

# 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*



# 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

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**Valerie Domcke,<sup>1</sup> Camilo Garcia-Cely,<sup>2</sup> Sung Mook Lee,<sup>3</sup> Nicholas L. Rodd<sup>1</sup>**

<sup>1</sup>*Theoretical Physics Department, CERN, 1 Esplanade des Particules, CH-1211 Geneva 23, Switzerland*

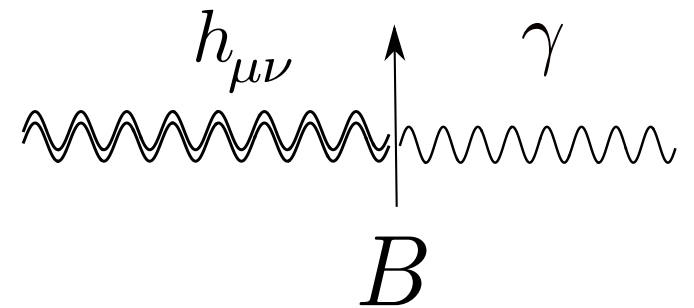
<sup>2</sup>*Instituto de Física Corpuscular (IFIC), Universitat de València-CSIC, Parc Científic UV, C/ Catedrático José Beltrán 2, E-46100 Burjassot, Spain*

<sup>3</sup>*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**

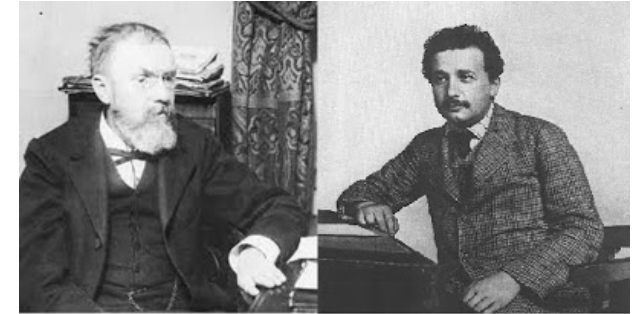


# Gravitational waves

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

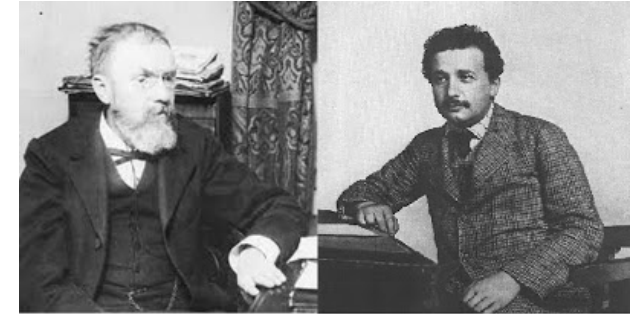
$$\square h_{\mu\nu} = -16\pi G T_{\mu\nu}$$

wave equation  
describing two  
polarization modes



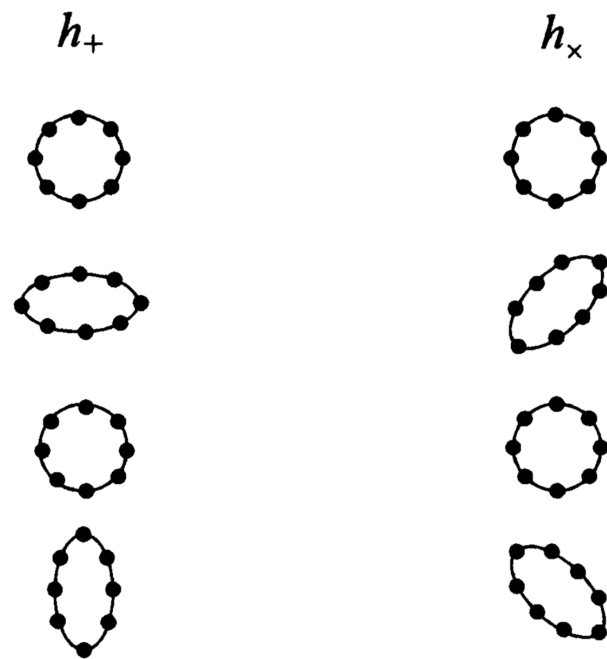
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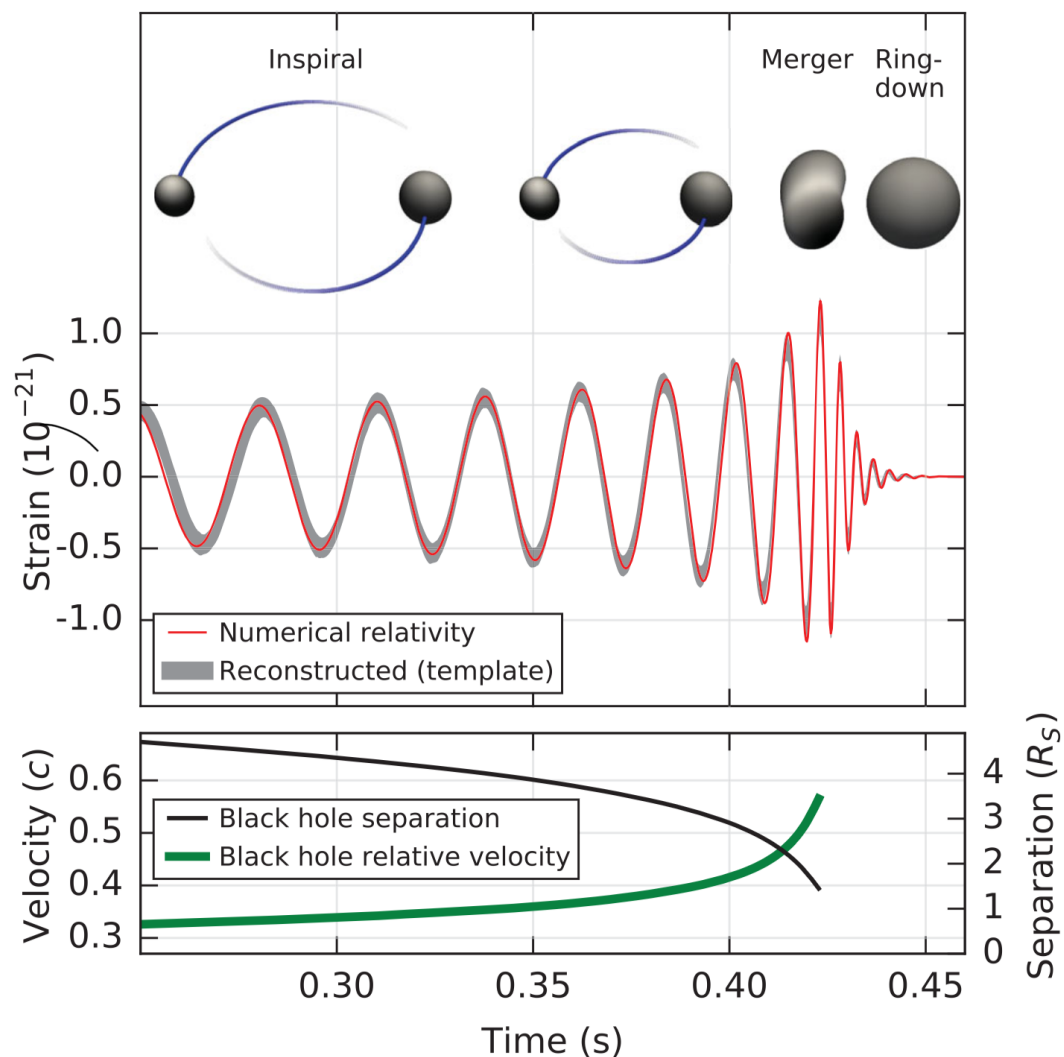


The deformation of a ring of test masses  
due to the different polarization

# Gravitational waves

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



PRL 116, 061102 (2016)

PHYSICAL REVIEW LETTERS

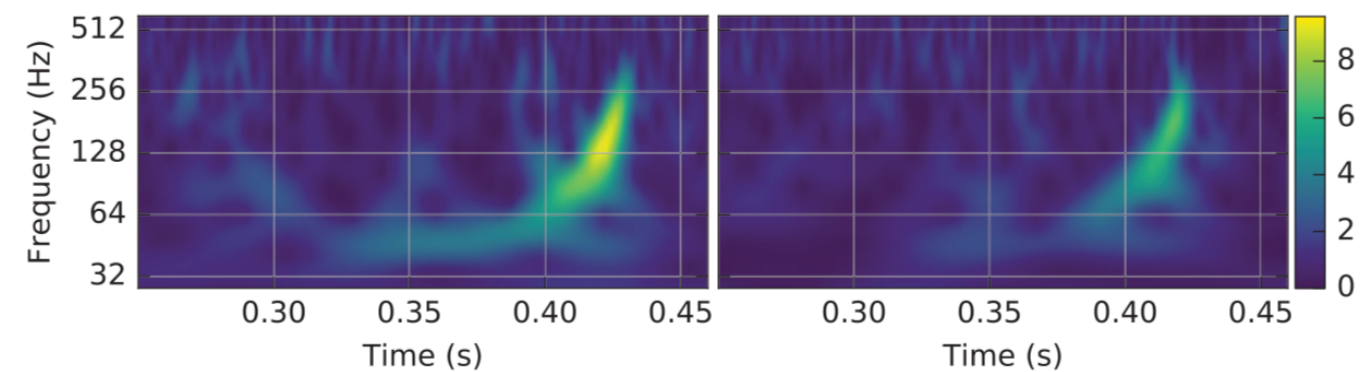
12 FEBRUARY 2016



## Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*\*

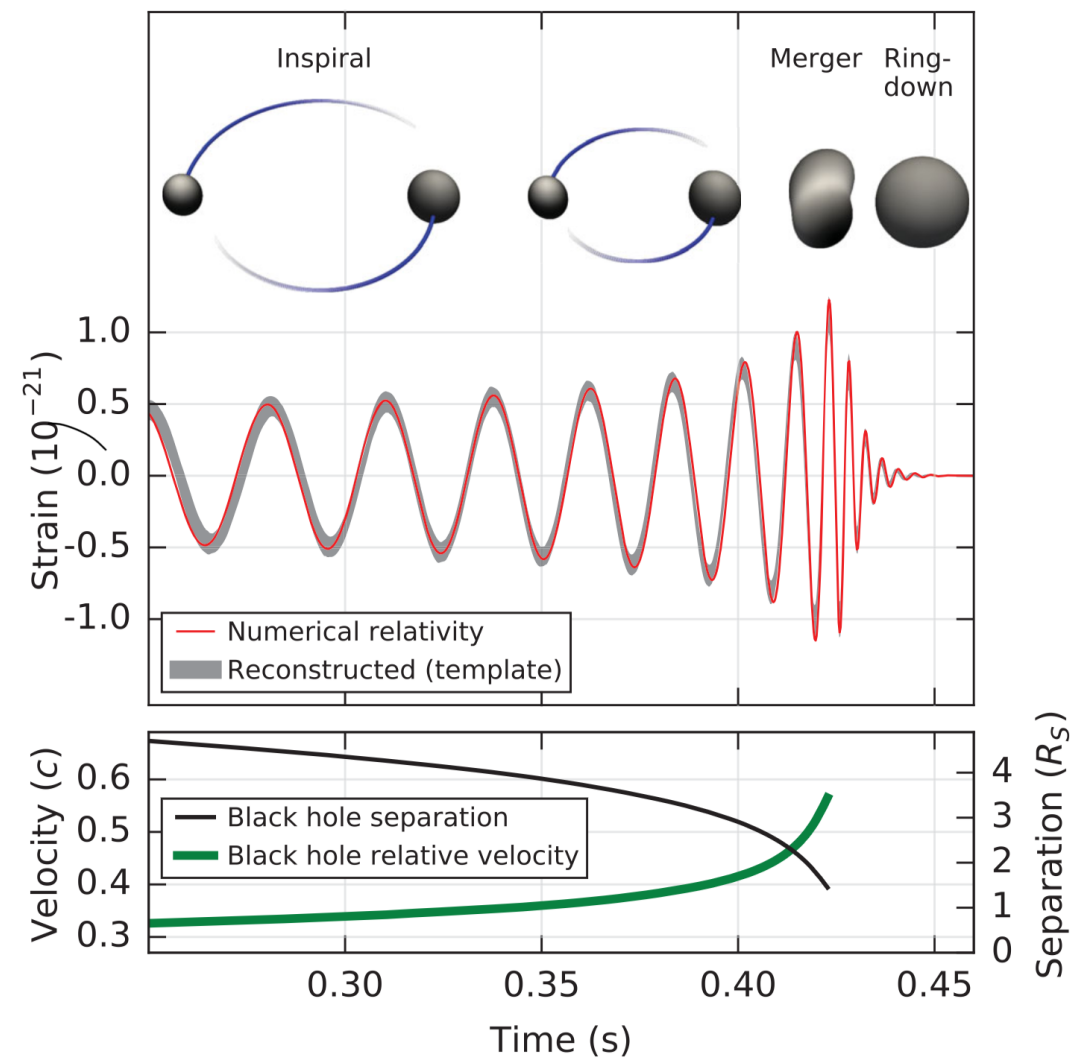
(LIGO Scientific Collaboration and Virgo Collaboration)



interferometers



# Gravitational waves



PRL **116**, 061102 (2016)

PHYSICAL REVIEW LETTERS

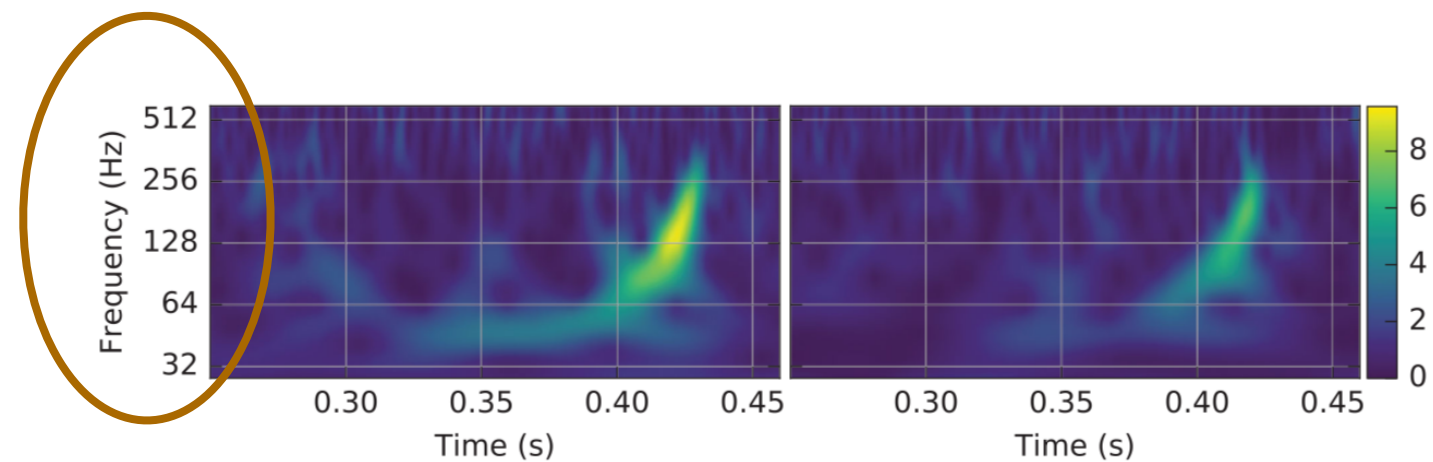
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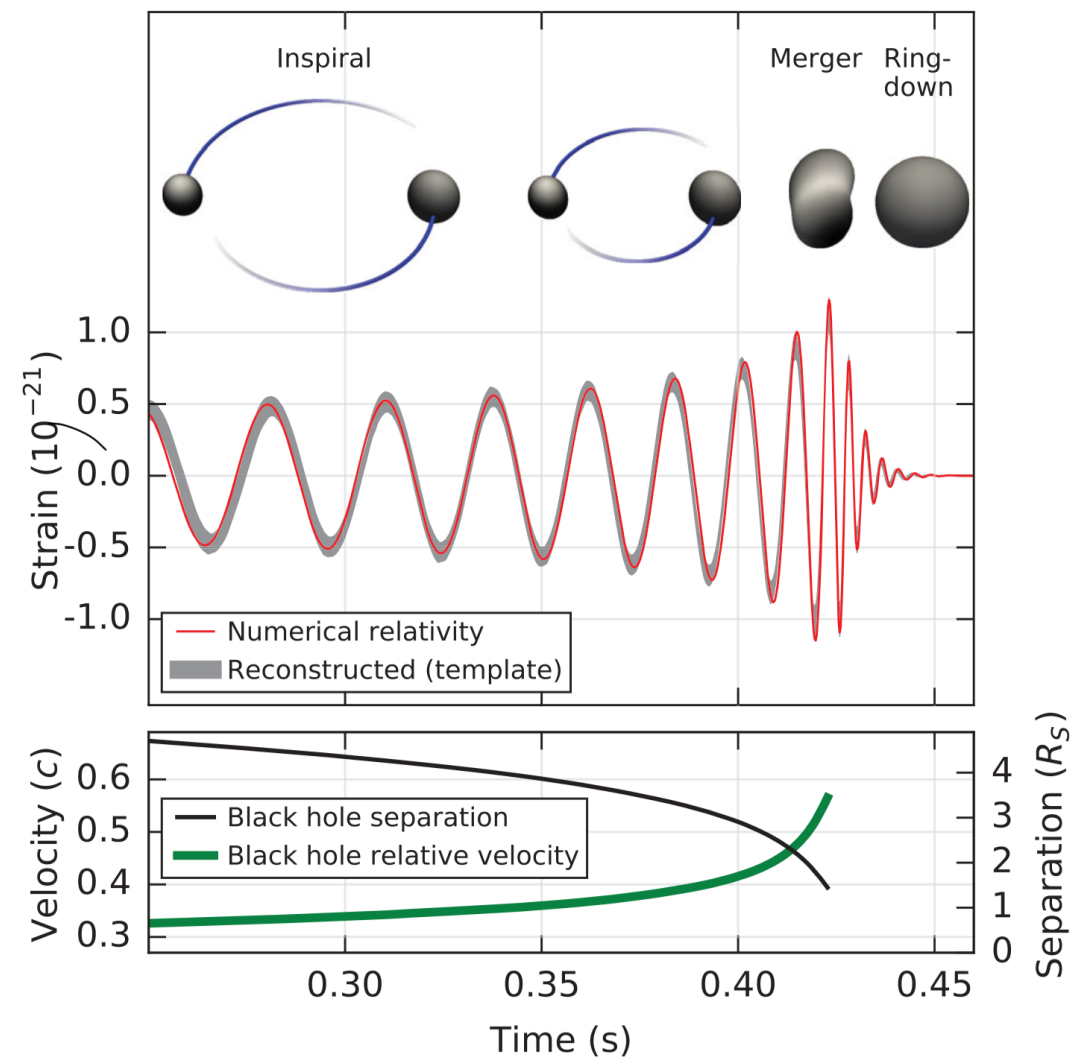
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$$f \approx \frac{1}{2\pi} \sqrt{\frac{GM}{R^3}}$$

# Gravitational waves



PRL **116**, 061102 (2016)

PHYSICAL REVIEW LETTERS

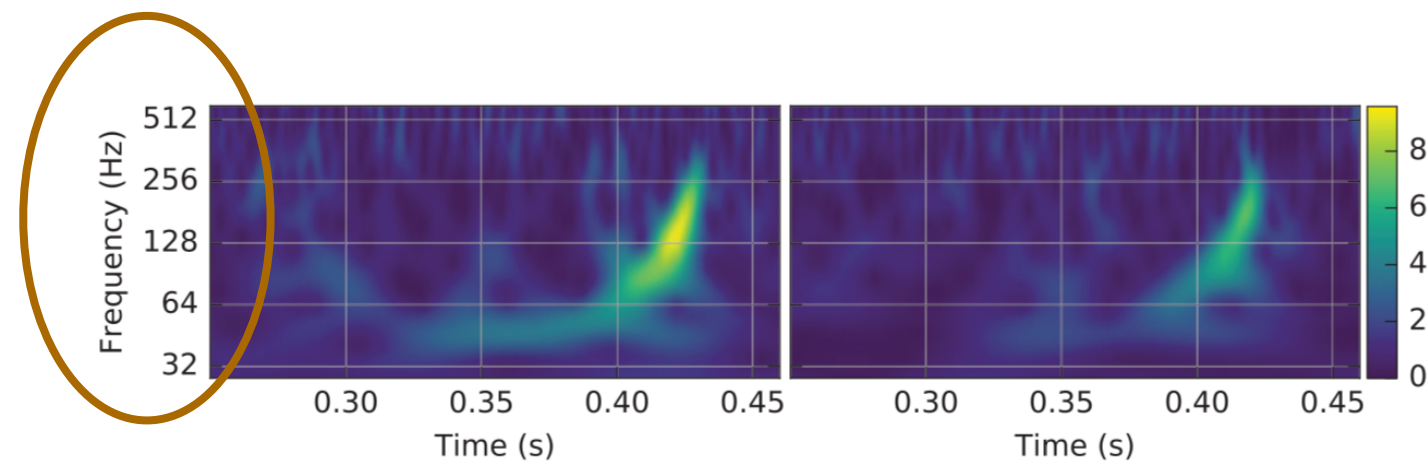
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## Observation of Gravitational Waves from a Binary Black Hole Merger

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(LIGO Scientific Collaboration and Virgo Collaboration)



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

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](#)

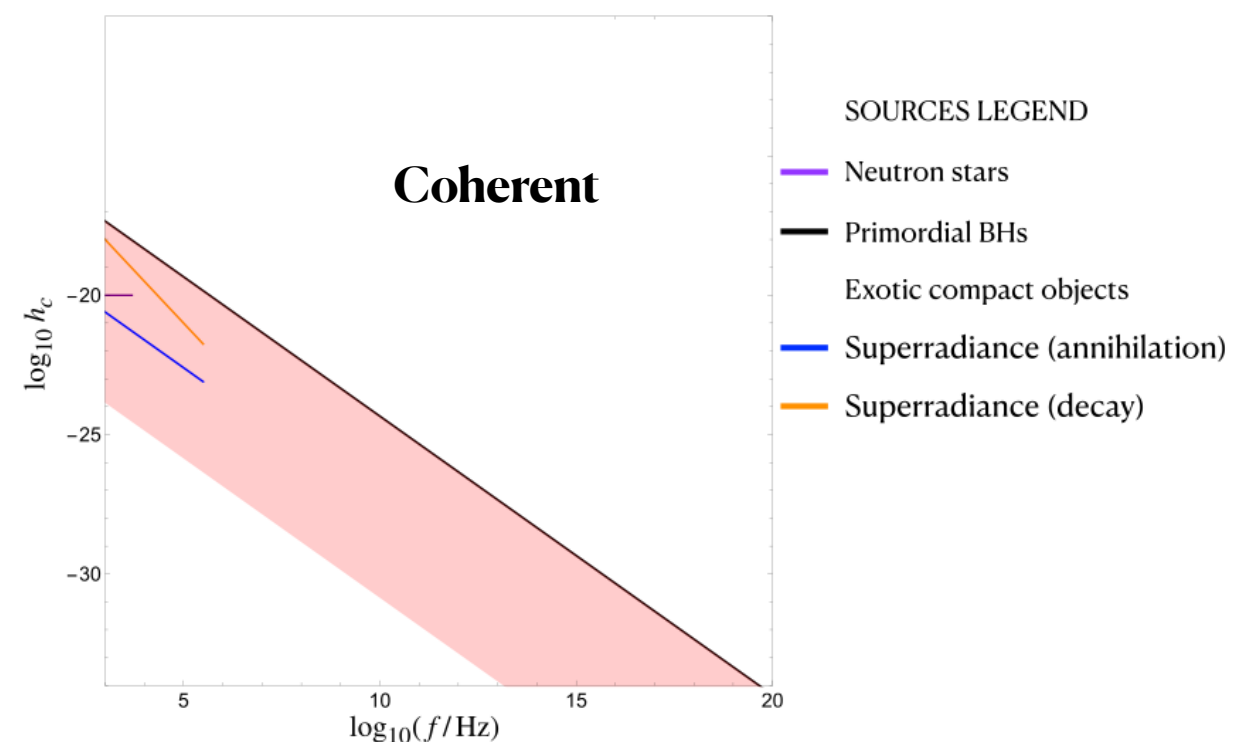
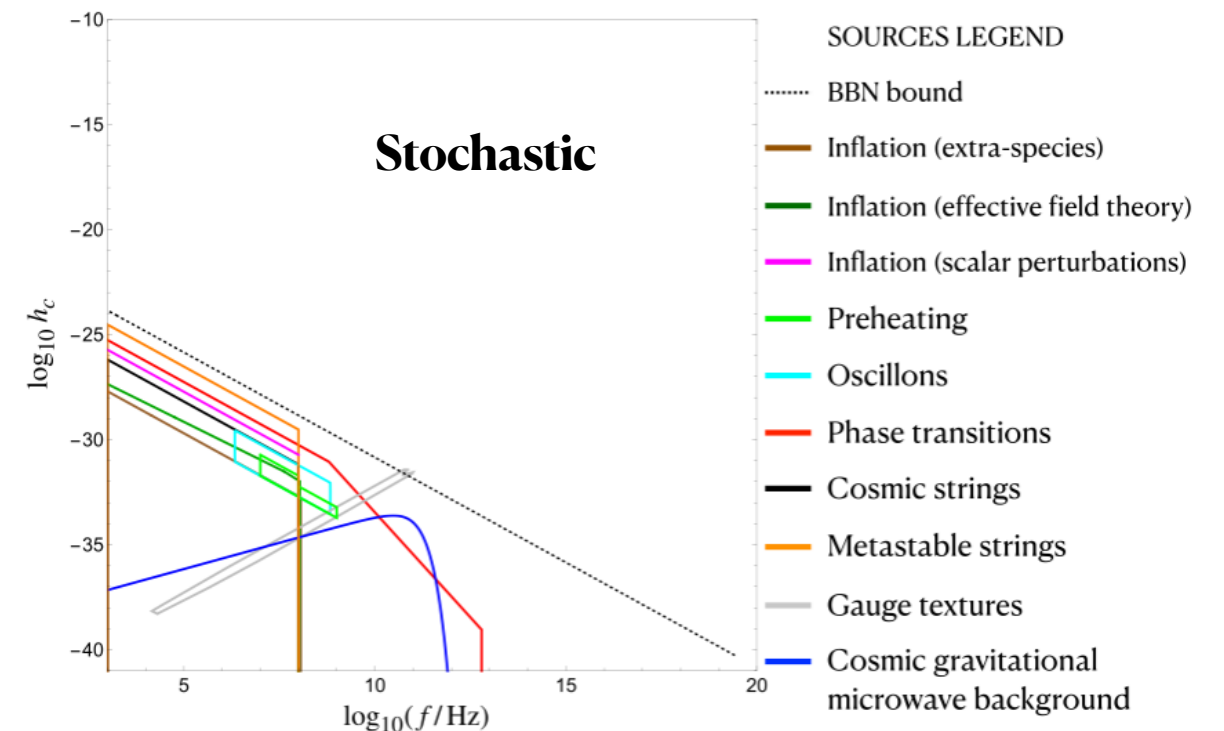
Review Article | [Open Access](#) | [Published: 06 December 2021](#)

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

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

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

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





# Revisiting Gertsenhstein's ideas

SOVIET PHYSICS JETP

VOLUME 16, NUMBER 2

FEBRUARY, 1963

## *ON THE DETECTION OF LOW FREQUENCY GRAVITATIONAL WAVES*

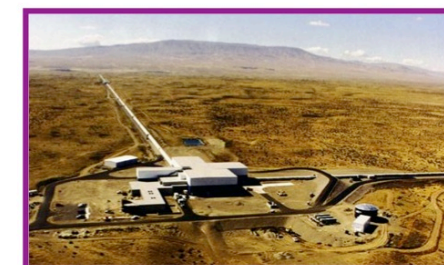
M. E. GERTSENSHTEIN and V. I. PUSTOVOIT

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.<sup>[1]</sup> 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

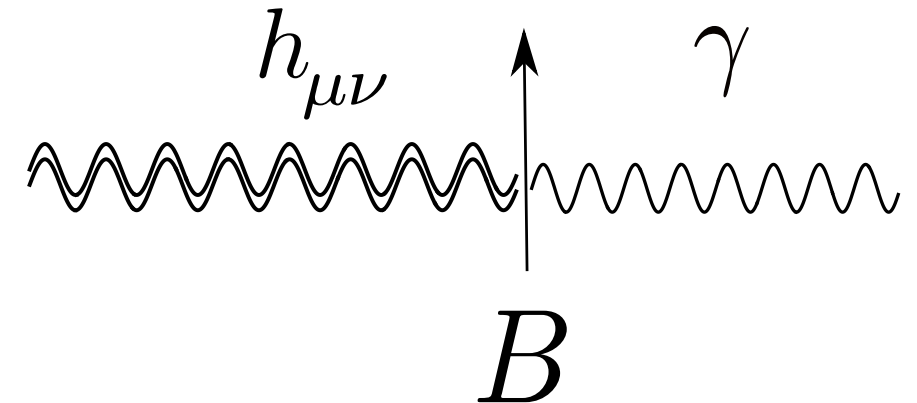
## WAVE RESONANCE OF LIGHT AND GRAVITATIONAL WAVES

M. E. GERTSENSHTEIN

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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# The (inverse) Gertsenhstein Effect

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

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

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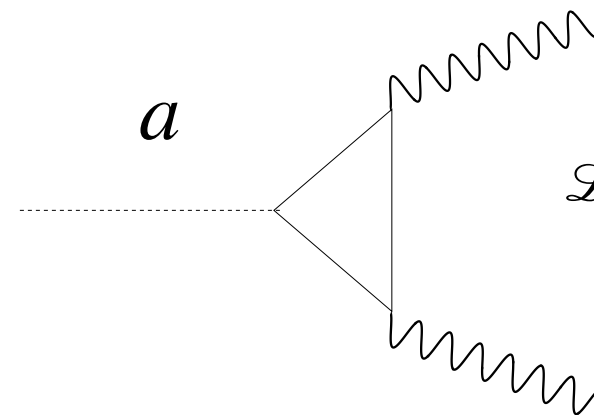
- The process is strictly analogous to axion dark matter conversion.

[Raffelt, Stodolski'89](#)

# The QCD axion as dark matter

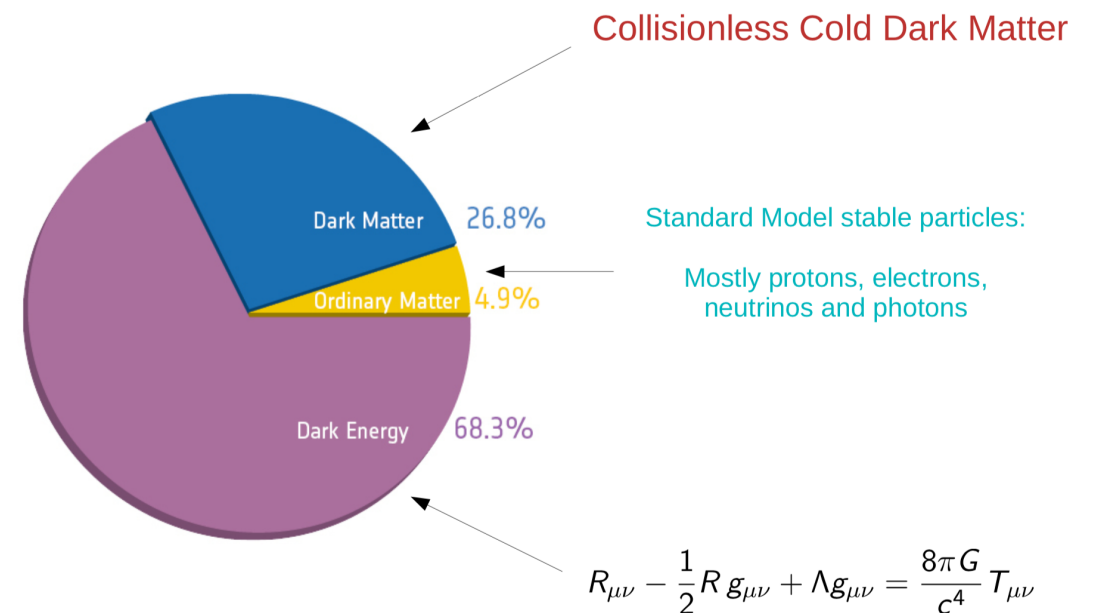
- Pseudoscalar field
- Solution to the strong CP problem

Peccei, Quinn 1977


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

- Excellent dark matter candidate

Weinberg, Wilczek 1978



# Axion electrodynamics

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

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

Sikivie, 1983

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

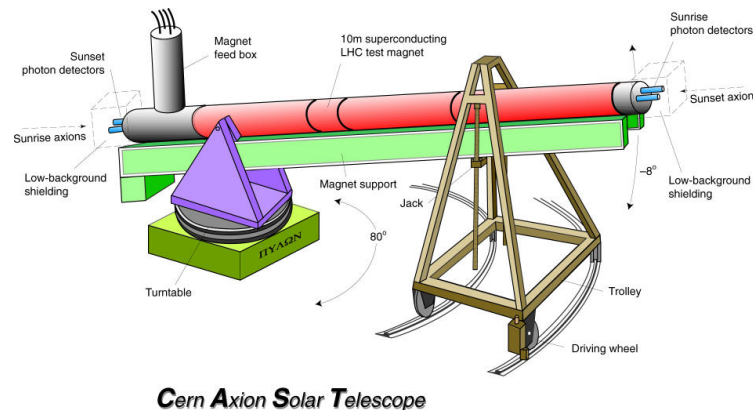
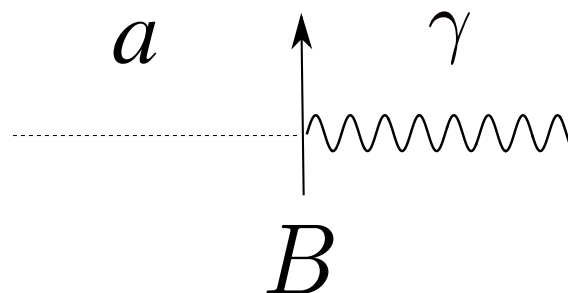
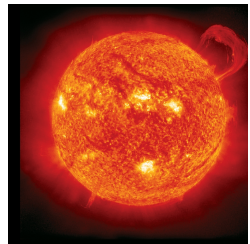
$$\nabla \cdot \mathbf{E} = j^0$$

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

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

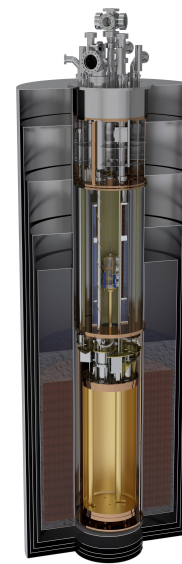
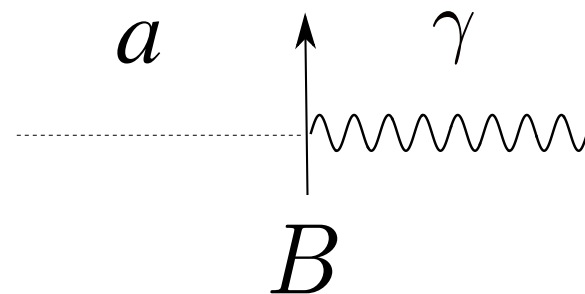
# Axion electrodynamics

- Helioscopes (X rays)



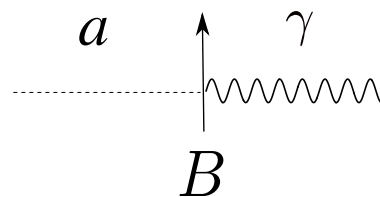
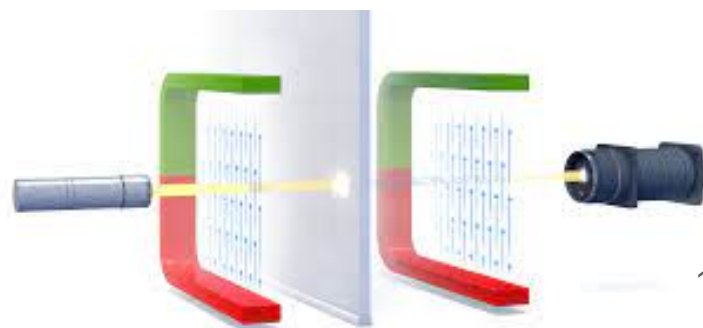
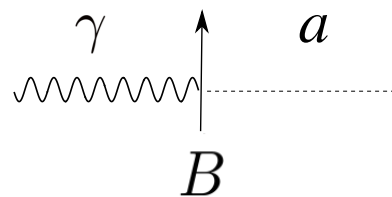
- CAST
- IAXO
- ....

- Haloscopes (radio frequencies)



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

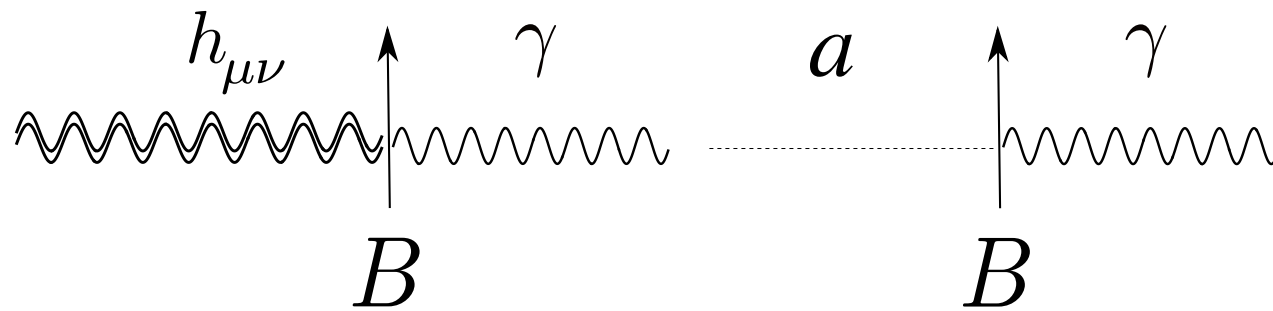
- Purely lab experiments



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

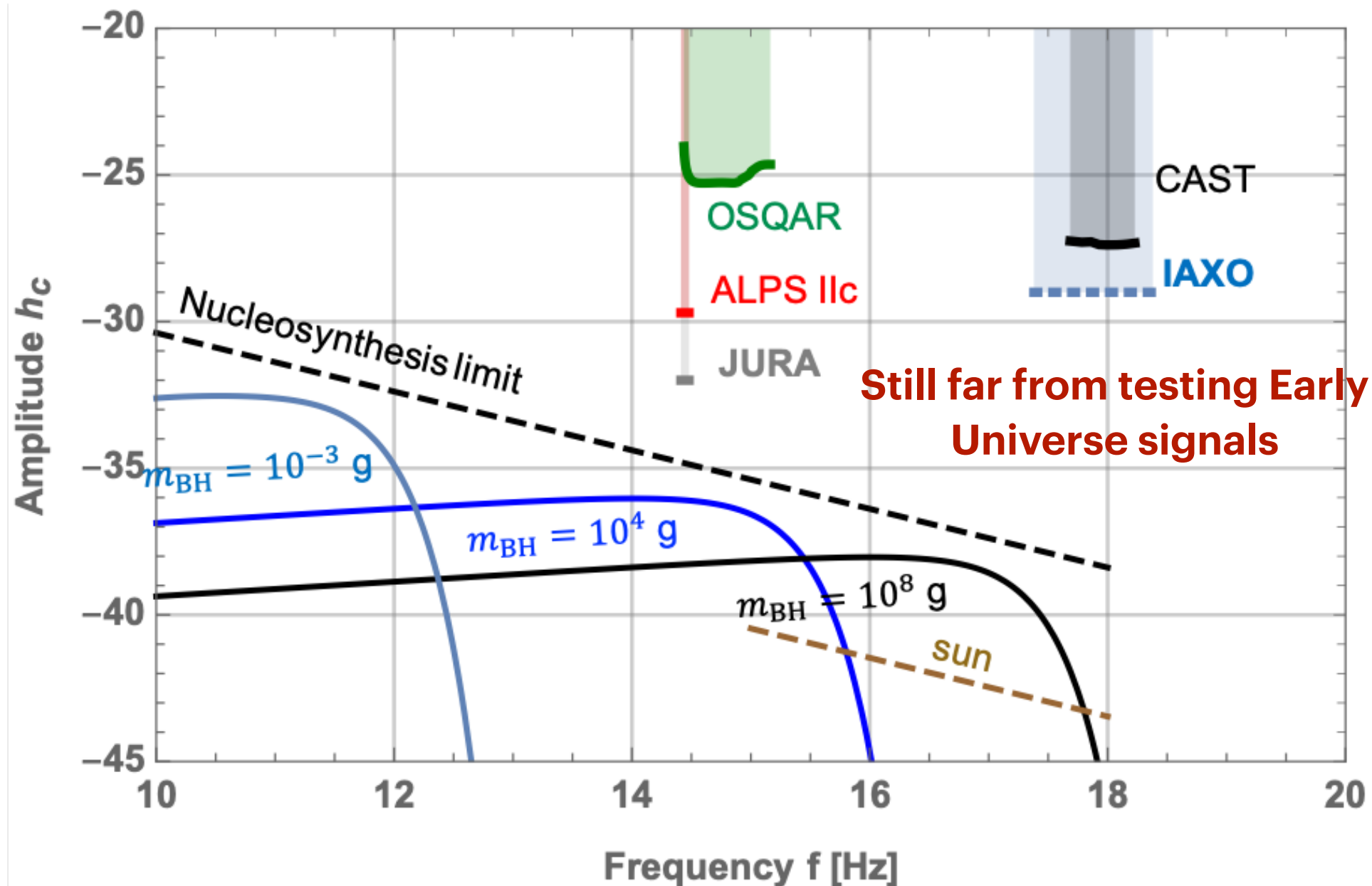


# The (inverse) Gertsenhstein Effect



[A. Ejlli](#) , [D. Ejlli](#), [A. M. Cruise](#), [G. Pisano](#) & [H. Grote](#)

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



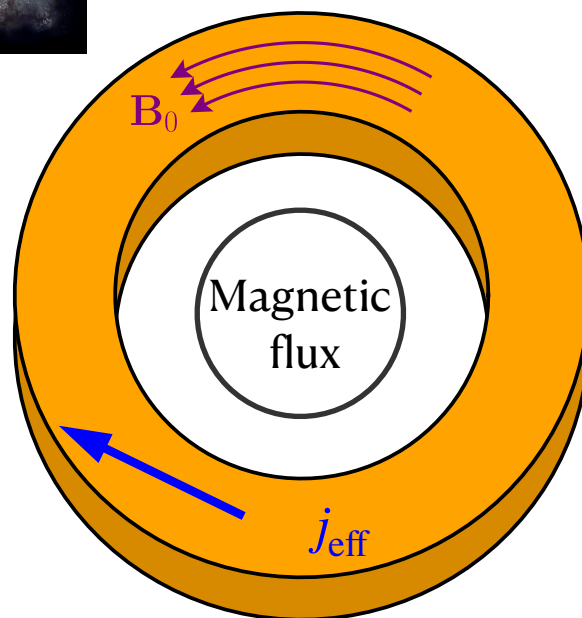
# Gravitational wave versus axion electrodynamics

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



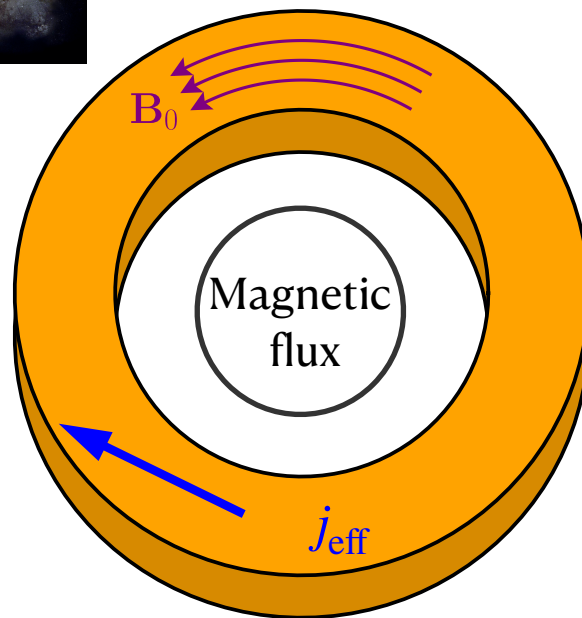
# Low mass axion haloscopes



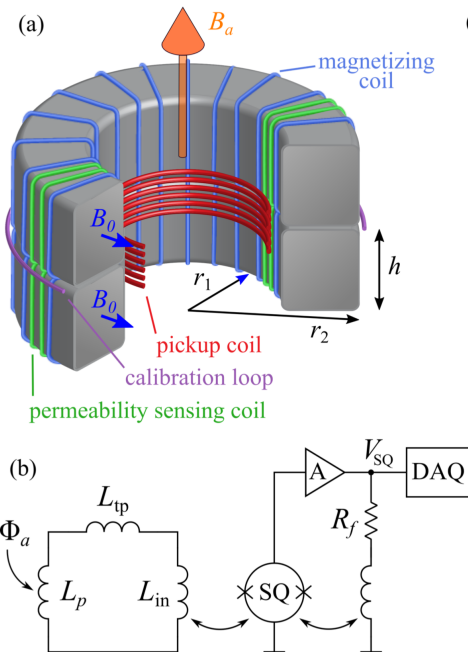
$$\nabla \times \mathbf{B} - \partial_t \mathbf{E} = \underbrace{g_{a\gamma\gamma} \partial_t a}_{j_{\text{eff}}} \mathbf{B}_0$$

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

# Low mass axion haloscopes



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



(c) SHAFT



physics <https://doi.org/>

## Search for axion-like dark matter with ferromagnets

Alexander V. Gramolin<sup>1</sup>, Deniz Aybas<sup>1,2</sup>, Dorian Johnson<sup>1</sup>, Janos Adam<sup>1</sup> and Alexander O. Sushkov<sup>1,2,3</sup>

PRL 117, 141801 (2016)

PHYSICAL REVIEW LETTERS

week ending  
30 SEPTEMBER 2016

## Broadband and Resonant Approaches to Axion Dark Matter Detection

Yonatan Kahn,<sup>1,\*</sup> Benjamin R. Safdi,<sup>2,†</sup> and Jesse Thaler<sup>2,‡</sup>

<sup>1</sup>Department of Physics, Princeton University, Princeton, New Jersey 08544, USA

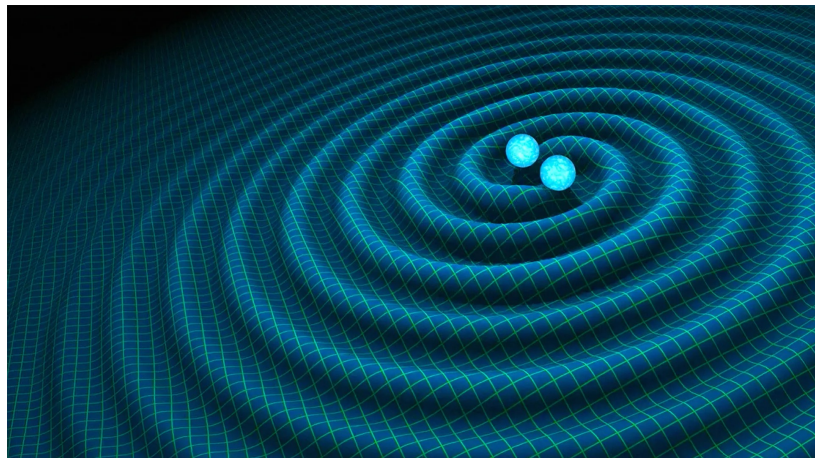
<sup>2</sup>Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA  
(Received 3 March 2016; published 30 September 2016)

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.**

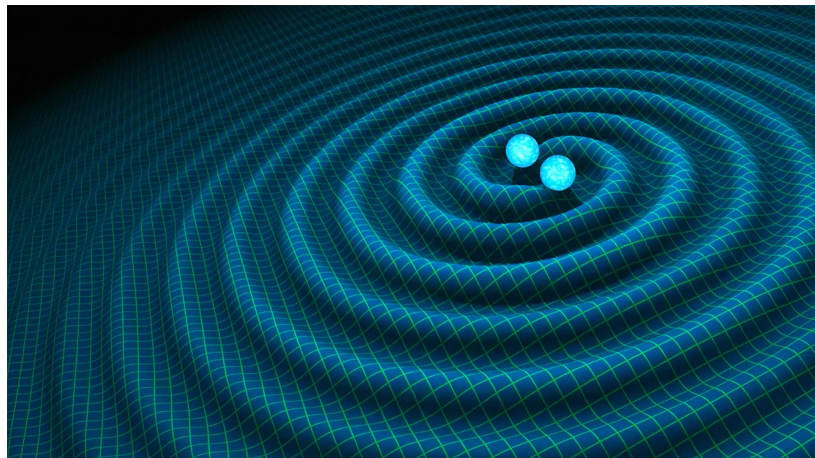
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \quad |h_{\mu\nu}| \ll 1$$



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

# More explicit comparison to axions

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



$$\nabla \cdot \mathbf{E} = -\nabla \cdot \mathbf{P}$$

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

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

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

$$P_i = -h_{ij}E_j \quad M_i = -h_{ij}B_j \quad (\text{in the TT gauge})$$

Domcke, CGC, Rodd, 2202.00695

# More explicit comparison to axions

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

$$\nabla \cdot \mathbf{E} = - \nabla \cdot \mathbf{P}$$

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

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

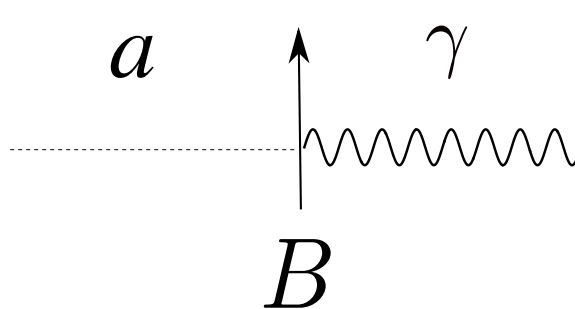
$$\nabla \times \mathbf{B} = \partial_t \mathbf{E} + \nabla \times \mathbf{M} + \partial_t \mathbf{P}$$

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

McAllister et al, 1803.07755

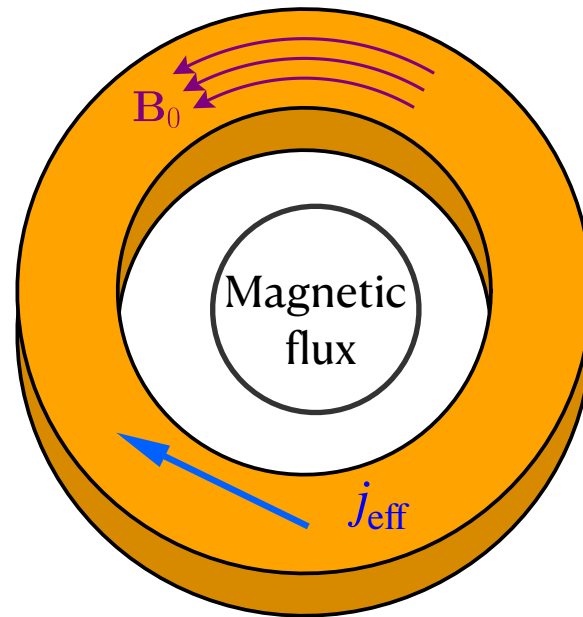
Tobar et al, 1809.01654

Ouellet et al, 1809.10709

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



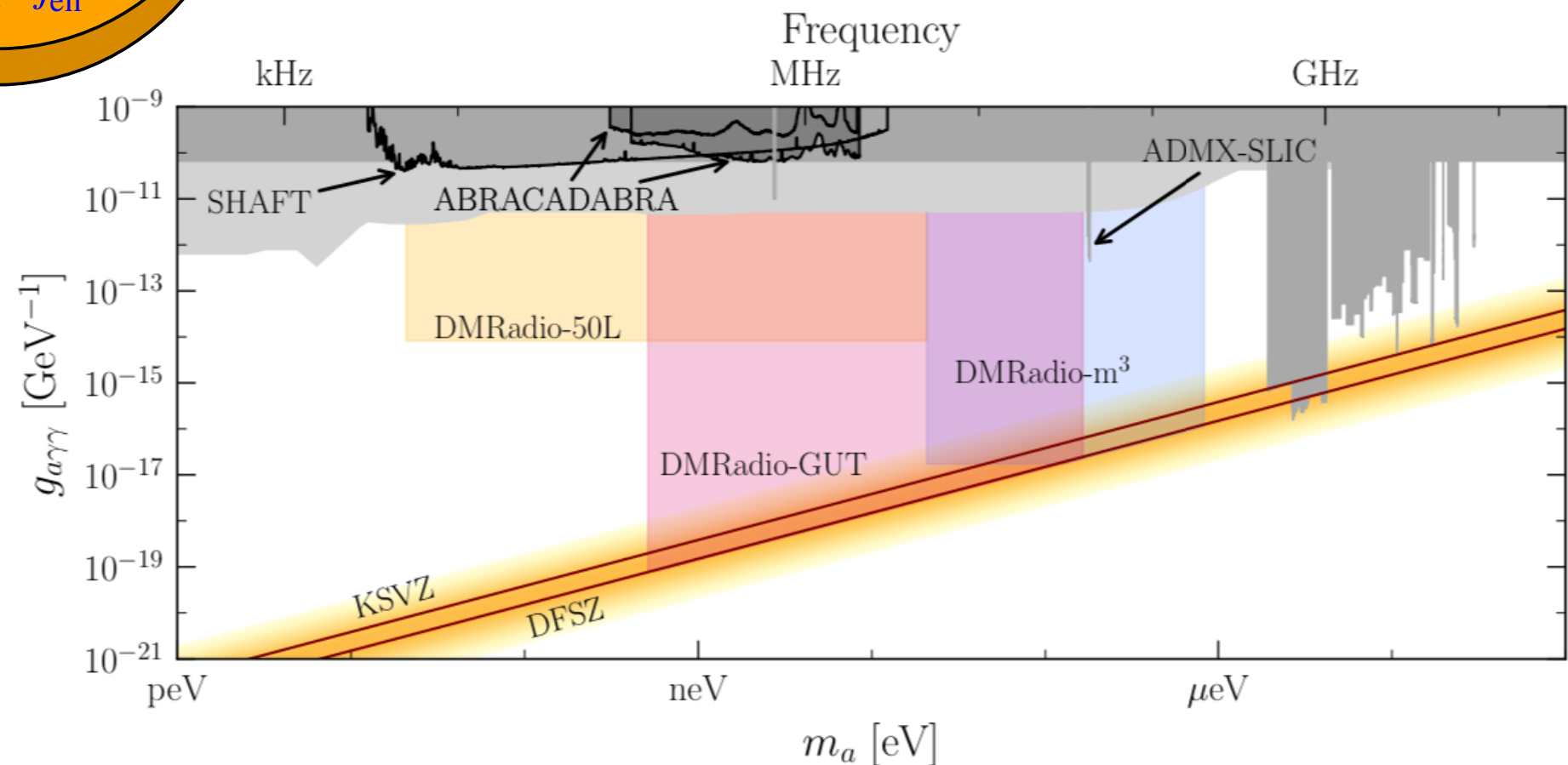
# DMRadio program



Proposal for a definitive search for GUT-scale QCD axions

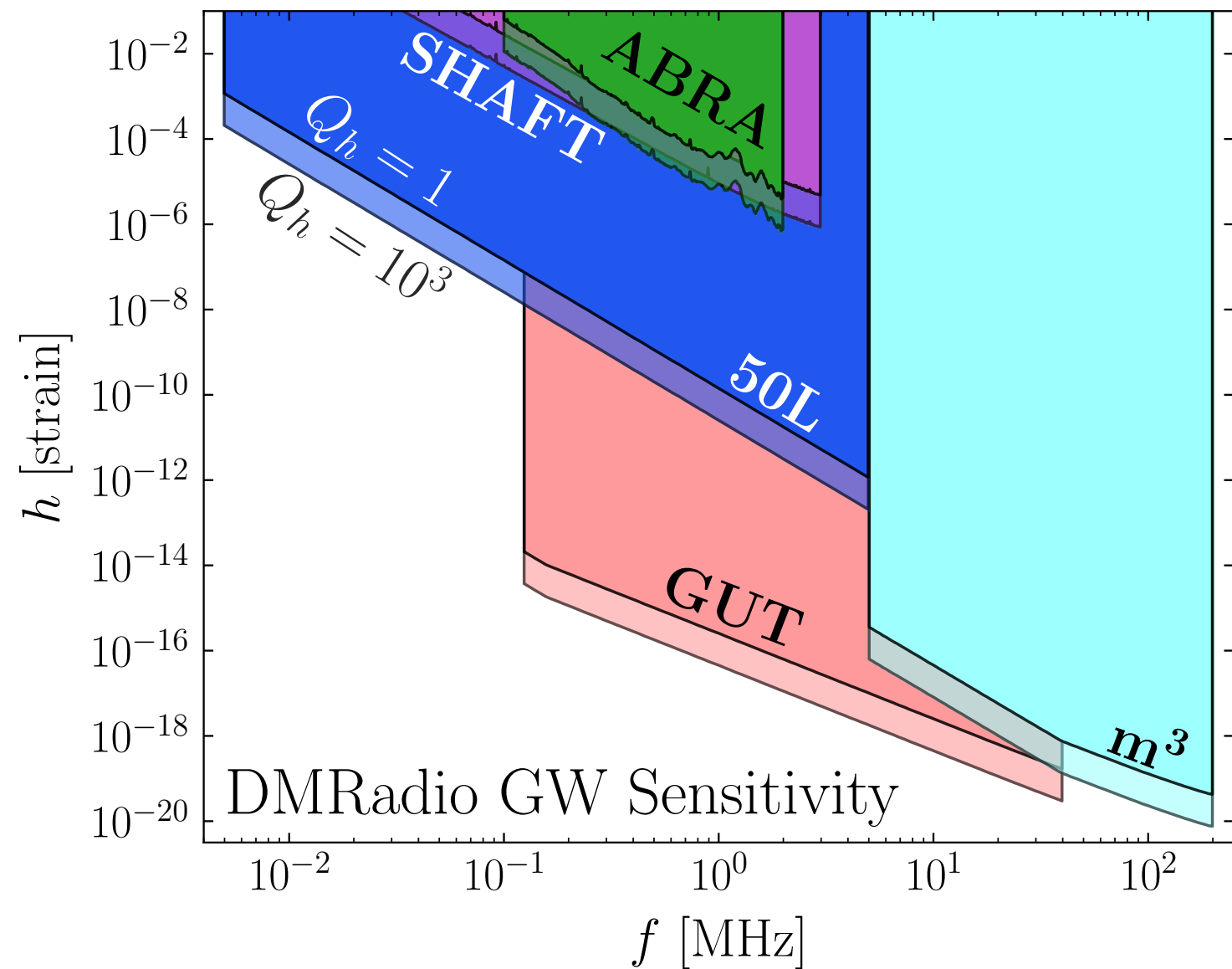
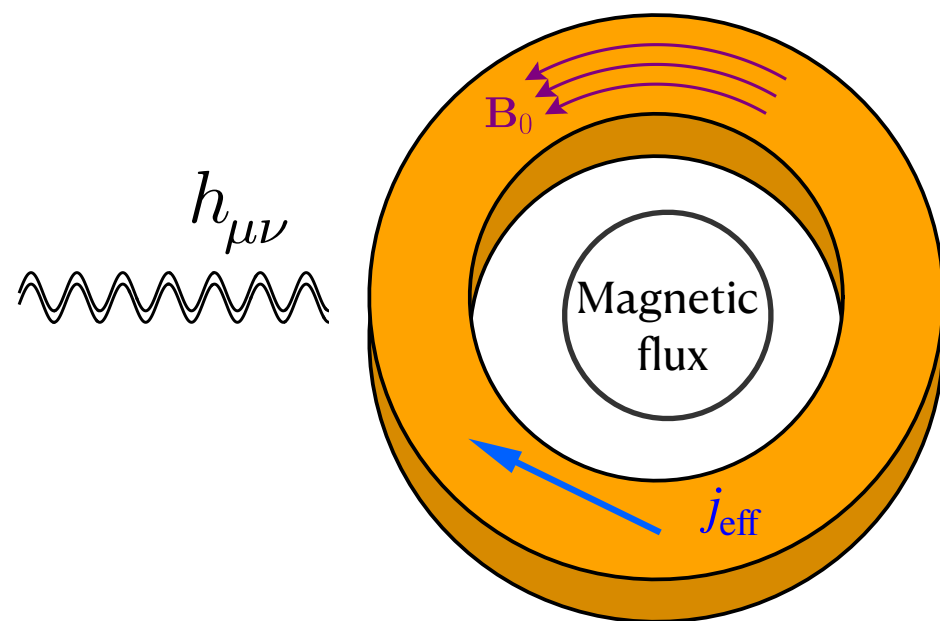
L. Brouwer *et al.* (DMRadio Collaboration)

Phys. Rev. D **106**, 112003 – Published 12 December 2022



# DMRadio program

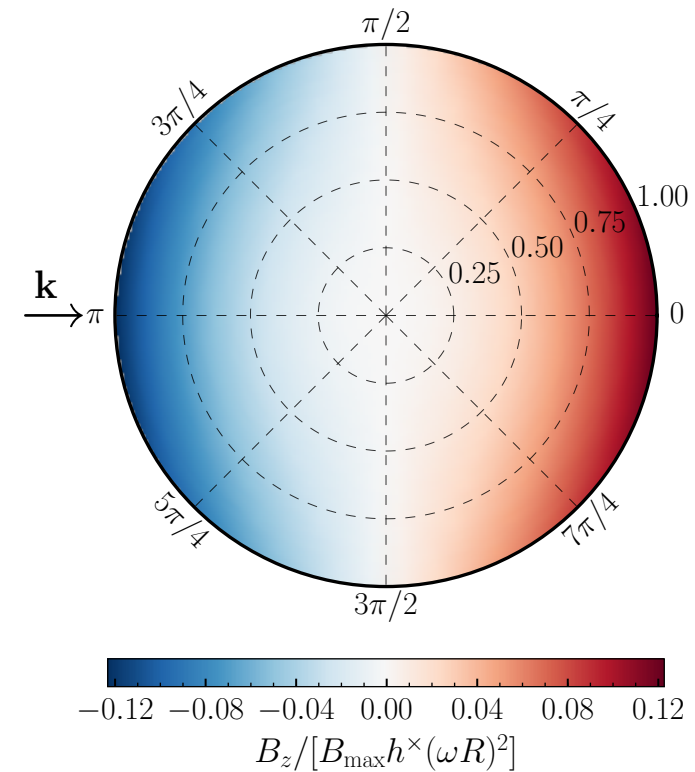
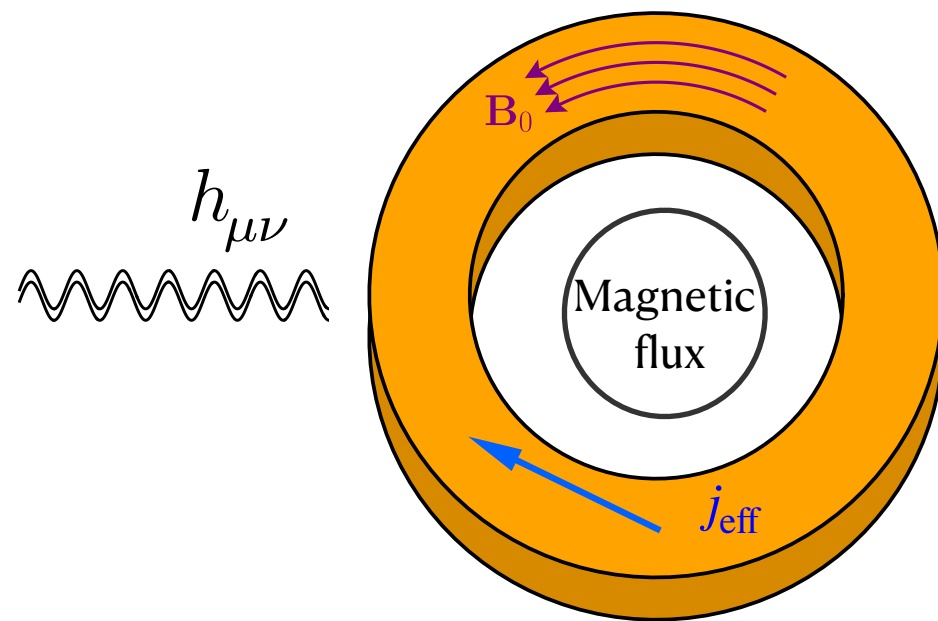
Domcke, CGC, Rodd, 2202.00695





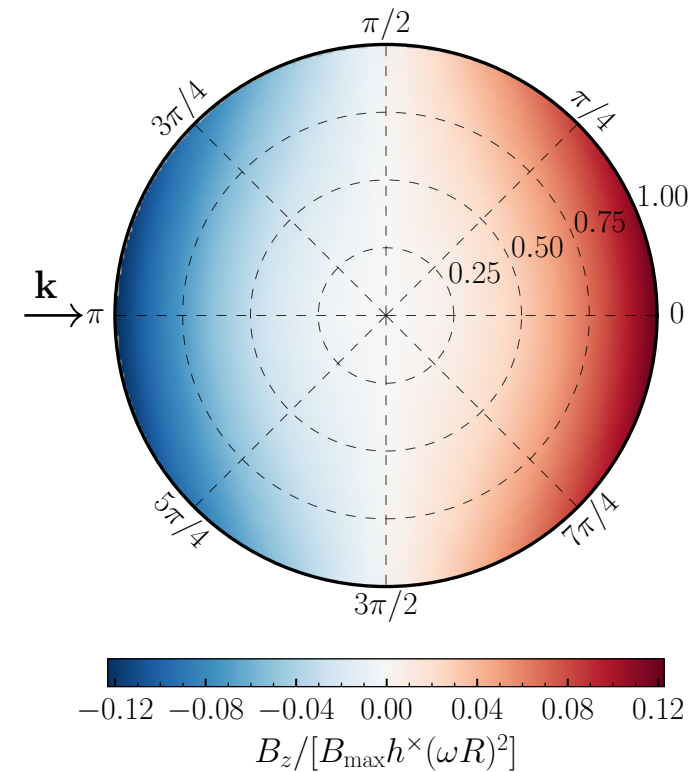
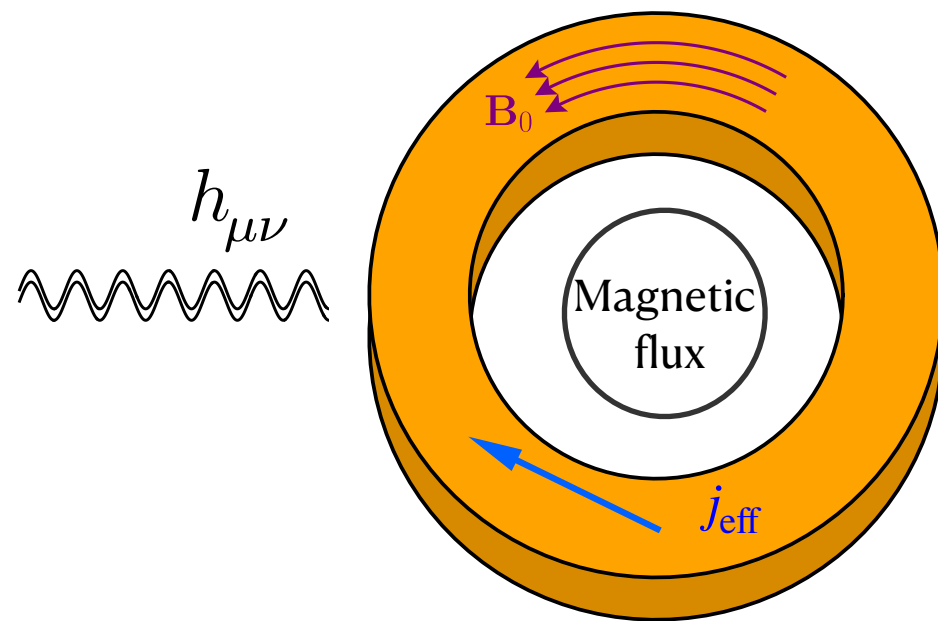
# Toroidal magnetic fields

Domcke, CGC, Rodd, 2202.00695



# Toroidal magnetic fields

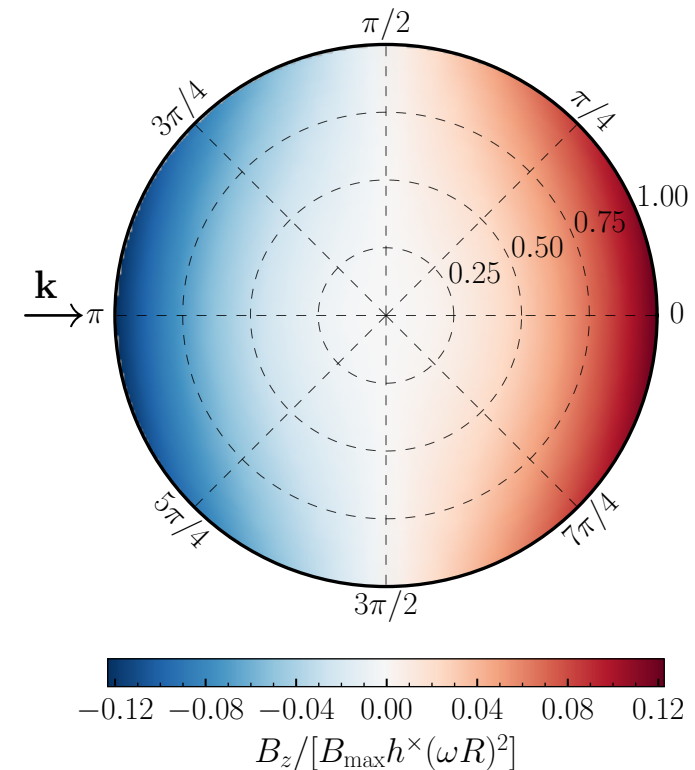
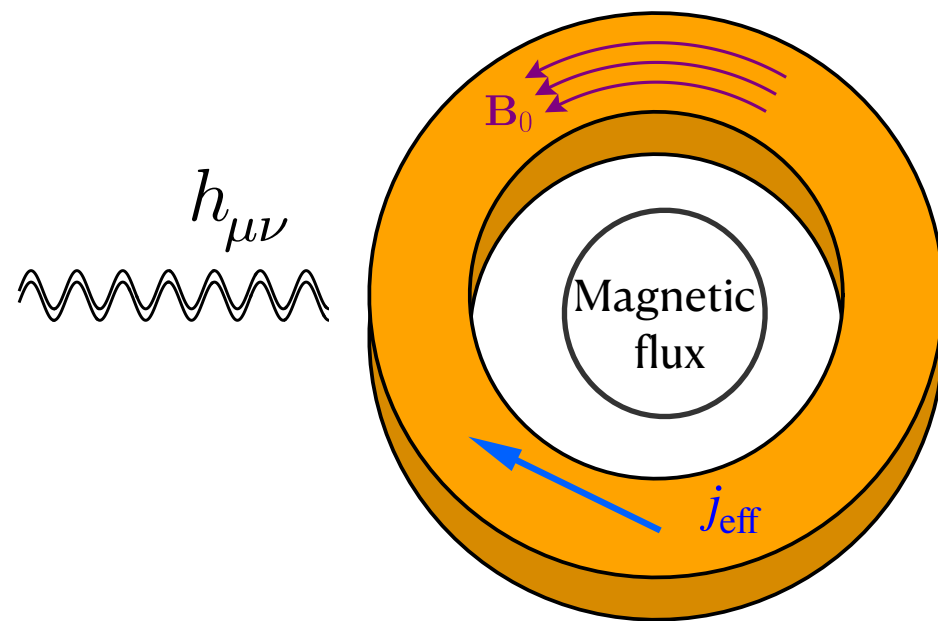
Domcke, CGC, Rodd, 2202.00695



- Only one polarization

# Toroidal magnetic fields

Domcke, CGC, Rodd, 2202.00695

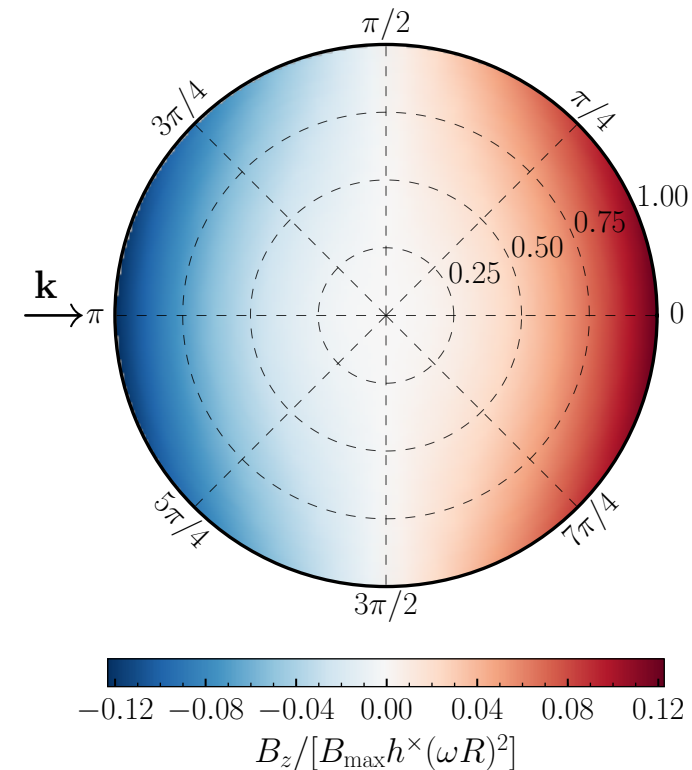
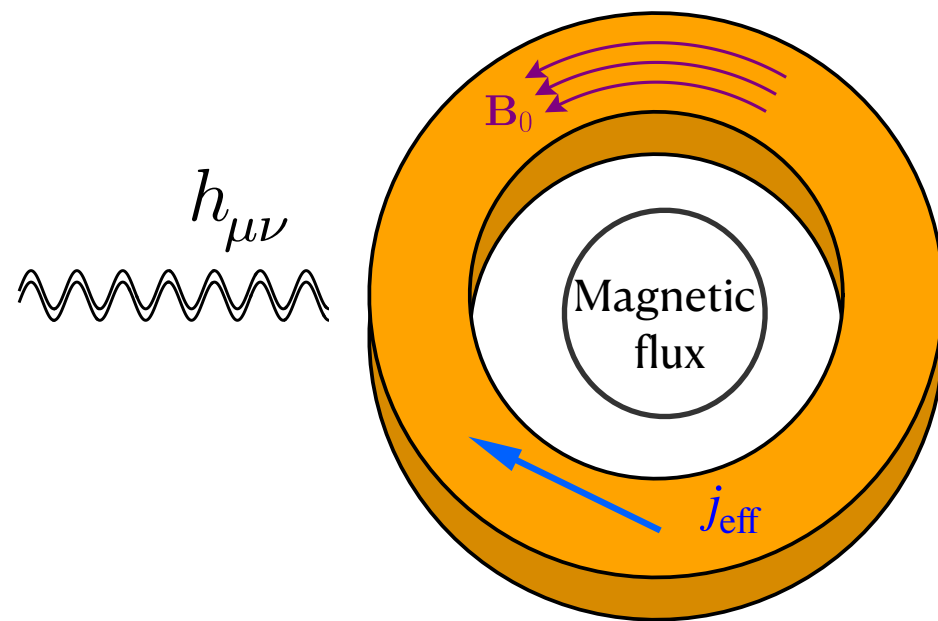


- Only one polarization
- Suppression at small frequencies

$$\omega R \ll 1$$

# Toroidal magnetic fields

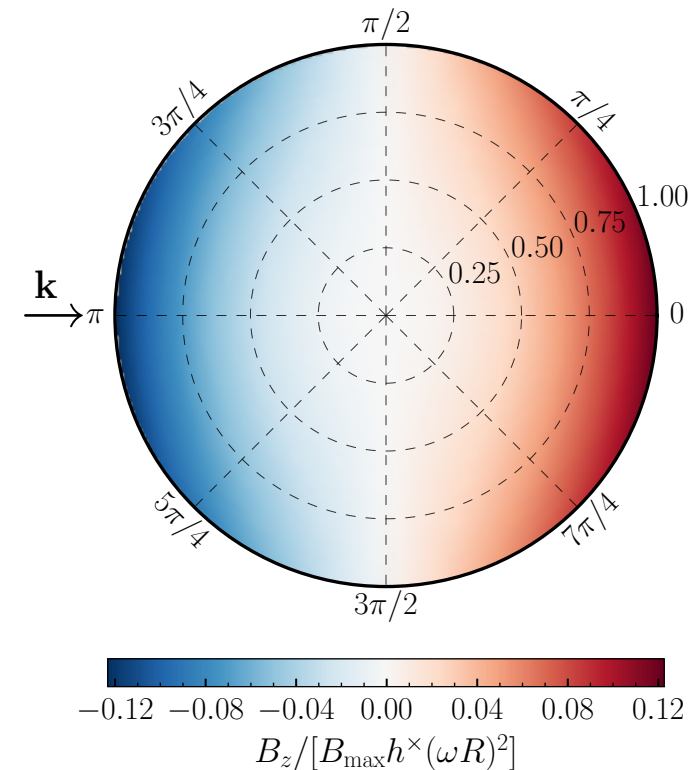
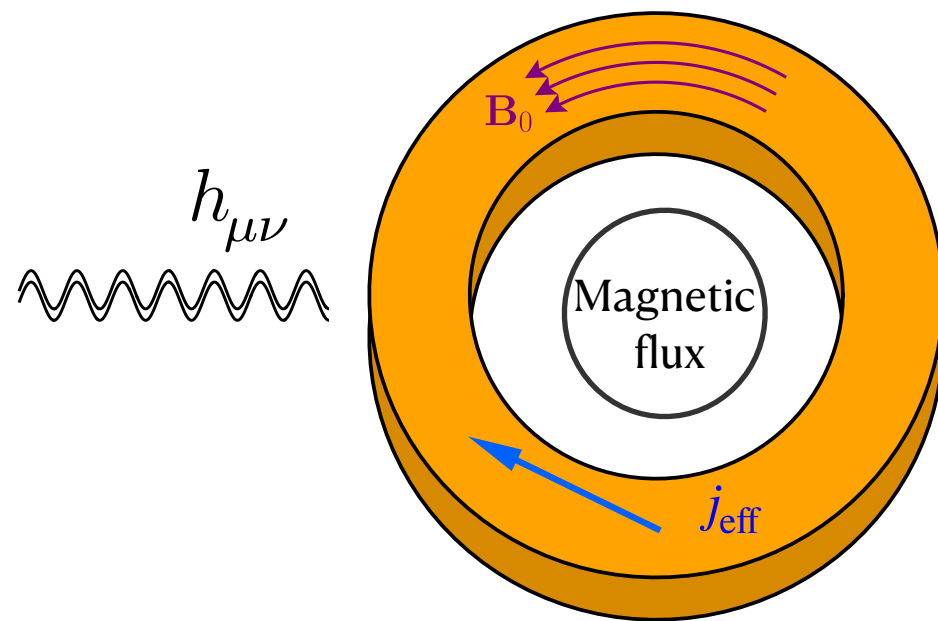
Domcke, CGC, Rodd, 2202.00695



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

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Domcke, CGC, Rodd, 2202.00695



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# Selection rules

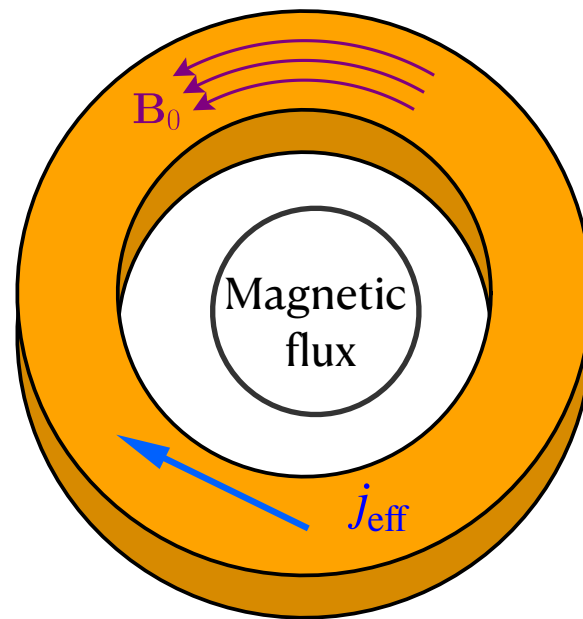
Optimizing the geometry of axion haloscopes for  
gravitational wave searches

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Valerie Domcke,<sup>1</sup> Camilo Garcia-Cely,<sup>2</sup> Sung Mook Lee,<sup>3</sup> Nicholas L. Rodd<sup>1</sup>

work in progress: 2306.xxxxx

# DMRadio program

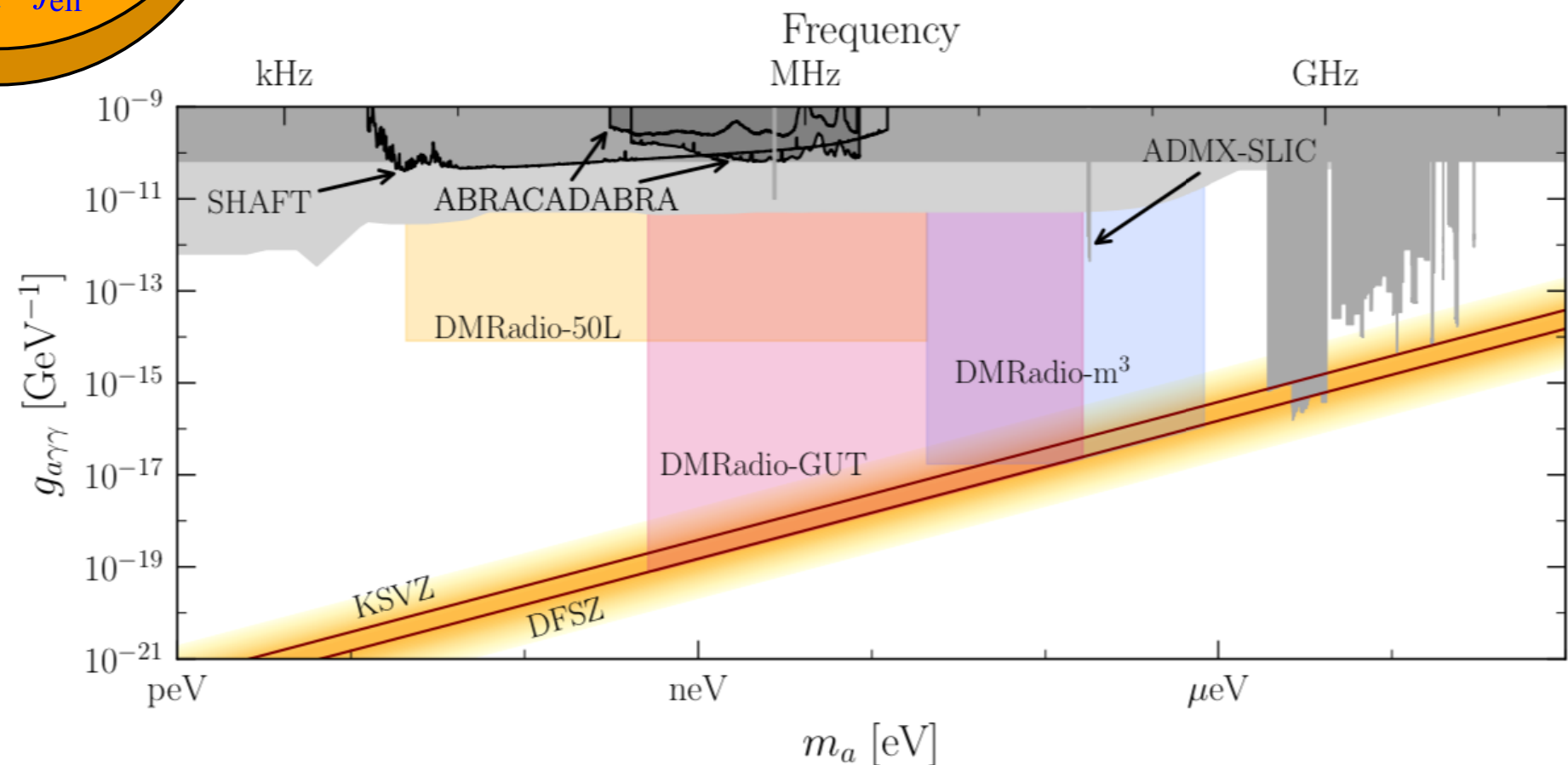


Proposal for a definitive search for GUT-scale QCD axions

L. Brouwer *et al.* (DMRadio Collaboration)

Phys. Rev. D **106**, 112003 – Published 12 December 2022

Toroidal and  
solenoidal  
geometries



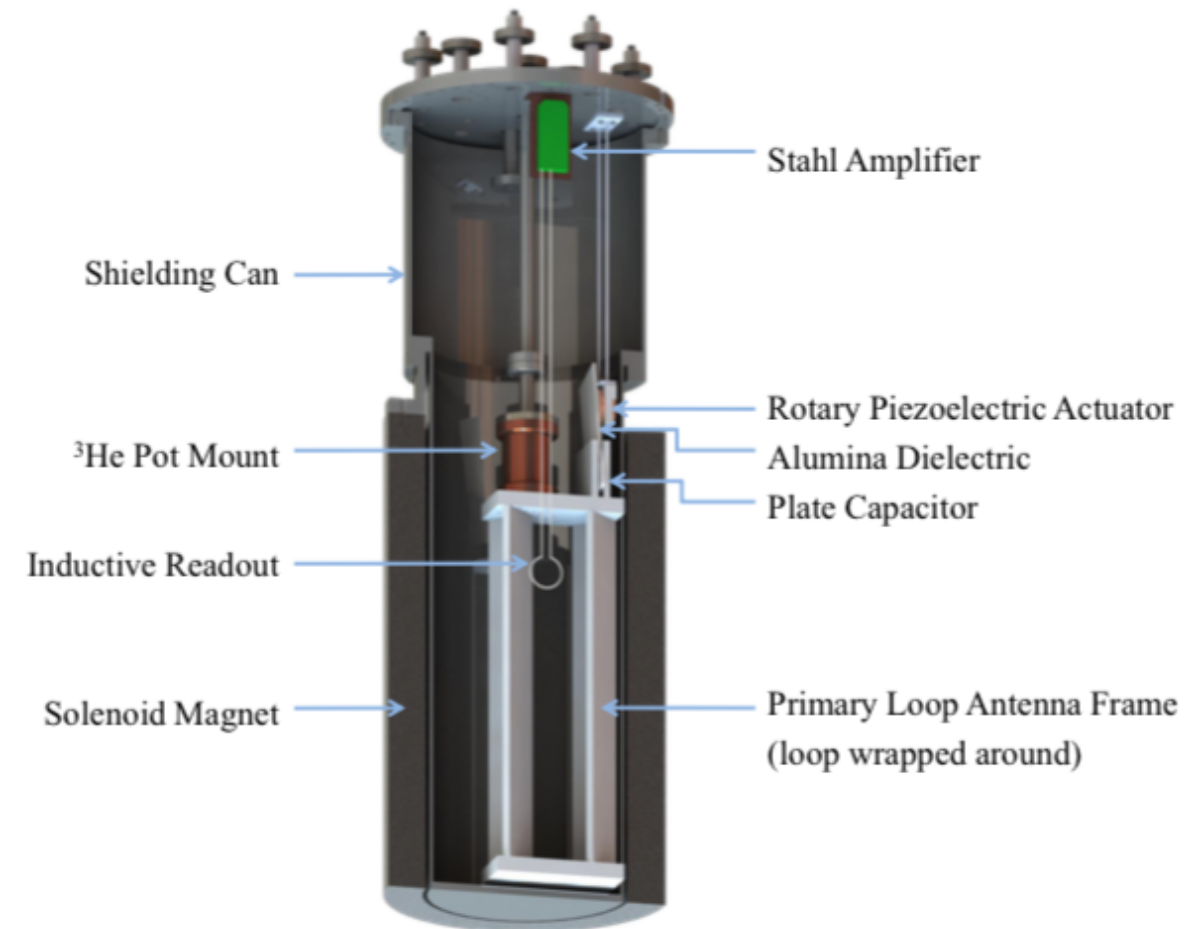
# Beyond toroidal configurations

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





# Selection rules

Domcke, CGC, Lee, Rodd (in progress)

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:

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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 $\mathcal{O}[(\omega L)^4]$

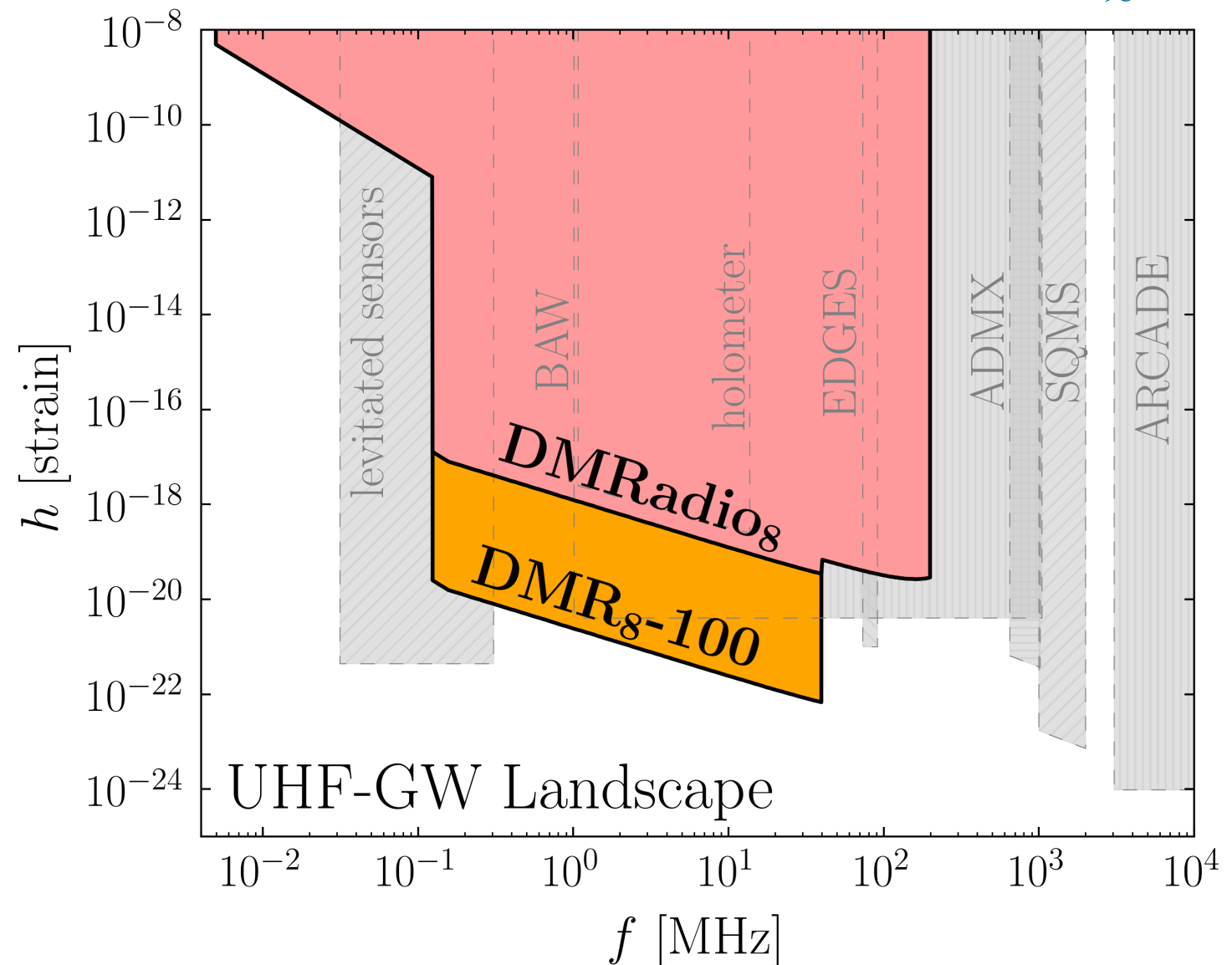
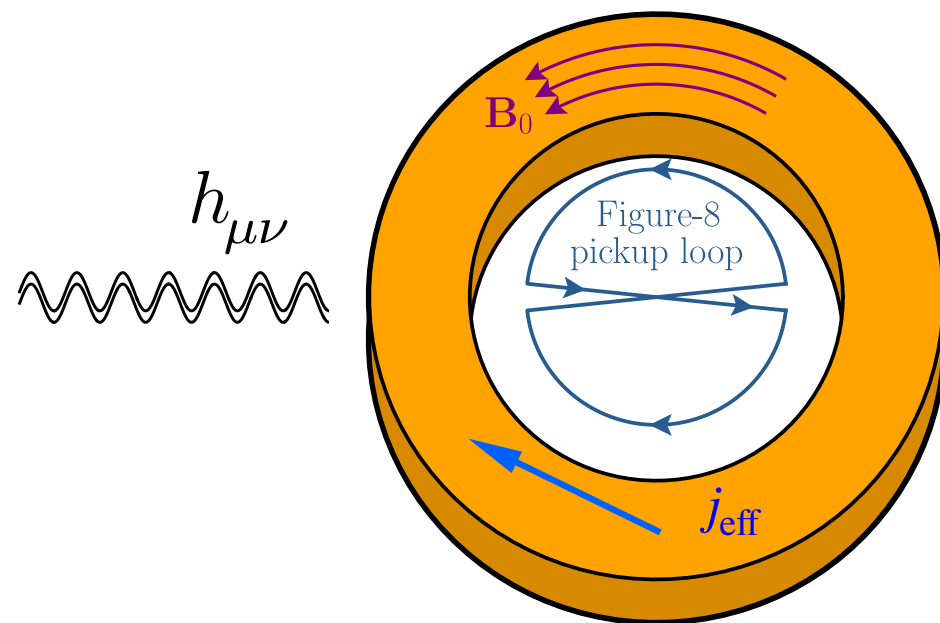
Expect  
 $\omega L \ll 1$

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

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

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

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

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

The  $\omega^2$  dependence is unavoidable

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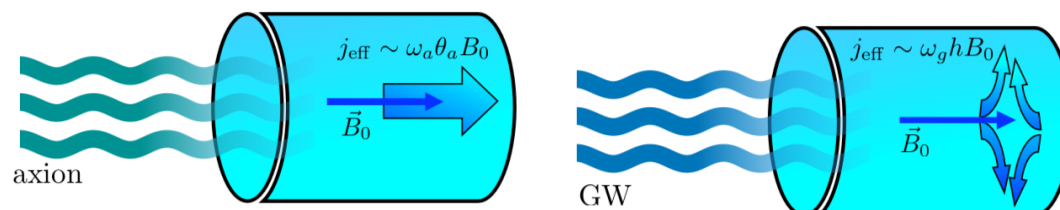
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Detecting High-Frequency Gravitational Waves with Microwave Cavities

Asher Berlin (New York U. and Fermilab), Diego Blas (Barcelona, Autonomia 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

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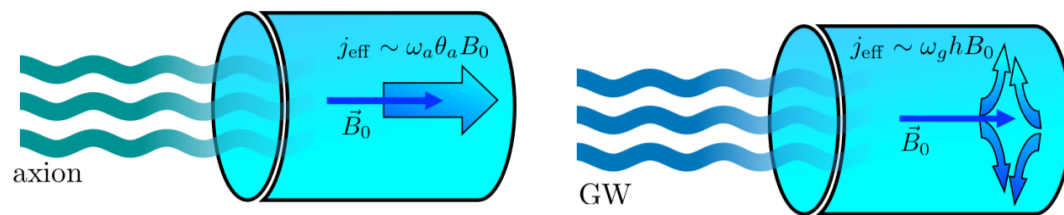
Different experimental proposals have coalesced on a strain sensitivity of  $10^{-22}$  for MHz GWs, **still orders of magnitude away from signals of the early Universe**. Whether we can hope to probe such strain sensitivities remains to be determined.

# Other possibilities

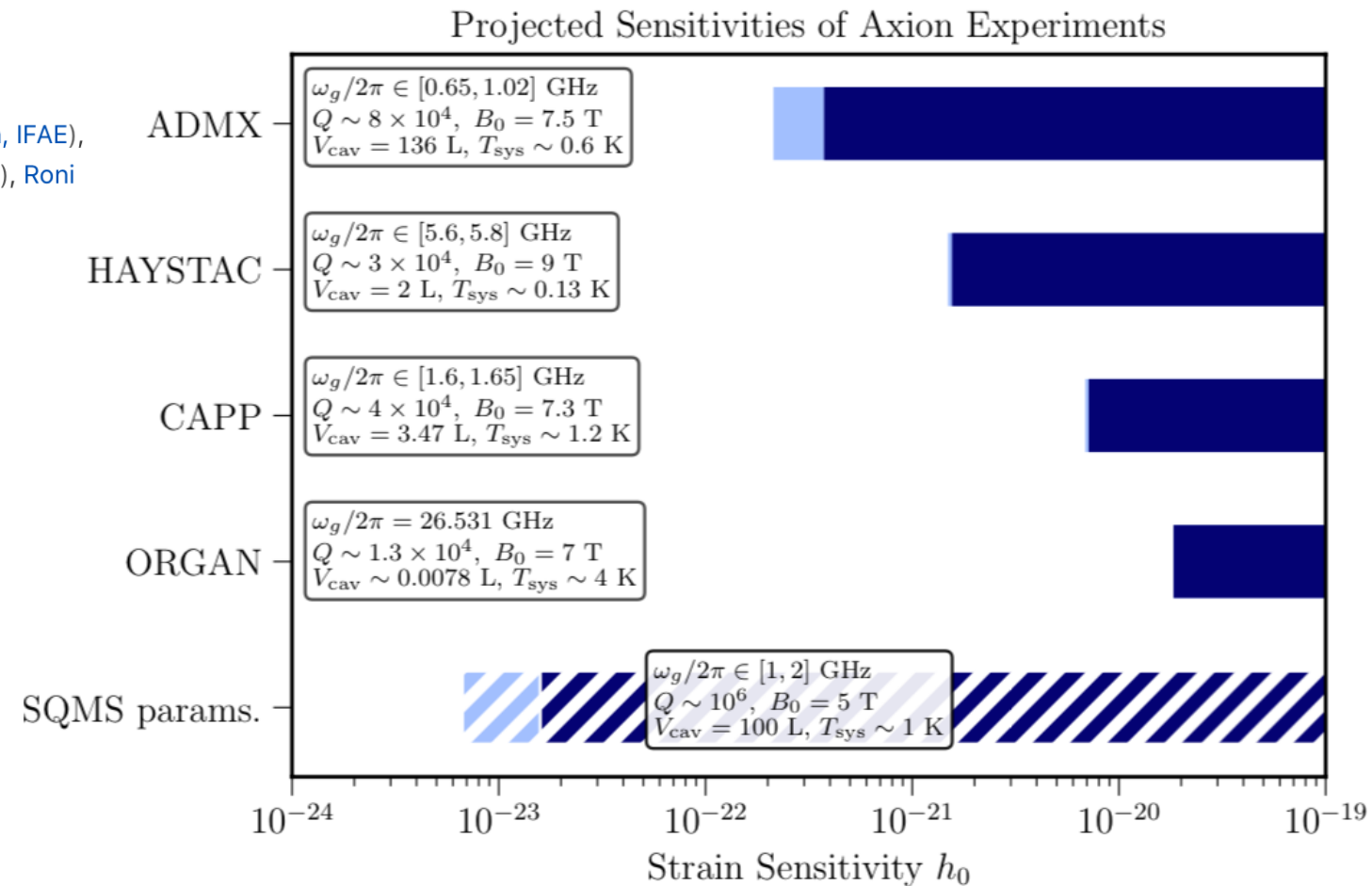
## Detecting High-Frequency Gravitational Waves with Microwave Cavities

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



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

Eigenmodes

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

# Oscillations after the formation of the CMB

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

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

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

The plasma frequency acts as an effective mass term

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

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

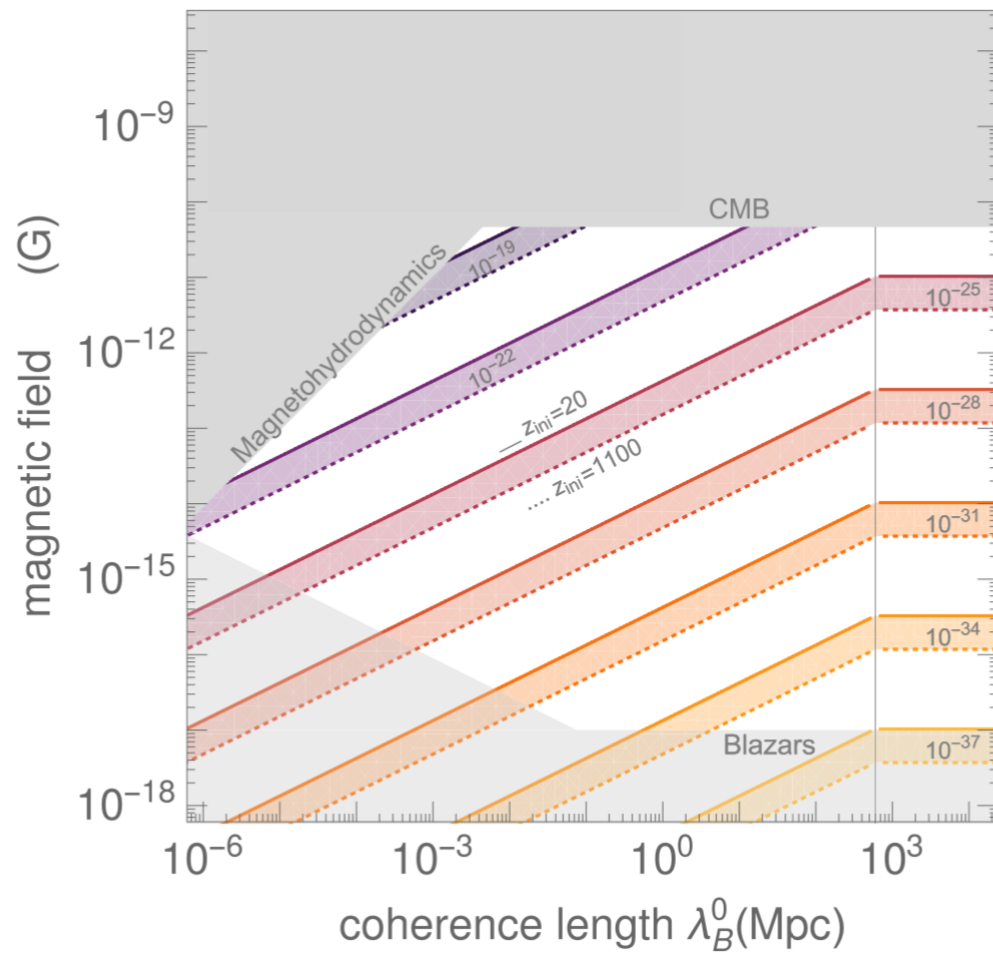
Although cosmic magnetic fields are not expected to be perfectly homogeneous, coherent oscillations take place in highly homogeneous patches.

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

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

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<sup>1,\*</sup> and Andrey Saveliev<sup>2,3,†</sup>

<sup>1</sup>Laboratoire Univers et Particules de Montpellier, UMR5299-CNRS, Université de Montpellier, 34095 Montpellier, France

<sup>2</sup>Institute of Physics, Mathematics and Information Technology, Immanuel Kant Baltic Federal University, 236016 Kaliningrad, Russia

<sup>3</sup>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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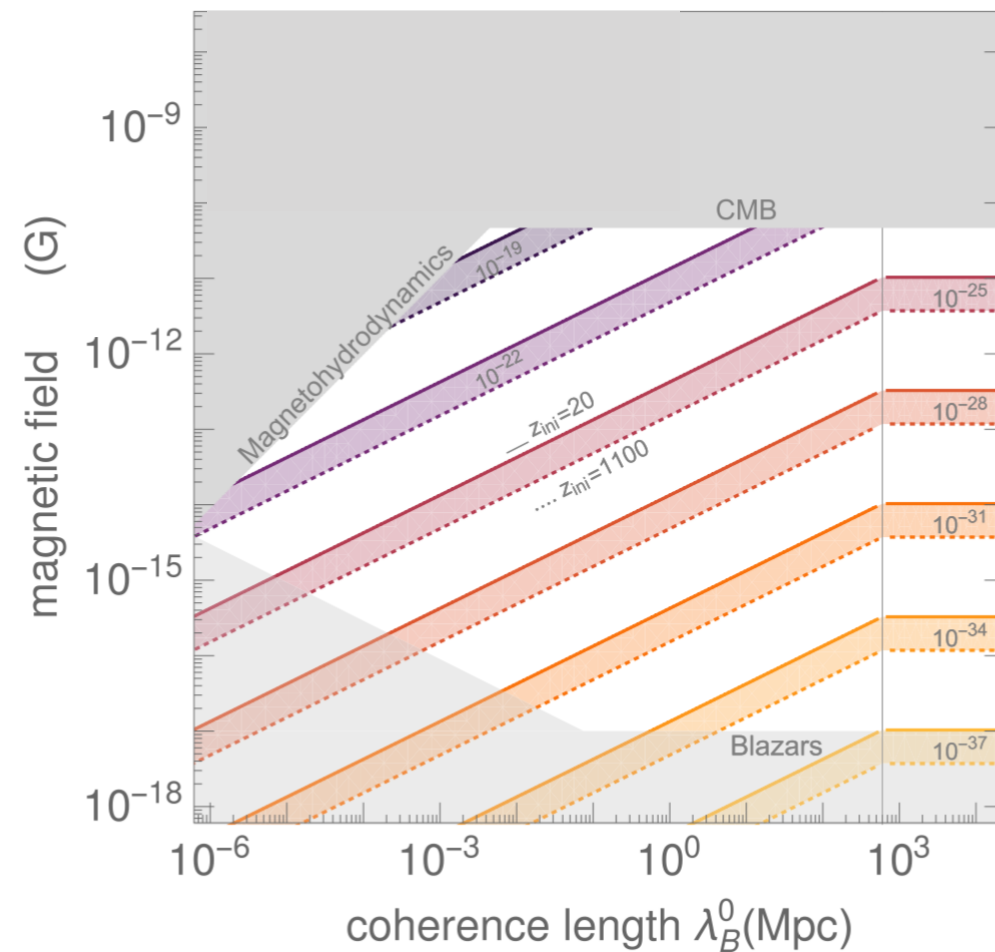
Science 02 Apr 2010  
Vol. 328, Issue 5974, pp. 73-75  
DOI: 10.1126/science.1184192

Article Figures & Data Info & Metrics eLetters PDF

Domcke, CGC 2021



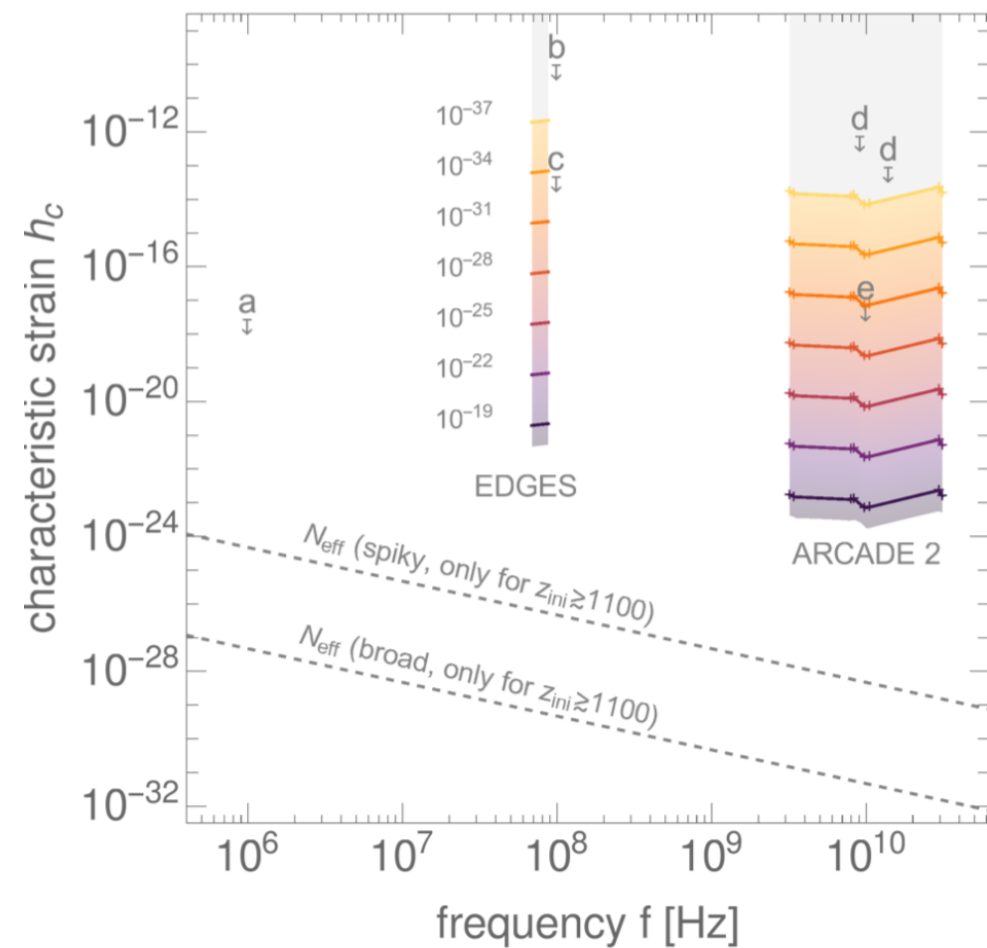
# Upper bounds on stochastic gravitational waves



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

Potential of Radio Telescopes as High-Frequency Gravitational Wave Detectors

Valerie Domcke<sup>1,2,3,\*</sup> and Camilo Garcia-Cely<sup>1,†</sup>



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](#)