Selection rules for the detection of gravitational waves in axion haloscopes

Next Hidden and Asymmetry Webminar
May 23, 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

Optimizing the geometry of axion haloscopes for gravitational wave searches

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

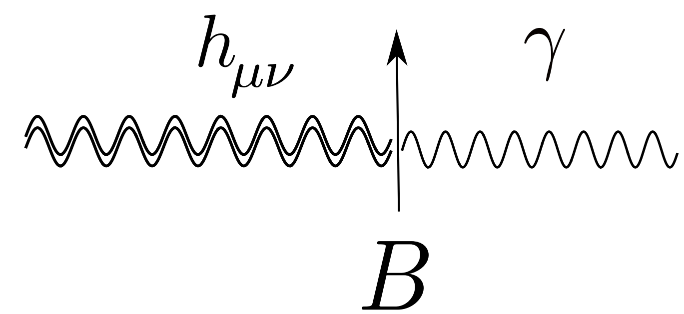
[1] *Theoretical Physics Department, CERN, 1 Esplanade des Particules, CH-1211 Geneva 23, Switzerland*
[2] *Instituto de Física Corpuscular (IFIC), Universitat de València-CSIC, Parc Científic UV, C/ Catedrático José Beltrán 2, E-46980 Paterna, Spain*
[3] *Department of Physics & IPAP & Lab for Dark Universe, Yonsei University, Seoul 03722, Korea*

work in progress: 2306.xxxxx

Outline

- Why high-frequency gravitational waves and ideas to detect them

- Gravitational-wave vs. Axion electrodynamics



- Conclusions

Why high-frequency gravitational waves and ideas to detect them

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

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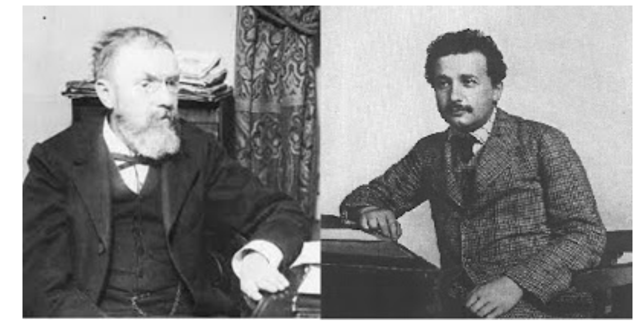

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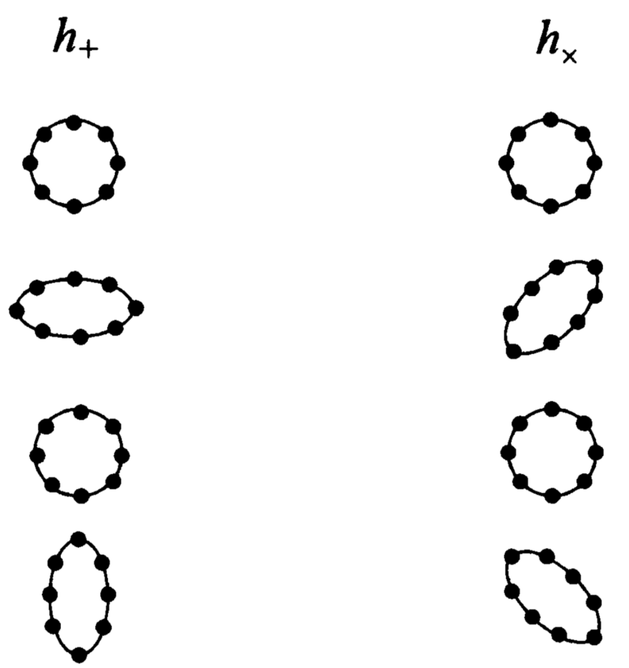

The deformation of a ring of test masses due to the different polarization

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Gravitational waves

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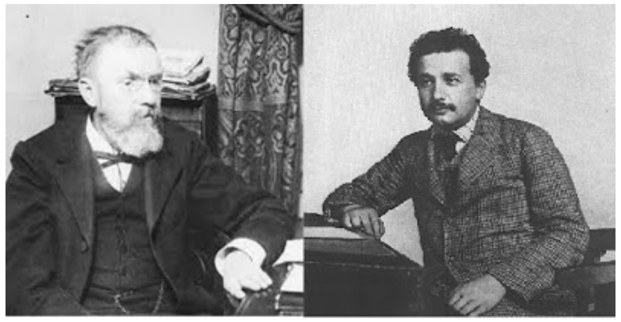


PRL 116, 061102 (2016) PHYSICAL REVIEW LETTERS 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

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

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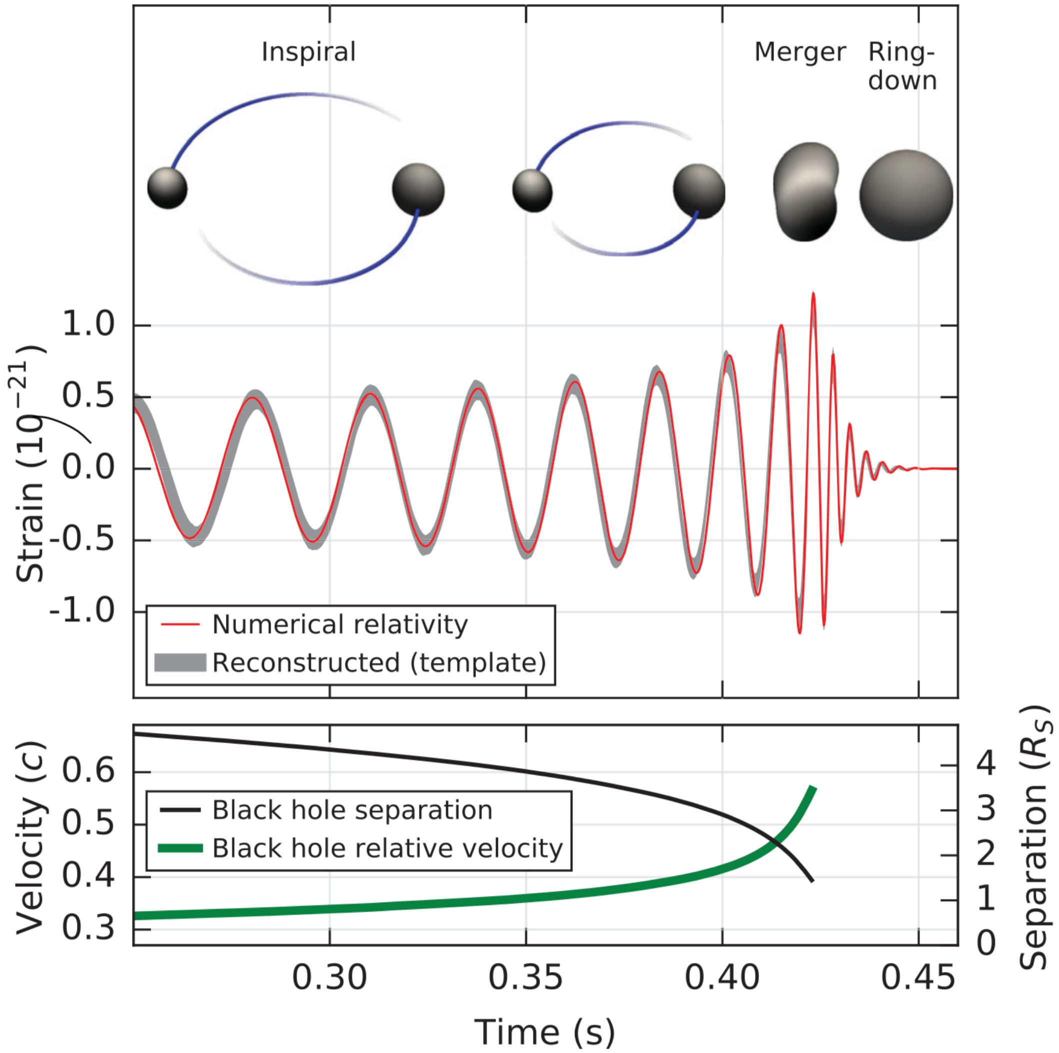
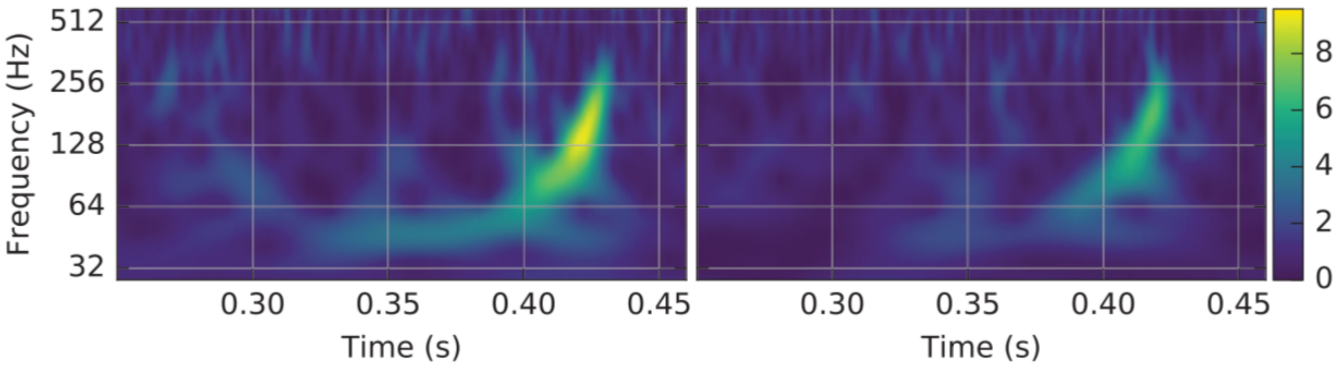
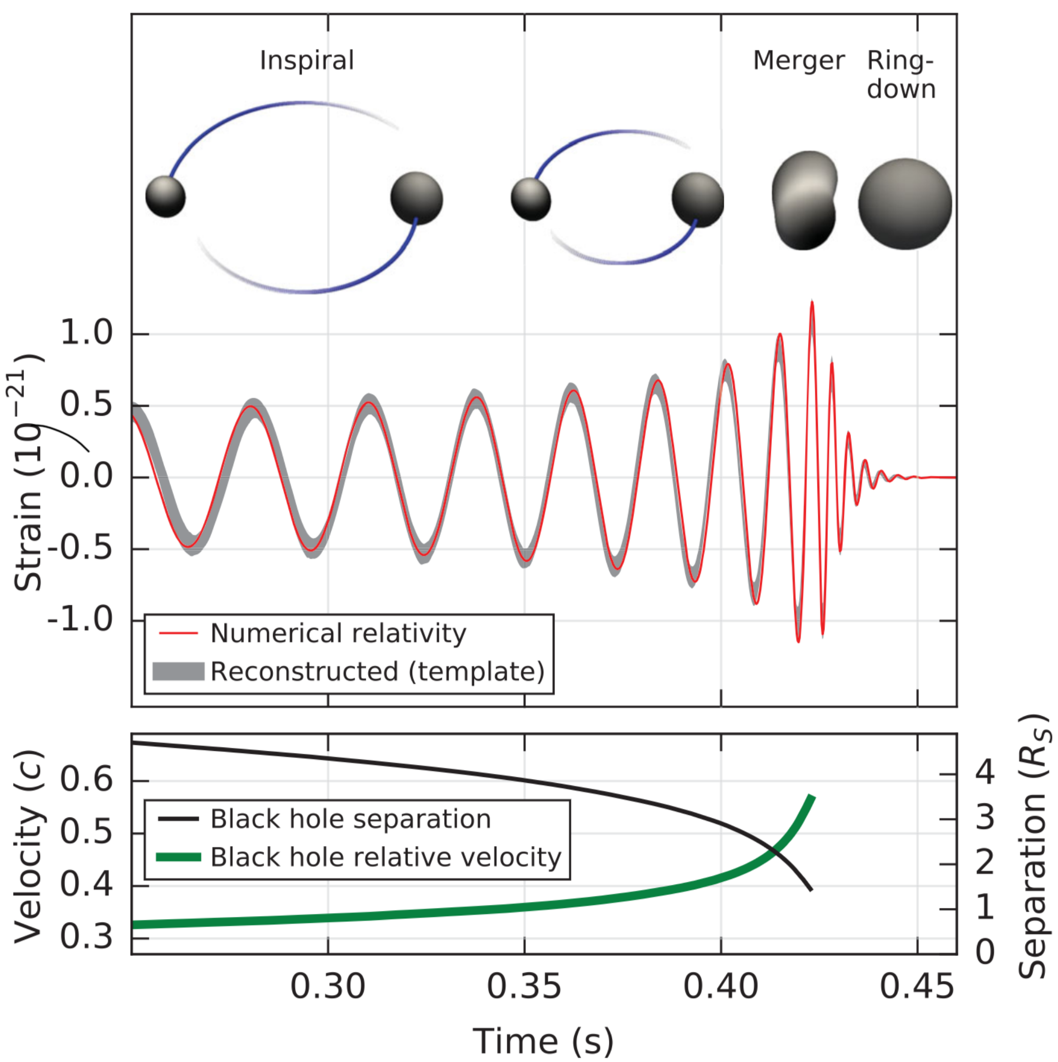
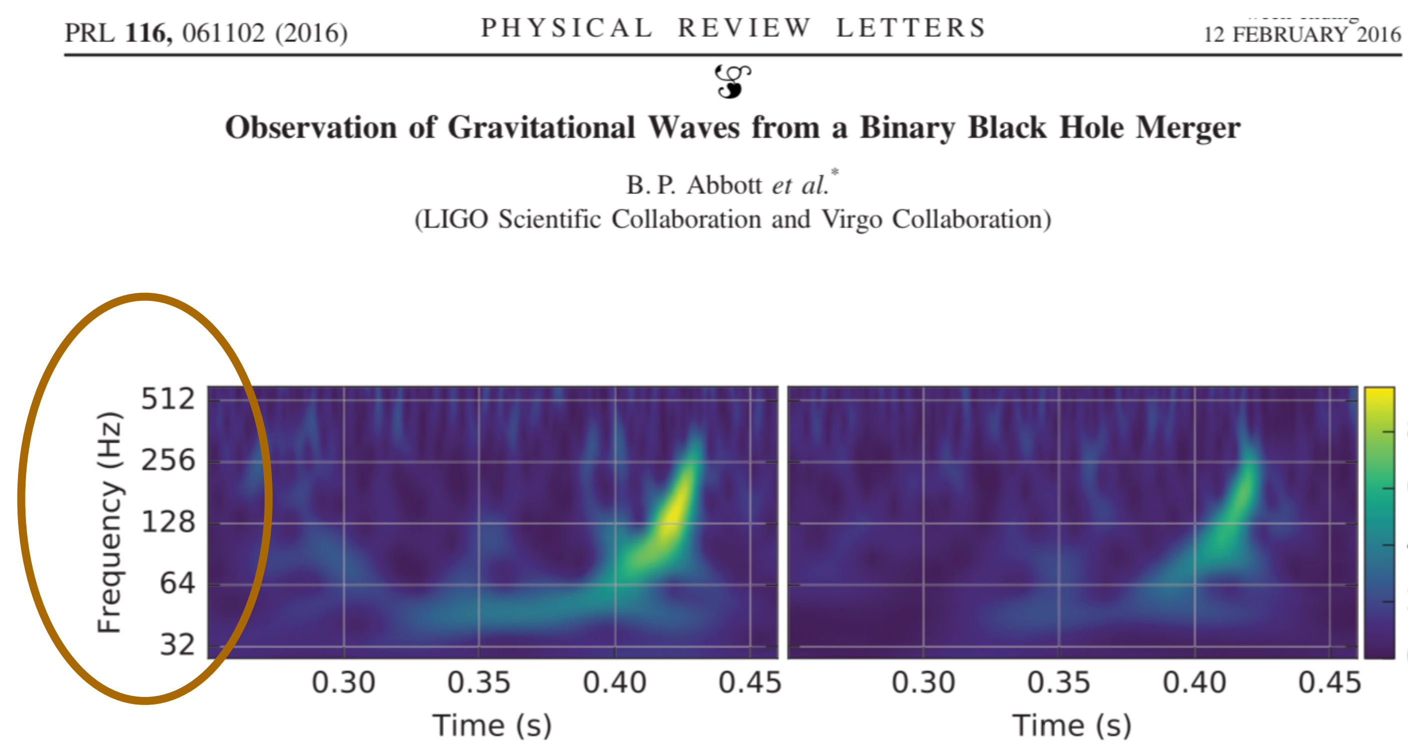




interferometers

Gravitational waves




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

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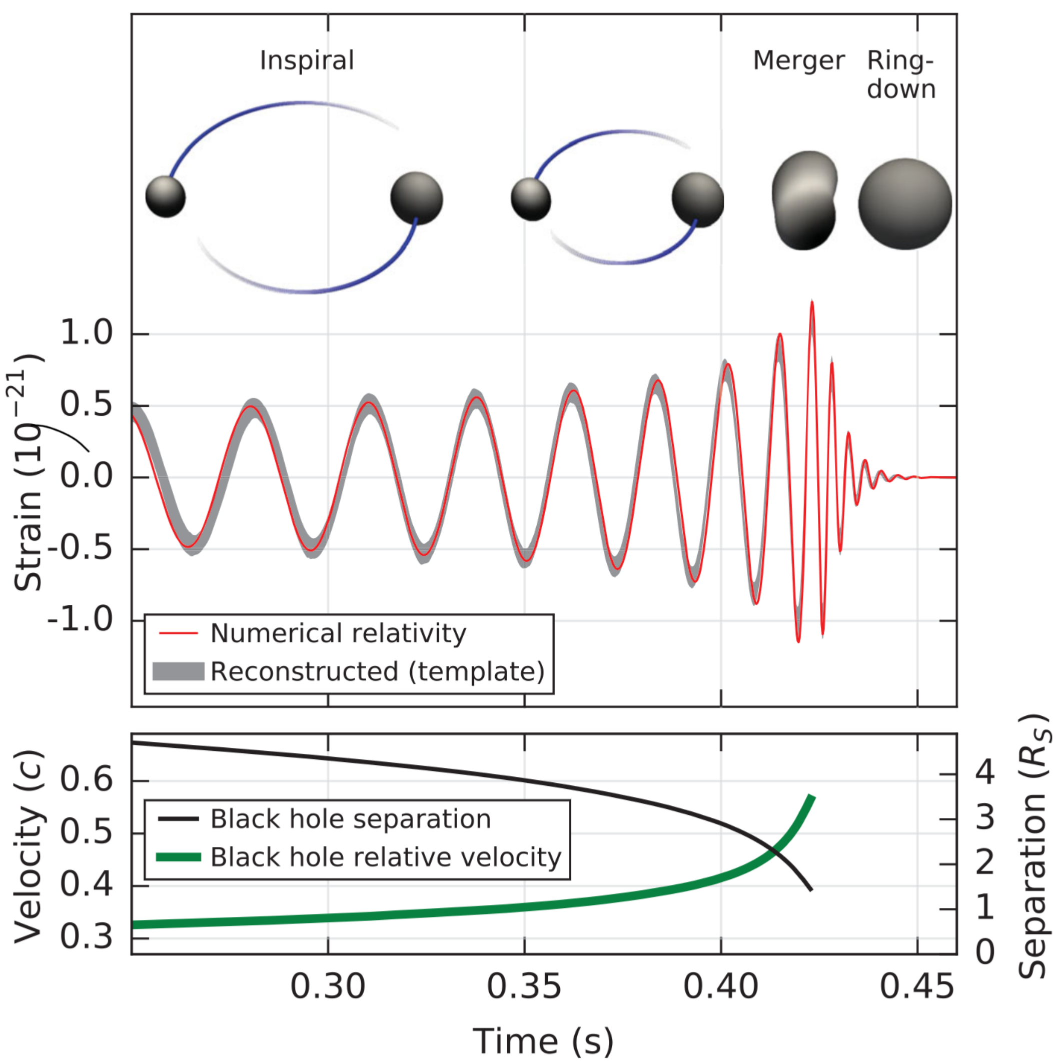
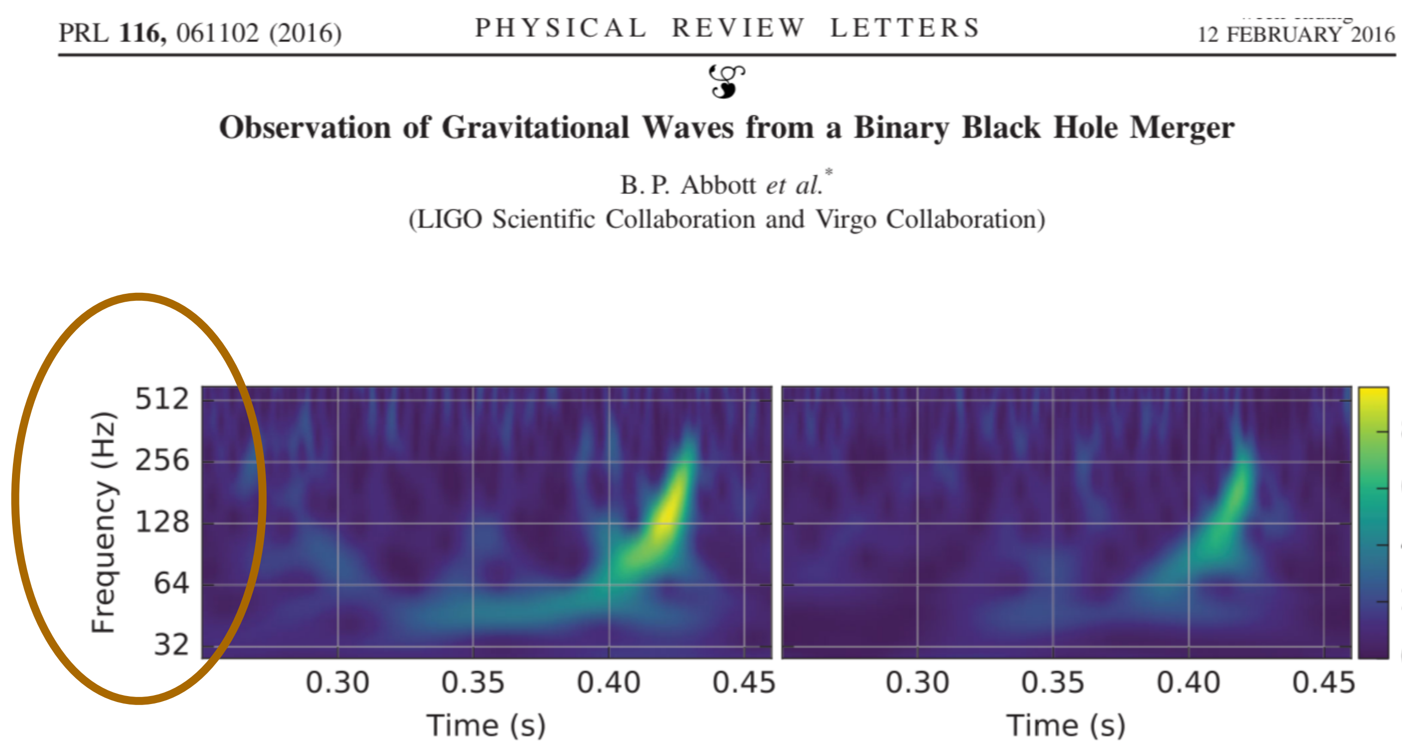
$$f \approx \frac{1}{2\pi}\sqrt{\frac{GM}{R^3}}$$

Gravitational waves





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

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

High-frequency gravitational waves

Part of a collection:

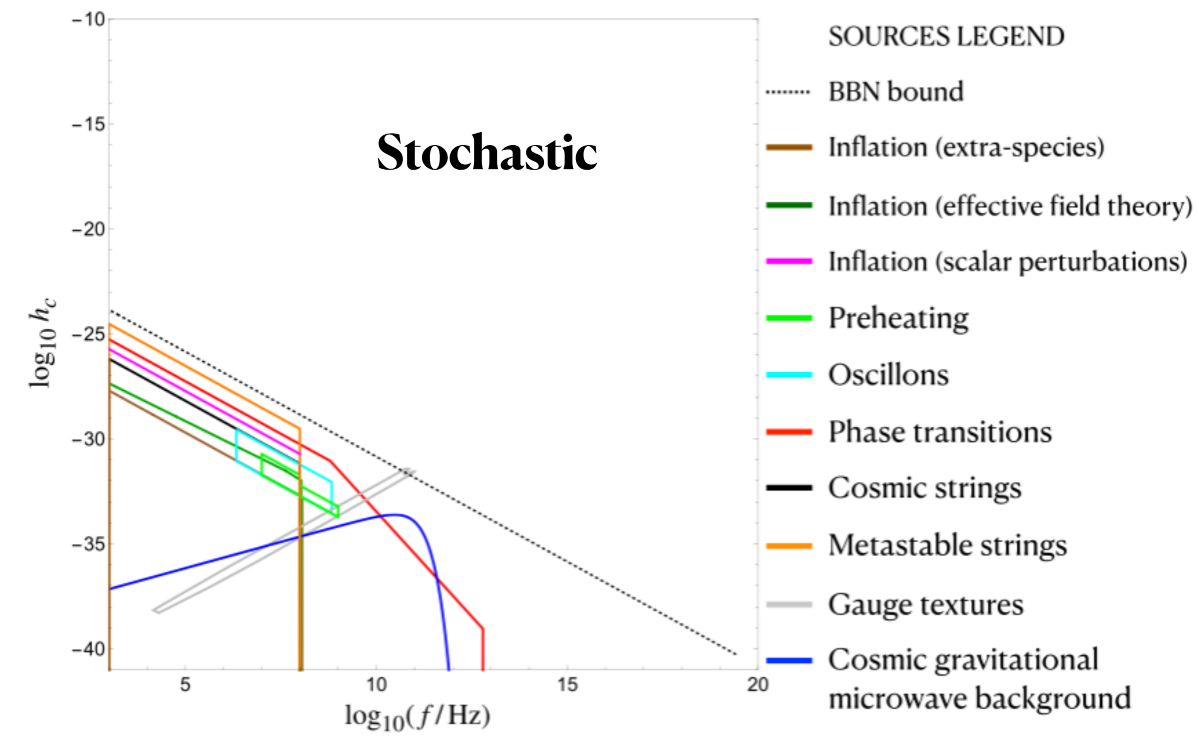
Gravitational Waves

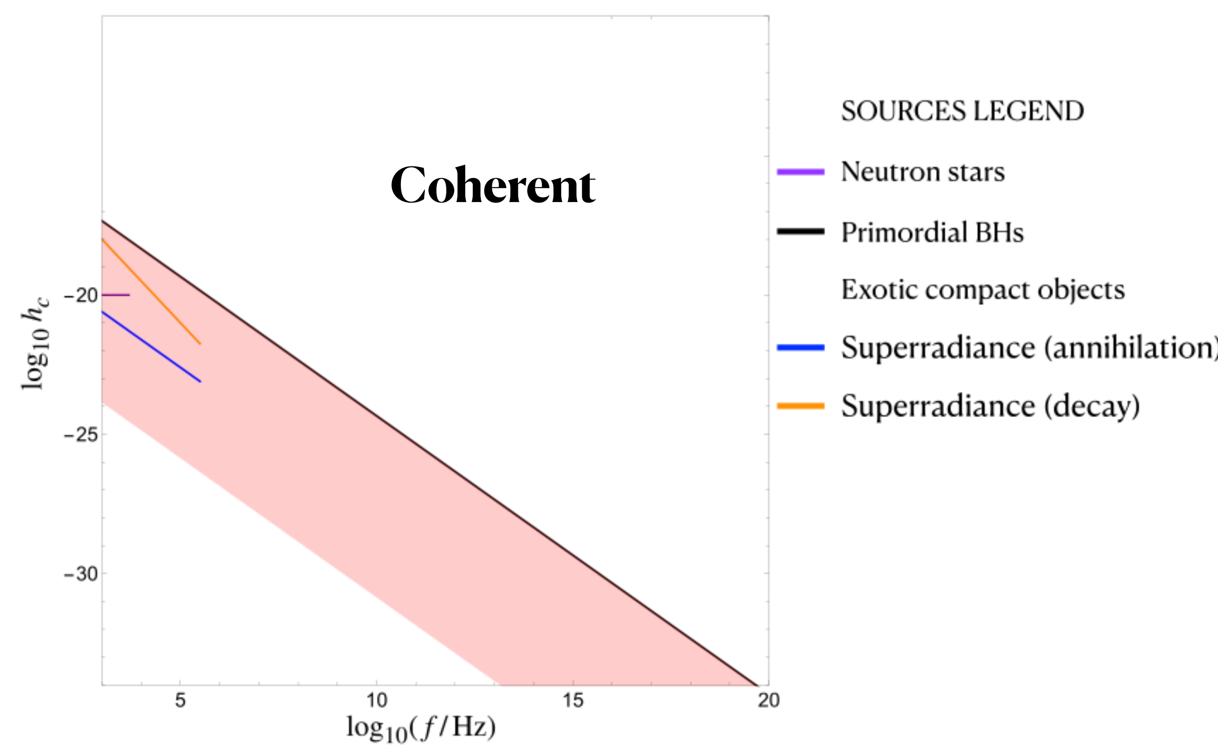
Review Article | Open Access | Published: 06 December 2021

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

Nancy Aggarwal, Odylio D. Aguiar, Andreas Bauswein, Giancarlo Cella, Sebastian Clesse, Adrian Michael Cruise, Valerie Domcke, Daniel G. Figueroa, Andrew Geraci, Maxim Goryachev, Hartmut Grote, Mark Hindmarsh, Francesco Muia, Nikhil Mukund, David Ottaway, Marco Peloso, Fernando Quevedo, Angelo Ricciardone, Jessica Steinlechner, Sebastian Steinlechner, Sichun Sun, Michael E. Tobar, Francisco Torrenti, Caner Ünal & Graham White

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





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

Camilo García Cely, University of Valencia

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

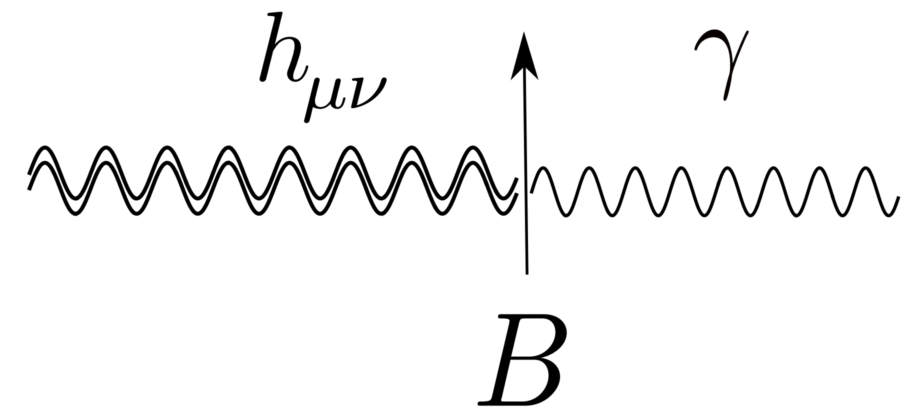
J. Exptl. Theoret. Phys. (U.S.S.R.) 43, 605-607 (August, 1962)

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

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 $\hbar$

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

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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

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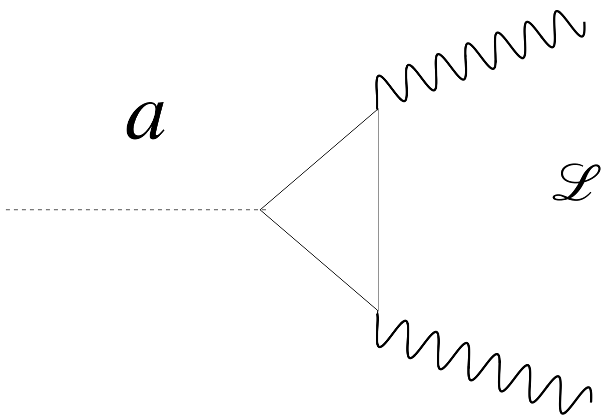
- The process is strictly analogous to axion dark matter conversion.

Raffelt, Stodolski'89

The QCD axion as dark matter

- Pseudoscalar field



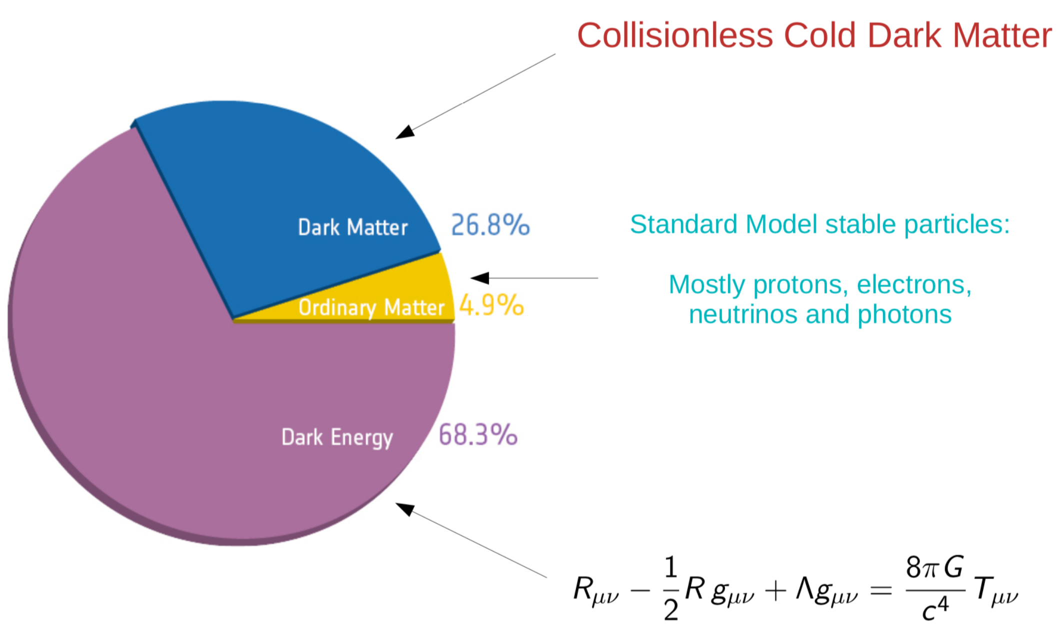
$$\mathscr{L} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

- Solution to the strong CP problem

Peccei, Quinn 1977

- Excellent dark matter candidate

Weinberg, Wilczek 1978



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Axion electrodynamics

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

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

Sikivie, 1983

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

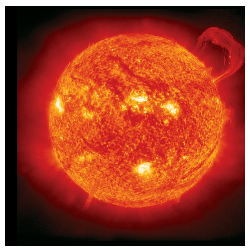
$$\nabla \cdot \mathbf{E} = j^0$$

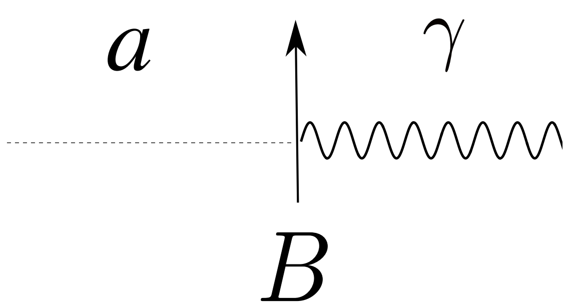
$$\nabla \times \mathbf{B} - \partial_t \mathbf{E} = \mathbf{j}$$

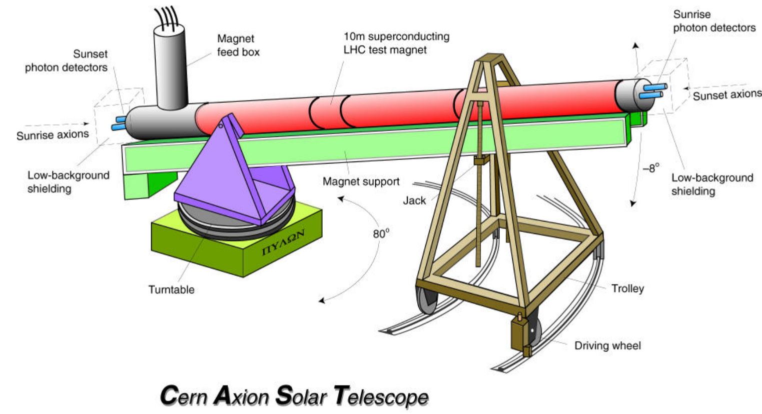
$$j^0 = -\, g_{a\gamma\gamma} \nabla a \cdot \mathbf{B} \qquad \mathbf{j} = g_{a\gamma\gamma} \left(\nabla a \times \mathbf{E} + \partial_t a \mathbf{B} \right)$$

Axion electrodynamics

- Helioscopes (X rays)

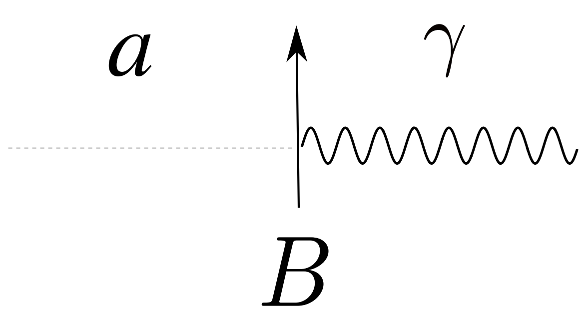


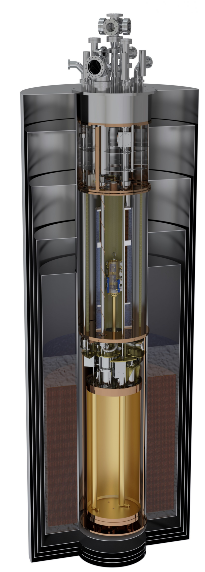




- CAST
- IAXO
- .....

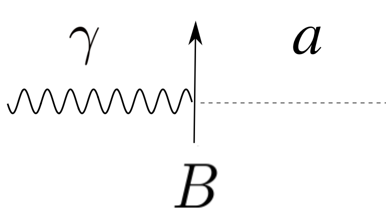
- Haloscopes (radio frequencies)

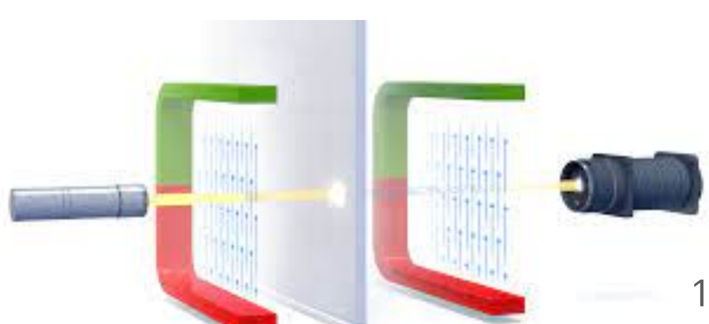


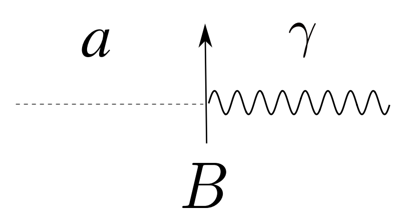


- microwave cavities
- MADMAX
- ADMX
- HAYSTAC
- ABRACADABRA
- Lumped element detectors
- ...

- Purely lab experiments

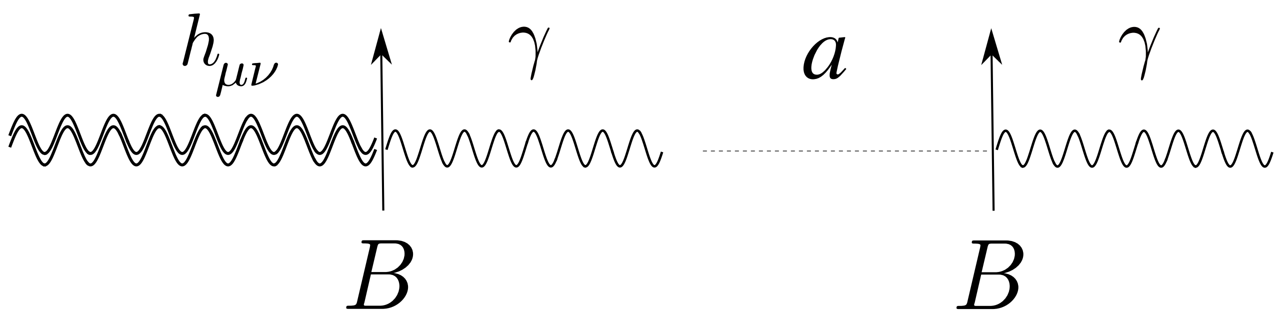






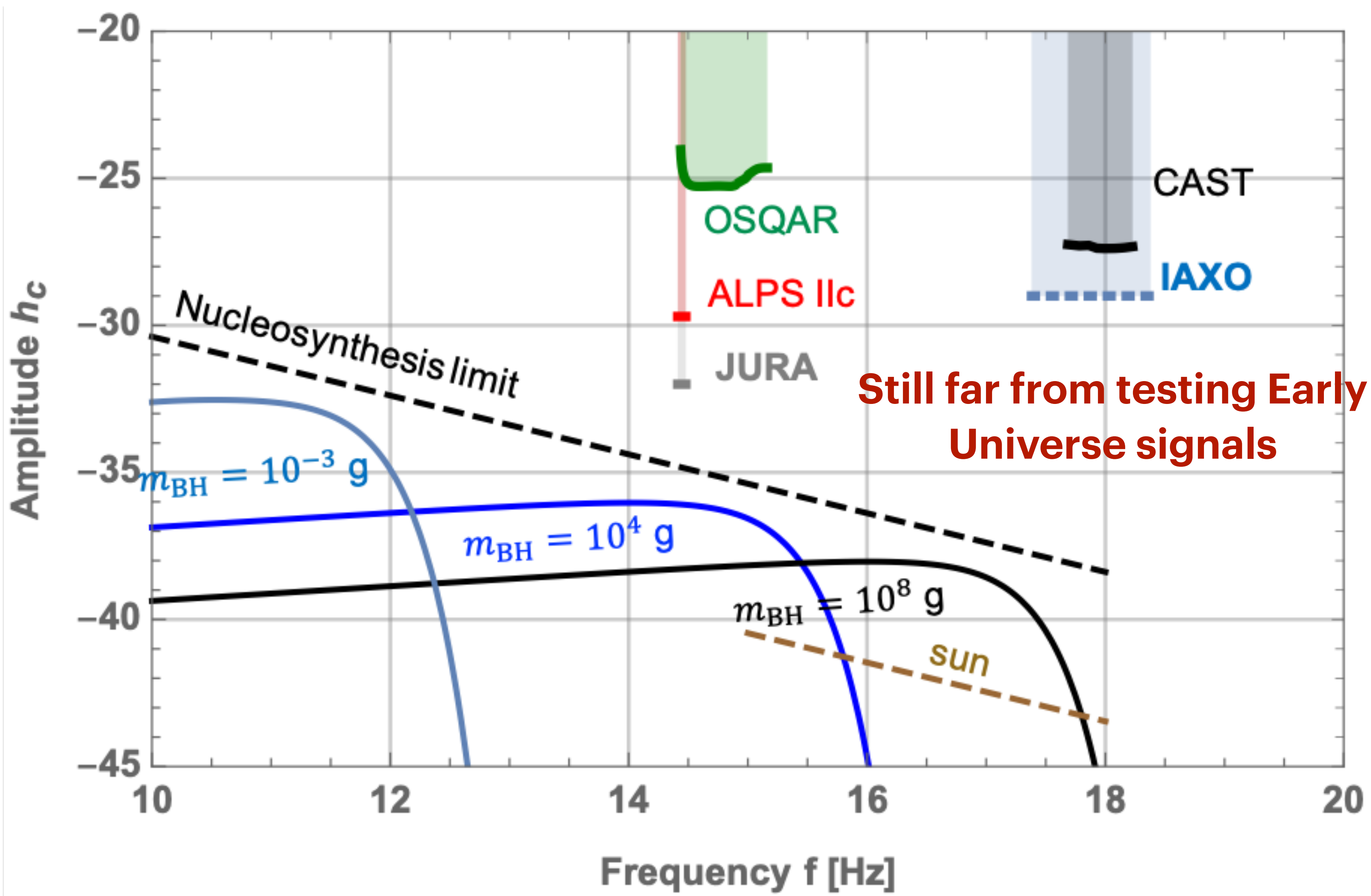
- Light shining through the walls
- OSCAR
- ALPS II
- ...

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)



Still far from testing Early Universe signals

Camilo García Cely, University of Valencia

Gravitational wave versus axion electrodynamics

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

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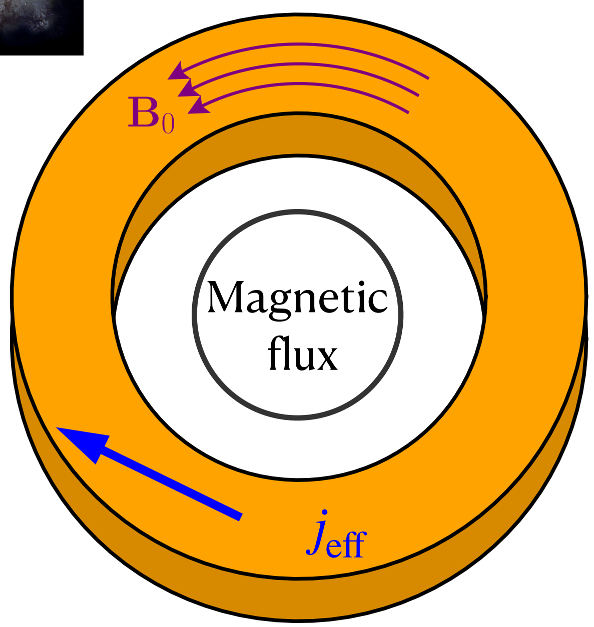
Phys. Rev. Lett. **129**, 041101 – Published 20 July 2022

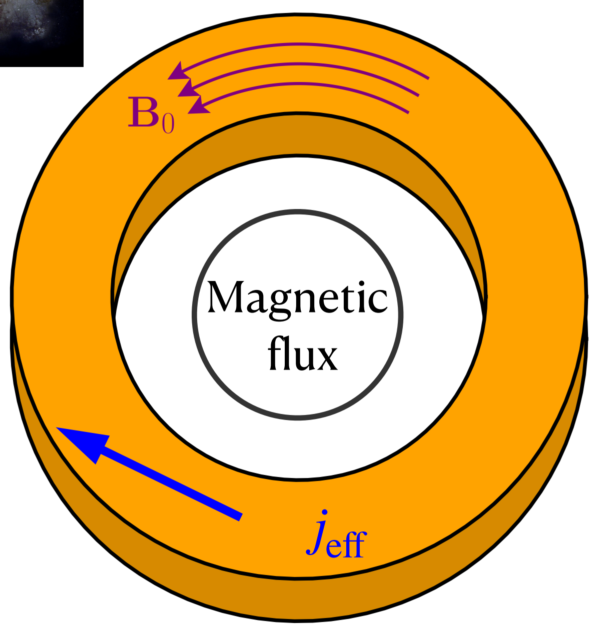
Low mass axion haloscopes



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

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

Low mass axion haloscopes



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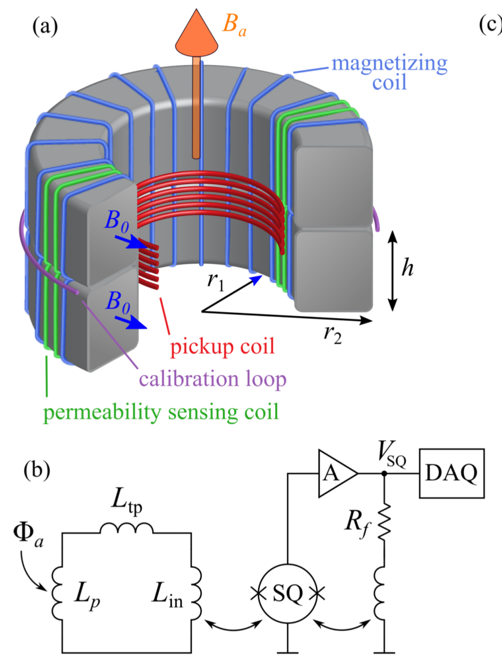


(c) SHAFT

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*

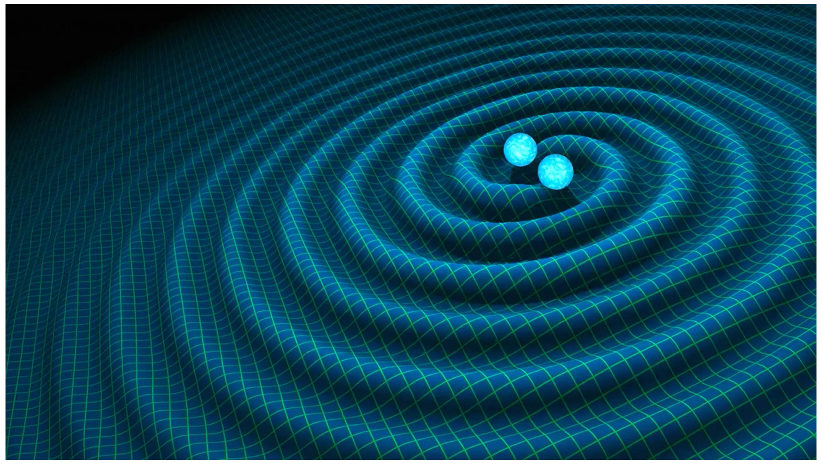
(Received 3 March 2016; published 30 September 2016)

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

Gravitational wave electrodynamics

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

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



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

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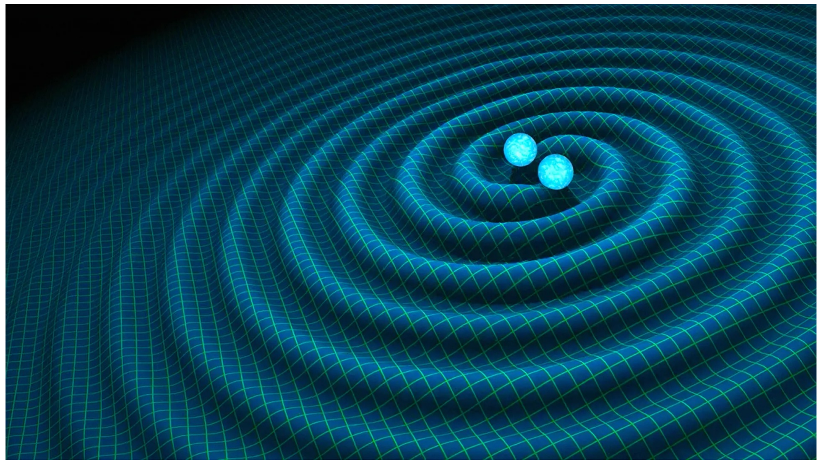
More explicit comparison to axions

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



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

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

(in the TT gauge)

Domcke, CGC, Rodd, 2202.00695

Camilo García Cely, University of Valencia

More explicit comparison to axions

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

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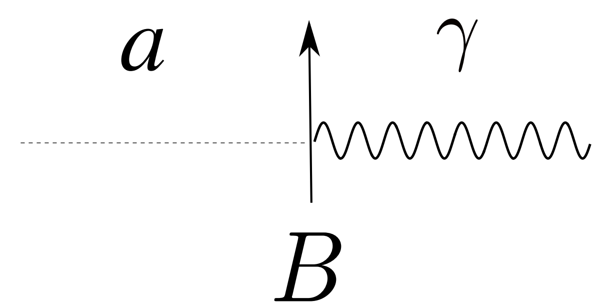
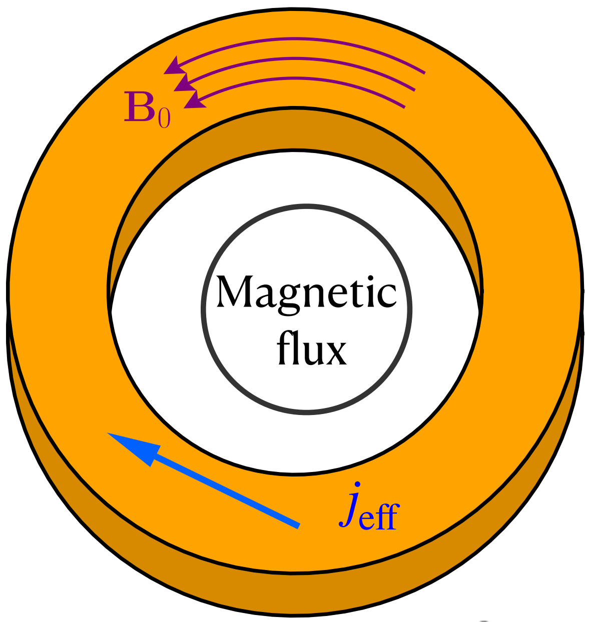
$$\nabla \times \mathbf{B} = \partial_t \mathbf{E} + \nabla \times \mathbf{M} + \partial_t \mathbf{P}$$

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

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

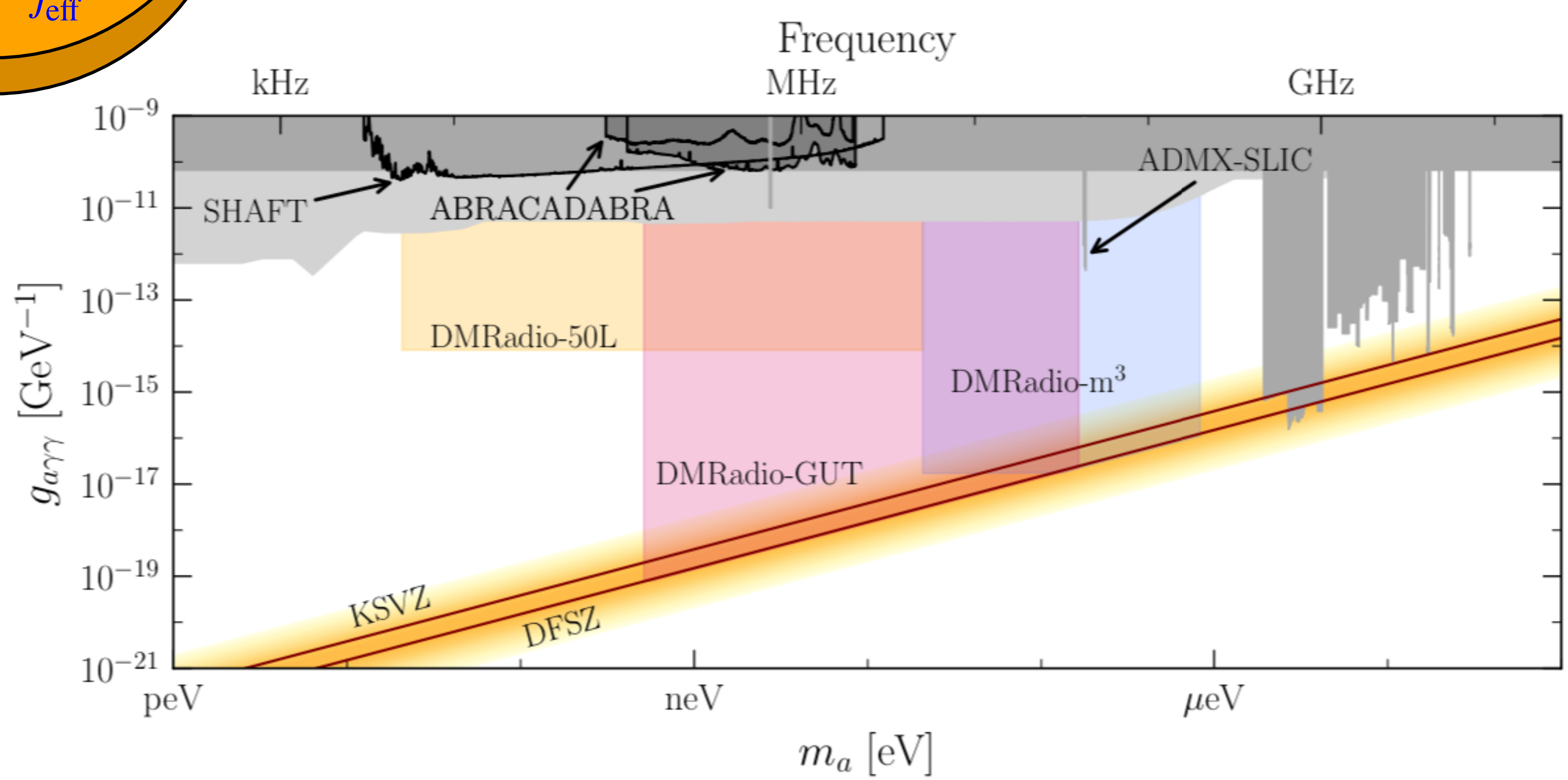
	Axion electrodynamics	Gravitational wave electrodynamics
An example		Gertsenshtein effect
Effective current $j^{\mu}_{\text{eff}} = \left(-\nabla \cdot \mathbf{P}, \nabla \times \mathbf{M} + \partial_t \mathbf{P}\right)$	$\mathbf{P} = g_{a\gamma\gamma} a \mathbf{B}, \quad \mathbf{M} = g_{a\gamma\gamma} a \mathbf{E}$ 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
Benchmark	QCD axion	$h \sim 10^{-22}$

DMRadio program



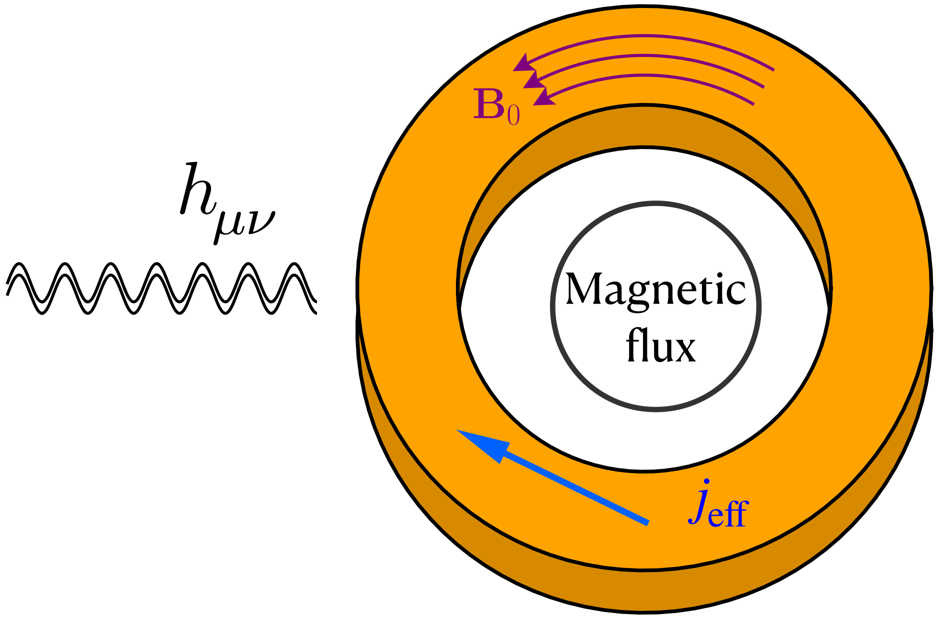
Proposal for a definitive search for GUT-scale QCD axions

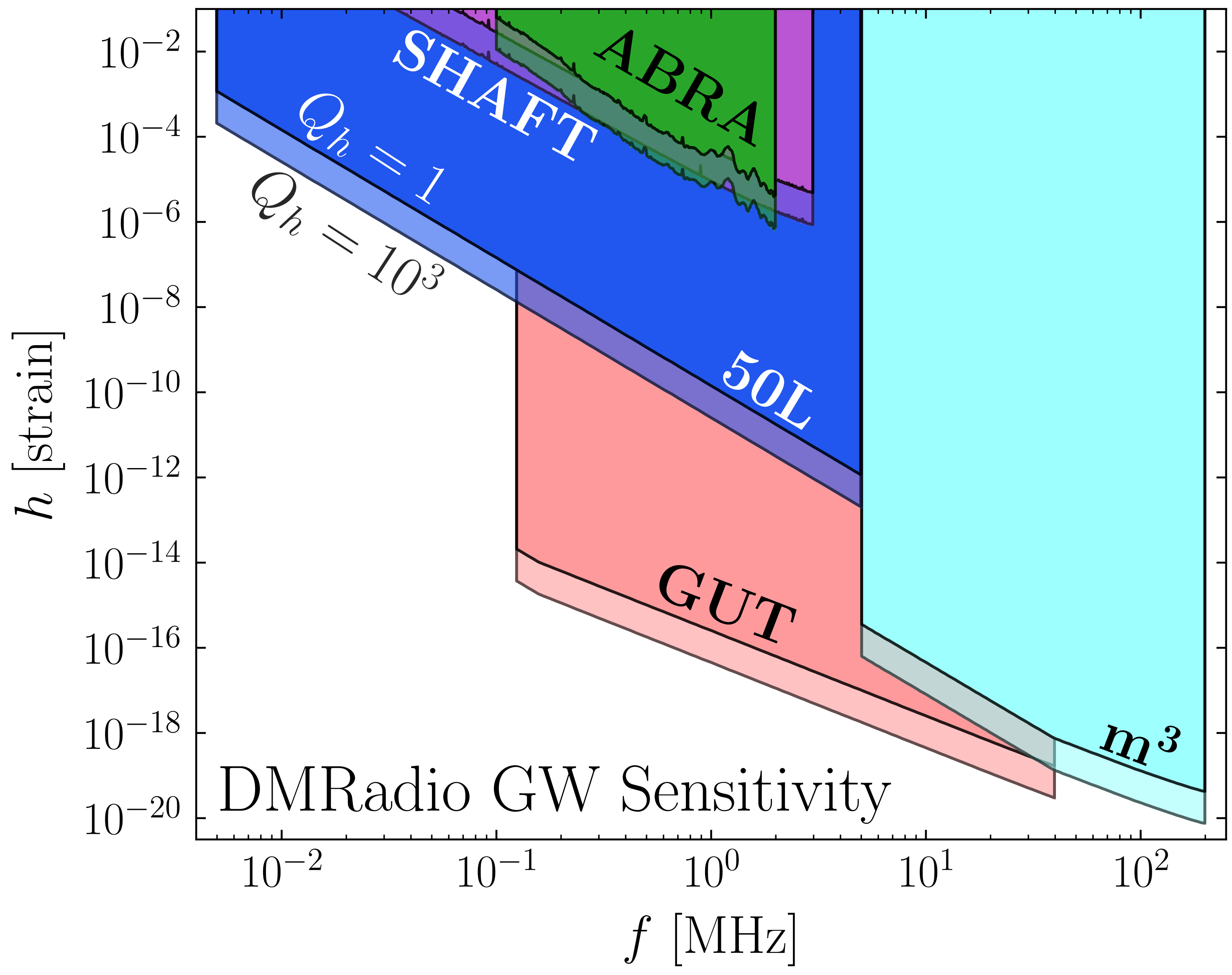
L. Brouwer *et al.* (DMRadio Collaboration)
Phys. Rev. D **106**, 112003 – Published 12 December 2022



DMRadio program

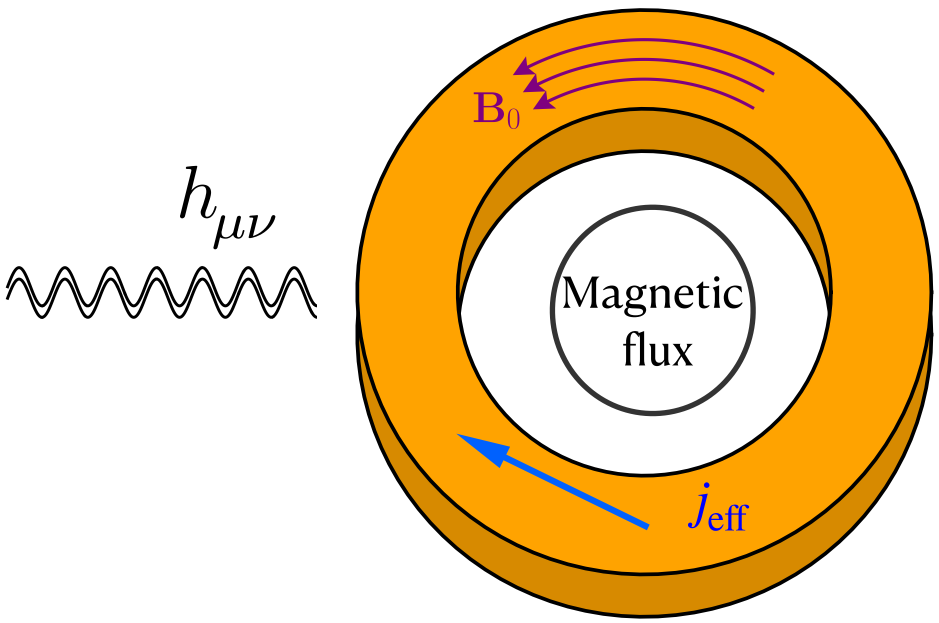
Domcke, CGC, Rodd, 2202.00695



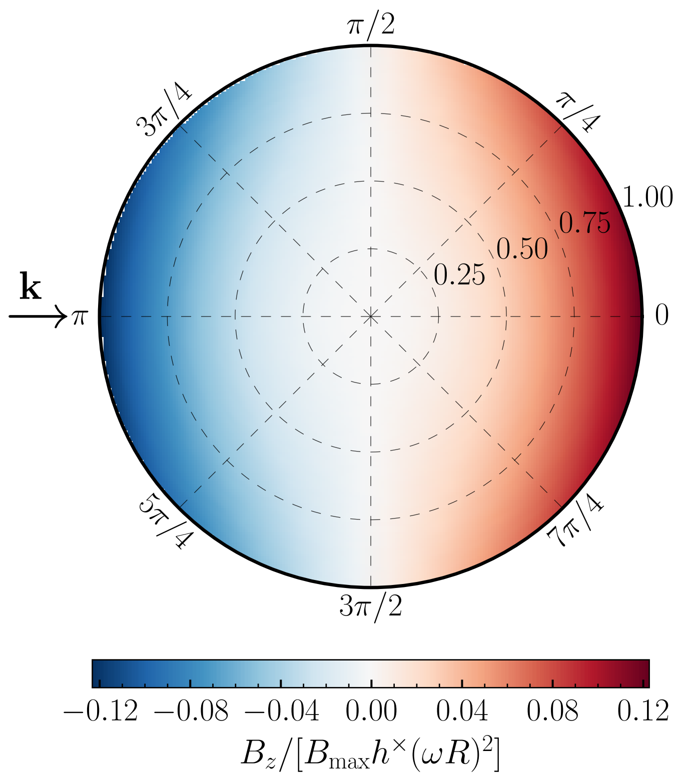


Camilo García Cely, University of Valencia

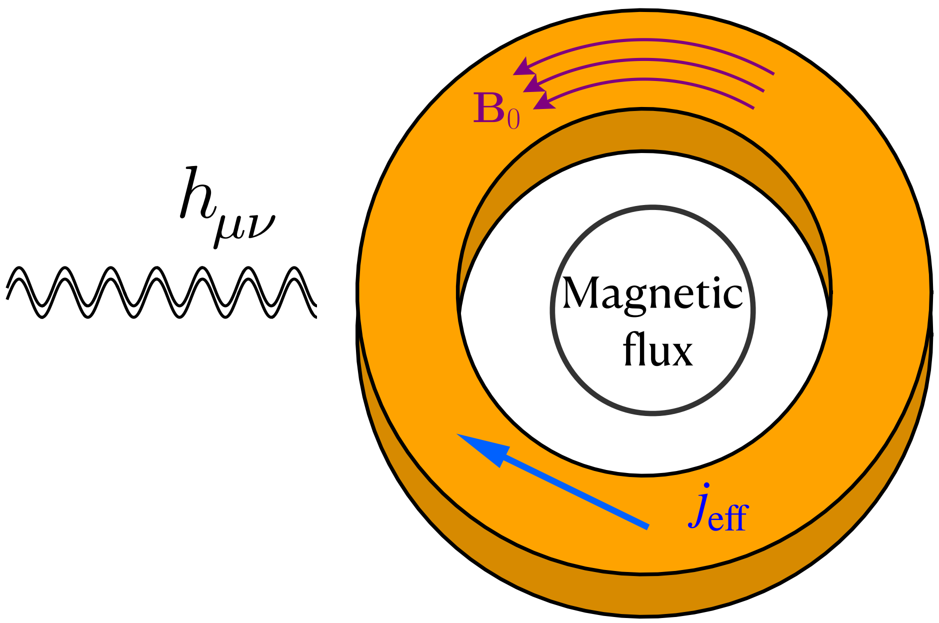
Toroidal magnetic fields



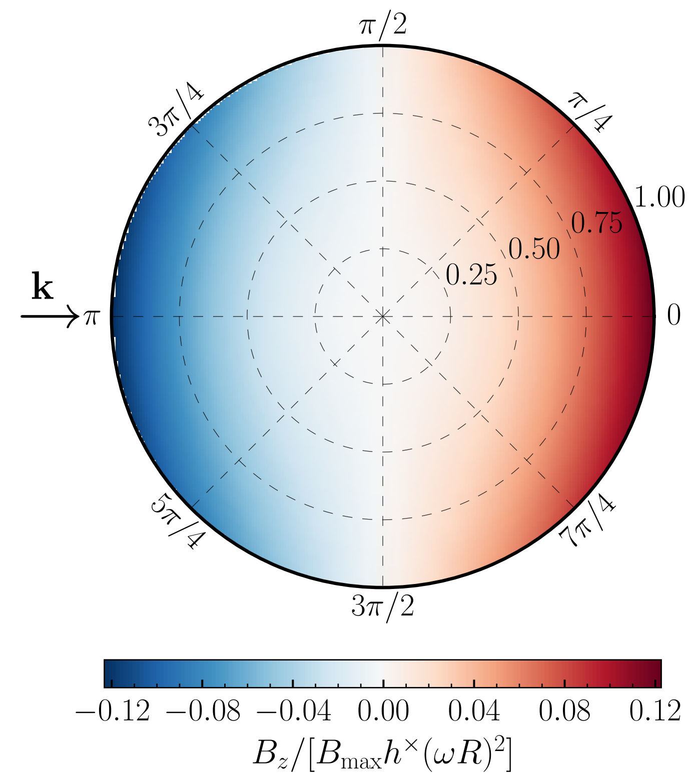
Domcke, CGC, Rodd, 2202.00695



Toroidal magnetic fields

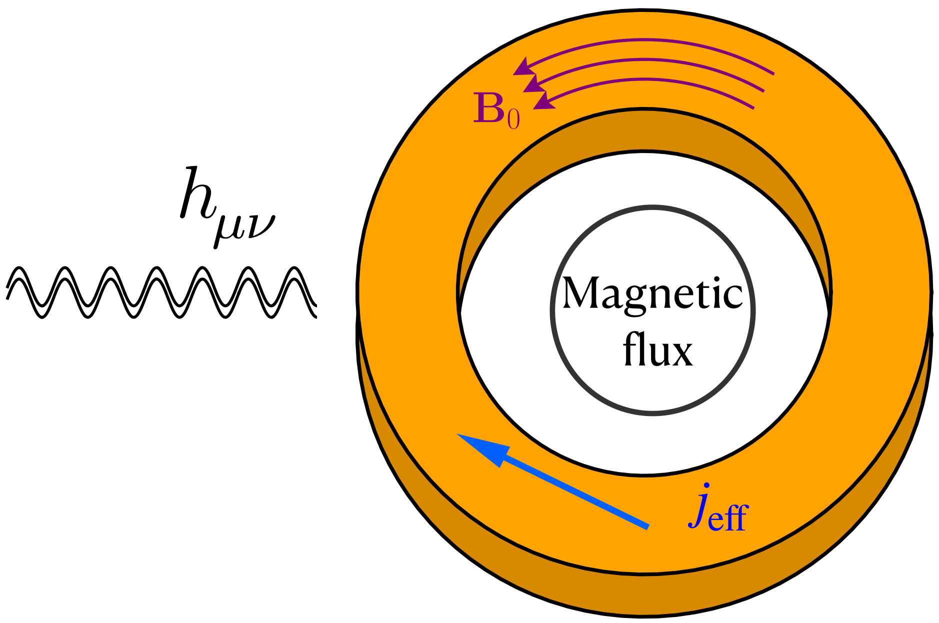


Domcke, CGC, Rodd, 2202.00695



- Only one polarization

Toroidal magnetic fields



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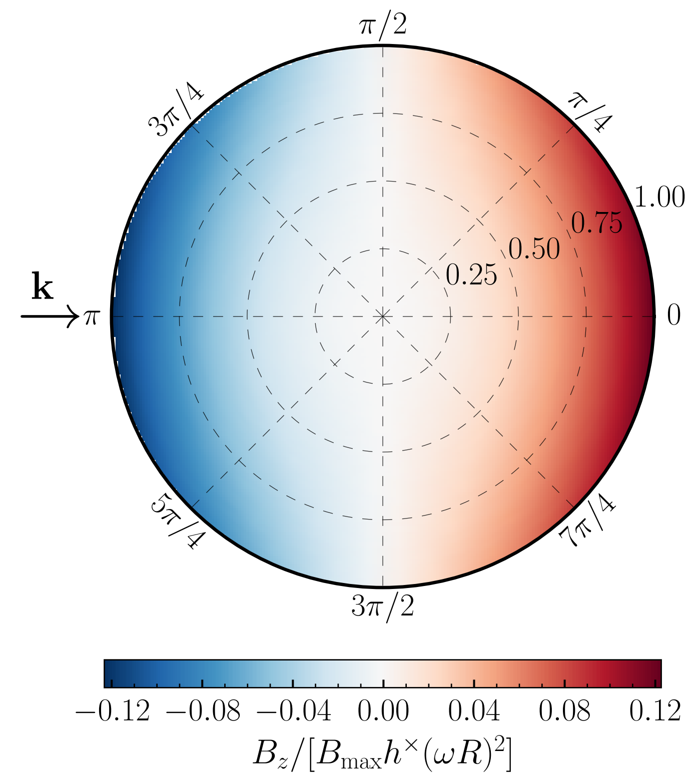

- Only one polarization
- Suppression at small frequencies $\omega R \ll 1$

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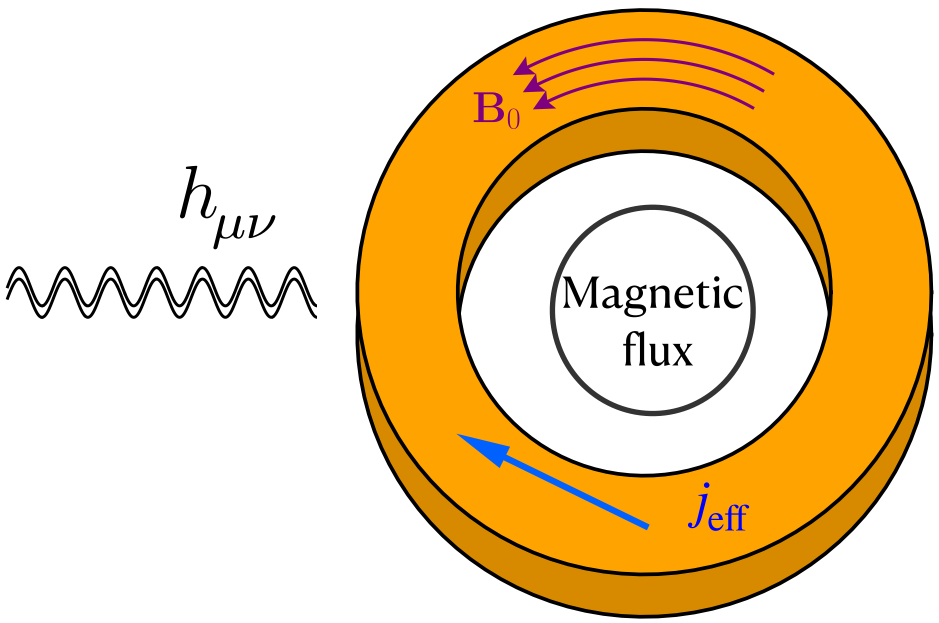
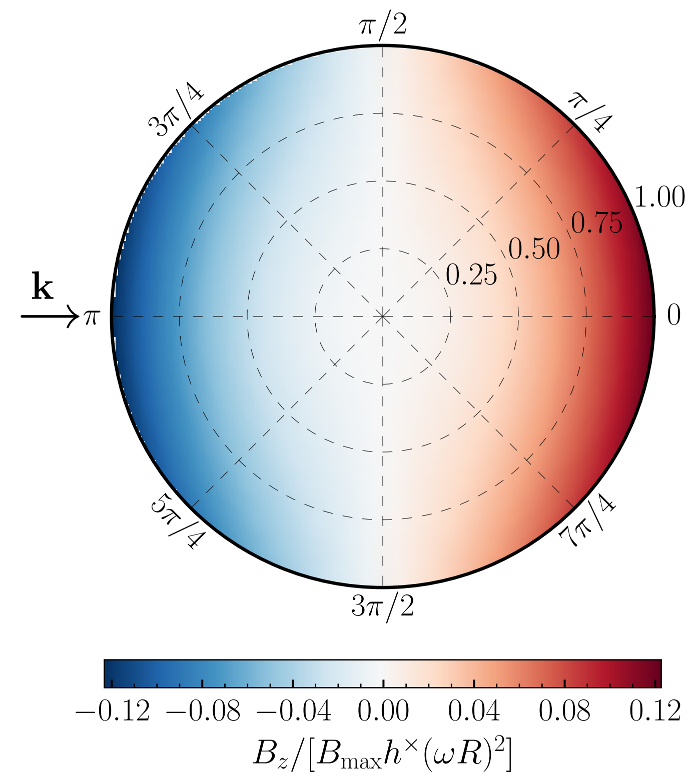
Toroidal magnetic fields



Domcke, CGC, Rodd, 2202.00695



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

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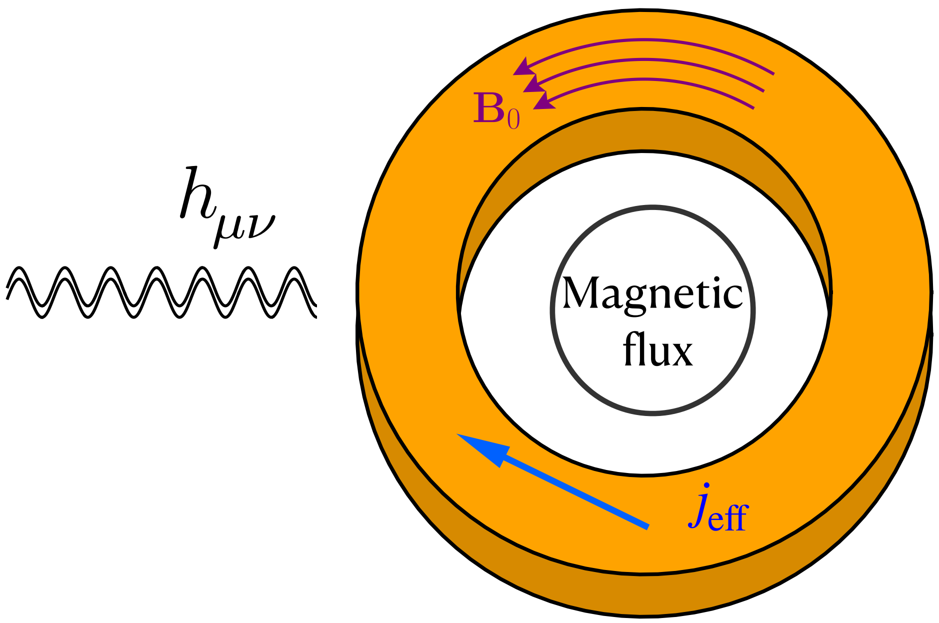

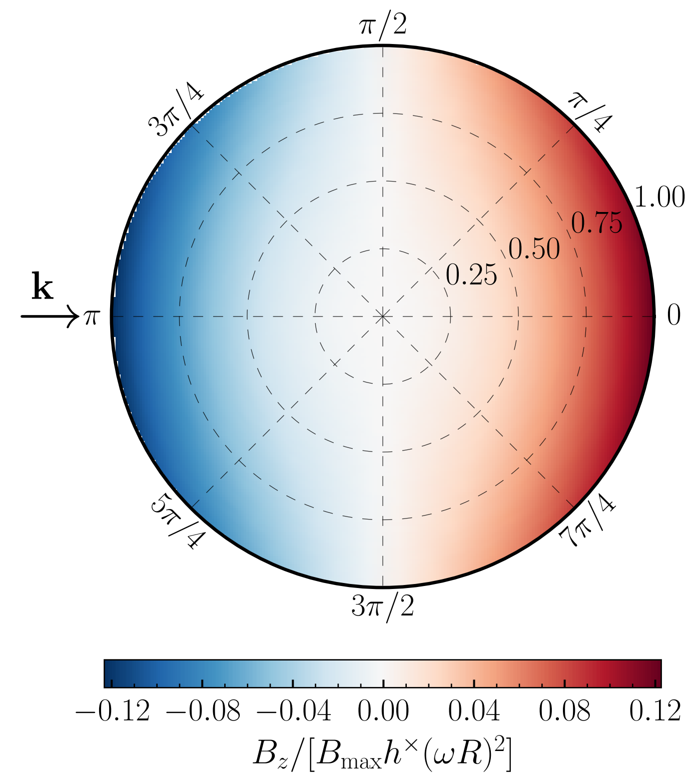

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- The sensitivity scaling with the volume is faster than for axions

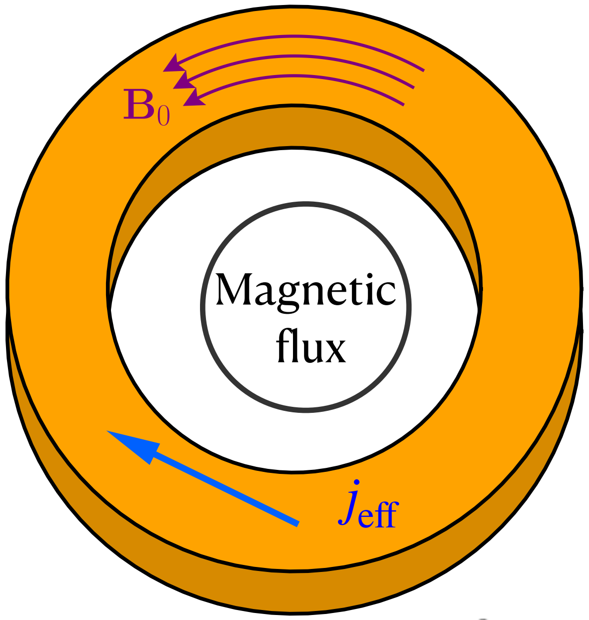
Selection rules

Optimizing the geometry of axion haloscopes for gravitational wave searches

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

work in progress: 2306.xxxxx

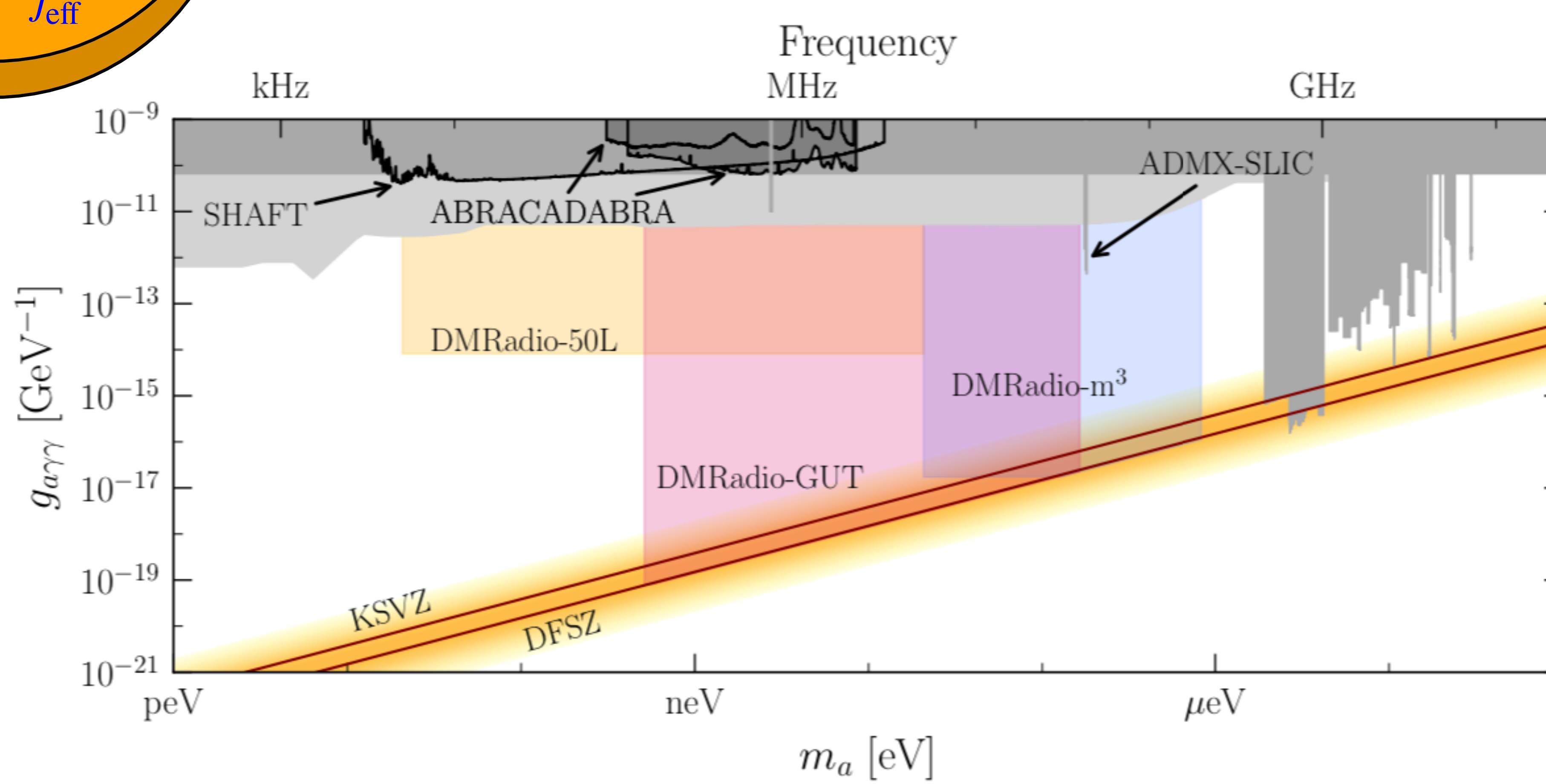
DMRadio program



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 and solenoidal geometries



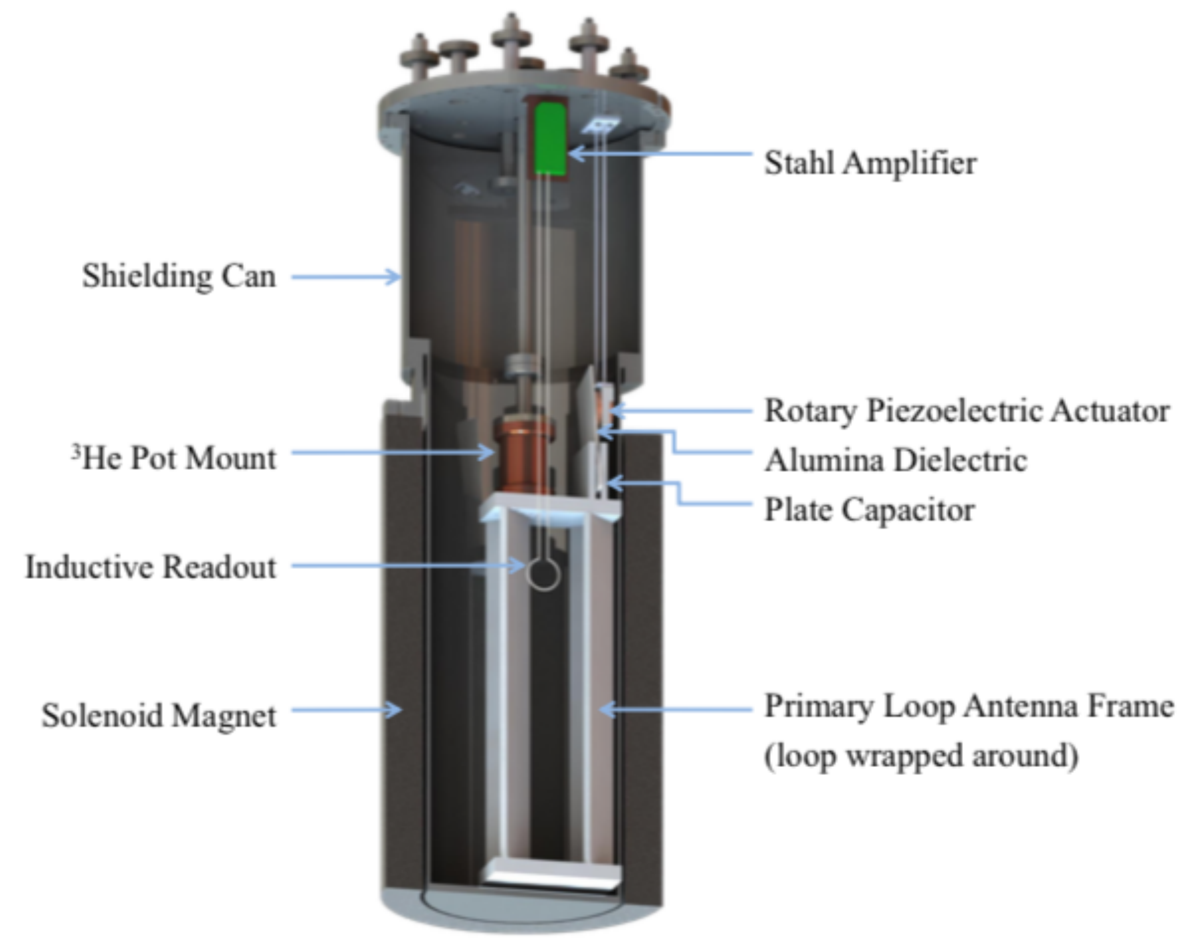
Beyond toroidal configurations

Domcke, CGC, Lee, Rodd (in progress)

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

Solenoidal external field and vertical pickup loop



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		$\mathbf{B}$	
		$\hat{\mathbf{e}}_z$ (Solenoid)	$\hat{\mathbf{e}}_\phi$ (Toroid)
$\hat{\mathbf{n}}'$	$\hat{\mathbf{e}}_z$	h_+ and $\mathcal{O}[(\omega L)^2]$	$h_\times$ and $\mathcal{O}[(\omega L)^3]$
	$\hat{\mathbf{e}}_\phi$	$h_\times$ and $\mathcal{O}[(\omega L)^3]$	h_+ and $\mathcal{O}[(\omega L)^2]$
	$\hat{\mathbf{e}}_\rho$	h_+ and $\mathcal{O}[(\omega L)^3]$	$h_\times$ and $\mathcal{O}[(\omega L)^4]$

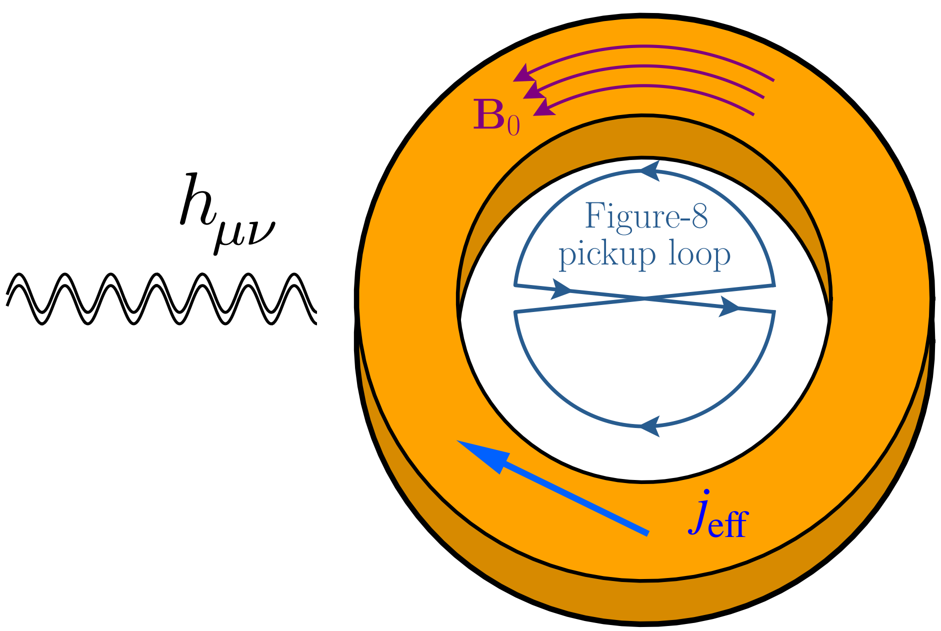
Expect $\omega L \ll 1$

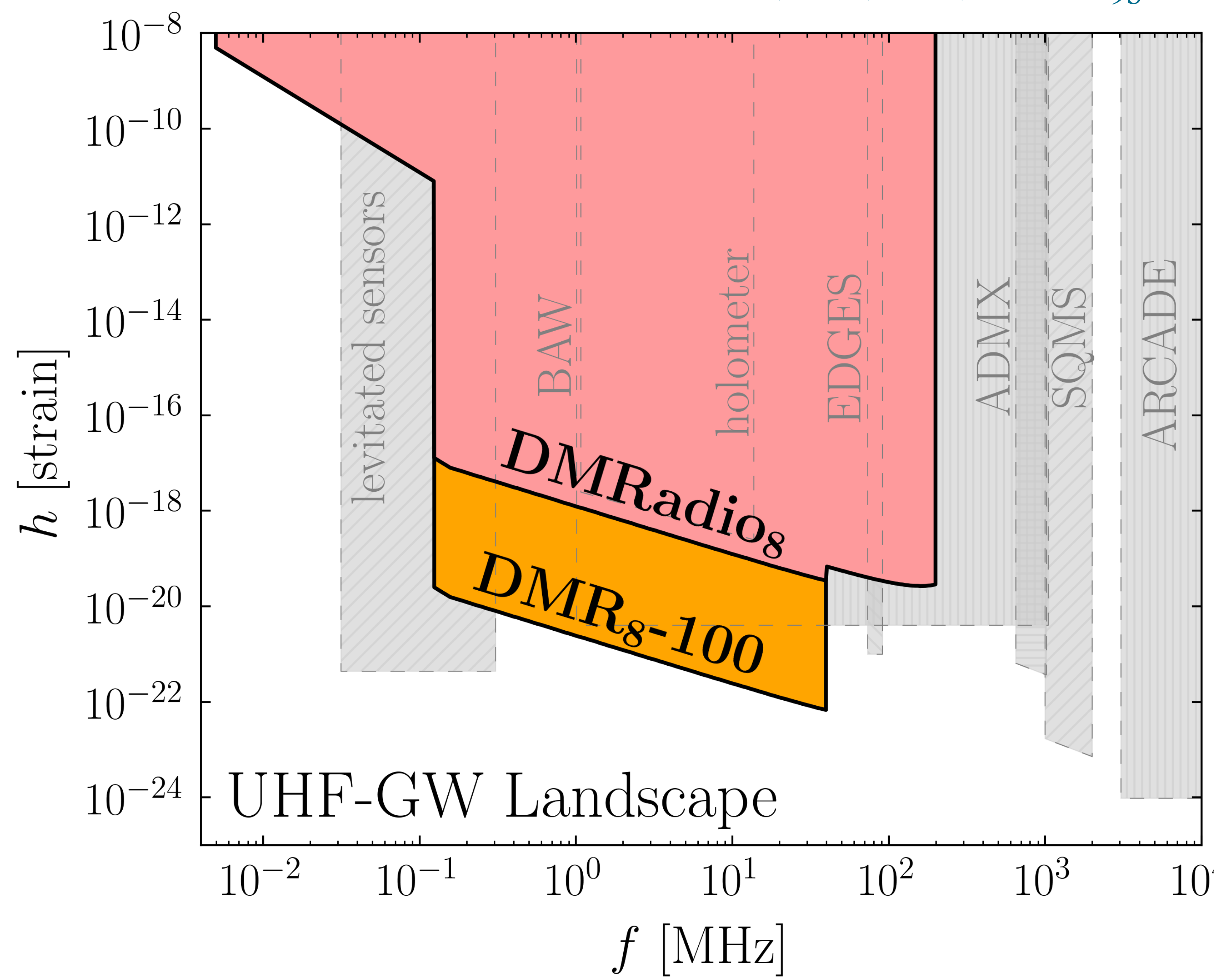
There are more rules: I warmly invite you to have a look at the paper in a few days

Gravitational waves in low mass axion haloscopes

Domcke, CGC, Rodd, 2202.00695

Break cylindrical symmetry





Domcke, CGC, Lee, Rodd (in progress)

Proper detector frame

In the proper detector frame the coordinate system closely matches the intuitive description of an Earth-based laboratory, with the gravitational wave acting as a Newtonian force.

Domcke, CGC, Rodd, 2202.00695

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

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

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

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

The ω^2 dependence is unavoidable

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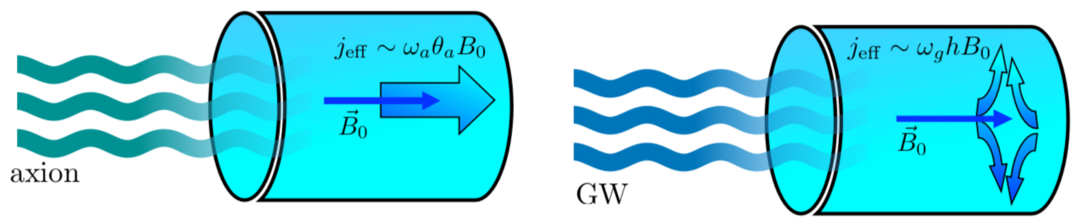

Detecting High-Frequency Gravitational Waves with Microwave Cavities

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]

Conclusions

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

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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.

Other possibilities

Detecting High-Frequency Gravitational Waves with Microwave Cavities

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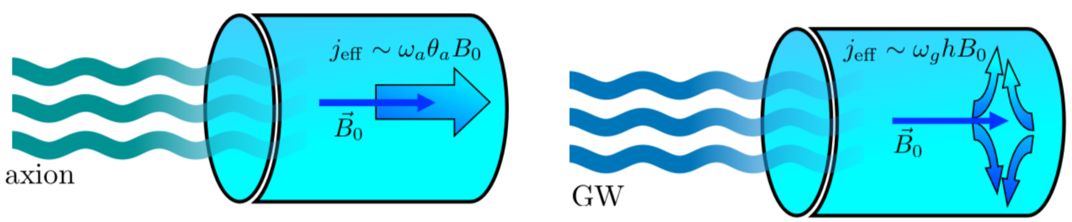
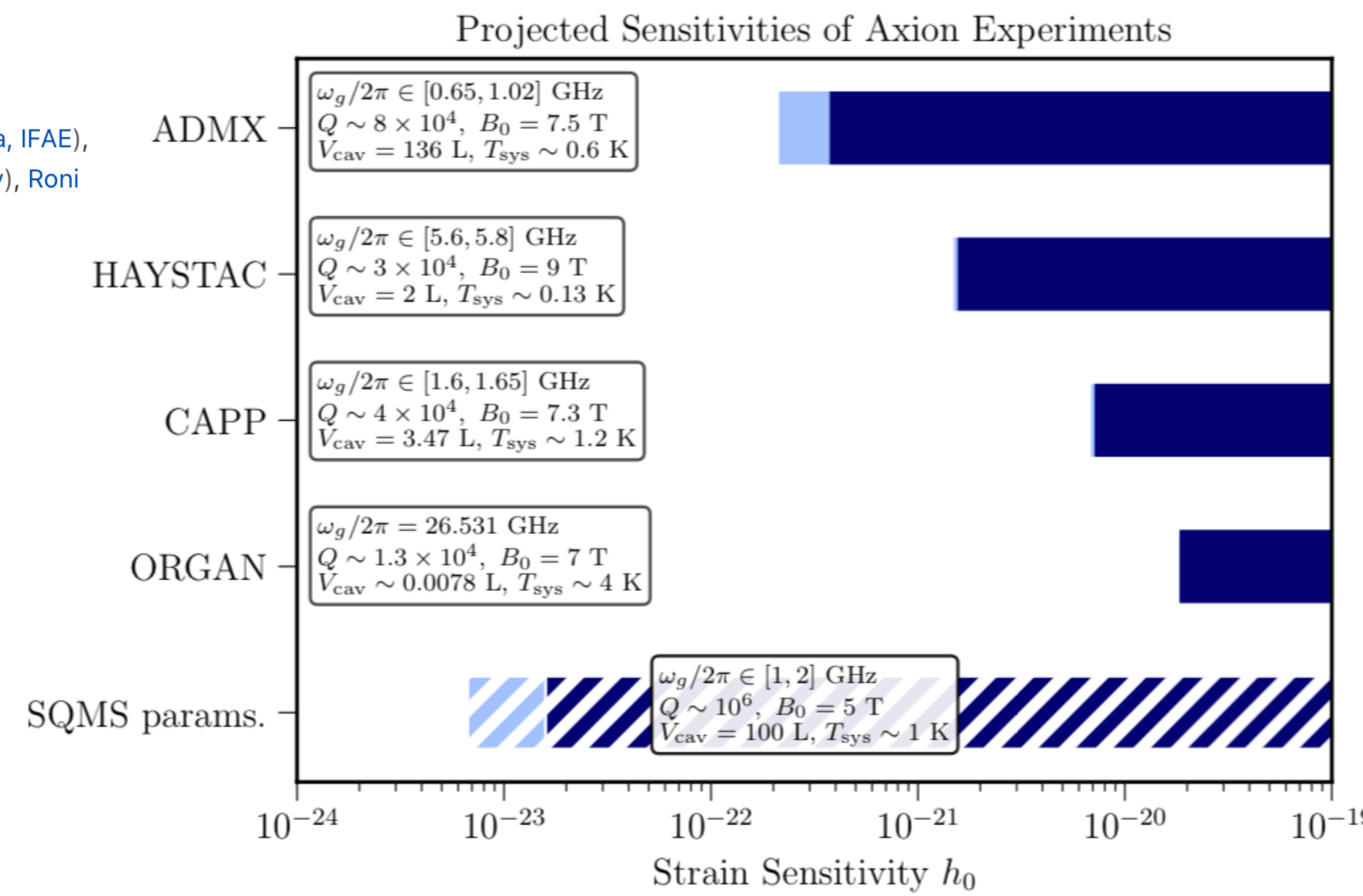




It resonates when the GW frequency matches one of the eigenmode frequencies

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

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

Oscillations after the formation of the CMB

$$\left(\Box + \omega_{\rm pl}^2\right) A_\lambda = -B\partial_\ell h_\lambda$$

$$\Box h_\lambda = 16\pi G B\, \partial_\ell A_\lambda$$

$$\omega_{\rm pl} = \sqrt{e^2 n_e / m_e}$$

The plasma frequency acts as an effective mass term

$$\ell_{\rm osc} \simeq 4\omega/\omega_{\rm pl}^2$$

$$\langle \Gamma_{g\leftrightarrow\gamma} \rangle = \frac{2\pi G B^2 \ell_{\rm osc}^2}{\Delta \ell}$$

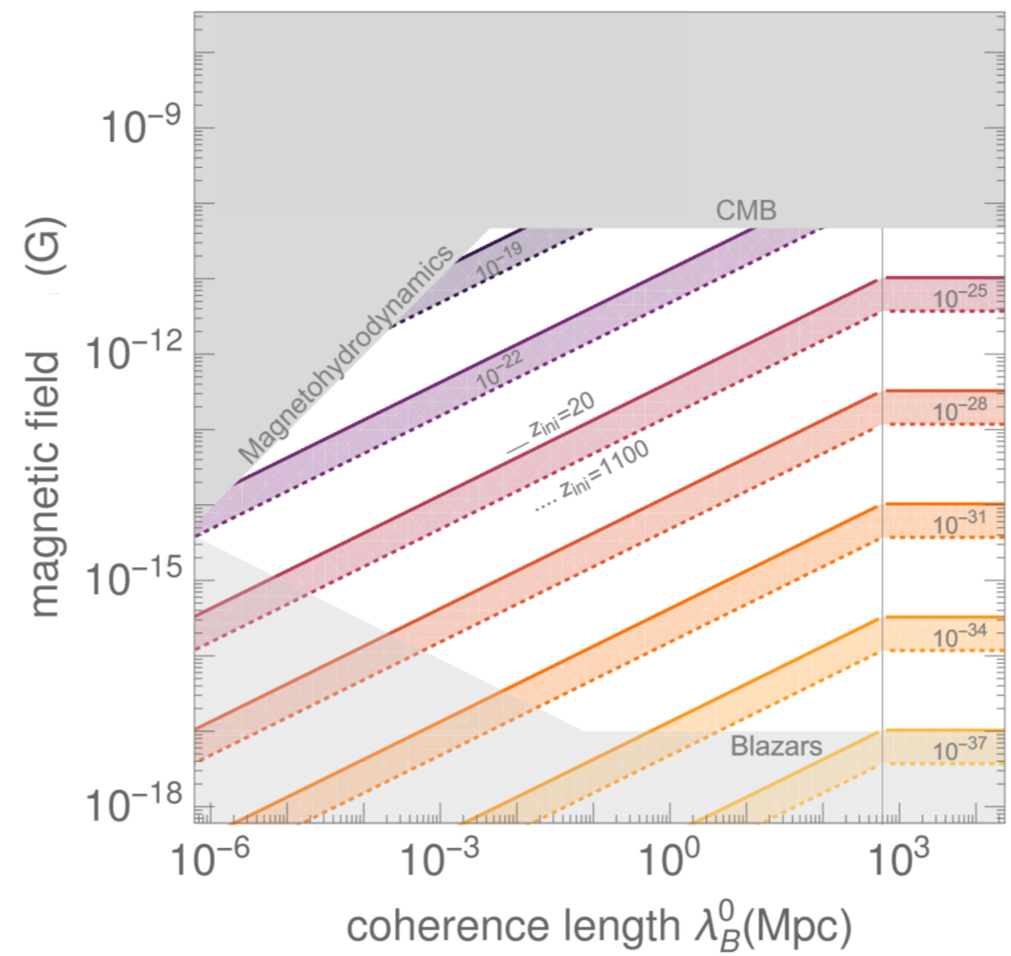
Although cosmic magnetic fields are not expected to be perfectly homogeneous, coherent oscillations take place in highly homogeneous patches.

$$\ell_{\rm osc} = 4\omega/(1+z)^2 X_e(z)\omega_{\rm pl,0}^2 \ll 1\ \rm pc$$

$$\mathscr{P} \equiv \int_{l.o.s.} \langle \Gamma_{g\leftrightarrow\gamma} \rangle dt = \int_0^{z_{\rm ini}} \frac{\langle \Gamma_{g\leftrightarrow\gamma} \rangle}{(1+z)\, H} dz$$

Domcke, CGC 2021

Cosmic magnetic fields



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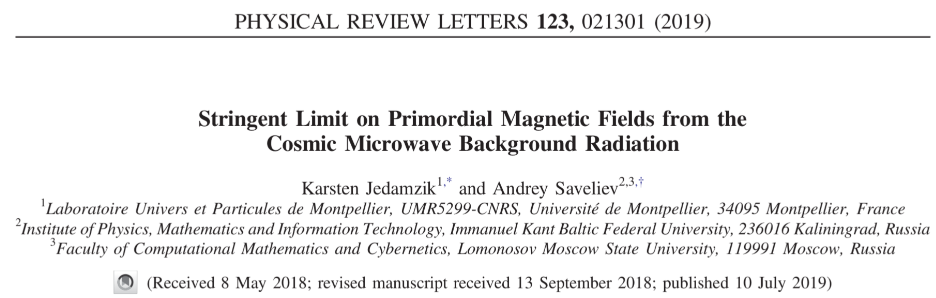
PHYSICAL REVIEW LETTERS **123,** 021301 (2019)

Stringent Limit on Primordial Magnetic Fields from the Cosmic Microwave Background Radiation

Karsten Jedamzik[1,*] and Andrey Saveliev[2,3,†]

[1]*Laboratoire Univers et Particules de Montpellier, UMR5299-CNRS, Université de Montpellier, 34095 Montpellier, France*
[2]*Institute of Physics, Mathematics and Information Technology, Immanuel Kant Baltic Federal University, 236016 Kaliningrad, Russia*
[3]*Faculty of Computational Mathematics and Cybernetics, Lomonosov Moscow State University, 119991 Moscow, Russia*

(Received 8 May 2018; revised manuscript received 13 September 2018; published 10 July 2019)


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Evidence for Strong Extragalactic Magnetic Fields from Fermi Observations of TeV Blazars

Andrii Neronov*, Ievgen Vovk

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Science 02 Apr 2010:
Vol. 328, Issue 5974, pp. 73-75
DOI: 10.1126/science.1184192

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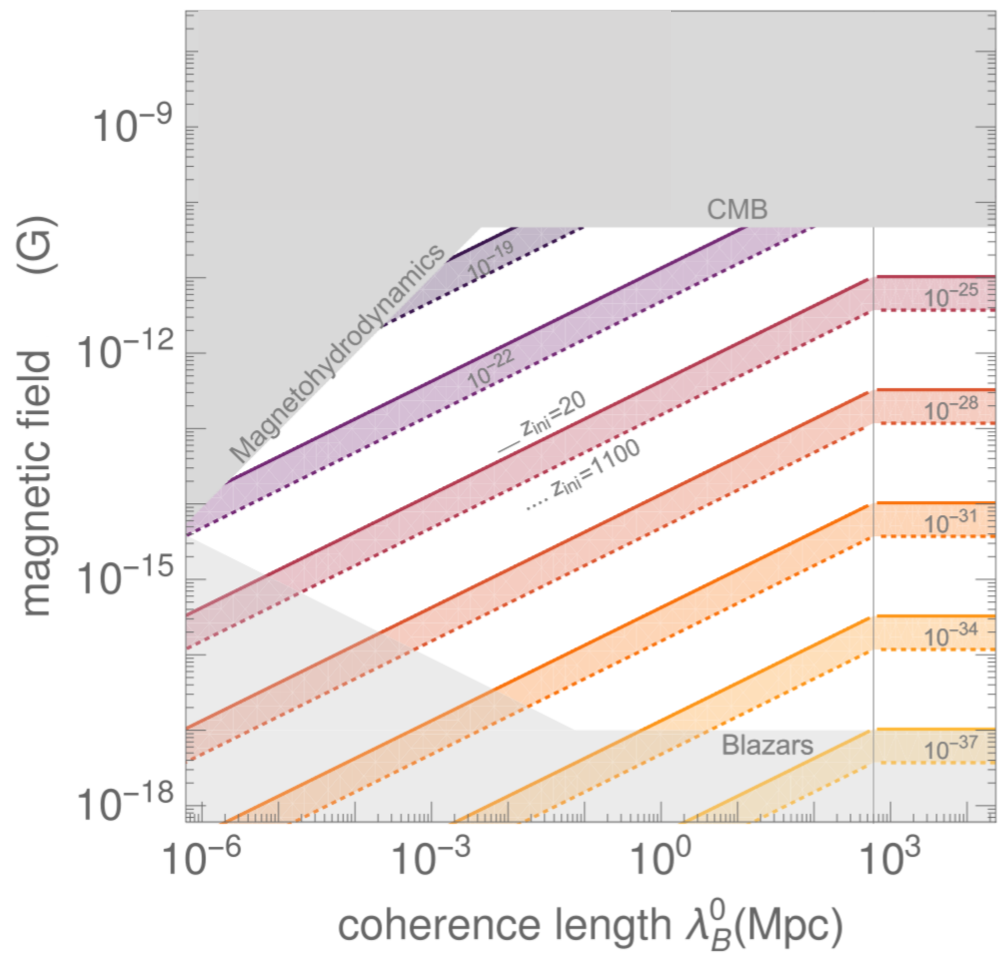
Domcke, CGC 2021

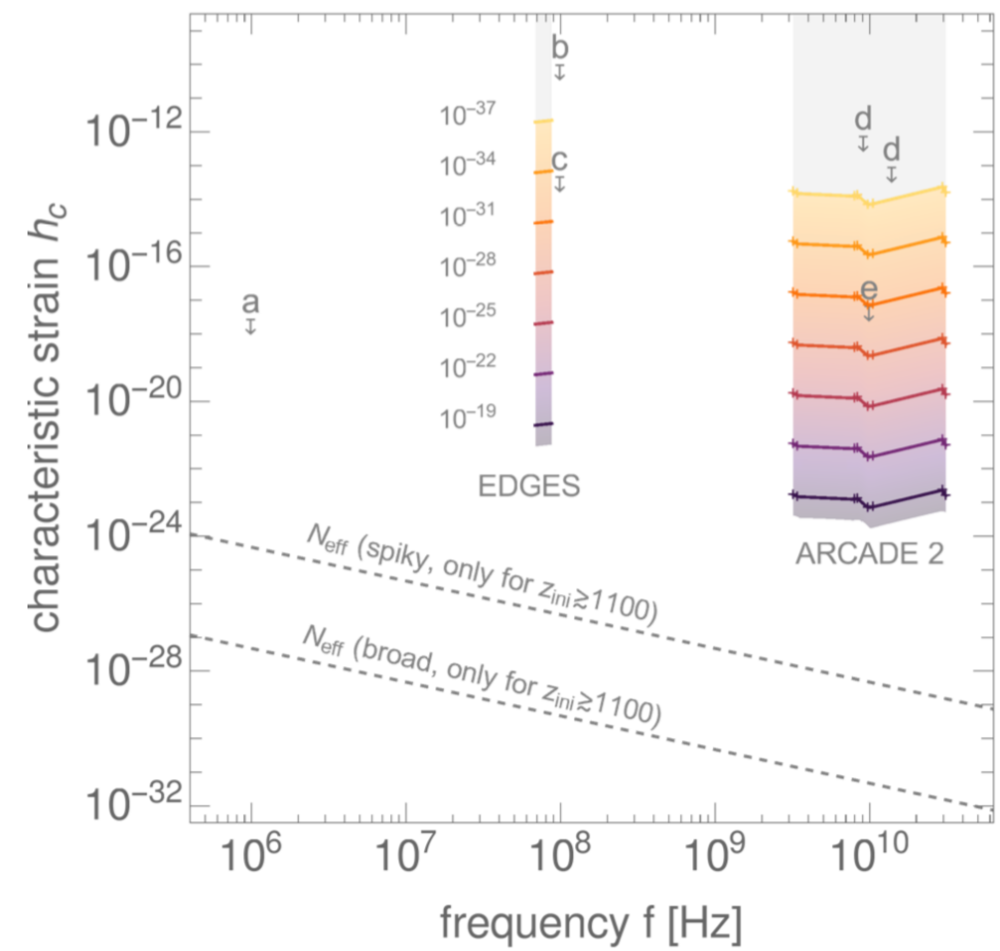
Upper bounds on stochastic gravitational waves



PHYSICAL REVIEW LETTERS **126,** 021104 (2021)

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