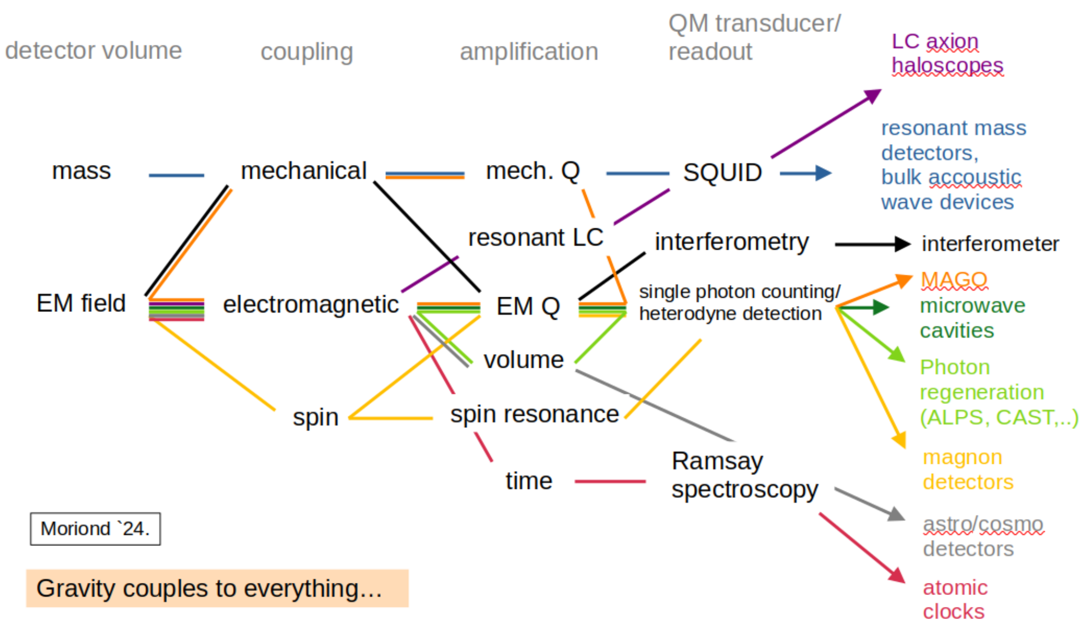
Searching for high-frequency gravitational waves



Moriond `24.

Gravity couples to everything…

Valerie Domcke
CERN

Astro@Paris-Saclay
Nov 10, 2025

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

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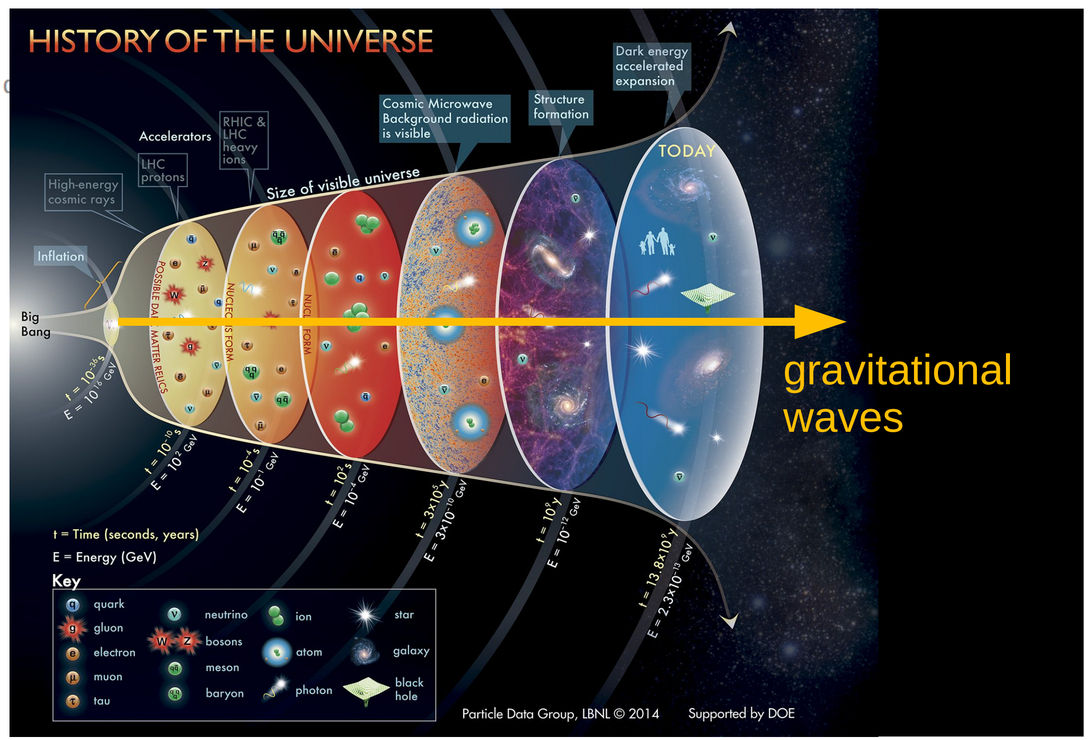

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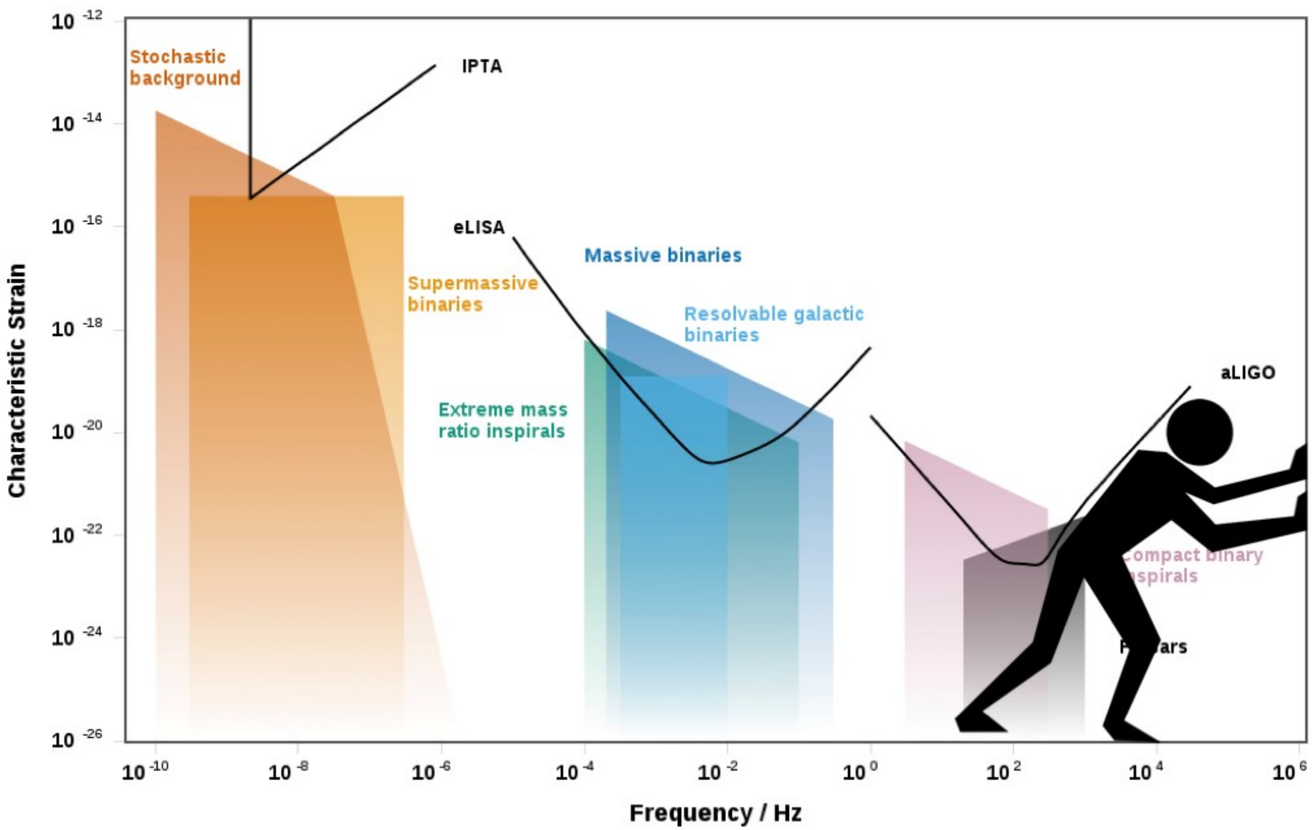
GW searches above ~ kHz ?



Why go here ?

No known astro foregrounds

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

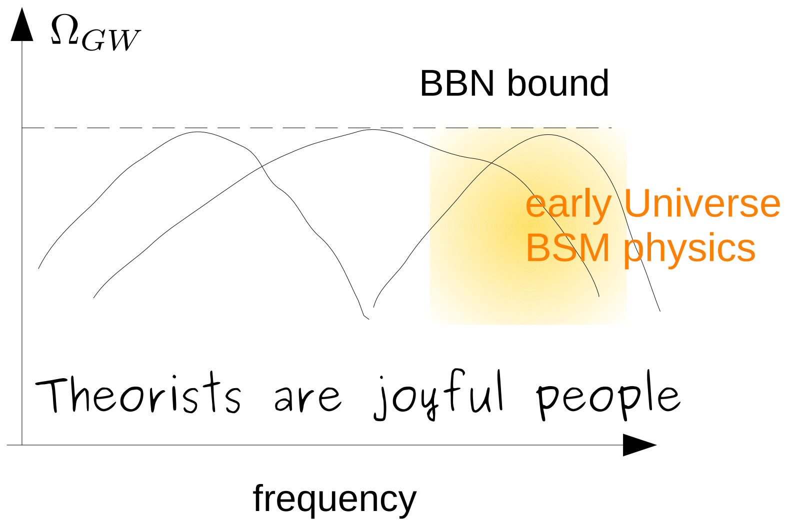
In the mean time:

Exotic astrophysical sources (PBHs, superradiance,..)

Neutron star signals up to ~ MHz ?

challenges in UHF GW detection

$$\Omega_{\rm GW} = \frac{{\rm d}\ln\rho_{\rm GW}}{\rho_c\,{\rm d}\ln f}$$

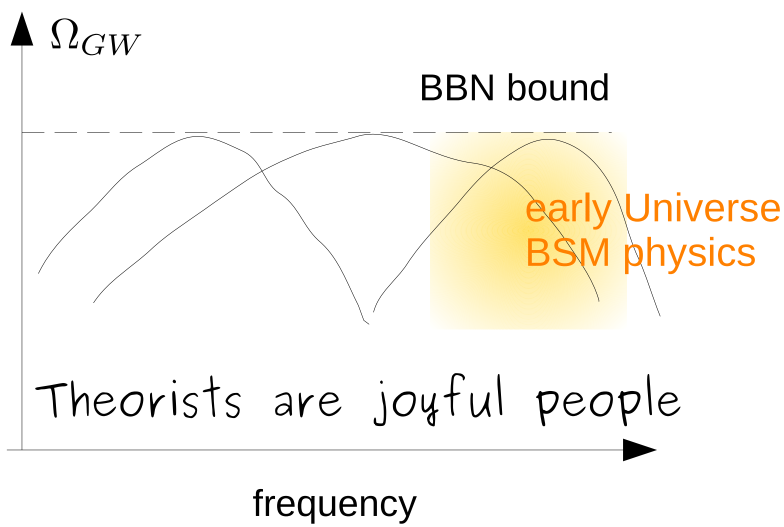


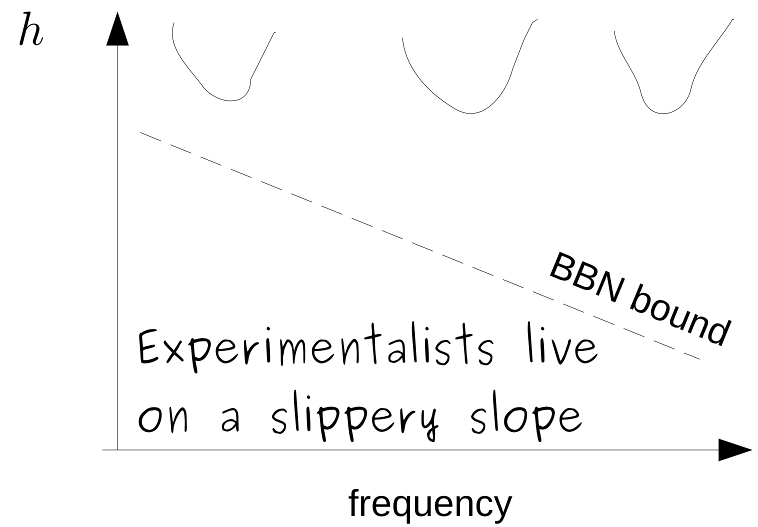
CMB/BBN bound constrains energy

challenges in UHF GW detection

$$\Omega_{\rm GW} = \frac{\mathrm{d}\ln\rho_{\rm GW}}{\rho_c\,\mathrm{d}\ln f}$$

$$\rho_{\rm GW} \sim f^2 h^2 M_P^2$$





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

CMB/BBN bound constrains energy

experiments measure displacement

challenges in UHF GW detection

$$\Omega_{\rm GW} = \frac{d \ln \rho_{\rm GW}}{\rho_c \, d \ln f}$$

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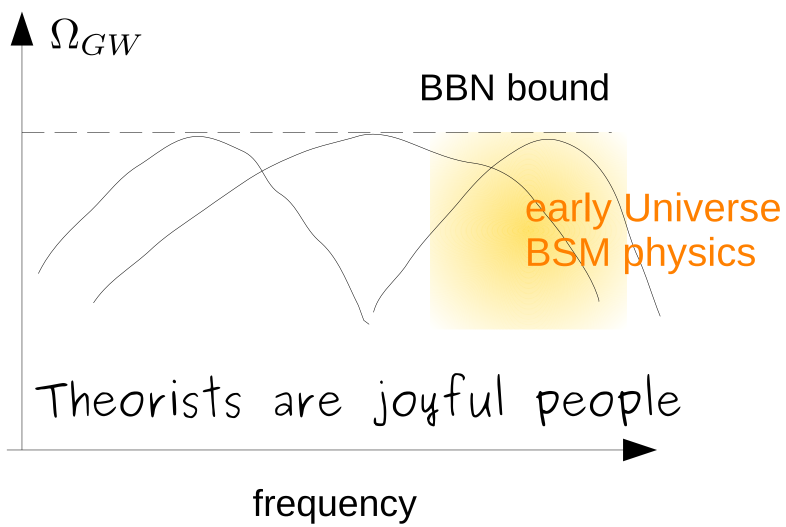
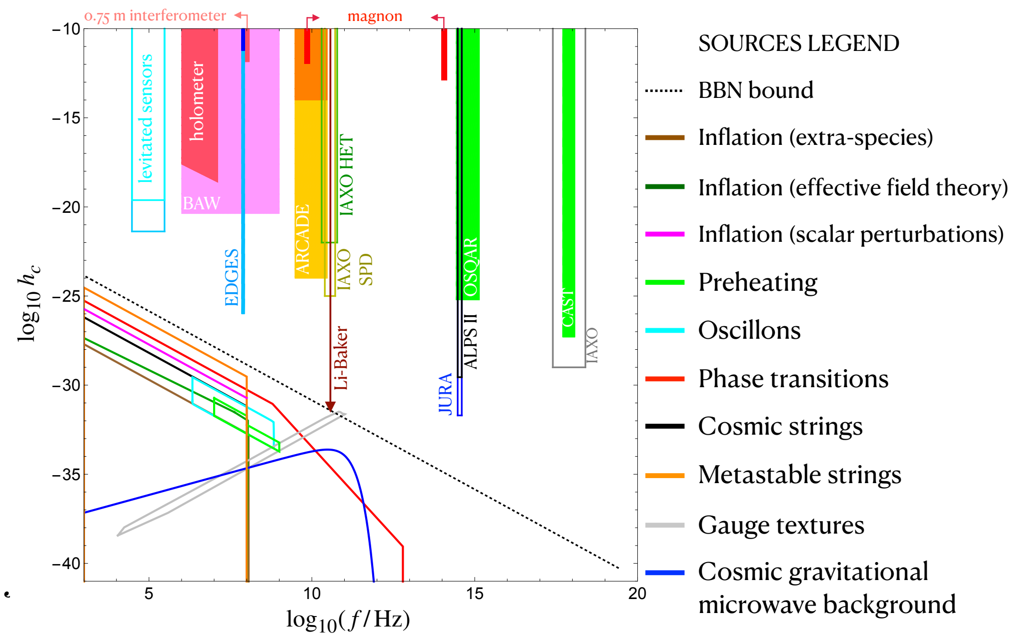
UHF GW initiative Living Review 2020



$\Omega_{GW} \propto$.



CMB/BBN bound constrains energy

experiments measure displacement

2025 Update of UHF GW Living Review

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

Challenges and Opportunities
of Gravitational Wave Searches above 10 kHz

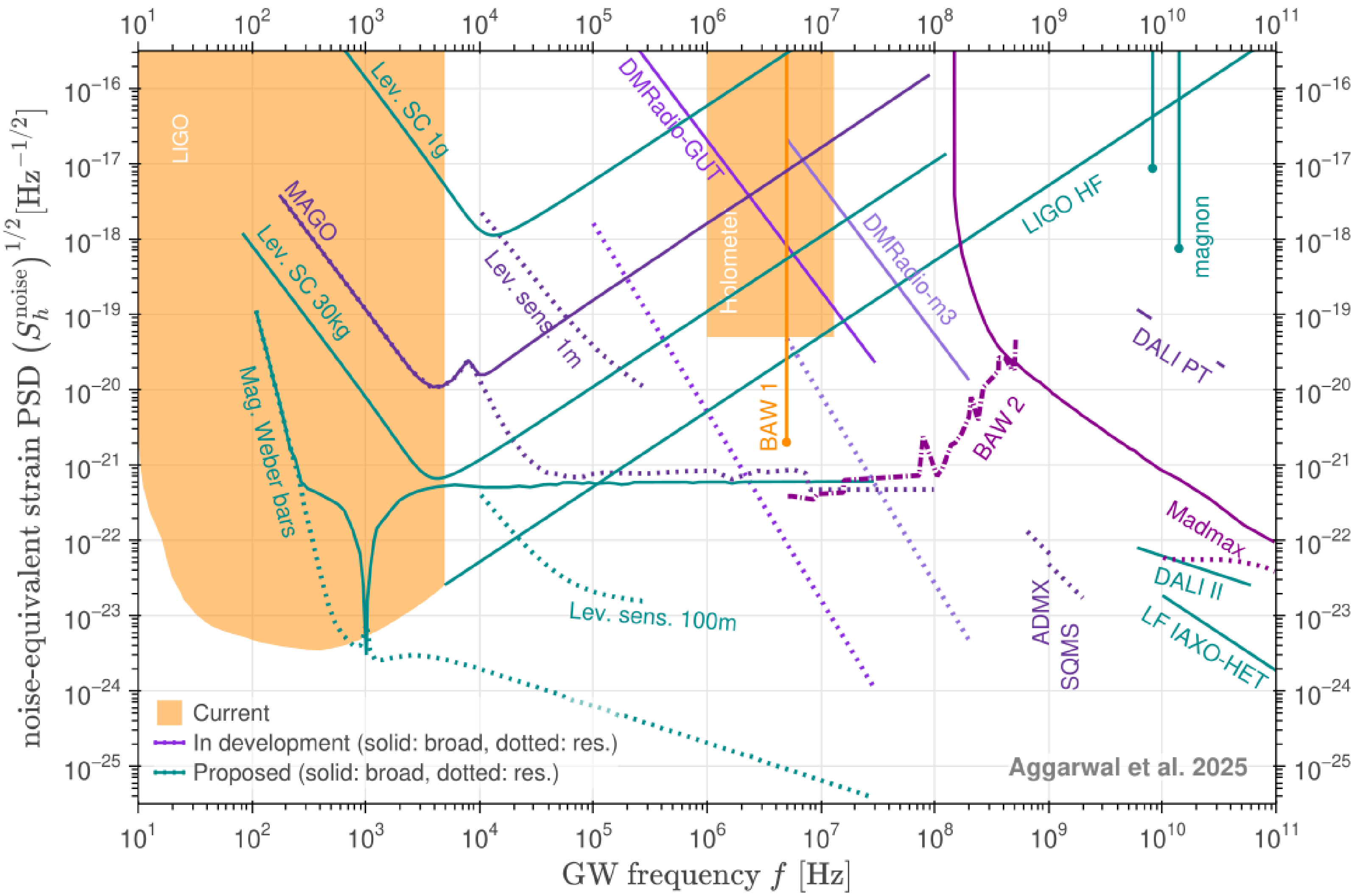
Nancy Aggarwal[a] · Odylio D. Aguiar[b] · Diego Blas[c,d] · Andreas Bauswein[e] · Giancarlo Cella[f] · Sebastian Clesse[g] · Adrian Michael Cruise[h] · Valerie Domcke[i,*] · Sebastian Ellis[j,*] · Daniel G. Figueroa[k] · Gabriele Franciolini[i,*] · Camilo Garcia-Cely[k] · Andrew Geraci[a] · Maxim Goryachev[l] · 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]

Corresponding authors: Valerie Domcke (E-mail: valerie.domcke@cern.ch) · Sebastian Ellis (E-mail: Sebastian.Ellis@unige.ch) · Gabriele Franciolini (E-mail: gabriele.franciolini@cern.ch) · Joachim Kopp (E-mail: jkopp@uni-mainz.de) · Sung Mook Lee (E-mail: sungmook.lee@cern.ch)

Very alive Living Review, 2025 update: 2501.11723

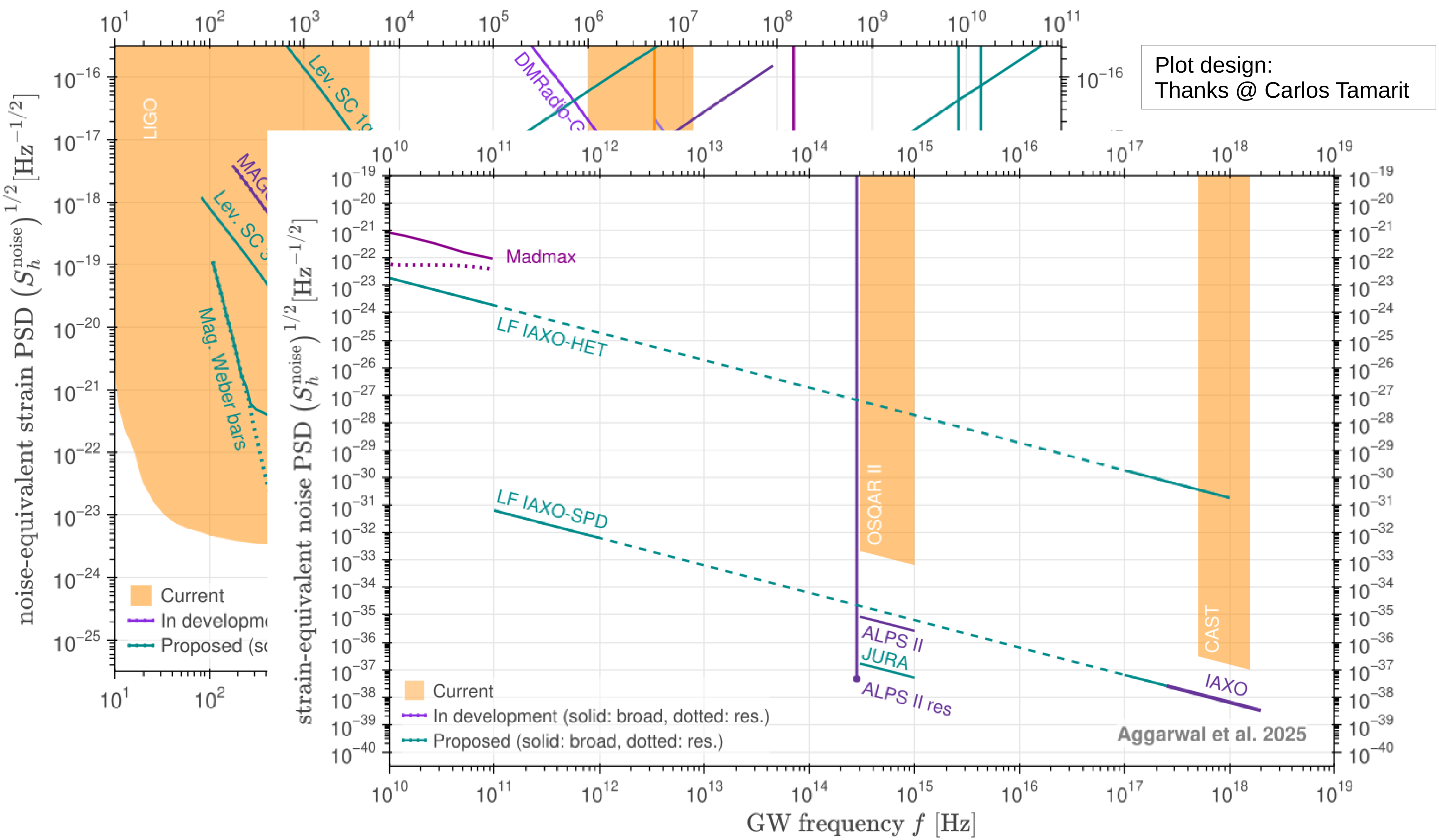
Big thank you to all contributors and in particular to the team of coordinators: Sebastian Ellis, Gabriele Franciolini, Joachim Kopp, and Sung Mook Lee.

Overview of experimental effort

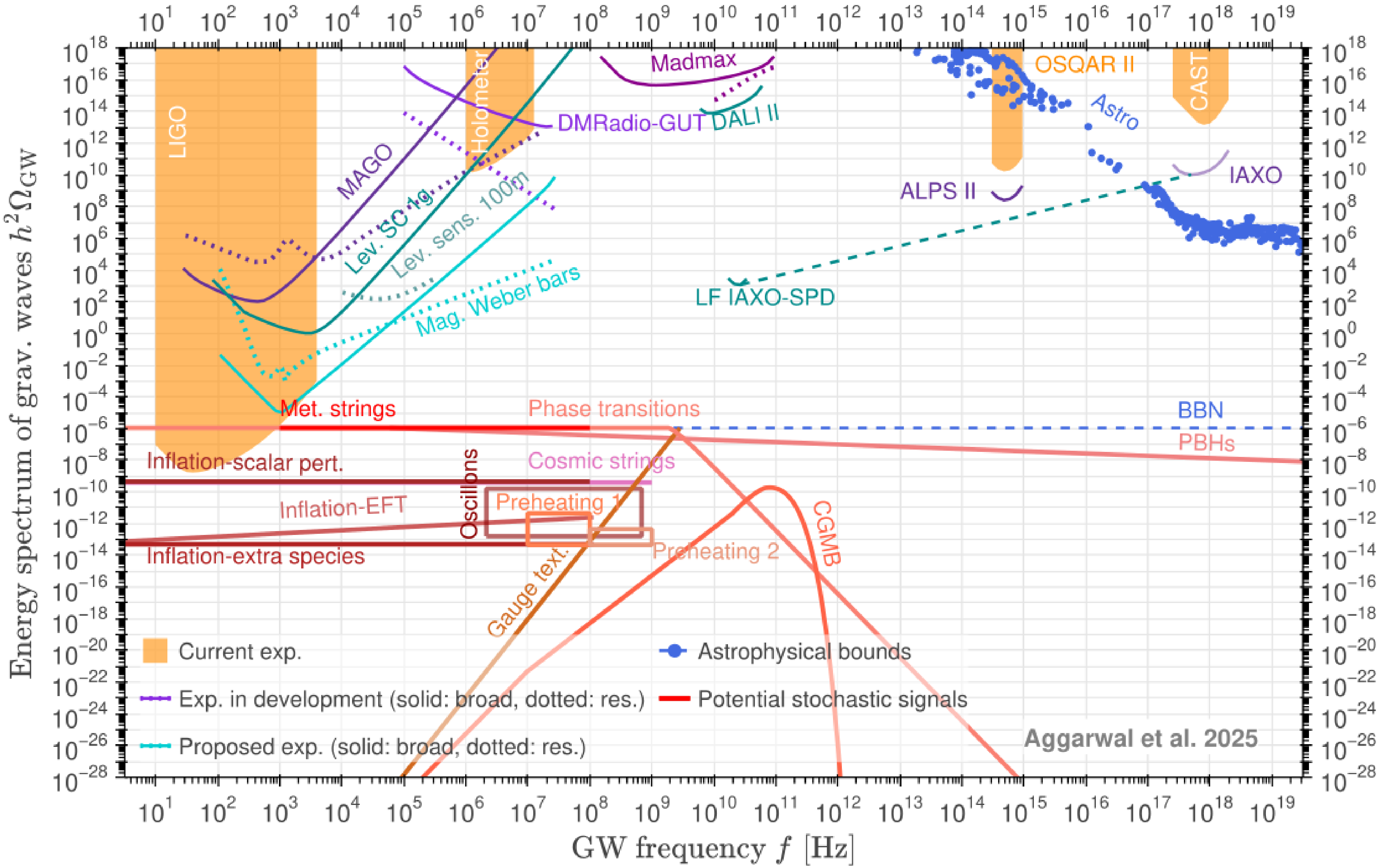


Plot design:
Thanks @ Carlos Tamarit

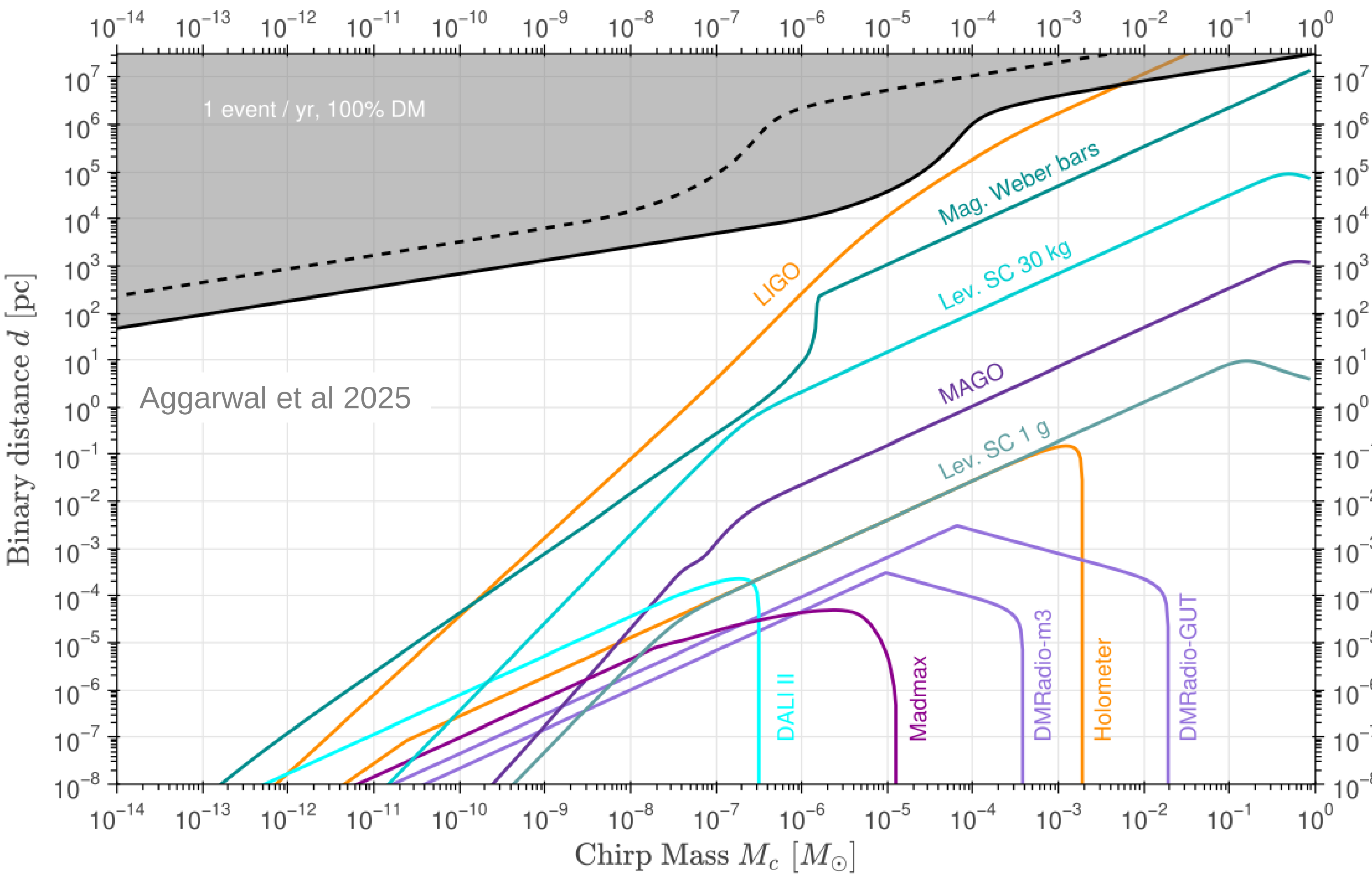
Overview of experimental effort



Sensitivity to stochastic GW backgrounds



Sensitivity to PBH mergers



For including also memory signal: see Gasparotto, Franciolini, VD `25

How to look for (high frequency) gravitational waves?

Easy – gravity couples to everything, so any experiment is a GW detector

…. but most of the time a very bad one.

GW electrodynamics

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

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

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

effective source term

effective current

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

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VD, Garcia-Cely, Rodd `22

Direct analogy with axion electrodynamics

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

McAllister et al `18

Tobar, McAllister, Goryachev `19

Quellet, Bogorad `19

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

induced at linear order in h
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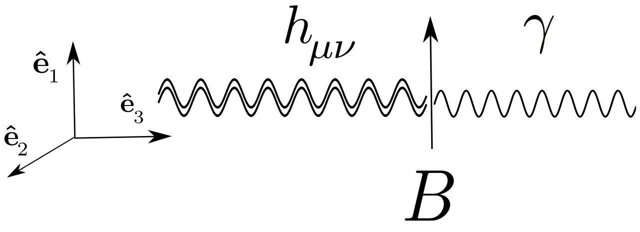
$$\mathcal{L} \supset g_{a\gamma\gamma} a\, \mathbf{E} \cdot \mathbf{B} \quad \rightarrow \quad \mathbf{P} = g_{a\gamma\gamma} a\, \mathbf{B}\,, \quad \mathbf{M} = g_{a\gamma\gamma} a\, \mathbf{E}$$

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

(Inverse) Gertsenshtein effect analogous to Primakoff effect

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



Axion experiments as GW detectors

Microwave cavities

eg ADMX, HAYSTAC, CAPP, ORGAN, *Cubic cavities, RADES-BabyIAXO*

Berlin et al 2112.11465, Navarro et al 2312.02270, Valero et al 2407.20482

Haloscopes

eg ABRACADABRA, SHAFT, ADMX SLIC, BASE, WISPLC, *DM-Radio*

Garcia-Cely et al 2202.00698, 2306.03125, Pappas et al 2505.02821

Photon regeneration experiments („Light shining through the wall“)

eg OSQAR, ALPS, CAST, *(Baby)IAXO*

Ejlli et al 1908.00232, Ringwald et al 2011.04732

Conceptual progress on Gws scattering off magnetized regions: Garcia-Cely, Lee, VD `25

Dielectric Haloscopes

eg MADMAX, DALI

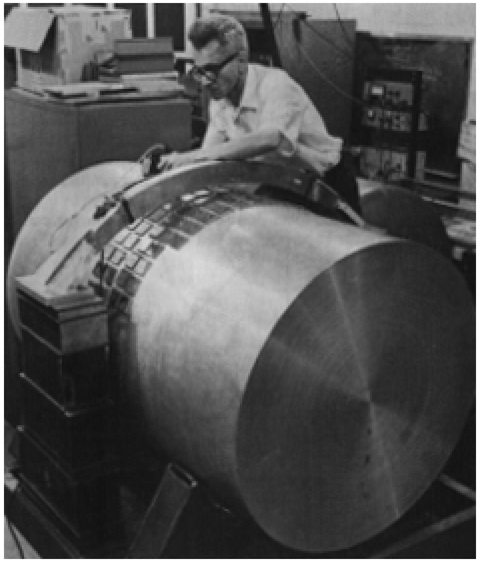
VD et al 2409.06462,
De Miguel et al 2303.03997

Astro detectors, eg neutron stars, CMB

Garcia-Cely et al 2006.01161, Ito et al 2305.13984,
Ito et al 2309.14765, McDonald et al 2406.18634,
Dandoy et al 2402.14092, Lella et al 2406.17853,...

An old idea revived

Maxwell’s equations are „stiff“, mechanical deformation is easier due to $v_s/c \sim 10^{-5}$



Original Weber Bar

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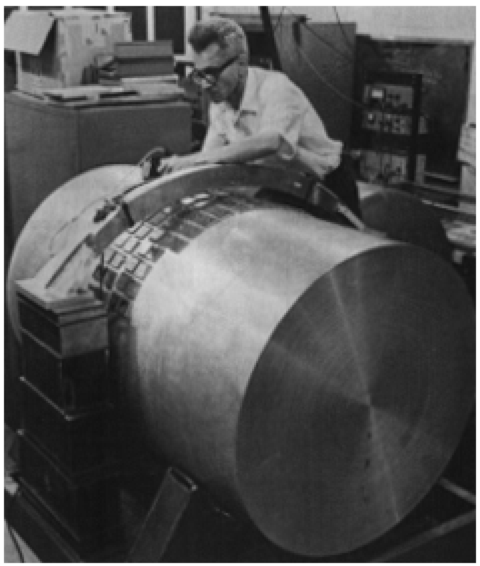

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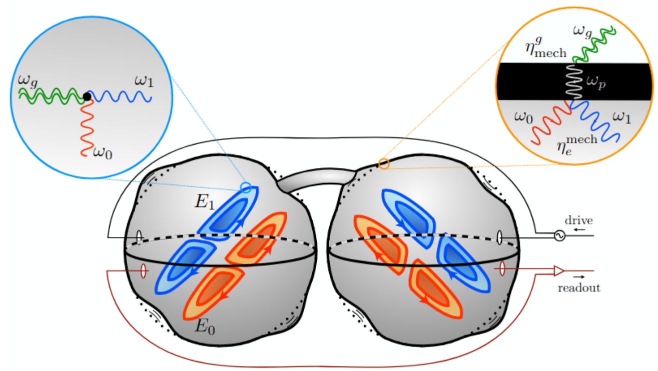

MAGO 2.0
optomechanical coupling
Berlin et al `23

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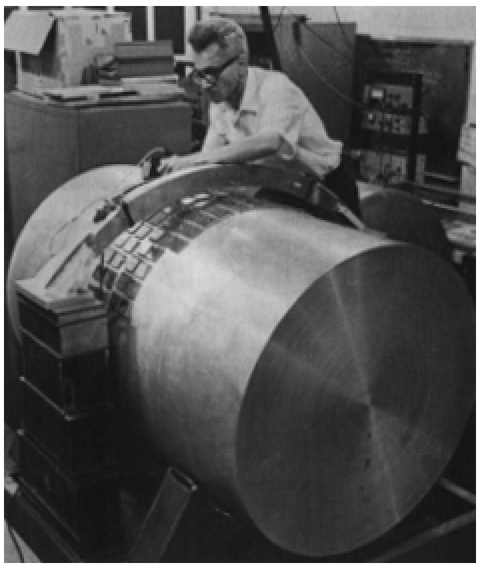

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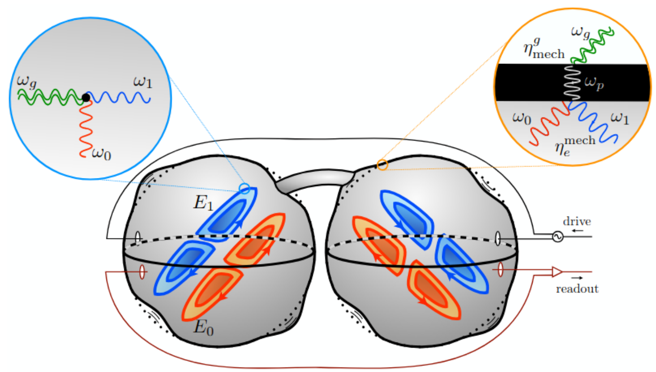

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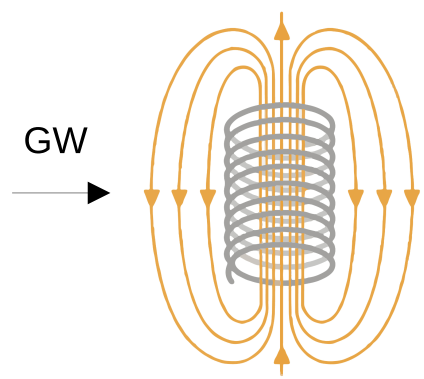

Magnetic Weber Bar
VD, Ellis, Rodd `24

→ **Sebastian's talk**

Conclusions and Outlook

Gravitational waves at > 10 kHz : a probe of new physics

- Very different experimental concepts probing uncharted territory
- Significant improvement in sensitivity needed to probe realistic signals

Synergies between axion and high-frequency GW searches

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

A lot of room for new ideas!

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A lot of room for new ideas!

„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)

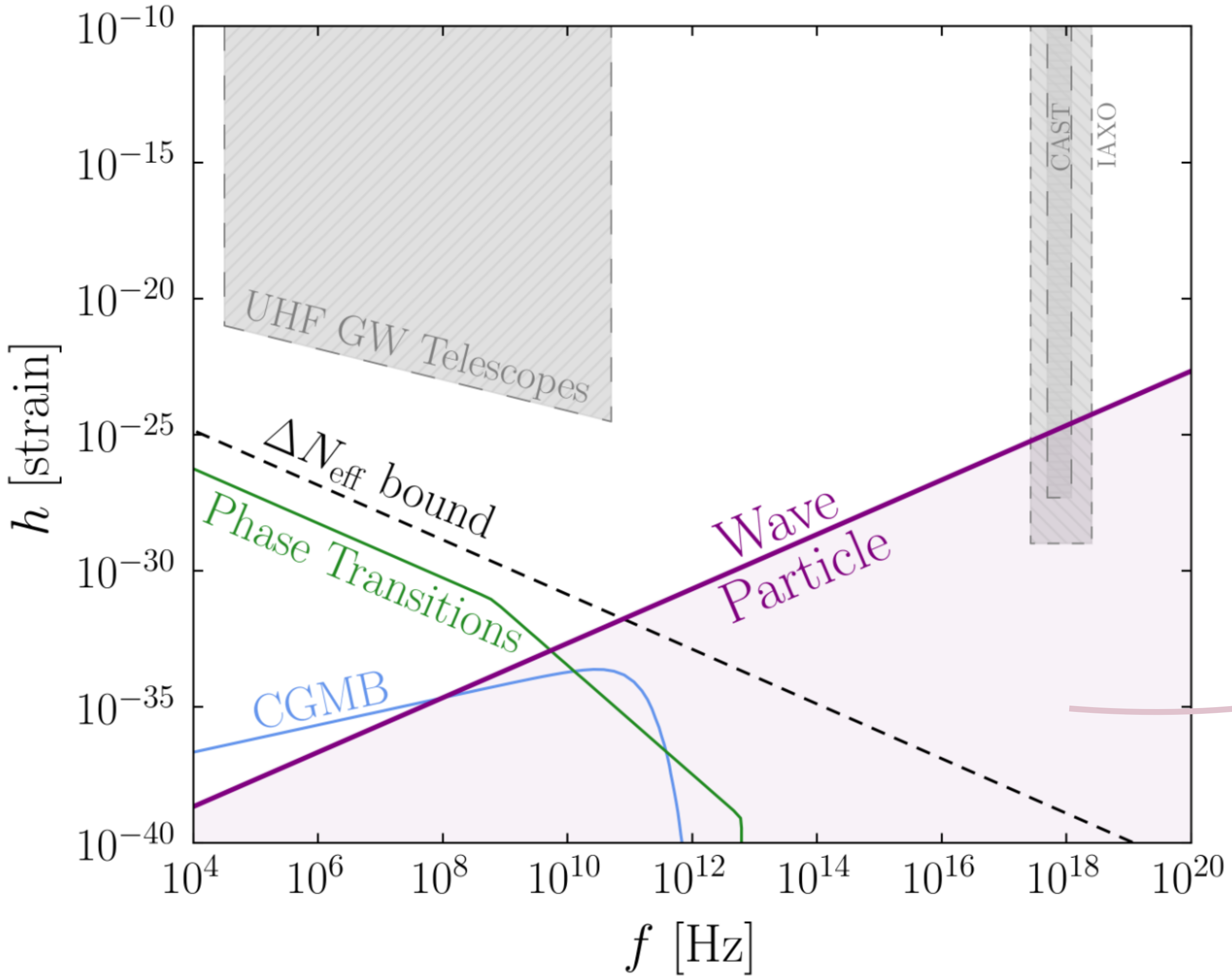
long term visits (> 3 months, usually sabbaticals)

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

2025 Update of UHF GW Living Review

Contents

notation / framework

summary plots

PBH discussion

Sebastian Ellis

Gabriele Franciolini

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

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

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

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

» 1

→ PLS (power law integrated sensitvity) curves

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→ PLS (power law integrated sensitvity) curves

Transient gravitational waves:

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

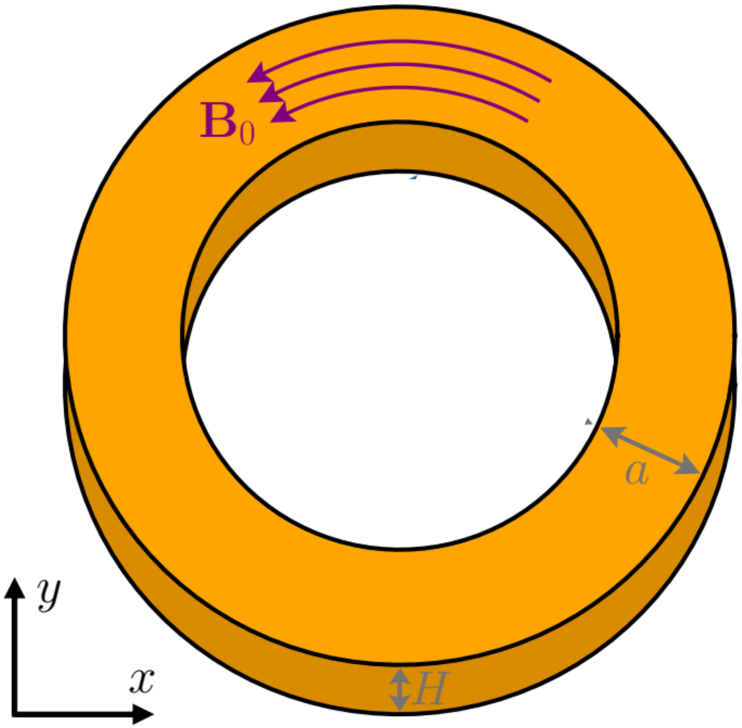
$$h_{c,\rm insp}(f) = 2f\tilde{h}(f) \simeq \sqrt{N_{\rm cycles}}\, h_0$$

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

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

eg ABRACADABRA, SHAFT, DM Radio:

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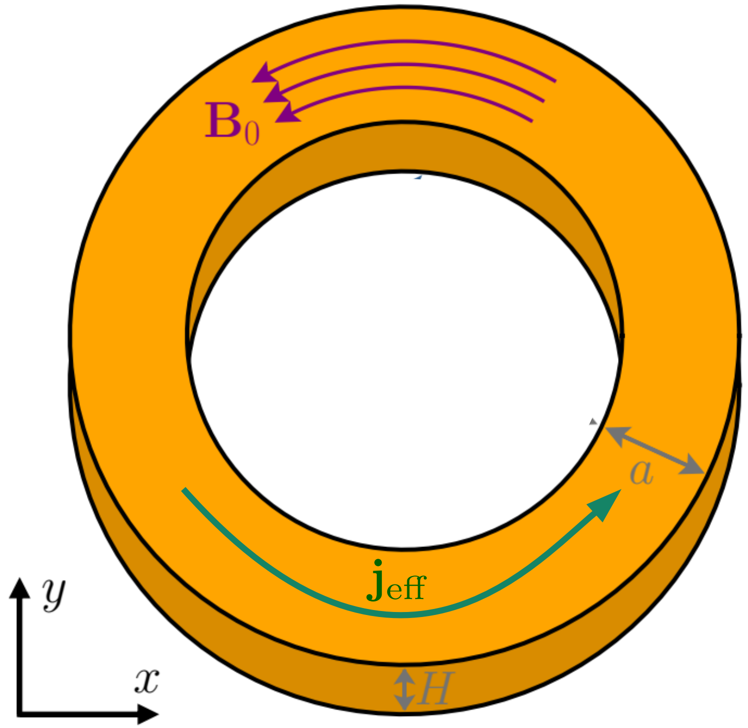

static magnetic field (i.e. rigid detector)

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

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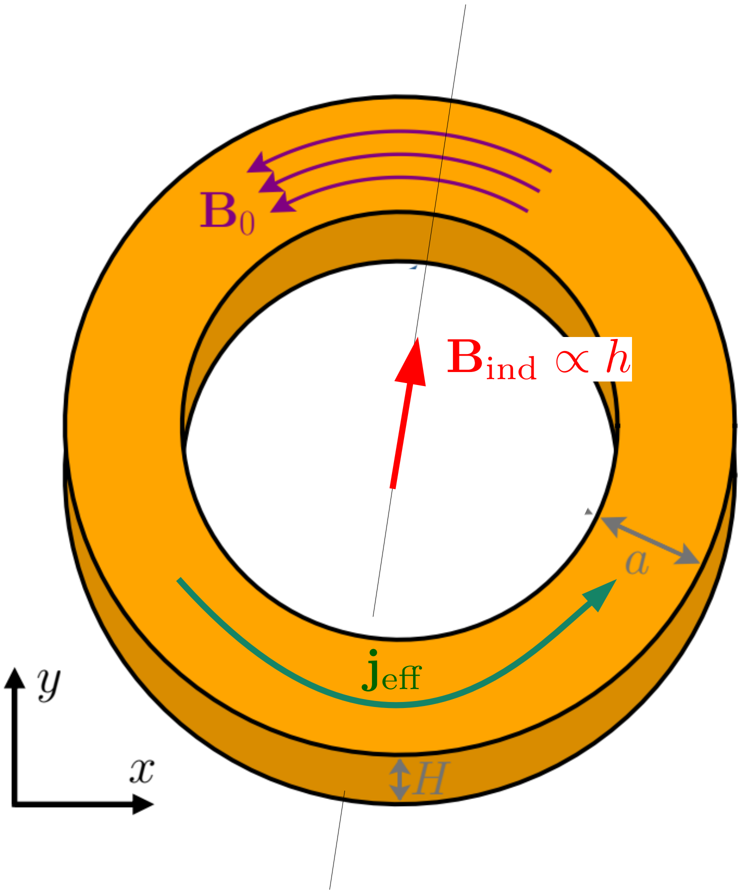

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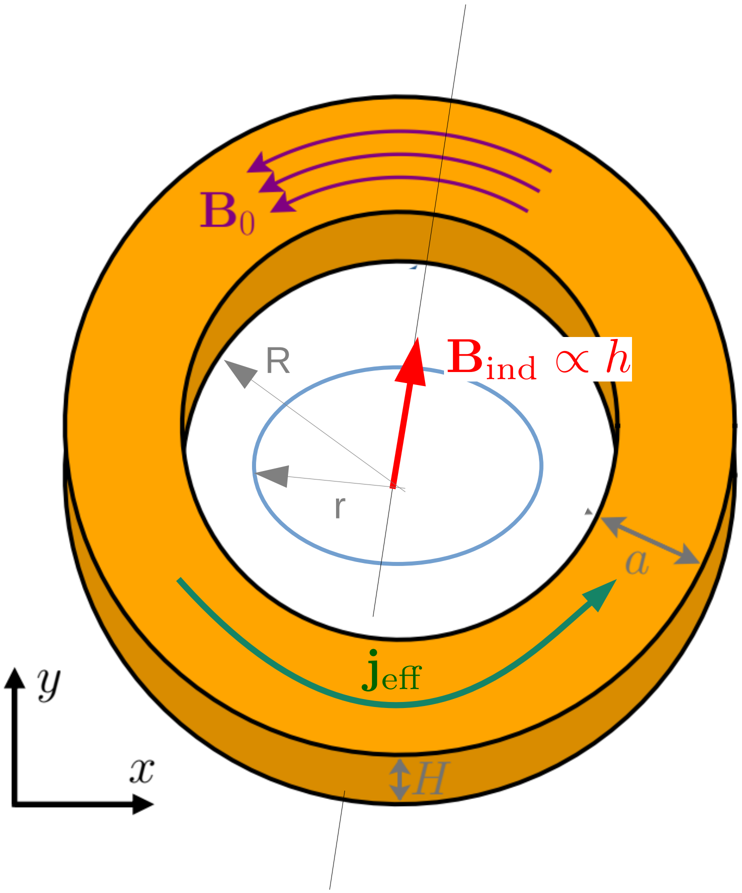

static magnetic field (i.e. rigid detector)

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induced oscillating magnetic field

measure magnetic flux (~ h) through pickup loop

at leading order in (ωR) :

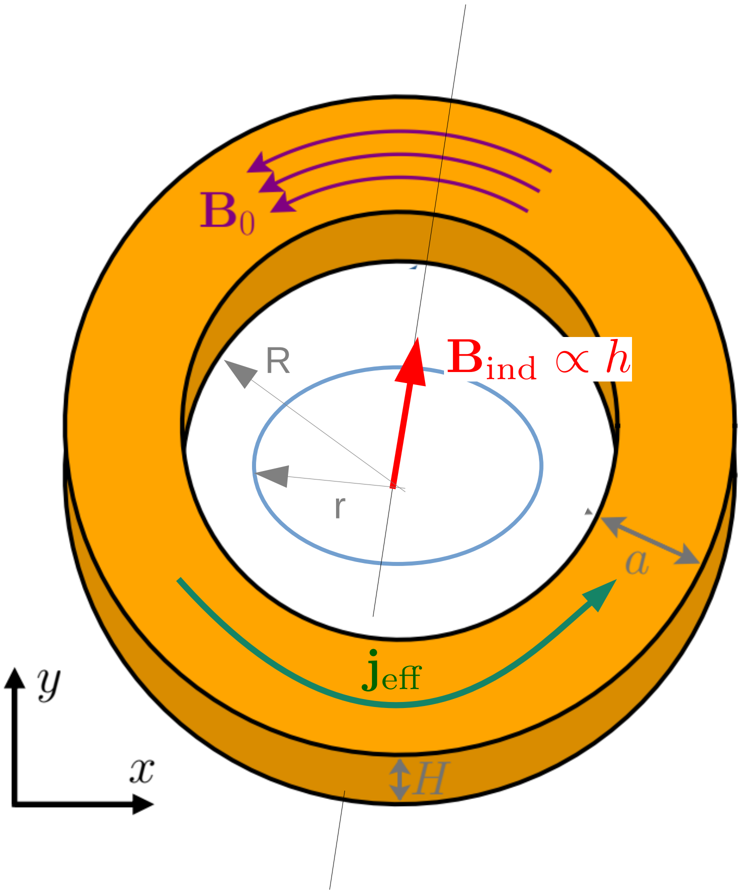
$$\Phi_{\rm gw} = \frac{i\, e^{-i\omega t}}{16\sqrt{2}} h^\times \omega^3 B_0 \pi r^2 R a (a + 2R) s_{\theta_h}^2$$

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

GW signal in low-mass axion haloscopes

eg ABRACADABRA, SHAFT, DM Radio:

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



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) :

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

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

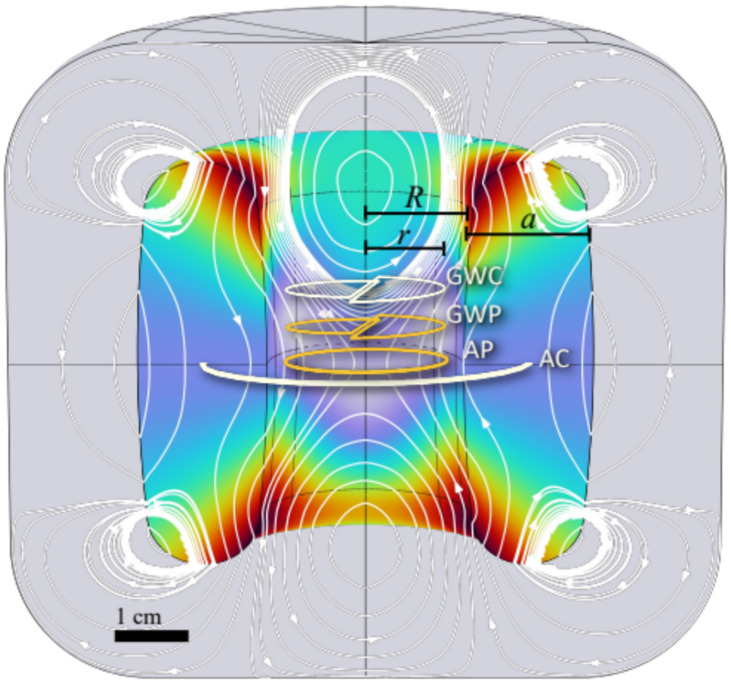
$$\Phi_a = e^{-i\omega t}\, g_{a\gamma\gamma} \sqrt{2\rho_{\rm DM}} B_0 \pi r^2 R \ln(1 + a/R)$$

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

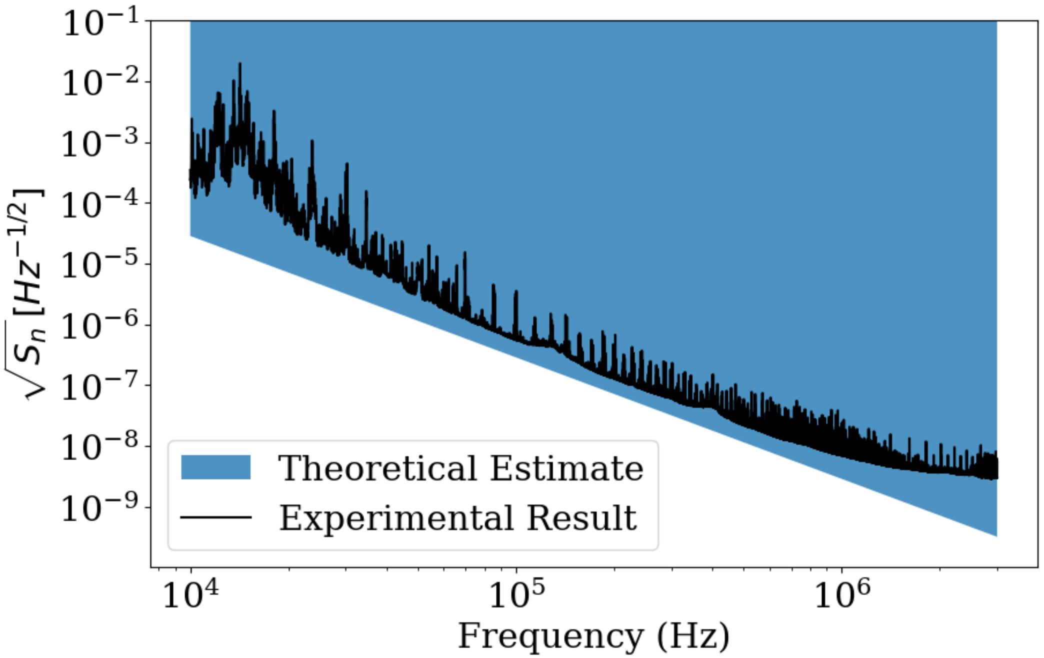
match to axion induced flux to estimate sensitivity to GW signals

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

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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dielectric constant

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

Maxwell equations:

effective current induced by Gws
dielectric constant

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

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

resonant conversion
in vacuum

Dielectric GW haloscope

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resonant conversion in vacuum

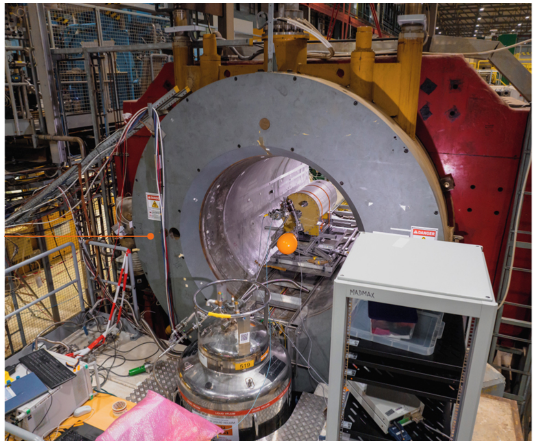
→ ALPs, IAXO,… as GW detectors [Ejlli et al `19]

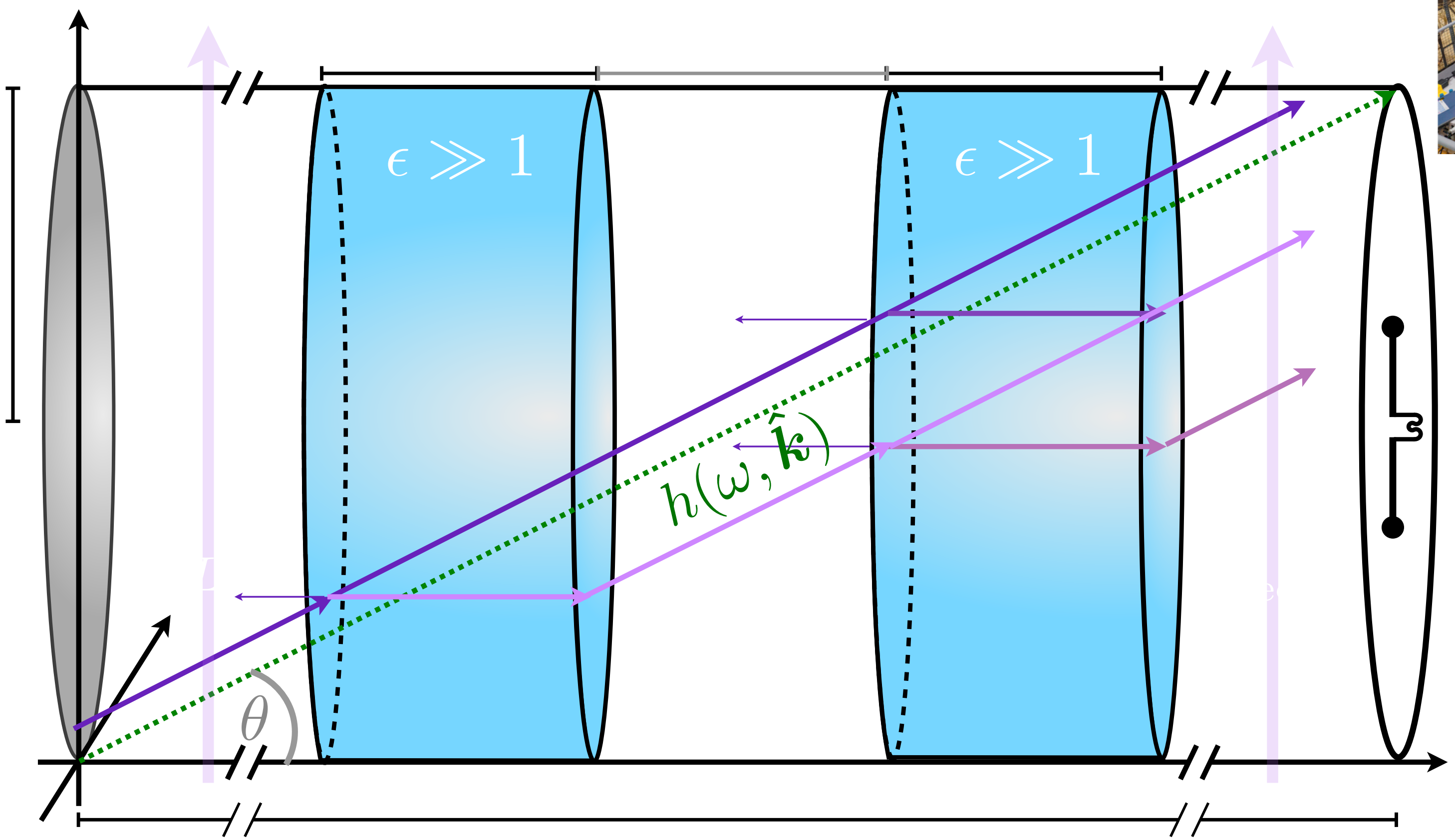
Boundary conditions at surface of dielectric medium

→ EM waves sourced at surfaces of dielectric disks

Dielectric GW haloscope

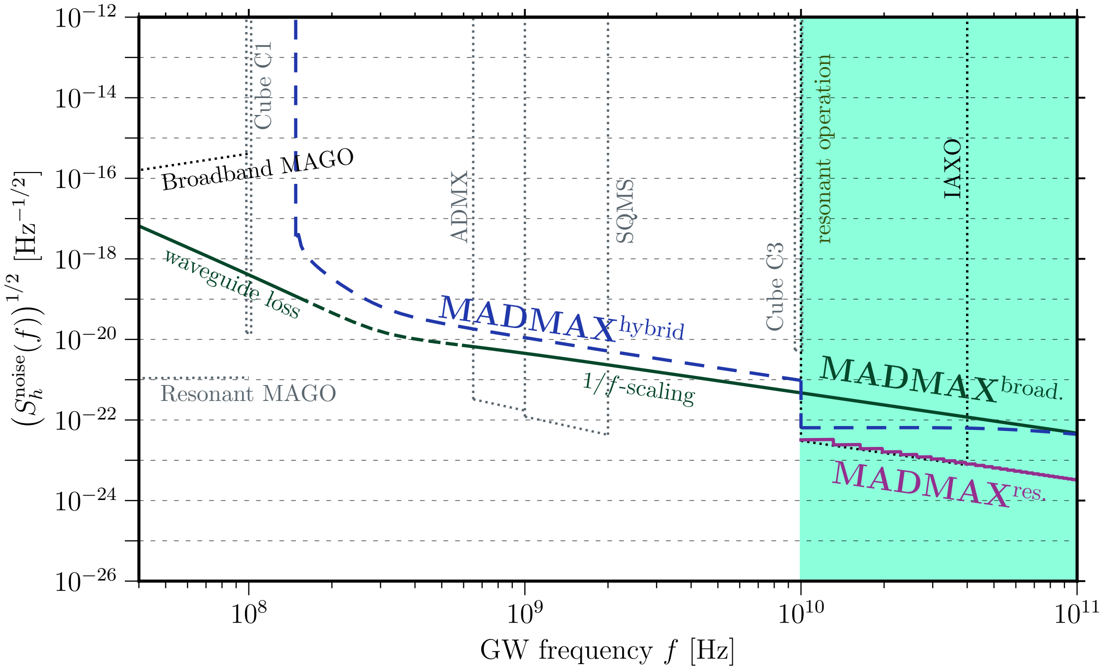
Madmax prototype
@ CERN





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

mechanical coupling

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

$\omega_{\rm gw} \ll \omega_n$ — rigid limit

$\omega_{\rm gw} \sim \omega_n$ — on resonance (Weber Bars)

$\omega_n \ll \omega_{\rm gw} \ll L^{-1}$ — free-falling limit →

$L^{-1} \ll \omega_{\rm gw}$ — response function may be suppressed by oscillation pattern

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 →	

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

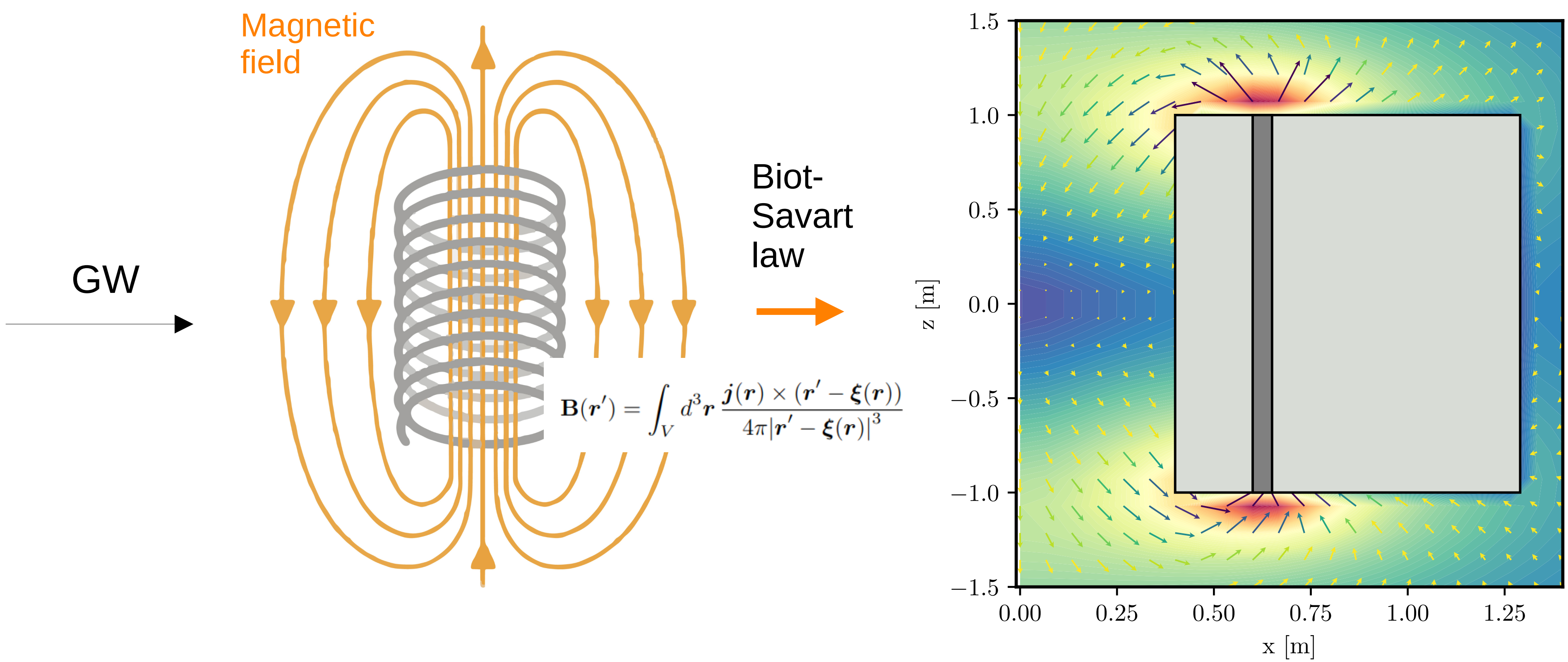
response function may be suppressed by oscillation pattern

- 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:



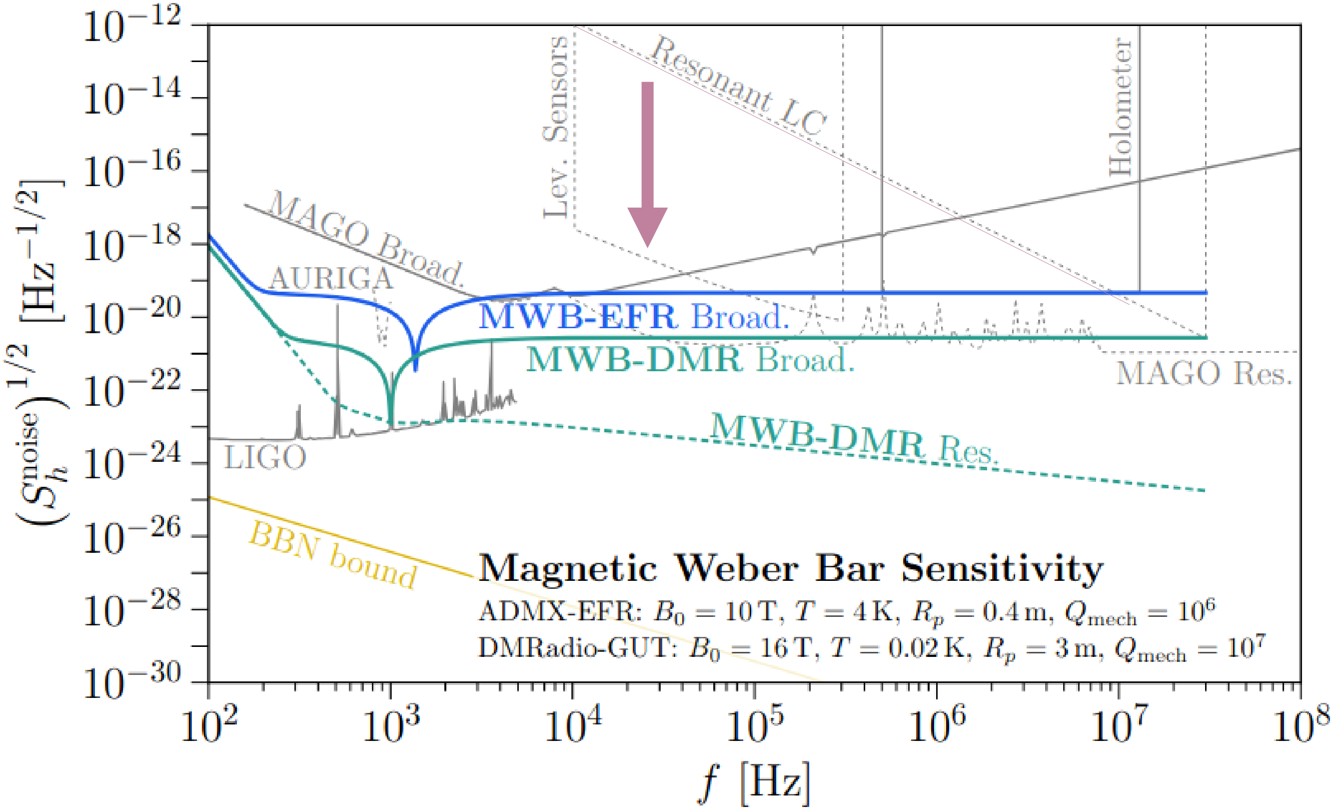
$$\mathbf{B}(\boldsymbol{r}') = \int_V d^3\boldsymbol{r}\, \frac{\boldsymbol{j}(\boldsymbol{r}) \times (\boldsymbol{r}' - \boldsymbol{\xi}(\boldsymbol{r}))}{4\pi |\boldsymbol{r}' - \boldsymbol{\xi}(\boldsymbol{r})|^3}$$

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

Magnetic Weber Bar

VD, Ellis, Rodd `24

mechanical vs
EM coupling



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 !