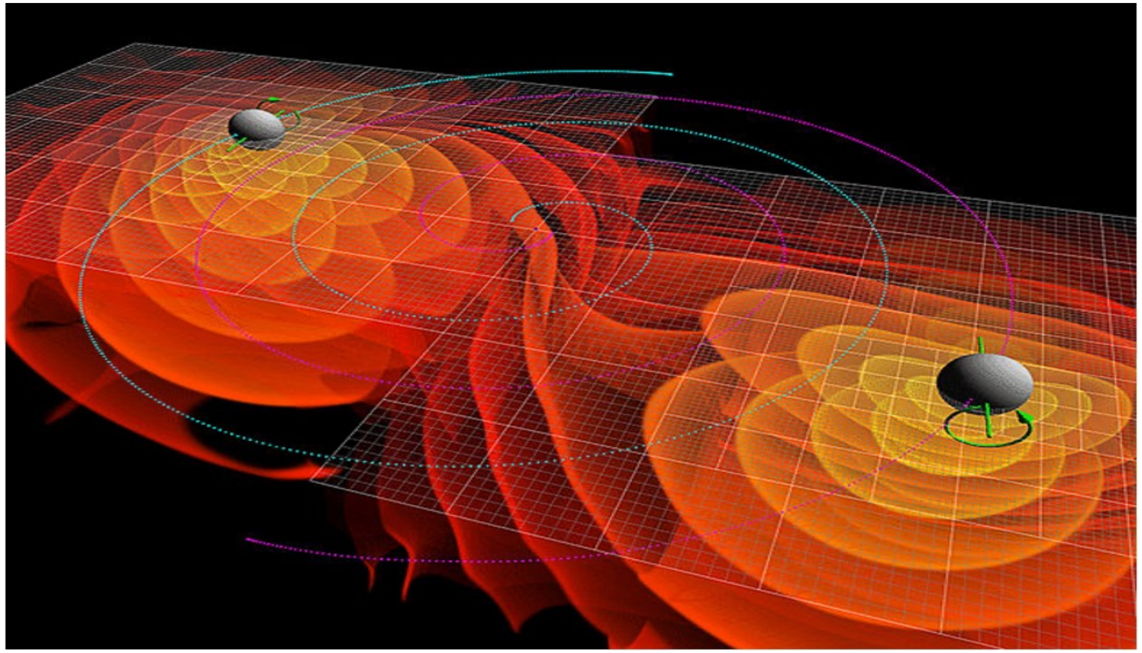
Opportunities for gravitational wave searches at high frequencies



Krisztian Peters

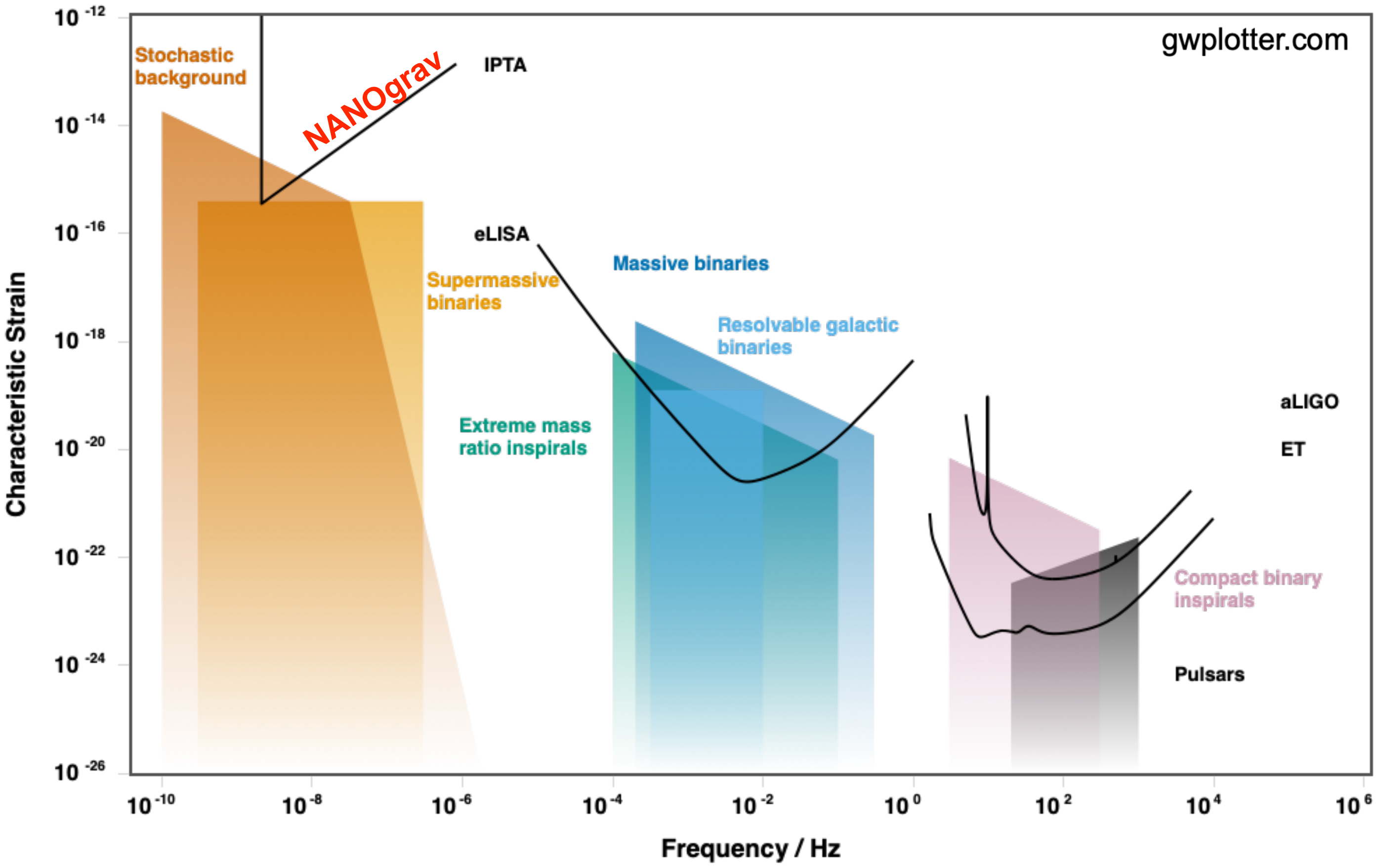
Rome, 15 February 2024
Workshop of the JENAS Initiative “Gravitational Wave Probes of Fundamental Physics”

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Gravitational wave experiments

Current landscape



Central focus on the Hz - kHz range

Universe expected to be populated by GWs over many decades in frequency (cf. to EM radiation)

Development of observational efforts at much lower frequencies (see previous talks in this session)

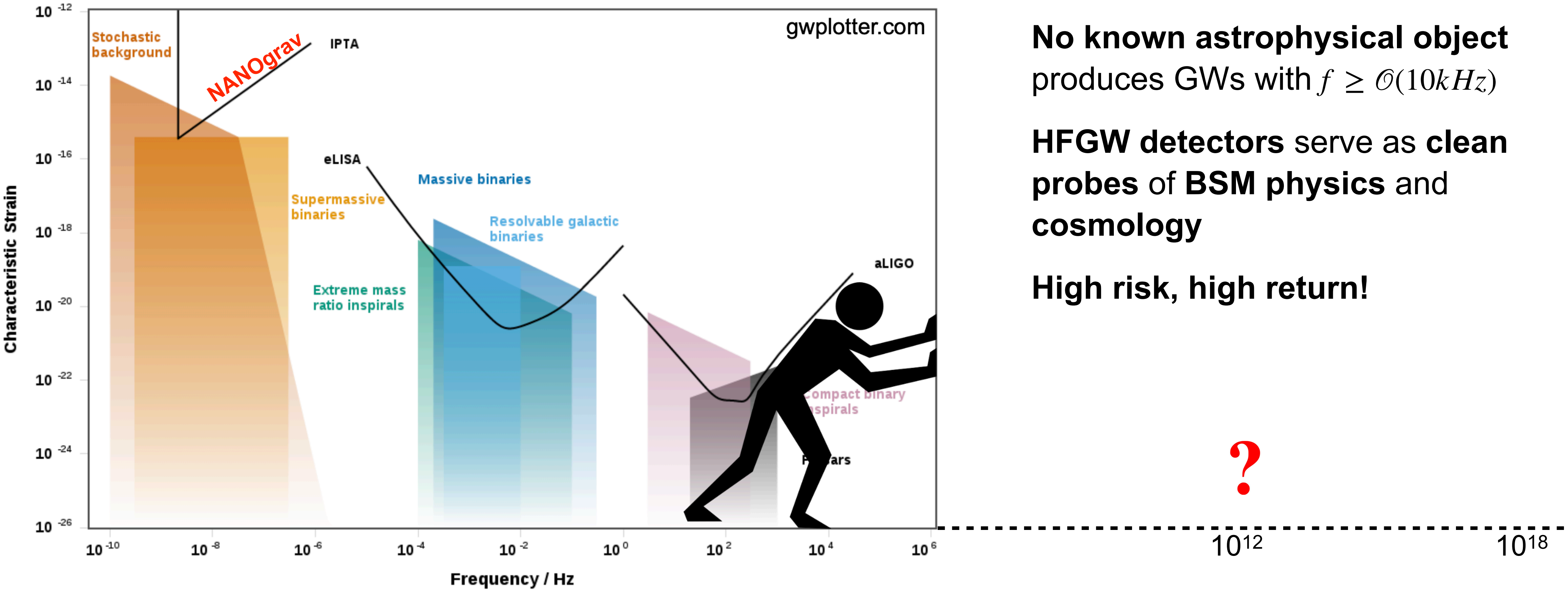
Extend detection reach beyond interferometers

Testing BSM physics with HFGWs

No known astrophysical object produces GWs with $f \geq \mathcal{O}(10kHz)$

HFGW detectors serve as **clean probes** of **BSM physics** and **cosmology**

High risk, high return!



Primordial black holes

PBHs expected to produce a variety of high-frequency GW signals

Stochastic GWs

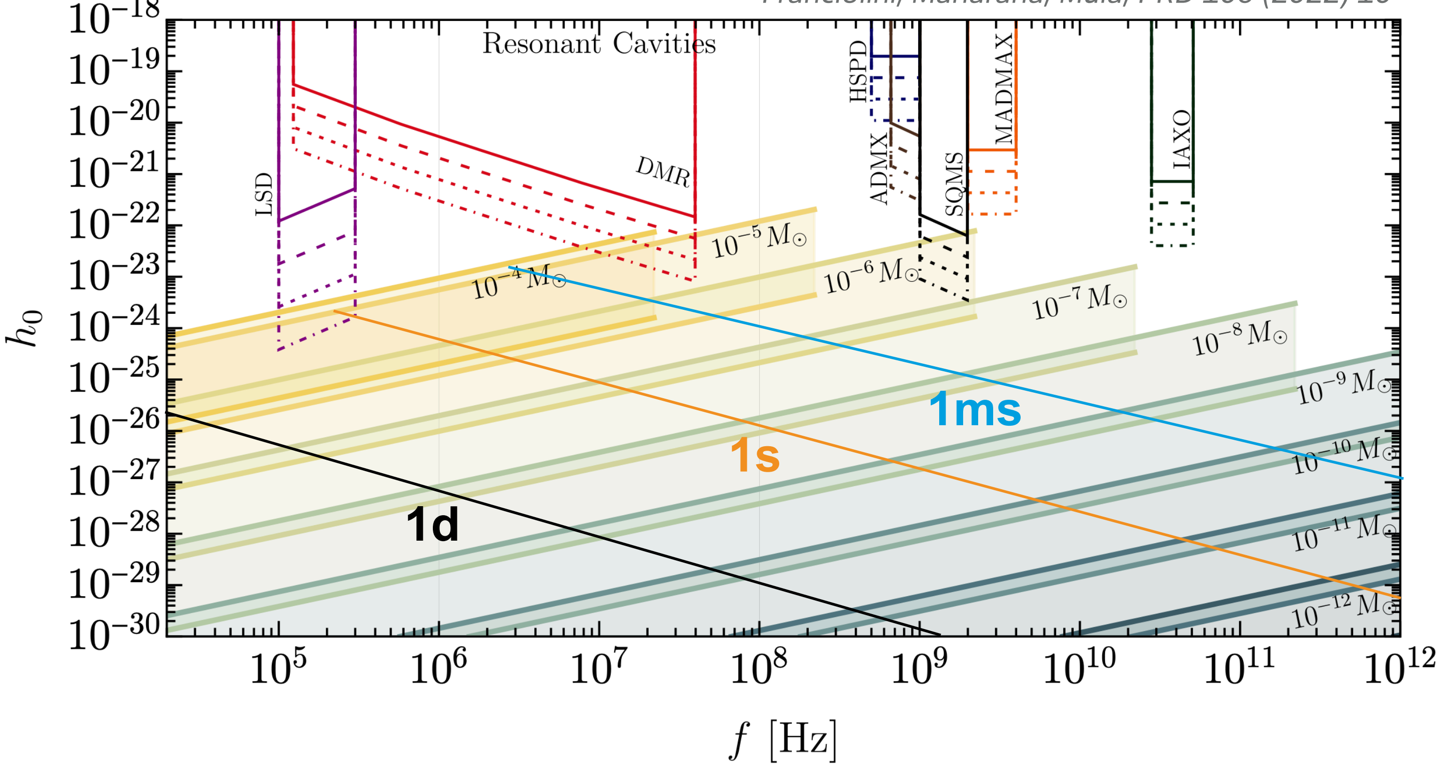
- PBH evaporation
- Unresolved PBH mergers

Coherent GWs

- PBH superradiance
- Resolved PBH mergers

Assume PBH distance, such that 1 event expected / year

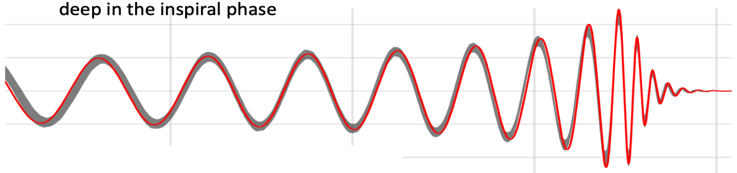
Franciolini, Maharana, Muia, PRD 106 (2022) 10



Frequency sweeping done by merger

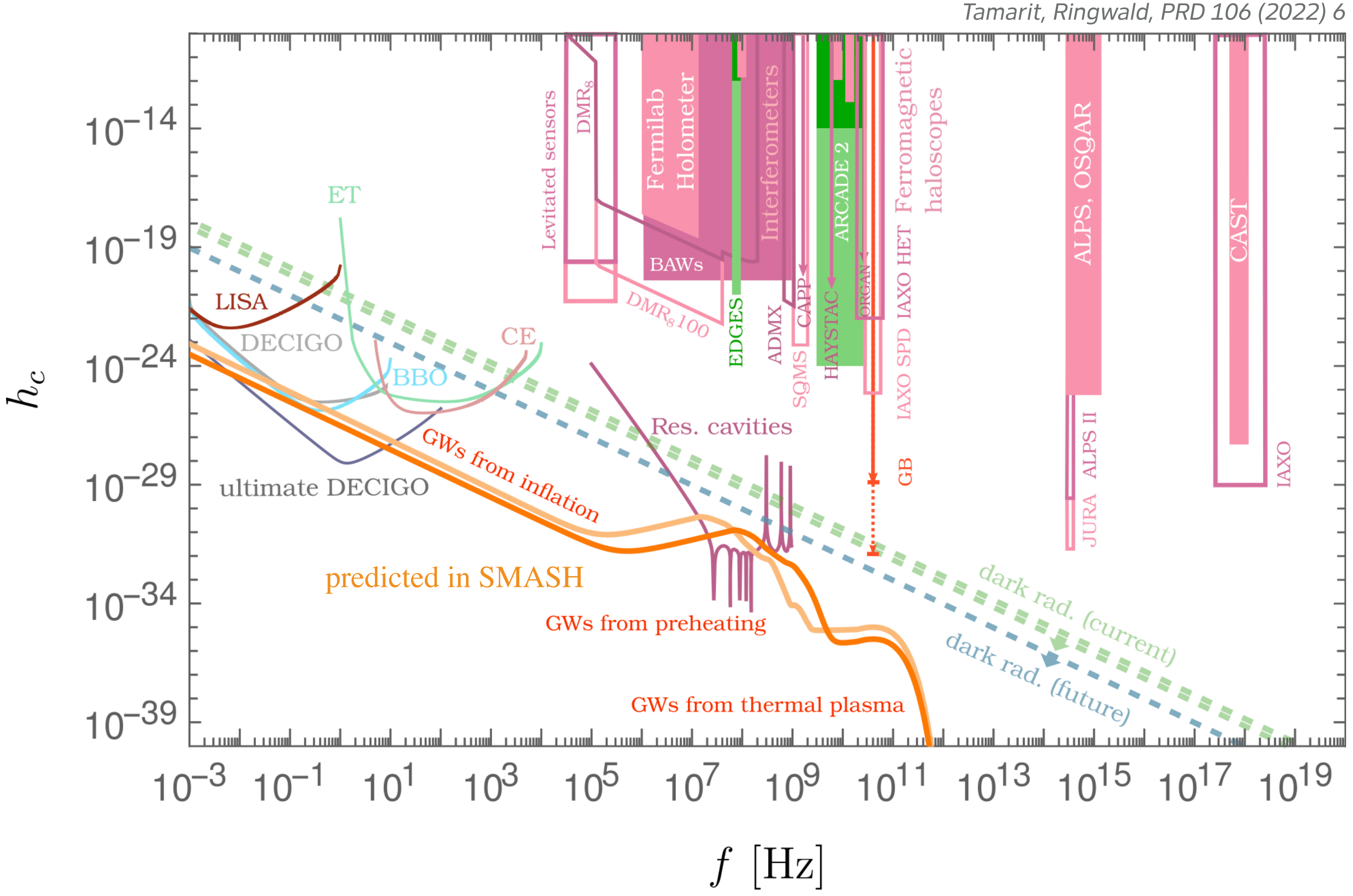
Highly transient signals close to merging (limits available integration time)

← Almost monochromatic only deep in the inspiral phase



Stochastic GW background

Cosmology of the early universe



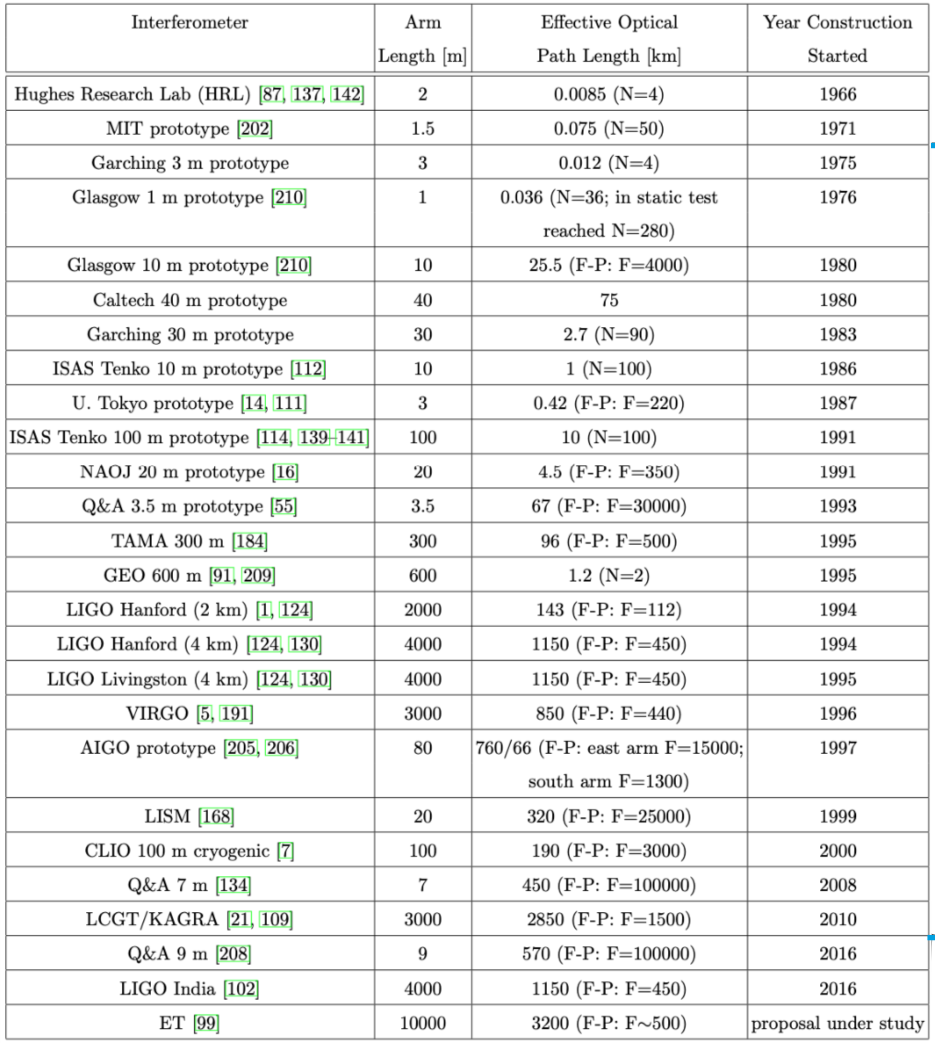
Example: Prediction from the BSM model SMASH

CGMB from thermal plasma guaranteed HFGW source, also in the SM

Important to measure entire spectrum!

Ambitious, but rewarding goal

Continue technology development



Interferometer	Arm Length [m]	Effective Optical Path Length [km]	Year Construction Started
Hughes Research Lab (HRL) [87, 137, 142]	2	0.0085 (N=4)	1966
MIT prototype [202]	1.5	0.075 (N=50)	1971
Garching 3 m prototype	3	0.012 (N=4)	1975
Glasgow 1 m prototype [210]	1	0.036 (N=36; in static test reached N=280)	1976
Glasgow 10 m prototype [210]	10	25.5 (F-P: F=4000)	1980
Caltech 40 m prototype	40	75	1980
Garching 30 m prototype	30	2.7 (N=90)	1983
ISAS Tenko 10 m prototype [112]	10	1 (N=100)	1986
U. Tokyo prototype [14, 111]	3	0.42 (F-P: F=220)	1987
ISAS Tenko 100 m prototype [114, 139–141]	100	10 (N=100)	1991
NAOJ 20 m prototype [16]	20	4.5 (F-P: F=350)	1991
Q&A 3.5 m prototype [55]	3.5	67 (F-P: F=30000)	1993
TAMA 300 m [184]	300	96 (F-P: F=500)	1995
GEO 600 m [91, 209]	600	1.2 (N=2)	1995
LIGO Hanford (2 km) [1, 124]	2000	143 (F-P: F=112)	1994
LIGO Hanford (4 km) [124, 130]	4000	1150 (F-P: F=450)	1994
LIGO Livingston (4 km) [124, 130]	4000	1150 (F-P: F=450)	1995
VIRGO [5, 191]	3000	850 (F-P: F=440)	1996
AIGO prototype [205, 206]	80	760/66 (F-P: east arm F=15000; south arm F=1300)	1997
LISM [168]	20	320 (F-P: F=25000)	1999
CLIO 100 m cryogenic [7]	100	190 (F-P: F=3000)	2000
Q&A 7 m [134]	7	450 (F-P: F=100000)	2008
LCGT/KAGRA [21, 109]	3000	2850 (F-P: F=1500)	2010
Q&A 9 m [208]	9	570 (F-P: F=100000)	2016
LIGO India [102]	4000	1150 (F-P: F=450)	2016
ET [99]	10000	3200 (F-P: F∼500)	proposal under study

From F. Muia

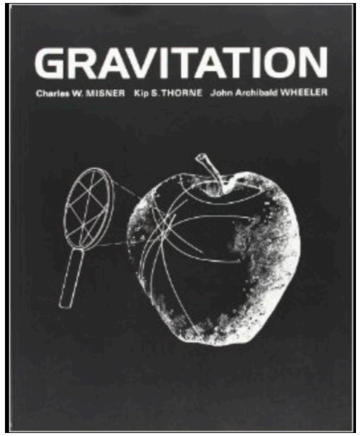
→ MTW book

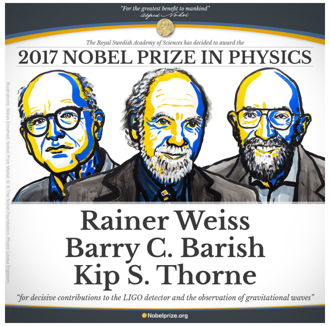
"[interferometers] have so low sensitivity that they are of little experimental interest"

page 1014

50 years
23 attempts

→ First direct detection





Two detection principles

Mechanical and EM coupling

Mechanical coupling

- GWs perturb detector, spreading power in frequency space

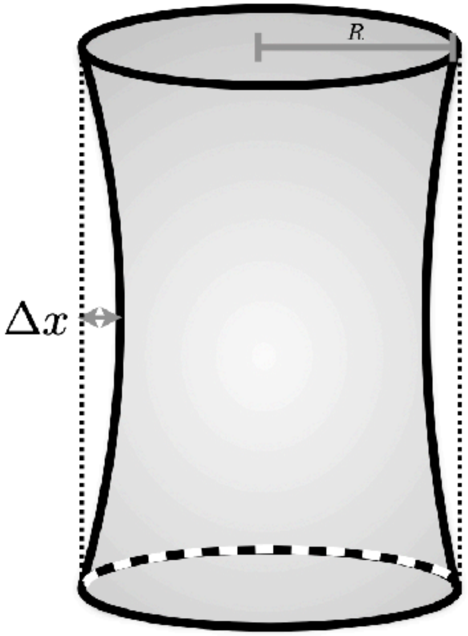
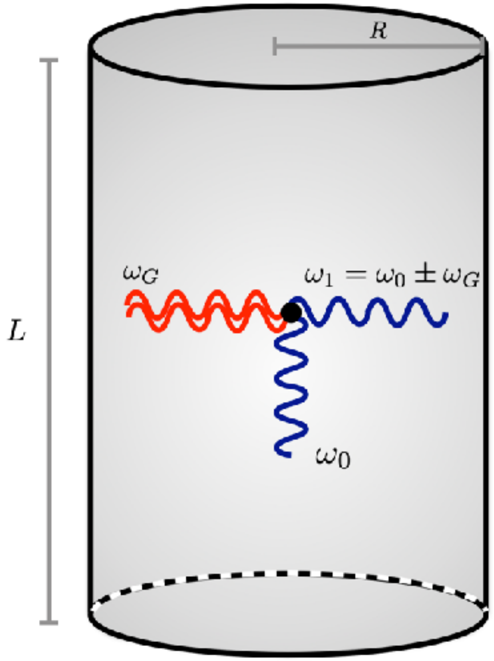


Image
S. Ellis

EM coupling

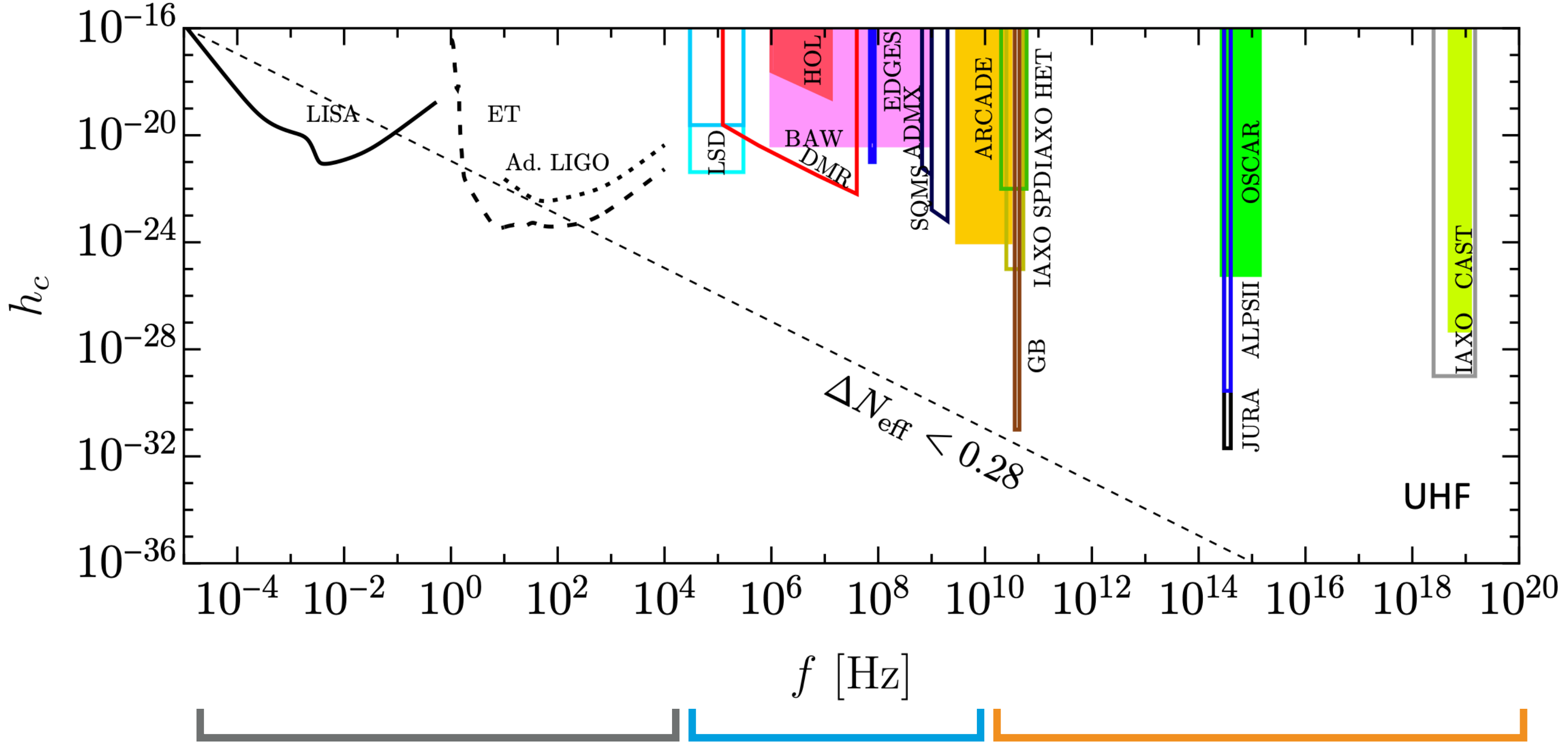
- Graviton - photon mixing (Gertsenshtein effect)
GWs induce in a magnetic field an effective current



Gertsenshtein, Sov Phys JETP, 1962, 14: 84, 85

Detector concepts

Spanning a wide range of frequencies



Interferometers **Resonators** **Photon regeneration**

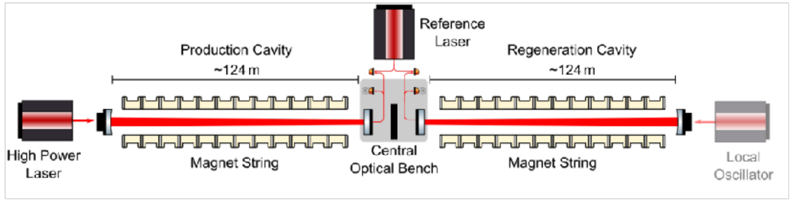
Energy density in GW:

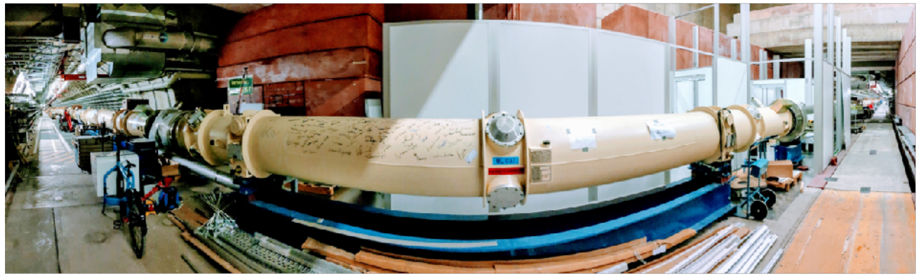
$$\rho = \frac{1}{4} h^2 \omega^2 M_{\rm Pl}^2$$

Discuss a representative set of experiments (with some personal bias) in the following

Complementary sensitivity across a broad frequency range

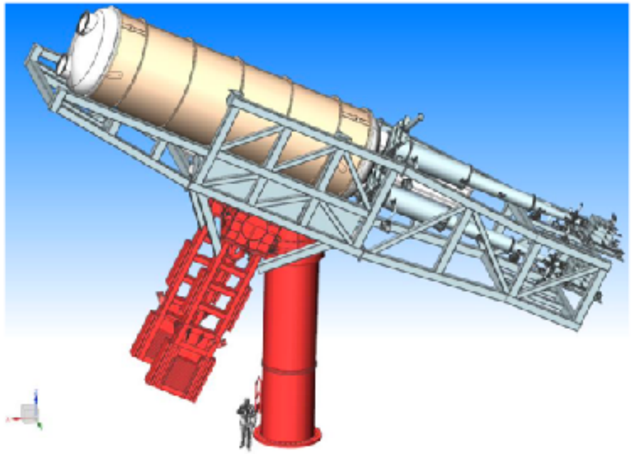
Axion search infrastructure



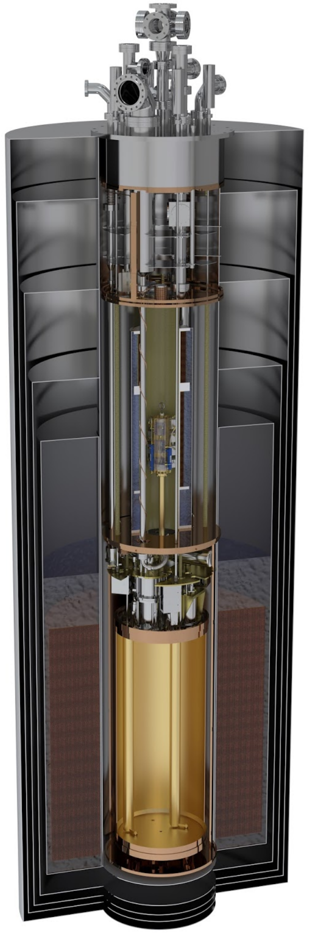


ALPS

IAXO



ADMX

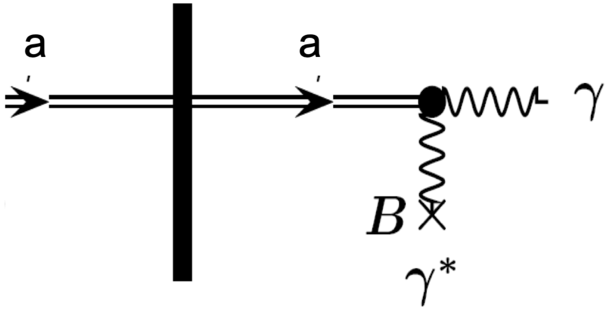


How to look: three kinds of experiments

Axion/ALP: different sources

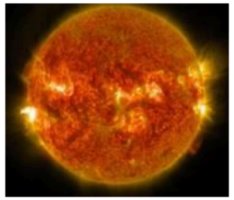
- Haloscopes
  looking for dark matter constituents,
  microwaves

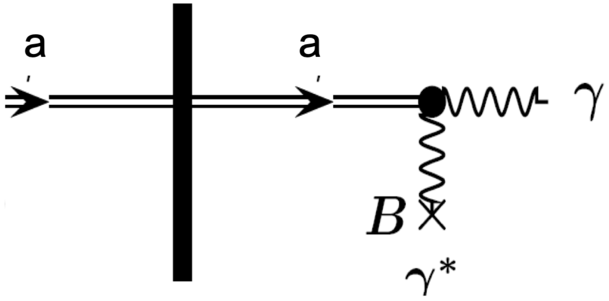
cosmological
assumptions



- Helioscopes
  Axions emitted by the sun,
  X-rays

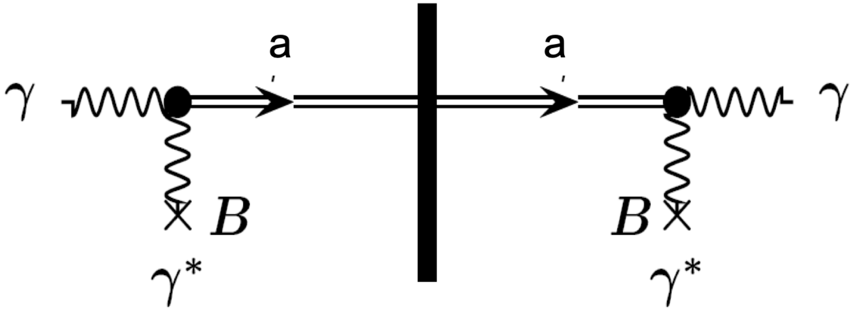
astrophysical
assumptions





- Purely laboratory experiments
  “light-shining-through-walls”,
  microwaves, optical photons

not depending on
cosmology or
astrophysics

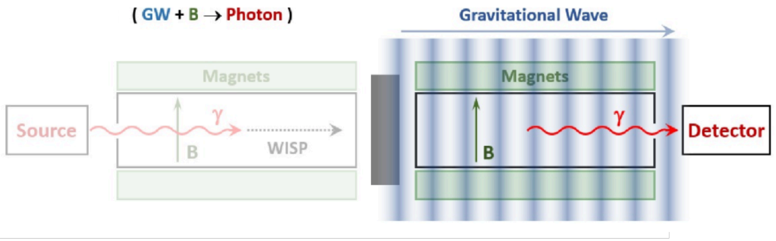


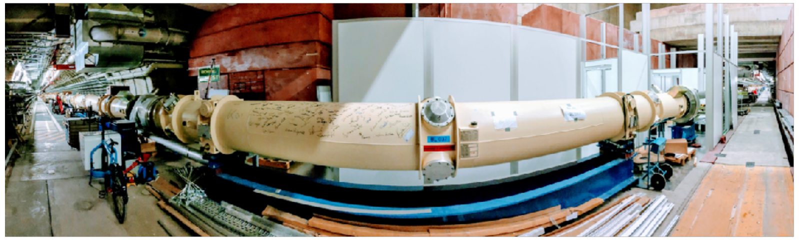
Graviton photon mixing

Main detection concepts

Photon regeneration

Detect GW to **photon conversion** in a **static magnetic field** (e.g. LSW experiments, helioscopes)

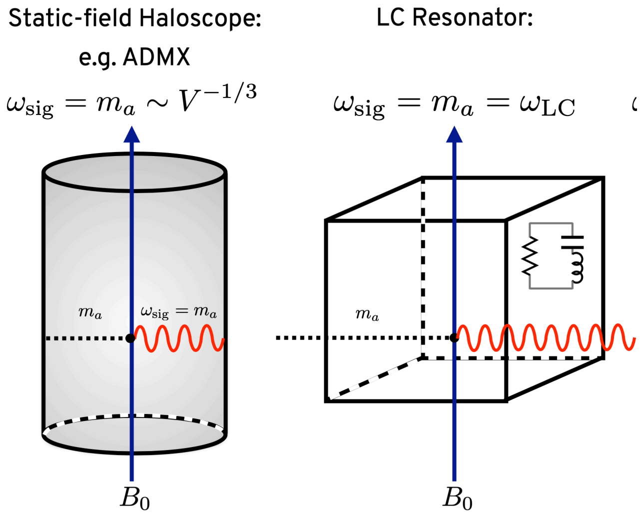




GW drives harmonic oscillator

GW produces **oscillating EM field** in a **microwave cavity** placed in **static magnetic field** (e.g. ADMX)

GW produces a **magnetic flux in a toroid** (resonant LC circuits, e.g. DM radio)



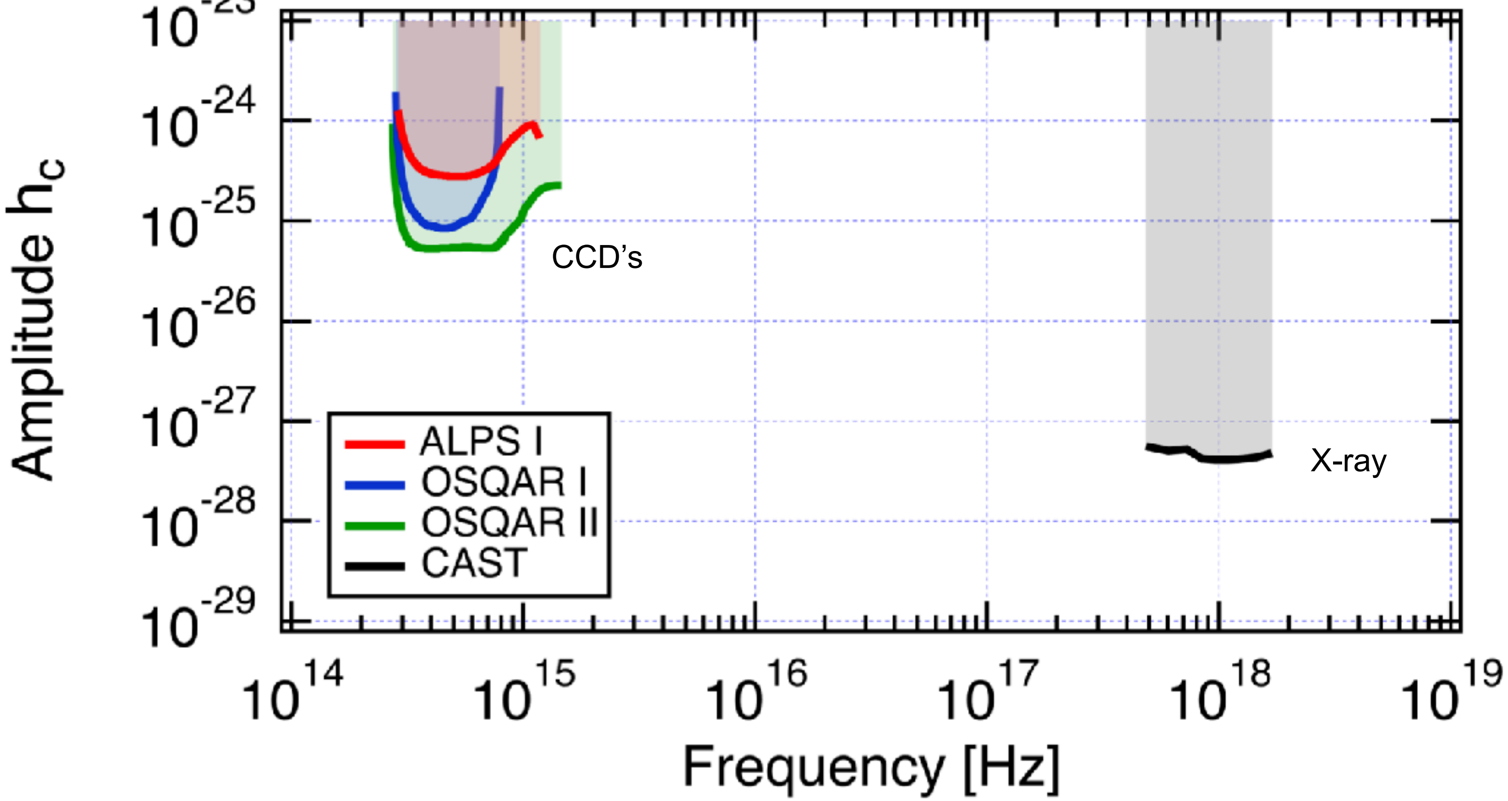
See talk from K. Schmieden

Current bounds

First experimental upper limits in these frequency regions

Bounds on the axion photon coupling obtained by ALPS, OSQAR, CAST can be translated into bounds on the characteristic amplitude of the stochastic GW background:

Ejlli et al. EPJC 79 (2019) 12



$$h_c^{\min}(0,\omega) \simeq \sqrt{\frac{4N_{\mathrm{exp}}}{AB^2L^2\varepsilon_\gamma(\omega)\,\Delta\omega}} \simeq 1.6\times 10^{-16}\times$$

$$\times\left(\frac{1\ \mathrm{T}}{B}\right)\left(\frac{1\ \mathrm{m}}{L}\right)\sqrt{\left(\frac{N_{\mathrm{exp}}}{1\ \mathrm{Hz}}\right)\left(\frac{1\ \mathrm{m}^2}{A}\right)\left(\frac{1\ \mathrm{Hz}}{\Delta f}\right)\left(\frac{1}{\varepsilon_\gamma}\right)}$$

ALPS

Light-shining-through wall experiment

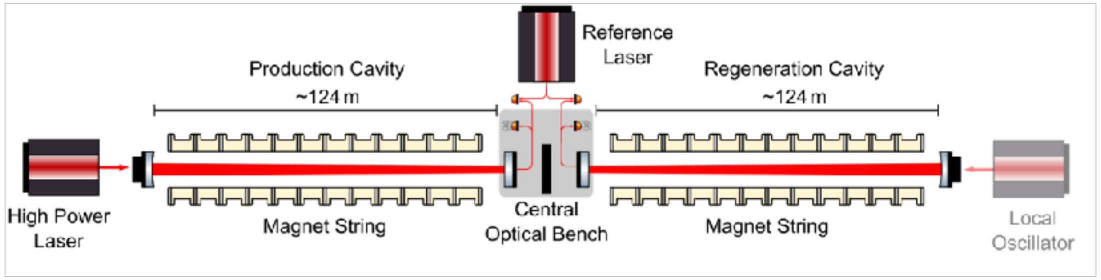
Any-Light-Particle-Search (ALPS) experiment @ DESY searches for the conversion of photons into light particles and vice versa in a strong transverse magnetic field

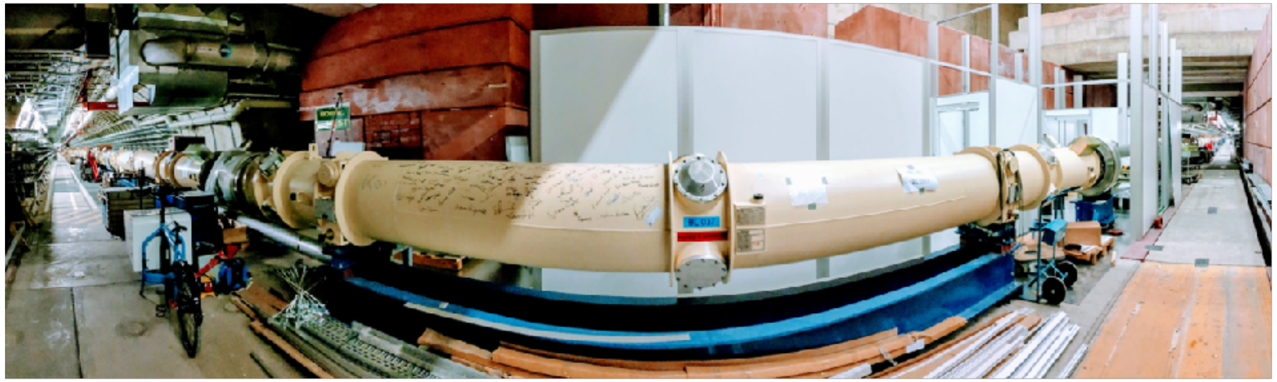
ALPS I (data taking 2009):

- 1 HERA dipole
- Optical cavity on generation side to enhance number of photons on generation side

ALPS II (data taking since 2023):

- 12 + 12 HERA dipoles
- Additional optical cavity on regeneration side to enhance reconversion

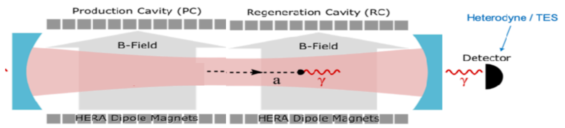




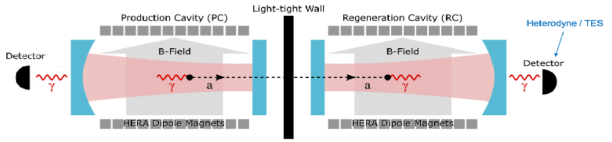
Options for ALPS II

Enhance sensitivity for GW detection

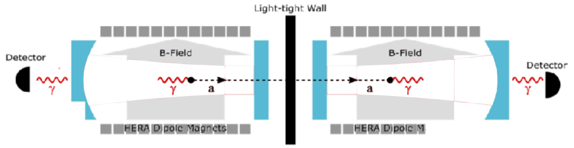
1.

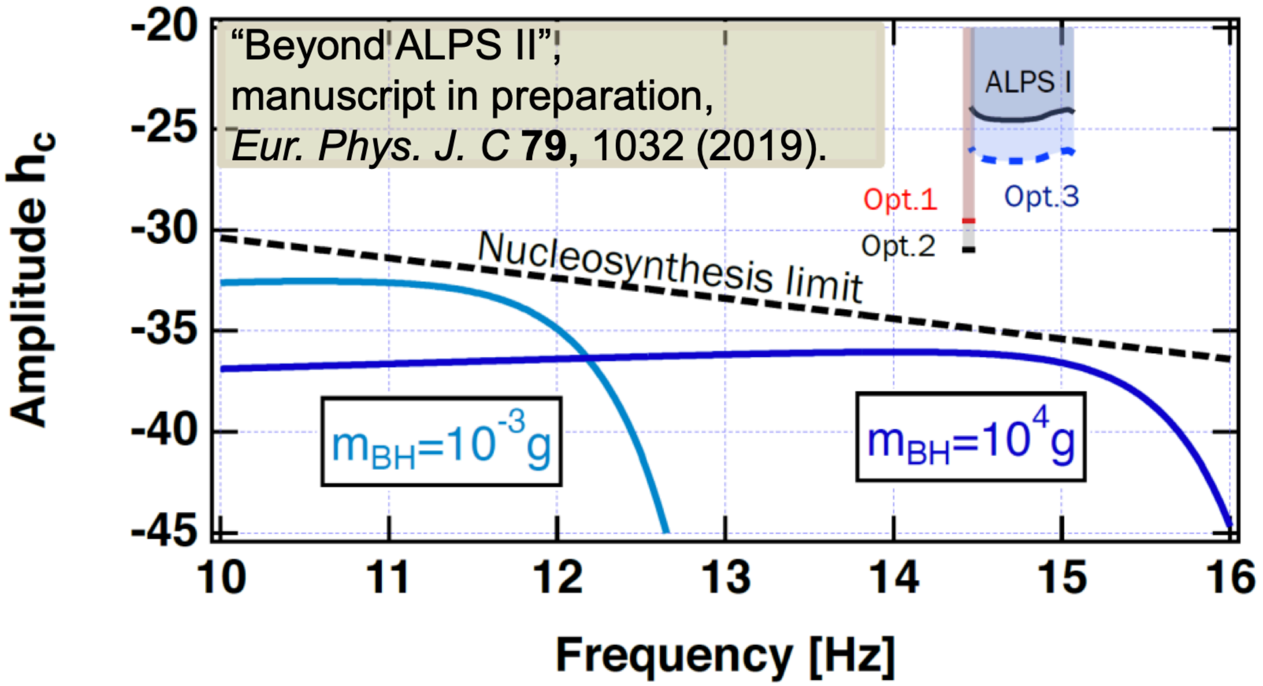


2.



3.




“Beyond ALPS II”, manuscript in preparation, *Eur. Phys. J. C* **79,** 1032 (2019).

Option 1: 212m long **single optical cavity** and single **TES detector**

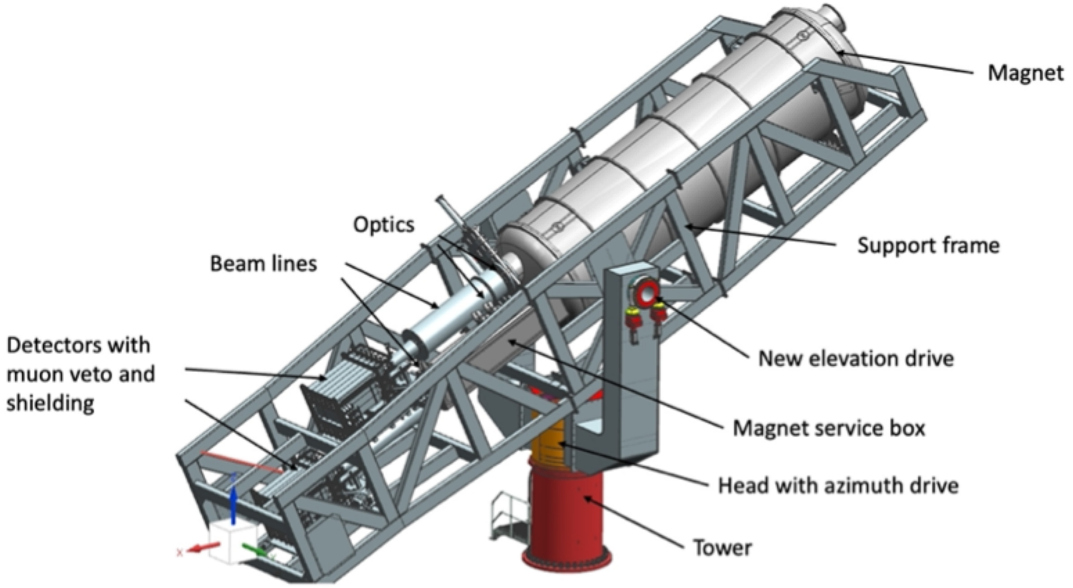
Option 2: Cross-correlating two 106m optical cavities with individual TES detectors to **lower statistical noise**

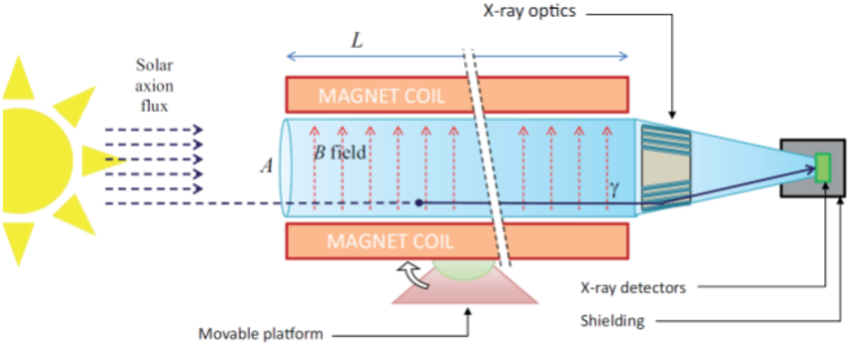
Option 3: No optical cavity, **broadband photon detection**

IAXO

Future helioscope

BabyIAXO: funded prototype





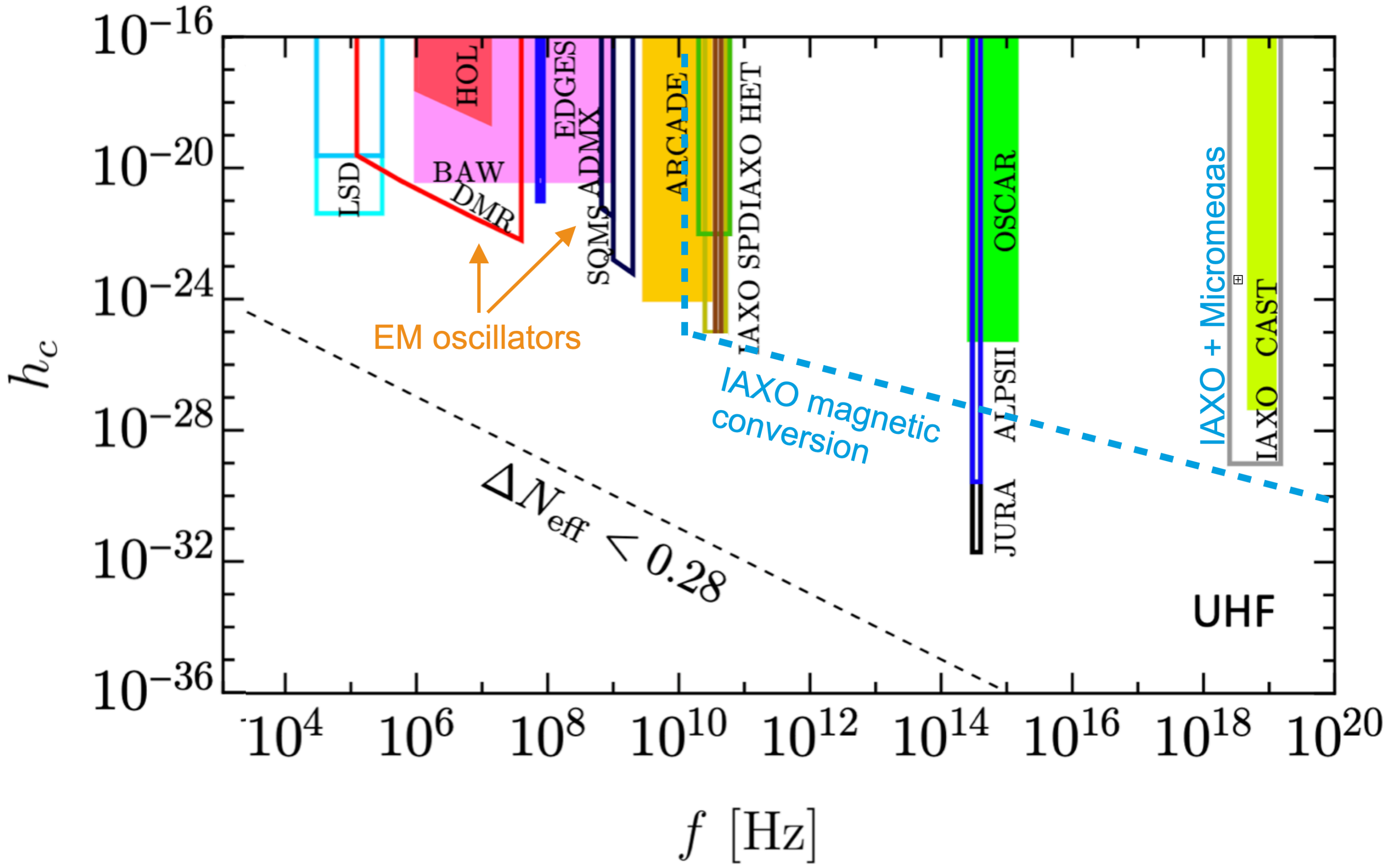
JHEP 05 (2021) 137

Conversion of solar axions to x-ray photons

Data taking expected in 2028 at DESY

Projected bounds

Based on the axion search infrastructure



Experiment	$BLA^{1/2}$ [Tm^2]	F_{low} [Hz]
ALPS I (for comparison)	2	$2 \cdot 10^{11}$
ALPS II	50	$5 \cdot 10^{12}$
BabyIAXO	22	$1 \cdot 10^9$
IAXO	88	$2 \cdot 10^9$
MADMAX	32	$2 \cdot 10^8$

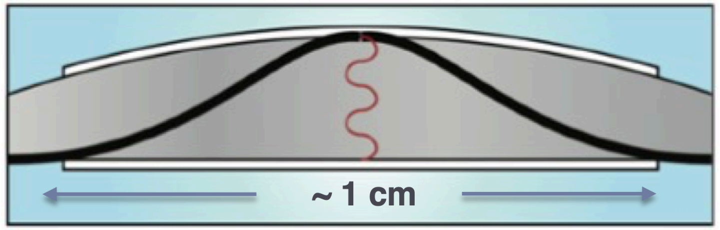
In photon regeneration experiments beam tube acts as EM waveguide, effective lower frequency cut-off

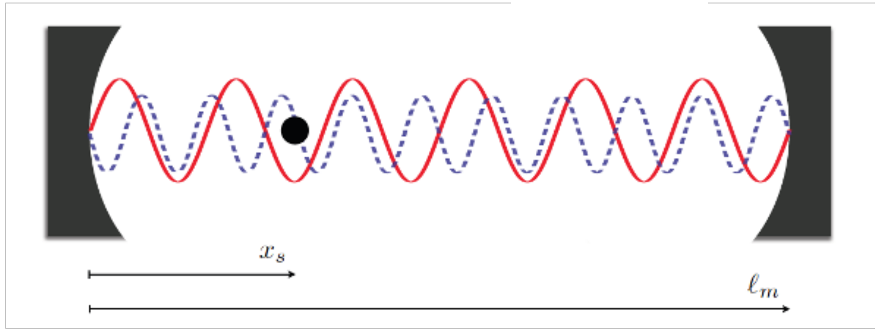
$$h_c^{\rm min}(0,\omega^*) \simeq 2.8\times10^{-16}\sqrt{\left(\frac{1}{\mathcal{F}}\right)\left(\frac{N_{\rm dark}}{1\ {\rm Hz}}\right)\left(\frac{1\ {\rm m}^2}{A}\right)\left(\frac{1\ {\rm T}}{B}\right)^2\left(\frac{1\ {\rm m}}{L}\right)^2\left(\frac{1\ {\rm Hz}}{\Delta f}\right)\left(\frac{1}{\epsilon_\gamma(\omega)}\right)}$$

Mechanical resonators

SRF cavities

Bulk acoustic wave devices





Levitated sensors

Levitated sensors

Basic idea

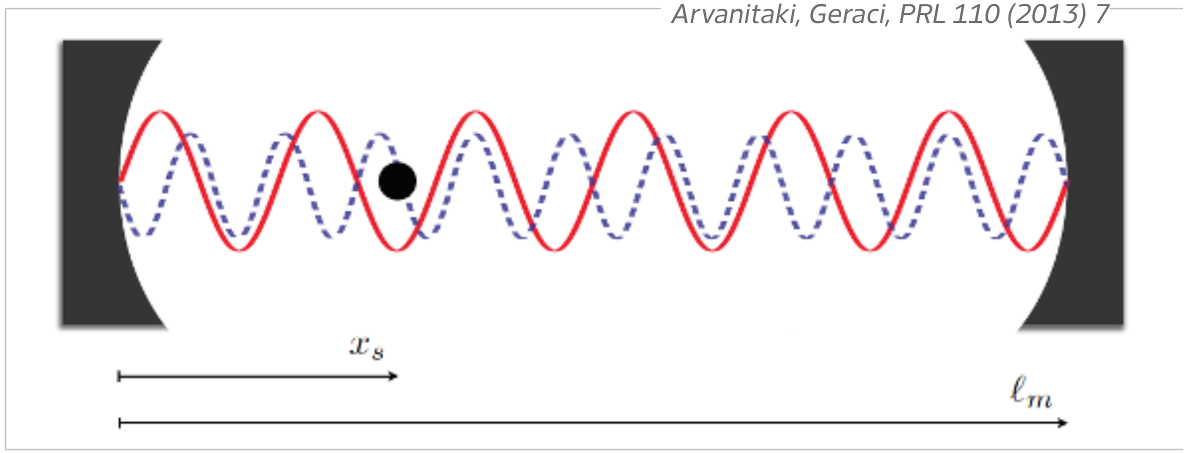
Trap a dielectric nanoparticle in a laser beam in an optical cavity

GW displaces particle from its equilibrium position and causes a harmonic restoring force

- Displacement is resonantly enhanced when ω_G coincides with trap frequency
- Similar to a resonant bar experiment, but sensor is levitated
- Relatively small sizes of the setups (10~100m)

Limited by thermal noise in the motion of the levitated particles and heating due to light scattering

Arvanitaki, Geraci, PRL 110 (2013) 7



Second light field to cool and read out axial position of the levitated object

- Displacement of the nanoparticle w.r.t. the trap minimum
  - $\Delta X = 1/2\, h(x_s - l_m) + \mathcal{O}(h^2)$

1-meter prototype

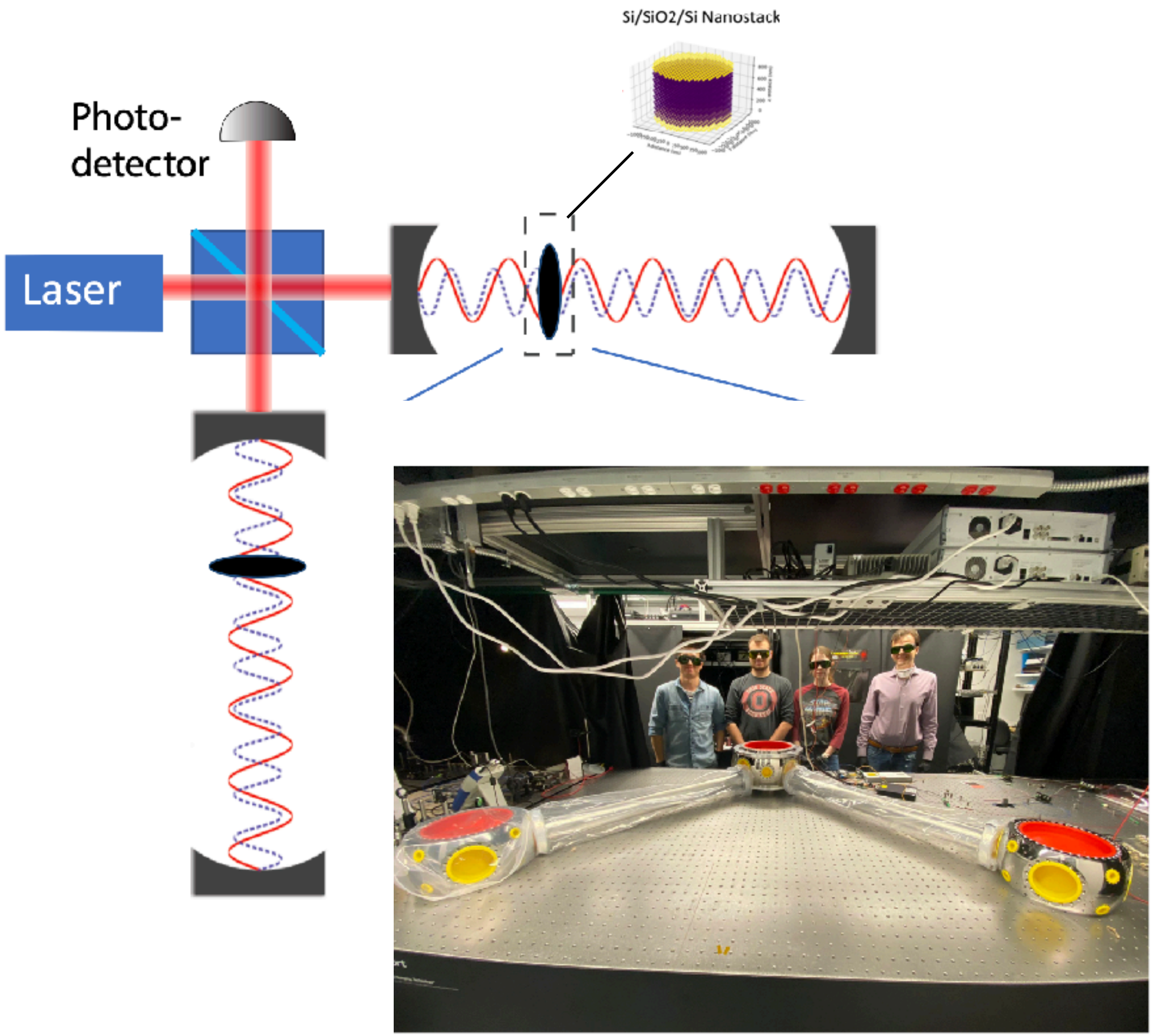
Levitated sensor detector

1-meter prototype under construction at Northwestern University

- Compact Michelson interferometer configuration (to reject common noise sources)
- Pilot run planed in ~1y
- Network of detectors with UC Davis and UCL

Stacked dielectric disc reduces photon recoil heating and increases mass of levitated object

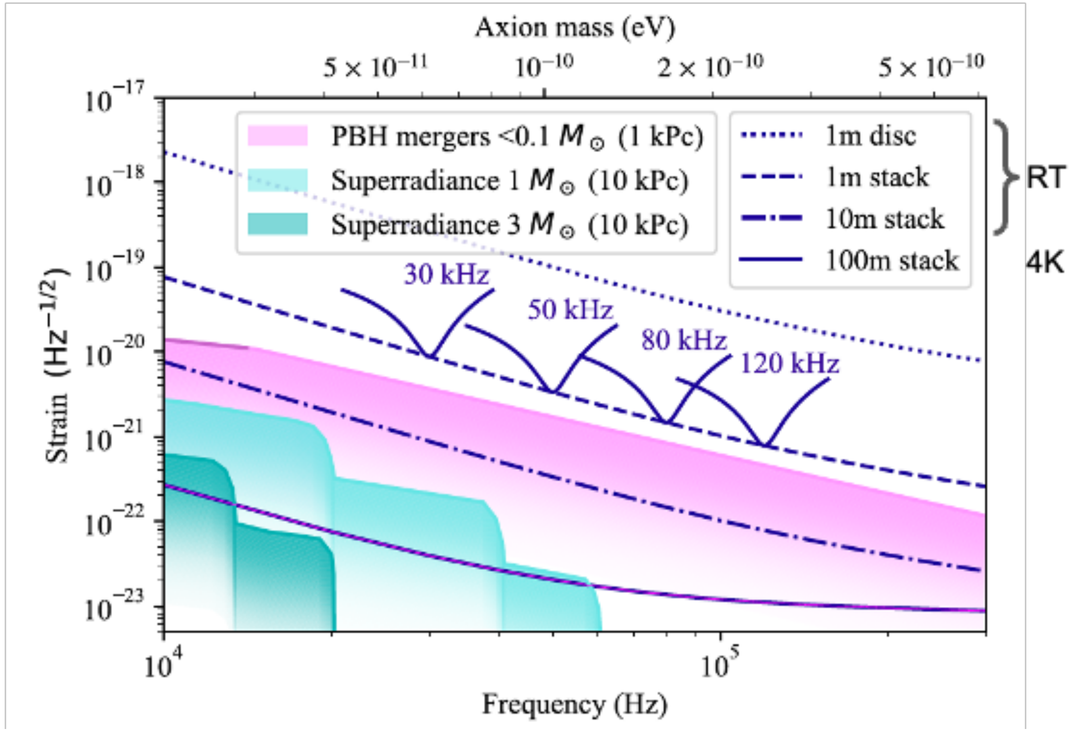
- Sphere → disc → stack
- Ongoing R&D at DESY to use partially-levitated membrane inside cavity (larger membrane size allows to reduce mirror radius)



Levitated sensors

Sensitivity projections

Aggarwal et al. PRL 128 (2022) 11



$$h_{\text{min}} \propto \frac{1}{l_m}\sqrt{\frac{T}{m}}$$

a) longer cavity.
b) lower temperature.
c) heavier particles.

Planned improvements

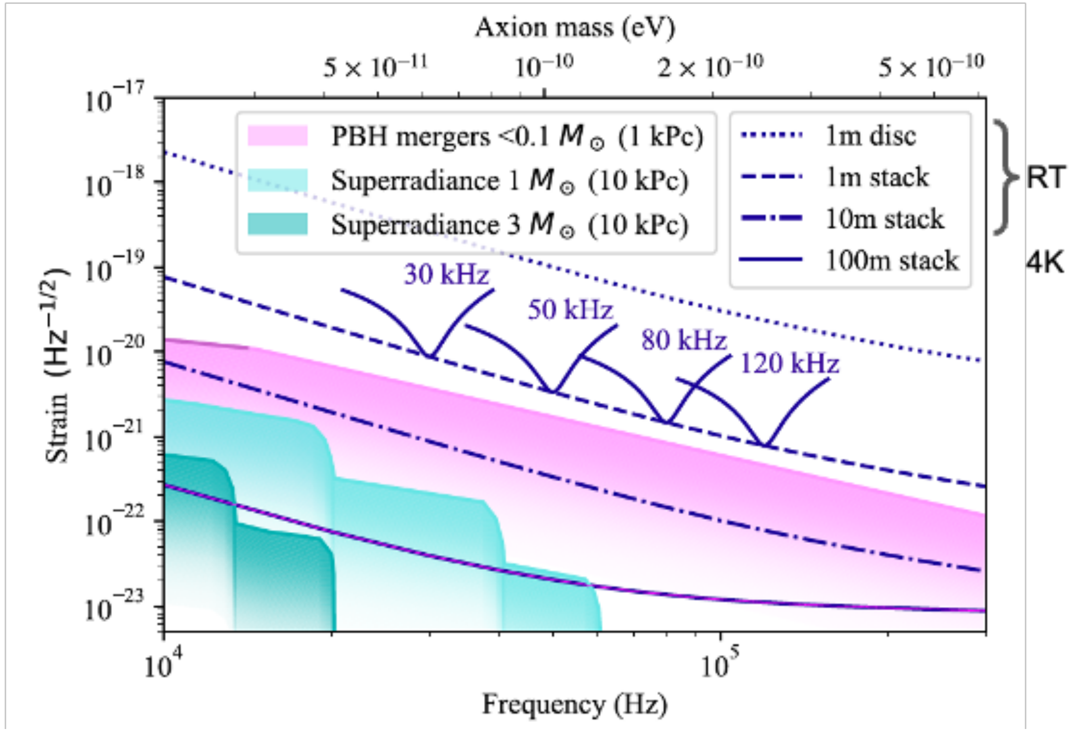
- 1-meter prototype under construction @ Northwestern University
- 10-meter instrument →1 order of magnitude
- 100-meter instrument → 2 orders of magnitude

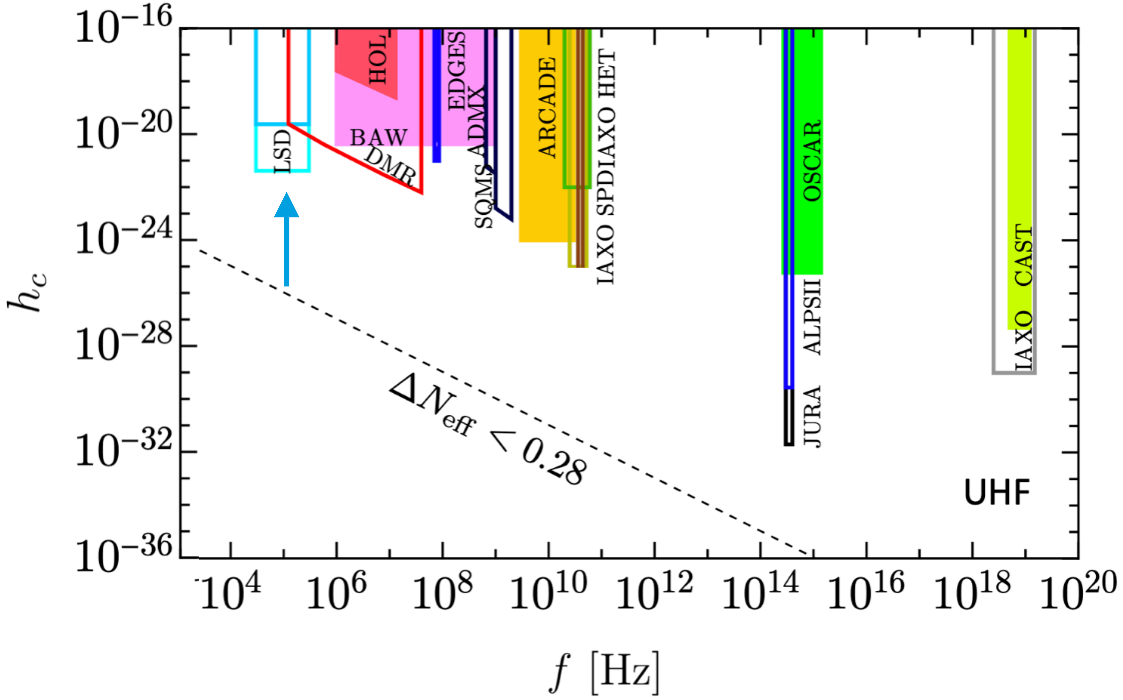
Resonance tunable from 10 to 300 kHz by varying the laser intensity

Levitated sensors

Sensitivity projections

Aggarwal et al. PRL 128 (2022) 11





Resonance tunable from 10 to 300 kHz by varying the laser intensity

Superconducting radio frequency cavities

Analogous to Weber bars, mechanical to EM transducer

GW perturbs cavity walls, which induces EM mode-mixing

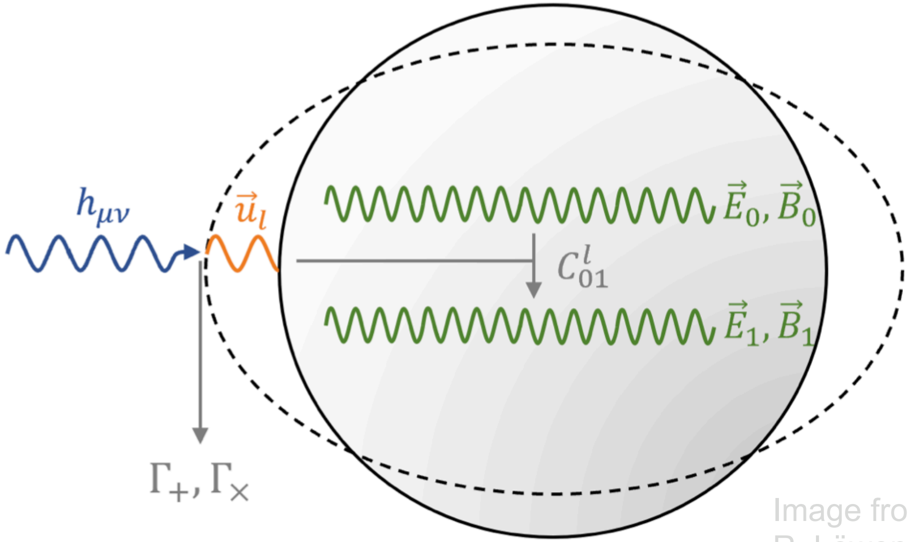
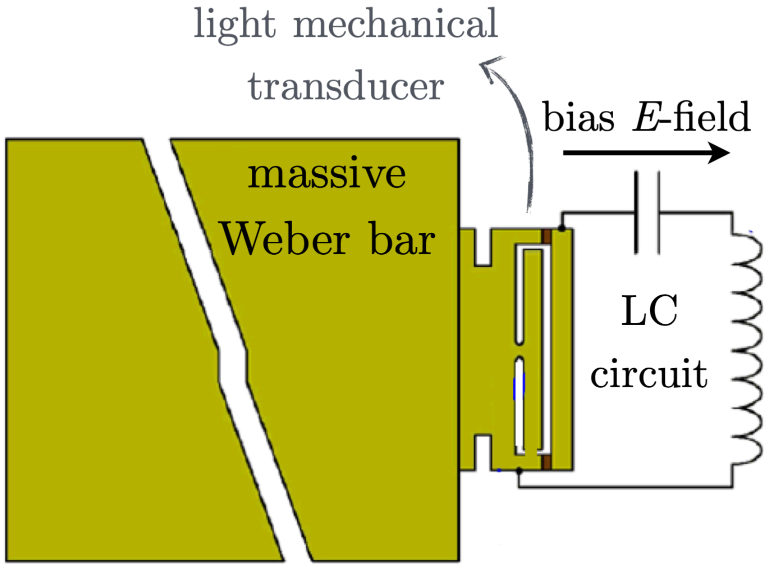


Image from R. Löwenberg thesis



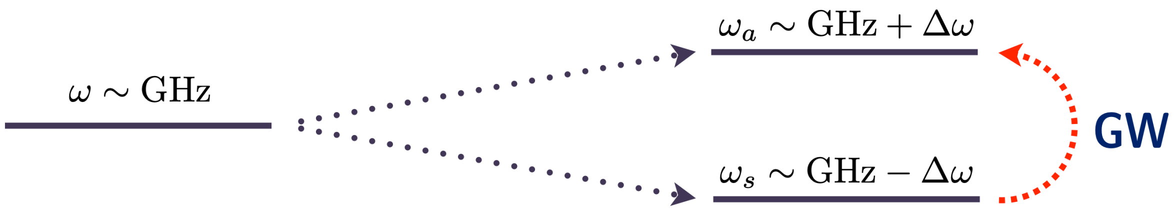
$$Q_{LC} \sim 10^6 \ll Q_{cav} \sim 10^{11}$$

Efficient converters of mechanical to EM energy

Operate with small readout noise

Heterodyne detection

GWs induce energy transfer between two levels of an EM resonator



$$\Delta\omega \sim (a/R)^3 \sim kHz - MHz$$

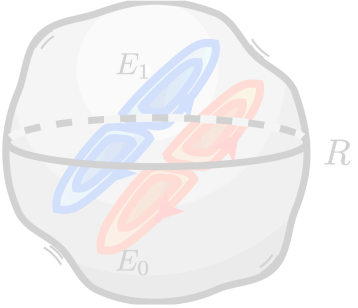
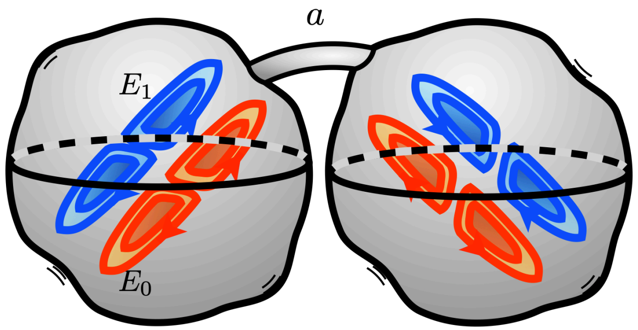


Image S. Ellis



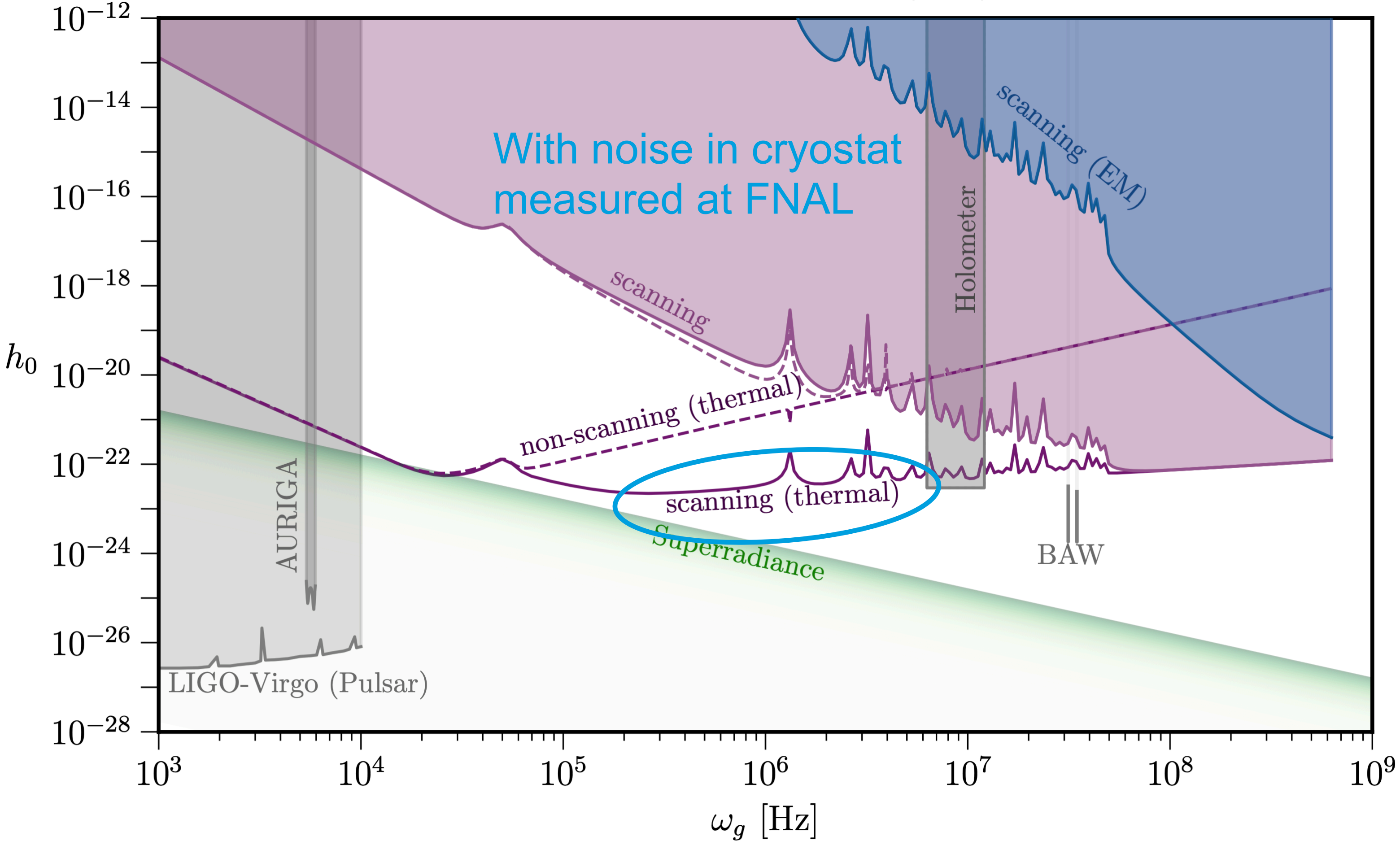
Two EM levels achieved by coupling identical cavities

- Each resonant mode of the individual cavities is split in two modes of the coupled resonator with different spacial field distribution (ω_0 and ω_π, symmetric and anti-symmetric modes)

Promising experimental reach

Unique broadband sensitivity

PRD 108, 084058 (2023) & private comm. with S. Ellis



With noise in cryostat measured at FNAL

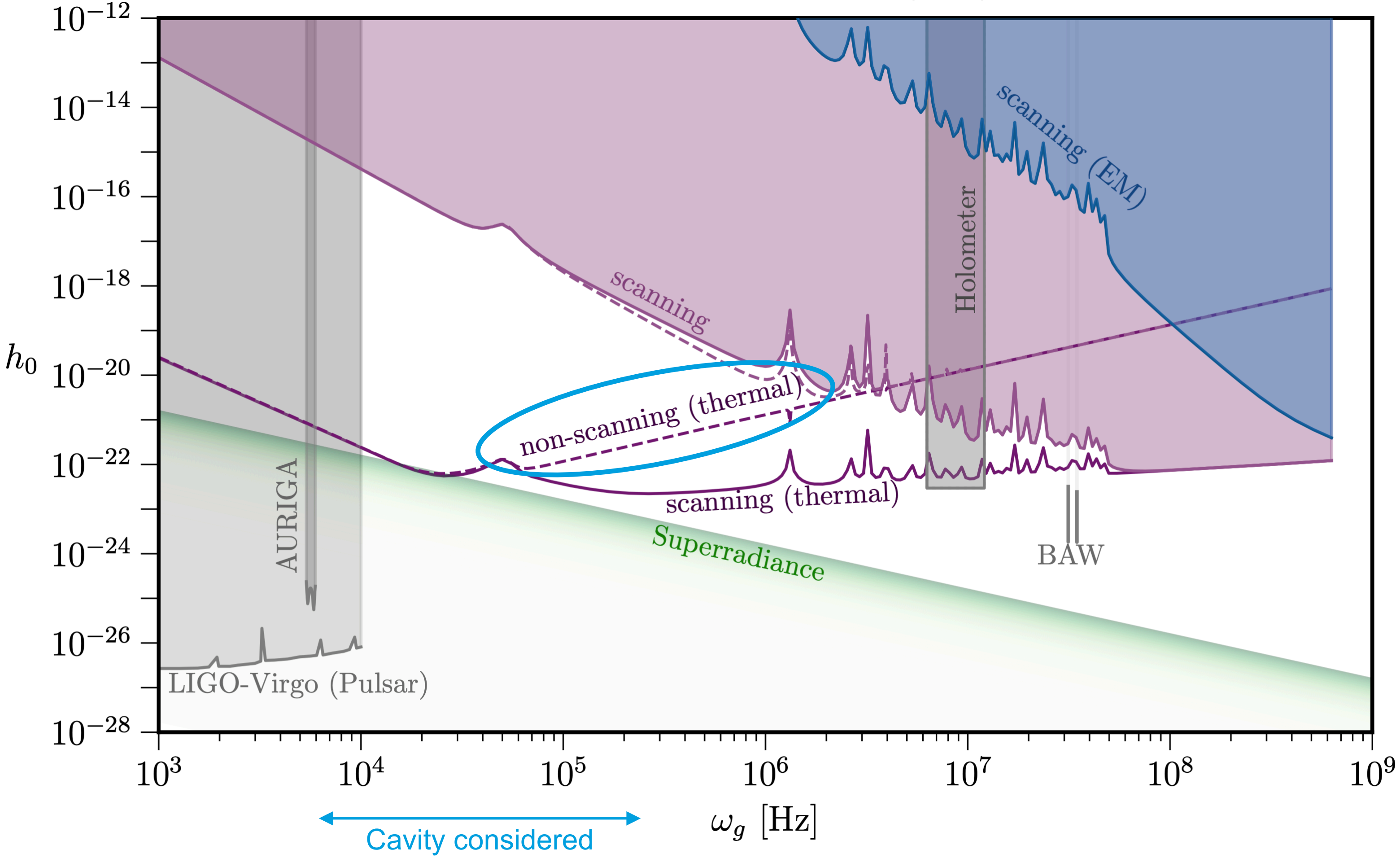
Already with a standard cryostat, explore novel frequency ranges (albeit week limits)

Strongly improve reach by attenuating vibrational noise to its thermal level

Promising experimental reach

Unique broadband sensitivity

PRD 108, 084058 (2023) & private comm. with S. Ellis



Cavity considered

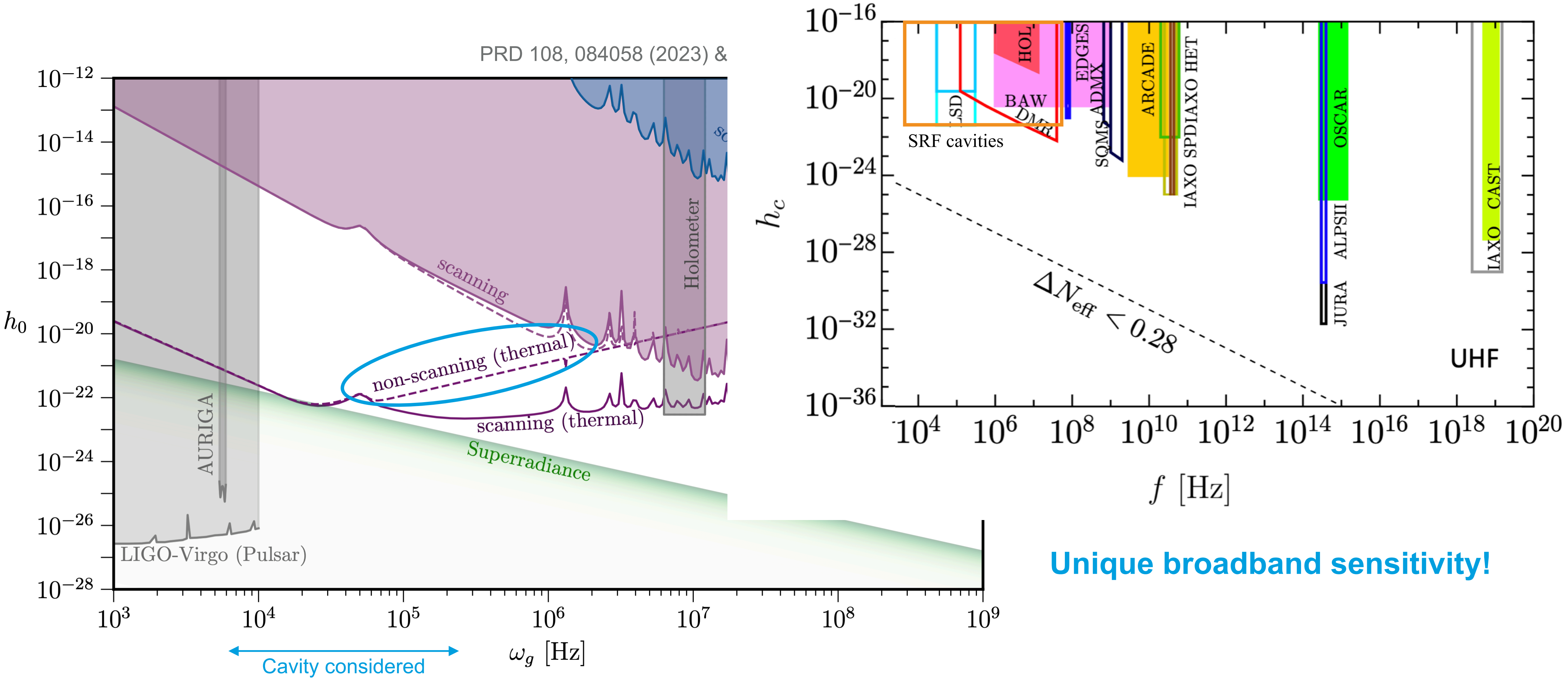
Already with a standard cryostat, explore novel frequency ranges (albeit week limits)

Strongly improve reach by attenuating vibrational noise to its thermal level

Unique broadband sensitivity!

Promising experimental reach

Unique broadband sensitivity

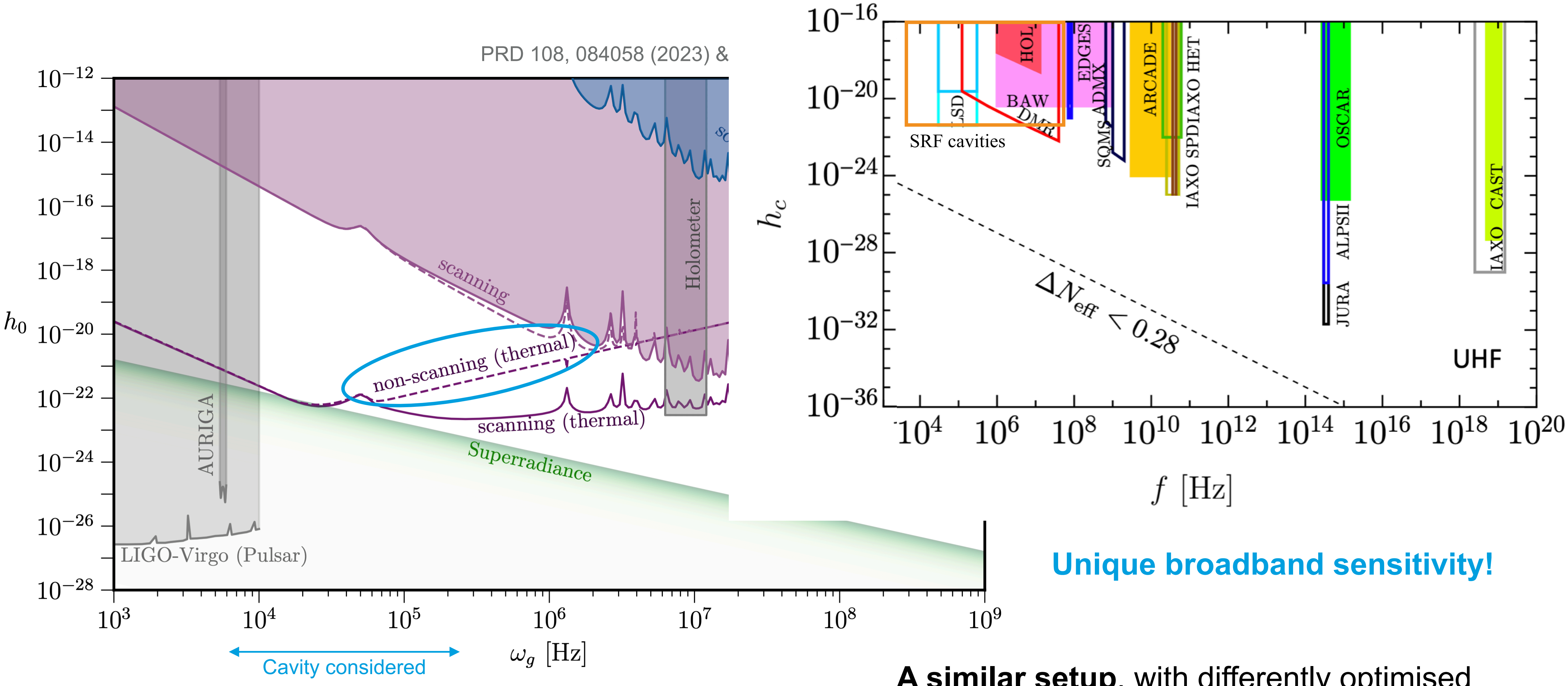


Unique broadband sensitivity!

Promising experimental reach

Unique broadband sensitivity

PRD 108, 084058 (2023) &

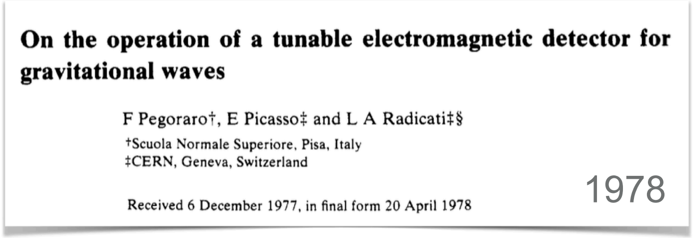


Unique broadband sensitivity!

A similar setup, with differently optimised cavities, can be used **to search for Axions**

The MAGO proposal

… and its revival



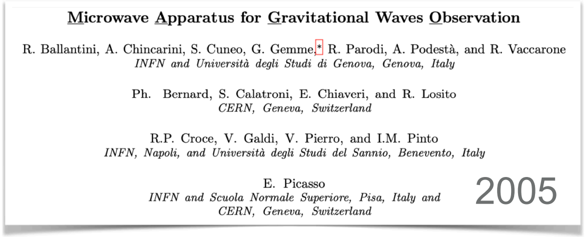
On the operation of a tunable electromagnetic detector for gravitational waves

F Pegoraro†, E Picasso‡ and L A Radicati‡§

†Scuola Normale Superiore, Pisa, Italy
‡CERN, Geneva, Switzerland

Received 6 December 1977, in final form 20 April 1978

1978



Microwave Apparatus for Gravitational Waves Observation

R. Ballantini, A. Chincarini, S. Cuneo, G. Gemme,* R. Parodi, A. Podestà, and R. Vaccarone
INFN and Università degli Studi di Genova, Genova, Italy

Ph. Bernard, S. Calatroni, E. Chiaveri, and R. Losito
CERN, Geneva, Switzerland

R.P. Croce, V. Galdi, V. Pierro, and I.M. Pinto
INFN, Napoli, and Università degli Studi del Sannio, Benevento, Italy

E. Picasso
INFN and Scuola Normale Superiore, Pisa, Italy and CERN, Geneva, Switzerland

2005

Initial idea from the 70s, which led to the **MAGO proposal** for a **scaled-up experiment** with 500 MHz cavities (not funded)

During the **R&D activities** 3 SRF cavities were built, the first one used for a **proof-of-principle experiment**

The third cavity

- 2-cell cavity with optimised geometry and variable coupling cell
- Never treated nor tested – on shelf for >15y @ INFN Genova

In a collaborative effort, DESY/UHH - FNAL - INFN, **continue the R&D studies** with a goal to have synchronised observatories

University Genova

Ultra-High-Frequency Gravitational Waves Initiative

Development of GW science in the frequency range above 10 kHz

Main aim to **promote scientific progress** in this new area of research, both from **theoretical** and **experimental** points of view

Regular workshops organised (last one in Dec. 2023) to **create a network of researchers** and **discuss the state-of-the-art** of the field

Summary of the first workshop published in a **white paper**

Currently being updated to include latest results and developments

arXiv:2011.12414v2 [gr-qc] 13 Dec 2021

Challenges and Opportunities of Gravitational Wave Searches at MHz to GHz Frequencies

N. Aggarwal^{a,*}, O.D. Aguiar^{b}, A. Bauswein^{c}, G. Cella^{d}, S. Clesse^{e}, A.M. Cruise^{f}, V. Domcke^{g,h,i,*}, D.G. Figueroa^{j}, A. Geraci^{k}, M. Goryachev^{l}, H. Grote^{m}, M. Hindmarsh^{n,o}, F. Muia^{p,i,*}, N. Mukund^{q}, D. Ottaway^{r,s}, M. Peloso^{t,u}, F. Quevedo^{p,*}, A. Ricciardone^{t,u}, J. Steinlechner^{v,w,x,*}, S. Steinlechner^{v,w,*}, S. Sun^{y,z}, M.E. Tobar^{l}, F. Torrenti$^{\alpha}$, C. Unal$^{\beta}$, G. White$^{\gamma}$

Abstract

The first direct measurement of gravitational waves by the LIGO and Virgo collaborations has opened up new avenues to explore our Universe. This white paper outlines the challenges and gains expected in gravitational wave searches at frequencies above the LIGO/Virgo band, with a particular focus on *Ultra High-Frequency Gravitational Waves* (UHF-GWs), covering the MHz to GHz range. The absence of known astrophysical sources in this frequency range provides a unique opportunity to discover physics beyond the Standard Model operating both in the early and late Universe, and we highlight some of the most promising gravitational sources. We review several detector concepts which have been proposed to take up this challenge, and compare their expected sensitivity with the signal strength predicted in various models. This report is the summary of the workshop *Challenges and opportunities of high-frequency gravitational wave detection* held at ICTP Trieste, Italy in October 2019, that set up the stage for the recently launched Ultra-High-Frequency Gravitational Wave (UHF-GW) initiative.

arXiv:2011.12414v2

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Fernando Quevedo (fq201@damtp.cam.ac.uk), Jessica Steinlechner (jessica.steinlechner@ligo.org),
Sebastian Steinlechner (s.steinlechner@maastrichtuniversity.nl)

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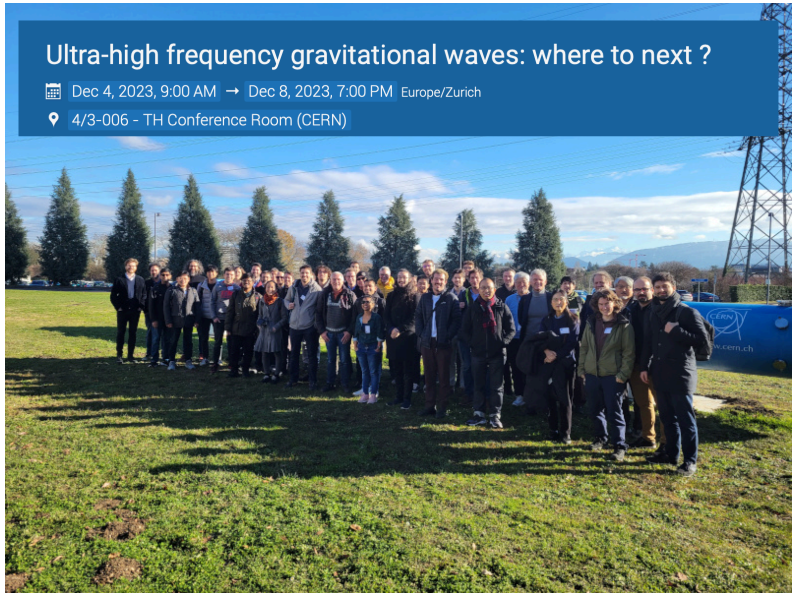
https://indico.cern.ch/event/1257532/



Ultra-high frequency gravitational waves: where to next ?

Dec 4, 2023, 9:00 AM → Dec 8, 2023, 7:00 PM Europe/Zurich

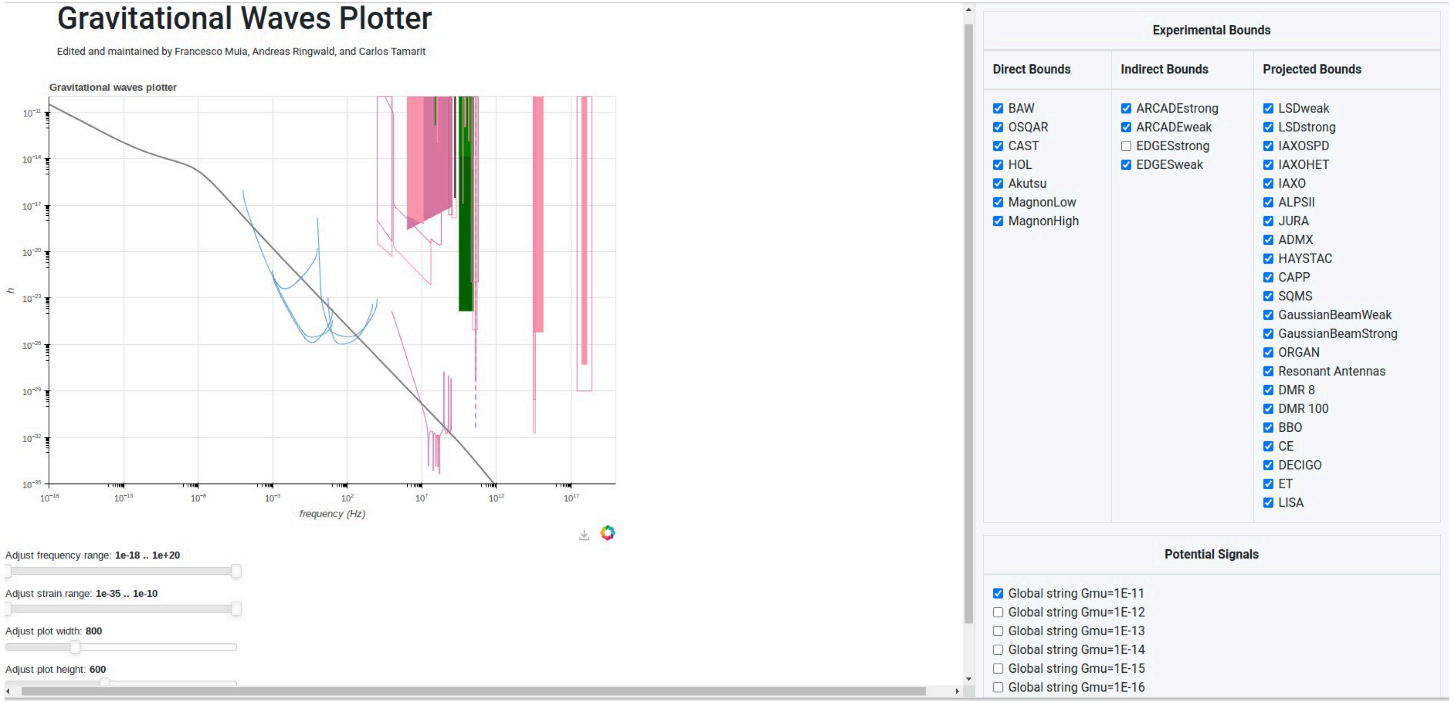
4/3-006 - TH Conference Room (CERN)

Towards a new gravitational wave plotter

Extend coverage to high frequencies and add cosmological signals

Aim to develop a **new gravitational wave plotter** that can cover the **ultra-high frequency range** and which adapts to the **needs of the community** (up to date and reactive to feedback)

Francesco Muia, Carlos Tamarit, Andreas Ringwald



Gravitational Waves Plotter

Edited and maintained by Francesco Muia, Andreas Ringwald, and Carlos Tamarit

Adjust frequency range: **1e-18 .. 1e+20**

Adjust strain range: **1e-35 .. 1e-10**

Adjust plot width: **800**

Adjust plot height: **600**

Experimental Bounds

Direct Bounds
☑ BAW
☑ OSQAR
☑ CAST
☑ HOL
☑ Akutsu
☑ MagnonLow
☑ MagnonHigh

Indirect Bounds
☑ ARCADEstrong
☑ ARCADEweak
☐ EDGESstrong
☑ EDGESweak

Projected Bounds
☑ LSDweak
☑ LSDstrong
☑ IAXOSPD
☑ IAXOHET
☑ IAXO
☑ ALPSII
☑ JURA
☑ ADMX
☑ HAYSTAC
☑ CAPP
☑ SQMS
☑ GaussianBeamWeak
☑ GaussianBeamStrong
☑ ORGAN
☑ Resonant Antennas
☑ DMR 8
☑ DMR 100
☑ BBO
☑ CE
☑ DECIGO
☑ ET
☑ LISA

Potential Signals
☑ Global string Gmu=1E-11
☐ Global string Gmu=1E-12
☐ Global string Gmu=1E-13
☐ Global string Gmu=1E-14
☐ Global string Gmu=1E-15
☐ Global string Gmu=1E-16

What would you like to see and have?
Please send feedback to:

https://forms.gle/Vw28pmgyLaMmgunb8

Current status still preliminary

For more details see talk by C. Tamarit at Dec. Workshop

Conclusions

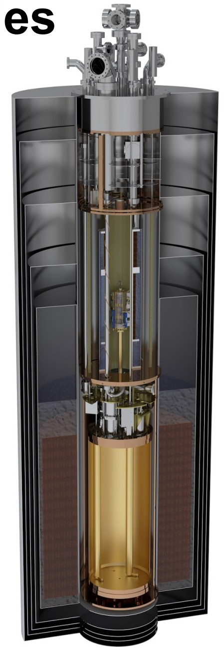
GW signals above 10 kHz a smoking gun for BSM physics, exciting scientific opportunities

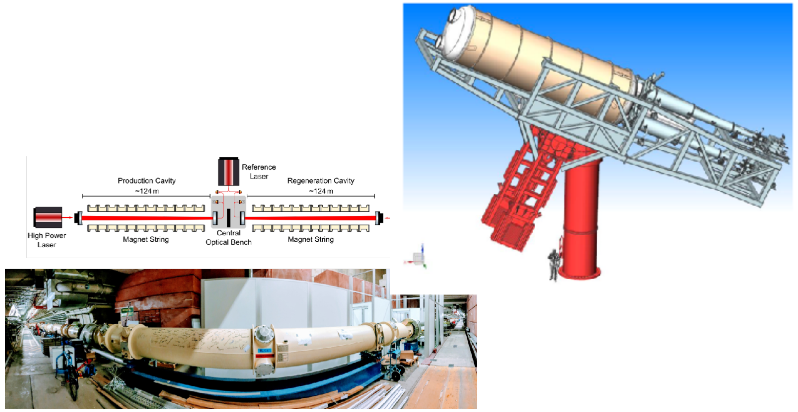
Strongly growing interest in the community

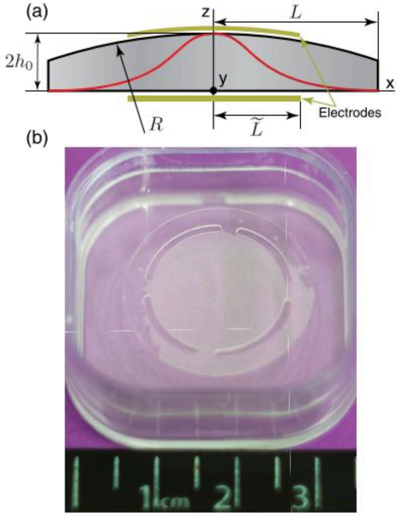
Important synergies between axion searches and HFGW searches

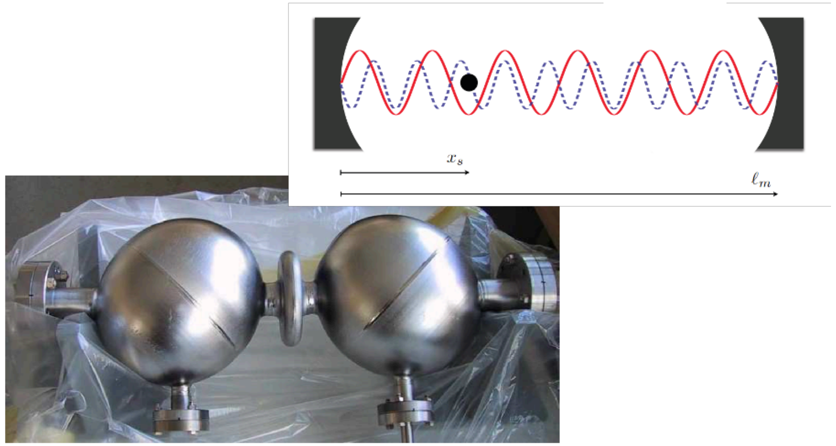
Experimental efforts started with several isolated attempts, will hopefully grow in more systematic approaches

Moderate size of experiments very attractive, allows also for several synchronised observatories









Thank you

With helpful input from Francesco Muia and many other members of the UHFGW initiative, and from speakers of our recent workshop https://indico.cern.ch/event/1257532/

Cosmic Gravitational Microwave Background (CGMB)

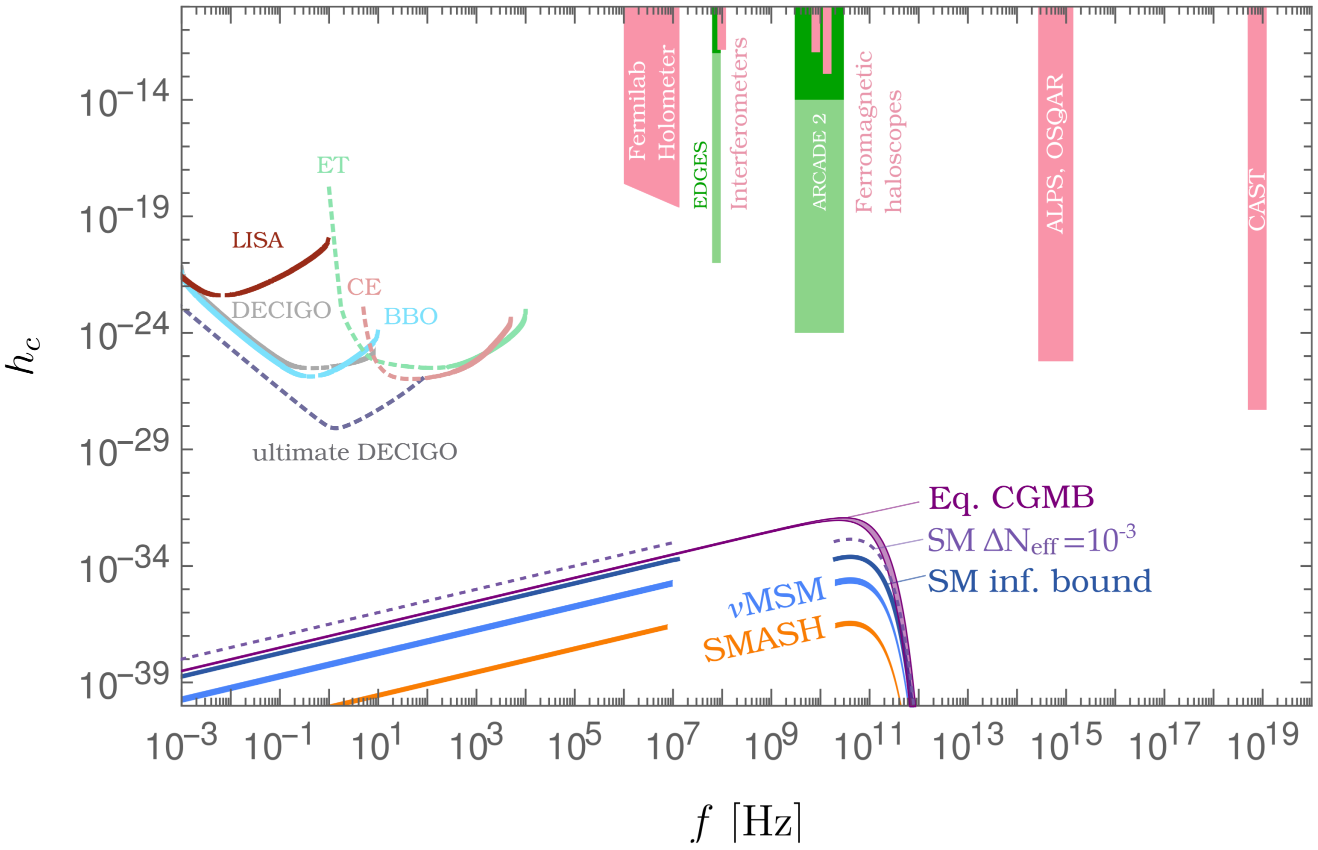
Guaranteed GW background

Particle collisions in the radiation dominated universe due to thermal fluctuations in the plasma

Results in GWs, enhanced and redshifted to the approx. same frequency today in the GHz range

Magnitude and peak frequency to distinguish between SM and BSM models

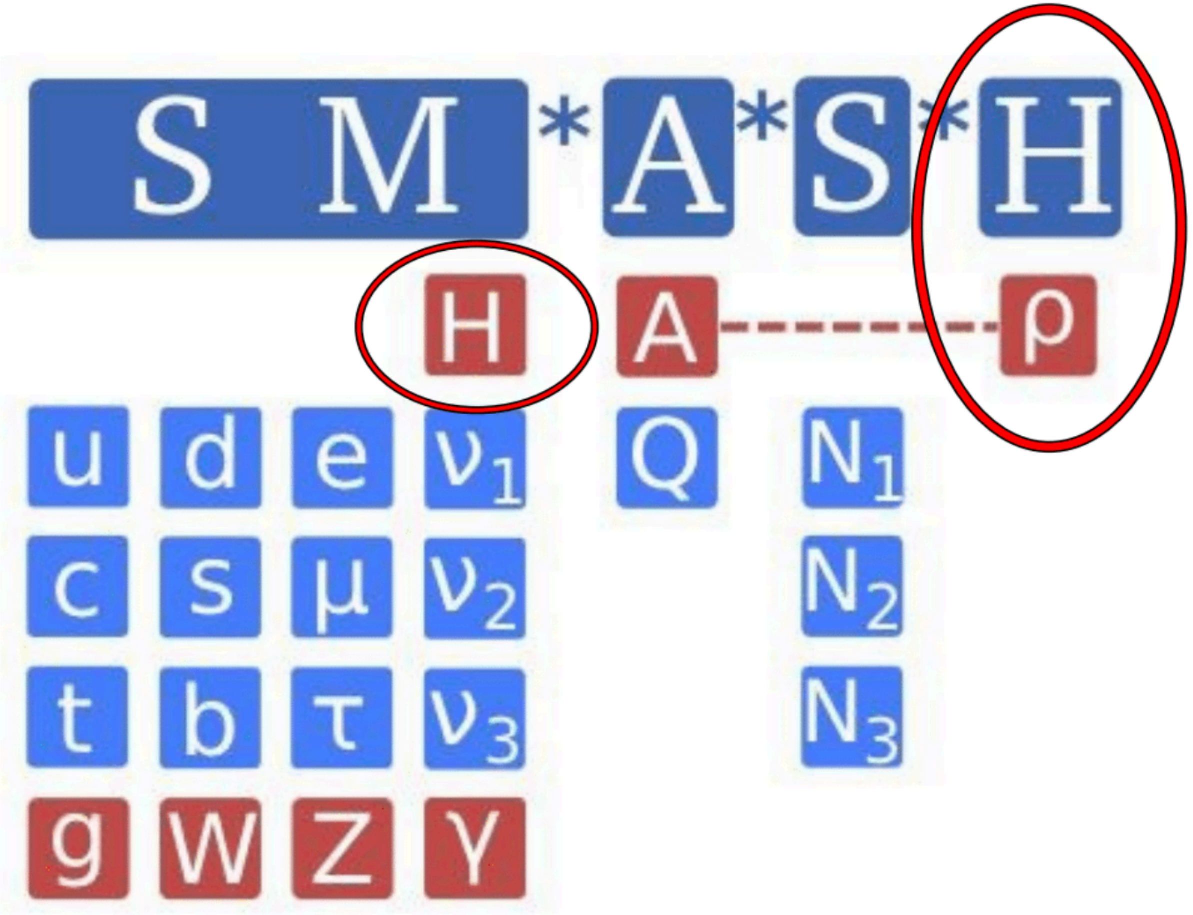
Ringwald et al, 2011.04731



Standard Model*Axion*Seesaw*Higgs-Portal Inflation

Minimal model of particle physics and cosmology

[Ballesteros, Redondo, AR, Tamarit, arXiv:1608.05414; 1610.01639]



SMASH extends the SM by

- 3 right-handed SM singlet neutrinos N_i
- a SM singlet complex scalar field σ
- a vector-like extra quark Q

all charged under a new global U(1)$_{PQ}$ symmetry, that is spontaneously broken by vev $\langle|\sigma|\rangle = v_\sigma/\sqrt{2} \sim 10^{11}\,\mathrm{GeV}$

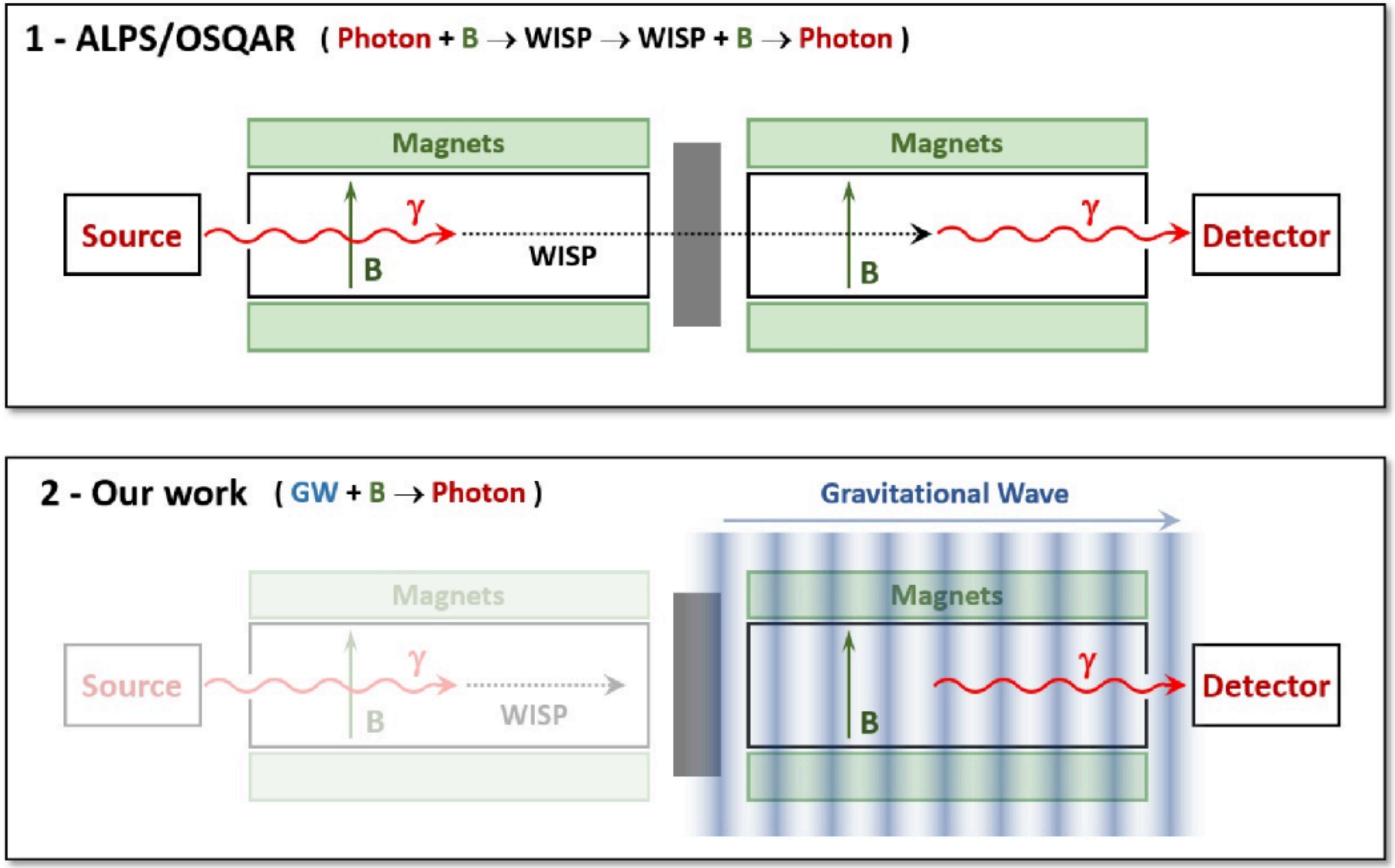
It solves five puzzles in particle physics and cosmology in one smash:

1. Strong CP problem (Peccei Quinn (PQ) mechanism)
2. Dark matter (Axion)
3. Neutrino masses and mixing (Typ I seesaw mech.)
4. Baryon asymmetry (Thermal leptogenesis)
5. **Inflation** (Higgs-portal inflation)

Gravitational wave searches with photon regeneration

LSW experiments (ALPS, OSQAR), helioscopes (CAST, IAXO)

Ejlli et al. Eur.Phys.J.C 79 (2019) 12

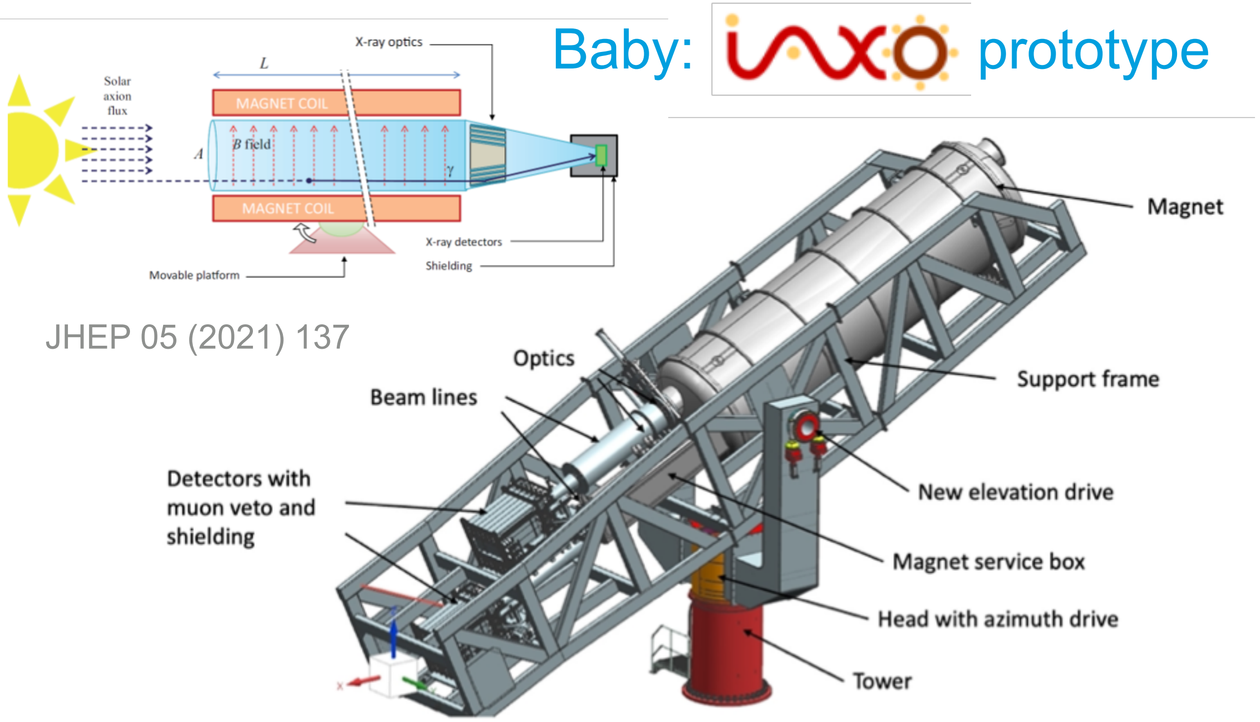


(Baby) IAXO and MADMAX

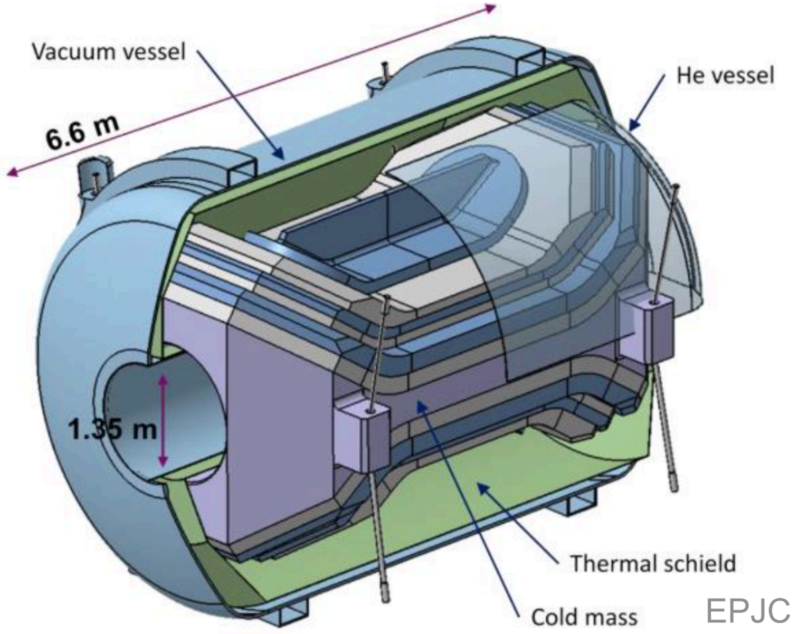
Looking for solar axions and direct DM search

MADMAX

Baby: IAXO prototype



JHEP 05 (2021) 137



EPJC 79 (2019) 3, 186

Conversion of solar axions to x-ray photons

Data taking in 2028 in HERA-South

Resonantly enhance axion-photon conversion with a stack of dielectric plates

10T dipole magnet with an aperture of 1m

In prototyping phase (operation ~2030 if funded)

Partially-levitated membrane inside cavity

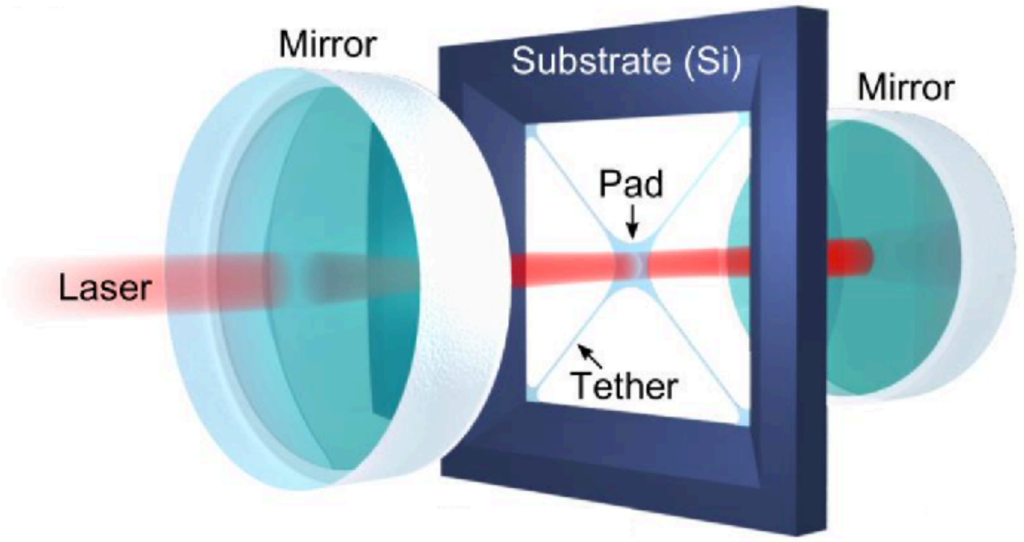
Alternative approach to levitated particle or disc

At a cavity length of 100m and disk radius of 75 µm requires an end mirror radius of 1m

- 3x considered for ET → requires new technology

Membrane, realized via microfabrication techniques, is structurally connected to the environment via a supporting substrate

- Membrane Q factor similar to levitated stacks, results in comparable sensitivity
- Allows to reduce mirror radius, enabling to rely on established mirror technology
- Membrane's connection to a substrate enables straight forward handling and installation in the cavity

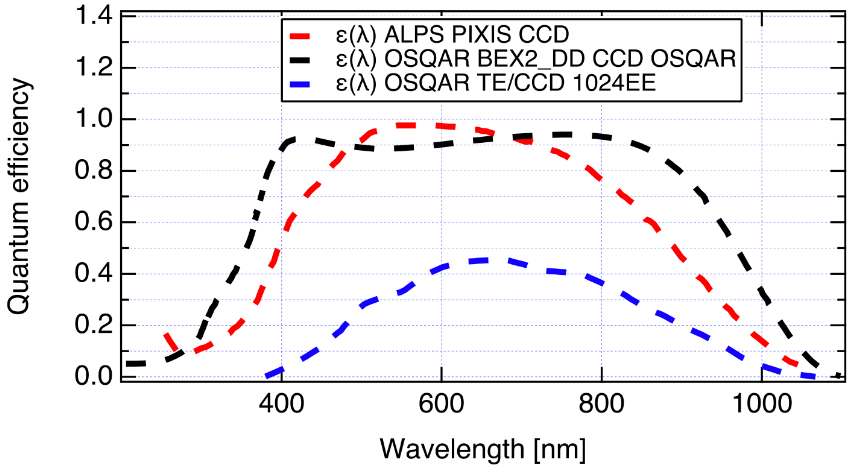


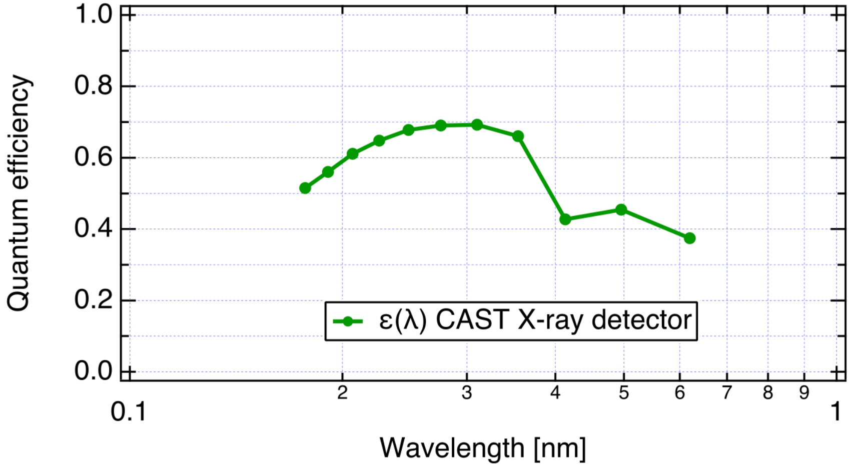
PRX, *6*(2), 021001

Parameters necessary to compute the characteristic amplitude

$$h_c^{\min}(0,\omega) \simeq \sqrt{\frac{4\,N_{\rm exp}}{A\,B^2\,L^2\,\epsilon_\gamma(\omega)\,\Delta\omega}} \simeq 1.6\times10^{-16}\sqrt{\left(\frac{N_{\rm exp}}{1\ \rm Hz}\right)\left(\frac{1\ \rm m^2}{A}\right)\left(\frac{1\ \rm T}{B}\right)^2\left(\frac{1\ \rm m}{L}\right)^2\left(\frac{1\ \rm Hz}{\Delta f}\right)\left(\frac{1}{\epsilon_\gamma(\omega)}\right)}$$

- N_{exp} - detected number of photons per second,
- A - cross-section of the detector,
- B - magnetic field amplitude,
- L - distance extension of the magnetic field,
- $\epsilon_\gamma(\omega)$ - quantum efficiency of the detector,
- Δf - operation frequency of the CCD.

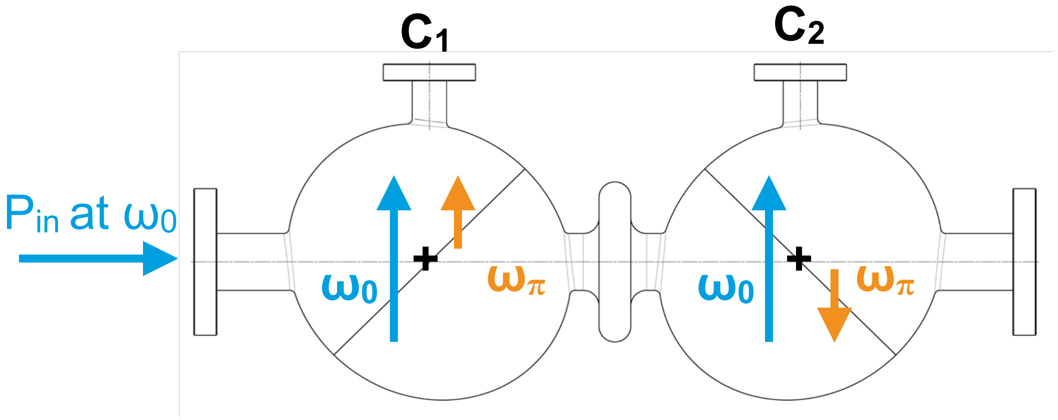


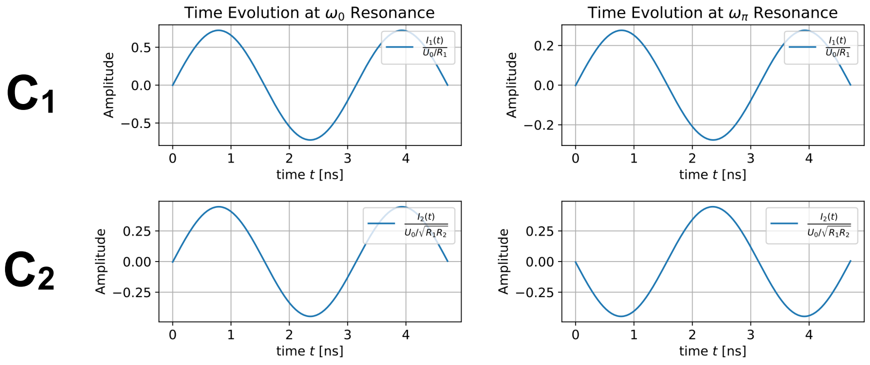


	$\epsilon_\gamma(\omega)$	$N_{\rm exp}$ (mHz)	A (m^2)	B (T)	L (m)	Δf (Hz)
ALPS I	see Fig 2	0.61	0.5×10^{-3}	5	9	9×10^{14}
OSQAR I	see Fig 2	1.76	0.5×10^{-3}	9	14.3	5×10^{14}
OSQAR II	see Fig 2	1.14	0.5×10^{-3}	9	14.3	1×10^{15}
CAST	see Fig 2	0.15	2.9×10^{-3}	9	9.26	1×10^{18}

MAGO’s readout

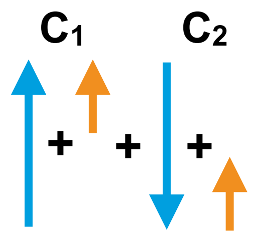
Phase shift in signal mode gives additional discrimination





loaded mode signal mode

Magic-tee



Magic-tee approach

- Shift signal phase of one cell by π
- Loaded mode cancels, signal mode amplified

Can be tested with injected signal or with mechanical deformation of cavity with piezos

Contact

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