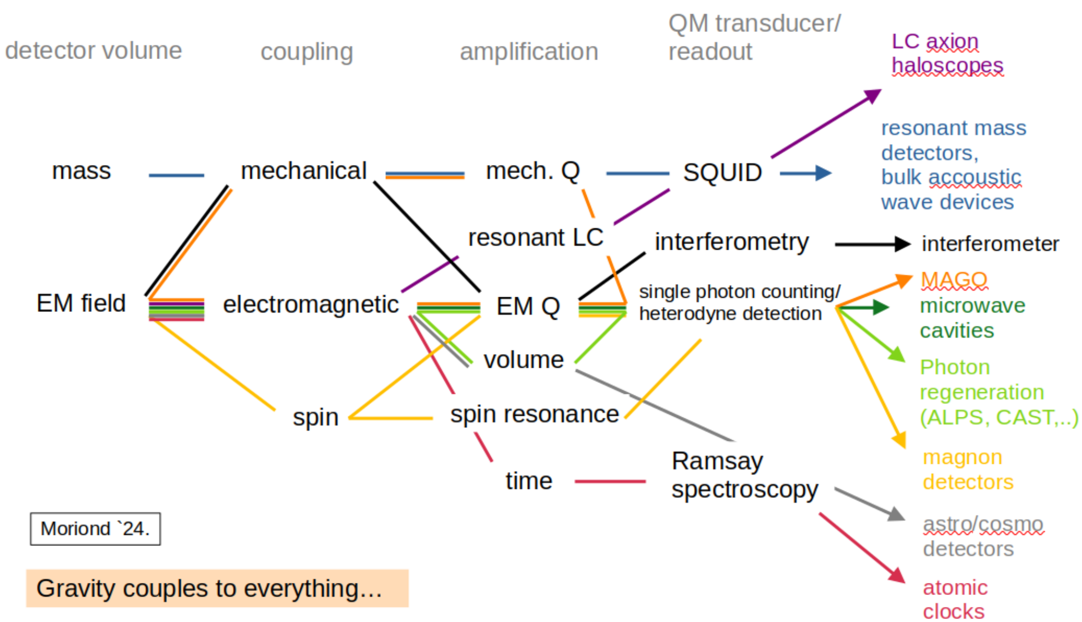
Searching for

high-frequency gravitational waves

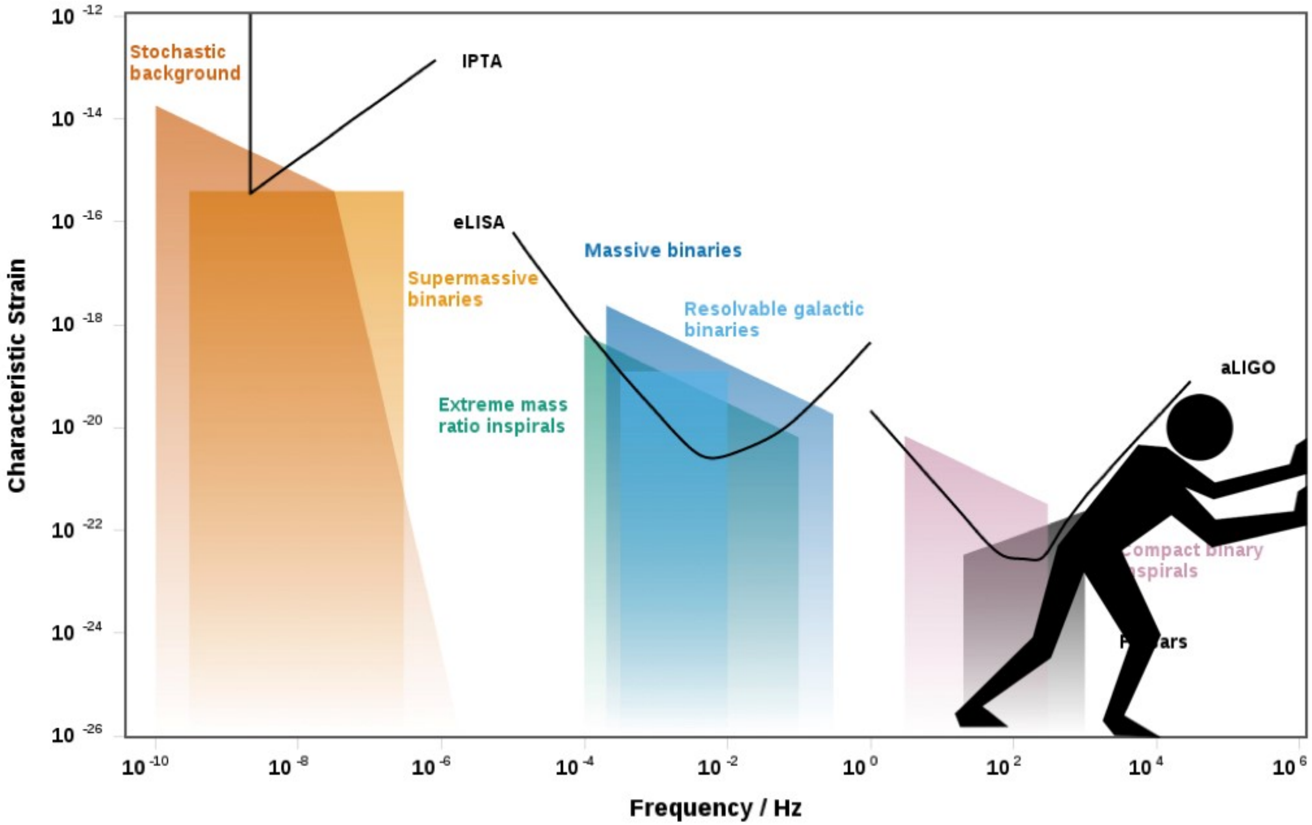


Valerie Domcke
CERN

MITP Workshop “Quantum Sensing meets UHF Gravitational Waves”
Juin 30, 2025

Based on work with
Sebastian Ellis, Camilo Garcia-Cely,
Joachim Kopp, Sung Mook Lee,
Kaliroe Pappas, Nick Rodd
+ the UHF-GW initiative
+ the ABRACADABRA collaboration

GW searches above ~ kHz ?



Why go here ?

No known astro foregrounds

SGWBs sourced at energies up to the GUT scale (hard!)

In the mean time:

Exotic astrophysical sources (PBHs, superradiance,..)

Neutron star signals up to ~ MHz ?

Outline

- 2025 Update of UHF GW Living Review
- ABRA-GW Results
- Madmax (dielectric axion haloscope) as a GW detector
- Magnetic Weber Bars

2025 Update of UHF GW Living Review

UHF GW initiative:
https://www.ctc.cam.ac.uk/activities/UHF-GW.php
Webpage, mailing list → to be updated

Challenges and Opportunities of Gravitational Wave Searches above 10 kHz

Nancy Aggarwal[a] · Odylio D. Aguiar[b] · Diego Blas[c,d] · Andreas Bauswein[e] · Giancarlo Cella[f] · Sebastian Clesse[g] · Adrian Michael Cruise[h] · Valerie Domcke[i,*] · Sebastian Ellis[j,*] · Daniel G. Figueroa[k] · Gabriele Franciolini[i,*] · Camilo Garcia-Cely[k] · Andrew Geraci[a] · Maxim Goryachev[l] · Hartmut Grote[m] · Mark Hindmarsh[n,o] · Asuka Ito[p,q] · Joachim Kopp[i,r,*] · Sung Mook Lee[i,*] · Killian Martineau[s] · Jamie McDonald[t] · Francesco Muia[u] · Nikhil Mukund[v] · David Ottaway[w] · Marco Peloso[x,y] · Krisztian Peters[z] · Fernando Quevedo[u,α] · Angelo Ricciardone[f,β] · Andreas Ringwald[z] · Jessica Steinlechner[γ,δ,ε] · Sebastian Steinlechner[γ,δ] · Sichun Sun[ζ] · Carlos Tamarit[r] · Michael E. Tobar[l] · Francisco Torrenti[η] · Caner Ünal[θ,λ] · Graham White[μ]

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Living Review update: 2501.11723

Big thank you to all contributors and in particular to the team of coordinators: Sebastian Ellis, Gabriele Franciolini, Joachim Kopp, and Sung Mook Lee.

2025 Update of UHF GW Living Review

Contents

notation / framework

summary plots

PBH discussion

Extended detector section, grouped by technology, with plots & tables

Sebastian Ellis

Gabriele Franciolini

Sung Mook Lee

Comparing apples to apples

Signal and noise:

$$s(f) = T_h(f)\, h(f)$$

Signal induced by GW,
e.g. phase shift ϕ in LIGO

Gravitational wave
(Fourier transform)

Signal transfer/response function, e.g.
$\mathcal{O}(1)\, \omega_\gamma L\, \mathrm{sinc}(\omega_{\rm gw} L)$

$$n(f) = T_n(f)\, \bar{n}(f)$$

Noise induced in the
signal observable,
e.g. phase shift ϕ in LIGO

Raw noise,
e.g. thermal, shot noise,...

Noise transfer function

Comparing apples to apples

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Noise-equivalent strain power spectral density:

$$\langle X(f) X^*(f) \rangle = S_X(f) \delta(f - f')$$

PSD convention. X = h, n, s, ...

$$S_h^{\rm noise}(f) = S_{\bar{n}}(f) \frac{|T_n(f)|^2}{|T_h(f)|^2}$$

Noise power spectrum
in units of GW strain

Characterization of
detector sensitivity

Comparing apples to apples

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Noise power spectrum in units of GW strain

Characterization of detector sensitivity

Signal-to-noise ratio:

$$\mathrm{SNR}^{\rm lin} = \left[2\, \Delta t \int_0^\infty df\, \frac{S_h(f)}{S_h^{\rm noise}(f)} \right]^{1/2},$$

Detector linear in h

$$\mathrm{SNR}^{\rm quad} = \left[2\, \Delta t \int_0^\infty df\, \left(\frac{S_h(f)}{S_h^{\rm noise}(f)} \right)^2 \right]^{1/2},$$

Detector quadratic in h

O(1)

Time and frequency regime in which signal and detector overlap

Different types of signals

Stochastic gravitational wave backgrounds:

$$\Omega_{\rm GW}(f) = \frac{4\pi^2}{3H_0^2}|f|^3\, S_h(|f|)$$

Overlap function < 1 if multiple detectors

$$\text{SNR} \simeq \frac{3H_0^2}{4\pi^2}\left[t_{\rm int}\int_0^\infty df \left(\frac{\Gamma(f)\,\Omega_{\rm GW}(f)}{f^3\, S_h^{\rm noise}(f)}\right)^2\right]^{1/2}$$

$$h_{c,\rm sto} \equiv \sqrt{f S_h(f)} = \frac{H_0}{2\pi f}\left(3\Omega_{\rm GW}(|f|)\right)^{1/2}$$

» 1

→ PLS (power law integrated sensitvity) curves

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» 1

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→ PLS (power law integrated sensitvity) curves

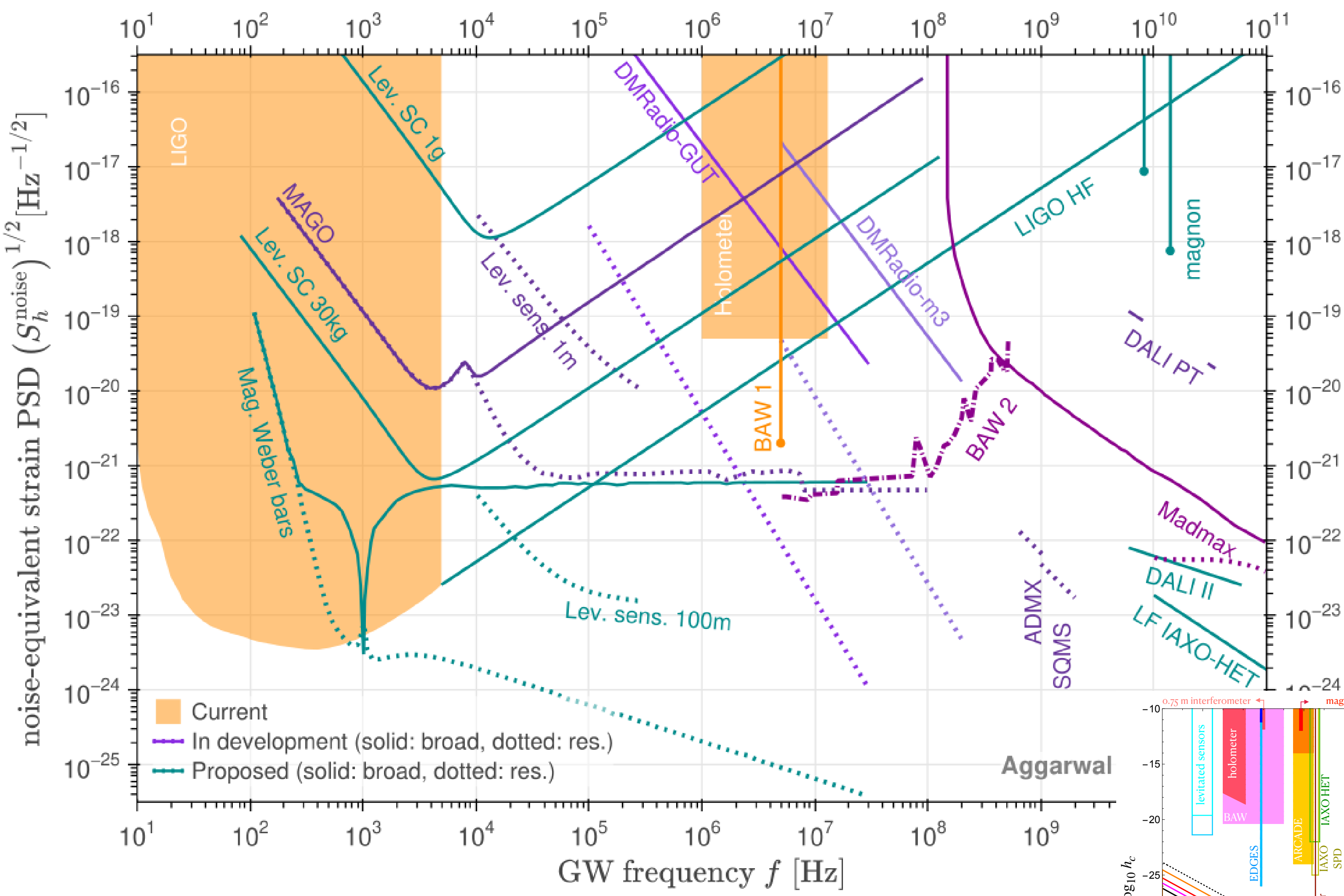
Transient gravitational waves:

$$S_h^{\text{lin(quad)}}(f) \gtrsim \text{SNR}^2 \times S_h^{\text{noise}}(f) \left(\frac{1}{\Delta f \, \Delta t} \right)^{1\,(1/2)}$$

$$h_{c,\text{insp}}(f) = 2 f \tilde{h}(f) \simeq \sqrt{N_{\text{cycles}}} \, h_0$$

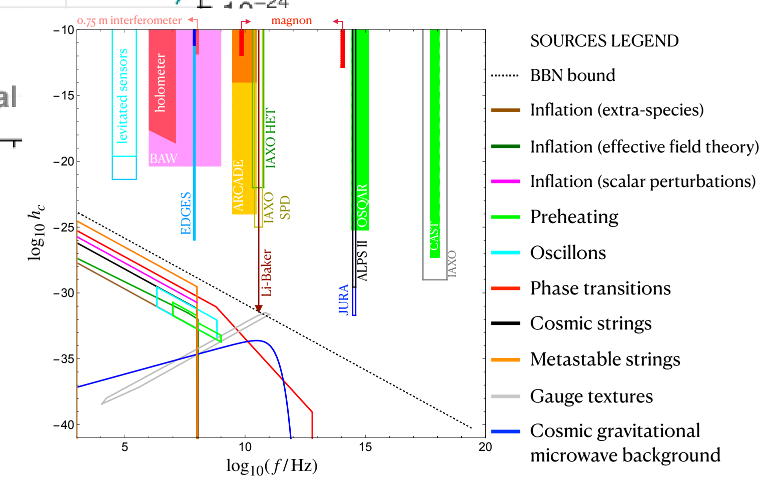
→ specifically for PBH mergers: translate to detector reach (in distance)

Noise-equivalent strain sensitivity

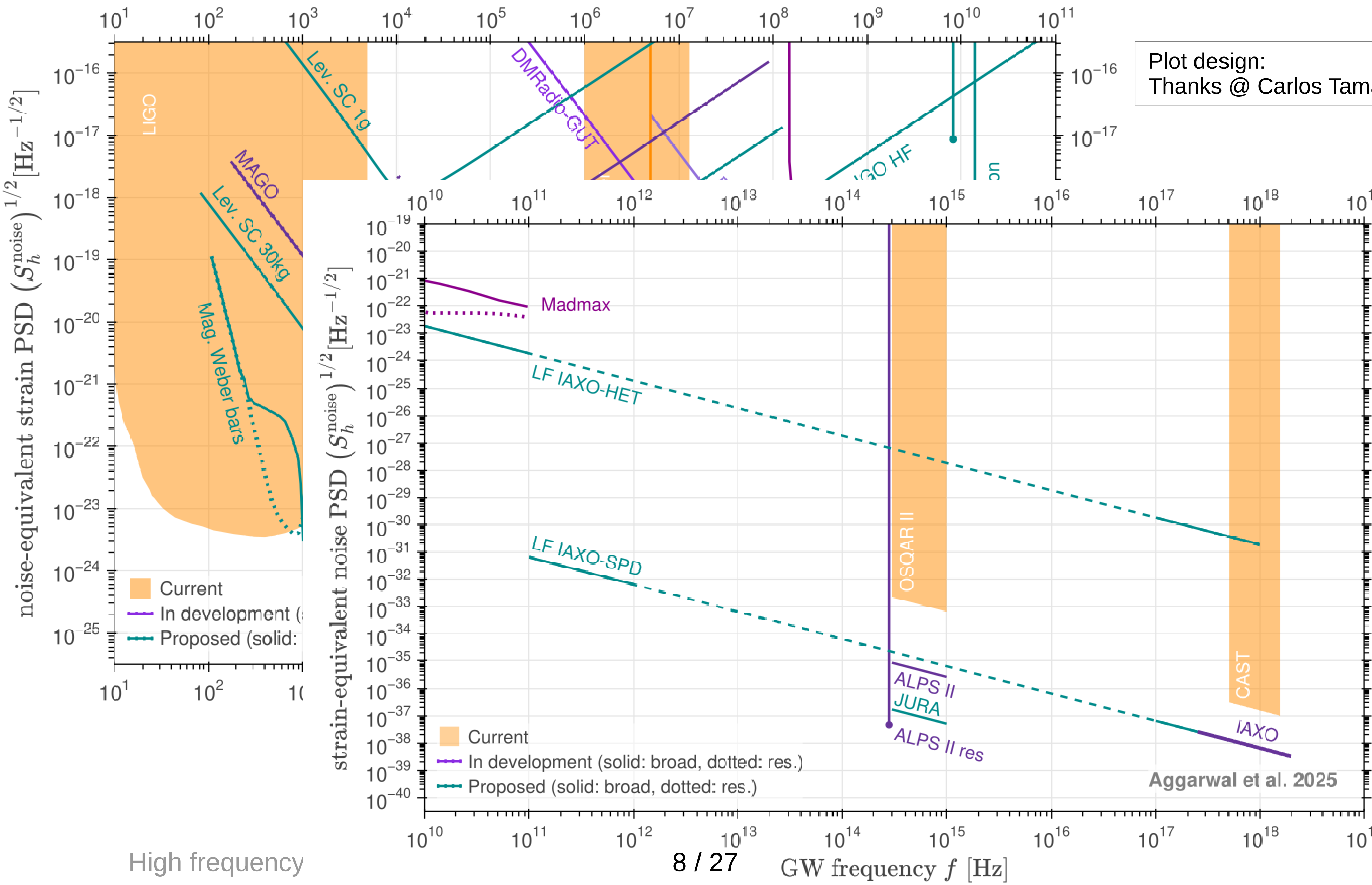


Plot design:
Thanks @ Carlos Tamarit

Previous version:

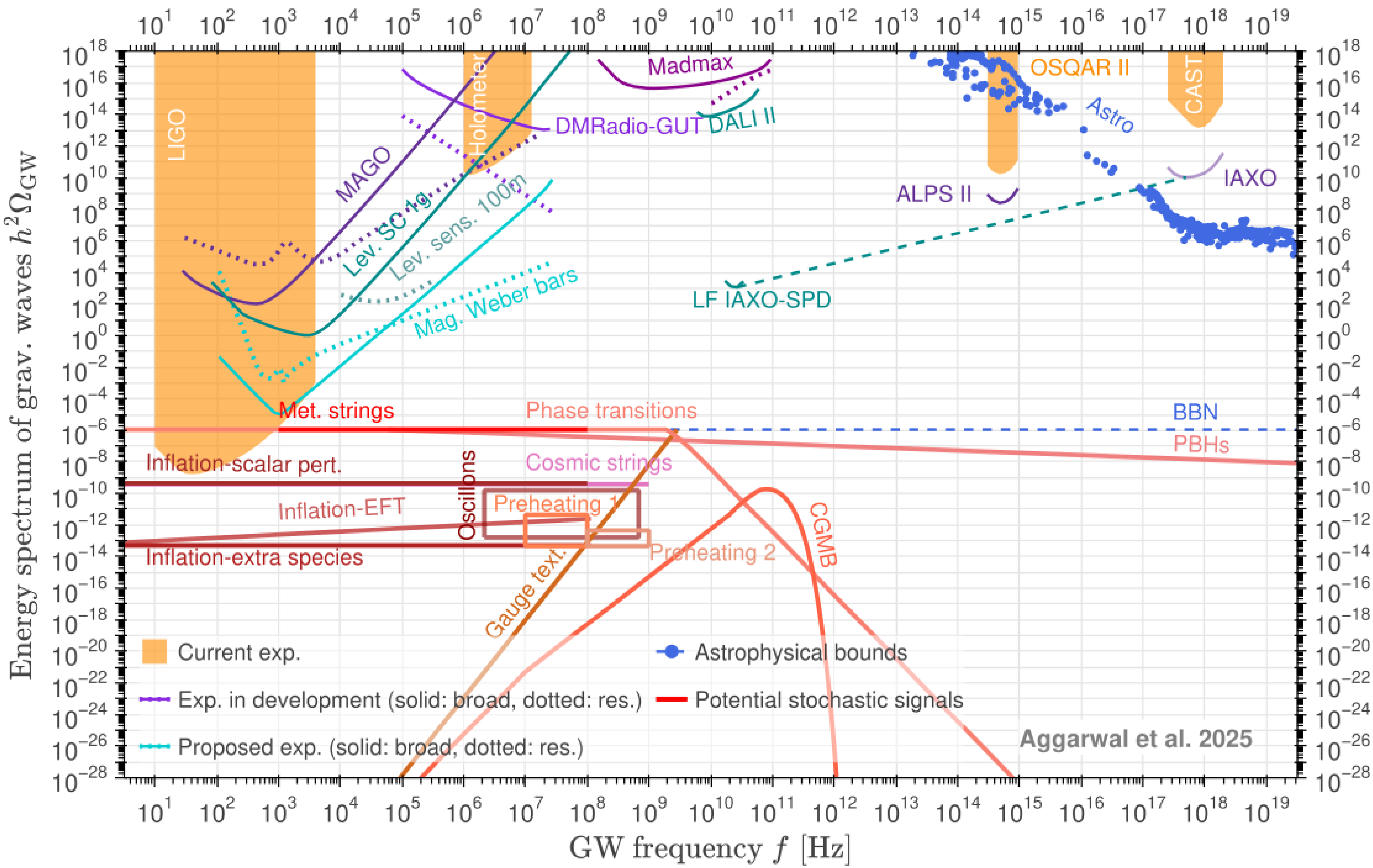


Noise-equivalent strain sensitivity

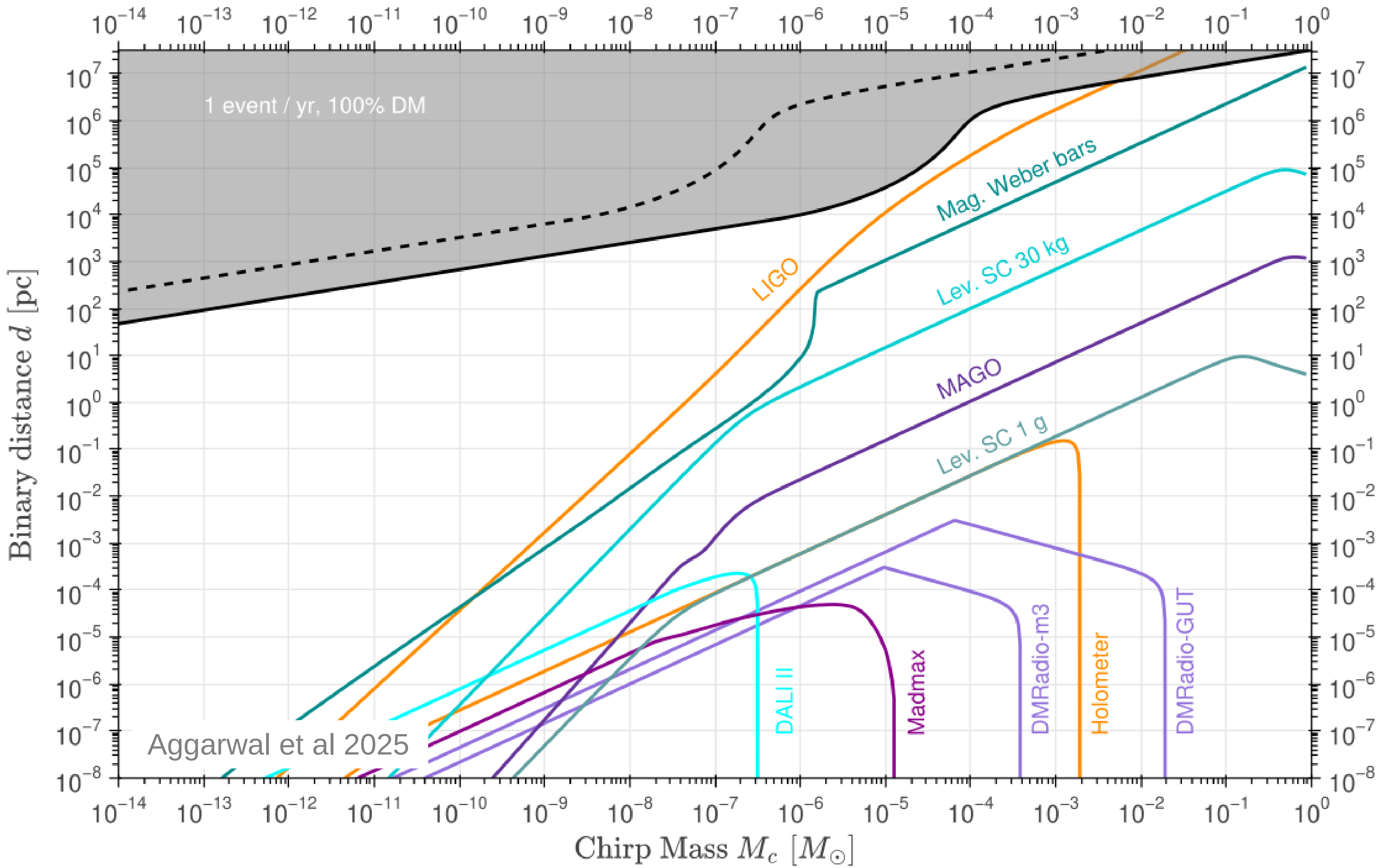


Plot design:
Thanks @ Carlos Tamarit

Sensitivity to stochastic GW backgrounds



Sensitivity to PBH mergers



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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

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

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

VD, Garcia-Cely, Rodd `22

Direct analogy with axion electrodynamics

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

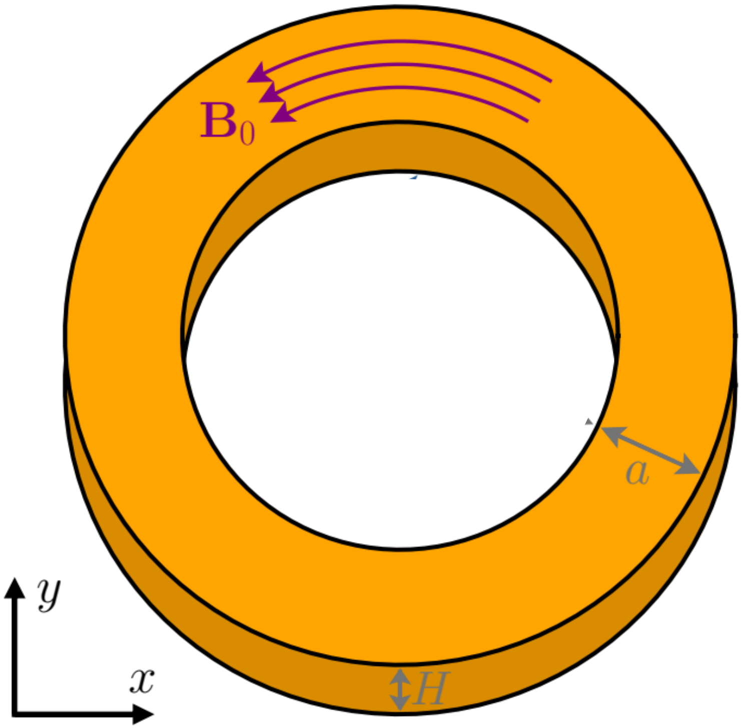
McAllister et al `18
Tobar, McAllister, Goryachev `19
Quellet, Bogorad `19

effective source terms in Maxwell‘s equation due to GW

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)

GW signal in low-mass axion haloscopes

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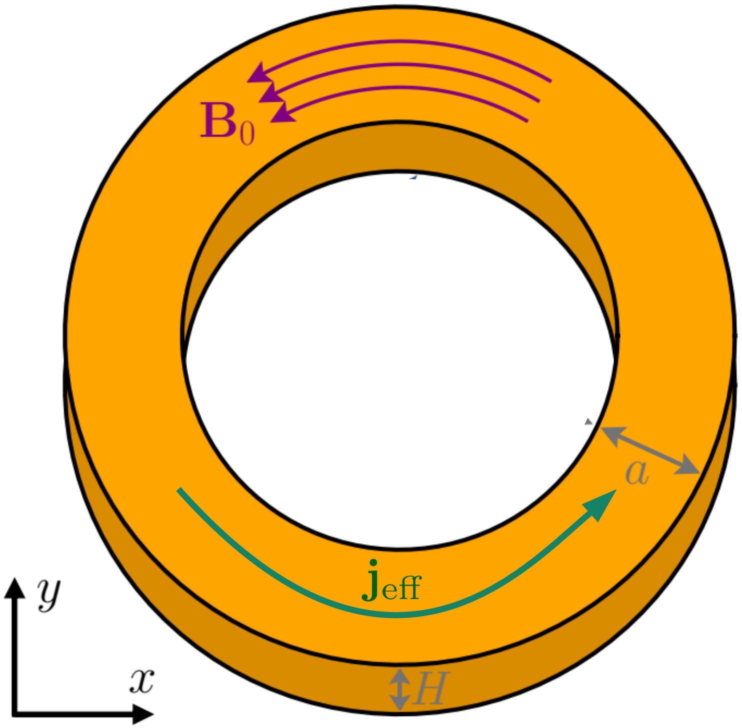

static magnetic field (i.e. rigid detector)

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

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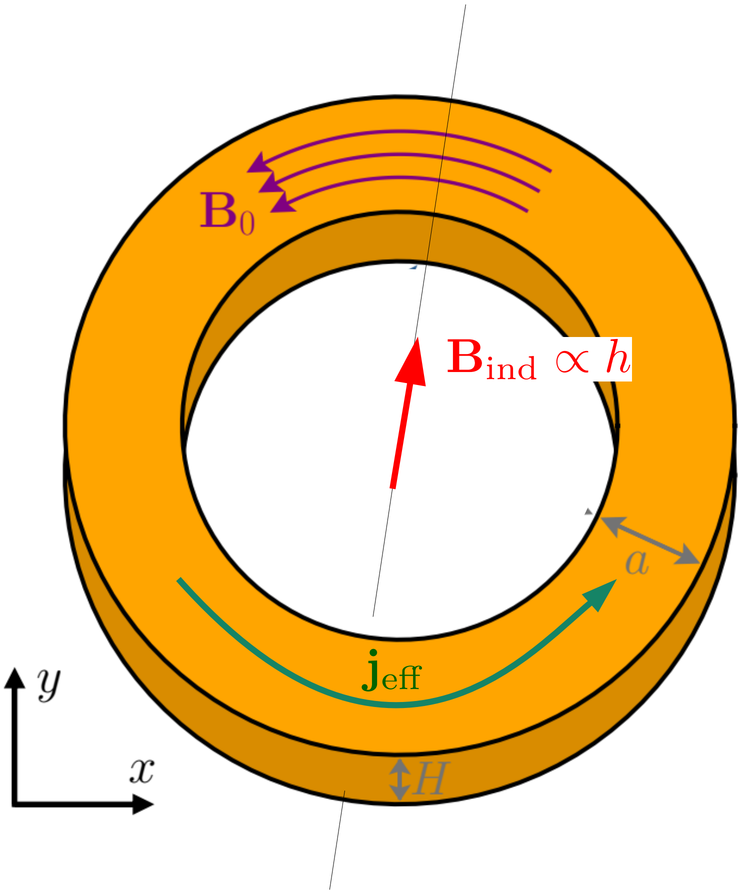

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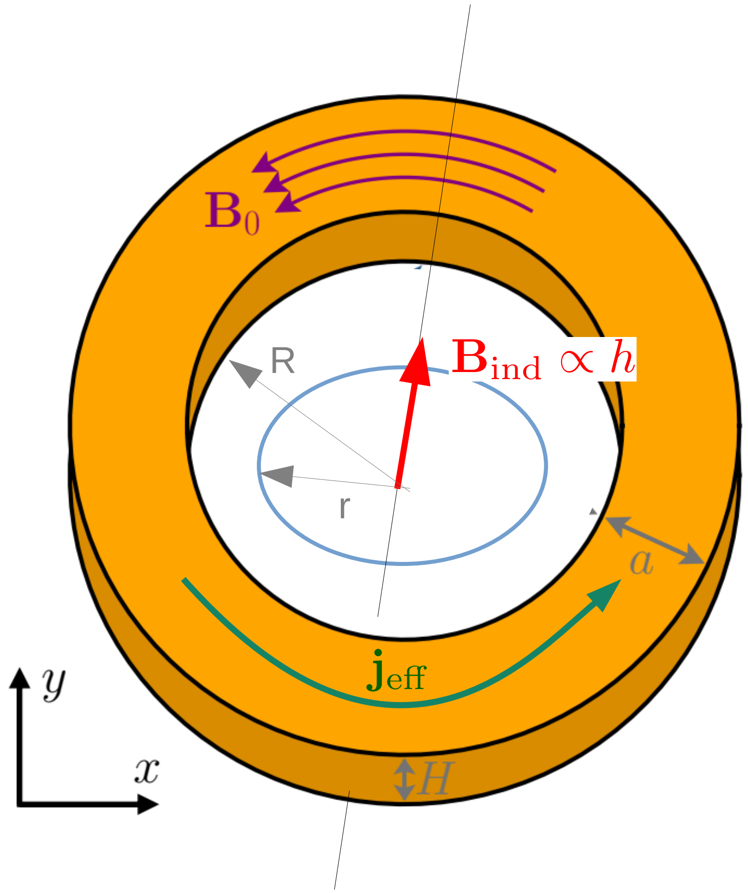

static magnetic field (i.e. rigid detector)

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

induced oscillating magnetic field

measure magnetic flux (~ h) through pickup loop

at leading order in (ωR) :

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

$$\sim (\omega L)^3 h B_0 L^2 \to (\omega L)^2 h B_0 L^2 \text{ fig-8 loop}$$

GW signal in low-mass axion haloscopes

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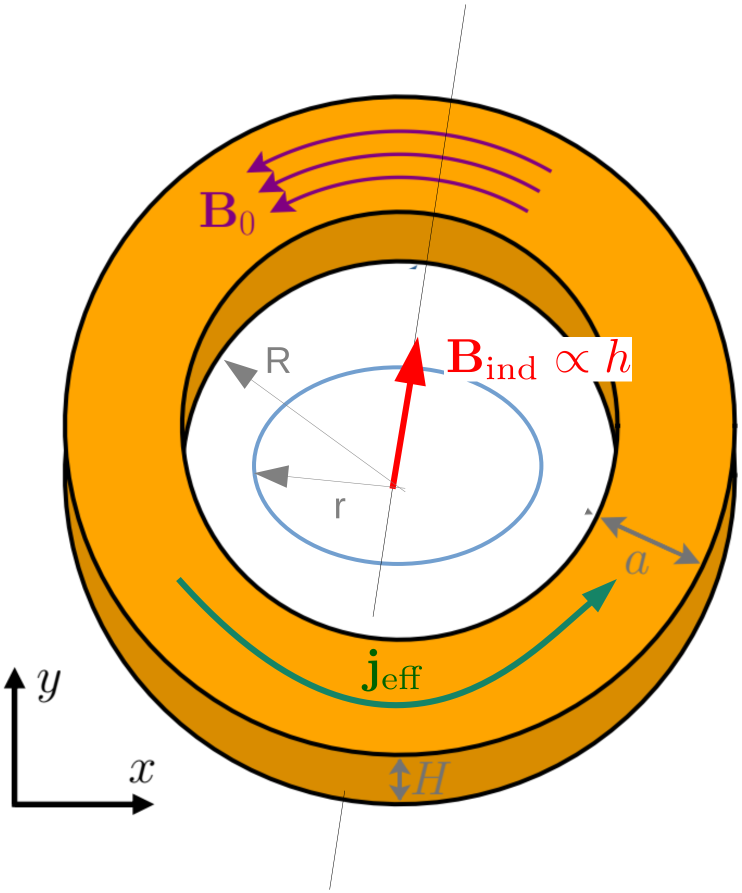

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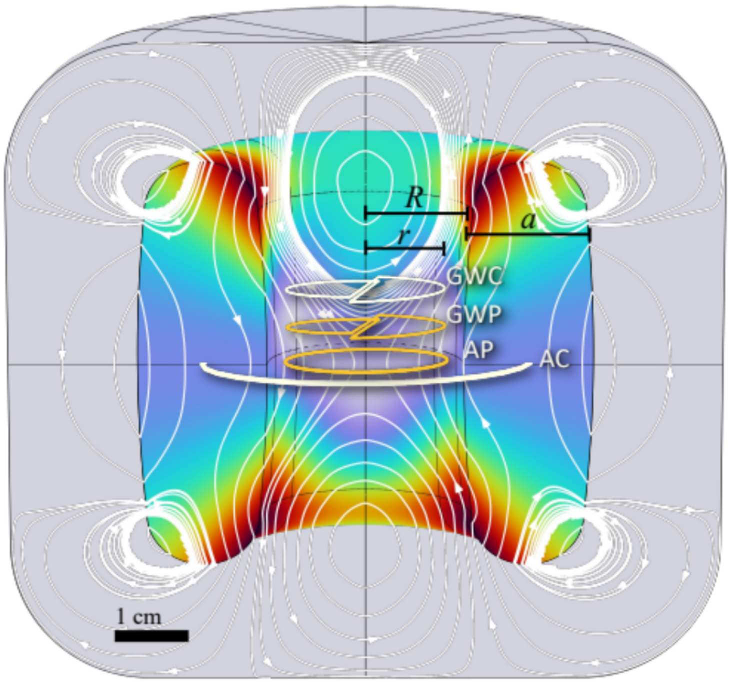
$$\Phi_a = e^{-i\omega t}\, g_{a\gamma\gamma} \sqrt{2\rho_{\text{DM}}} B_0 \pi r^2 R \ln(1 + a/R)$$

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

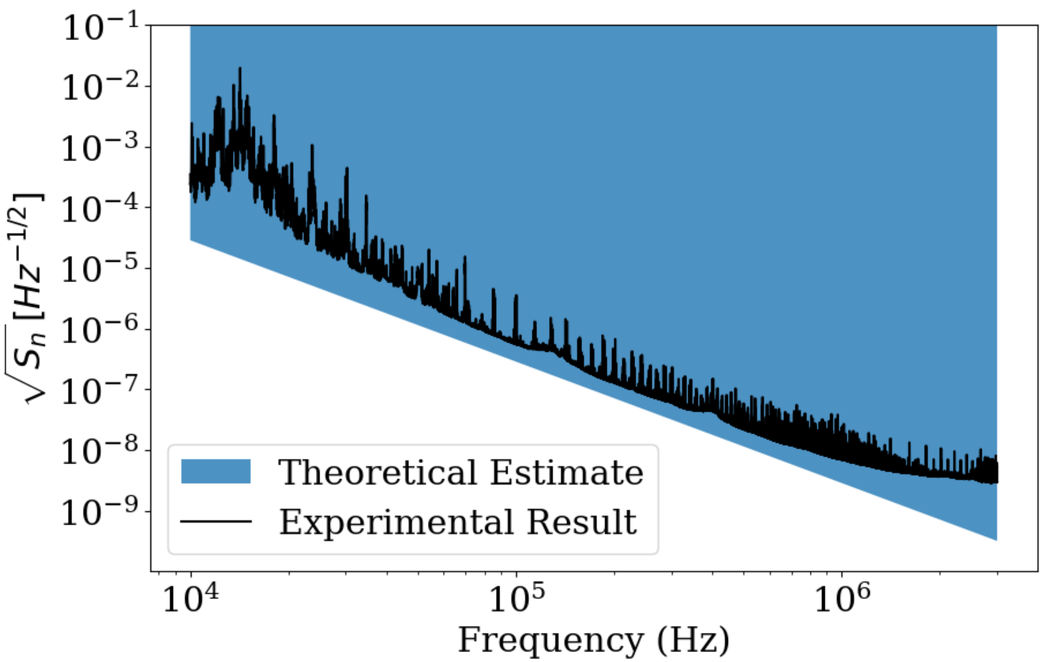
match to axion induced flux to estimate sensitivity to GW signals

Demonstrator: ABRA-GW results

Kaliroe Pappas et al, 2505.02821



Comsol simulation for calibration & signal



Noise measurement in agreement with theory projection

Some lessons learned:

- No 0.01 Msol PBH merger found withing 46 km of MIT
- Scaling to DM RadioGUT, gives a reach of 3 pc
- Data analysis: match filtering at MHz is a computational callenge

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Dielectric GW haloscope

Maxwell equations:

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

effective current induced by Gws
dielectric constant

Dielectric GW haloscope

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particular solutions in medium and vacuum

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

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

Dielectric GW haloscope

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effective current induced by Gws
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ALPs, IAXO,…
as GW detectors
[Ejlli et al `19]

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

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resonant conversion in vacuum

Dielectric GW haloscope

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

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

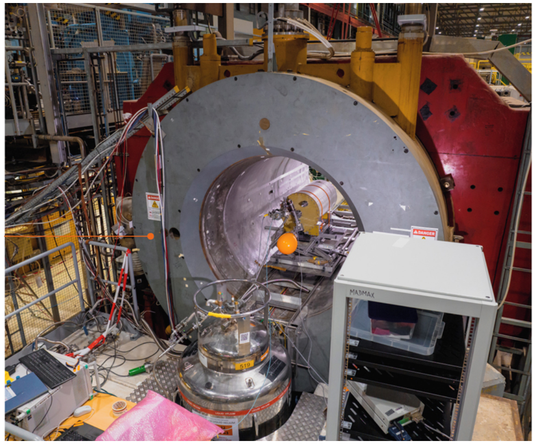
resonant conversion in vacuum

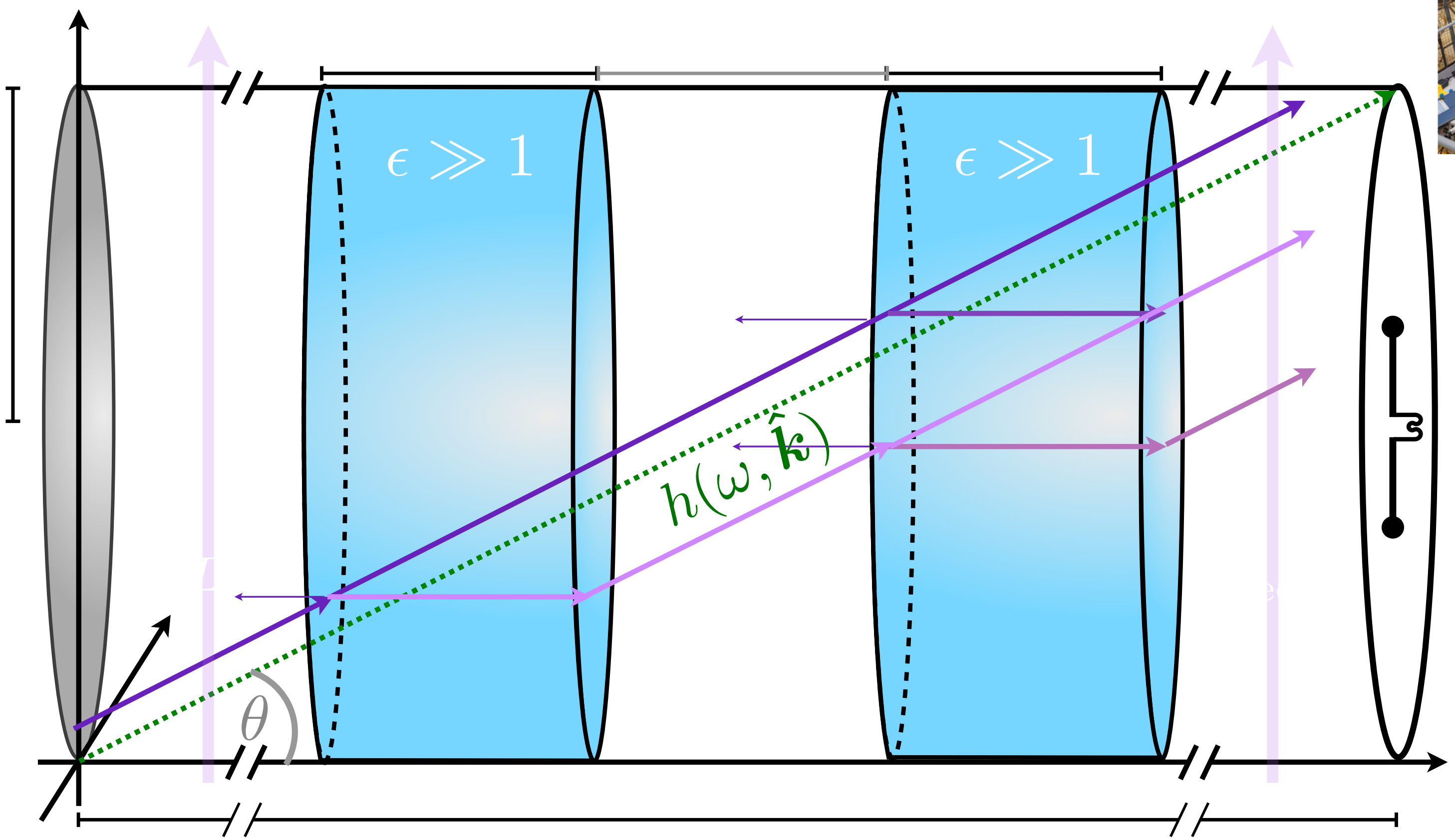
Boundary conditions at surface of dielectric medium

→ EM waves sourced at surfaces of dielectric disks

Dielectric GW haloscope

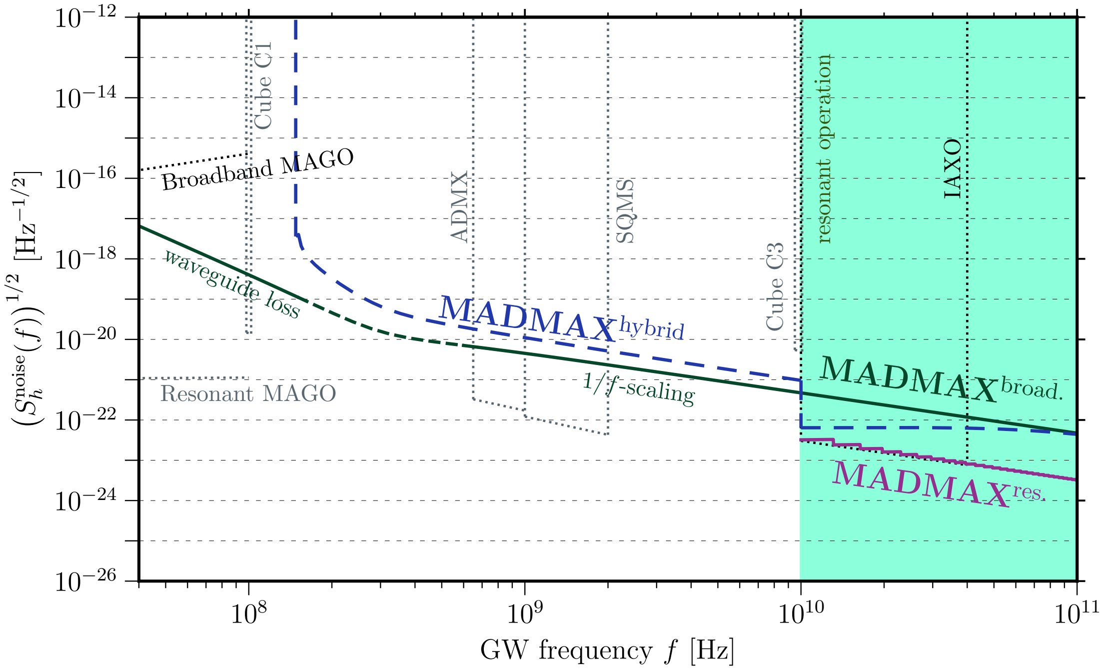
Madmax prototype
@ CERN





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

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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

mechanical coupling

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rigid limit	on resonance (Weber Bars)	free-falling limit →	

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

response function may be suppressed by oscillation pattern

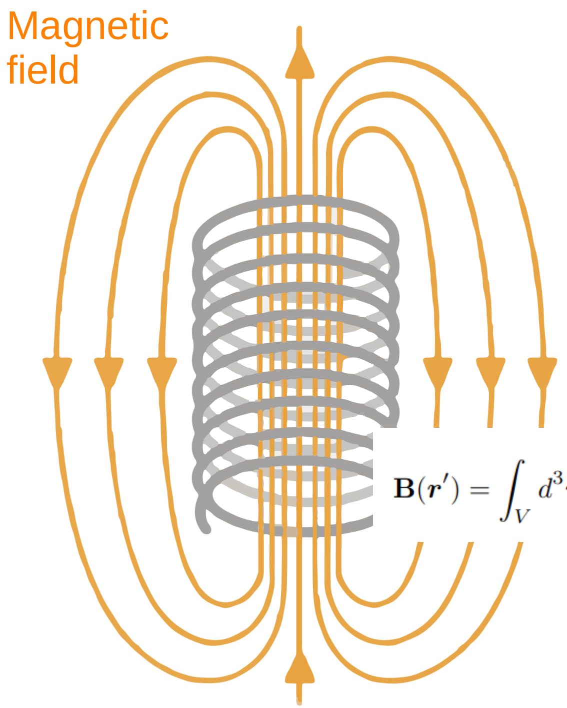
- mechanical coupling can be significantly more efficient
- challenge of transducing mechanical deformation to EM signal for quantum readout

Magnetic Weber Bar

VD, Ellis, Rodd `24

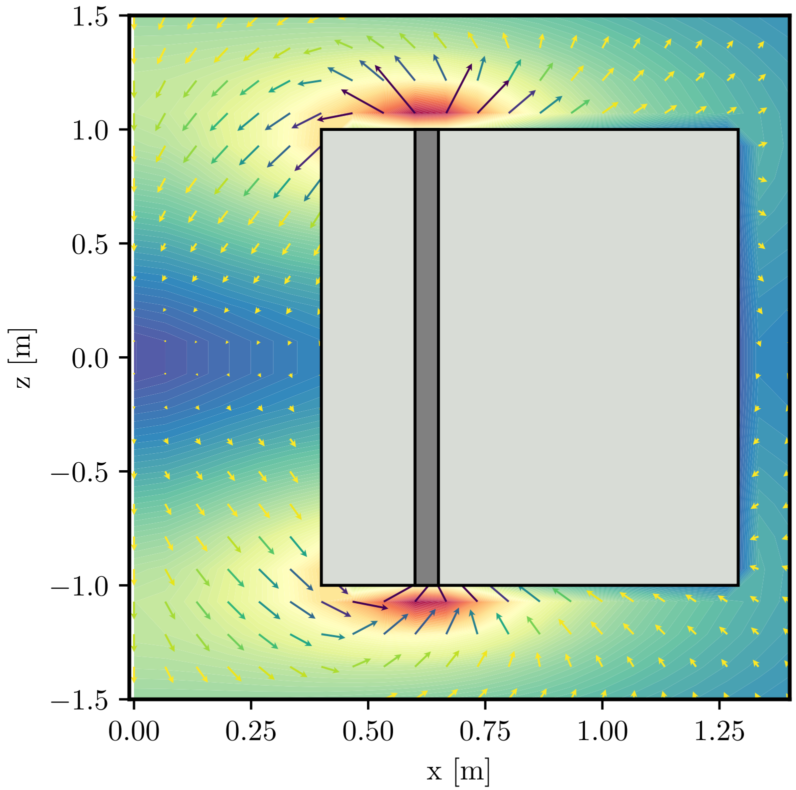
GW acts as a mechanical force on (current-carrying) wires:

GW



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

Biot-Savart law

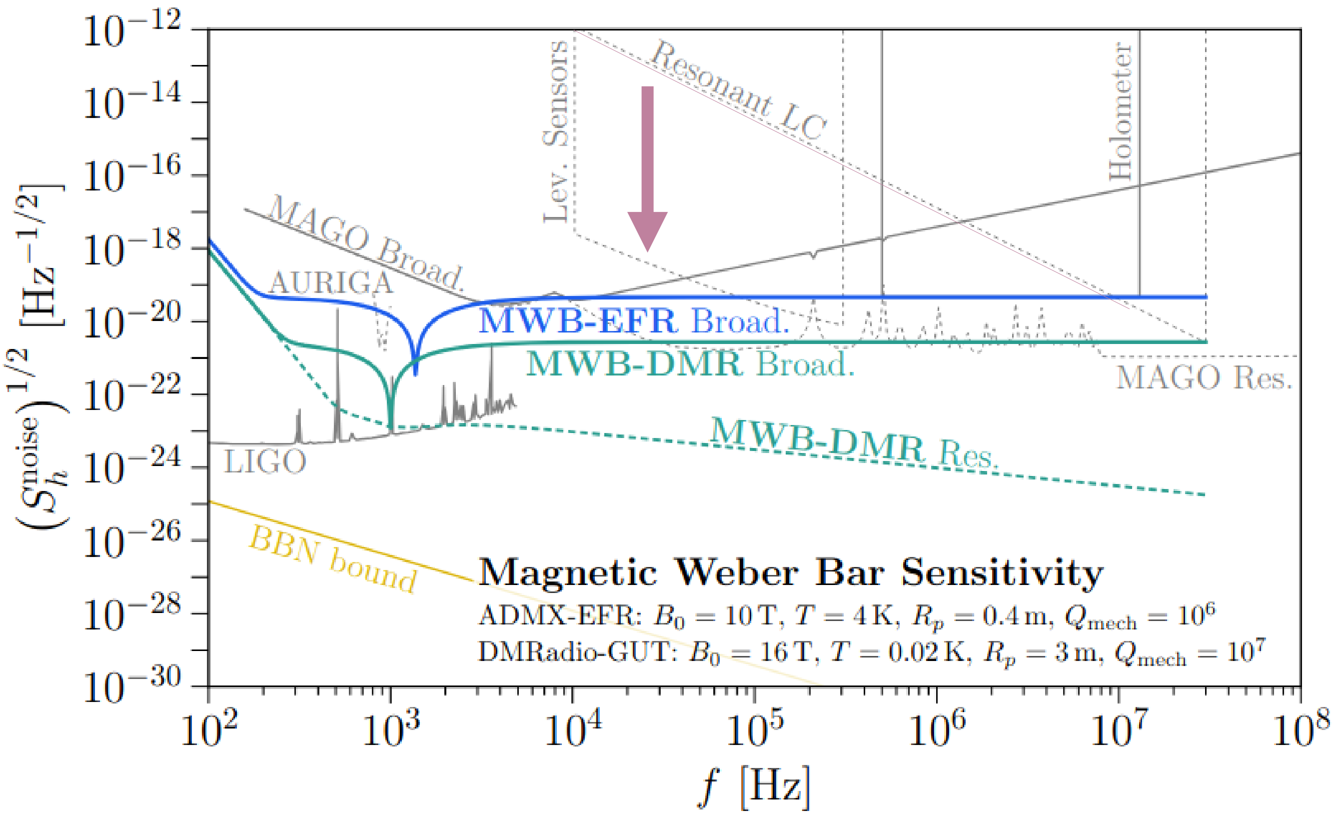


Induced AC magnetic field ~ h B, read out with pickup loop + SQUID

Magnetic Weber Bar

VD, Ellis, Rodd `24

mechanical vs
EM coupling



effects at O(h):

- deformation of magnet coil
- motion of pickup loop

Noise contributions:

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

Very competitive broadband sensitivity !

Conclusions and Outlook

UHF GW searches as an interdisciplinary challenge with an active community

- Precision measurments and quantum sensing
- New ideas and prototype devolopment
- Experiment, theory and data analysis

Some recent progress:

- ABRA-GW demonstrator: first results
- Operating dielectric axion haloscopes as GW detectors
- Promising estimates for Magnetic Weber Bars → needs testing / demonstrator

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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

… and an advertisement:

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

short-term visits typically O(week)

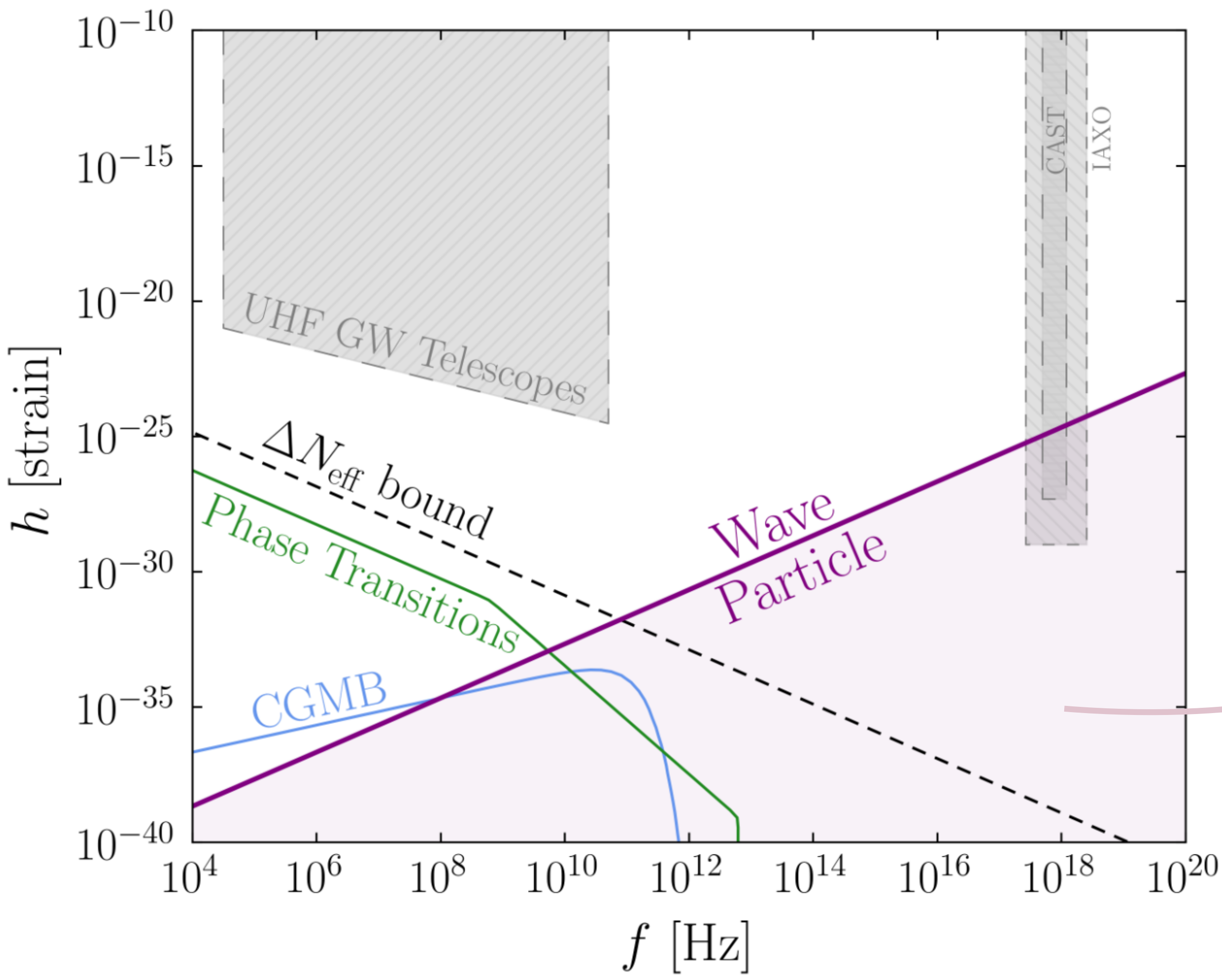
long term visits (> 3 months, usually sabbaticals)

consider applying!

backup slides

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