Adopting axion dark matter ideas to detect high-frequency gravitational waves

Camilo García Cely

Ramón y Cajal Researcher

RENCONTRES DE BLOIS, May 24

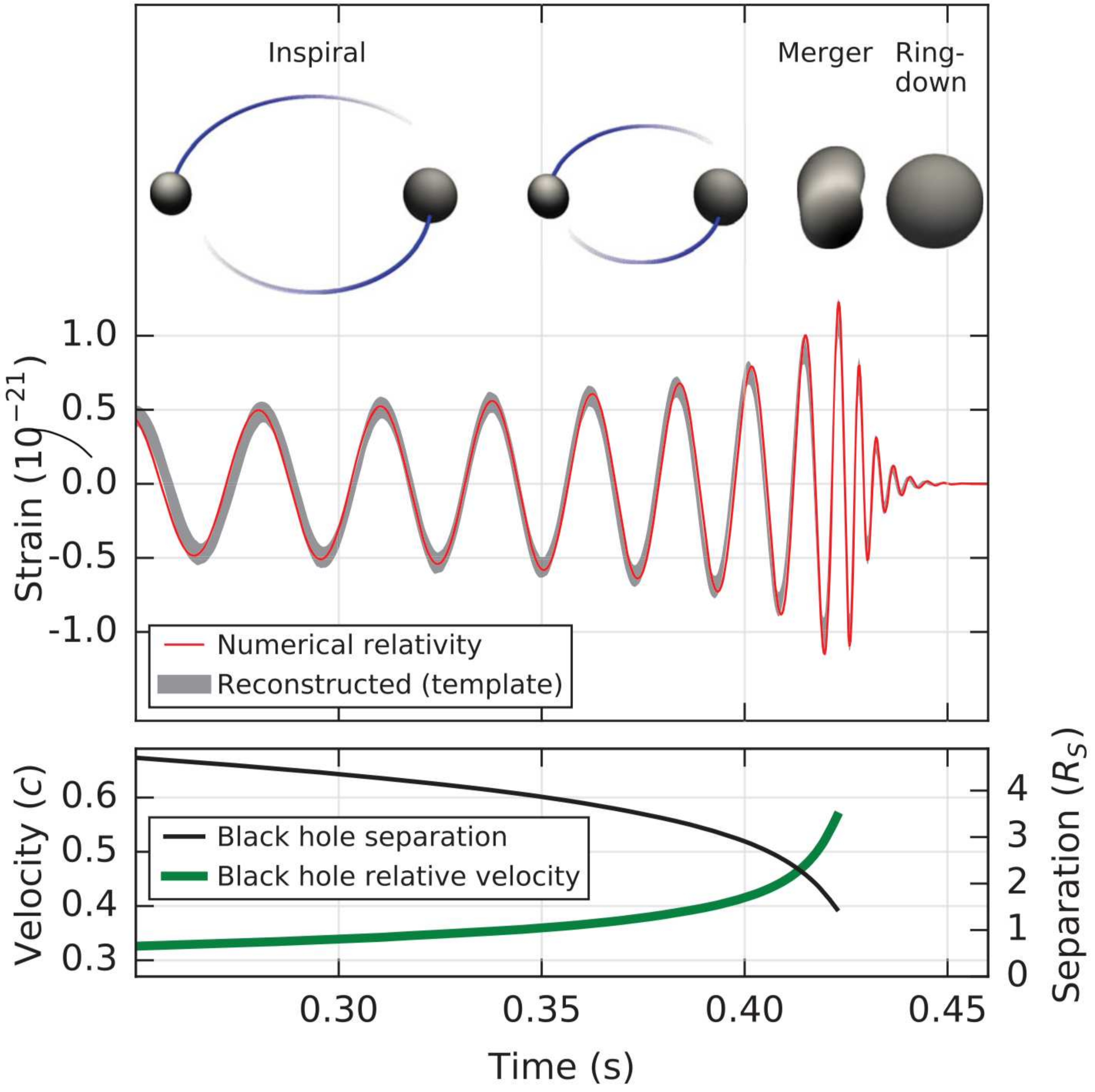
IFIC INSTITUT DE FÍSICA CORPUSCULAR

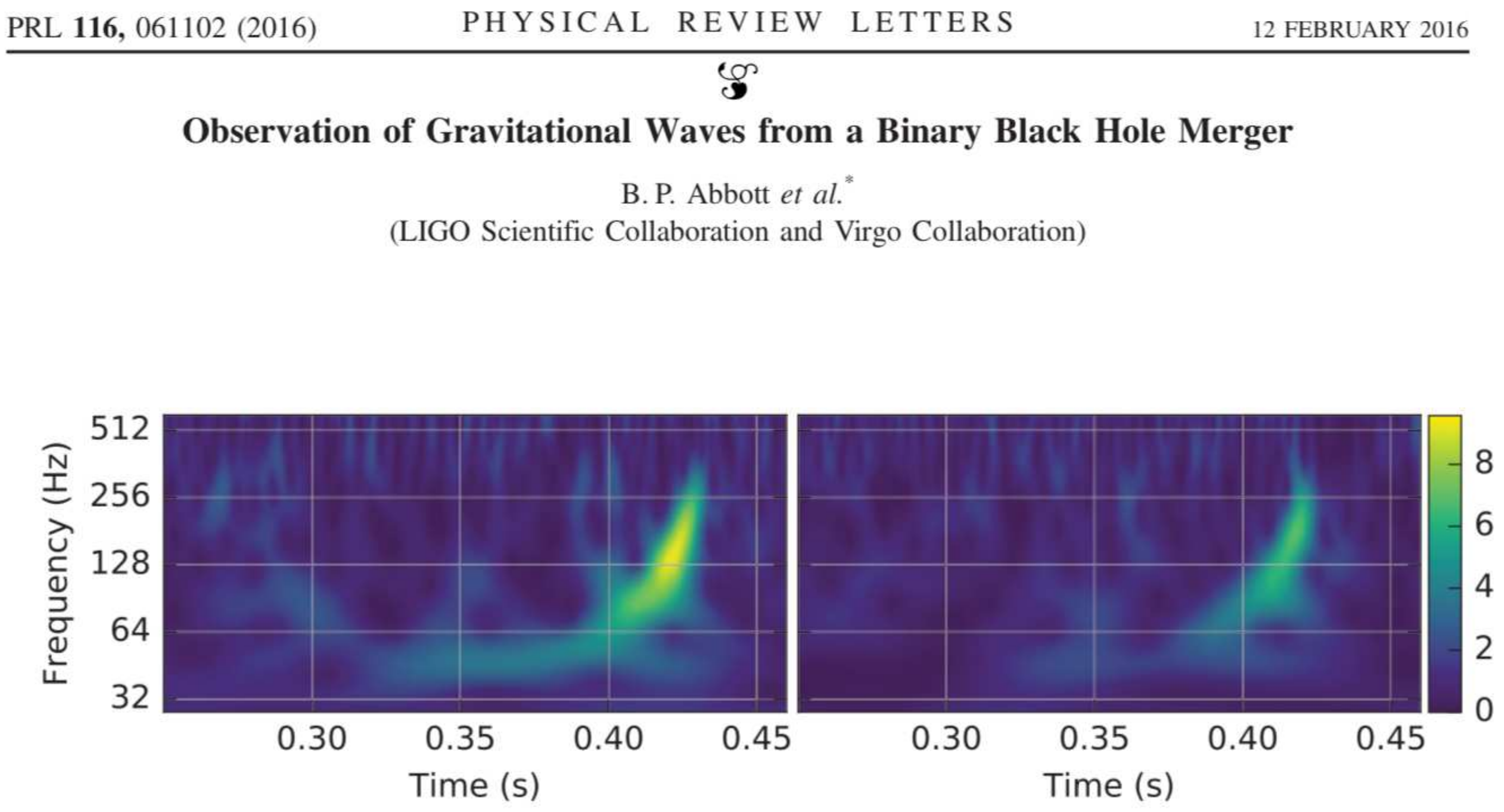
CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

VNIVERSITAT DE VALÈNCIA

Based on 2202.00695 with Domcke, CGC, Rodd
and PRL (2021) 2, 021104 with Domcke, CGC

High-frequency gravitational waves





$$f \ll 10\,\mathrm{kHz}$$

There are no known astrophysical objects that are small and dense enough to produce gravitational waves beyond 10 kHz

High-frequency gravitational waves

Part of a collection:

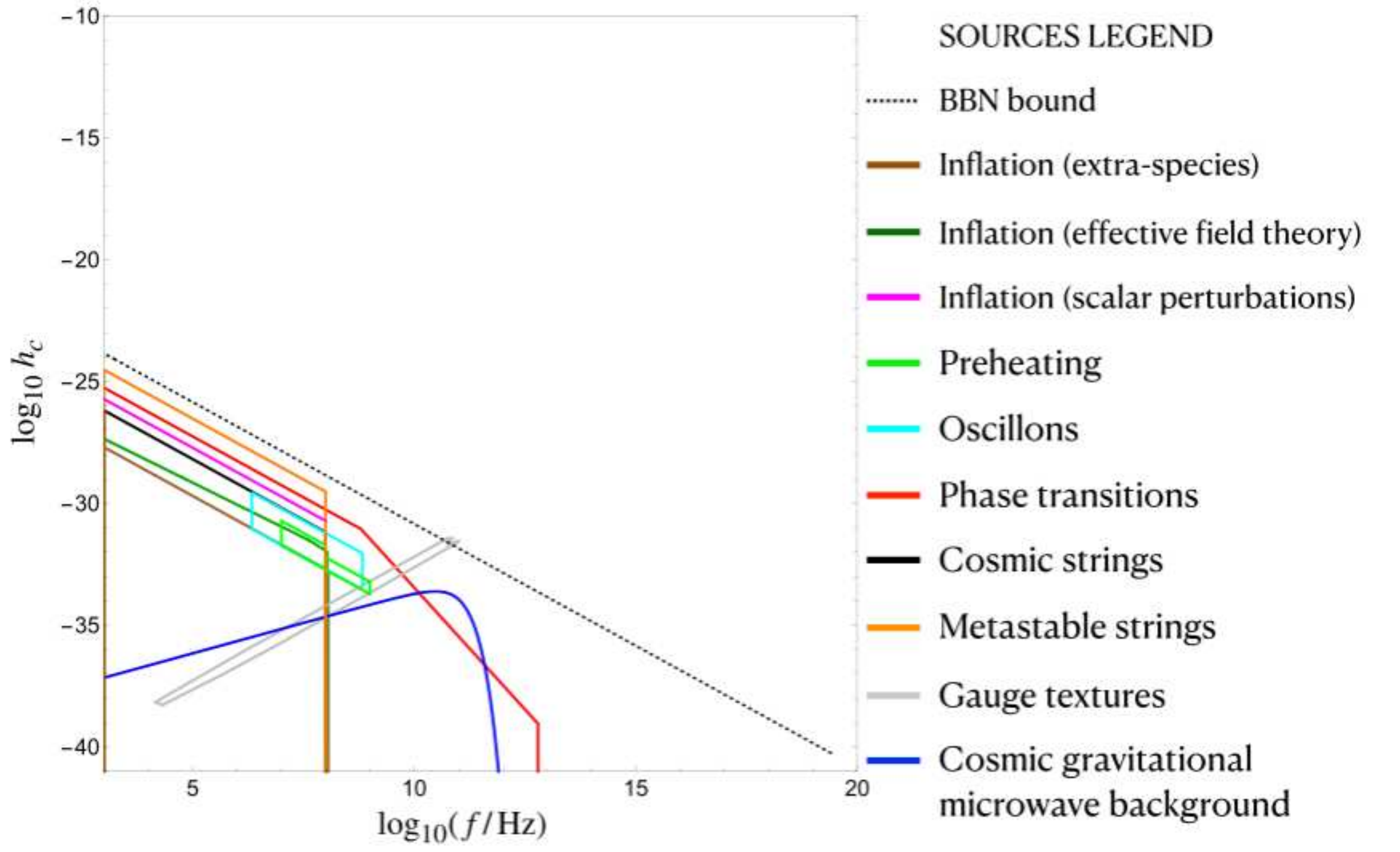
[Gravitational Waves]

Review Article | Open Access | Published: 06 December 2021

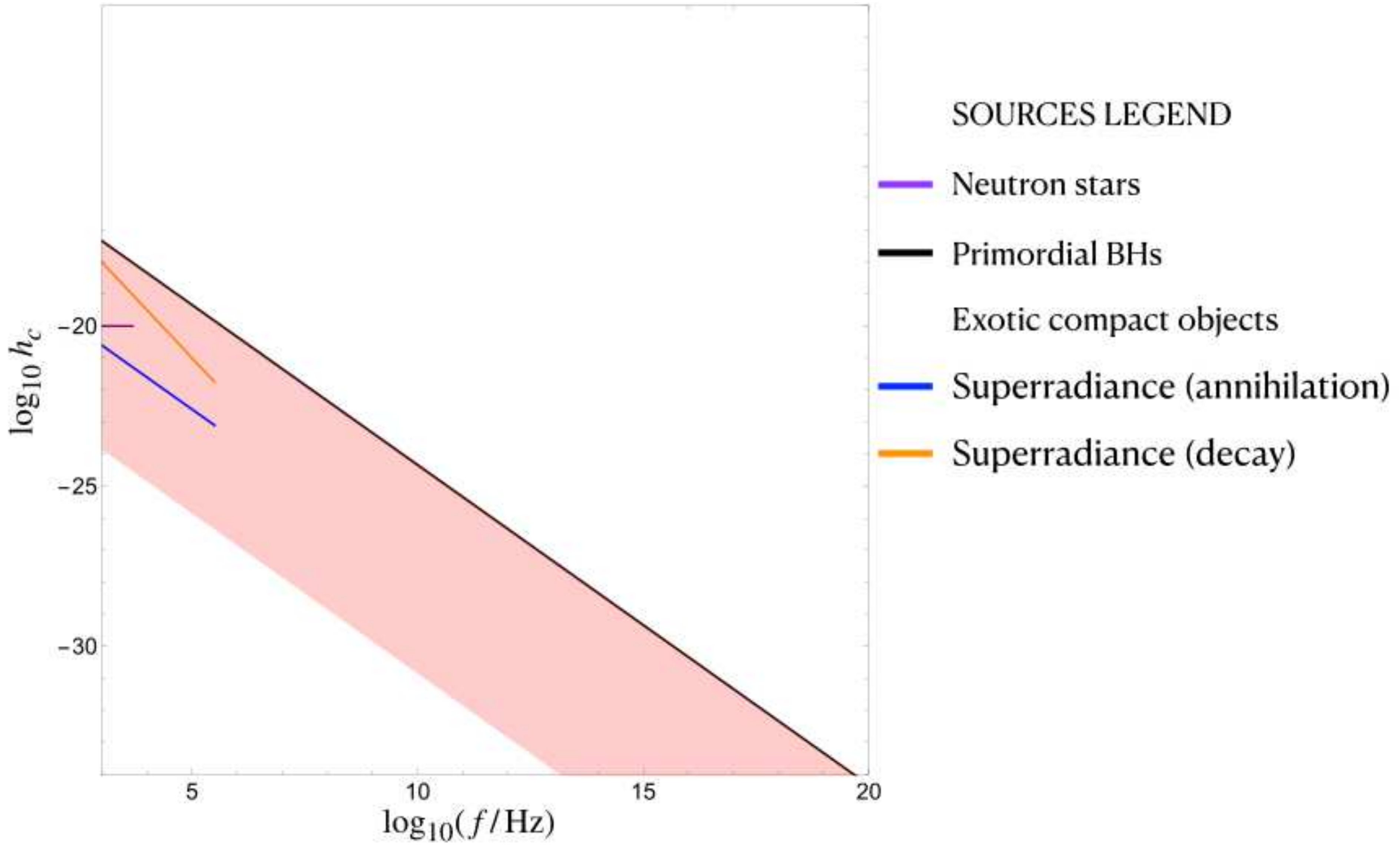
Challenges and opportunities of gravitational-wave searches at MHz to GHz frequencies

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



Axion Dark Matter

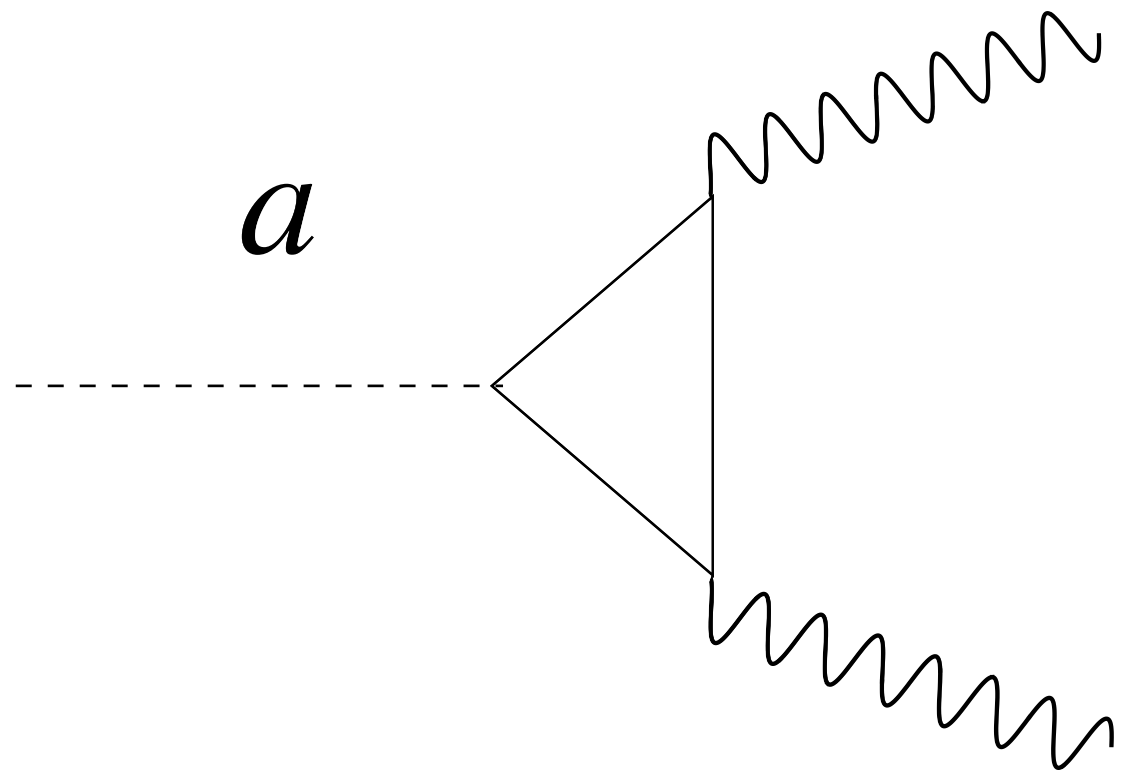
- Solution to the strong CP problem — Peccei, Quinn 1977

- Excellent dark matter candidate — Weinberg, Wilczek 1978

Axion Dark Matter

- Solution to the strong CP problem

Peccei, Quinn 1977

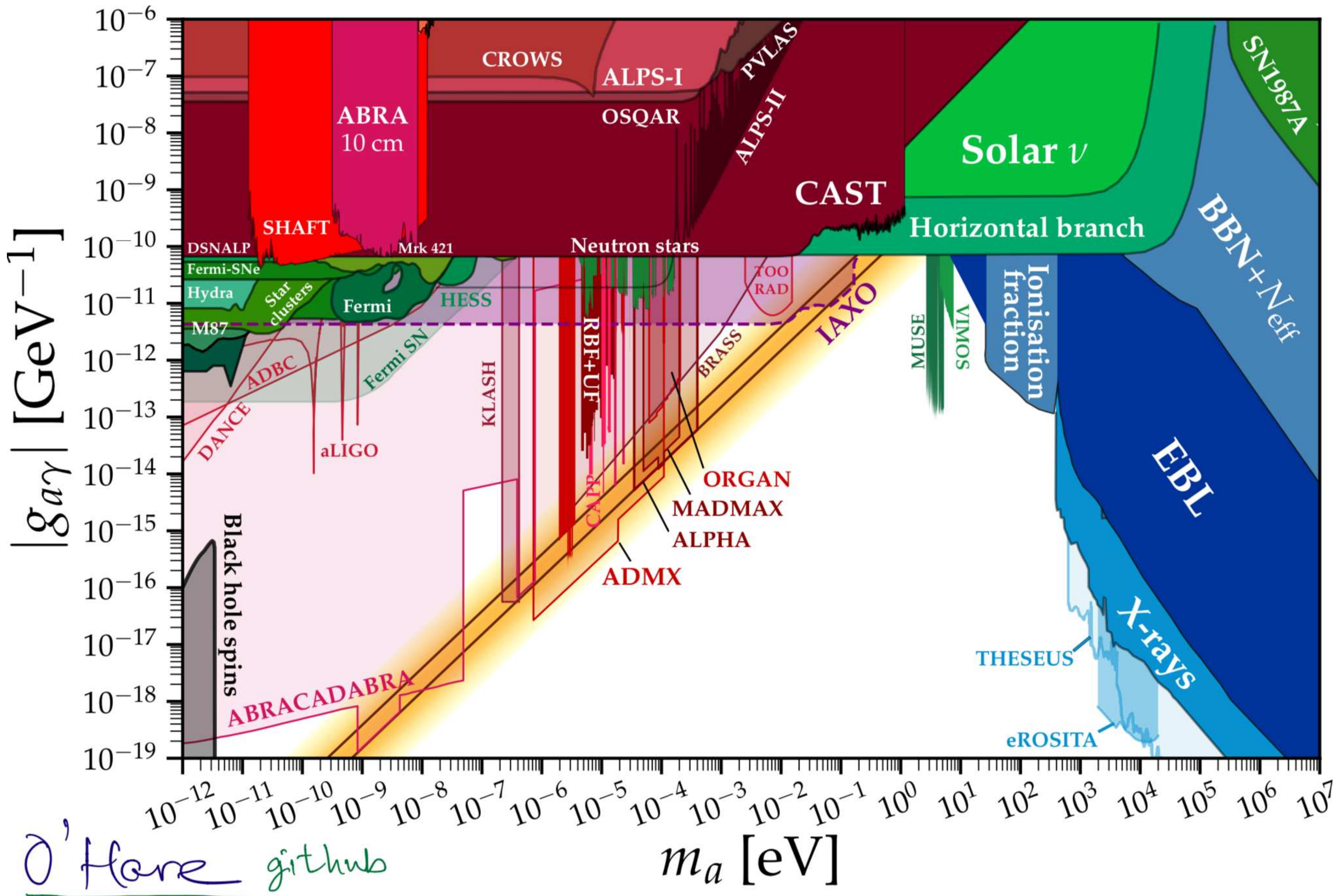


- Excellent dark matter candidate

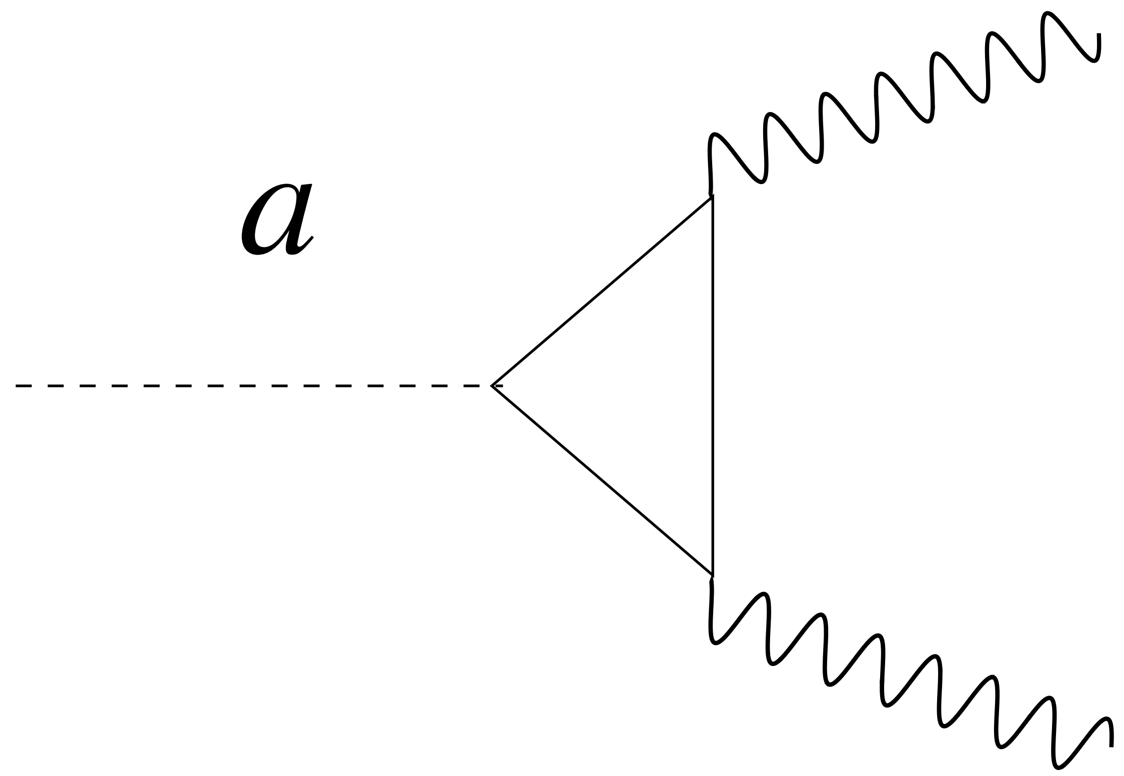
Weinberg, Wilczek 1978

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

Axion Dark Matter



O'Hare github



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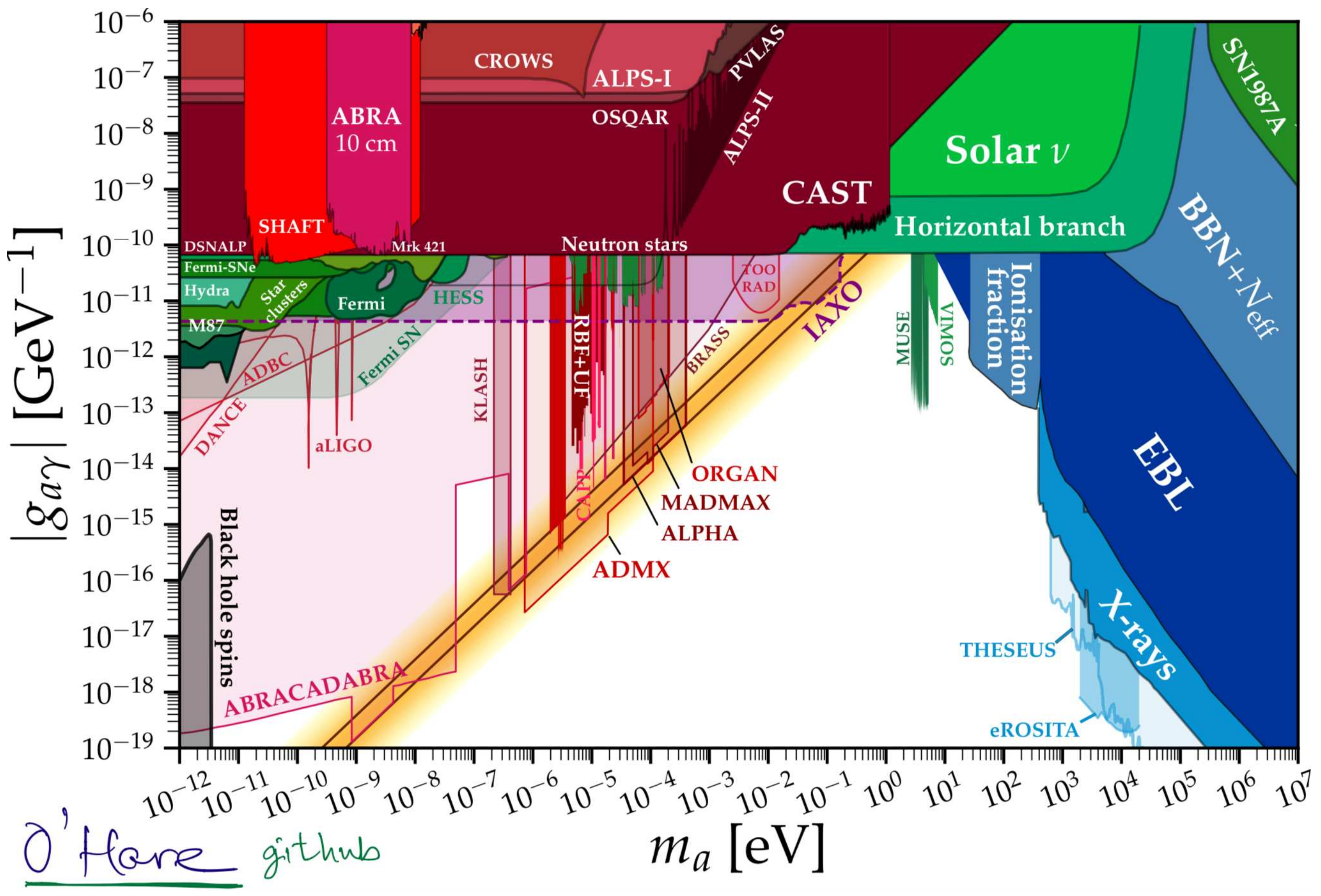
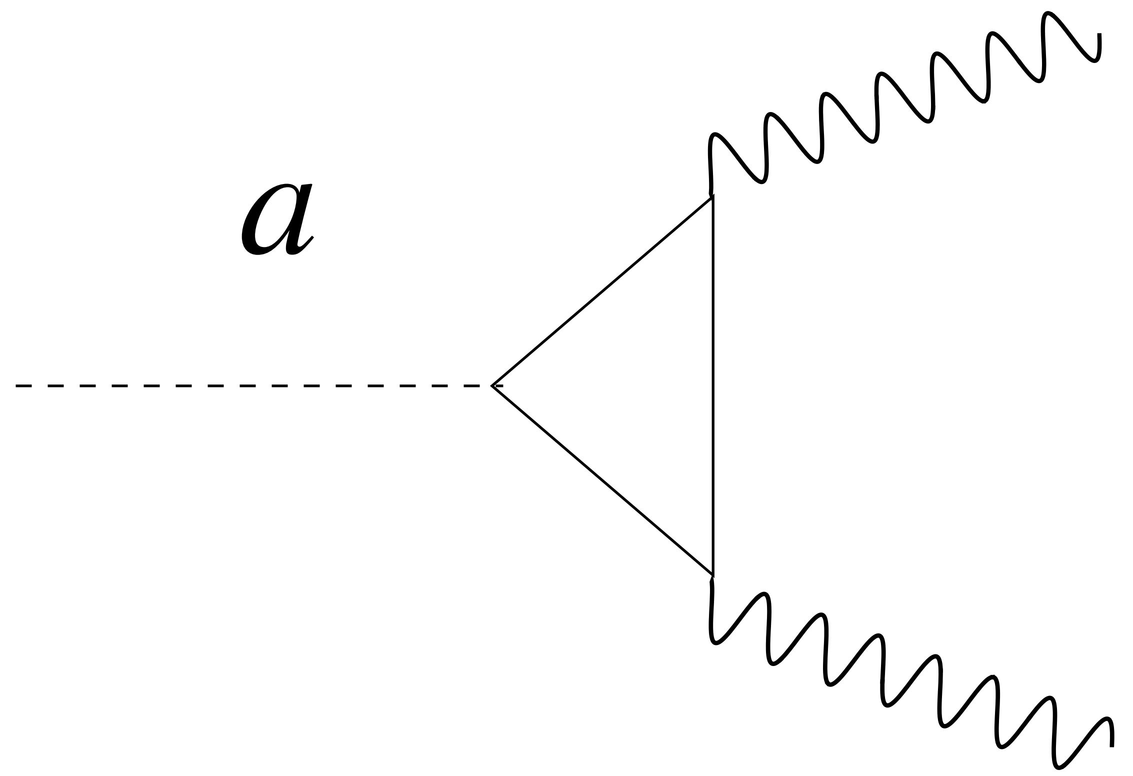
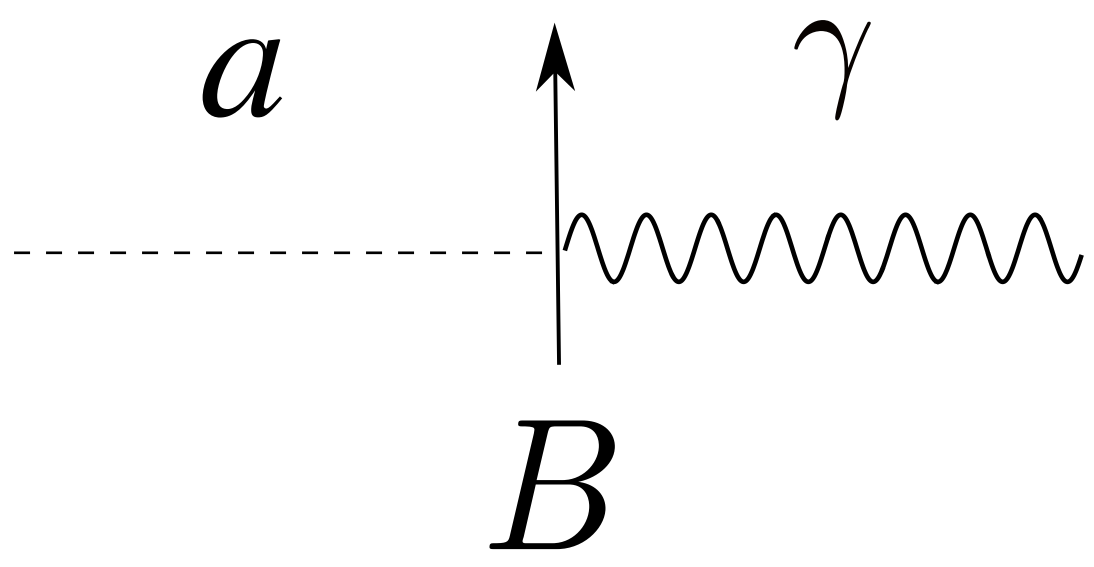


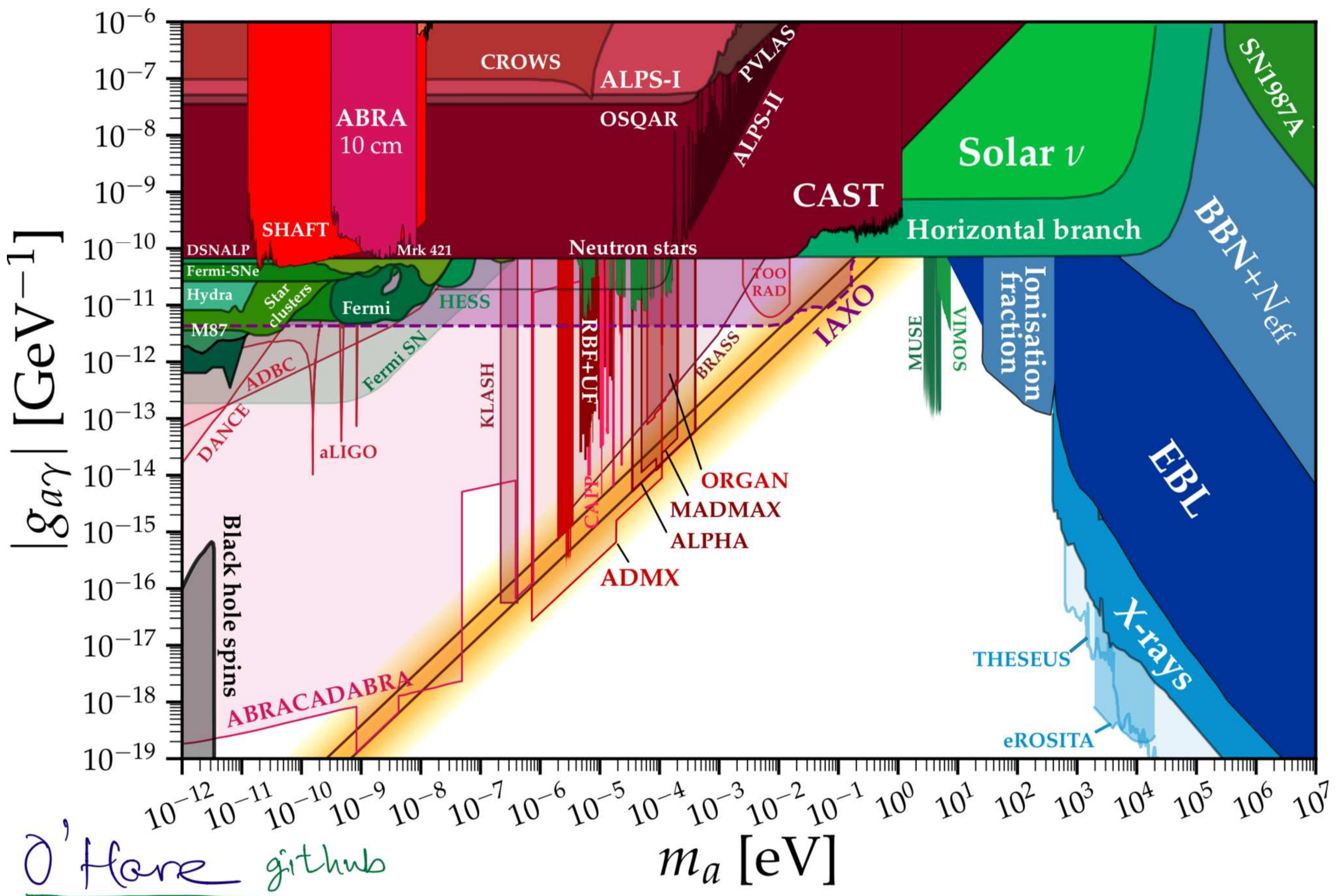


$$\mathscr{L} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

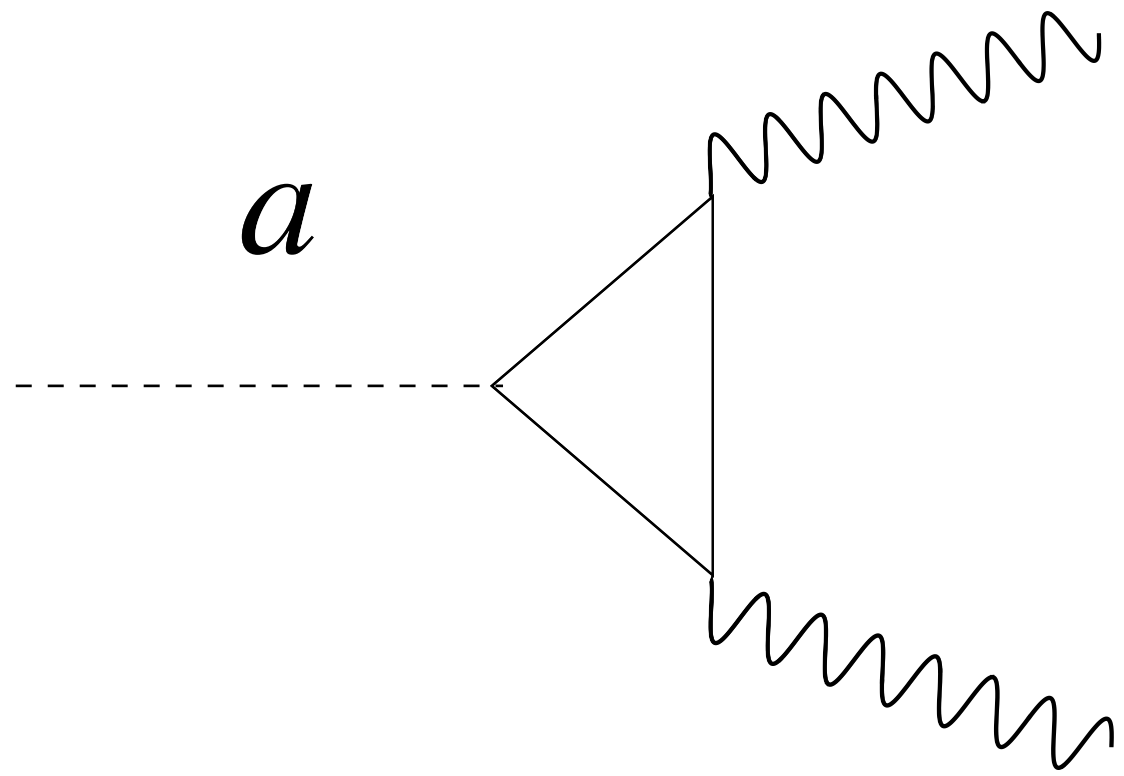
- Axions are converted into electromagnetic waves in static E & B fields



Axion Dark Matter



O'Hare github



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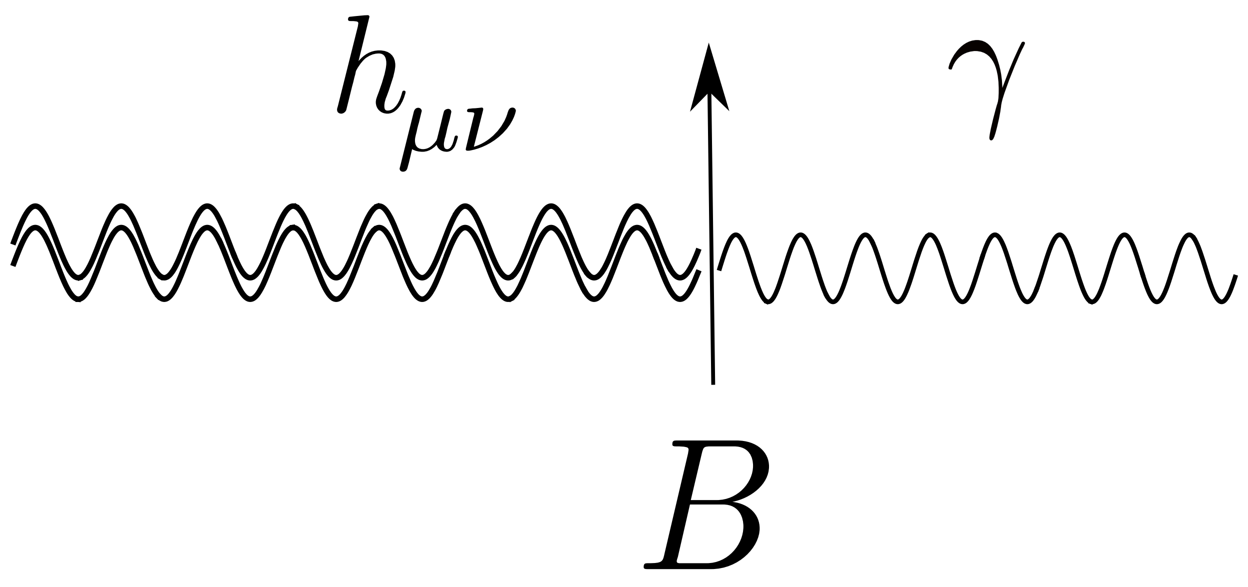

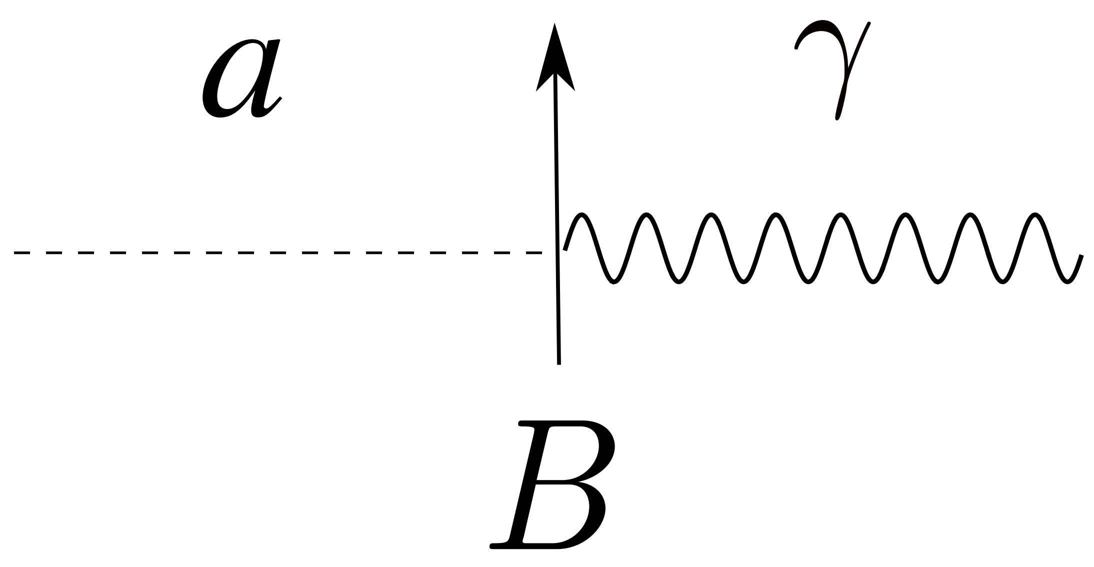

Ideas and techniques developed for axions can be adapted to gravitational waves Raffelt, Stodolski'89

The Gertsenshtein Effect

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.

$$\Box h_\times = 16\pi G B\, \partial_\ell A_\times \qquad \Box A_\times = -B \partial_\ell h_\times$$

(The same equation holds for $+$ instead of $\times$ polarization)

The (inverse) Gertsenhstein Effect

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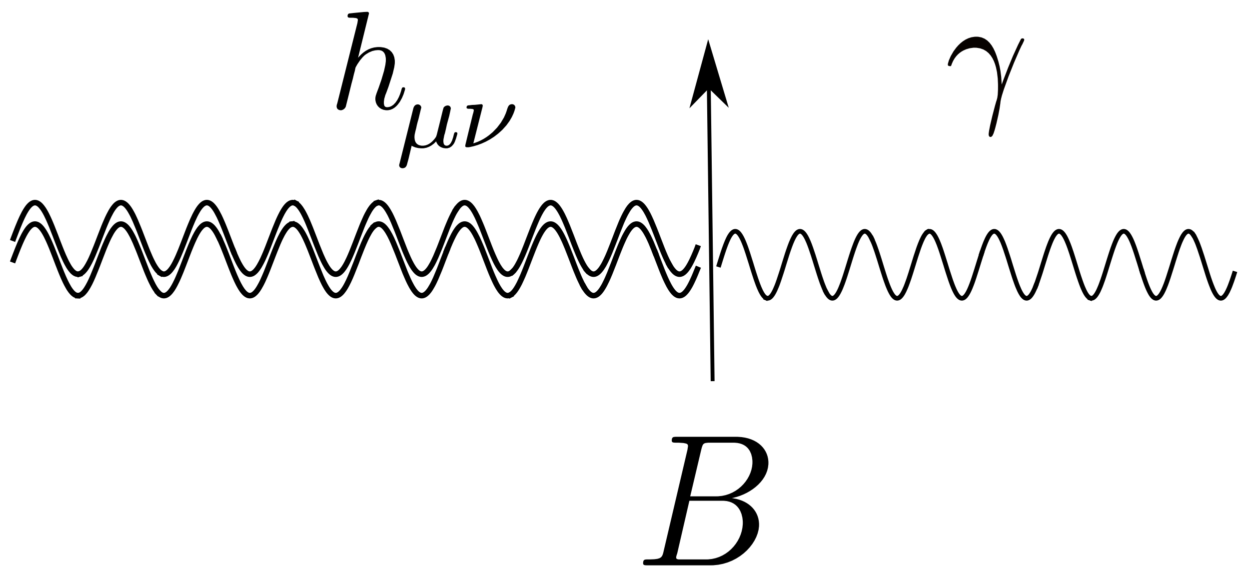

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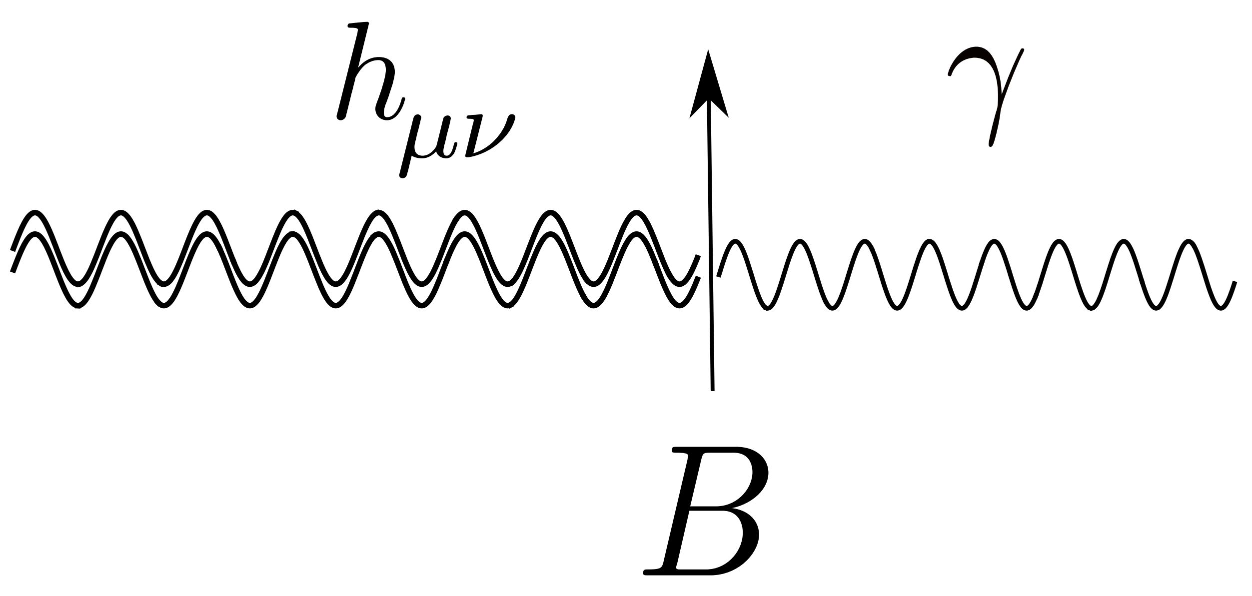
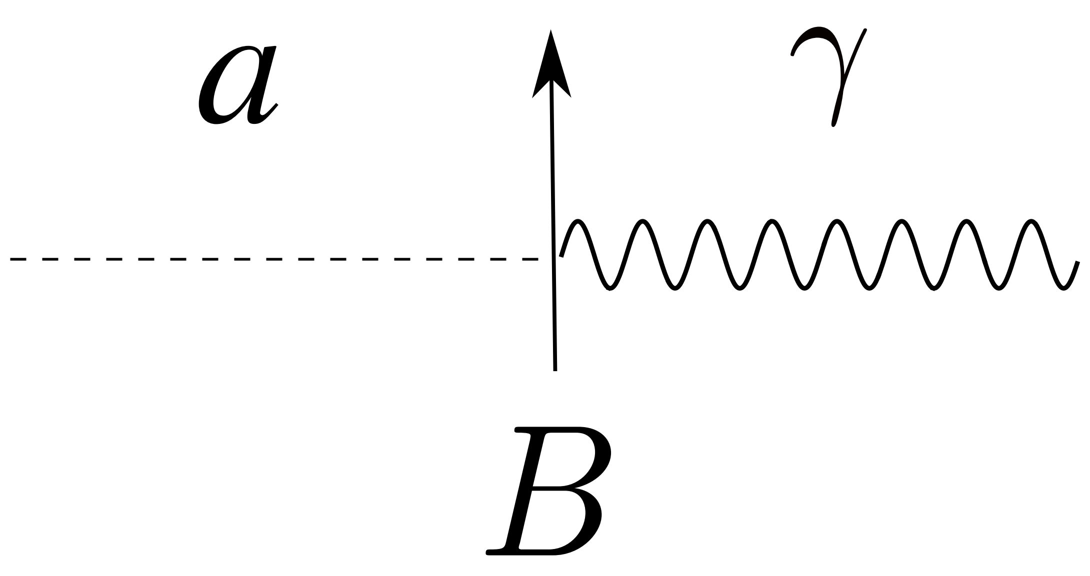
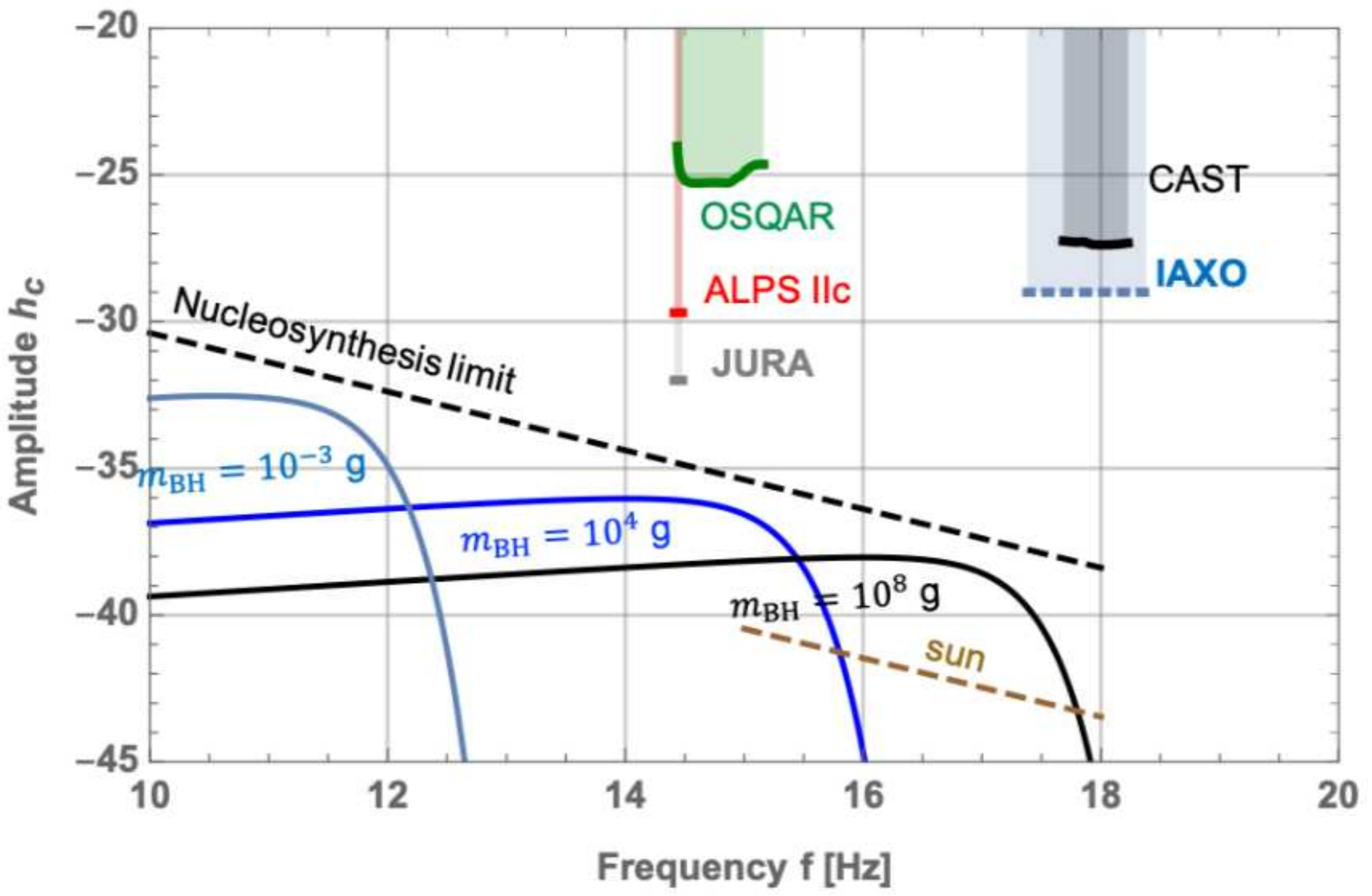




Upper limits on the amplitude of ultra-high-frequency gravitational waves from graviton to photon conversion

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

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



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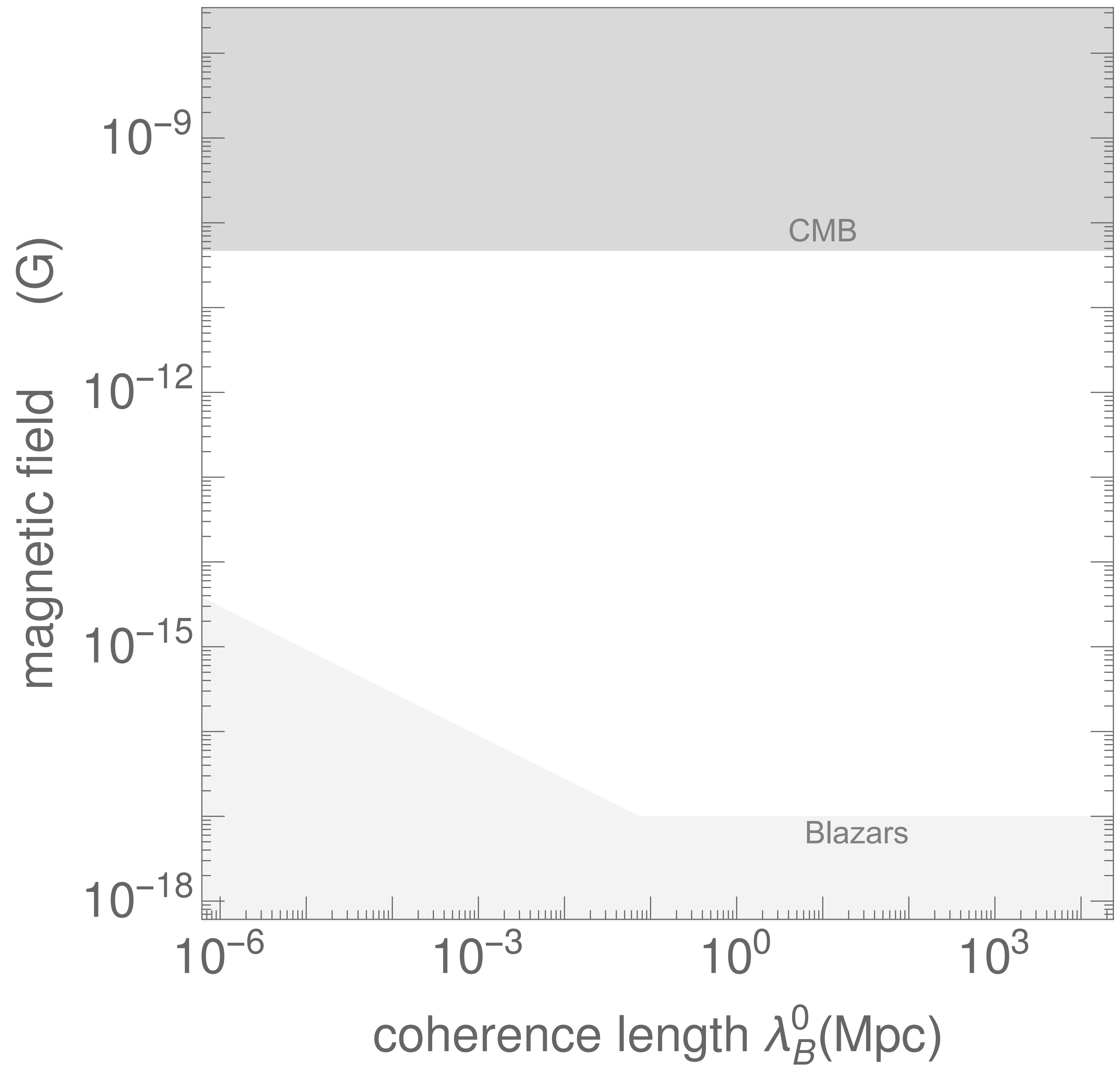
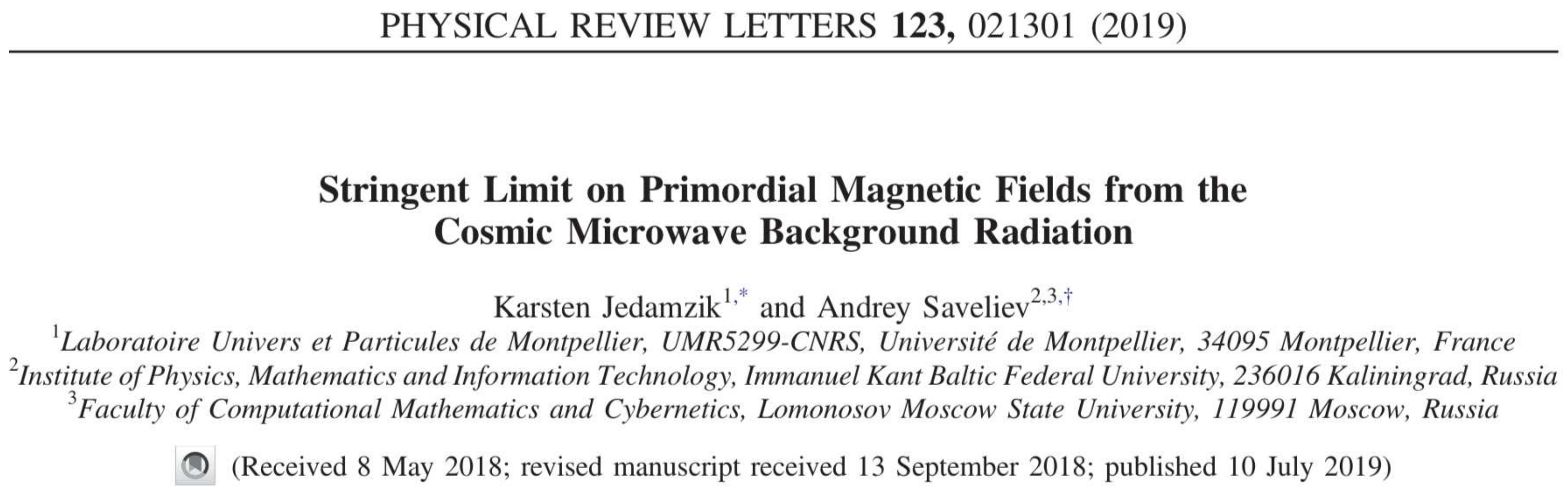
Raffelt, Stodolski'89

Cosmic magnetic fields




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)


Science Contents News Careers Journals

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REPORT

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

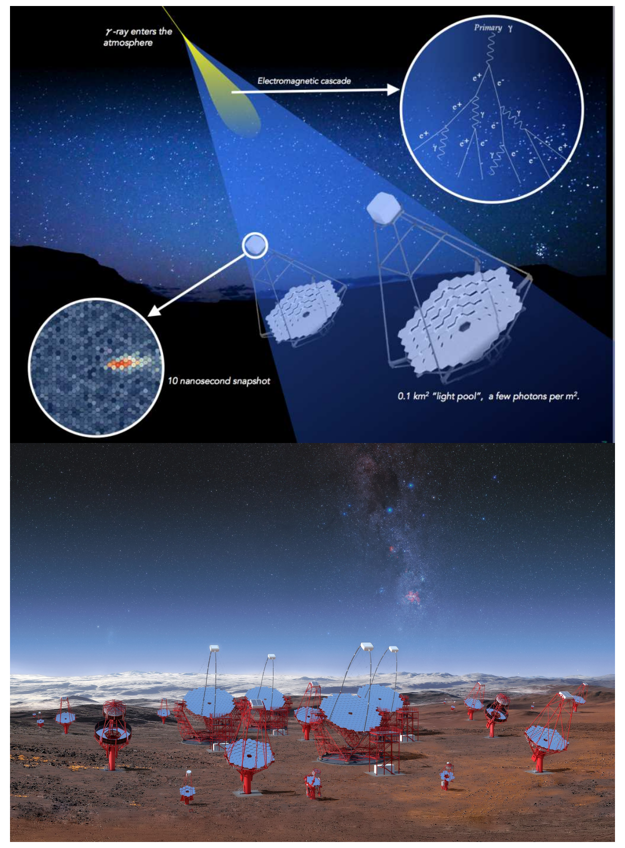
Andrii Neronov*, Ievgen Vovk

+ See all authors and affiliations

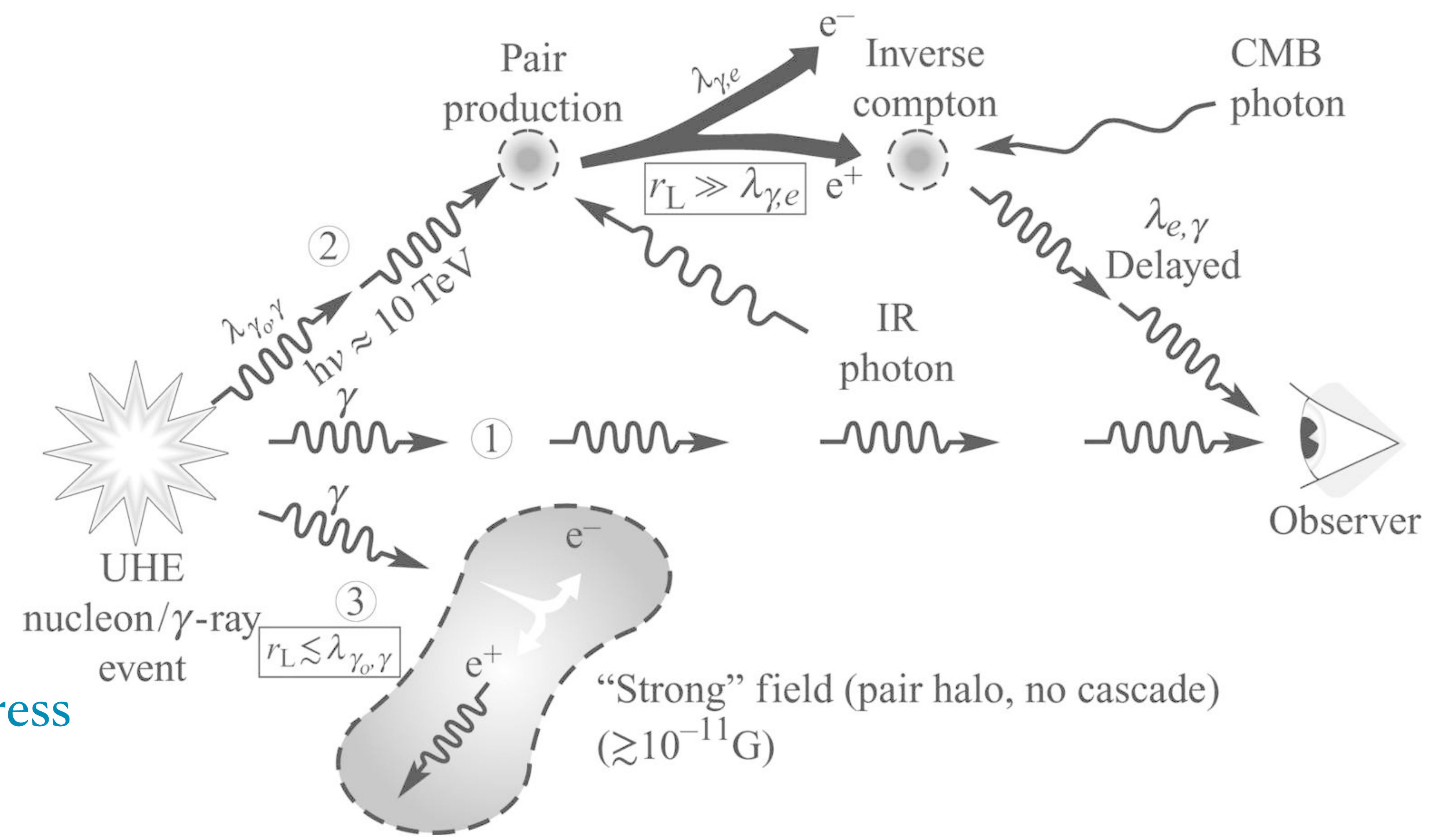
Science 02 Apr 2010:
Vol. 328, Issue 5974, pp. 73-75
DOI: 10.1126/science.1184192

Article | Figures & Data | Info & Metrics | eLetters | PDF

Evidence from TeV Blazars

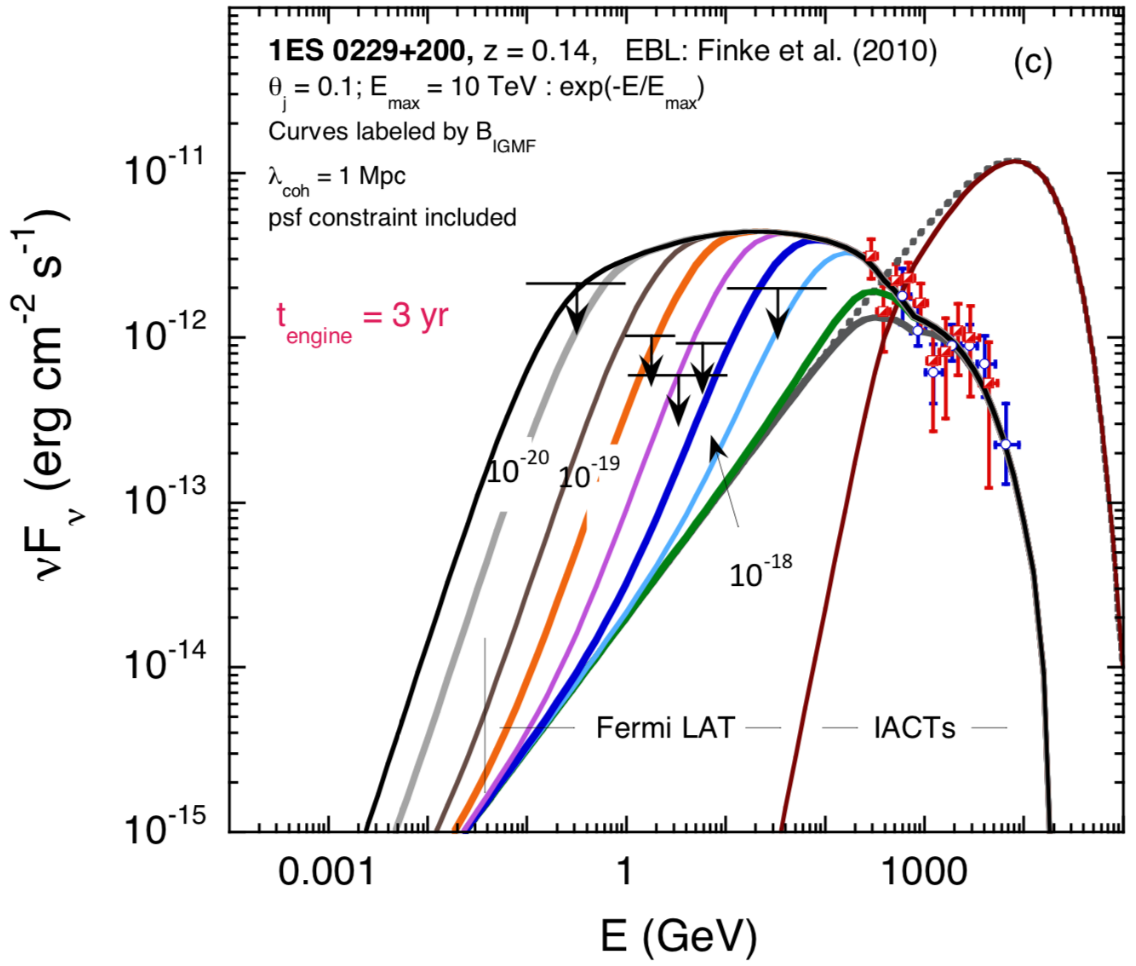


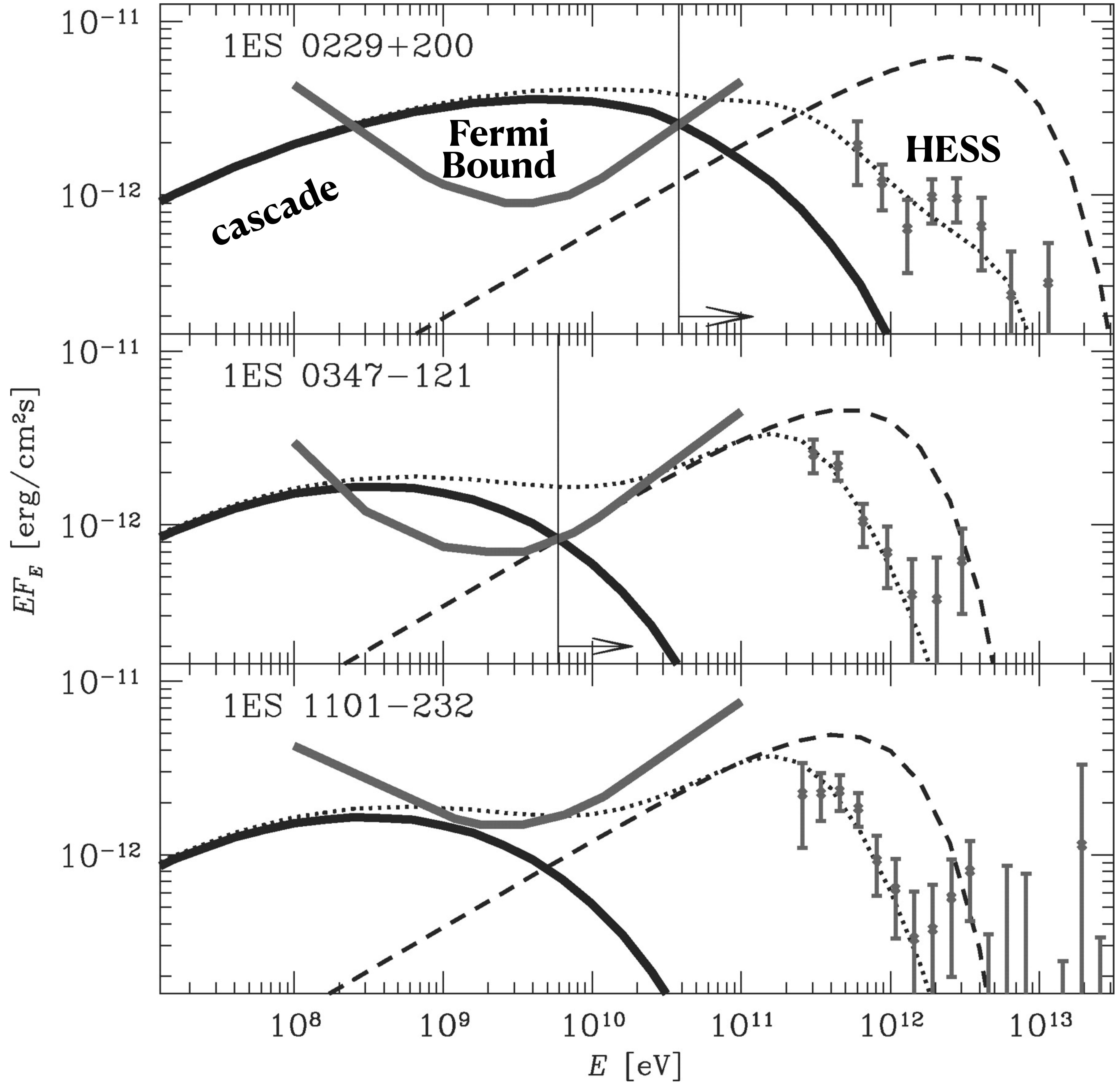
High energy $h\nu$ –e^+e^- cascades in the intergalactic medium



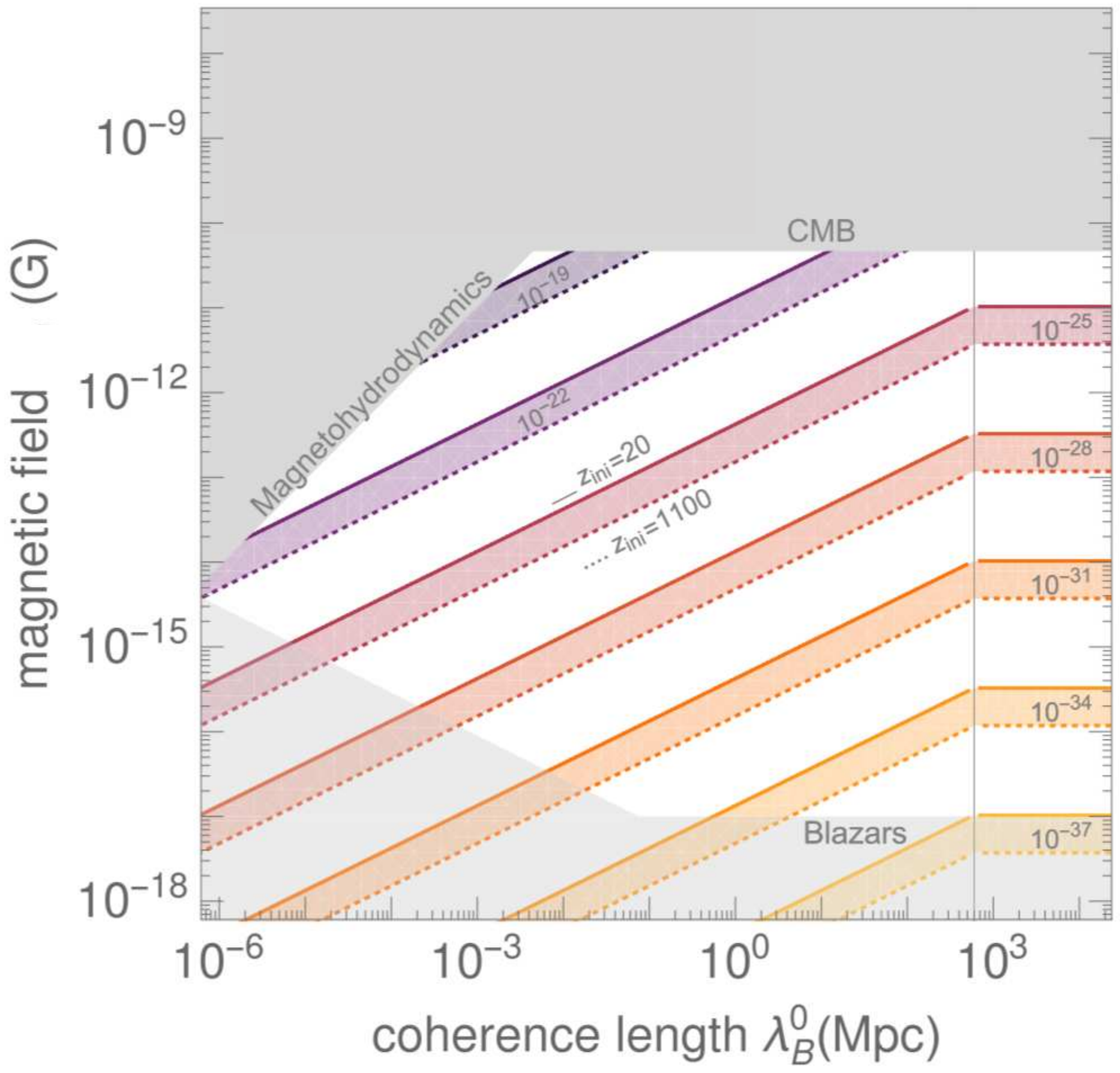
Kronberg , 2016
Cambridge University Press

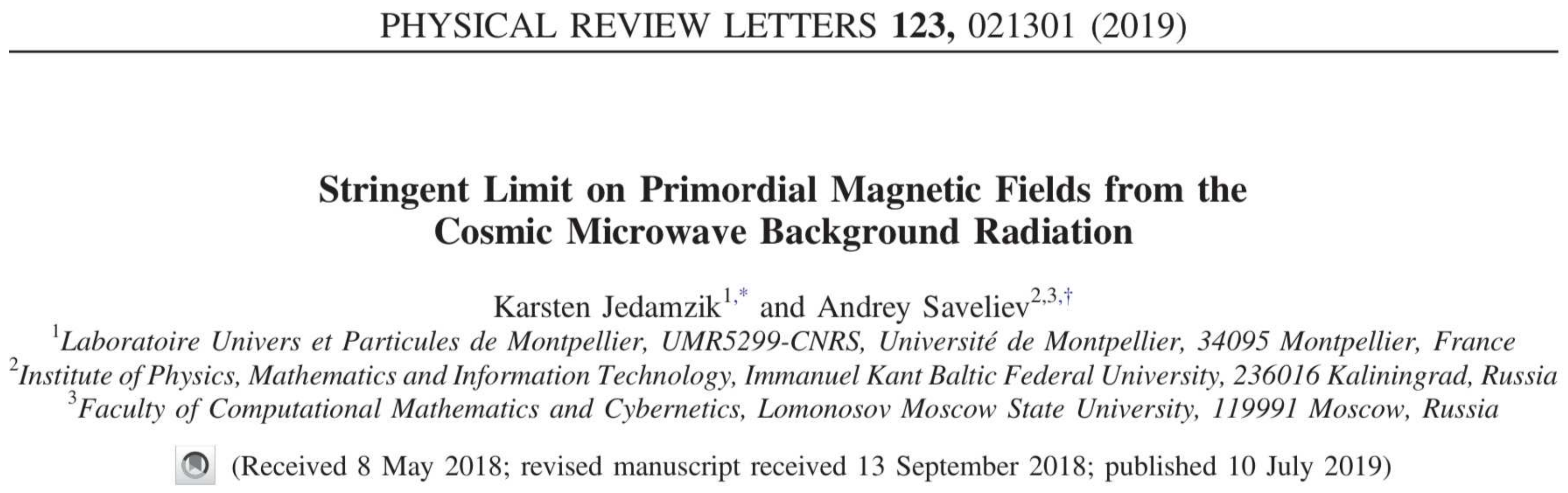
CTA consortium 2017 Dermer et al





Cosmic magnetic fields

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Science 02 Apr 2010:
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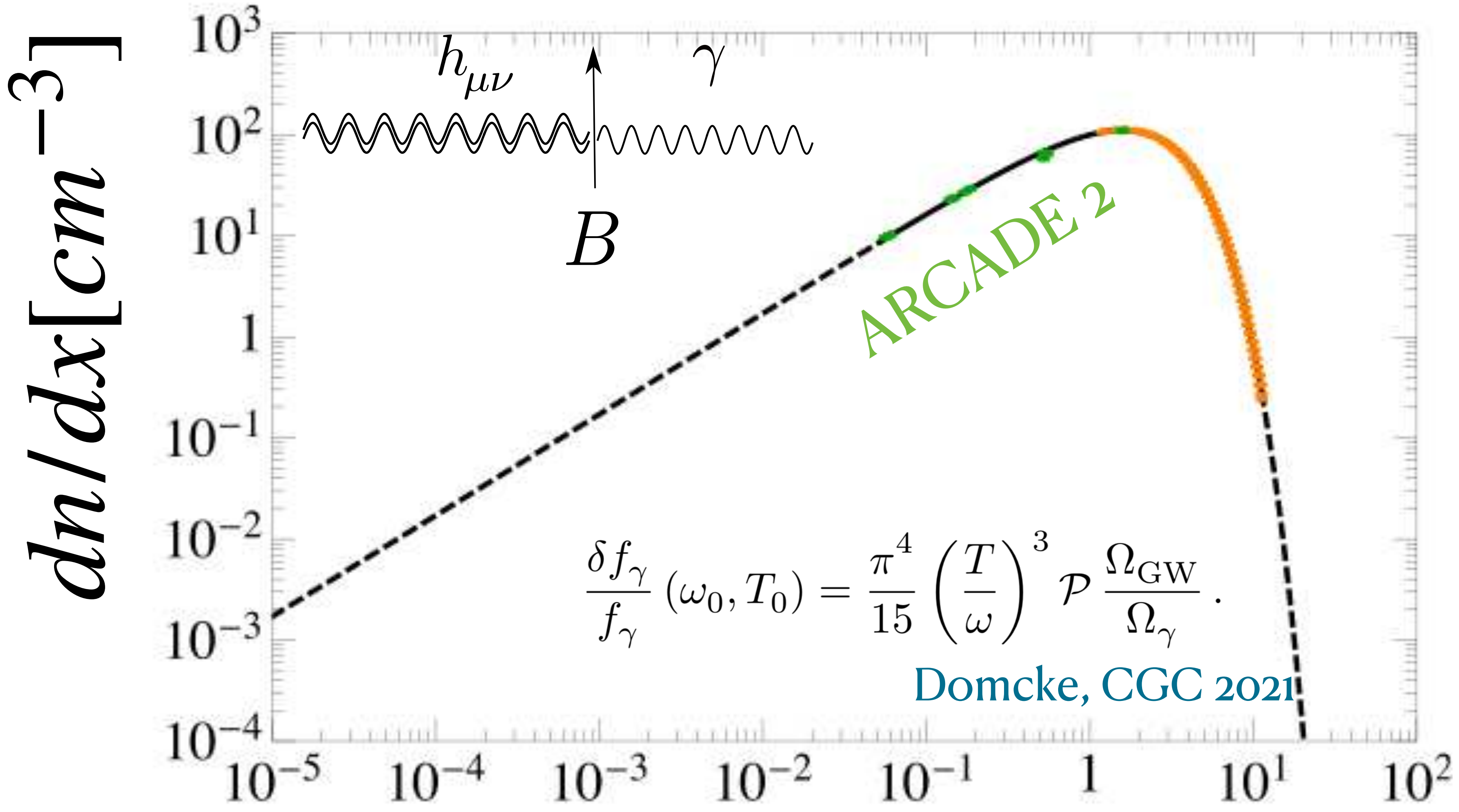
Article | Figures & Data | Info & Metrics | eLetters | PDF

Domcke, CGC 2021

Rayleigh-Jeans tail



Largely unexplored with upcoming advances in radio astronomy probing it in the near future.

Puzzling signal by EDGES. (Experiment to Detect the Global Epoch of Reionization Signature)

THE ASTROPHYSICAL JOURNAL

ARCADE 2 MEASUREMENT OF THE ABSOLUTE SKY BRIGHTNESS AT 3-90 GHz

D. J. Fixsen[1], A. Kogut[2], S. Levin[3], M. Limon[4], P. Lubin[5], P. Mirel[6], M. Seiffert[3], J. Singal[7], E. Wollack[2], T. Villela[8] +Show full author list

Published 2011 May 17 • © 2011. The American Astronomical Society. All rights reserved.

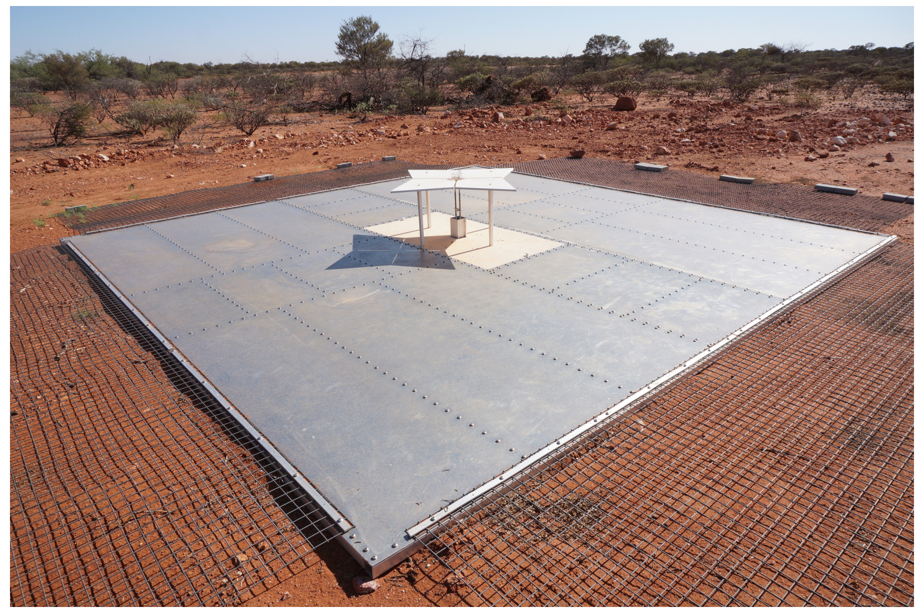
The Astrophysical Journal, Volume 734, Number 1

nature

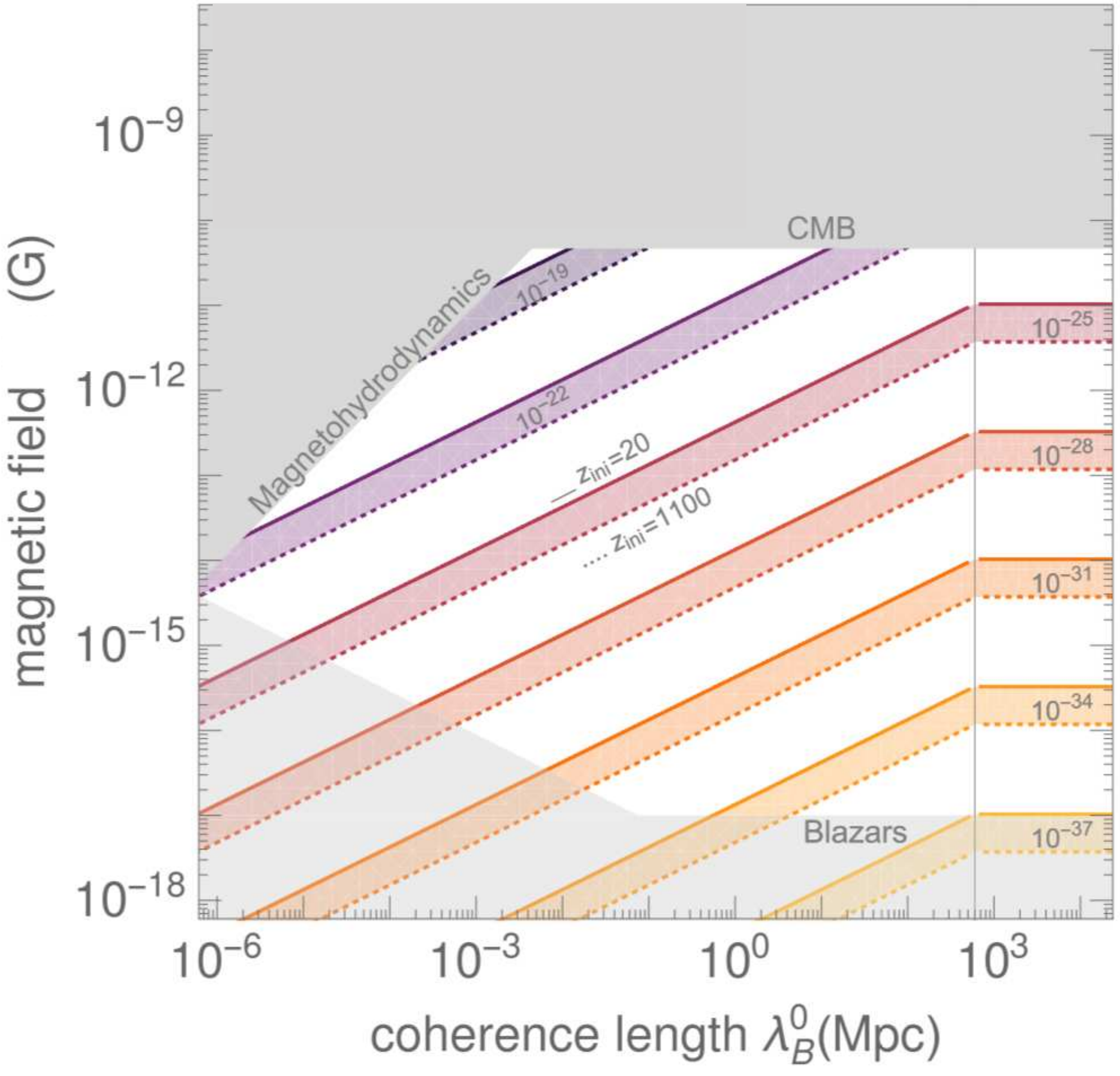
An absorption profile centred at 78 megahertz in the sky-averaged spectrum

Judd D. Bowman, Alan E. E. Rogers, Raul A. Monsalve, Thomas J. Mozdzen & Nivedita Mahesh

Nature **555**, 67–70(2018) | Cite this article



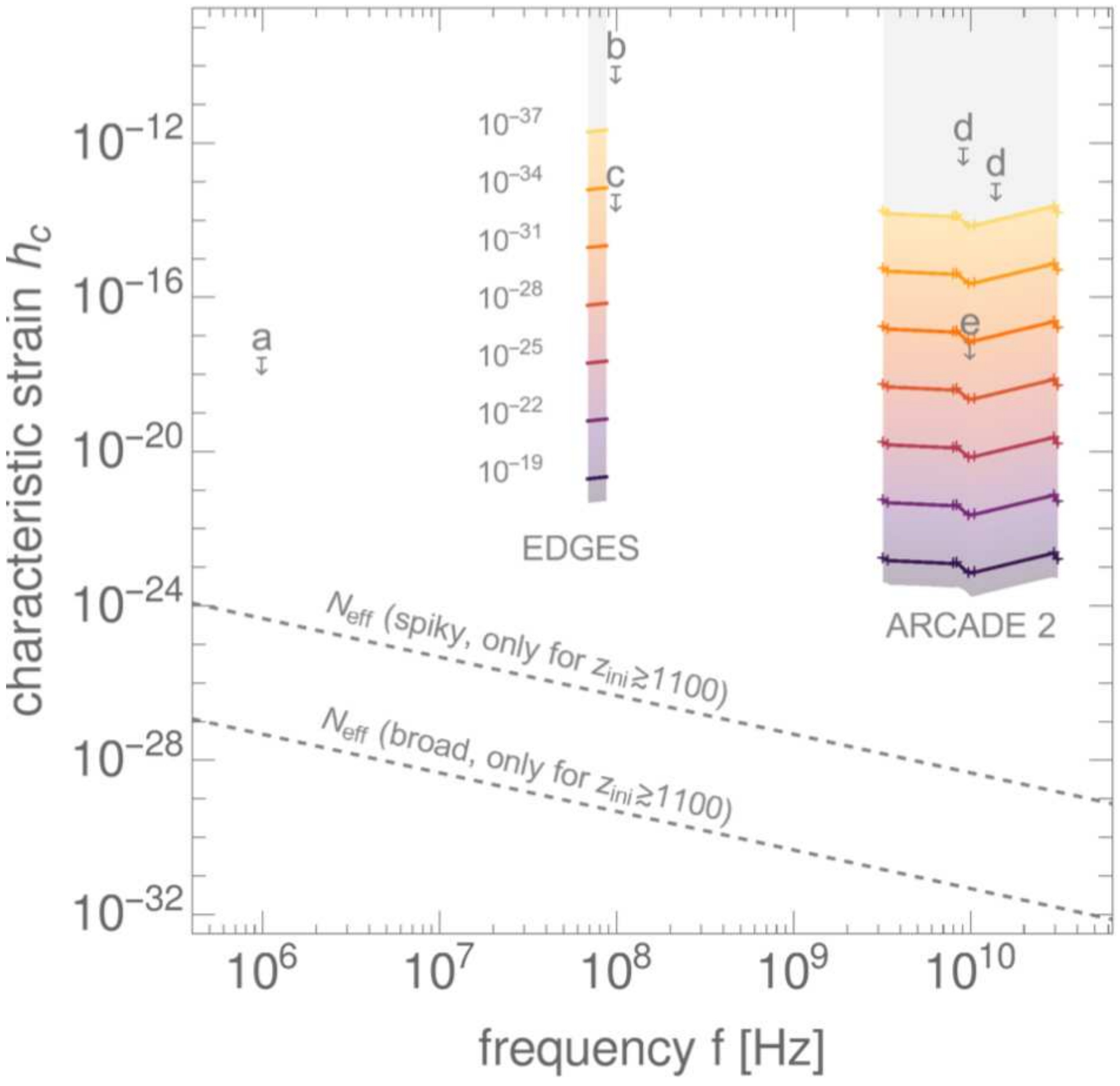
Upper bounds on stochastic gravitational waves



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,†]



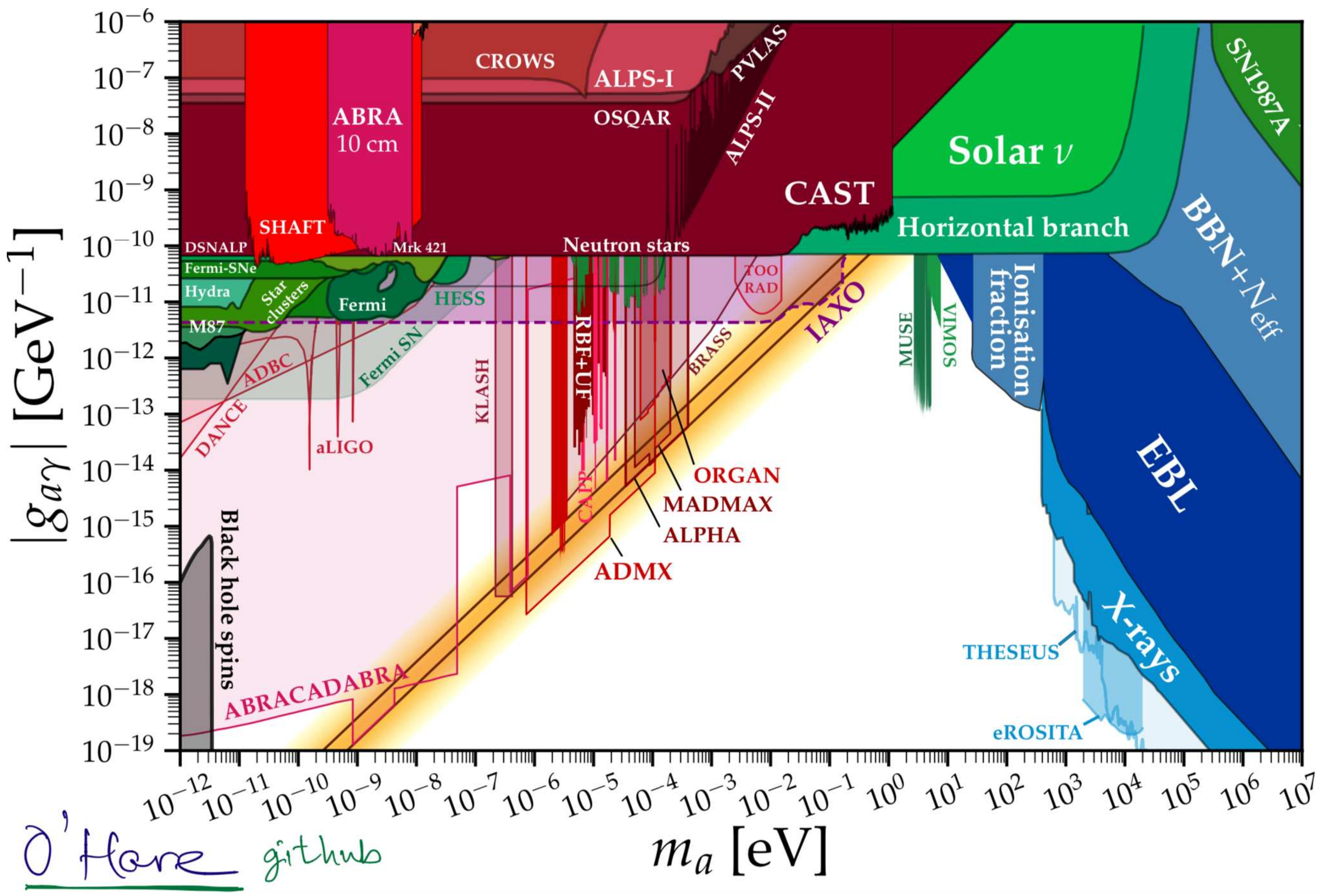
existing laboratory bounds from

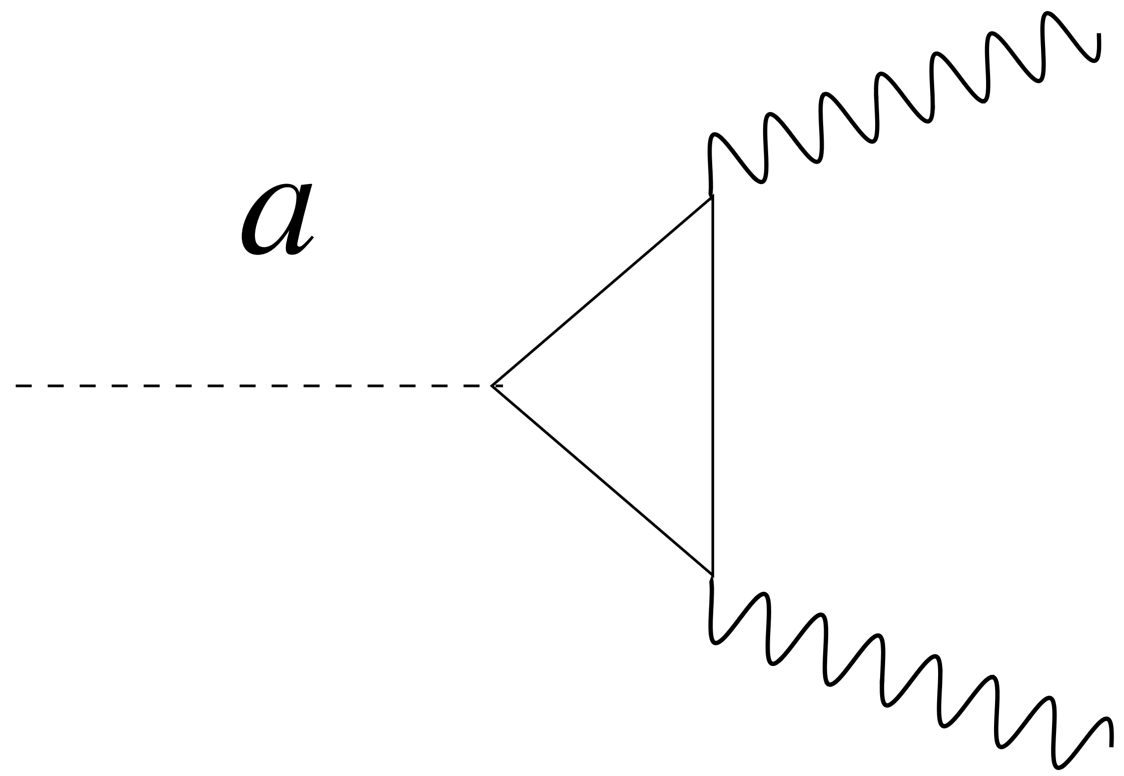
a) superconducting parametric converter Reece et al '84
b) waveguide Cruise Ingley '06
c) 0.75 m interferometer Akutsu '08
d) magnon detector Ito, Soda '04
e) magnetic conversion detector Cruise et al '12

Gravitational-Wave versus Axion electrodynamics

	Axion electrodynamics	Gravitational wave electrodynamics
An example	Axion-Photon conversion	Gertsenshtein effect

Axion electrodynamics



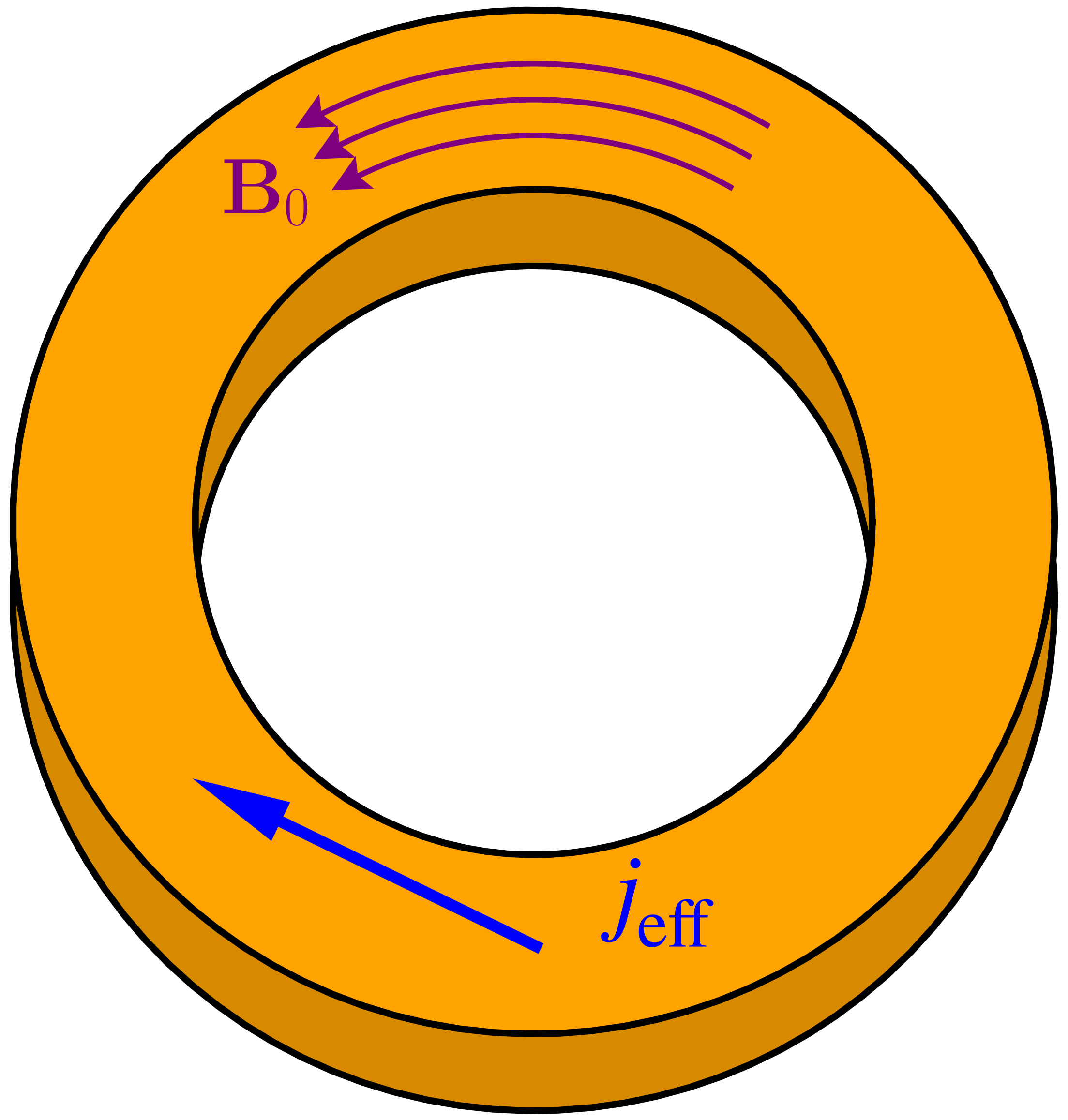


$$\mathscr{L} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

In the presence of an external electromagnetic field, axions act as a source term to Maxwell's equations, effectively inducing an electromagnetic current.

$$\partial_\nu F^{\mu\nu} = j^\mu_{\text{eff}} = \partial_\nu \left(g_{a\gamma\gamma} a \tilde{F}^{\nu\mu} \right)$$

Axion electrodynamics



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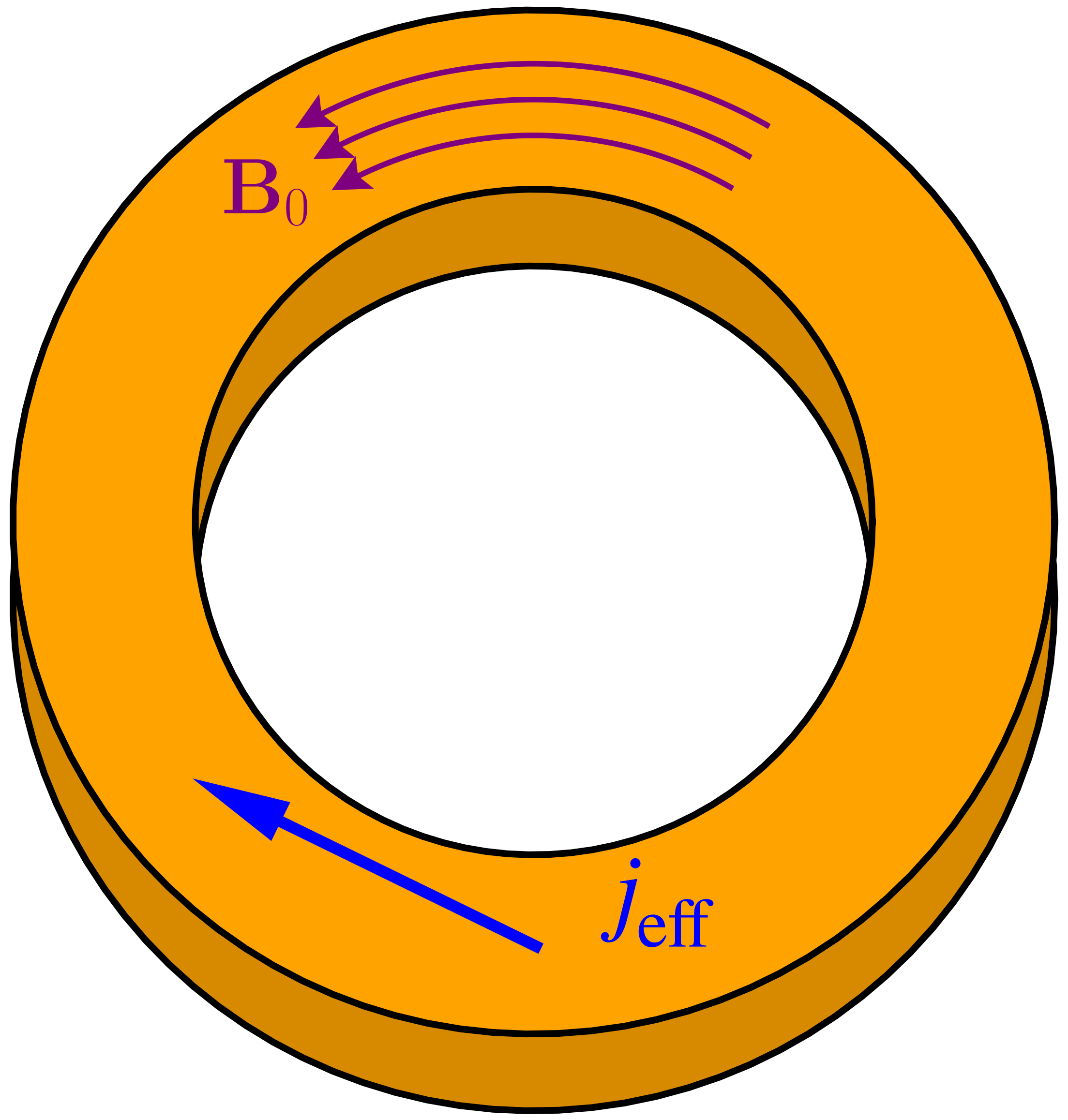
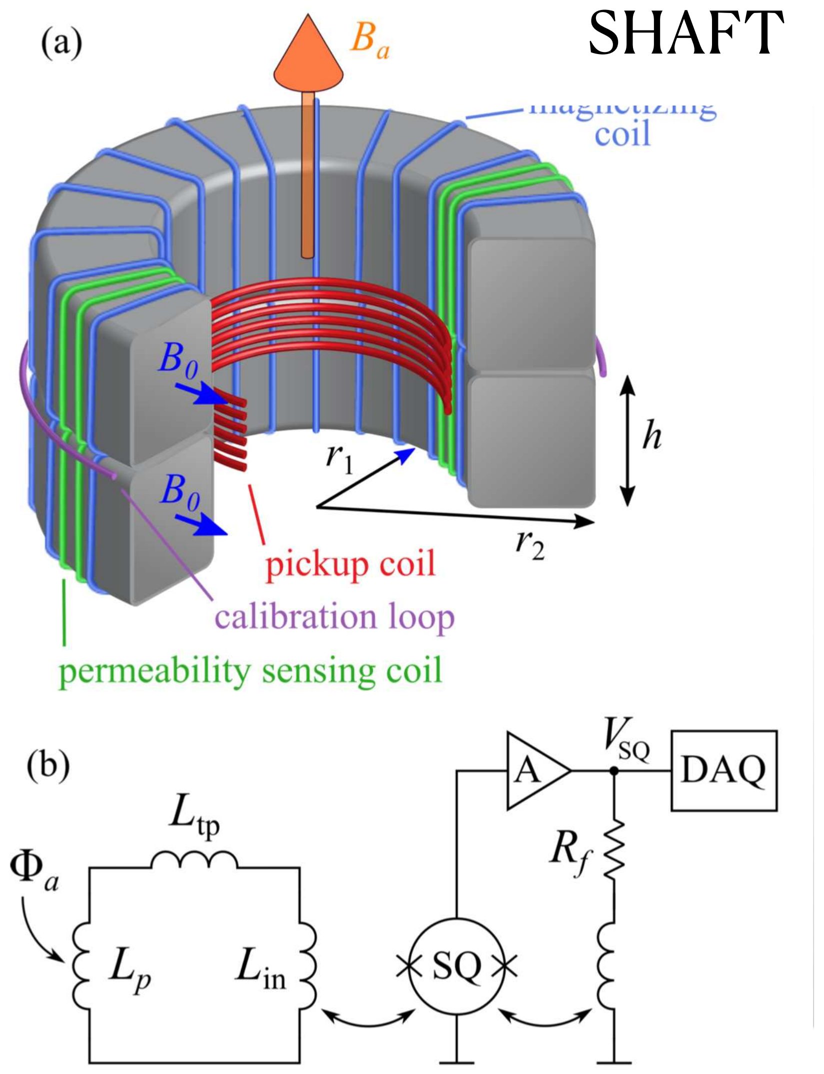
$$\nabla \times \mathbf{B} = \partial_t \mathbf{E} + \underbrace{g_{a\gamma\gamma}\, \partial_t a\, \mathbf{B_0}}_{j_{\text{eff}}}$$

Axion electrodynamics



haloscopes based on lumped-element detectors



PRL 117, 141801 (2016) PHYSICAL REVIEW LETTERS week ending 30 SEPTEMBER 2016

Broadband and Resonant Approaches to Axion Dark Matter Detection

Yonatan Kahn,[1,*] Benjamin R. Safdi,[2,†] and Jesse Thaler[2,‡]
[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)

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]

In the presence of an external electromagnetic field, axions act as a source term to Maxwell's equations, effectively inducing an electromagnetic current.

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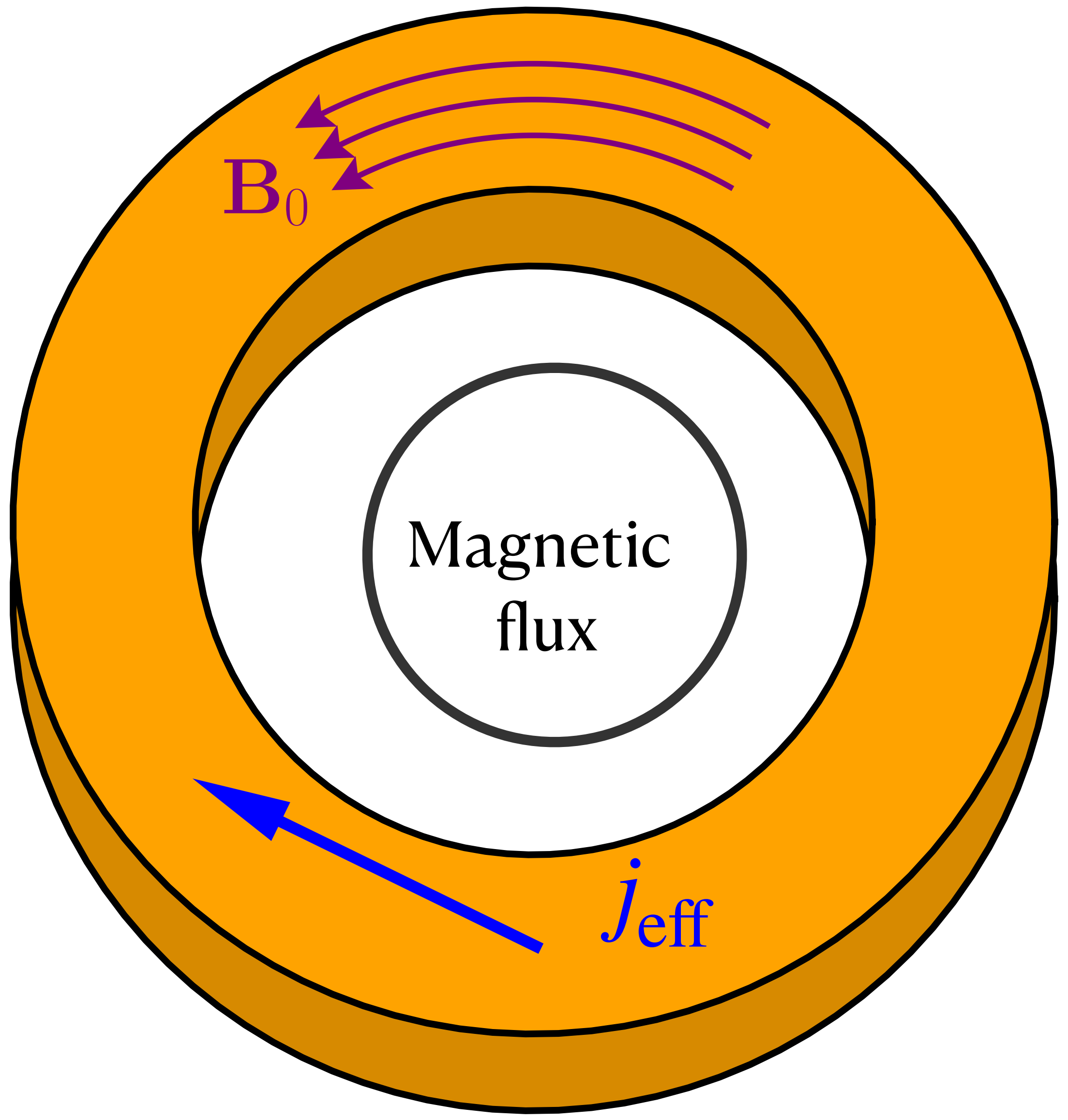

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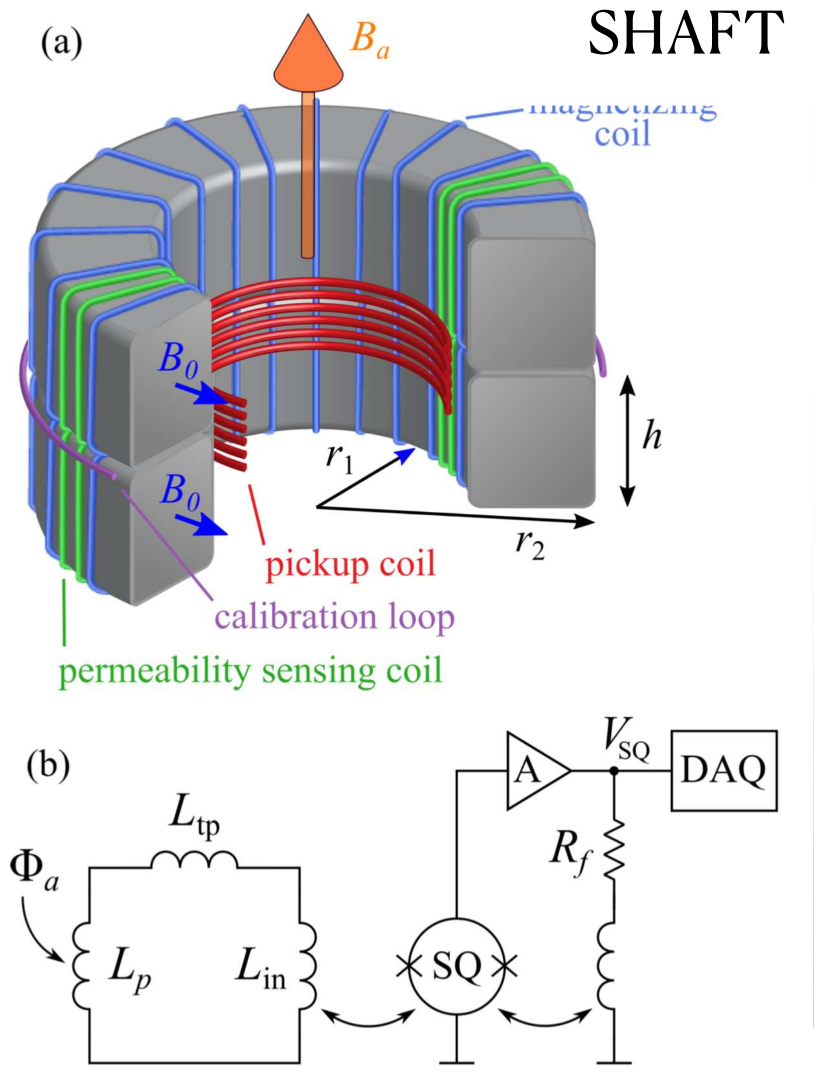

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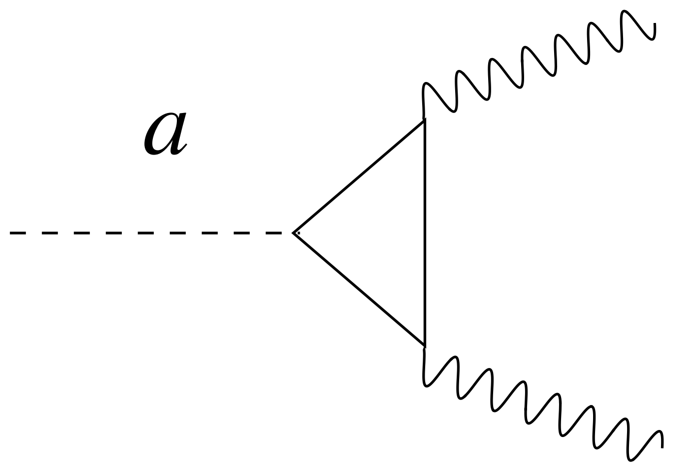
Effective currents

Axions



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

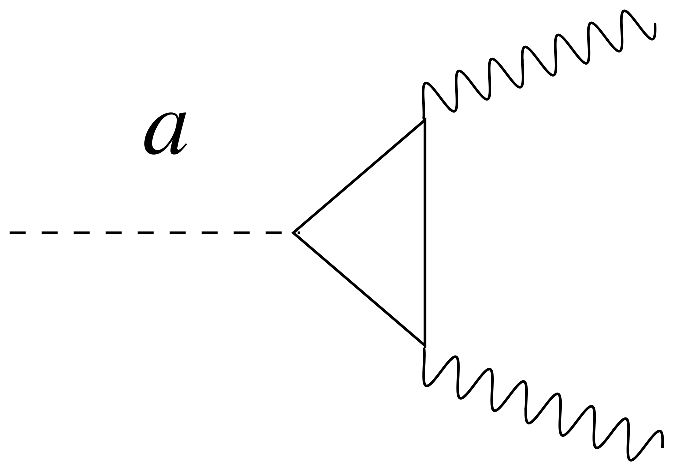
$$\nabla \cdot \mathbf{E} = -\nabla \cdot \mathbf{P}$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\partial_t \mathbf{B}$$
$$\nabla \times \mathbf{B} = \partial_t \mathbf{E} + \nabla \times \mathbf{M} + \partial_t \mathbf{P}$$

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

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

Effective currents

Axions



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

Gravitational waves

$$S \supset \int d^4x \sqrt{-g} \left(-\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \right)$$

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

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

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

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

(in the TT gauge)

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

Domcke, CGC, Rodd, 2202.00695

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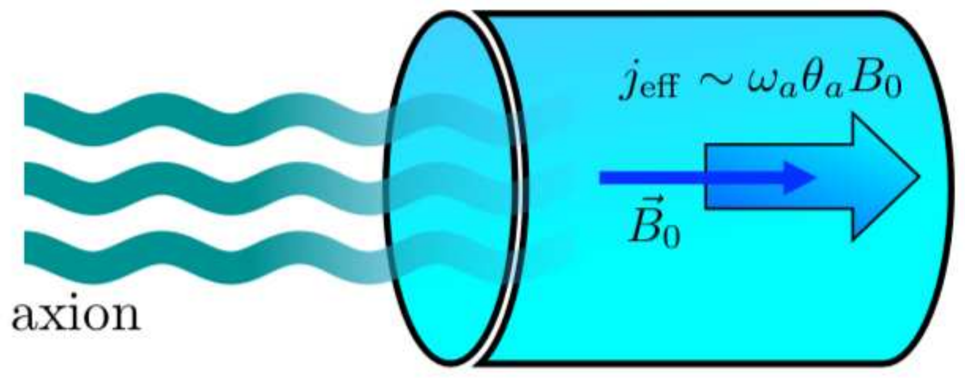
Gravitational wave electrodynamics

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

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

,

Gravitational wave electrodynamics

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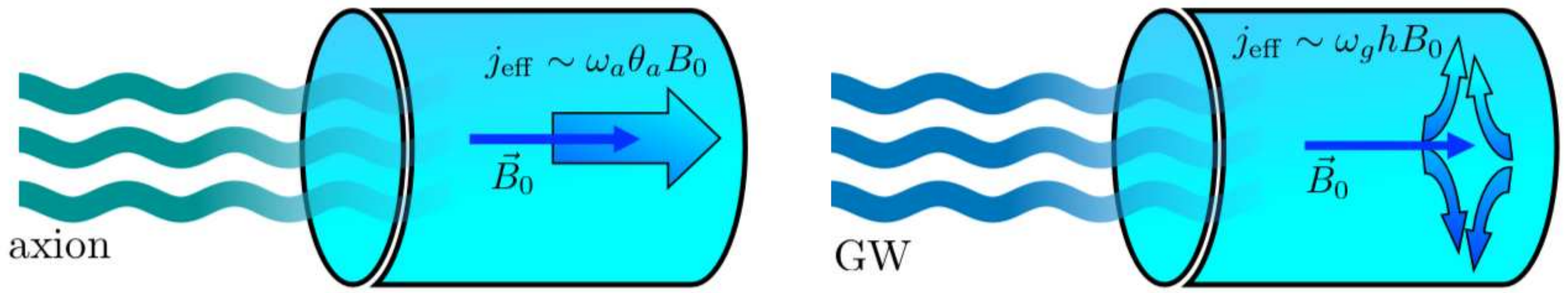

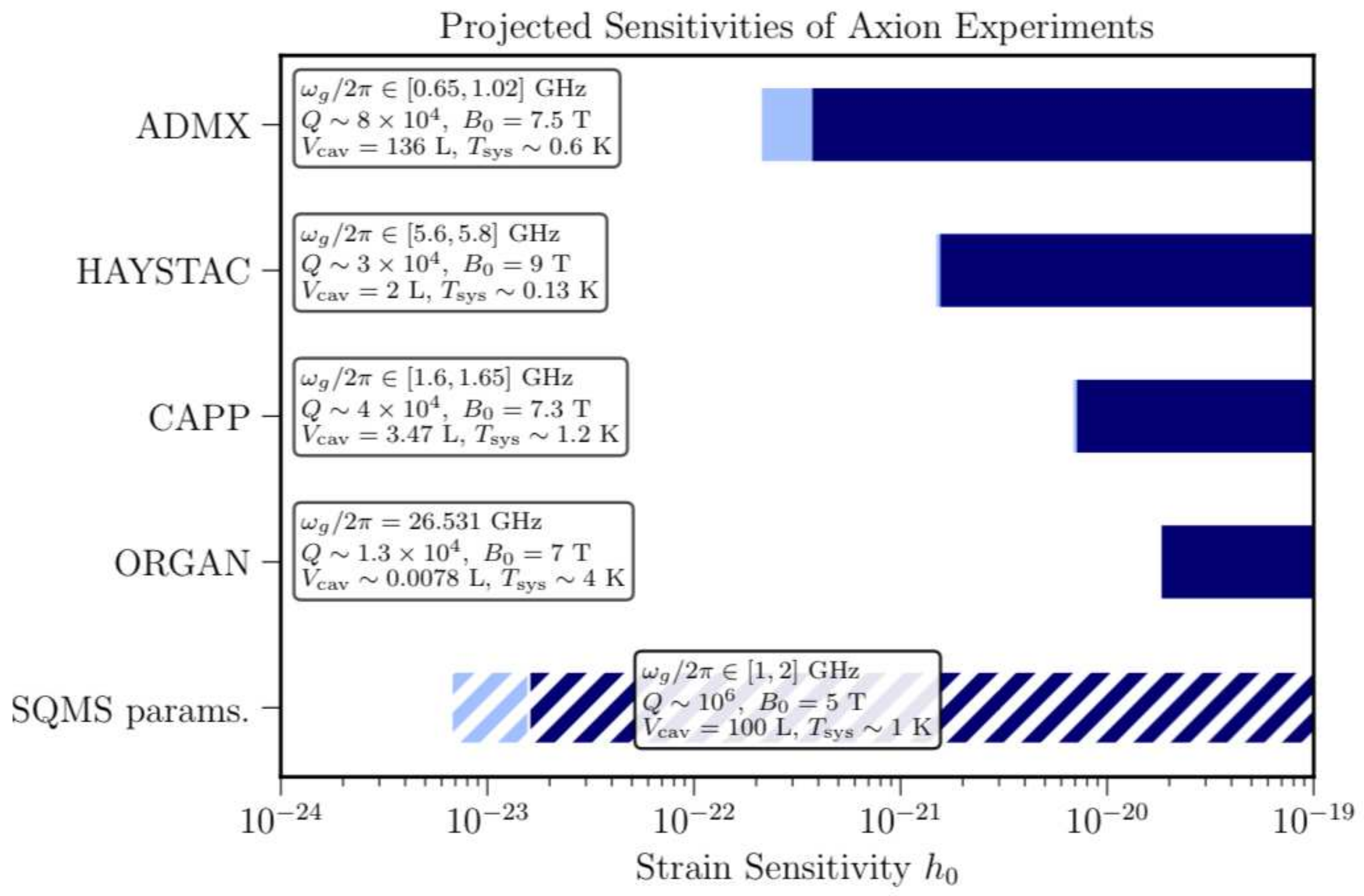

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Subtleties due to gauge fixing (TT vs detector frame gauge)

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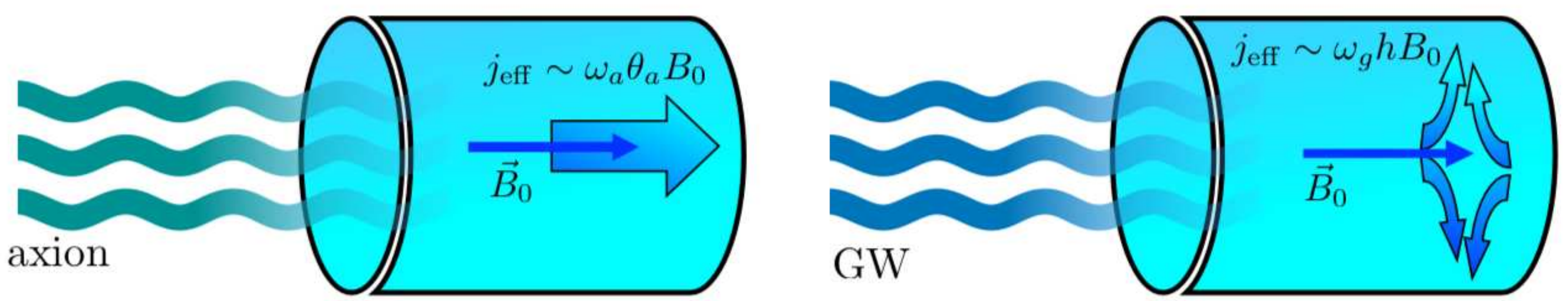

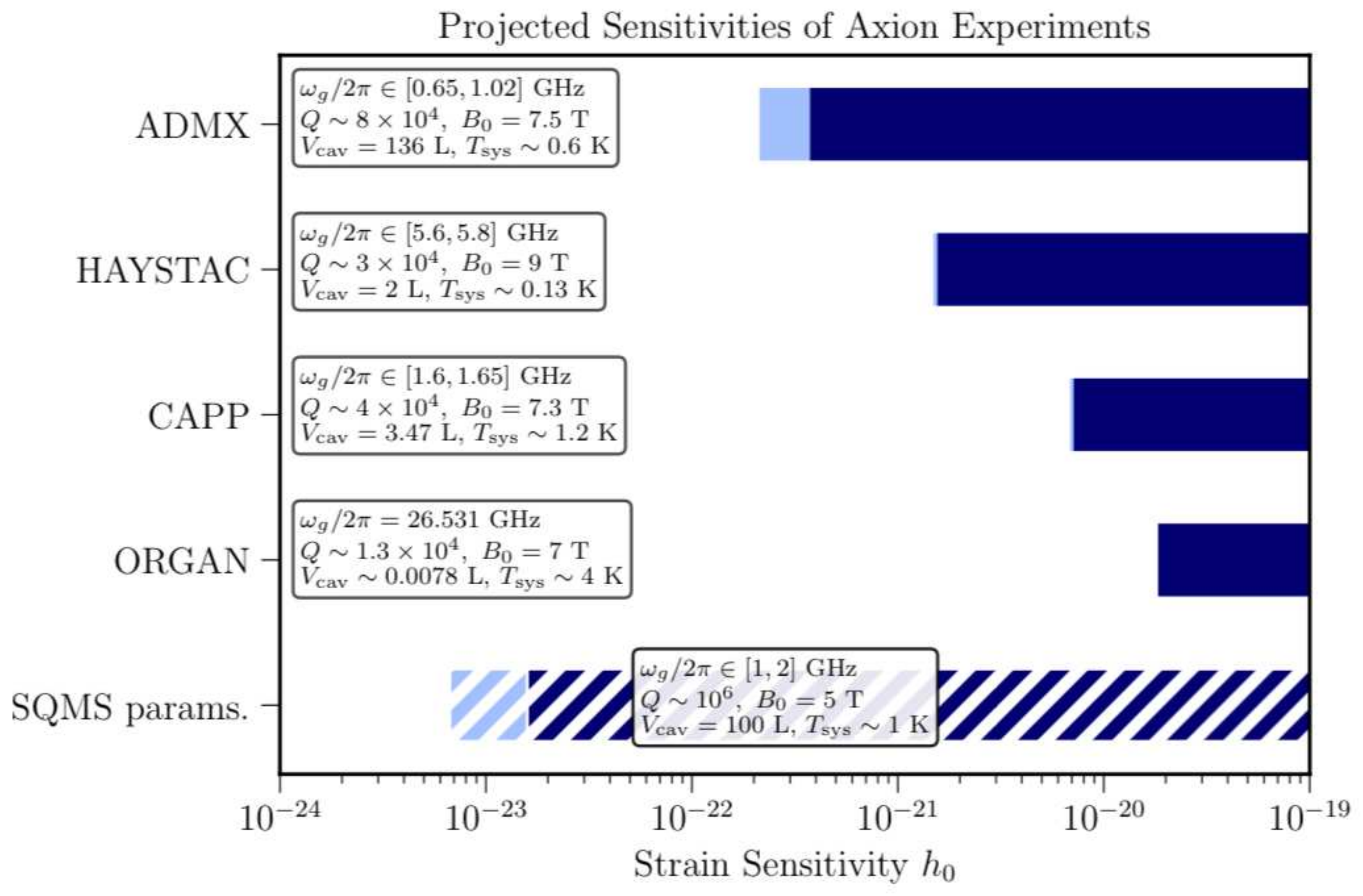

- In the TT frame, the description of rigid bodies becomes unintuitive, as their coordinates are deformed by a passing GW due to the motion of the coordinate system. **This is crucial to implement boundary conditions.**
- In the proper detector frame the coordinate system is defined by rigid rulers and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

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

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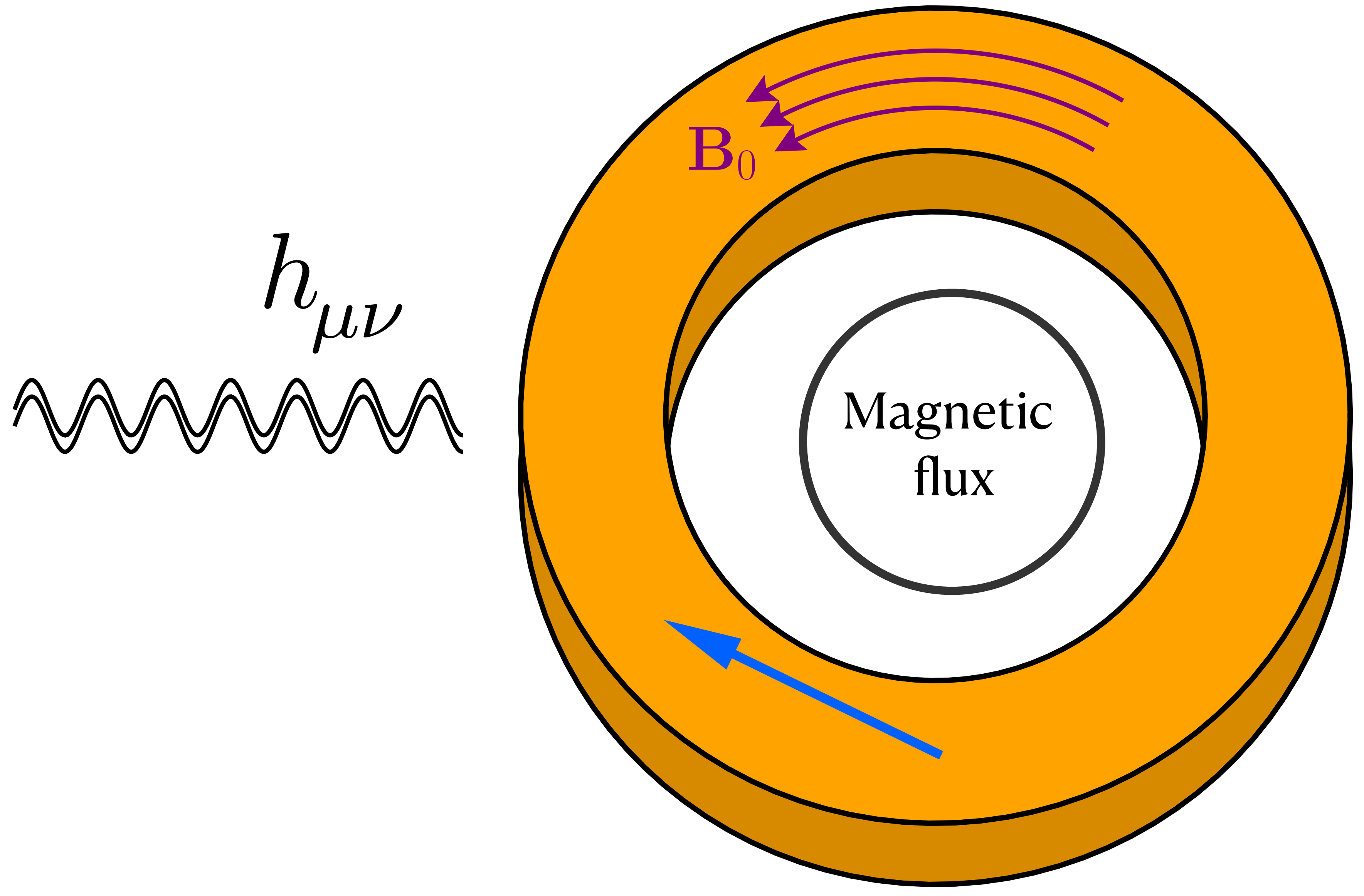
Gravitational wave electrodynamics



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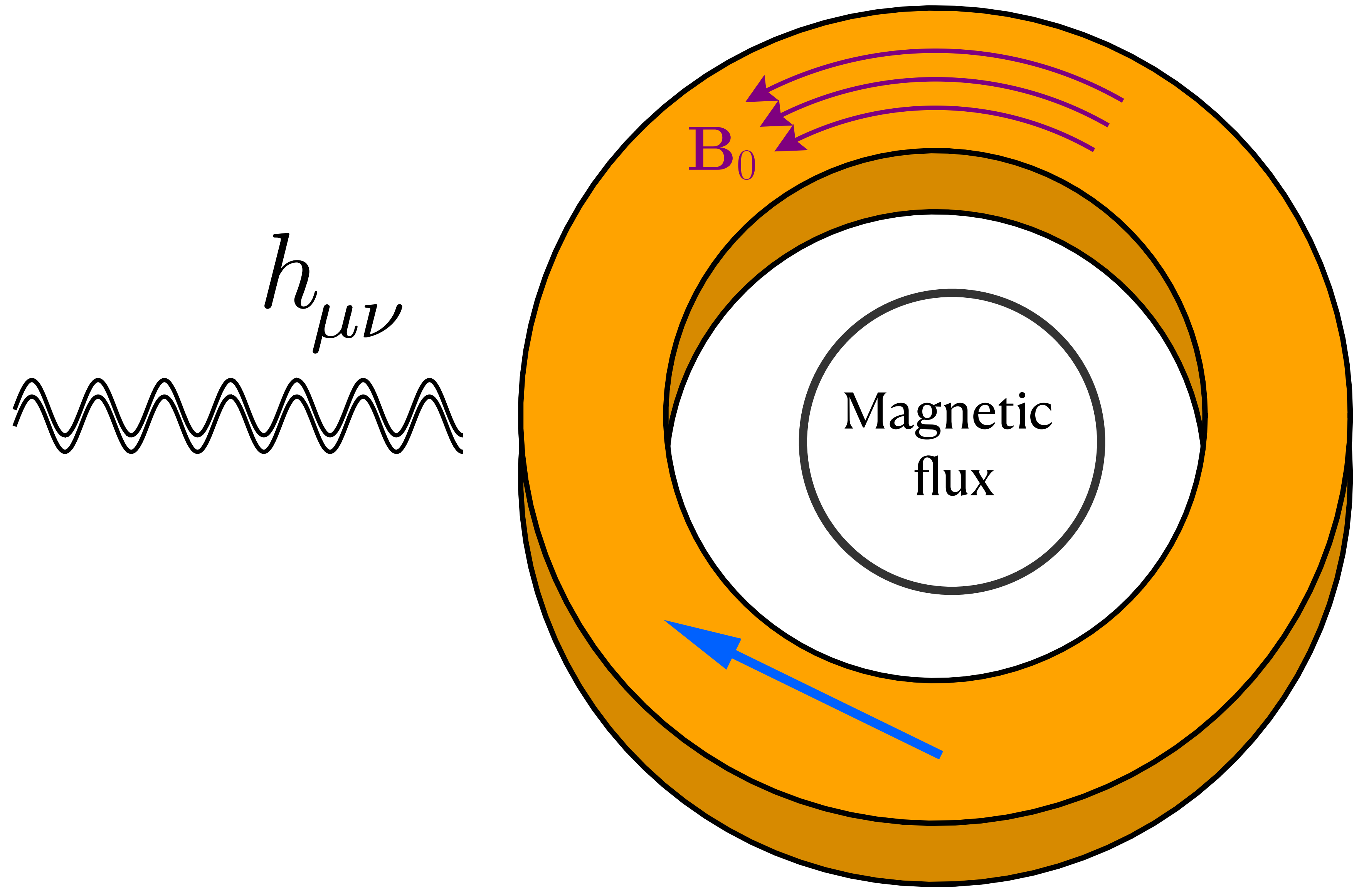

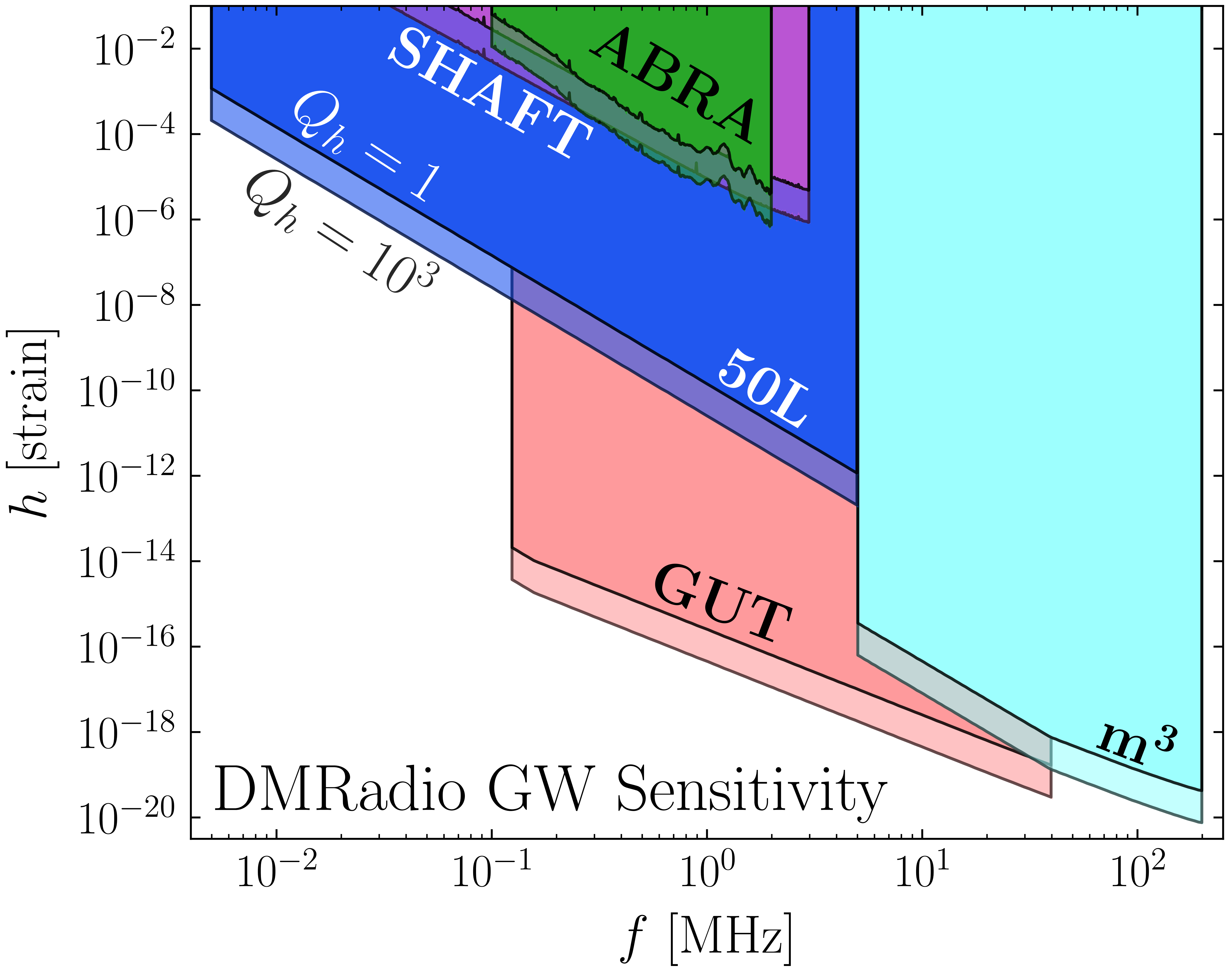

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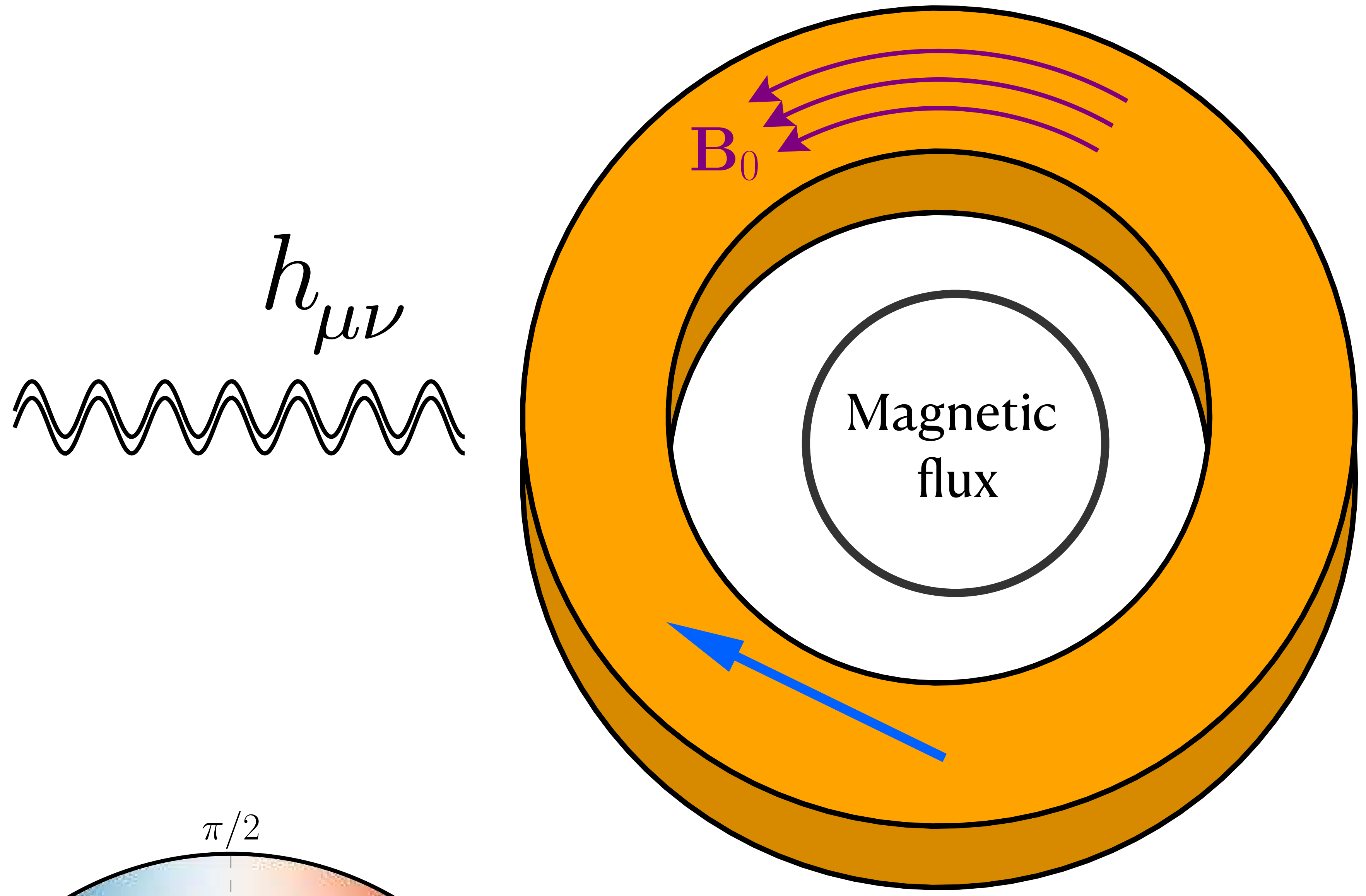
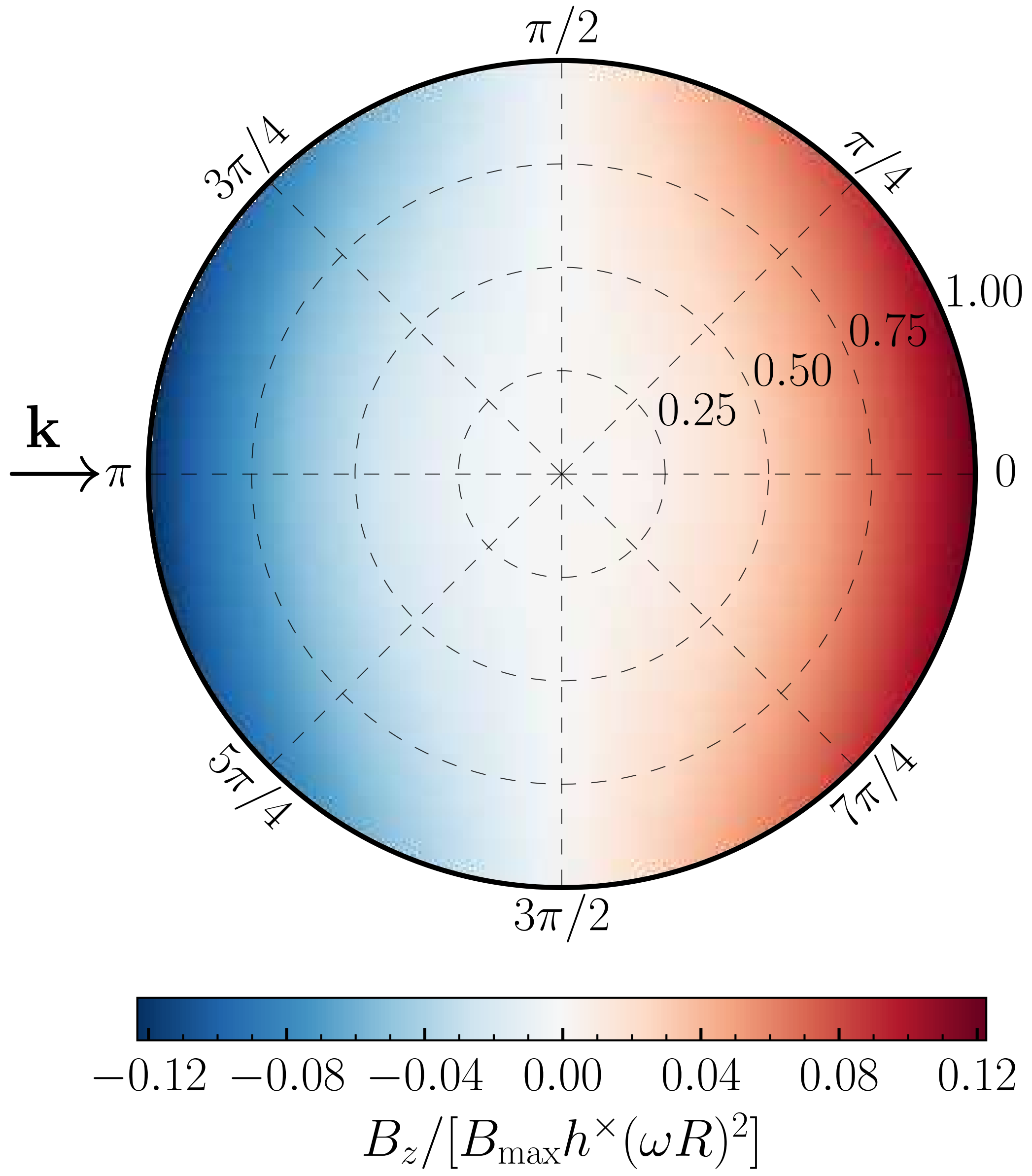
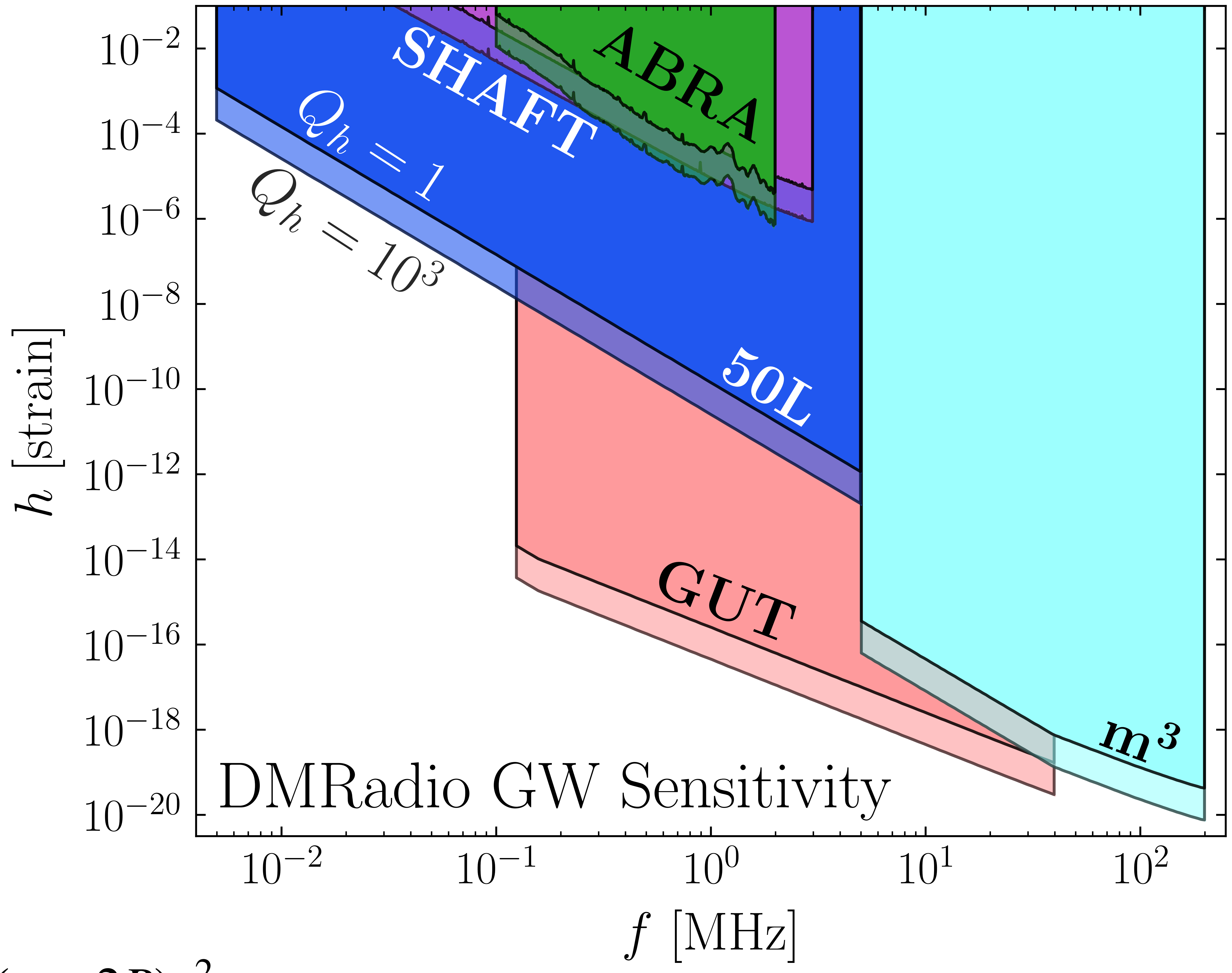




$$\Phi = \frac{\mathrm{i}e^{-\mathrm{i}\omega t}}{16\sqrt{2}} h^\times \omega^3 B_{\max} \pi r^2 R a (a + 2R) s_{\theta_h}^2$$



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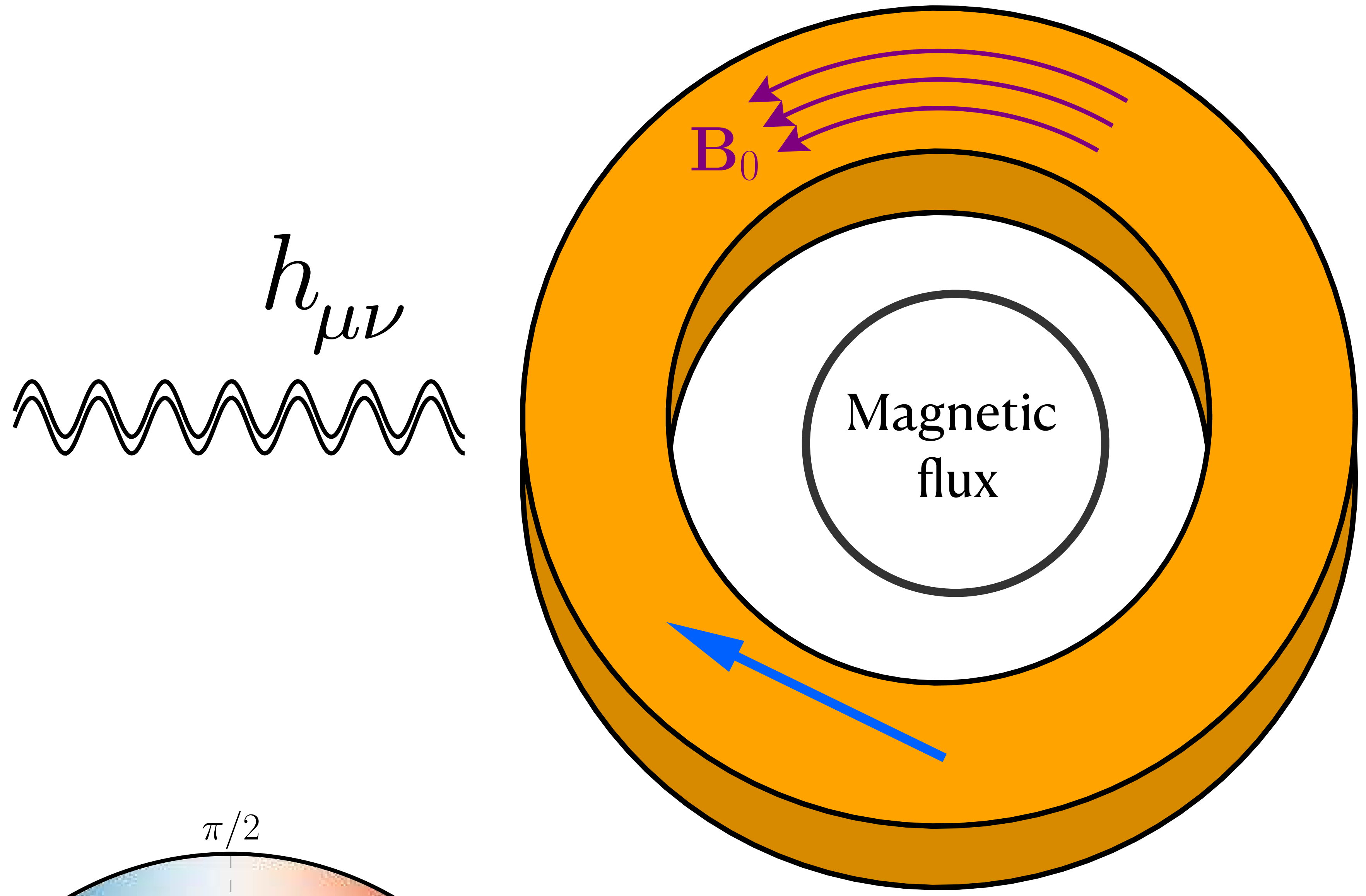

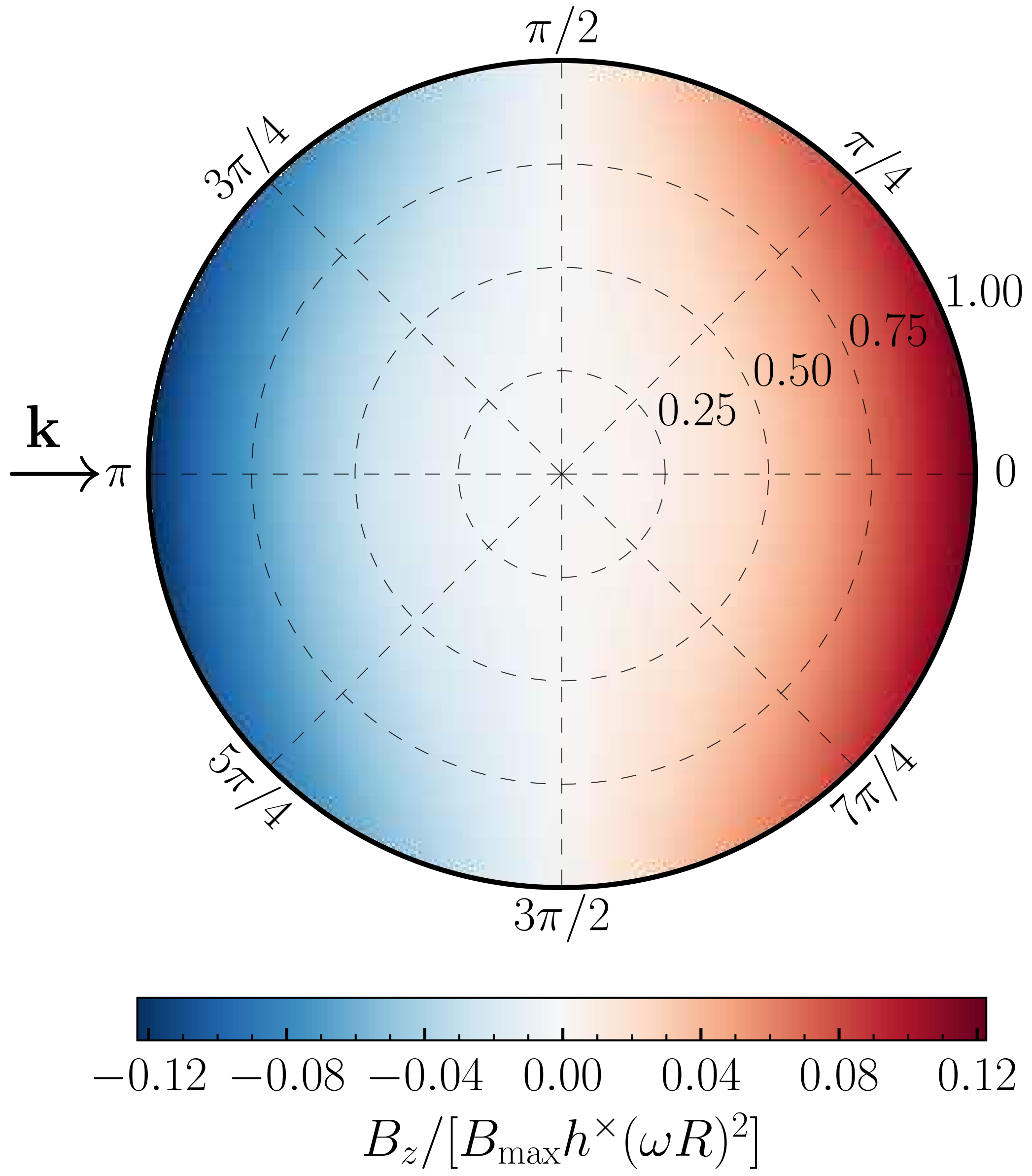

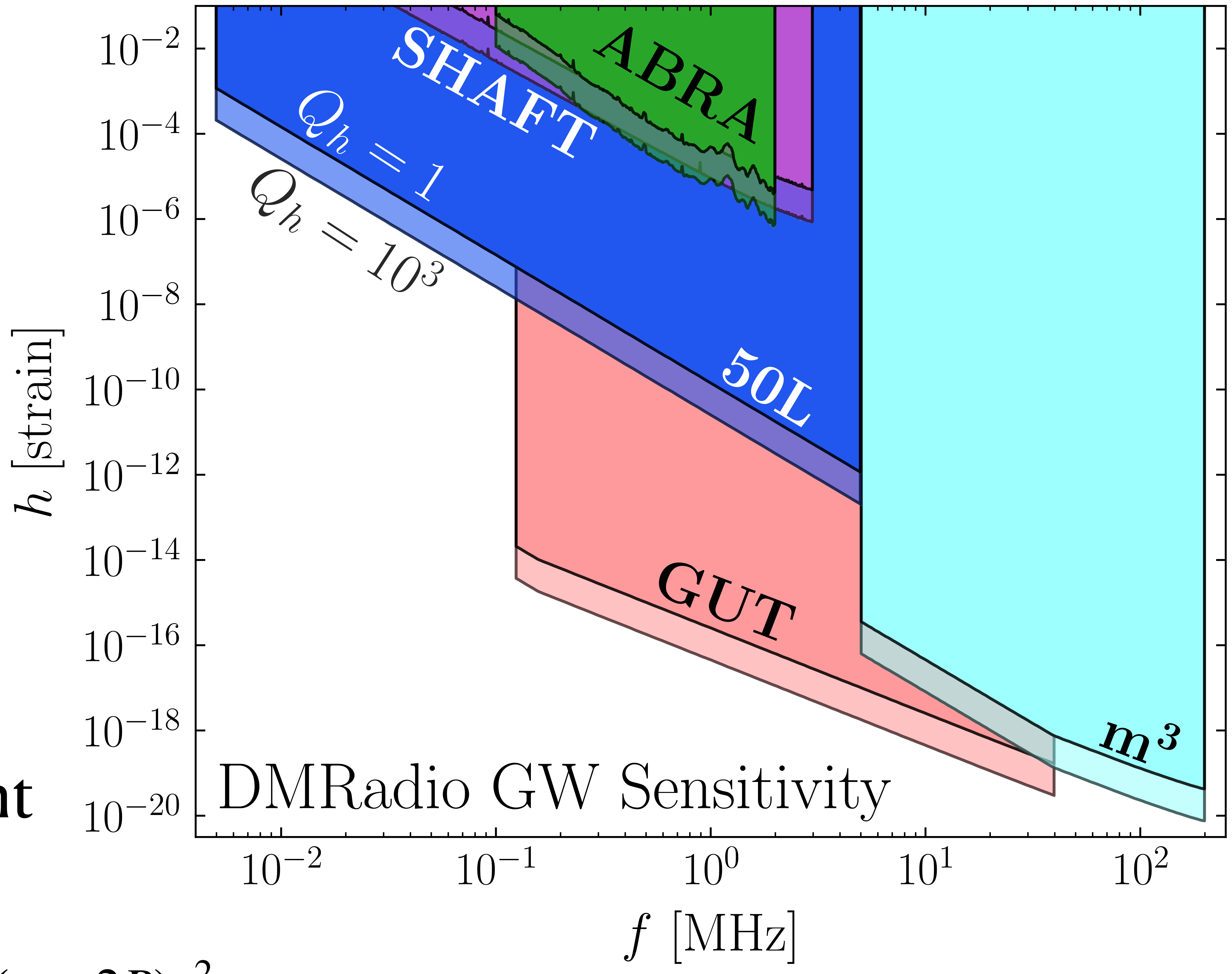

Room for improvement

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

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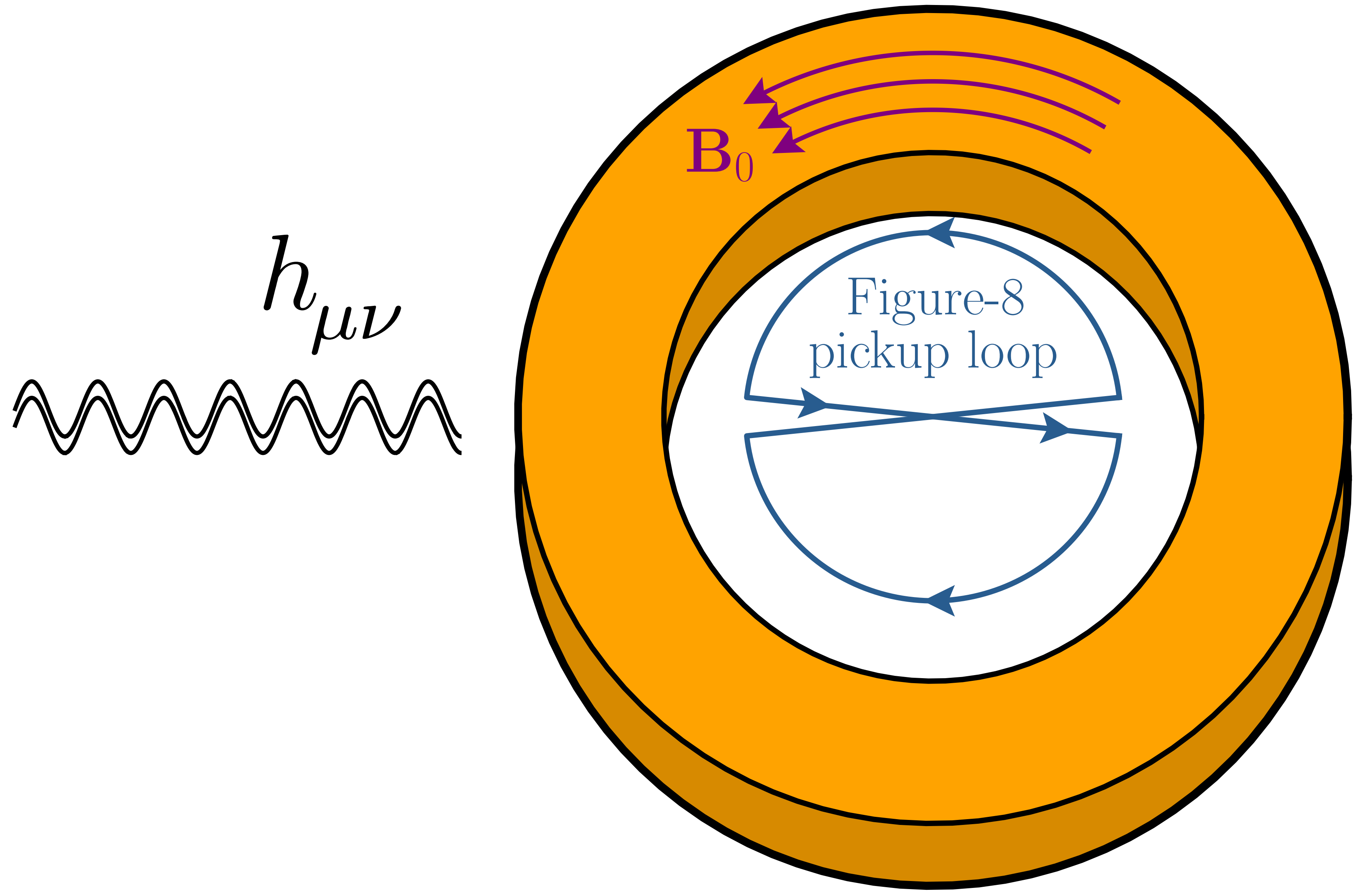

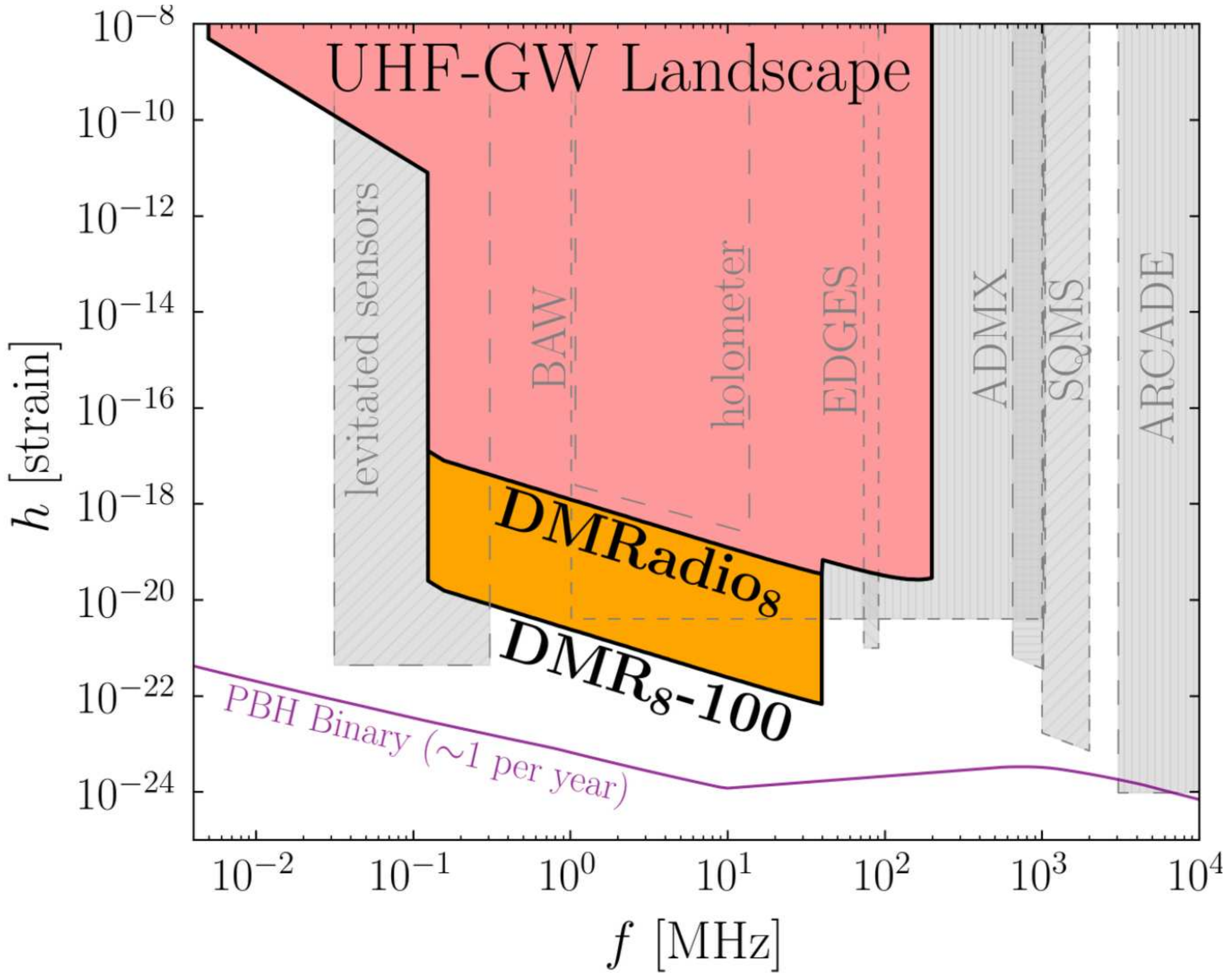

$$\Phi_8 = \frac{e^{-i\omega t}}{3\sqrt{2}}\omega^2 B_{\max} r^3 R \ln(1 + a/R) s_{\theta_h} \times \left(h^\times s_{\phi_h} - h^+ c_{\theta_h} c_{\phi_h}\right).$$

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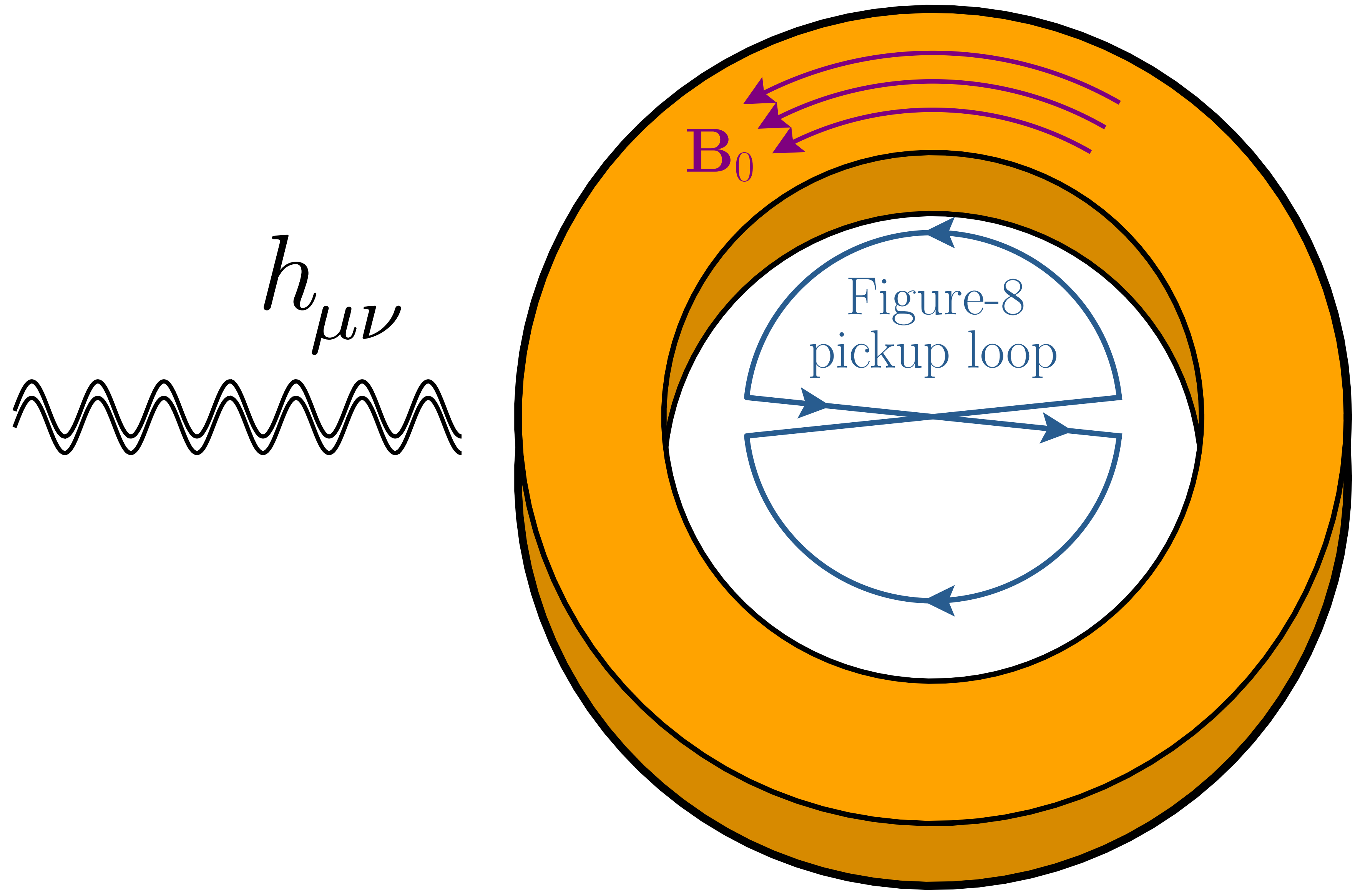
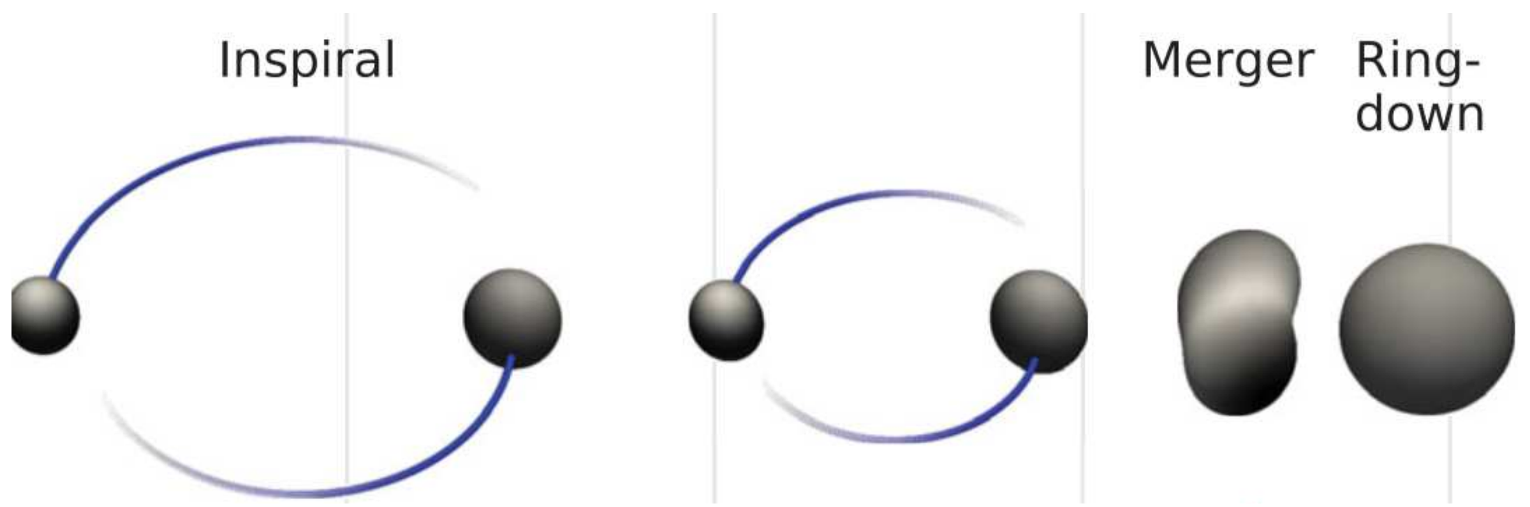
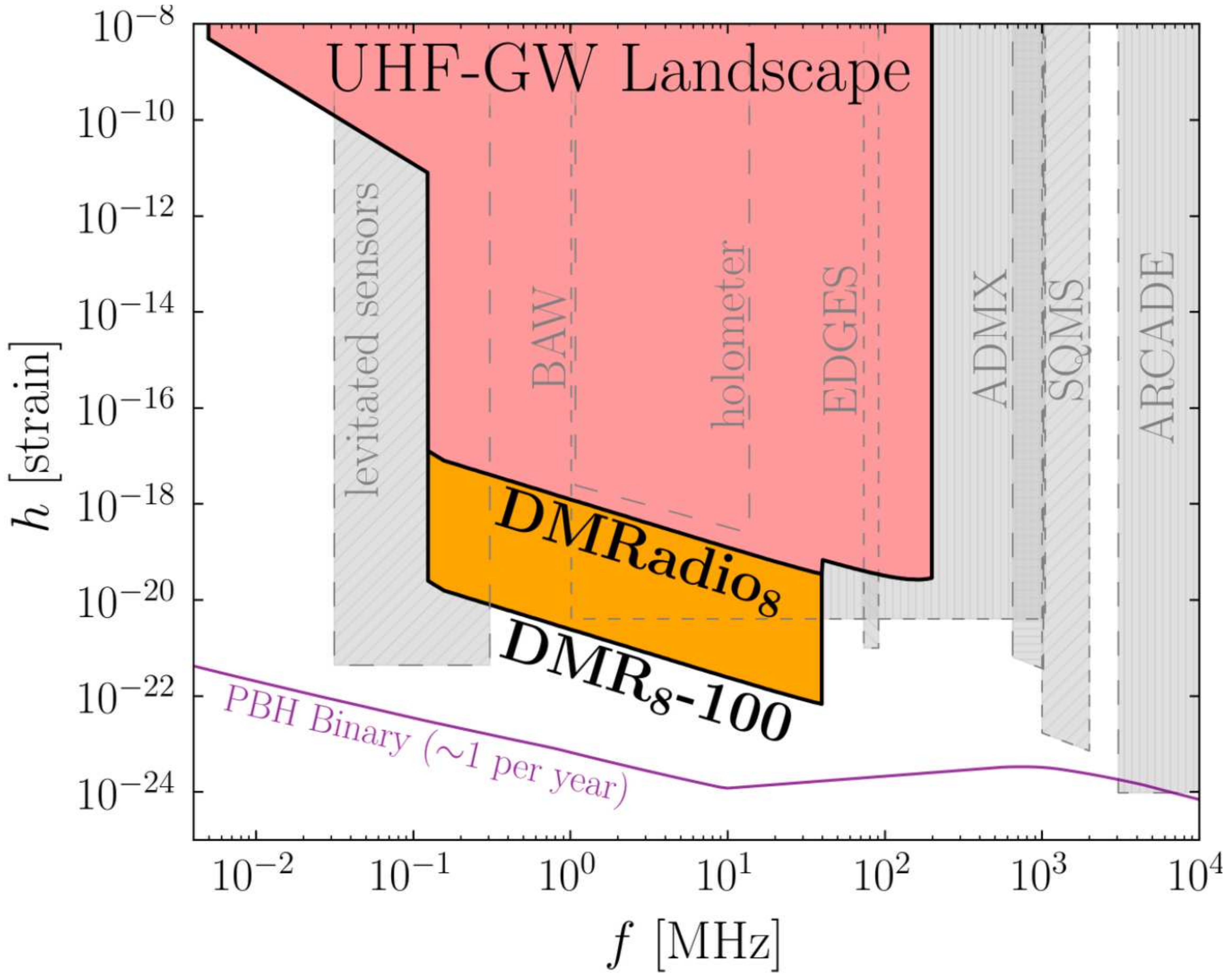
Gravitational wave electrodynamics





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,

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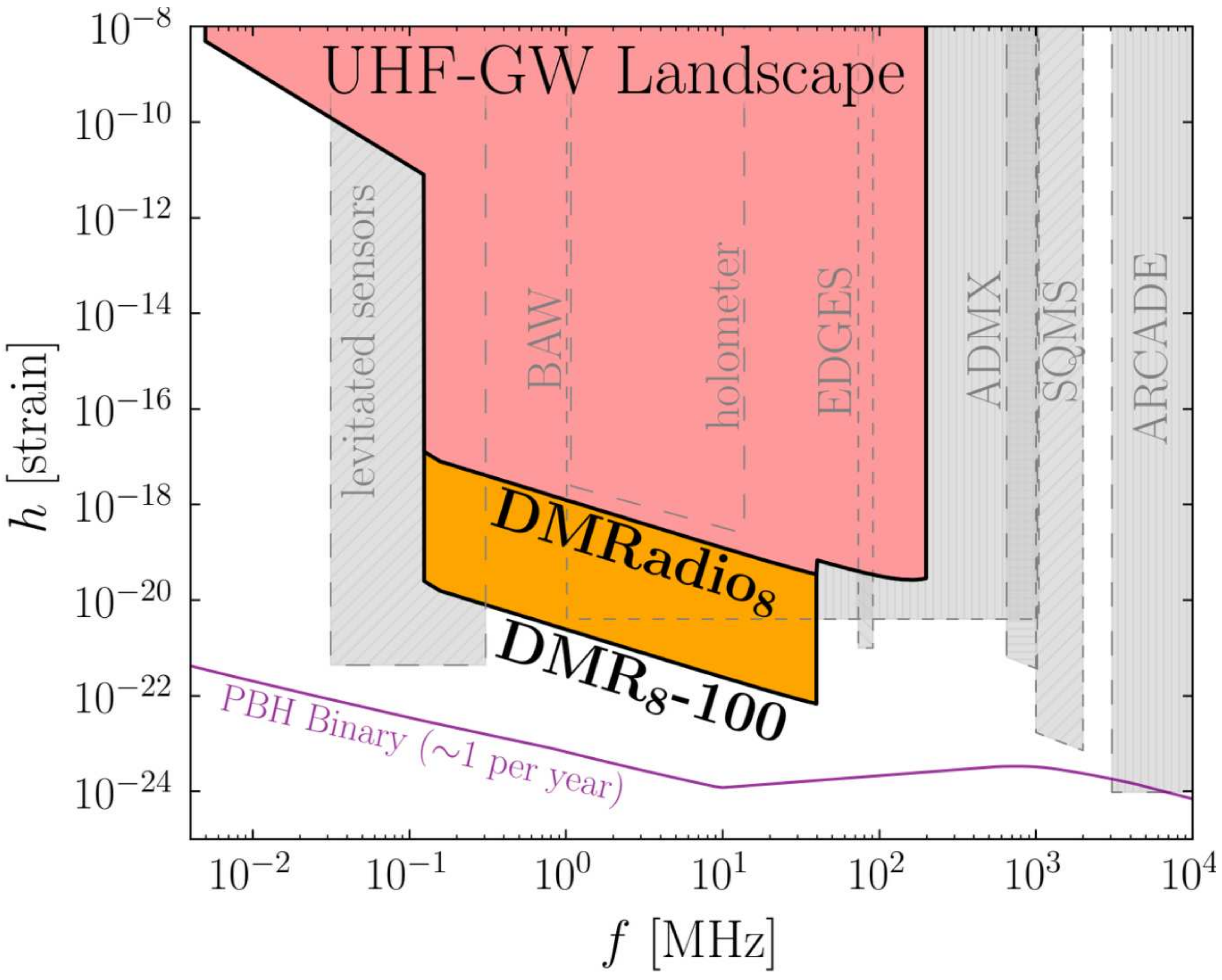
Benchmark	QCD axion $g_{a\gamma\gamma} a \sim \frac{\alpha \sqrt{\rho_{\text{DM}}}}{2\pi m_a f_a} \sim \frac{\alpha \sqrt{\rho_{\text{DM}}}}{2\pi m_\pi f_\pi} \sim 10^{-22}$	$h \sim 10^{-22}$

Conclusions

The Gertsenshtein effect during the dark ages provides a powerful way to probe gravitational waves in the MHz-GHz range from distortions of the Rayleigh-Jeans CMB tail.

I provide a formulation of GW electrodynamics which demonstrates that low-mass axion haloscopes are also UHF-GW telescopes.

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.



Cosmic magnetic fields

$$\langle \mathbf{B}_i(\mathbf{x})\mathbf{B}_j(\mathbf{x}')\rangle = \frac{1}{(2\pi)^3 a(t)^4}\int d^3k e^{i\mathbf{k}\cdot(\mathbf{x}'-\mathbf{x})}\left(\left(\delta_{ij}-\hat{k}_i\hat{k}_j\right)P_B(k) - i\epsilon_{ijk}\hat{k}_k P_{aB}(k)\right),$$

Durrer, Neronov, 2013

The adiabatic evolution of the magnetic field due to cosmic expansion is determined by the scale factor.

$$\langle B^2\rangle = \frac{1}{\pi^2 a(t)^4}\int_0^\infty dk k^2 P_B(k) = \int_{-\infty}^{\infty} d\log\lambda\, B_\lambda^2$$

average magnetic field

$$\text{where}\quad B_\lambda^2 \equiv \frac{8\pi}{\lambda^3 a(t)^4} P_B\left(\frac{2\pi}{\lambda}\right),$$

$$\lambda_B = \int_0^\infty d\lambda \frac{B_\lambda^2}{\langle B^2\rangle}$$

the coherence length

Oscillations after the formation of the CMB

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

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

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

The plasma frequency acts as an effective mass term

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

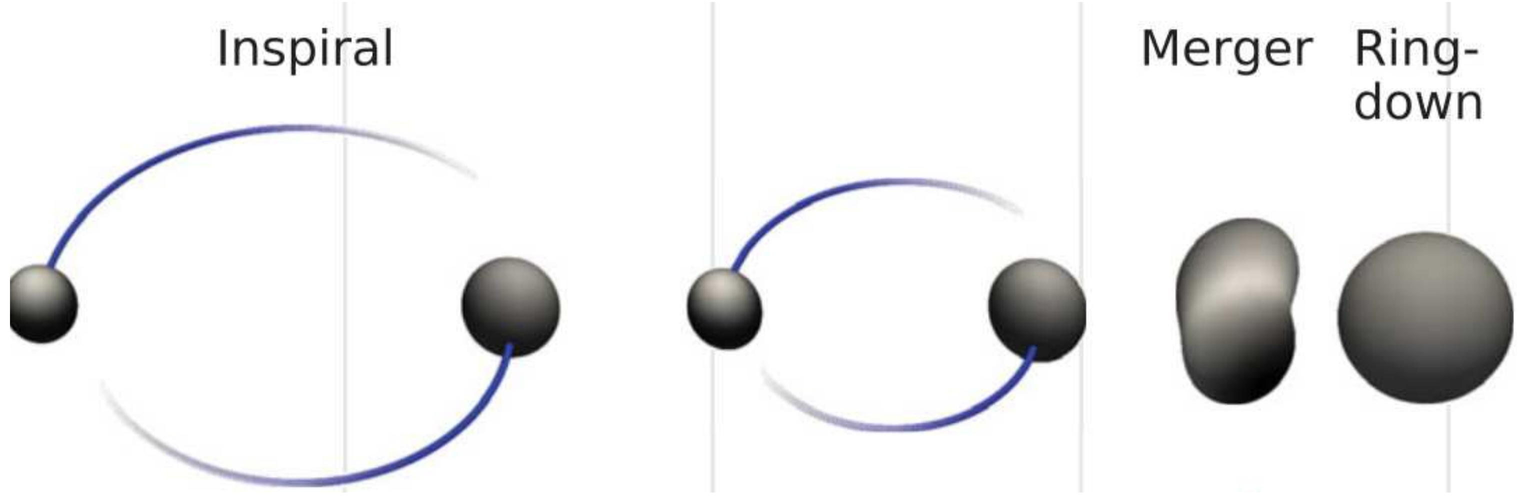
$$\langle \Gamma_{g\leftrightarrow\gamma} \rangle = \frac{2\pi G B^2 \ell_{\text{osc}}^2}{\Delta \ell}$$

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

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

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

Domcke, CGC 2021



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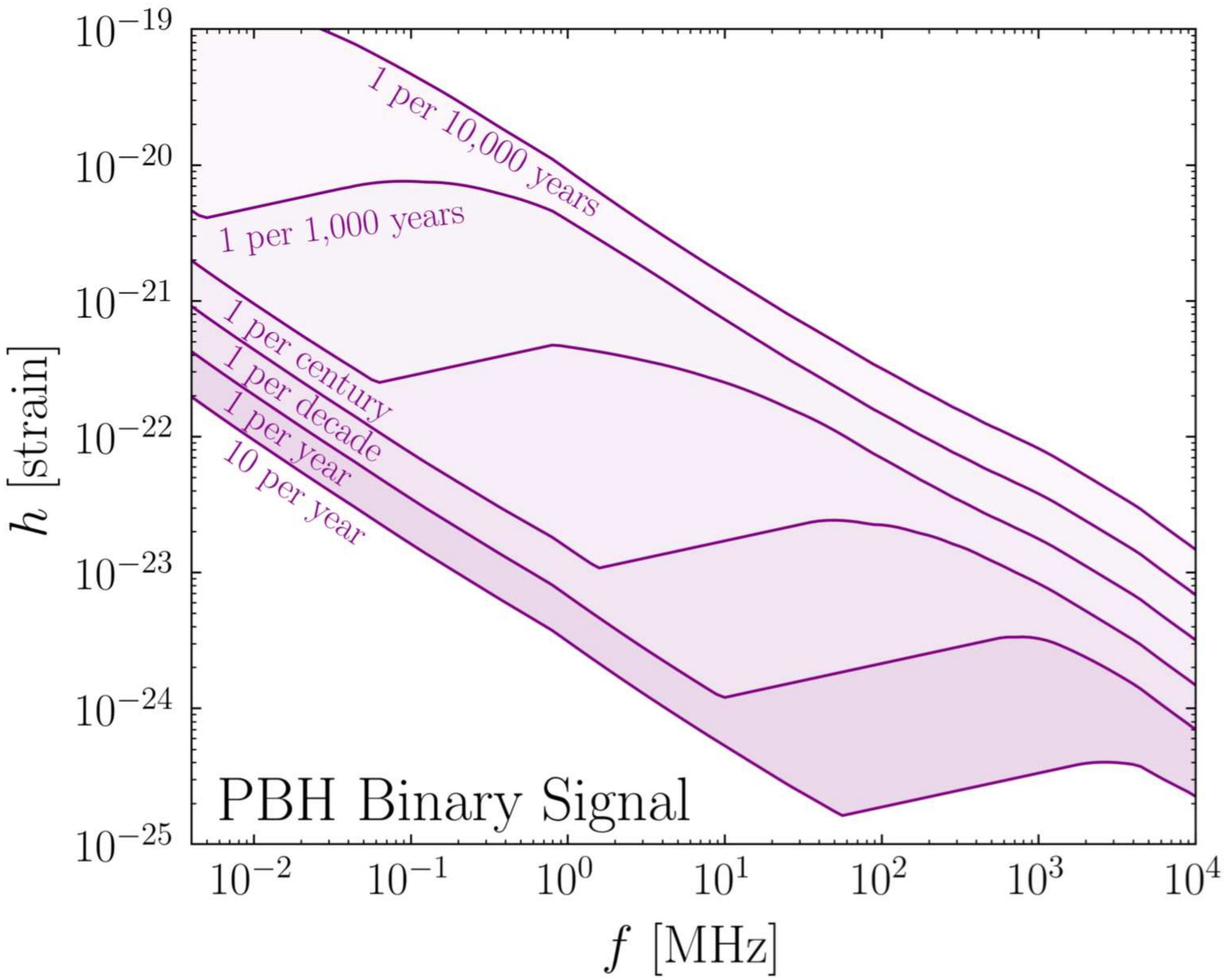

Merger rates

$$R_0(m_{\rm PBH}, f_{\rm PBH}) \simeq 6.6 \times 10^{-8}\,{\rm kpc}^{-3}\,{\rm yr}^{-1}\, f_{\rm PBH}^{53/37} \left(\frac{m_{\rm PBH}}{10^{-5} M_\odot}\right)^{-32/37} S_{\rm early}(f_{\rm PBH})\, S_{\rm late}(f_{\rm PBH}),$$

$$S_{\rm early}(f_{\rm PBH}) = \min\left\{1, \left(\frac{f_{\rm PBH}}{0.01}\right)^{1/2}\right\},$$

$$S_{\rm late}(f_{\rm PBH}) = \min\left\{1, 9.6 \times 10^{-3} f_{\rm PBH}^{-0.65} e^{0.03 \ln^2 f_{\rm PBH}}\right\},$$

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