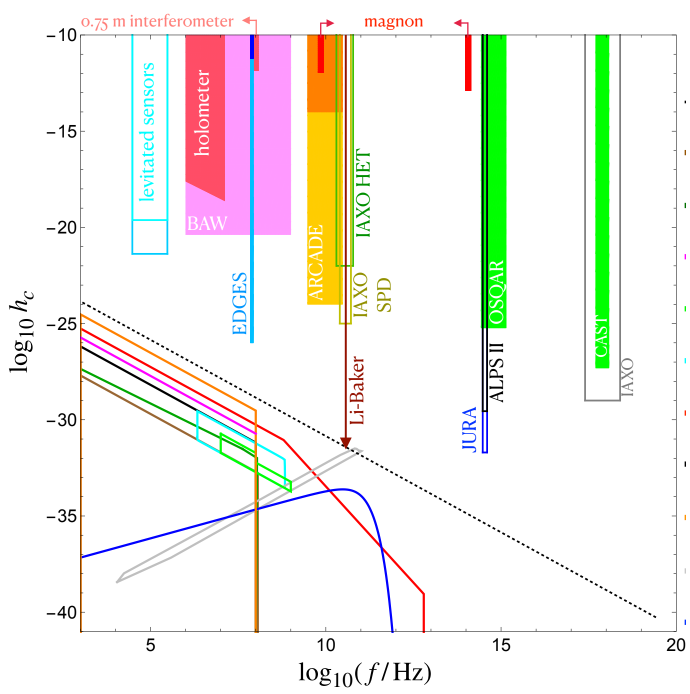
Searching for high-frequency gravitational waves with axion experiments

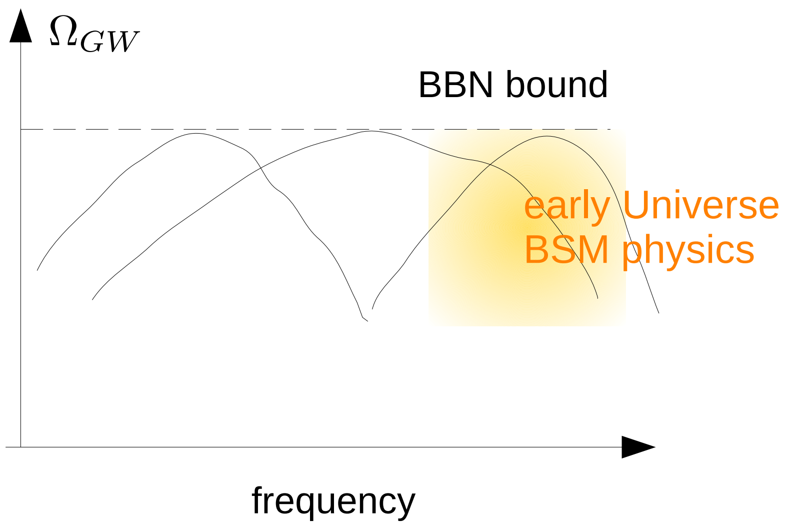


Valerie Domcke
CERN

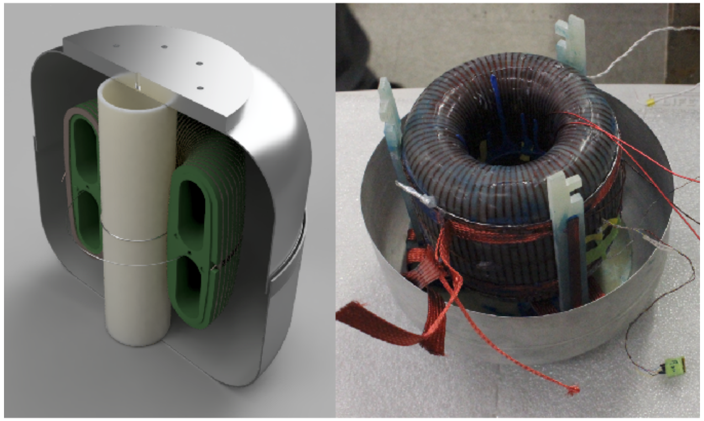
Bethe workshop ‘axions’
Oct 10 2022

Outline

- GW sources in the MHz to THz range



- Searching for HFGWs with axion experiments
    - LSW experiments (ALPs,CAST,..)
    - astrophysical probes
    - low-mass haloscopes
      (ABRA, ADMX-SLIC, DM Radio,...)
    - microwave cavities (ADMX,..)



ABRACADABRA

high frequency (> kHz) GW sources

Cosmological

- sourced by violent cosmological event in the early Universe
- stochastic GW background (SGWB): stationary, isotropic, broad spectrum
- GW frequency determined by Hubbe horizon at sourcing time
  → high frequency = early Universe
- observationally bounded by BBN and CMB (extra radiation)
- vanilla cosmology: SGWB from cosmic inflation & CGWB very small. But in many BSM models, saturating BBN bound is easy

Astrophysical

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Astrophysical

- localized GW sources, both coherent and incoherent signals possible
- no known astrophysical objects emit (significantly) in UHF band
- eg mergers of light primordial black holes or exotic compact objects, superradiance
- large signals require near-by events
  → rare events with GW strain far above BBN bound are possible
- SGWB from unresolved sources, typically harder to detect

UHF GW searches are always a search for New Physics

cosmological sources

Amplitude: BBN / CMB bound

$$\frac{\rho_{GW}^0}{\rho_c^0} = \Omega_\gamma^0 \left(\frac{g_s^0}{g_s(T)}\right)^{4/3} \underbrace{\frac{\rho_{GW}(T)}{\rho_\gamma(T)}}_{\lesssim 10\%}\Bigg|_{T_{\text{CMB, BBN}}} \leq 10^{-5}\,\Delta N_{eff} \;\simeq\; 10^{-6}$$

for a broadband SGWB: $\rightarrow \quad h_{c,\text{sto}} \lesssim 10^{-29}\,(100\ \text{MHz}/f)\,\Delta N_{\text{eff}}^{1/2}$

cosmological sources

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Frequency: tied to energy scale of cosmic event

during radiation era: $f \sim 100\ \text{MHz}/\epsilon_*\,(T_*/10^{10}\ \text{GeV})\,, \quad \epsilon_* \lesssim 1$

during inflation: $f \sim 10^{-18}\ \text{Hz}\ e^{N_{\rm CMB}-N} \lesssim 10^8\ \text{Hz}\ e^{-N}\,, \quad N_{\rm CMB} \lesssim 60$

cosmological sources

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Examples: (Axion) inflation, (p)reheating, relic cosmic GW background, phase transitions (first order PT and/or topological defects from PTs) ,...

see Living Review: https://arxiv.org/abs/2011.12414

astrophysical sources

Example:
mergers of light primordial black holes

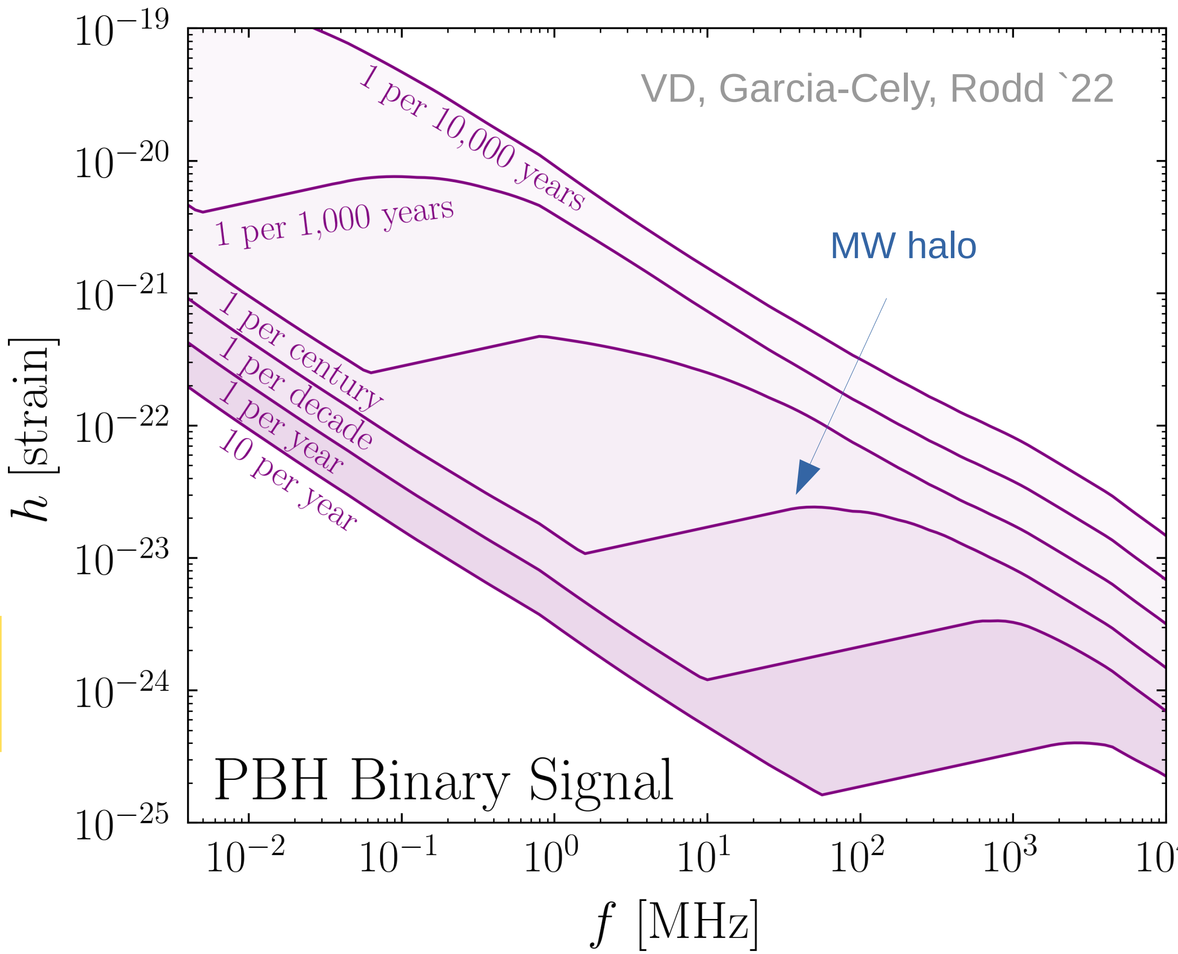
$$h_{+,\times}^{\rm PBH} \simeq 10^{-23} \left(\frac{10\ {\rm kpc}}{D}\right) \left(\frac{m_{\rm PBH}}{10^{-5} M_\odot}\right)^{5/3} \left(\frac{f}{100\ {\rm MHz}}\right)^{2/3} .$$

event rate:

$$\langle \Gamma \rangle = \int_0^\infty dr\, 4\pi r^2\, \delta(r)\, R_0(m_{\rm PBH}, f_{\rm PBH})$$

MW halo merger rate

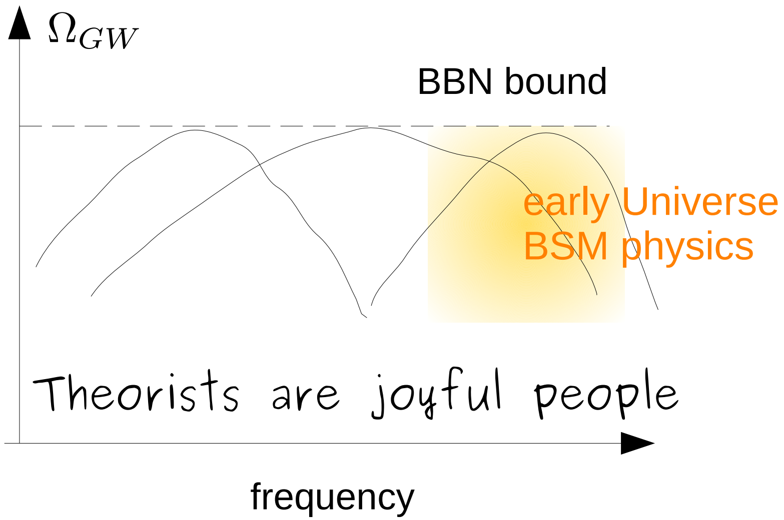
$$\times \Theta\left[Q^{1/4}\, h_{+,\times}^{\rm PBH}(f, m_{\rm PBH}, r) - h_{\rm th}\right]$$



large GW amplitudes possible for rare events

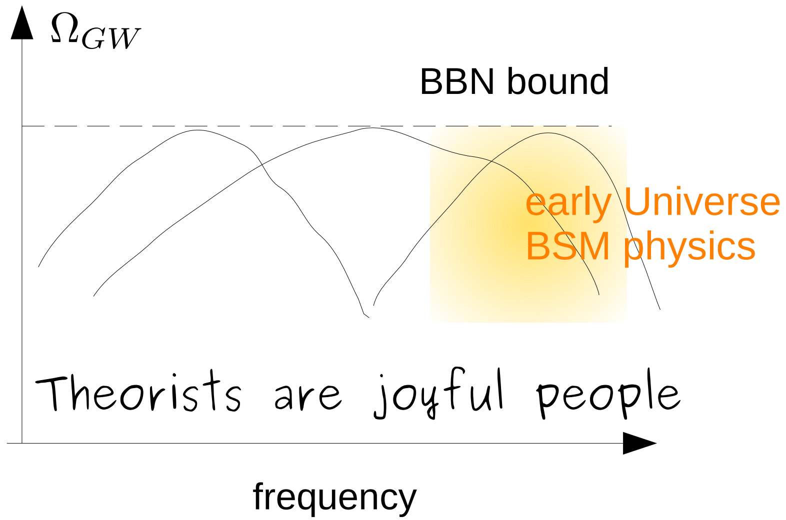
see also Franciolini, Maharana, Muia `22

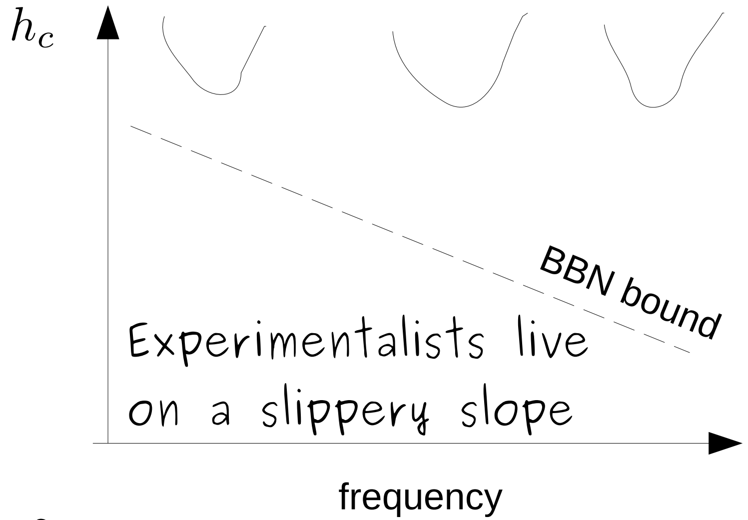
challenges in UHF GW detection



CMB/BBN bound constrains energy

challenges in UHF GW detection



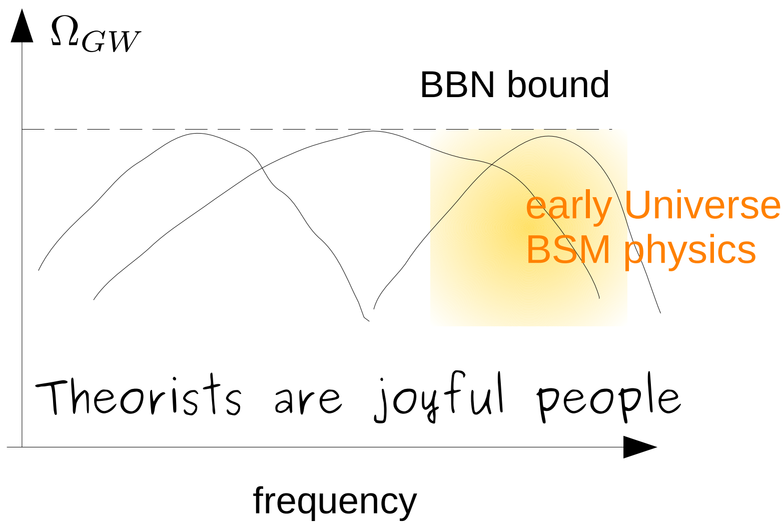


$$\Omega_{GW} \propto f^2 h_c^2$$

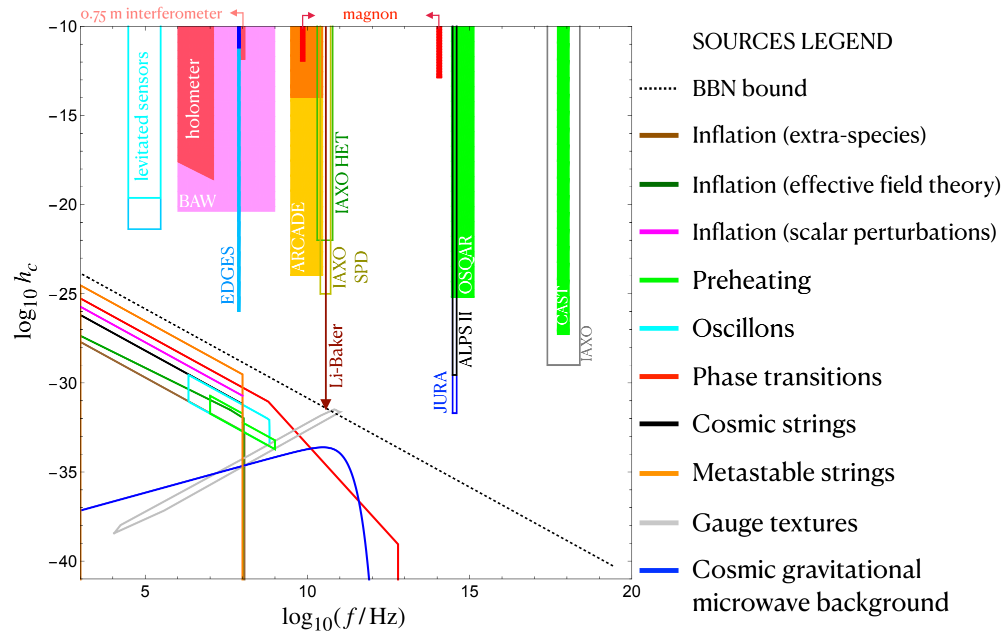
CMB/BBN bound constrains energy

experiments measure displacement

challenges in UHF GW detection



$\Omega_{GW} \propto$



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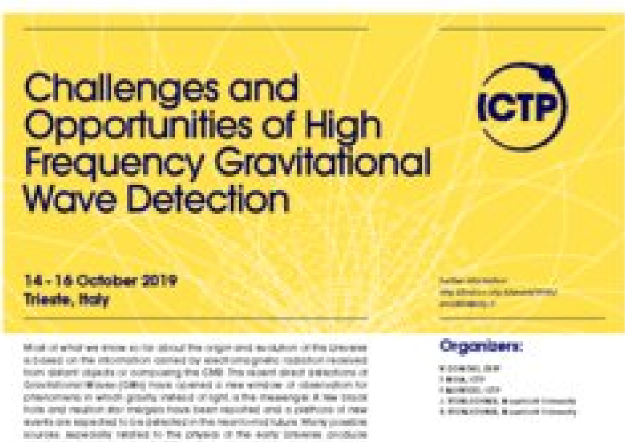
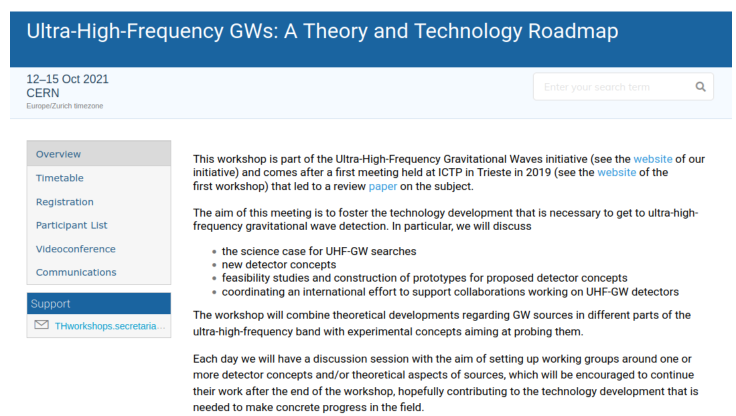


Challenges and Opportunities of High Frequency Gravitational Wave Detection

ICTP

14 - 18 October 2019
Trieste, Italy

Organizers:



Ultra-High-Frequency GWs: A Theory and Technology Roadmap

12–15 Oct 2021
CERN
Europe/Zurich timezone

Enter your search term

- Overview
- Timetable
- Registration
- Participant List
- Videoconference
- Communications

Support

THworkshops.secretaria...

This workshop is part of the Ultra-High-Frequency Gravitational Waves initiative (see the website of our initiative) and comes after a first meeting held at ICTP in Trieste in 2019 (see the website of the first workshop) that led to a review paper on the subject.

The aim of this meeting is to foster the technology development that is necessary to get to ultra-high-frequency gravitational wave detection. In particular, we will discuss

- the science case for UHF-GW searches
- new detector concepts
- feasibility studies and construction of prototypes for proposed detector concepts
- coordinating an international effort to support collaborations working on UHF-GW detectors

The workshop will combine theoretical developments regarding GW sources in different parts of the ultra-high-frequency band with experimental concepts aiming at probing them.

Each day we will have a discussion session with the aim of setting up working groups around one or more detector concepts and/or theoretical aspects of sources, which will be encouraged to continue their work after the end of the workshop, hopefully contributing to the technology development that is needed to make concrete progress in the field.

all talks available online:

1st workshop
http://indico.ictp.it/event/9006/

2nd workshop:
https://indico.cern.ch/event/1074510/

Living Review:
https://arxiv.org/abs/2011.12414

join UHF GW initiative

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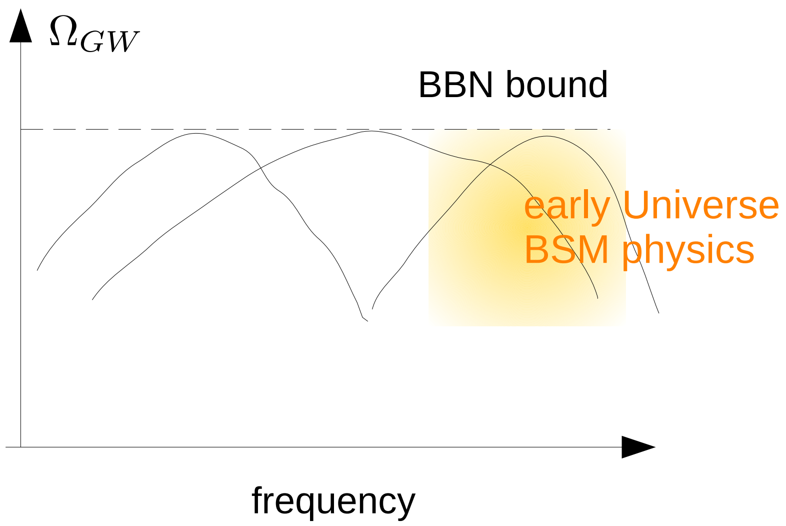

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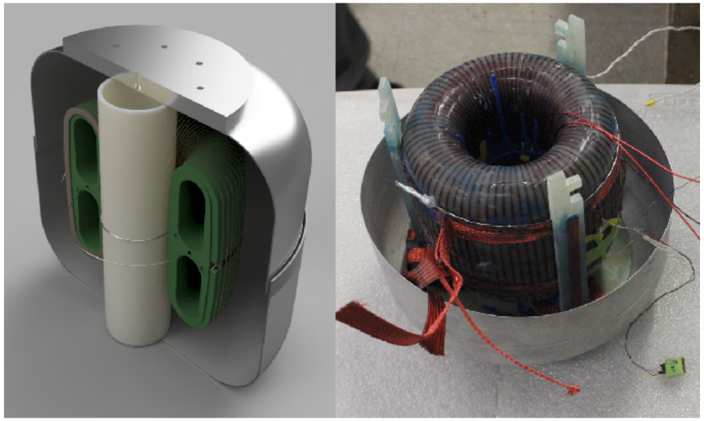


ABRACADABRA

GW to photon conversion

(inverse) Gertsenshtein effect:

[Gertsenshtein `62, Boccaletti et al `70, Raffelt, Stodolsky `88]

$$\left(\Box + \omega_{\rm pl}^2/c^2\right) A_\lambda = -B\partial_z h_\lambda \,, \quad \Box h_\lambda = \kappa^2 B \partial_z A_\lambda$$

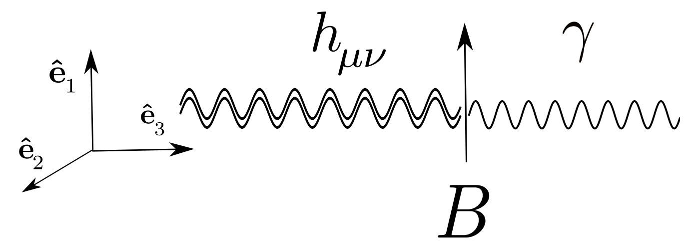
$$\begin{aligned} A_\lambda &= \text{photon} \\ h_\lambda &= \text{GW} \\ B &= \text{ext. transv. B - field} \\ \omega_{\rm pl} &= \text{ plasma frequency} \\ \mu^2 &= 1 - \omega_{\rm pl}^2/\omega^2 \end{aligned}$$

plane waves:

$$\to \quad \psi(t,z) \equiv \begin{pmatrix} \sqrt{\mu}\, A_\lambda \\ \frac{1}{\kappa}\, h_\lambda \end{pmatrix} = e^{-i\omega t} e^{iKz} \psi(0,0)\,,$$

$$K = \begin{pmatrix} \frac{\mu}{c}\sqrt{\omega^2 + \left(\frac{\kappa B}{1+\mu}\right)^2} & -i\frac{\sqrt{\mu}\,\kappa B}{1+\mu} \\ i\frac{\sqrt{\mu}\,\kappa B}{1+\mu} & \frac{1}{c}\sqrt{\omega^2 + \left(\frac{\kappa B}{1+\mu}\right)^2} \end{pmatrix}$$

EM wave in curved space time (i.e. classical linearized general relativity) → purely SM process

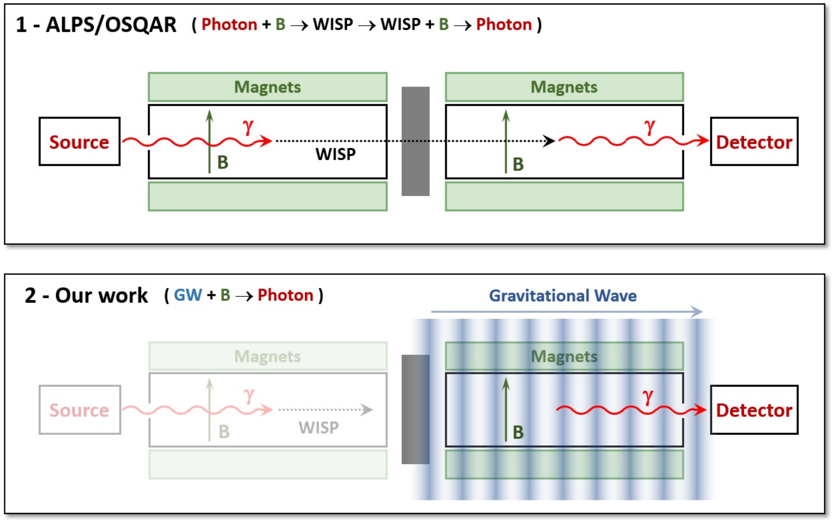


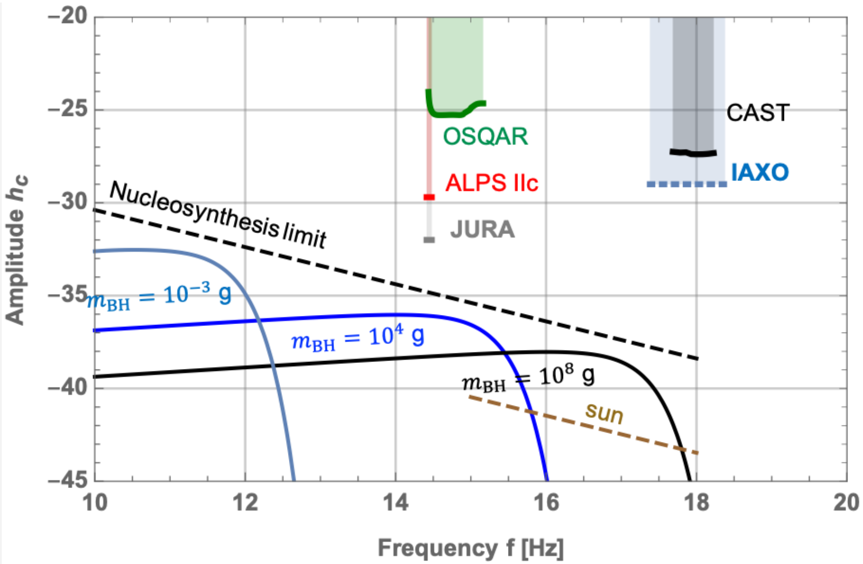
analogous to axion to photon conversion

LSW experiments

Light-shining-through-the-wall (LSW) experiments:

[Ejilli et al `19]



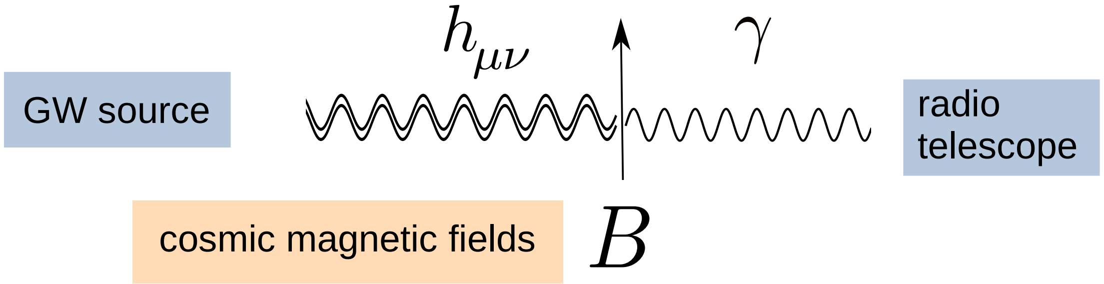


axion bounds recast as HFGW bounds

a cosmic GW detector

idea: compensate small GW to EM coupling with cosmologically big detector:

VD, Garcia-Cely
PRL 126 (2021) 2, 021104



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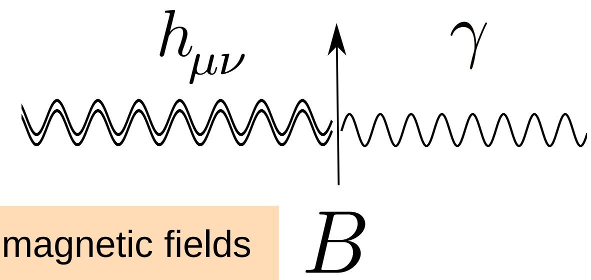
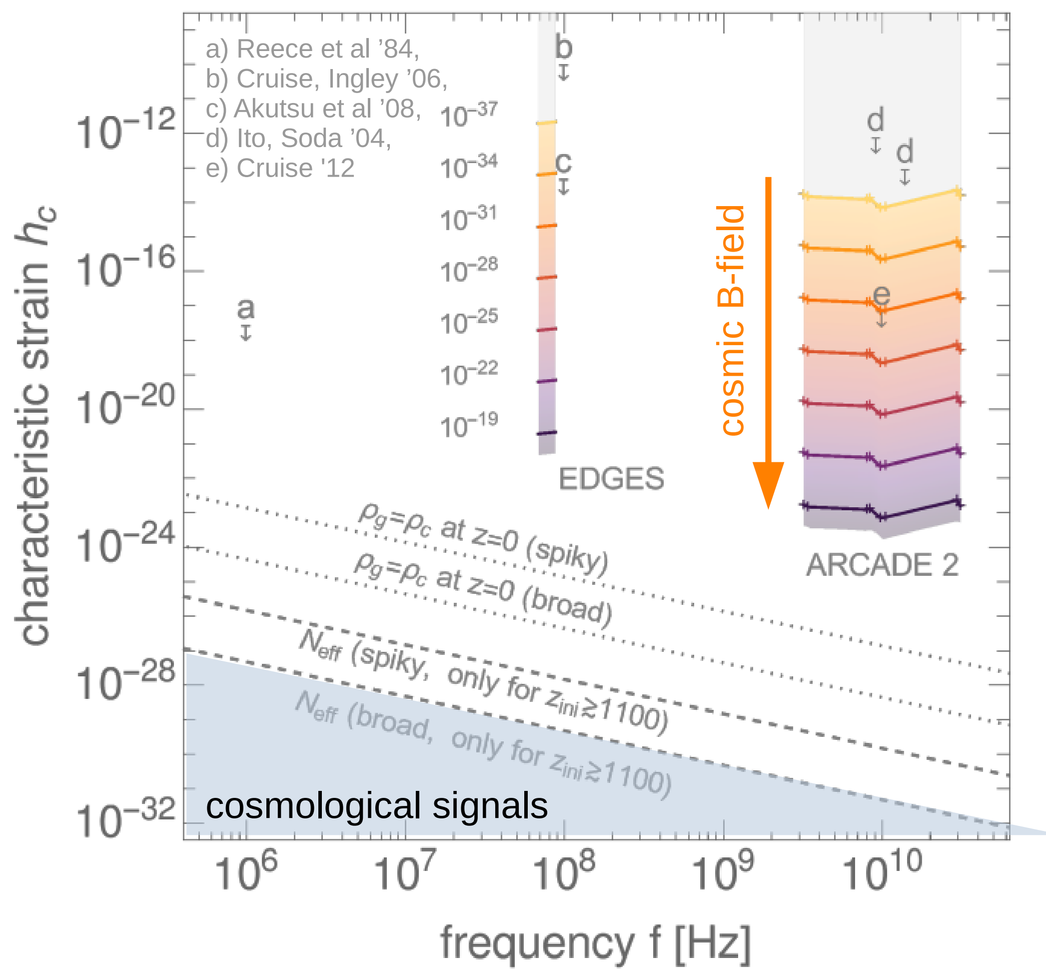
GW source

cosmic magnetic fields





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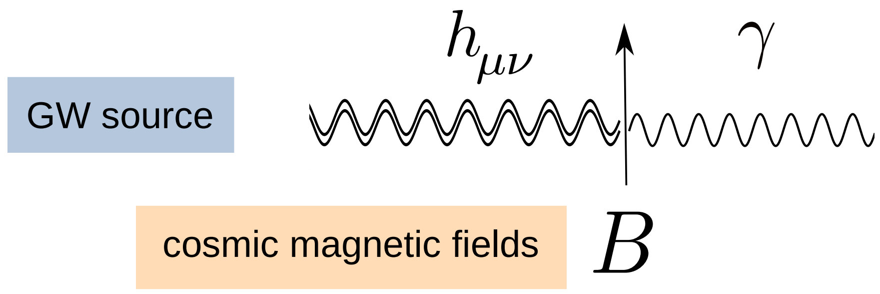
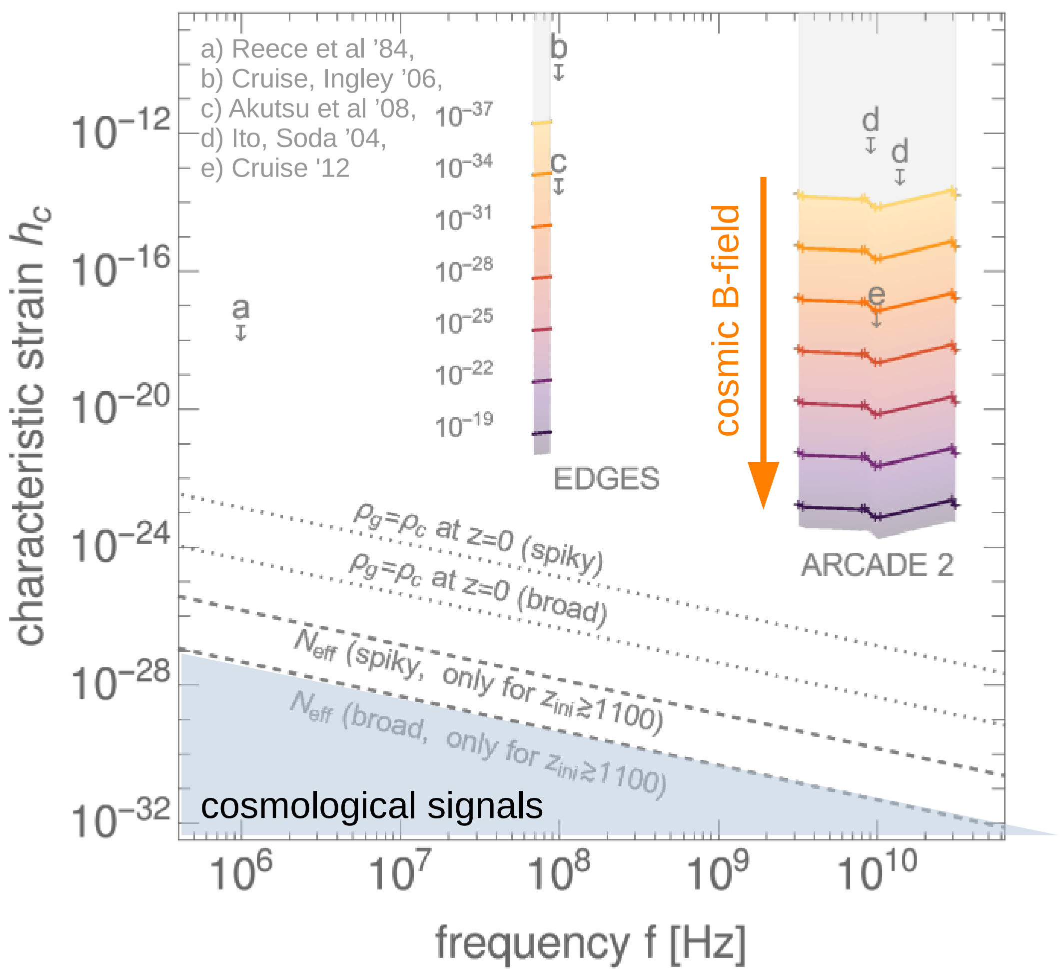




- promising, but significant improvements needed
- a lot of room for new ideas (laboratory & cosmo)
- other astro environments: [Raffelt, Stodolsky `88; Chen `95, Dolgov, Ejlli `12, Fujita et al `20, Pshirkov, Baskaran `09,..]

GW electrodynamics

Classical electrodynamics + linearized GR, $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$:

$$\partial_\nu F^{\mu\nu} = j^\mu_{\text{eff}} = (-\nabla \cdot \mathbf{P},\, \nabla \times \mathbf{M} + \partial_t \mathbf{P})$$
$$\partial_\nu \tilde{F}^{\mu\nu} = 0$$

effective current
effective polarization vector
effective magnetization vector

with

$$P_i = -h_{ij} E_j + \tfrac{1}{2} h E_i + h_{00} E_i - \epsilon_{ijk} h_{0j} B_k ,$$
$$M_i = -h_{ij} B_j - \tfrac{1}{2} h B_i + h_{jj} B_i + \epsilon_{ijk} h_{0j} E_k ,$$

induced at linear order in h
in presence of external E,B field

VD, Garcia-Cely, Rodd `22

Direct analogy with axion electrodynamics

$$\mathcal{L} \supset g_{a\gamma\gamma} a\, \mathbf{E} \cdot \mathbf{B} \quad \rightarrow \quad \mathbf{P} = g_{a\gamma\gamma} a\, \mathbf{B} \,, \quad \mathbf{M} = g_{a\gamma\gamma} a\, \mathbf{E}$$

McAllister et al `18
Tobar, McAllister, Goryachev `19
Ouellet, Bogorad `19

effective source terms in Maxwell‘s equation due to GW

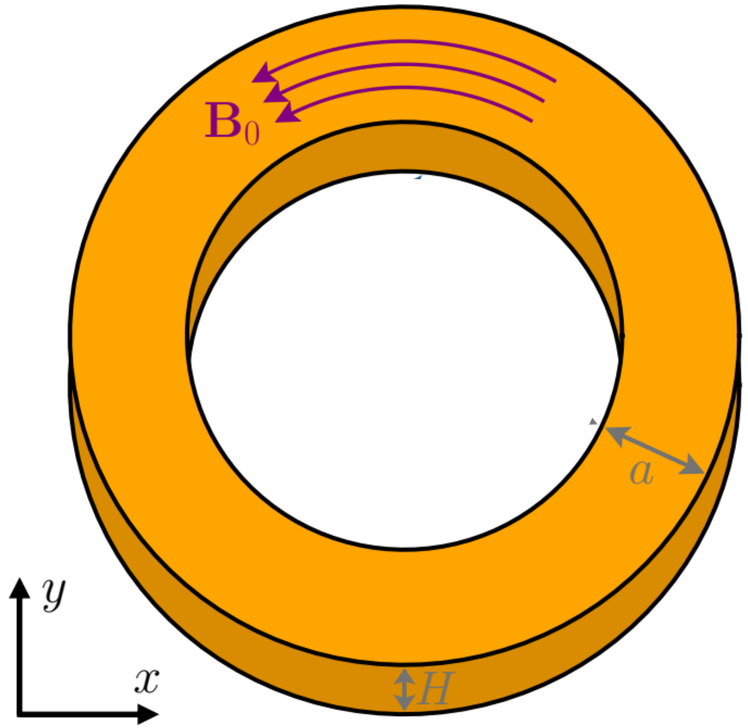
GW signal in axion haloscopes

eg ABRACADABRA, SHAFT, DM Radio:

VD, Garcia-Cely, Rodd `22

[other configurations in progress, w C. Garcia-Cely, S. M. Lee, N. Rodd]

static magnetic field



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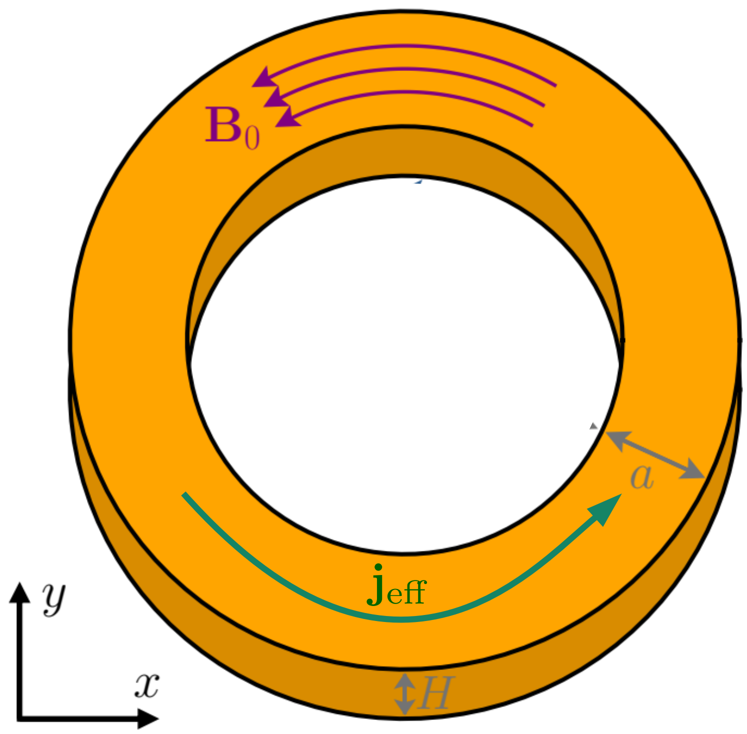

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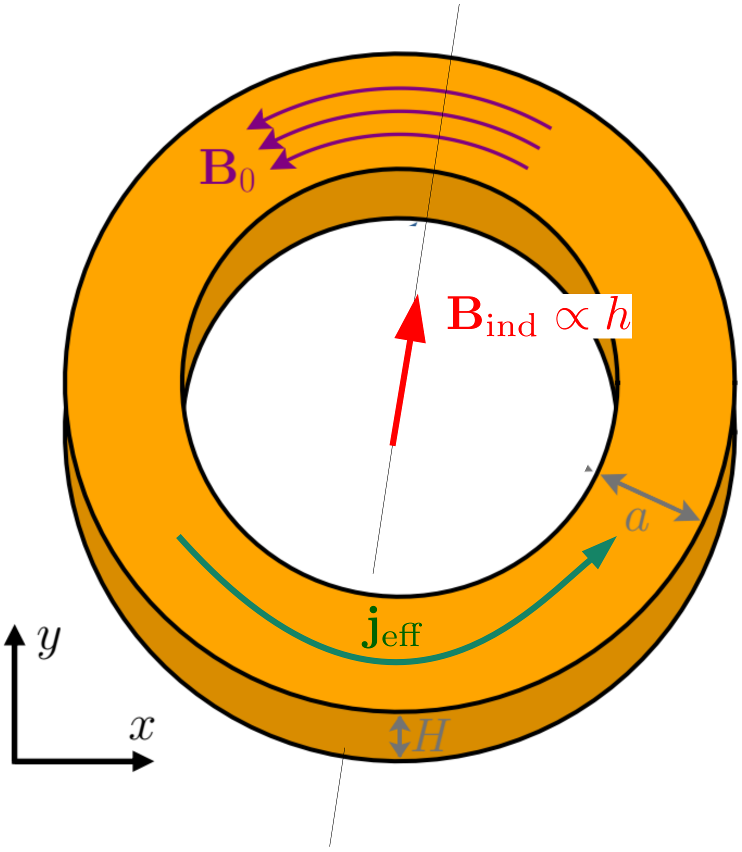

static magnetic field

effective current

induced oscillating magnetic field

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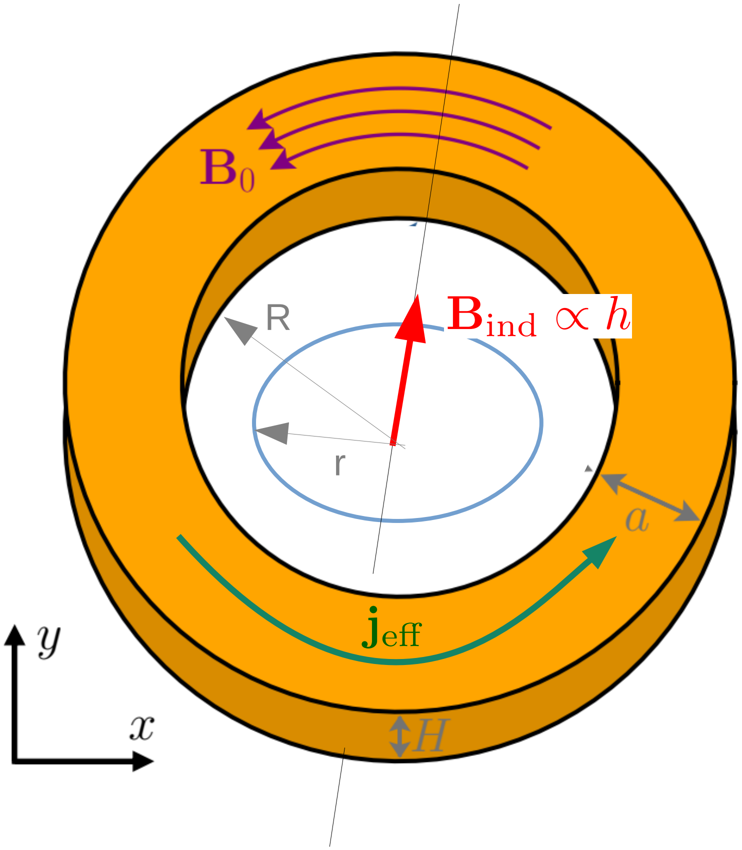

static magnetic field

effective current

induced oscillating magnetic field

measure magnetic flux (~ h) through pickup loop

at leading order in (ωR) :

$$\Phi_{\rm gw} = \frac{i\, e^{-i\omega t}}{16\sqrt{2}}\, h^\times \omega^3 B_0 \pi r^2 R a (a + 2R) s^2_{\theta_h}$$

GW signal in axion haloscopes

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VD, Garcia-Cely, Rodd `22

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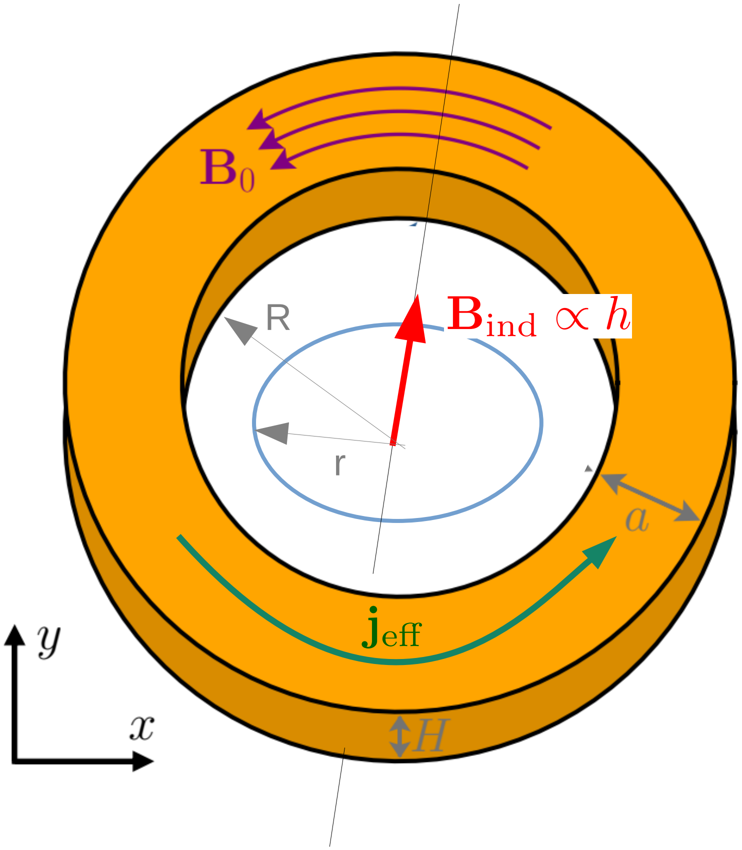

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match to axion induced flux to recast axion-photon coupling bounds as GW bounds

$$\Phi_a = e^{-i\omega t} g_{a\gamma\gamma} \sqrt{2\rho_{\rm DM}} B_0 \pi r^2 R \ln(1 + a/R)$$

suppression at low frequencies as $(\omega R)^3$

implies very good volume scaling

bounds and prospects

VD, Garcia-Cely, Rodd `22

circular pickup loop

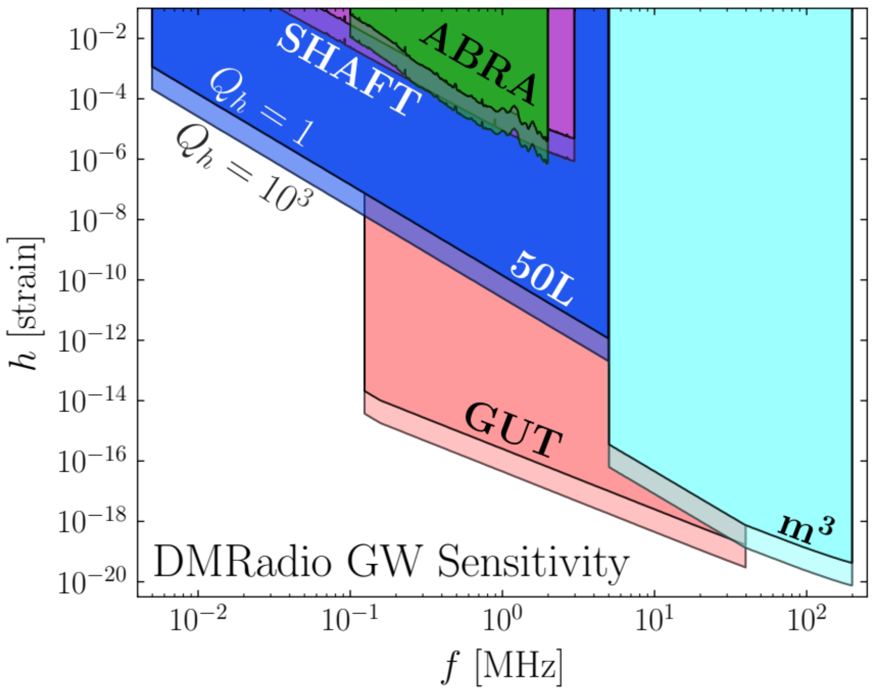
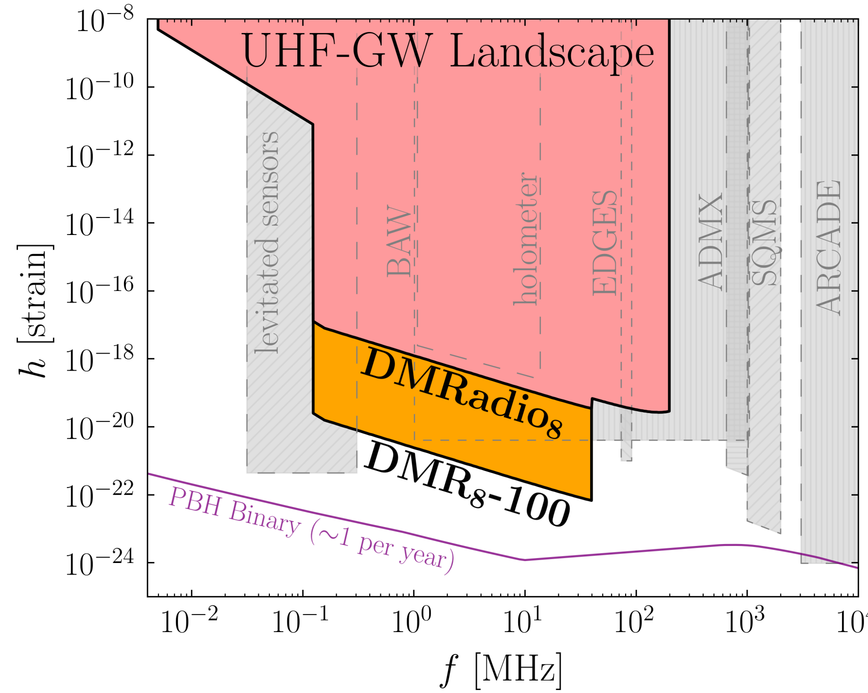


fig-8 pickup loop



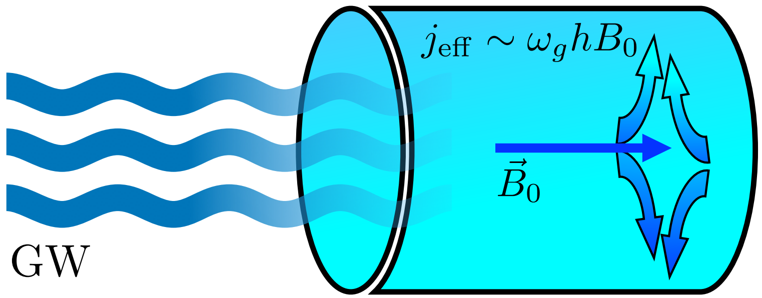
bounds from recasting ABRA [2102.06722] and SHAFT limits [2003.03348]

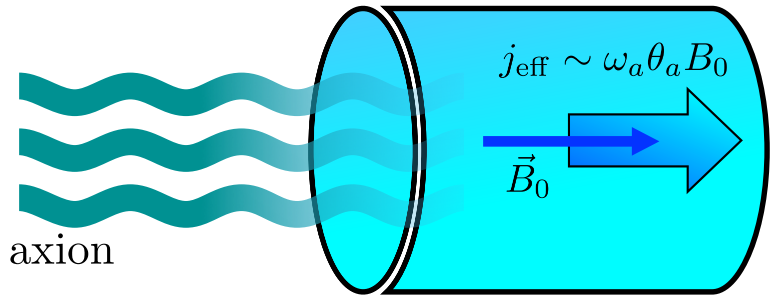
prospects for DM Radio proposals [Snowmass Letters of Interest CF2]

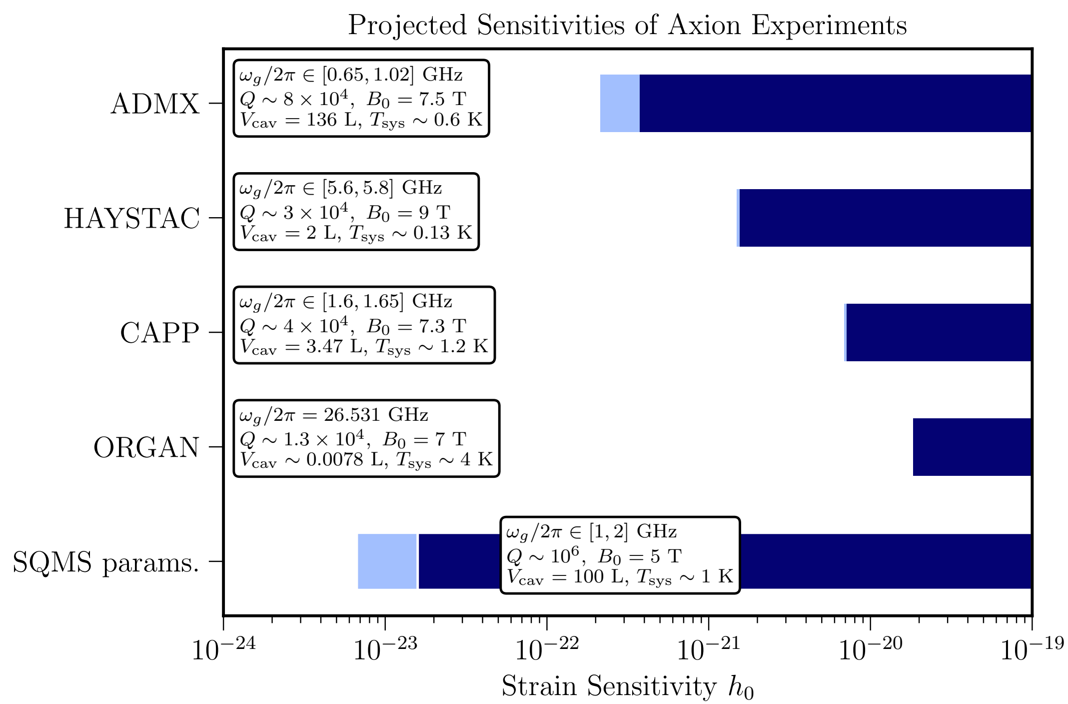
still far away from BBN bound, but clear synergies with axion searches

microwave cavities

[Berlin et al `21]







Questions and discussion ?

BBN bound

radiation energy after electron decoupling:

photons neutrinos BSM

$$\rho_{rad} = \frac{\pi^2}{30}\left(2 + \frac{7}{4}\left(\frac{4}{11}\right)^{4/3}(3.046 + \Delta N_{eff})\right)T^4$$

at BBN or CMB decoupling:

$$\rho_{GW}(T) < \Delta\rho_{rad}(T) \quad \Rightarrow \quad \left(\frac{\rho_{GW}}{\rho_\gamma}\right)_{T_{BBN,CMB}} \leq \frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\Delta N_{eff} \simeq 0.05$$

→ at BBN, CMB decoupling ~ 5 % GW energy density allowed

today:

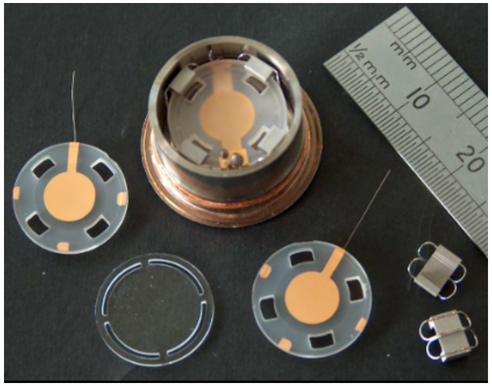
$$\frac{\rho^0_{GW}}{\rho^0_c} = \Omega^0_\gamma\left(\frac{g^0_s}{g_s(T)}\right)^{4/3}\frac{\rho_{GW}(T)}{\rho_\gamma(T)} \leq 10^{-5}\Delta N_{eff} \simeq 10^{-6}$$

note: constraint on *total* GW energy

→ today, energy fraction < 10^{-6} (for GWs present at BBN / CMB decoupling)

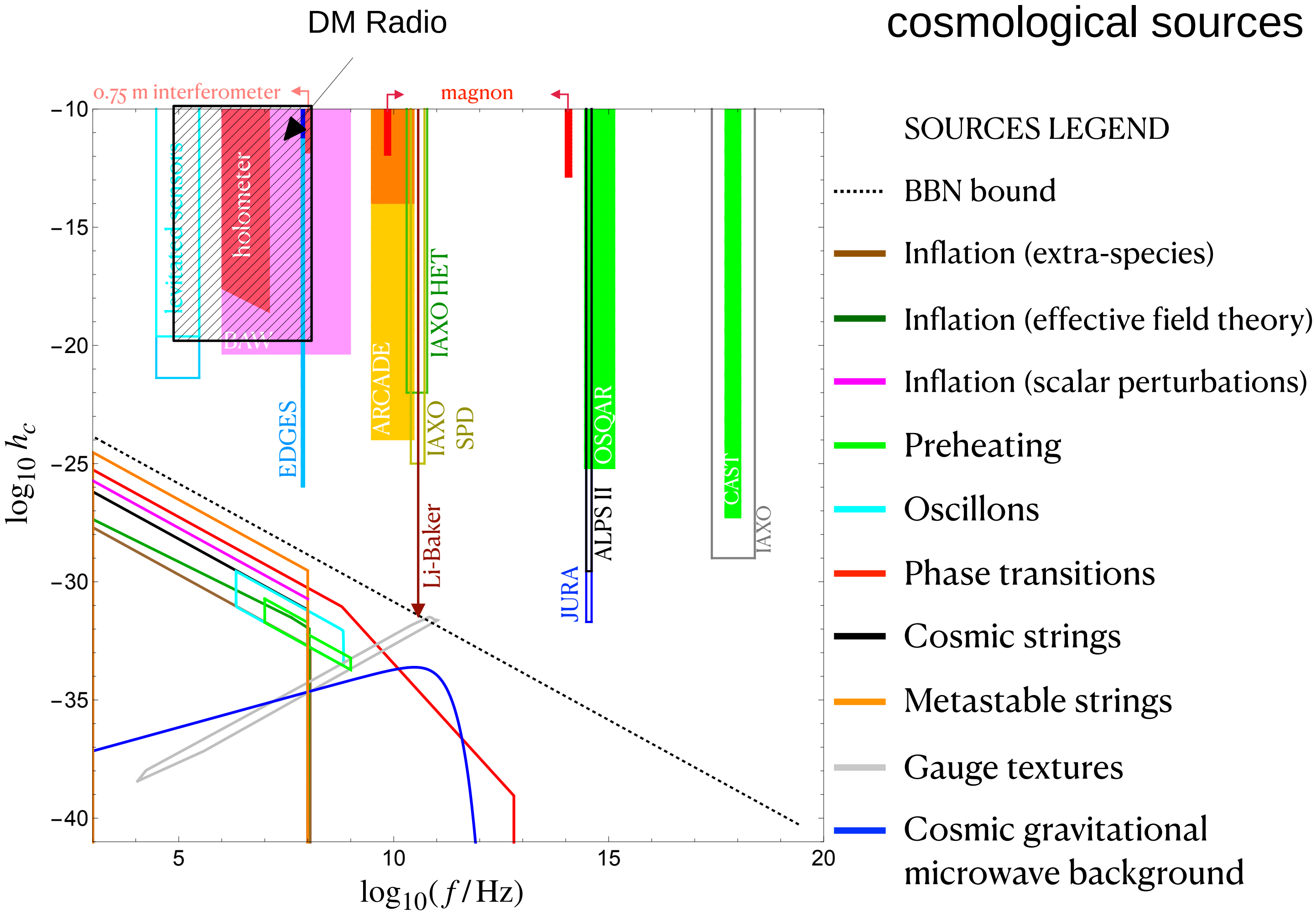
current TH and EP landscape

ALPS II at DESY



Bulk accoustic wave devices at U. of Western Australia

cosmological sources



Living Review on sources & detectors: https://arxiv.org/abs/2011.12414

[a note on frames]

GR is invariant under coordinate transformations, but linearized GR is not

Transverse traceless (TT) gauge

$$h_{ij}^{TT} = (h^+ e_{ij}^+(\phi_h, \theta_h) + h^\times e_{ij}^\times(\phi_h, \theta_h)) e^{i(\mathbf{k}\cdot\mathbf{r} - \omega \mathbf{t})}$$

- coordinates fixed by freely falling test masses
- GW takes very simple form $h_{0\mu} = 0, h_i^i = 0, \partial_j h^{ij} = 0$
- rigid body seems to 'oscillate' in presence of GW

Proper detector frame

- coordinates fixed by laboratory frame
- GW takes a more involved form
- description of experimental setup and observables is straightforward

$$h_{00} = \omega^2 F(\mathbf{k}\cdot\mathbf{r})\, \mathbf{b}\cdot\mathbf{r}, \qquad b_j \equiv r_i h_{ij}^{\mathrm{TT}}\big|_{\mathbf{r}=0},$$
$$h_{0i} = \frac{1}{2}\omega^2 \left[F(\mathbf{k}\cdot\mathbf{r}) - iF'(\mathbf{k}\cdot\mathbf{r})\right]\left(\hat{\mathbf{k}}\cdot\mathbf{r}\; b_i - \mathbf{b}\cdot\mathbf{r}\; \hat{k}_i\right),$$
$$h_{ij} = -i\omega^2 F'(\mathbf{k}\cdot\mathbf{r})\left(|\mathbf{r}|^2 h_{ij}^{\mathrm{TT}}\big|_{\mathbf{r}=0} + \mathbf{b}\cdot\mathbf{r}\,\delta_{ij} - b_i r_j - b_j r_i\right),$$

VD, Garcia-Cely, Rodd `22
s.a. Berlin et al `21

we will consider a plane wave plane wave in the proper detector frame

GW electrodynamics

homogeneous Maxwell equation

$$0 = \nabla_\mu F_{\nu\rho} + \nabla_\nu F_{\rho\mu} + \nabla_\rho F_{\mu\nu} = \partial_\mu F_{\nu\rho} + \partial_\nu F_{\rho\mu} + \partial_\rho F_{\mu\nu}$$

$\rightarrow F_{\alpha\beta} = \partial_\alpha A_\beta - \partial_\beta A_\alpha$ independent of background metric

inhomogeneous Maxwell equation

$$\nabla_\nu \left(g^{\alpha\mu} F_{\alpha\beta} g^{\beta\nu} \right) = j^\mu \qquad \rightarrow \partial_\nu \left(\sqrt{-g}\, g^{\alpha\mu} F_{\alpha\beta}\, g^{\beta\nu} \right) = \sqrt{-g}\, j^\mu$$

expand in h: $g^{\alpha\mu} F_{\alpha\beta}\, g^{\beta\nu} \simeq F^{\mu\nu} - F_\alpha{}^\nu h^{\alpha\mu} - F^\mu{}_\beta h^{\beta\nu}, \quad \sqrt{-g} \simeq 1 + h/2$

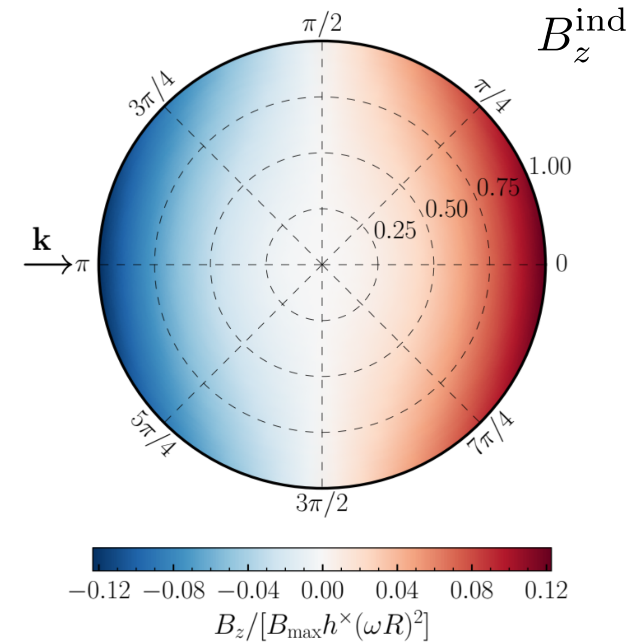
$$\partial_\nu \left(\left(1 + \frac{h}{2}\right) F^{\mu\nu} - F_\alpha{}^\nu h^{\alpha\mu} - F^\mu{}_\beta h^{\beta\nu} \right) = \left(1 + \frac{h}{2}\right) j^\mu + \mathcal{O}(h^2),$$

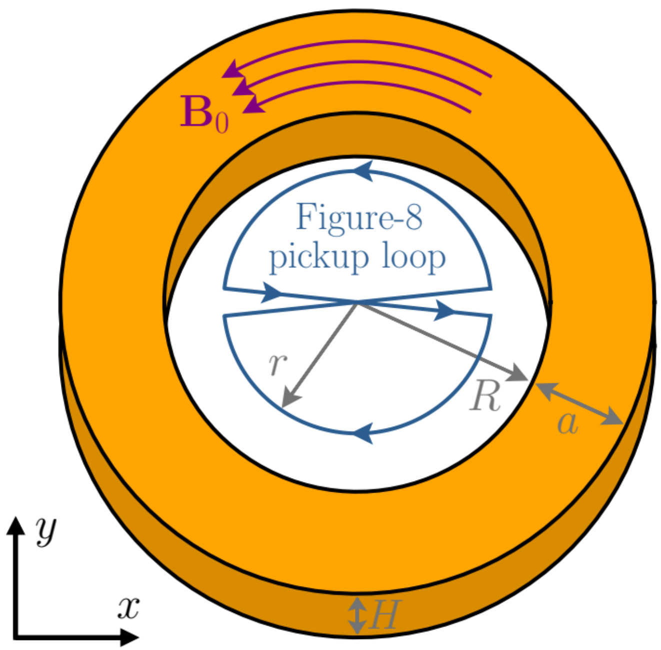
$$\partial_\nu F^{\mu\nu} = \left(1 + \frac{1}{2} h\right) j^\mu + \underbrace{\partial_\nu \left(-\frac{1}{2} h\, F^{\mu\nu} + F_\alpha{}^\nu h^{\alpha\mu} + F^\mu{}_\beta h^{\beta\nu} \right)}_{j^\mu_{\rm eff}} + \mathcal{O}(h^2)$$

optimized pickup loop geometry

spin 2 structure of GW induces angular modulation of induced B field

leading order $(\omega R)^2$ contribution can be captured with a figure-8 geometry for the pickup loop



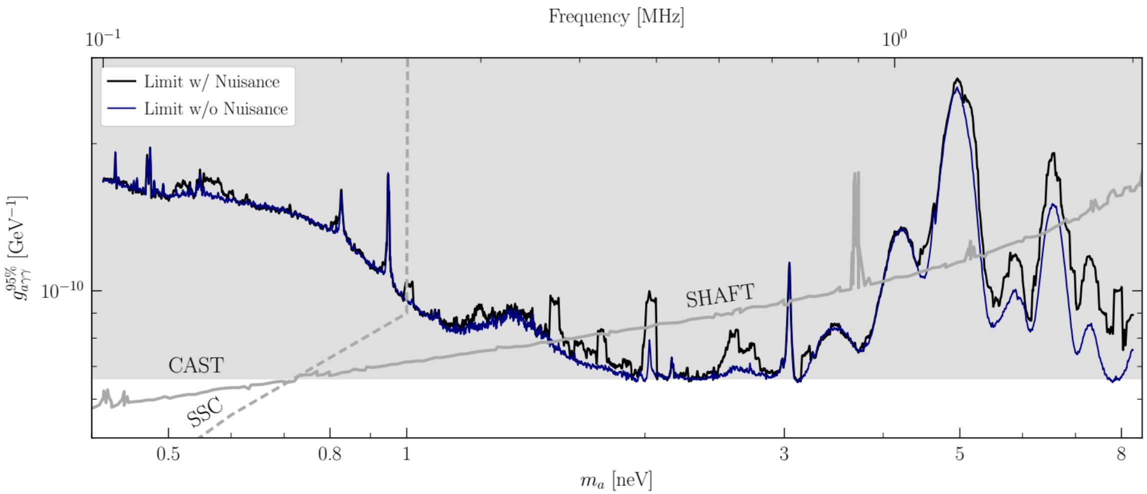


$$\Phi_{\mathrm{gw},8} = \frac{e^{-i\omega t}}{3\sqrt{2}}\, \omega^2 B_0 r^3 R \ln\left(1 + a/R\right) s_{\theta_h} \times \left(h^\times s_{\phi_h} - h^+ c_{\theta_h} c_{\phi_h}\right)$$

VD, Garcia-Cely, Rodd \`22

parametric improvement for modified pickup loop

recasting axion searches



ABRA [2102.06722]
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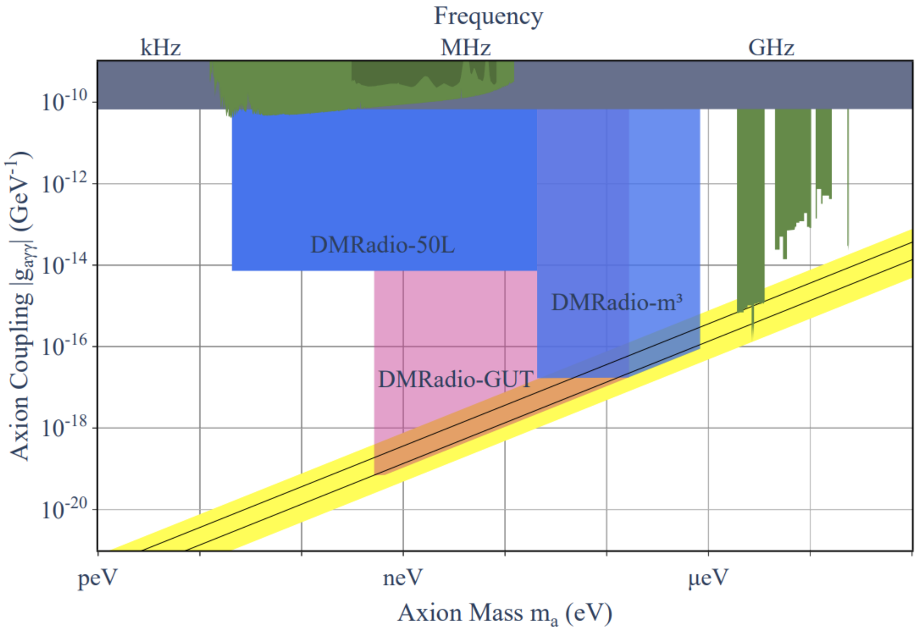

DM Radio proposals
[Snowmass Letters of Interest CF2]

→ recast as bound on h taking into account reduced quality factor

$$\Phi_{\rm gw} = \Phi_a (Q_a / Q_{\rm gw})^{1/4}$$

$\propto g_{a\gamma\gamma}$