Gravitational waves in dark matter experiments

Universidad del Valle
Cali, Nov 24

Camilo García Cely

Ramón y Cajal Researcher

IFIC INSTITUT DE FÍSICA CORPUSCULAR

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

VNIVERSITAT DE VALÈNCIA

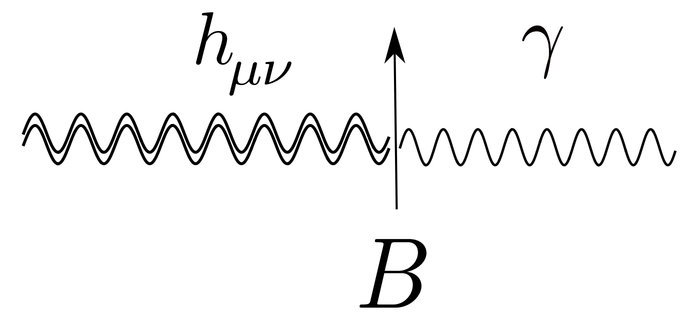
Outline

- What is dark matter?

- Why HF gravitational waves?

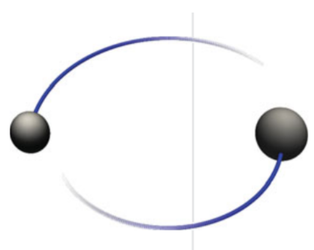
- Gravitational-wave vs. Axion electrodynamics

- Conclusions



What is dark matter?

Lessons from the two-body problem



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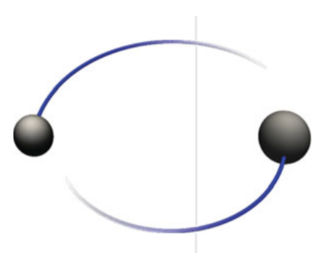

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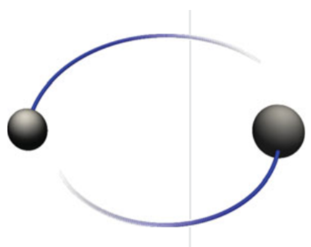

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$$v^2_{\text{rotation}} = \frac{GM_{\text{enclosed}}}{r}$$

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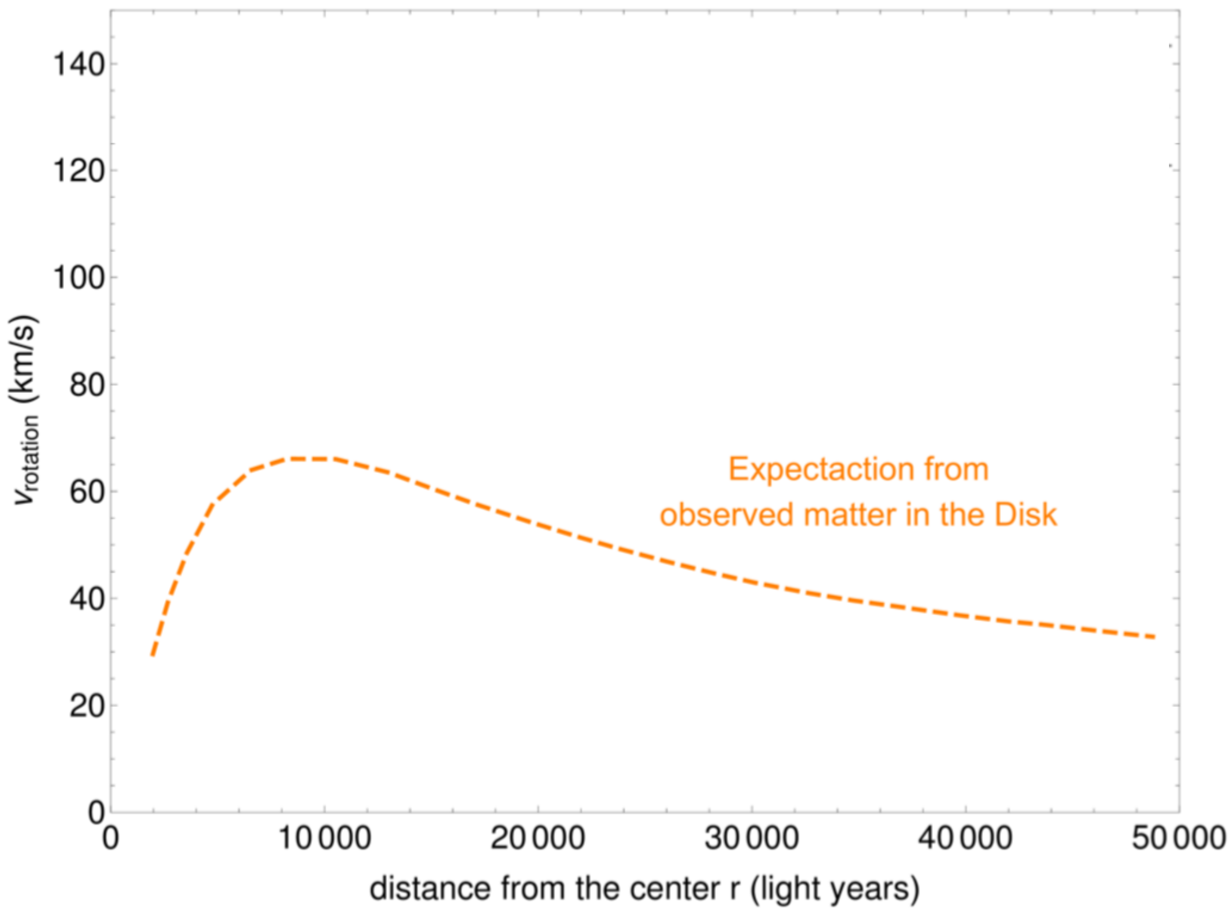

Triangulum Galaxy (M33)

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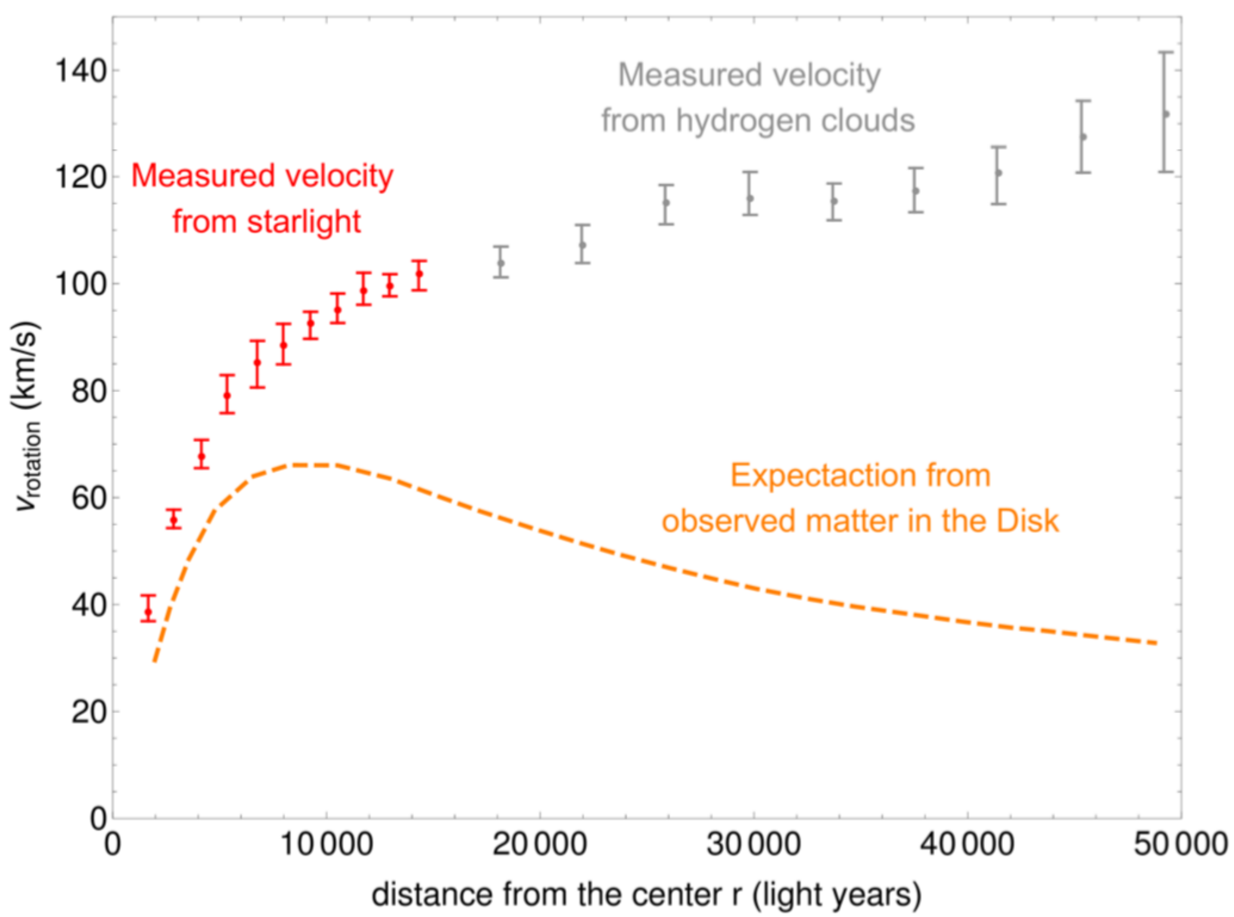

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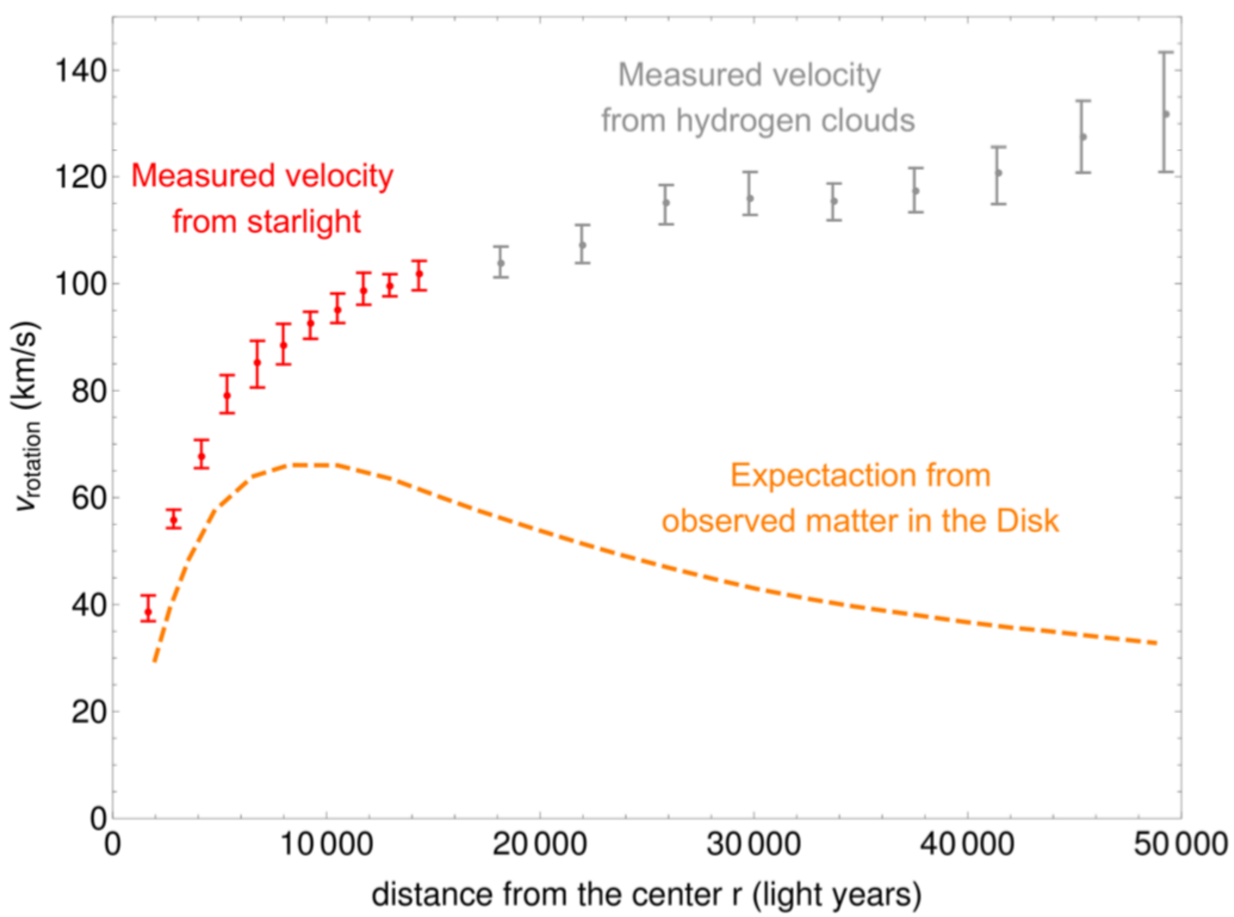
Dark Matter



Triangulum Galaxy (M33)

There must be some ***matter that we don't see*** or Newton's Laws don't work in galaxies

Vera Rubin

Dark Matter

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

Velocity measurements

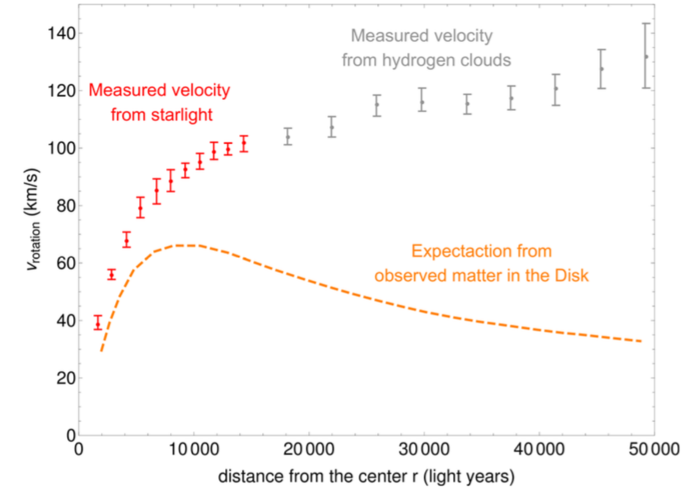
- Flat rotation curves of spiral galaxies
- Velocity dispersion of stars in giant elliptical and dwarf spheroidal galaxies
- Velocity dispersion of galaxies in clusters

Lensing

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

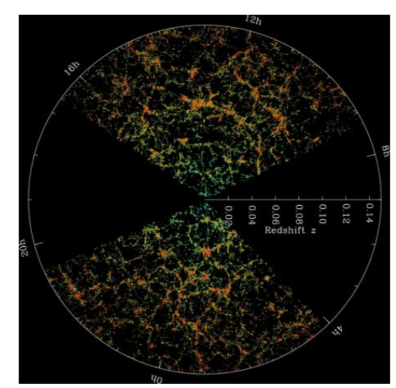
Universe at large scales

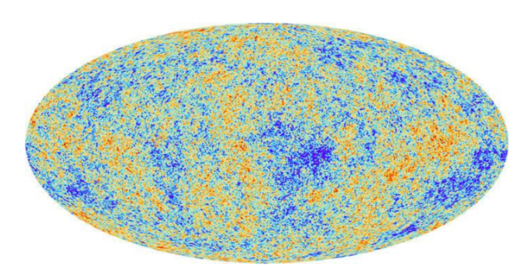
- Abundance of clusters
- Large-scale distribution of galaxies
- Power spectrum of CMB anisotropies



kpc

Mpc





Gpc

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Collisionless Cold
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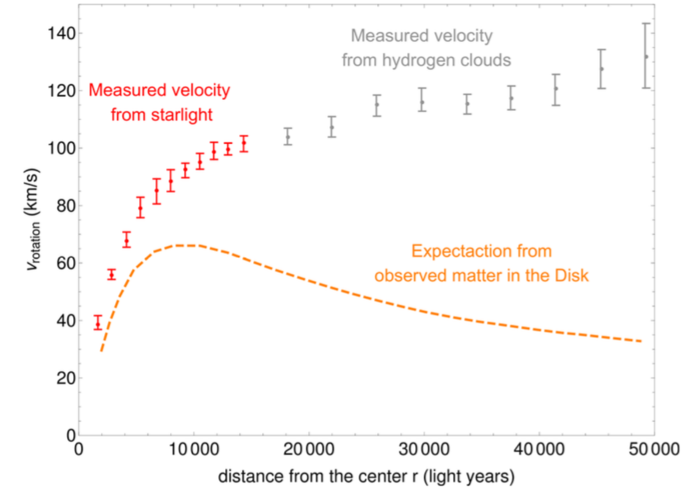

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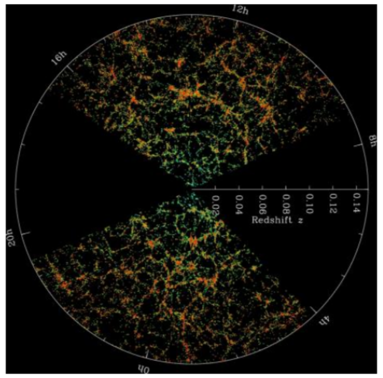

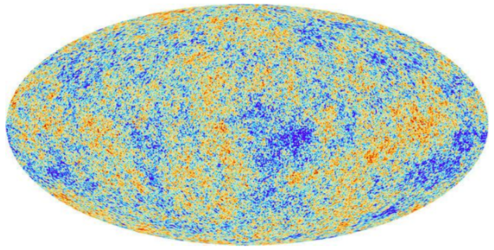

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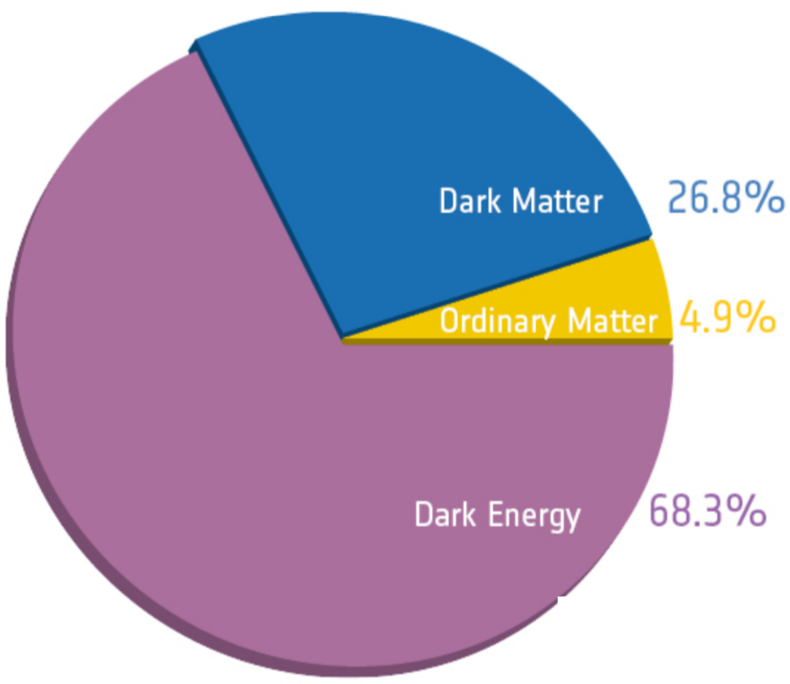

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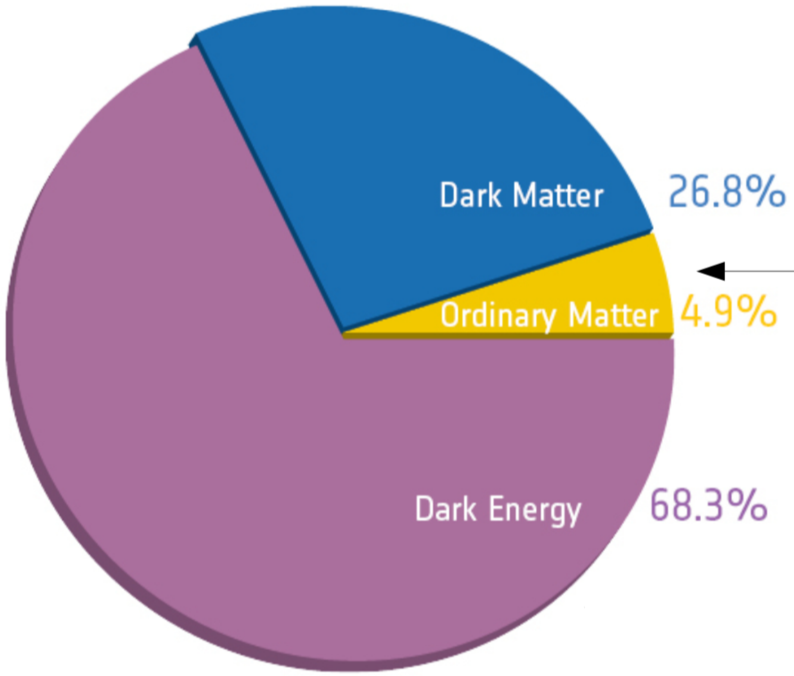

Standard Model stable particles:

Mostly protons, electrons, neutrinos and photons

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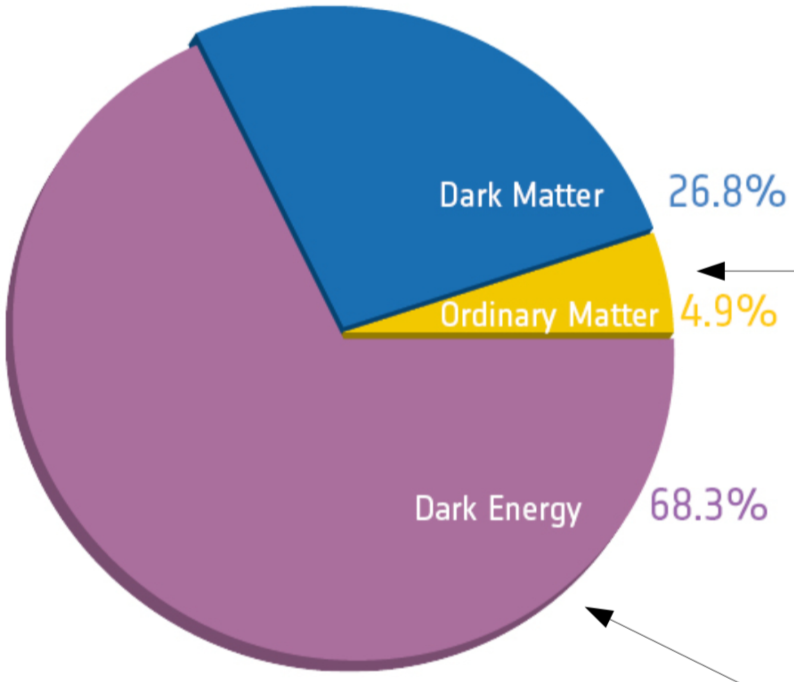

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$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

?

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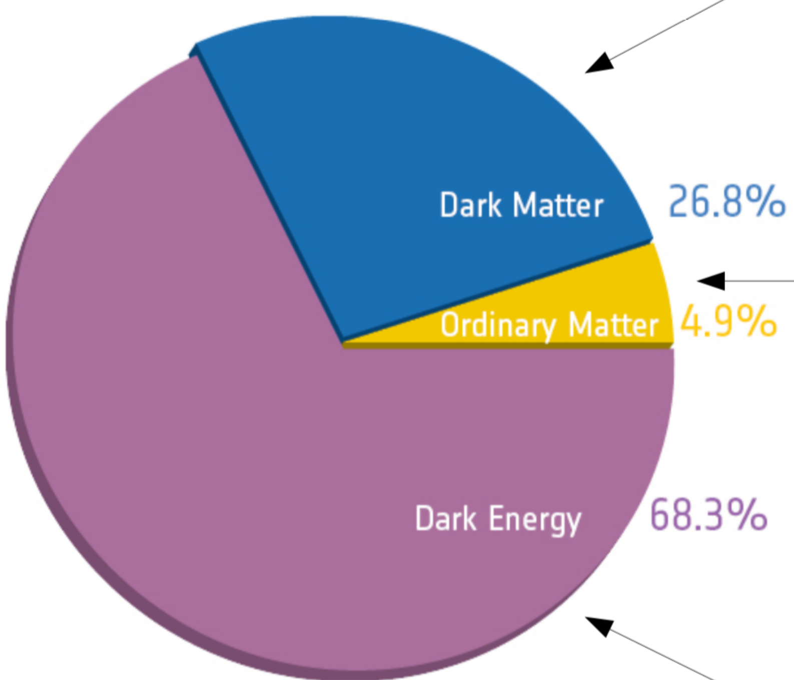

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Bertone Tait, 2018

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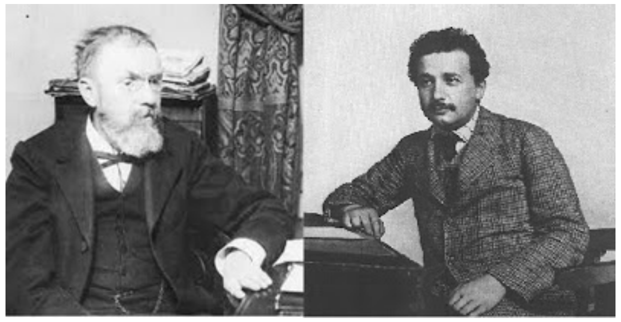
Why HF gravitational waves?

Gravitational Waves

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



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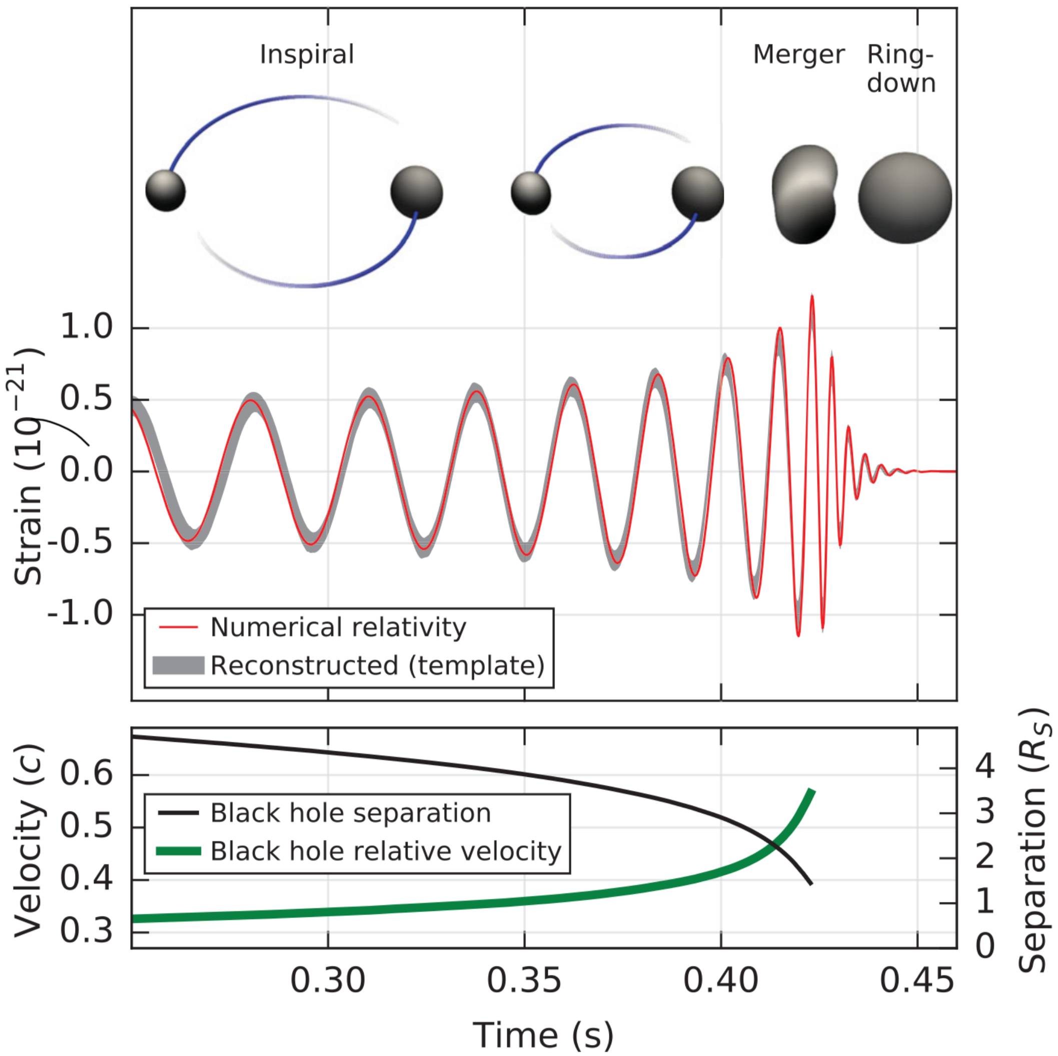
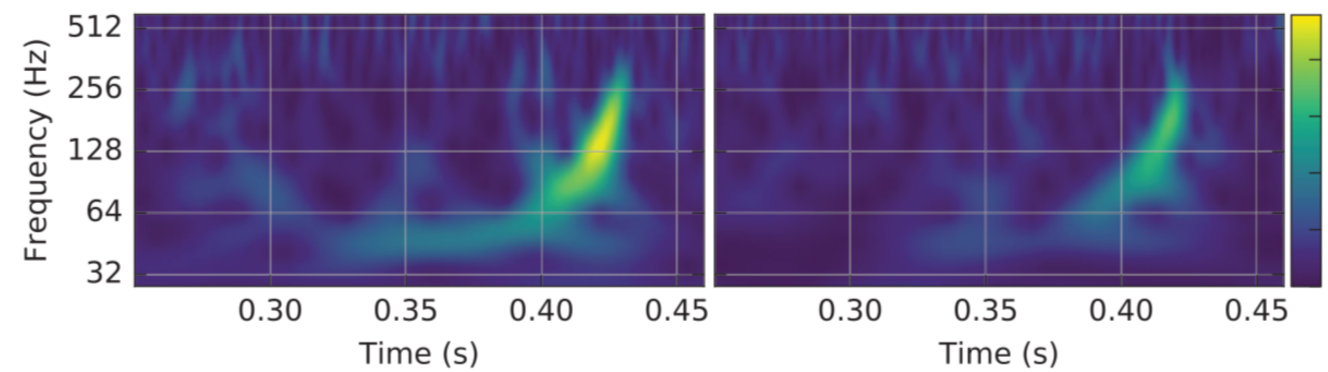


PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

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



interferometers

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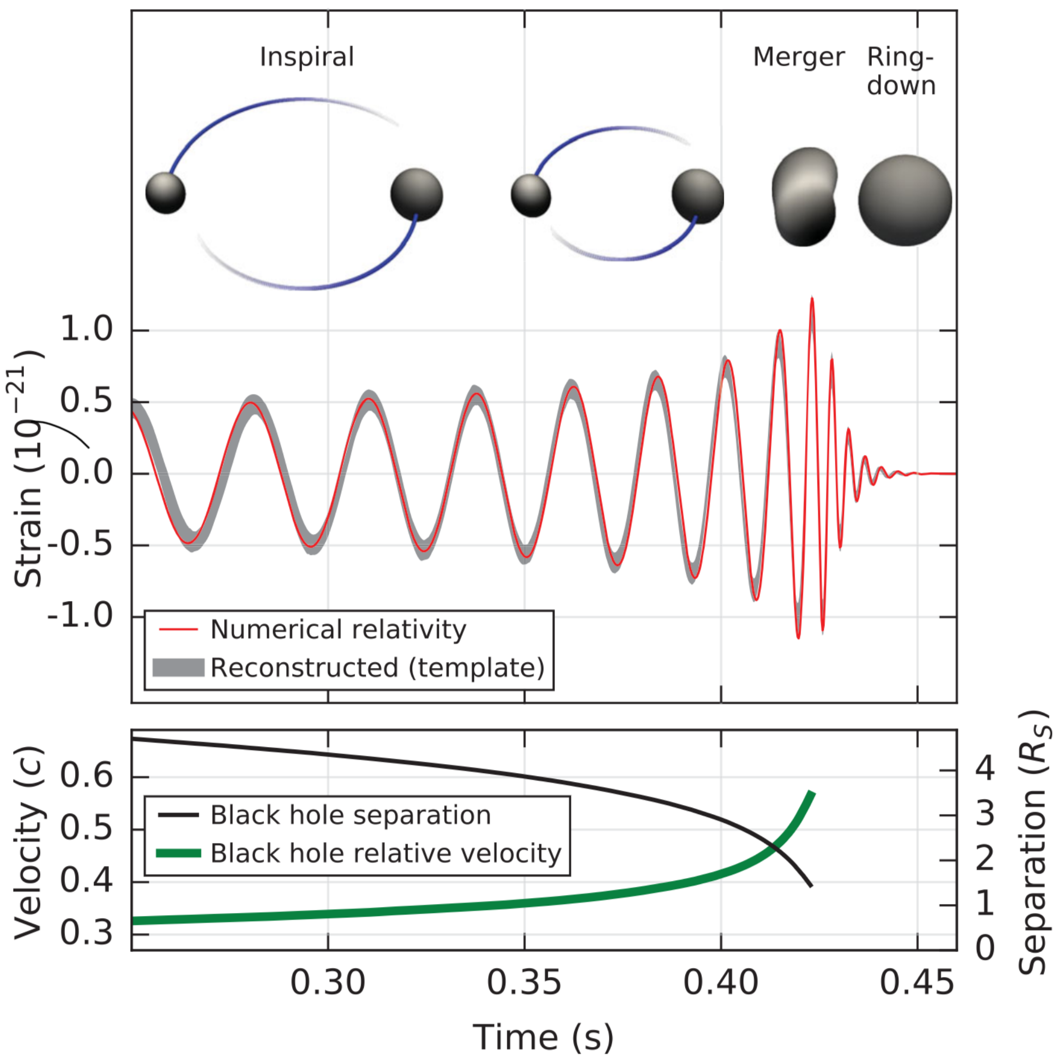

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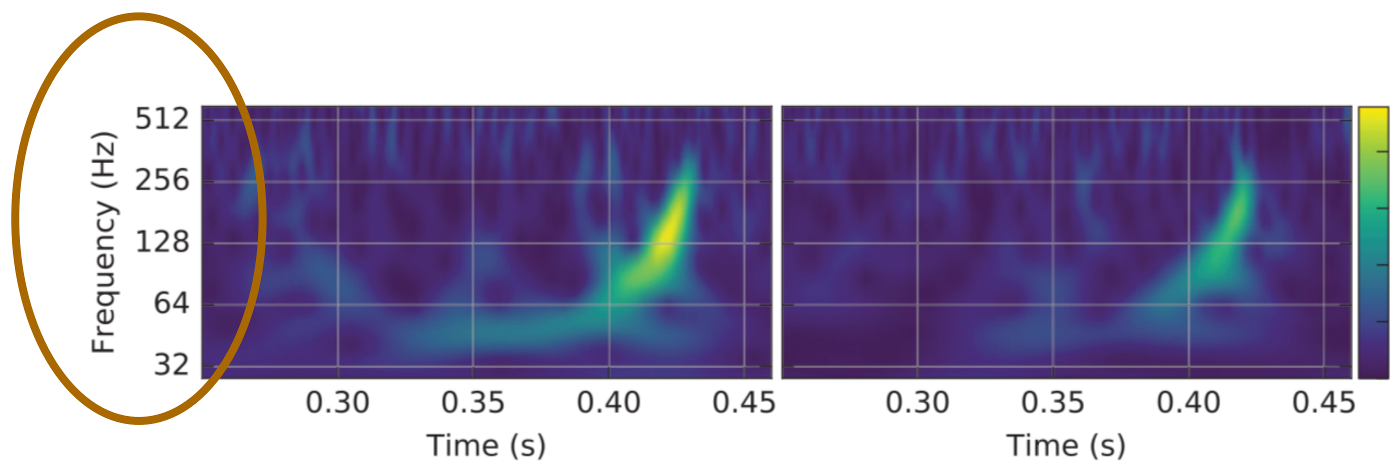

interferometers

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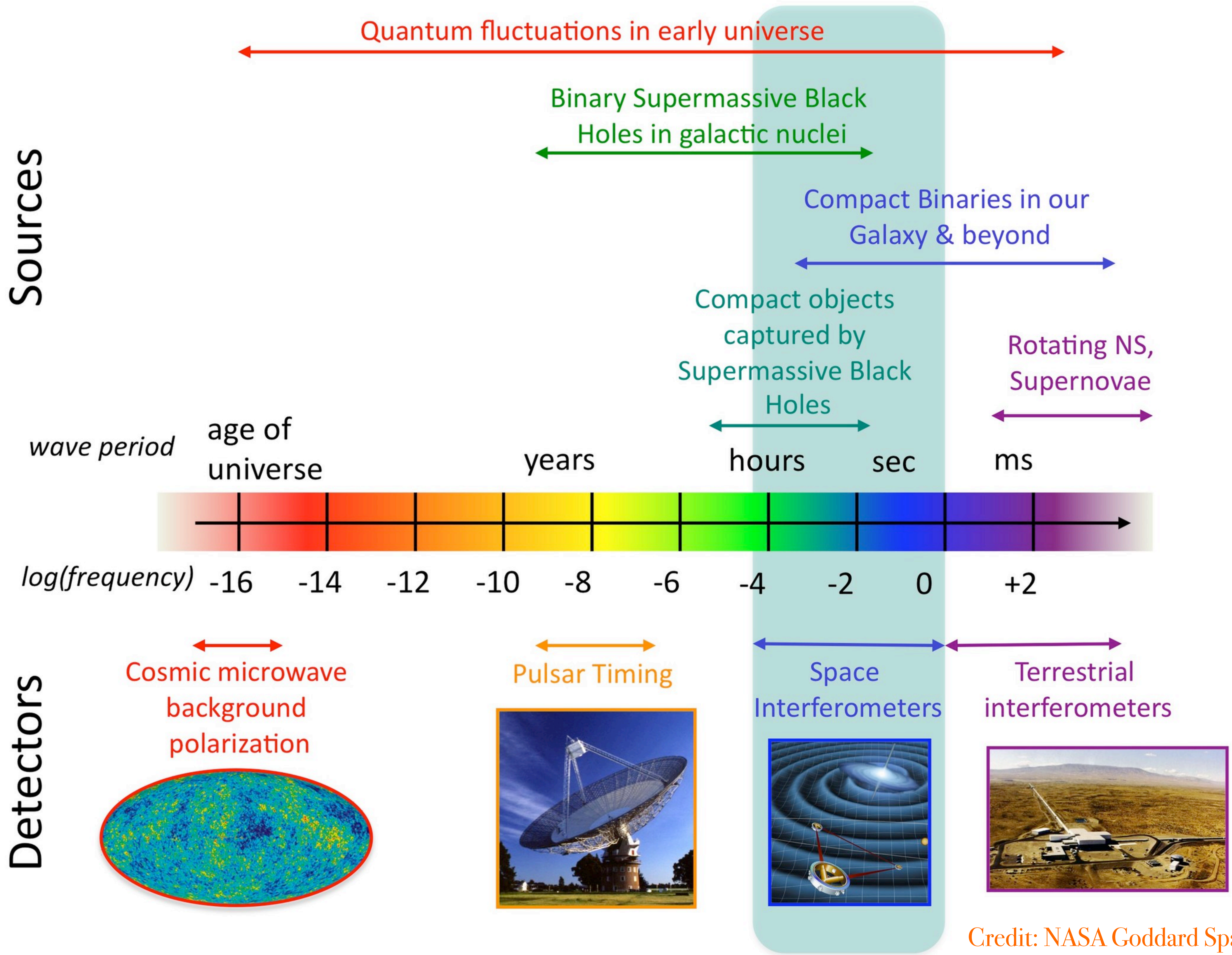
Gravitational Wave Spectrum



Credit: NASA Goddard Space Flight Center

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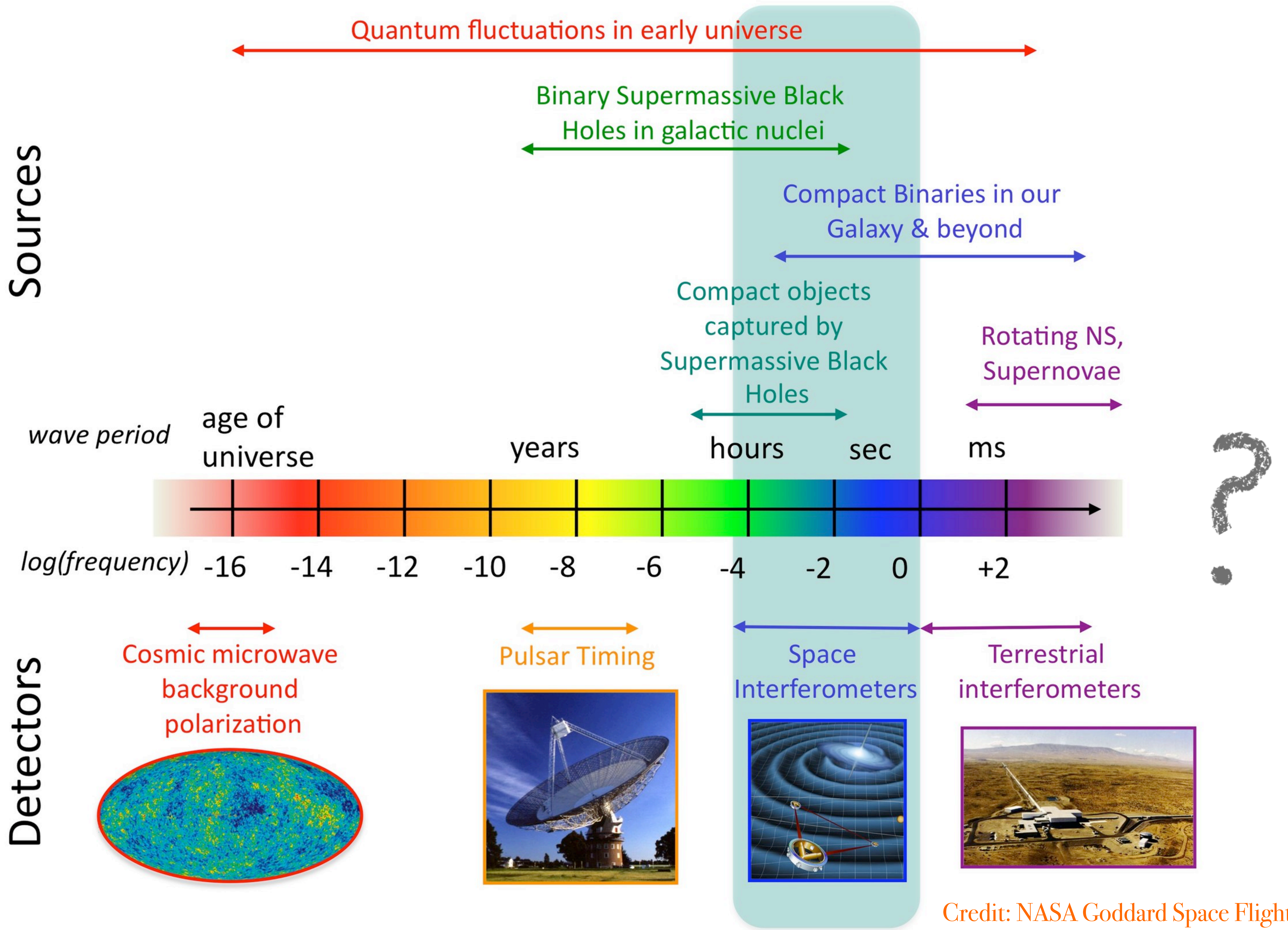

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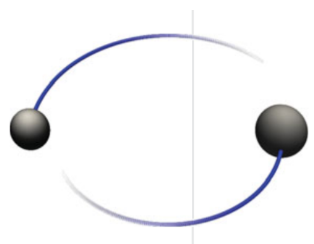
Lessons from the two-body problem



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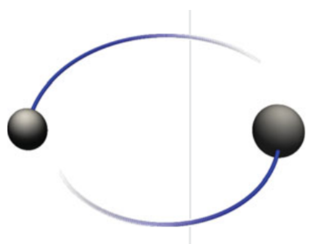

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$$f \approx \frac{1}{2\pi}\sqrt{\frac{GM}{R^3}}$$

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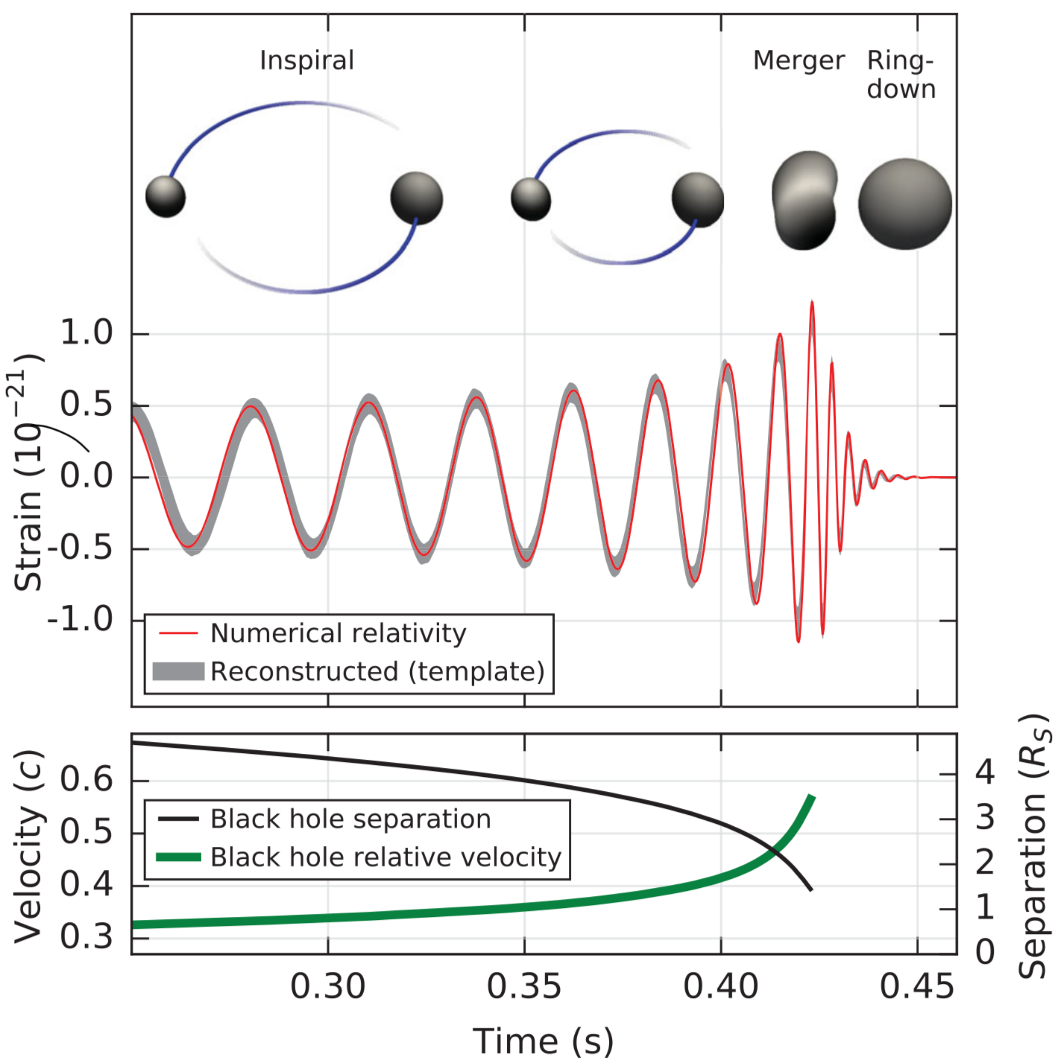

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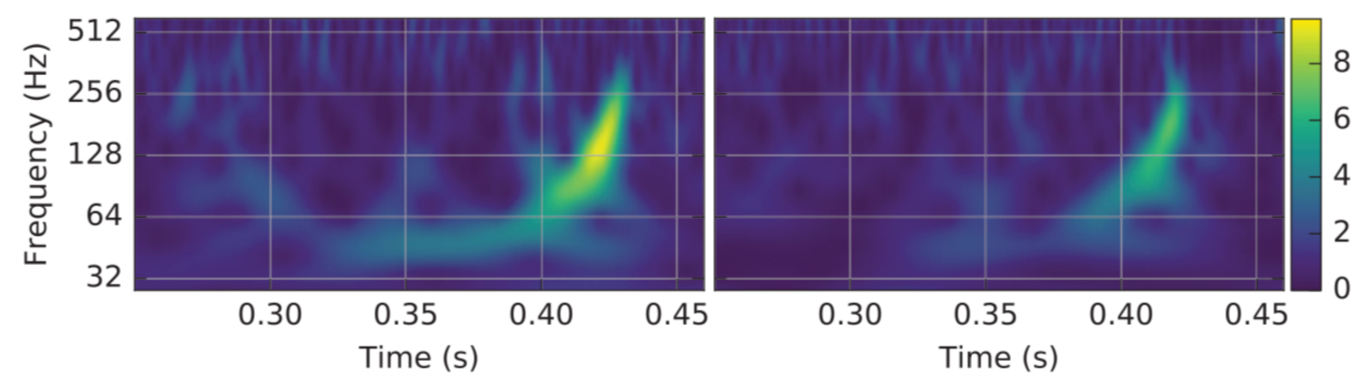

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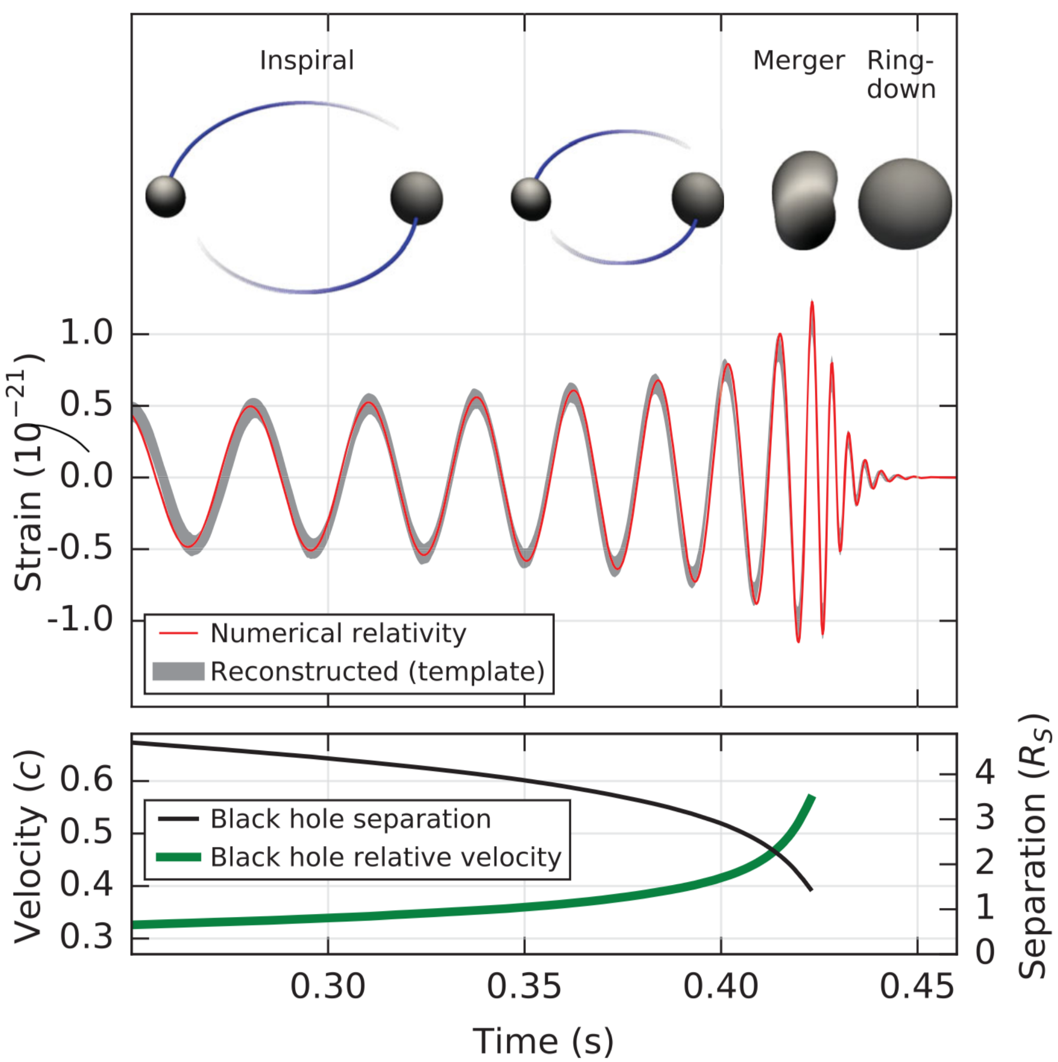

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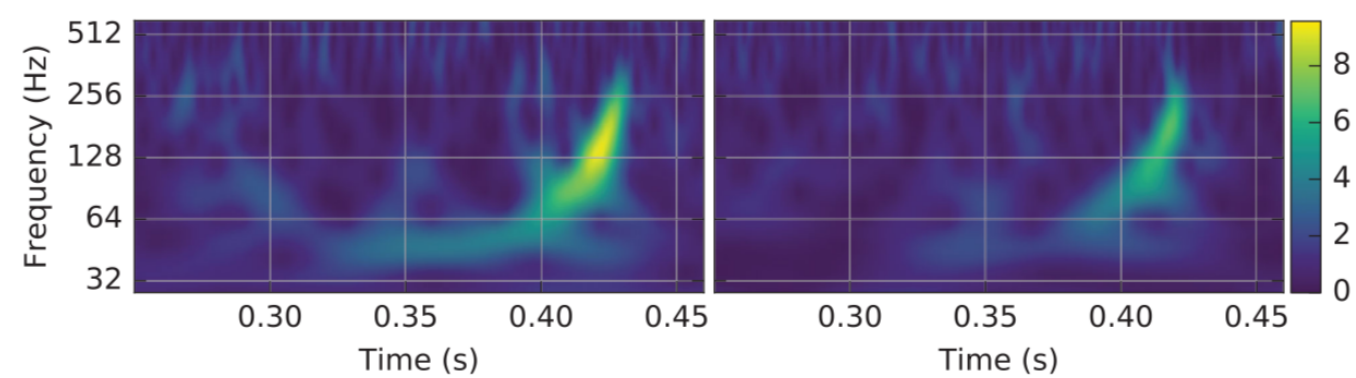


$$f \approx \frac{1}{2\pi}\sqrt{\frac{GM}{R^3}} \ll 10\,\mathrm{kHz}$$

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

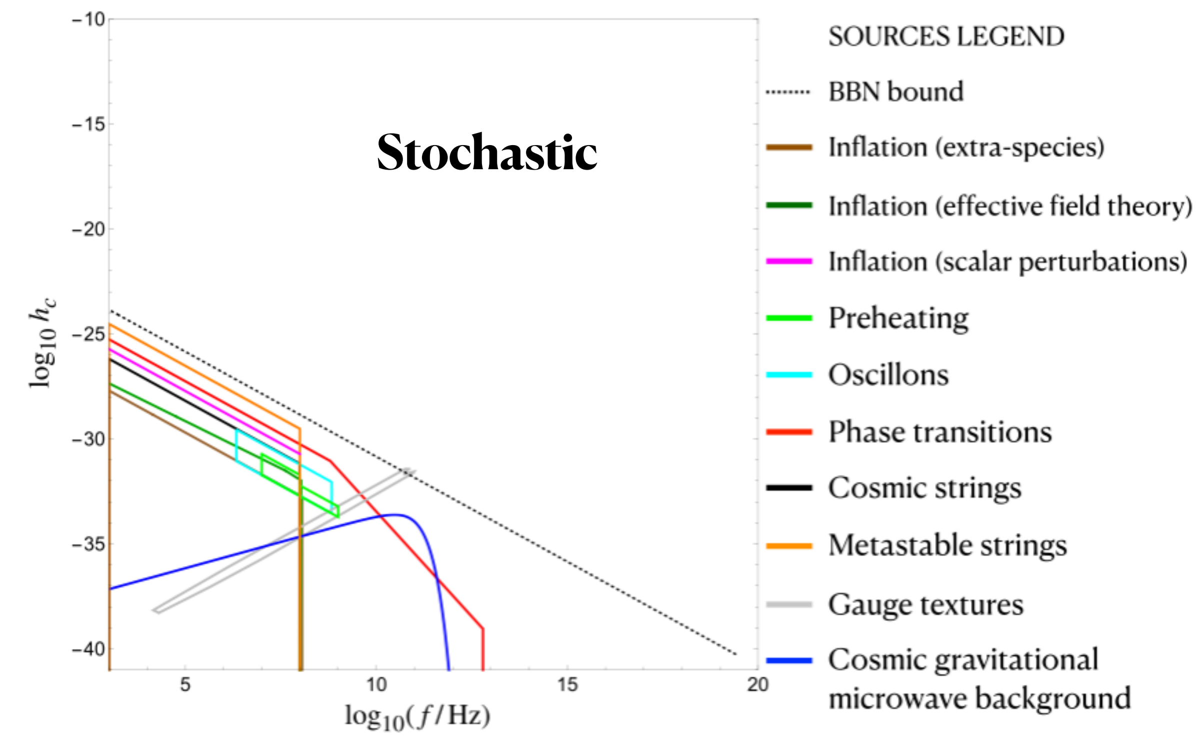
Review Article | Open Access | Published: 06 December 2021

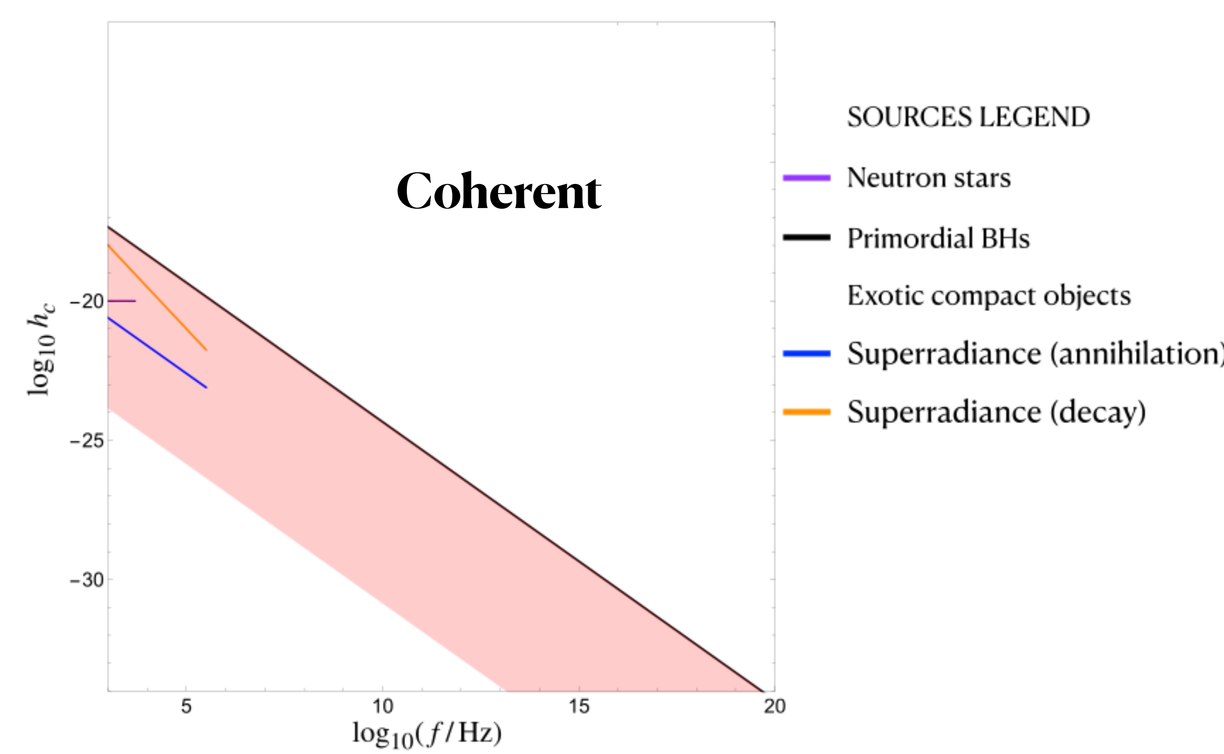
Challenges and opportunities of gravitational-wave searches at MHz to GHz frequencies

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

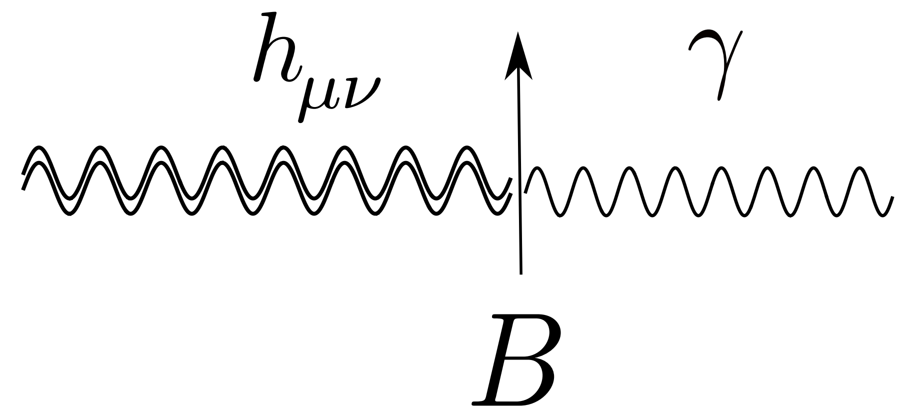
J. Exptl. Theoret. Phys. (U.S.S.R.) 43, 605-607 (August, 1962)

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 $\hbar$

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

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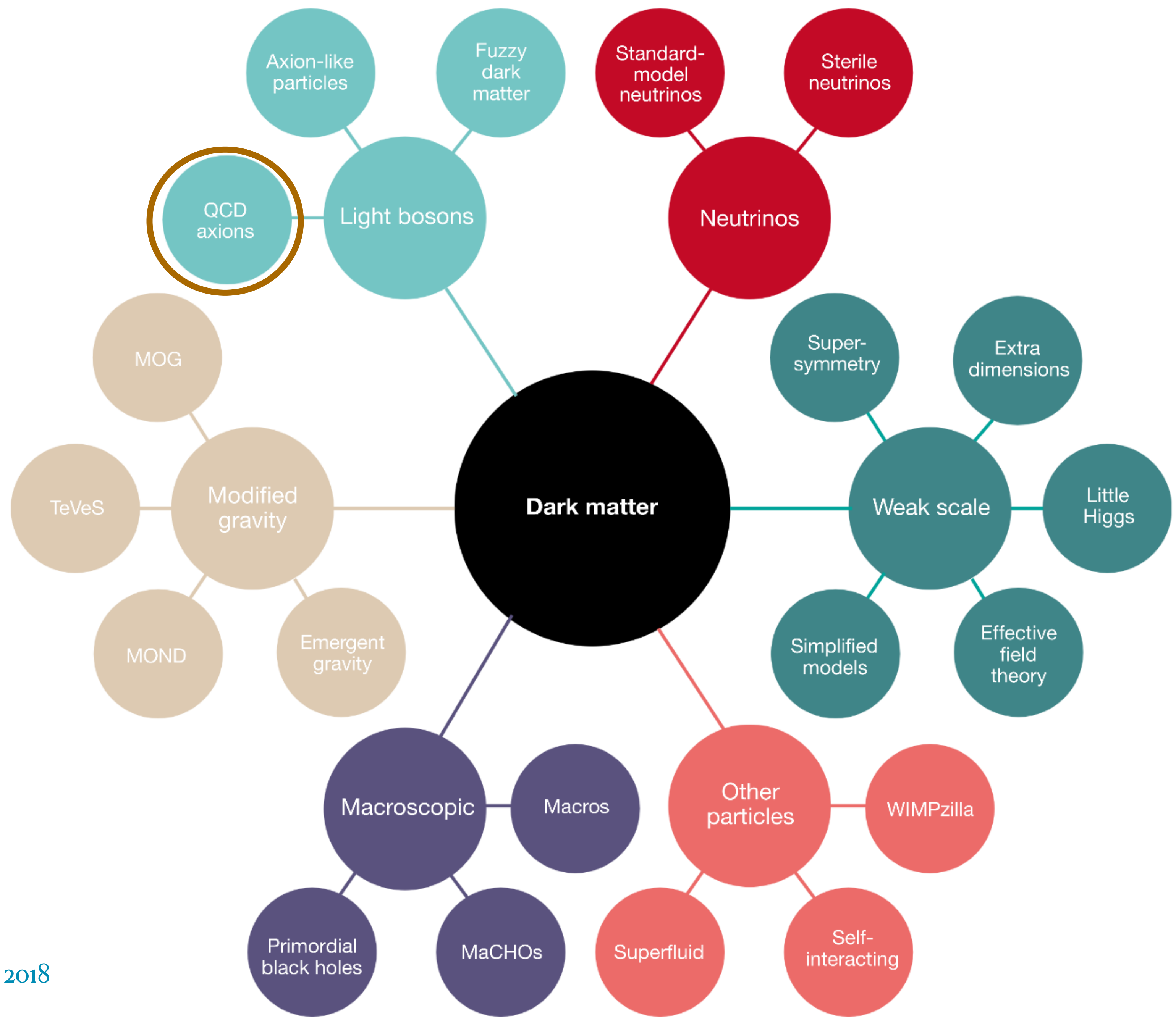
- The process is strictly analogous to axion dark matter conversion.

Raffelt, Stodolski'89

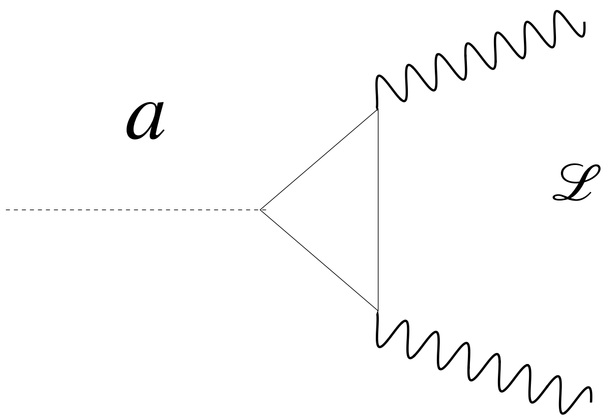
Collisionless Cold
Dark Matter



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

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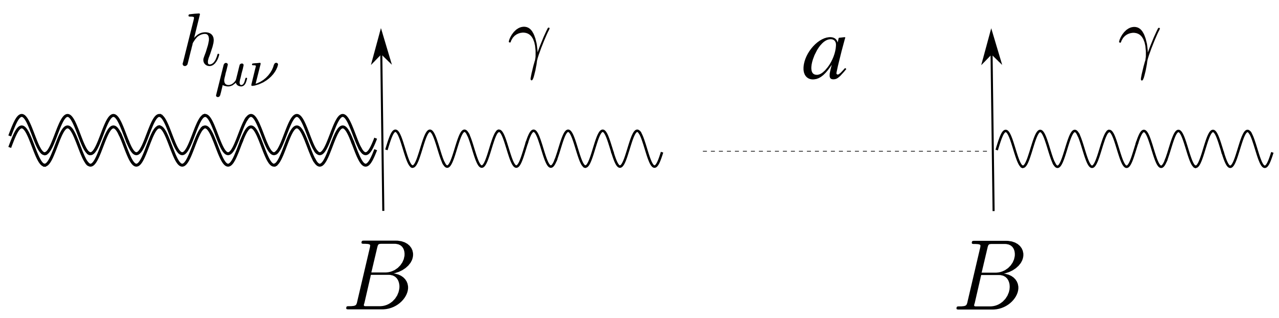
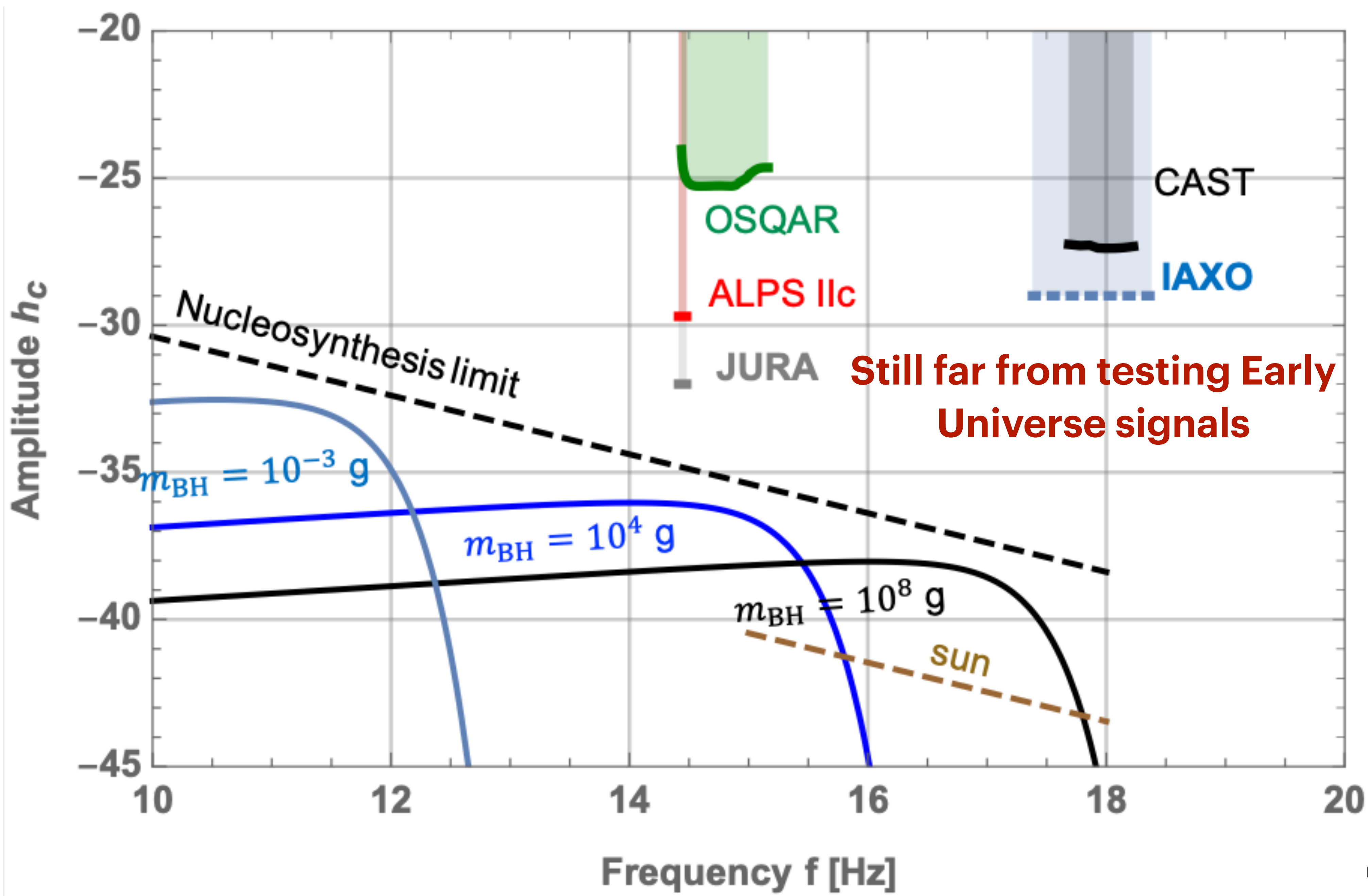
The (inverse) Gertsenhstein Effect



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

Axion electrodynamics

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

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

Sikivie, 1983

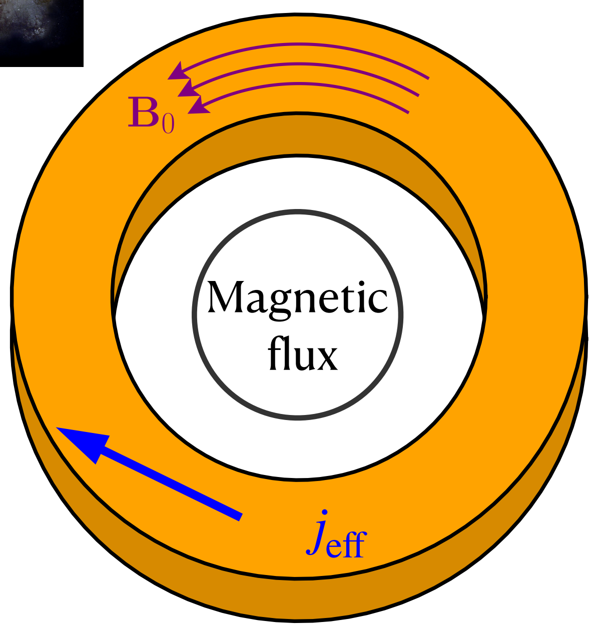
$$\nabla \times \mathbf{E} + \partial_t \mathbf{B} = 0$$

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

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

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

Low mass axion haloscopes

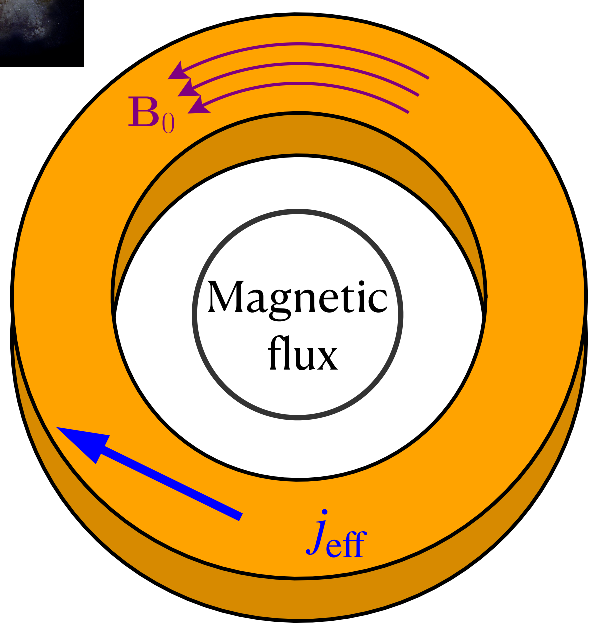


$$\nabla \times \mathbf{B} - \partial_t \mathbf{E} = \underbrace{g_{a\gamma\gamma}\, \partial_t a\, \mathbf{B_0}}_{j_{\text{eff}}}$$

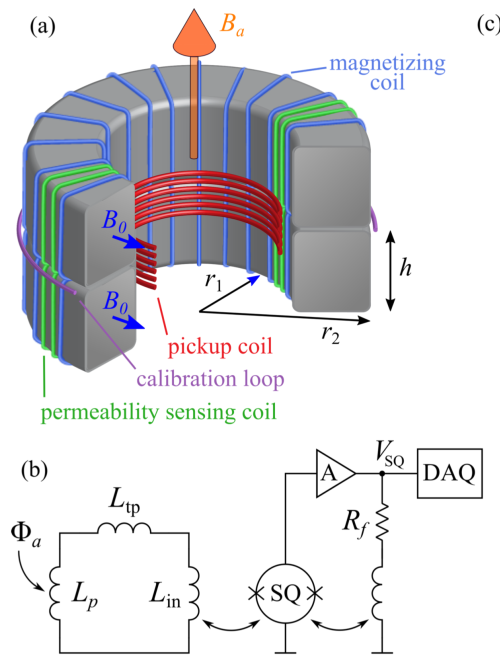
The electromagnetic fields produced by the axion drive a current through a pickup coil

Camilo García Cely, University of Valencia

Low mass axion haloscopes



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



(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,‡]
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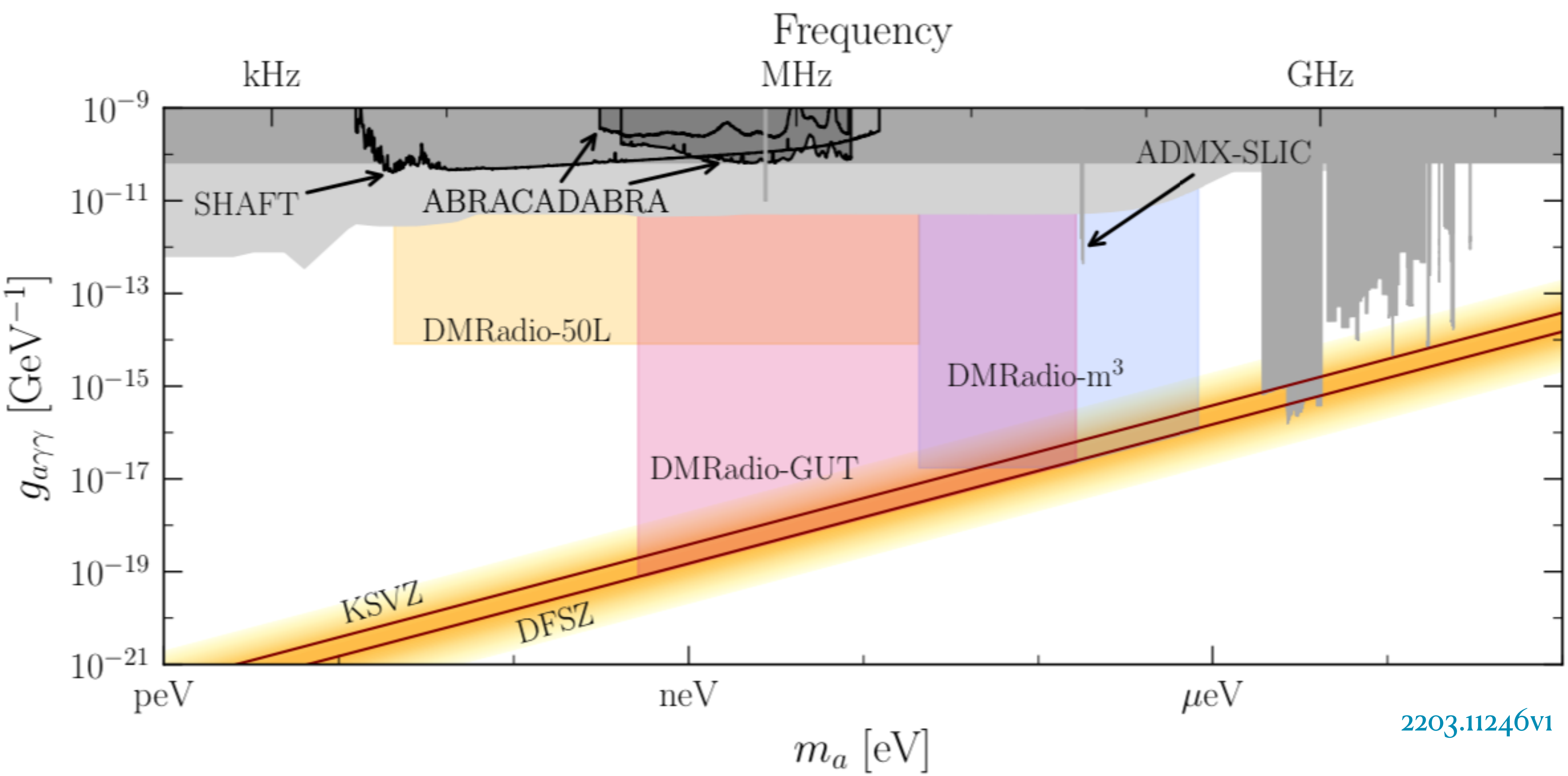
(Received 3 March 2016; published 30 September 2016)

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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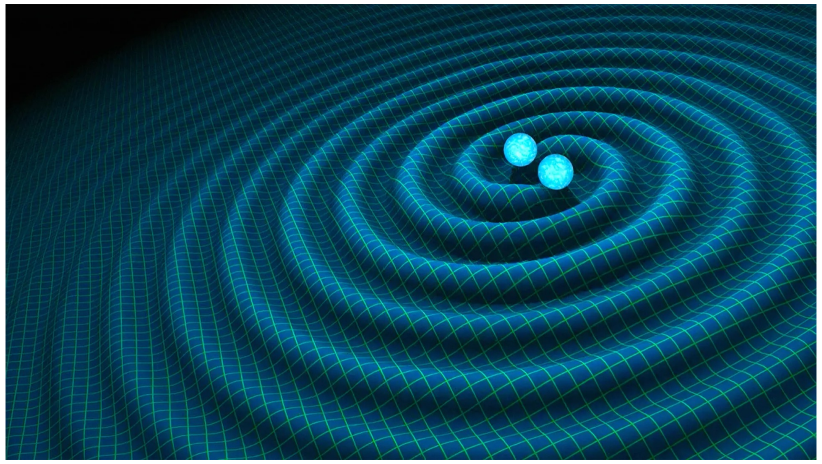
Gravitational-wave electrodynamics

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

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



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

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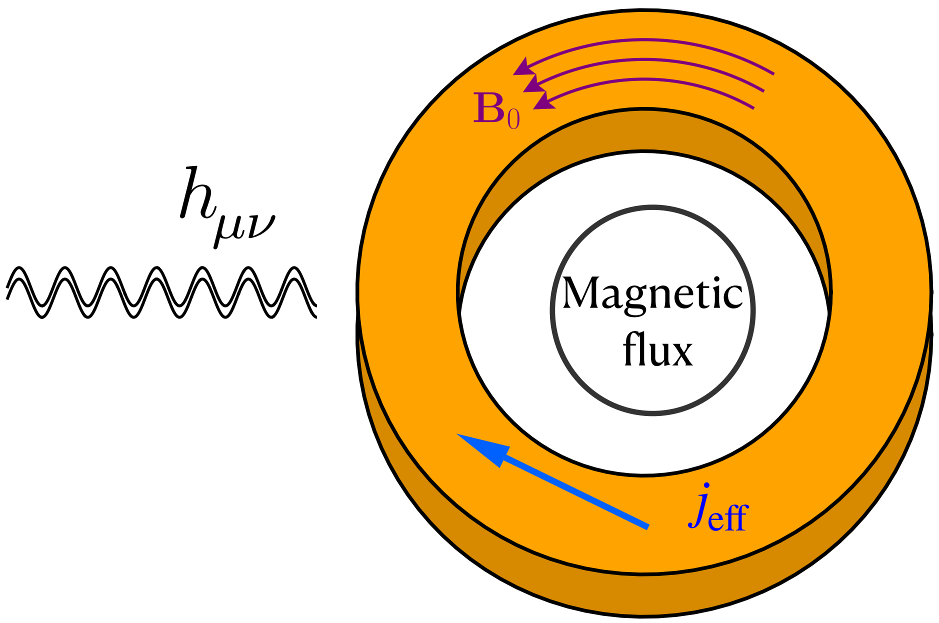
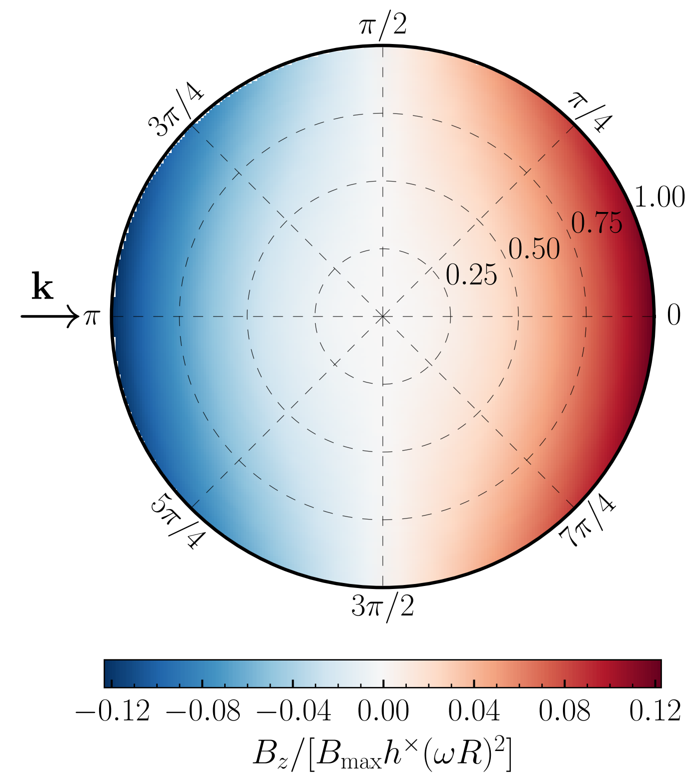
Gravitational waves in low mass axion haloscopes

Domcke, CGC, Rodd, 2202.00695





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

Only one polarization

Suppression at small frequencies

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

The sensitivity scaling with the volume is faster than for axions

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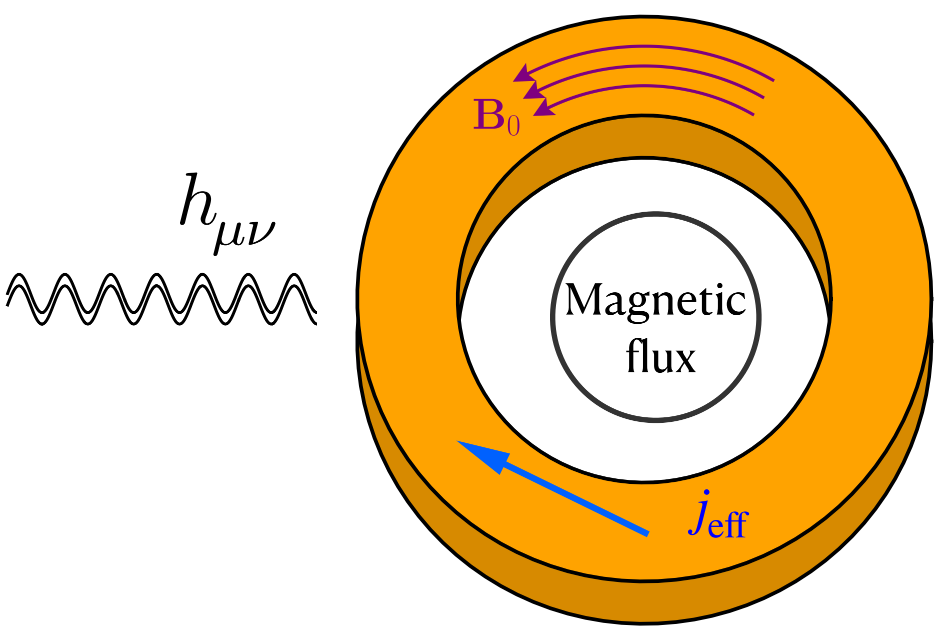
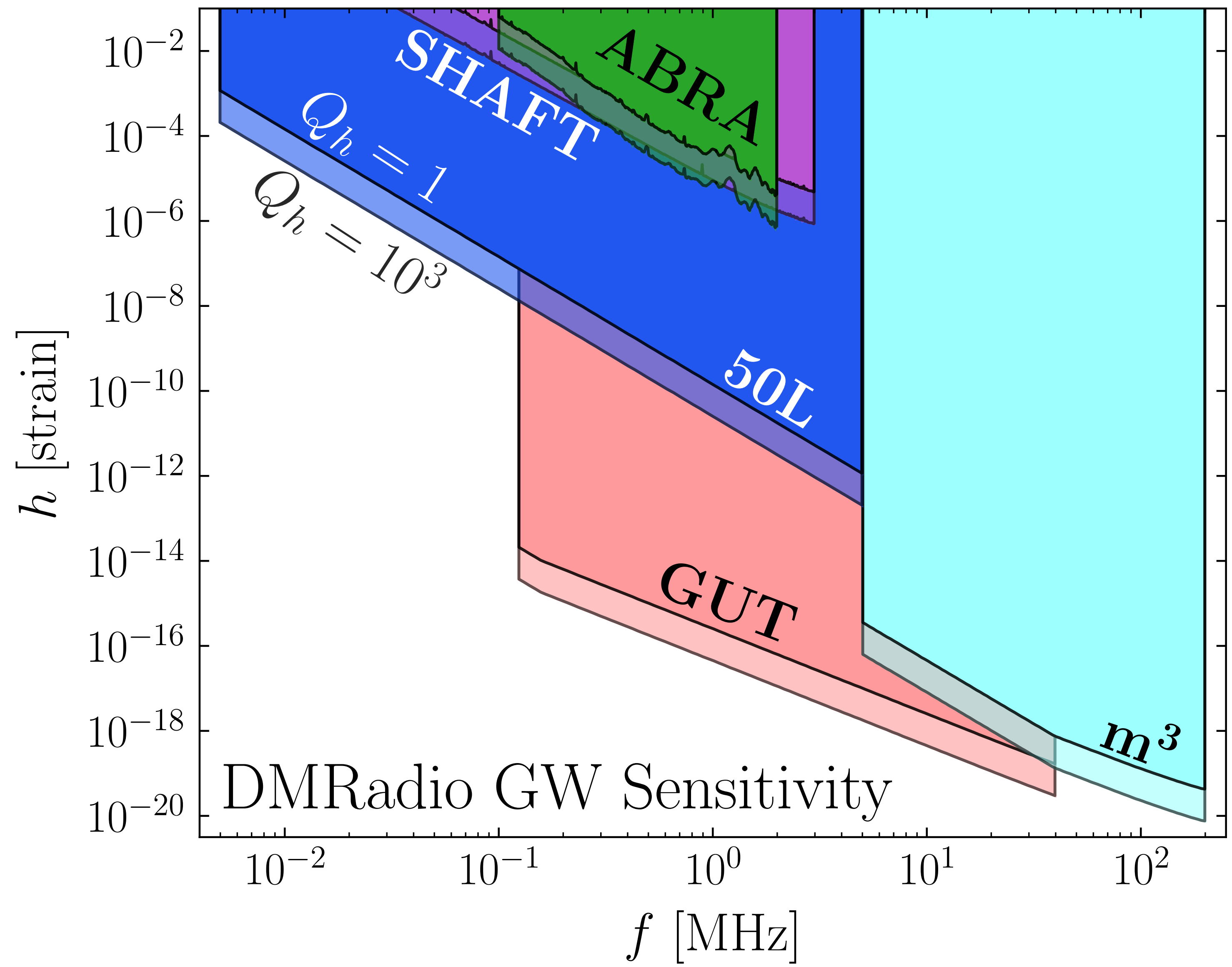
Gravitational waves in low mass axion haloscopes

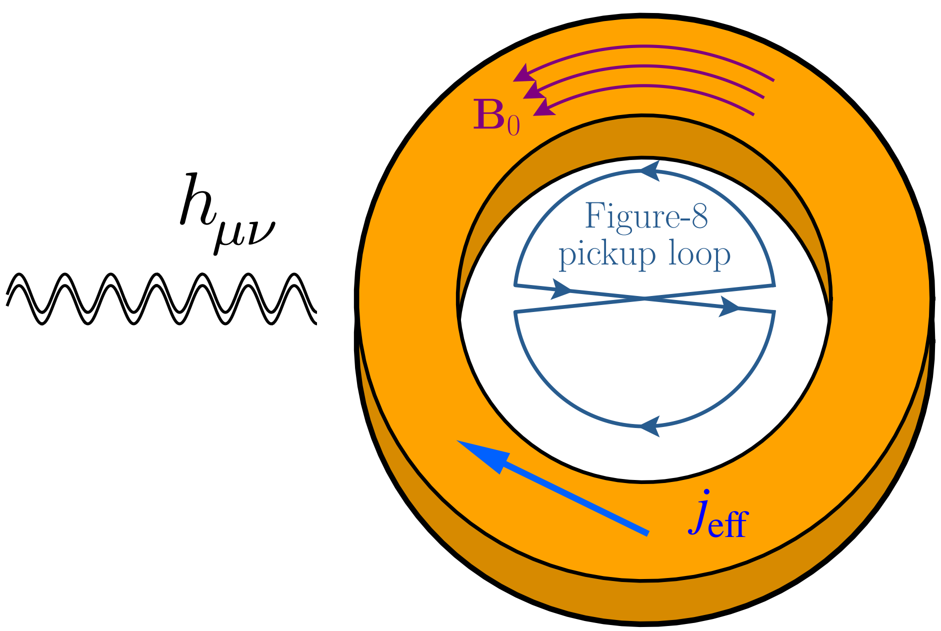


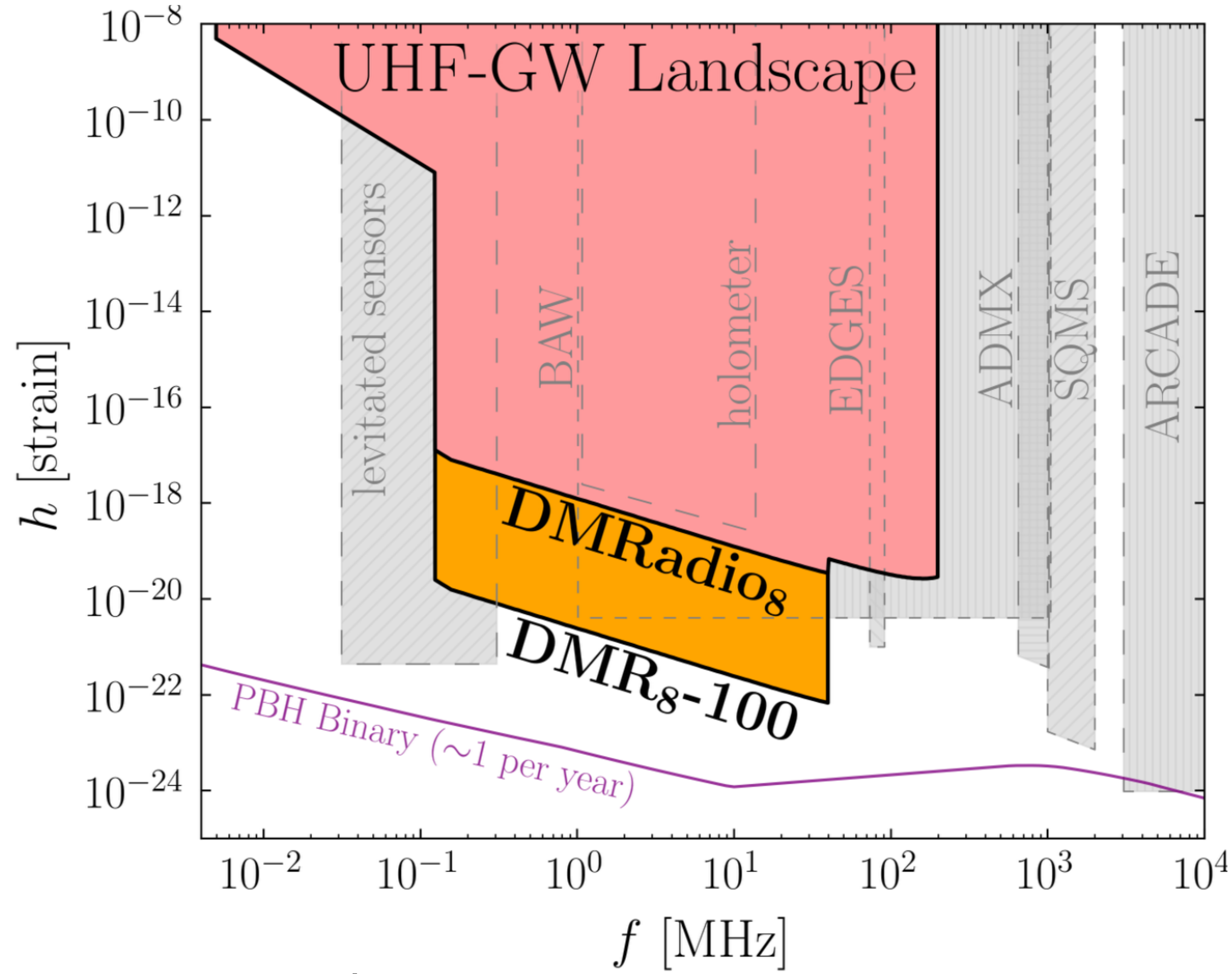
Domcke, CGC, Rodd, 2202.00695



Gravitational waves in low mass axion haloscopes

Domcke, CGC, Rodd, 2202.00695



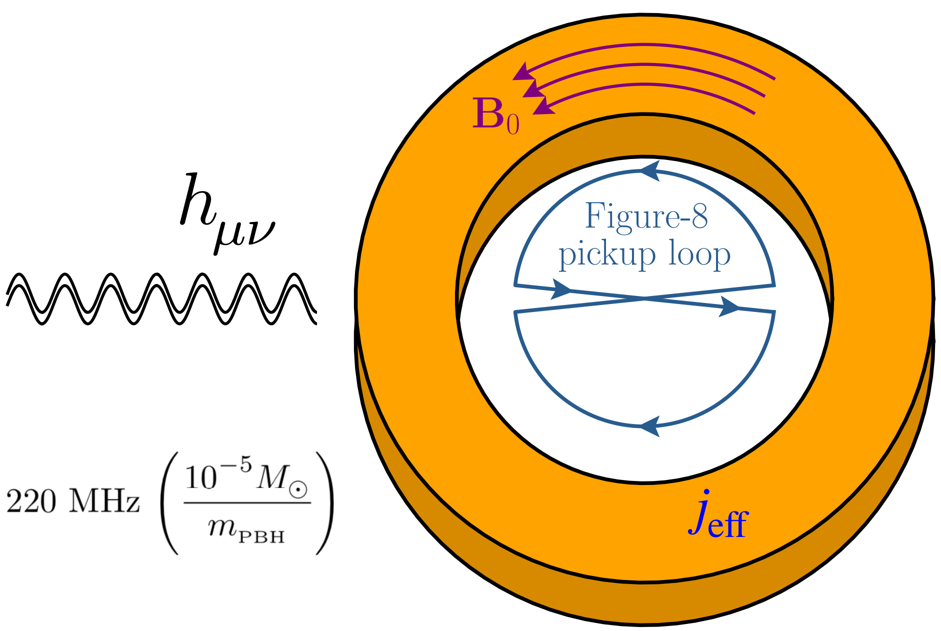


$$\Phi_8 \approx \frac{e^{-i\omega t}}{3\sqrt{2}}\,\omega^2 B_{\max} r^3 R s_{\theta_h}\left(h^{\times} s_{\phi_h} - h^{+} c_{\theta_h} c_{\phi_h}\right)$$

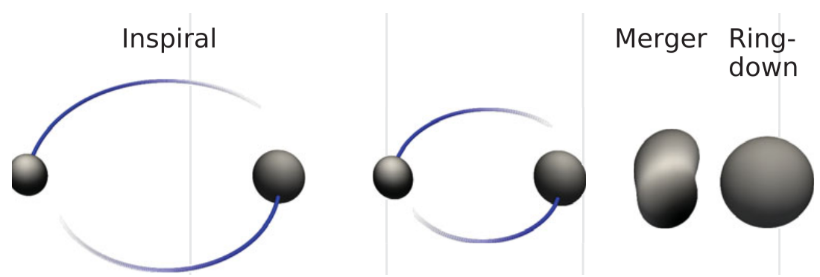
Small modification allows to measure both polarizations

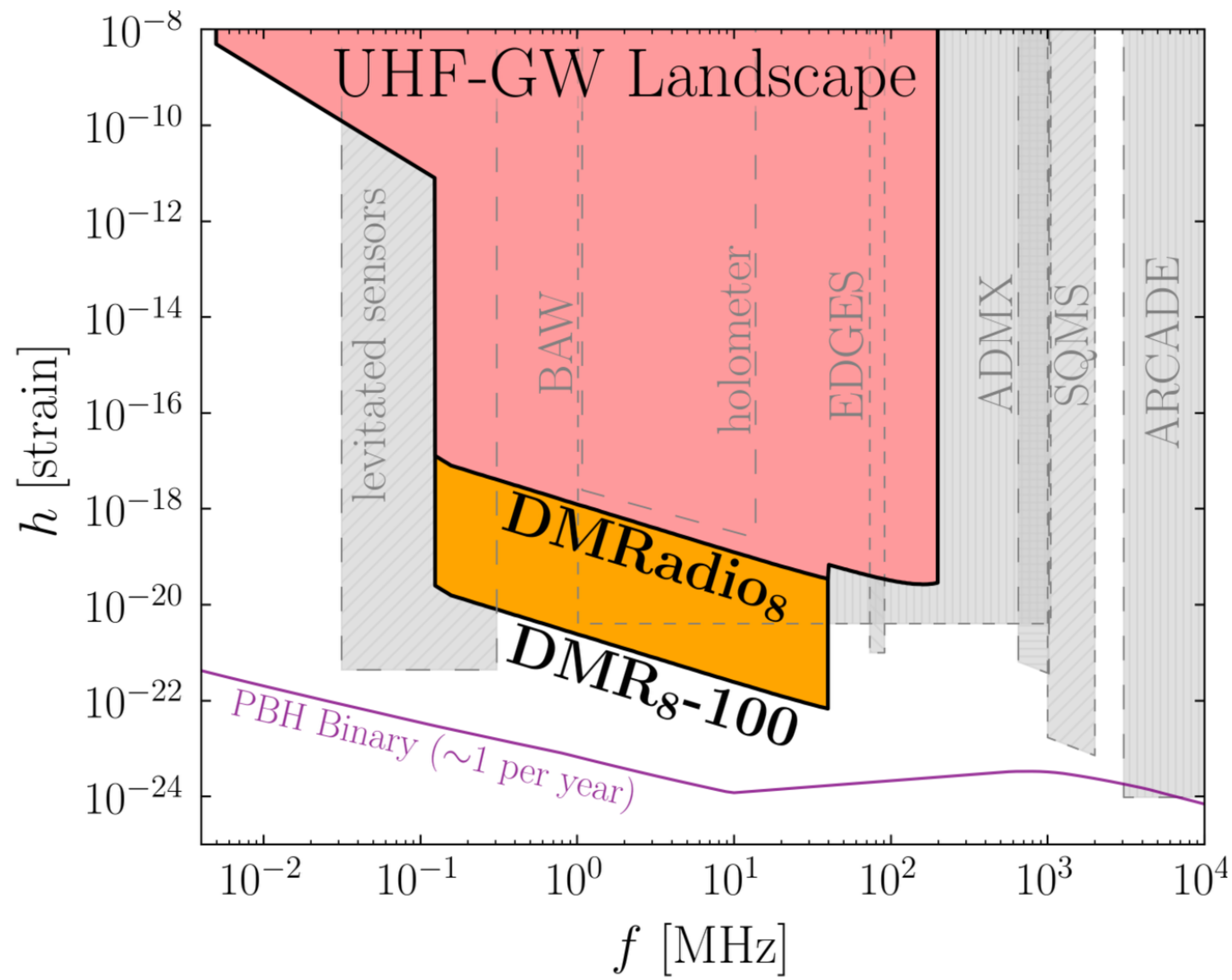
Gravitational waves in low mass axion haloscopes

Domcke, CGC, Rodd, 2202.00695



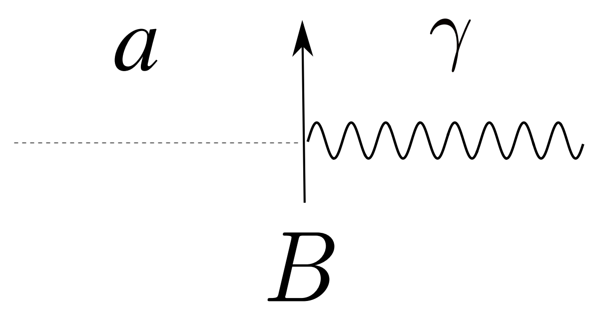
$f \simeq 220\ \text{MHz} \left(\frac{10^{-5} M_\odot}{m_{\rm PBH}}\right)$



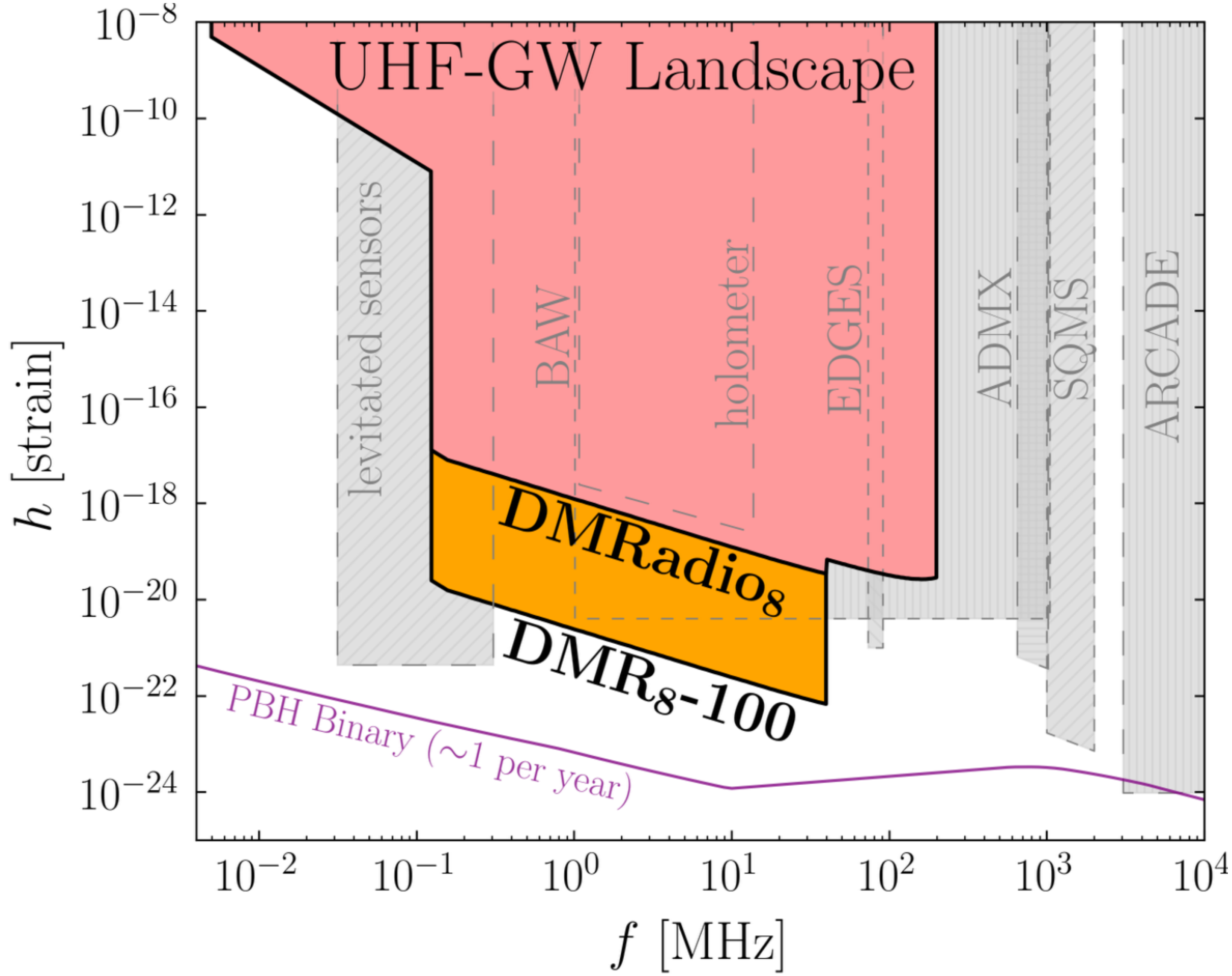


Up-to-date estimate of PBH in binaries and their expected merger rate accounting for the local overdensity in the Milky Way

See also 2205.02153 by Franciolini, A. Maharana, and F. Muia,

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

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.

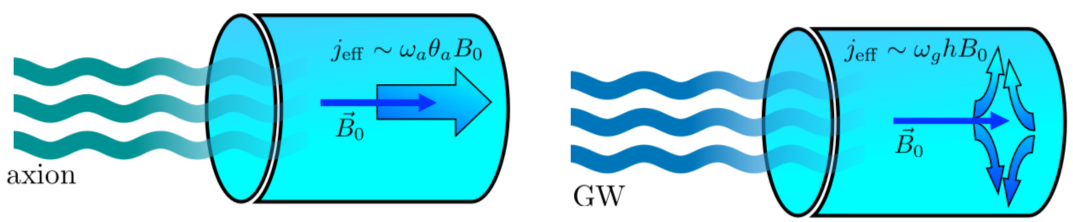
Camilo García Cely, University of Valencia

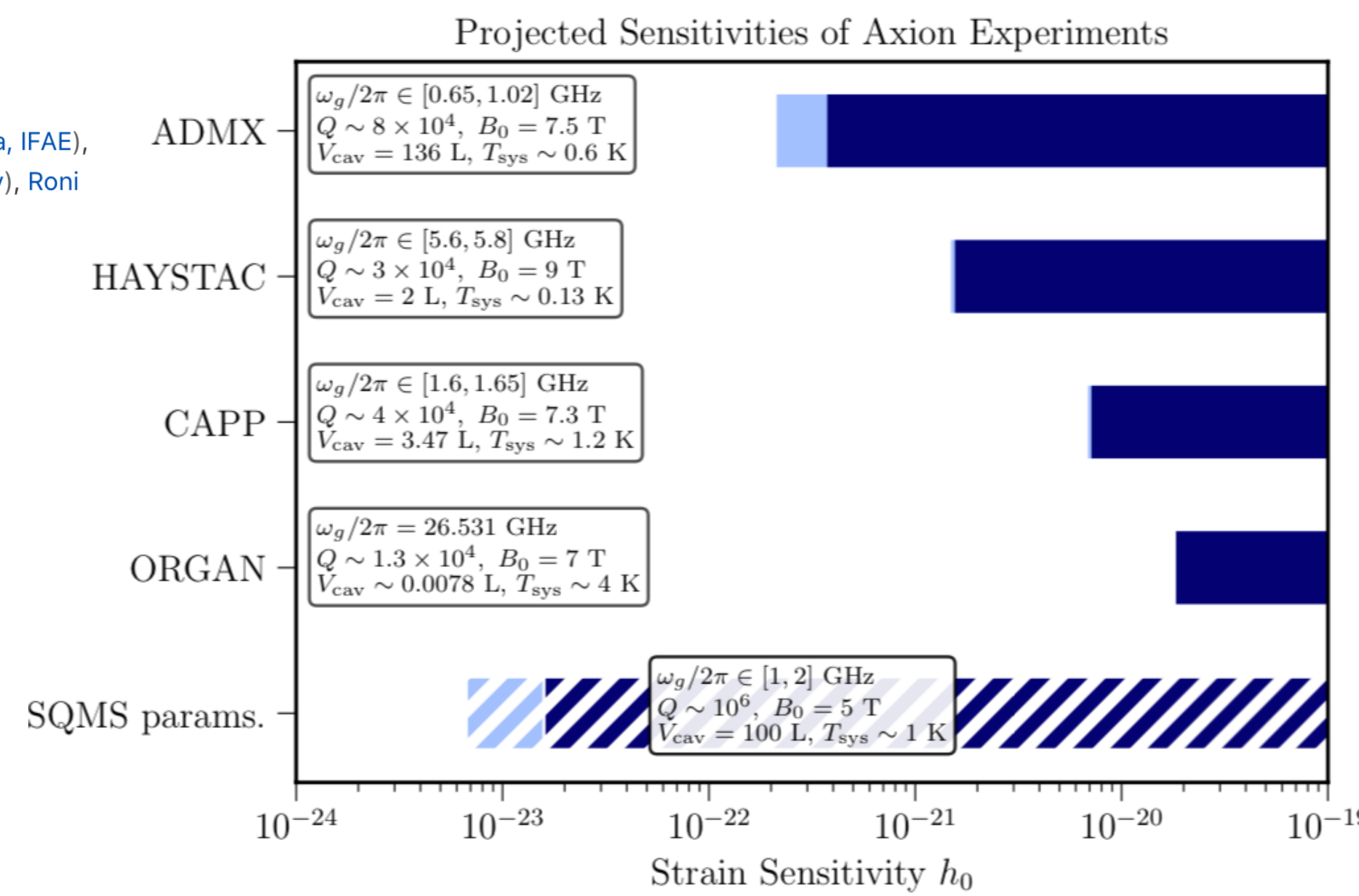
Other possibilities

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

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

Detecting High-Frequency Gravitational Waves with Microwave Cavities

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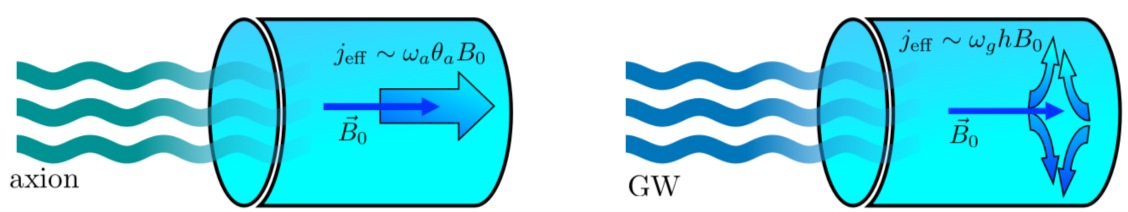
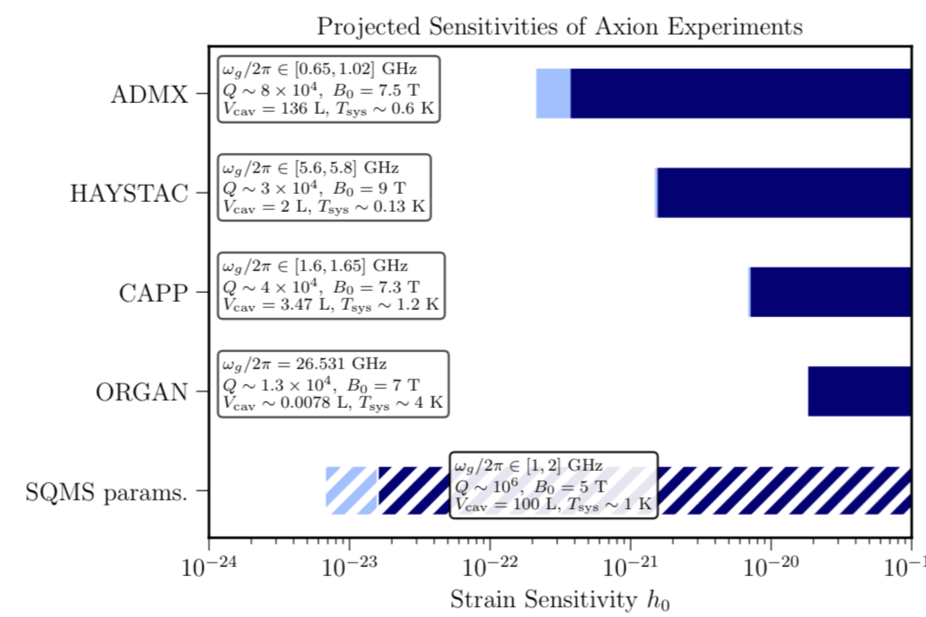




$$\left(\partial_t^2 + \frac{\omega_n}{Q_n}\partial_t + \omega_n^2\right) e_n(t) = -\frac{\int_{V_{\rm cav}} d^3\mathbf{x}\,\mathbf{E}_n^* \cdot \partial_t \boldsymbol{j}_{\rm eff}}{\int_{V_{\rm cav}} d^3\mathbf{x}\,\left|\mathbf{E}_n\right|^2}$$

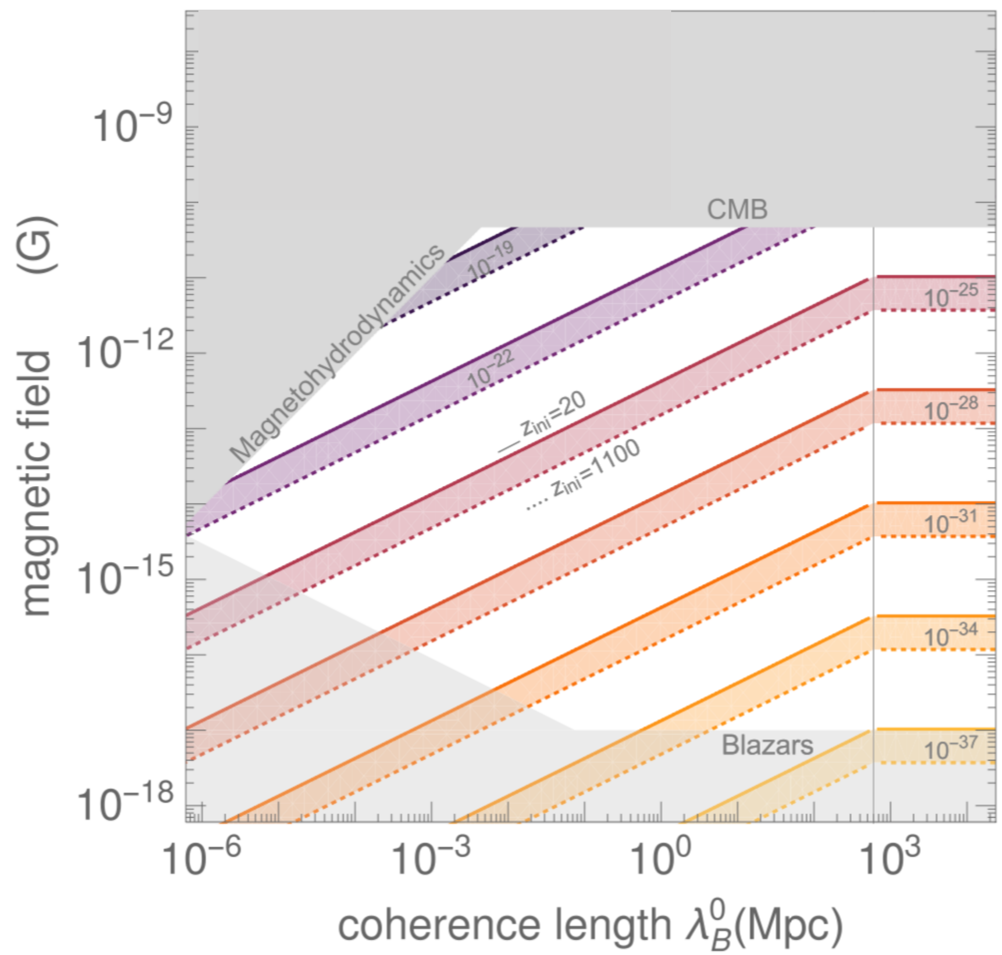
Eigenmodes

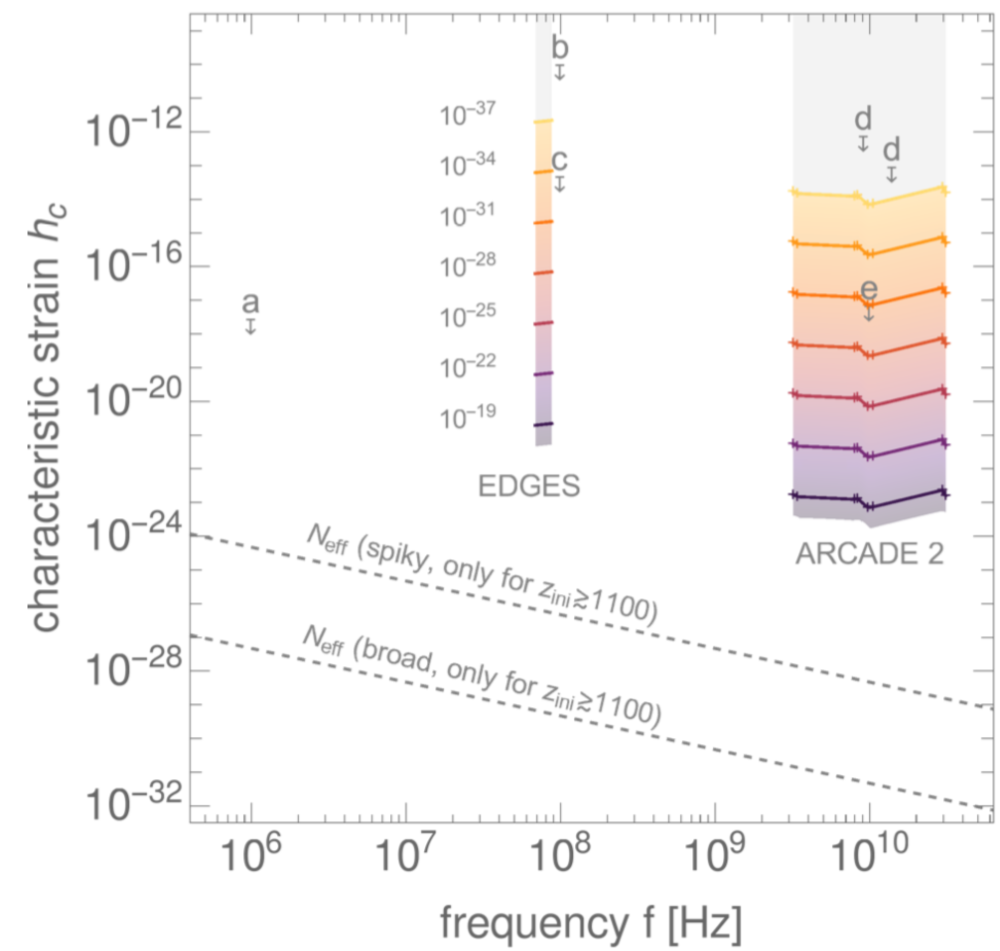
$$\mathbf{E}(\mathbf{x}, t) = \sum_n e_n(t)\mathbf{E}_n(\mathbf{x})$$

- 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)

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

Oscillations after the formation of the CMB

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

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

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

The plasma frequency acts as an effective mass term

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

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

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

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

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

Domcke, CGC 2021