Prospects of detecting gravitational waves from primordial black holes in axion haloscopes

MITP Workshop

Mainz, Germany
August 3, 2022

Camilo García Cely

Ramón y Cajal Researcher

IFIC INSTITUT DE FÍSICA CORPUSCULAR

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

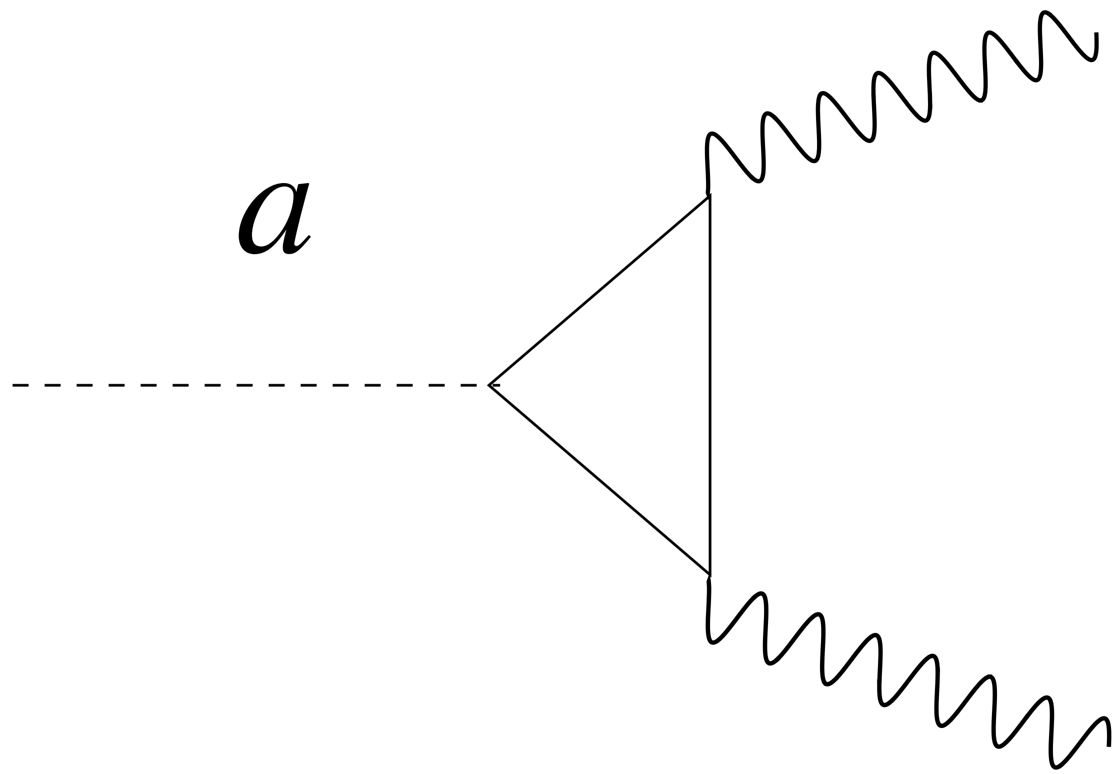
VNIVERSITAT DE VALÈNCIA

Novel search for high-frequency gravitational waves with low-mass axion haloscopes

Phys. Rev. Lett.

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

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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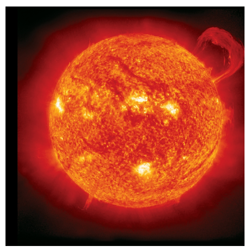
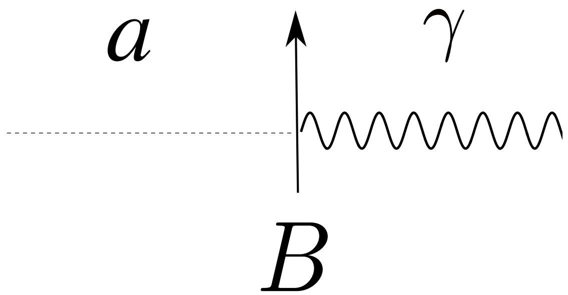
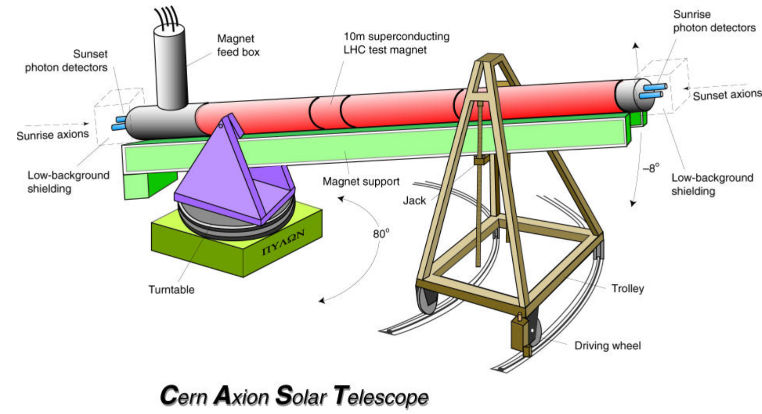
Axion electrodynamics

- Helioscopes (X rays)

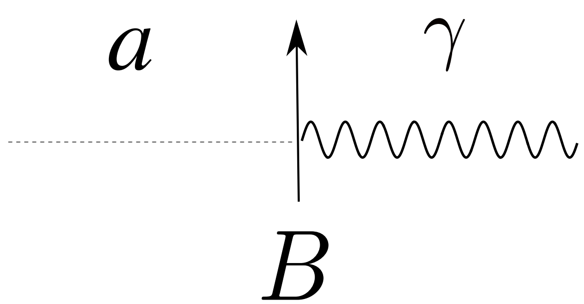


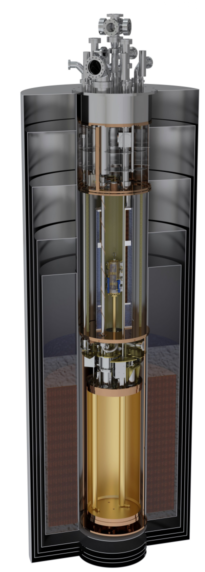




- CAST
- IAXO
- .....

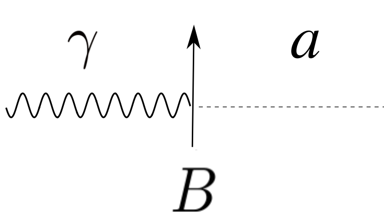
- Haloscopes (radio frequencies)

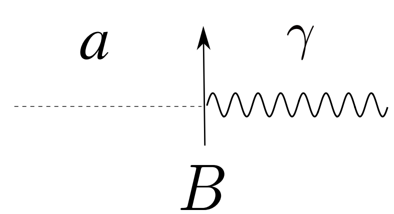


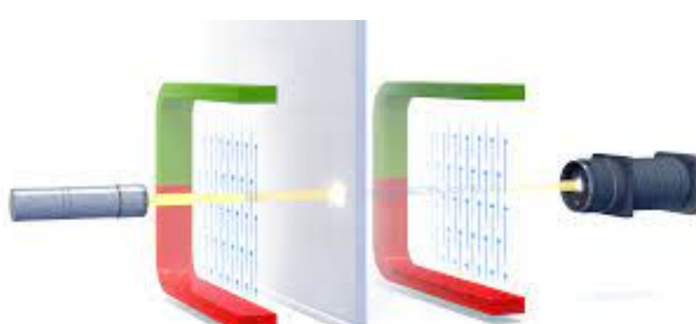


- microwave cavities
- MADMAX
- ADMX
- HAYSTAC
- ABRACADABRA
- Lumped element detectors
- ...

- Purely lab experiments







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

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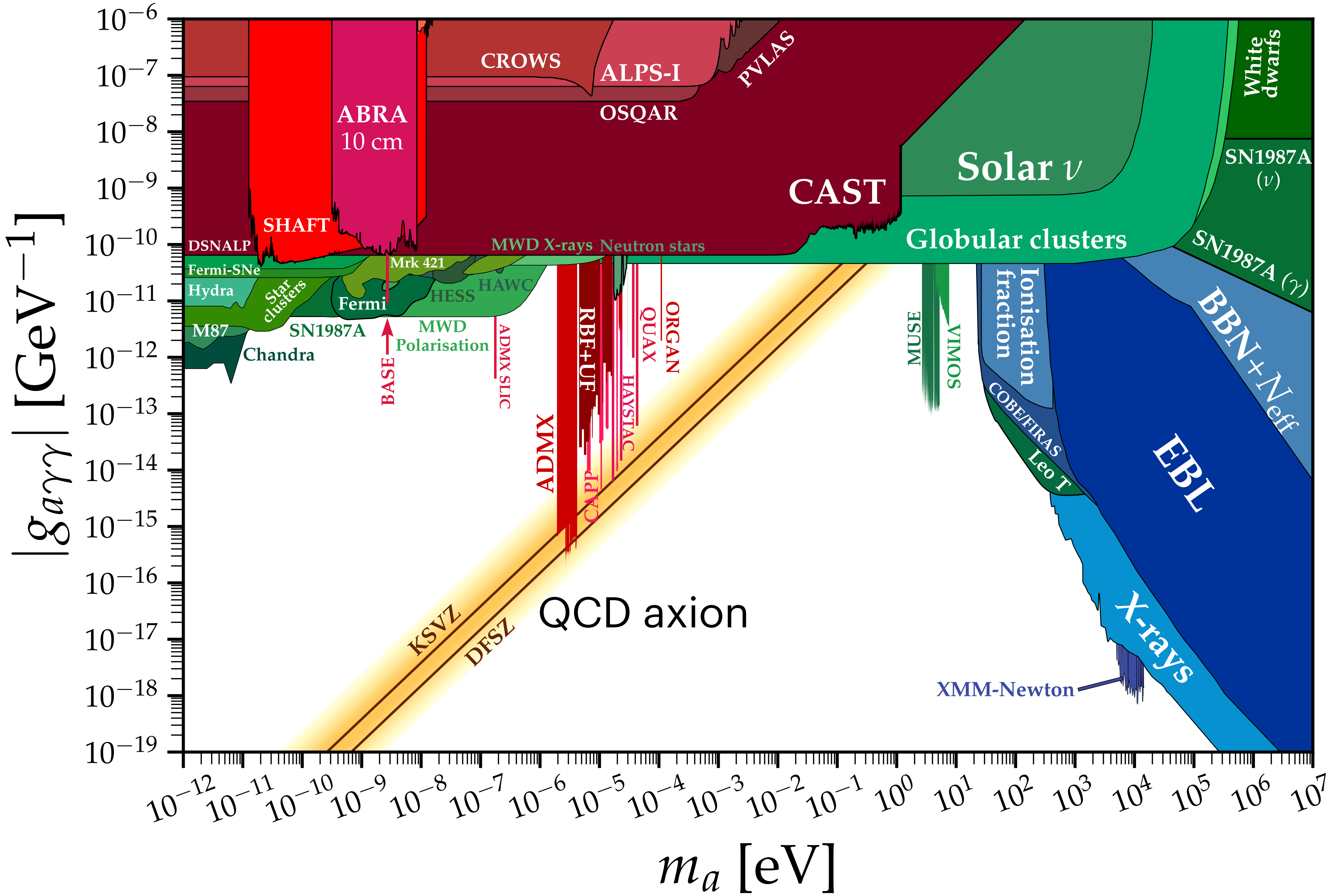
Axion electrodynamics



https://github.com/cajohare/AxionLimits

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

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. $E/N = 0$

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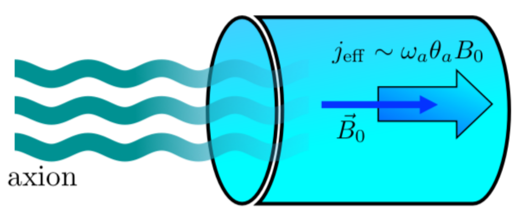
Haloscopes based on microwave cavities



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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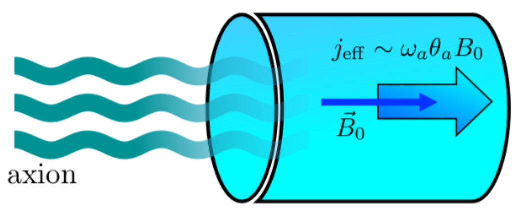
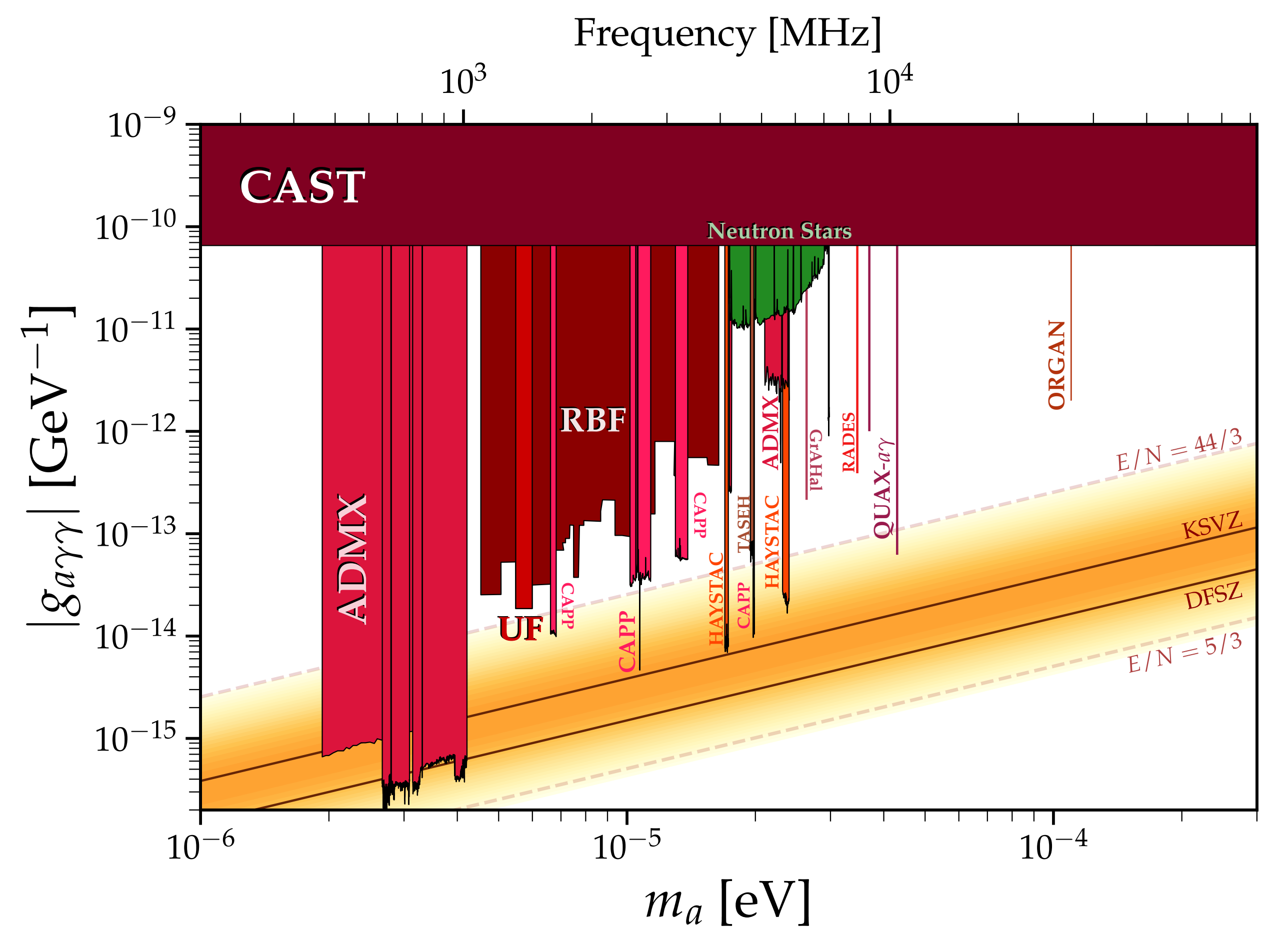
Haloscopes based on microwave cavities





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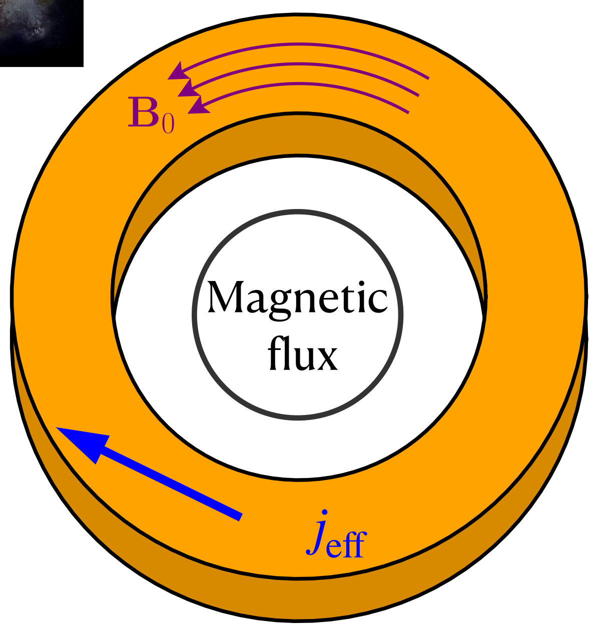
Eigenmodes $\mathbf{E}(\mathbf{x}, t) = \sum_n e_n(t)\mathbf{E}_n(\mathbf{x})$

Haloscopes based on lumped-element detectors

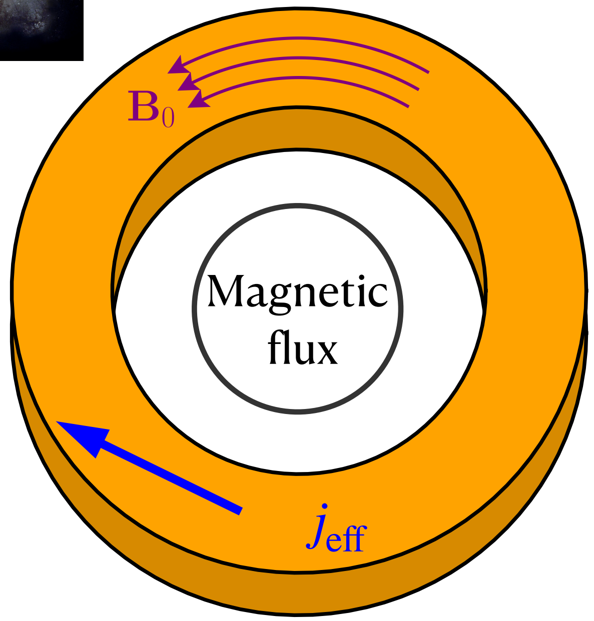


$$\nabla \times \mathbf{B} - \partial_t \mathbf{E} = \underbrace{g_{a\gamma\gamma}\, \partial_t a\, \mathbf{B_0}}_{j_{\text{eff}}}$$

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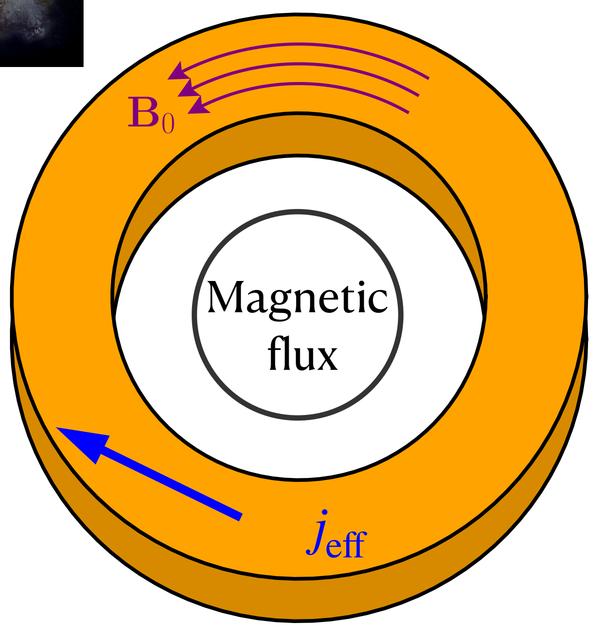
The electromagneticfields produced by the axion drive a current through a pickup coil

Searches at frequencies lower than those achieved with conventional cavity haloscopes.

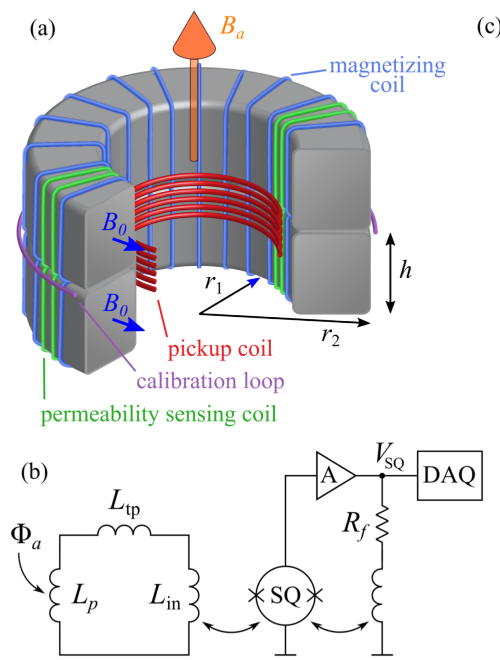
Kahn, Safdi, Thaler 2016
Sikivie, Sullivan and Tanner 2014

Haloscopes based on lumped-element detectors



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

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)

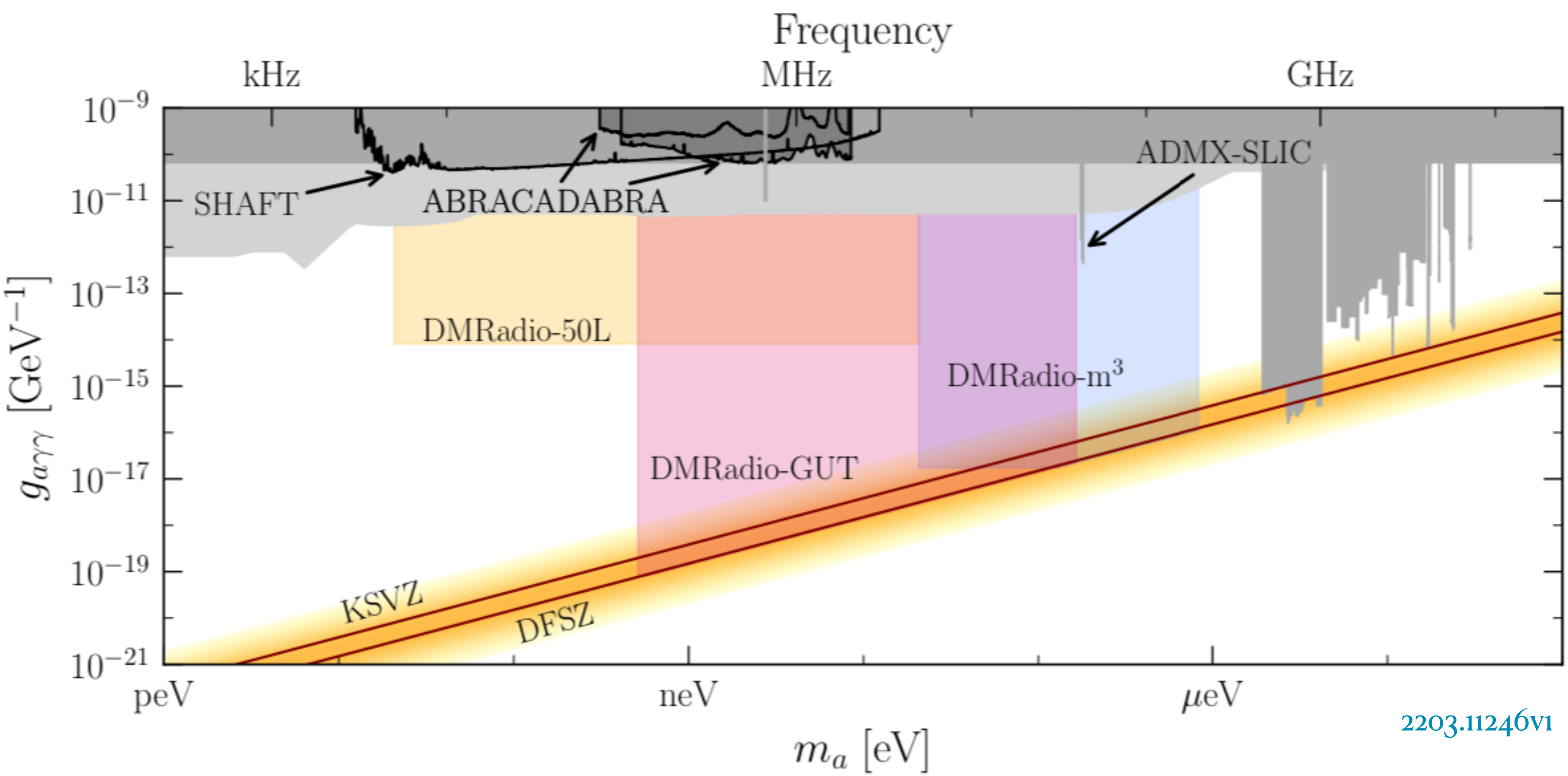
The electromagneticfields produced by the axion drive a current through a pickup coil

Searches at frequencies lower than those achieved with conventional cavity haloscopes.

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

DMRadio program

Searches at frequencies lower than those achieved with conventional cavity haloscopes.



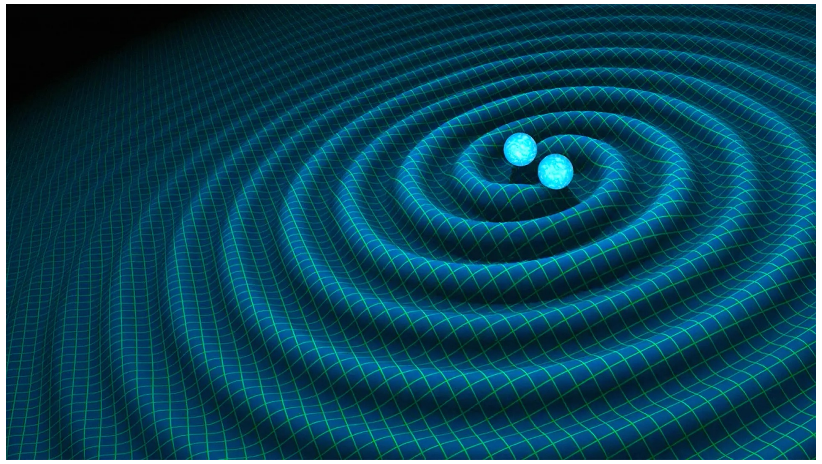
2203.11246v1

talk by Nicholas M. Rapidis

Effective current for gravitational waves

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

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



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

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Axion electrodynamics

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

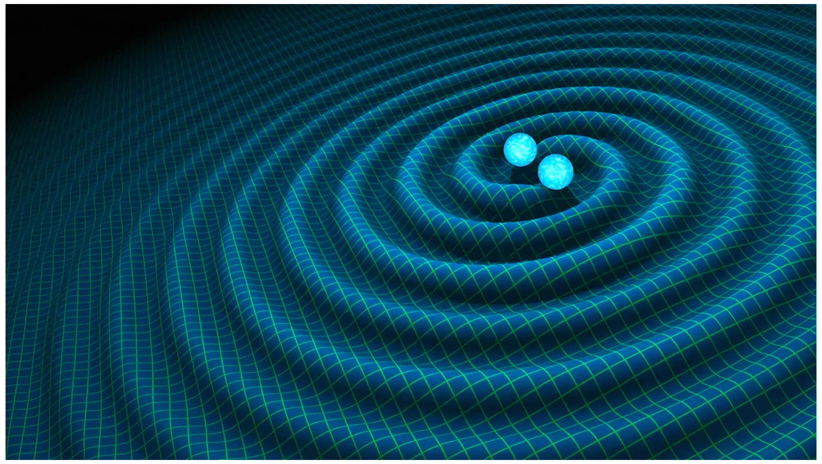
$$\nabla \cdot \mathbf{E} = -\nabla \cdot \mathbf{P}$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\partial_t \mathbf{B}$$
$$\nabla \times \mathbf{B} = \partial_t \mathbf{E} + \nabla \times \mathbf{M} + \partial_t \mathbf{P}$$

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

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

Effective current for gravitational waves

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



$$\nabla \cdot \mathbf{E} = - \nabla \cdot \mathbf{P}$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = - \partial_t \mathbf{B}$$
$$\nabla \times \mathbf{B} = \partial_t \mathbf{E} + \nabla \times \mathbf{M} + \partial_t \mathbf{P}$$

$$P_i = - h_{ij} E_j \qquad M_i = - h_{ij} B_j$$

(in the TT gauge)

Domcke, CGC, Rodd, 2202.00695

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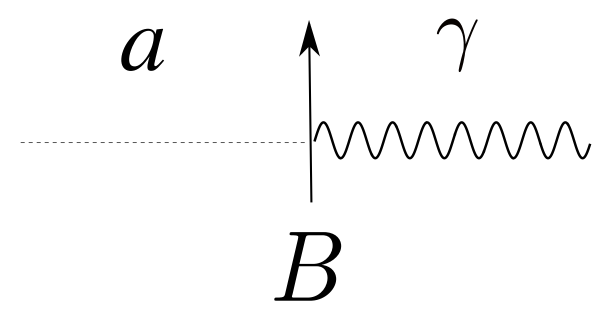
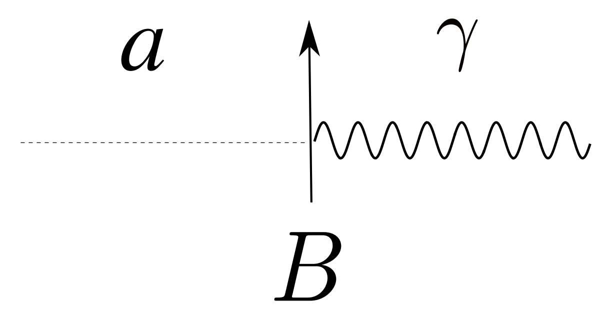
	Axion electrodynamics	Gravitational wave electrodynamics
An example		
Effective current $j^{\mu}_{\text{eff}} = \left(-\nabla \cdot \mathbf{P}, \nabla \times \mathbf{M} + \partial_t \mathbf{P}\right)$	$\mathbf{P} = g_{a\gamma\gamma} a \mathbf{B}, \quad \mathbf{M} = g_{a\gamma\gamma} a \mathbf{E}$ McAllister et al, 1803.07755 Tobar et al, 1809.01654 Ouellet et al, 1809.10709	$P_i = -h_{ij} E_j \qquad M_i = -h_{ij} B_j$ (in the TT gauge) Domcke, CGC, Rodd, 2202.00695
Benchmark	QCD axion	

	Axion electrodynamics	Gravitational wave electrodynamics
An example		Gertsenshtein effect
Effective current $j^{\mu}_{\text{eff}} = \left(-\nabla\cdot\mathbf{P}, \nabla\times\mathbf{M}+\partial_t\mathbf{P}\right)$	$\mathbf{P} = g_{a\gamma\gamma}a\mathbf{B}, \quad \mathbf{M} = g_{a\gamma\gamma}a\mathbf{E}$ McAllister et al, 1803.07755 Tobar et al, 1809.01654 Ouellet et al, 1809.10709	$P_i = -h_{ij}E_j \qquad M_i = -h_{ij}B_j$ (in the TT gauge) Domcke, CGC, Rodd, 2202.00695
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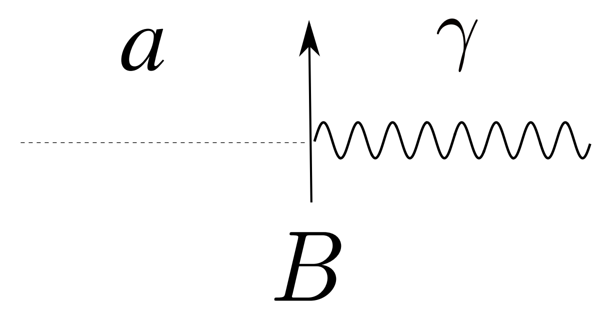
An example		Gertsenshtein effect
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Benchmark	QCD axion	$h \sim 10^{-22}$

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

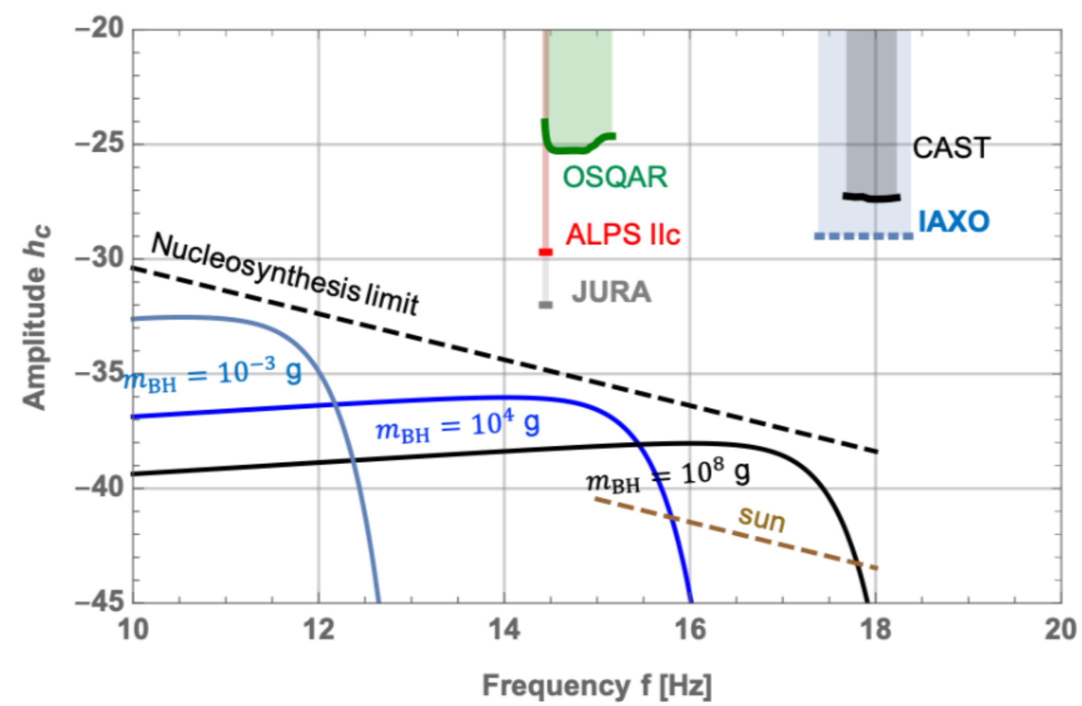
J. Exptl. Theoret. Phys. (U.S.S.R.) **41**, 113-114 (July, 1961)

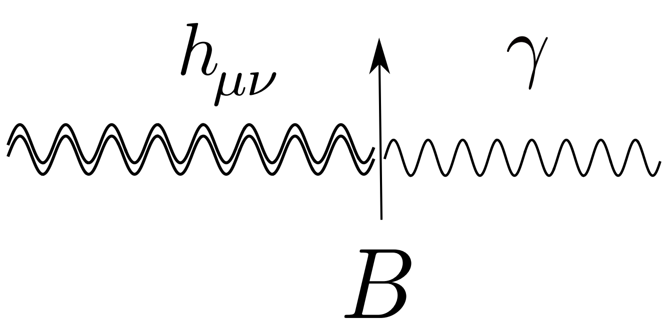
The energy of gravitational waves excited during the propagation of light in a constant magnetic or electric field is estimated.

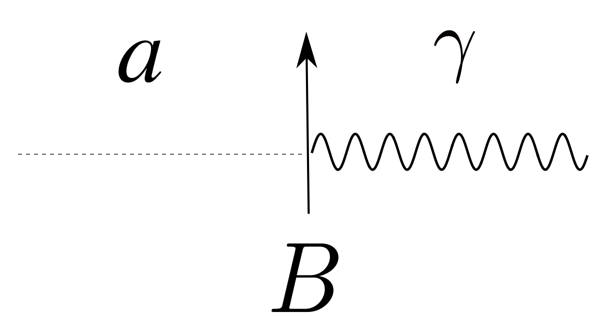
Upper limits on the amplitude of ultra-high-frequency gravitational waves from graviton to photon conversion

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

The European Physical Journal C **79**, Article number: 1032 (2019) | Cite this article







Ideas and techniques developed for axions can be adapted to gravitational waves

Raffelt, Stodolski'89

The (inverse) Gertsenhstein Effect

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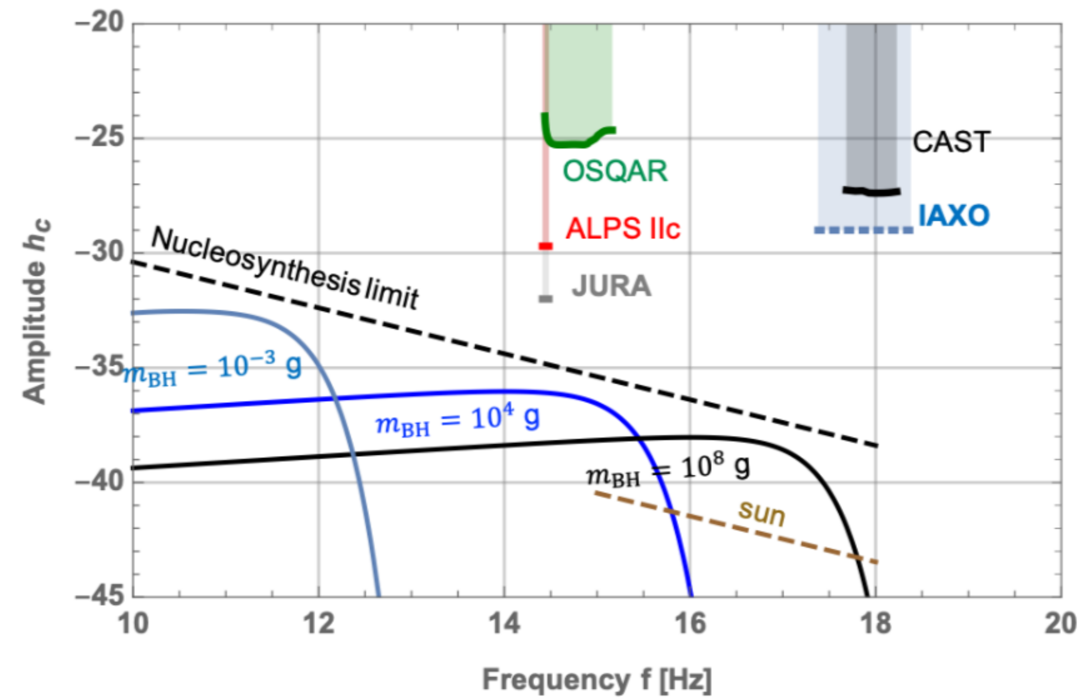
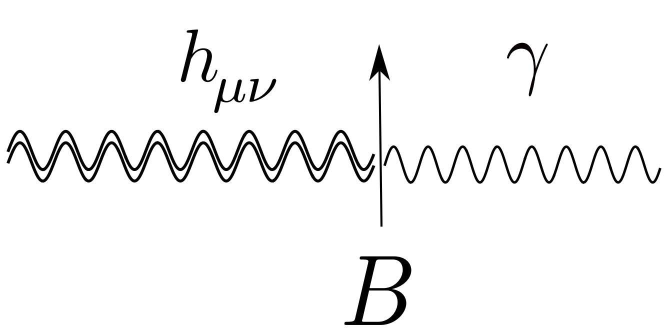
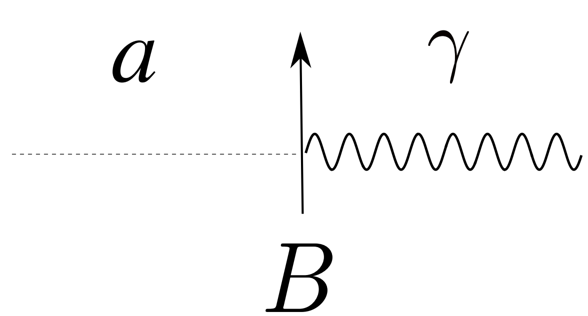


Far from testing Early Universe signals





Ideas and techniques developed for axions can be adapted to gravitational waves

Raffelt, Stodolski'89

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High-frequency gravitational waves

Part of a collection:

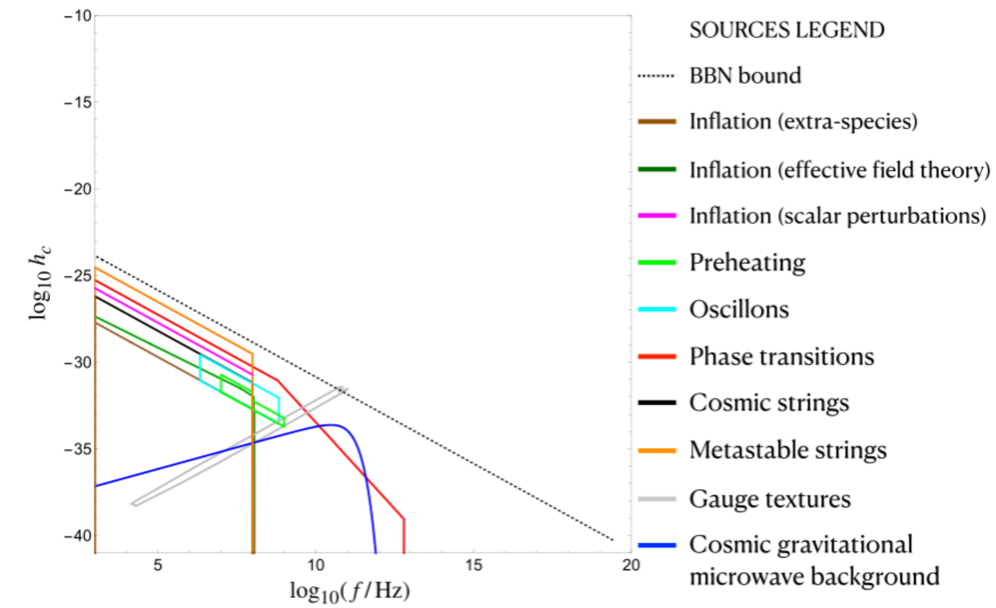
Gravitational Waves

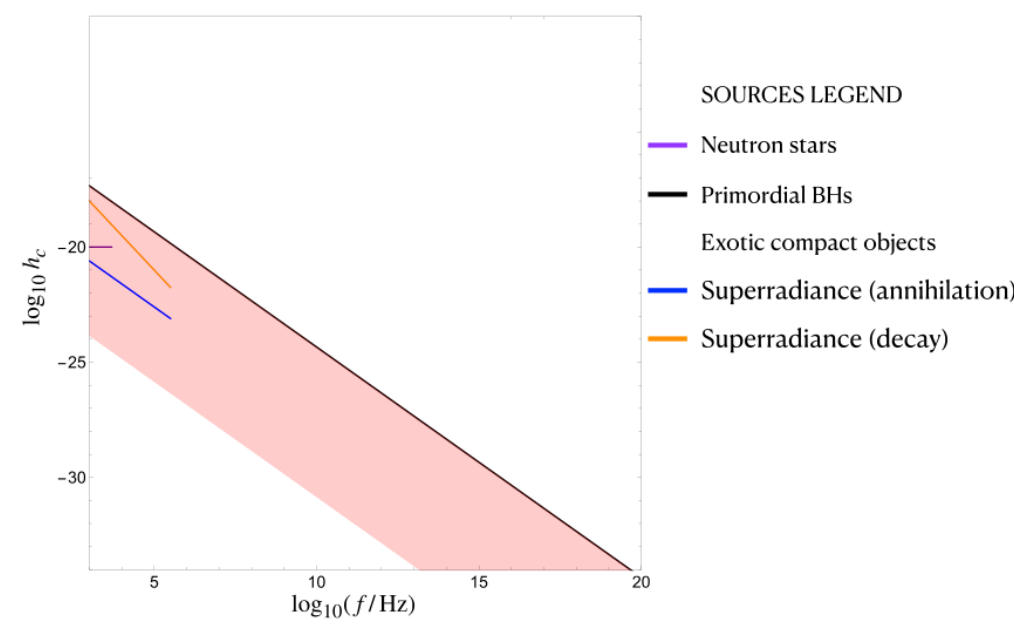
Review Article | Open Access | Published: 06 December 2021

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





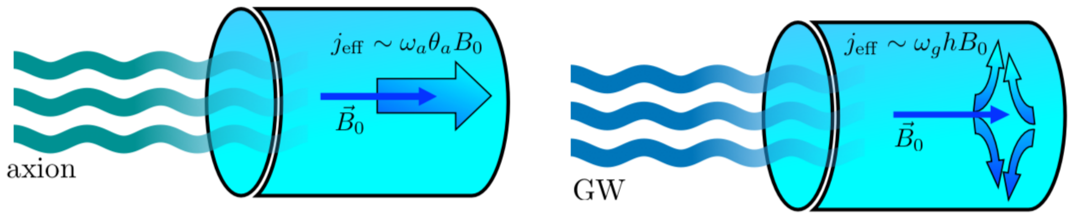
A growing community is seriously considering the search of high frequency gravitational waves

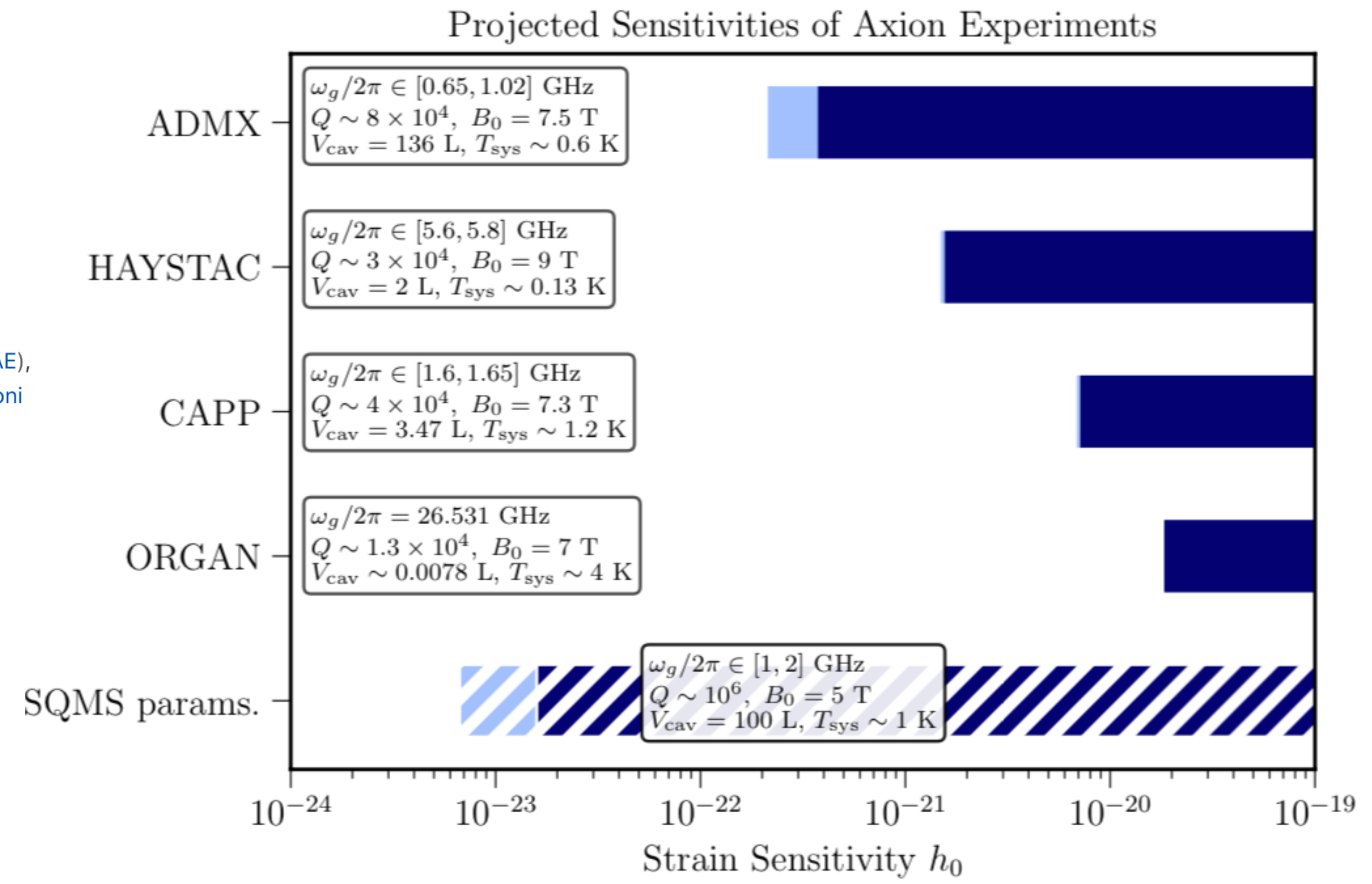
Haloscopes based on microwave cavities

Detecting High-Frequency Gravitational Waves with Microwave Cavities

Asher Berlin (New York U. and Fermilab), Diego Blas (Barcelona, Autonoma U. and Barcelona, IFAE), Raffaele Tito D'Agnolo (IPhT, Saclay), Sebastian A.R. Ellis (U. Geneva (main) and IPhT, Saclay), Roni Harnik (Fermilab) et al. (Dec 21, 2021)

e-Print: 2112.11465 [hep-ph]



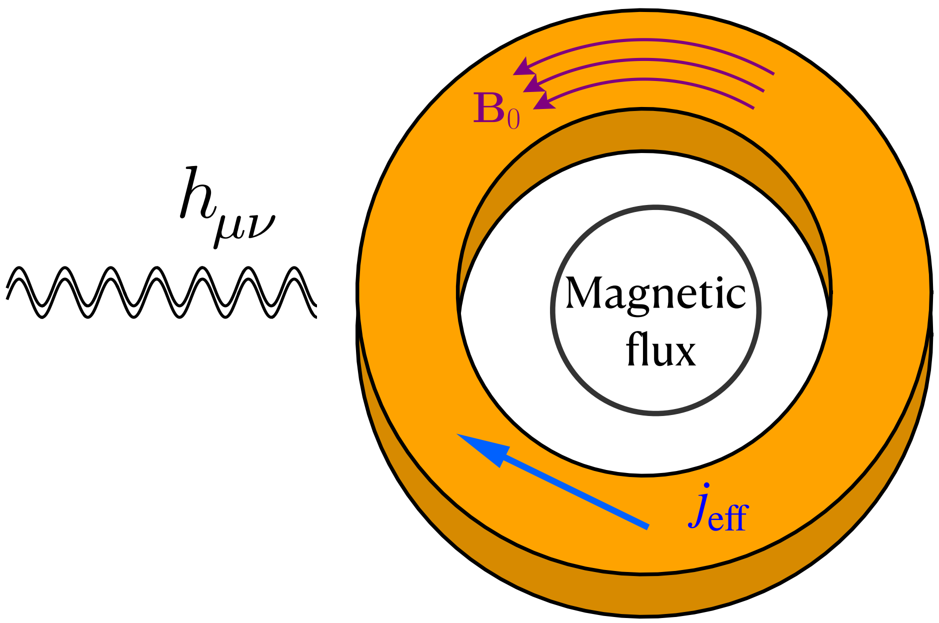


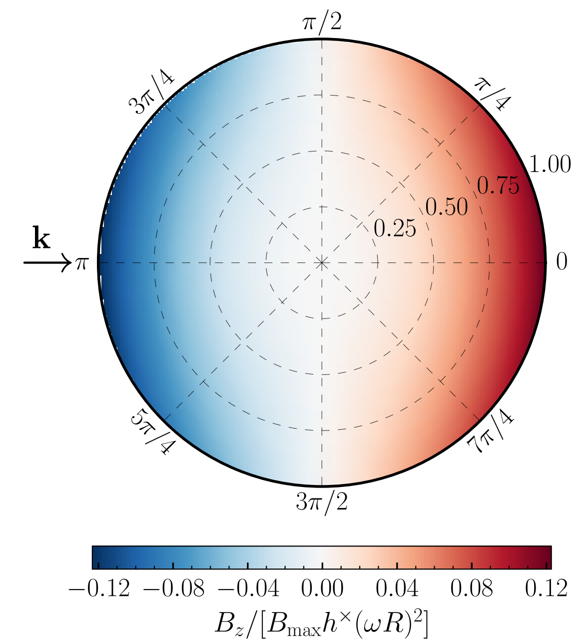
It resonates when the GW frequency matches one of the eigenmode frequencies

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

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

Haloscopes based on lumped-element detectors

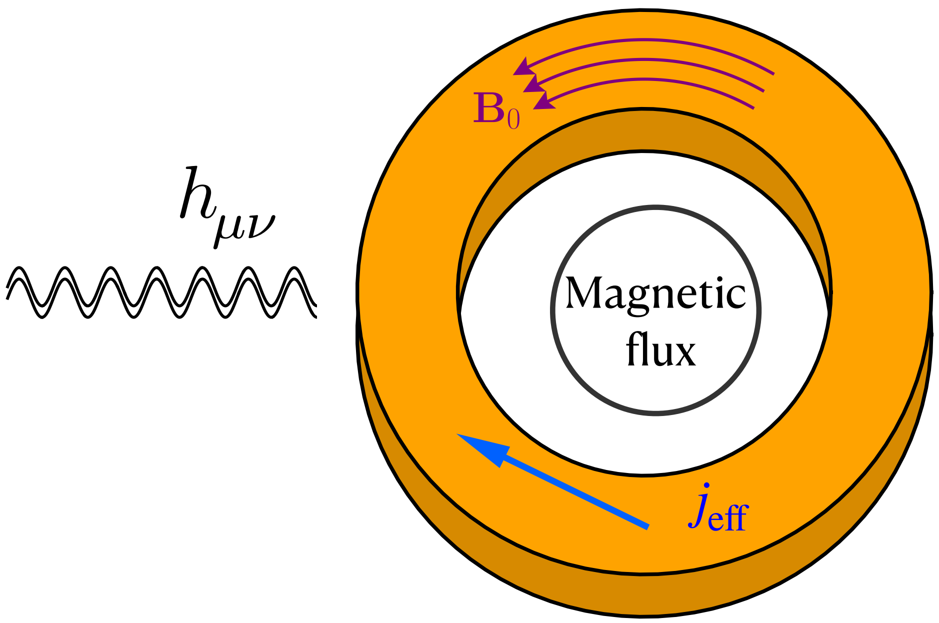


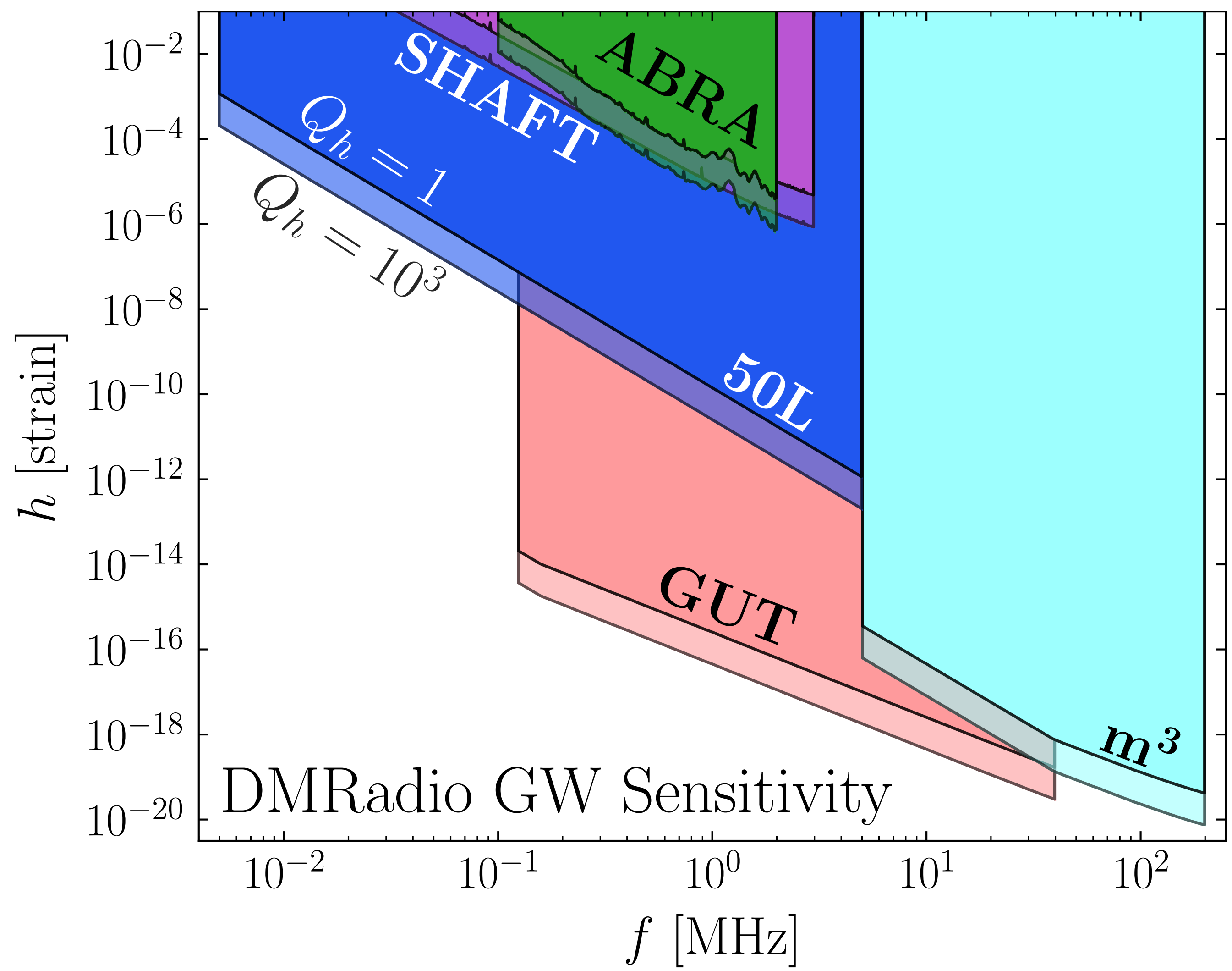


Domcke, CGC, Rodd, 2202.00695

Camilo García Cely, University of Valencia

Haloscopes based on lumped-element detectors





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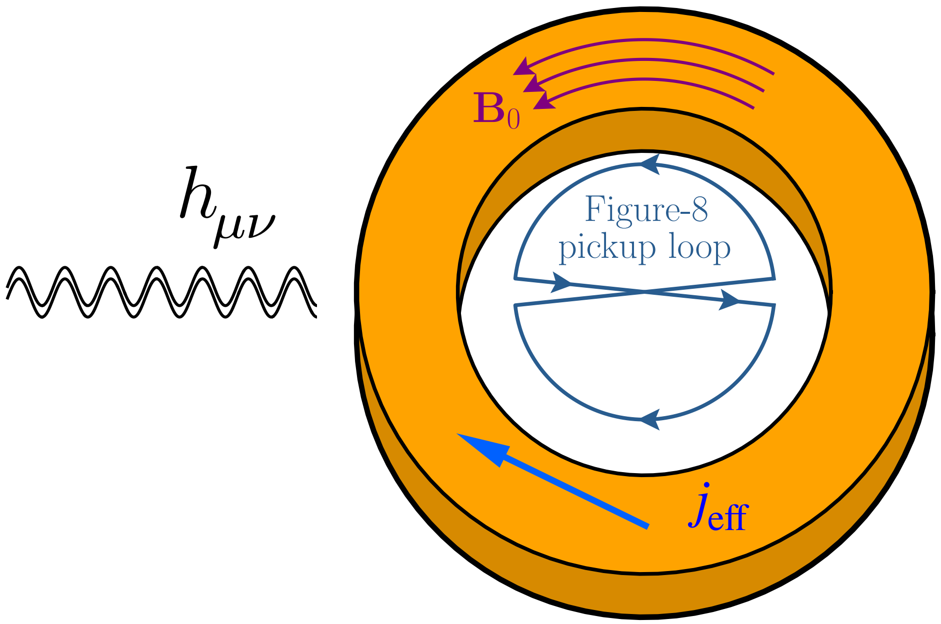

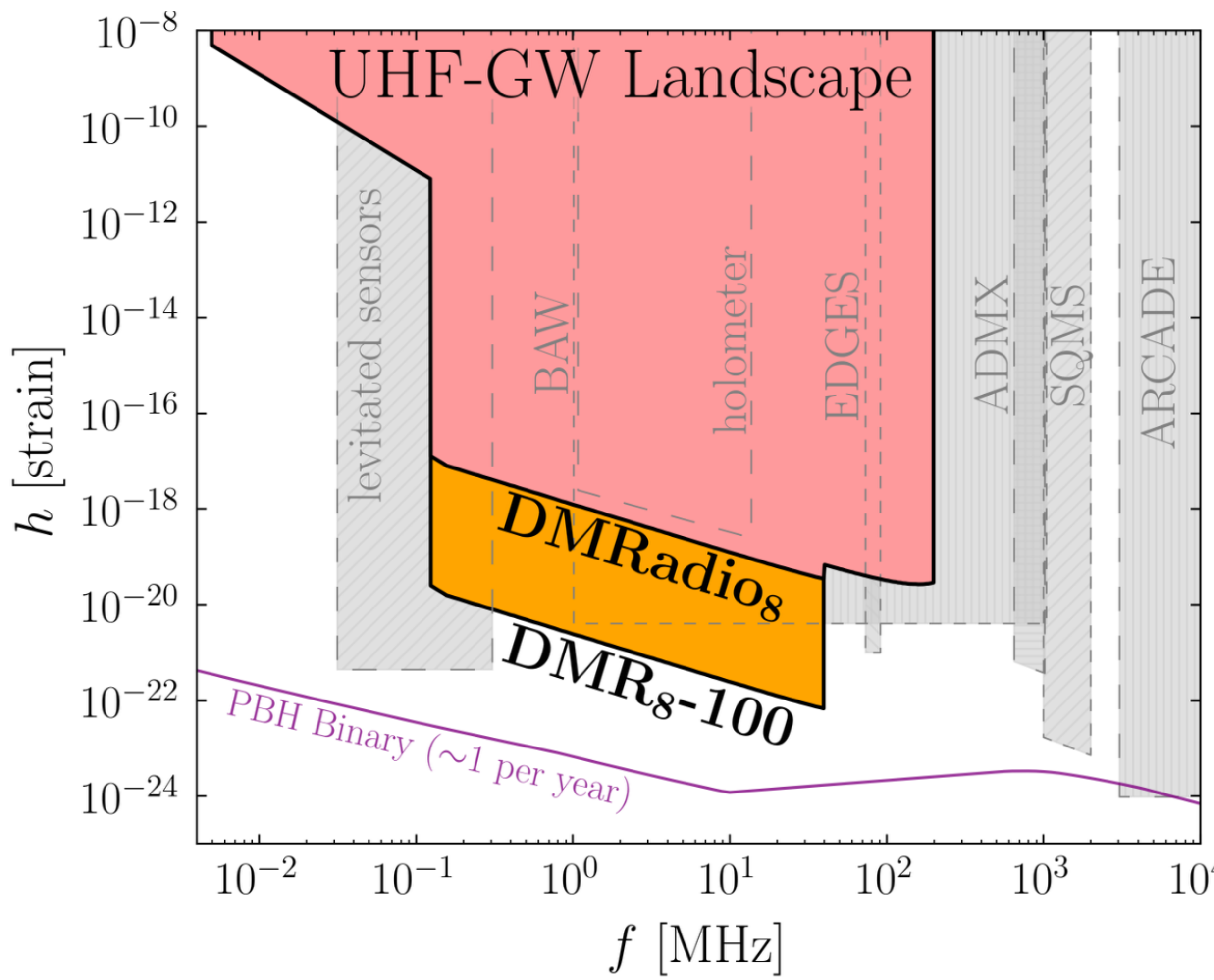

Domcke, CGC, Rodd, 2202.00695

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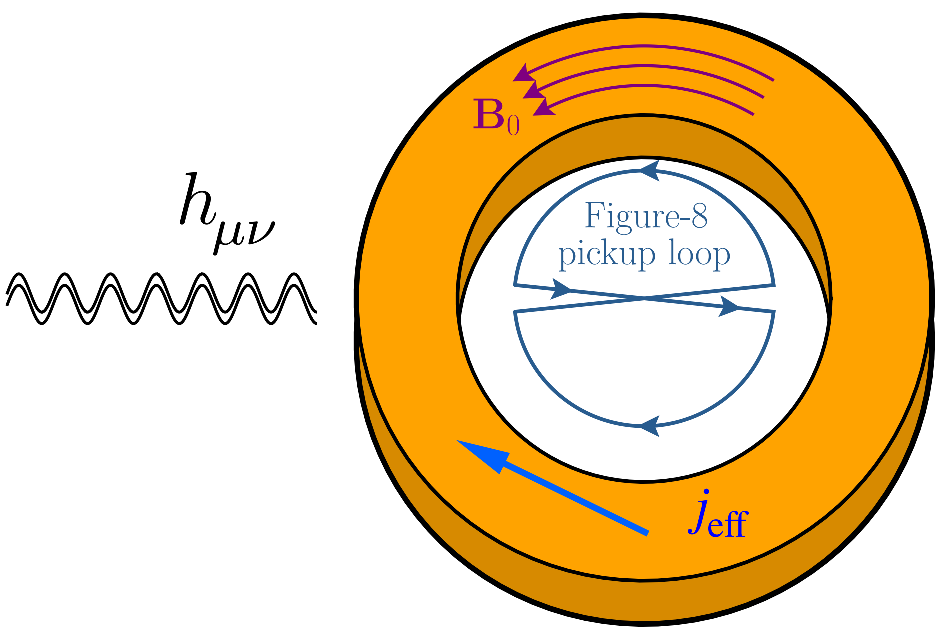
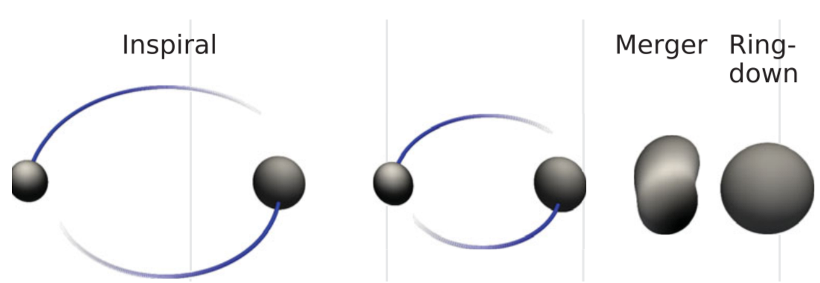
Haloscopes based on lumped-element detectors

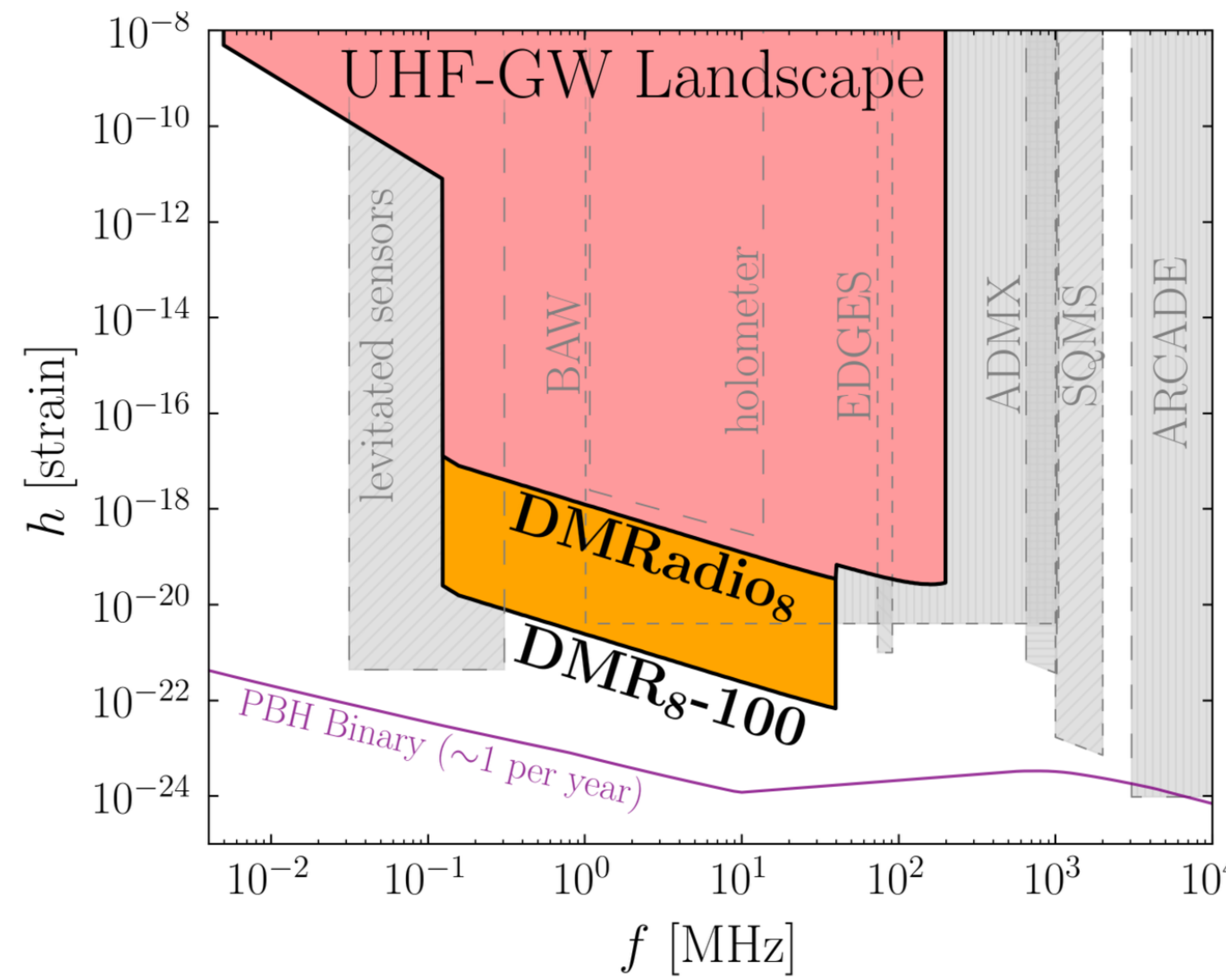
$$f \simeq 220\ \text{MHz} \left(\frac{10^{-5} M_\odot}{m_{\text{PBH}}} \right)$$





Up-to-date estimate of PBH in binaries and their expected merger rate accounting for the local overdensity in the Milky Way

See also 2205.02153 by Franciolini, A. Maharana, and F. Muia,



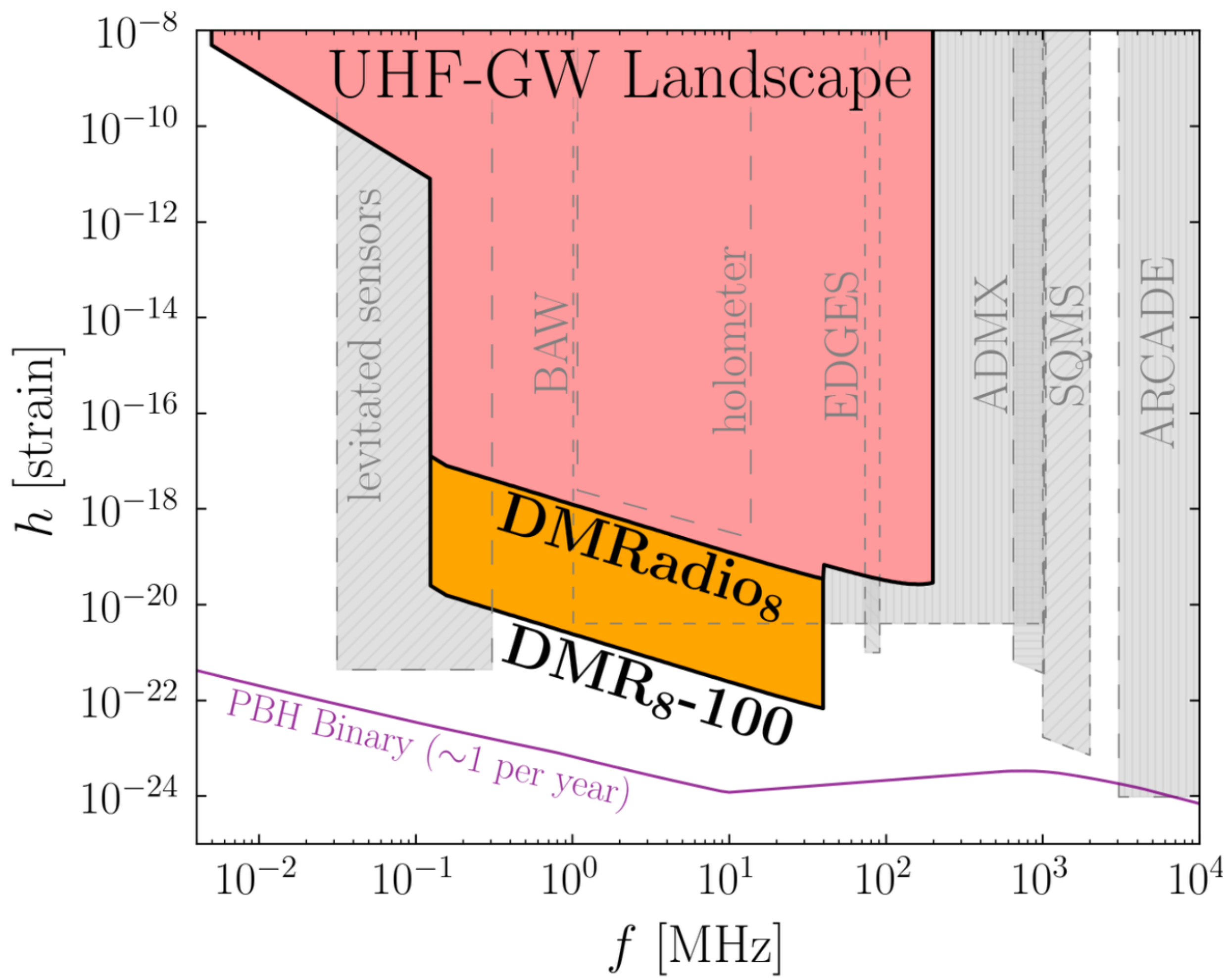
Domcke, CGC, Rodd, 2202.00695

Camilo García Cely, University of Valencia

Conclusions

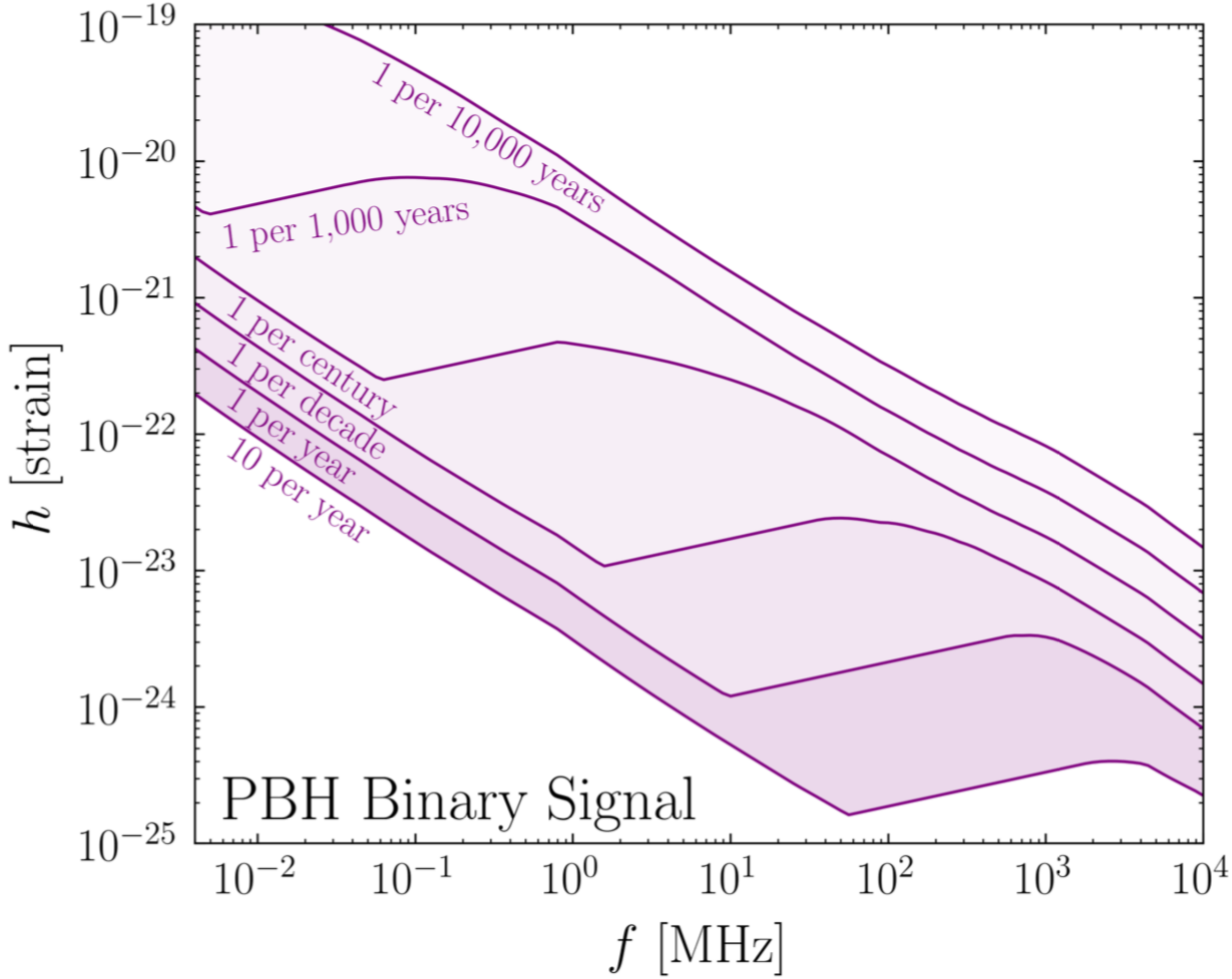
The axion program may discover not only the dark matter of our Universe, but also exotic sources of gravitational waves

A number of distinct experimental proposals have coalesced on a strain sensitivity of 10^{-22} for MHz GWs, a level that is still orders of magnitude away from any signal of the early Universe. Whether we can hope to probe such strain sensitivities remains to be determined.



Domcke, CGC, Rodd, 2202.00695

Backup slides



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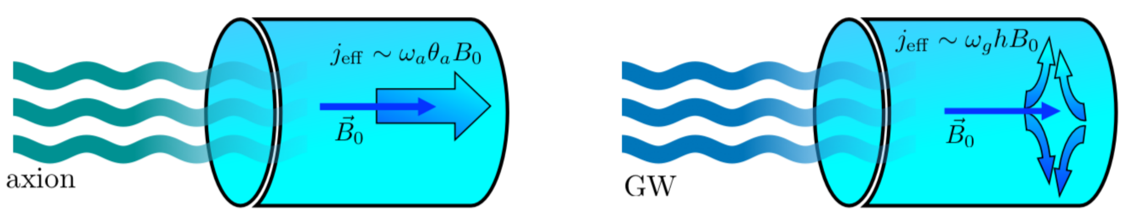
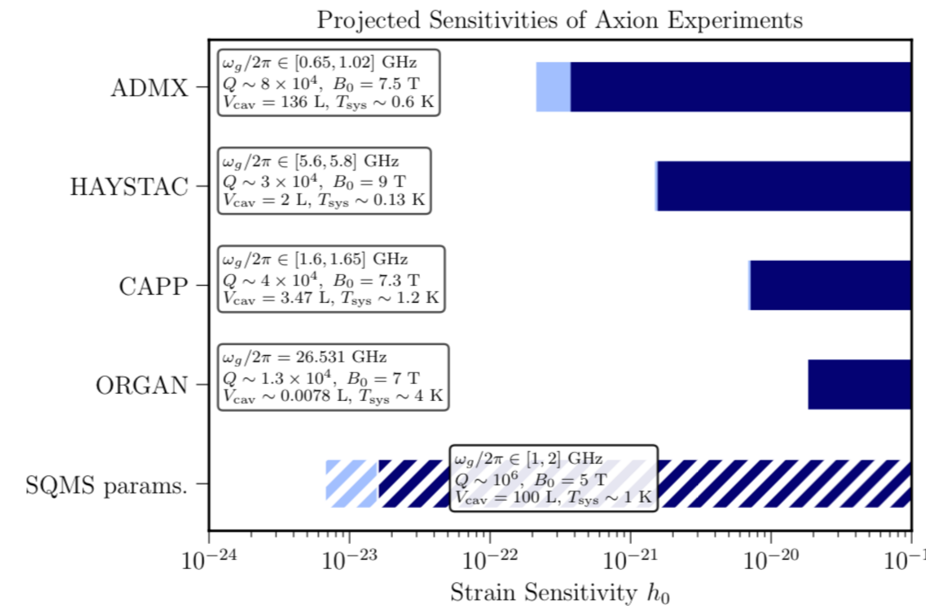
Subtleties due to gauge fixing (TT vs detector frame gauge)

Detecting High-Frequency Gravitational Waves with Microwave Cavities

Asher Berlin (New York U. and Fermilab), Diego Blas (Barcelona, Autonoma U. and Barcelona, IFAE), Raffaele Tito D'Agnolo (IPhT, Saclay), Sebastian A.R. Ellis (U. Geneva (main) and IPhT, Saclay), Roni Harnik (Fermilab) et al. (Dec 21, 2021)

e-Print: 2112.11465 [hep-ph]

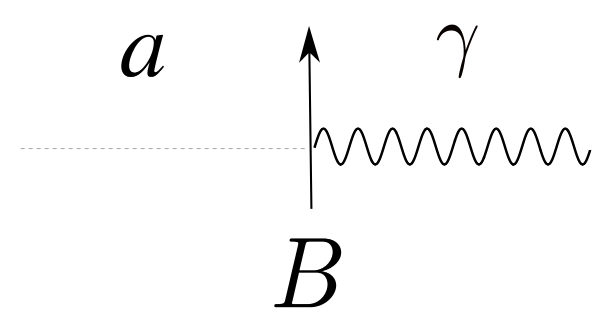




- In the TT frame, the description of rigid bodies becomes unintuitive, as their coordinates are deformed by a passing GW due to the motion of the coordinate system. **This is crucial to implement boundary conditions.**
- In the proper detector frame the coordinate system is defined by rigid rulers and closely matches the intuitive description of an Earth-based laboratory, with the GW acting as a Newtonian force.
- Previous confusion in the literature due to this (see e.g. 2012.12189)

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

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

	Axion electrodynamics	Gravitational wave electrodynamics
An example		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	$h \sim 10^{-22}$

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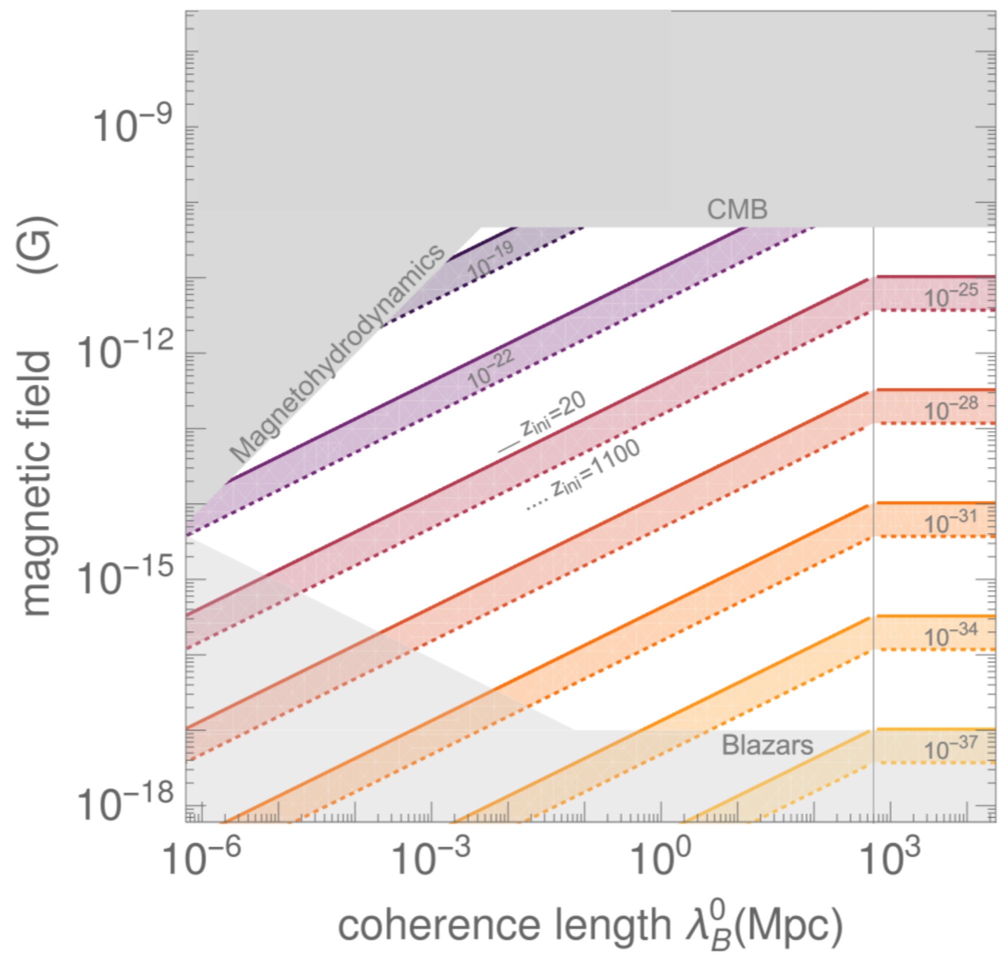
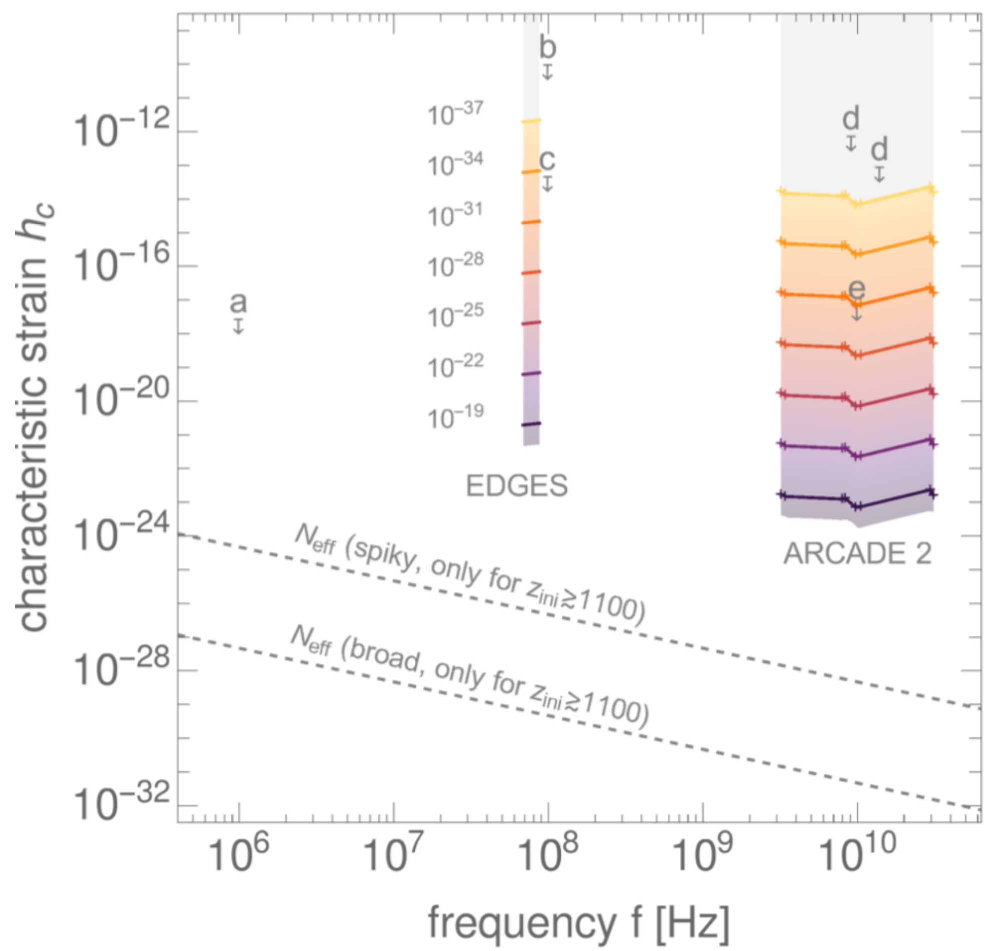
Upper bounds on stochastic gravitational waves





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Potential of Radio Telescopes as High-Frequency Gravitational Wave Detectors

Valerie Domcke[1,2,3,*] and Camilo Garcia-Cely[1,†]

existing laboratory bounds from

a) superconducting parametric converter Reece et al '84
b) waveguide Cruise Ingley '06
c) 0.75 m interferometer Akutsu '08
d) magnon detector Ito, Soda '04
e) magnetic conversion detector Cruise et al '12