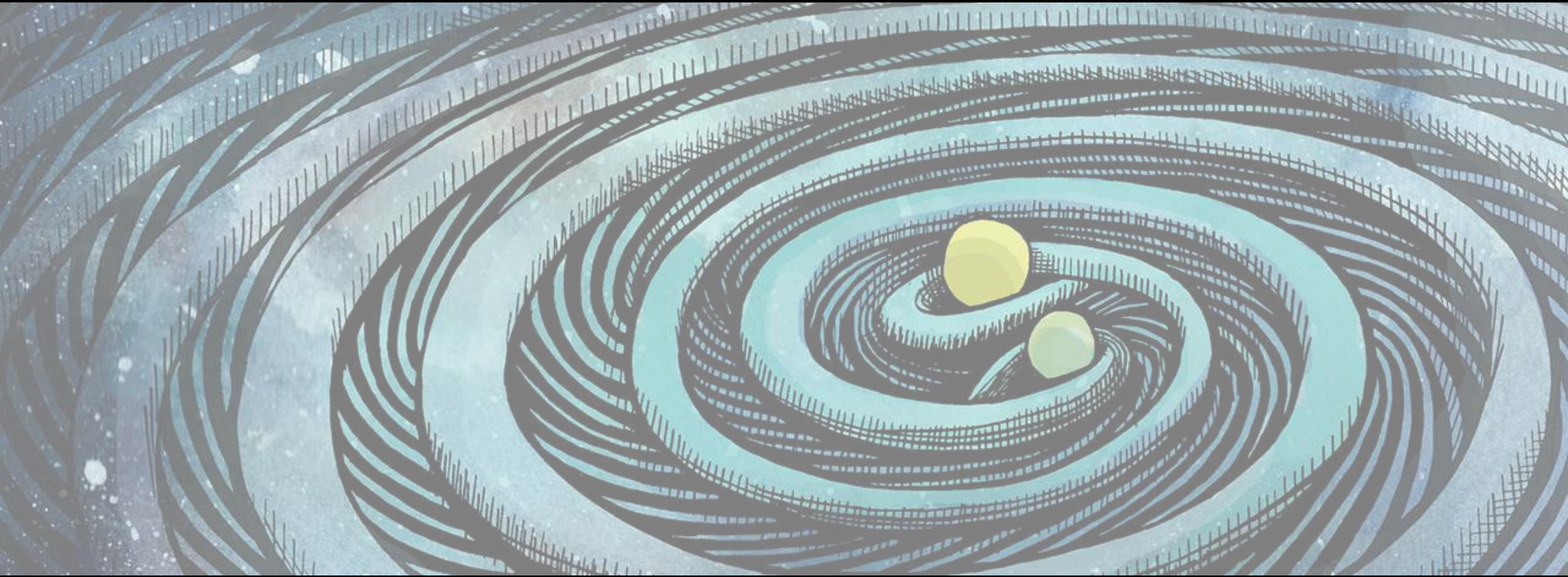
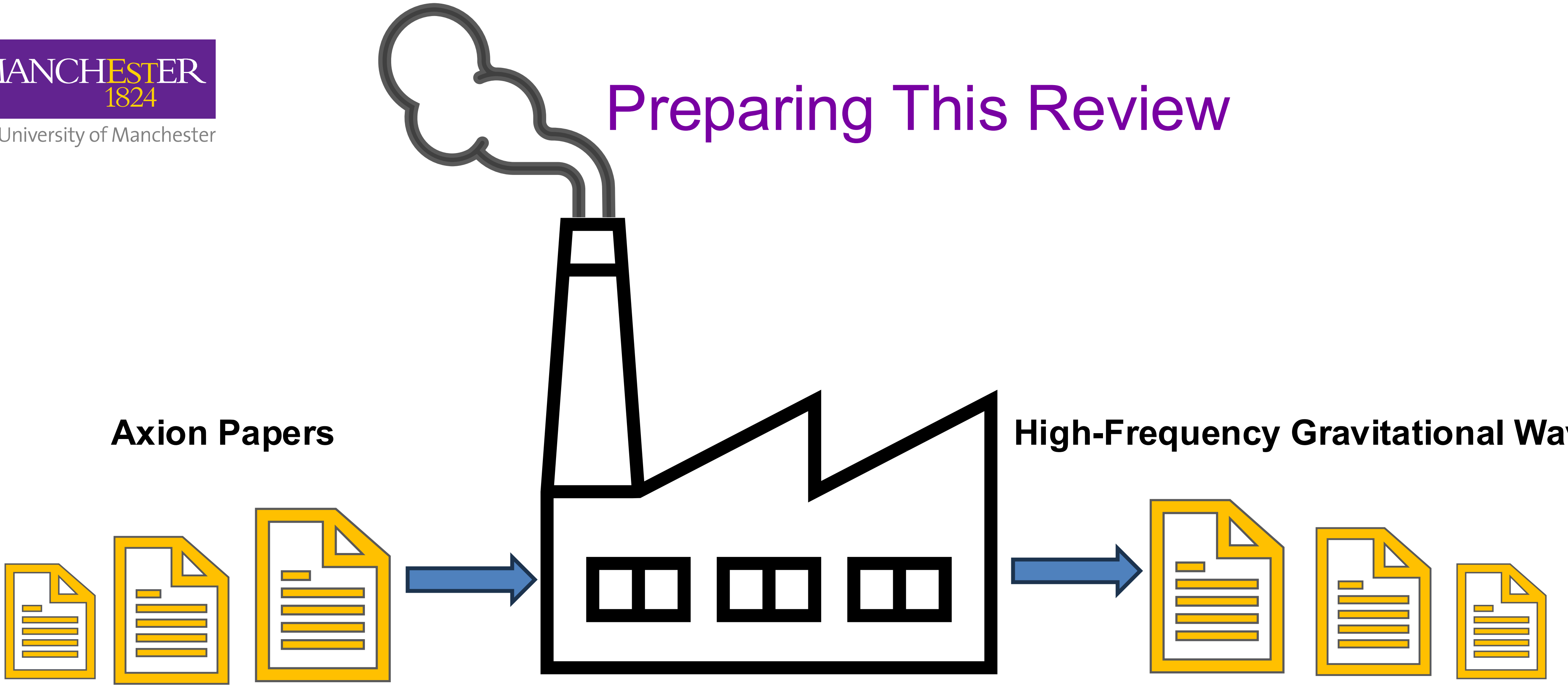
Axion Experiments As High Frequency GW Detectors

Jamie McDonald - University of Manchester



Axions In Stockholm 2025

Preparing This Review



$$N_{Papers}^{GW} \simeq \eta \, N_{Papers}^{Axion} \qquad \lim_{t \to \infty} \eta \to 1$$

Further Reading

The University of Manchester

The Global Network of Cavities to Search for Gravitational Waves (GravNet):
A novel scheme to hunt gravitational waves signatures from the early universe
Kristof Schmieden and Matthias Schott

Detecting High-Frequency Gravitational Waves with Microwave Cavities
Asher Berlin, Diego Blas, Raffaele Tito D'Agnolo, Sebastian A. R. Ellis, Roni Harnik, Yonatan Kahn, Jan Schutte-Engel

Magnets are Weber Bar Gravitational Wave Detectors
Valerie Domcke, Sebastian A. R. Ellis, Nicholas L. Rodd

Upper limits on the amplitude of ultra-high-frequency gravitational waves from graviton-photon mixing
Aldo Ejlli, Damian Ejlli, Adrian Mike Cruise, Giampaolo Pisano, Hartmut Grote

A Coordinate-Independent Formalism for Detecting High-Frequency Gravitational Waves
Wolfram Ratzinger, Sebastian Schenk, Pedro Schwaller

Gravitational Wave Detection With Plasma Haloscopes
Rodolfo Capdevilla, Graciela B. Gelmini, Jonah Hyman, Alexander J. Millar, Edoardo Vitagliano

Symmetries and Selection Rules: Optimising Axion Haloscopes for Gravitational Wave Searches
Valerie Domcke, Camilo Garcia-Cely, Sung Mook Lee, Nicholas L. Rodd

Study of a cubic cavity resonator for gravitational waves detection in the microwave frequency range
Pablo Navarro, Benito Gimeno, Juan Monzo-Cabrera, Alejandro Dıaz-Morcillo, Diego Blas

Further Reading

The University of Manchester

Cavity Detection of Gravitational Waves: Where Do We Stand?
Claudio Gatti, Luca Visinelli, Michael Zantedeschi

Classical (and Quantum) Heuristics for Gravitational Wave Detection
Raffaele Tito D'Agnolo, Sebastian A.R. Ellis

Hunt for light primordial black hole dark matter with ultra-high-frequency gravitational waves
Gabriele Franciolini, Anshuman Maharana, Francesco Muia
[very important]
Dielectric Haloscopes as Gravitational Wave Detectors
Valerie Domcke, Sebastian A. R. Ellis and Joachim Kopp

Symmetries and Selection Rules: Optimising Axion Haloscopes for Gravitational Wave Searches
Valerie Domcke, Camilo Garcia-Cely, Sung Mook Lee, Nicholas L. Rodd

The Maximal Gravitational Wave Signal from Asteroid-Mass Primordial Black Hole Mergers At Resonant Microwave Cavities
Profumo, Brown, Ewasiuk, Ricarte, Su

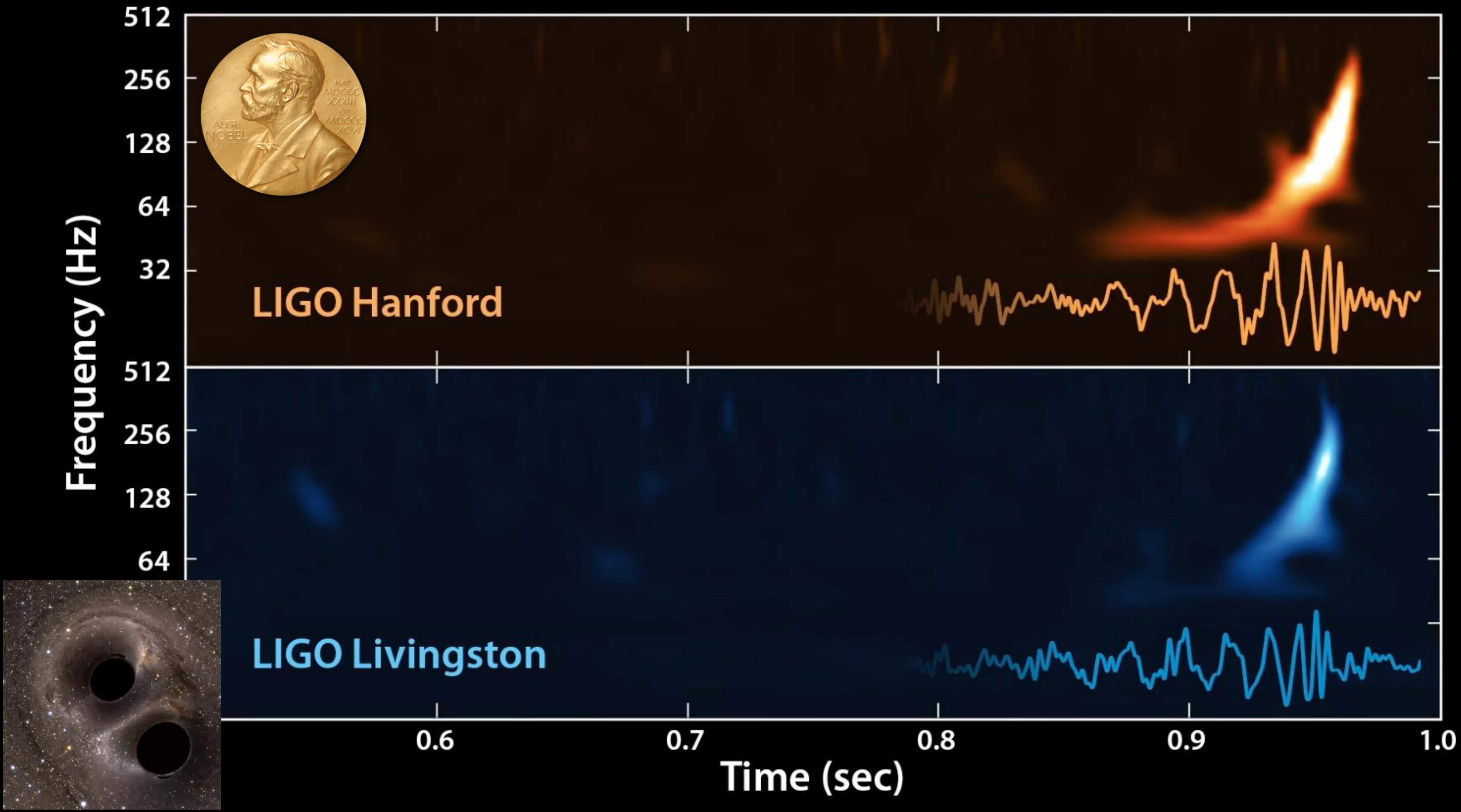
A novel search for high-frequency gravitational waves with low-mass axion haloscopes
Valerie Domcke,Camilo Garcia-Cely, Nicholas L. Rodd

Contents – Axion Experiments as HFGW Detectors

Introduction

- Background
- Arguments for HFGWs & Sources
- Community Activities

Repurposing Axion Detectors
- Cavities & GravNet
- Magnetic Weber bars
- Plasma haloscopes
- Low mass axion detectors
- ALP searches with helioscopes and LSW
- Dielectric halosocopes



LIGO Hanford
LIGO Livingston
Frequency (Hz)
512
256
128
64
32
Time (sec)
0.6
0.7
0.8
0.9
1.0

Pulsar Timing

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NEWS

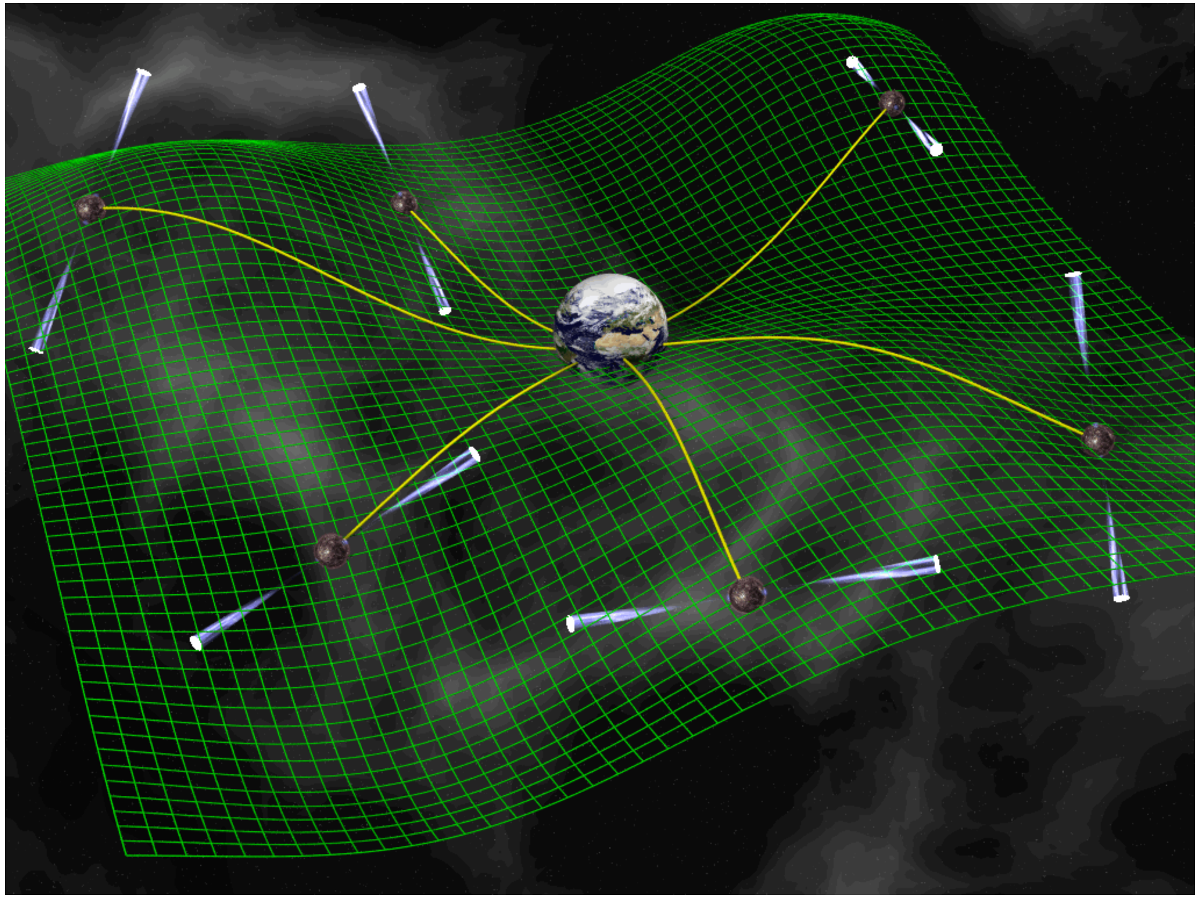
Home | InDepth | Israel-Gaza war | Cost of Living | War in Ukraine | Climate | UK | World | Business | Politics

Science & Environment

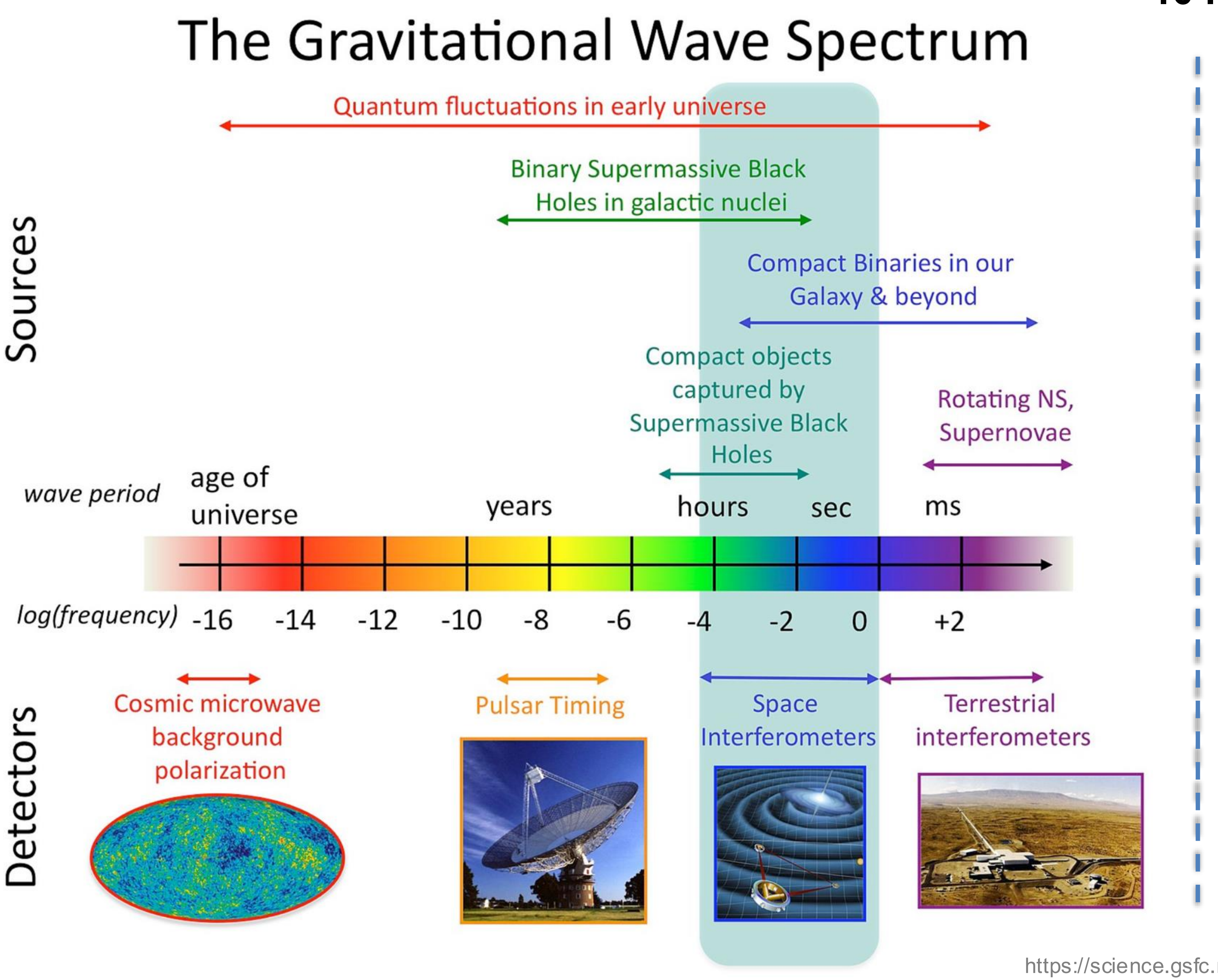
Scientists pick up shock waves from colliding galaxies

29 June 2023

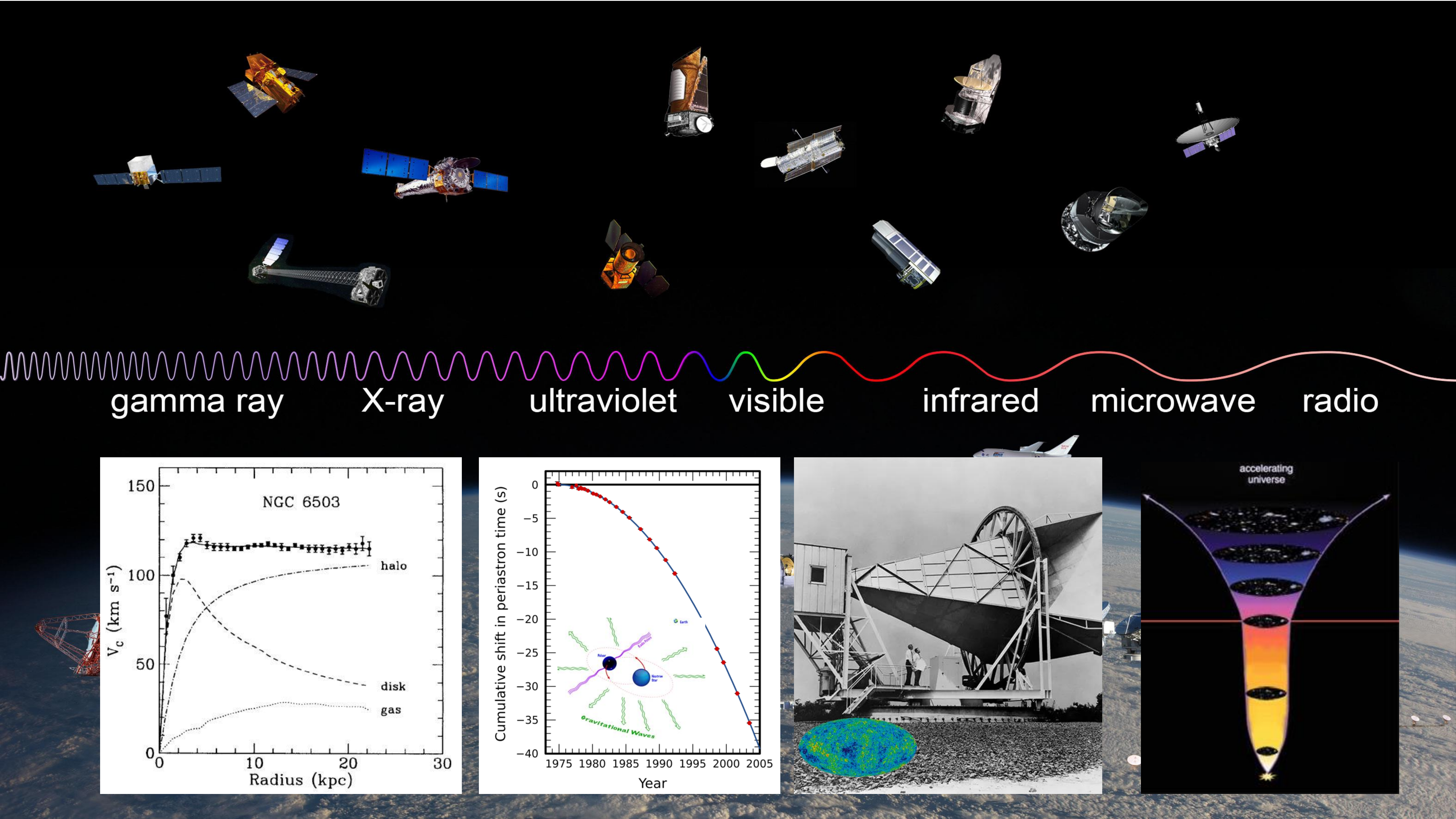
EPTA/STELIOS THOUKIDIDES

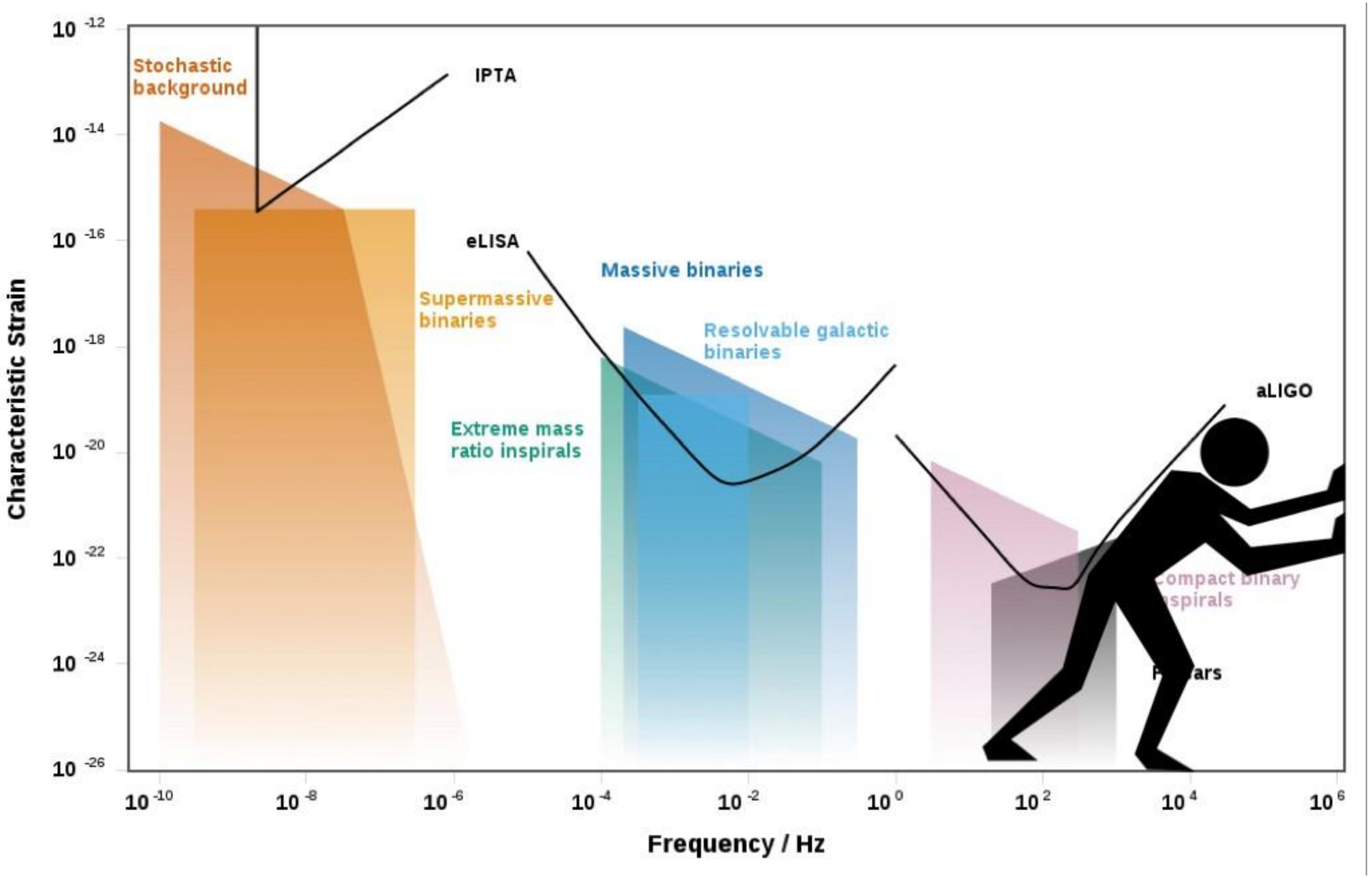


~10 kHz



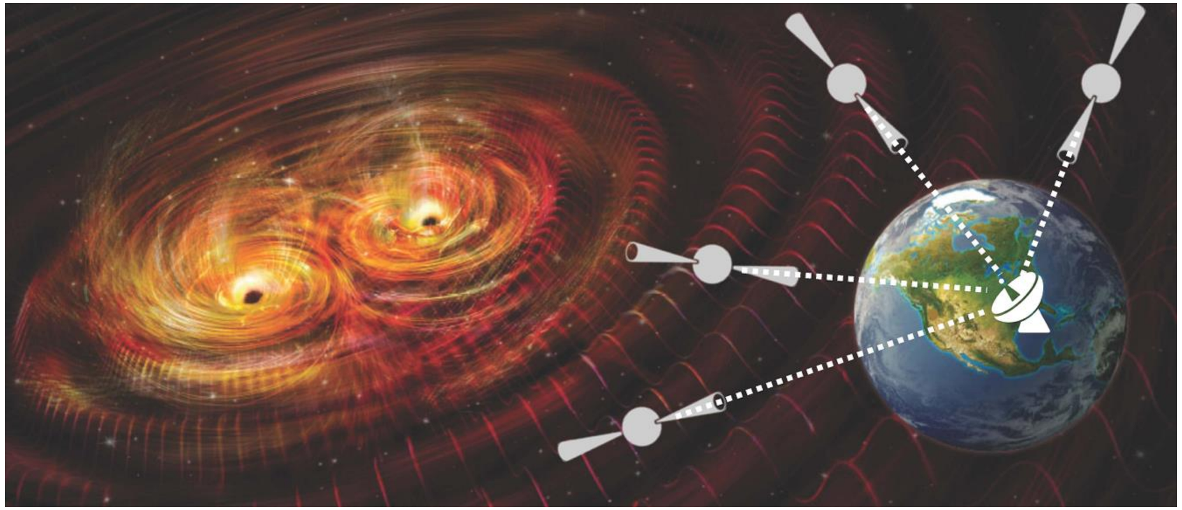
https://science.gsfc.nasa.gov/663/research/index.html


gamma ray
X-ray
ultraviolet
visible
infrared
microwave
radio
NGC 6503
150
100
50
0
halo
disk
gas
V_c (km s^-1)
0
10
20
30
Radius (kpc)
Cumulative shift in periastron time (s)
0
−5
−10
−15
−20
−25
−30
−35
−40
1975
1980
1985
1990
1995
2000
2005
Year
Gravitational Waves
accelerating universe


Stochastic background
IPTA
eLISA
Massive binaries
Supermassive binaries
Resolvable galactic binaries
Extreme mass ratio inspirals
aLIGO
Characteristic Strain
Frequency / Hz
10 -12
10 -14
10 -16
10 -18
10 -20
10 -22
10 -24
10 -26
10 -10
10 -8
10 -6
10 -4
10 -2
10 0
10 2
10 4
10 6

General Points

HFGWs free of Standard Model Backgrounds

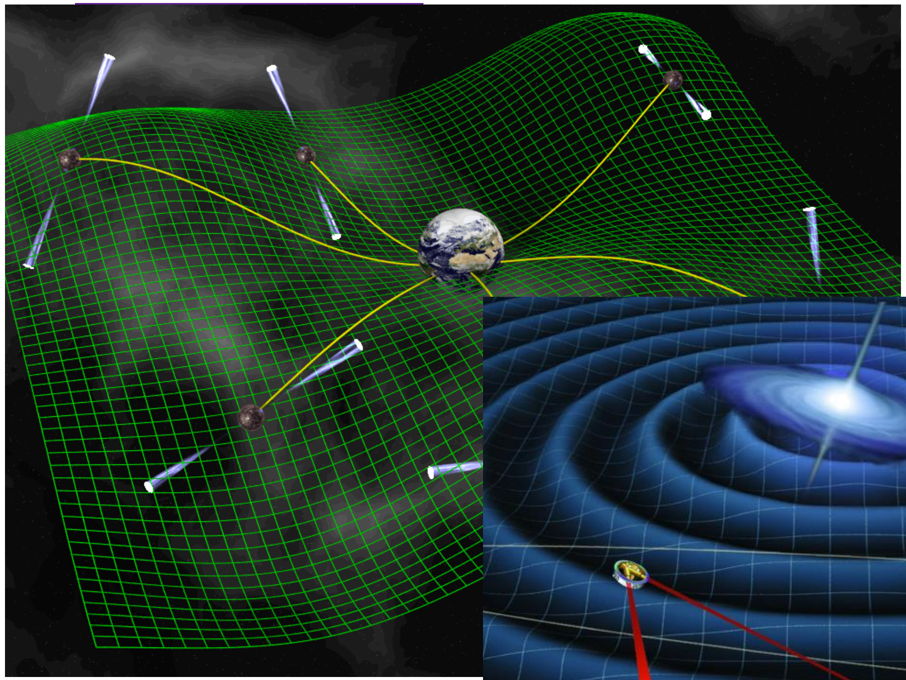


Contrast with PTAs…

General Points

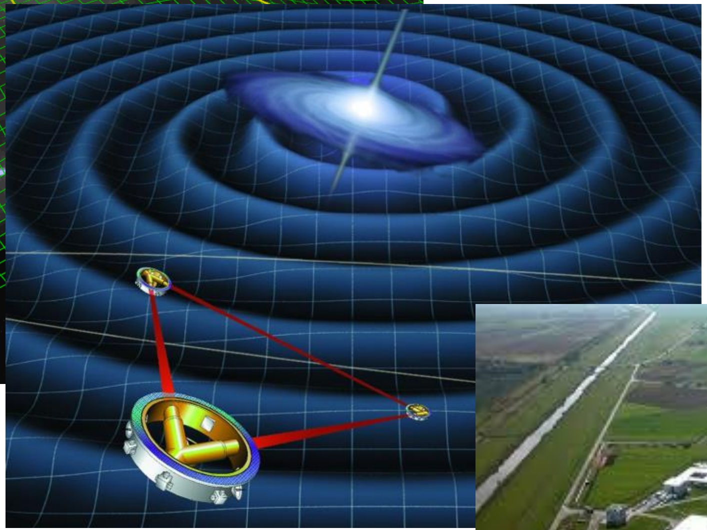
- Cheaper small-scale detectors
- commercially-motivated sensors
- Repurpose BSM searches

$10^{-9} Hz$



10 kpc ~ 10^{20} m

$10^{-2} Hz$



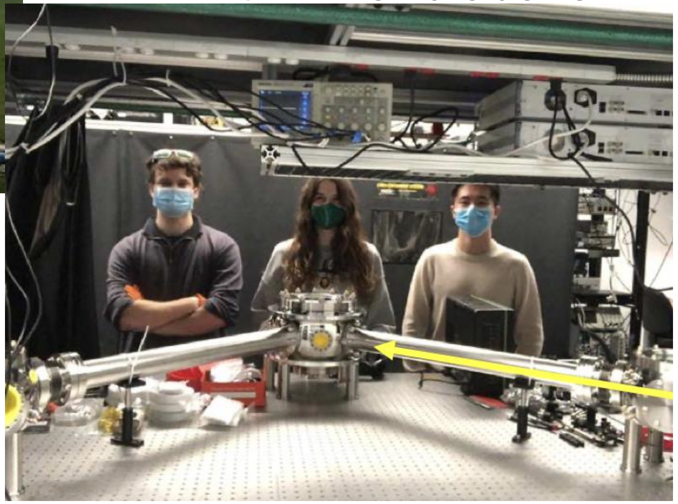
0.01 Au ~ 10^{9} m

$100\ Hz$

1 km ~ 10^{3} m

High Frequency GWs

$10^{4} Hz$ and above



Tabletop ~ m

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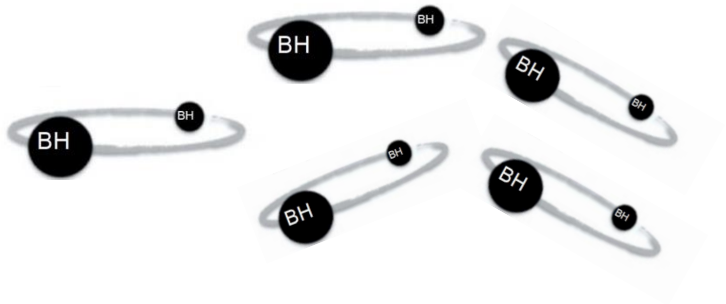
Sources

Late Universe

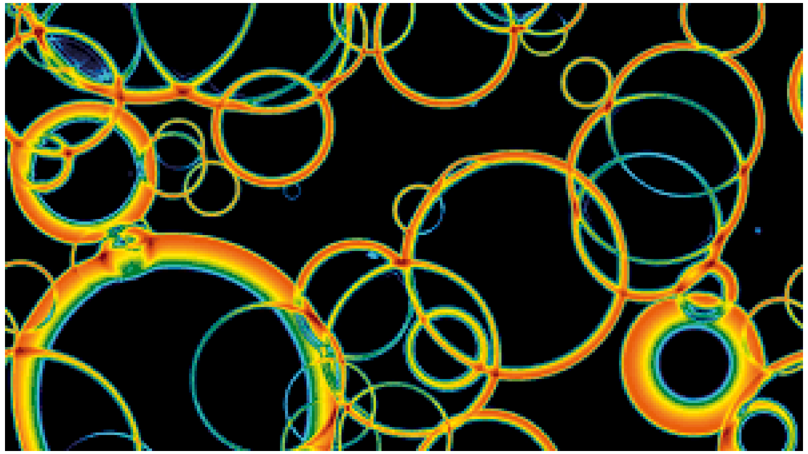
e.g. transient

stochastic

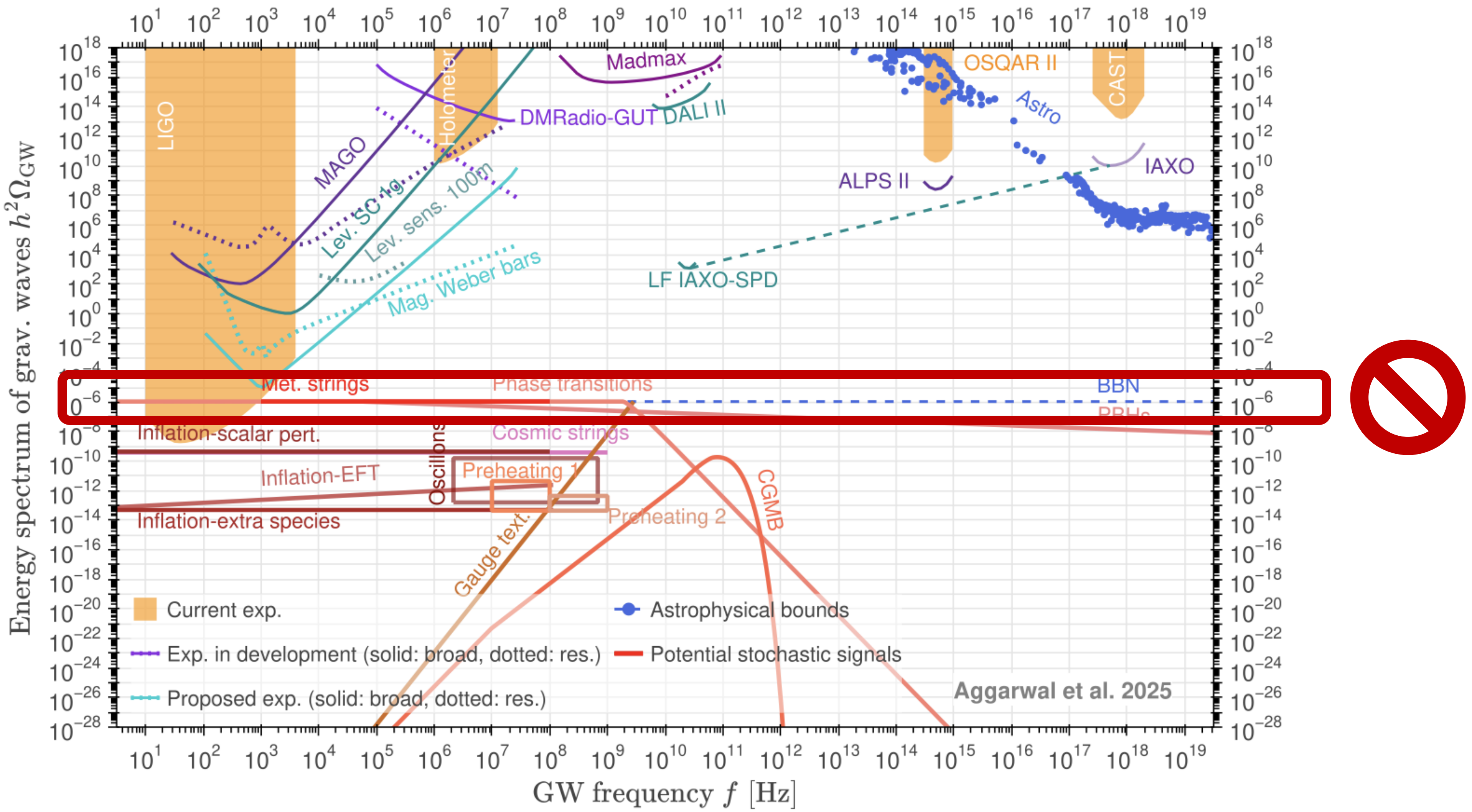


Early Universe

stochastic



Early Universe Sources



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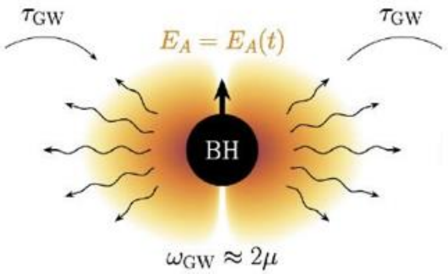
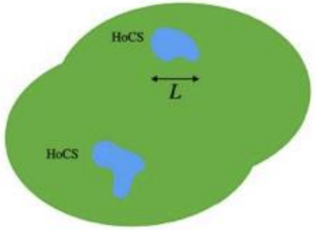
Late Universe Sources

- **SR**
  Tsukada et al, ‘20



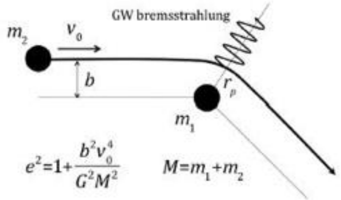
- **BBH merger**
  Franciolini et al 2205.02153

- **NS/NS mergers**
  Casalderrey et al. 2210.03171



Standard Model

- **Hyperbolic encounters of PBH**
  Garcia Bellido & S. Nesseris 1706.02111



Slide: GravNet Collaboration Meeting

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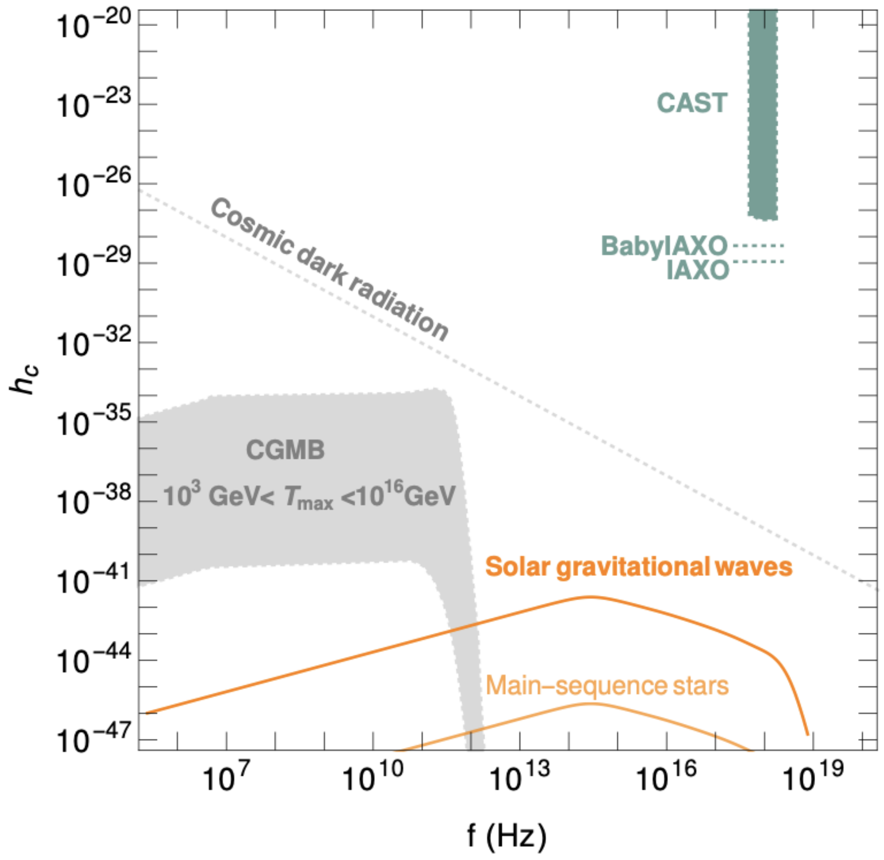
Standard Model



Ringwald, Garcia-Cely, 2024

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Growing Community

Ultra-high frequency gravitational waves: where to next ?

4 Dec 2023, 09:00 → 8 Dec 2023, 19:00 Europe/Zurich

4/3-006 - TH Conference Room (CERN)

CERN

Excellent Talks All Online

https://indico.cern.ch/event/1257532/

GravNet Collaboration Meeting

26–27 Jun 2025
HIM

A Global Network for the Search for High Frequency Gravitational Waves

HIM
HELMHOLTZ
Helmholtz-Institut Mainz

erc
European Research Council

Quantum Sensing Meets Ultra-high Frequency Gravitational Waves

June 30 – July 11, 2025

https://indico.mitp.uni-mainz.de/event/405

Growing Community

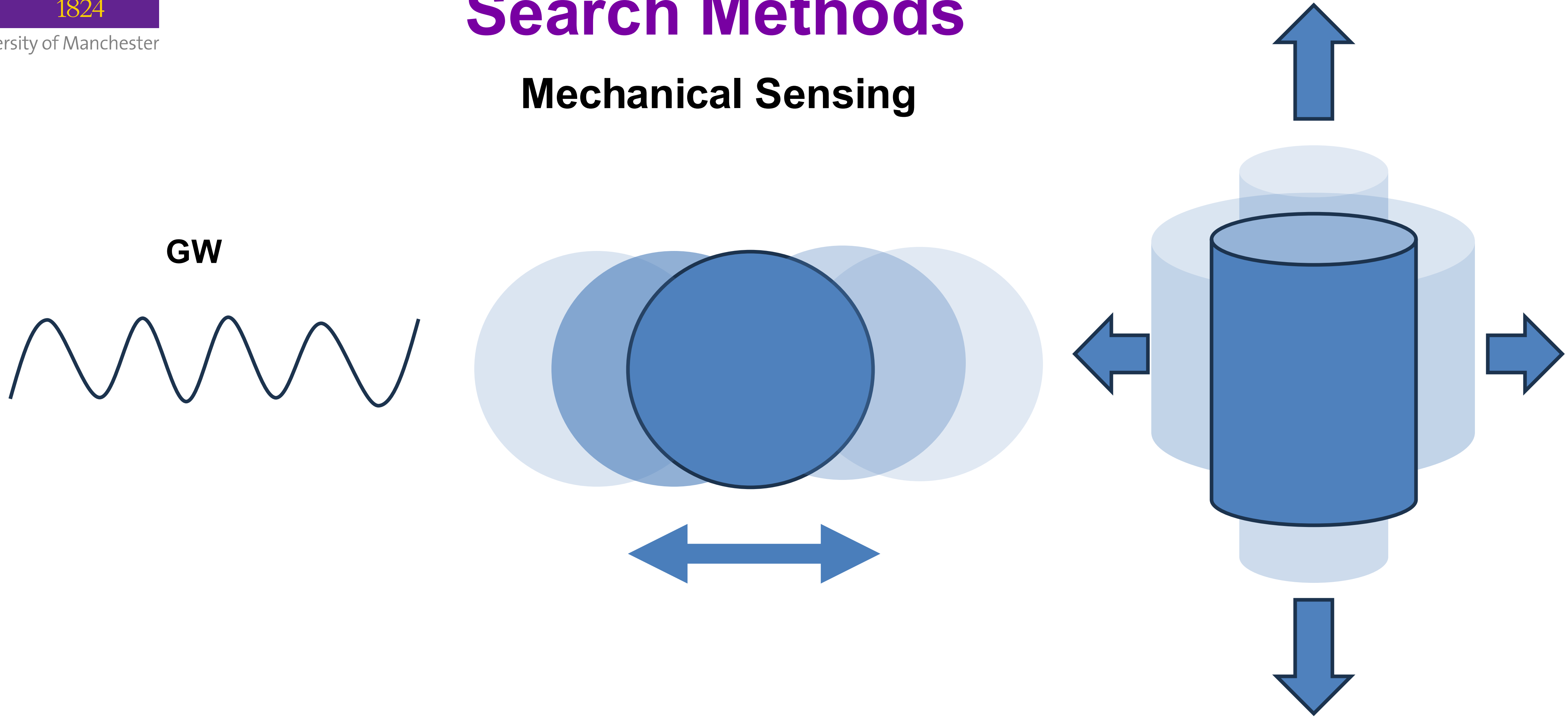
Challenges and Opportunities of Gravitational Wave Searches above 10 kHz

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]

https://arxiv.org/pdf/2501.11723 - update to 2021 review

Search Methods

Mechanical Sensing

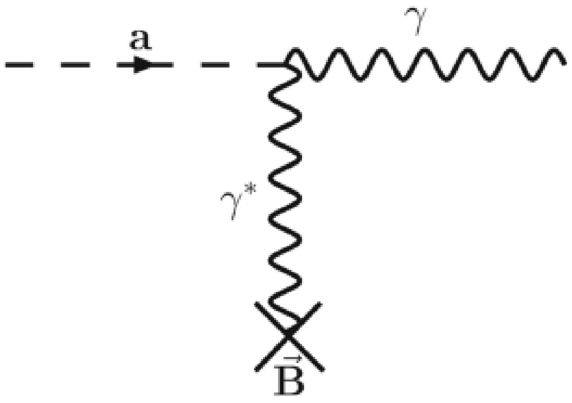


Search Methods

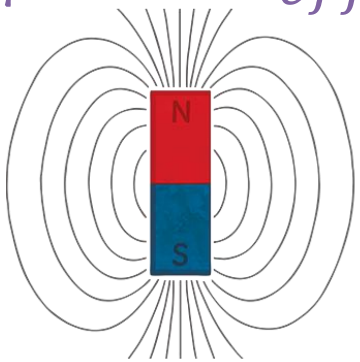
Electromagnetic Sensing

Axions

$$\mathcal{L}_{\rm int} = -\frac{g_{\phi\gamma}}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

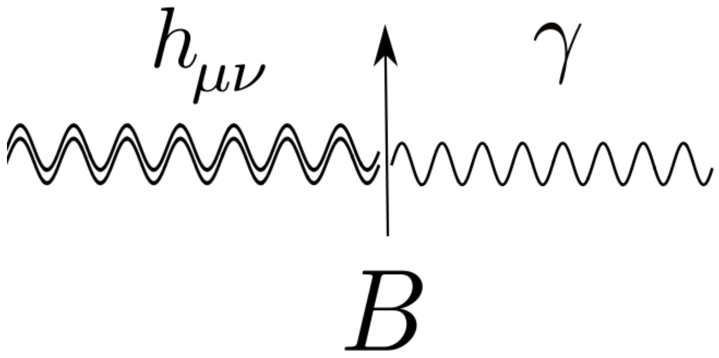


$$\partial_\mu F^{\mu\nu} = j^\mu_{eff}$$



High-Frequency Gravitational Waves

$$S = \int d^4x\,\sqrt{-g}\left(-\frac{1}{4}\,g^{\mu\alpha}\,g^{\nu\beta}\,F_{\mu\nu}\,F_{\alpha\beta}\right),$$

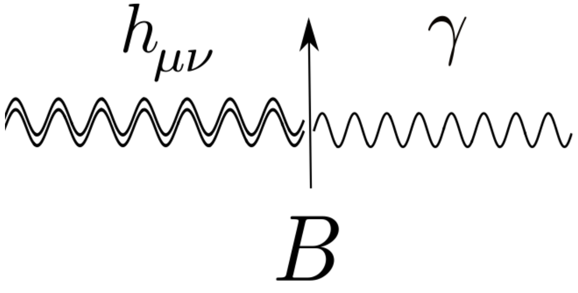


``Gertsenshtein”

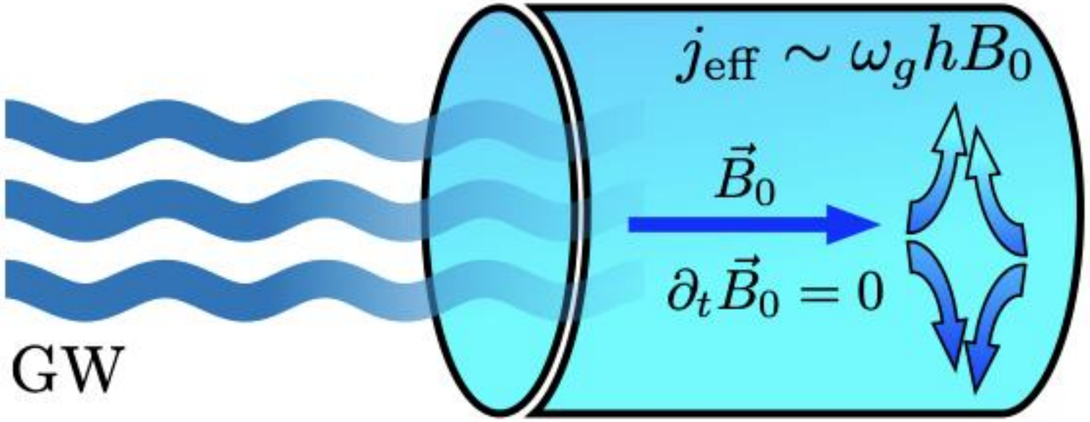
$$j^\mu_{axion} = \partial_\mu\phi\tilde{F}^{\mu\nu}$$

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

Cavities



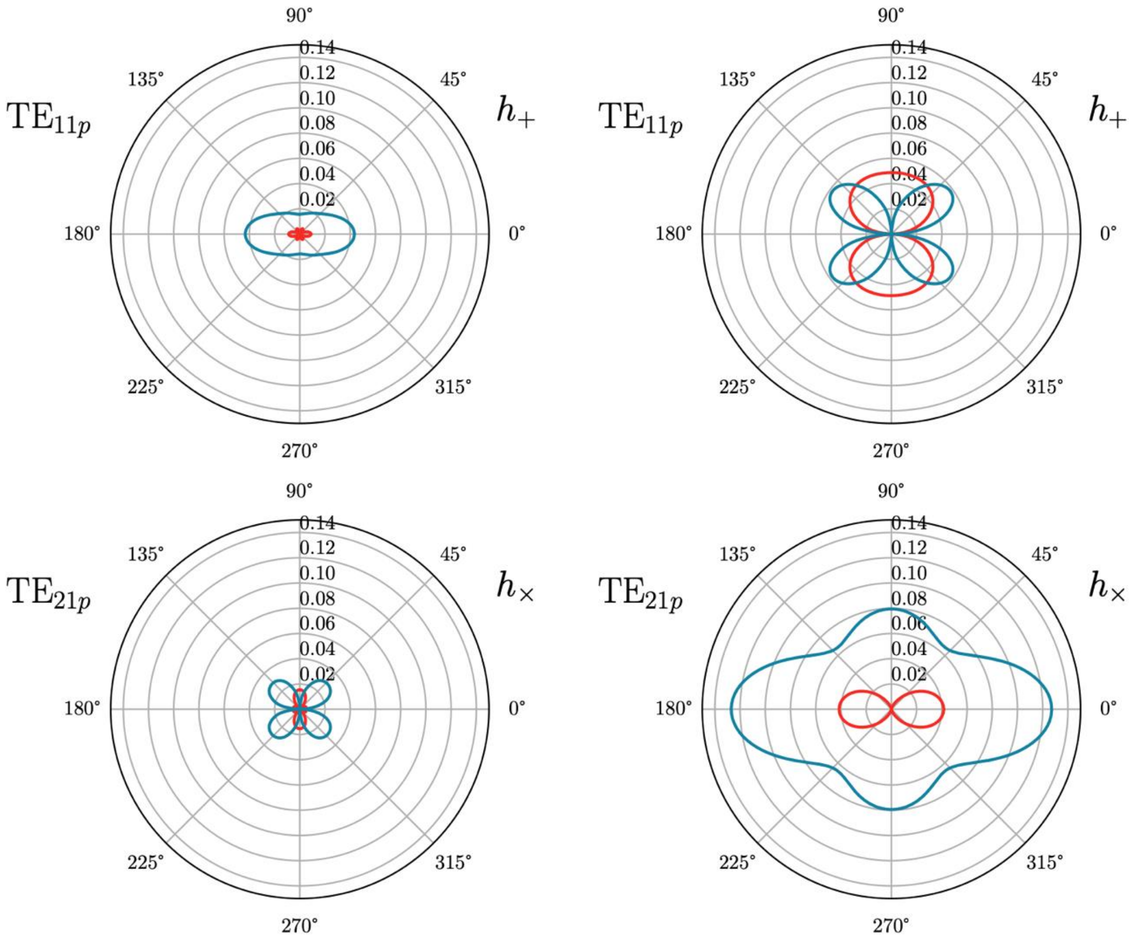
$$P_{\rm sig} = \frac{1}{2} Q_{\rm eff}\, \omega_g^3\, V_{\rm cav}^{5/3}\, (\eta_n\, h_0\, B_0)^2$$



$$\eta_n \equiv \frac{\left| \int_{V_{\rm cav}} d^3\mathbf{x}\ \mathbf{E}_n^* \cdot \hat{\boldsymbol{j}}_{+,\times} \right|}{V_{\rm cav}^{1/2} \left(\int_{V_{\rm cav}} d^3\mathbf{x}\ |\mathbf{E}_n|^2 \right)^{1/2}}$$

Berlin, et al, *PRD* 105 (2022) 11, 116011

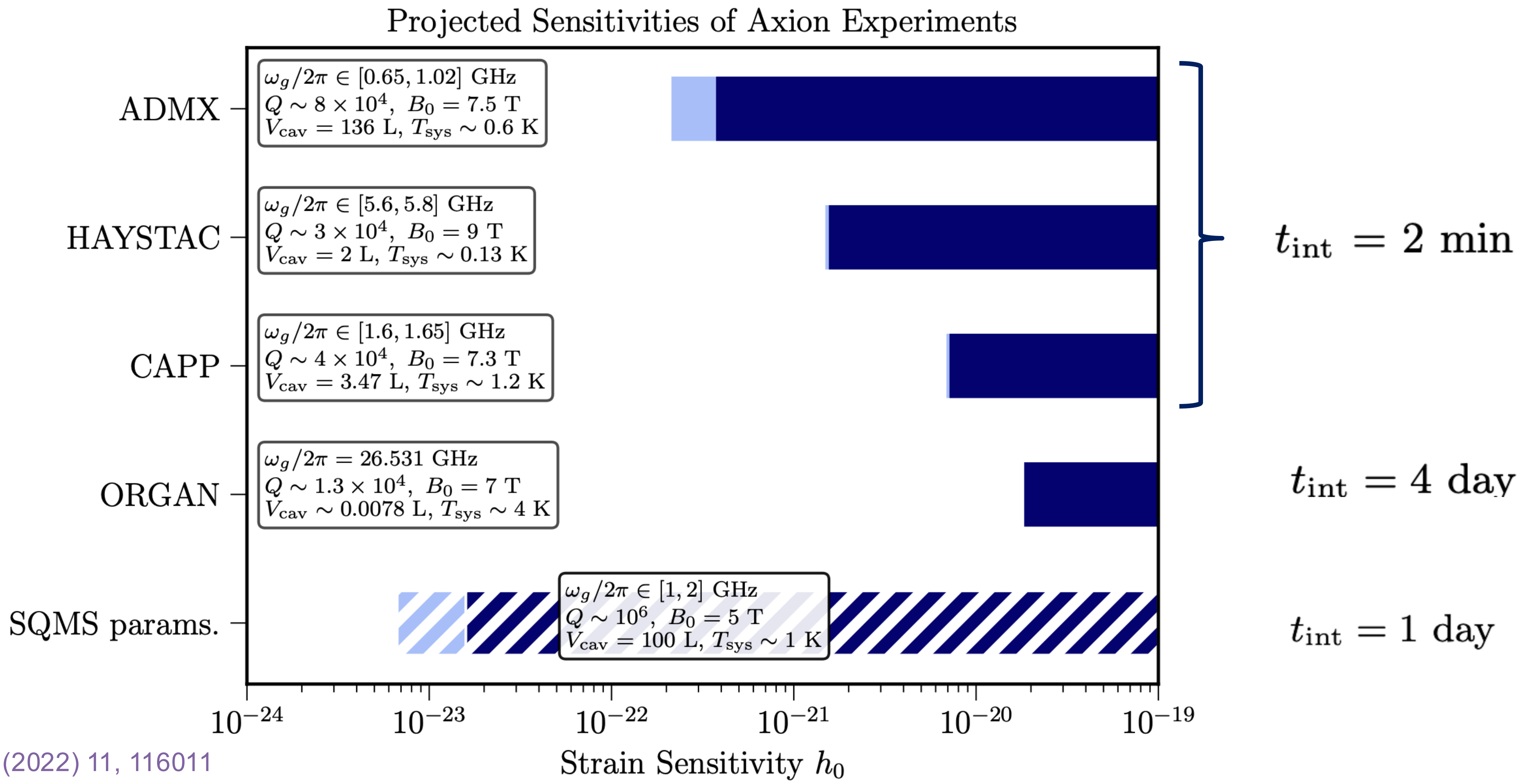
Cavities



$$\eta_n \equiv \frac{\left| \int_{V_{\mathrm{cav}}} d^3\mathbf{x}\ \mathbf{E}_n^* \cdot \hat{\boldsymbol{j}}_{+,\times} \right|}{V_{\mathrm{cav}}^{1/2} \left(\int_{V_{\mathrm{cav}}} d^3\mathbf{x}\ |\mathbf{E}_n|^2 \right)^{1/2}}$$

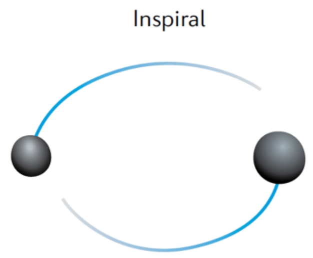
Berlin, et al, *PRD* 105 (2022) 11, 116011

Cavities

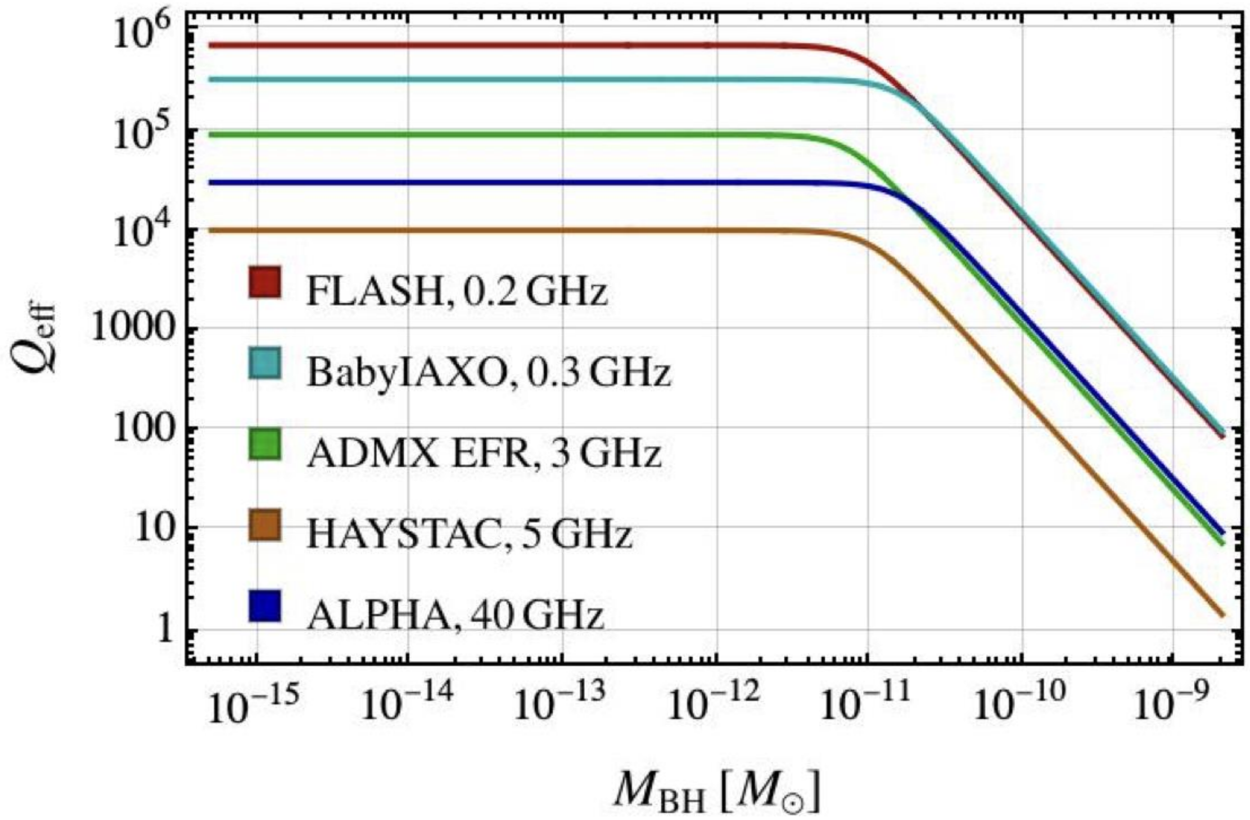


Berlin, et al, *PRD* 105 (2022) 11, 116011

Cavities



Incomplete Ring-up



$$P_{\rm sig} = \frac{1}{2} Q_{\rm eff}\, \omega_g^3\, V_{\rm cav}^{5/3}\, (\eta_n\, h_0\, B_0)^2$$

$$Q_{\rm eff} \equiv \min(Q, N_{\rm cycles})$$

$$N_{\rm cycles}^{\rm na\ddot{i}ve} = \frac{f^2}{\dot{f}} \simeq \left(\frac{M}{2.2\times 10^{-5}\, M_\odot}\right)^{-5/3} \left(\frac{f}{200\,{\rm MHz}}\right)^{-5/3}$$

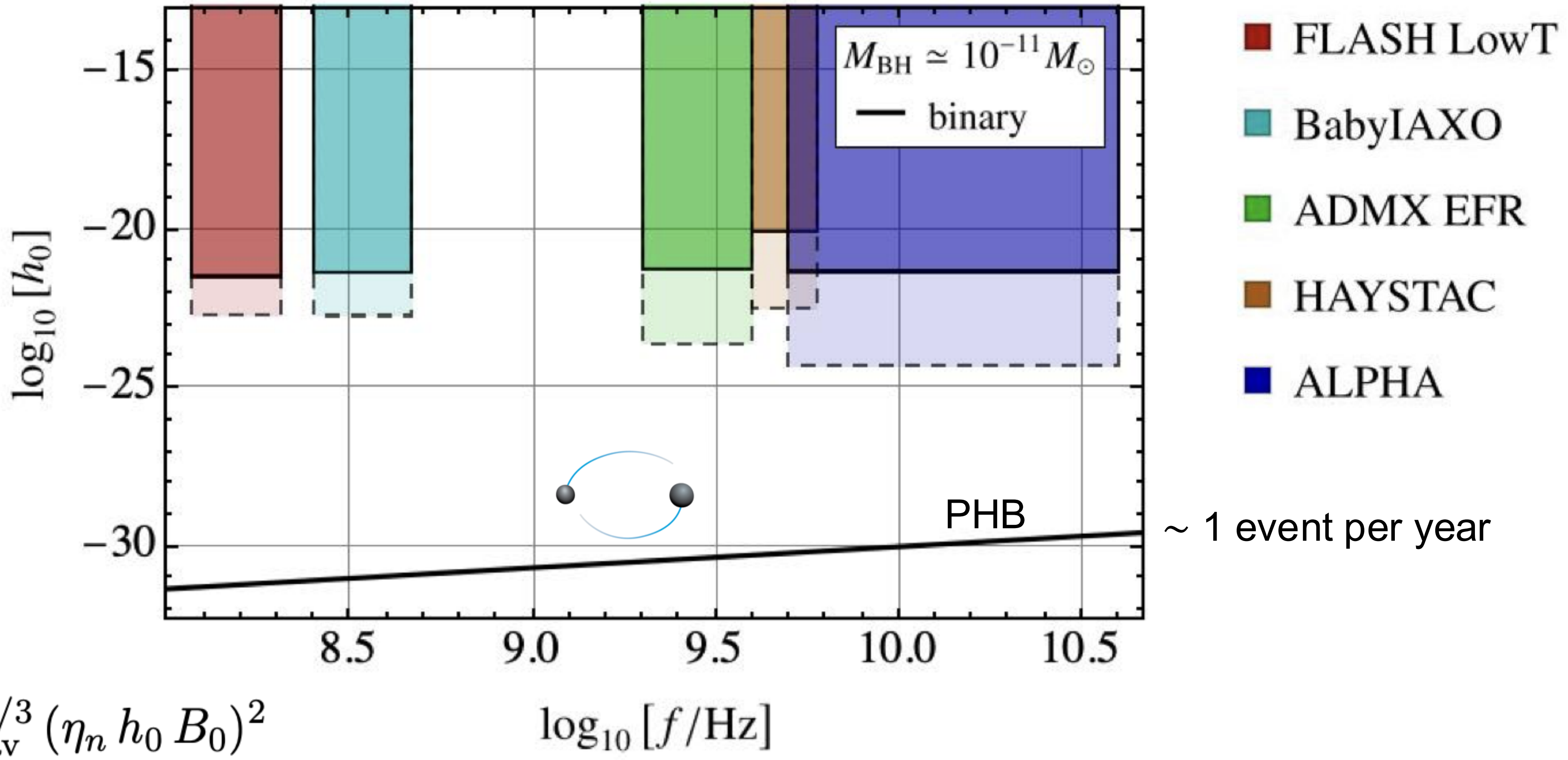
$$h(f) = 2\times 10^{-37}\,{\rm sec}\left(\frac{\rm kpc}{D}\right)\left(\frac{m_{\rm PBH}}{10^{-12}\,{\rm M}_\odot}\right)^{5/6}\left(\frac{f}{\rm GHz}\right)^{-7/6}$$

$$f_{\rm ISCO} = 4400\,{\rm Hz}\,\frac{M_\odot}{M}$$

Gatti, Visinelli, Zantedeschi *PRD* 110 (2024) 2, 023018

Cavities

Sensitivities to PBHs

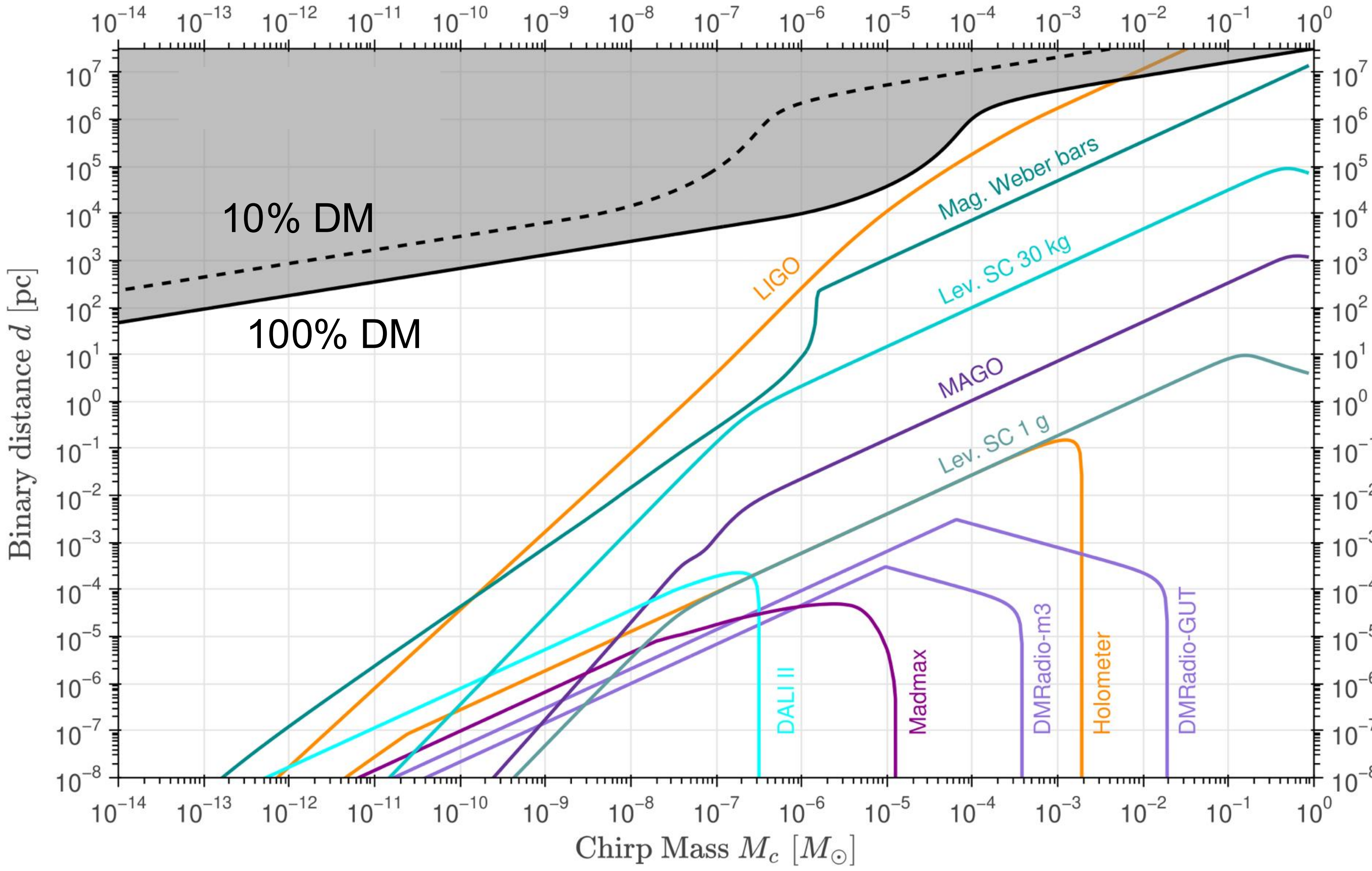


~ 1 event per year

$$P_{\rm sig} = \frac{1}{2} Q_{\rm eff} \omega_g^3 V_{\rm cav}^{5/3} (\eta_n h_0 B_0)^2$$

Gatti, Visinelli, Zantedeschi *PRD* 110 (2024) 2, 023018

PBH Mergers



Binary distance d [pc]
Chirp Mass M_c $[M_\odot]$
10% DM
100% DM
LIGO
Mag. Weber bars
Lev. SC 30 kg
MAGO
Lev. SC 1 g
DALI II
Madmax
DMRadio-m3
Holometer
DMRadio-GUT

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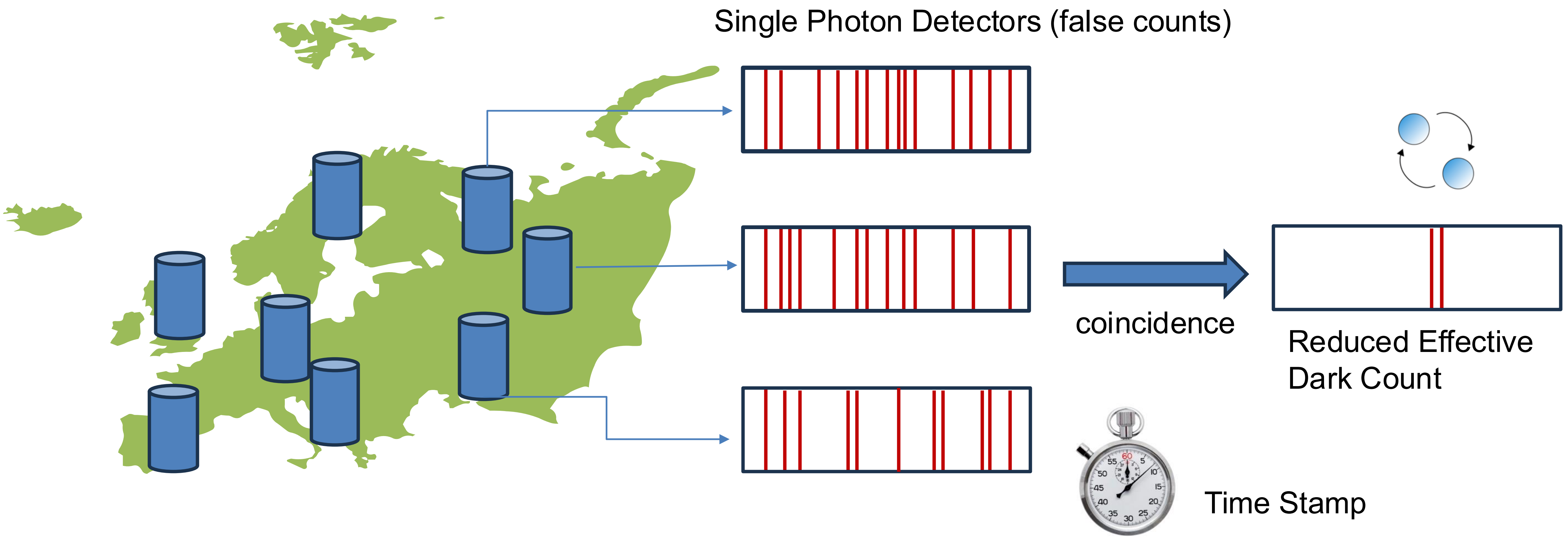
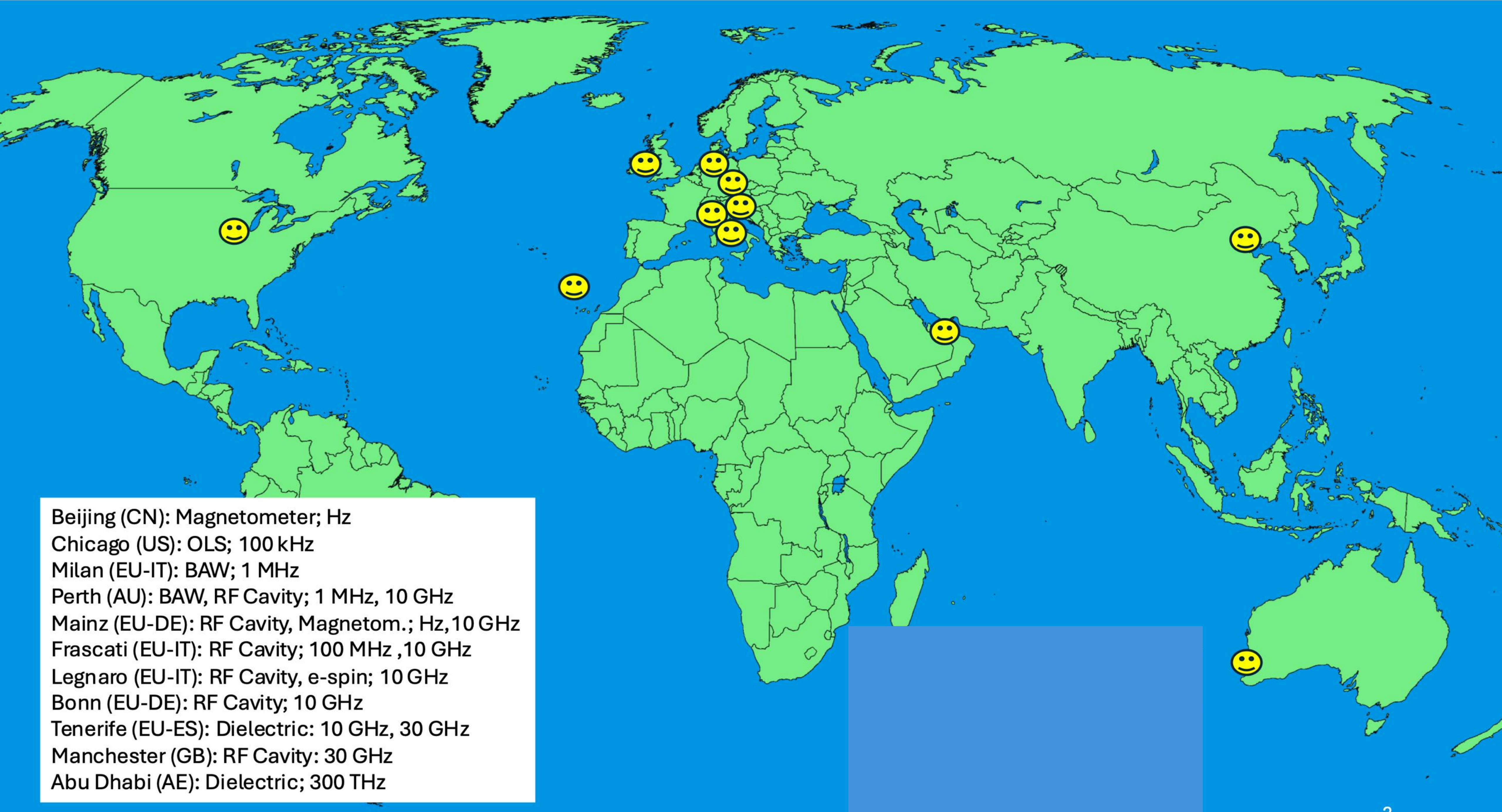
GravNet

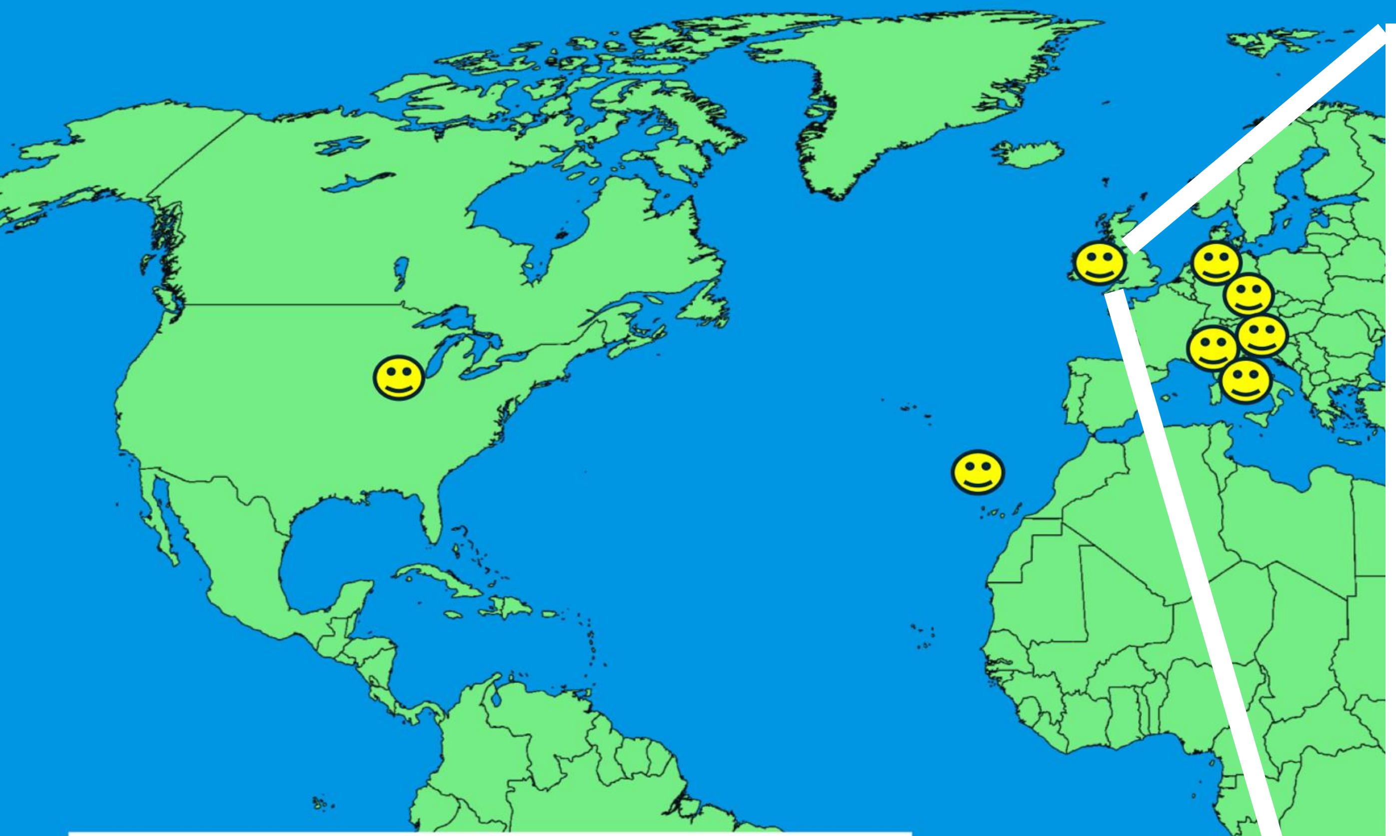


Schmieden, Schott gr-wc/2023



Beijing (CN): Magnetometer; Hz
Chicago (US): OLS; 100 kHz
Milan (EU-IT): BAW; 1 MHz
Perth (AU): BAW, RF Cavity; 1 MHz, 10 GHz
Mainz (EU-DE): RF Cavity, Magnetom.; Hz, 10 GHz
Frascati (EU-IT): RF Cavity; 100 MHz ,10 GHz
Legnaro (EU-IT): RF Cavity, e-spin; 10 GHz
Bonn (EU-DE): RF Cavity; 10 GHz
Tenerife (EU-ES): Dielectric: 10 GHz, 30 GHz
Manchester (GB): RF Cavity: 30 GHz
Abu Dhabi (AE): Dielectric; 300 THz

Slide from GravNet Collaboration Meeting (courtesy Blas, Budker, Gatti, Schott)



Beijing (CN): Magnetometer; Hz
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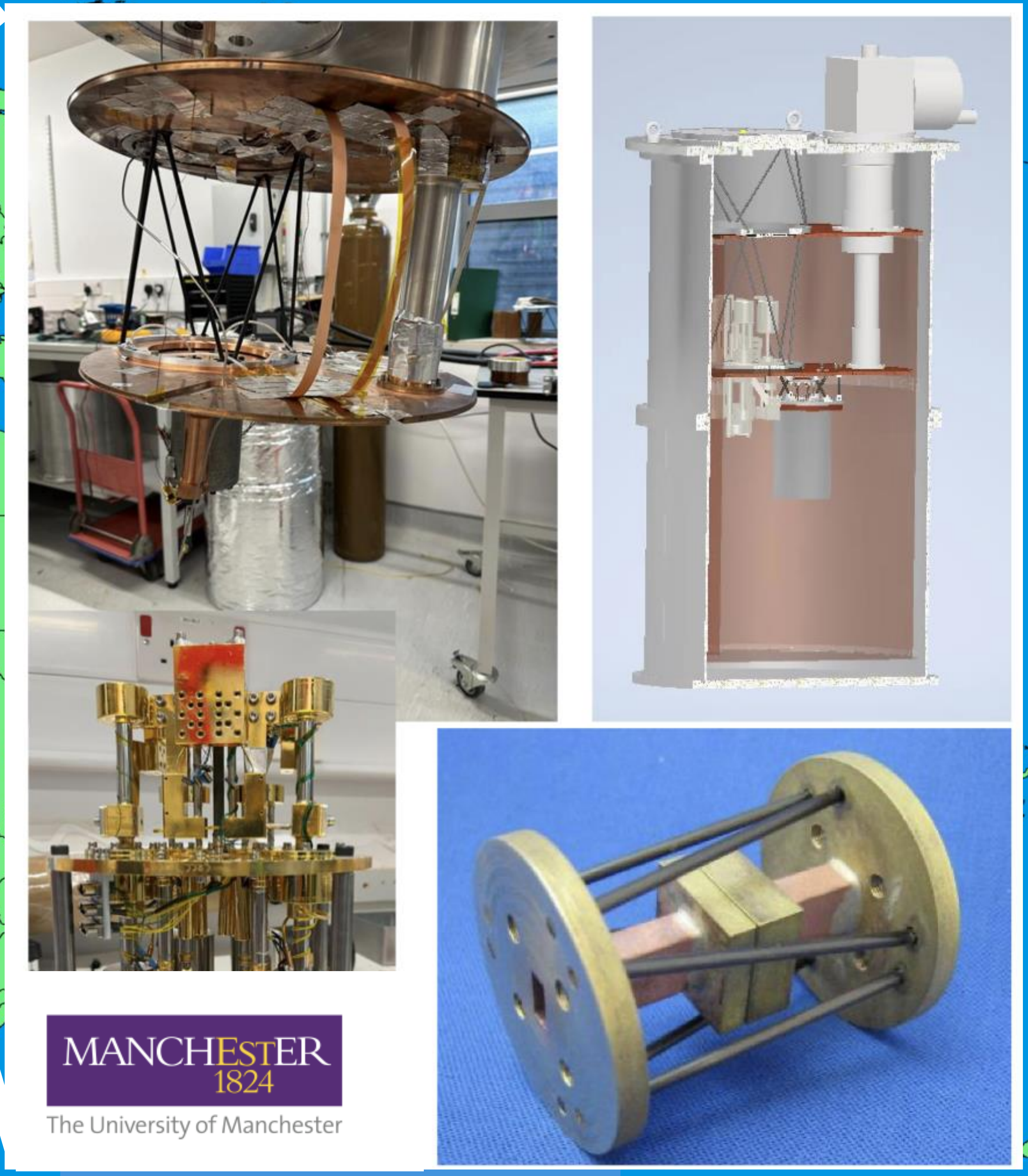

Slide from GravNet Collaboration Meeting (courtesy Blas, Budker, Gatti, Schott

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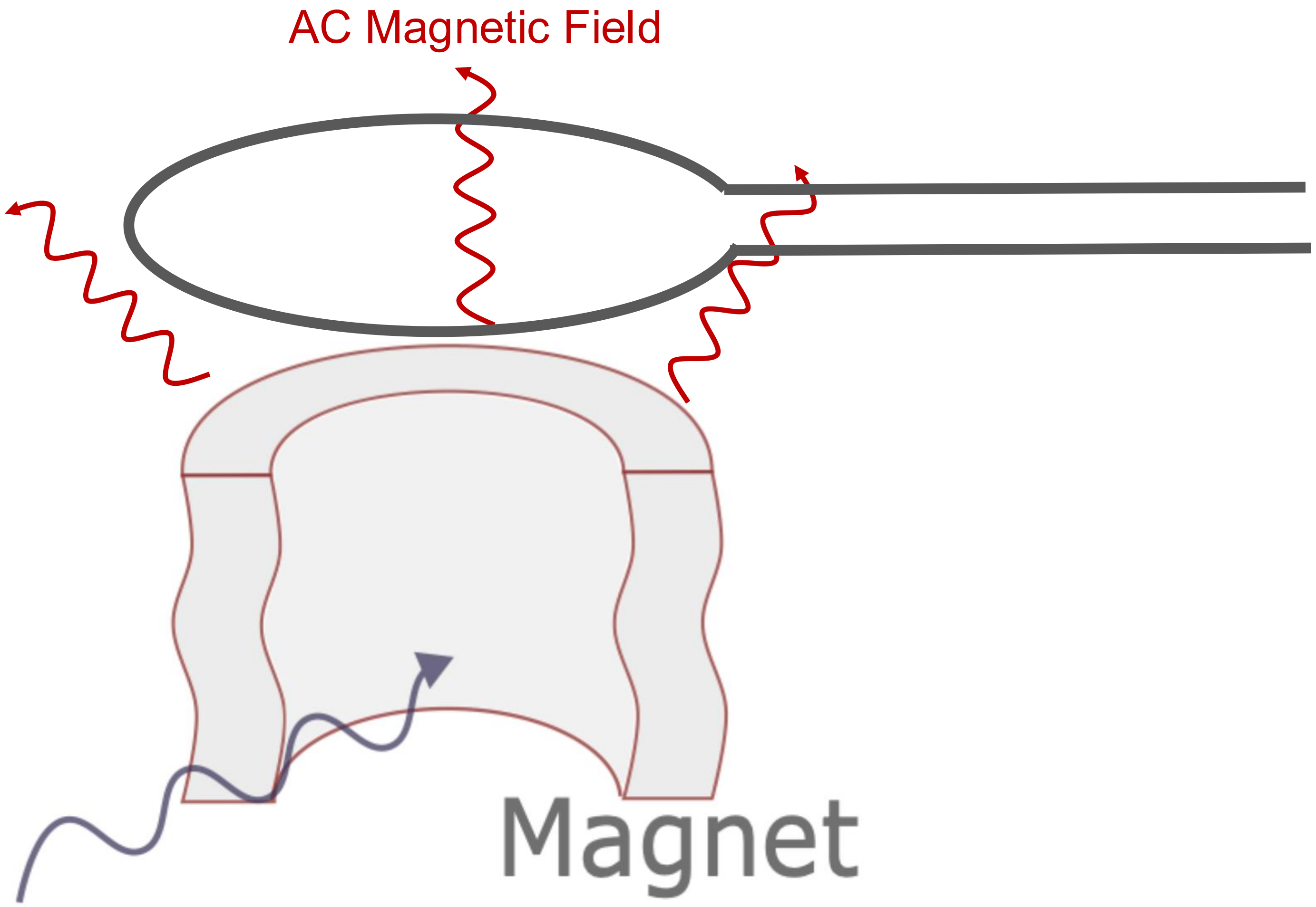
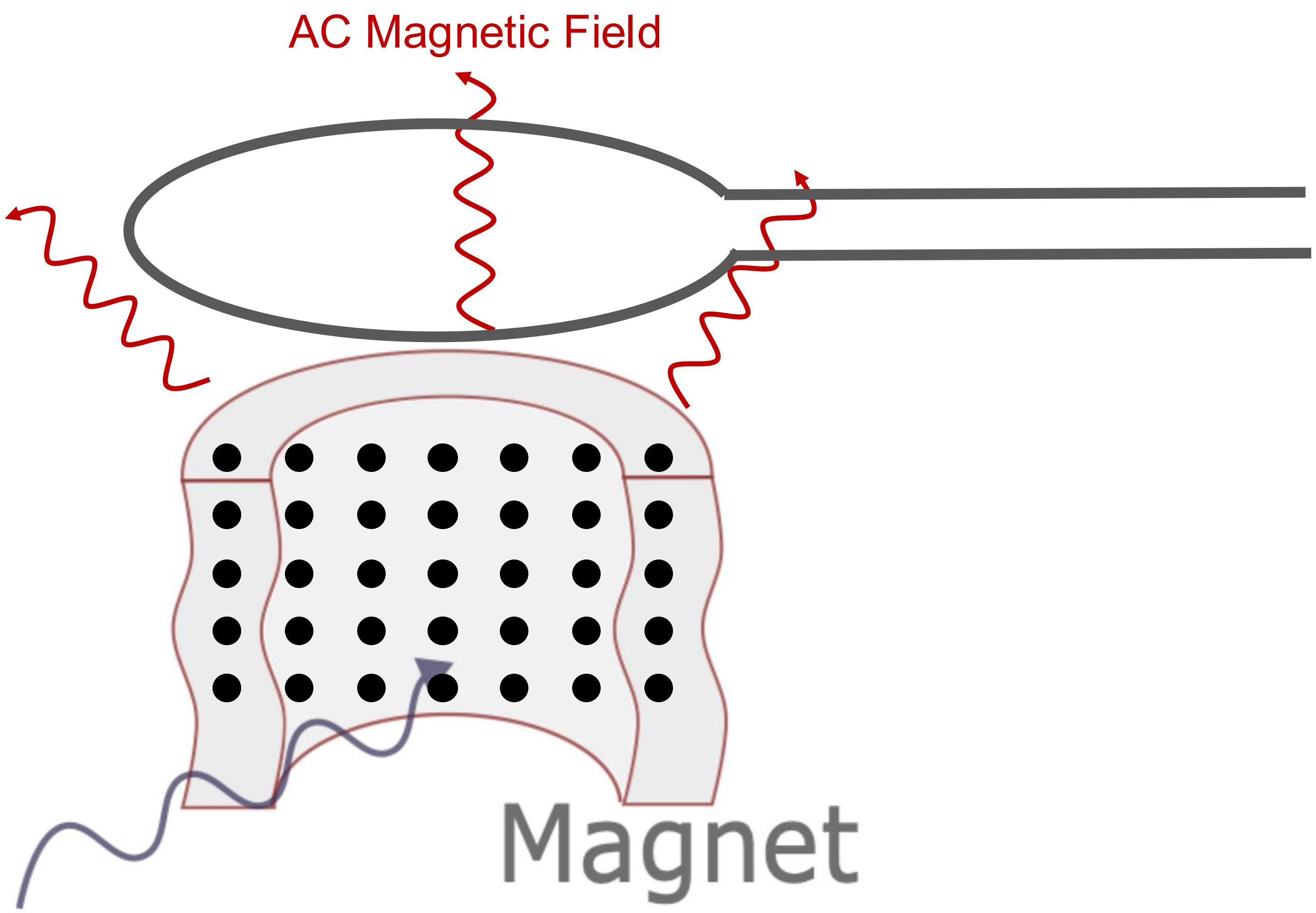
Magnetic Weber Bars



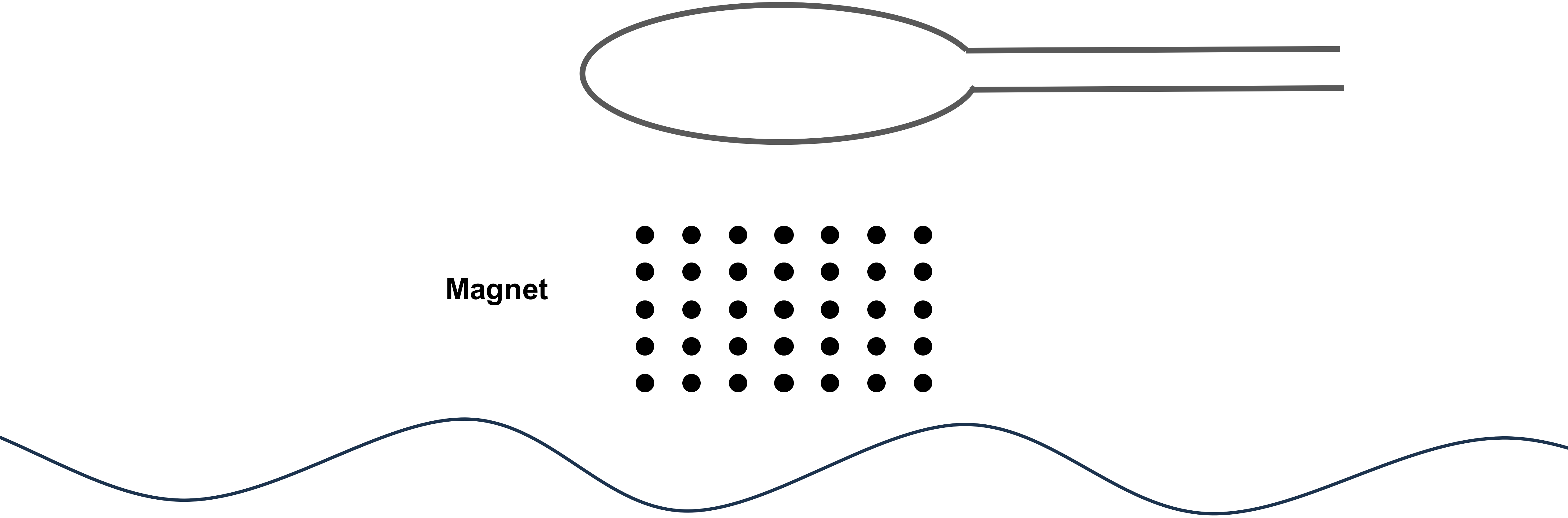
Domcke, S. Ellis, Rodd PRL 134 (2025) 23, 231401

Magnetic Weber Bars



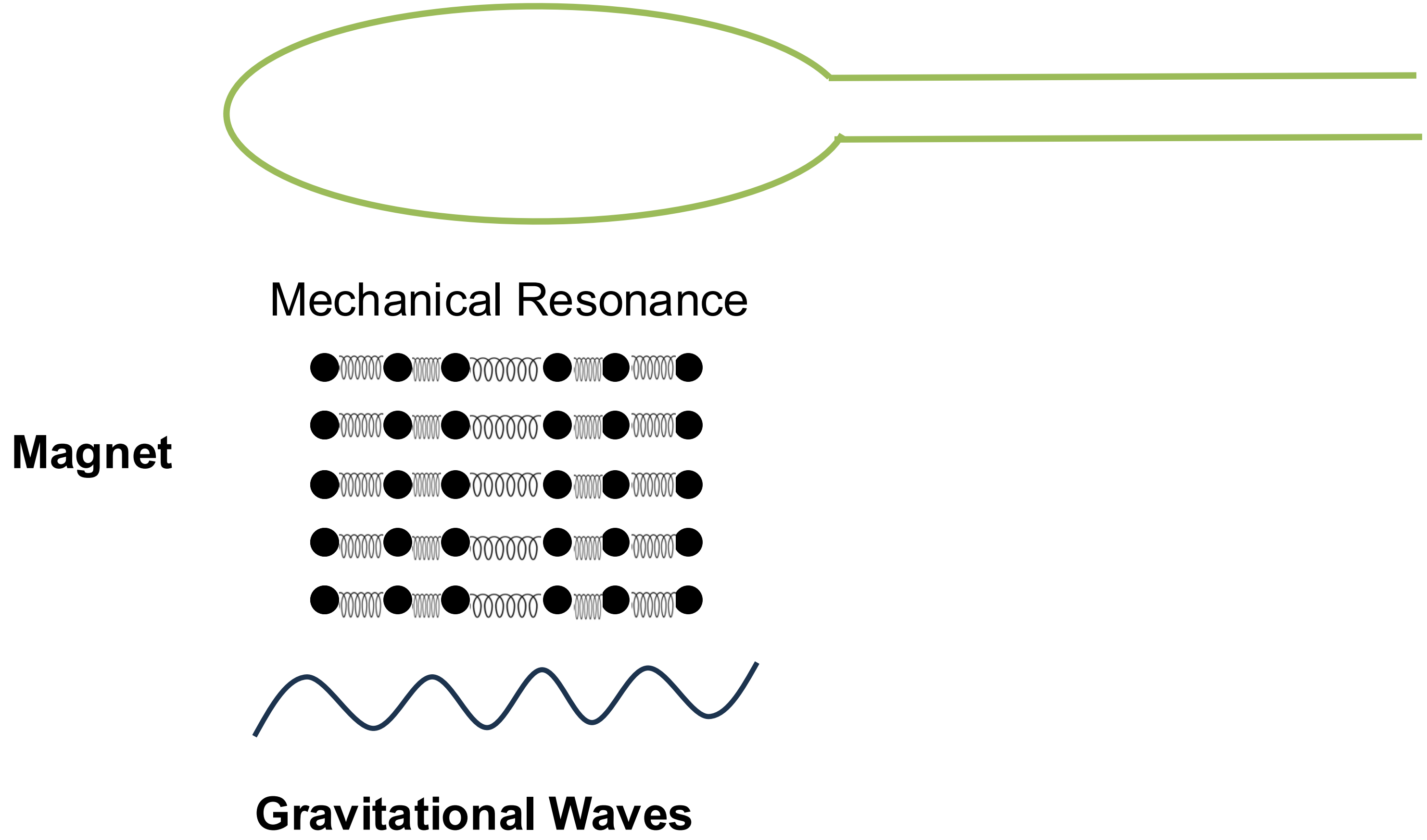
Domcke, S. Ellis, Rodd PRL 134 (2025) 23, 231401

Magnetic Weber Bars



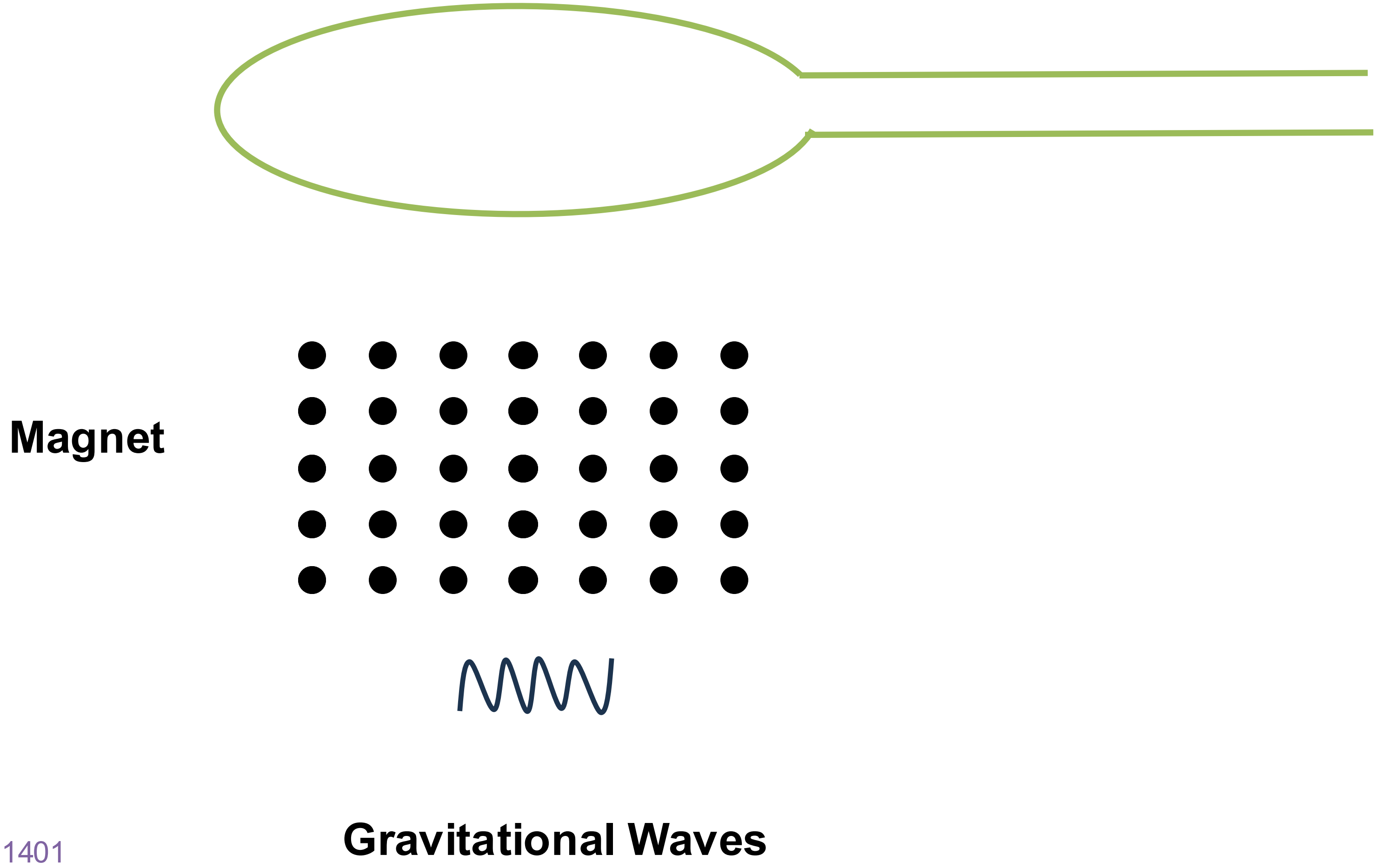
Domcke, S. Ellis, Rodd PRL 134 (2025) 23, 231401

Magnetic Weber Bars



Domcke, S. Ellis, Rodd PRL 134 (2025) 23, 231401

Magnetic Weber Bars



Domcke, S. Ellis, Rodd PRL 134 (2025) 23, 231401

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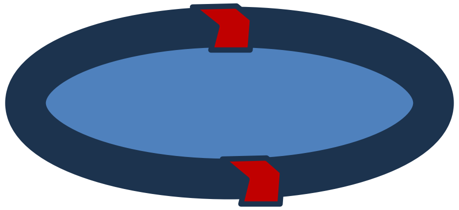
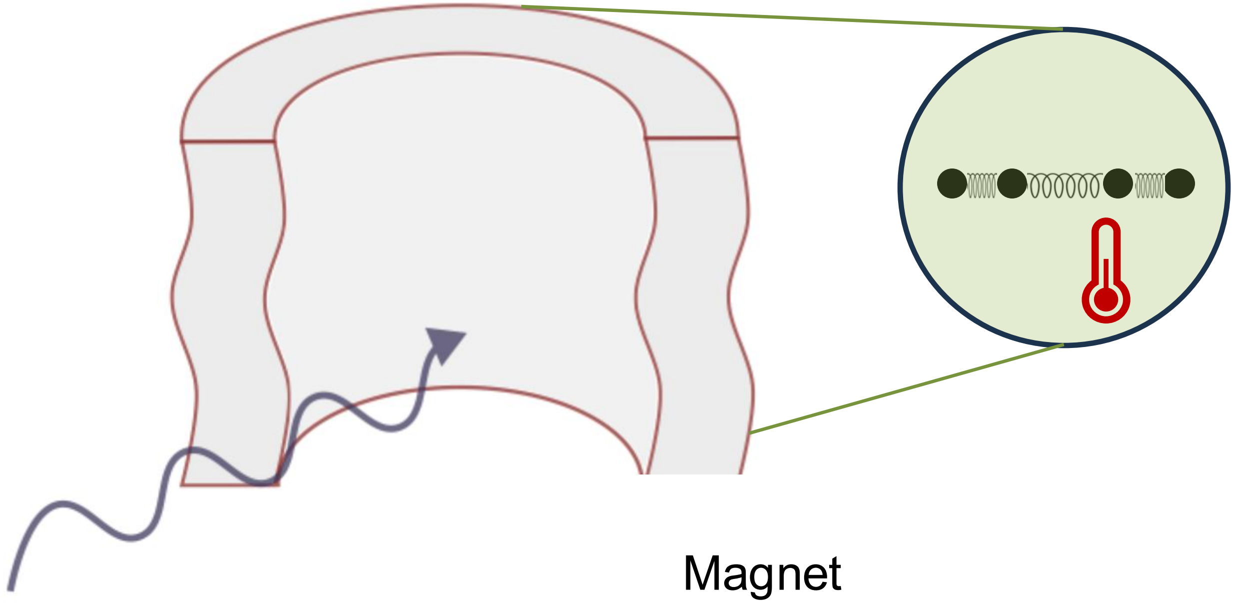
Noise Sources

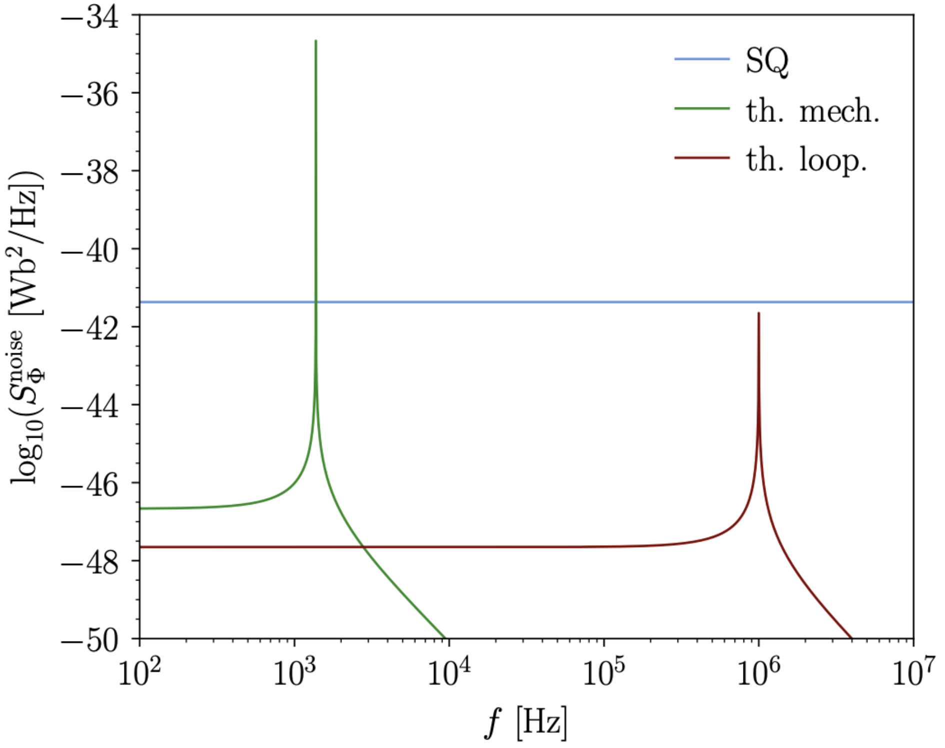
Loop

SQUID



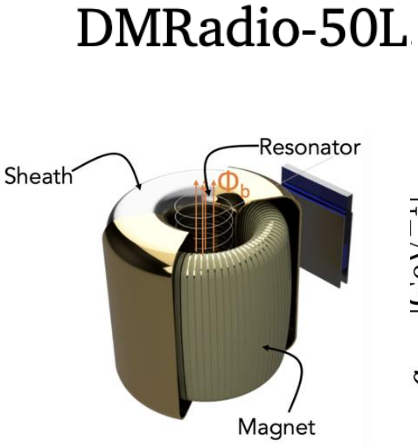


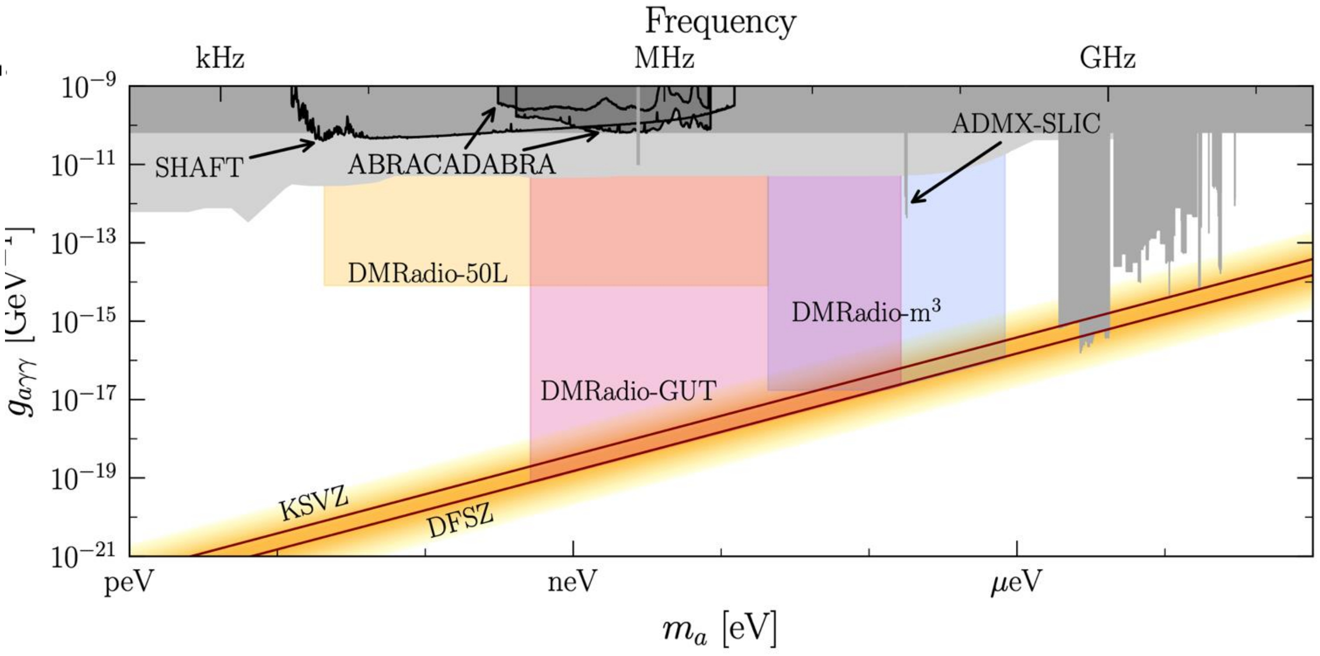
Magnet

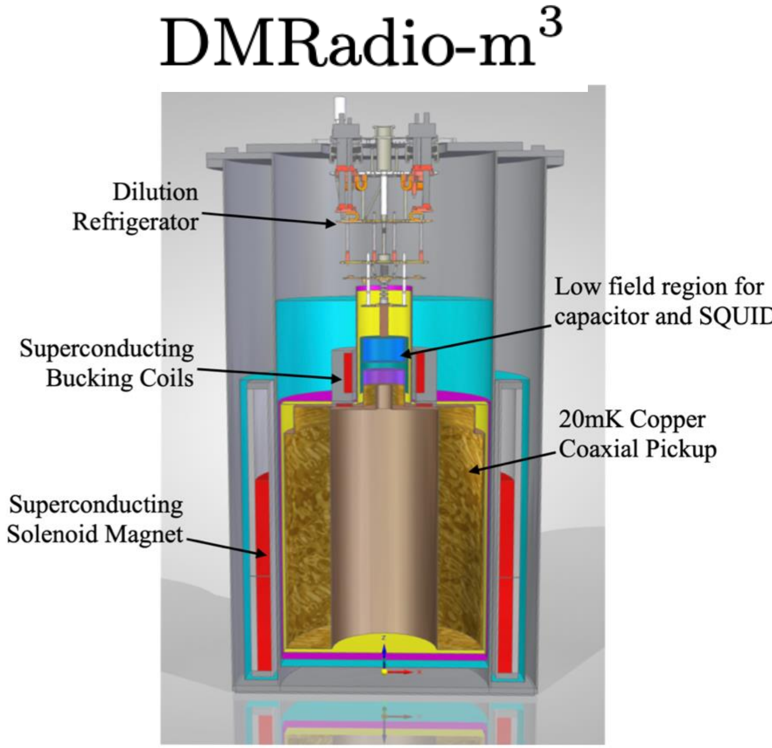


Domcke, S. Ellis, Rodd PRL 134 (2025) 23, 231401

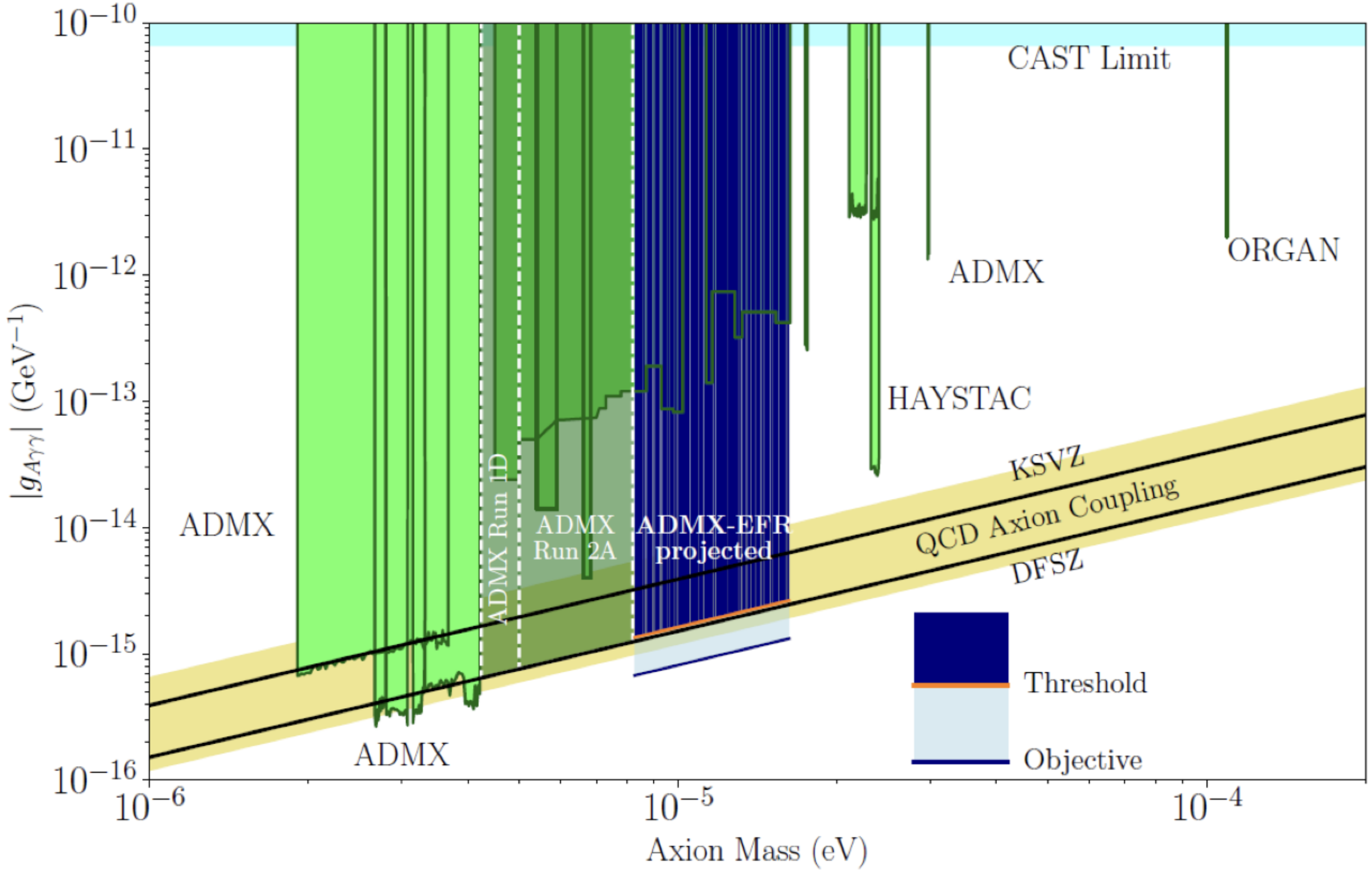
Real Experiments

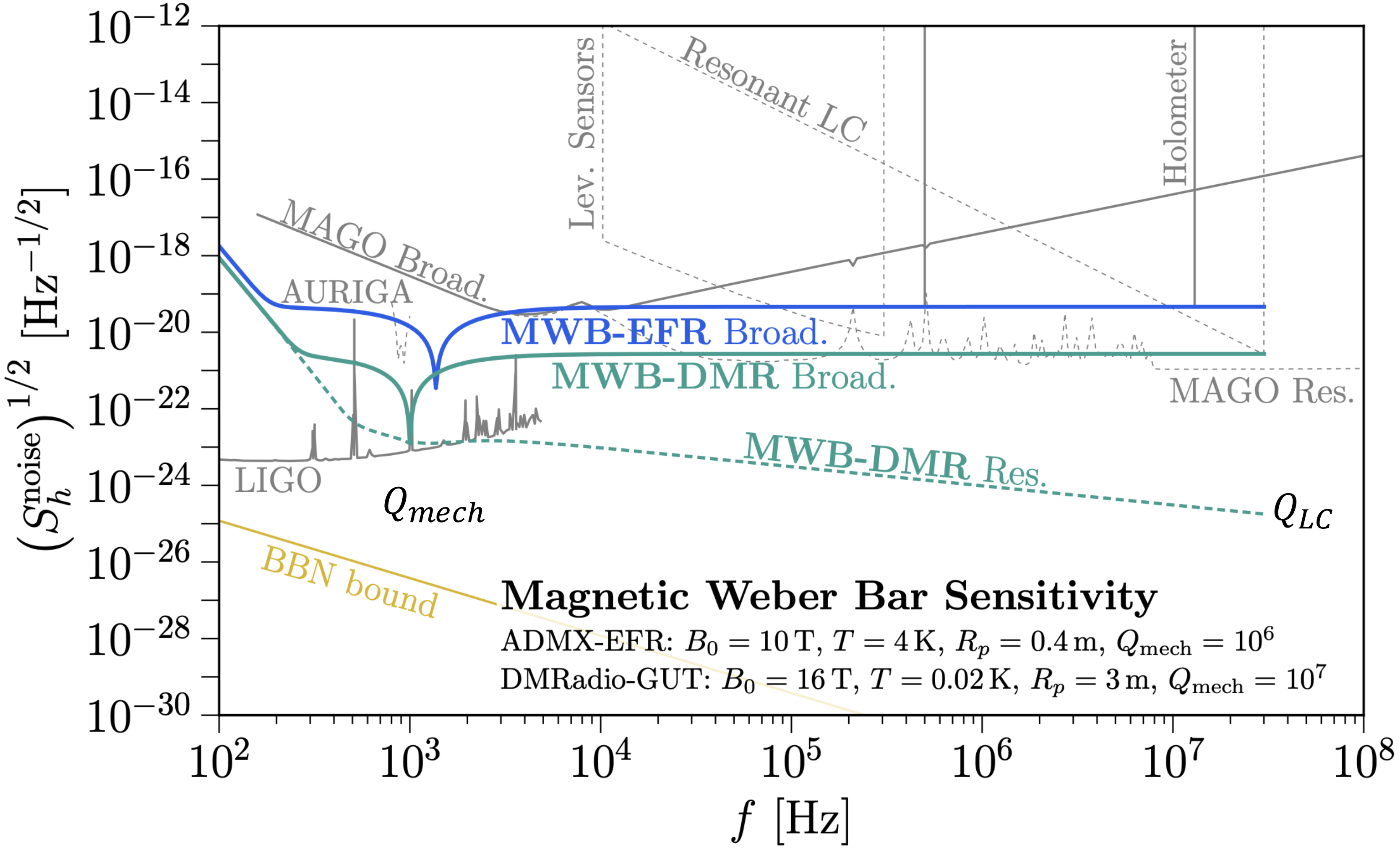




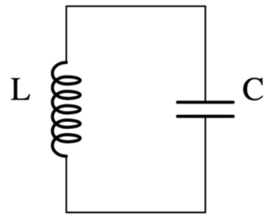


ADMX **E**xtended **F**requency **R**ange (ERF)





MAGO Broad.
AURIGA
Lev. Sensors
Resonant LC
Holometer
MWB-EFR Broad.
MWB-DMR Broad.
MAGO Res.
MWB-DMR Res.
LIGO
Q_{mech}
Q_{LC}
BBN bound
Magnetic Weber Bar Sensitivity
ADMX-EFR: $B_0 = 10\,\mathrm{T}$, $T = 4\,\mathrm{K}$, $R_p = 0.4\,\mathrm{m}$, $Q_{\mathrm{mech}} = 10^6$
DMRadio-GUT: $B_0 = 16\,\mathrm{T}$, $T = 0.02\,\mathrm{K}$, $R_p = 3\,\mathrm{m}$, $Q_{\mathrm{mech}} = 10^7$
$\left(S_h^{\mathrm{noise}}\right)^{1/2}$ $[\mathrm{Hz}^{-1/2}]$
f [Hz]



L
C

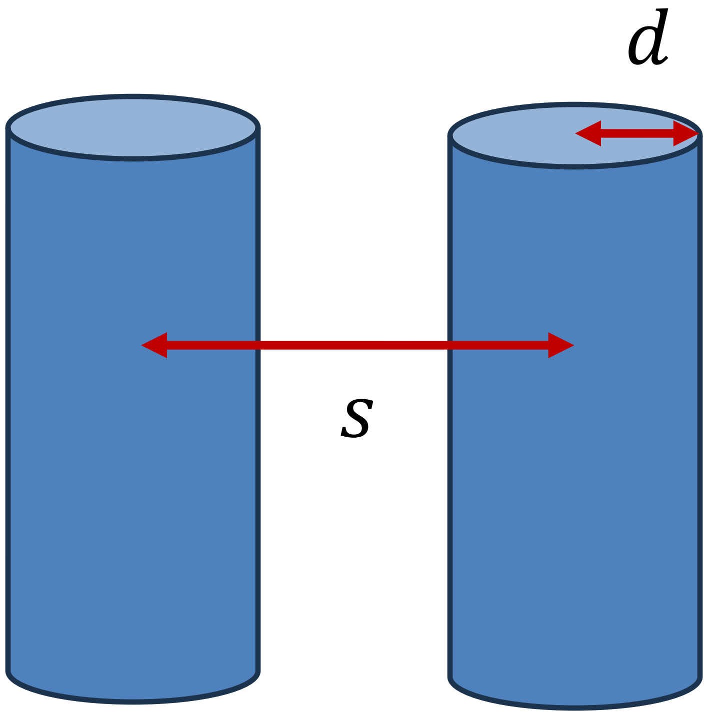
Q_{LC}

Plasma Haloscopes

$$\omega_p^2 = \frac{2\pi}{s^2 \log(s/d)}$$

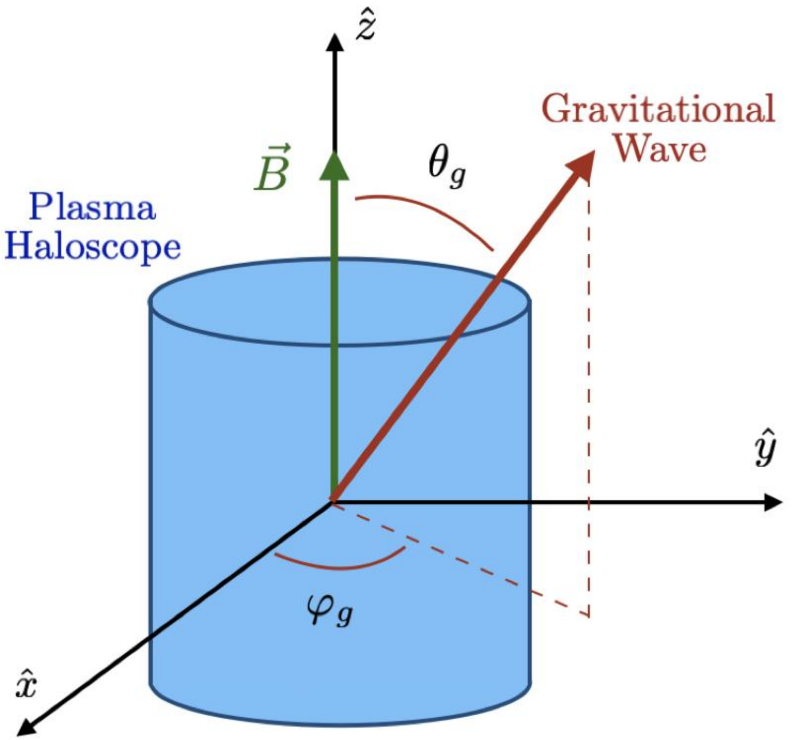
Resonant axion conversion

$$\omega_p^2 = m_a^2$$

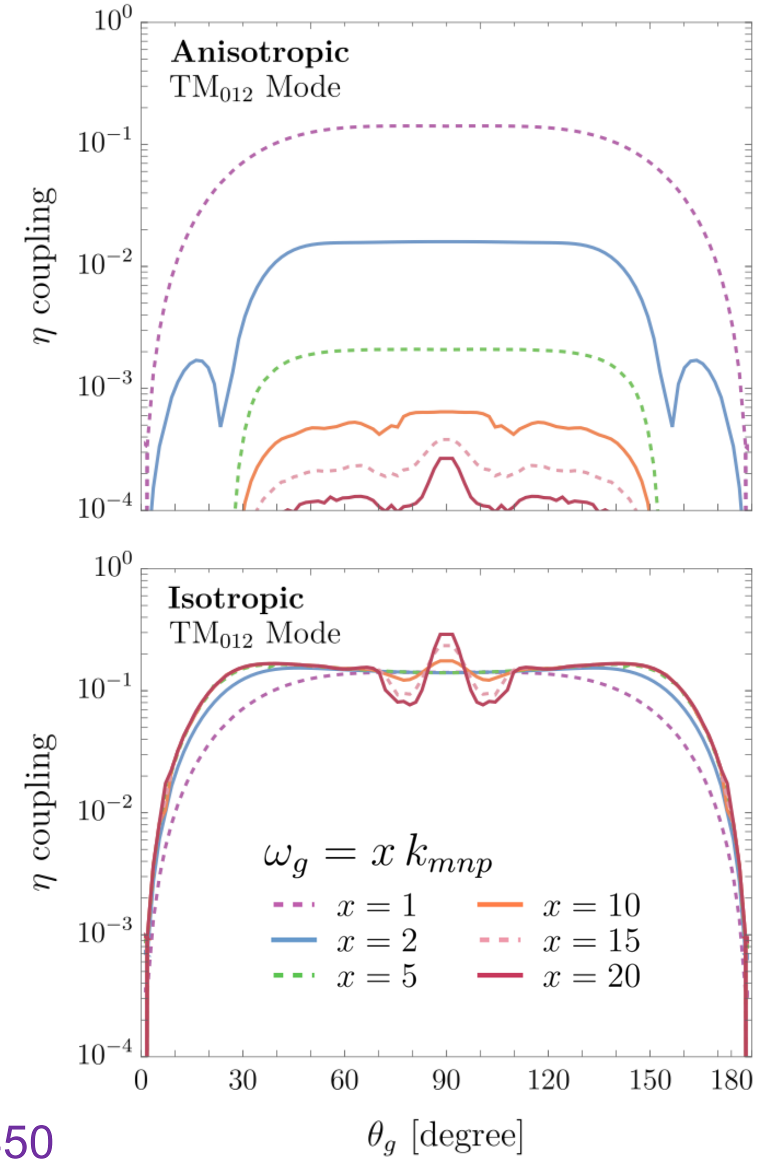


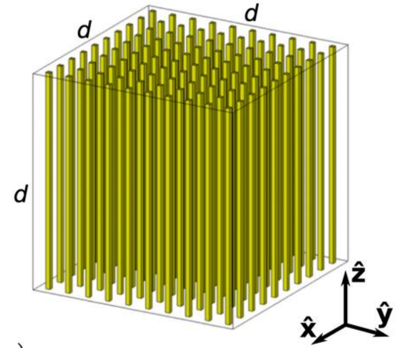
Lawson et al PRL 123 (2019) 14, 141802
Millar et al PRD 107 (2023) 5, 055013
ALPHA Collaboration

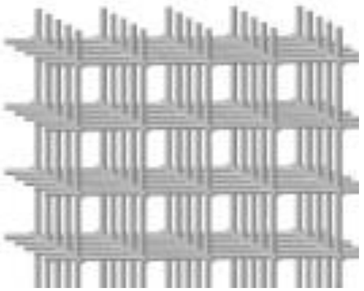
Plasma Haloscopes



$$\eta_{\alpha,n} = \frac{\int dV \mathbf{j}_{\text{eff}}(\mathbf{x}) \cdot \mathbf{E}^*_{\alpha,n}(\mathbf{x})}{\int dV |\mathbf{E}_{\alpha,n}(\mathbf{x})|^2}$$







Capdevilla, Gelmini, Hyman, Millar, Vitagliano hep-ph/2412.14450

Plasma Haloscopes

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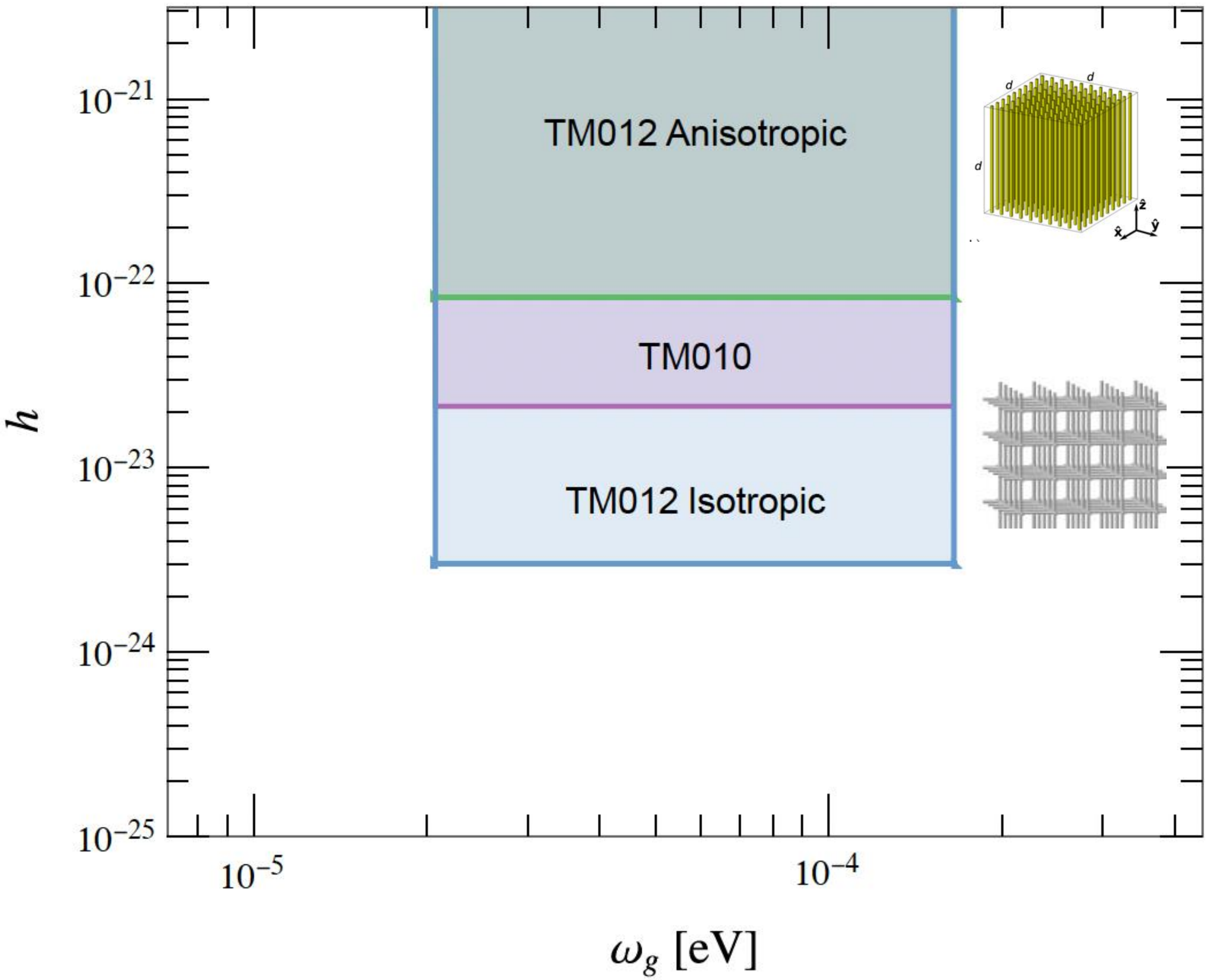

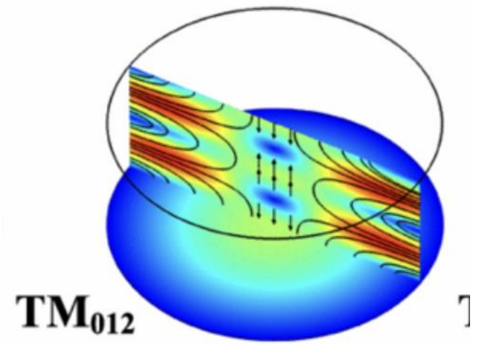

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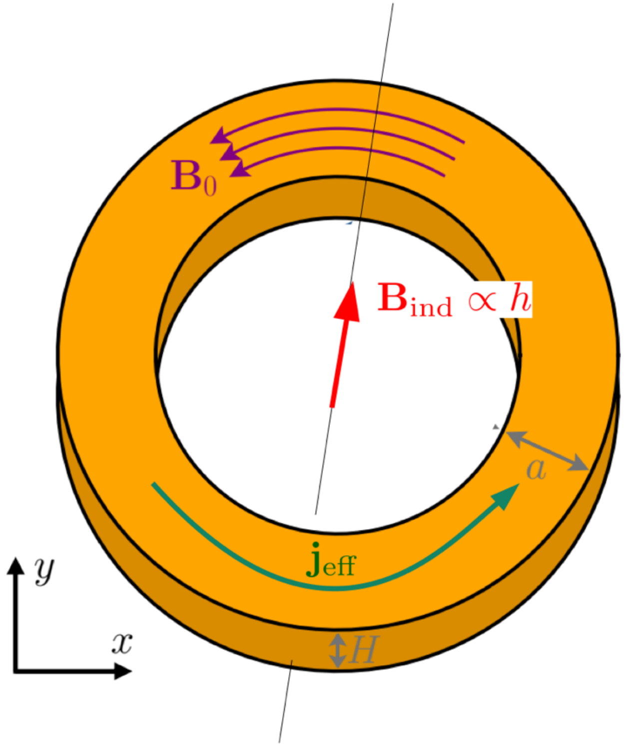
Low Mass Axion Detectors



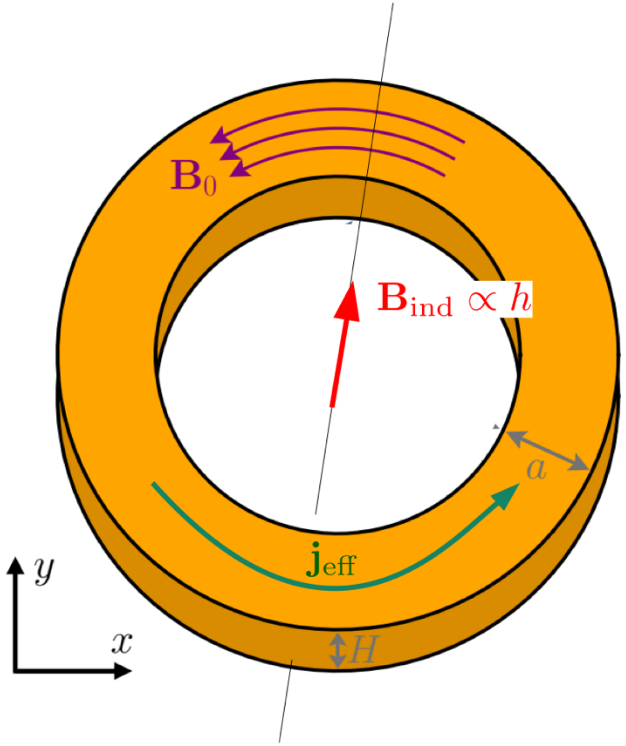
$$j^{\mu}_{axion} = \partial_\mu \phi \tilde{F}^{\mu\nu}$$

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

Domcke, Garcia-Cely, Rodd *PRL 129 (2022) 4, 041101*

The University of Manchester

Low Mass Axion Detectors



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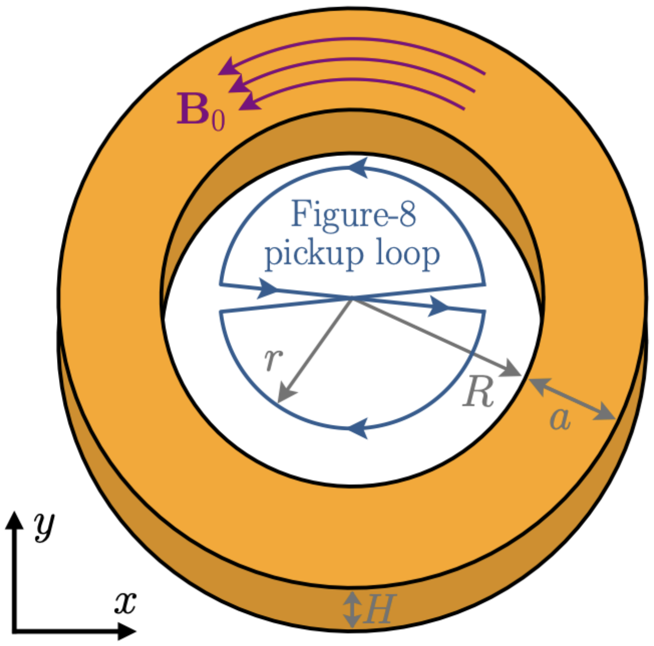
$$j^{\mu}_{GW} = \partial_{\nu}\left(\frac{1}{2}\,h\,F^{\mu\nu} + h^{\nu}{}_{\alpha}F^{\alpha\mu} - h^{\mu}{}_{\alpha}F^{\alpha\nu}\right)$$

Domcke, Garcia-Cely, Rodd *PRL 129 (2022) 4, 041101*

Low Mass Axion Detectors



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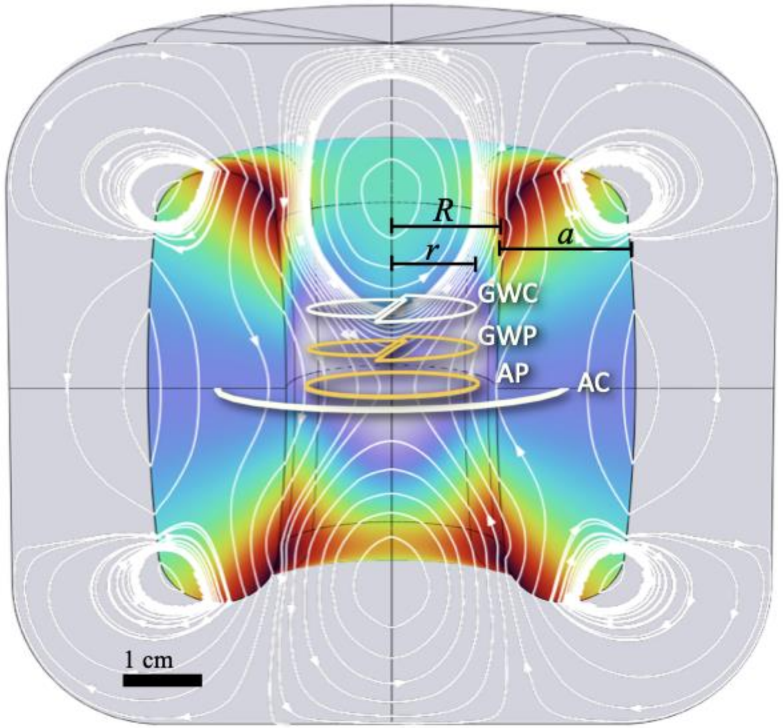
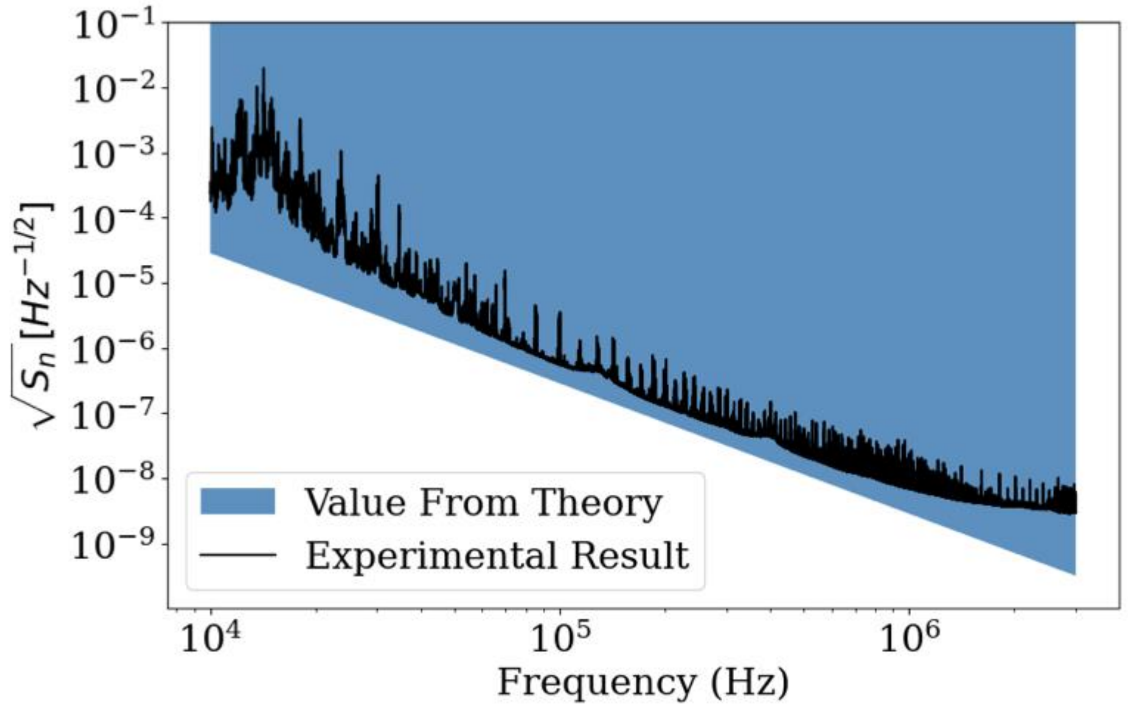
Domcke, Garcia-Cely, Rodd *PRL 129 (2022) 4, 041101*

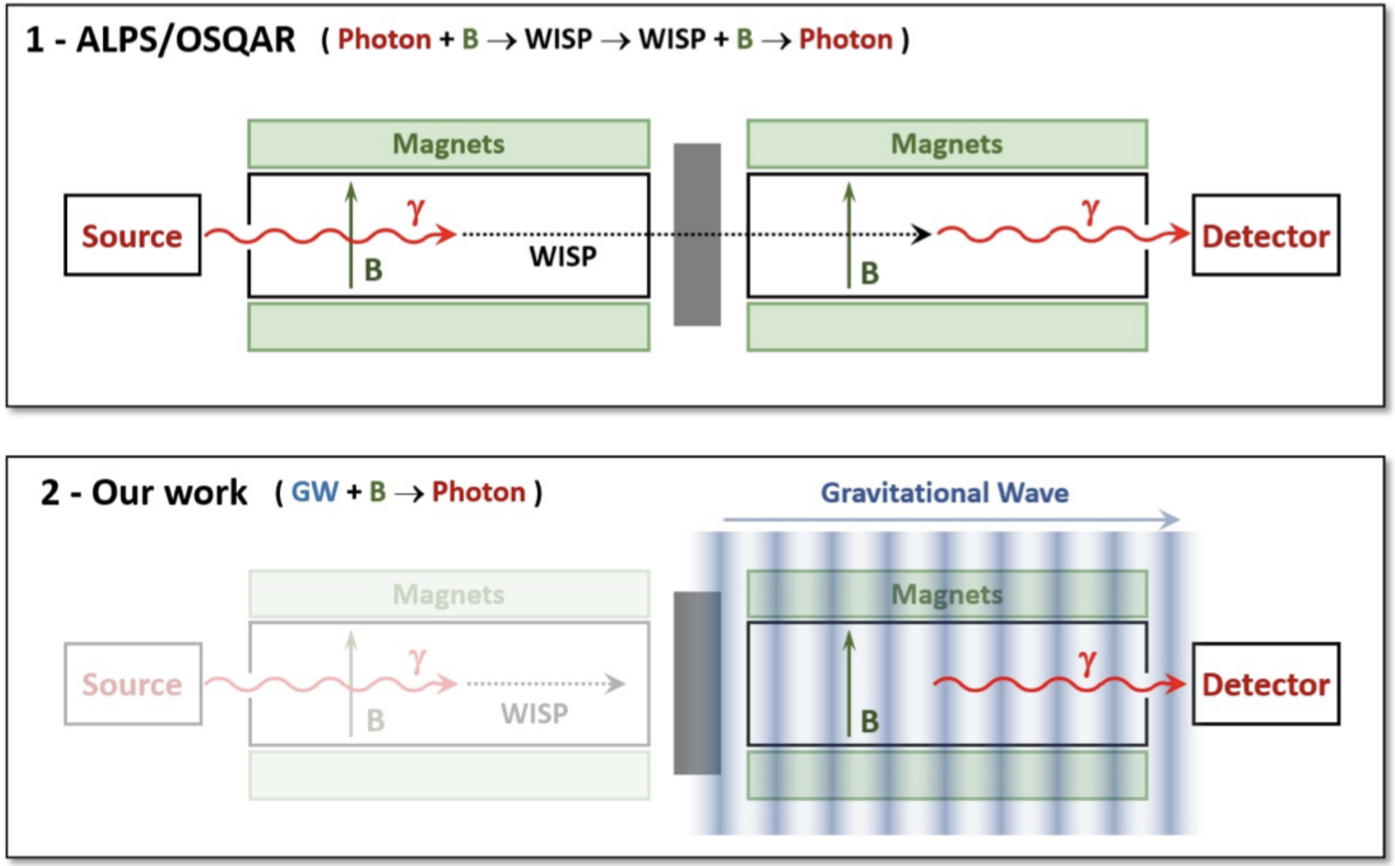
Low Mass Axion Detectors





Pappas et al hep-ex/2505.02821

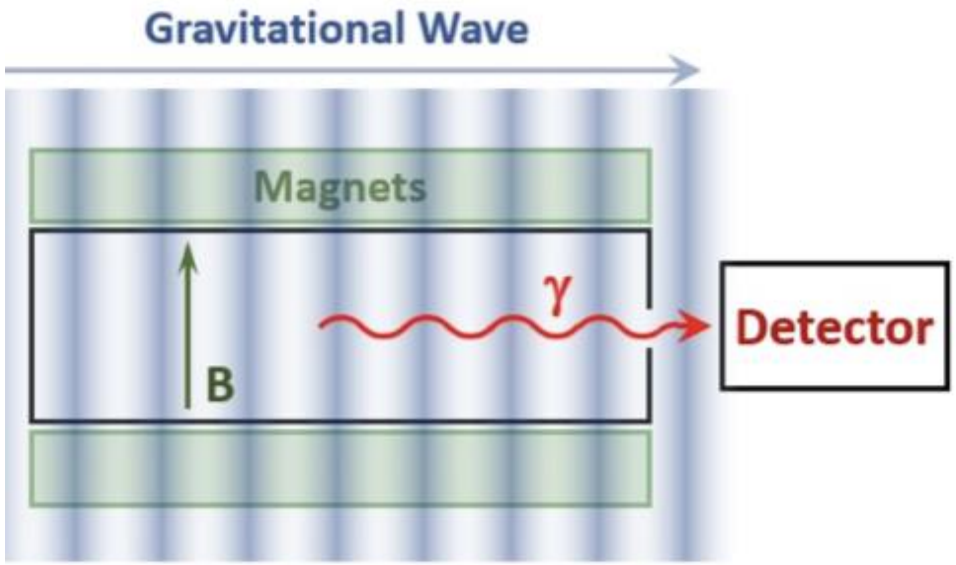
Helioscopes & Light Through Wall Experiments

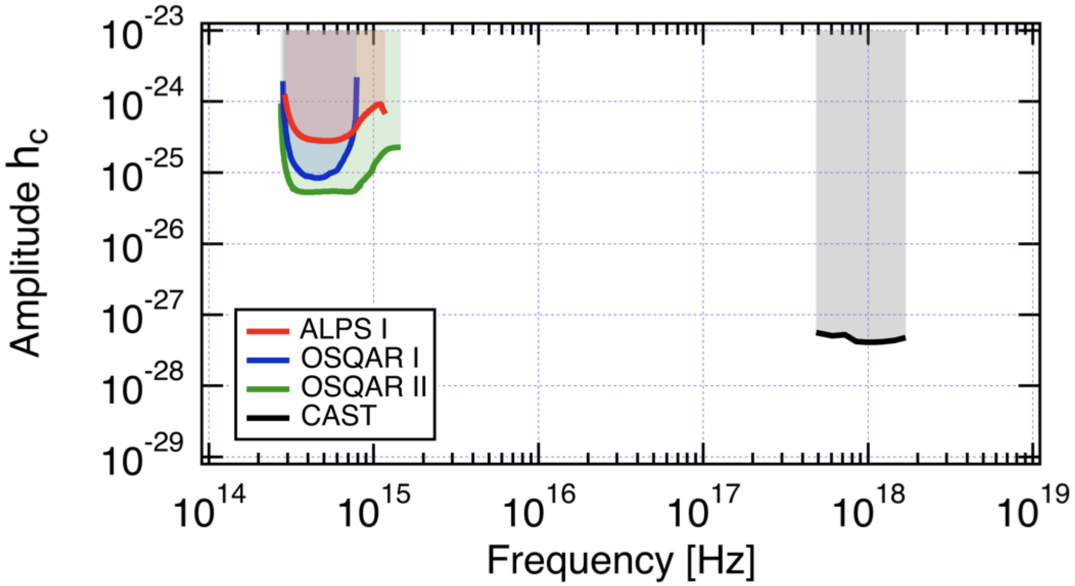


Ejlli, Ejlli, Cruise, Pisano, Grote, Eur. Phys. J. C 79, 1032 (2019)

Helioscopes & Light Through Wall Experiments

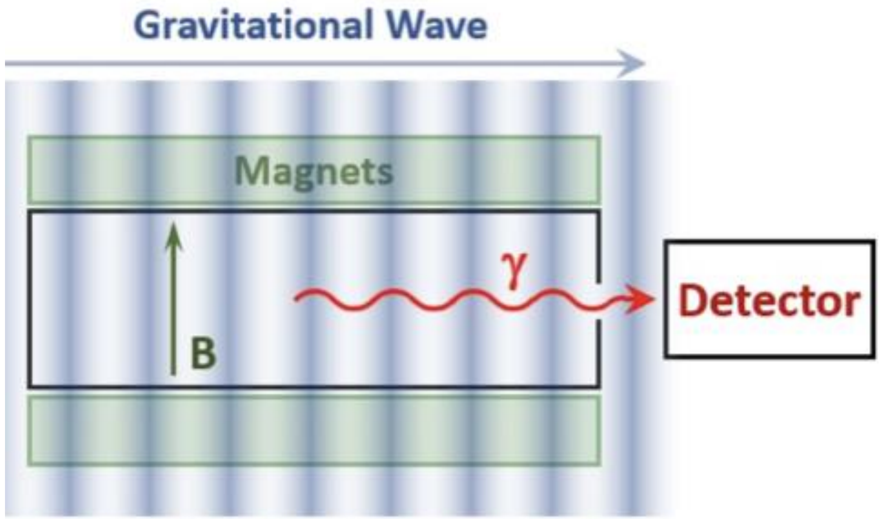
Ejlli, Ejlli, Cruise, Pisano, Grote, Eur. Phys. J. C 79, 1032 (2019)

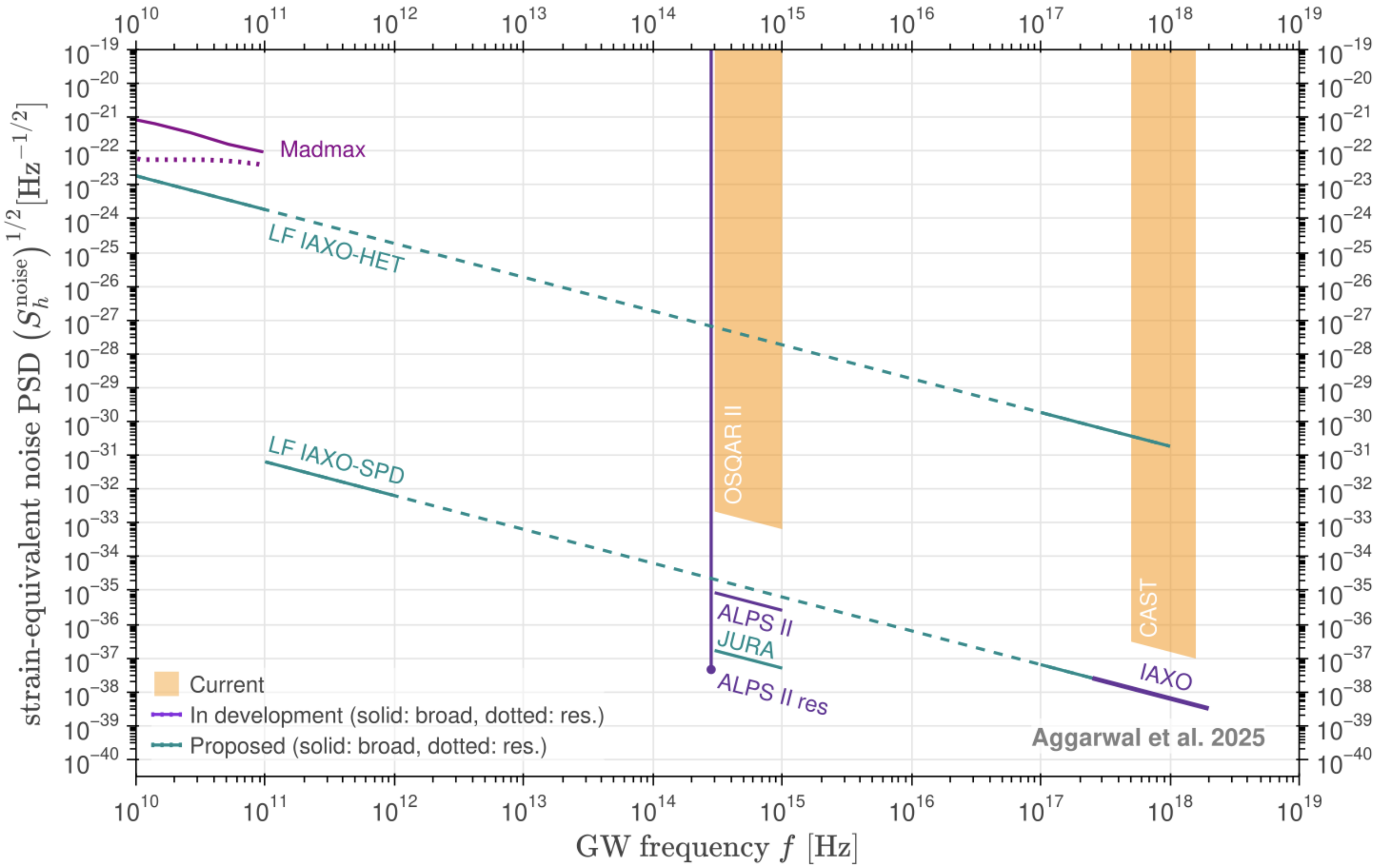




Helioscopes & Light Through Wall Experiments

Ejlli, Ejlli, Cruise, Pisano, Grote, Eur. Phys. J. C 79, 1032 (2019)





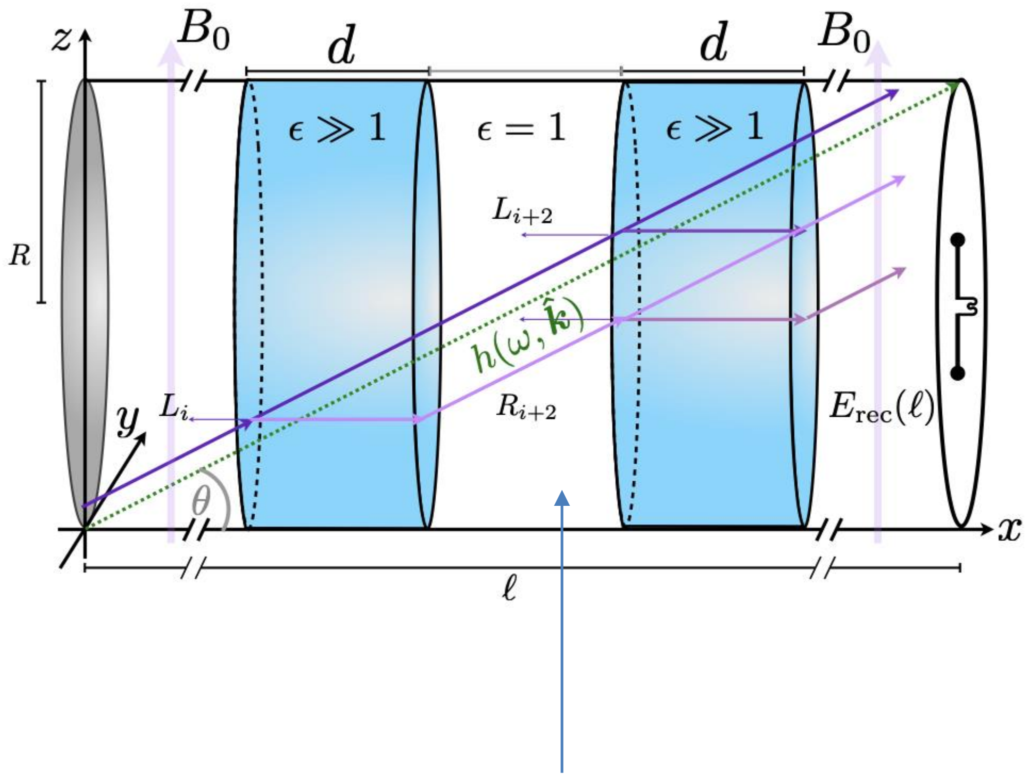
Dielectric Haloscopes

*Domcke, Ellis, Kopp 2024 PRD **111**, 035031*

Resonant Mode

$$d_{\max}\sqrt{\epsilon}\cos\theta_{\epsilon} = \pi/(2\omega)$$

$$D_{\max}\,\omega = k\pi - \arcsin\left(\frac{2\sqrt{\epsilon}\cos(\pi/N_d)}{1+\epsilon}\right)$$



Resonant HFGW Conversion

The University of Manchester

Dielectric Haloscopes

*Domcke, Ellis, Kopp 2024 PRD **111**, 035031*

Resonant Mode

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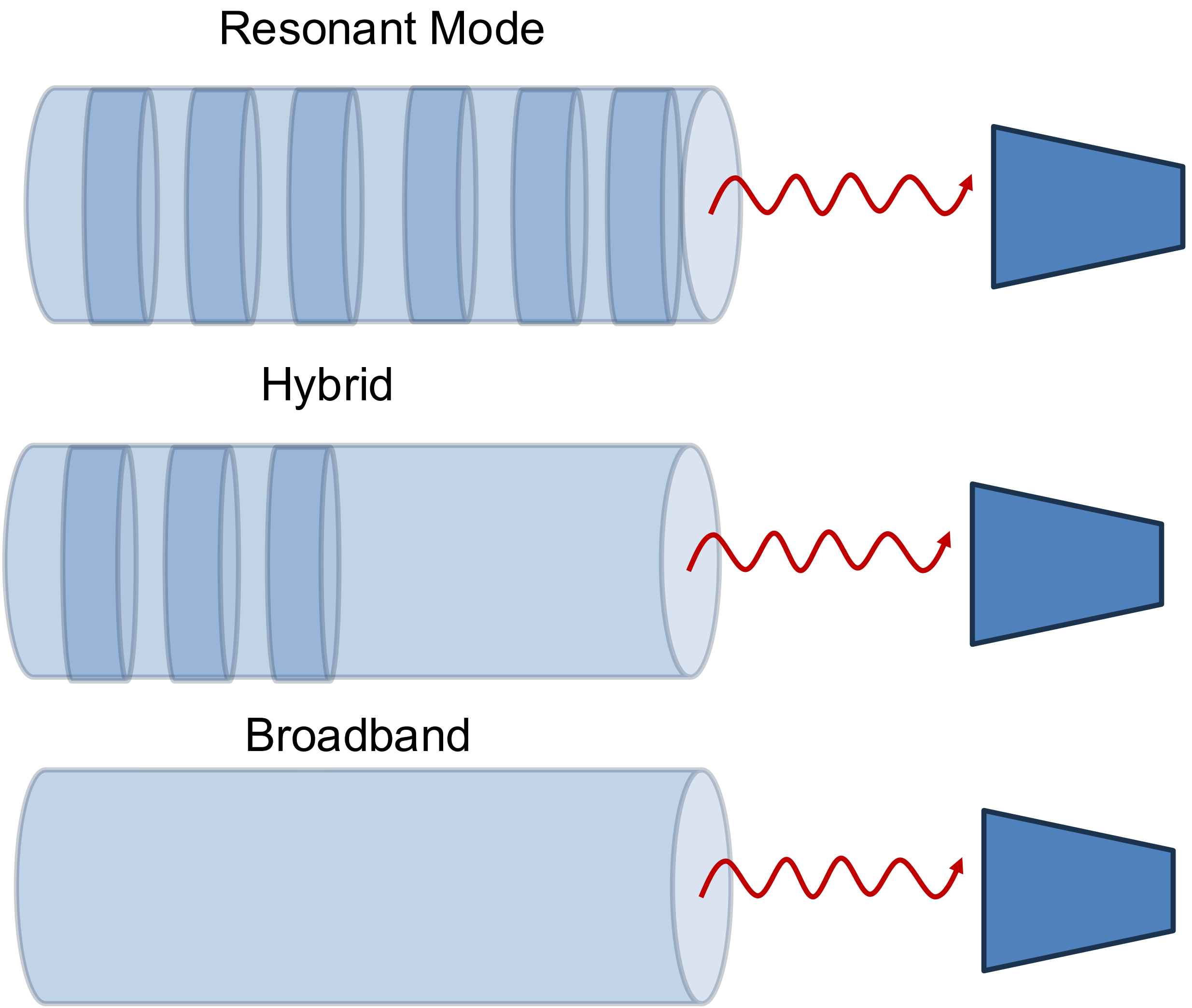
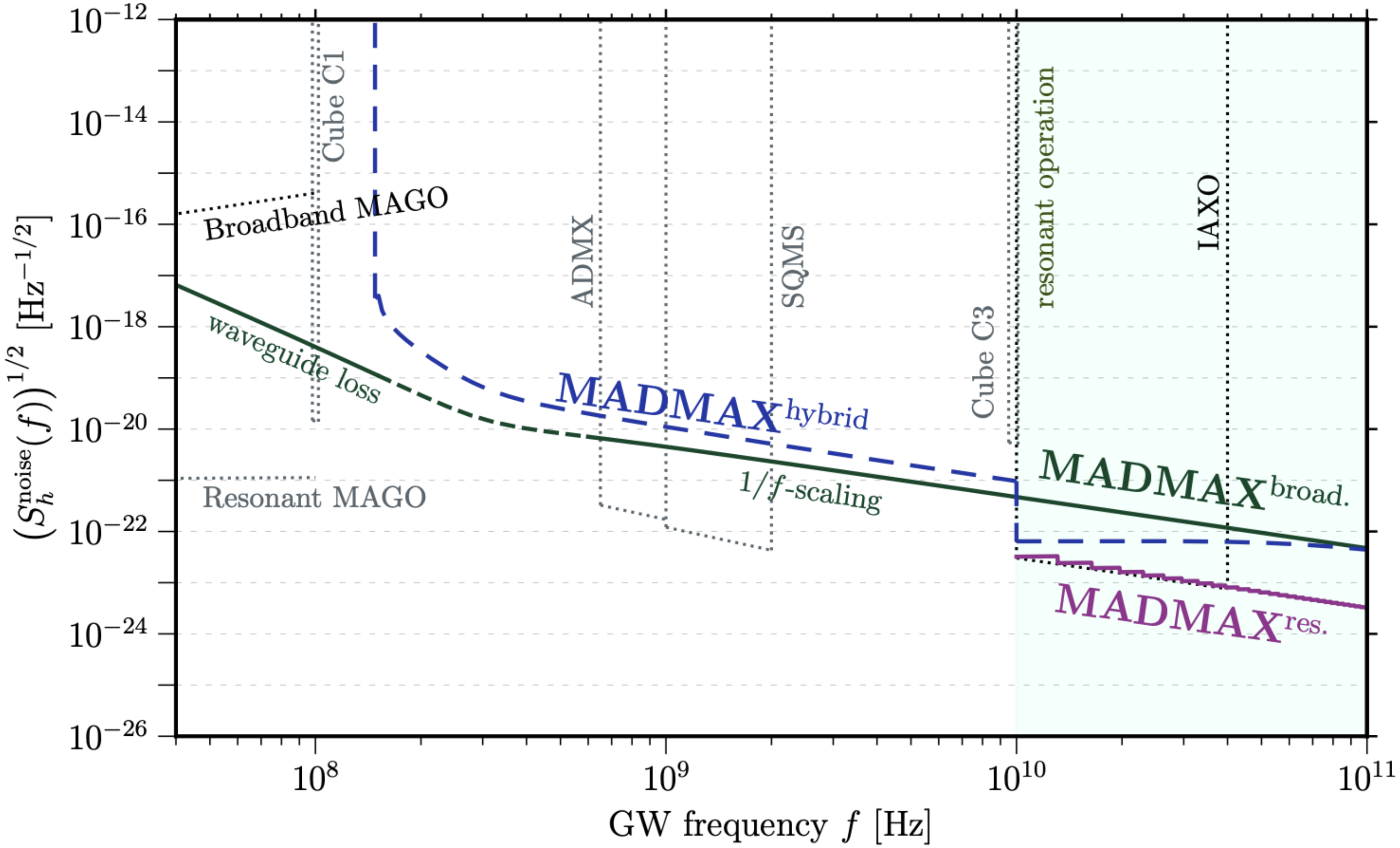


Dielectric Haloscopes



Common R&D

- Amplifiers/Single Photon Counting/Squeezing
- Magnets
- Fridges

Summary Plot of Sensitivities

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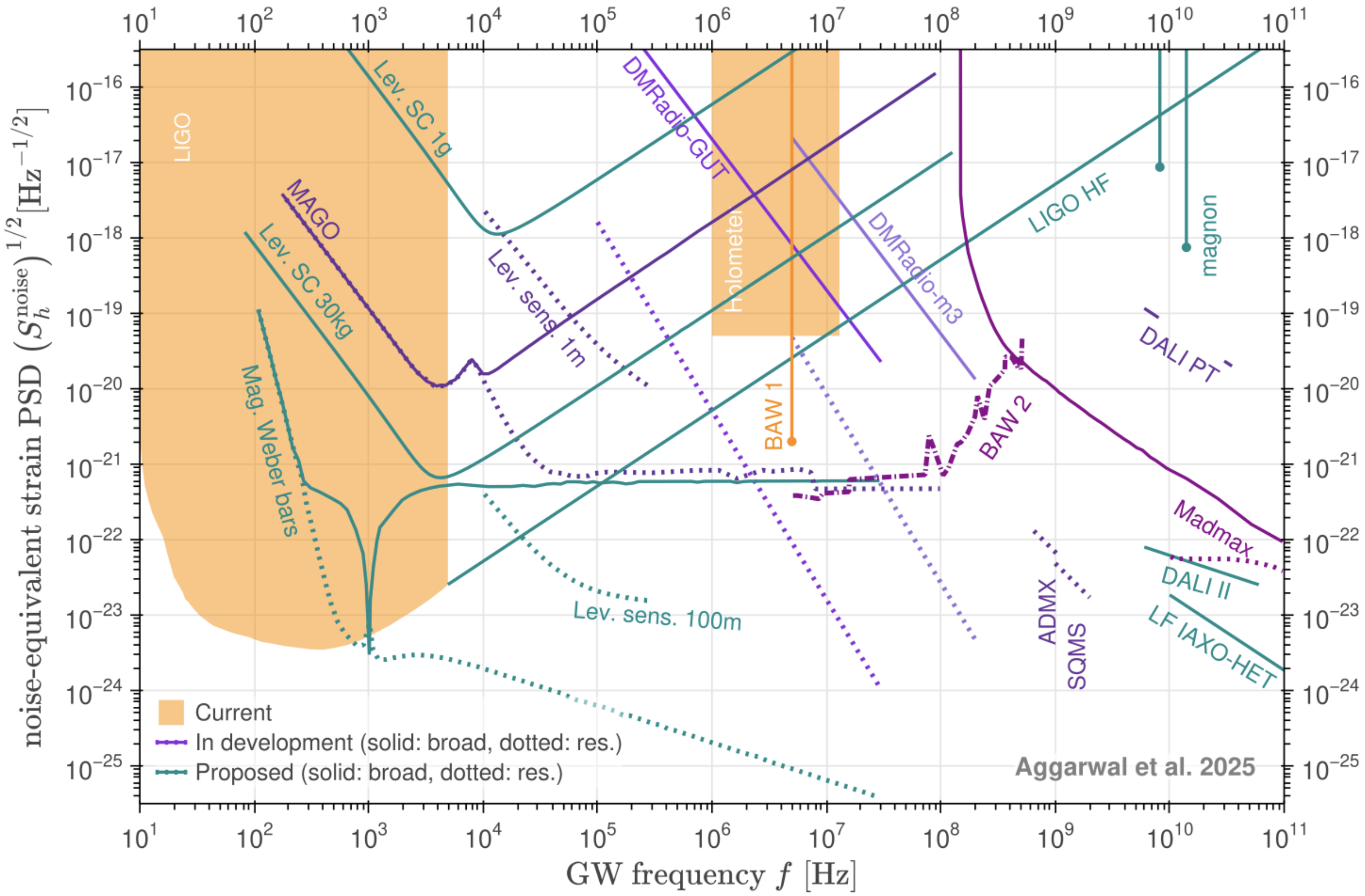


Interactive web applications for visualizing and analysing sensitivity curves for GW experiments

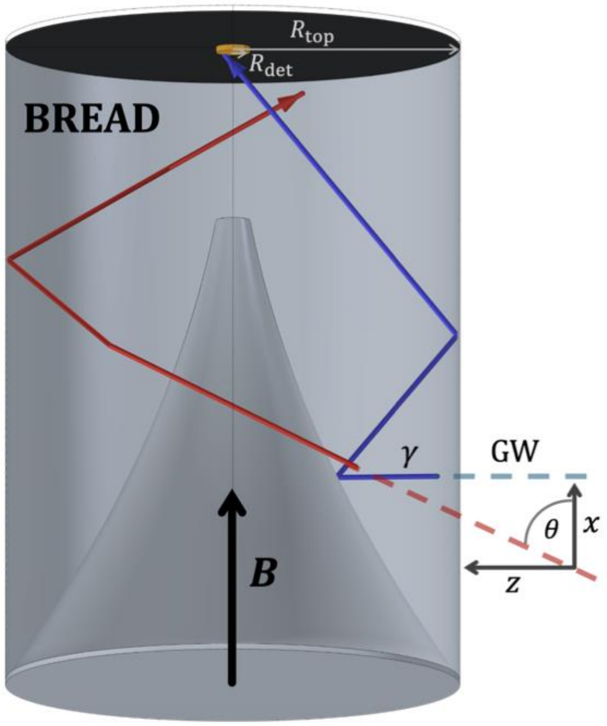
Francesco Muia, Andreas Ringwald, Carlos Tamarit,

"High frequency gravitational wave plotter: Noise-equivalent strain", https://doi.org/10.5281/zenodo.15720342

"High frequency gravitational wave plotter: Stochastic signals", https://doi.org/10.5281/zenodo.15720443

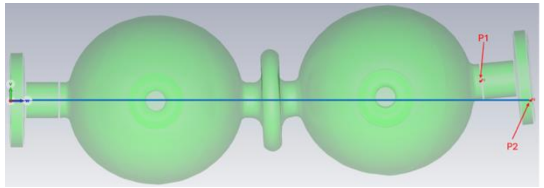
Honorable Mentions

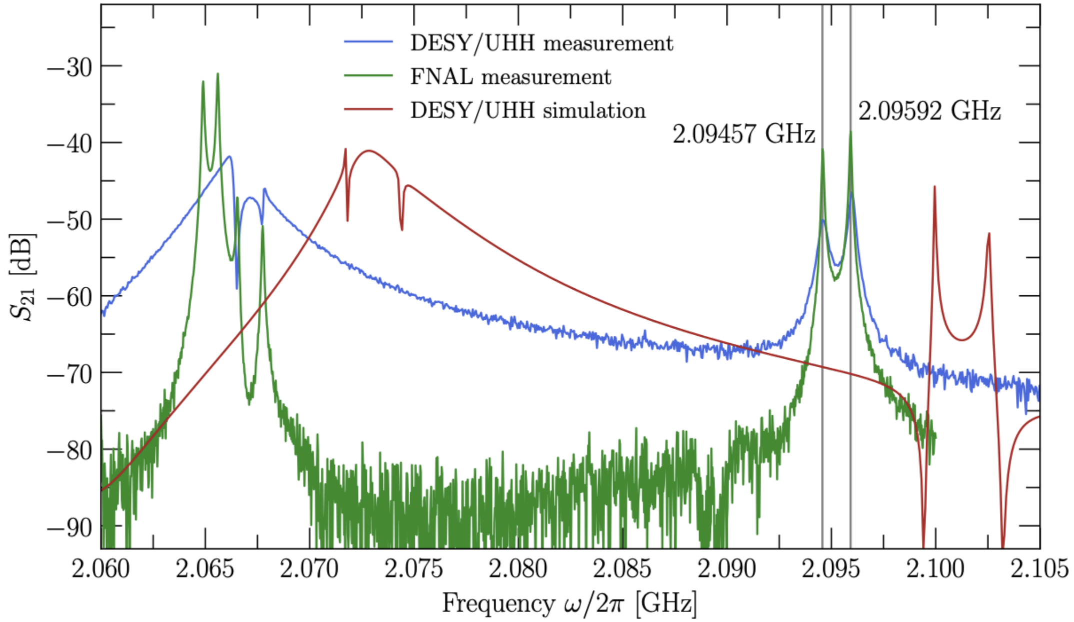
BREAD



Capdevilla, Harnik, Kim, Krokotsch (May 2025)

MAGO 2.0





Lars Fischera et al 2024

First Experimental Results!

We are at the beginning

1960s

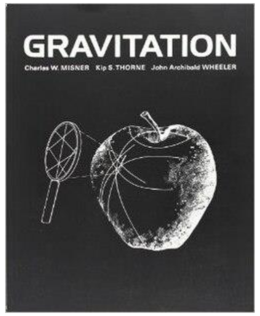
Weber Bars

50 Years of R&D

2010s

Modern GW Interferometry

“such detectors [laser interferometers] have so low sensitivity that they are of little experimental interest ”



Misner, Thorne, Wheeler 1974

The University of Manchester

Thank You!

MANCHESTER 1824
The University of Manchester

Backup Slides

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. $\mathcal{O}(1)\, \omega_\gamma L\, \mathrm{sinc}(\omega_{\mathrm{gw}} L)$

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

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

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

Noise transfer function

Noise-equivalent strain power spectral density:

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

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

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

Noise power spectrum in units of GW strain

Characterization of detector sensitivity

Signal-to-noise ratio:

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

Detector linear in h

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

Detector quadratic in h

O(1)

Time and frequency regime in which signal and detector overlap

Slide Courtesy:

Valerie Domcke - CERN

PBHs

However, such GW signals are highly transient near the ISCO, as the frequency of the emitted GW evolves in time according to $d\omega_g/dt \propto (M_b/r_b)^{11/6}$, which can limit the sensitivity of resonant experiments. In particular, GWs from the merger of light binaries can typically only resonantly excite a cavity for a short amount of time that decreases for heavier masses. This is quantified by the number of orbital cycles $\mathcal{N}_{\rm cyc}$ a binary spends emitting GWs within the resonator bandwidth ω_g/Q, given by $\mathcal{N}_{\rm cyc} \sim 10^{-3} \times (10^{-6}\ M_\odot/M_b)^{5/3}\,(10^5/Q)$ for $\omega_g \sim$ GHz. Requiring that a typical cavity is fully rung up by the GW signal, i.e., $\mathcal{N}_{\rm cyc} \gtrsim Q \sim 10^5$, requires that $M_b \lesssim 10^{-11}\ M_\odot$, which, amusingly, is a scenario where PBHs could constitute an $\mathcal{O}(1)$ fraction of the cosmological dark matter abundance [92–95]. The expected strain from inspirals at a distance D from Earth is

$$h_0 \sim 10^{-29} \times \left(\frac{1\ \text{pc}}{D}\right)\left(\frac{M_b}{10^{-11}\ M_\odot}\right)^{5/3}\left(\frac{\omega_g}{1\ \text{GHz}}\right)^{2/3}. \qquad (26)$$

The best case strain can be estimated under the assumption that the PBHs are 100% of the dark matter and all PBHs are paired in binaries. In this case we get $D = 10^{-3}$ pc and hence a best case sensitivity of $h_0 \sim 10^{-26}$.

Berlin et al *PRD* 105 (2022) 11, 116011

PBH Distance