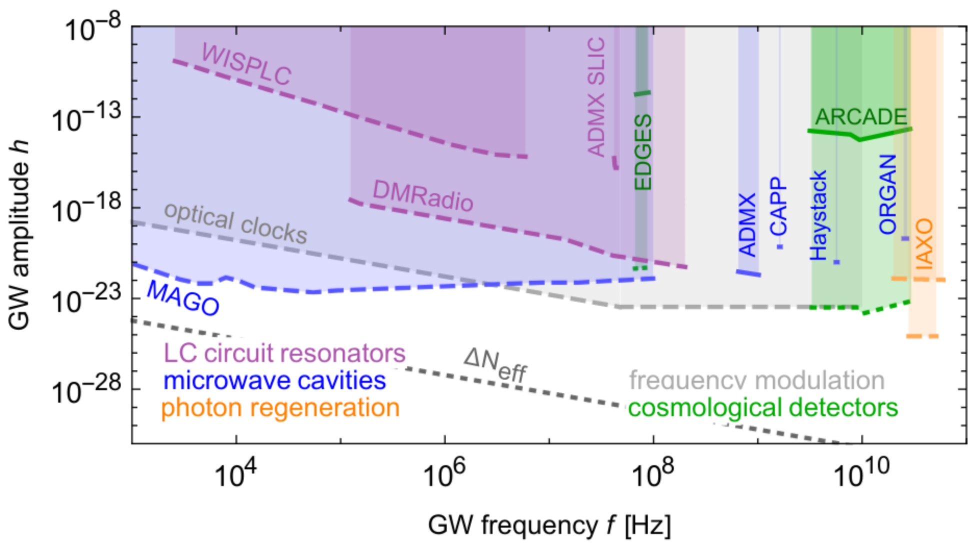
Axions and gravitational waves



Valerie Domcke
CERN

Axions++
September 25 - 28, 2023

based in part on

2011.12414
Living Review on UHF GW searches,

2202.00695, 2306.03125, 2306.04496
w. Camilo Garcia-Cely, Sung Mook Lee and Nick Rodd

Axions and GWs

Axions and GWs

Axions as a source of GWs

$\phi F_{\mu\nu}\tilde{F}^{\mu\nu} \quad \text{with } \dot{\phi} \neq 0$ → tachyonic gauge field instability → GW source (eg axion inflation)

Turner, Widrow `88; Garretson, Field, Caroll `92

axion superradiance around BHs → GW source

review: Brito, Cardoso, Pani `15

see talks by Francesca Day, Yifan Chen

axion strings, domain walls → GW source

see talks by Marco Gorghetto, Yann Goutnoire

Axions and GWs

Axions as a source of GWs

$\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$ with $\dot{\phi} \neq 0$ → tachyonic gauge field instability → GW source (eg axion inflation)

Turner, Widrow `88; Garretson, Field, Caroll `92

axion superradiance around BHs → GW source

review: Brito, Cardoso, Pani `15

see talks by Francesca Day, Yifan Chen

axion strings, domain walls → GW source

see talks by Marco Gorghetto, Yann Goutnoire

Synergies between axion and GW searches ← this talk

- GW electrodynamics vs axion electrodynamics
- Searching for high-frequency GWs with axion haloscopes
- [Possible high-frequency GW sources]
- Photon regeneration experiments and cosmological detectors

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

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

induced at linear order in h
in presence of external E,B field
VD, Garcia-Cely, Rodd `22

Direct analogy with axion electrodynamics

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

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

effective source terms in Maxwell‘s equation due to GW

[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

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

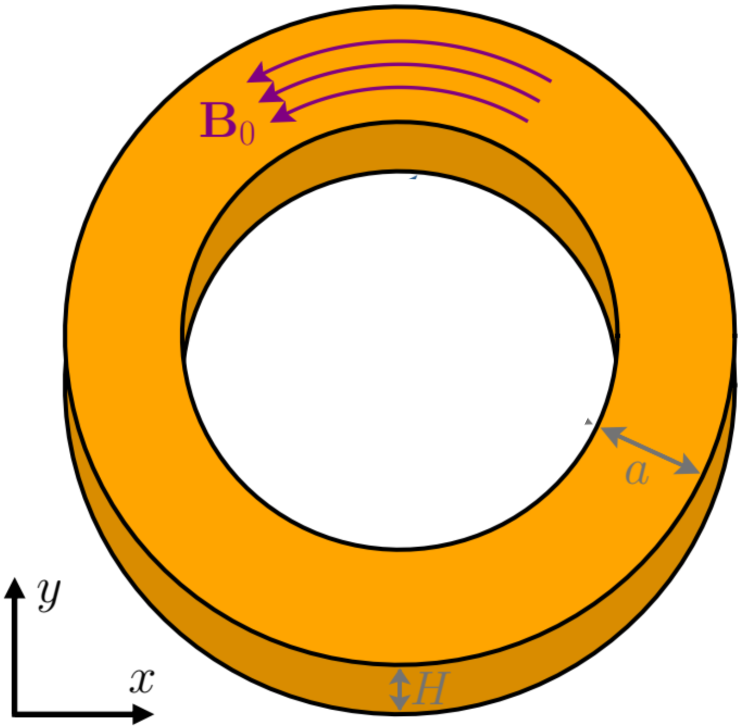
VD, Garcia-Cely, Rodd `22
s.a. Berlin et al `21

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

GW signal in axion haloscopes

eg ABRACADABRA, SHAFT, DM Radio:

VD, Garcia-Cely, Rodd `22

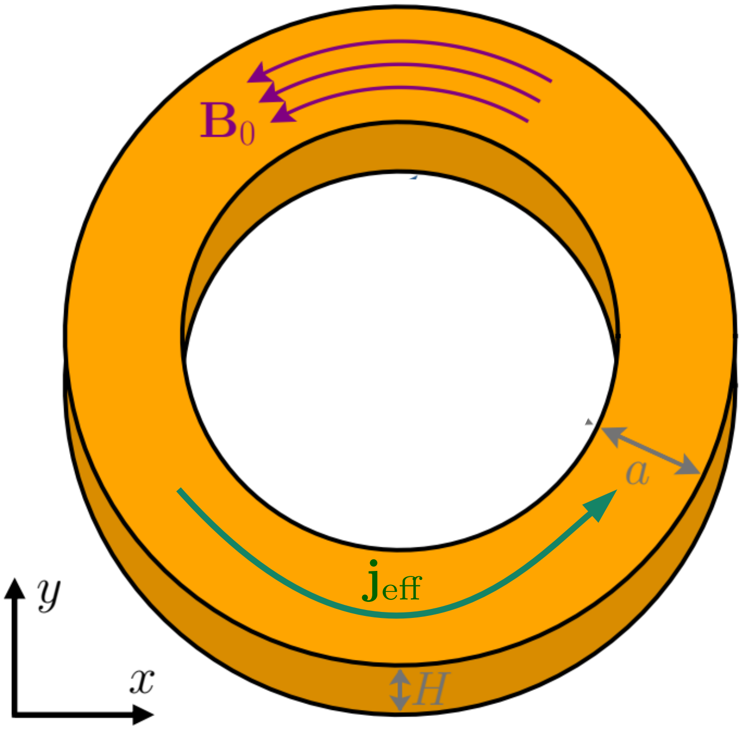


static magnetic field

GW signal in axion haloscopes

eg ABRACADABRA, SHAFT, DM Radio:

VD, Garcia-Cely, Rodd `22



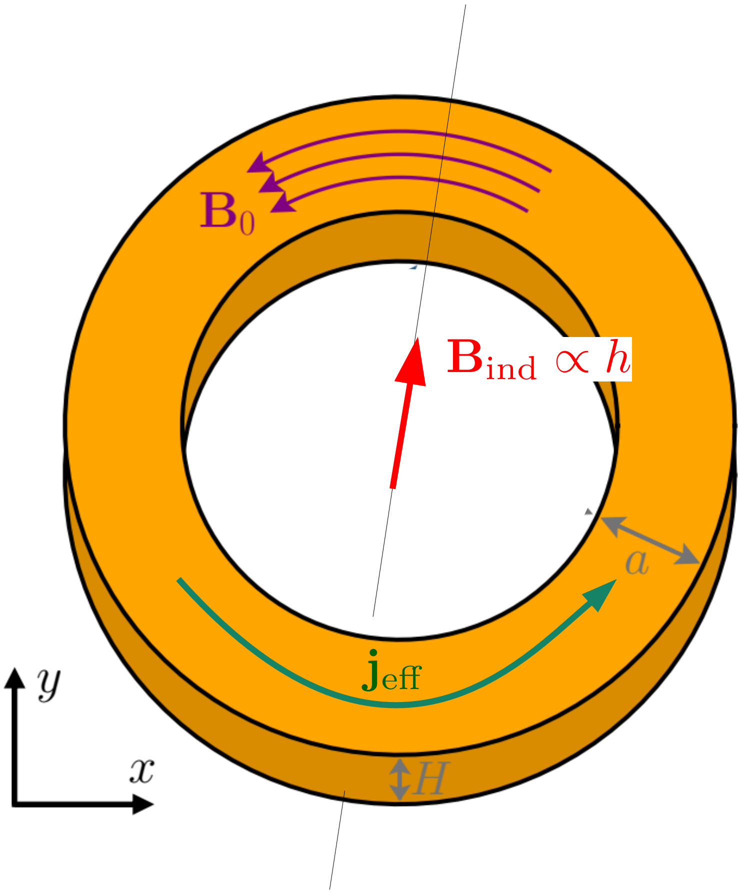
static magnetic field

effective current

GW signal in axion haloscopes

eg ABRACADABRA, SHAFT, DM Radio:

VD, Garcia-Cely, Rodd `22



static magnetic field

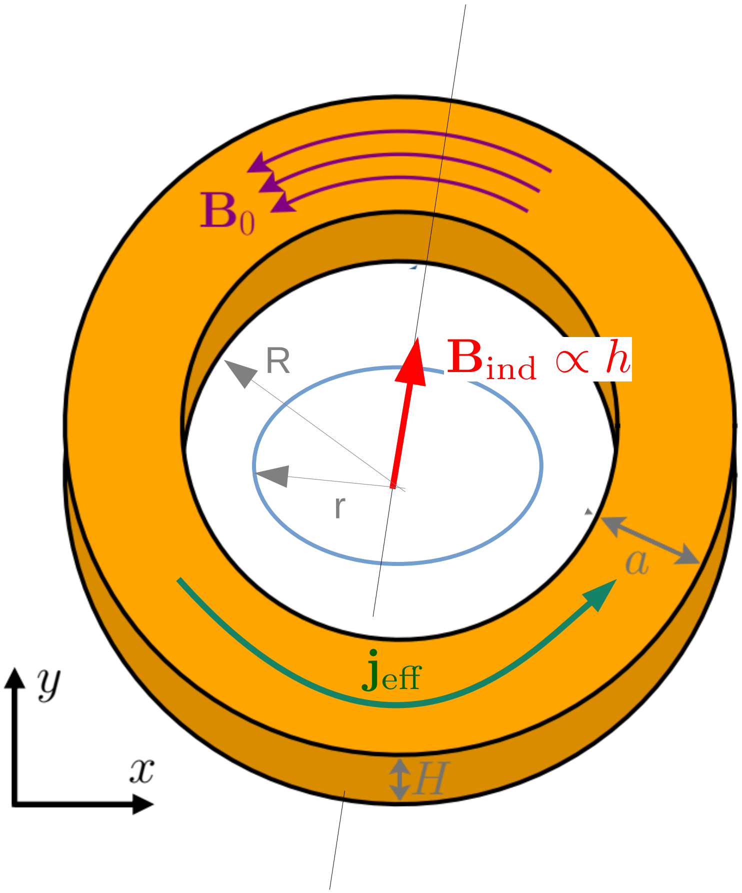
effective current

induced oscillating magnetic field

GW signal in axion haloscopes

eg ABRACADABRA, SHAFT, DM Radio:

VD, Garcia-Cely, Rodd `22



static magnetic field

effective current

induced oscillating magnetic field

measure magnetic flux (~ h) through pickup loop

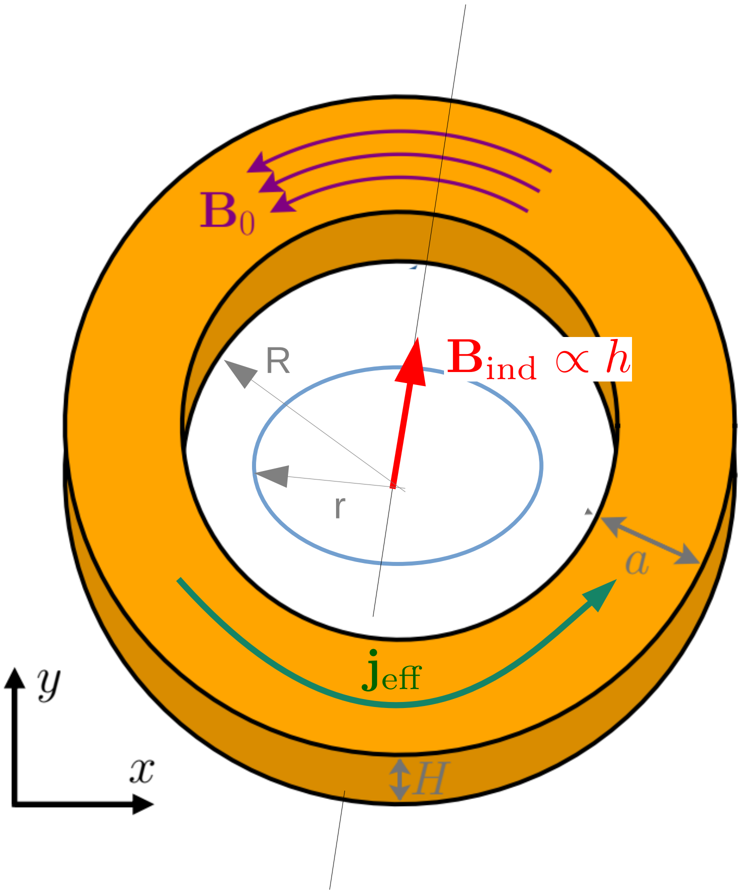
at leading order in (ωR) :

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

GW signal in axion haloscopes

eg ABRACADABRA, SHAFT, DM Radio:

VD, Garcia-Cely, Rodd `22



static magnetic field

effective current

induced oscillating magnetic field

measure magnetic flux (~ h) through pickup loop

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

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

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

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

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

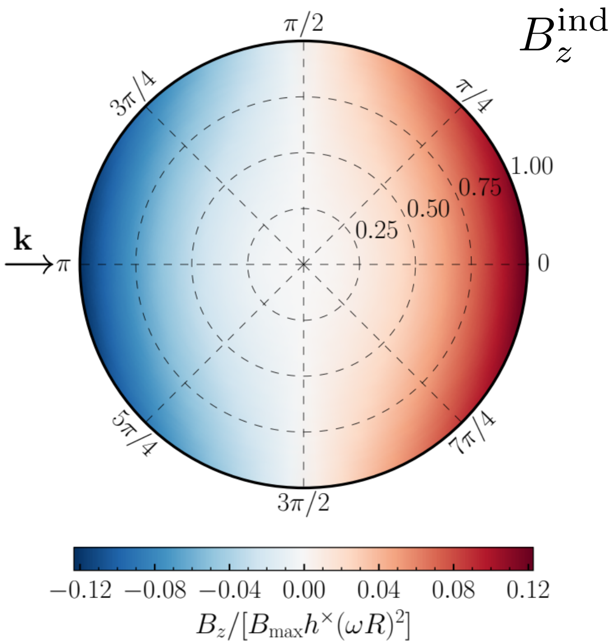
suppression at low frequencies as $(\omega L)^3$

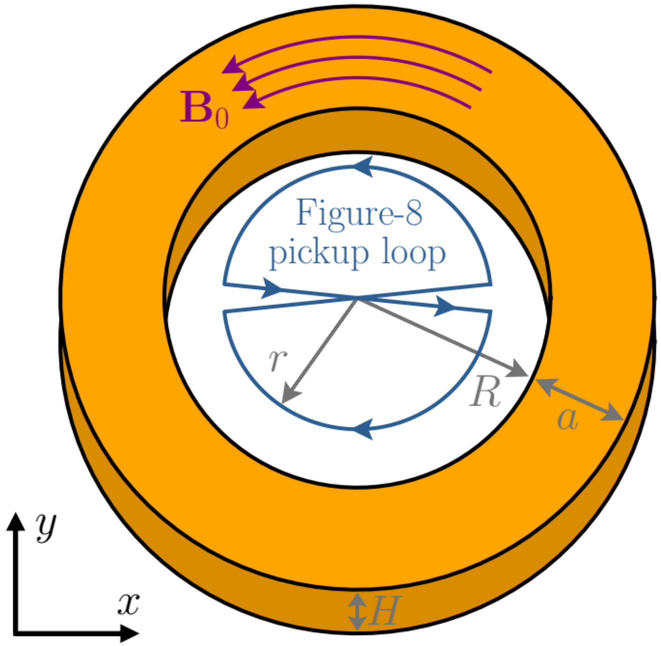
implies very good volume scaling

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 if cylindrical symmetry is broken, here by using a figure-8 geometry for the pickup loop





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

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

parametric improvement for modified pickup loop

geometry and time scales

VD, Garcia-Cely, Lee, Rodd `23

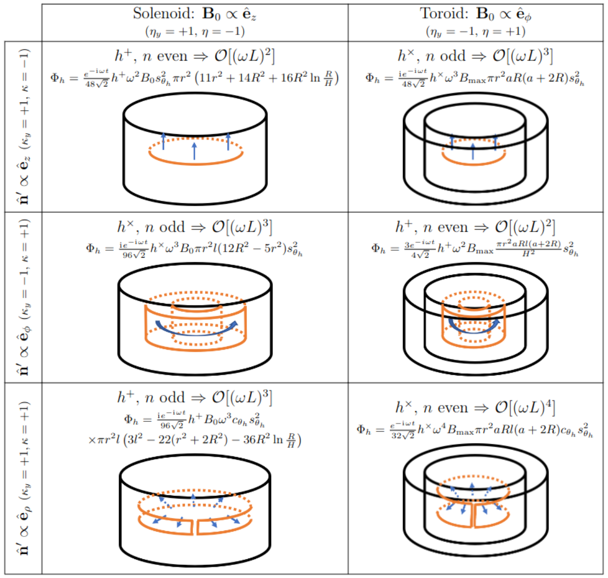
Symmetries and selection rules:

- For an instrument with azimuthal symmetry, $\Phi_h \propto h^+ \text{ at } \mathcal{O}[(\omega L)^2]$
- For an instrument with azimuthal symmetry, the flux is proportional to either h^+ or h^x
- 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

Symmetries and selection rules:

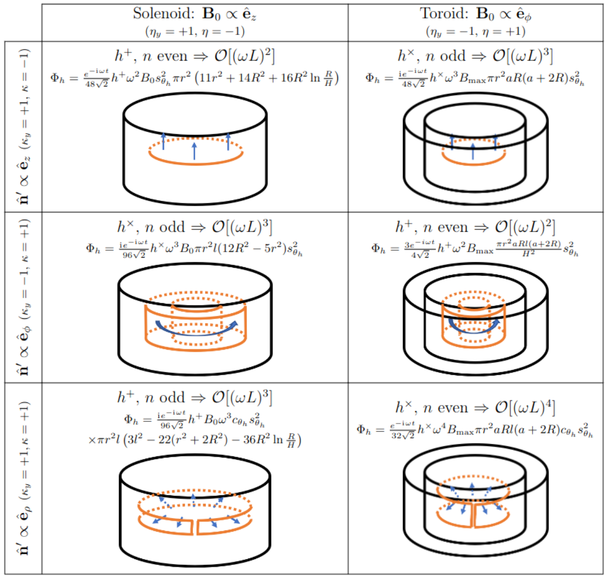


- For an instrument with azimuthal symmetry, $\Phi_h \propto h^+$ at (
- For an instrument with azimuthal symmetry, the flux is propor
- For an instrument with full cylindrical symmetry, ϕ_h contains (

geometry and time scales

VD, Garcia-Cely, Lee, Rodd `23

Symmetries and selection rules:



- For an instrument with azimuthal symmetry, $\Phi_h \propto h^+$ at (
- For an instrument with azimuthal symmetry, the flux is propor
- For an instrument with full cylindrical symmetry, ϕ_h contains (

Time scales:

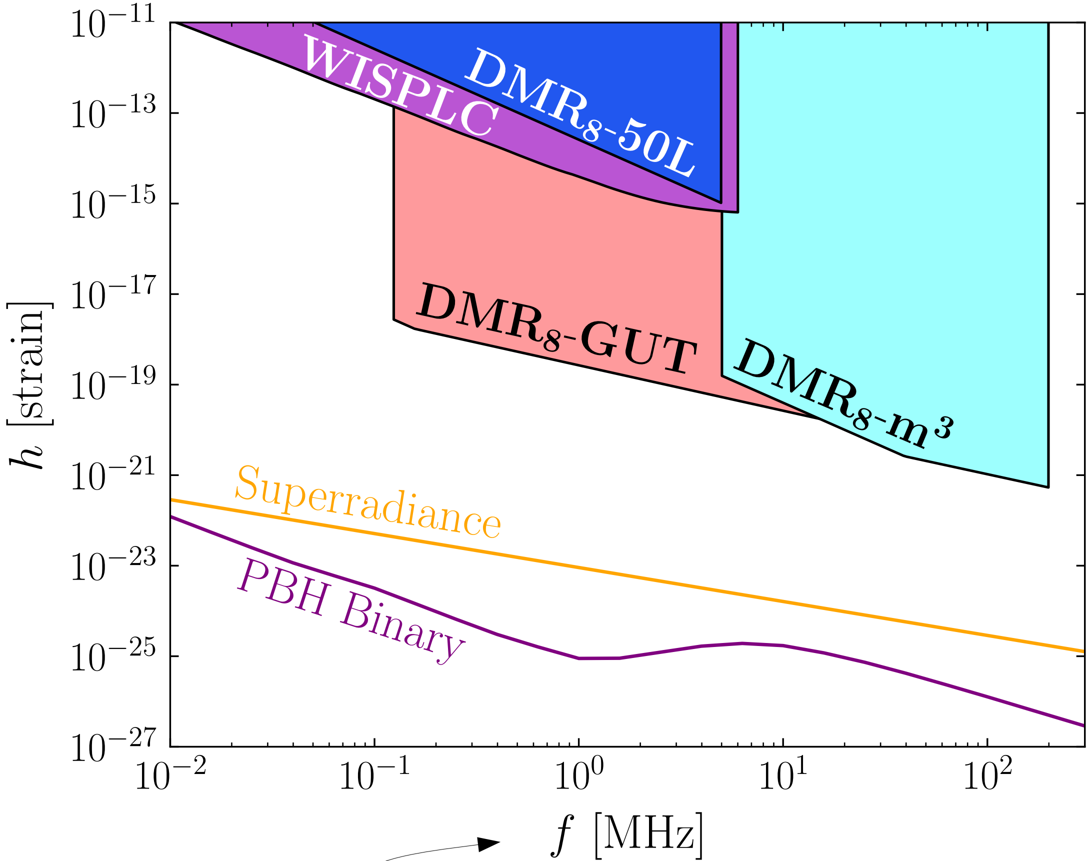
$$\Phi_h(h^+, h^\times; \phi_h, \theta_h) = \mathcal{R}_c \, \Phi_a(g_{a\gamma\gamma}),$$

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

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

→ will reduce detectability

bounds and prospects



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

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

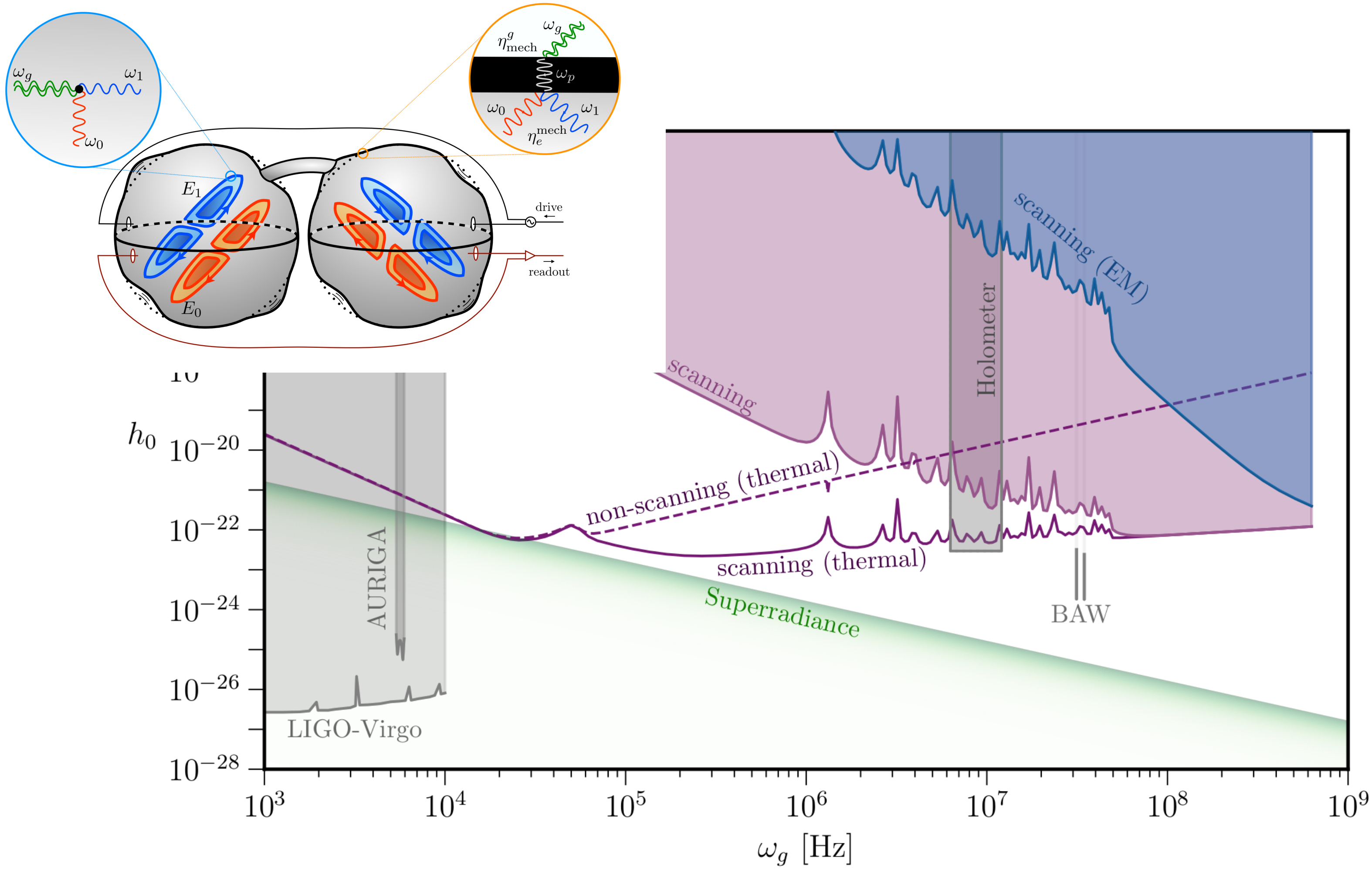
axion haloscopes as **high frequency** GW detectors

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

microwave cavities

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

Berlin, Blas, D'Agnolo et al `23



Axions and GWs

- GW electrodynamics vs axion electrodynamics
- Searching for high-frequency GWs with axion haloscopes
- [Possible high-frequency GW sources]
- Photon regeneration experiments and cosmological detectors

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

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

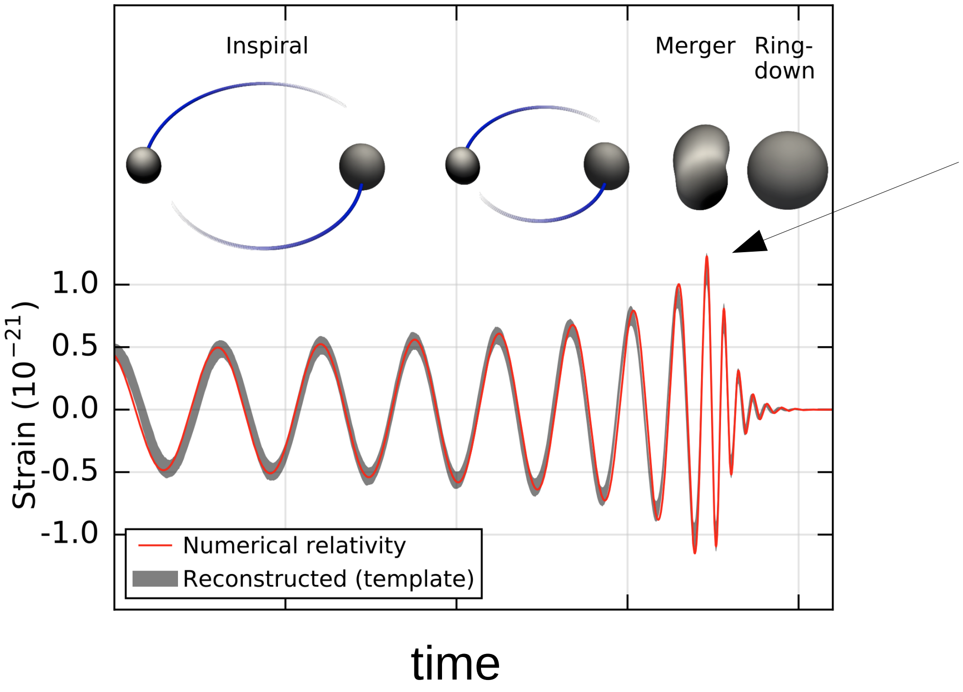
- localized GW sources, both coherent and incoherent signals possible
- no known astrophysical objects emit (significantly) in UHF band
- eg mergers of light primordial black holes or exotic compact objects, superradiance
- large signals require near-by events
  → rare events with GW strain far above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

UHF GW searches are always a search for New Physics

astrophysical sources

Example:
mergers of light primordial black holes

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



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

astrophysical sources

Example:
mergers of light primordial black holes

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

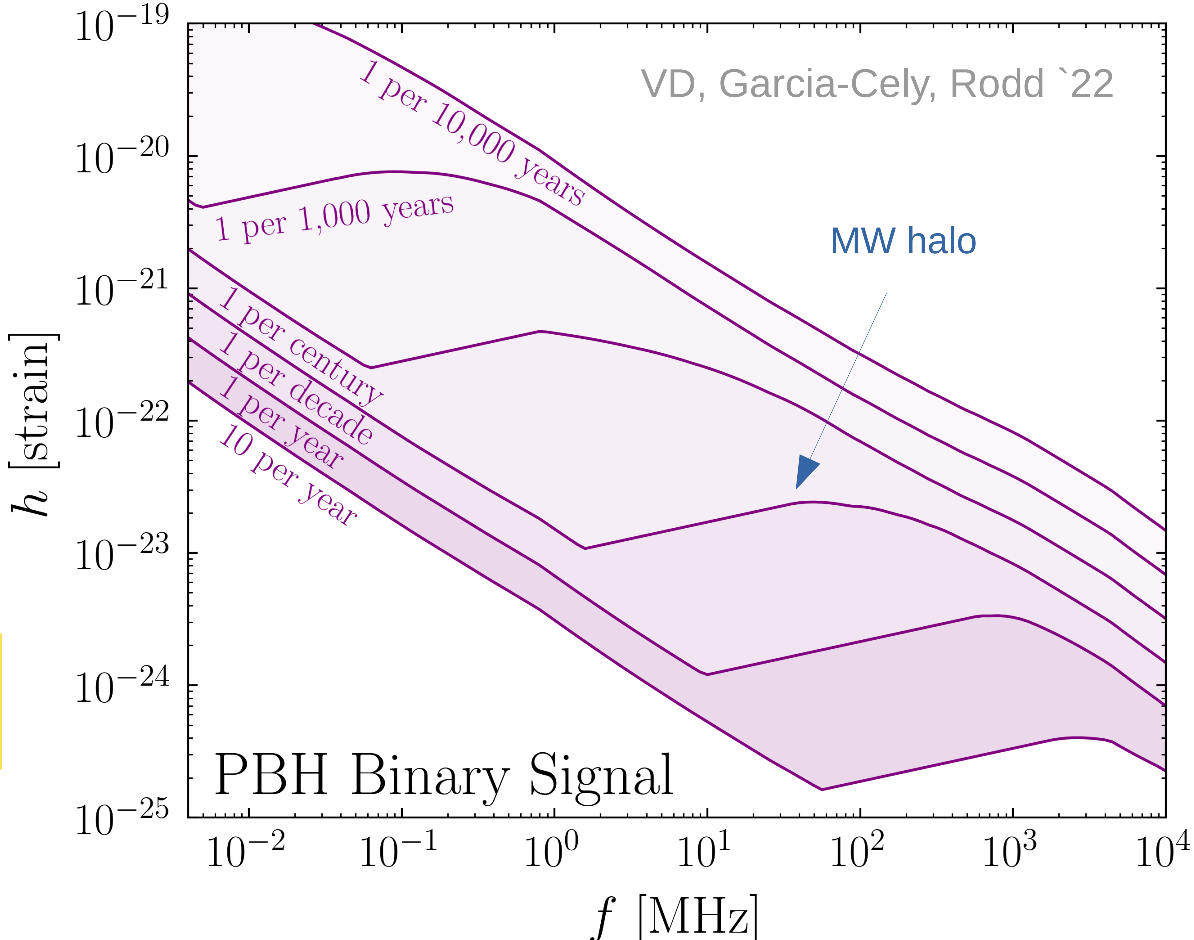
event rate:

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

MW halo — merger rate

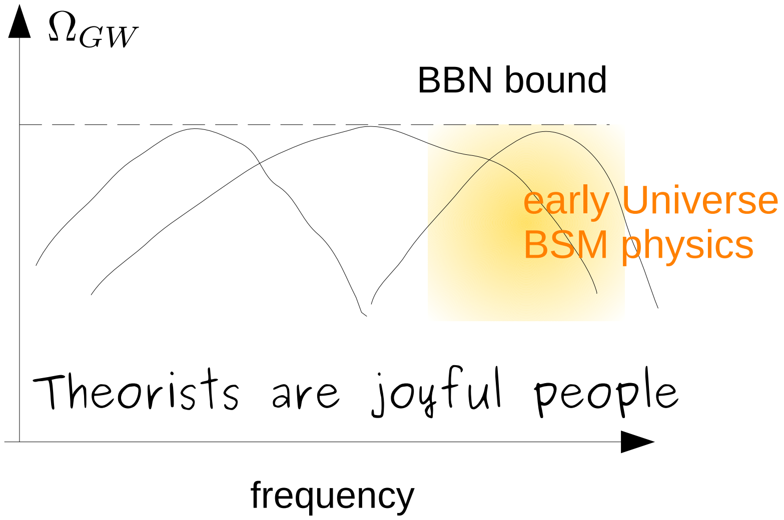
$$\times \Theta \left[Q^{1/4}\, h_{+,\times}^{\rm PBH}(f, m_{\rm PBH}, r) - h_{\rm th} \right]$$

large GW amplitudes possible for rare events



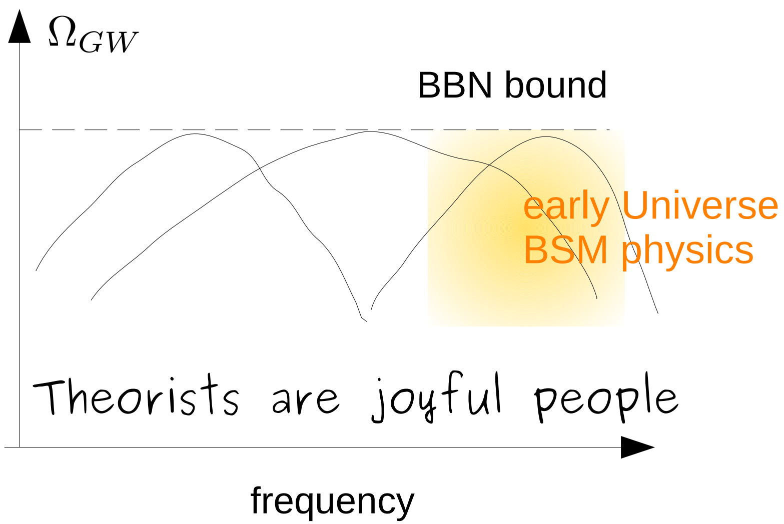
see also Franciolini, Maharana, Muia `22

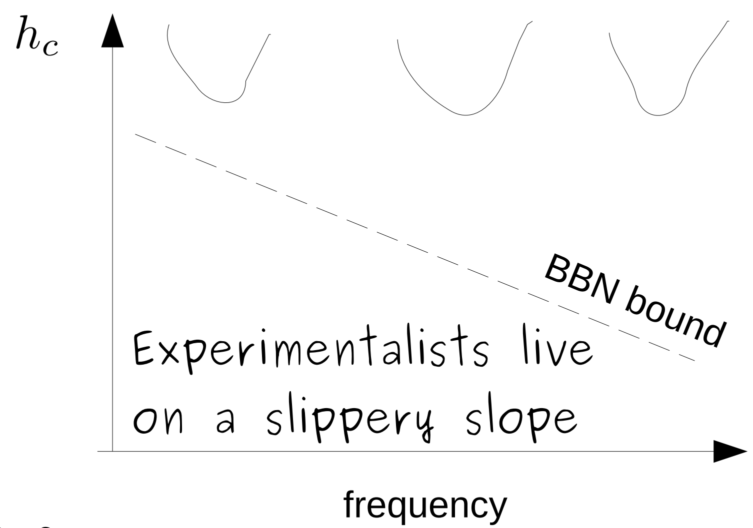
challenges in UHF GW detection



CMB/BBN bound constrains energy

challenges in UHF GW detection



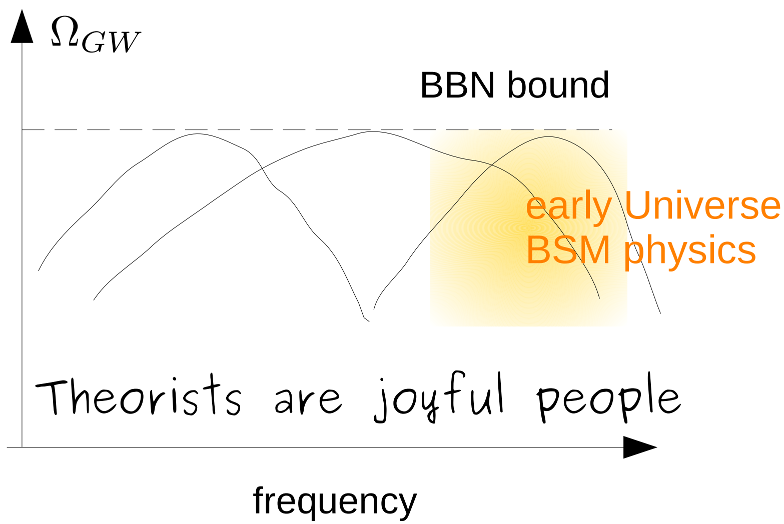


$$\Omega_{GW} \propto f^2 h_c^2$$

CMB/BBN bound constrains energy

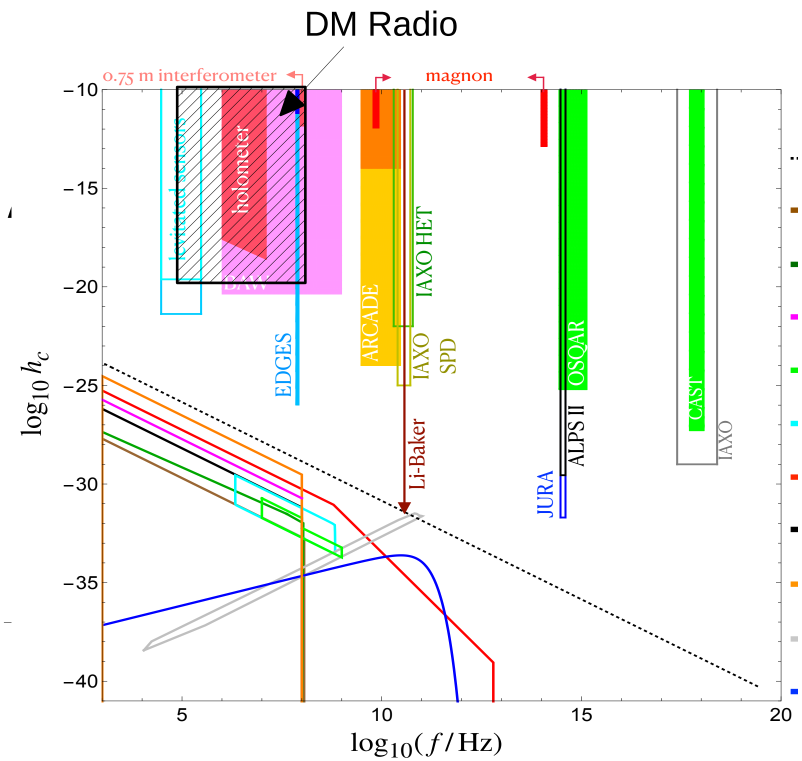
experiments measure displacement

challenges in UHF GW detection



h_c

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



CMB/BBN bound constrains energy

experiments measure displacement

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

Axions and GWs

- GW electrodynamics vs axion electrodynamics
- Searching for high-frequency GWs with axion haloscopes
- [Possible high-frequency GW sources]
- Photon regeneration experiments and cosmological detectors

GW to photon conversion

(inverse) Gertsenshtein effect:

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

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

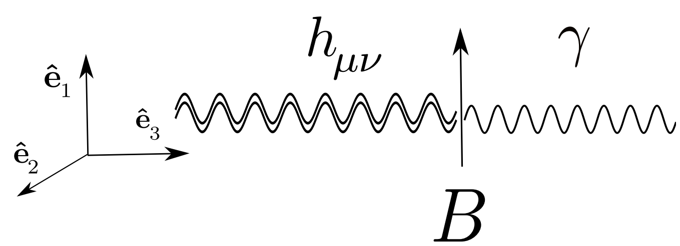
$A_\lambda =$ photon
$h_\lambda =$ GW
$B =$ ext. transv. B - field
$\omega_{\rm pl} =$ plasma frequency
$\mu^2 = 1 - \omega_{\rm pl}^2/\omega^2$

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

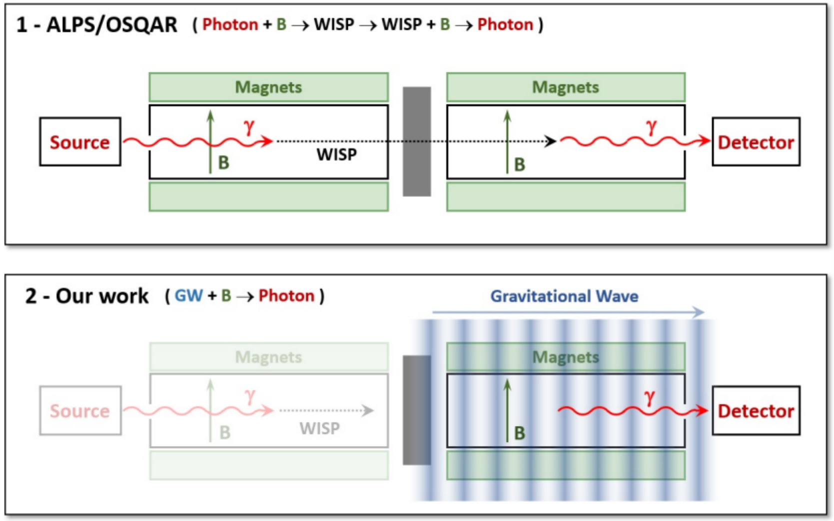


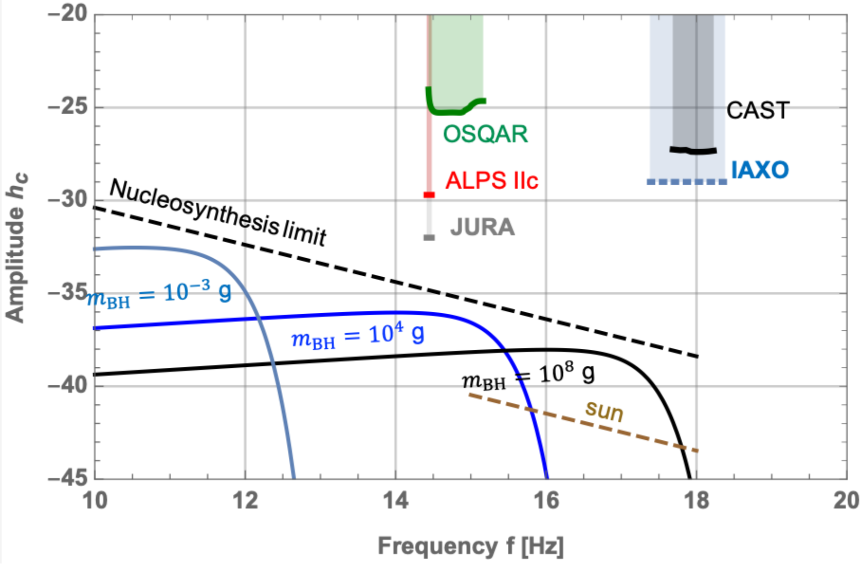
analogous to axion to photon conversion

LSW experiments

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

[Ejilli et al `19]

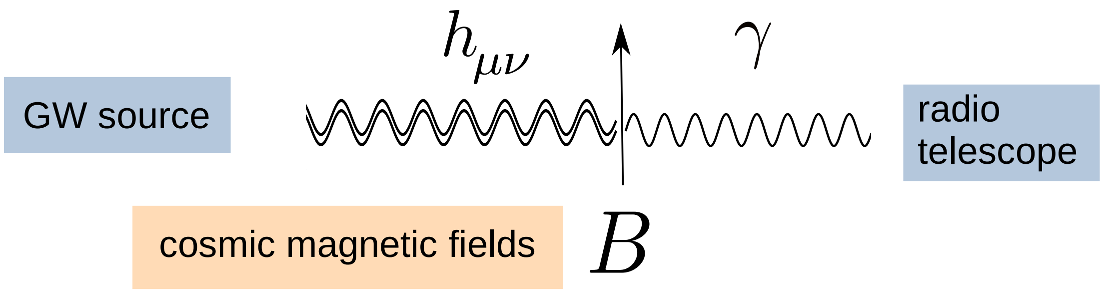




axion bounds recast as HFGW bounds

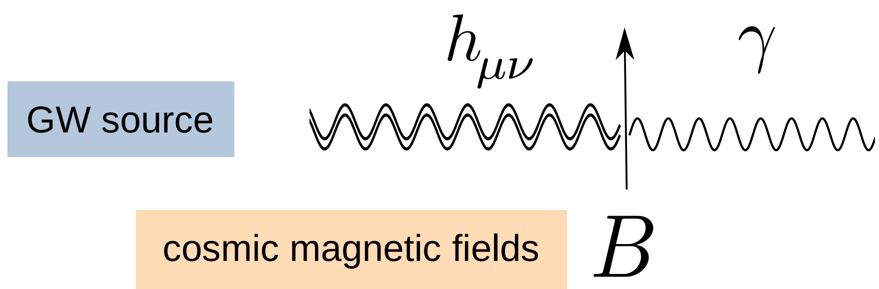
a cosmic GW detector

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

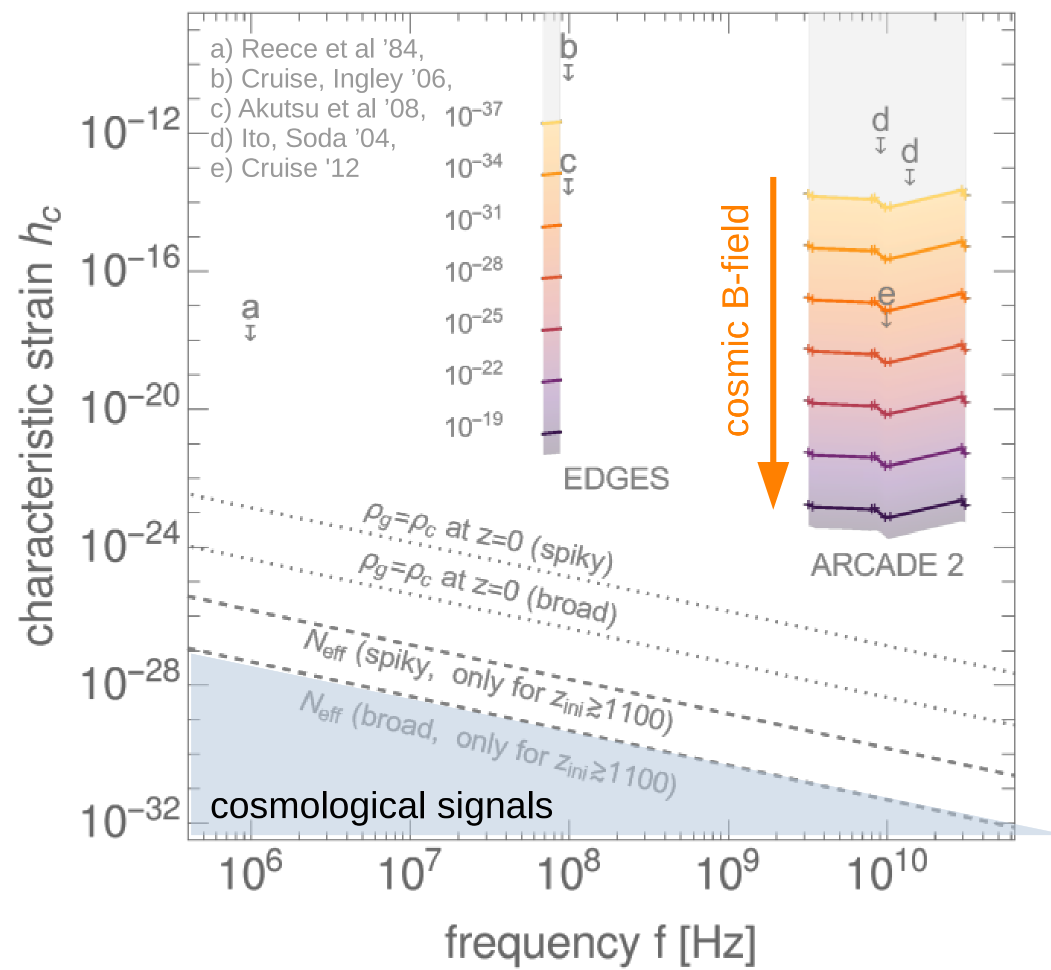


a cosmic GW detector

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

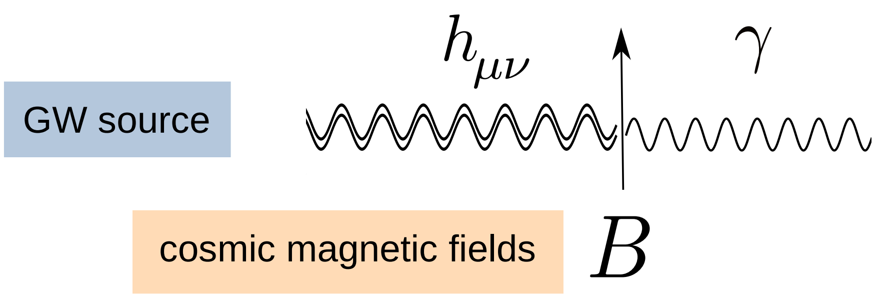


VD, Garcia-Cely `21

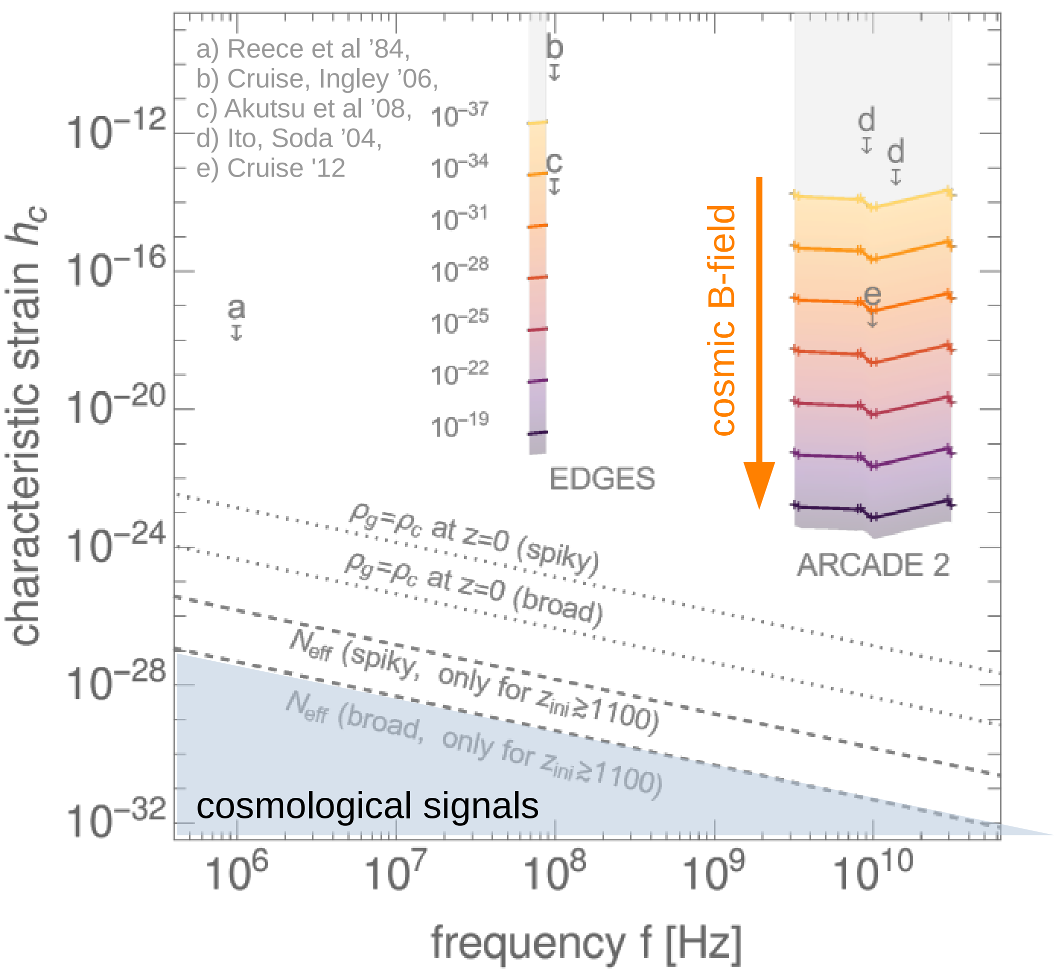


a cosmic GW detector

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



VD, Garcia-Cely `21



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

See also :

neutron stars: Feng et al `22, Liu e al `23, Ito et al `23

Milky Way: Ramazanov et al `23

CMB depletion: Fujita et al `20

Conclusions and Outlook

Synergies between GW and axion searches

- GW electrodynamics has clear similarities with axion electrodynamics:

  Important synergies between axion searches and UHF GW searches
- New bounds and prospects for low-mass axion haloscopes as GW detectors
- Also SRF cavities, LSW experiments, cosmological detectors,….

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

Conclusions and Outlook

Synergies between GW and axion searches

- GW electrodynamics has clear similarities with axion electrodynamics:

  Important synergies between axion searches and UHF GW searches
- New bounds and prospects for low-mass axion haloscopes as GW detectors
- Also SRF cavities, LSW experiments, cosmological detectors,….

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

Thank you!

backup slides

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

Amplitude: BBN / CMB bound

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

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

Frequency: tied to energy scale of cosmic event

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

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

cosmological sources

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

Frequency: tied to energy scale of cosmic event

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

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

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

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

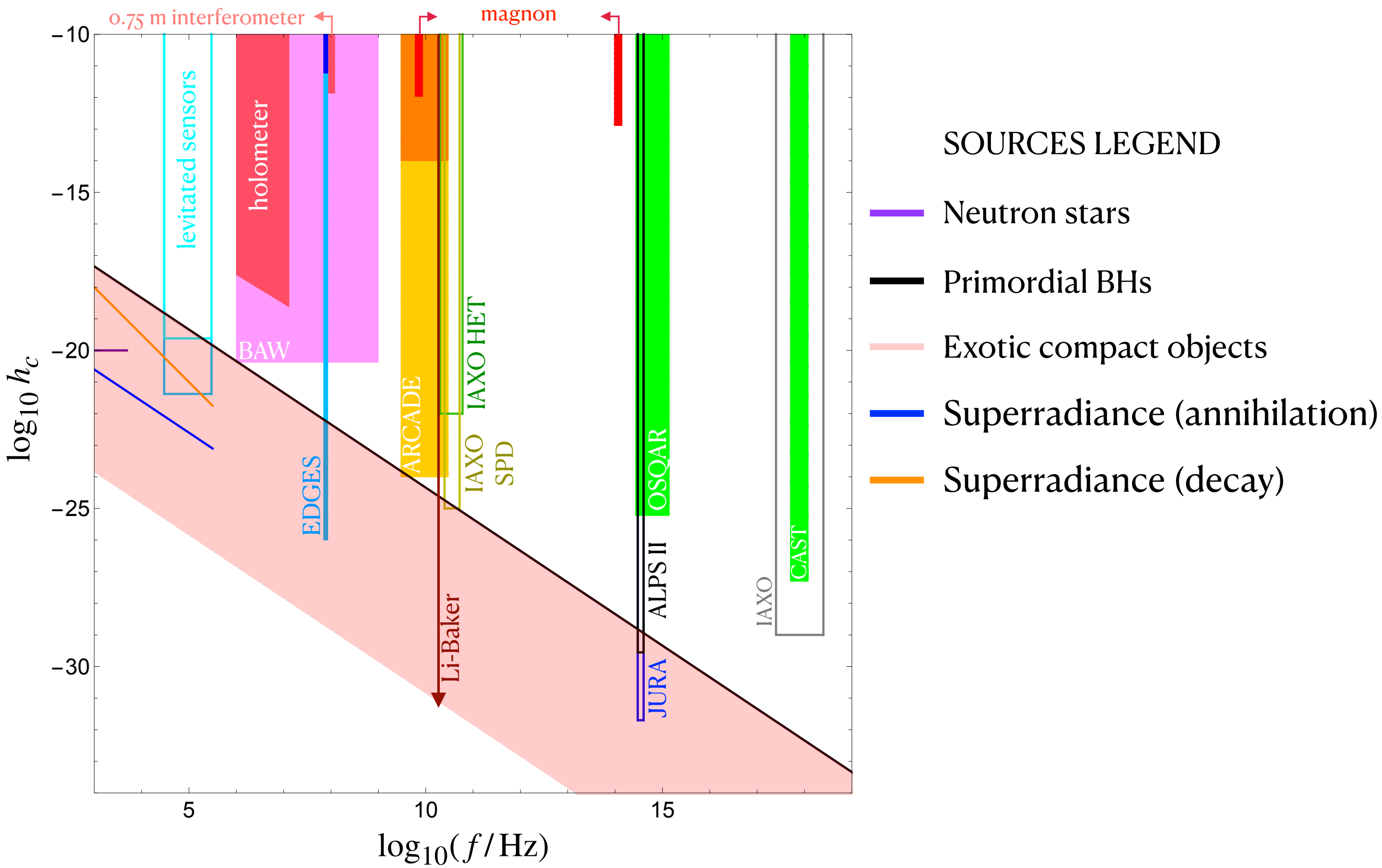
today:

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

note: constraint on *total* GW energy

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

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

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

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

GW to photon conversion

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

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

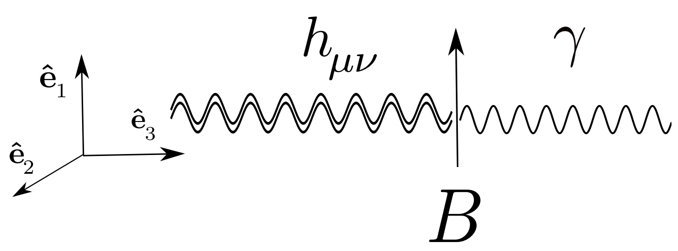
A_λ = photon
h_λ = GW
B = ext. transv. B - field
$\omega_{\rm pl}$ = plasma frequency
$\mu^2 = 1 - \omega_{\rm pl}^2/\omega^2$

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

microwave cavities

[Berlin et al `21]