A novel search for gravitational waves inspired by axion dark matter

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

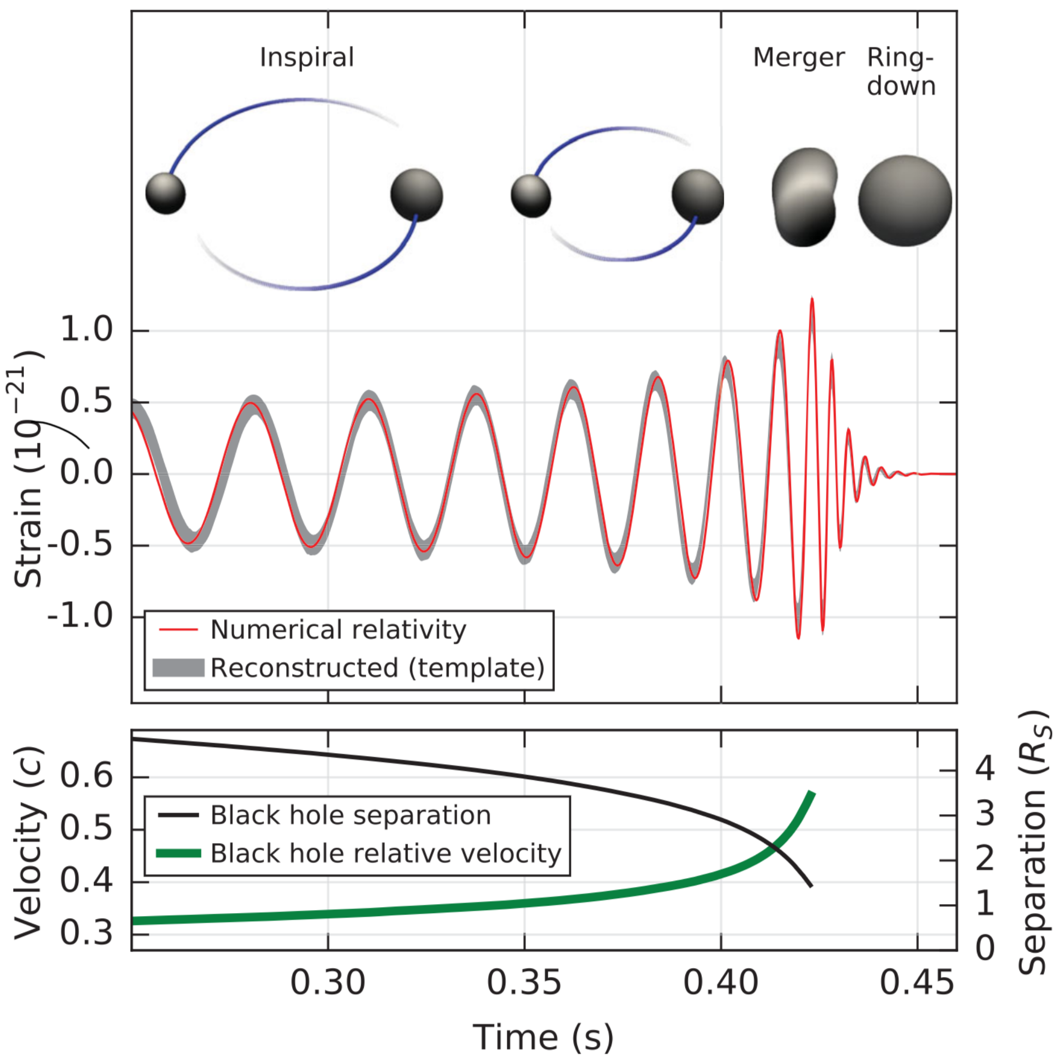
Valerie Domcke, Camilo Garcia-Cely, and Nicholas L. Rodd
Phys. Rev. Lett. **129**, 041101 – Published 20 July 2022

Outline

- Motivation
- Adapting axion experiments to detect gravitational waves
- Conclusions

Motivation

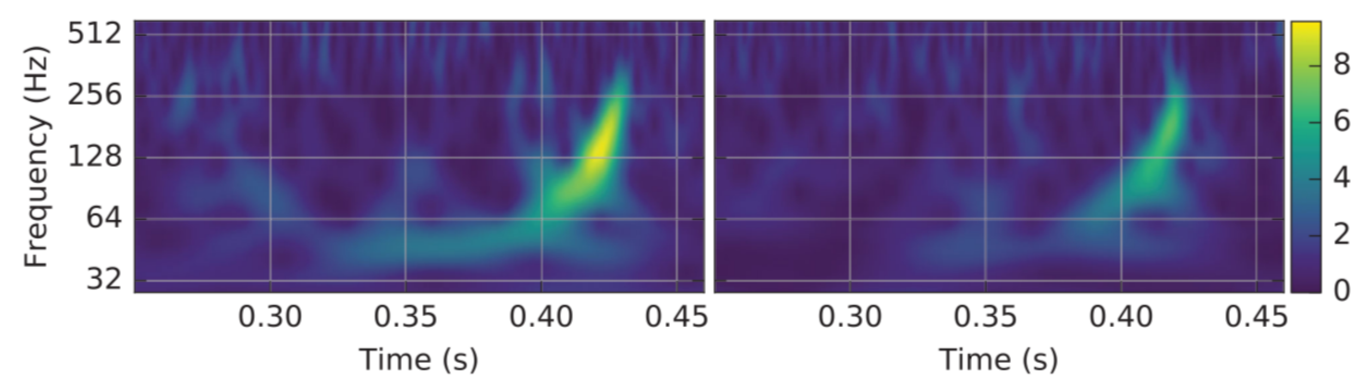
Gravitational waves from black holes



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)
(Received 21 January 2016; published 11 February 2016)



$$f \approx 2.2 \text{ kHz} \left(\frac{M_\odot}{m_{\text{BH}}} \right)$$

High-frequency gravitational waves

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

Part of a collection:

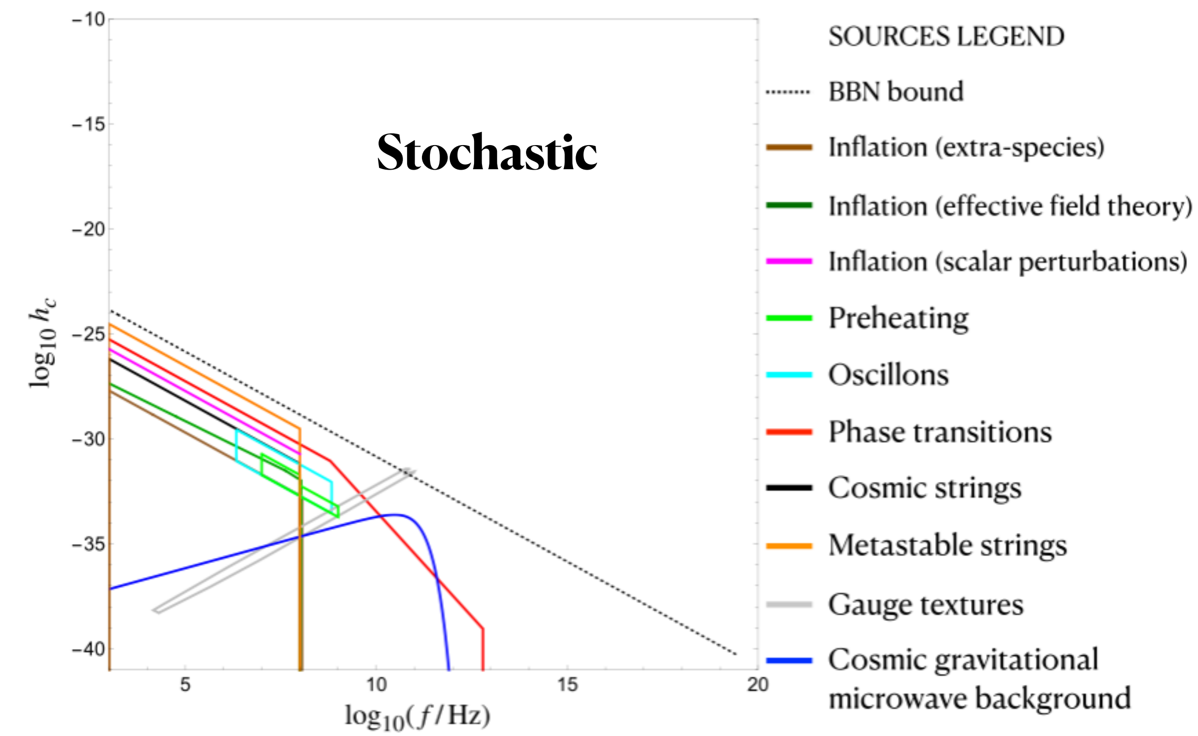
Gravitational Waves

Review Article | Open Access | Published: 06 December 2021

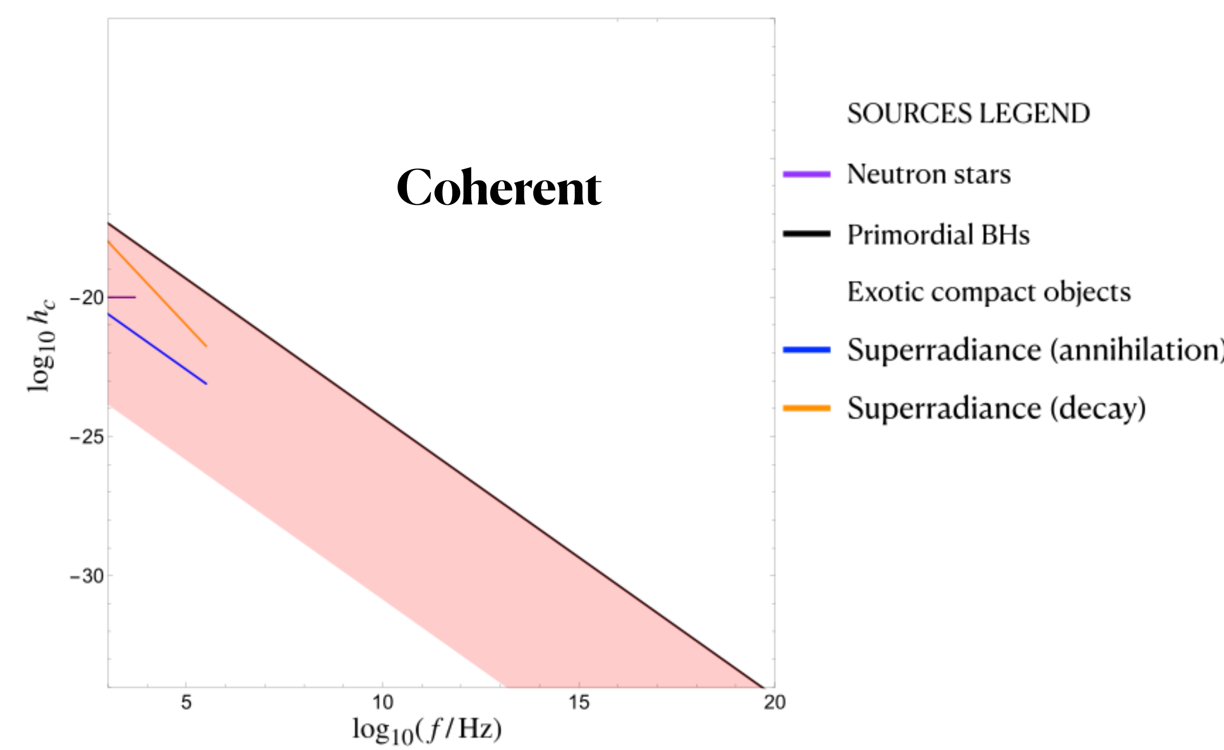
Challenges and opportunities of gravitational-wave searches at MHz to GHz frequencies

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



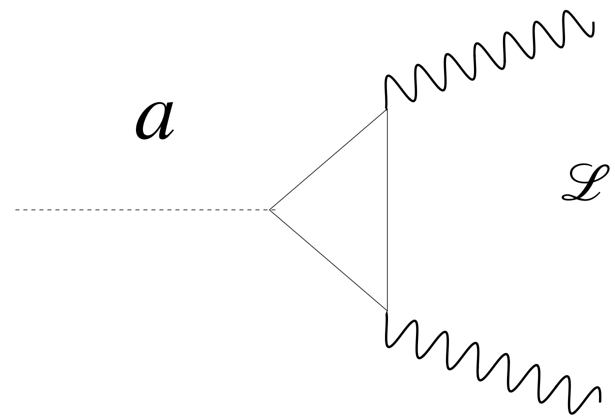
A growing community is seriously considering the search of high frequency gravitational waves



Talk by James Dent

Axion dark matter

- Pseudoscalar field



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

- Solution to the strong CP problem

Peccei, Quinn 1977

- Excellent dark matter candidate

Weinberg, Wilczek 1978

Effective current for axions

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

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

Sikivie, 1983

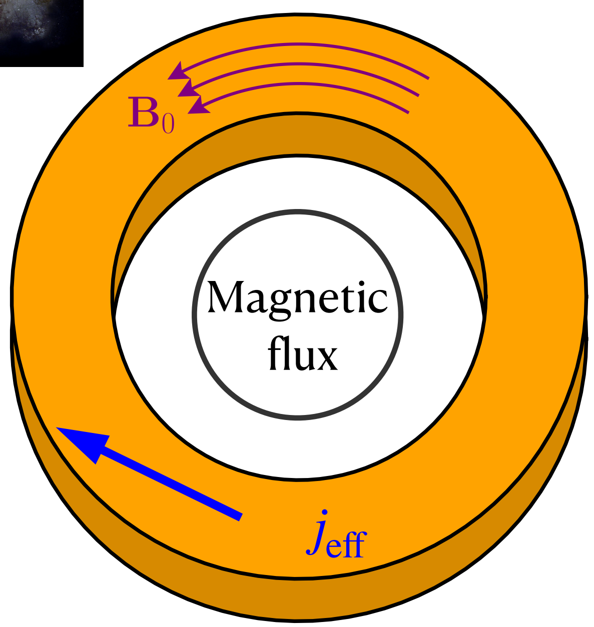
$$\nabla \times \mathbf{E} + \partial_t \mathbf{B} = 0$$

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

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

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

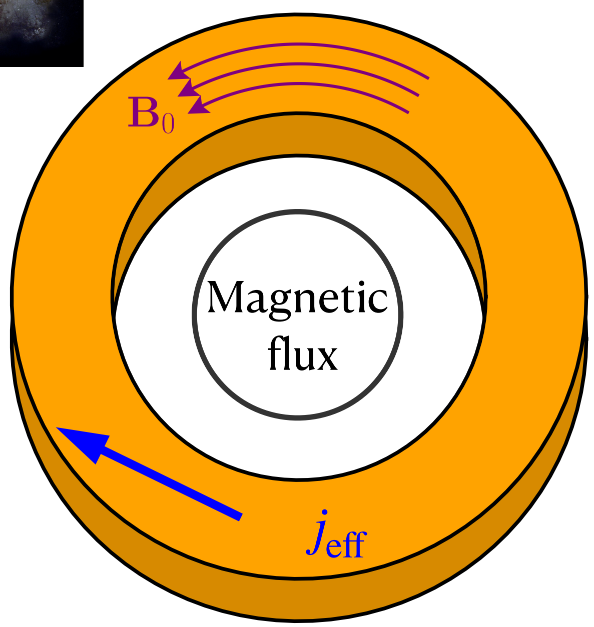
Low mass axion haloscopes



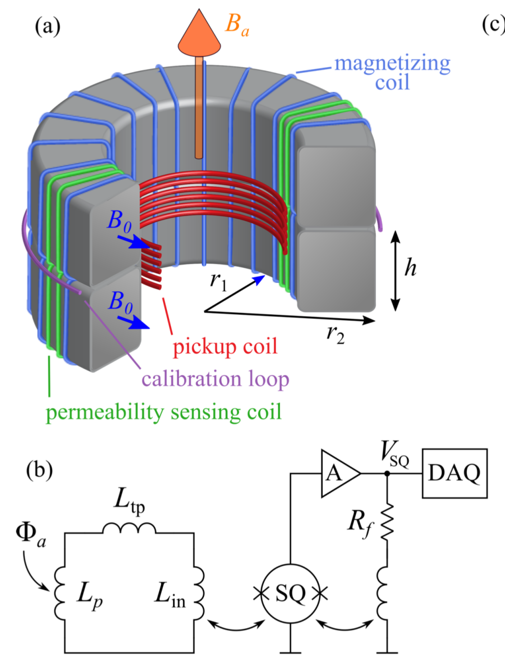
$$\nabla \times \mathbf{B} - \partial_t \mathbf{E} = \underbrace{g_{a\gamma\gamma}\, \partial_t a\, \mathbf{B_0}}_{j_{\text{eff}}}$$

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

Low mass axion haloscopes



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



(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

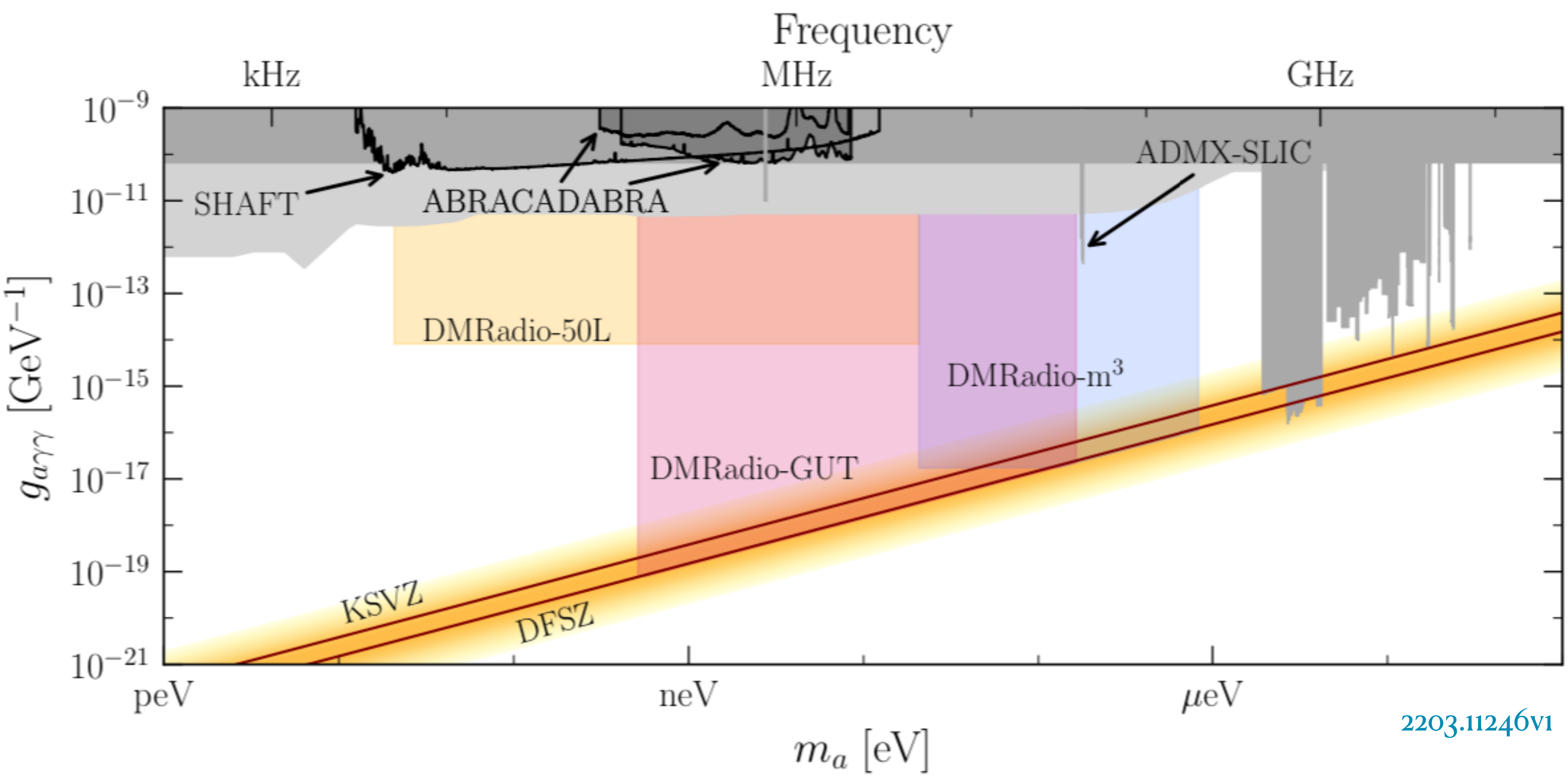
Yonatan Kahn,[1,*] Benjamin R. Safdi,[2,†] and Jesse Thaler[2,‡]
[1]Department of Physics, Princeton University, Princeton, New Jersey 08544, USA
[2]Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

(Received 3 March 2016; published 30 September 2016)

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

Low mass axion haloscopes

DMRadio program



2203.11246v1

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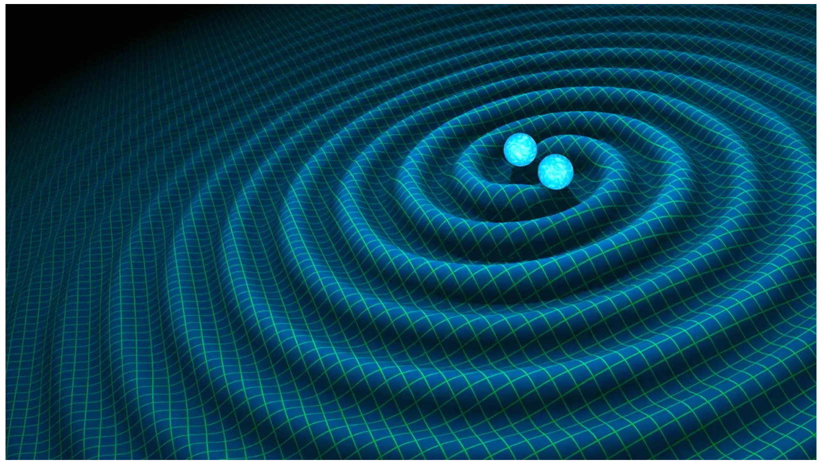
Adapting axion experiments to detect gravitational waves

Effective current for gravitational waves

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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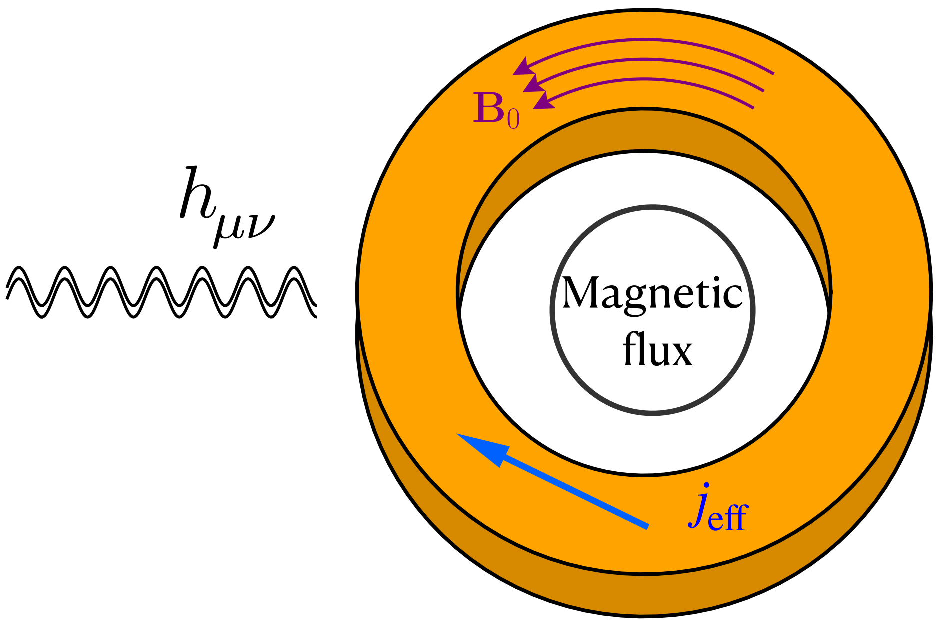
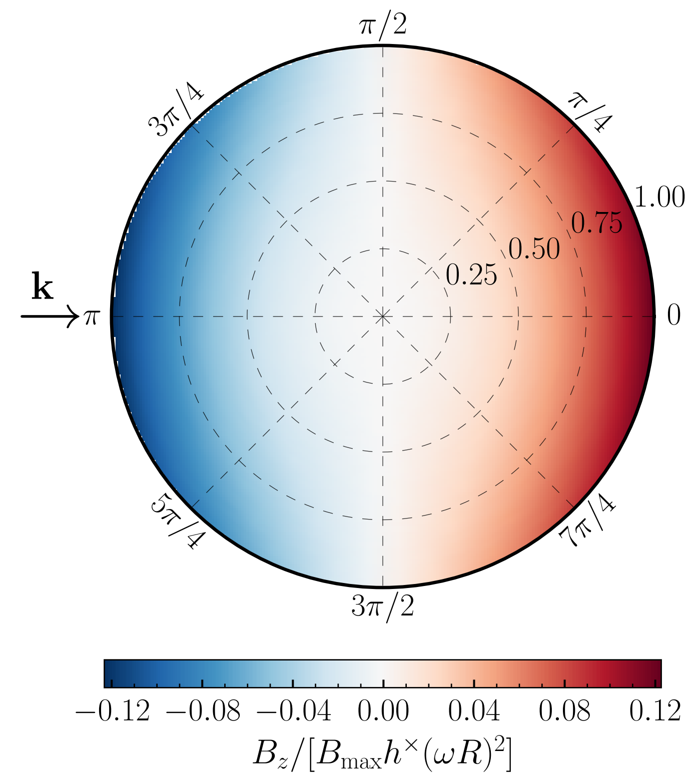
Gravitational waves in low mass axion haloscopes

Domcke, CGC, Rodd, 2202.00695





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

Only one polarization

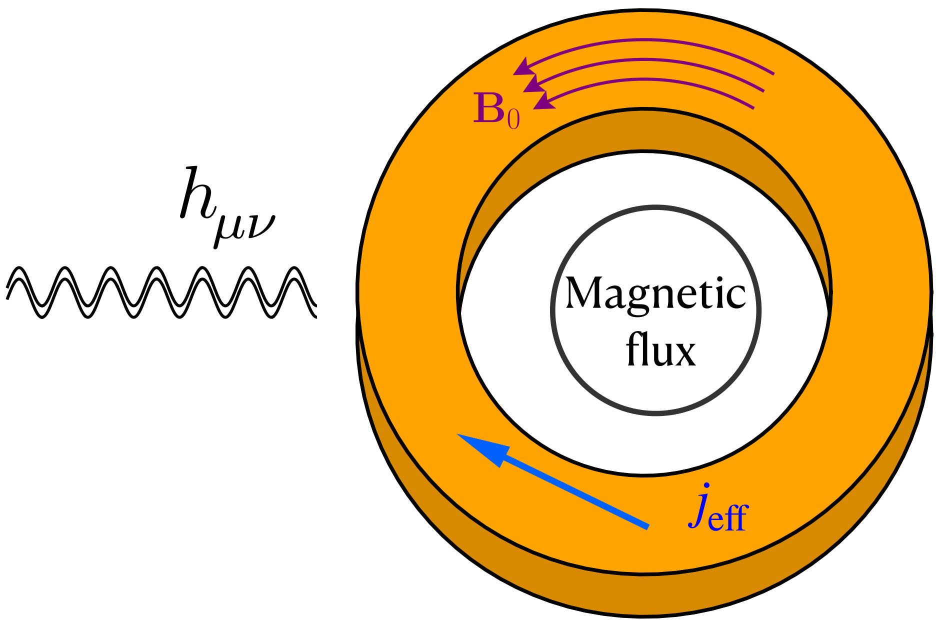
Suppression at small frequencies

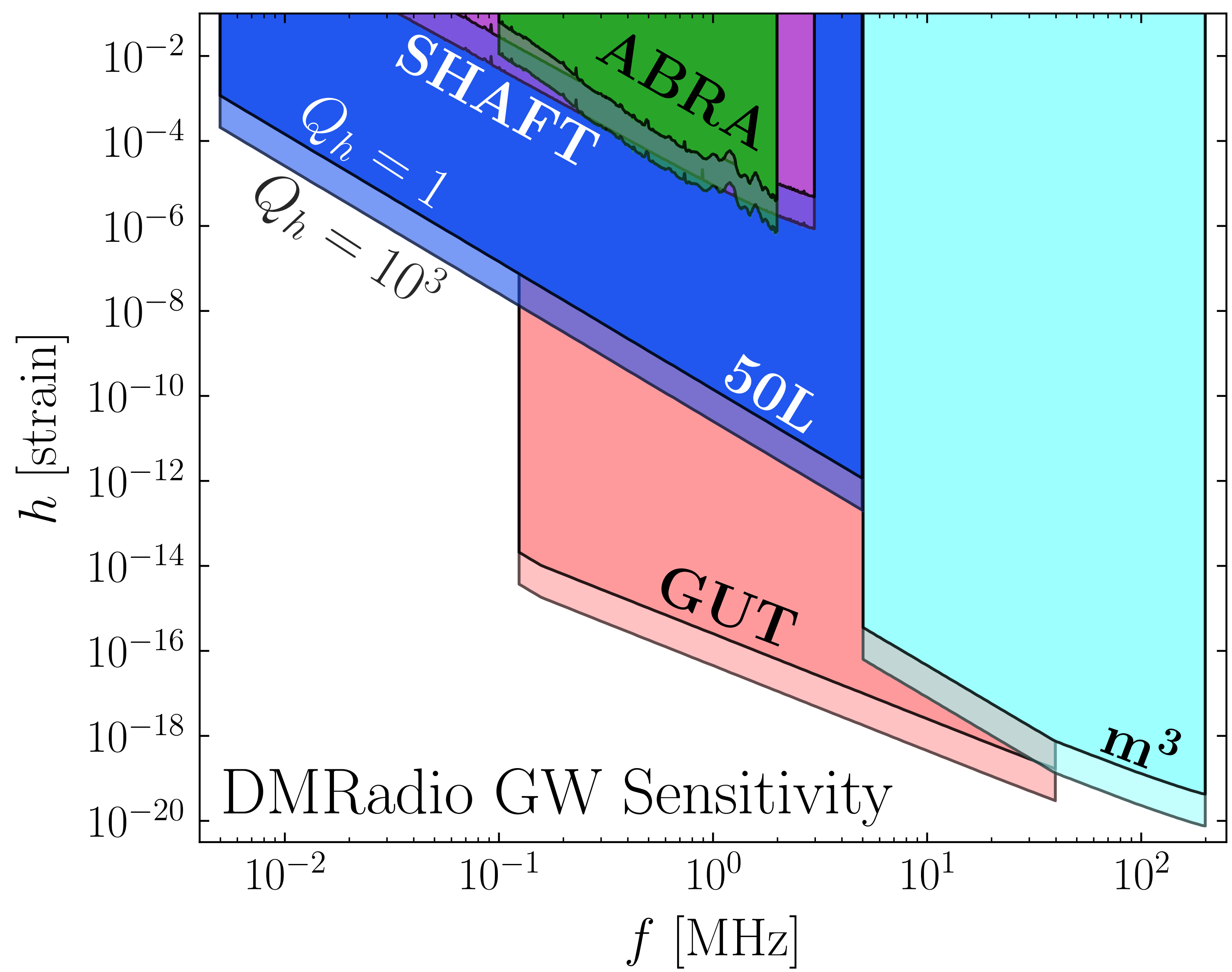
$$\Phi_{\rm axions} \approx e^{-\mathrm{i}\omega t} g_{a\gamma\gamma}\sqrt{2\rho_{\rm DM}} B_{\rm max}\pi r^2 R$$

The sensitivity scaling with the volume is faster than for axions

Gravitational waves in low mass axion haloscopes

Domcke, CGC, Rodd, 2202.00695





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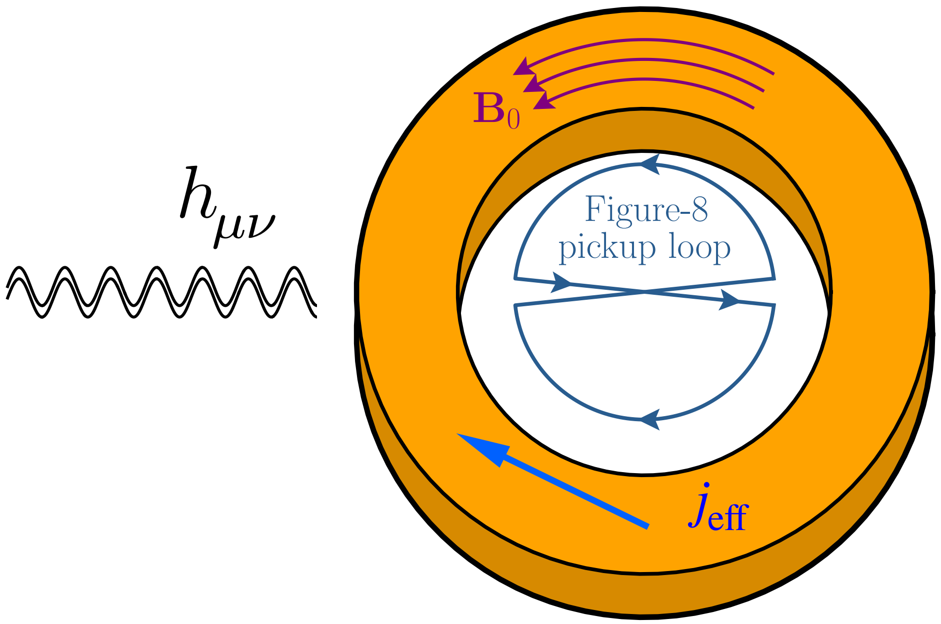
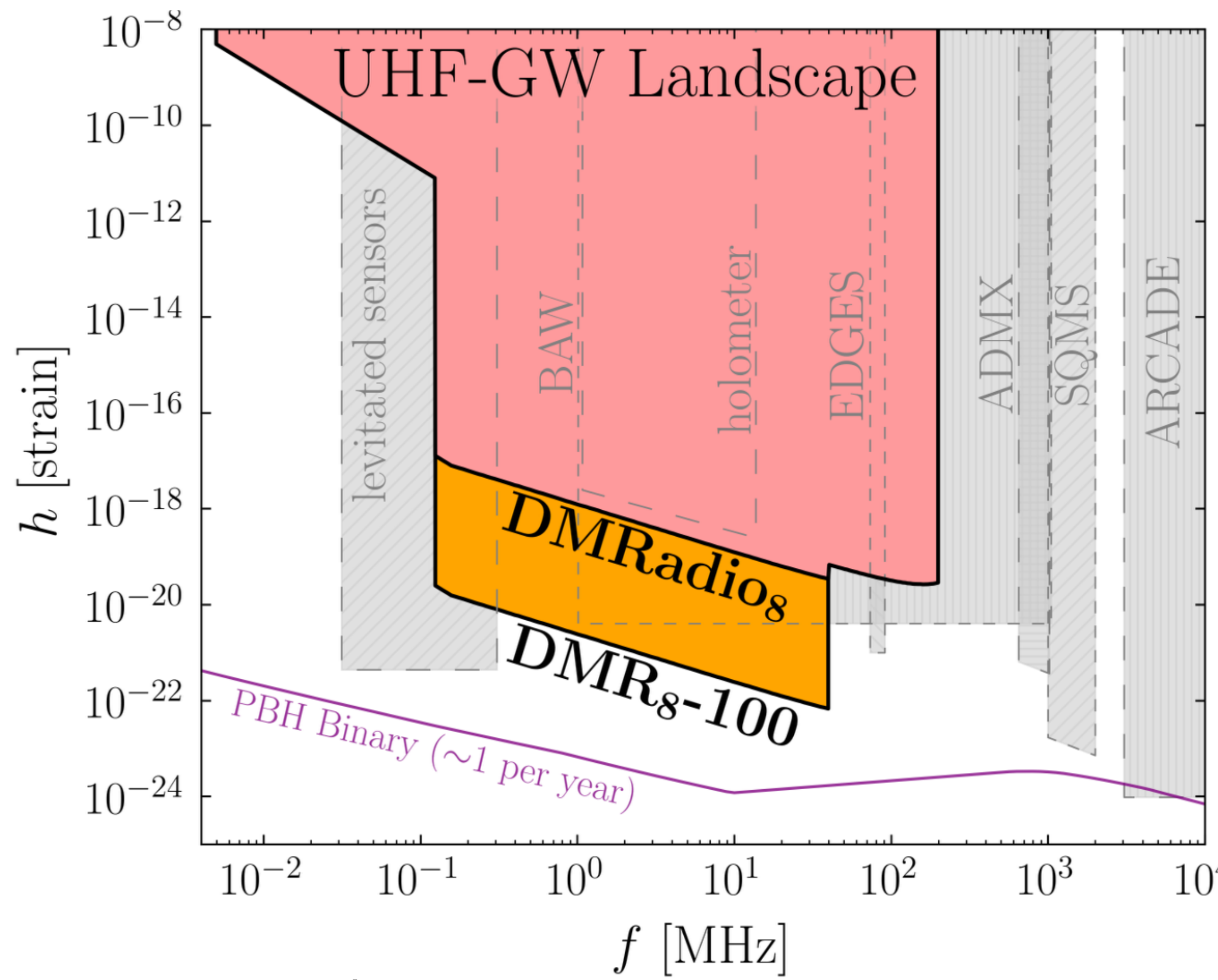
Gravitational waves in low mass axion haloscopes

Domcke, CGC, Rodd, 2202.00695

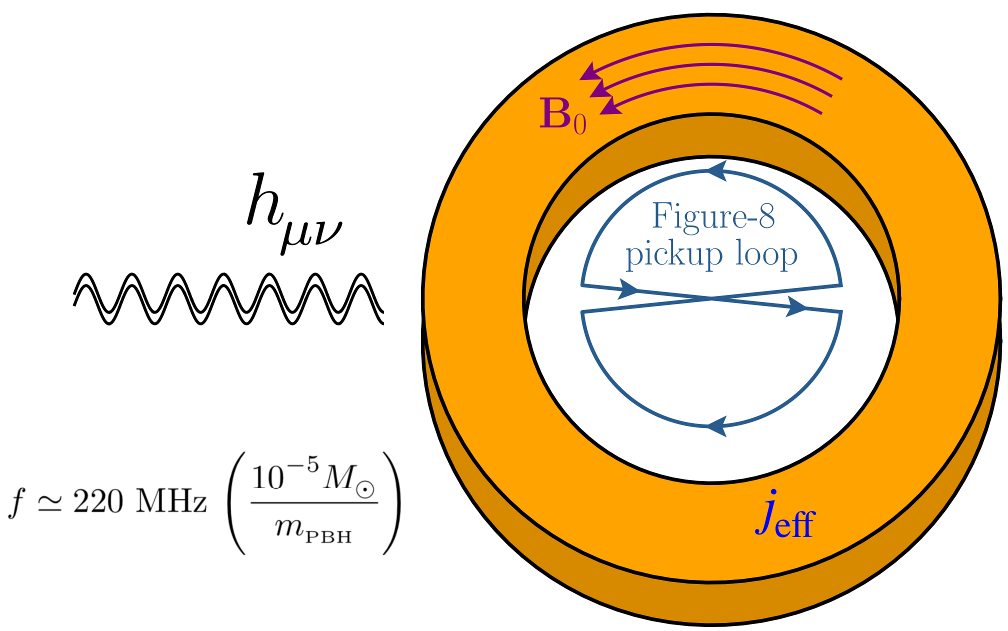


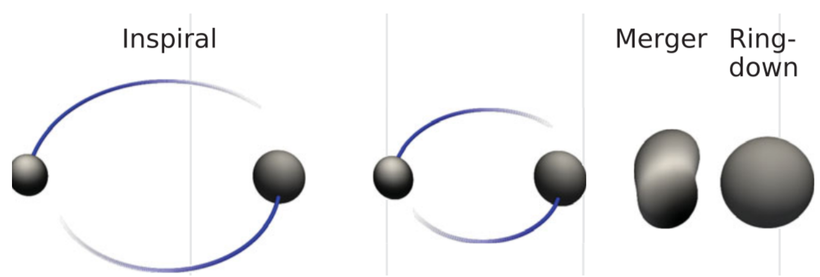


$$\Phi_8 \approx \frac{e^{-i\omega t}}{3\sqrt{2}} \omega^2 B_{\rm max} r^3 R s_{\theta_h} \left(h^\times s_{\phi_h} - h^+ c_{\theta_h} c_{\phi_h} \right)$$

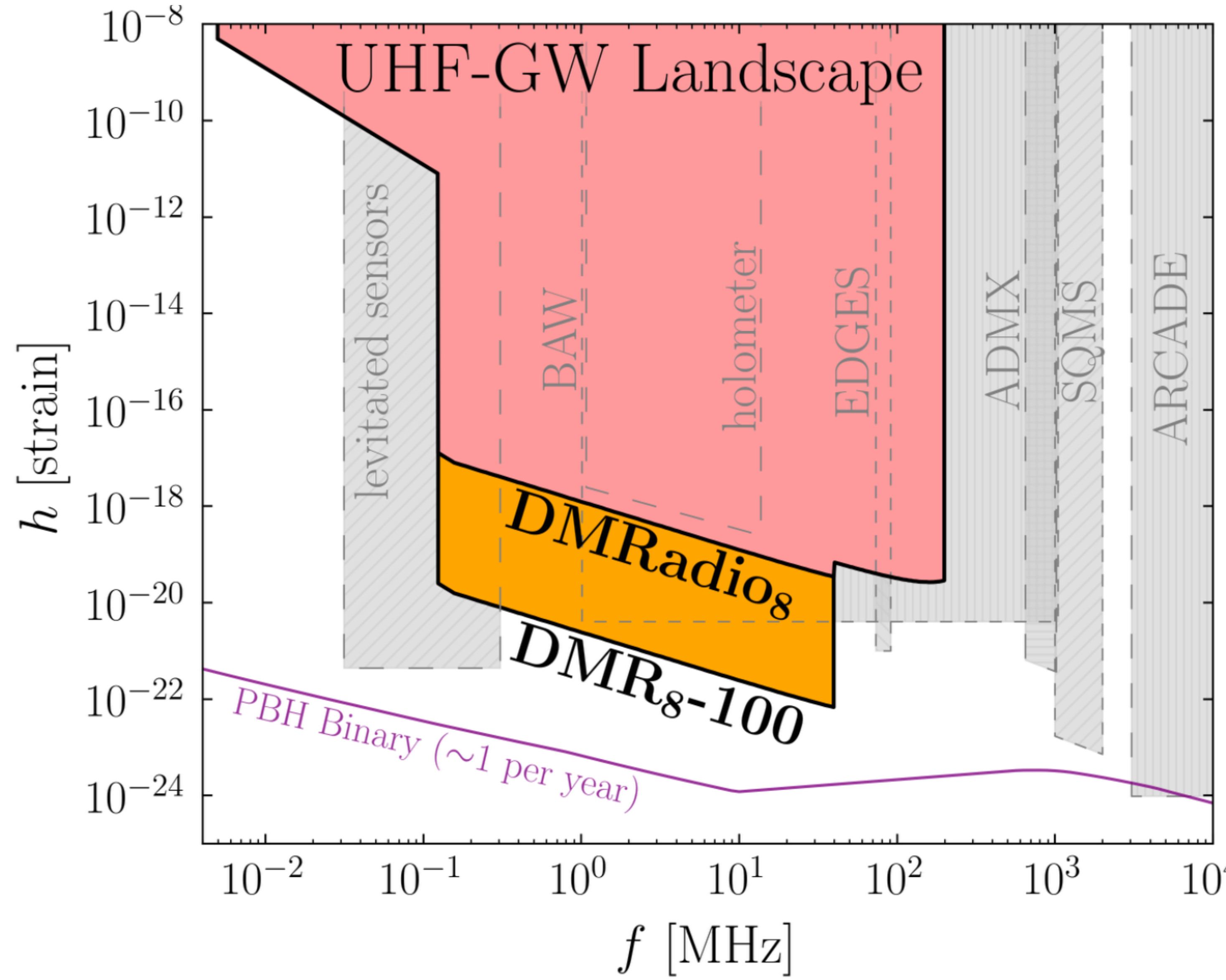
Small modification allows to measure both polarizations

Gravitational waves in low mass axion haloscopes





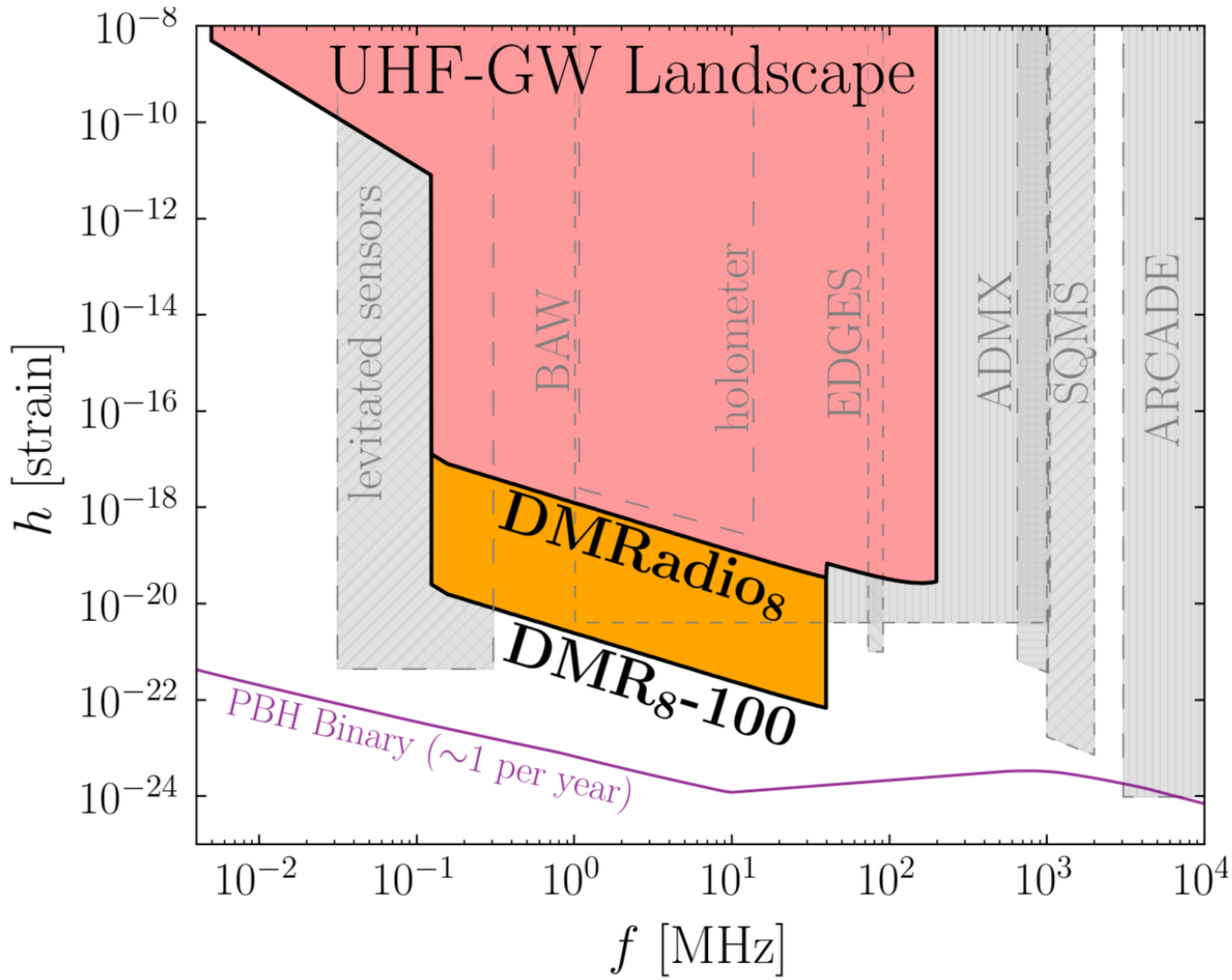
Domcke, CGC, Rodd, 2202.00695



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,

Conclusions



Axion experiments may discover not only dark matter, but also exotic sources of gravitational waves

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

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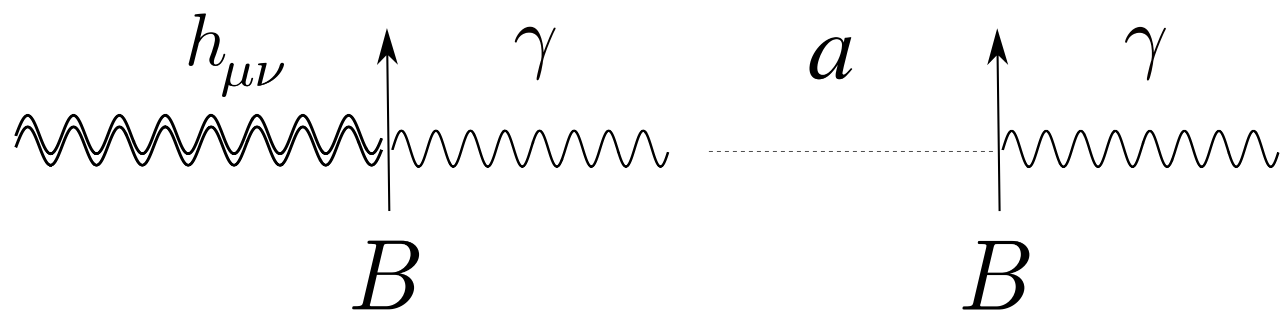
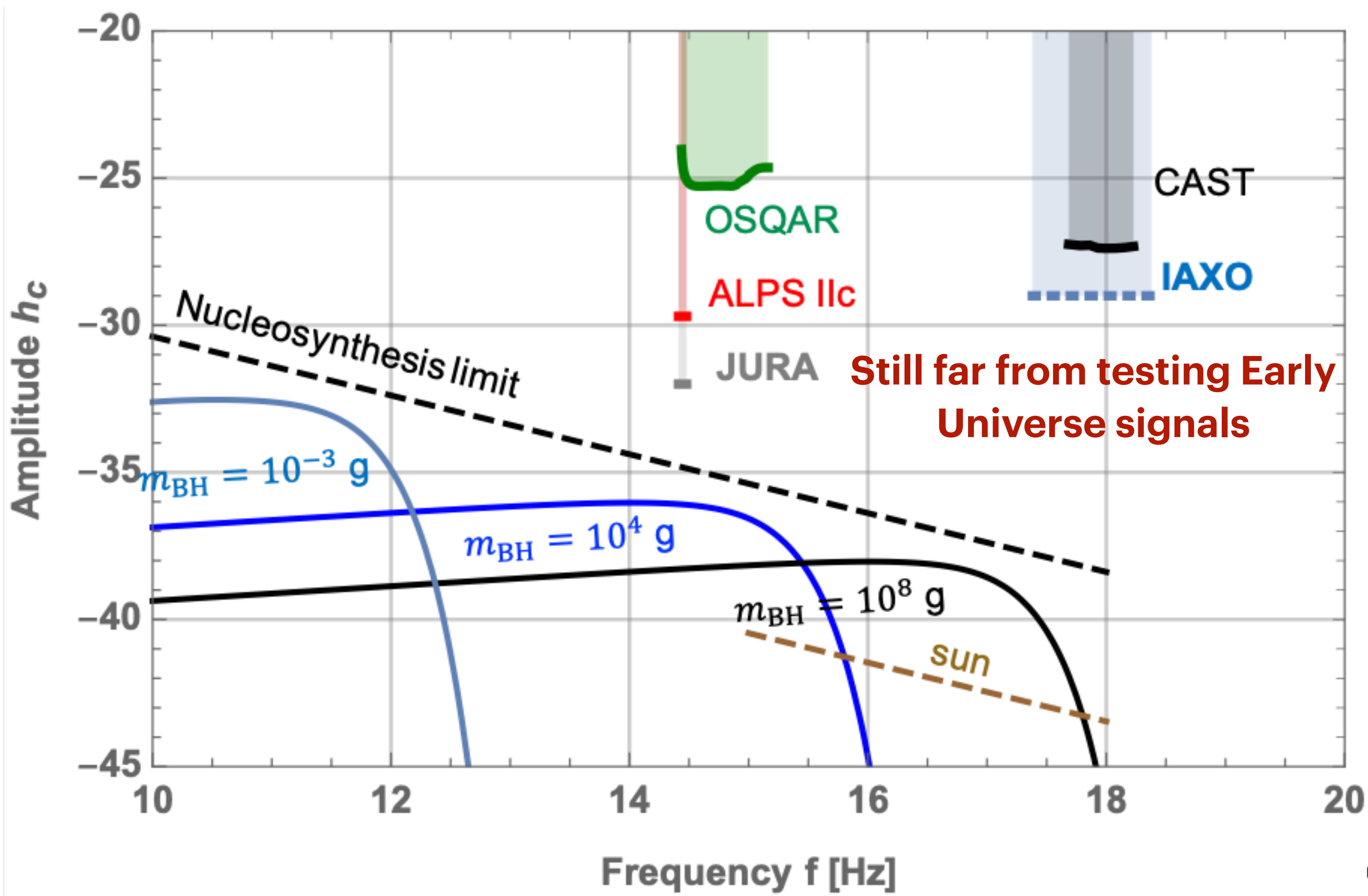
Other possibilities



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

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

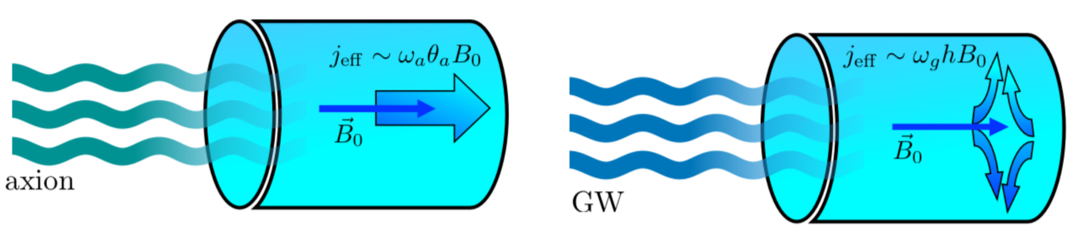


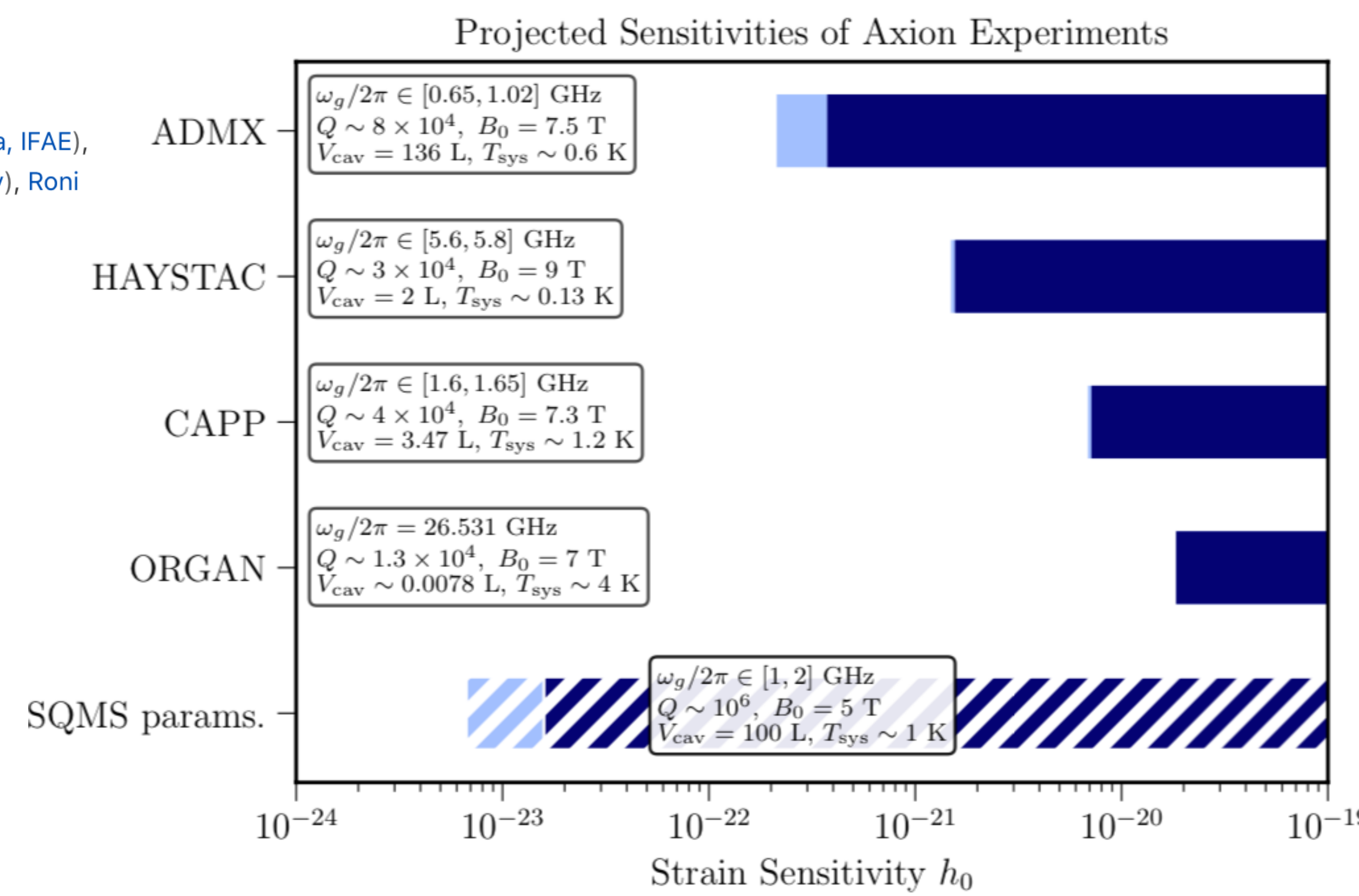
Other possibilities

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

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

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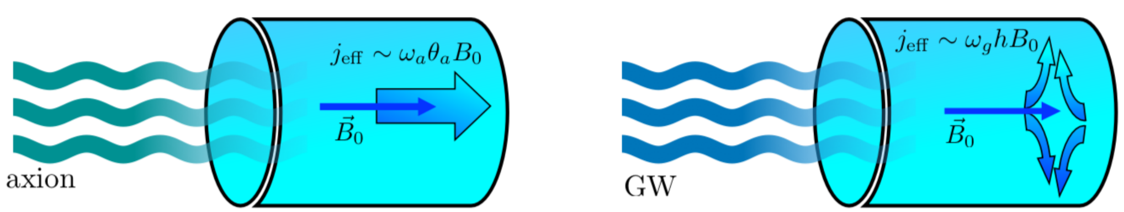

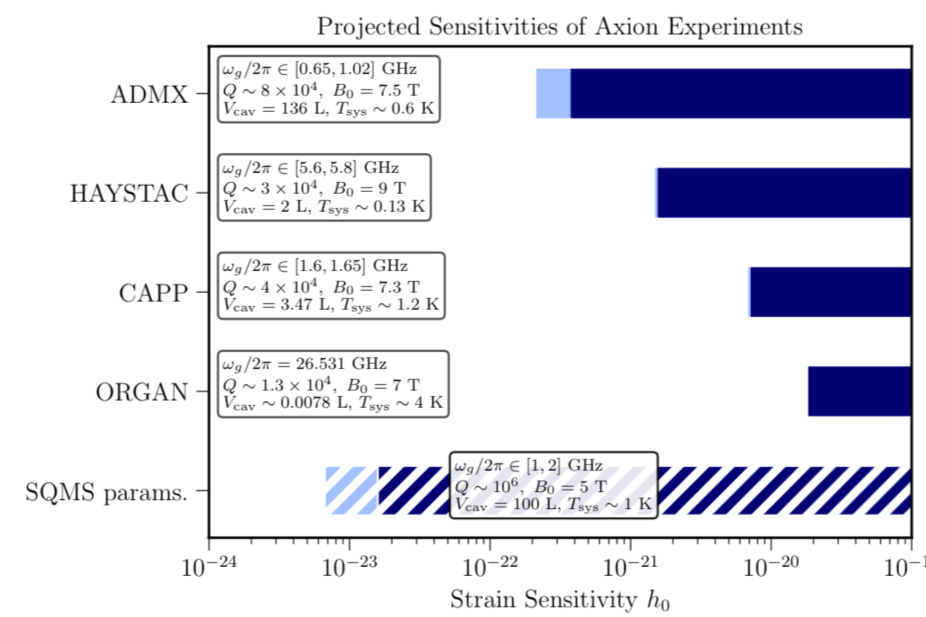

- In the TT frame, the description of rigid bodies becomes unintuitive, as their coordinates are deformed by a passing GW due to the motion of the coordinate system. **This is crucial to implement boundary conditions.**
- In the proper detector frame the coordinate system is defined by rigid rulers and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

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

Eigenmodes

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