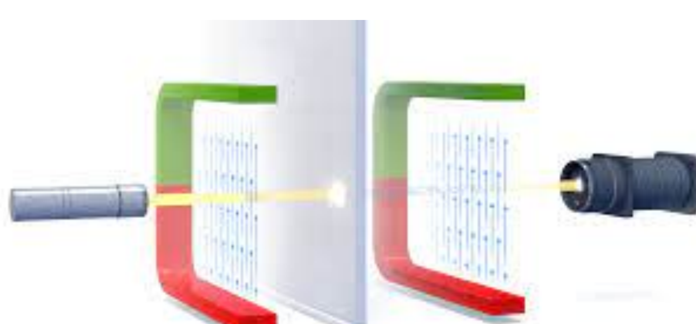
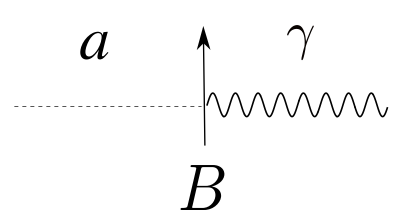





- microwave cavities
- MADMAX
- ADMX
- HAYSTAC
- ABRACADABRA
- Lumped element detectors
- ...

- Purely lab experiments



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

Talks by van Bibber, Doan, Krieger, Spector and Smith

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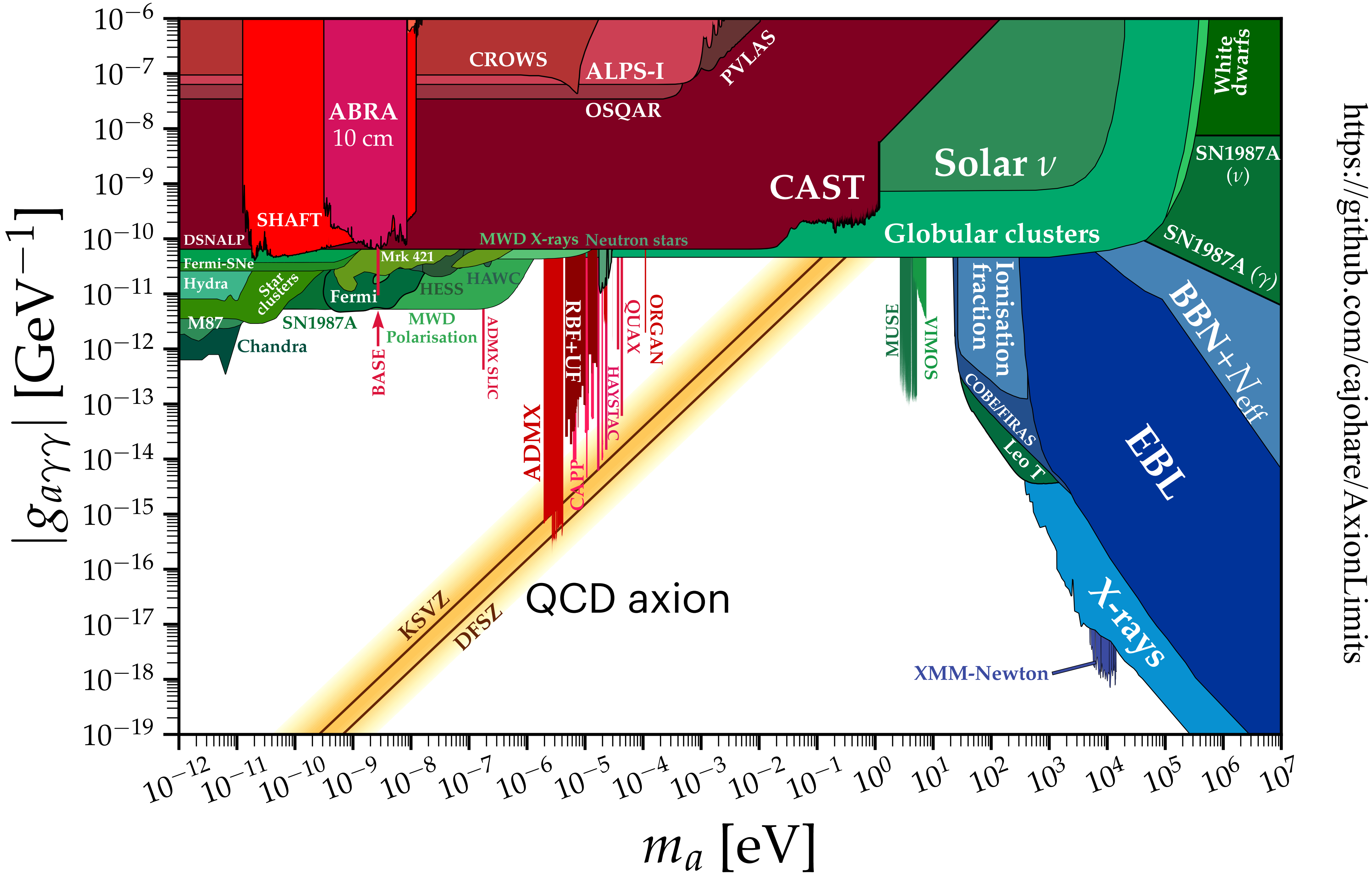
Axion electrodynamics



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

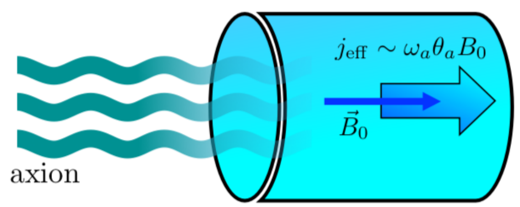
DFSZ (Dine, Fischler, Srednicki, Zhitniskii)

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

KSVZ (Kim, Shifman, Vainshetein, Zakharov)

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

Haloscopes based on microwave cavities



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

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

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

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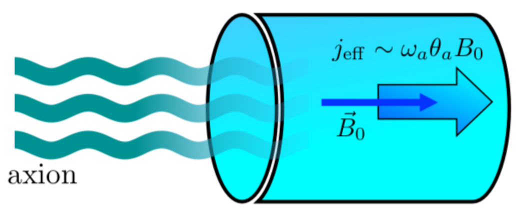
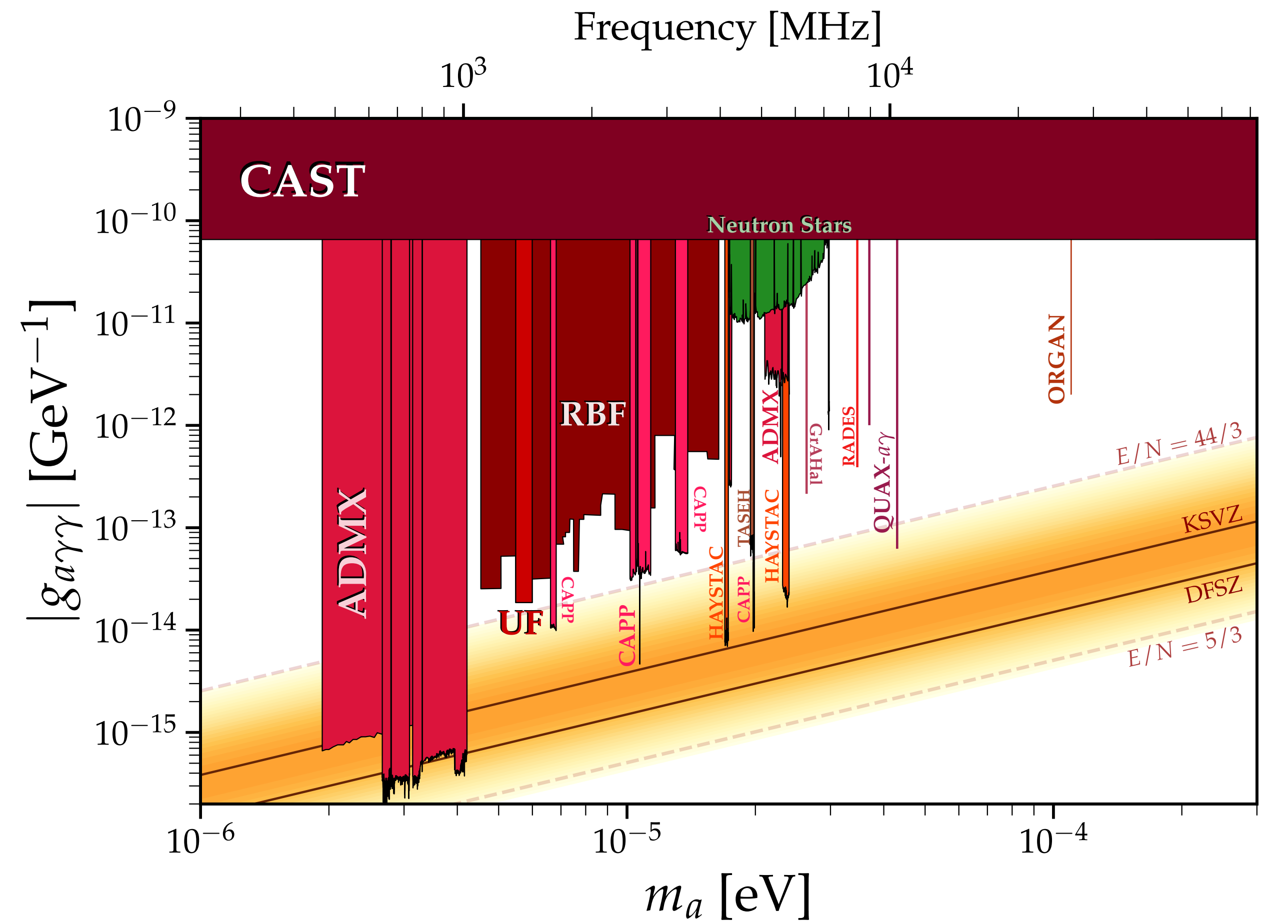
Haloscopes based on microwave cavities





https://github.com/cajohare/AxionLimits

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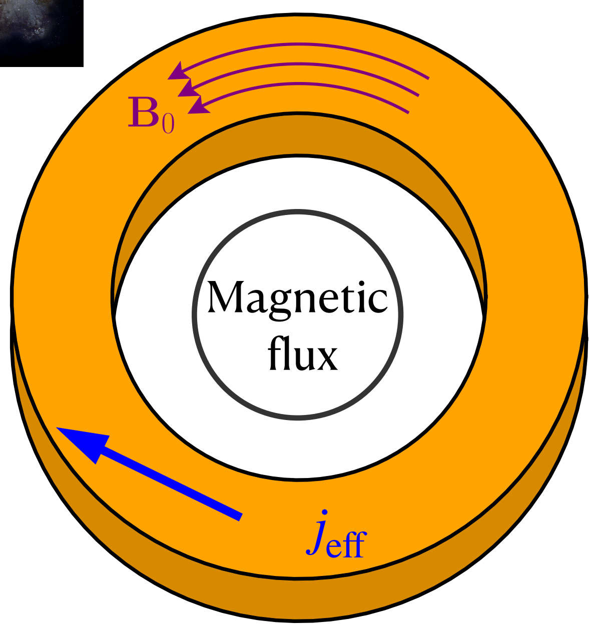
Haloscopes based on lumped-element detectors

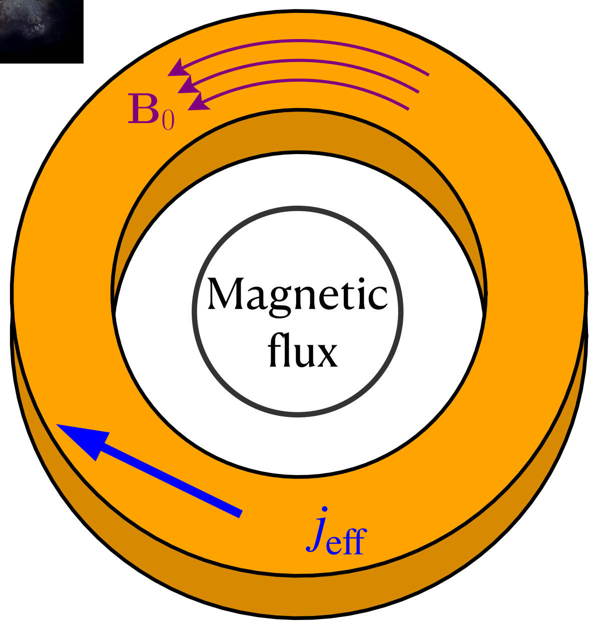


$$\nabla \times \mathbf{B} - \partial_t \mathbf{E} = \underbrace{g_{a\gamma\gamma}\, \partial_t a\, \mathbf{B_0}}_{j_{\mathrm{eff}}}$$

The electromagneticfields produced by the axion drive a current through a pickup coil

Kahn, Safdi, Thaler 2016
Sikivie, Sullivan and Tanner 2014

Haloscopes based on lumped-element detectors



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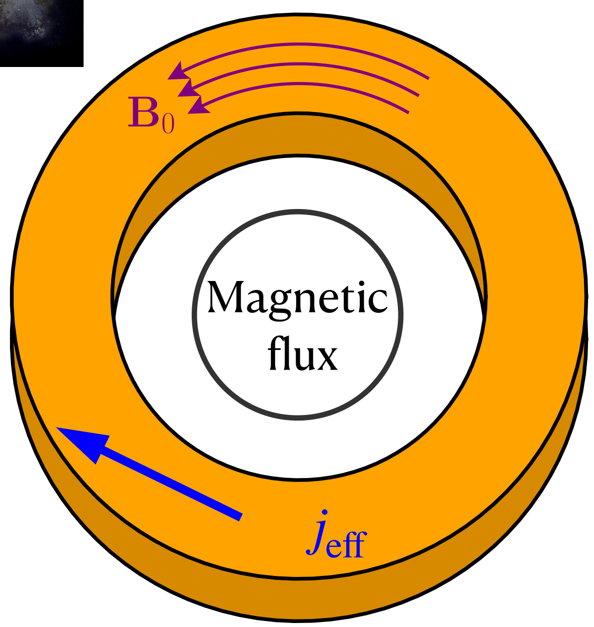

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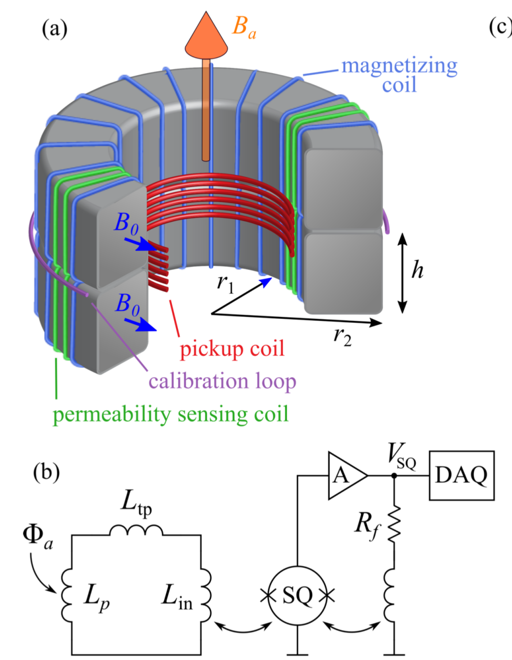

(c) SHAFT

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)

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DMRadio program

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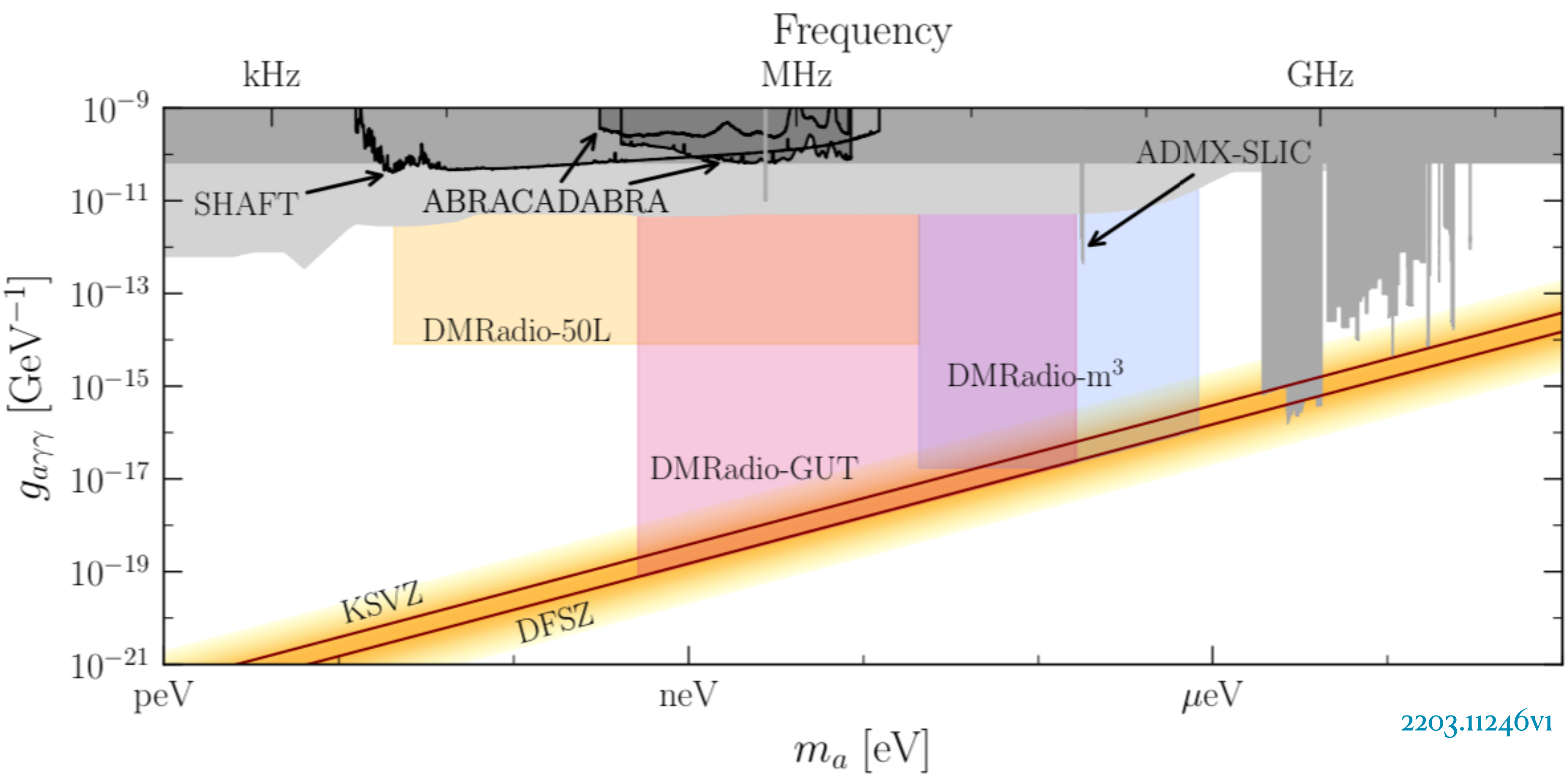

2203.11246v1

talk by Nicholas M. Rapidis

Gravitational-wave electrodynamics

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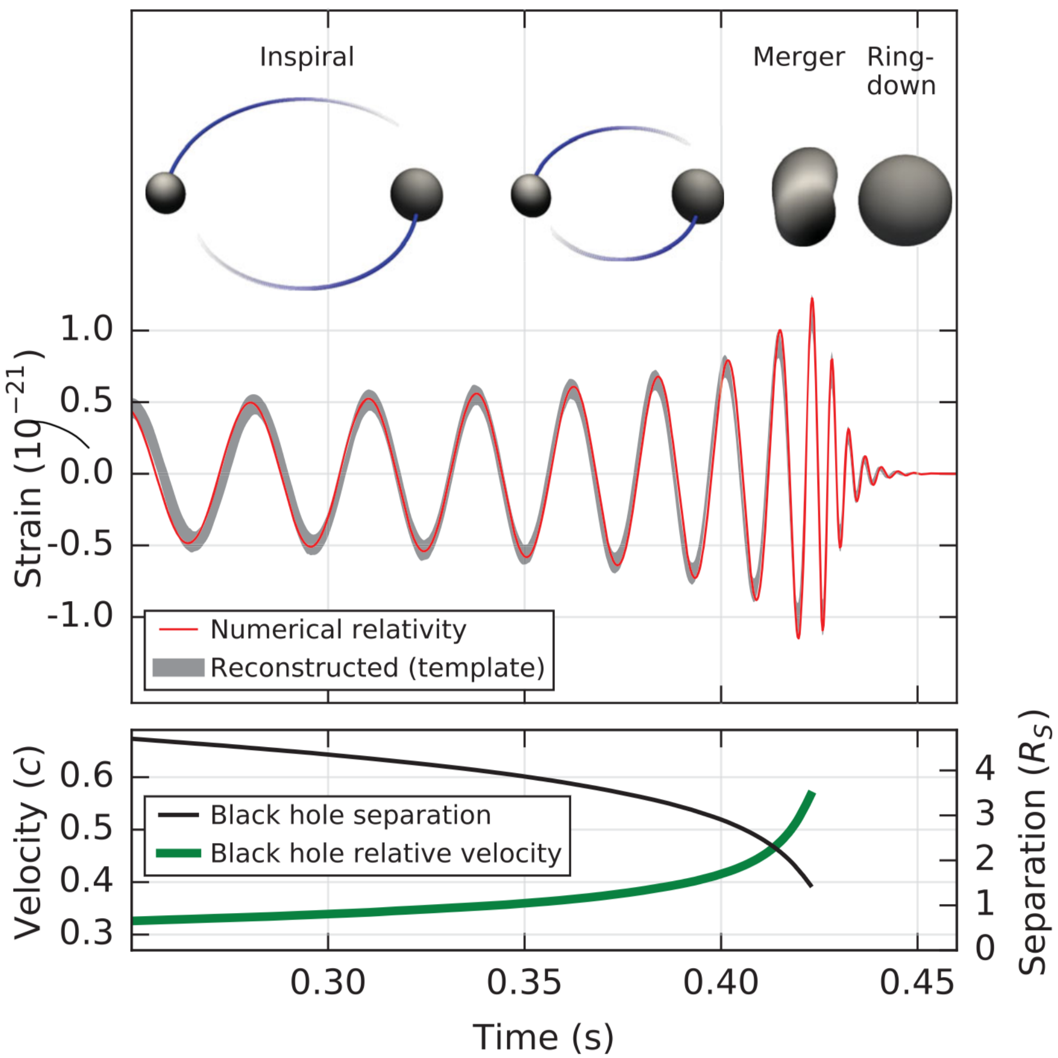
Gravitational Waves

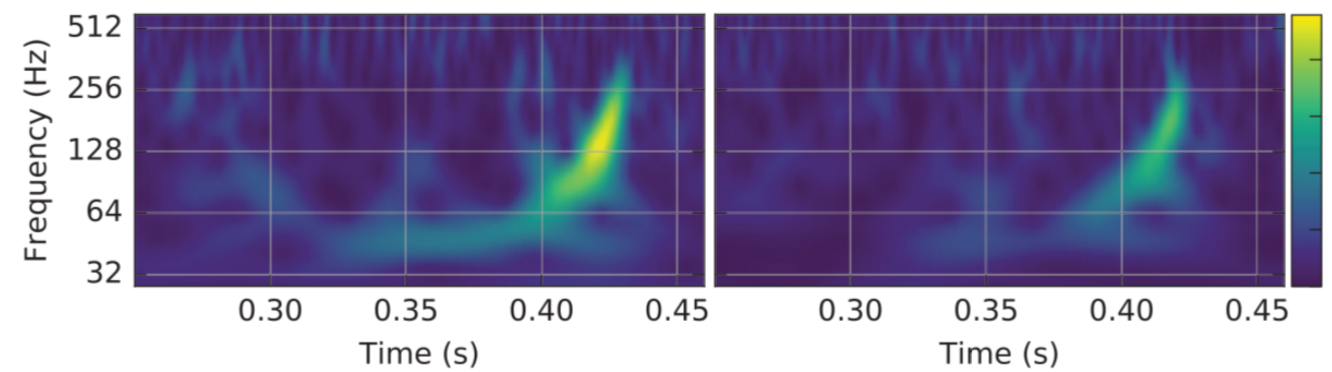
- Speculation by Poincaré (1905)
- Einstein provided a firm theoretical background for them (1916)



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

Revisiting Gertsenhstein's ideas

SOVIET PHYSICS JETP VOLUME 16, NUMBER 2 FEBRUARY, 1963

ON THE DETECTION OF LOW FREQUENCY GRAVITATIONAL WAVES

M. E. GERTSENSHTEĬN and V. I. PUSTOVOĬT

Submitted to JETP editor March 3, 1962

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

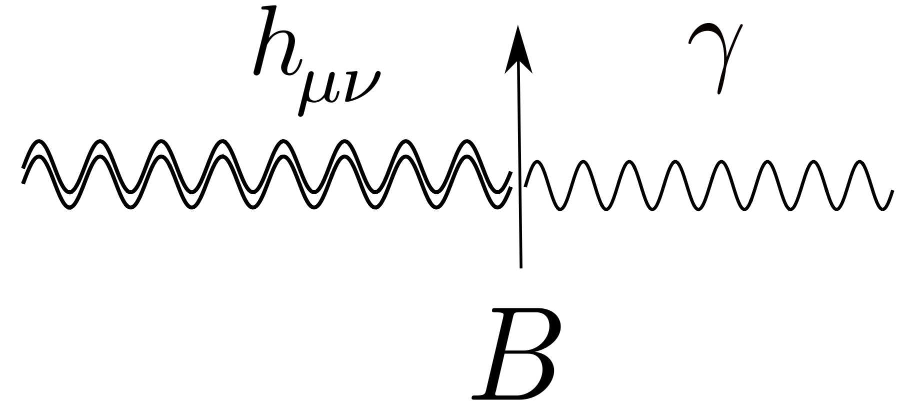
It is shown that the sensitivity of the electromechanical experiments for detecting gravitational waves by means of piezocrystals is ten orders of magnitude worse than that estimated by Weber.[1] In the low frequency range it should be possible to detect gravitational waves by the shift of the bands in an optical interferometer. The sensitivity of this method is investigated.

Terrestrial interferometers

Camilo García Cely, University of Valencia

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

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Terrestrial interferometers

The (inverse) Gertsenhstein Effect

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

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

- Cosmological conversion

Potential of Radio Telescopes as High-Frequency Gravitational Wave Detectors

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

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

Raffelt, Stodolski'89

High-frequency gravitational waves

Part of a collection:

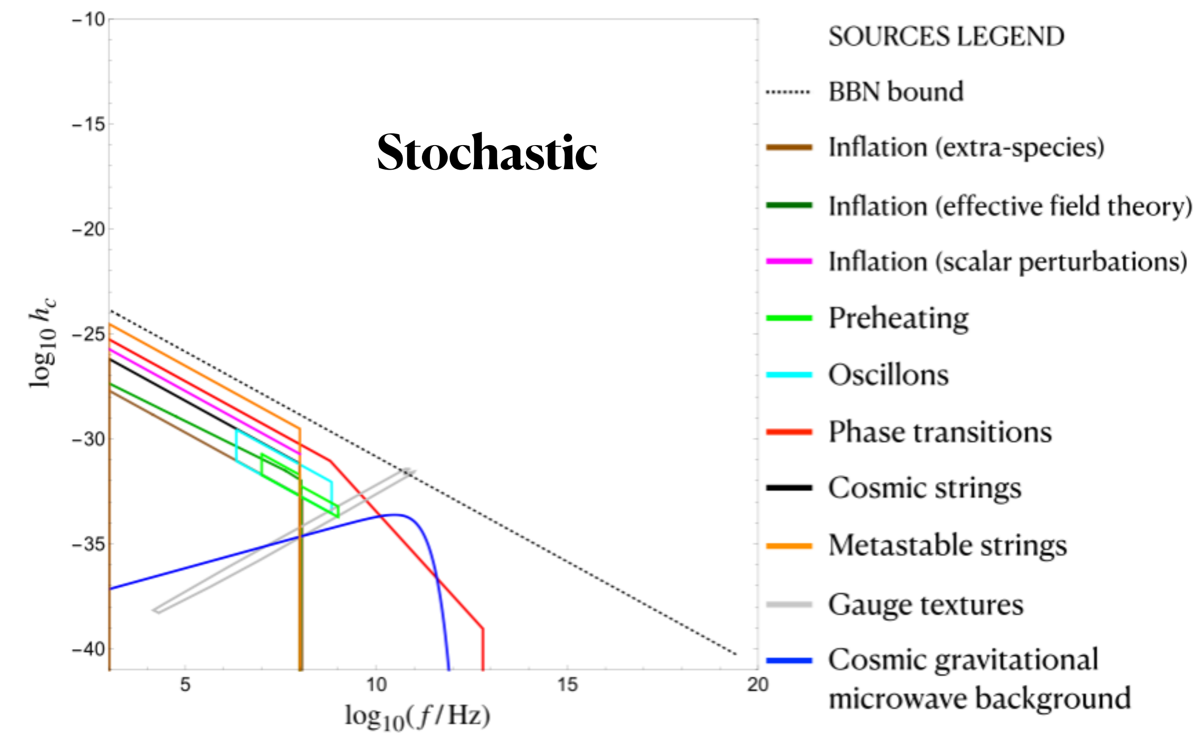
Gravitational Waves

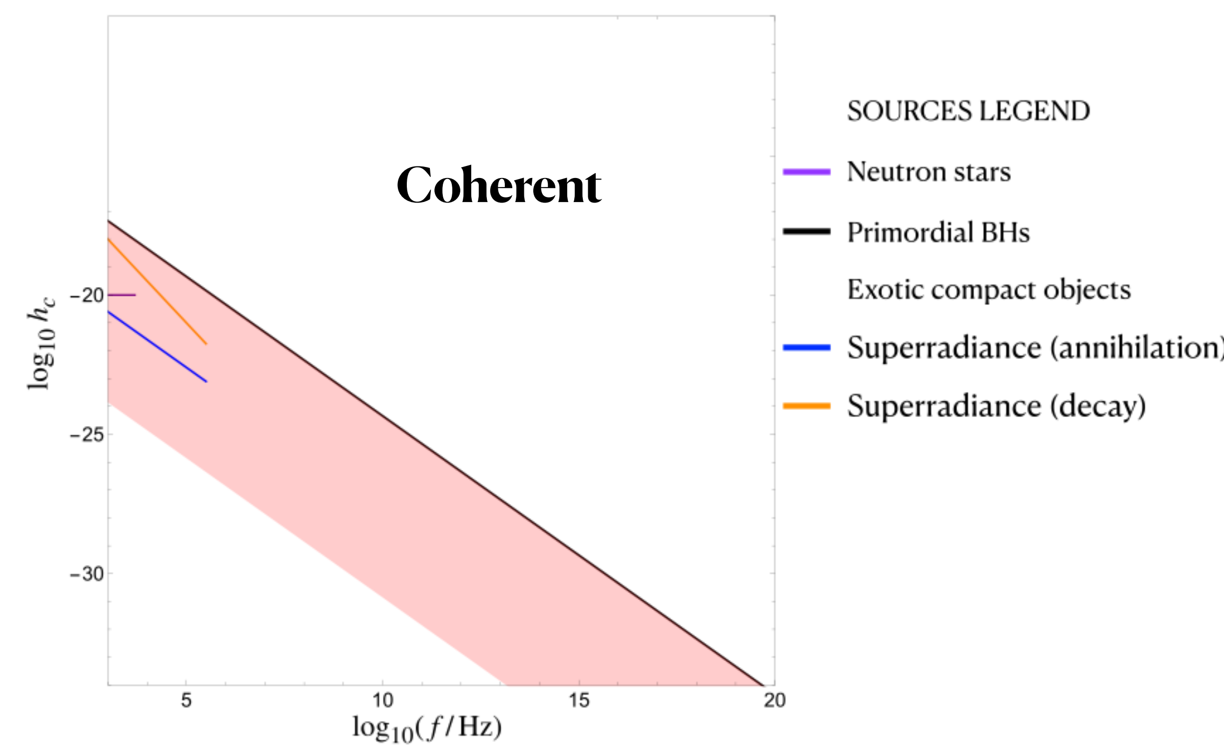
Review Article | Open Access | Published: 06 December 2021

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

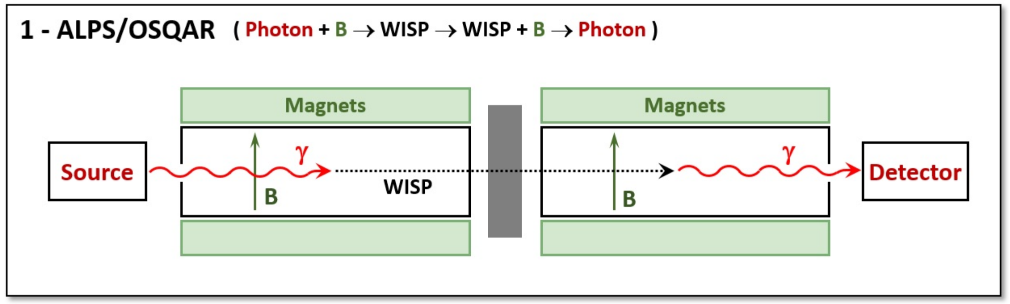
Living Reviews in Relativity 24, Article number: 4 (2021) | Cite this article

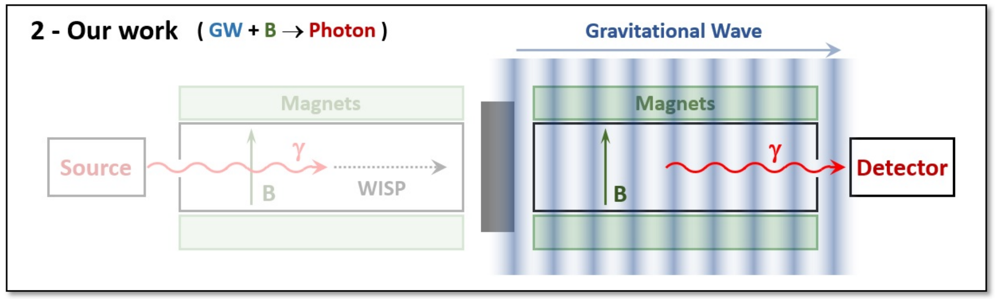




A growing community is seriously considering the search of high frequency gravitational waves

The (inverse) Gertsenhstein Effect

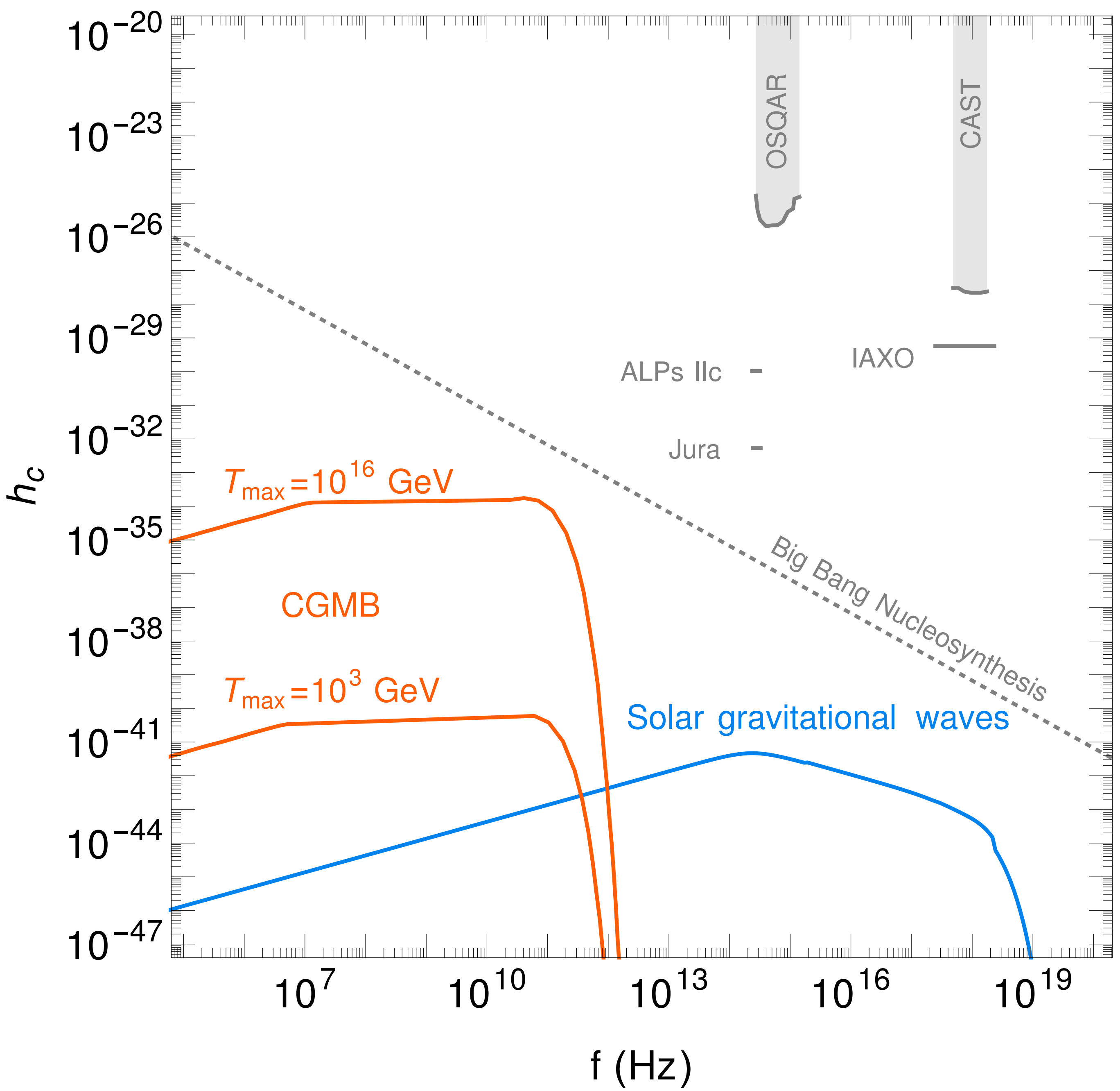




Ejlli et al, 2019

The solar spectrum is similar to that of sub-keV spin-2 particles

CGC, Ringwald **PRELIMINARY**



How does it work?

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

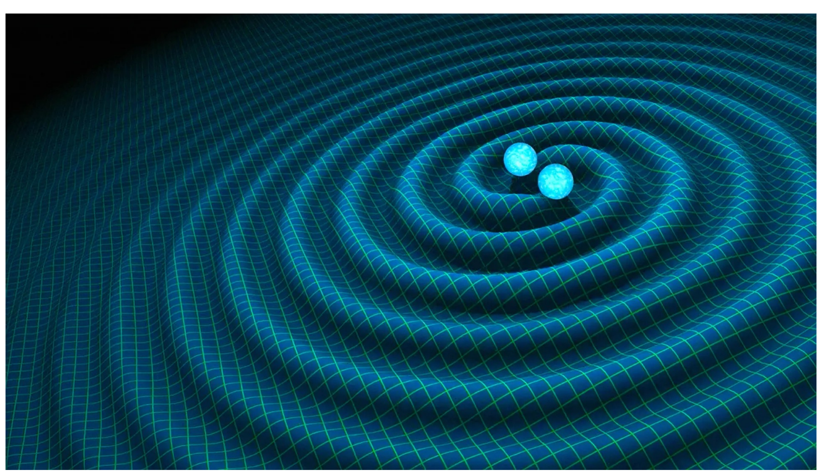
$$j^0 = -\,g_{a\gamma\gamma} \nabla a \cdot \mathbf{B} \qquad\qquad \mathbf{j} = g_{a\gamma\gamma} \left(\nabla a \times \mathbf{E} + \partial_t a \mathbf{B} \right)$$

Camilo García Cely, University of Valencia

How does it work?

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

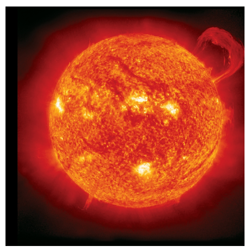
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \qquad \left|h_{\mu\nu}\right| \ll 1$$

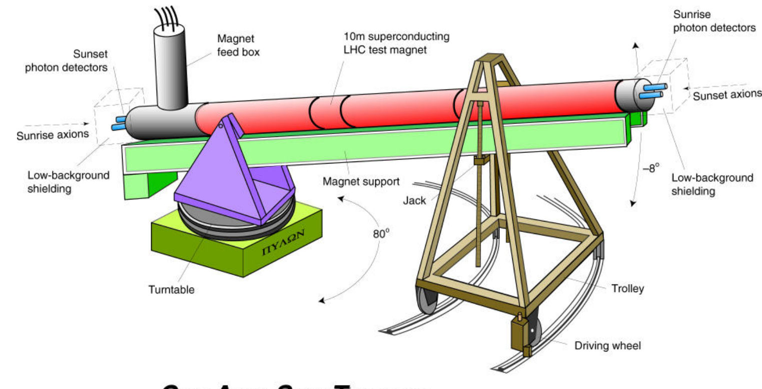


$$j^{\mu}_{\rm eff} = \partial_\nu \left(-\frac{1}{2} h\, F^{\mu\nu} + F^{\mu\alpha} h^{\nu}{}_{\alpha} - F^{\nu\alpha} h^{\mu}{}_{\alpha} \right)$$

Many possibilities

- Helioscopes (X rays)





- CAST
- IAXO
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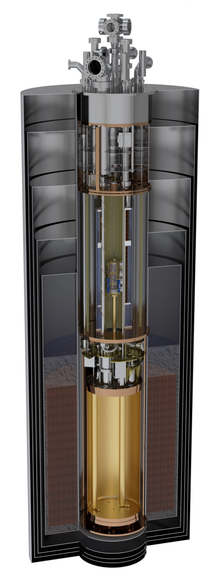
- Haloscopes (radio frequencies)



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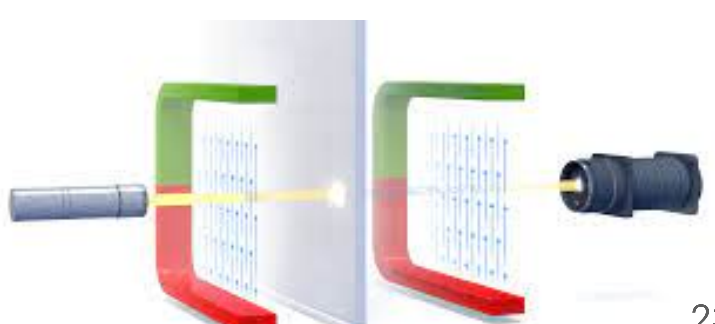
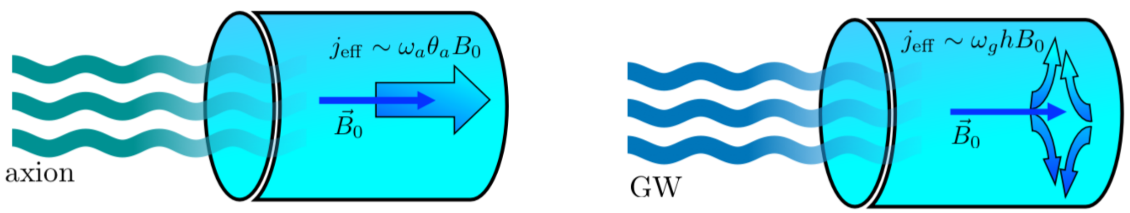
- ABRACADABRA
- Lumped element detectors
- ...

- Purely lab experiments



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

Haloscopes based on microwave cavities



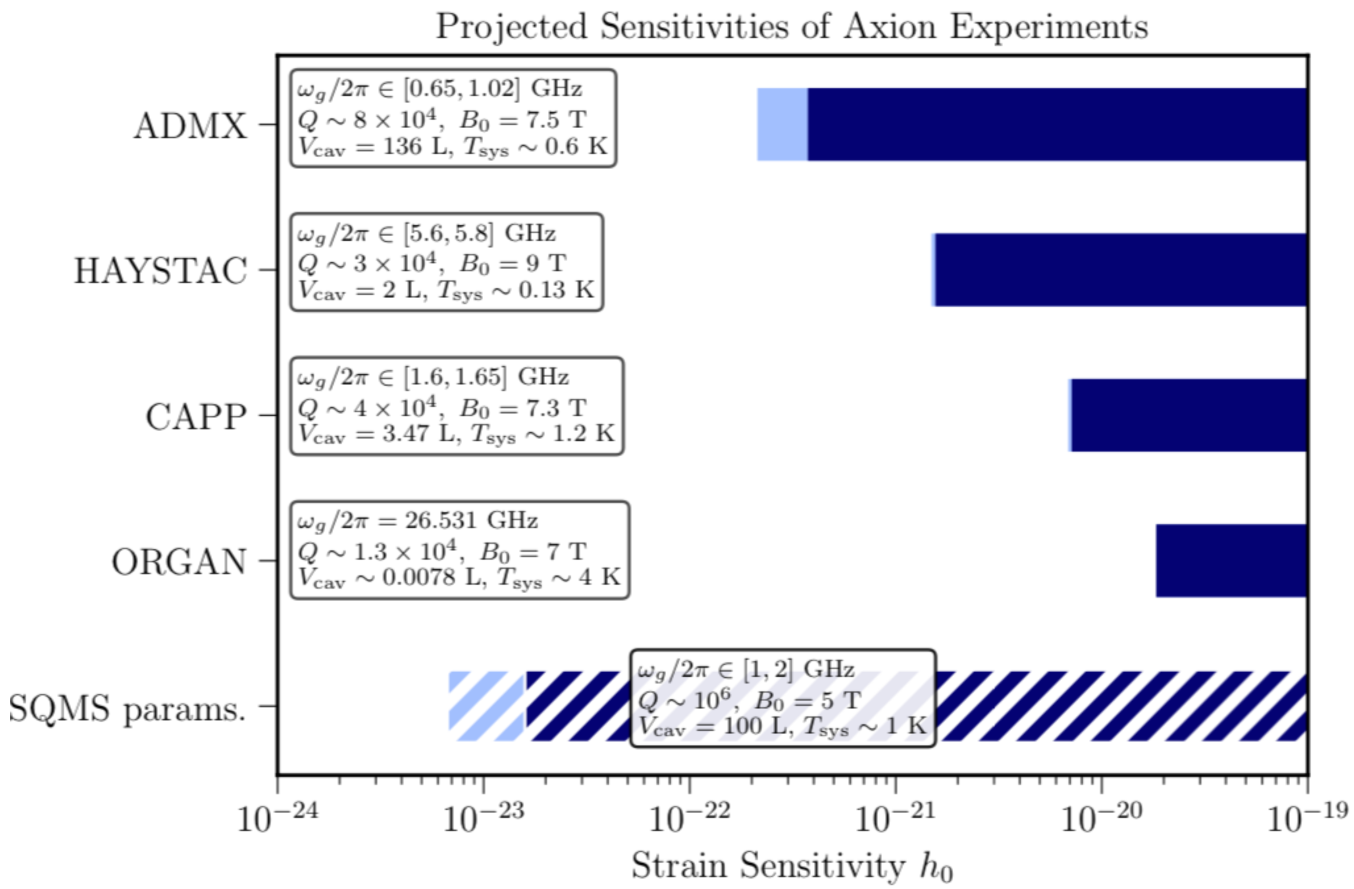
It resonates when the GW frequency matches one of the eigenmode frequencies

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

Nicolas Herman, André Füzfa, 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



Proper detector frame

The coordinate system closely matches the intuitive description of an Earth-based laboratory

Fermi, 1922
Manasse and Misner, 1963
Ni and Zimmermamn, 1978

- Coordinates given by ideal rigid rulers

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

Proper detector frame

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- The gravitational wave acts as a Newtonian force.

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

Proper detector frame

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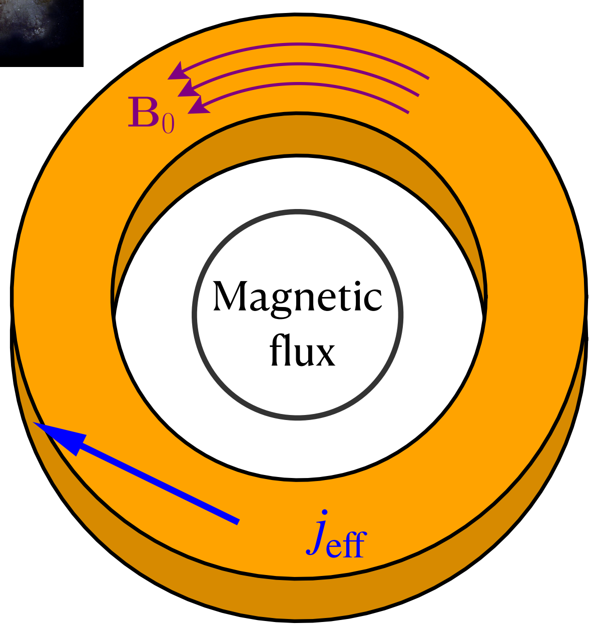
- Crucial for haloscopes

Berlin et al 2022

Haloscopes based on lumped-element detectors

Camilo García Cely, University of Valencia

Haloscopes based on lumped-element detectors



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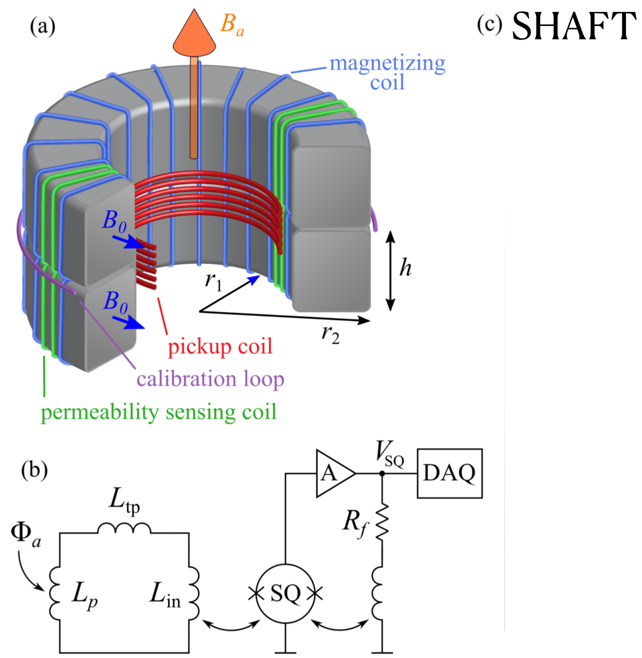

physics https://doi.org/

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

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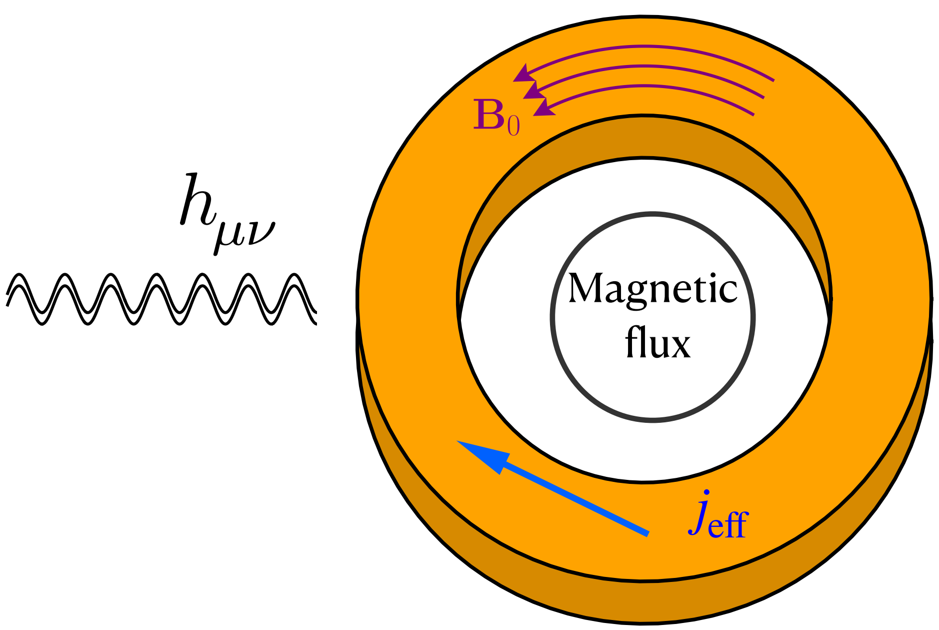
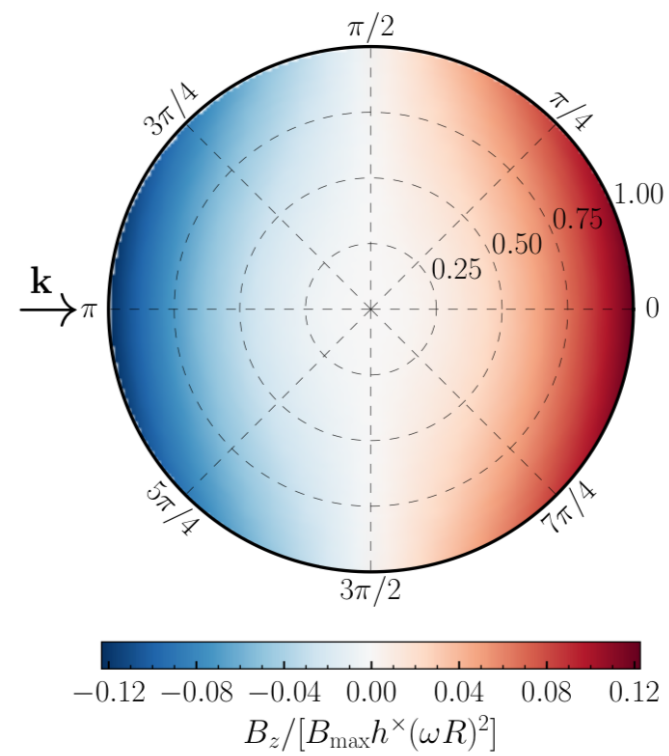
The electromagnetic fields produced by the axion drive a current through a pickup coil

Haloscopes based on lumped-element detectors



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



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

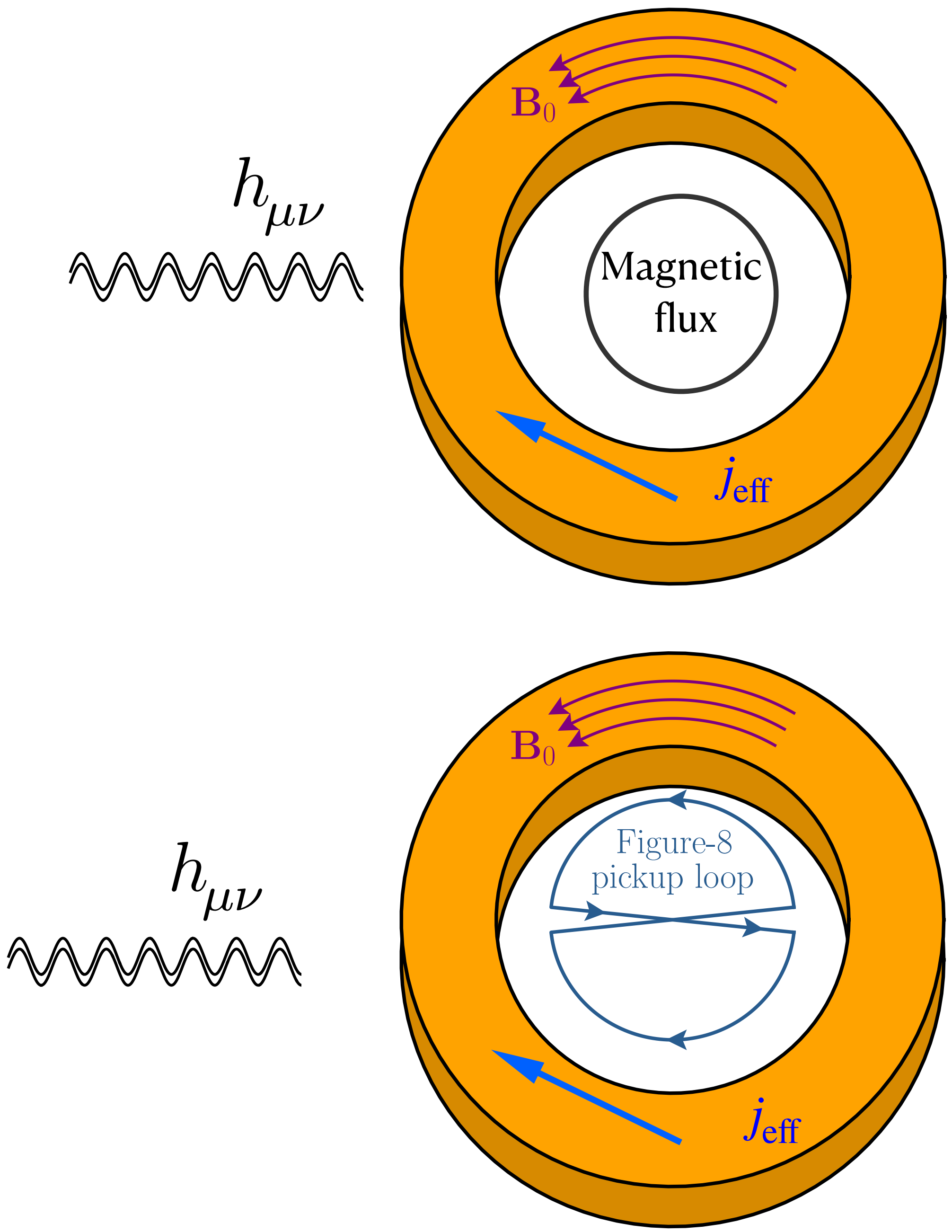
Only one polarization

Suppression at small frequencies

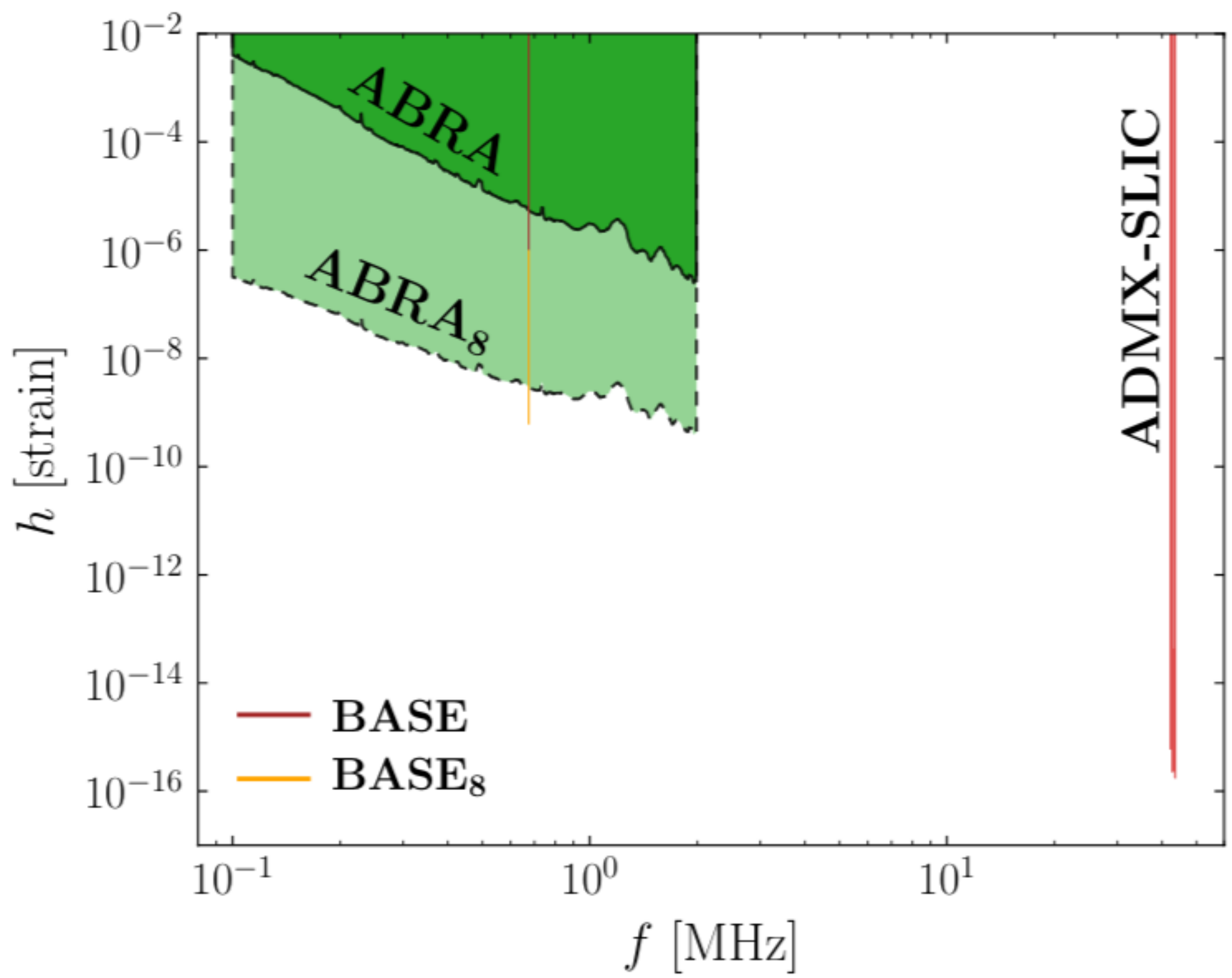
$$\Phi_{\text{axions}} \approx e^{-\mathrm{i}\omega t} g_{a\gamma\gamma}\sqrt{2\rho_{\text{DM}}} B_{\max} \pi r^2 R$$

The sensitivity scaling with the volume is faster than for axions

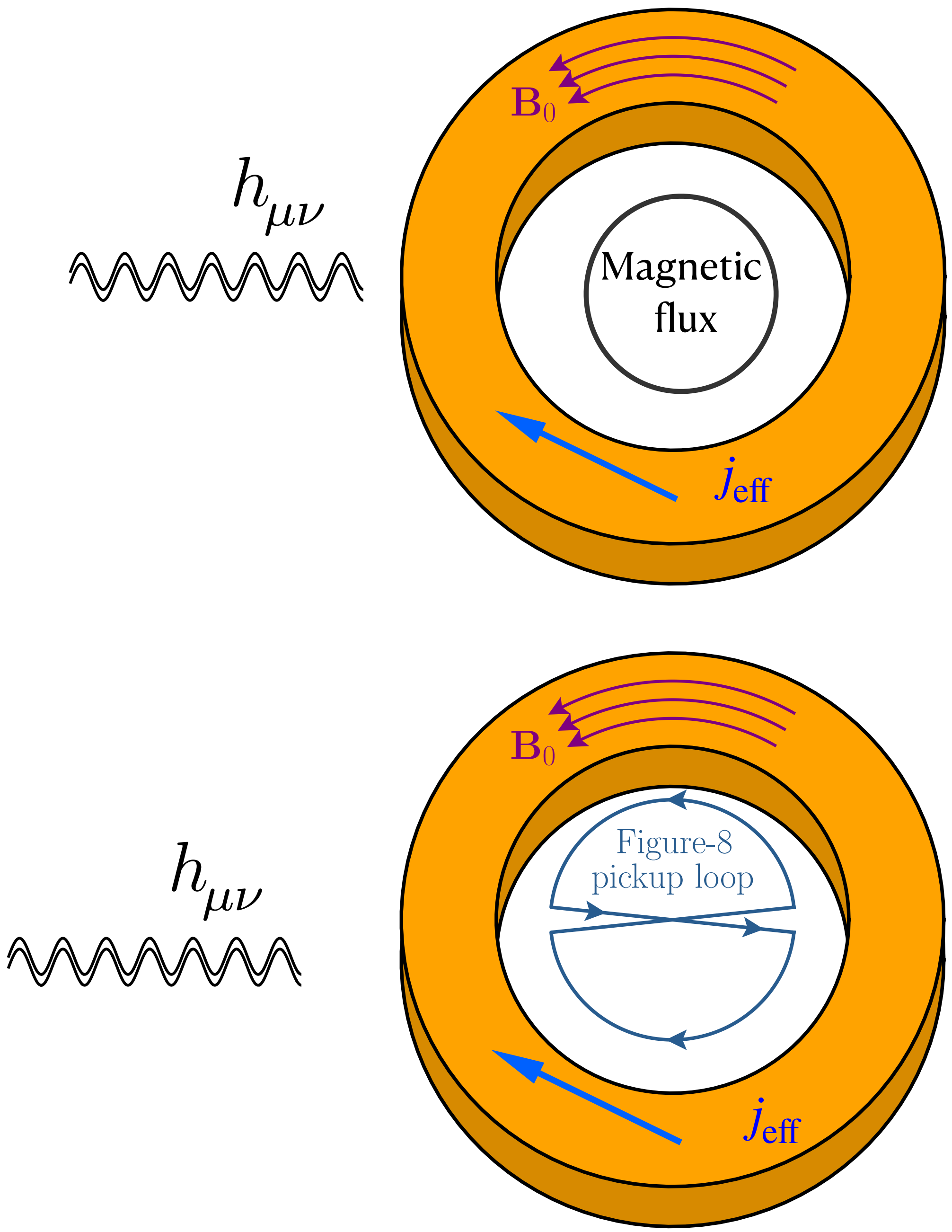
Toroidal magnetic fields



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



Toroidal magnetic fields



Valerie Domcke, Camilo Garcia-Cely, and Nicholas L. Rodd
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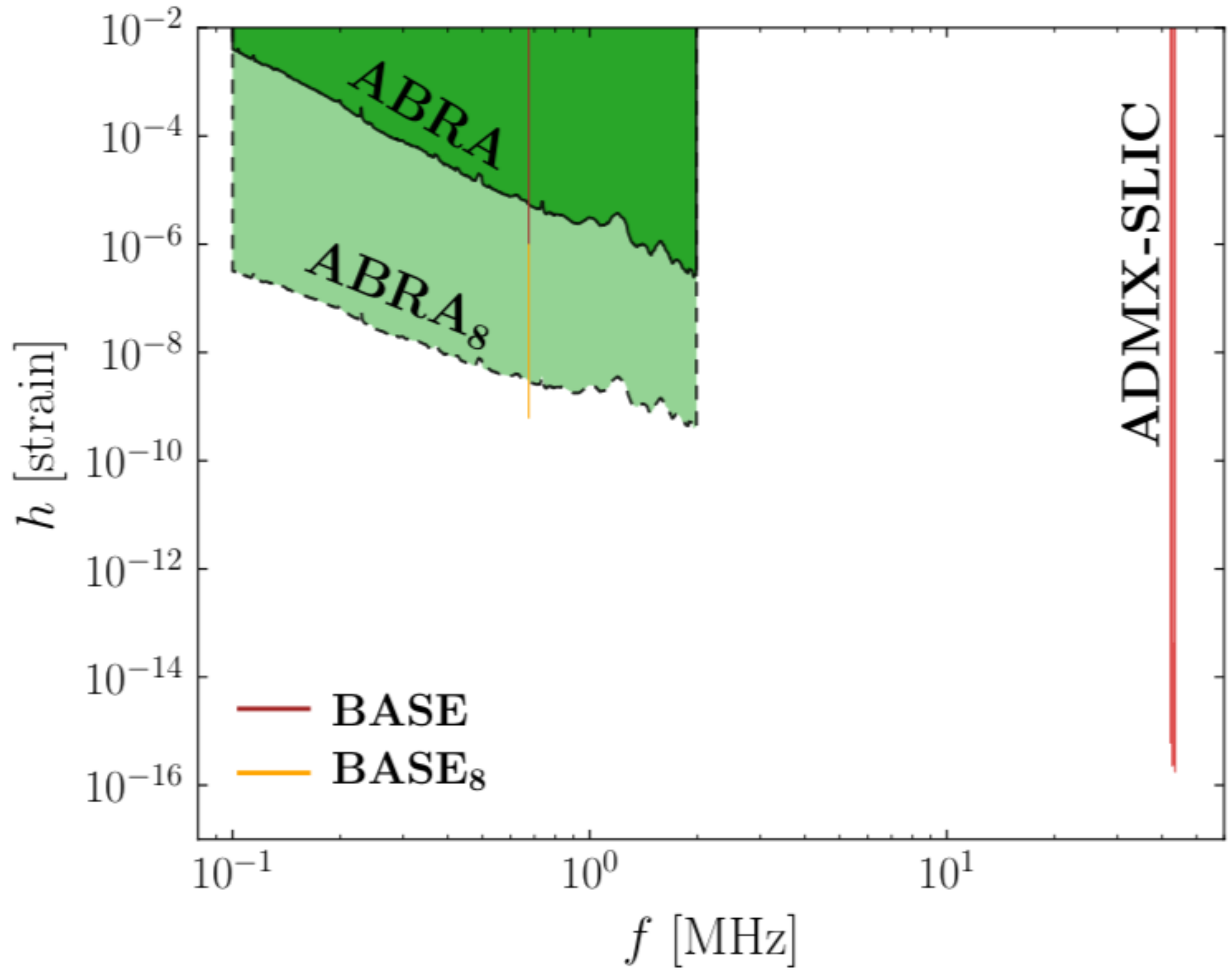
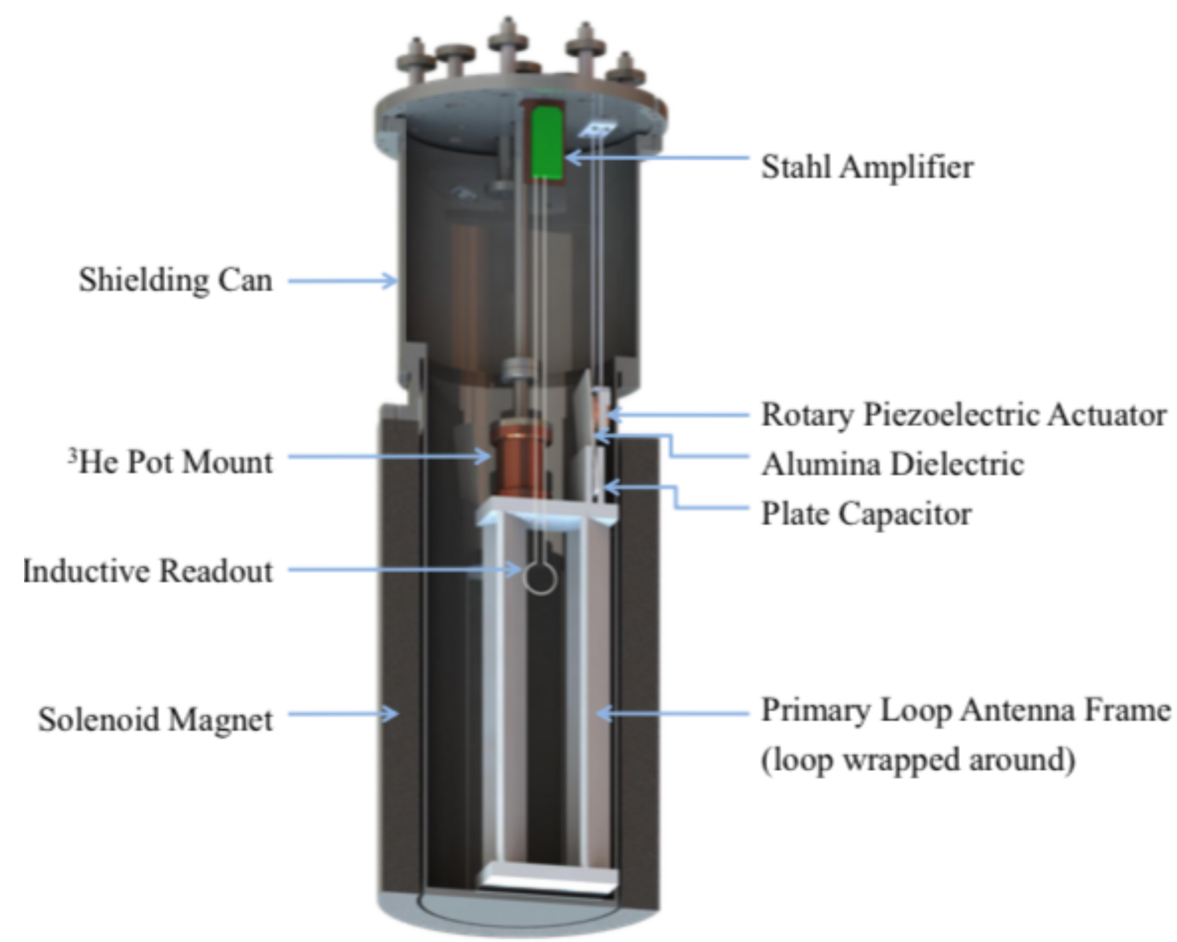


Solenoidal configurations

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

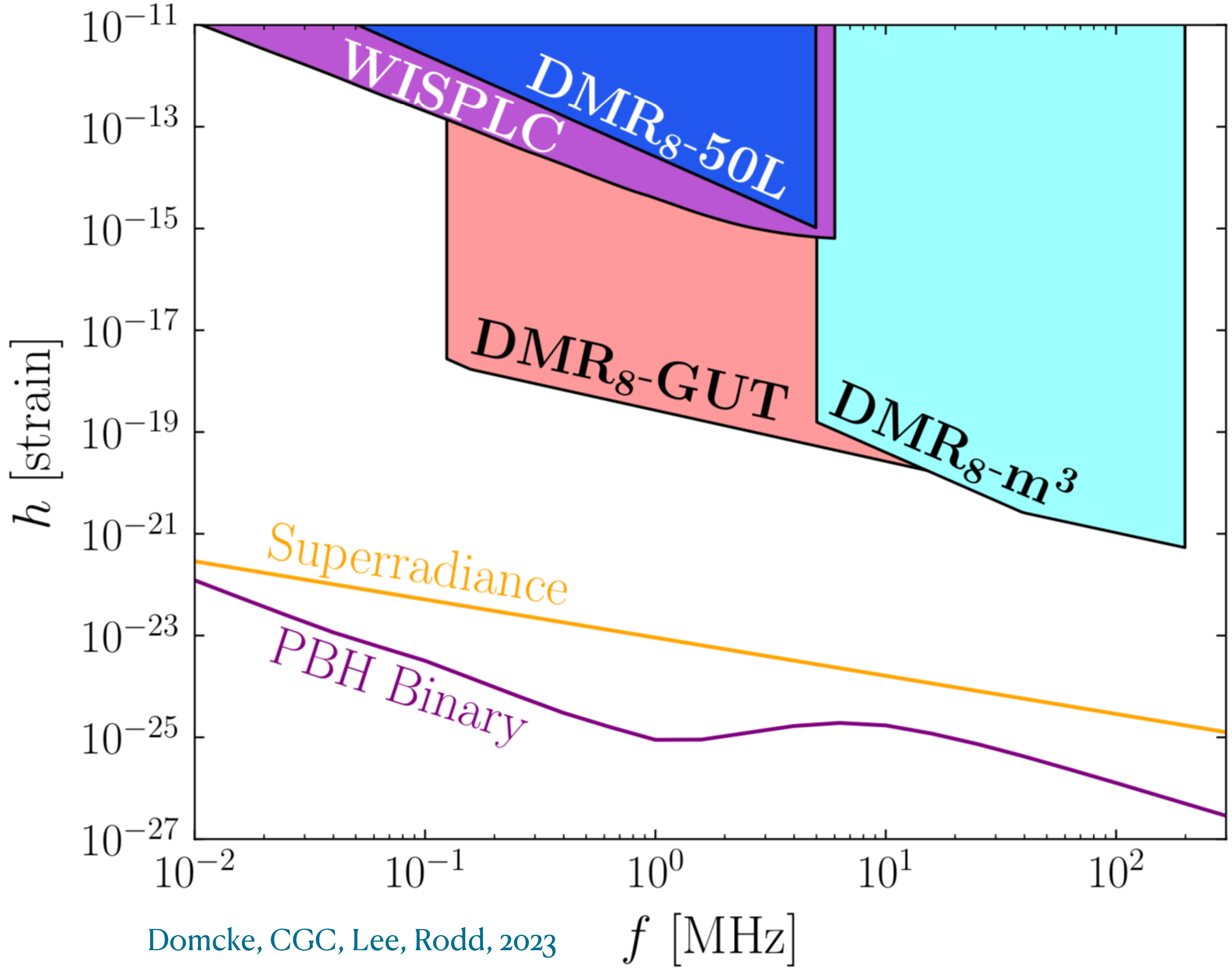
Jack A. Devlin, Matthias J. Borchert, Stefan Erlewein, Markus Fleck, James A. Harrington, Barbara Latacz, Jan Warncke, Elise Wursten, Matthew A. Bohman, Andreas H. Mooser, Christian Smorra, Markus Wiesinger, Christian Will, Klaus Blaum, Yasuyuki Matsuda, Christian Ospelkaus, Wolfgang Quint, Jochen Walz, 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

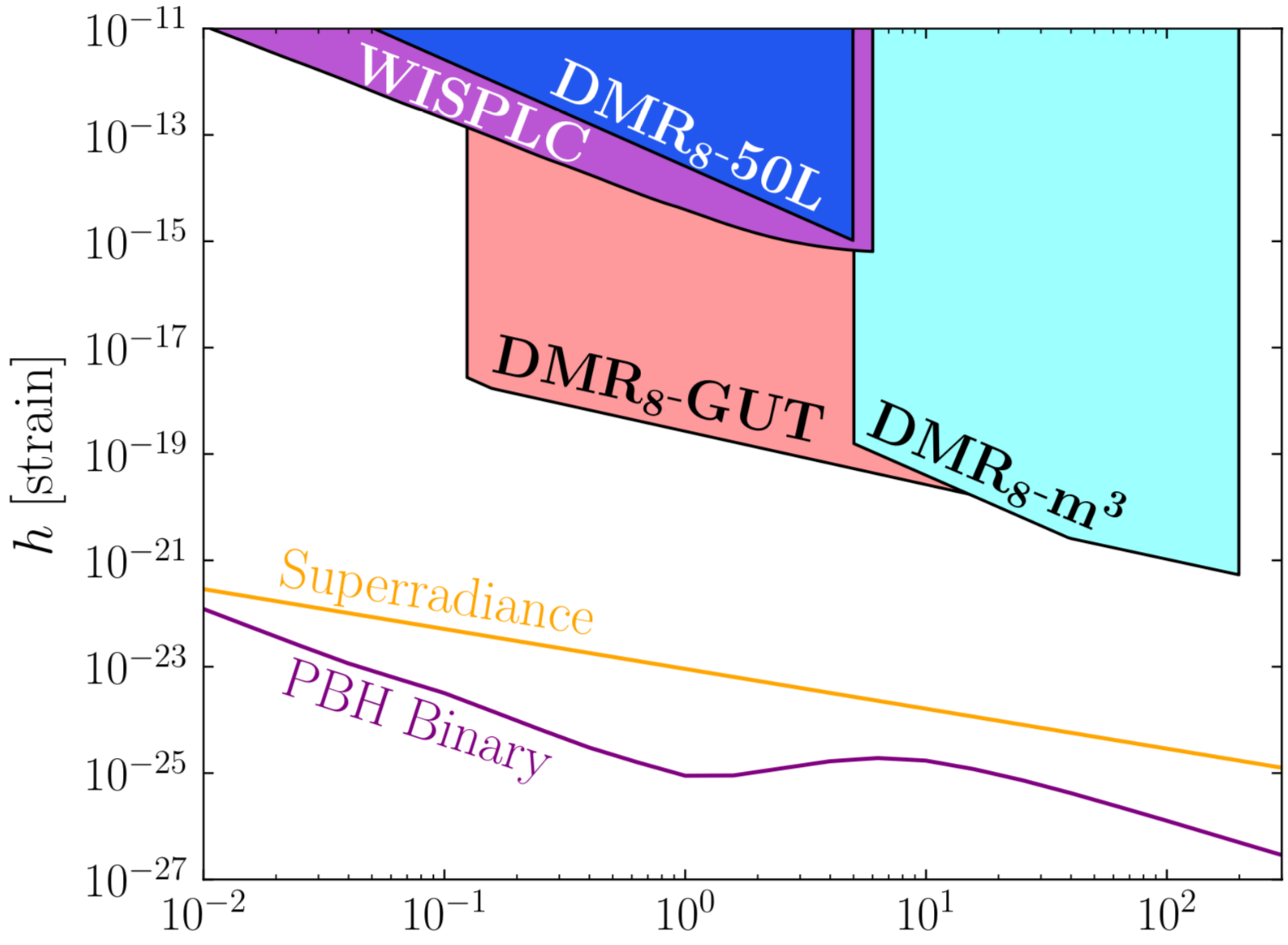
Haloscopes based on lumped-element detectors



Domcke, CGC, Lee, Rodd, 2023

Camilo García Cely, University of Valencia

How should we compare signals?



Domcke, CGC, Lee, Rodd, 2023

We propose a coherence ratio to recast axion searches taking into account the different time scales involved in the signals and detectors.

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

Camilo García Cely, University of Valencia

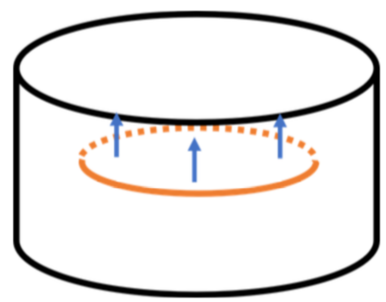
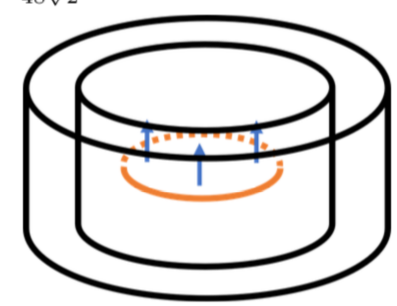
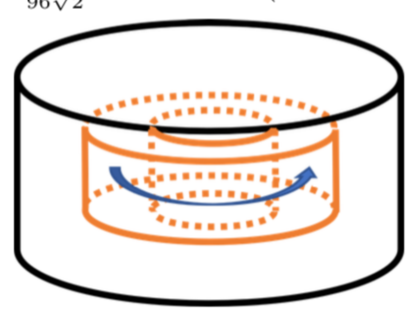
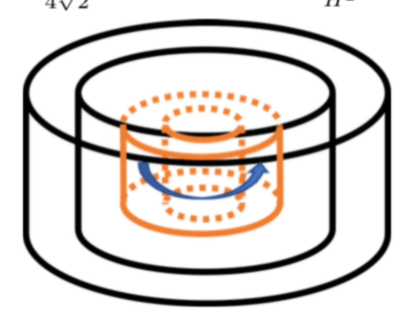
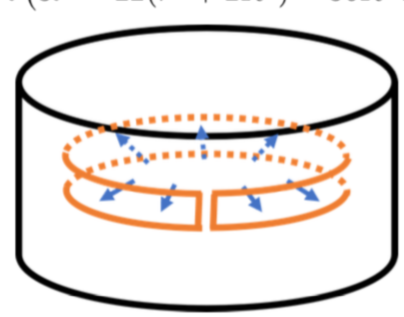
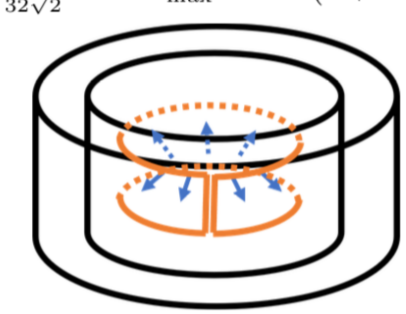
Impact of the geometry and selection rules

Impact of the geometry

Type of external field

Domcke, CGC, Lee, Rodd, 2023

Pickup loop orientation

	Solenoid: $\mathbf{B}_0 \propto \hat{\mathbf{e}}_z$	Toroid: $\mathbf{B}_0 \propto \hat{\mathbf{e}}_\phi$
$\hat{\mathbf{n}}' \propto \hat{\mathbf{e}}_z$	h^+, n even $\Rightarrow \mathcal{O}[(\omega L)^2]$ $\Phi_h = \frac{e^{-i\omega t}}{48\sqrt{2}} h^+ \omega^2 B_0 s^2_{\theta_h} \pi r^2 \left(11r^2 + 14R^2 + 16R^2 \ln \frac{R}{H}\right)$ 	$h^\times$, n odd $\Rightarrow \mathcal{O}[(\omega L)^3]$ $\Phi_h = \frac{ie^{-i\omega t}}{48\sqrt{2}} h^\times \omega^3 B_{\max} \pi r^2 aR(a+2R) s^2_{\theta_h}$ 
$\hat{\mathbf{n}}' \propto \hat{\mathbf{e}}_\phi$	$h^\times$, n odd $\Rightarrow \mathcal{O}[(\omega L)^3]$ $\Phi_h = \frac{ie^{-i\omega t}}{96\sqrt{2}} h^\times \omega^3 B_0 \pi r^2 l(12R^2 - 5r^2) s^2_{\theta_h}$ 	h^+, n even $\Rightarrow \mathcal{O}[(\omega L)^2]$ $\Phi_h = \frac{3e^{-i\omega t}}{4\sqrt{2}} h^+ \omega^2 B_{\max} \frac{\pi r^2 aRl(a+2R)}{H^2} s^2_{\theta_h}$ 
$\hat{\mathbf{n}}' \propto \hat{\mathbf{e}}_\rho$	h^+, n odd $\Rightarrow \mathcal{O}[(\omega L)^3]$ $\Phi_h = \frac{ie^{-i\omega t}}{96\sqrt{2}} h^+ B_0 \omega^3 c_{\theta_h} s^2_{\theta_h}$ $\times \pi r^2 l \left(3l^2 - 22(r^2 + 2R^2) - 36R^2 \ln \frac{R}{H}\right)$ 	$h^\times$, n even $\Rightarrow \mathcal{O}[(\omega L)^4]$ $\Phi_h = \frac{e^{-i\omega t}}{32\sqrt{2}} h^\times \omega^4 B_{\max} \pi r^2 aRl(a+2R) c_{\theta_h} s^2_{\theta_h}$ 

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Selection rules

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

Domcke, CGC, Lee, Rodd, 2023

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

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

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

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

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 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.

Novel effects

Effective magnetization and polarization

$$j^{\mu}_{\text{eff}} = \left(-\nabla\cdot\mathbf{P}, \nabla\times\mathbf{M} + \partial_t\mathbf{P}\right)$$

$$\mathbf{P} = g_{a\gamma\gamma}a\mathbf{B}, \quad \mathbf{M} = g_{a\gamma\gamma}a\mathbf{E}$$

McAllister et al, 1803.07755
Tobar et al, 1809.01654
Ouellet et al, 1809.10709

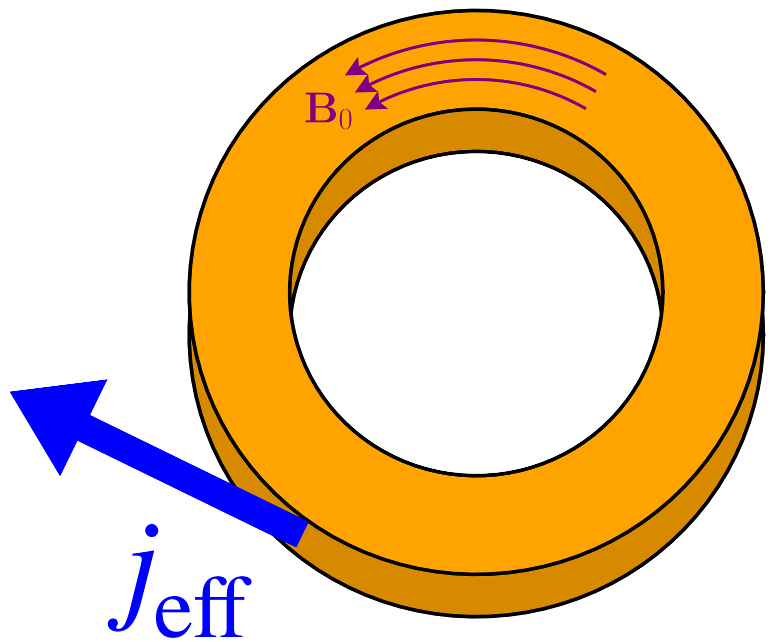
$$P_i = -h_{ij}E_j + \frac{1}{2}hE_i + h_{00}E_i - \epsilon_{ijk}h_{0j}B_k$$

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

Domcke, CGC, Rodd, 2202.00695

Non-zero *effective* surface currents

Domcke, CGC, Lee, Rodd, 2023



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

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

Sizeable effects. This should also be relevant for cavities

Excitation of mechanical modes

The proper detector frame closely matches the intuitive description of an Earth-based laboratory

Fermi, 1922
Manasse and Misner, 1963
Ni and Zimmermamn, 1978

- Coordinates given by ideal rigid rulers

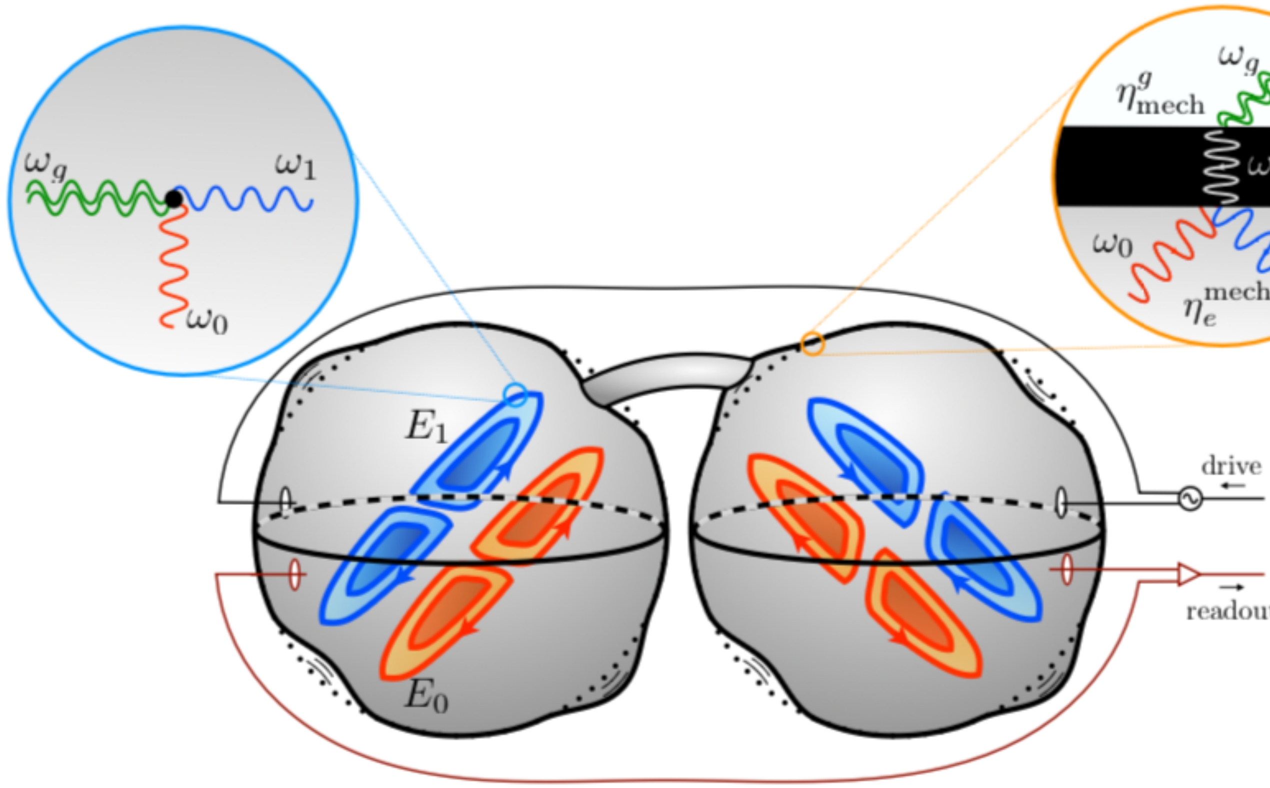
$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu = \eta_{\mu\nu} dx^\mu dx^\nu \text{ for } dx^\mu = (0, dr\,\hat{\mathbf{r}})$$

- The gravitational wave acts as a Newtonian force.

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

Berlin et al 2022

Excitation of mechanical modes



- The gravitational wave acts as a Newtonian force. If not negligible, coupling of the mechanical modes can play an important role (this is certainly the case at frequencies above the first mechanical resonance)

- This can enhance the sensitivity

Berlin et al 2022

Conclusions

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

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

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

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

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