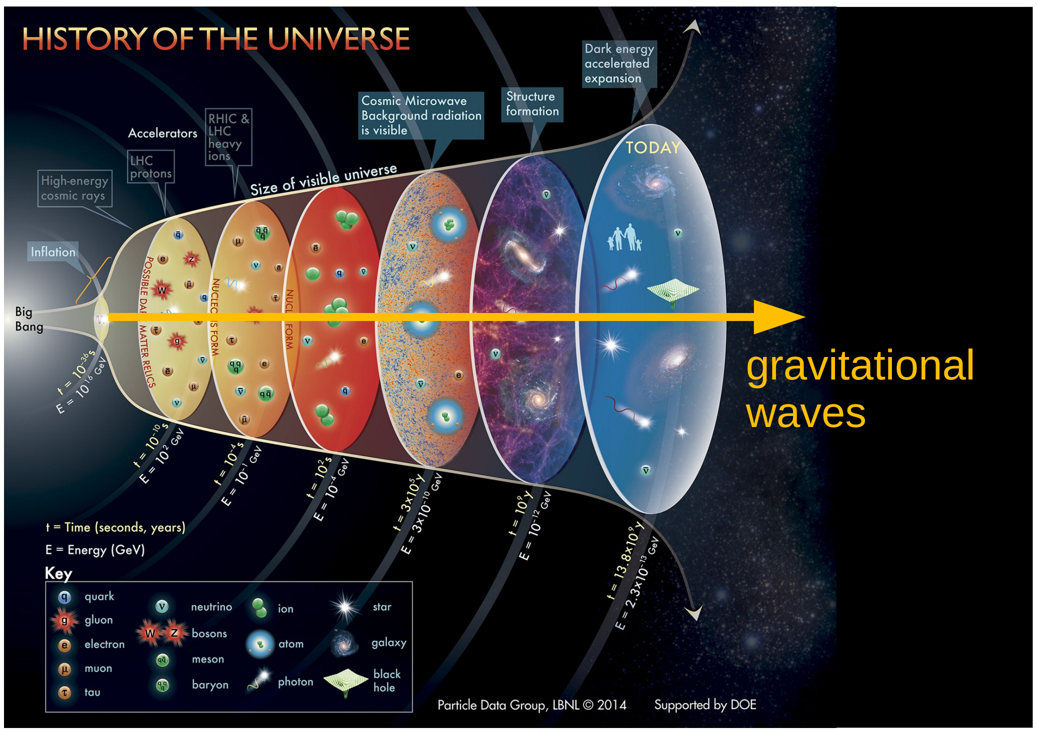
Electromagnetic

high-frequency gravitational wave detection



Valerie Domcke
CERN

Moriond Conference, La Thuile
March 18 – 25, 2023

based on 2011.12414
Living Review on UHF GW searches,

and work with Camilo Garcia-Cely, Torsten Bringmann, Elina Fuchs, Joachim Kopp, Sung Mook Lee and Nick Rodd

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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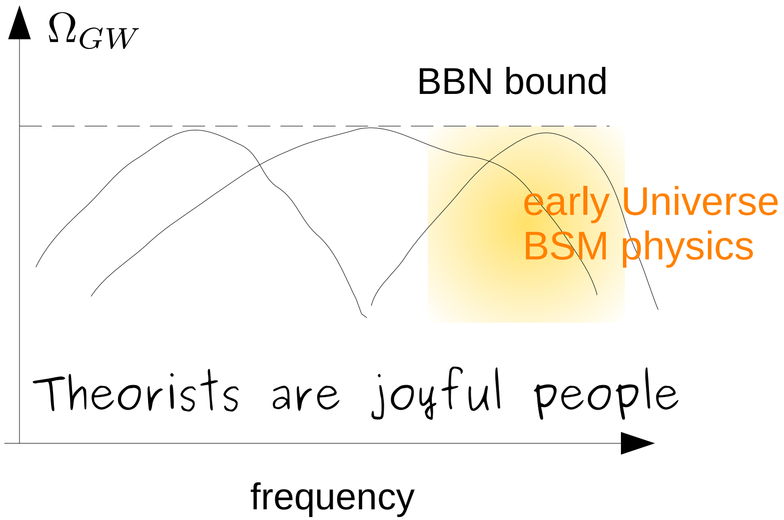
Astrophysical

- localized GW sources, both coherent and incoherent signals possible
- no strong astrophysical sources guaranteed in UHF band
- eg mergers of light primordial black holes or exotic compact objects, superradiance, neutron star mergers depending on QCD EoS.
- 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

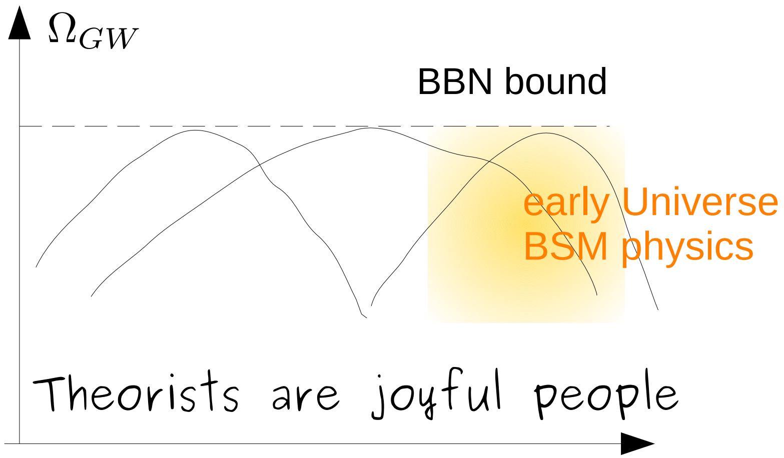
UHF GW searches are always a search for New Physics

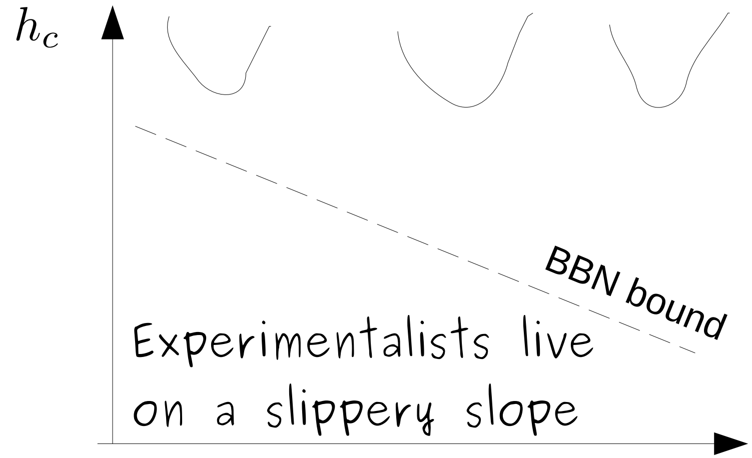
challenges in UHF GW detection



CMB/BBN bound constrains energy

challenges in UHF GW detection



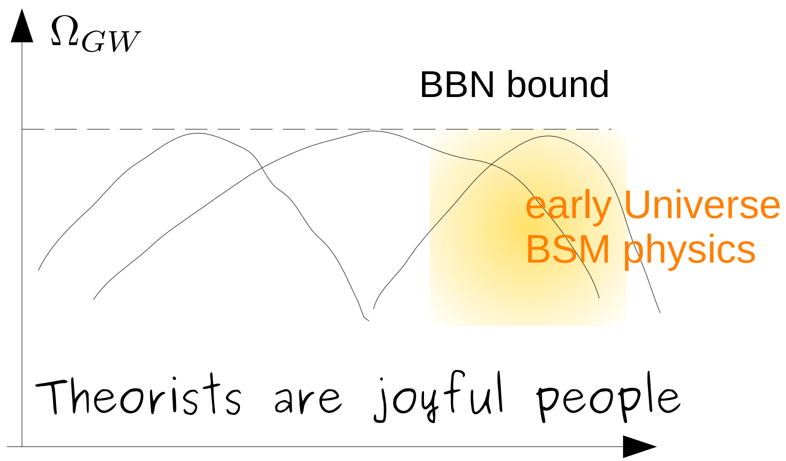


$$\Omega_{GW} \propto f^2 h_c^2$$

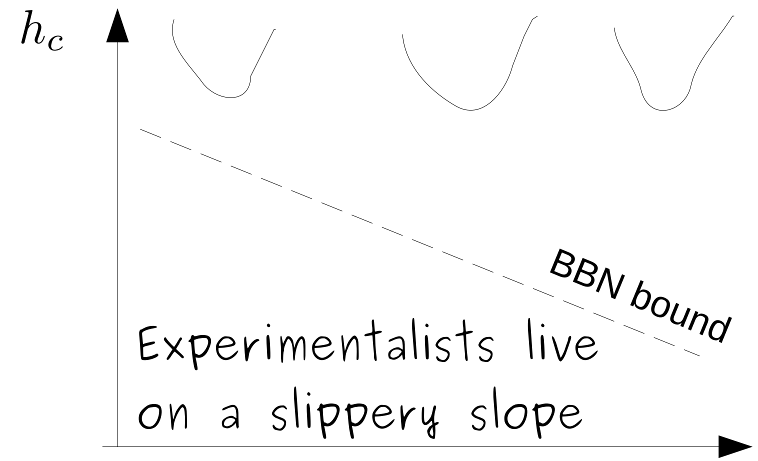
CMB/BBN bound constrains energy

experiments measure displacement

challenges in UHF GW detection



frequency



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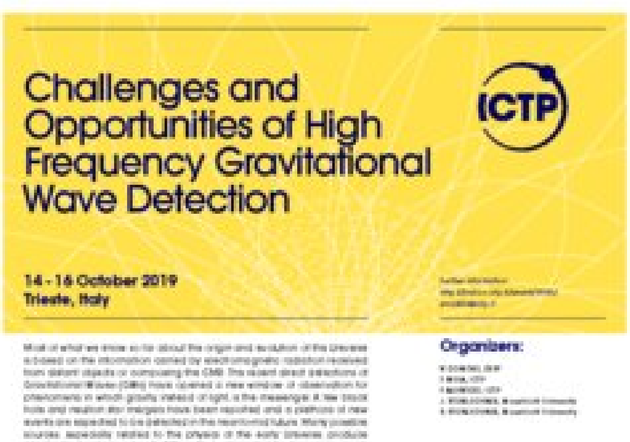

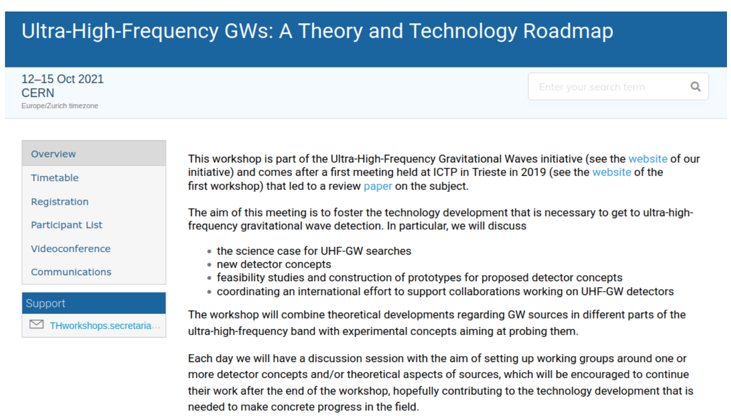
Ultra-High-Frequency GWs: A Theory and Technology Roadmap

12–15 Oct 2021
CERN
Europe/Zurich timezone

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

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all talks available online:

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

2nd workshop:
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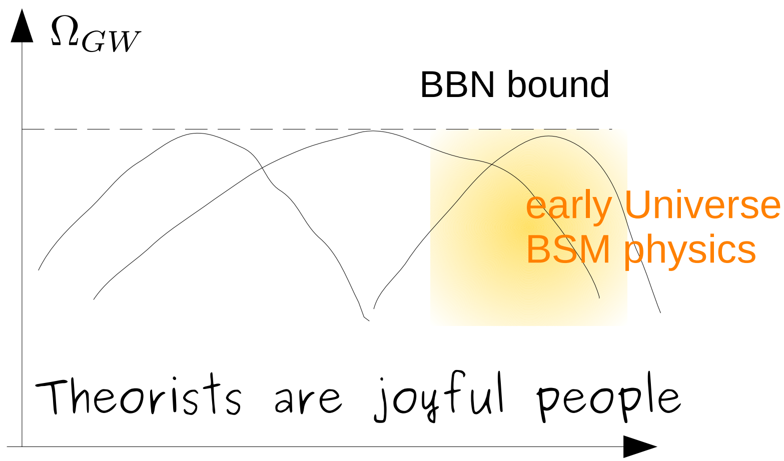
3rd workshop: Dec 4 – 8 2023 @ CERN !

challenges in UHF GW detection



Ω_G

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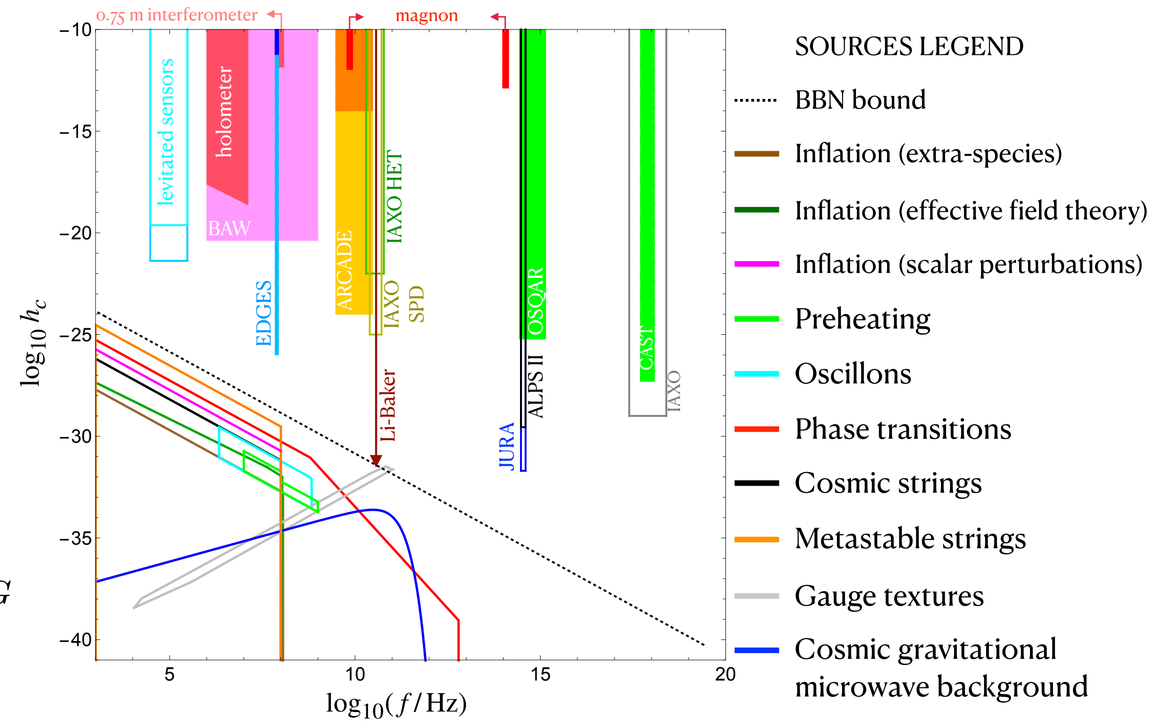
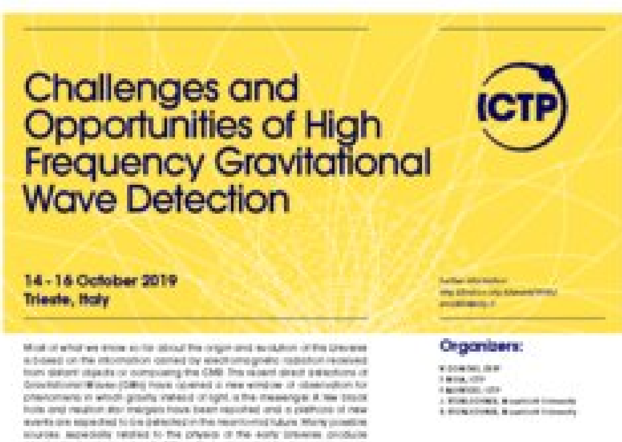
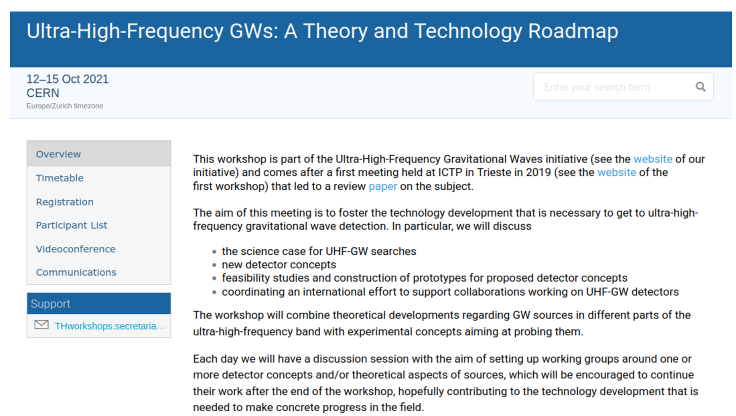



Challenges and Opportunities of High Frequency Gravitational Wave Detection

ICTP

14 - 16 October 2019
Trieste, Italy

Organizers: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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

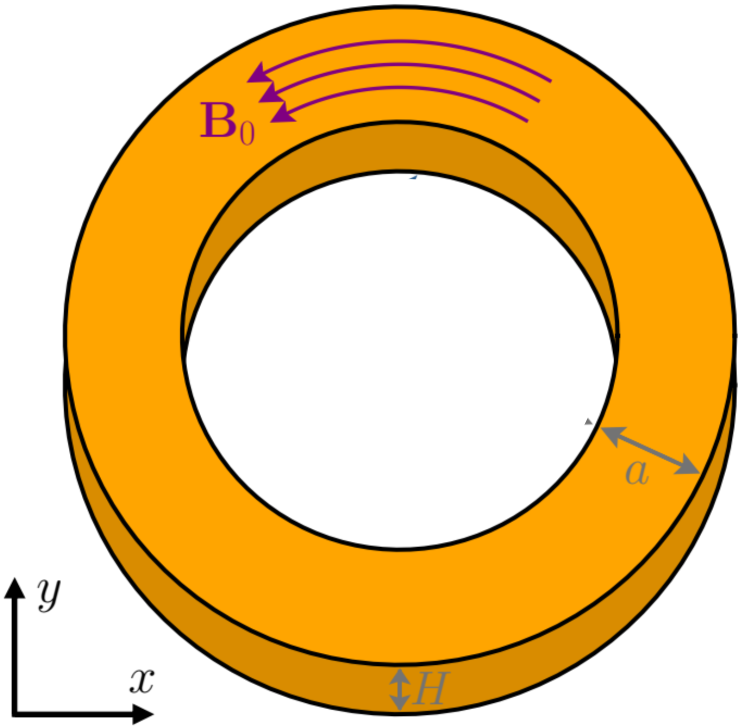
effective source terms in Maxwell‘s equation due to GW

GW signal in axion haloscopes

eg ABRACADABRA, SHAFT, DM Radio:

VD, Garcia-Cely, Rodd `22

static magnetic field



low-mass axion haloscopes are high frequency GW detectors

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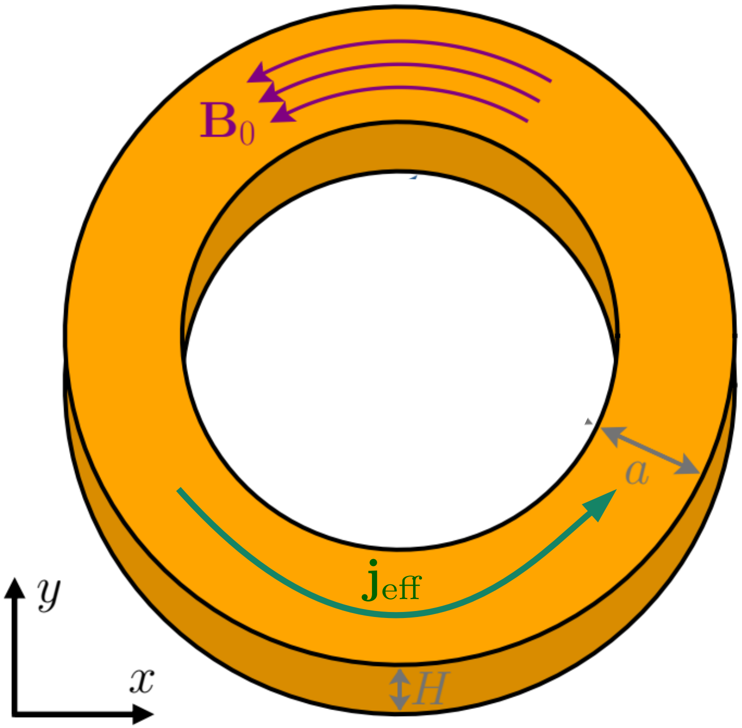

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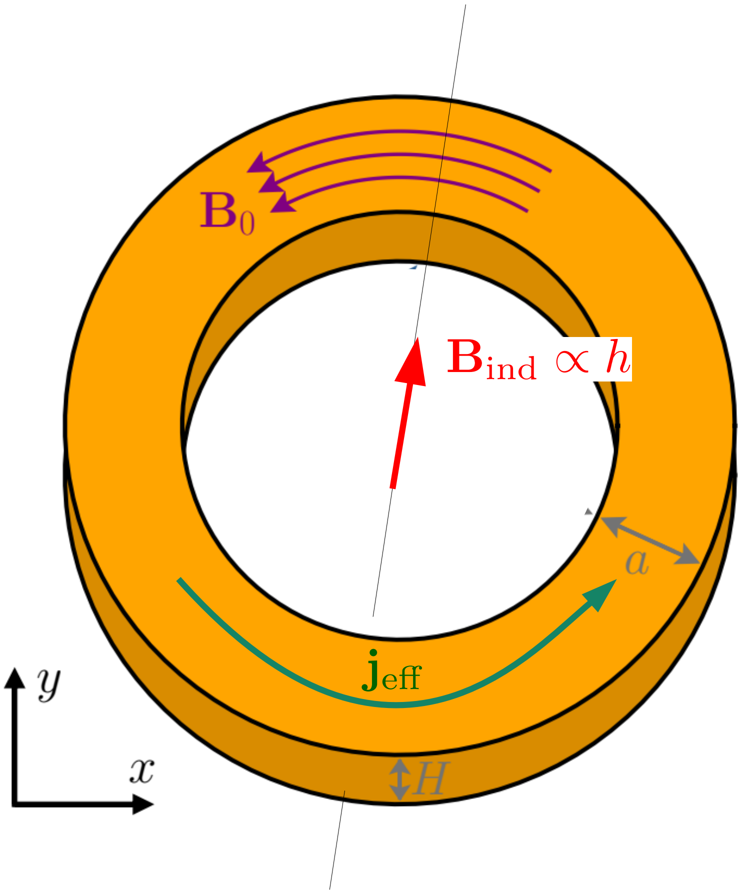

static magnetic field

effective current

induced oscillating magnetic field

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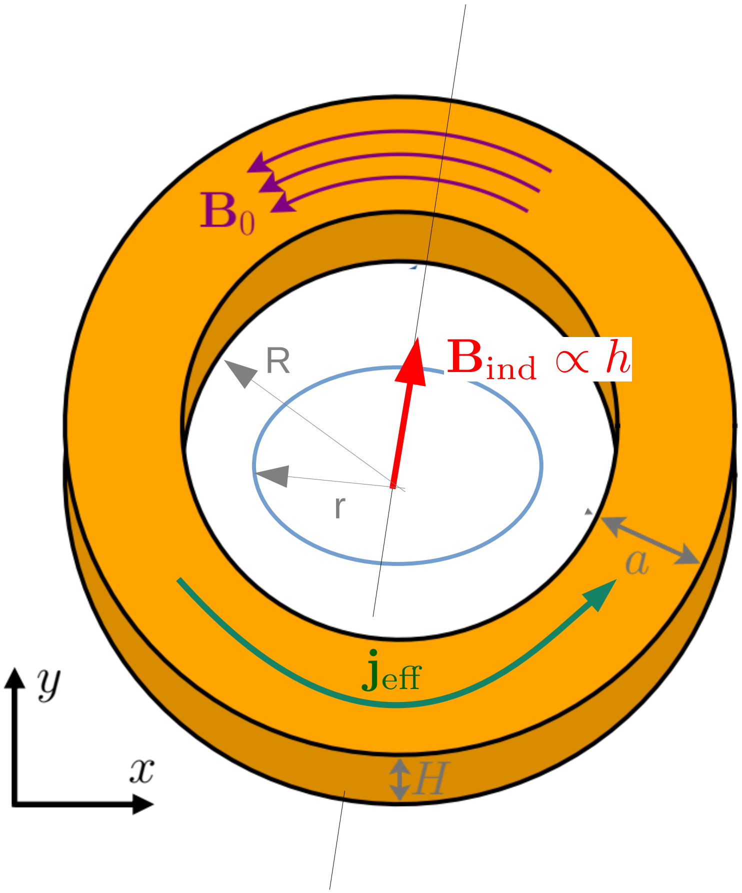

static magnetic field

effective current

induced oscillating magnetic field

measure magnetic flux (~ h) through pickup loop

at leading order in (ωR) :

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

low-mass axion haloscopes are high frequency GW detectors

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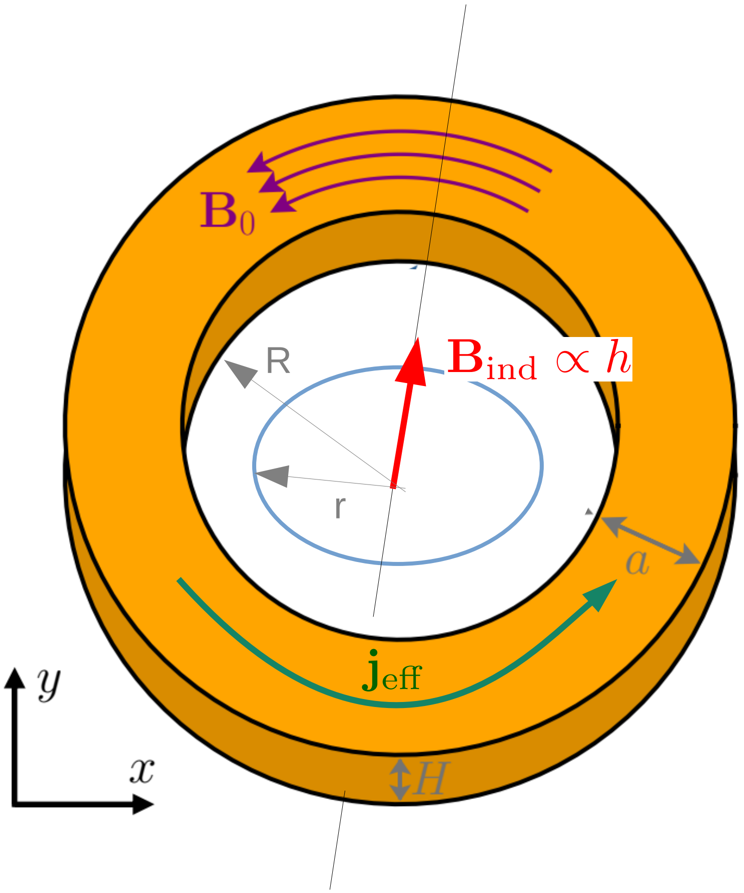


static magnetic field

effective current

induced oscillating magnetic field

measure magnetic flux (~ h) through pickup loop

at leading order in (ωR) : $\sim (\omega L)^3 h B_0 L^2$

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

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

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

$$\sim (\omega L)\, g_{a\gamma\gamma} B_0 L^2$$

low-mass axion haloscopes are high frequency GW detectors

bounds and prospects

VD, Garcia-Cely, Rodd `22

circular pickup loop

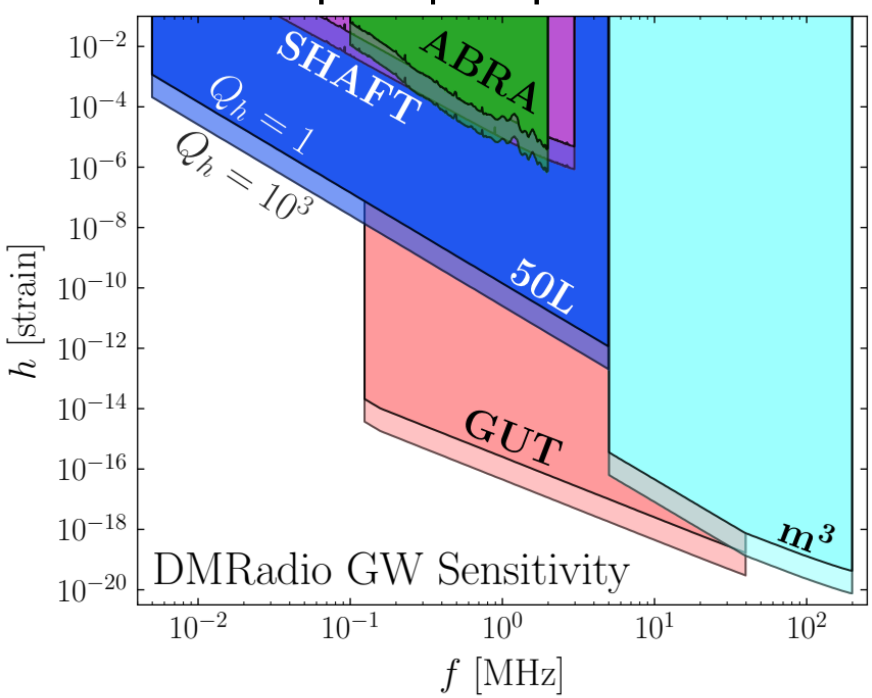
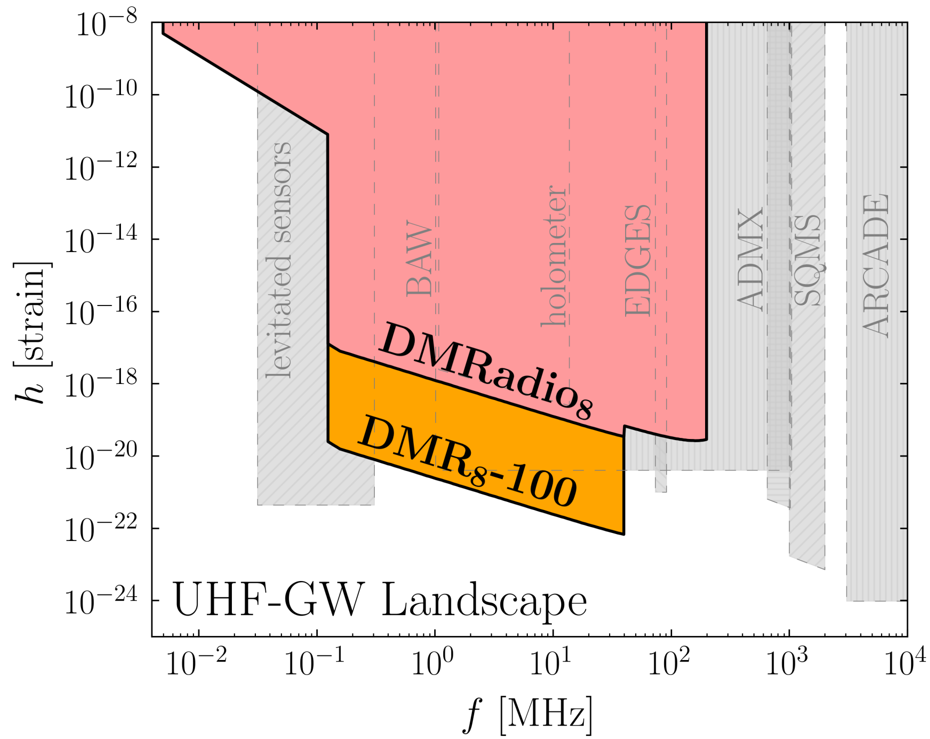


fig-8 pickup loop



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

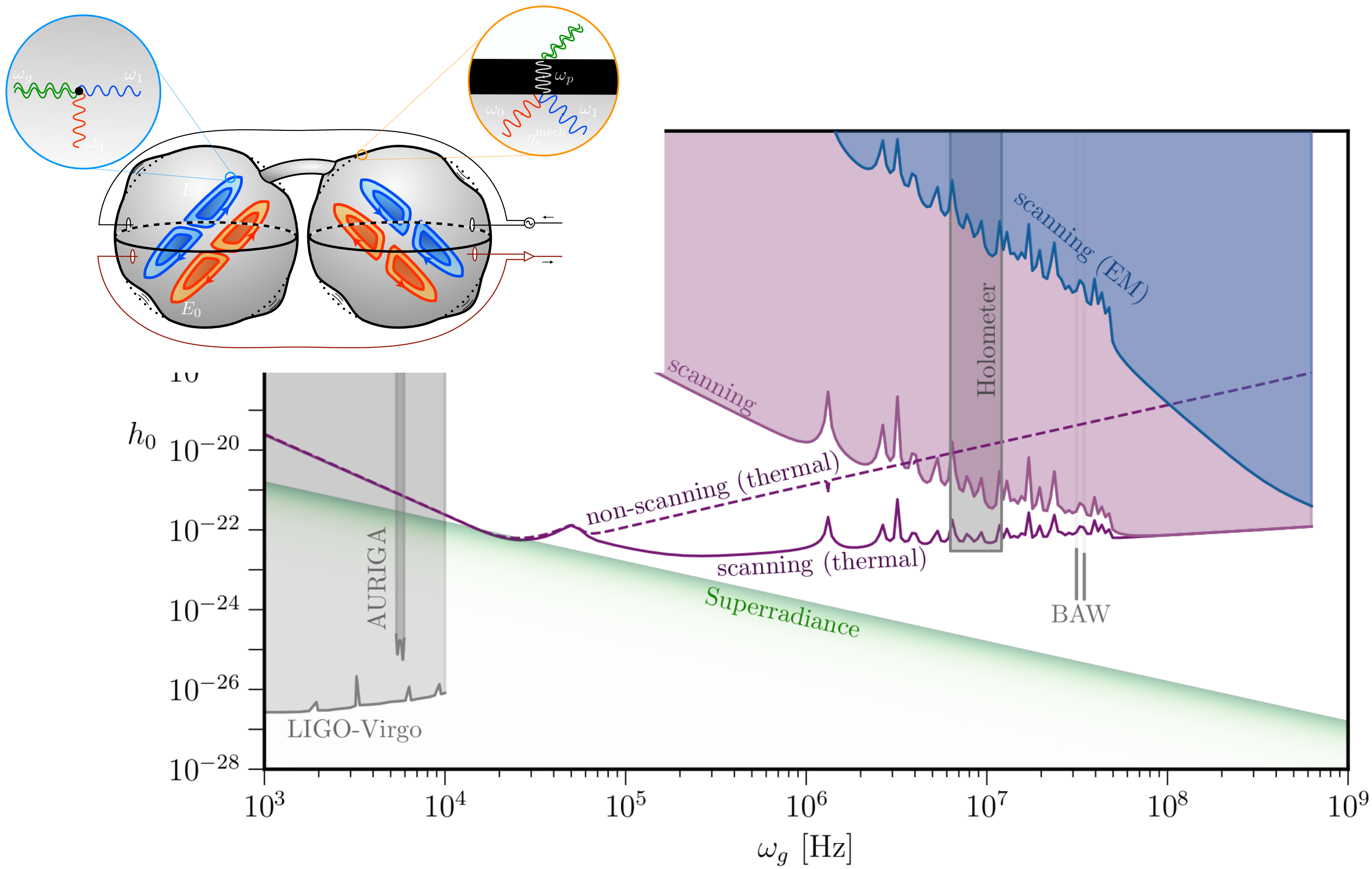
prospects for DM Radio proposals [Snowmass Letters of Interest CF2]

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

microwave cavities

Berlin, Blas, D'Agnolo et al `23

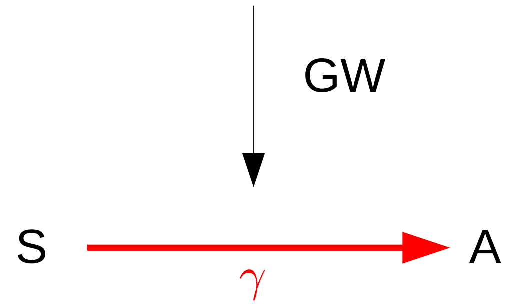
effective current can also induce power in microwave cavities,
in addition consider mechanical deformation of cavity walls:



see also Ejlli et al [1908.00232] :
GW searches with LSW axion experiments

optical frequency modulation

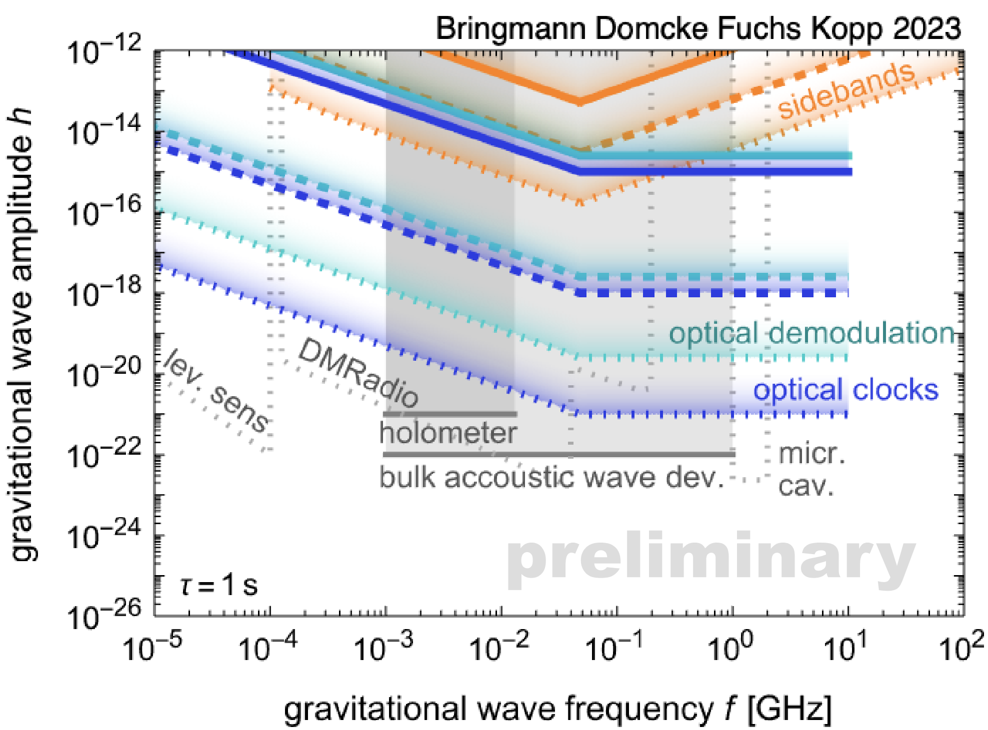
Bringmann, VD, Fuchs, Kopp – in preparation



$$\frac{\omega_\gamma^A - \omega_\gamma^S}{\omega_\gamma^A} = -\frac{1}{2} h_+ \times \left\{ \cos\left[\omega_g L + \varphi_0\right] - \cos\varphi_0 \right\}$$

(for free-falling S & A)

GW phase at (0,0)



frequency measurement by

amplification of side bands in cavities

optical demodulation via de-tuned cavities

optical clocks measuring frequency shift after pass through optical rectifier

Conclusions and Outlook

- GW signals >> kHz would be a smoking gun of BSM physics

- New techniques currently being explored for high-frequency GW detection, among them different electromagnetic GW detectors
(also: ‘light-shining-through the wall’ axion searches, magnon detectors,...)

- Important synergies between axion searches and UHF GW searches

- A lot of room for new (and old?) ideas!

Next workshop Dec 4 – 8 @ CERN:
https://indico.cern.ch/event/1257532/

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Thank you !

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backup slides

BBN bound

radiation energy after electron decoupling:

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

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

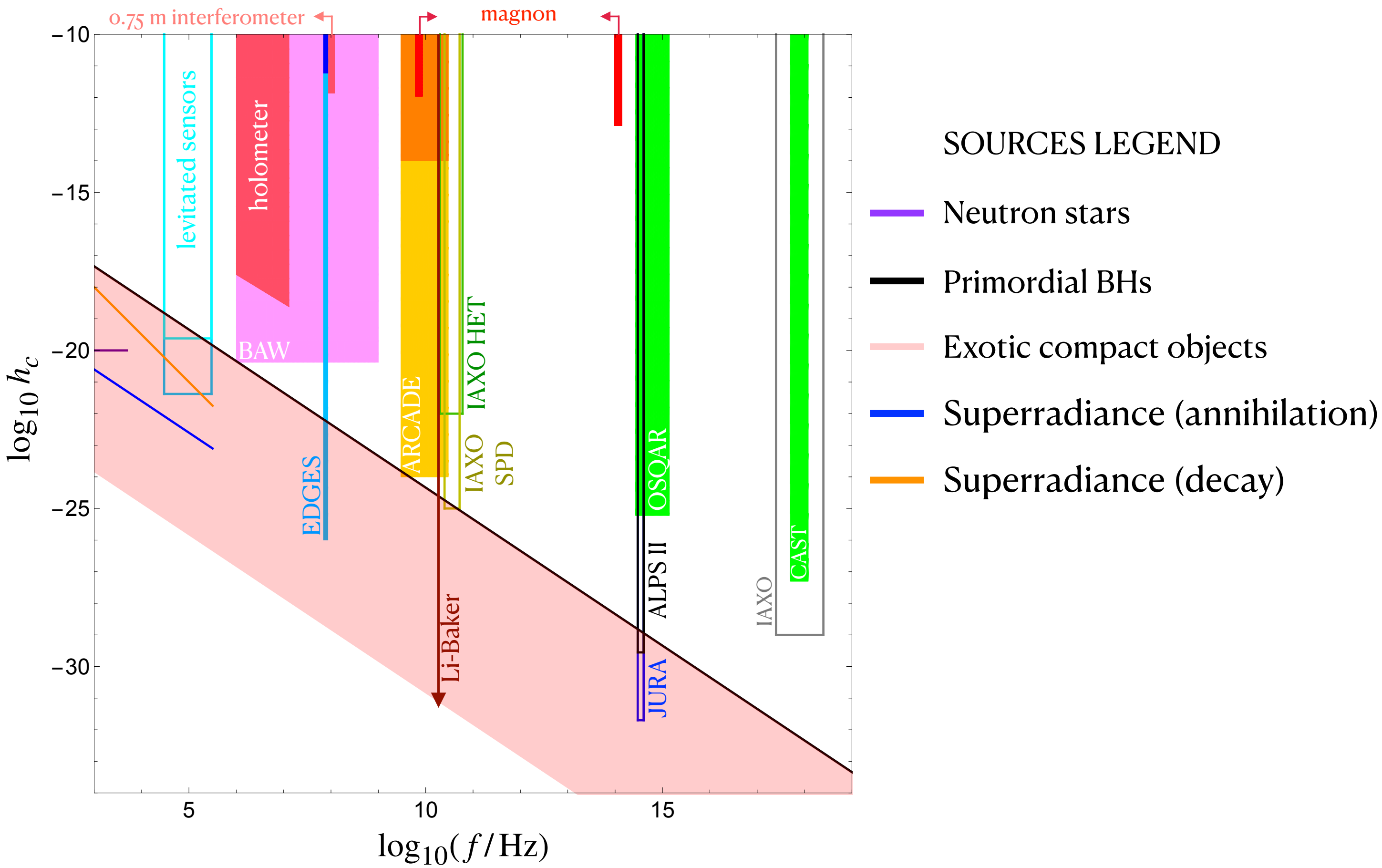
today:

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

note: constraint on *total* GW energy

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

astrophysical sources



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

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

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

[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

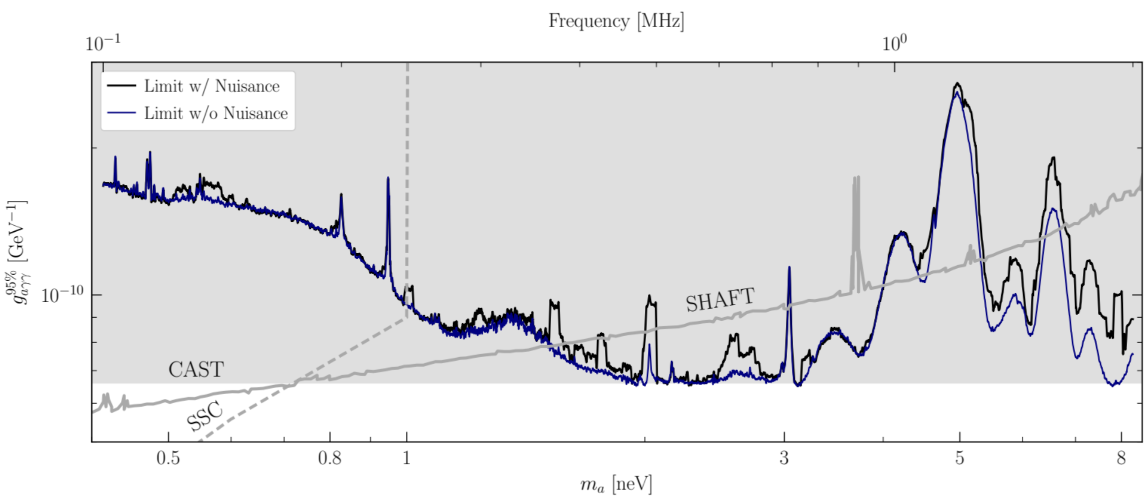
- coordinates fixed by laboratory frame
- GW takes a more involved form
- description of experimental setup and observables is straightforward

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

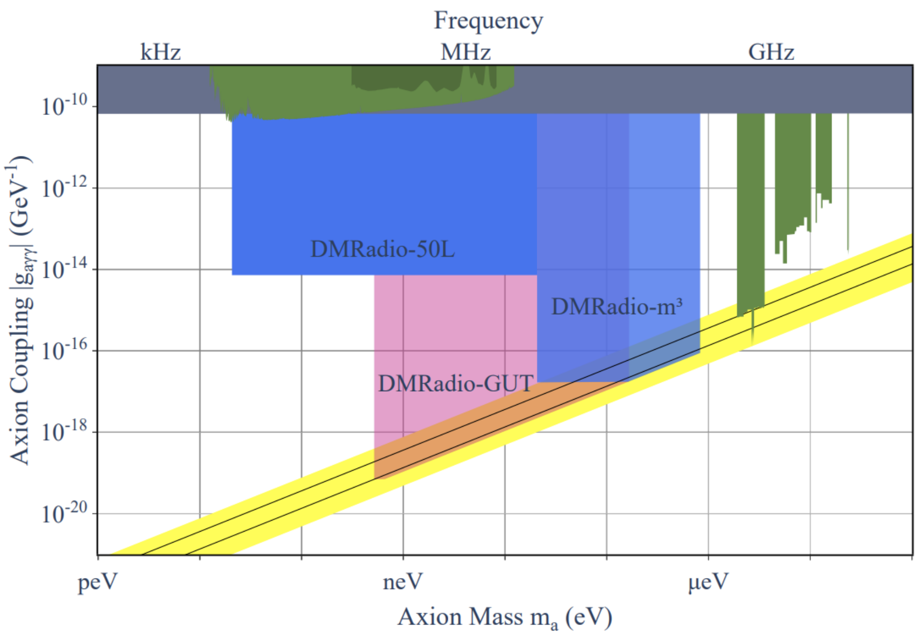
VD, Garcia-Cely, Rodd `22
s.a. Berlin et al `21

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

recasting axion searches



ABRA [2102.06722]
SHAFT [2003.03348]



DM Radio proposals
[Snowmass Letters of Interest CF2]

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

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

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

GW to photon conversion

(inverse) Gertsenshtein effect: [Gertsenshtein `62, Boccaletti et al `70, Raffelt, Stodolsky `88]

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

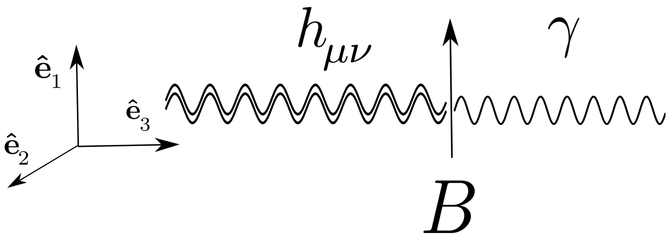
$A_\lambda =$ photon
$h_\lambda =$ GW
$B =$ ext. transv. B - field
$\omega_{\rm pl} =$ plasma frequency
$\mu^2 = 1 - \omega_{\rm pl}^2/\omega^2$

plane waves:

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

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

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

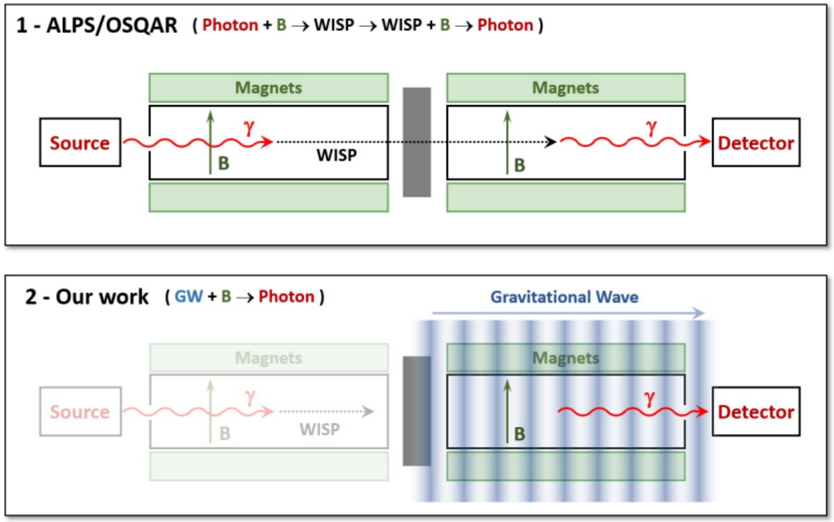


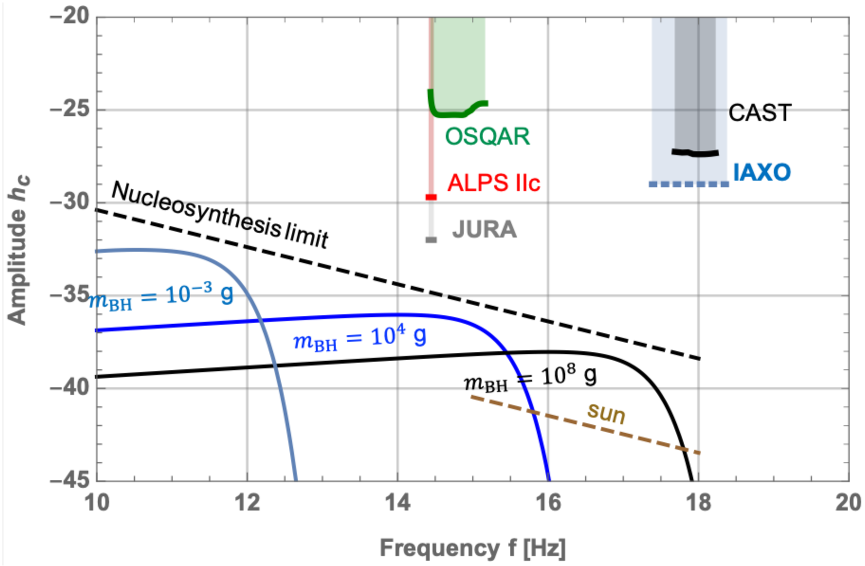
analogous to axion to photon conversion

LSW experiments

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

[Ejilli et al `19]





axion bounds recast as HFGW bounds