Session IV : Beyond axions

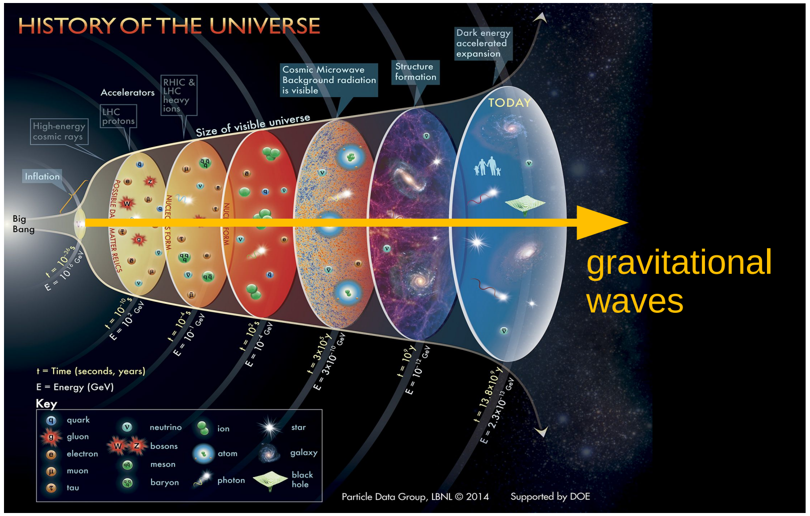
(More fundamental physics with axion technologies)

Axionfest DESY: Axions beyond the DM paradigm

Jan 29 - 31, 2024

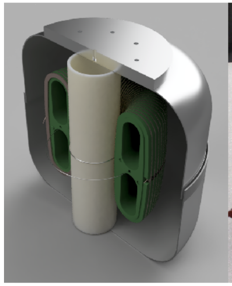
• Overview: High frequency GW searches with axion detectors	Valerie Domcke
• Overview: Vacuum magnetic birefringence	Laura Roberts
• High frequency GW @ ALPs	Aldo Ejili
• Vacuum magnetic birefringence searches @ ALPs	Aaron Spector
• Polarometry for DM (pseudo)scalar searches	Qazal Rokn
• **More** questions and discussion	**Everyone**

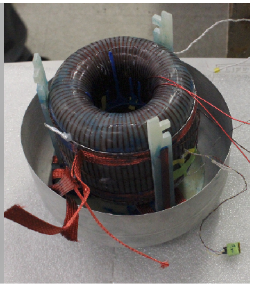
High frequency GW searches with axion detectors



- UHF GW sources

- Theory of GW to photon conversion





- recasting axion bounds

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
  $\rightarrow$ 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
  $\rightarrow$ 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

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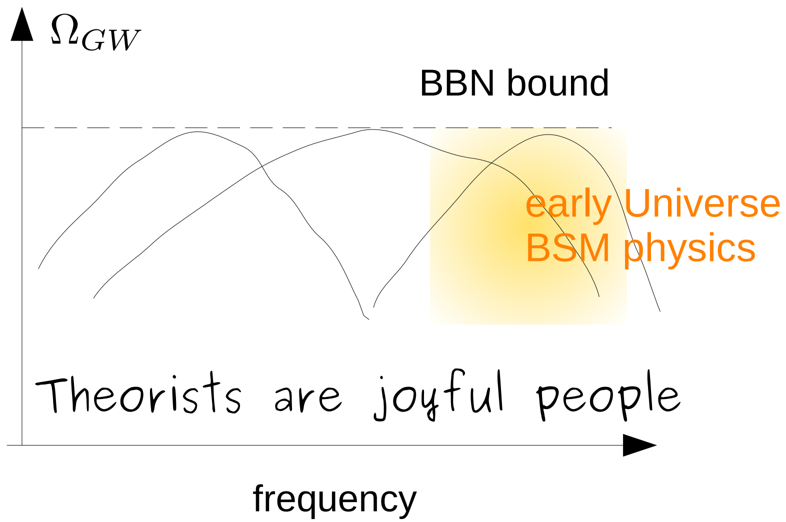
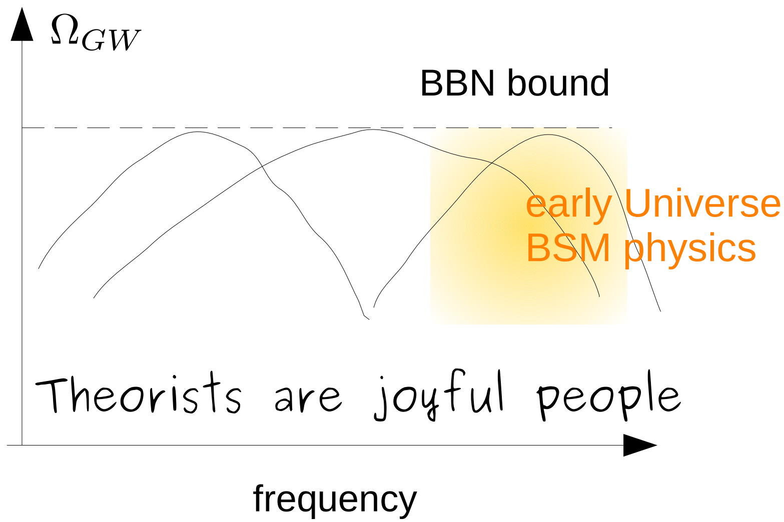
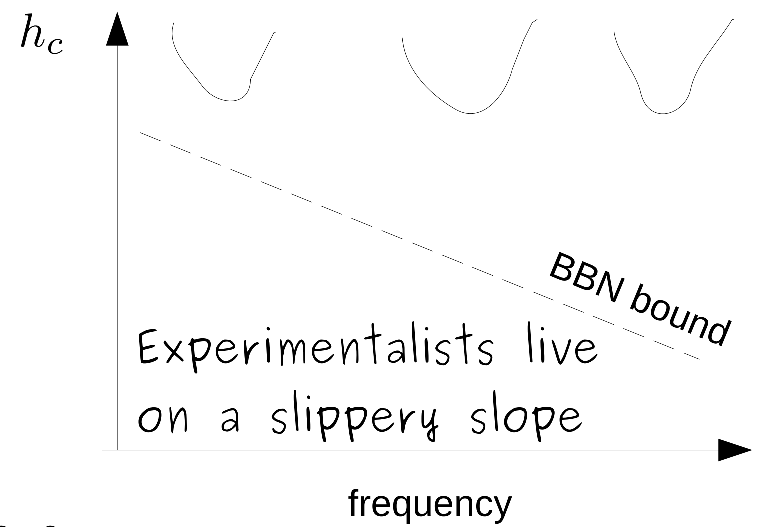
challenges in UHF GW detection



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

UHF GW initiative: https://www.ctc.cam.ac.uk/activities/UHF-GW.php

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

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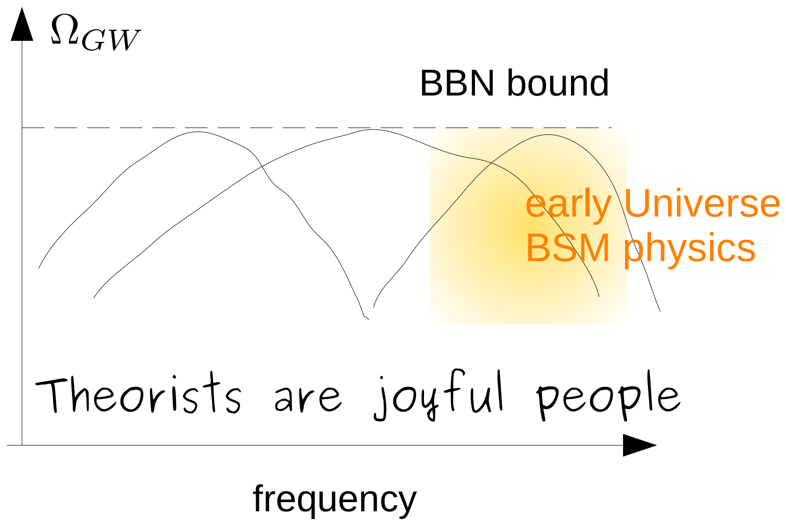

h_c

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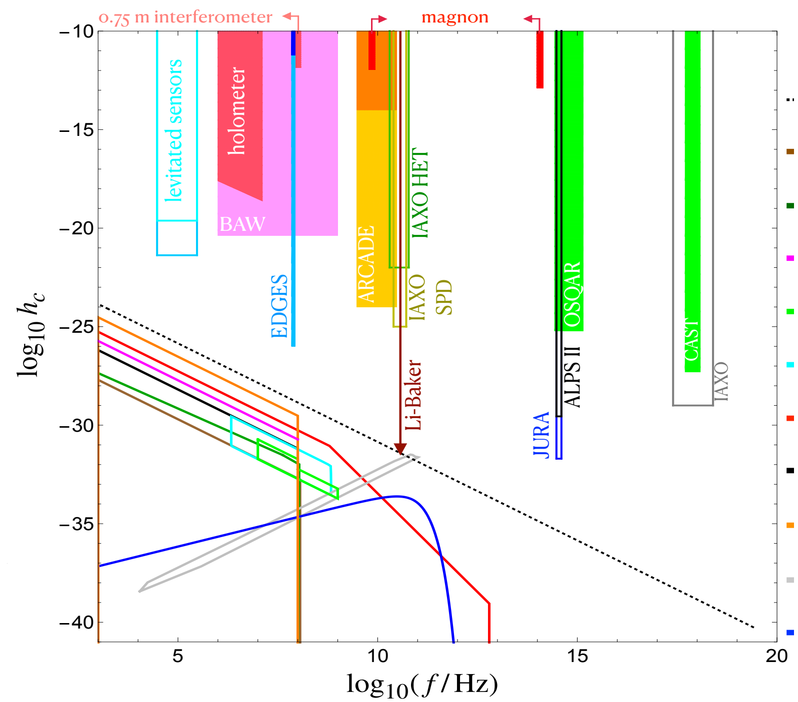

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GW electrodynamics

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

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

effective current
effective polarization vector
effective magnetization vector

with

$$\begin{aligned} P_i &= -h_{ij}E_j + \tfrac{1}{2}hE_i + h_{00}E_i - \epsilon_{ijk}h_{0j}B_k, \\ M_i &= -h_{ij}B_j - \tfrac{1}{2}hB_i + h_{jj}B_i + \epsilon_{ijk}h_{0j}E_k, \end{aligned}$$

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 – EM oscillations

(inverse) Gertsenshtein effect: [Gertsenshtein `62, Boccaletti et al `70, Raffelt, Stodolsky `88]
include backreaction of EM on Einsteins equations:

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

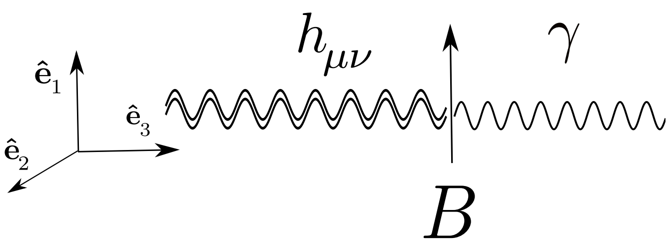
$$\begin{aligned} A_\lambda &= \text{photon} \\ h_\lambda &= \text{GW} \\ B &= \text{ext. transv. B - field} \\ \omega_{\rm pl} &= \text{plasma frequency} \\ \mu^2 &= 1 - \omega_{\rm pl}^2/\omega^2 \end{aligned}$$

plane waves:

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

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

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

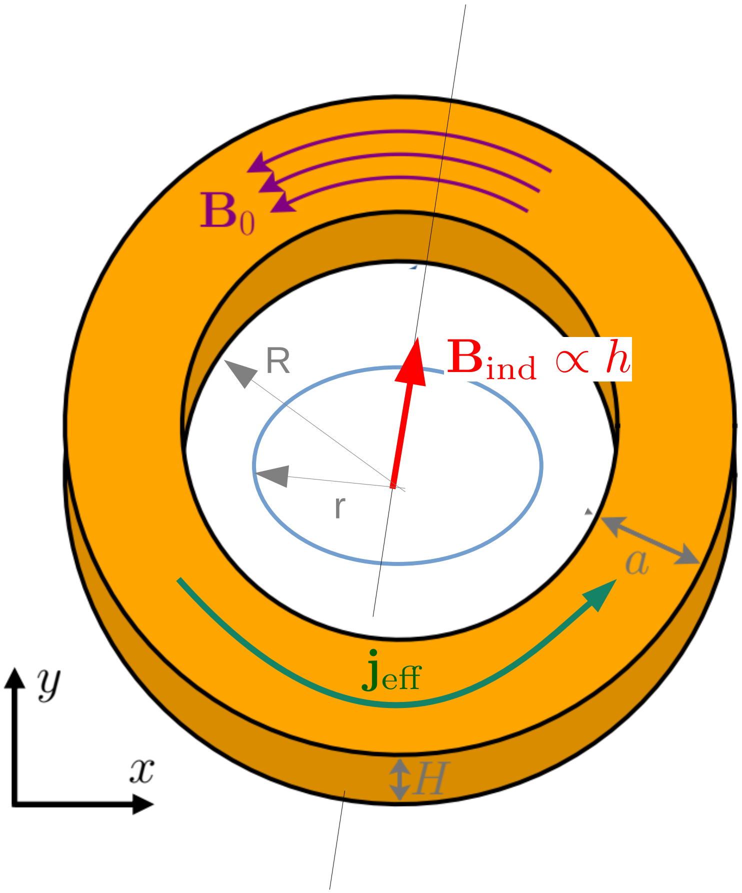


analogous to axion to photon conversion

low mass axion haloscopes

eg ABRACADABRA, SHAFT, DM Radio:

VD, Garcia-Cely, Rodd `22



static magnetic field (i.e. rigid detector)

effective current

induced oscillating magnetic field

measure magnetic flux (~ h) through pickup loop

at leading order in (ωR) :

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

$$\sim (\omega L)^3 h B_0 L^2$$

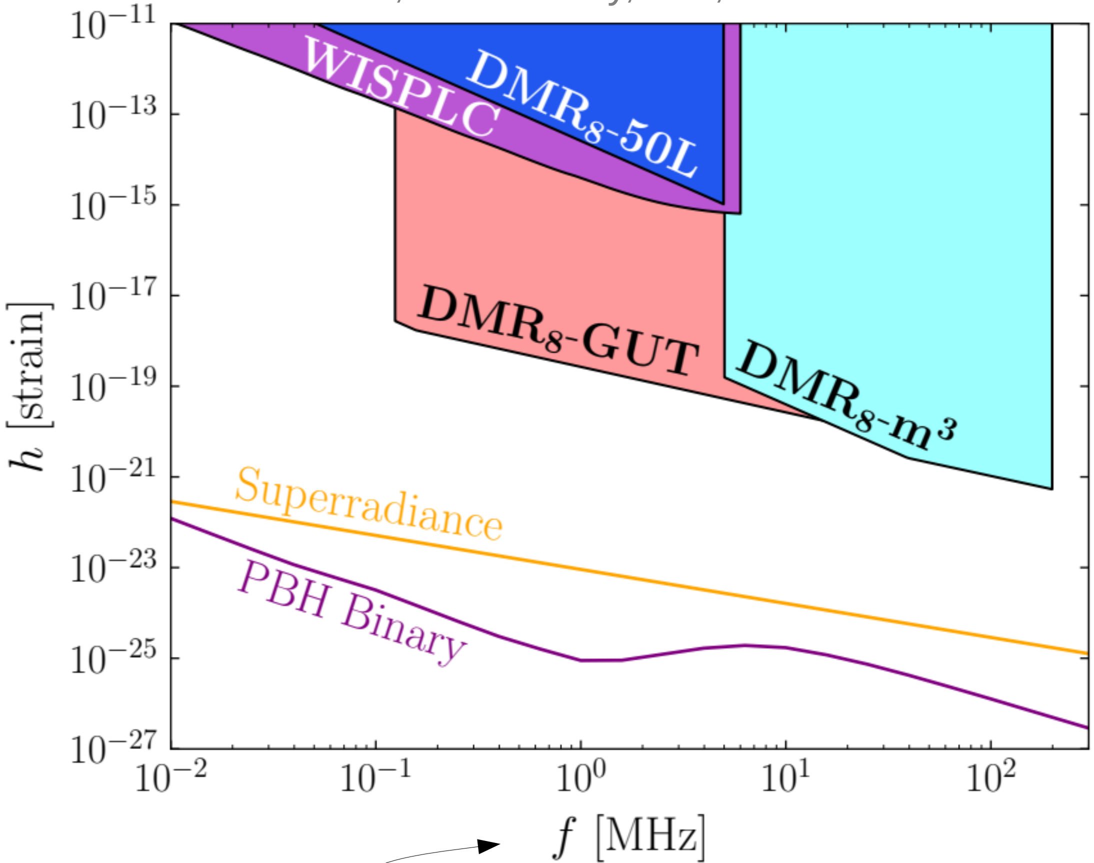
match to axion induced flux to recast axion-photon coupling bounds as GW bounds:

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

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

Low mass haloscopes

VD, Garcia-Cely, Lee, Rodd `23



$$\Phi_h(h^+, h^\times; \phi_h, \theta_h) = \mathcal{R}_c\, \Phi_a(g_{a\gamma\gamma}),$$

coherence ratio factor:
coherence & observation time

sensitivity to signal with $\mathcal{R}_c = 1$

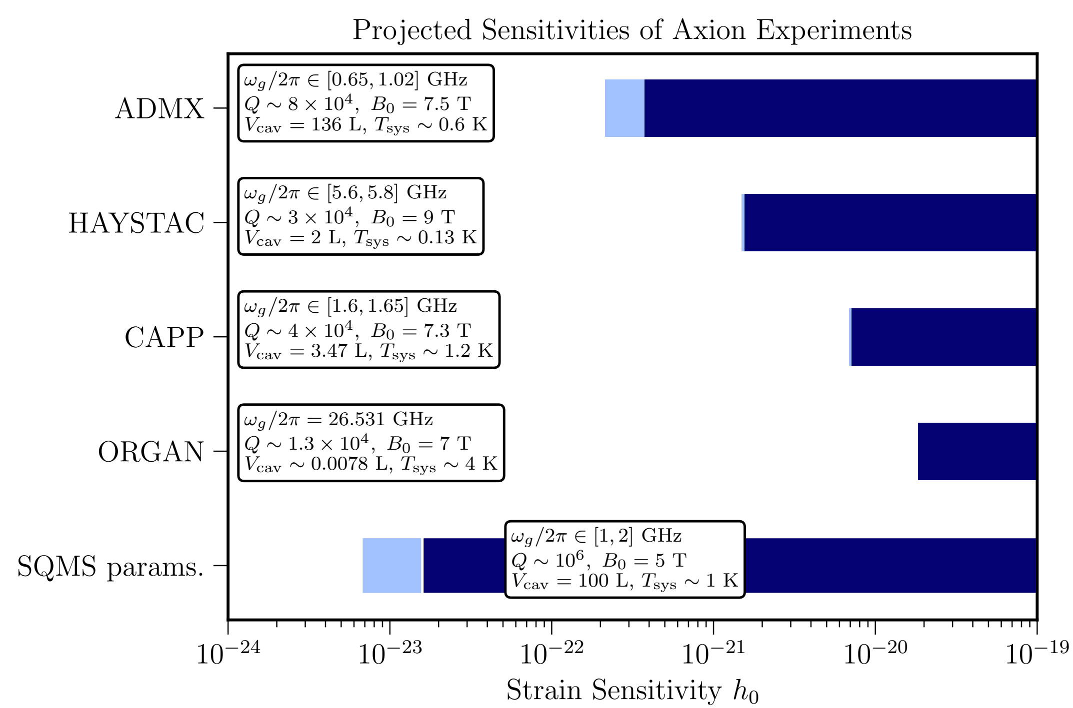
$\mathcal{R}_c$ computed assuming $Q_r = 10^4, T_m = 10^3\, s\, (10^{-3}\, s)$

axion haloscopes as **high frequency** GW detectors

still far away from BBN bound, but clear synergies of UHF GW and axion searches

microwave cavities

[Berlin et al `21]

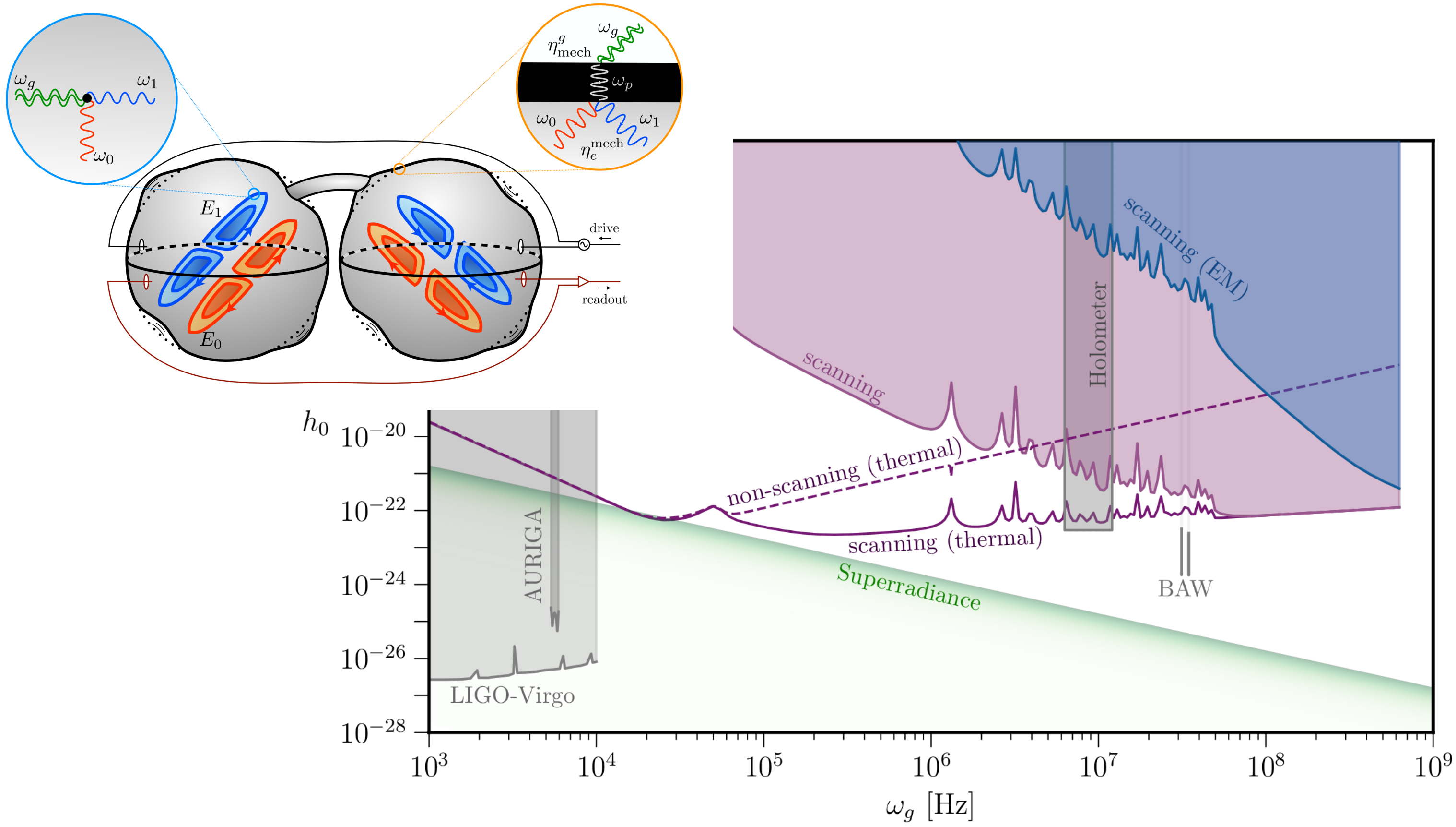


bound on monochromatic coherent GW

microwave cavities

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

Berlin, Blas, D'Agnolo et al `23

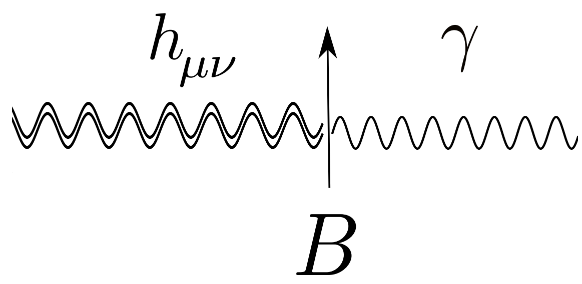


MAGO 2.0

bound on monochromatic coherent GW

photon (re-)generation experiments

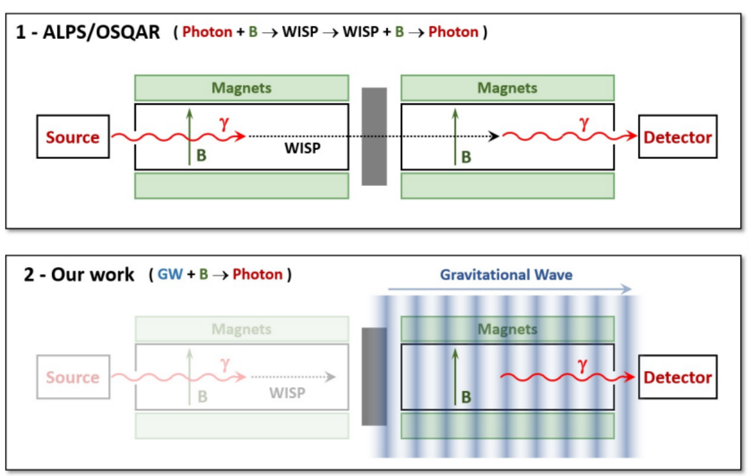
[Gertsenshtein `62, Boccaletti et al `70, Raffelt, Stodolsky `88]

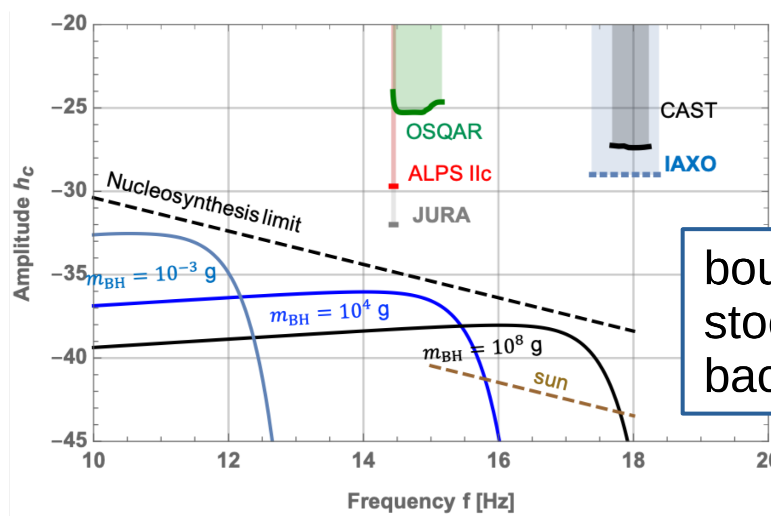


see Aldo's talk

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

Ejilli et al `19





bound on stochastic GW background

astro/cosmo environments: Fujita et al `20, VD, Garcia-Cely `21, Feng et al `22, Liu e al `23, Ito et al `23, Ramazanov et al `23,...

current status

note of caution: different experiments and sources on the same plot is often misleading, many hidden parameters

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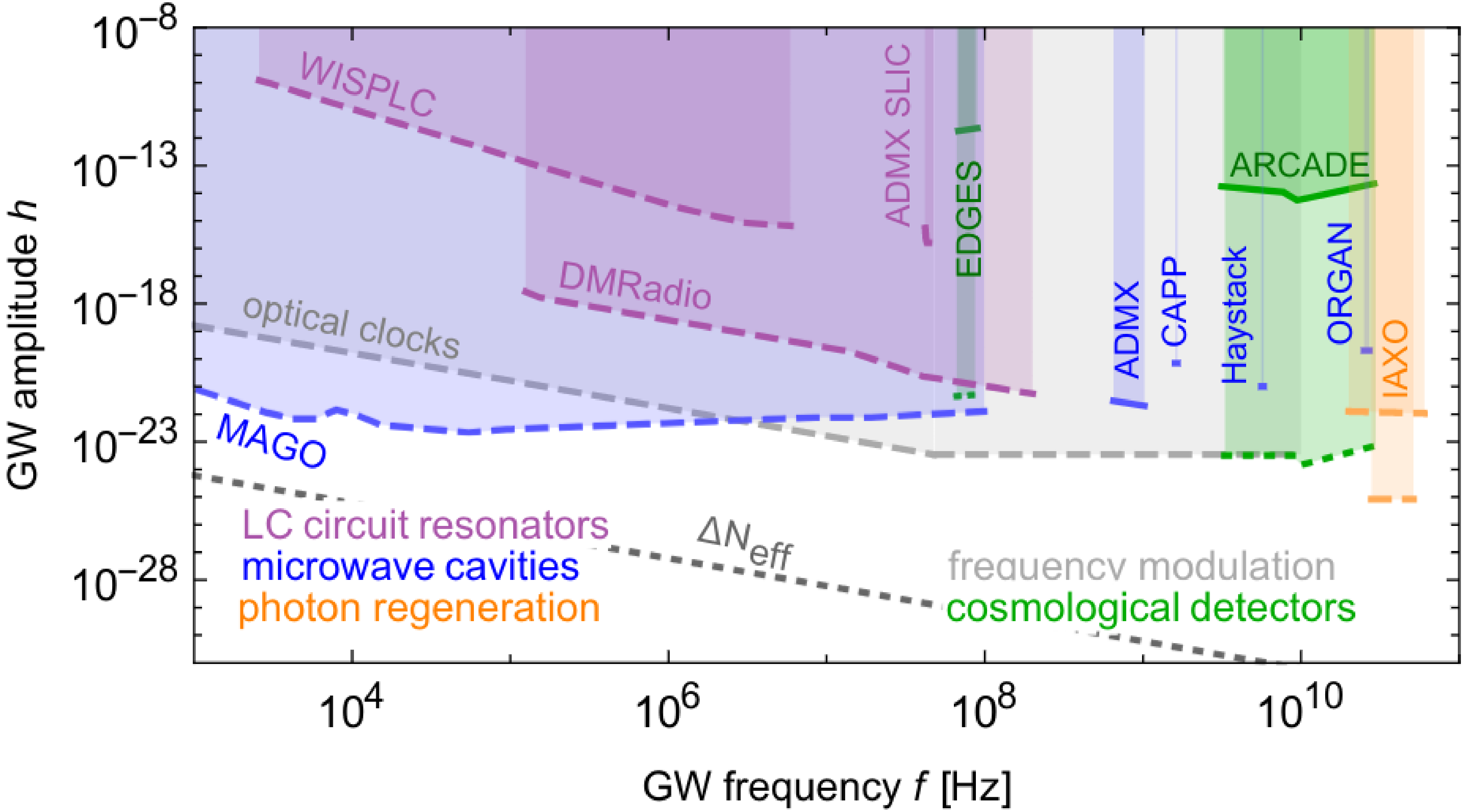
…. but let‘s do it anyway...

current status

sensitivity to coherent GW

VD, 2306.04496



Conclusions and Outlook

GW sources at high frequencies

- GW signals >> kHz would be a smoking gun of BSM physics
- Cosmological signals well motivated, but amplitude constrained by BBN and CMB
- Larger astrophysical signals from rare exotic events possible, e.g. light PBHs

GW searches with axion detectors

- GW electrodynamics has clear similarities with axion electrodynamics:

  Important synergies between axion searches and UHF GW searches
- low-mass axion haloscopes, SRF cavities, LSW experiments,... as GW detectors

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„such detectors [laser interferometers] have so low sensitivity that they are of little experimental interest" [Misner, Thorne, Wheeler 1974]

nobel prize 2016 for detection of GWs with LIGO

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Thank you!

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Some questions for discussion:

- Different data taking and analysis techniques compared to axion searches?

- Development of tools for estimating HFGW sensitivities

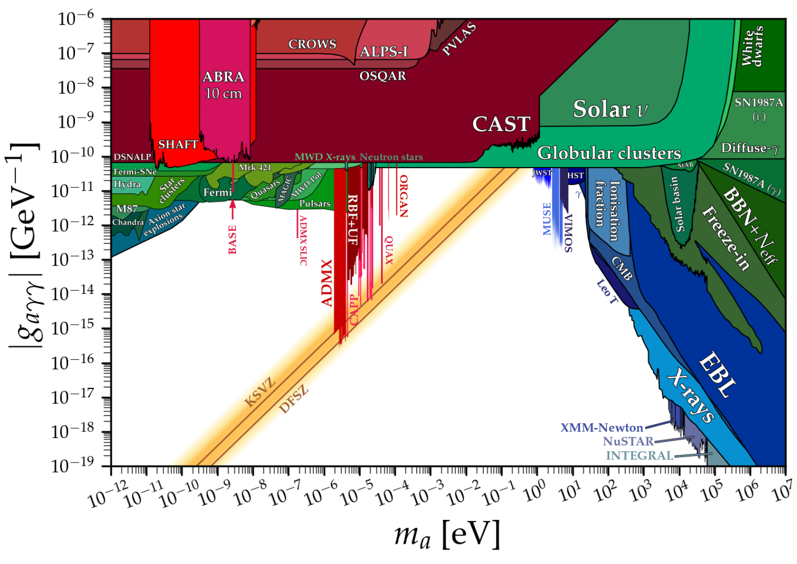
persistent and coherent ?

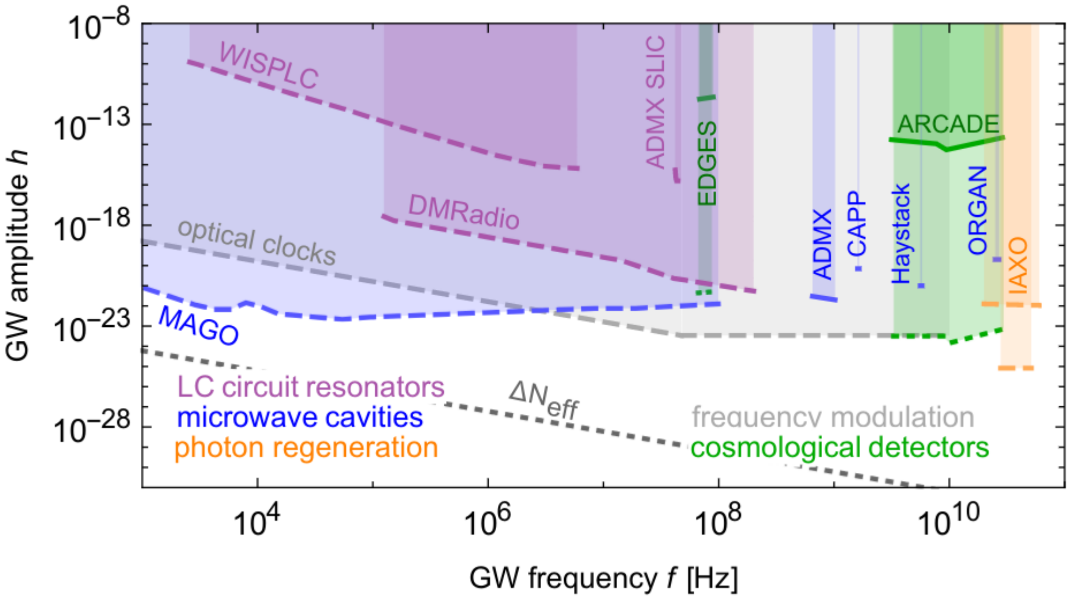
large SNR but not persistent ?

Some questions for discussion:

- Overlooked opportunities for existing axion experiments?

- Potential of (minor) modifications to existing experiments versus dedicated GW instruments?





Some questions for discussion:

- Potential for two-way synergies?

- Other BSM fundamental physics that might be probed?

backup slides

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

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

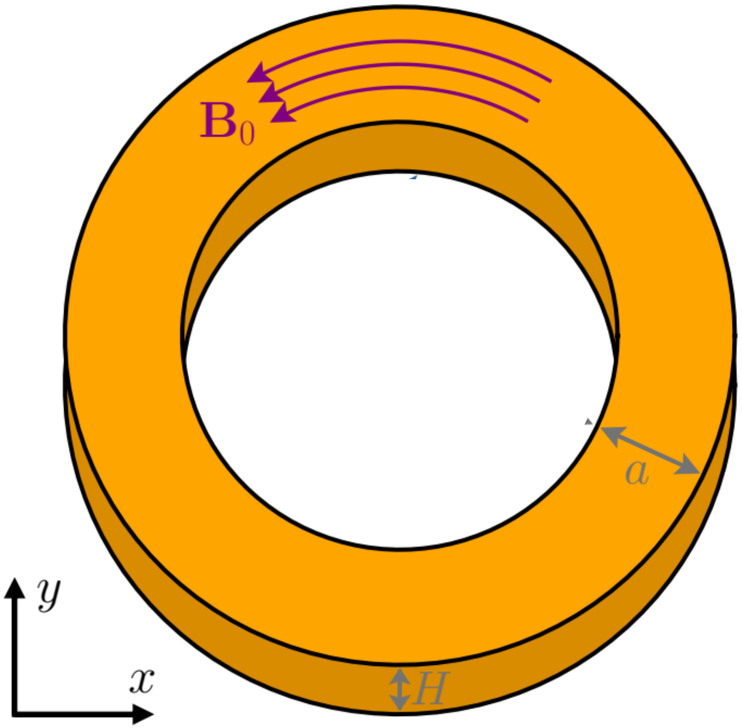
VD, Garcia-Cely, Rodd `22
s.a. Berlin et al `21

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

GW signal in axion haloscopes

eg ABRACADABRA, SHAFT, DM Radio:

VD, Garcia-Cely, Rodd `22



static magnetic field (i.e. rigid detector)

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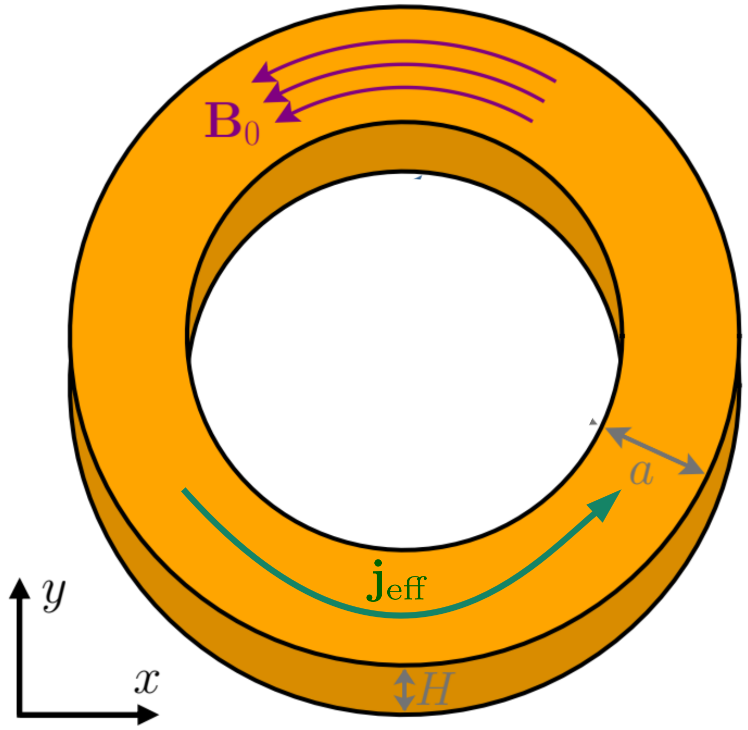

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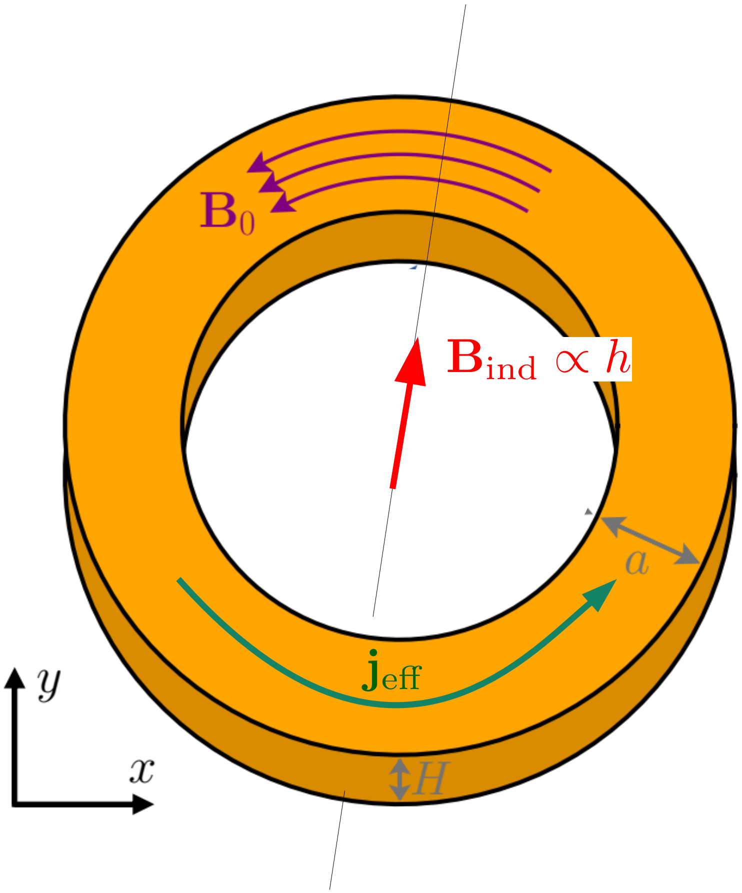

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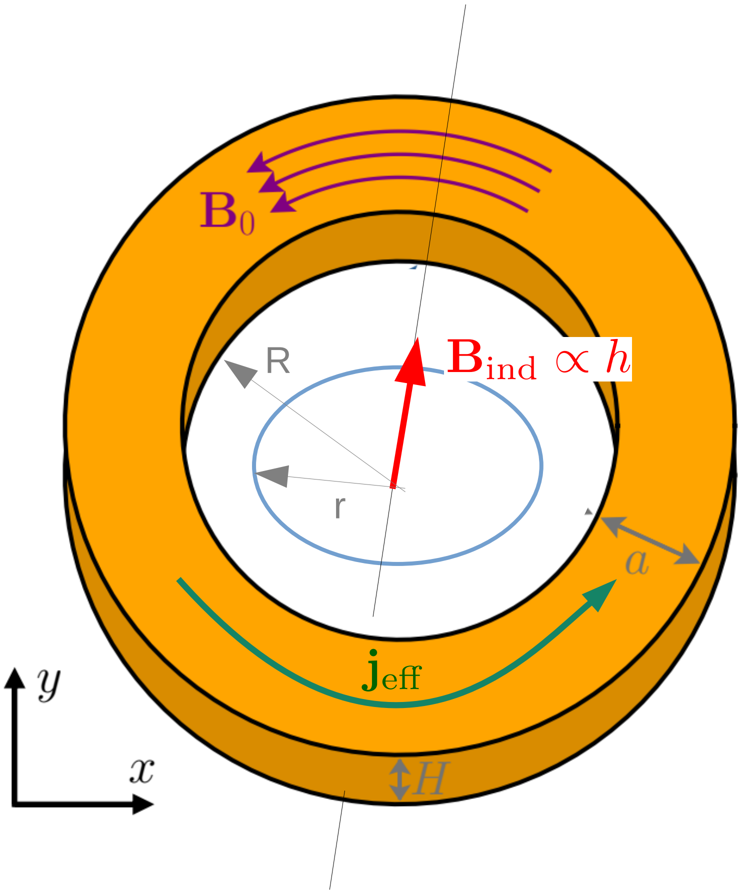

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at leading order in (ωR) :

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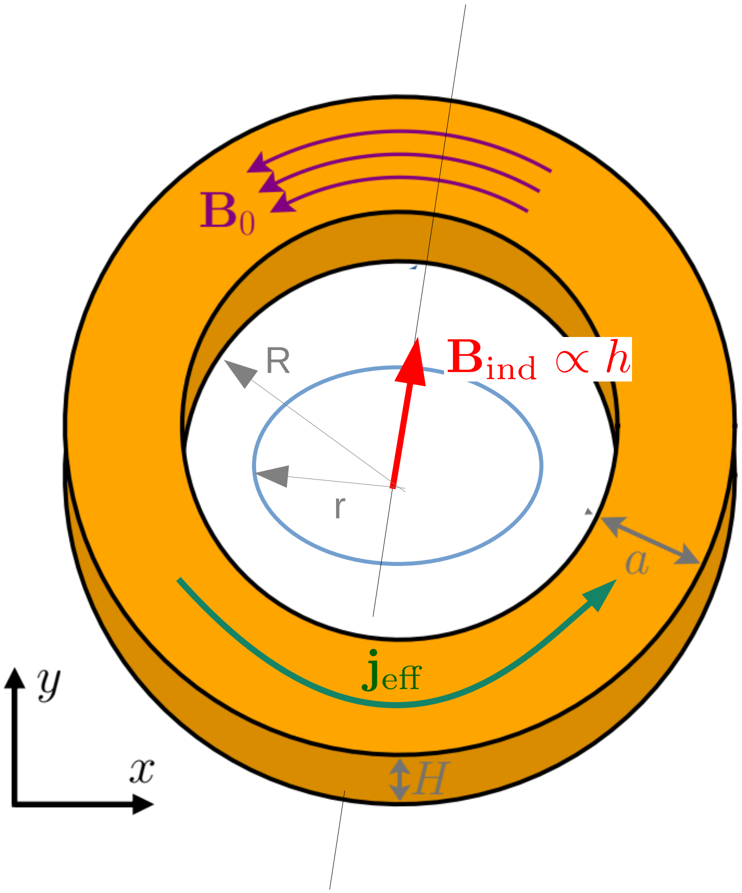

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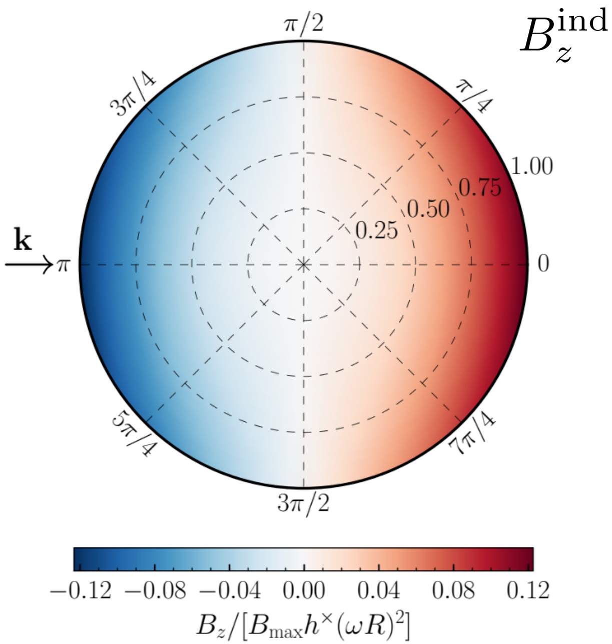
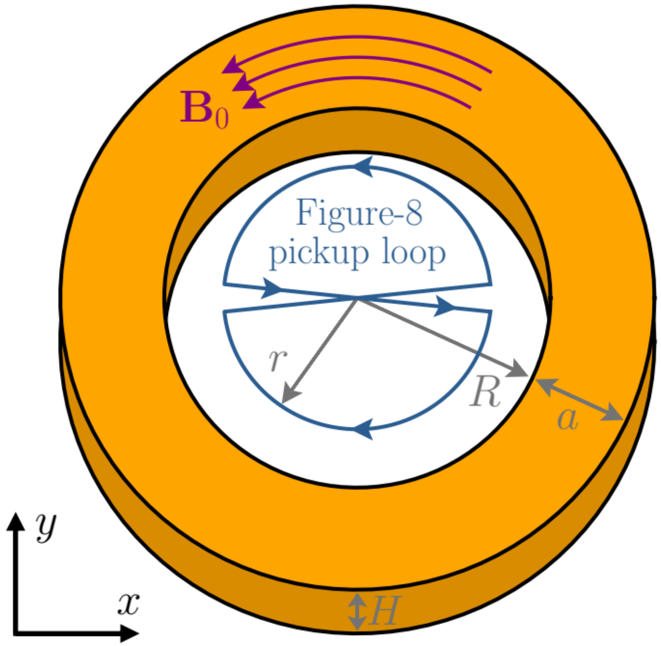
optimized pickup loop geometry

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

leading order $(\omega R)^2$ contribution captured by breaking cylindrical symmetry, e.g. using a figure-8 pickup loop

[VD, Garcia-Cely, Lee, Rodd `23] Symmetries and selection rules





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

$$\sim (\omega L)^2 h B_0 L^2$$

parametric improvement for modified pickup loop

geometry and time scales

VD, Garcia-Cely, Lee, Rodd `23

Symmetries and selection rules:

- For an instrument with azimuthal symmetry, at leading $\mathcal{O}[(\omega L)^2]$: $\Phi_h \propto h^+$
- For an instrument with azimuthal symmetry, the flux is proportional to either h^+ or $h^\times$
- For an instrument with full cylindrical symmetry, ϕ_h contains only even or odd powers of ω

geometry and time scales

VD, Garcia-Cely, Lee, Rodd `23

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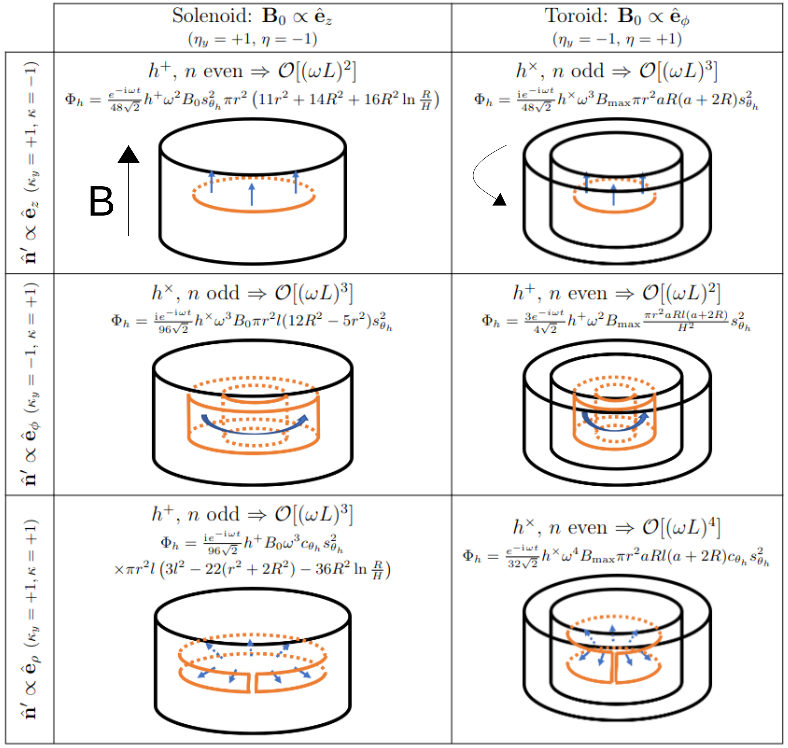

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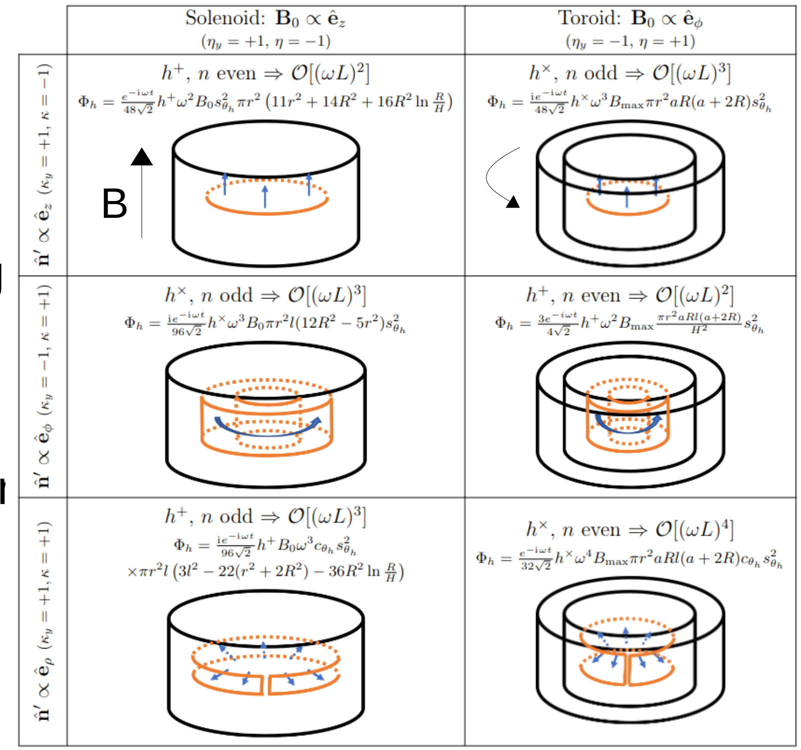

Time scales:

$$\Phi_h(h^+, h^\times; \phi_h, \theta_h) = \mathcal{R}_c\, \Phi_a(g_{a\gamma\gamma}),$$

$$\mathcal{R}_c = \left(\frac{T_m}{\tau_h}\right)^{1/4} \left(\frac{Q_a}{Q_h}\right)^{1/4} \begin{cases} 1 & Q_r < Q_a,\, Q_h, \\ (Q_a/Q_r)^{1/4} & Q_a < Q_r < Q_h, \\ Q_r/Q_h & Q_h < Q_r < Q_a, \\ (Q_a/Q_r)^{1/4} Q_r/Q_h & \text{otherwise.} \end{cases}$$

signal duration, coherence time < ring up time, axion coherence time, measurement time

→ will reduce detectability

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

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Frequency: tied to energy scale of cosmic event

during radiation era: $\quad f \sim 100\text{ MHz}/\epsilon_*\,(T_*/10^{15}\text{ GeV})\,, \quad \epsilon_* \lesssim 1$

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

cosmological sources

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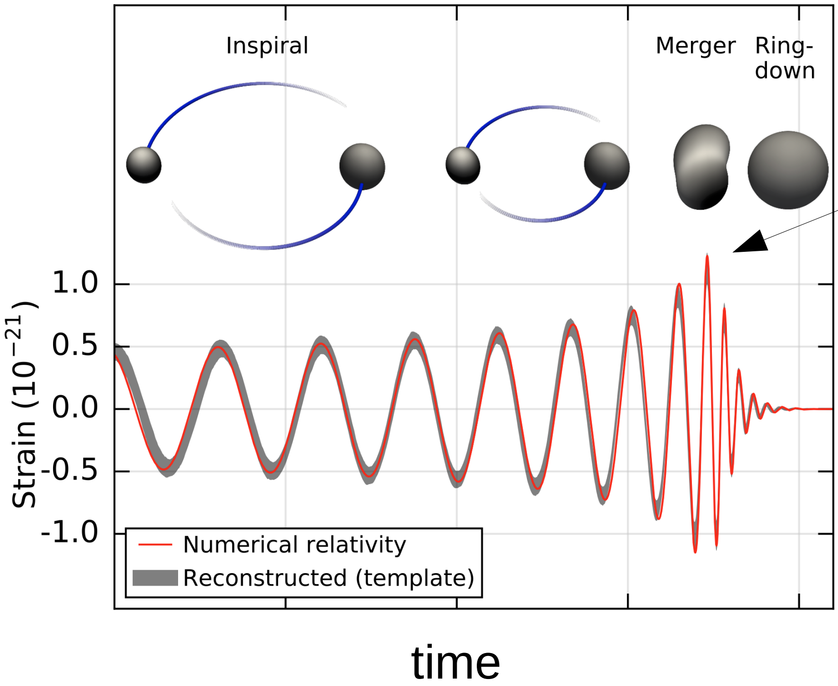
Examples: (Axion) inflation, (p)reheating, relic cosmic GW background, phase transitions (first order PT and/or topological defects from PTs) ,...
see Living Review: https://arxiv.org/abs/2011.12414

astrophysical sources

Example:
mergers of light primordial black holes

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



$$f_{\rm ISCO} = 220\ \rm MHz \left(\frac{10^{-5} M_\odot}{m_{\rm PBH}}\right)$$

astrophysical sources

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

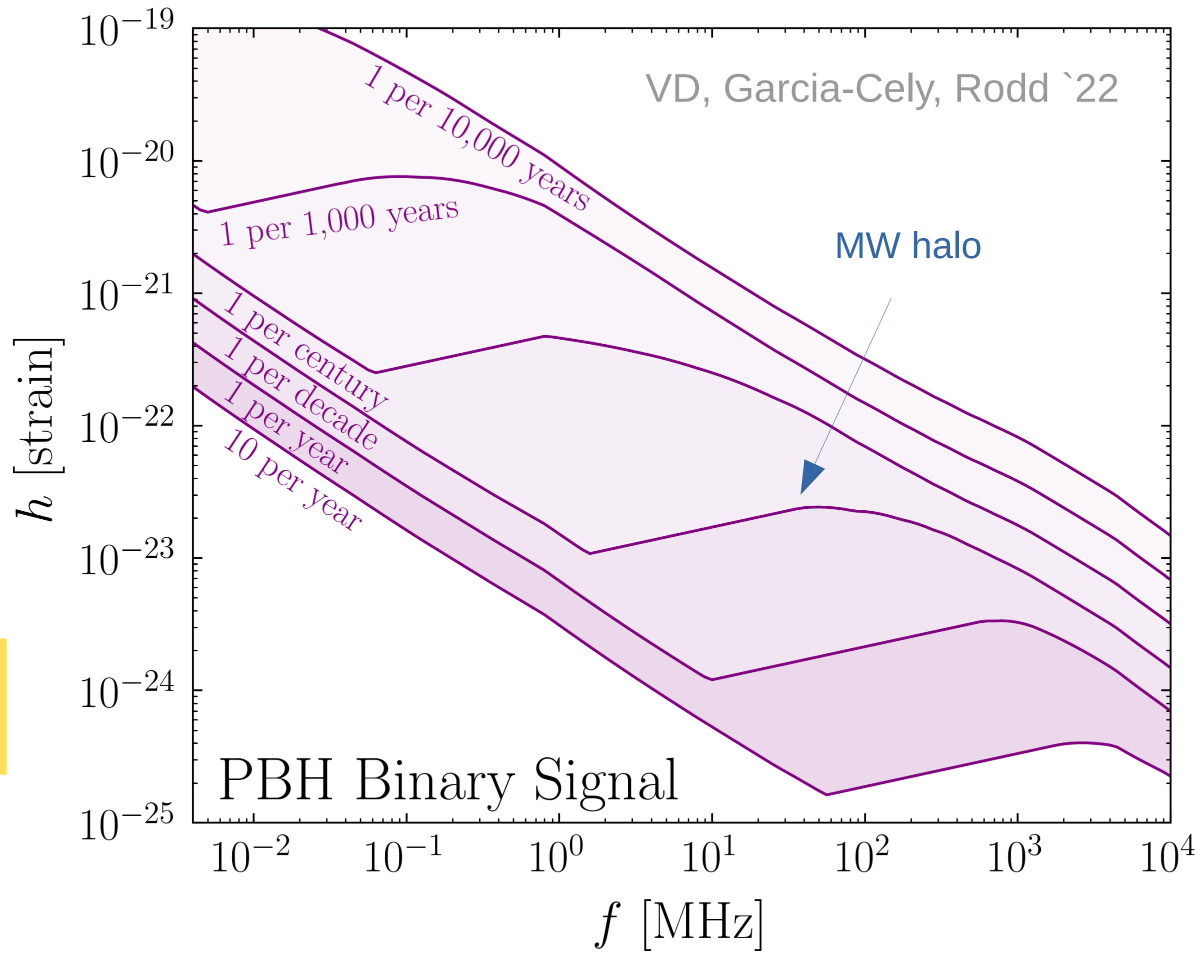
event rate:

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

MW halo ($\delta(r)$) merger rate ($R_0(m_{\rm PBH}, f_{\rm PBH})$)

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

large GW amplitudes possible for rare events

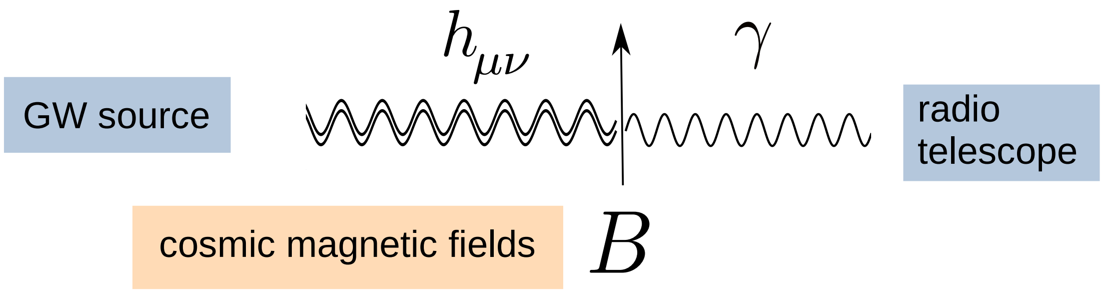


see also Franciolini, Maharana, Muia `22

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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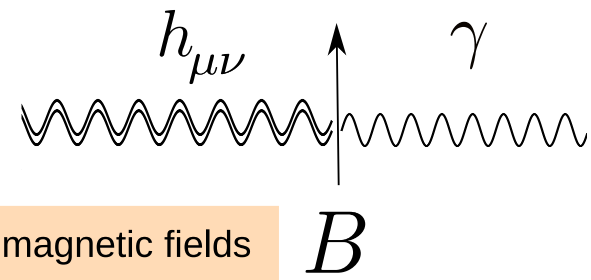
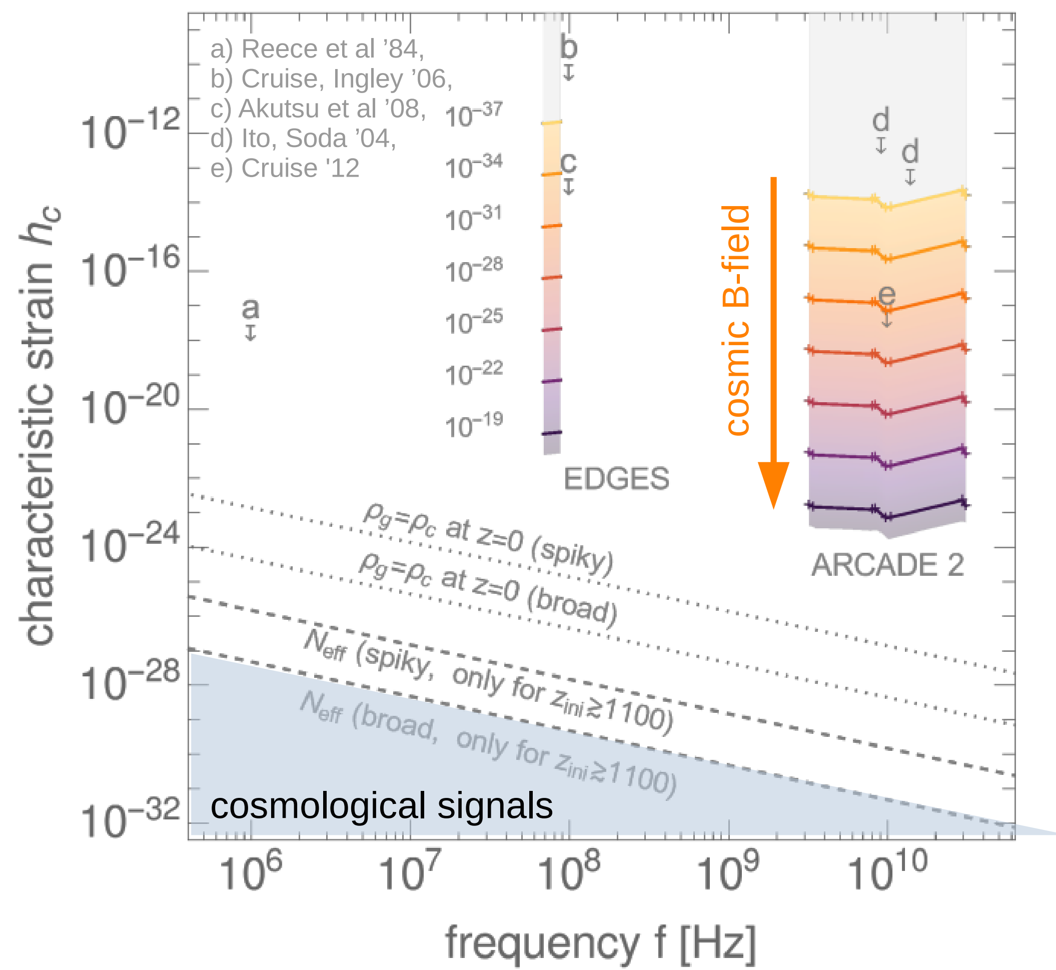
PRL 126 (2021) 2, 021104

GW source

cosmic magnetic fields





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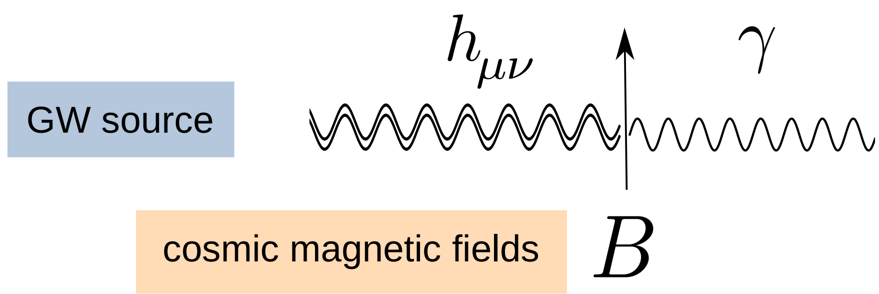
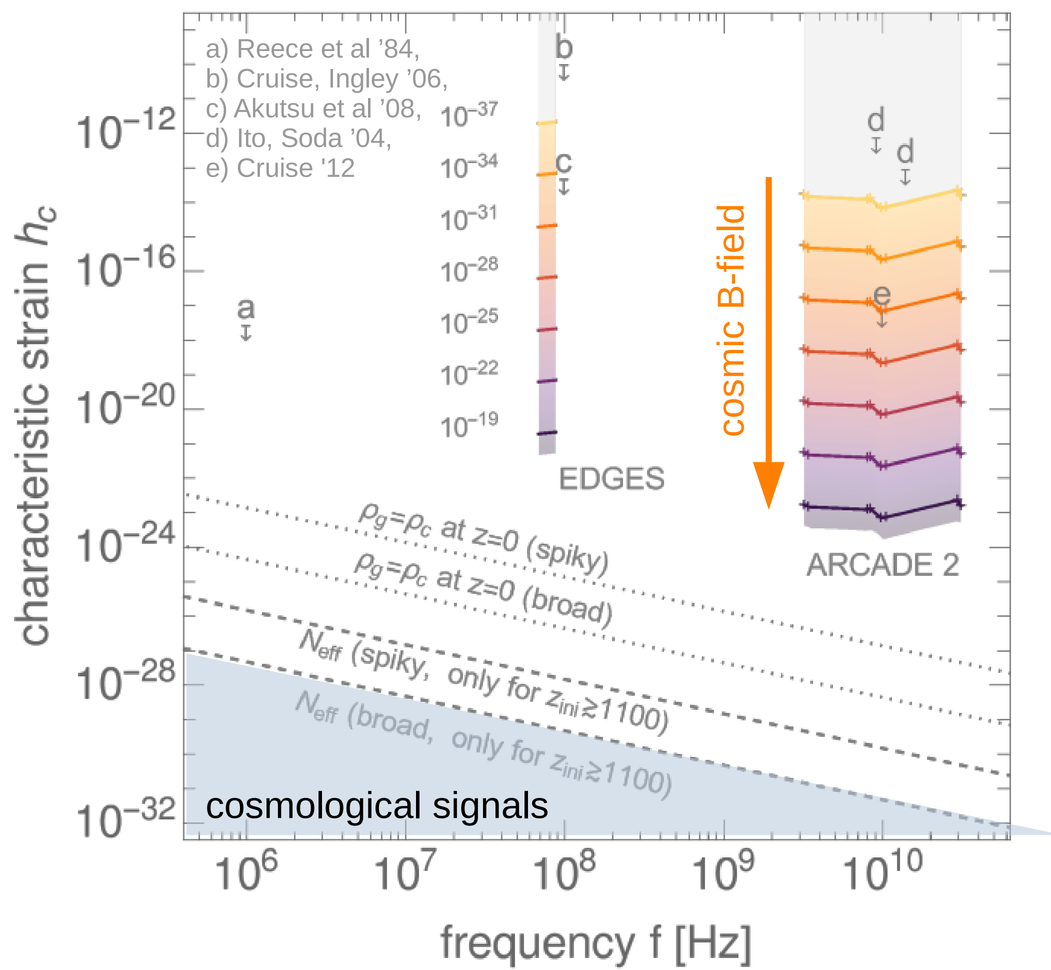


- promising, but significant improvements needed
- a lot of room for new ideas (laboratory & cosmo)



wave versus particle regime

energy density of GW:

$$\rho \sim h^2 \omega^2 M_{\rm pl}^2$$

number of GW `quanta‘ in de-Broglie volume:

$$n = \rho/\omega \,, \quad \lambda_{\rm dB} \sim 1/\omega \quad \Rightarrow \quad n\,\lambda_{\rm dB}^3 \sim h^2 M_{\rm pl}^2/\omega^2$$

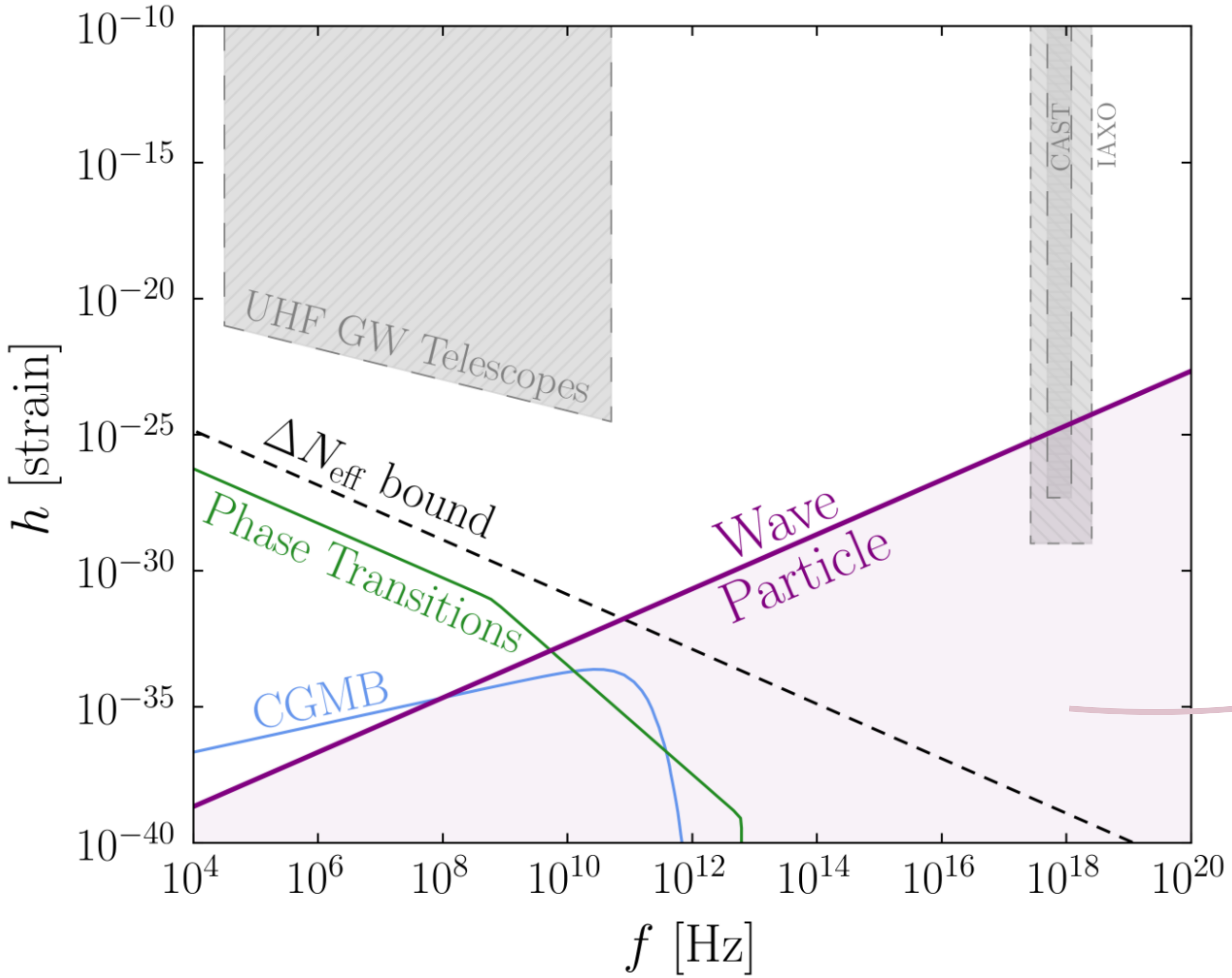
single graviton limit:

$$N = n\lambda_{\rm dB}^3 < 1 \quad \Rightarrow \quad h \lesssim \omega/M_{\rm pl}$$

(at LIGO, $N \sim 10^{37}(h/10^{-22})^2$)

single graviton detection ?

Carney, VD, Rodd `23



- dilute graviton gas vs classical GW
- CAST has the *sensitivity* to detect single gravitons (the source is the issue)

see also F. Dyson `13

test of quantum gravity ?

Carney, VD, Rodd `23

Do ‚discrete clicks‘ in CAST (assuming perfect noise control) imply quantum gravity ?

test of quantum gravity ?

Carney, VD, Rodd `23

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No. Classical EM model + quantum detector can give same response.
(though classical model may need to be a bit baroque)

test of quantum gravity ?

Carney, VD, Rodd `23

Do ‚discrete clicks' in CAST (assuming perfect noise control) imply quantum gravity ?

No. Need to measure e.g.

- sub-Poisson distribution (requires `quantum', e.g. squeezed GW state!)
  → de facto impossible
- or other entanglement measurement (similarly difficult)
- or sufficiently convincing circumstantial evidence (CMB tensor modes)

Does the photo electric effect (discrete clicks due to EM wave) prove EM quantization ?

No. Classical EM model + quantum detector can give same response.
(though classical model may need to be a bit baroque)