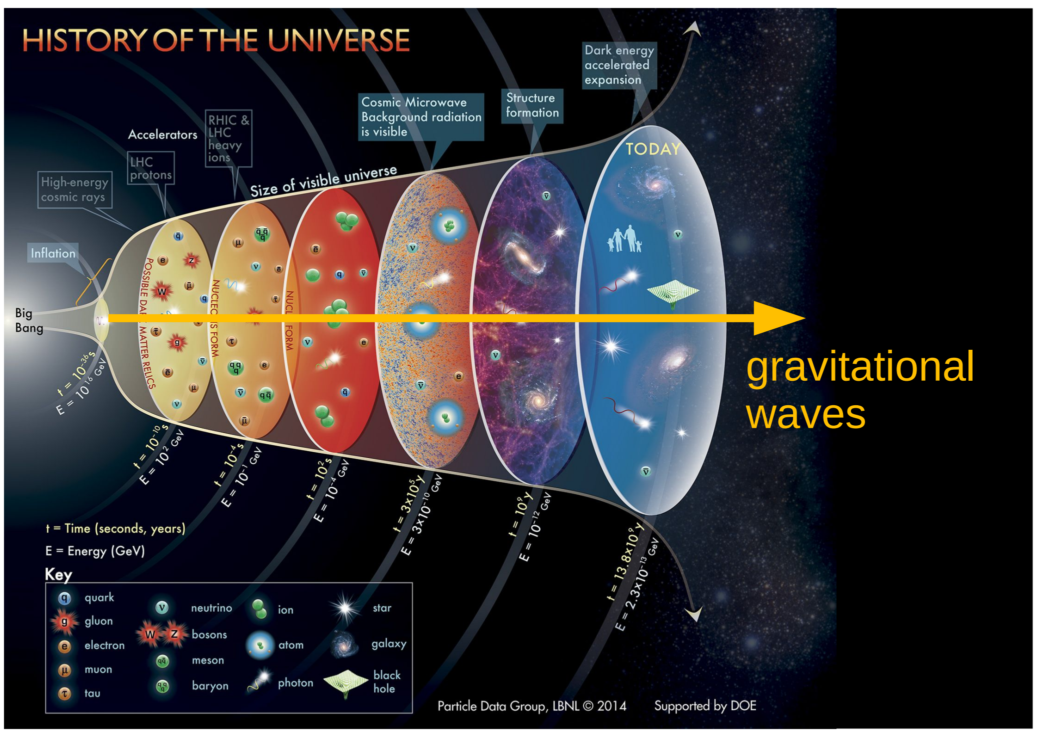
# Searching for

# high-frequency gravitational waves

# with axion detectors





Valerie Domcke
CERN


*Cosmic Whispers Online Seminar*
November 26, 2024

Based on work with
Sebastian Ellis, Camilo Garcia-Cely,
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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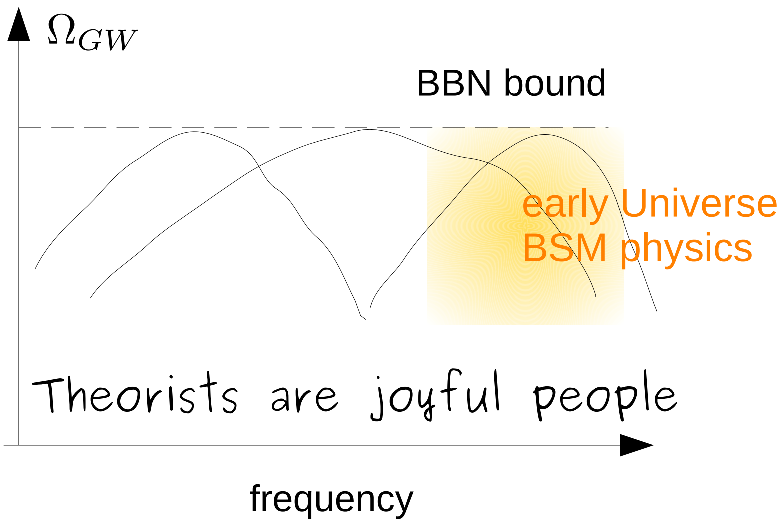
**Astrophysical**

- localized GW sources, both coherent and incoherent signals possible
- no 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

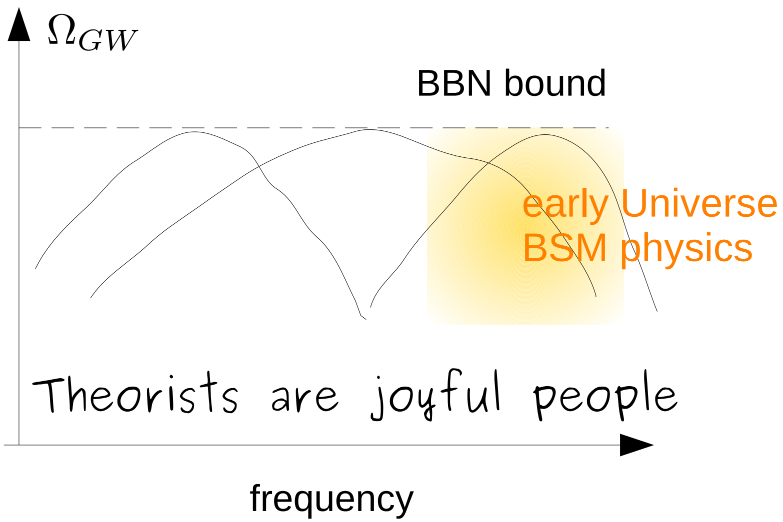
UHF GW searches are searches for new physcics

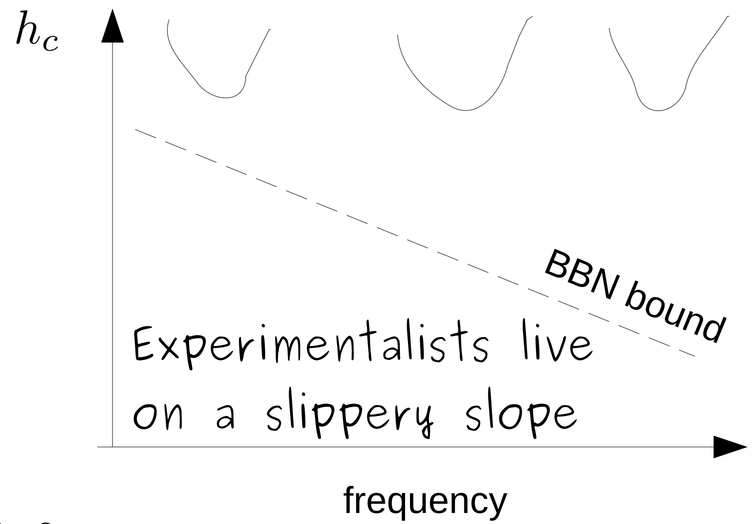
# challenges in UHF GW detection




CMB/BBN bound constrains energy

# challenges in UHF GW detection




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

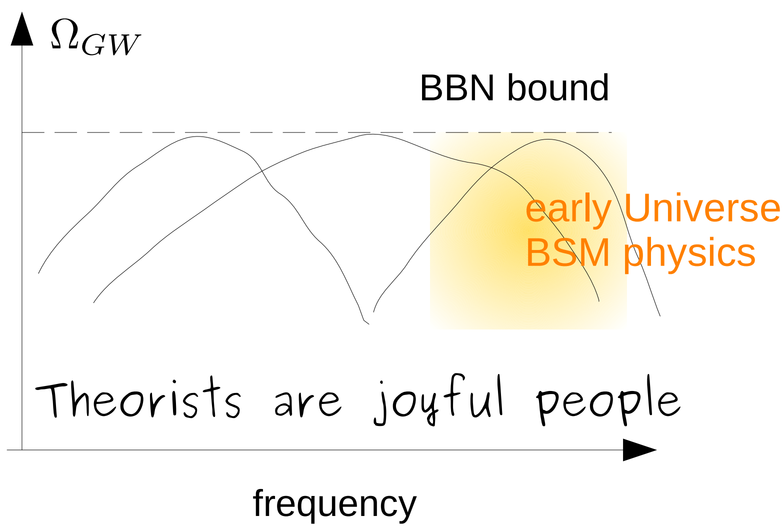
CMB/BBN bound constrains energy

experiments measure displacement

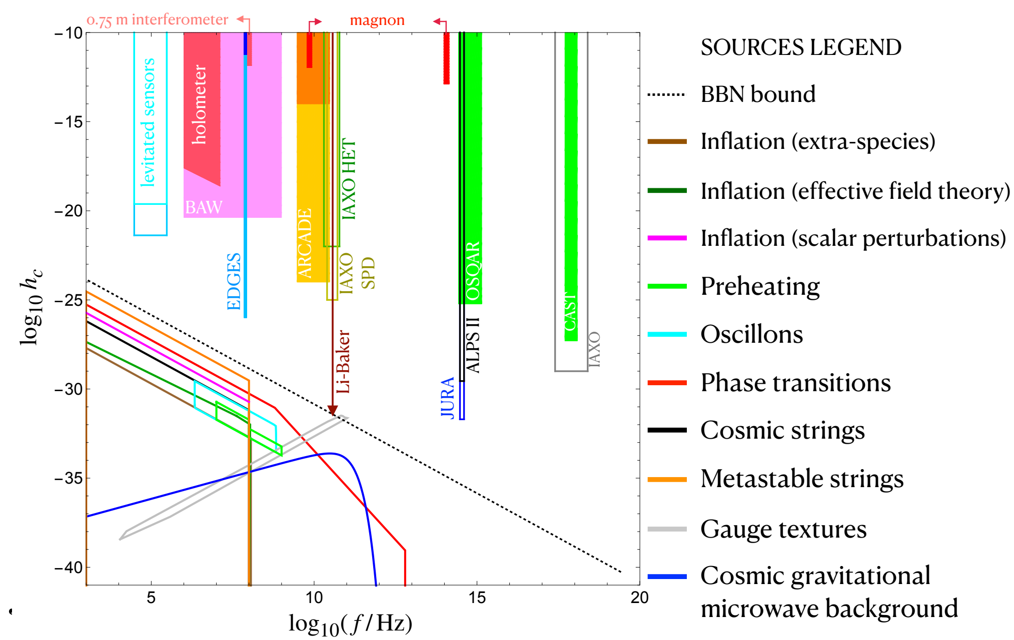
# challenges in UHF GW detection

update coming!

UHG GW initiative Living Review:
https://arxiv.org/abs/2011.12414




$\Omega_{GW} \propto$ .

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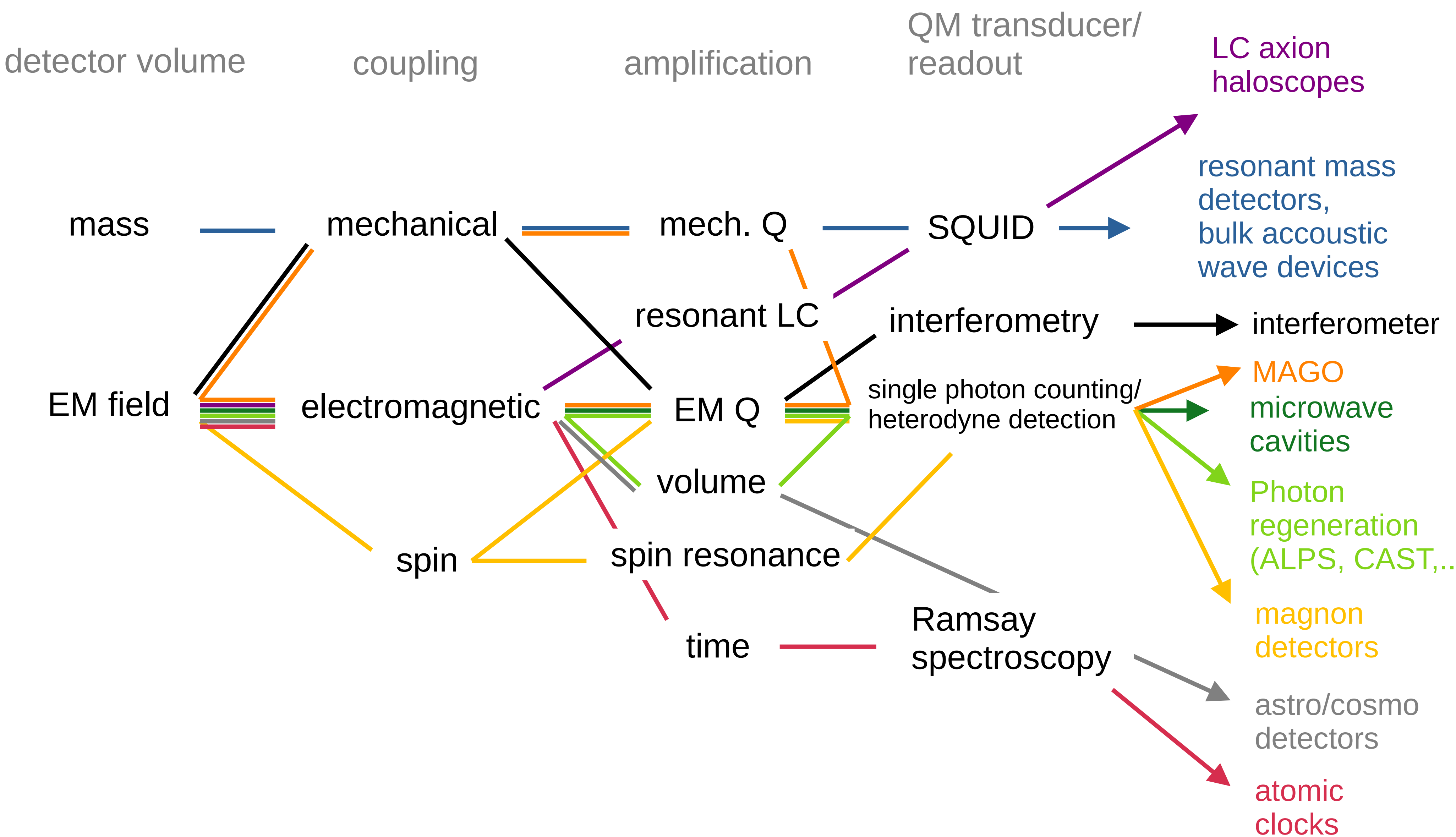
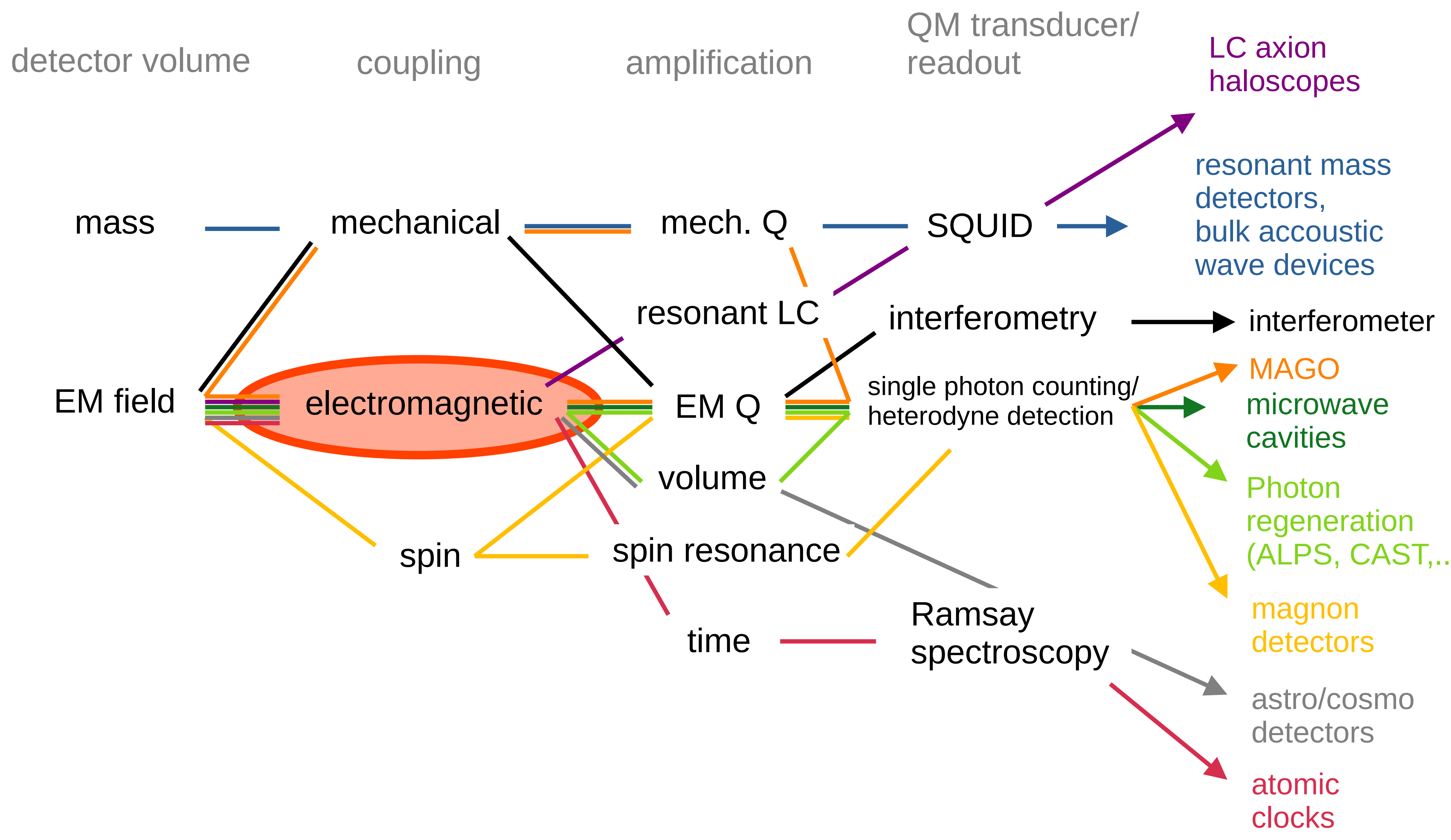
UHF GW initiative:
https://www.ctc.cam.ac.uk/activities/UHF-GW.php

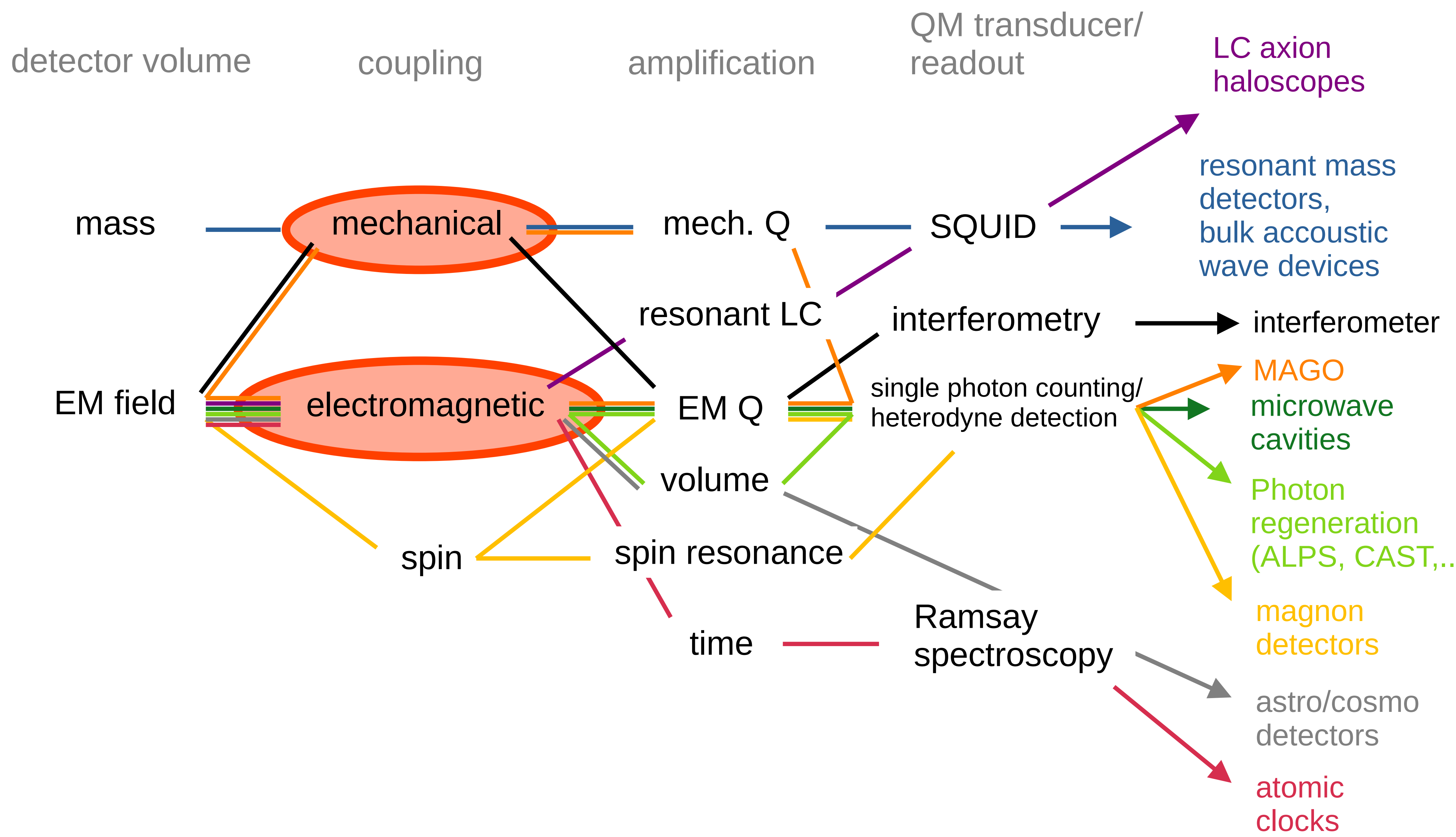
# detection strategies



# detection strategies



# detection strategies



# GW electrodynamics

Classical electrodynamics + linearized GR, $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}\,, \quad F_{\mu\nu} = \bar{F}_{\mu\nu} + F^h_{\mu\nu}$ :

$$\partial_\mu(\sqrt{-g}\, g^{\mu\alpha} F_{\alpha\beta} g^{\beta\nu}) = 0$$

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

effective curent
effective polarization vector
effective magnetization vector

with

$$\begin{aligned} P_i &= -h_{ij}\bar{E}_j + \tfrac{1}{2} h \bar{E}_i + h_{00}\bar{E}_i - \epsilon_{ijk} h_{0j} \bar{B}_k, \\ M_i &= -h_{ij}\bar{B}_j - \tfrac{1}{2} h \bar{B}_i + h_{jj}\bar{B}_i + \epsilon_{ijk} h_{0j} \bar{E}_k, \end{aligned}$$

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
Quellet, Bogorad `19

effective source terms in Maxwell‘s equation due to GW

# Dielectric GW haloscope

Maxwell equations:

$$\nabla \cdot \boldsymbol{E} = 0\,, \quad \nabla \times \boldsymbol{B} - \underline{\epsilon}\dot{\boldsymbol{E}} = \underline{\boldsymbol{j}_{\rm eff}}\,,$$
$$\nabla \cdot \boldsymbol{B} = 0\,, \quad \nabla \times \boldsymbol{E} + \dot{\boldsymbol{B}} = 0\,,$$

effective current induced by Gws

dielectric constant

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effective current induced by Gws
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particular solutions in medium and vacuum

$$\boldsymbol{E}^p_m = \frac{c_\theta B_0}{\epsilon - 1} (h_\times \hat{\boldsymbol{p}} + h_+ \hat{\boldsymbol{s}})\, e^{-i\omega(t - \hat{\boldsymbol{k}} \cdot \boldsymbol{x})} \quad \sim hB_0$$

$$\boldsymbol{E}^p_v = -\frac{B_0}{2} \left[ i\omega x (h_\times \hat{\boldsymbol{p}} + h_+ \hat{\boldsymbol{s}}) + h_\times s_\theta \hat{\boldsymbol{k}} \right] e^{-i\omega(t - \hat{\boldsymbol{k}} \cdot \boldsymbol{x})} \quad \sim hB_0 \omega x$$

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ALPs, IAXO,…
as GW detectors
[ Ejlli et al `19 ]

resonant conversion in vacuum

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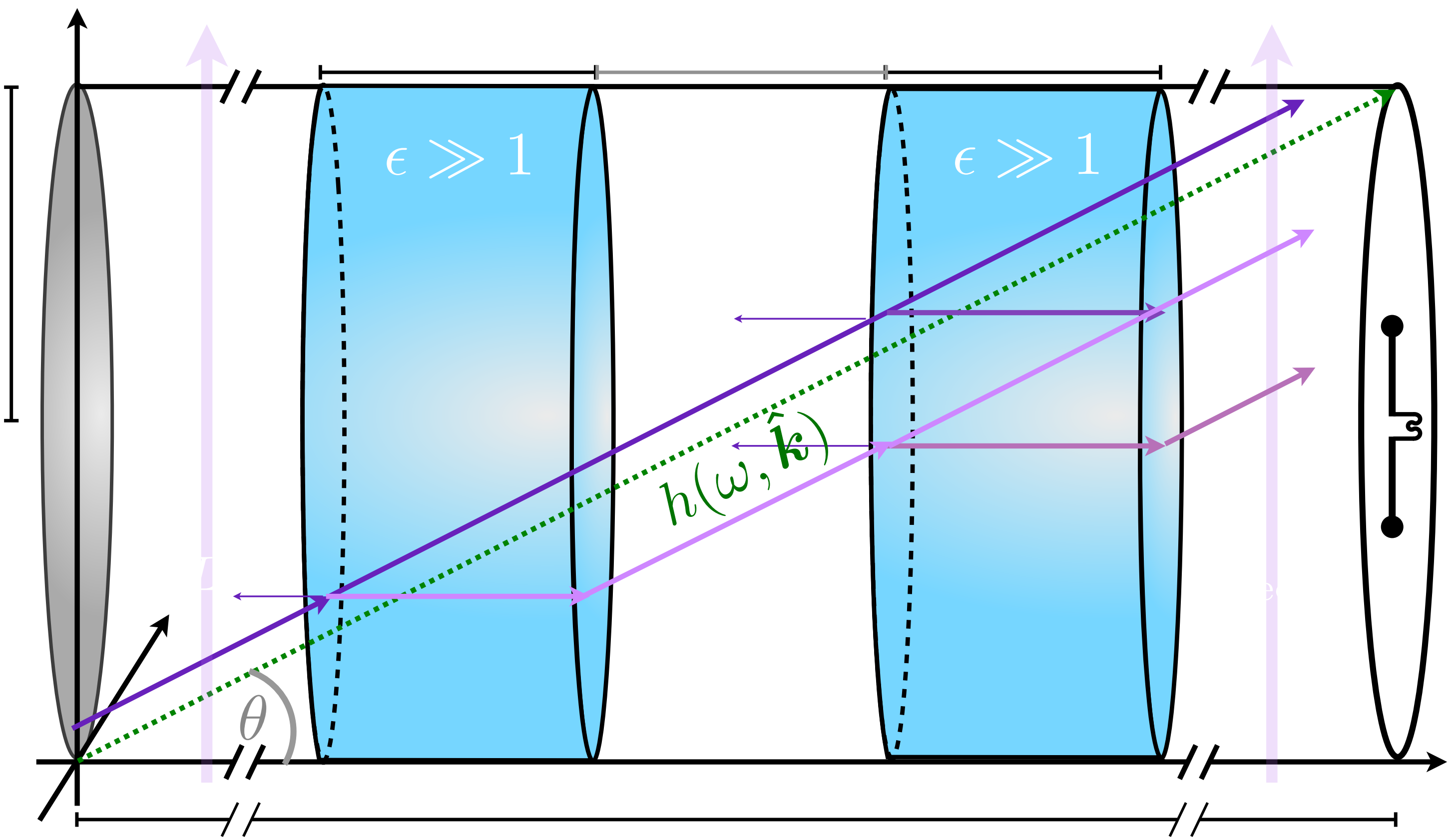
Boundary conditons at surface of dielectric medium

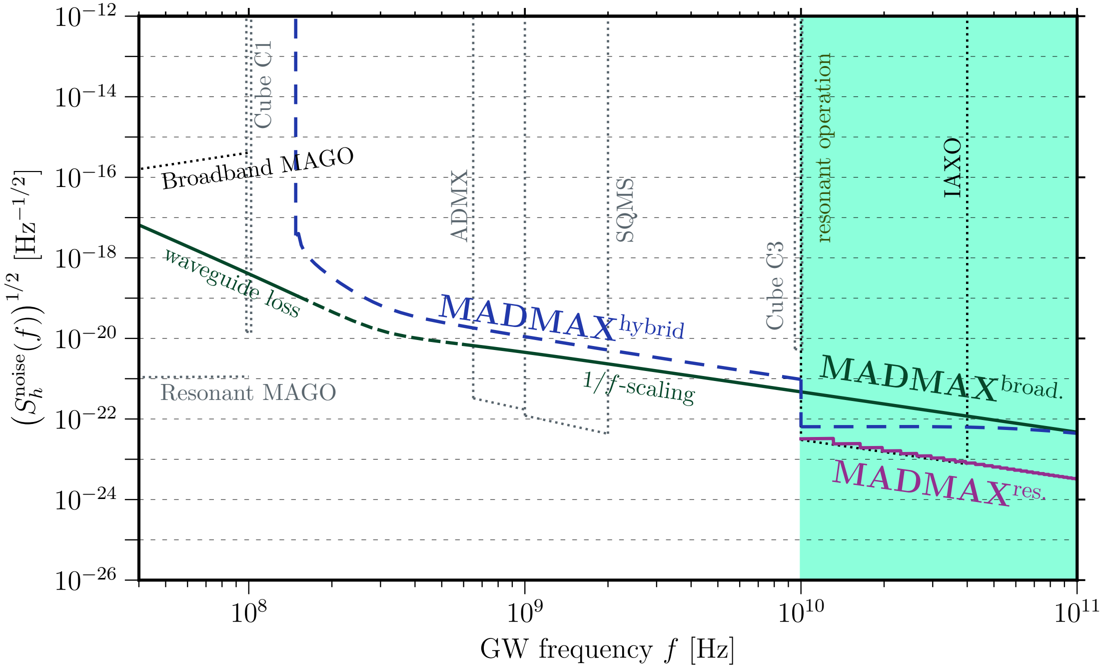
→ EM waves sourced at surfaces of dielectric disks

# Dielectric GW haloscope



# Dielectric GW Haloscope

VD, Ellis, Kopp `24




GWs vs axions

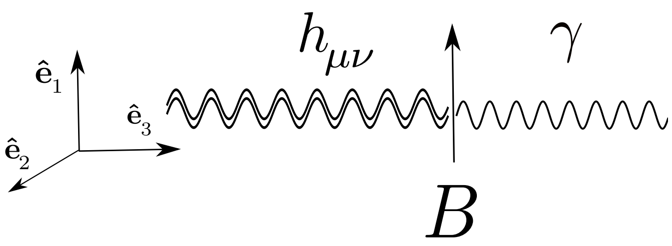
GWs are relativistic:

+ resonant conversion in vacuum
+ relaxed requirement on disk surface
- new requirement on effective disk width

- MADMAX can be operated as GW detector
- Hybrid resonant / broadband mode particularly interesting

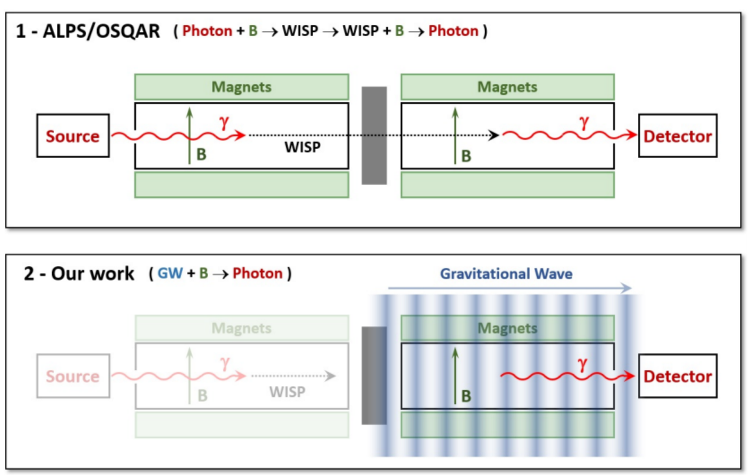
# photon (re-)generation experiments

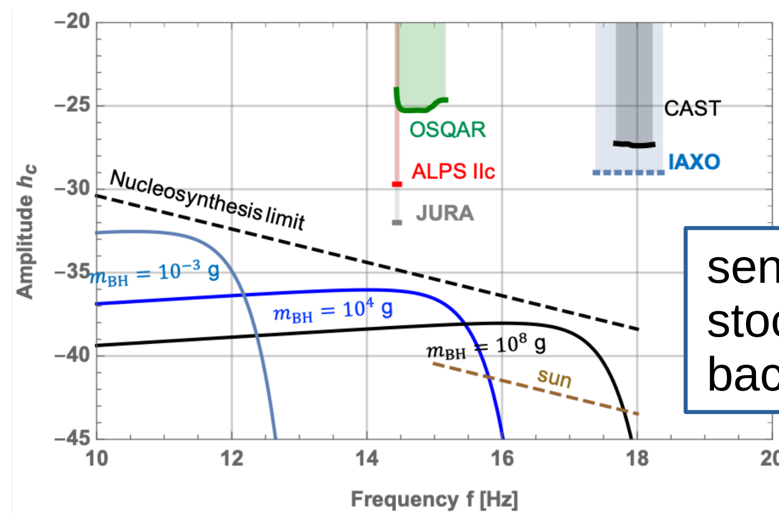
[Gertsenshtein `62, Boccaletti et al `70, Raffelt, Stodolsky `88]




analogous to axion to photon conversion

Light-shining-through-the-wall (LSW) experiments, helioscopes: Ejilli et al `19




sensitivity to stochastic GW background

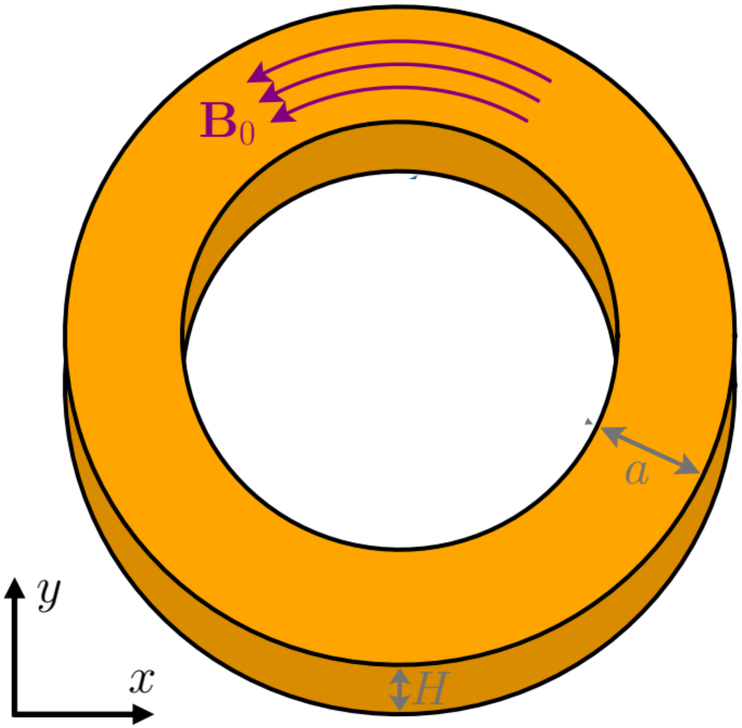
Microwave cavities: Berlin et al `21, `23

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,...

# GW signal in low-mass axion haloscopes

eg ABRACADABRA, SHAFT, DM Radio:

VD, Garcia-Cely, Lee, Rodd `22,`23




static magnetic field (i.e. rigid detector)

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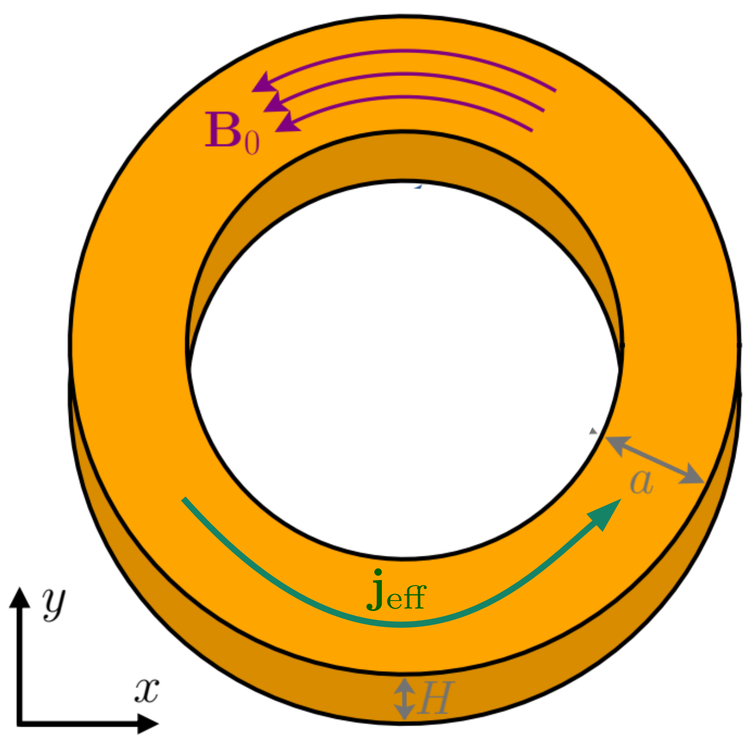


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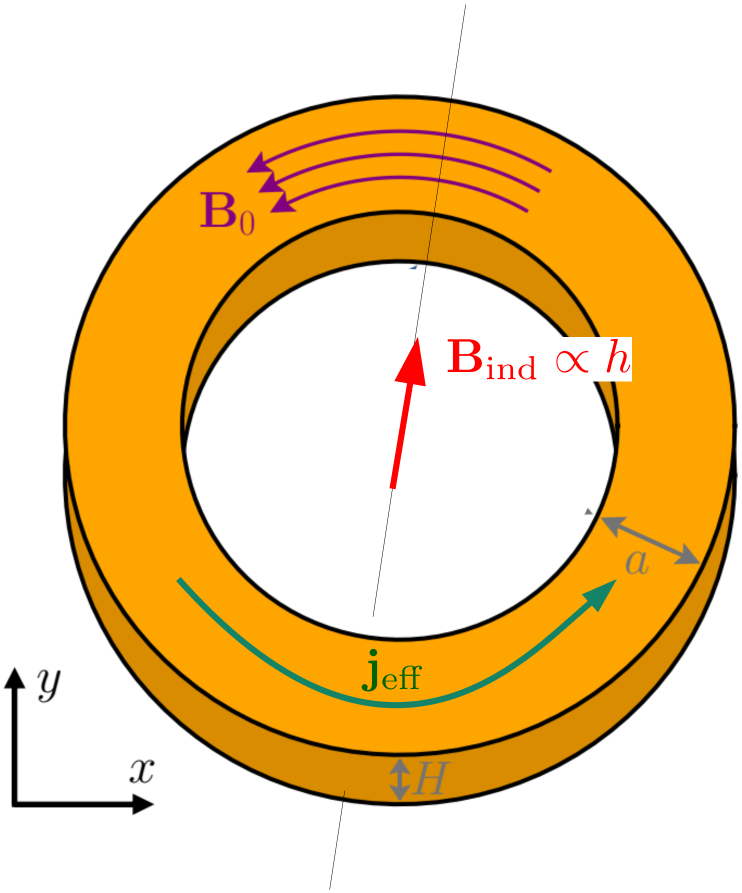


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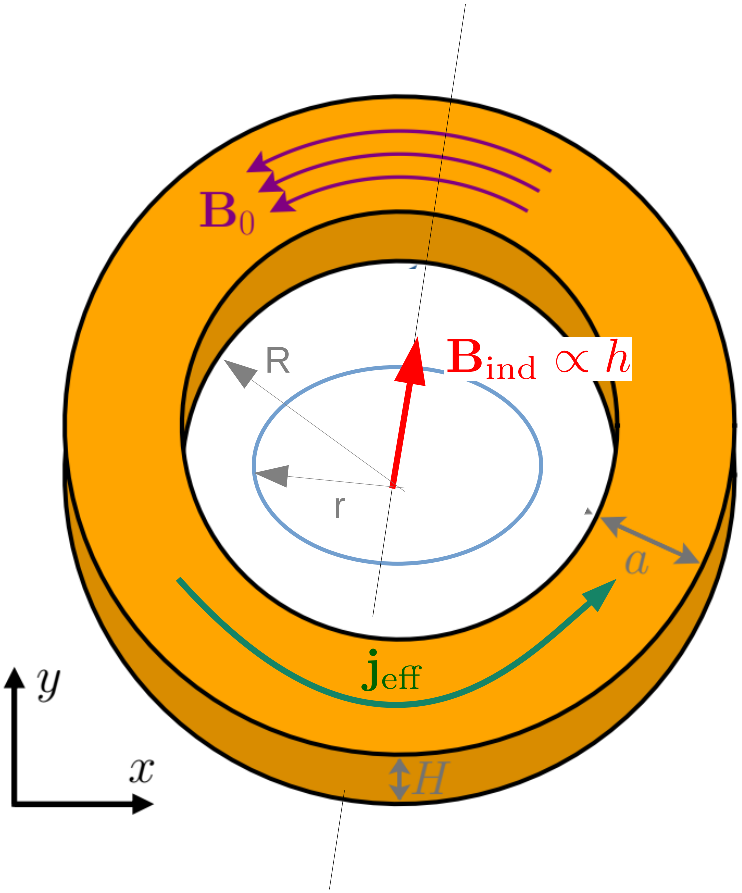


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measure magnetic flux (~ h) through pickup loop

at leading order in $(\omega R)$ :

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

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

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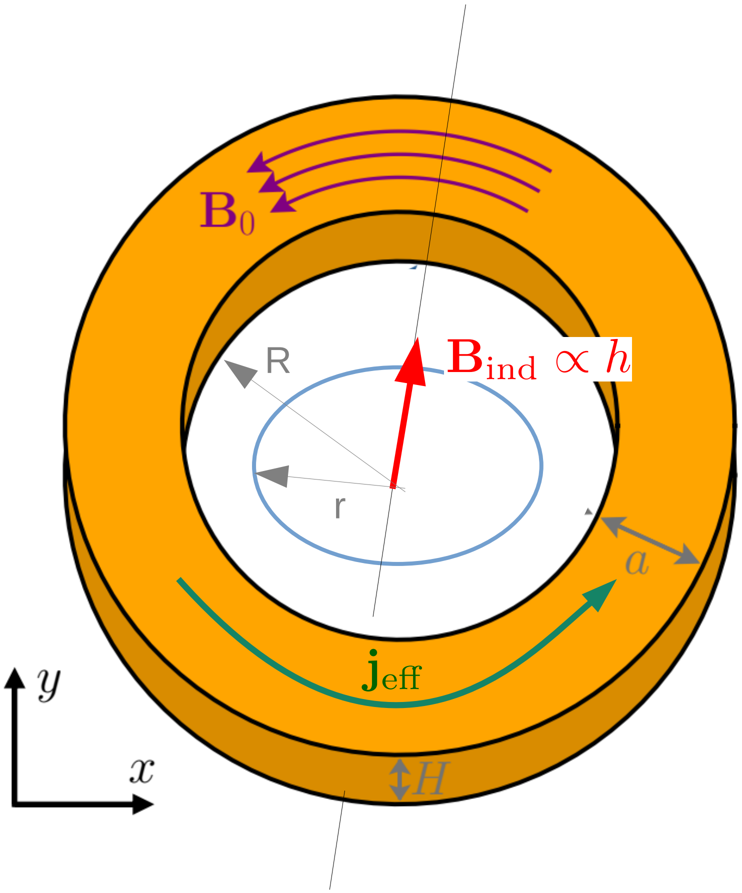


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$$\Phi_a = e^{-i\omega t}\, g_{a\gamma\gamma}\sqrt{2\rho_{\text{DM}}} B_0 \pi r^2 R \ln(1 + a/R)$$

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

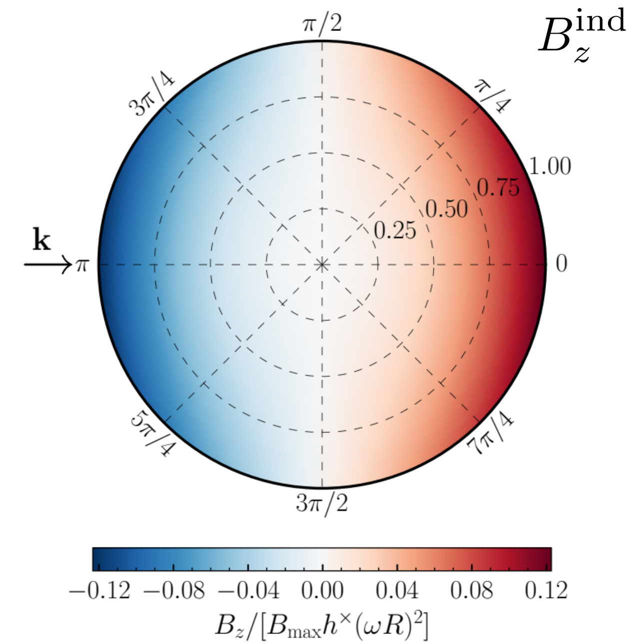
match to axion induced flux to estimate sensitivity to GW signals

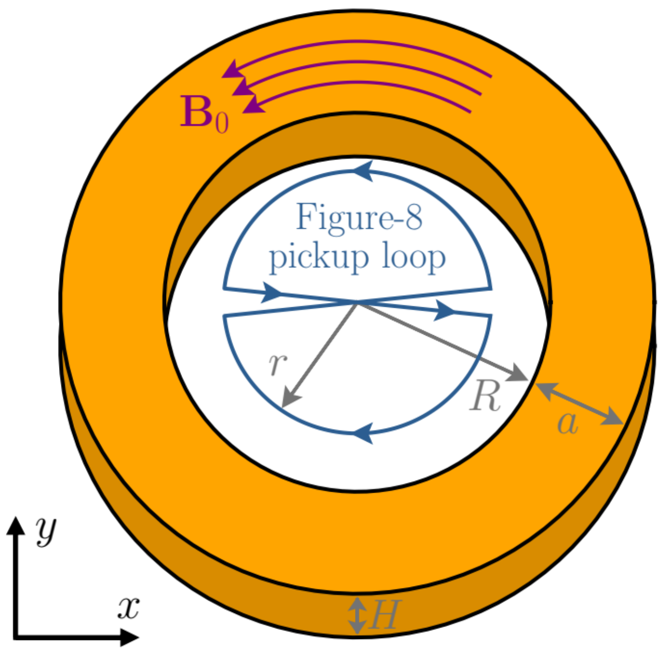
# optimized pickup loop geometry

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



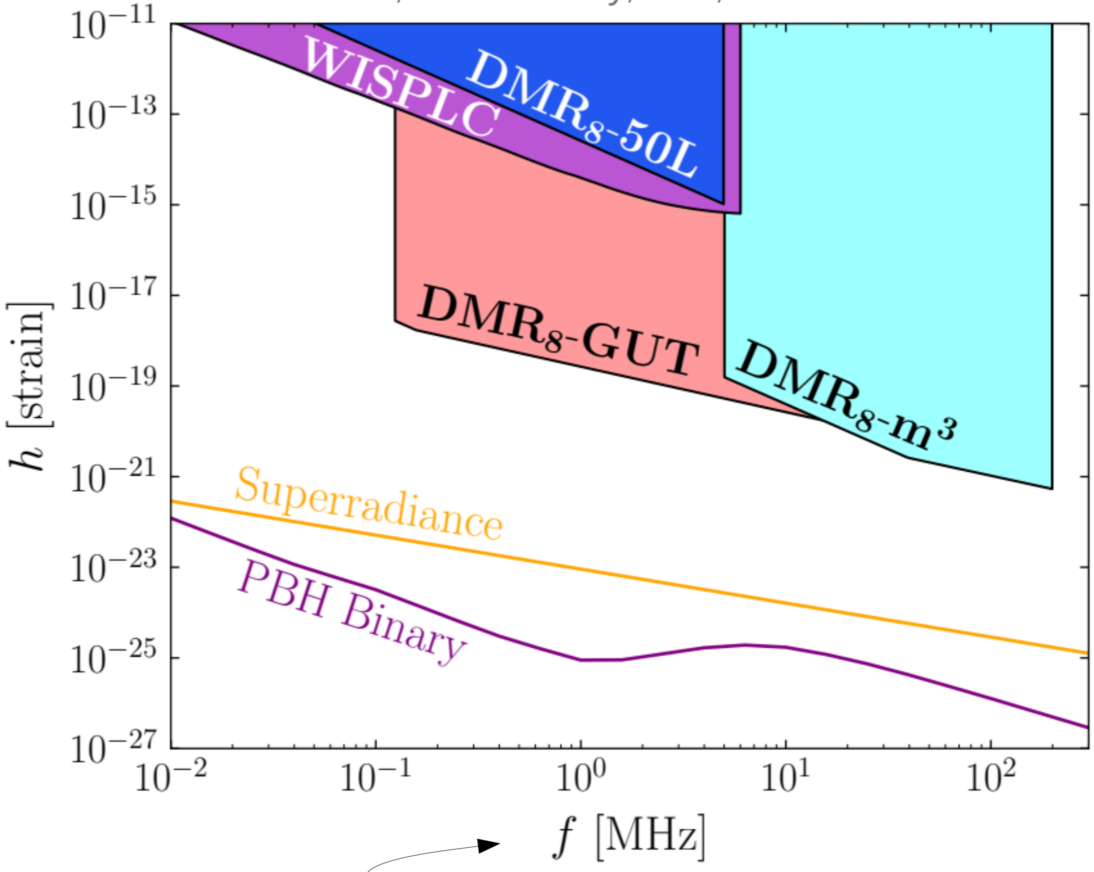

$$\Phi_{\rm gw,8} = \frac{e^{-i\omega t}}{3\sqrt{2}} \omega^2 B_0 r^3 R \ln(1 + a/R)\, s_{\theta_h} \times (h^\times s_{\phi_h} - h^+ c_{\theta_h} c_{\phi_h})$$

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

parametric improvement for modified pickup loop

# 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 $\mathcal{R}_c = 1$

sensitivity to `axion-like' signal

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

axion haloscopes as **MHz** GW detectors

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

# mechanical coupling

mechanical response to GWs $\omega_n \sim n\, v_s L^{-1} \sim 10^{-5} L^{-1}$ mech. eigenmodes

| $\omega_{\rm gw} \ll \omega_n$ | $\omega_{\rm gw} \sim \omega_n$ | $\omega_n \ll \omega_{\rm gw} \ll L^{-1}$ | $L^{-1} \ll \omega_{\rm gw}$ |
|---|---|---|---|
| rigid limit | on resonance (Weber Bars) | free-falling limit → | |
| | | | response function may be suppressed by oscillation pattern |

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mechanical deformations less stiff than Maxwell's equations by factor $v_s/c \sim 10^{-5}$

response function may be suppressed by oscillation pattern

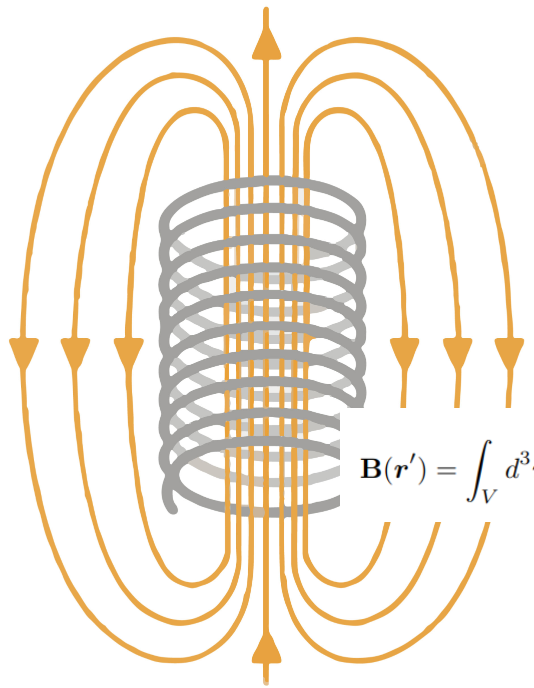
- mechanical coupling can be significantly more efficient
- challenge of transducing mechanical deformation to EM signal for quantum readout

# Magnetic Weber Bar

VD, Ellis, Rodd `24

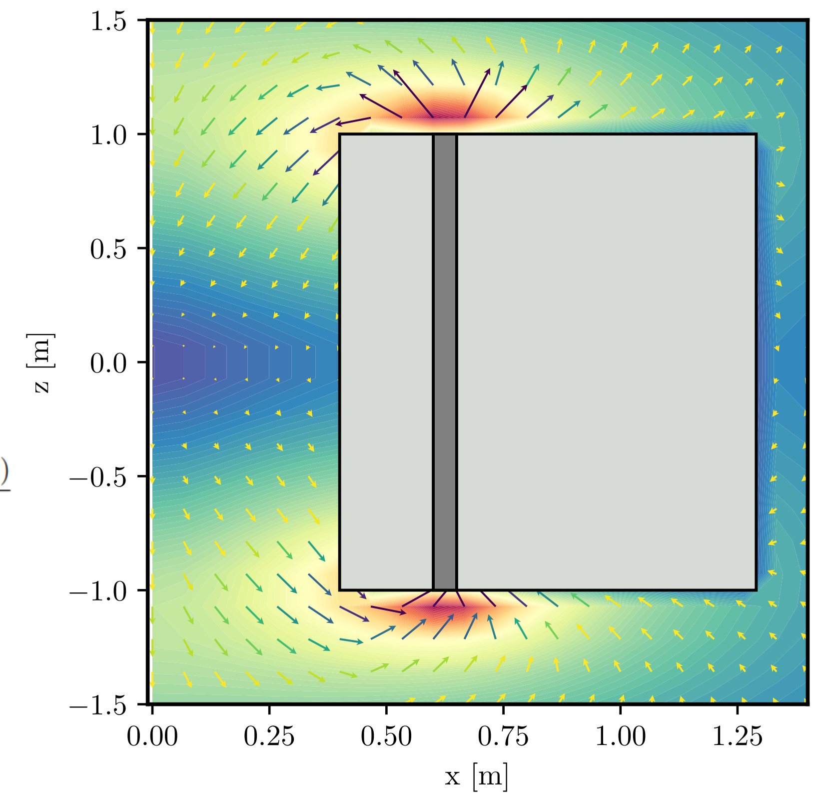
GW acts as a mechanical force on (current-carrying) wires:

GW



Biot-Savart law

$$\mathbf{B}(\boldsymbol{r}') = \int_V d^3\boldsymbol{r}\, \frac{\boldsymbol{j}(\boldsymbol{r}) \times (\boldsymbol{r}' - \boldsymbol{\xi}(\boldsymbol{r}))}{4\pi|\boldsymbol{r}' - \boldsymbol{\xi}(\boldsymbol{r})|^3}$$

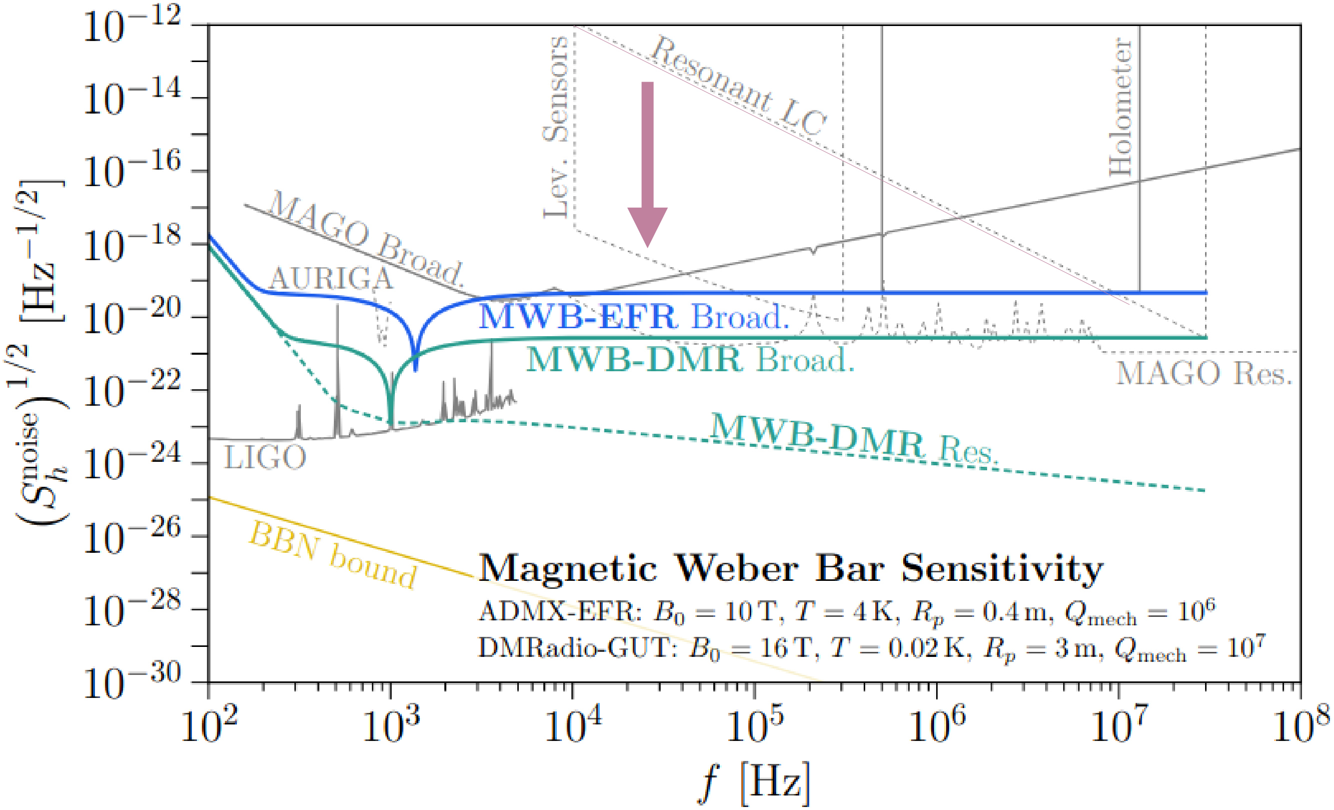



→ Induced AC magnetic field ~ h B, read out with pickup loop + SQUID

# Magnetic Weber Bar

VD, Ellis, Rodd `24

mechanical vs
EM coupling




3 effects at O(h):

- deformation of magnet coil
- motion of pickup loop
- modulation of supercurrent

Noise contributions:

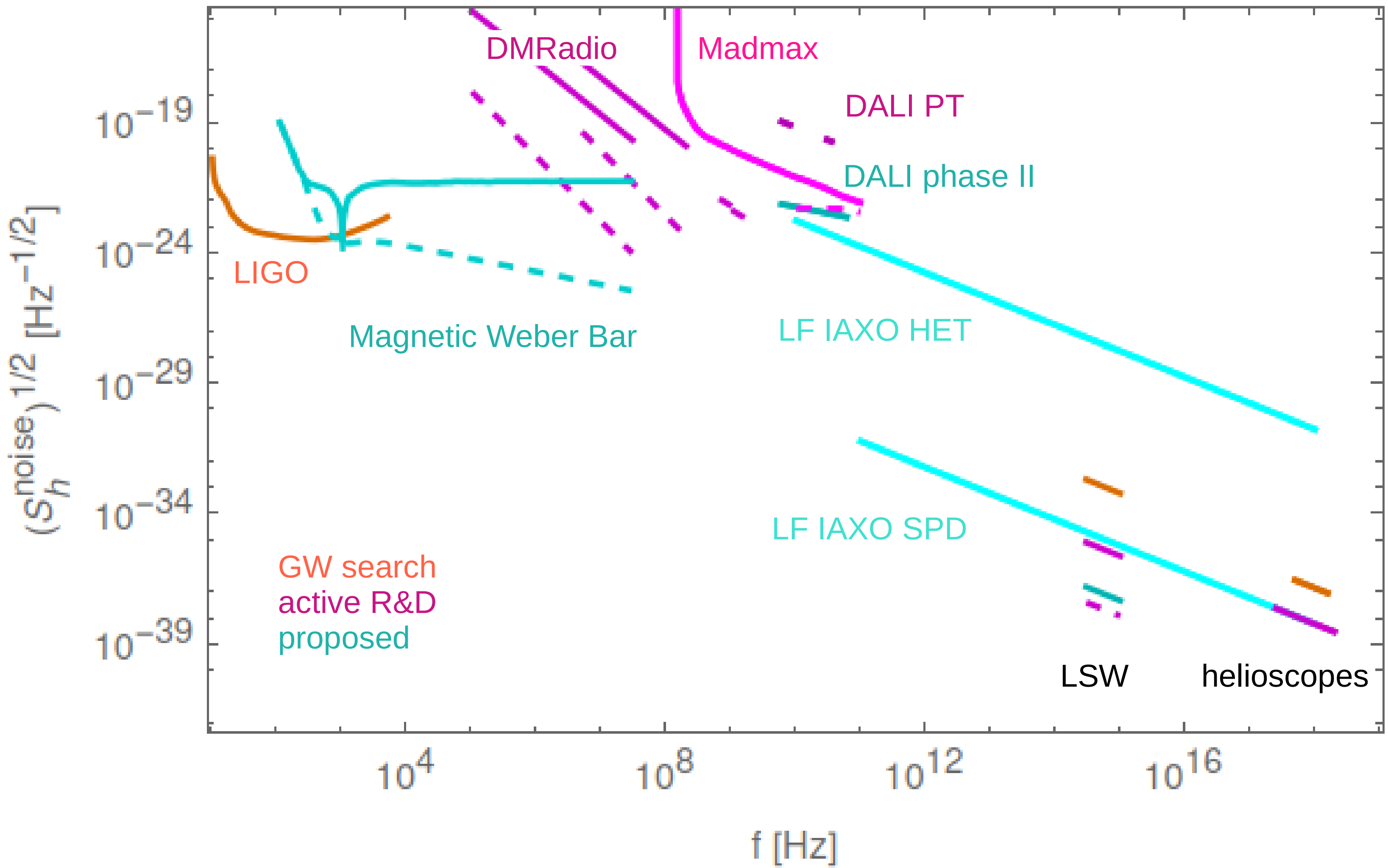
SQUID, thermal mechanical, seismic, thermal noise of resonant readout

Very competitive broadband sensitivity !

# Charting the GW landscape

UHG GW initiative Living Review:
https://arxiv.org/abs/2011.12414

update coming!



# Conclusions and Outlook

**Synergies between axion and high-frequency GW searches**

$$(g_{a\gamma\gamma}a)F_{\mu\nu}\tilde{F}^{\mu\nu} \quad \leftrightarrow \quad hF_{\mu\nu}F^{\mu\nu}$$

**Key differences to leverage:**

pseudoscalar versus spin 2 : optimize geometry

massive axion versus relativistic GWs : different resonance conditions

mechanical coupling of GWs : powers of $\omega L \, , v_s/c$ , can be missed by NDA

...

**A lot of room for new ideas!**

# ... and an advertisement:

**CERN TH visitor program** https://theory.cern/visitor-info

short-term visits typically O(week)

long term visits (> 3 months, usually sabbaticals)

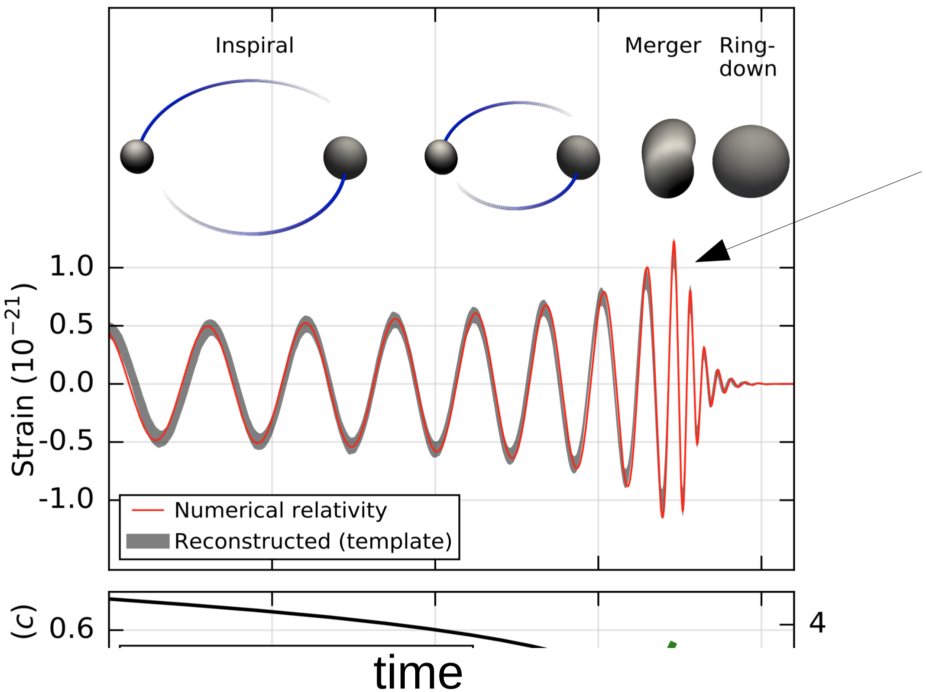
**consider applying!**

backup slides

# astrophysical sources

Example:
mergers of light primordial black holes

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




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

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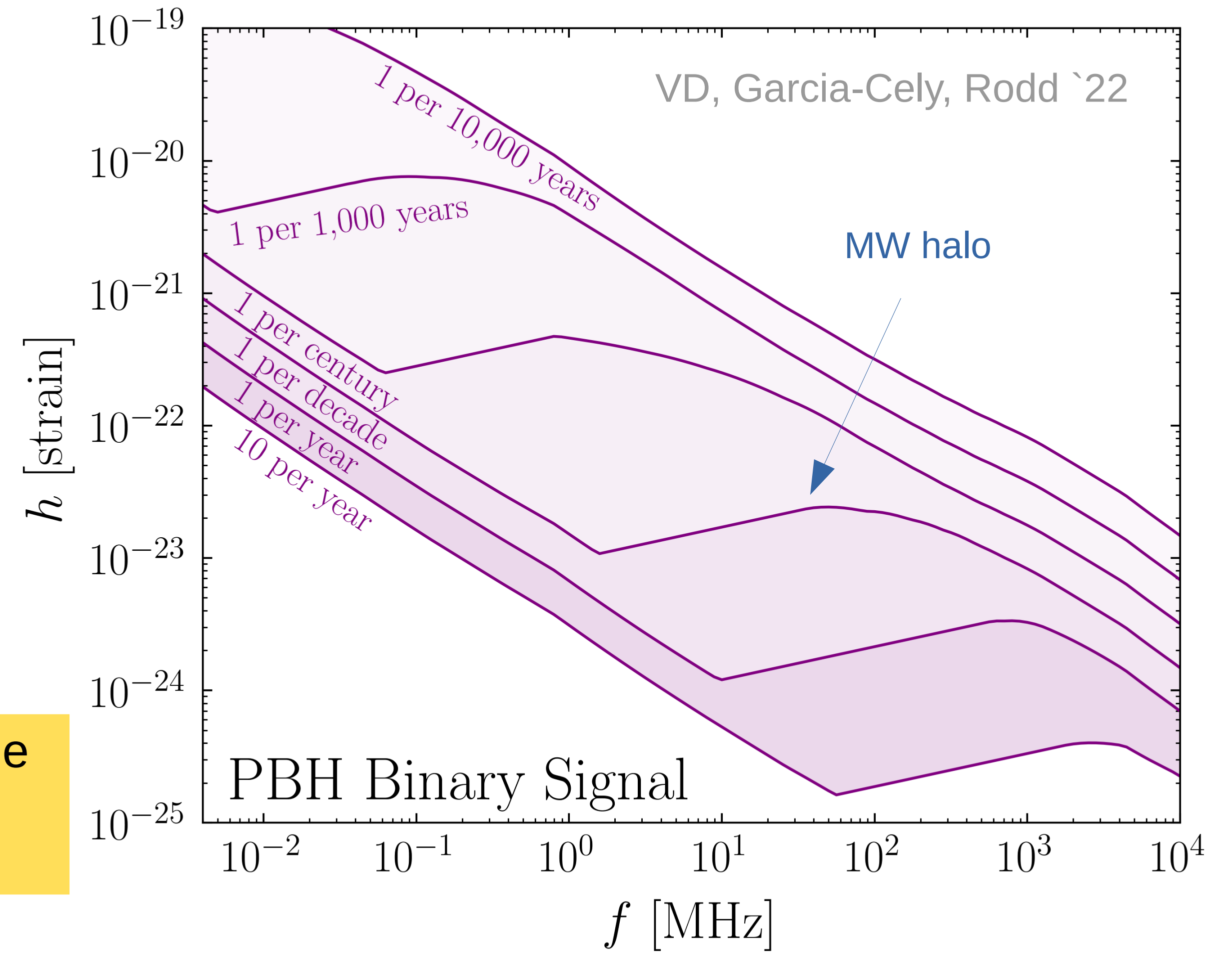
event rate:

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

MW halo  merger rate

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




large GW amplitudes possible for rare events, but signal duration very short!

see also Franciolini, Maharana, Muia `22

# 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

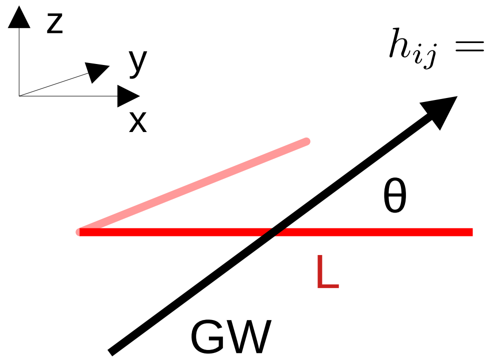
today:

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

note: constraint on *total* GW energy

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

# warm-up: LIGO



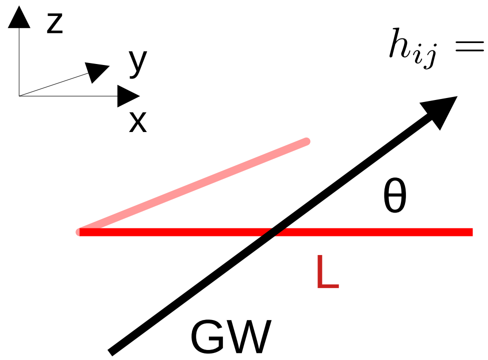

$$h_{ij} = h_+ e^+_{ij} \cos[\omega(t - c_\theta x - s_\theta z)]$$

VD, Kopp `24

$$\partial_\nu F_h^{\mu\nu} = j^\mu_{\text{eff}}$$

$$\vec{A} = \vec{A}_0 + \Delta\vec{A} = A_0 \cos[\omega_\gamma(t - x)]\hat{e}_z + \Delta\vec{A}(t, \vec{x})$$

# warm-up: LIGO




$$h_{ij} = h_+ e^+_{ij} \cos[\omega(t - c_\theta x - s_\theta z)]$$

VD, Kopp `24

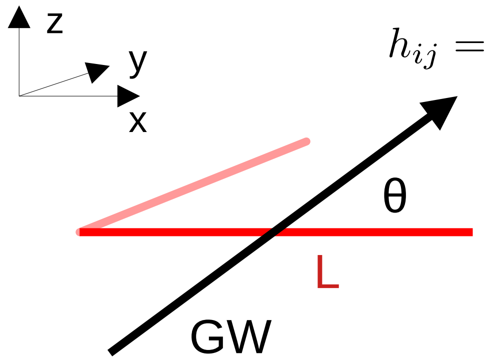
$$\partial_\nu F_h^{\mu\nu} = j^\mu_{\text{eff}}$$

$$\vec{A} = \vec{A}_0 + \Delta\vec{A} = A_0 \cos[\omega_\gamma(t - x)]\hat{e}_z + \Delta\vec{A}(t, \vec{x})$$

particular solution along x-axis:

$$\Delta A_z^p(t,x) = -\sum_{\lambda=\pm} \lambda \frac{A_0 h_+}{4} \frac{\omega_\gamma}{\omega}(1 + c_\theta)\cos[(\omega_\gamma + \lambda\omega)t - (\omega_\gamma + \lambda\omega c_\theta)x] + \mathcal{O}(\omega_\gamma/\omega)^0$$

# warm-up: LIGO

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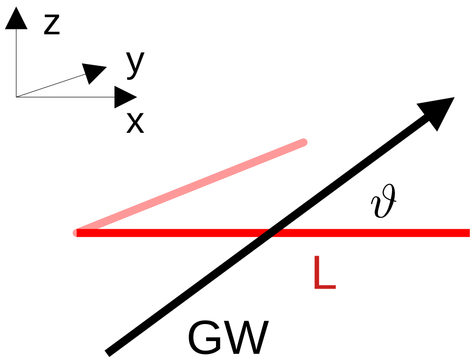
Add plane waves with frequencies $\omega_\gamma \pm \omega$ to match boundary condition $\vec{A}(t,0) = \vec{A}_0(t,0)$

→ full solution for EM wave propagating in GW background

→ compute phase shift: $\Delta\phi = -\frac{1}{2} h_+ \omega_\gamma L \sin^2\theta\,, \quad \Delta\phi_{\rm LIGO} = h_+ \omega_\gamma L \cos(2\theta)$ ✔

→ at next order in $\omega/\omega_\gamma$ : amplitude modulation, rotation of polarization

# Interferometers revisited




$$h_{ij} = h_+ e^+_{ij} \cos[\omega(t - c_\theta x - s_\theta z)]$$

$$\boldsymbol{A} = \bar{\boldsymbol{A}} + \mathscr{A} = A_0 \cos[\omega_\gamma (t - x)]\, \hat{e}_z + \mathscr{A}\,,$$

$$\mathscr{A}_i = a_i^- \cos_- + a_i^+ \cos^+$$

$$\cos_+ \equiv \cos[(\omega_\gamma + \omega_g)\,t - \omega_\gamma x - \hat{\boldsymbol{k}}_g \cdot \boldsymbol{x}]$$

$$\cos_- \equiv \cos[(\omega_\gamma - \omega_g)\,t - \omega_\gamma x + \hat{\boldsymbol{k}}_g \cdot \boldsymbol{x}]$$

$$a_x^\pm = A_0 h_+ s_\vartheta \frac{(\omega_g \pm \omega_\gamma(1 - c_\vartheta))}{4(\omega_g \pm \omega_\gamma)} = \frac{1}{4} A_0 h^+ s_\vartheta (1 - c_\vartheta) + \mathcal{O}(\omega_g/\omega_\gamma)\,,$$

$$a_y^\pm = \tfrac{1}{4} A_0 h_\times\,,$$

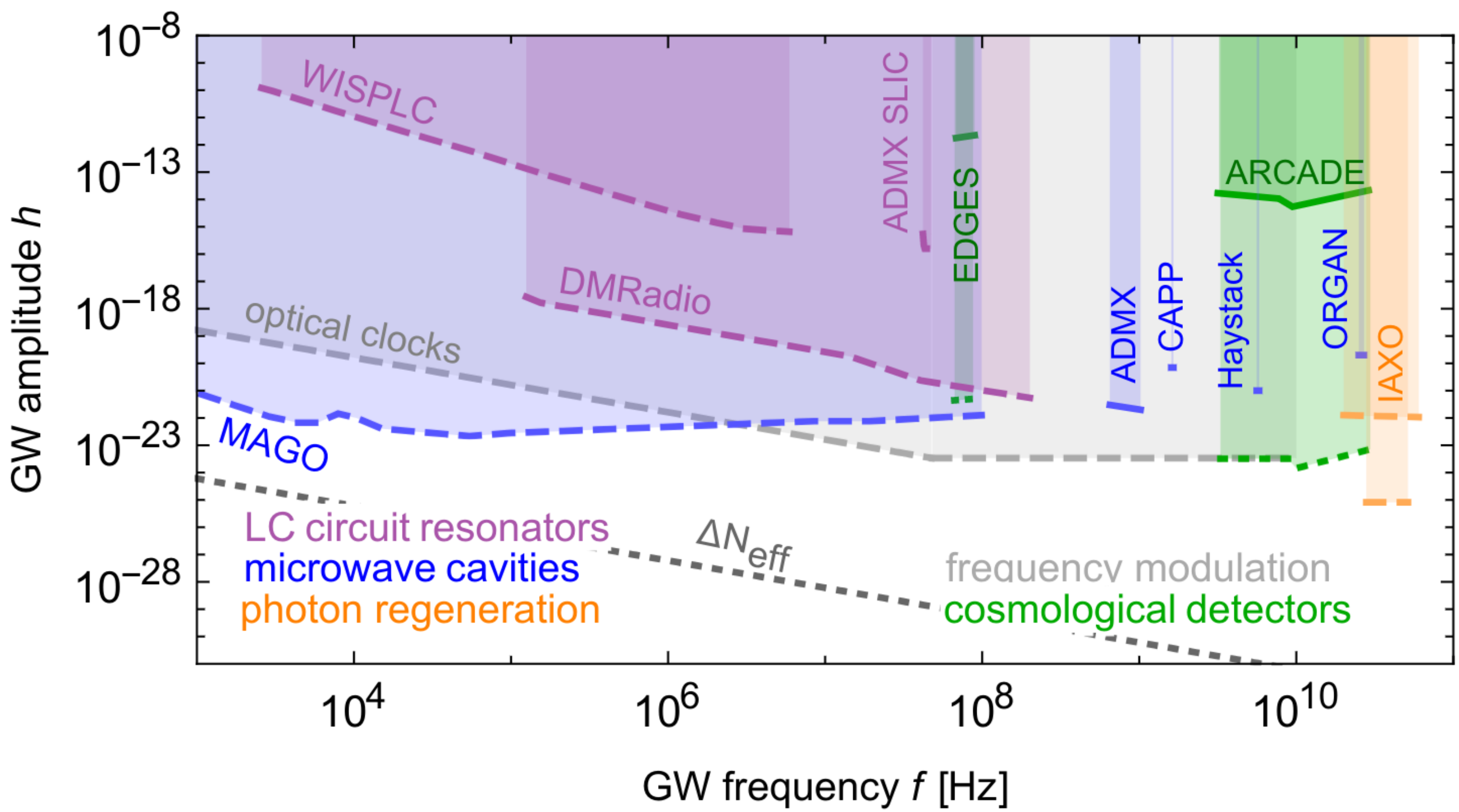
$$a_z^\pm = -A_0 h_+ \frac{\omega_\gamma}{\omega_g} \left(8\omega_\gamma(\omega_g \pm \omega_\gamma)\right)^{-1} \cdot \left(2c_\vartheta(\omega_g^2 \pm \omega_g\omega_\gamma + \omega_\gamma^2) \pm \omega_\gamma(\omega_g \pm 2\omega_\gamma - \omega_g c_{2\vartheta})\right)$$

$$= \mp \frac{1}{4} A_0 h^+ \frac{\omega_\gamma}{\omega_g} (1 + c_\vartheta) + \mathcal{O}[(\omega_g/\omega_\gamma)^0]\,.$$

change in polarization

# electromagnetic HF GW detectors

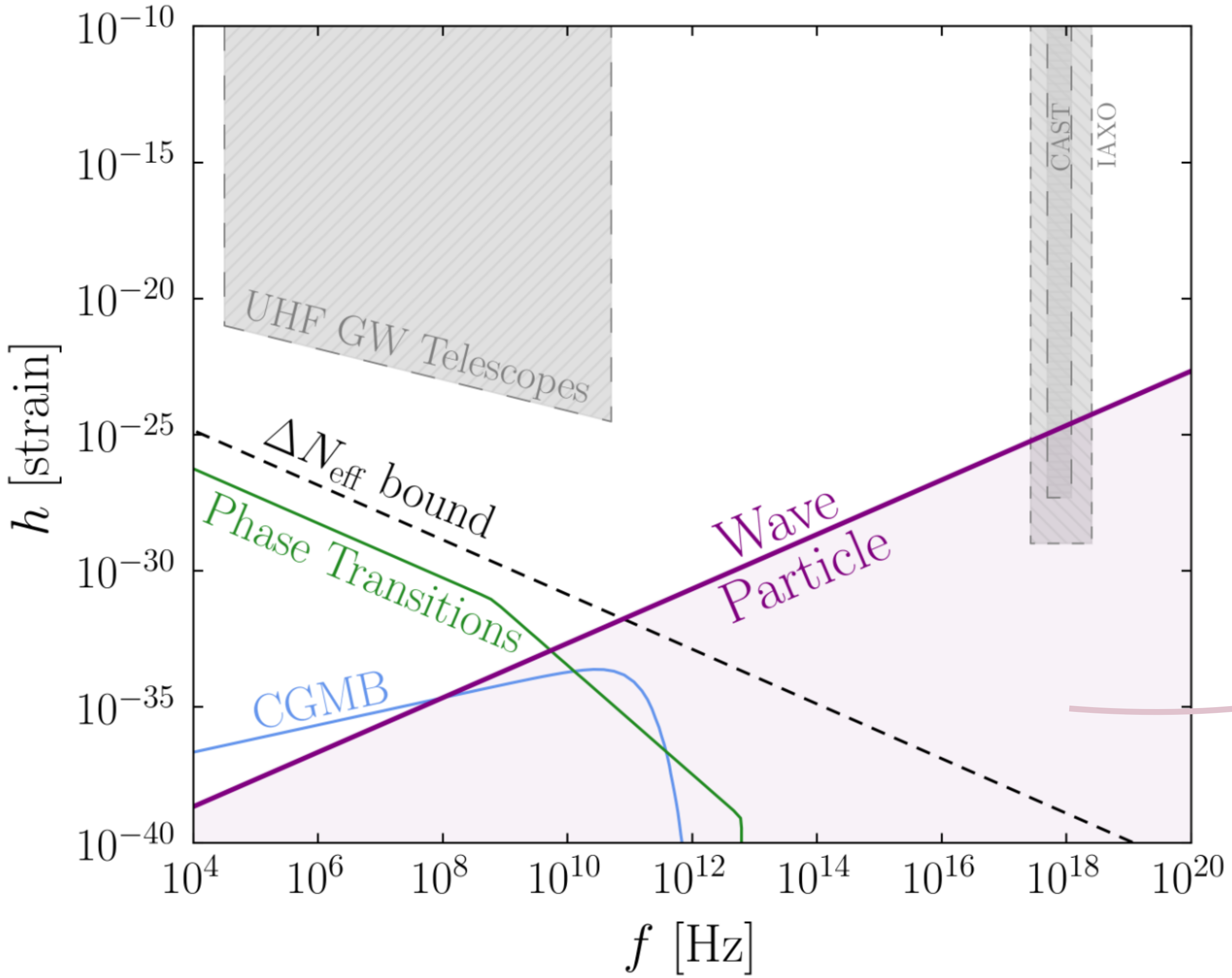
VD, Moriond proceedings `23




exploit synergies with axion searches

# tests of quantum gravity ?

Carney, VD, Rodd `23




- dilute graviton gas vs classical GW
- CAST has the sensitivity to detect single gravitons (the source is the issue)
- Rigorous test of quantisation de facto impossible

see also F. Dyson `13

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