Ideas to probe gravitational waves with axion haloscopes

Laboratori Nazionali di Frascati
June 12, 2023

IFIC INSTITUT DE FÍSICA CORPUSCULAR

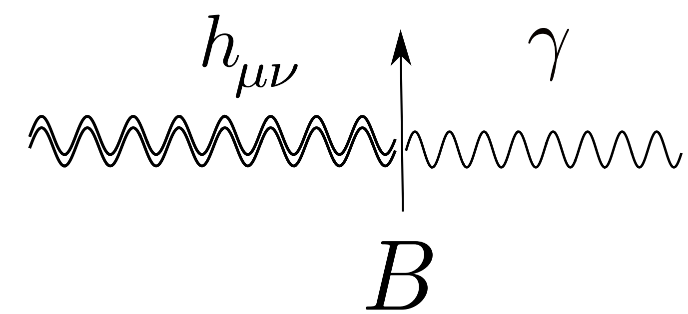
CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

VNIVERSITAT DE VALÈNCIA

Camilo García Cely

Outline

- Why high-frequency gravitational waves?
- Gravitational waves in axion haloscopes



- Experimental efforts at home
- Conclusions

Why high-frequency gravitational waves?

Gravitational Waves

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

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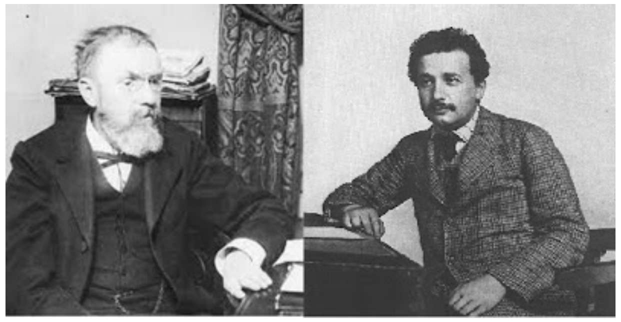
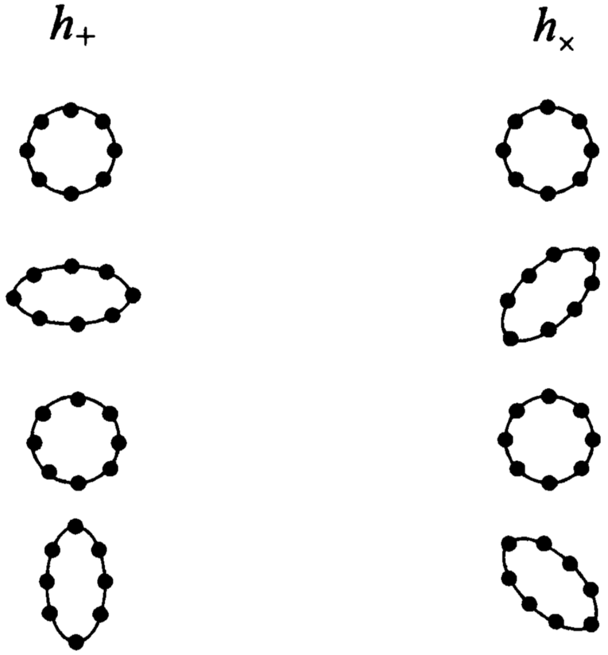


$$\Box h_{\mu\nu} = -16\pi G T_{\mu\nu}$$

wave equation describing two polarization modes



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

Camilo García Cely, University of Valencia

Gravitational Waves

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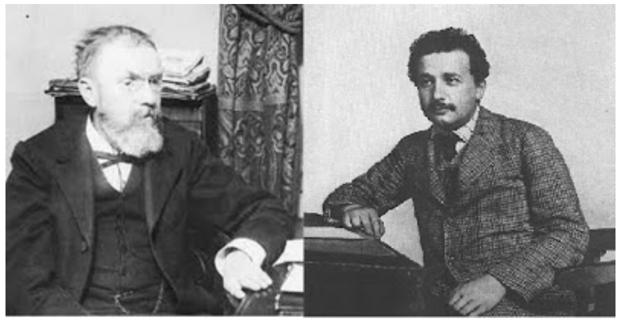

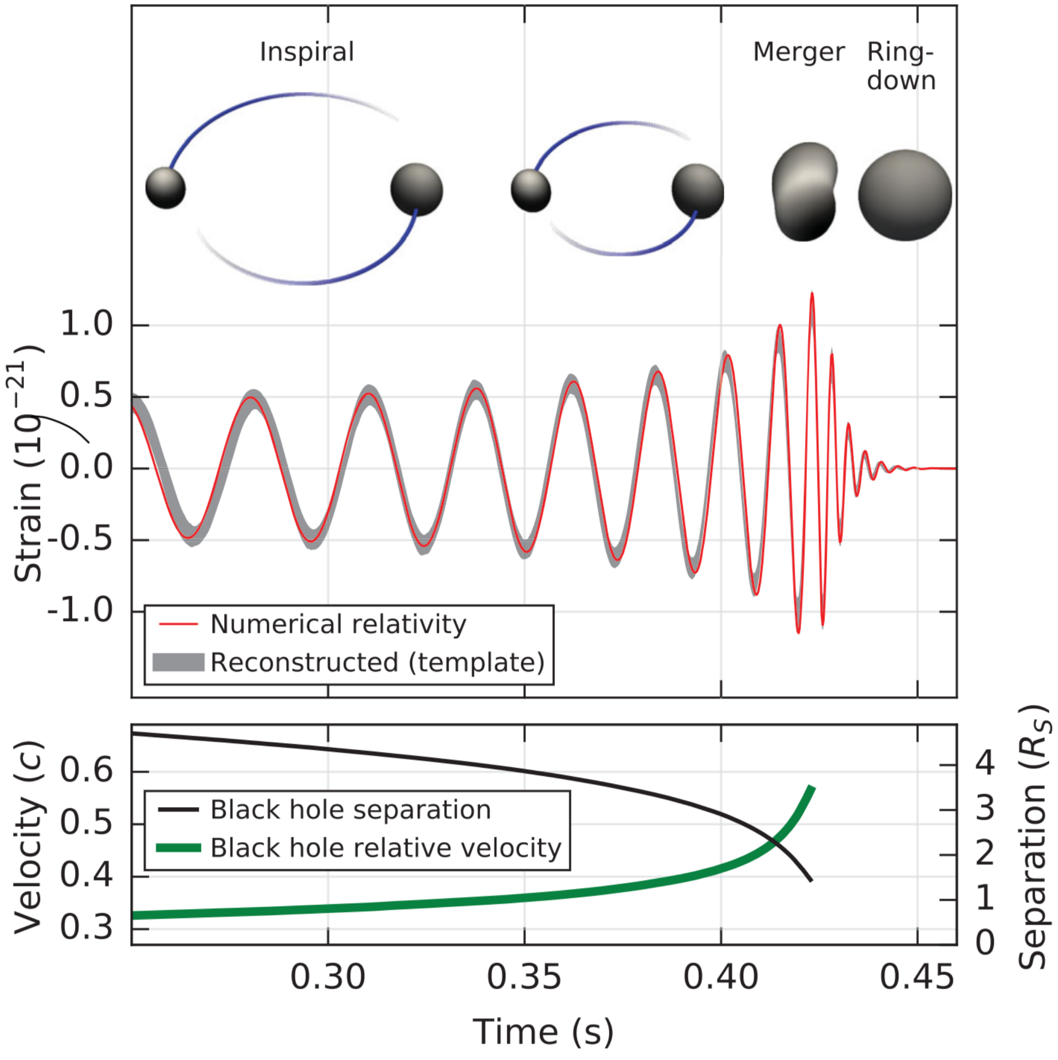

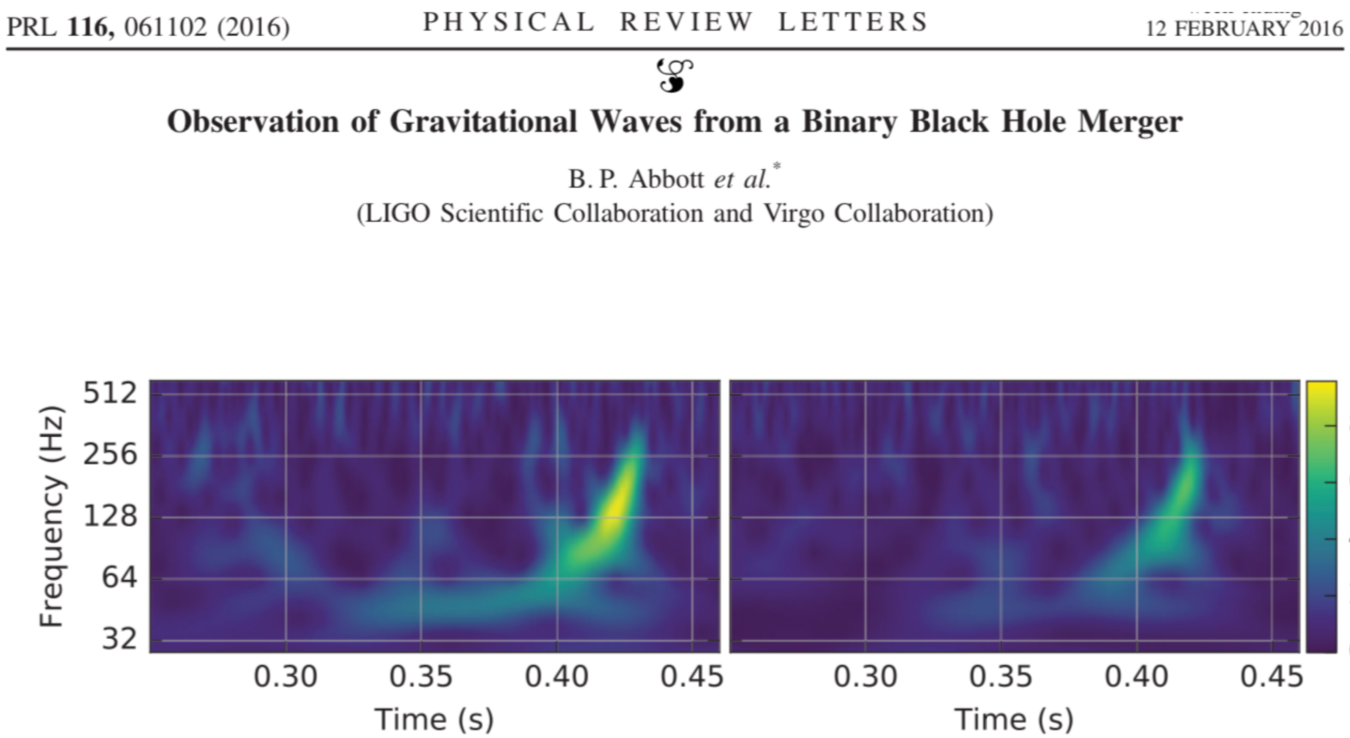

interferometers

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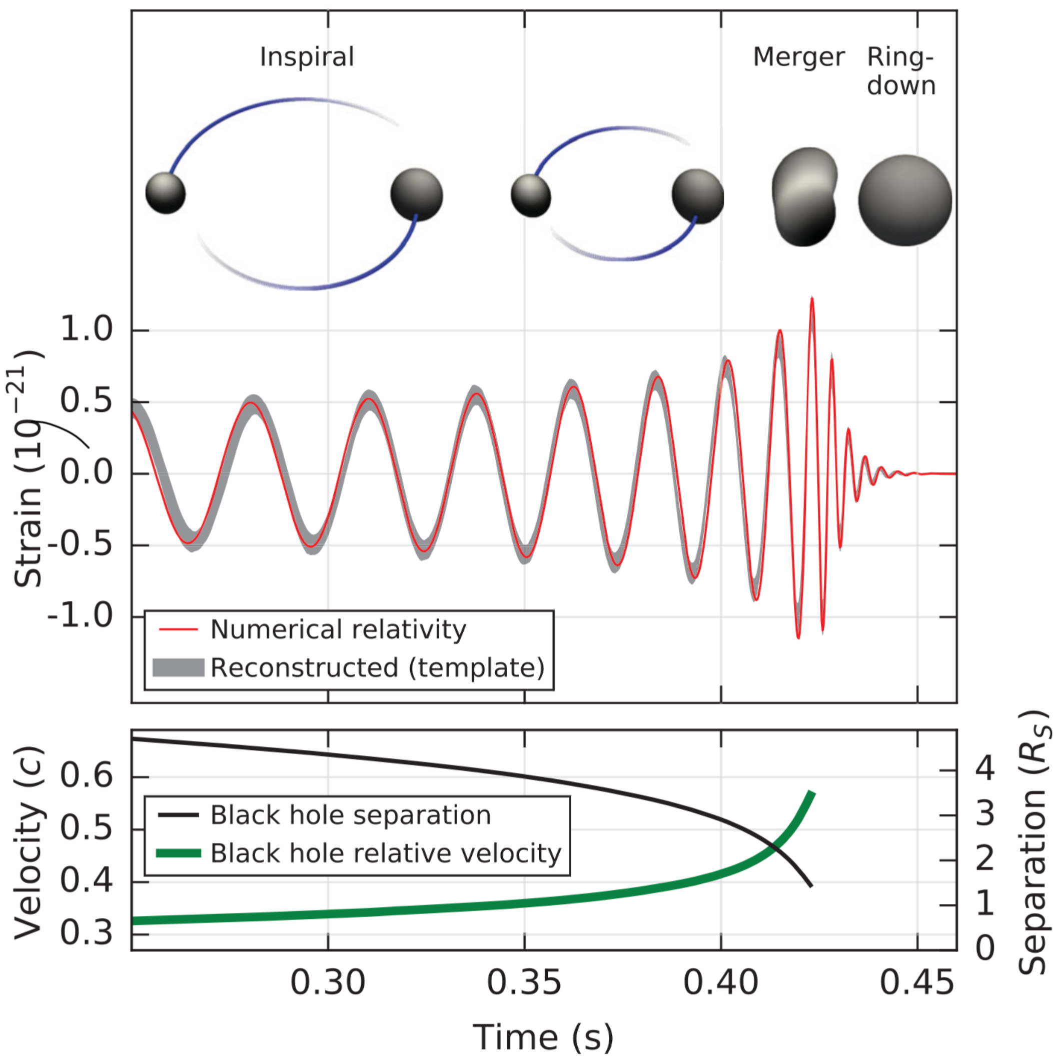
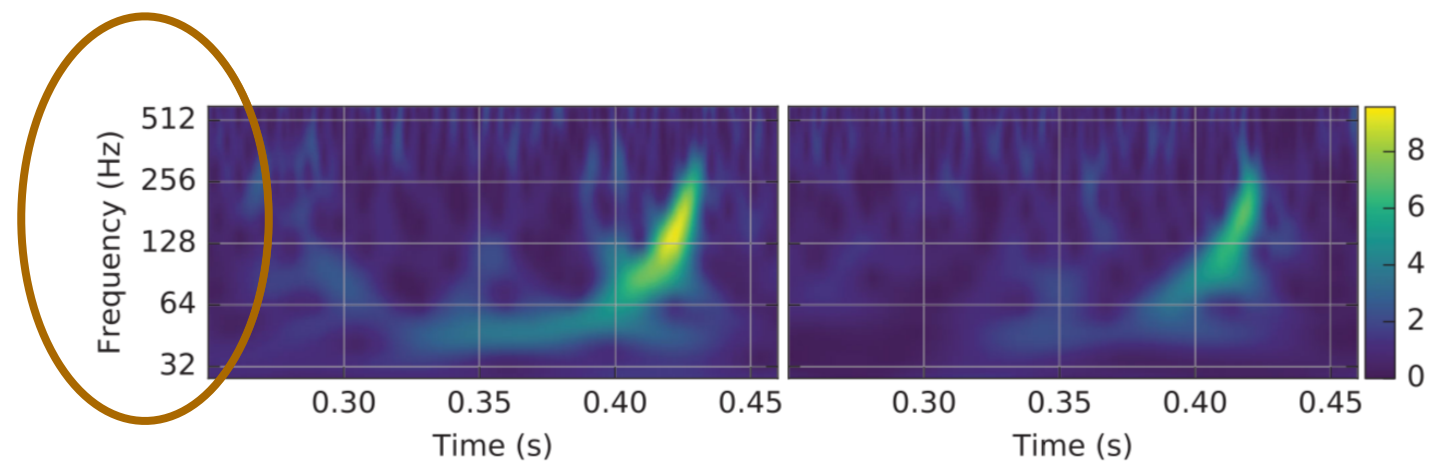


PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

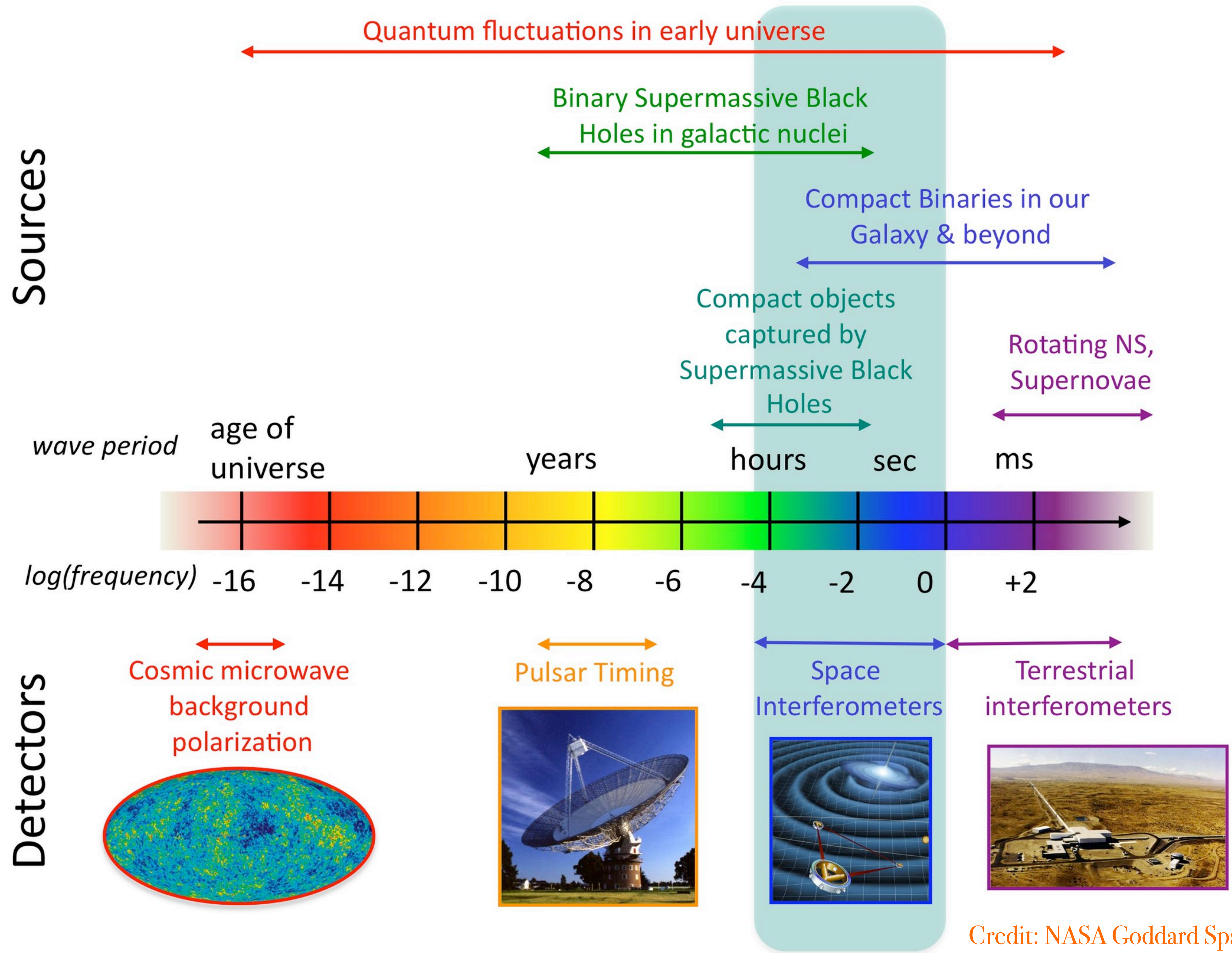
B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)



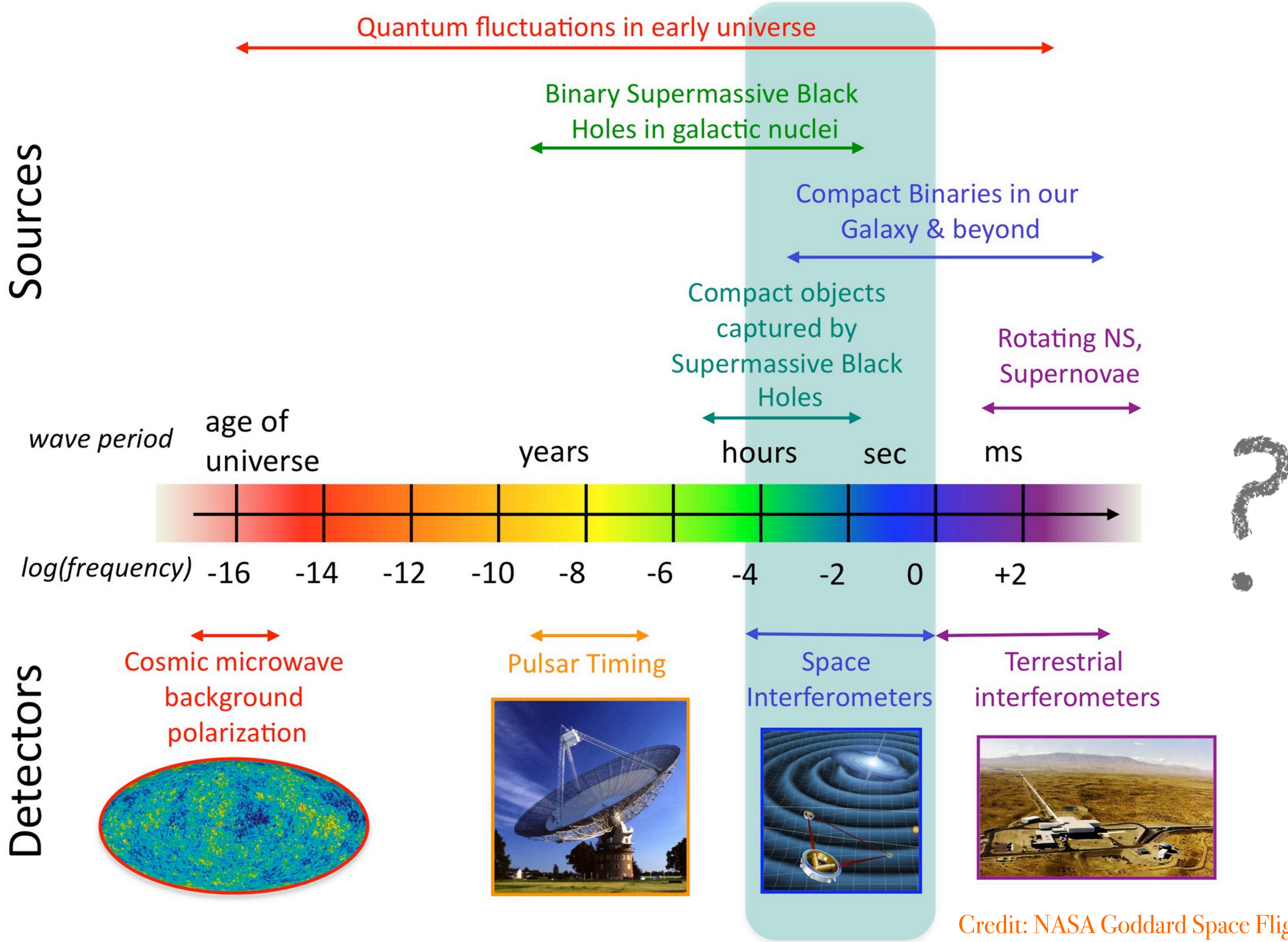
interferometers

Gravitational Wave Spectrum



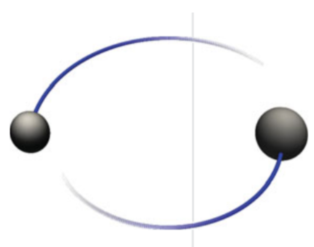
Credit: NASA Goddard Space Flight Center

Gravitational Wave Spectrum



Credit: NASA Goddard Space Flight Center

Lessons from the two-body problem



Third law

"I first believed I was dreaming… But it is absolutely certain and exact that the ratio which exists between the period times of any two planets is precisely the ratio of the 3/2th power of the mean distance." Kepler (1619)

Planet	r (AU)	T (days)	r^3/T^2 ($10^{-6}\mathrm{AU}^3/\mathrm{day}^2$)
Mercury	0.3871	87.9693	7.496
Venus	0.72333	224.701	7.496
Earth	1	365.256	7.496
Mars	1.52366	686.98	7.495
Jupiter	5.20336	4332.82	7.504
Saturn	9.53707	10775.6	7.498
Uranus	19.1913	30687.2	7.506
Neptune	30.069	60190.	7.504

$$\frac{GM}{4\pi^2}$$

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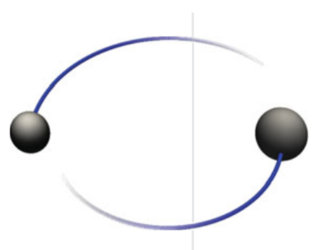

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$$f \approx \frac{1}{2\pi}\sqrt{\frac{GM}{R^3}}$$

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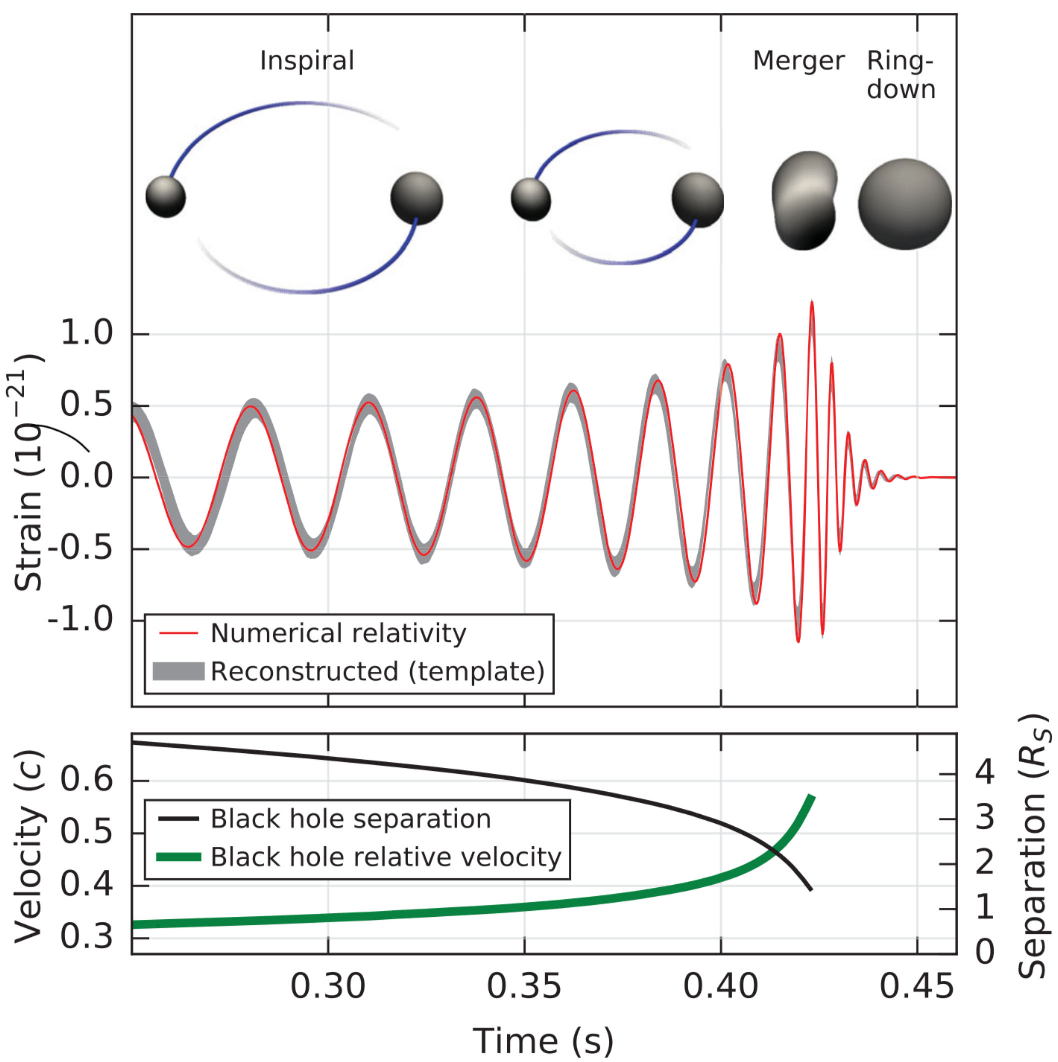

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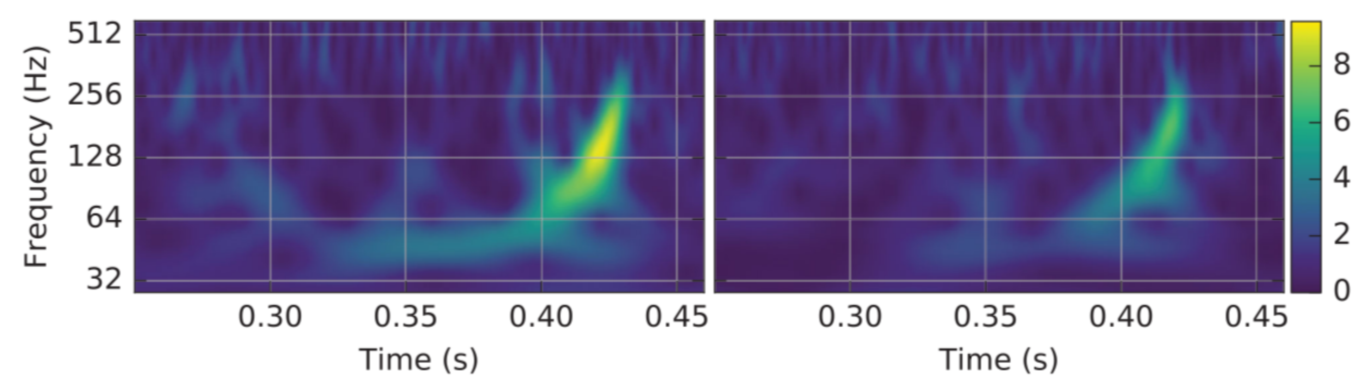

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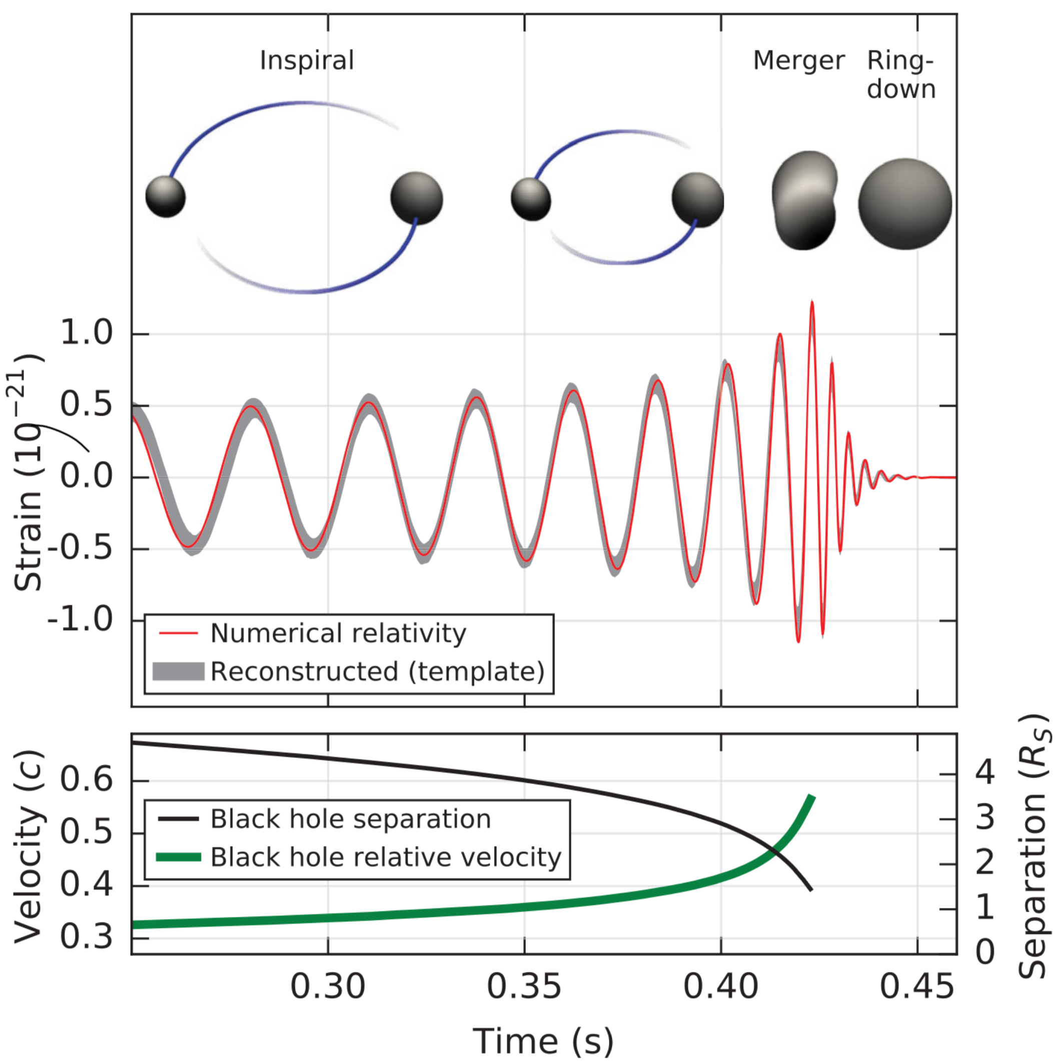

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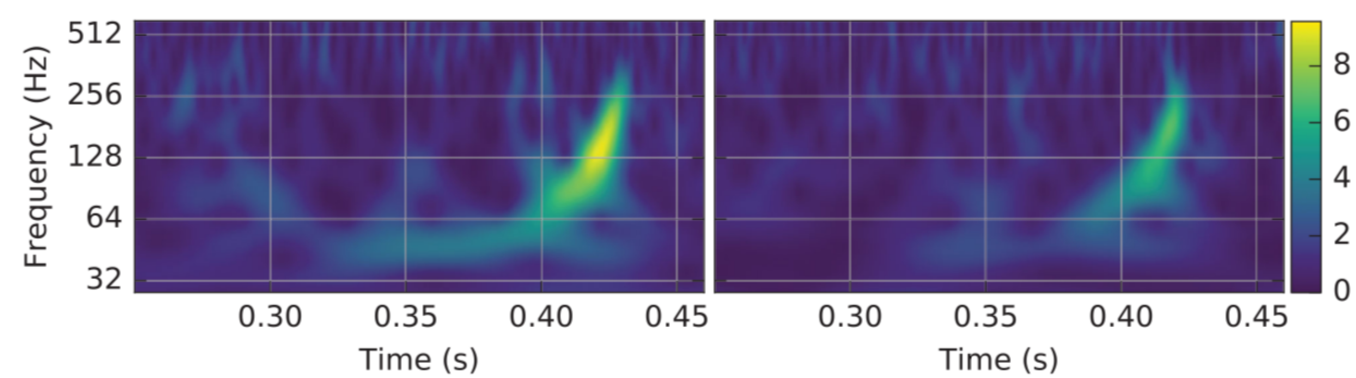


$$f \approx \frac{1}{2\pi}\sqrt{\frac{GM}{R^3}} \ll 10\,\mathrm{kHz}$$

High-frequency gravitational waves

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

Part of a collection:

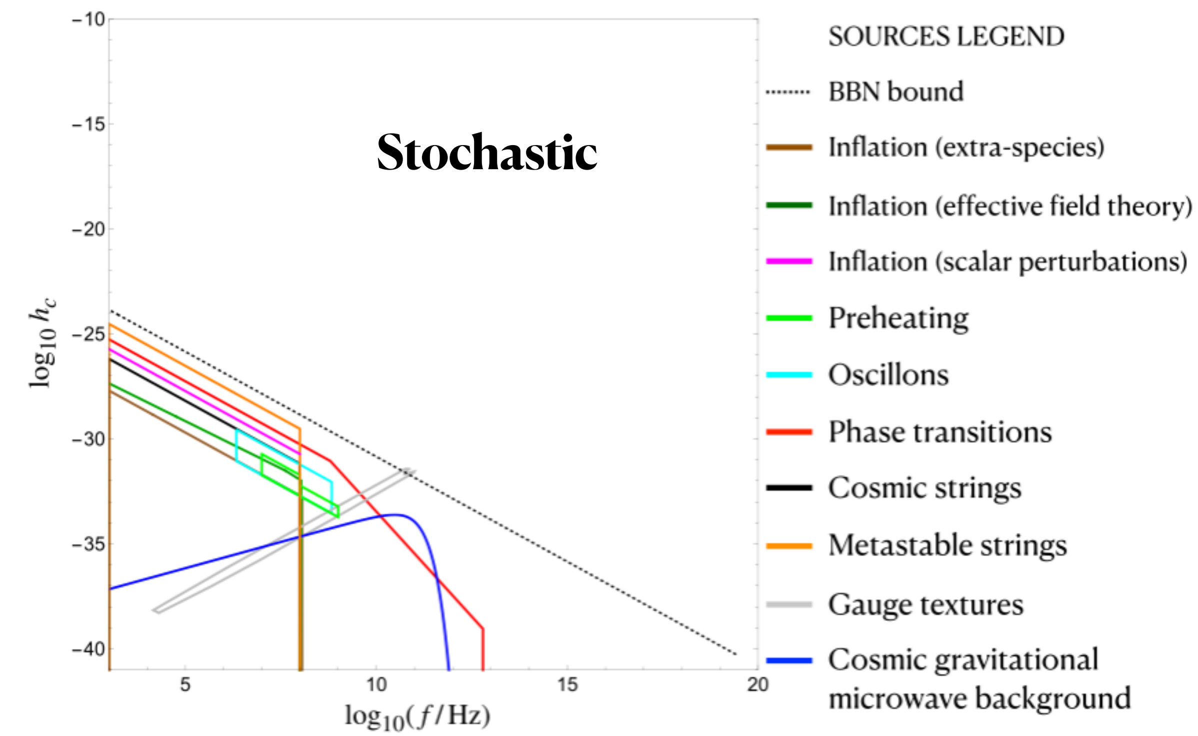
Gravitational Waves

Review Article | Open Access | Published: 06 December 2021

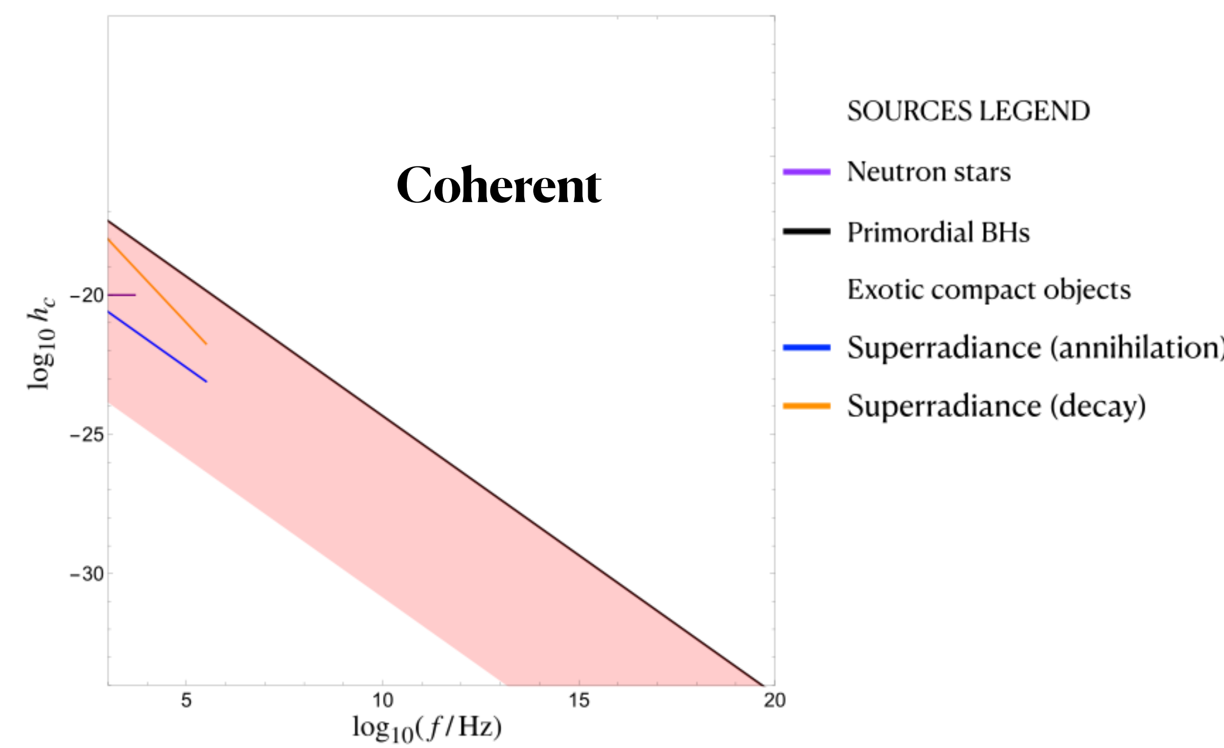
Challenges and opportunities of gravitational-wave searches at MHz to GHz frequencies

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



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

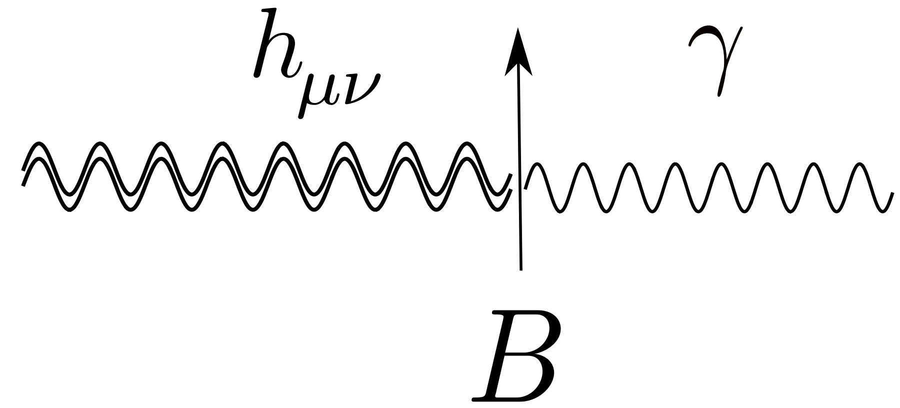
J. Exptl. Theoret. Phys. (U.S.S.R.) 43, 605-607 (August, 1962)

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

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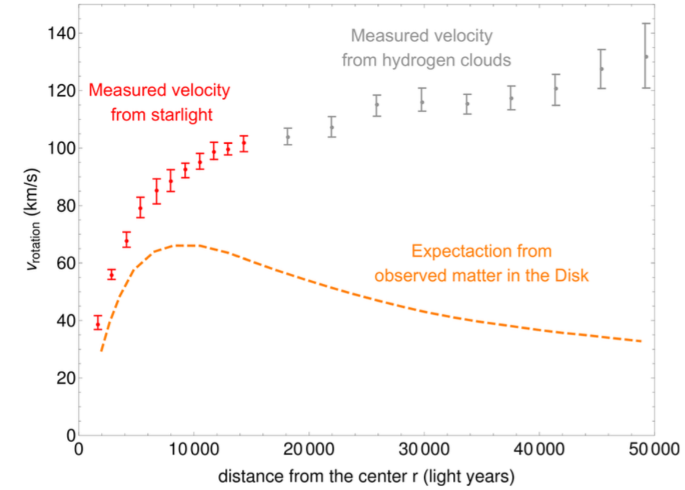
- The process is strictly analogous to axion dark matter conversion.

Raffelt, Stodolski'89

Dark Matter

The dark matter hypothesis is remarkably simple and explain observations at many other scales



kpc

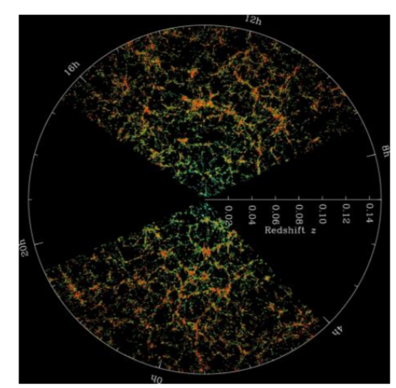
Velocity measurements

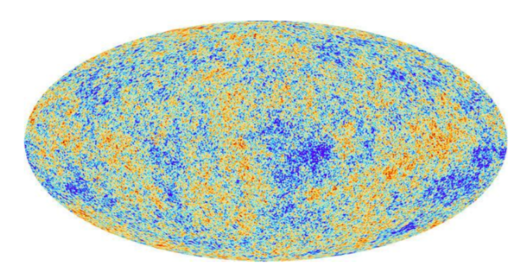
- Flat rotation curves of spiral galaxies
- Velocity dispersion of stars in giant elliptical and dwarf spheroidal galaxies
- Velocity dispersion of galaxies in clusters

Mpc

Lensing

- Weak lensing by large-scale structure and cluster mergers
- Strong lensing by individual galaxies and clusters





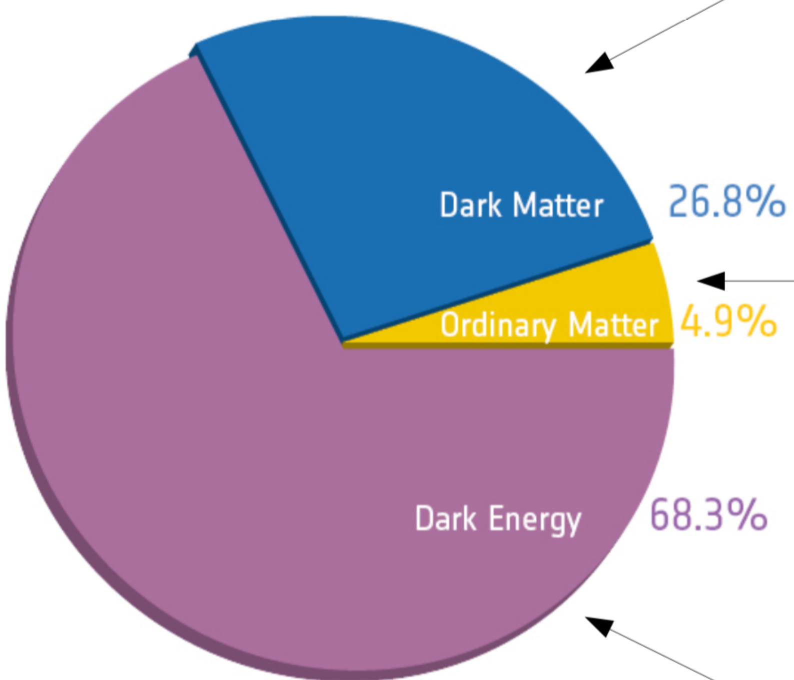
Gpc

Universe at large scales

- Abundance of clusters
- Large-scale distribution of galaxies
- Power spectrum of CMB anisotropies

Dark Matter

?



Standard Model stable particles:

Mostly protons, electrons, neutrinos and photons

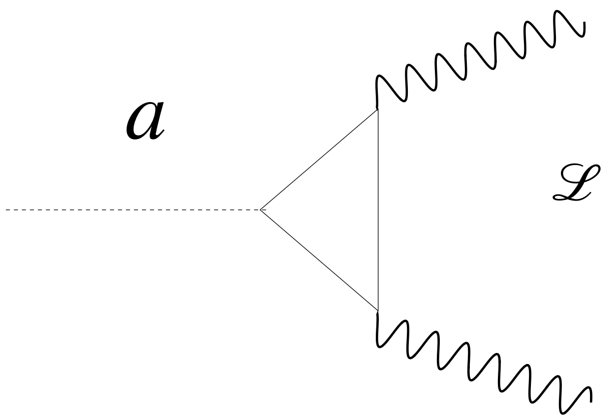
$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Dark Matter

Bertone Tait, 2018

QCD axion as dark matter

- Pseudoscalar field



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

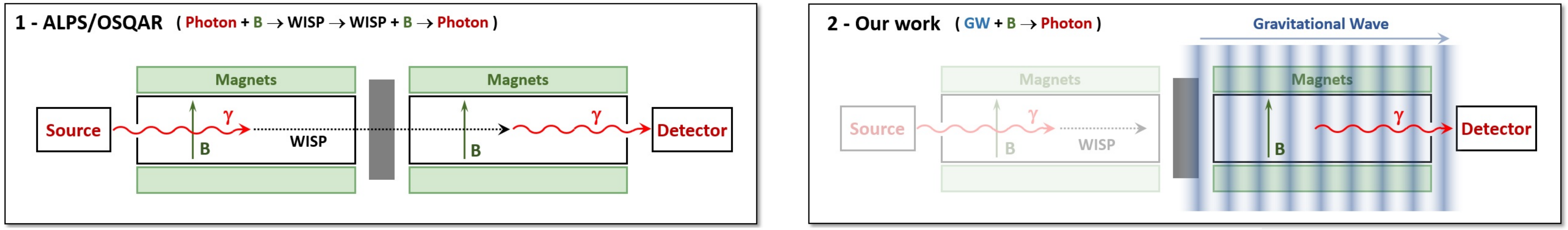
- Solution to the strong CP problem

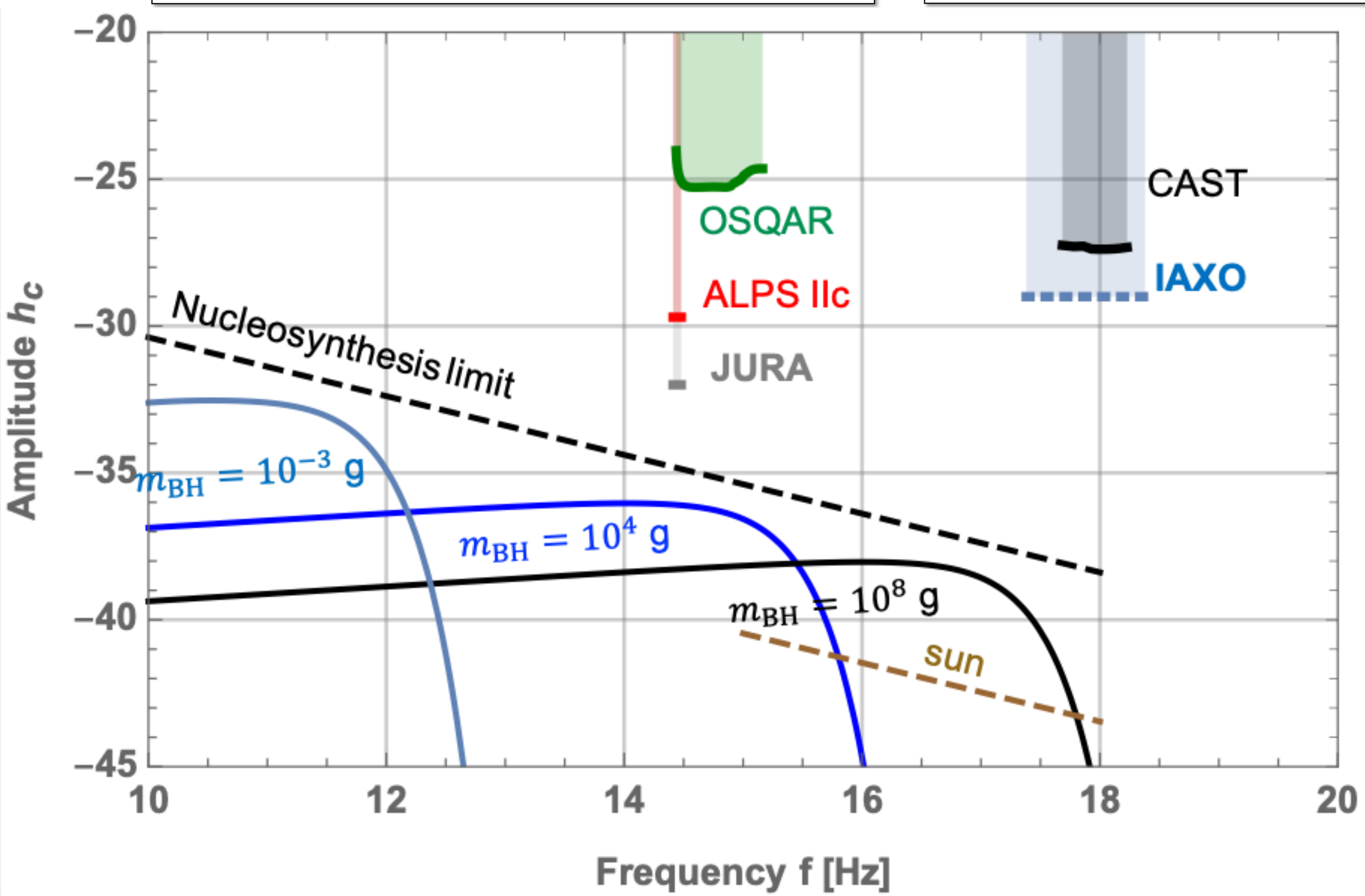
Peccei, Quinn 1977

- Excellent dark matter candidate

Weinberg, Wilczek 1978

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)

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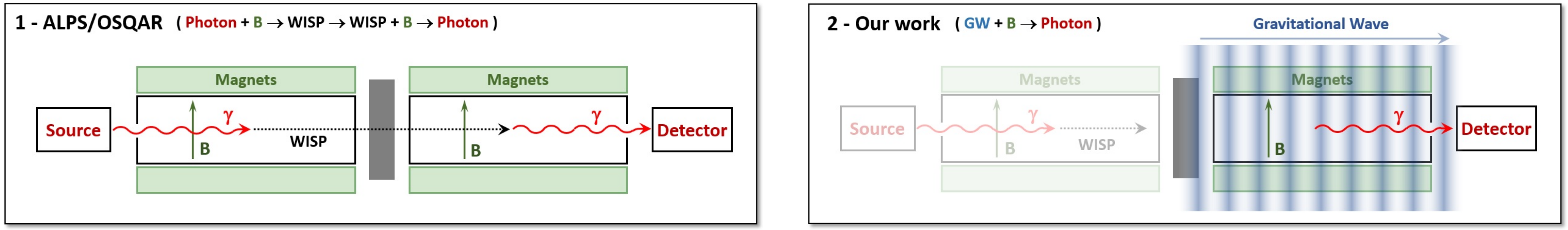
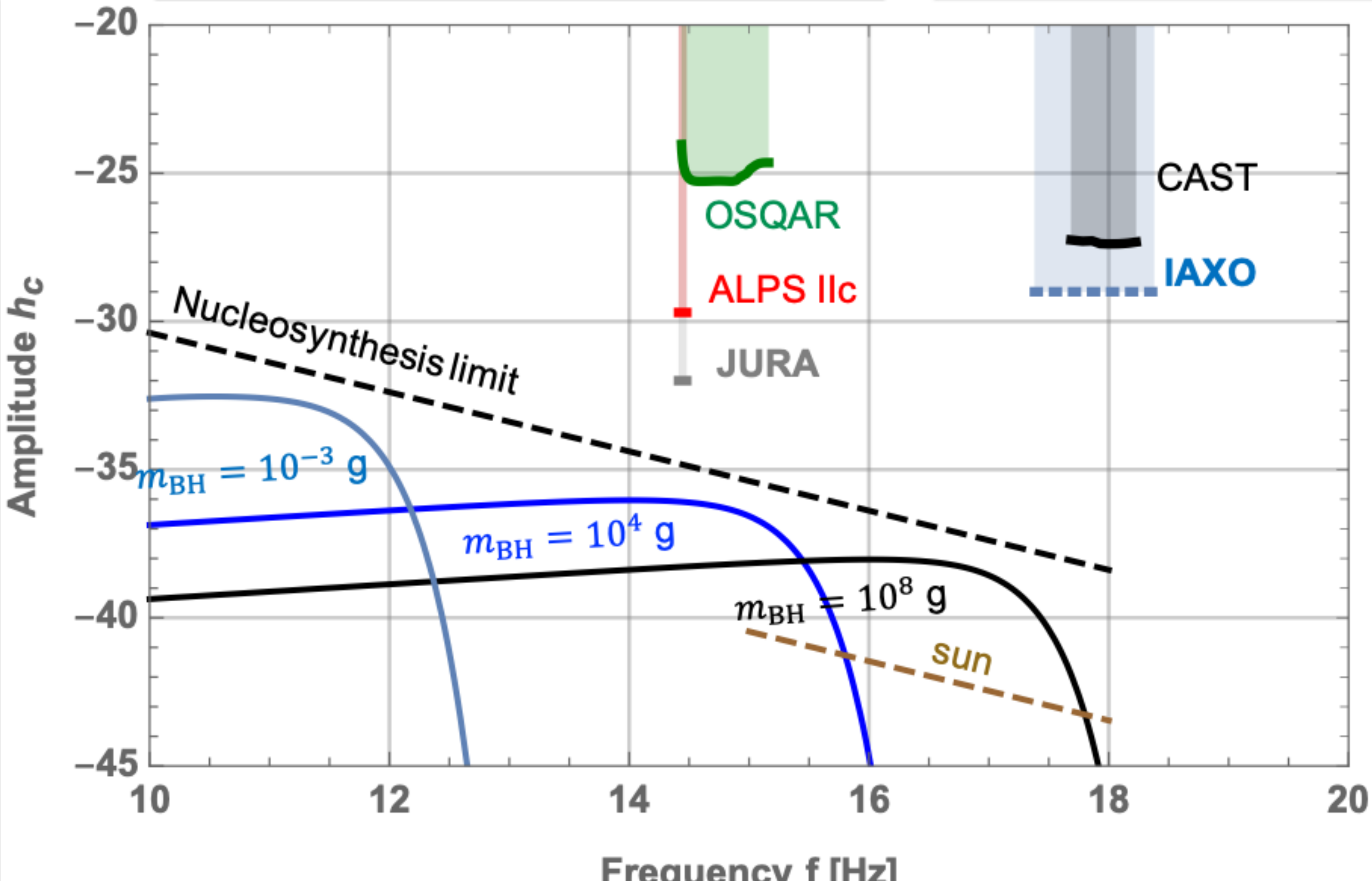




Still far from testing Early Universe signals

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

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

Gravitational waves in axion haloscopes

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

Symmetries and Selection Rules: Optimising Axion Haloscopes for Gravitational Wave Searches

Valerie Domcke (CERN), Camilo Garcia-Cely (Valencia U., IFIC), Sung Mook Lee, Nicholas L. Rodd (CERN)
Jun 5, 2023

22 pages
e-Print: 2306.03125 [hep-ph]

Axion electrodynamics

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

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

Sikivie, 1983

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

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

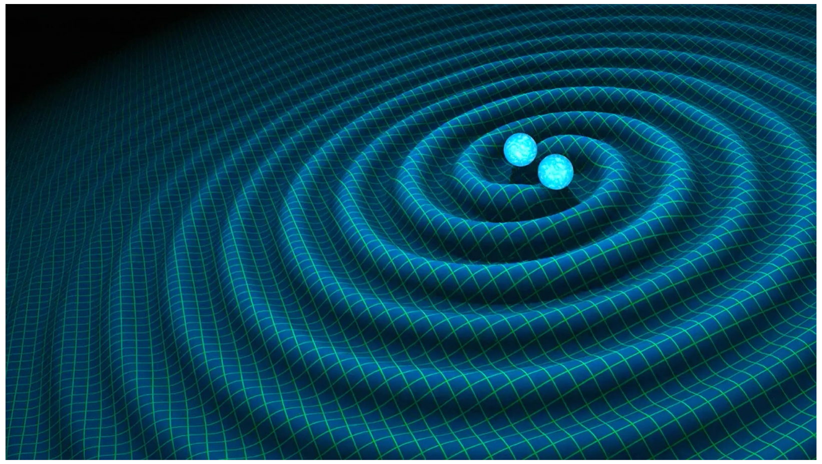
$$\nabla \times \mathbf{B} - \partial_t \mathbf{E} = \mathbf{j}$$

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

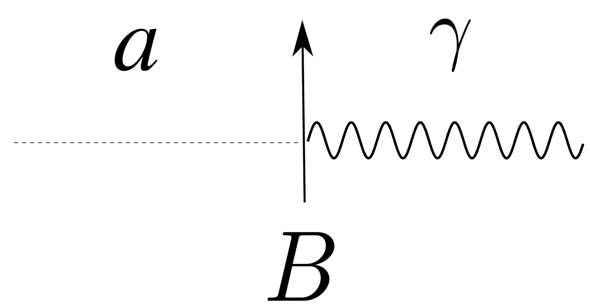
Gravitational-wave electrodynamics

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

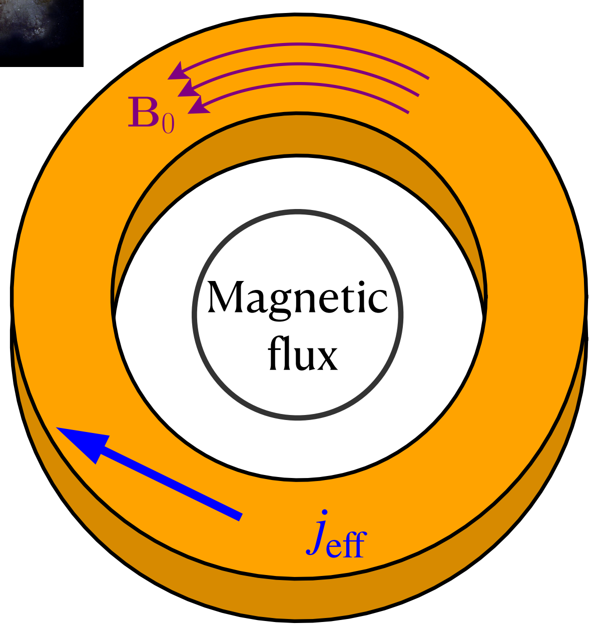
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \qquad \left| h_{\mu\nu} \right| \ll 1$$



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

	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	$h \sim 10^{-22}$

Low mass axion haloscopes

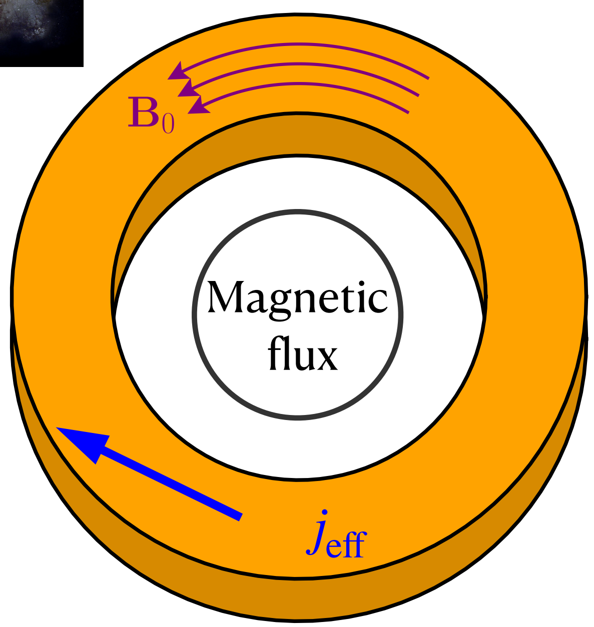


$$\nabla \times \mathbf{B} - \partial_t \mathbf{E} = \underbrace{g_{a\gamma\gamma}\, \partial_t a\, \mathbf{B_0}}_{j_{\text{eff}}}$$

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

Camilo García Cely, University of Valencia

Low mass axion haloscopes



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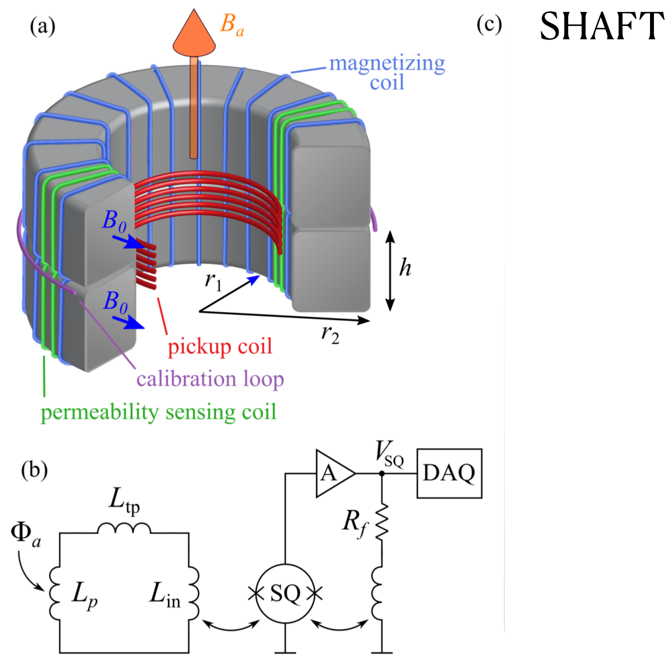


physics https://doi.org/

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

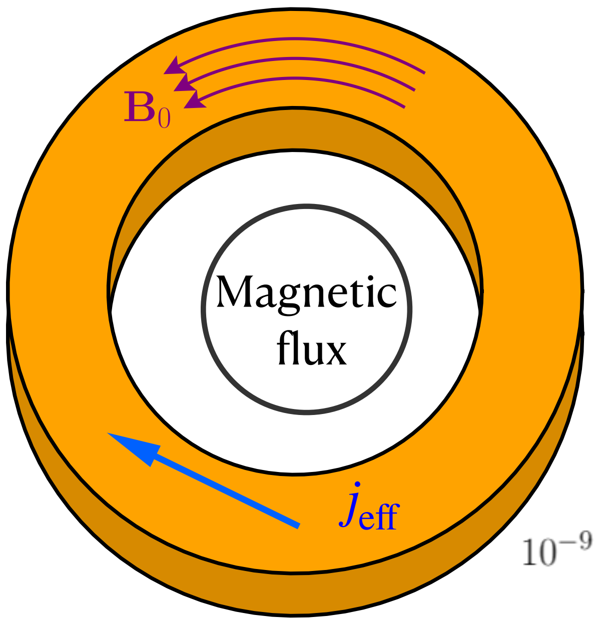
Broadband and Resonant Approaches to Axion Dark Matter Detection

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)

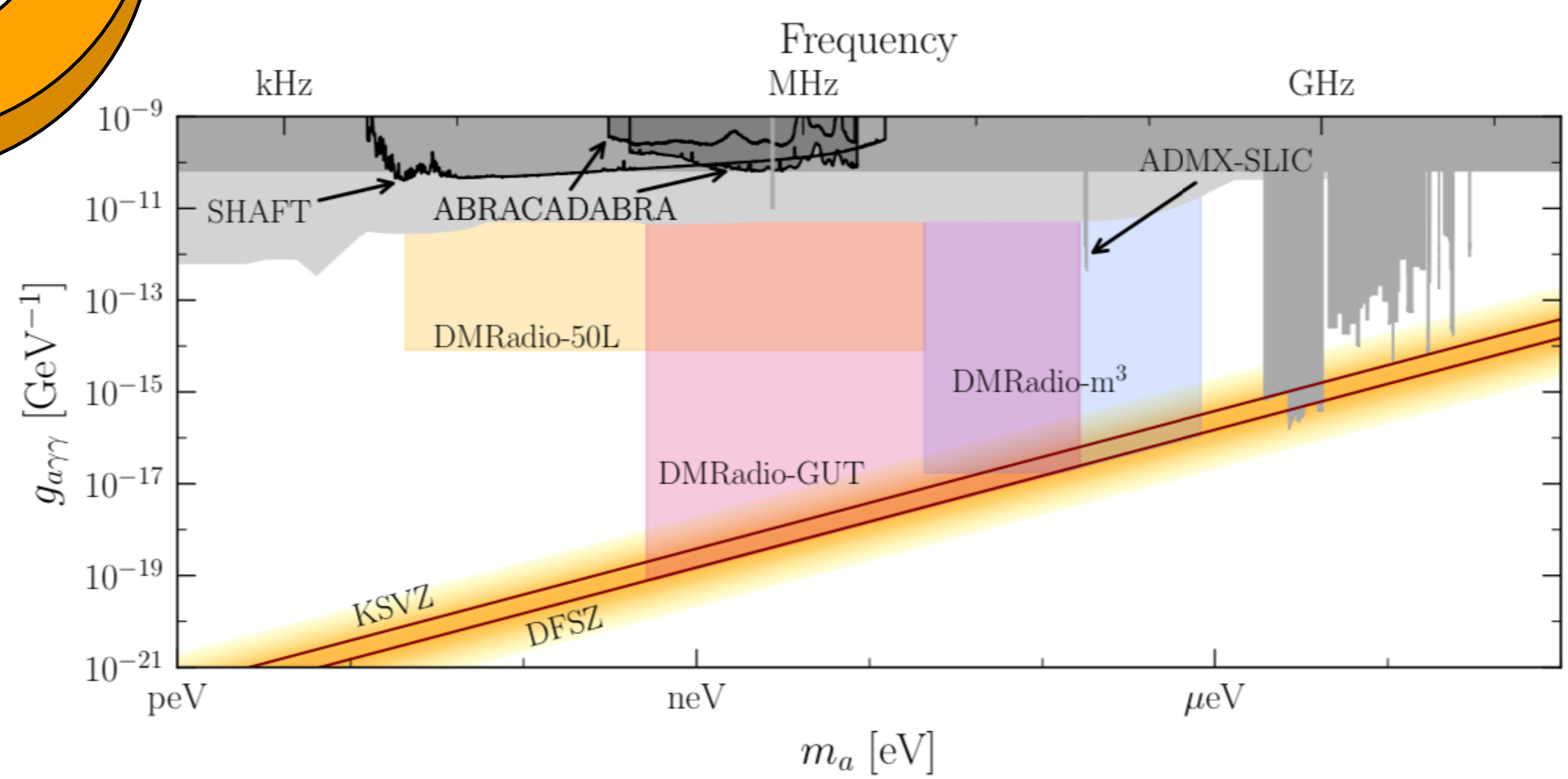
The electromagnetic fields produced by the axion drive a current through a pickup coil

Haloscopes based on lumped-element detectors



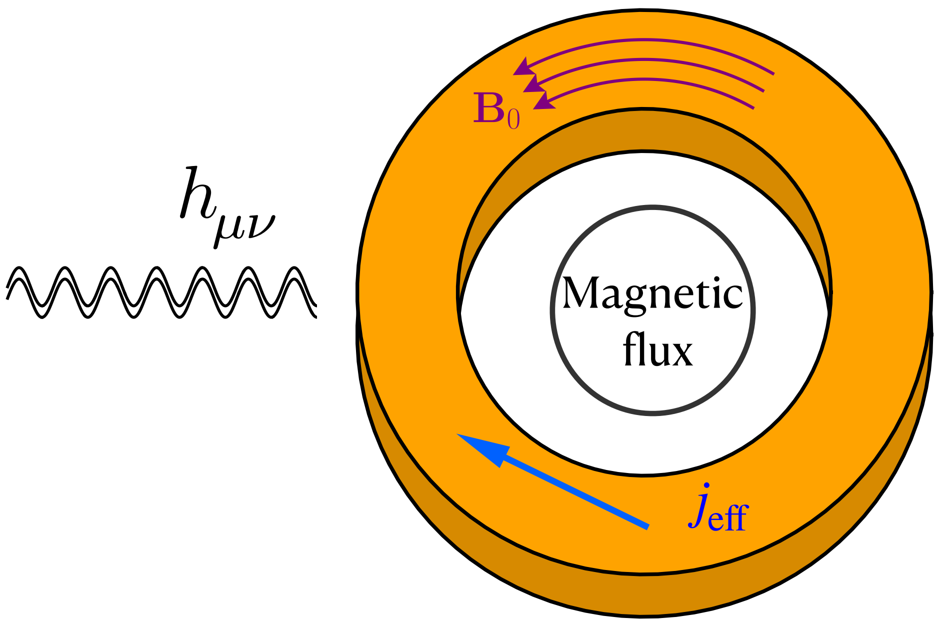
Proposal for a definitive search for GUT-scale QCD axions

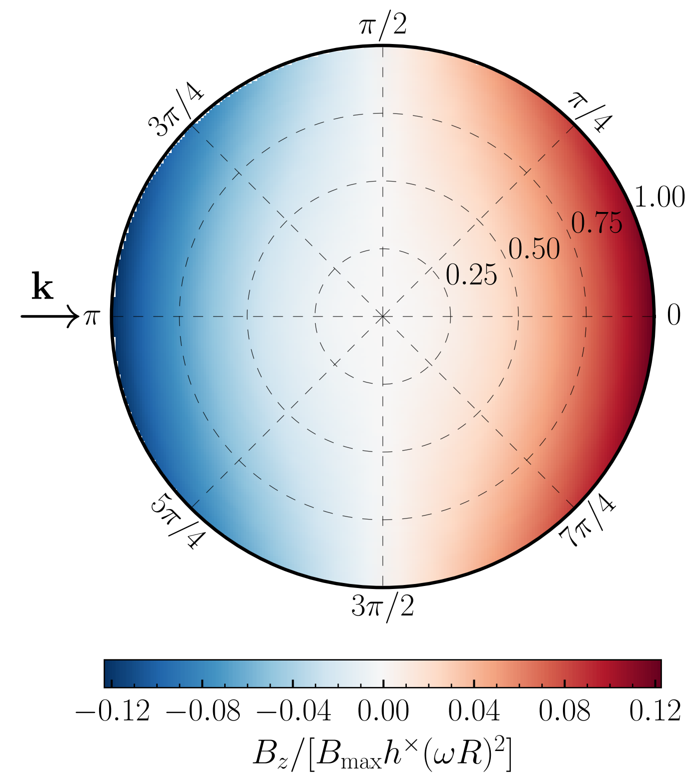
L. Brouwer *et al.* (DMRadio Collaboration)
Phys. Rev. D **106**, 112003 – Published 12 December 2022



Gravitational waves in low mass axion haloscopes

Domcke, CGC, Rodd, 2202.00695





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

Only one polarization

Suppression at small frequencies

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

The sensitivity scaling with the volume is faster than for axions

Selection rules

Domcke, CGC, Lee, Rodd, 2023

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:

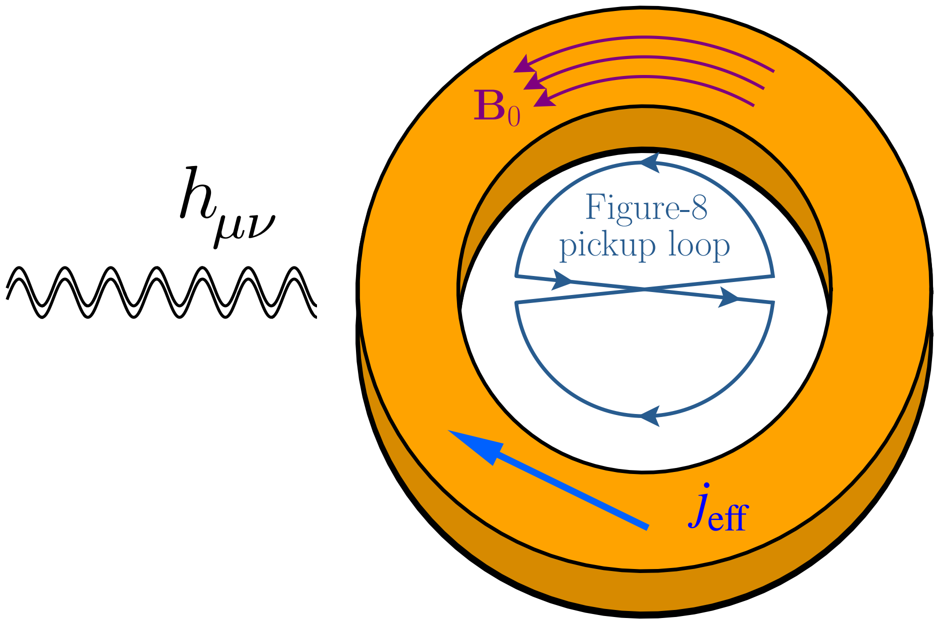
Selection Rule 1: For an instrument with azimuthal symmetry, $\Phi_h \propto h^+$ at $\mathcal{O}[(\omega L)^2]$

Selection Rule 2: For an instrument with azimuthal symmetry, the flux is proportional to either h^+ or $h^\times$, but not both. This holds to all orders in (ωL).

Selection Rule 3: For an instrument with full cylindrical symmetry, Φ_h will contain only even or odd powers of ω.

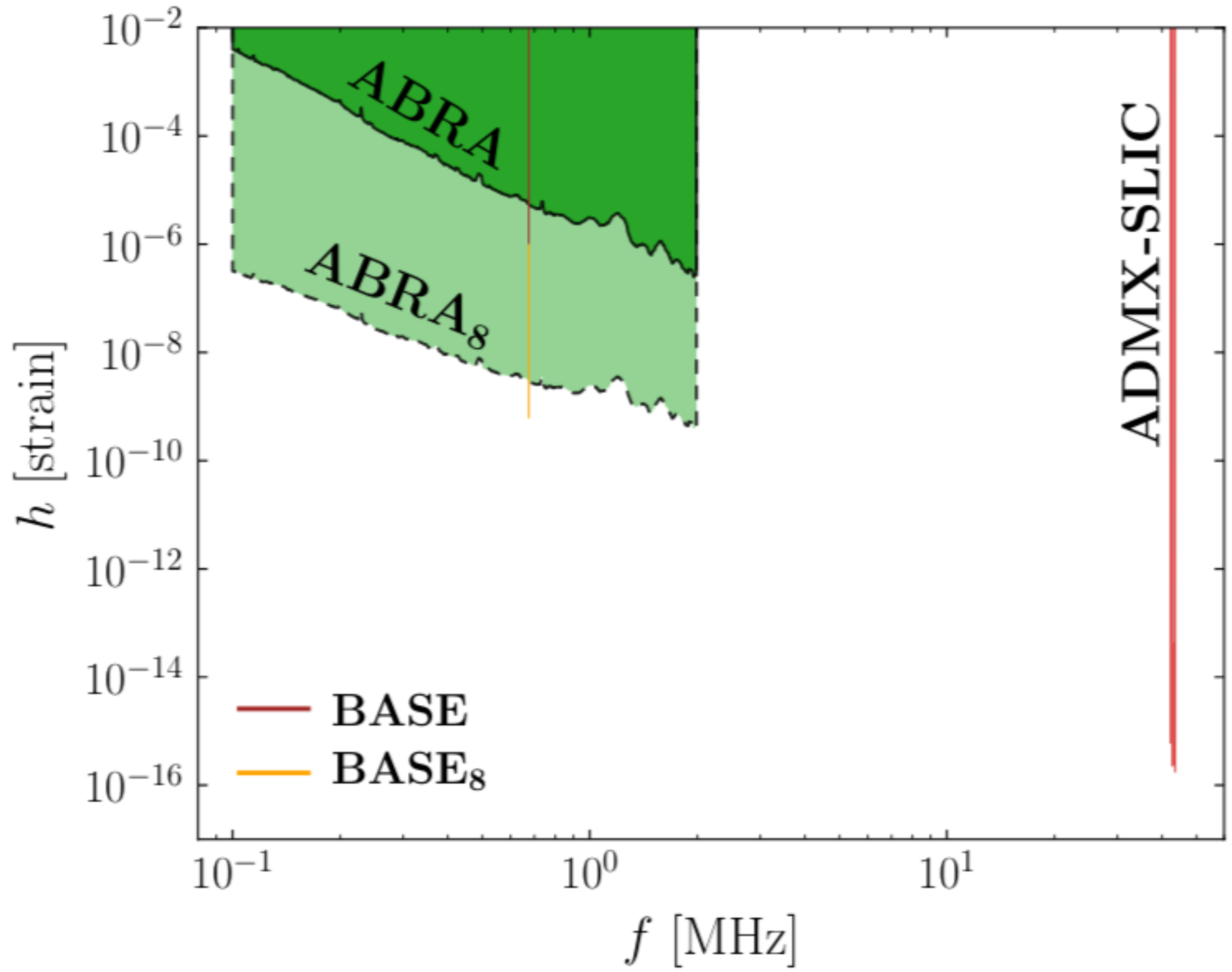
Toroidal magnetic fields

Break cylindrical symmetry



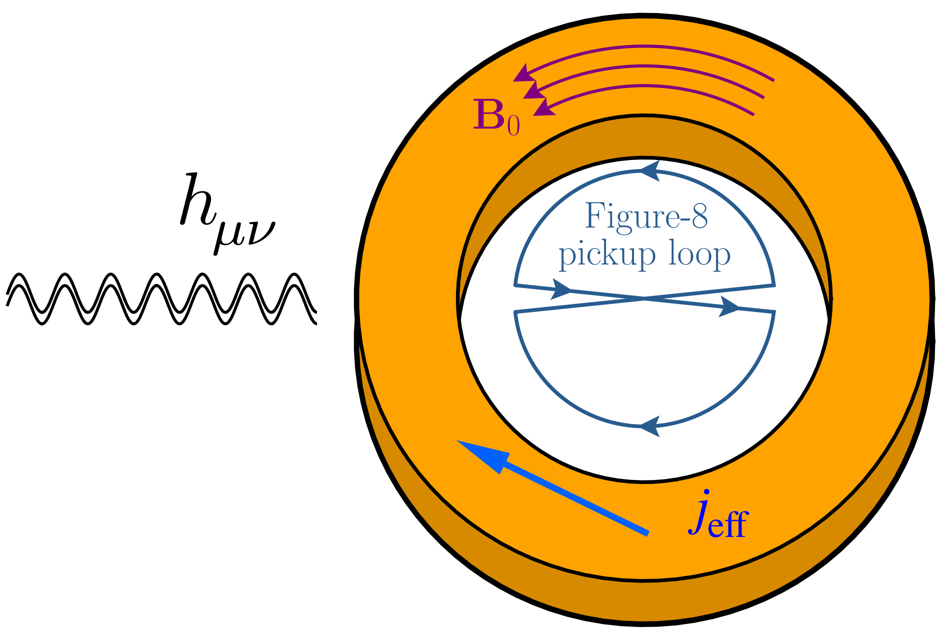
Valerie Domcke, Camilo Garcia-Cely, and Nicholas L. Rodd
Phys. Rev. Lett. **129**, 041101 – Published 20 July 2022

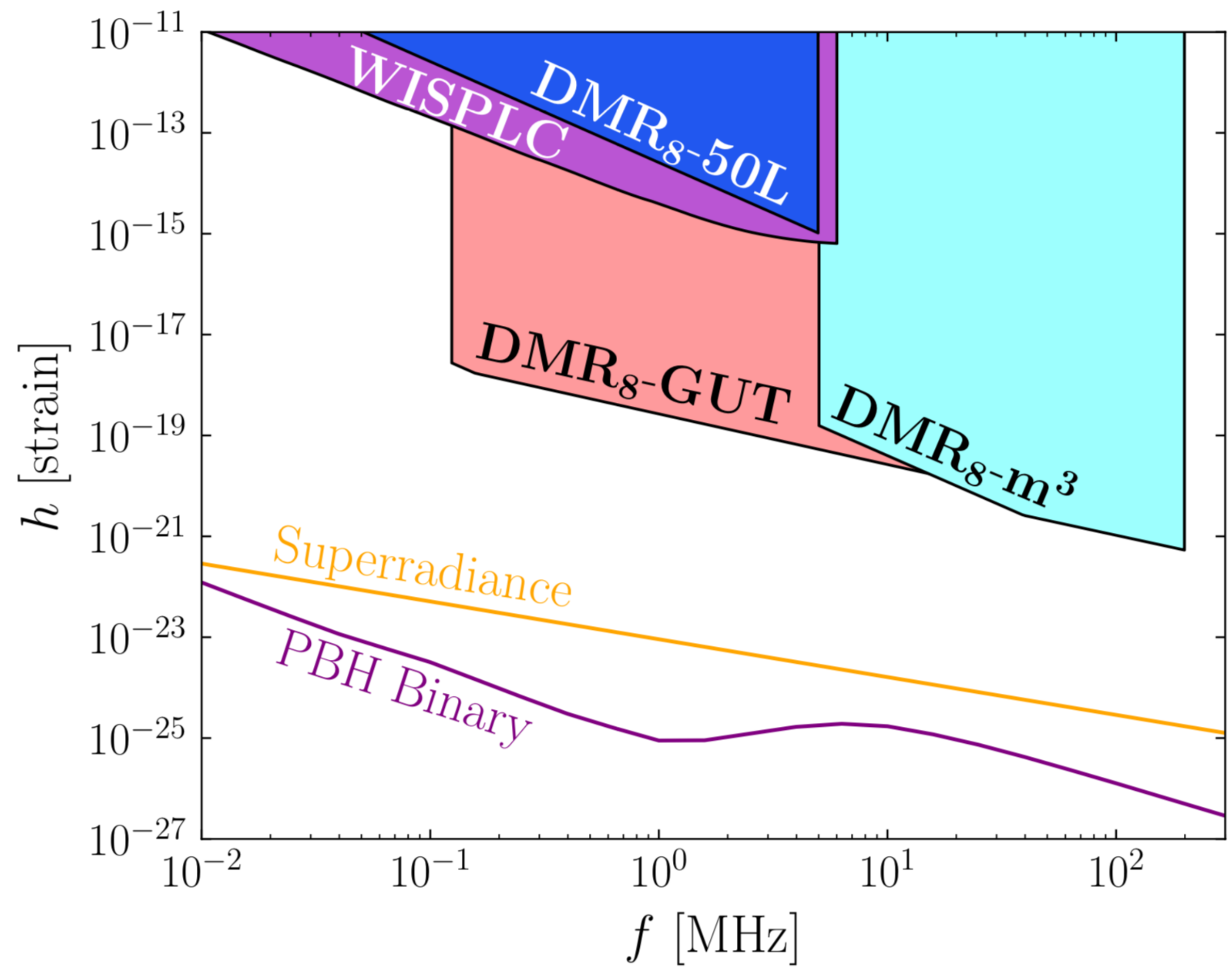
Domcke, CGC, Lee, Rodd, 2023



Haloscopes based on lumped-element detectors

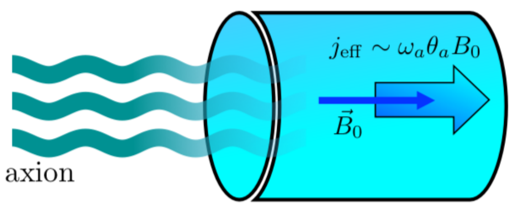
Domcke, CGC, Lee, Rodd, 2023

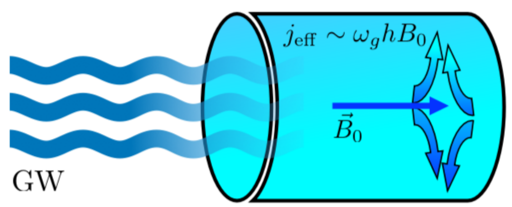




Recast of axion searches to establish GW sensitivity, taking into account the different time scales involved in the signals and detectors.

Haloscopes based on microwave cavities





Detecting high-frequency gravitational waves with microwave cavities

Asher Berlin, Diego Blas, Raffaele Tito D'Agnolo, Sebastian A. R. Ellis, Roni Harnik, Yonatan Kahn, and Jan Schütte-Engel

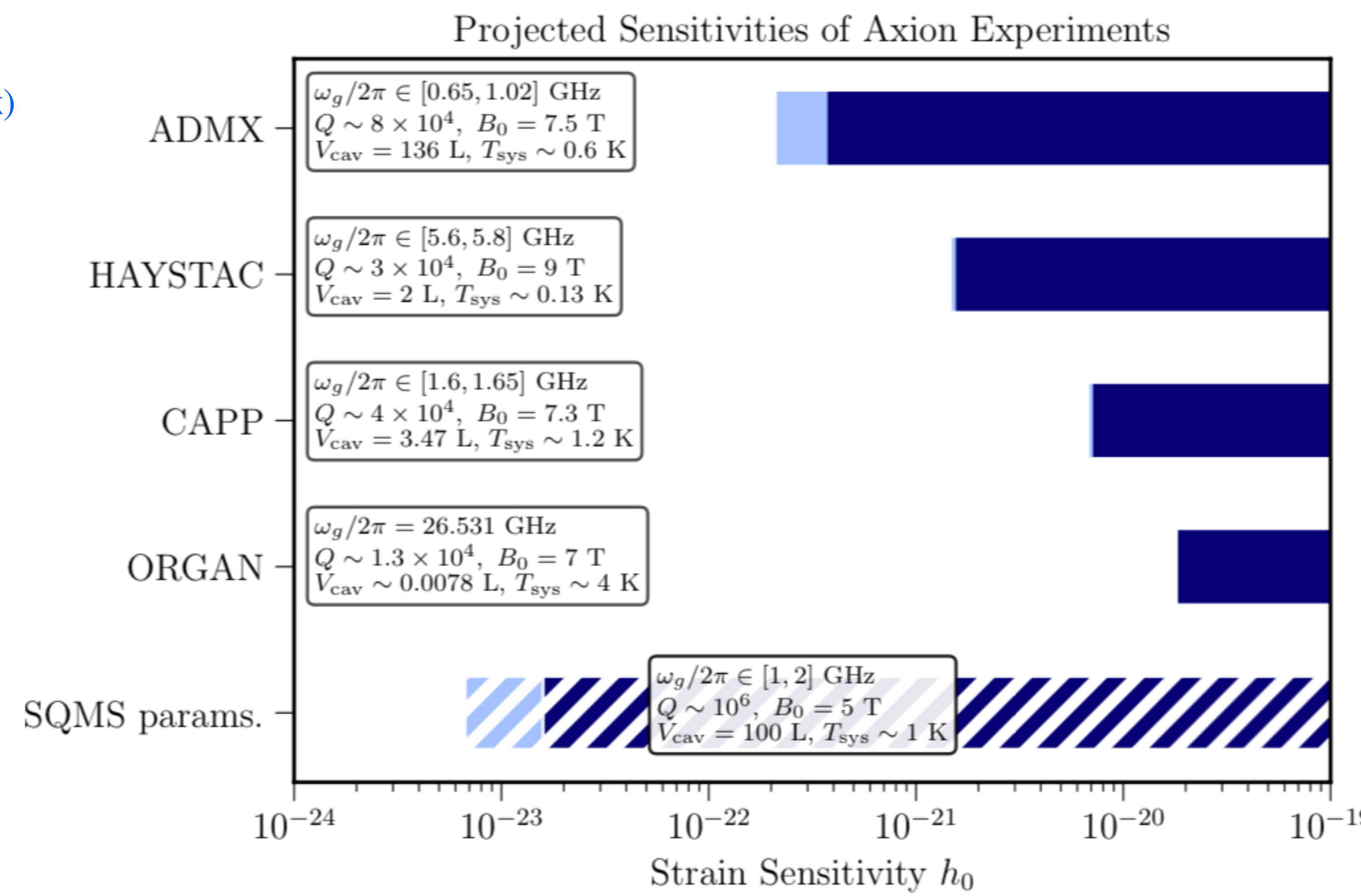
Phys. Rev. D **105**, 116011 – Published 17 June 2022

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

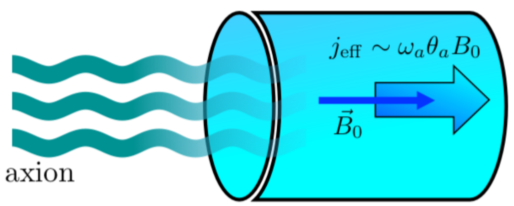
Eigenmodes

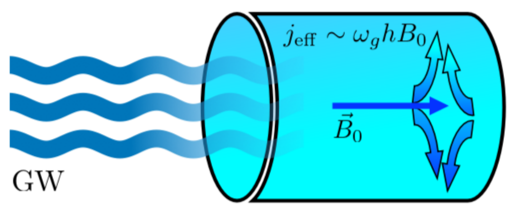
$$\mathbf{E}(\mathbf{x},t) = \sum_n e_n(t)\mathbf{E}_n(\mathbf{x})$$

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



Haloscopes based on microwave cavities





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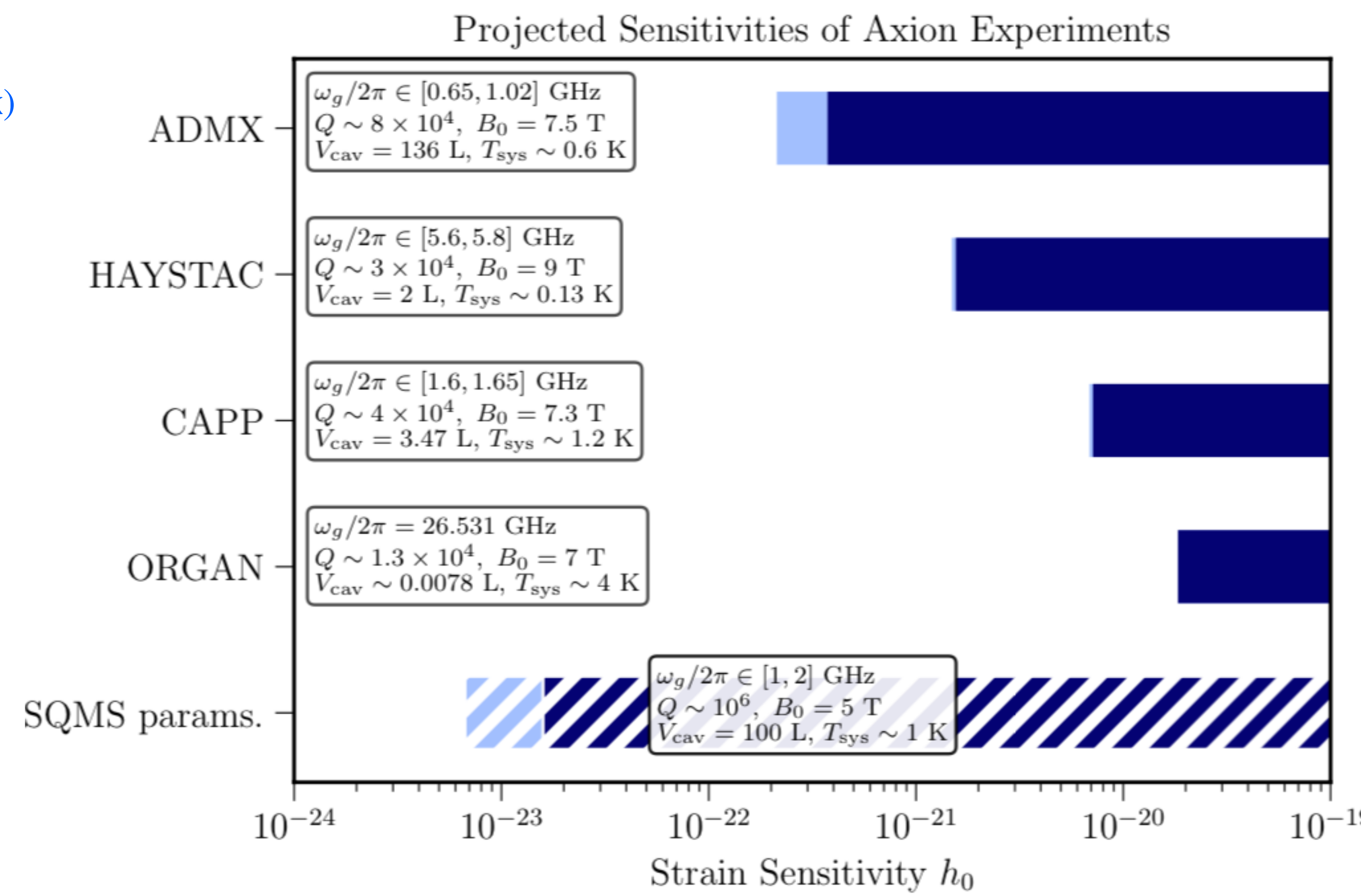
Eigenmodes $$\mathbf{E}(\mathbf{x},t) = \sum_n e_n(t)\mathbf{E}_n(\mathbf{x})$$

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

The coupling of the mechanical modes can play an important role
2303.01518



Camilo García Cely, University of Valencia

Experimental efforts at home

Study of a cubic cavity resonator for gravitational waves detection in the microwave frequency range

work in progress

Pablo Navarro,[a] **Benito Gimeno,**[b] **Juan Monzó,**[a] **Alejandro Díaz-Morcillo,**[a] **Diego Blas**[c,d]

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[b]Instituto de Física Corpuscular (IFIC), CSIC-University of Valencia, 46980 Valencia, Spain,
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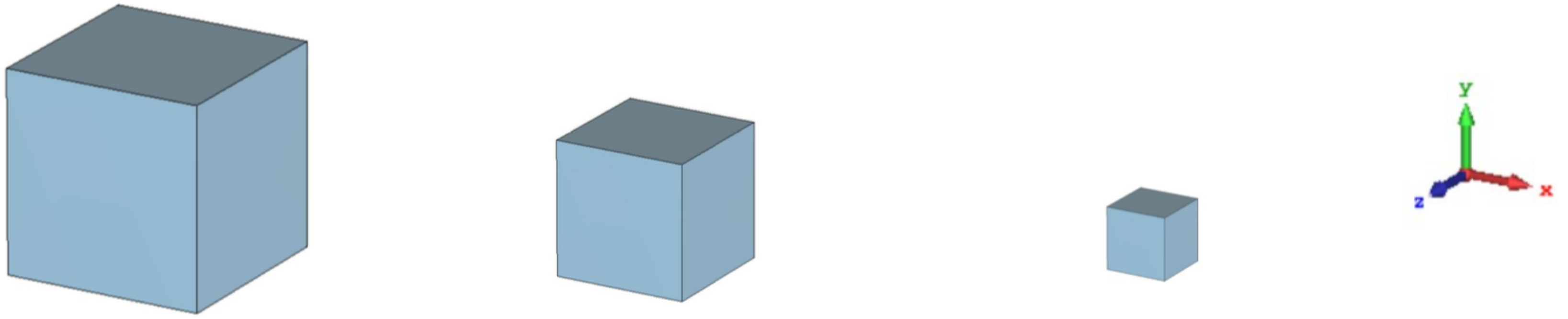
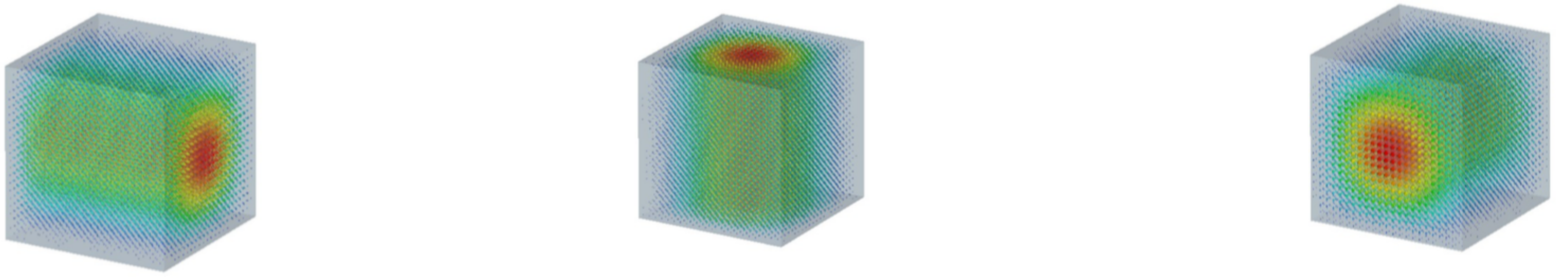
- Objective: study of a microwave cubic cavity for Gravitational Waves (GWs) detection based on the inverse Gertsenhstein effect.
- The magnetostatic field B is oriented in the z axis.



CAVITY 100 MHz CAVITY 1 GHz CAVITY 10 GHz

- 3 coaxial probes (antennas) in orthogonal directions.

(courtesy of B. Gimeno)



TE 011 TE 101 TM 110

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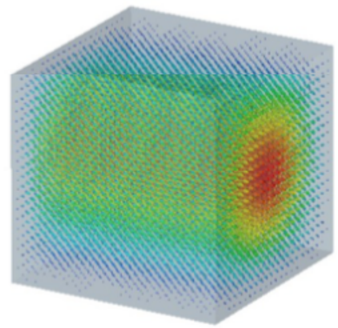
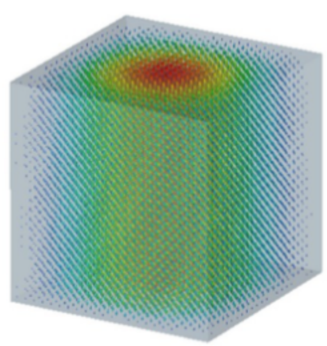
work in progress

TE 011



CAVITY 100 MHZ

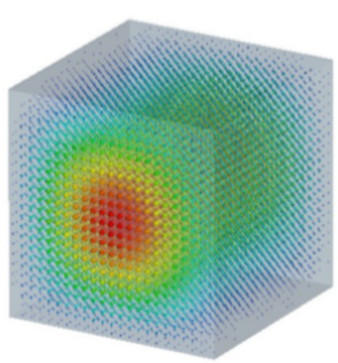
TE 101



J_cross

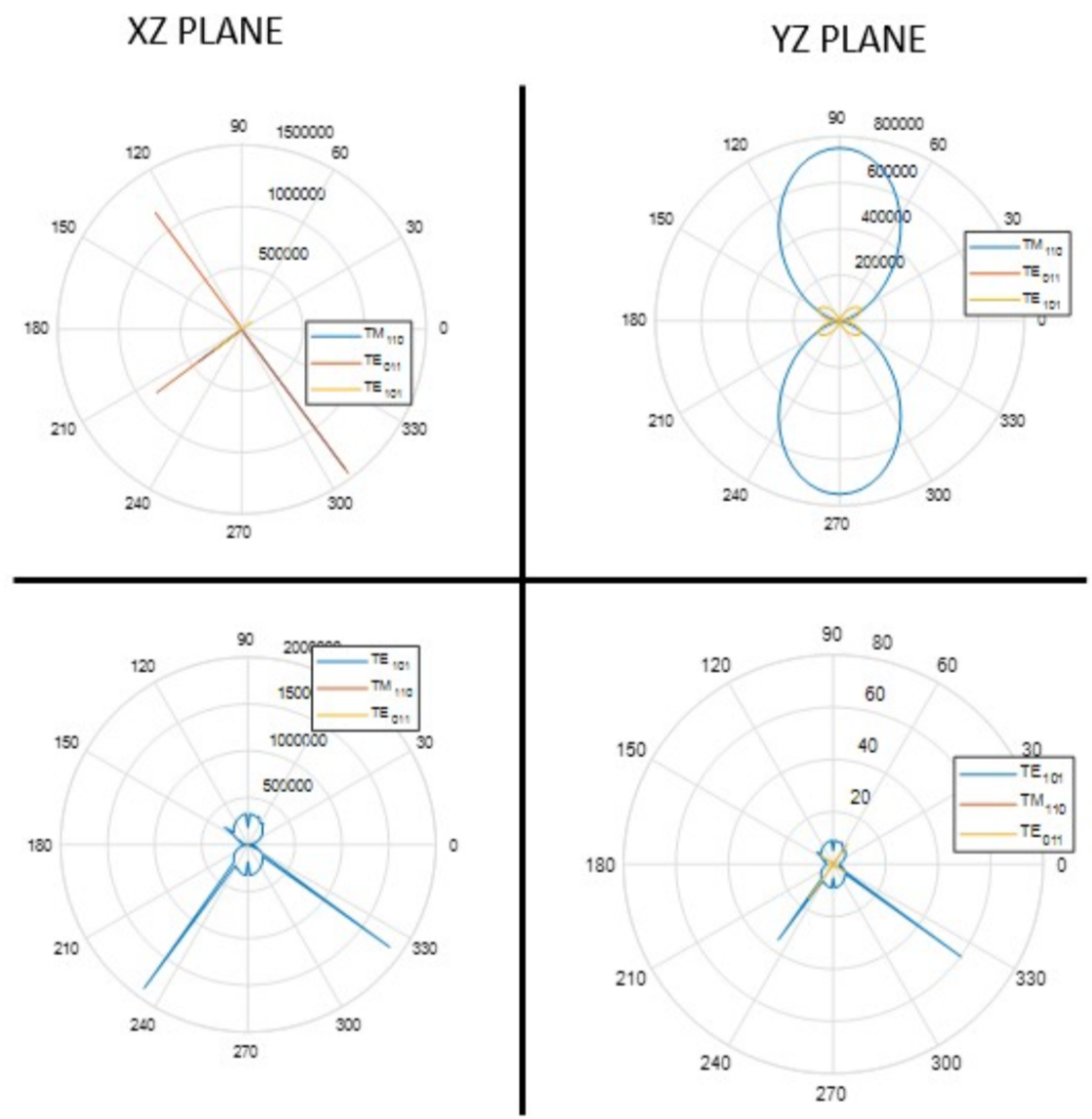
$$\eta_n \equiv \frac{\left| \int_{V_{\rm cav}} d^3\mathbf{x}\; \mathbf{E}_n^* \cdot \hat{\boldsymbol{j}}_{+,\times} \right|}{V_{\rm cav}^{1/2} \left(\int_{V_{\rm cav}} d^3\mathbf{x}\; |\mathbf{E}_n|^2 \right)^{1/2}}$$

TM 110



J_plus

(courtesy of B. Gimeno)



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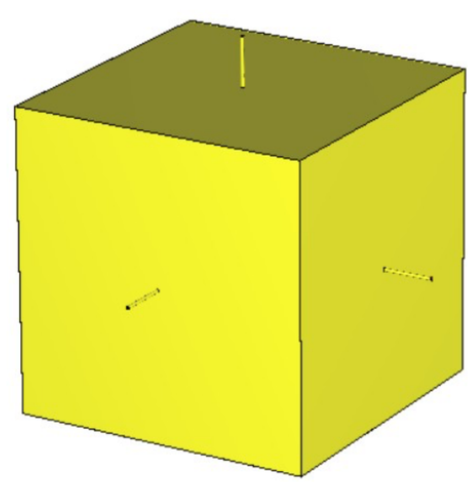
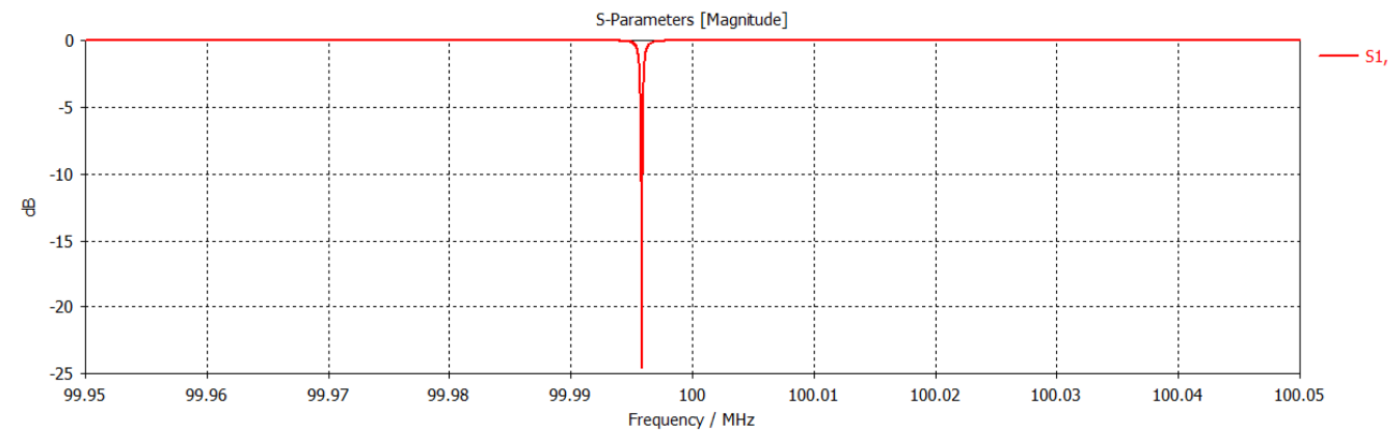
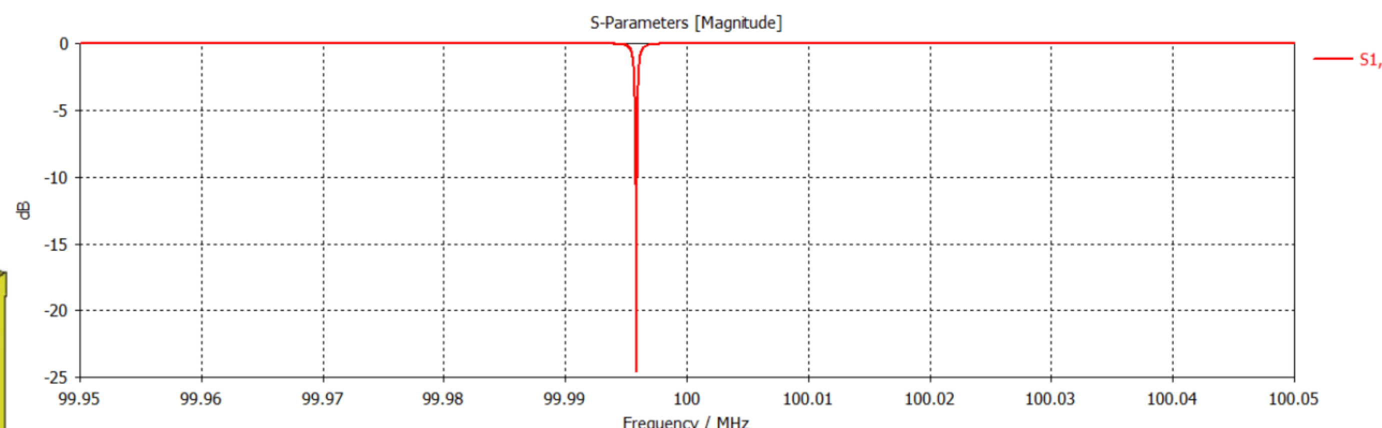
work in progress

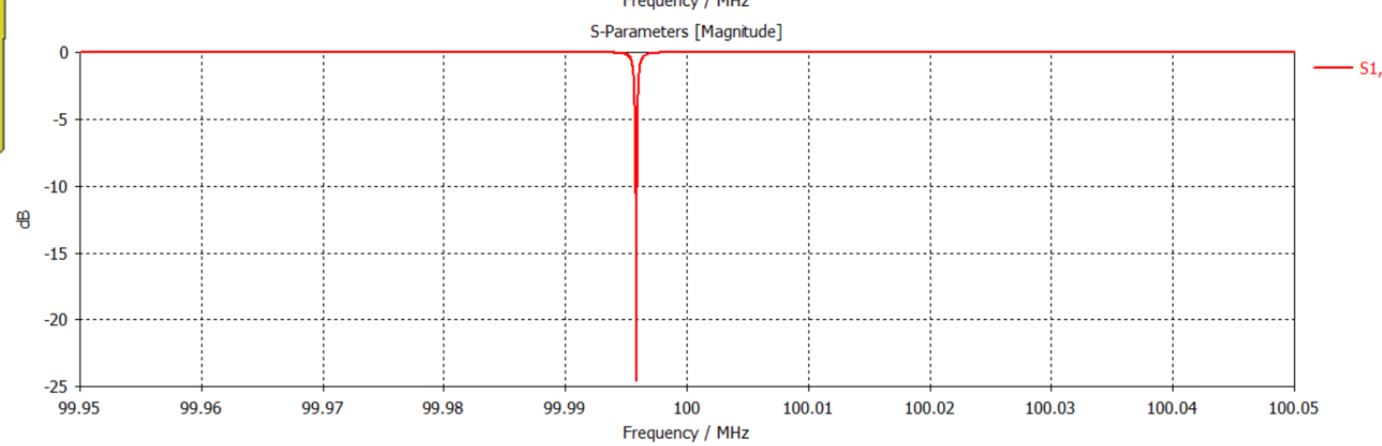
CAVITY 100 MHZ

3 coupling ports for each resonant mode (critical coupling regime)









(courtesy of B. Gimeno)

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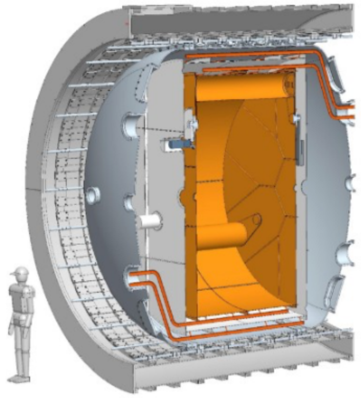
For instance, we use a sentitivity value of a spectrum analyzer S = -160 dbW with a two stage amplifier with total gain G = 50 dB ✉ P min = 10^-21 W

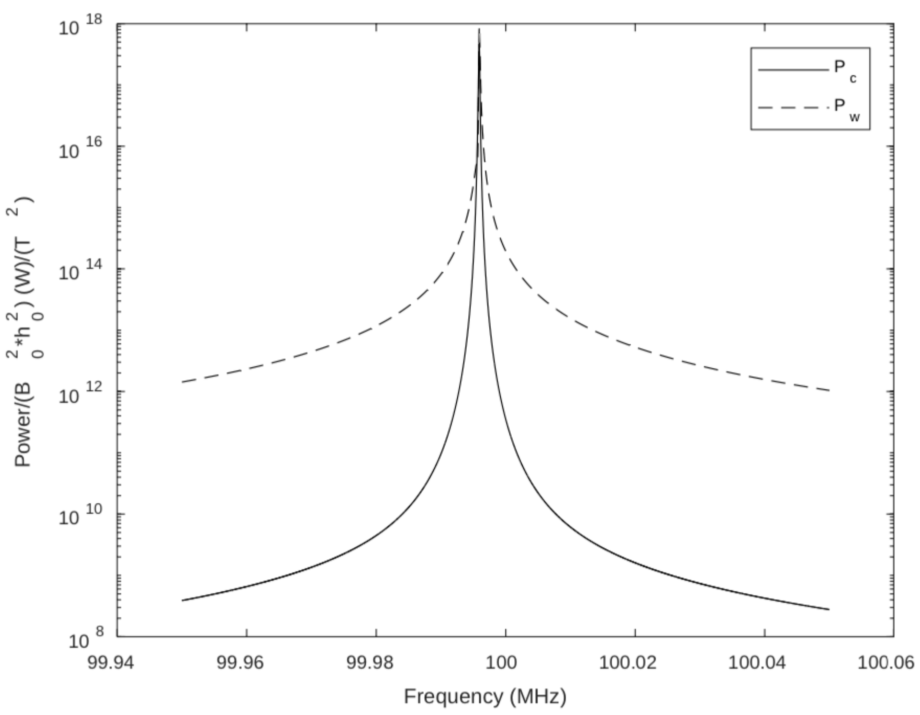
$$P_w\,(W) = \frac{P_w}{B^2 h_0^2}\, B^2\, h_0^2 = 10^{-21}\, W$$

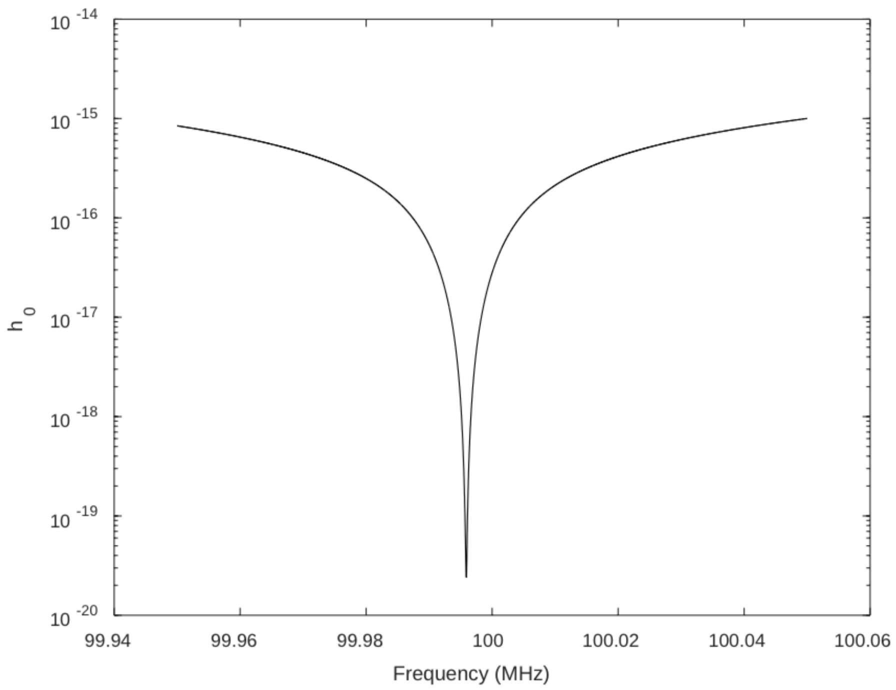
INFN-Frascati
KLASH

B = 0.6T



CAVITY 100 MHZ





(courtesy of B. Gimeno)

Conclusions

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

Selection rules in detectors exhibiting cylindrical symmetry enforce cancellations in the flux associated to gravitational waves.

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.