Axions as Dark Matter Candidates

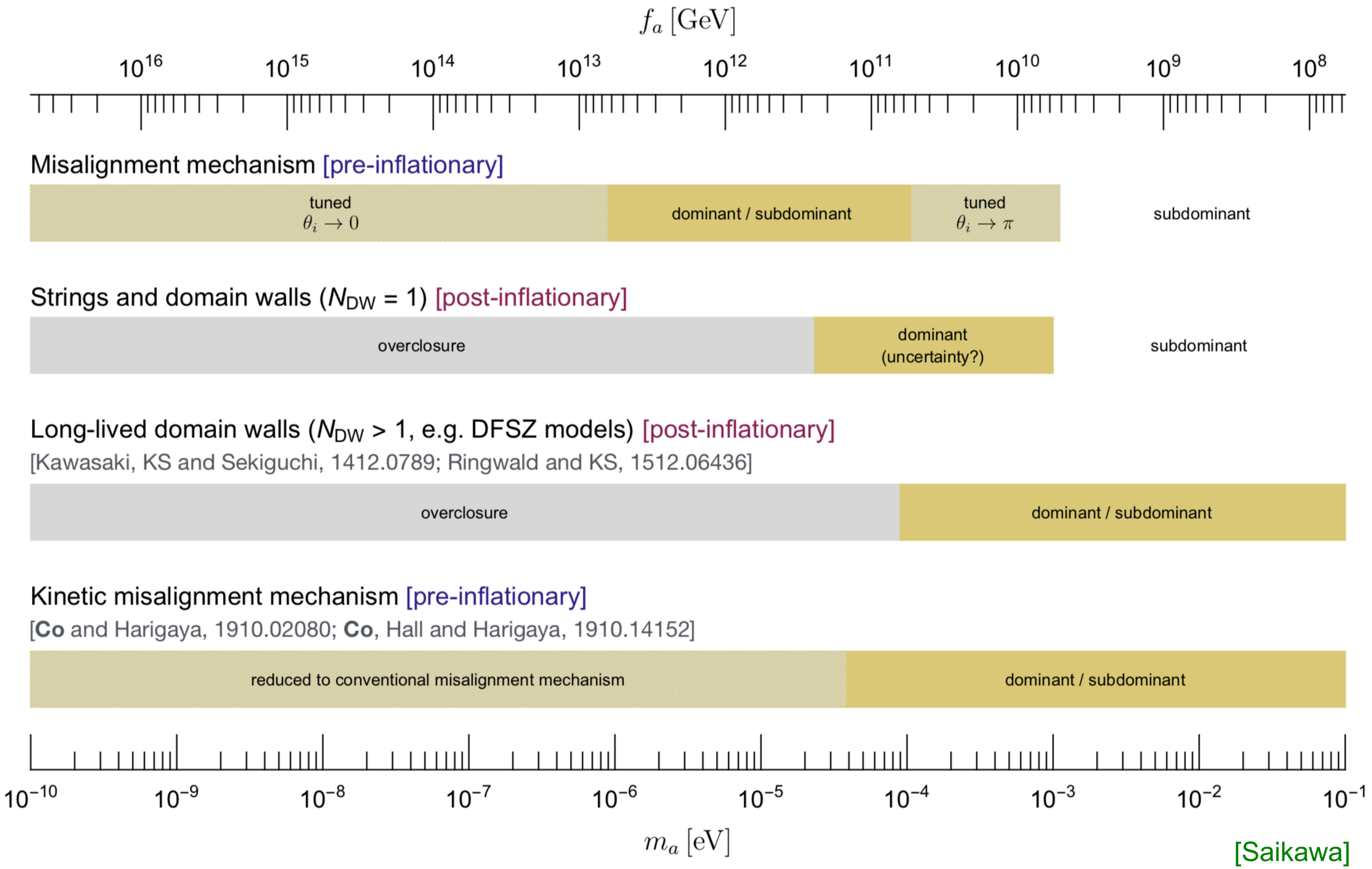
Andreas Ringwald
FNHP 2022
Frontiers in Nuclear and Hadronic Physics
Galileo Galilei Institute School
Online Event
Feb 21, 2022 - Mar 04, 2022

Today's Plan

- Vacuum Structure in Quantum Chromodynamics
- Strong CP Puzzle
- The Axion
- Axion Dark Matter
- **Axion Experiments (continued)**

Axion Dark Matter Detection

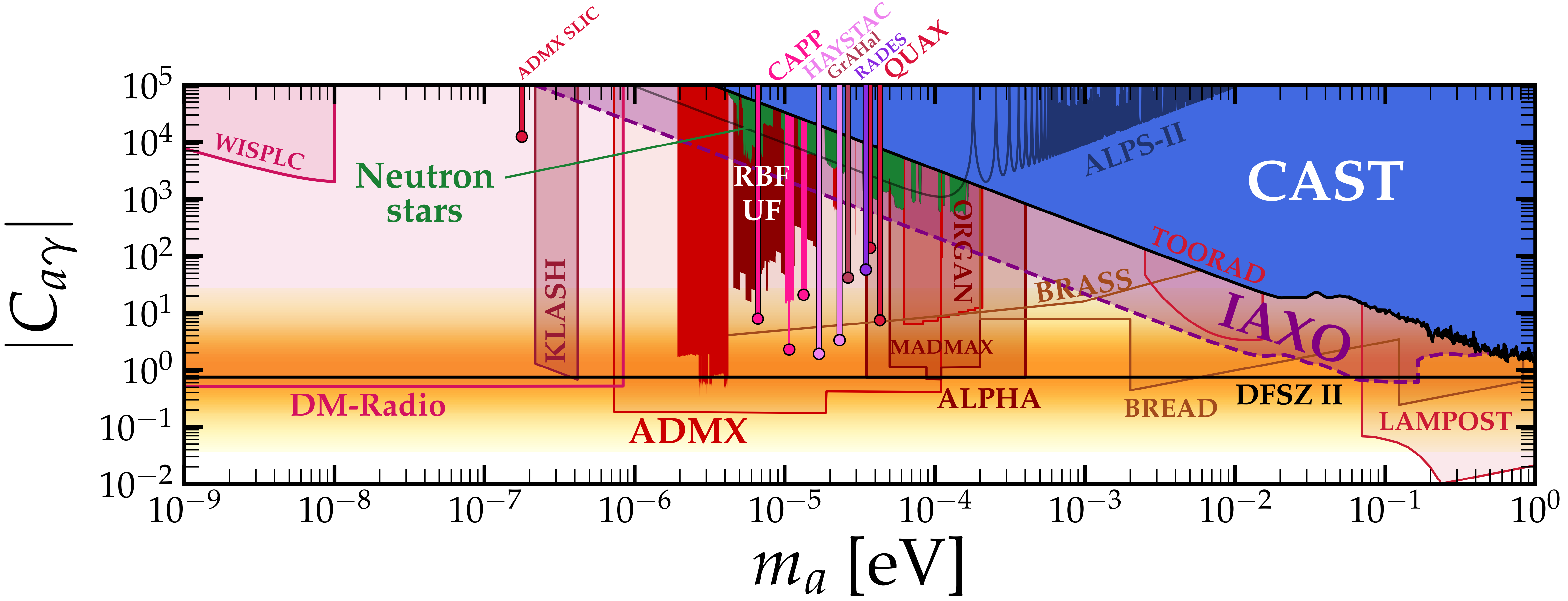
Recap :Dark Matter axion mass spans a huge range



[Saikawa]

Axion Dark Matter Detection

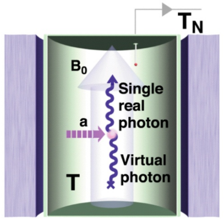
Recap: Projections of experiments

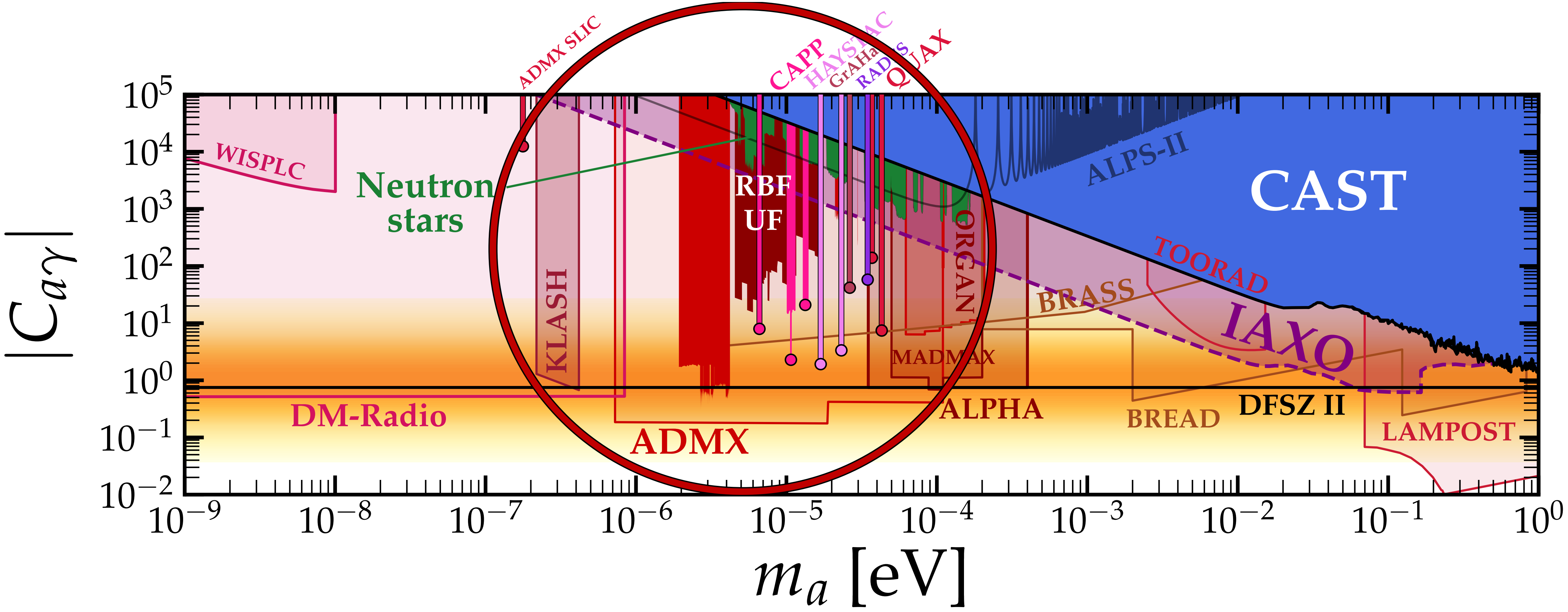


[https://github.com/cajohare/AxionLimits/blob/master/plots/AxionPhoton_Rescaled.pdf]

Axion Dark Matter Detection

Recap: Microwave cavities





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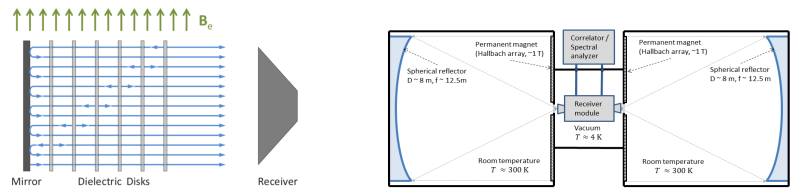
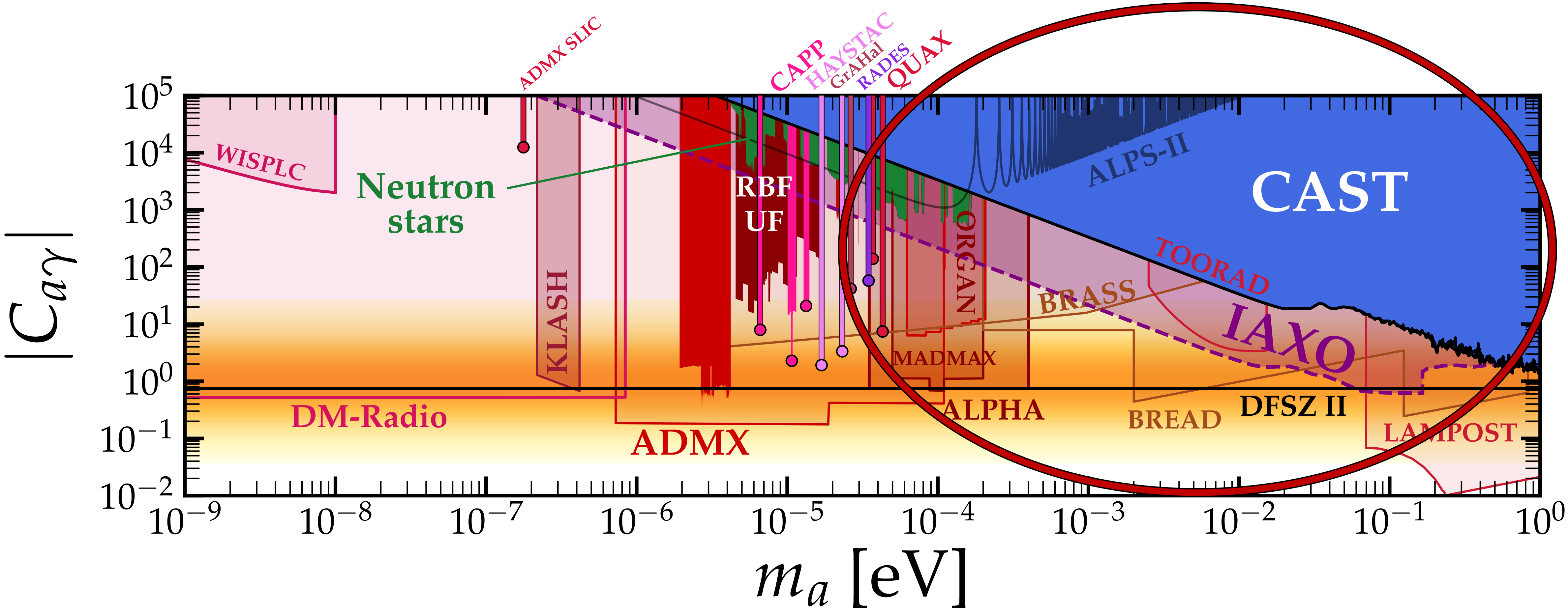
Axion Dark Matter Detection

Recap: Dish antennas





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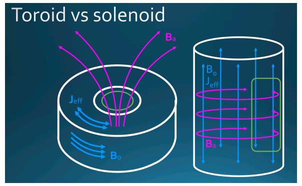
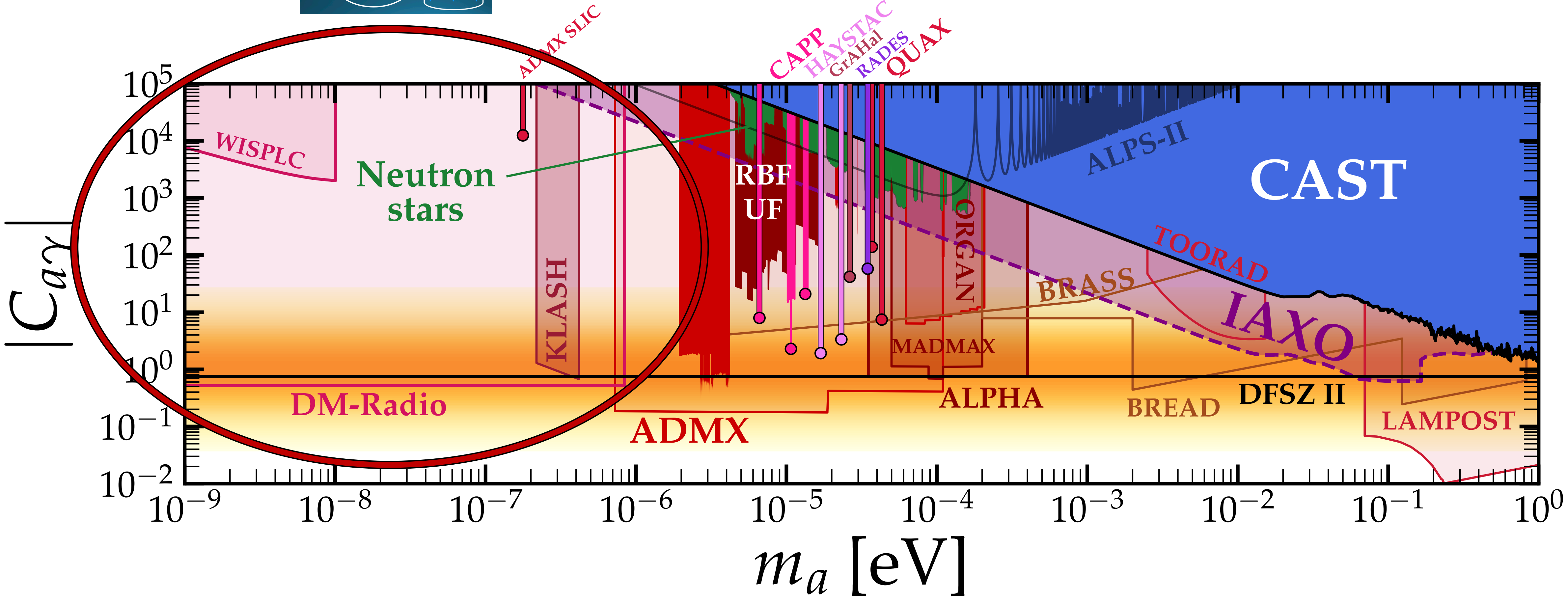
Axion Dark Matter Detection

Searches employing lumped elements





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Axion Dark Matter Detection

Searching for Axion-induced Magnetic Fields

[Sikivie,Sullivan,Tanner 14; Kahn,Safdi,Thaler `16]

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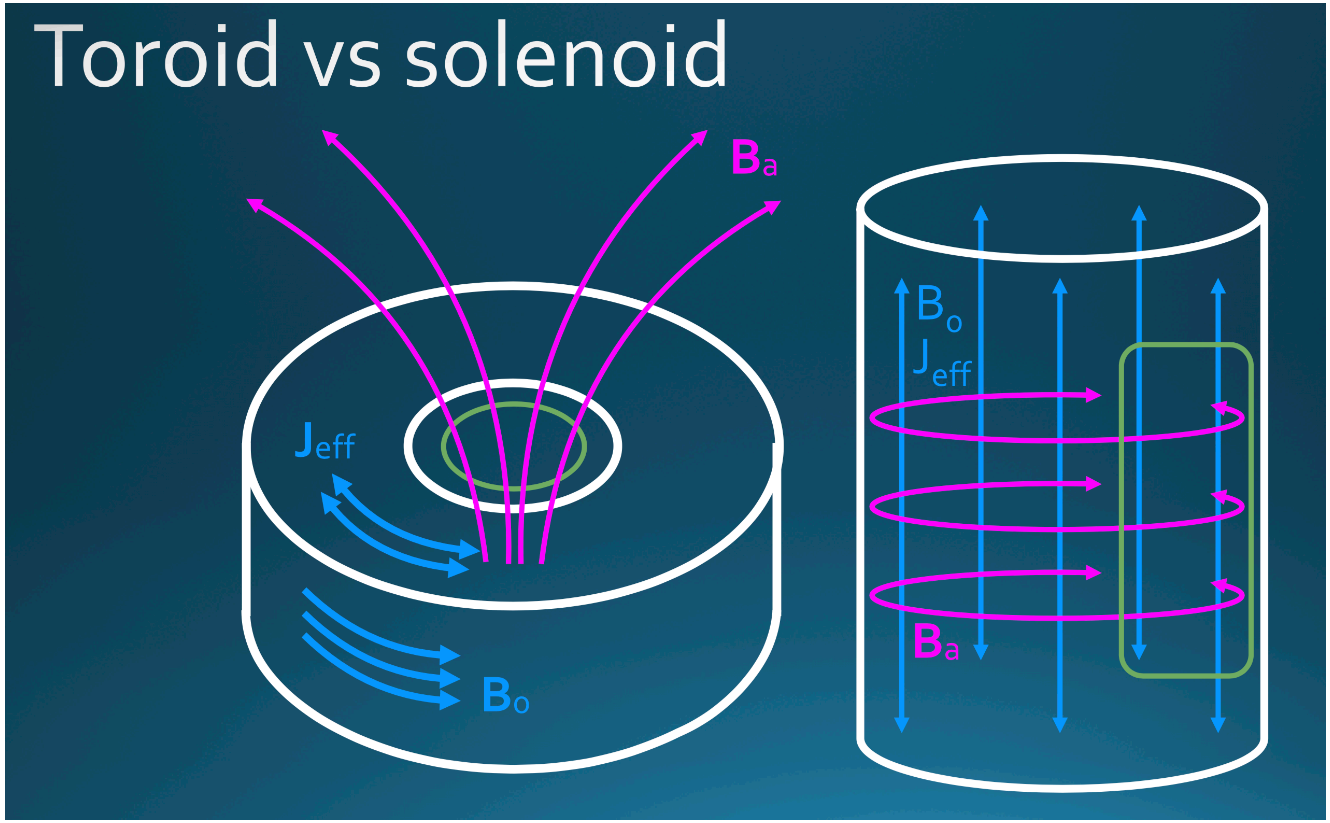

[Salemi '21]

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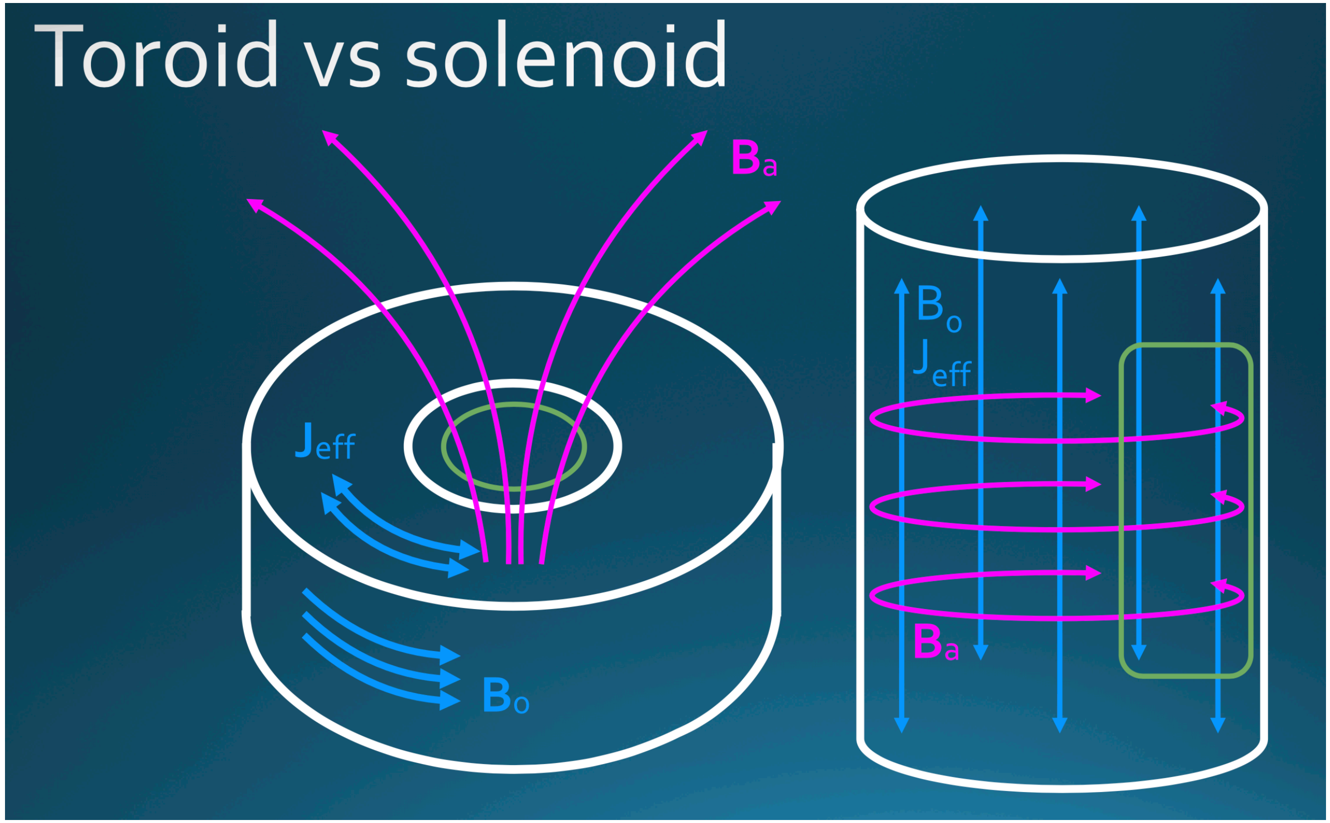

$$\mathbf{J}_{eff} = g_{a\gamma\gamma}\sqrt{2\rho_{DM}}\cos(m_a t)\mathbf{B}$$

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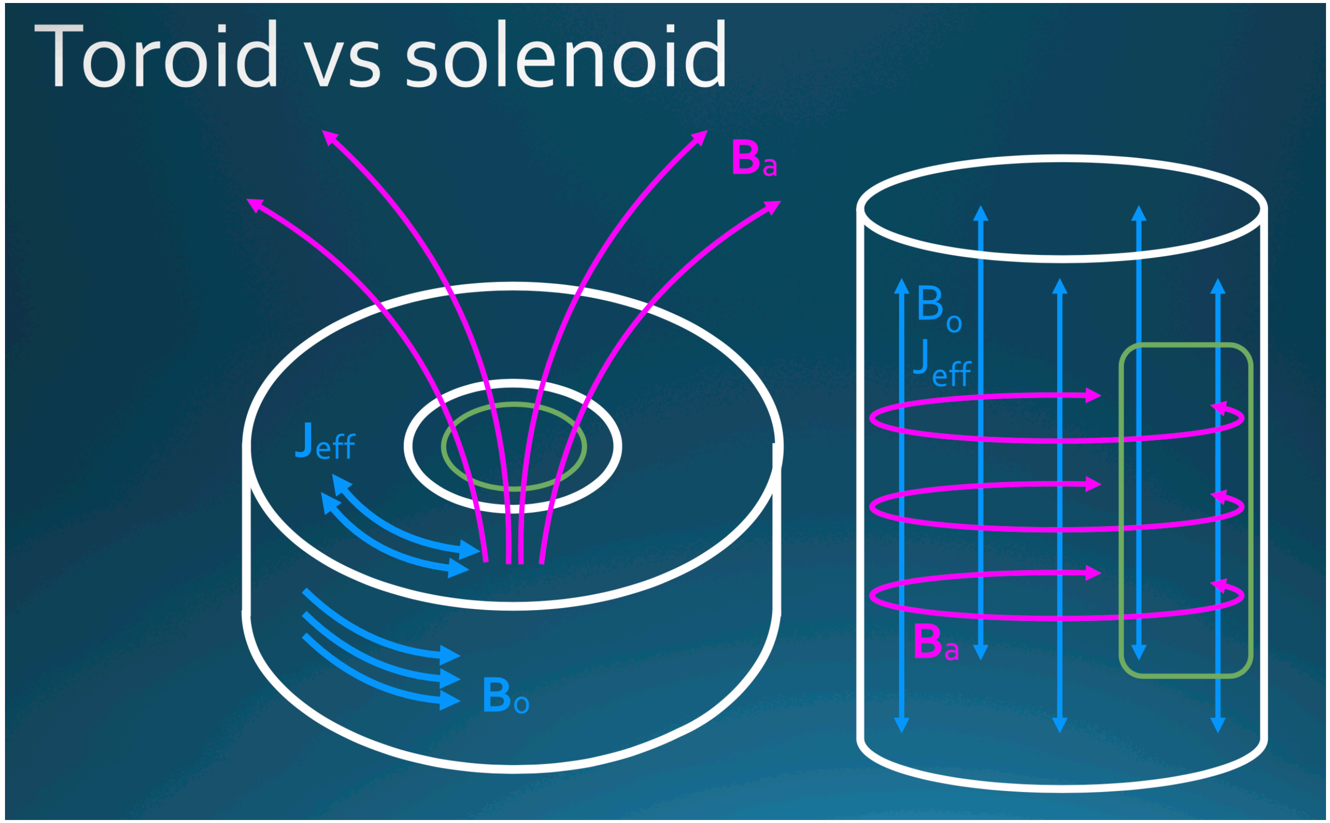

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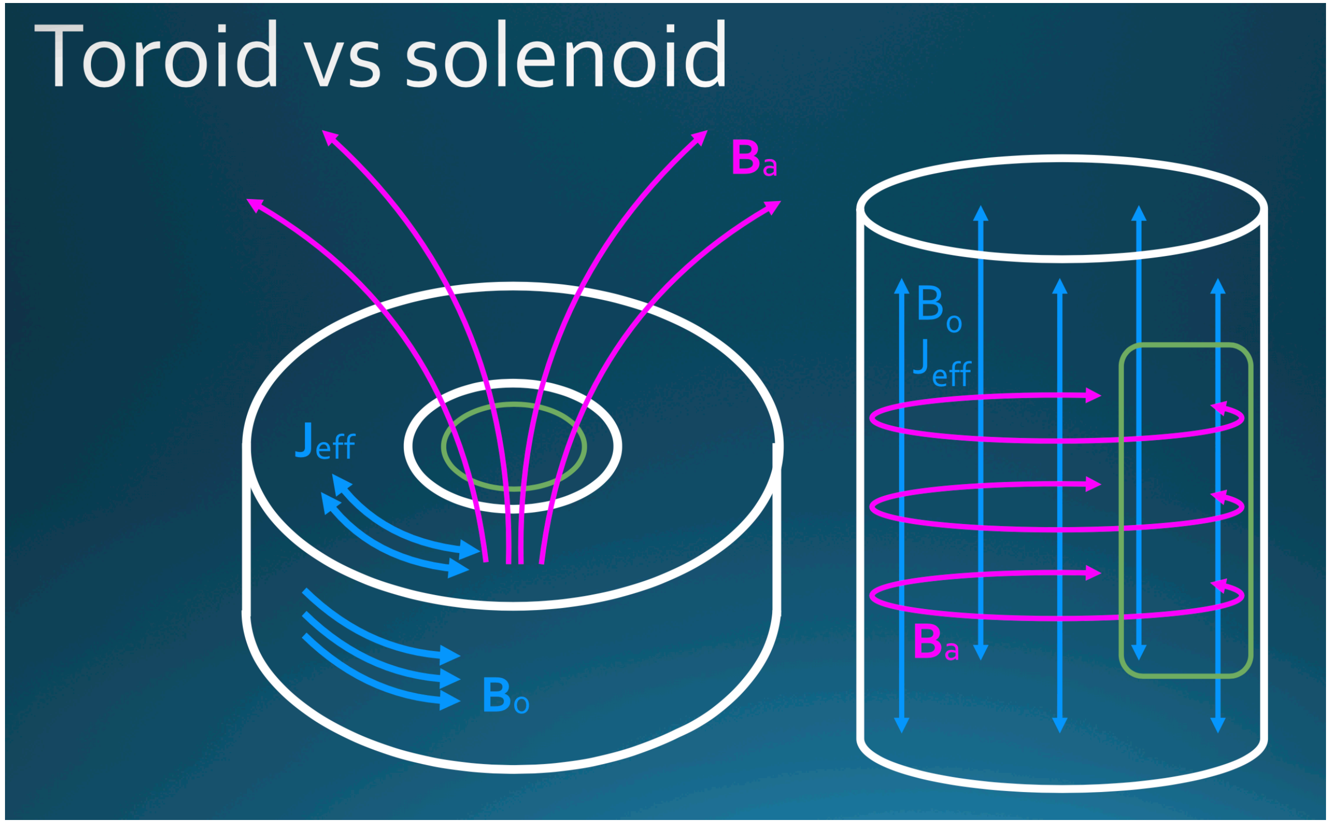

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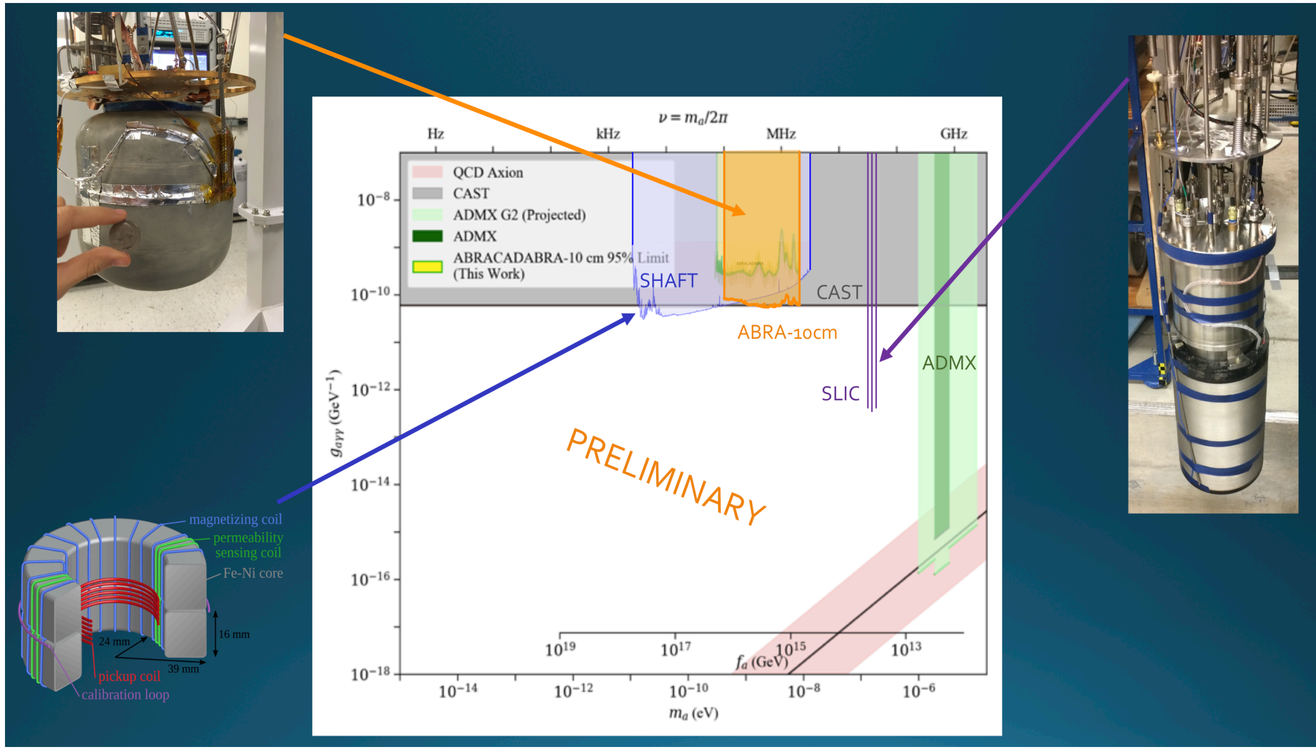

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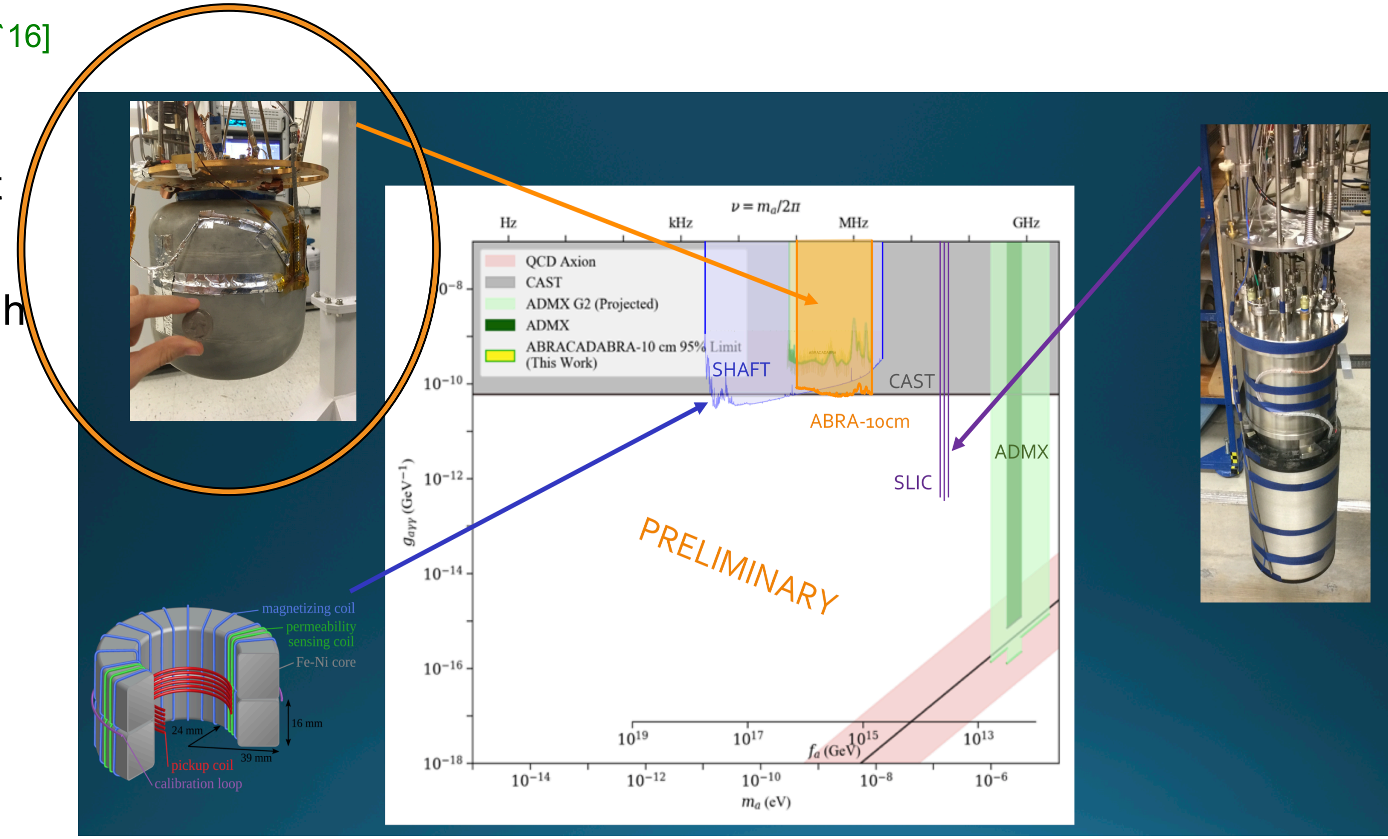

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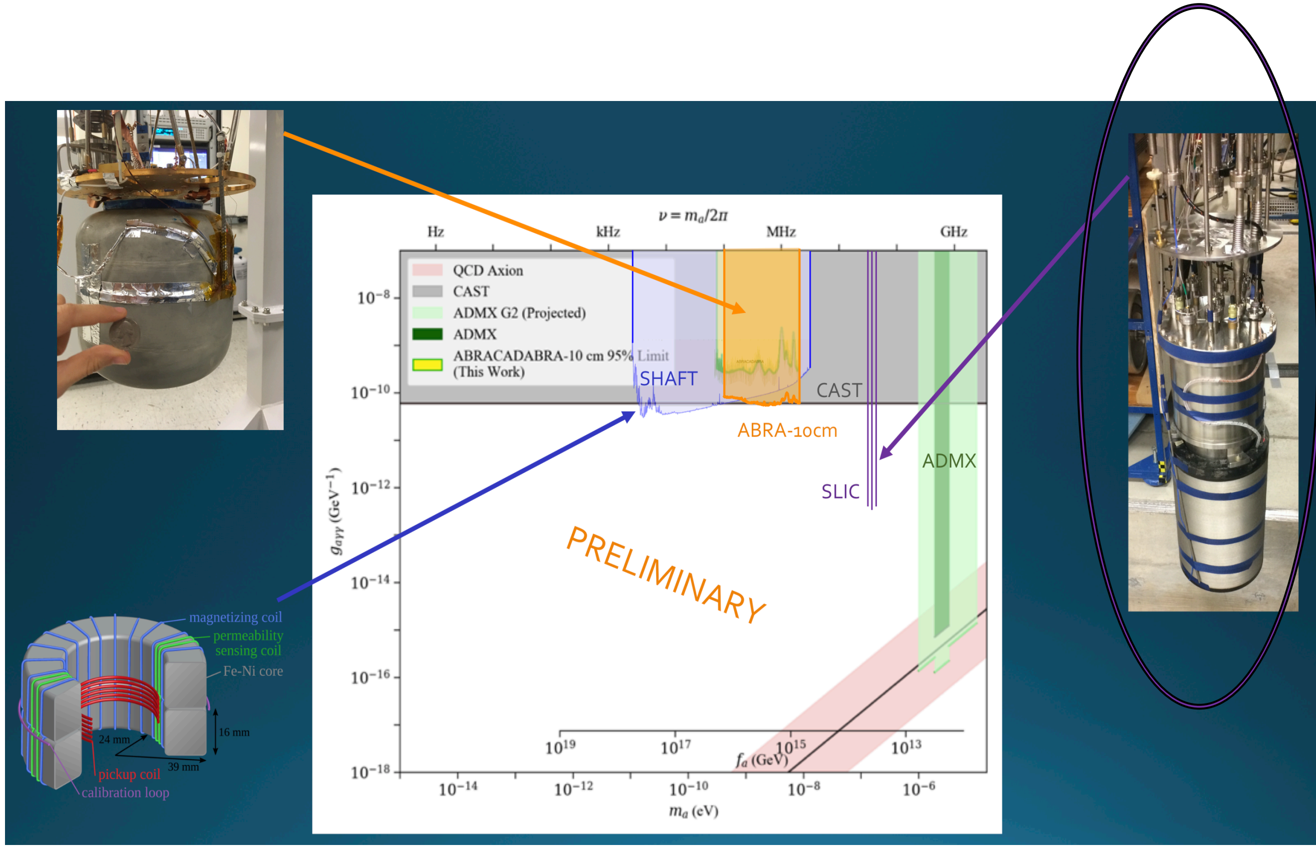

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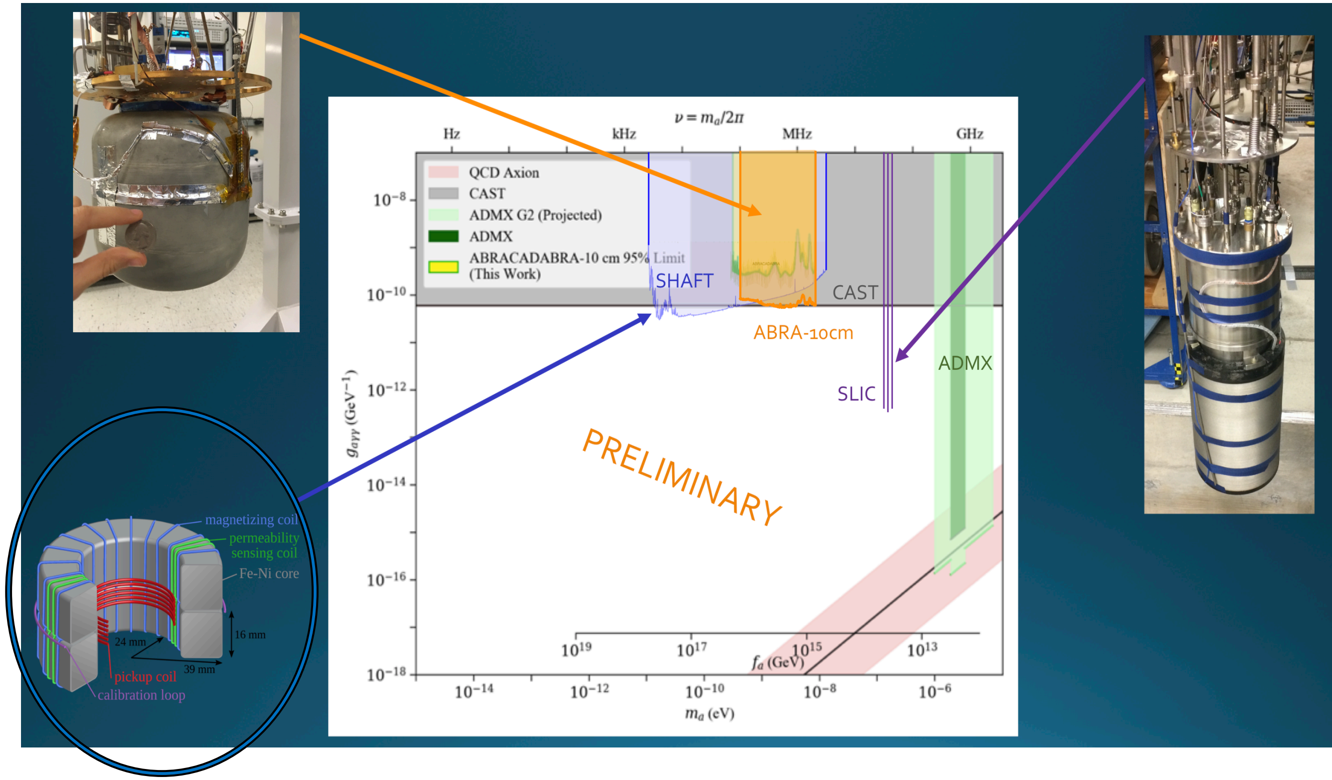

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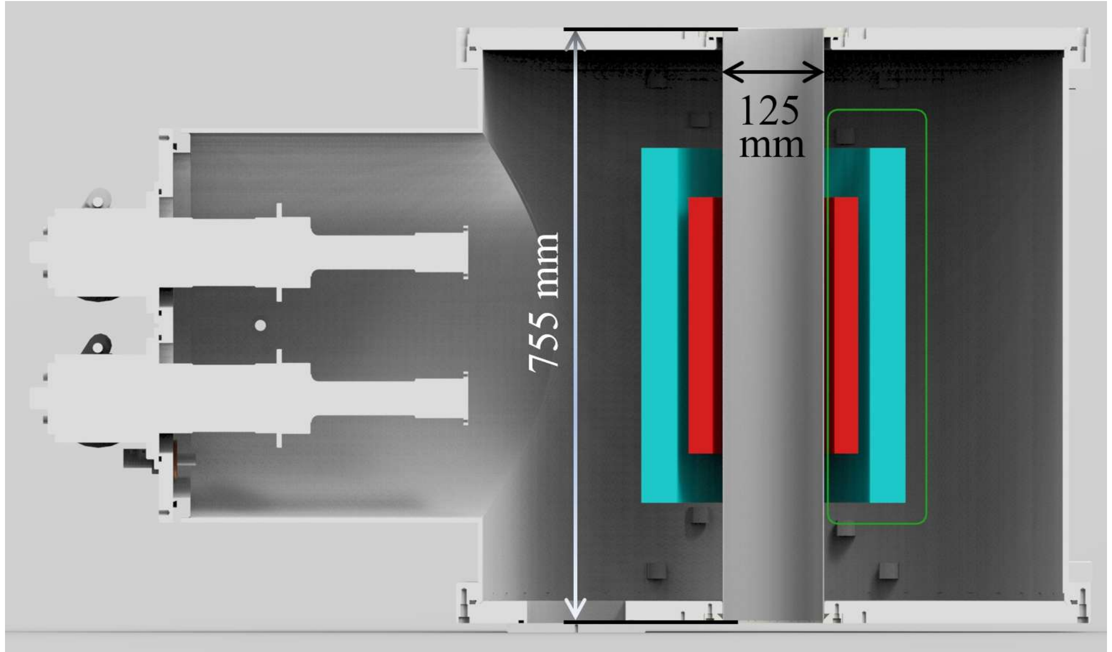

[Zhang,Horns,Ghosh 21]

TABLE I. Comparison of experimental parameters between WISPLC, ABRA. and SHAFT, $C = |\vec{B}_{\max}| V_{\text{magnet}}\, \mathcal{G}_V$.

	$\lvert\vec{B}_{\max}\rvert$ (T)	$\mathcal{G}_V$	V_{magnet} (m^3)	C/C_{SHAFT}
SHAFT[a]	1.5	0.108[b]	9.5×10^{-5}	1
ABRA.[c]	1	0.027	8.9×10^{-4}	1.55
WISPLC	14	0.074	2.4×10^{-2}	1.60×10^{3}

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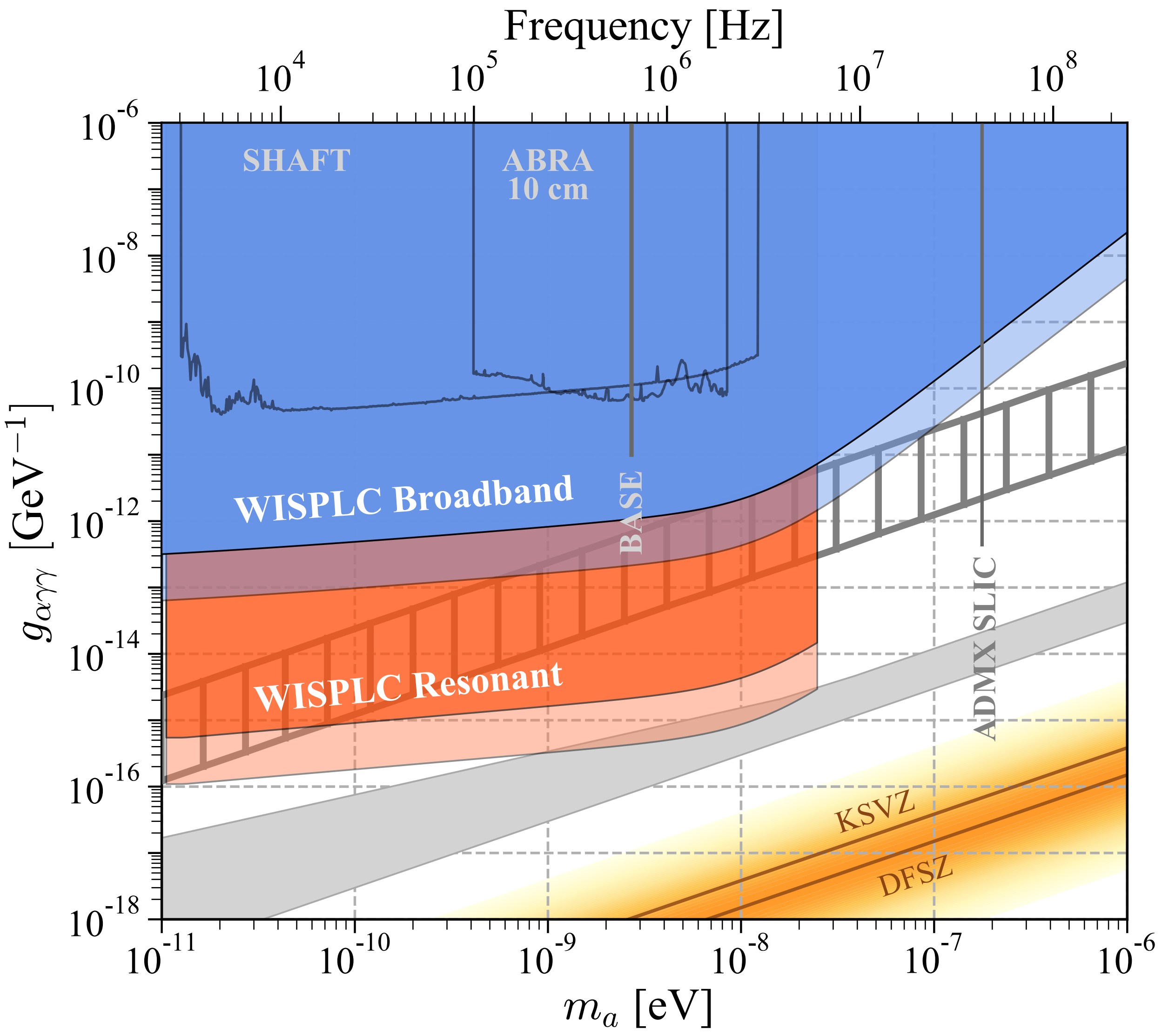

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- DM-Radio Cubic Meter Consortium

DM Radio Cubic Meter Consortium

Funded as part of DOE New Initiatives in Dark Matter program

R&D Phase Consortium Leadership:

Project manager for R&D phase: Dale Li

Name	Institution	Role / Team Lead
Kent Irwin	SLAC and Stanford	Consortium PI
Karl van Bibber	UC Berkeley	Magnet
Lindley Winslow	MIT	Magnetic shielding, vibration
Saptarshi Chaudhuri	Princeton	Control system, scan
Peter Graham	Stanford	Theory
Reyco Henning	UNC Chapel Hill	Calibration and DAQ
Dale Li	SLAC	Cryomechanical
Hsiao-Mei Cho	SLAC	SQUID
Wes Craddock	SLAC	Lead Engineer
Nadine Kurita	SLAC	Project Management Plan

DMRm3consortium v1 20191104

[Salemi ‘21]

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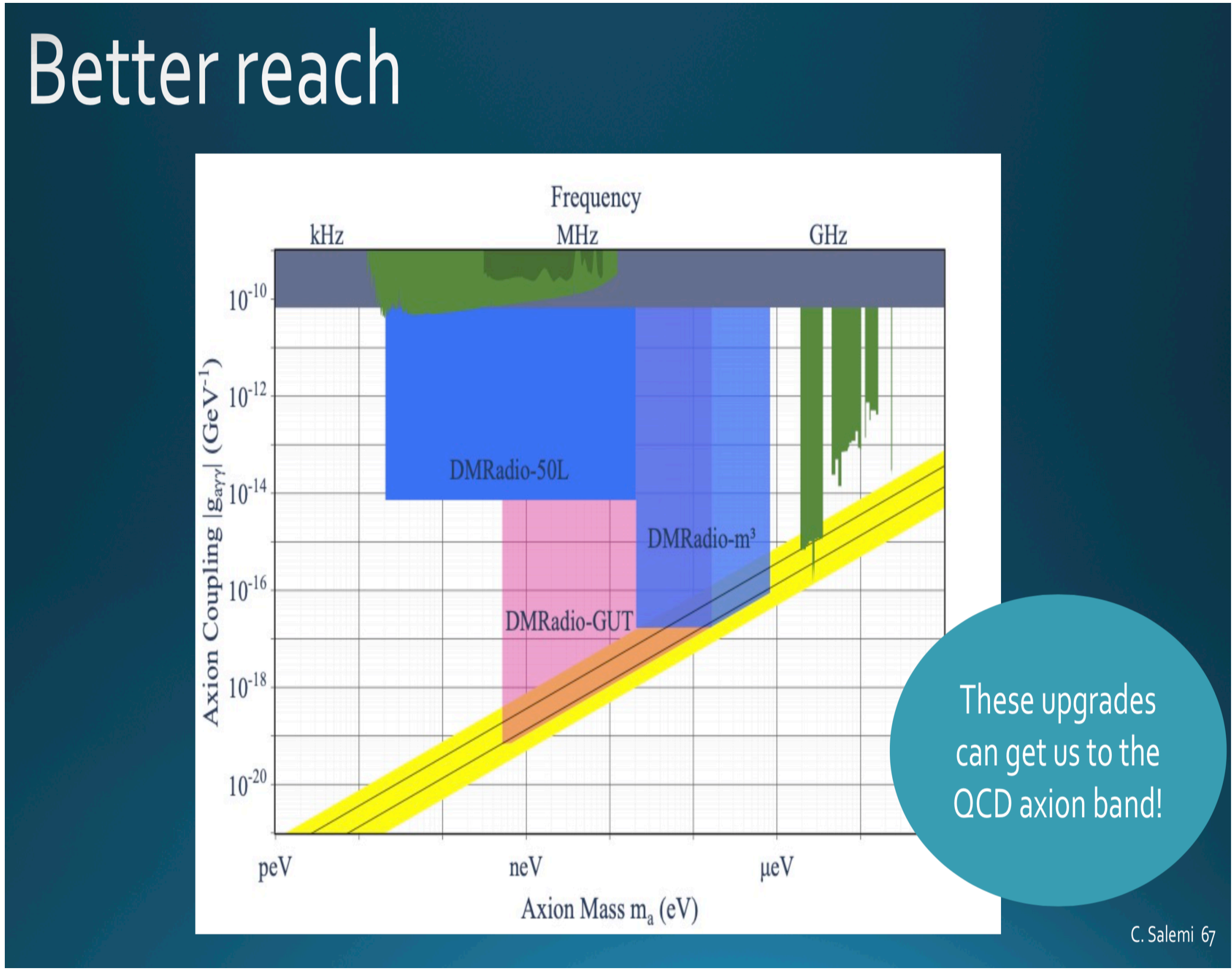
- DM-Radio Cubic Meter Consortium: aims to reach the canonical axion band, even reaching predictions from GUTs

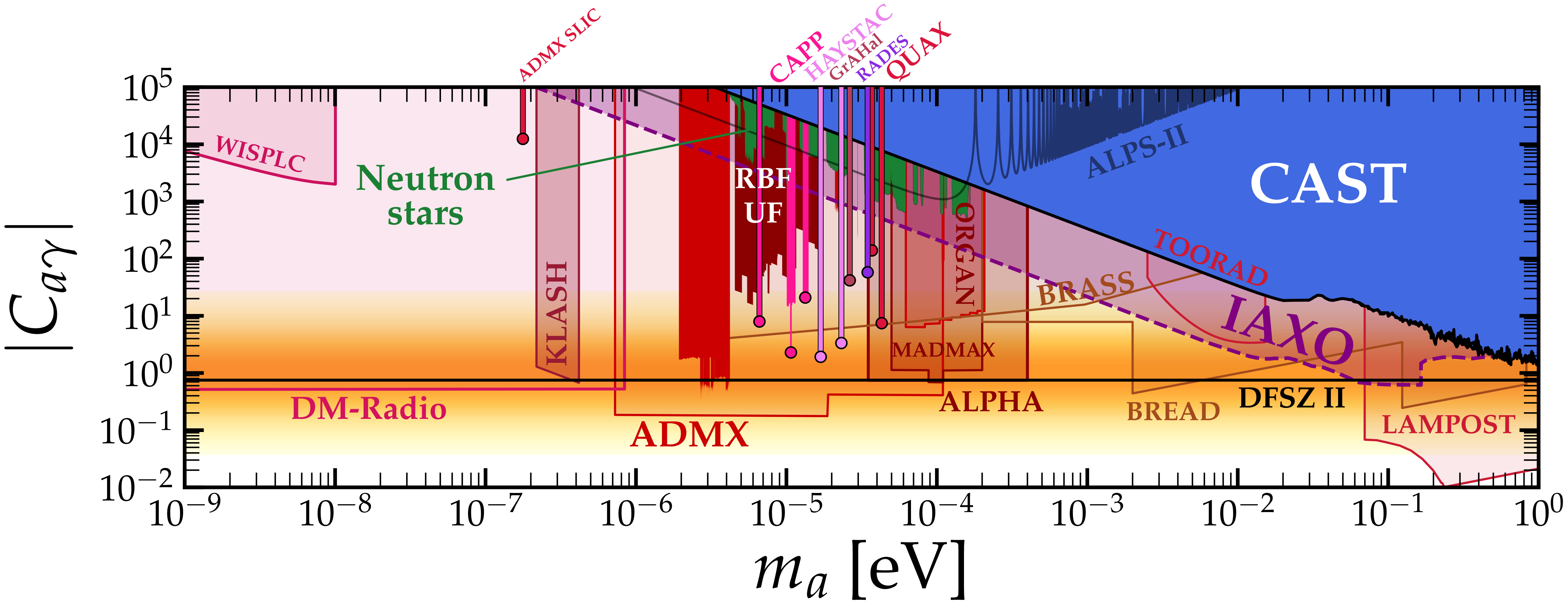
[Ernst,AR,Tamarit 18; Di Luzio,AR,Tamarit 18]



[Salemi '21]

Axion Dark Matter Detection

Planned haloscopes may indeed cover whole mass range within foreseeable future



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Magnetic Resonance Searches

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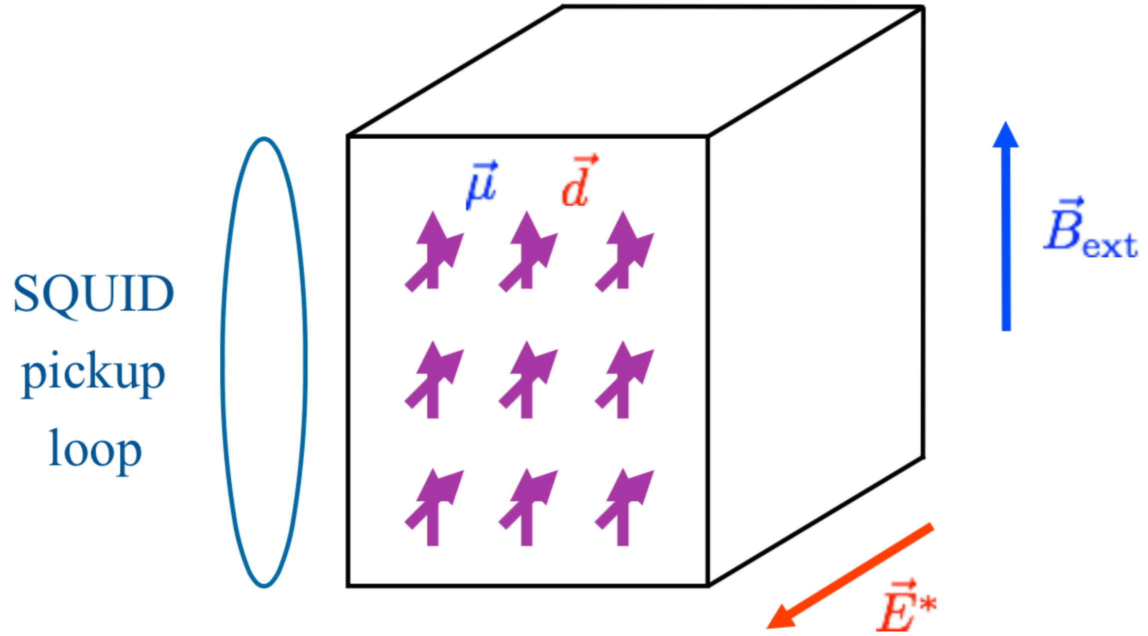

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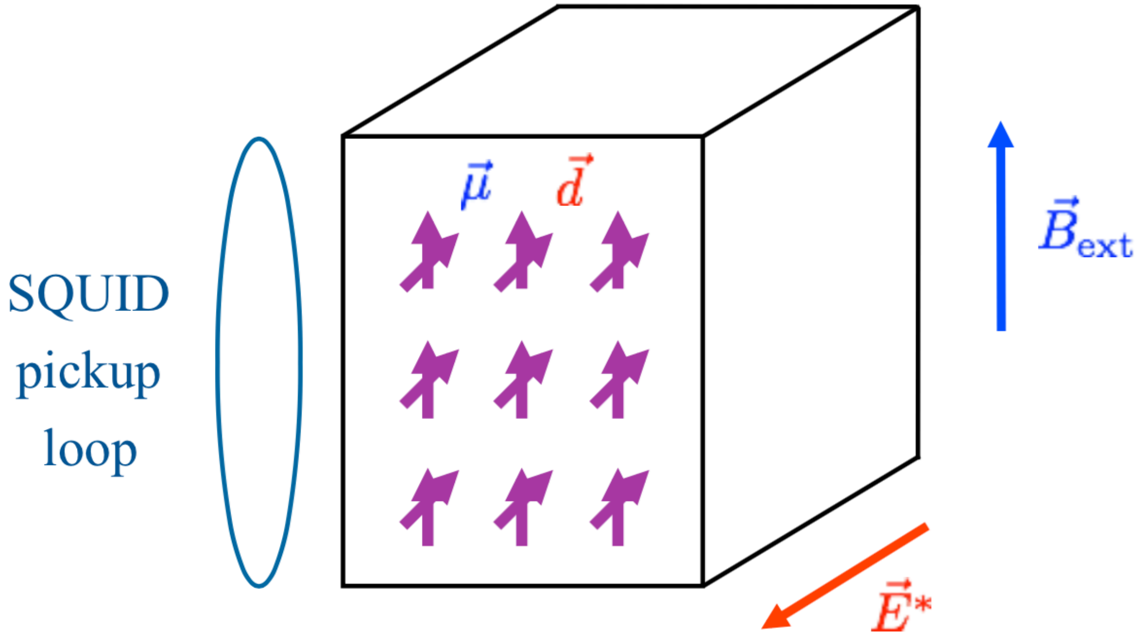

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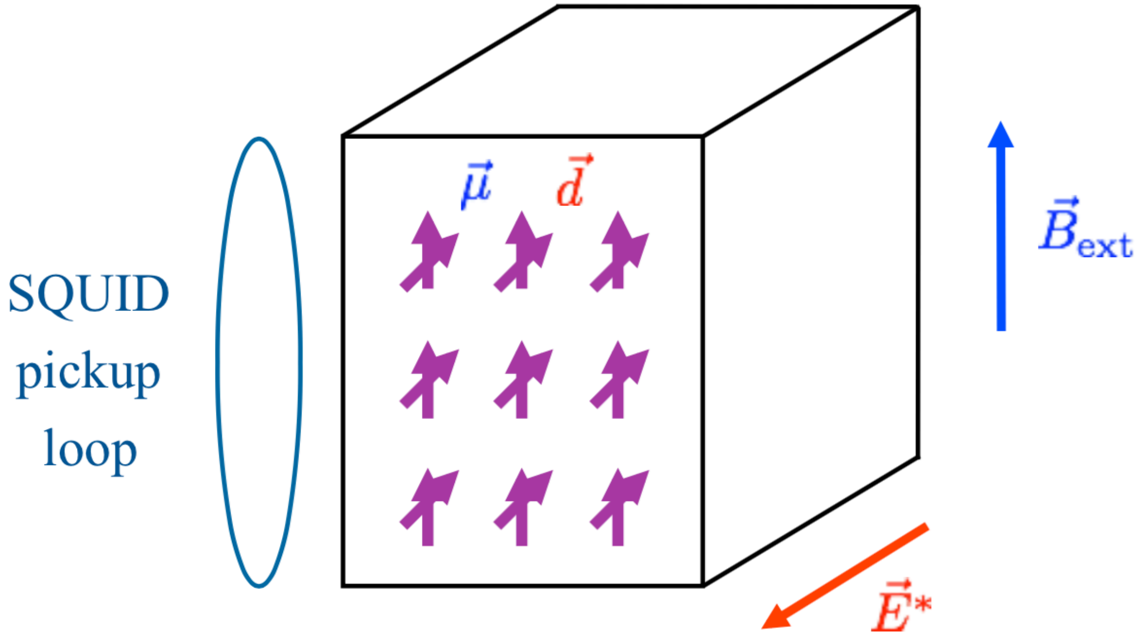

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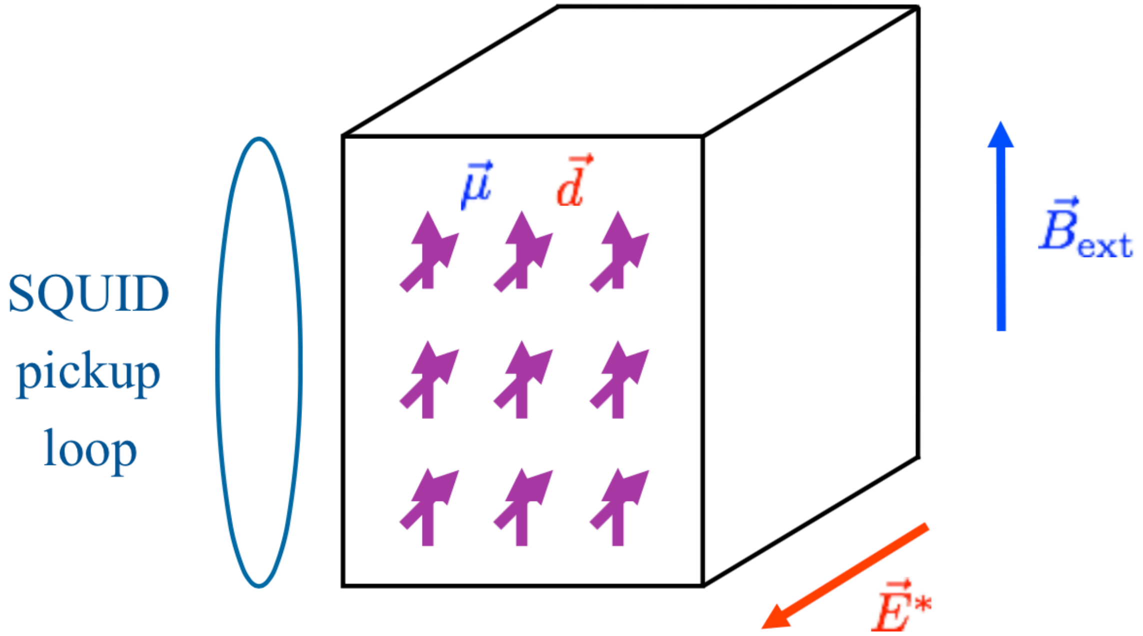

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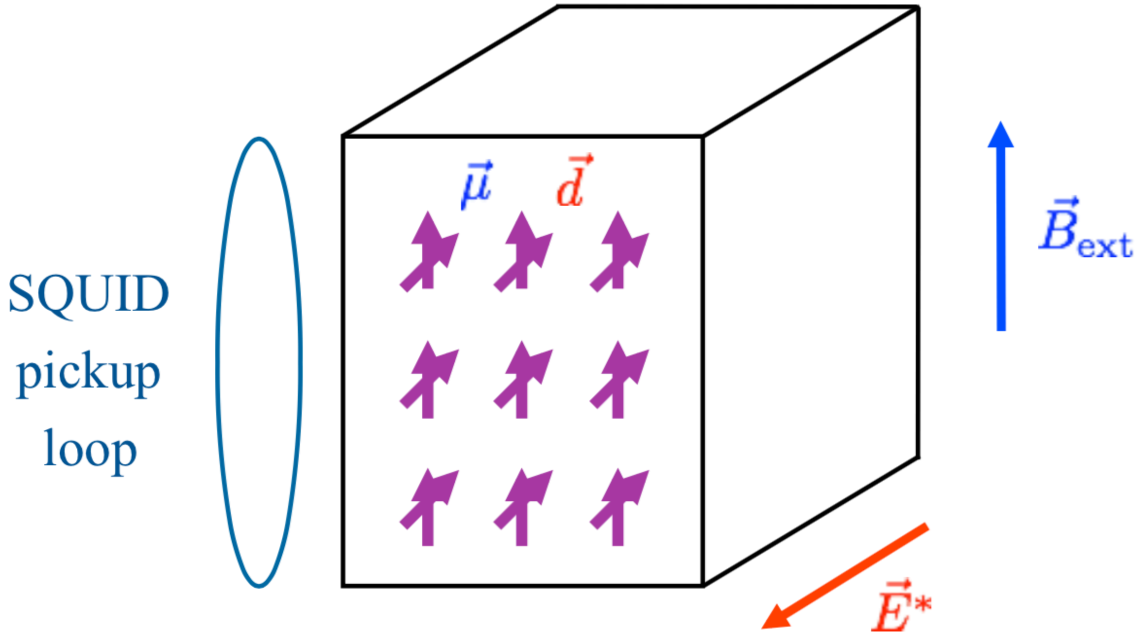

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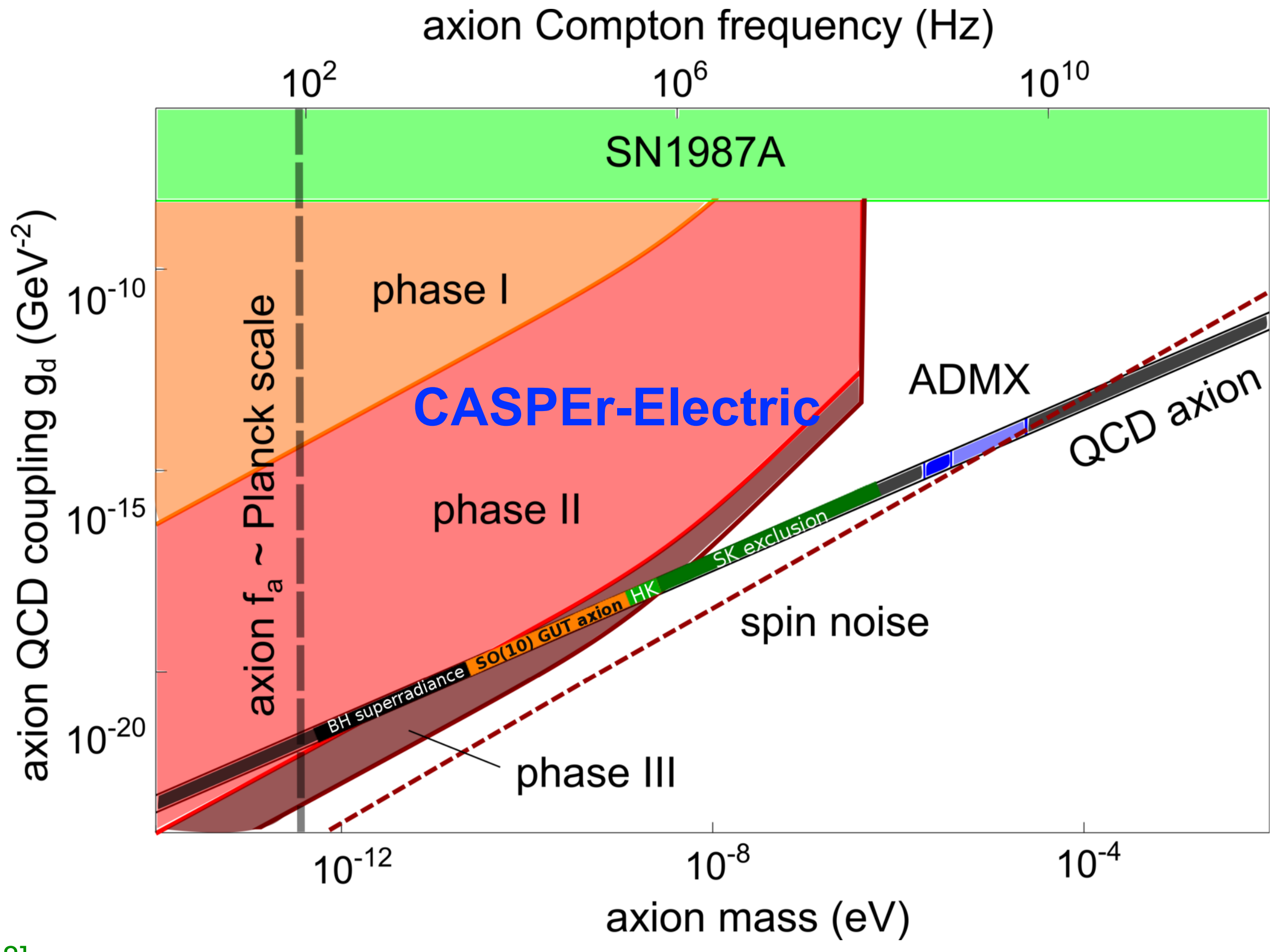

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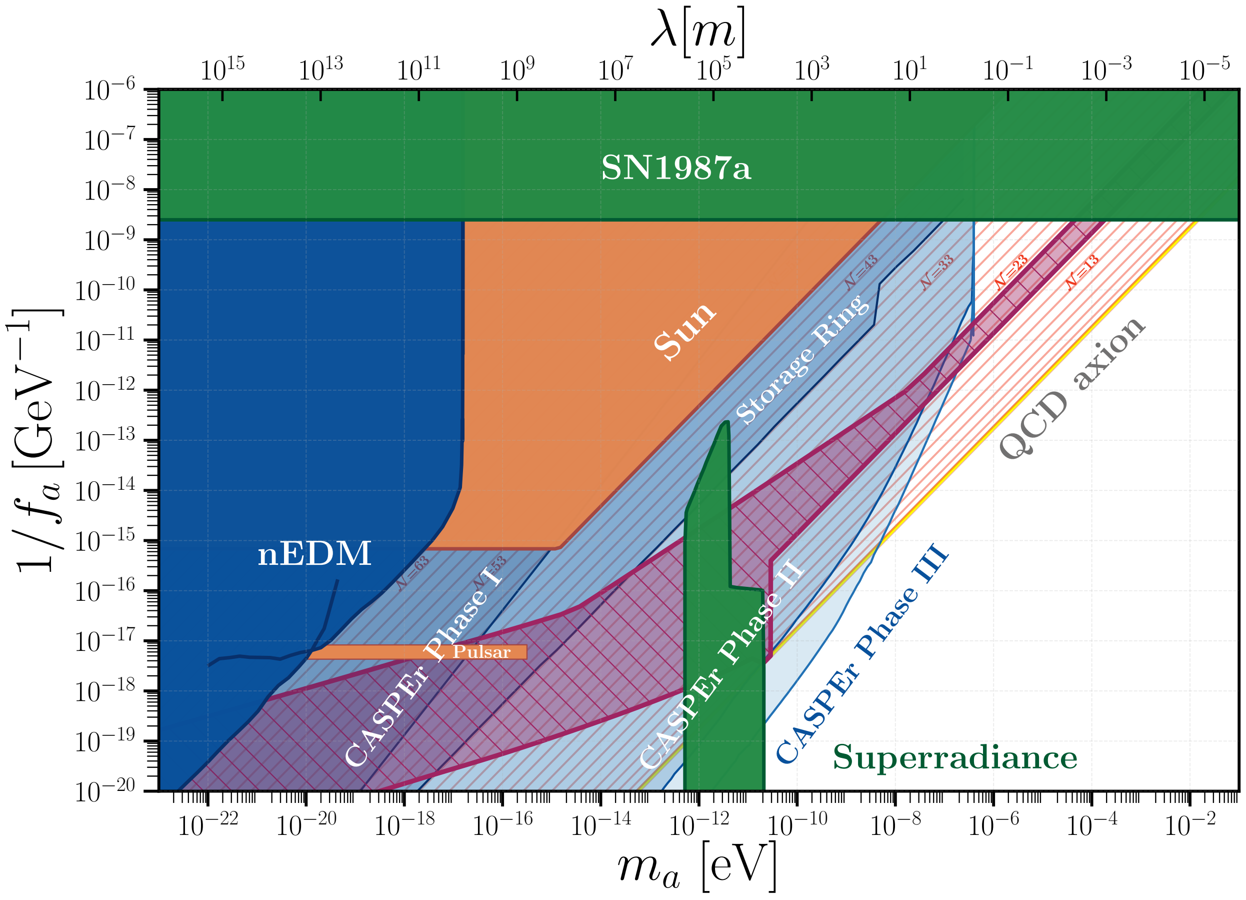
  - In phase I and II: probes Z_N axion dark matter

[Di Luzio, Gavela, Quilez, AR 2102.00012]



[Di Luzio, Gavela, Quilez, AR 2102.00012]

Light-Shining-through-a-Wall Searches

Searching for Home-Made Axions

$$\mathcal{L} \supset -\frac{g_{a\gamma}}{4}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} \equiv g_{a\gamma}\, a\, \mathbf{E}\cdot\mathbf{B}$$

$$\left(g_{A\gamma} \equiv \frac{\alpha}{2\pi f_A} C_{A\gamma}\right)$$

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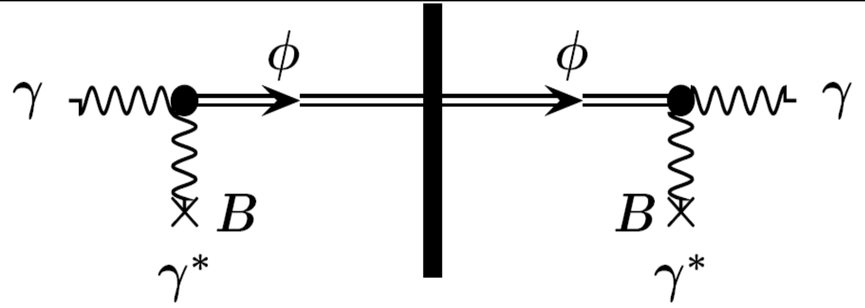

[Sikivie 1983, Ansel'm 1985, van Bibber et al. 1987]

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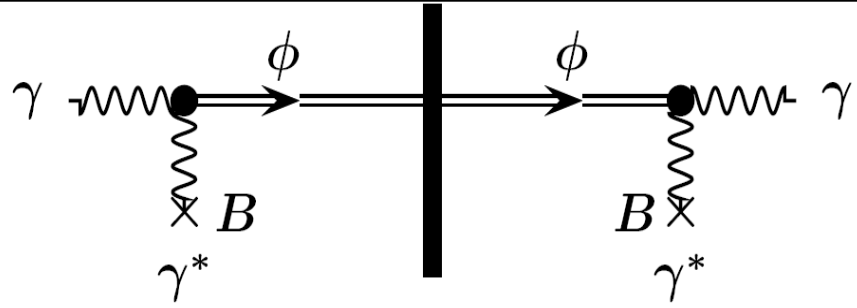

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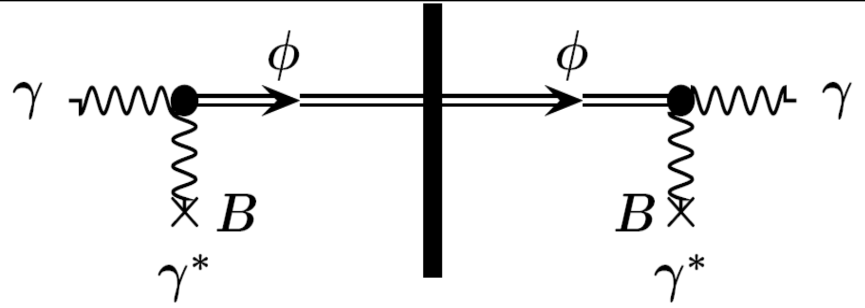

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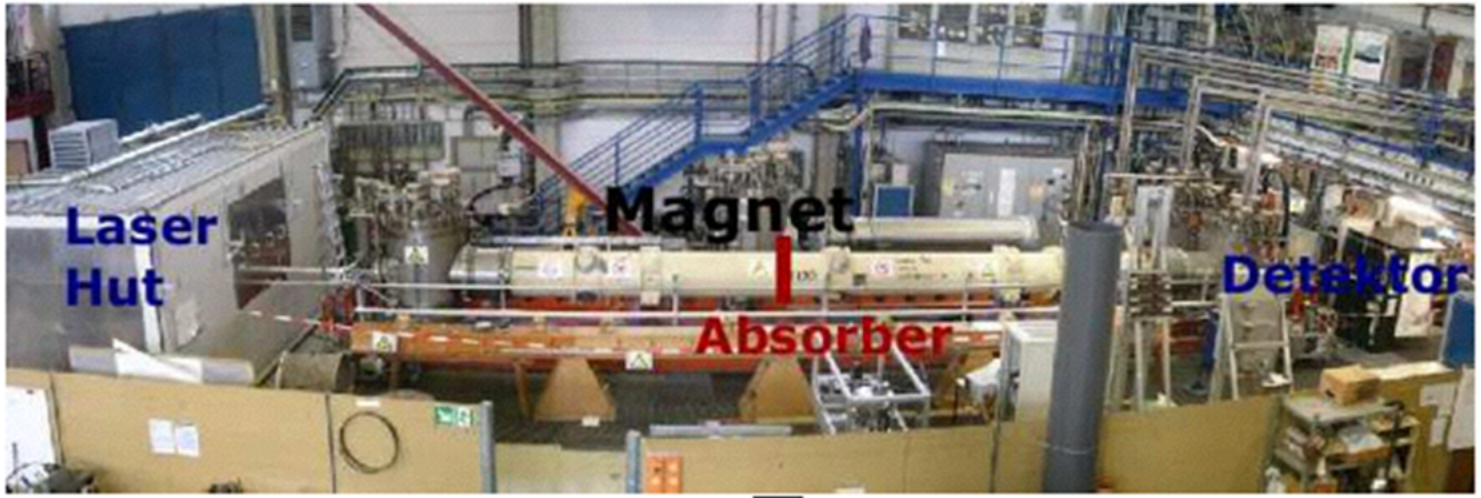
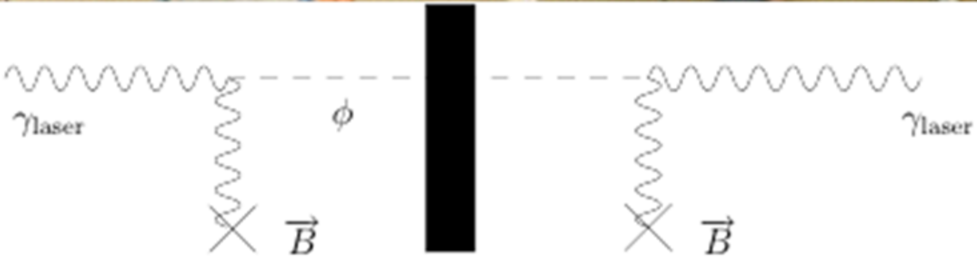
- Best sensitivity for $m_a \ll \left(\frac{4\pi\omega}{L_B}\right)^{1/2}$: $\quad P(\gamma \leftrightarrow a) \simeq \frac{1}{4}\,(g_{a\gamma} B L_B)^2$

Light-Shining-through-a-Wall Searches

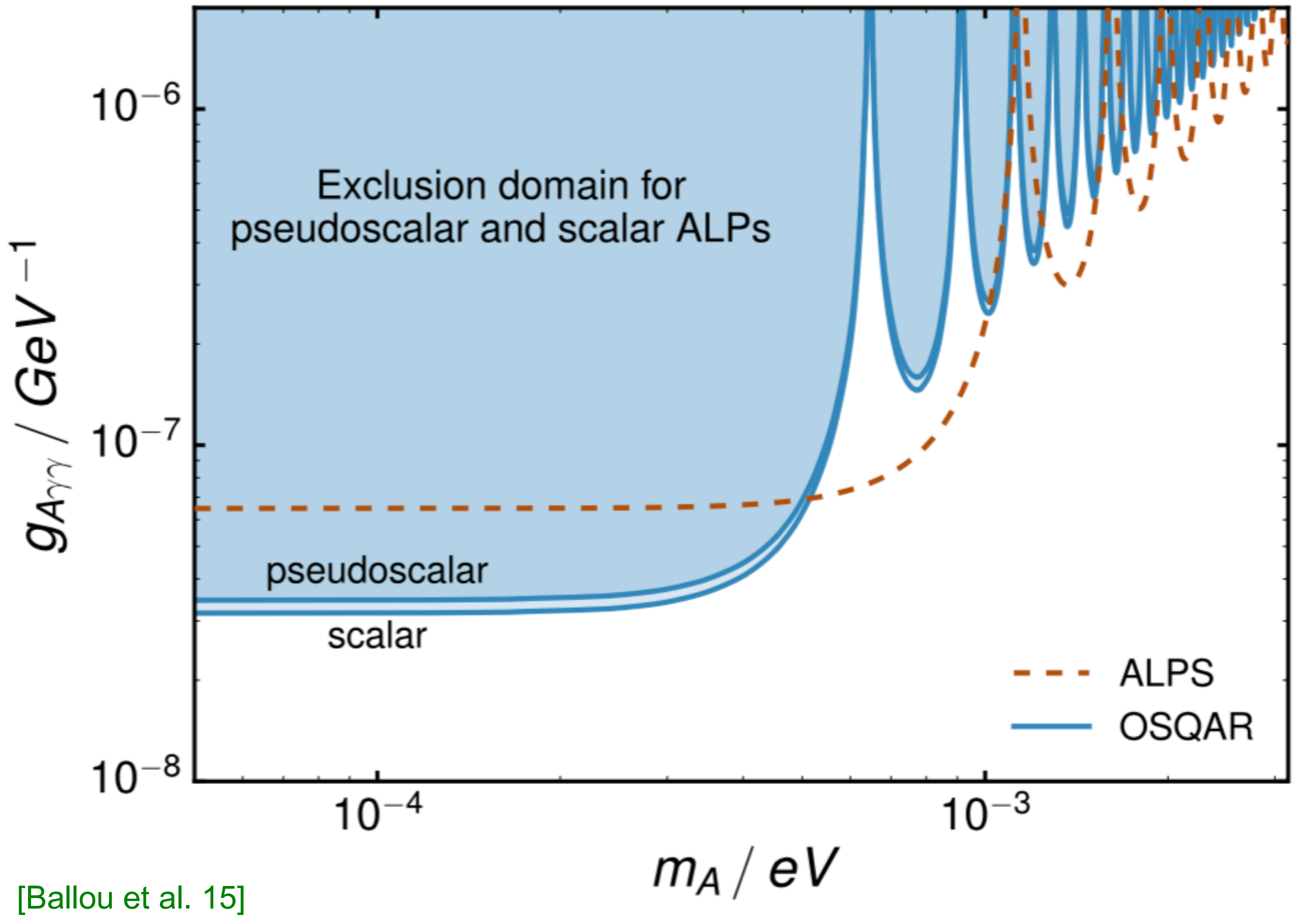
- ALPS I @ DESY (in collaboration with AEI Hannover and U Hamburg) [AR 03;....;Ehret et al. 10]





Light-Shining-through-a-Wall Searches

- ALPS I and OSQAR @ CERN give currently the best purely laboratory limit on low mass ALPs:



[Ballou et al. 15]

Light-Shining-through-a-Wall Searches

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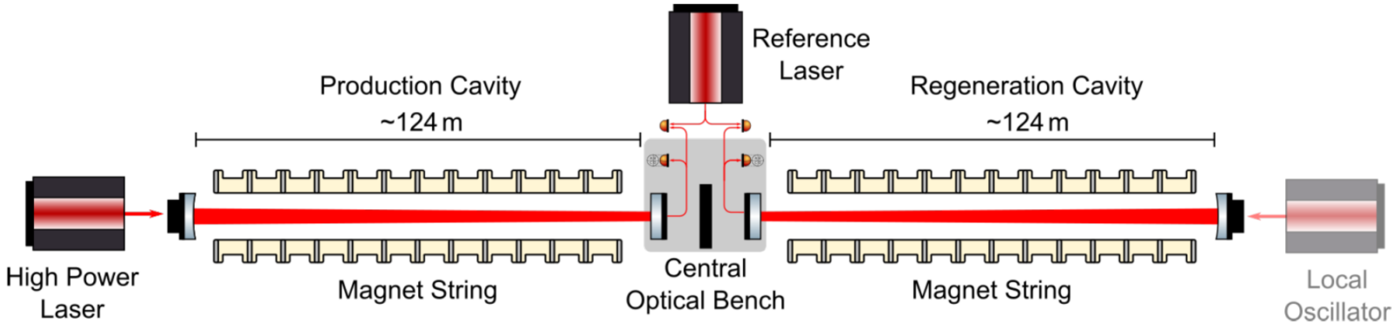

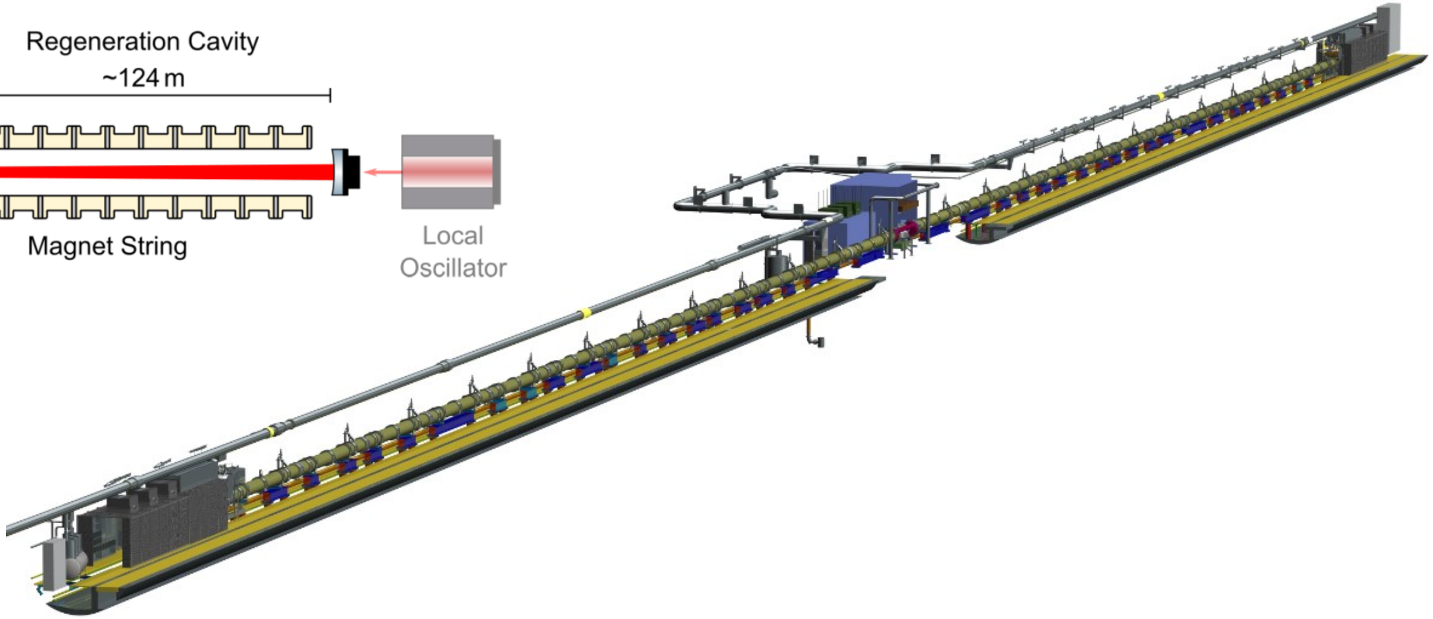

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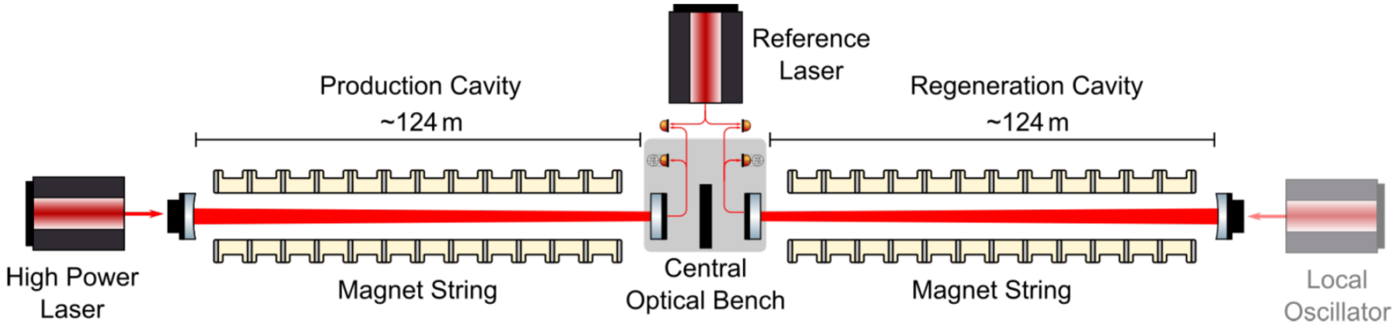

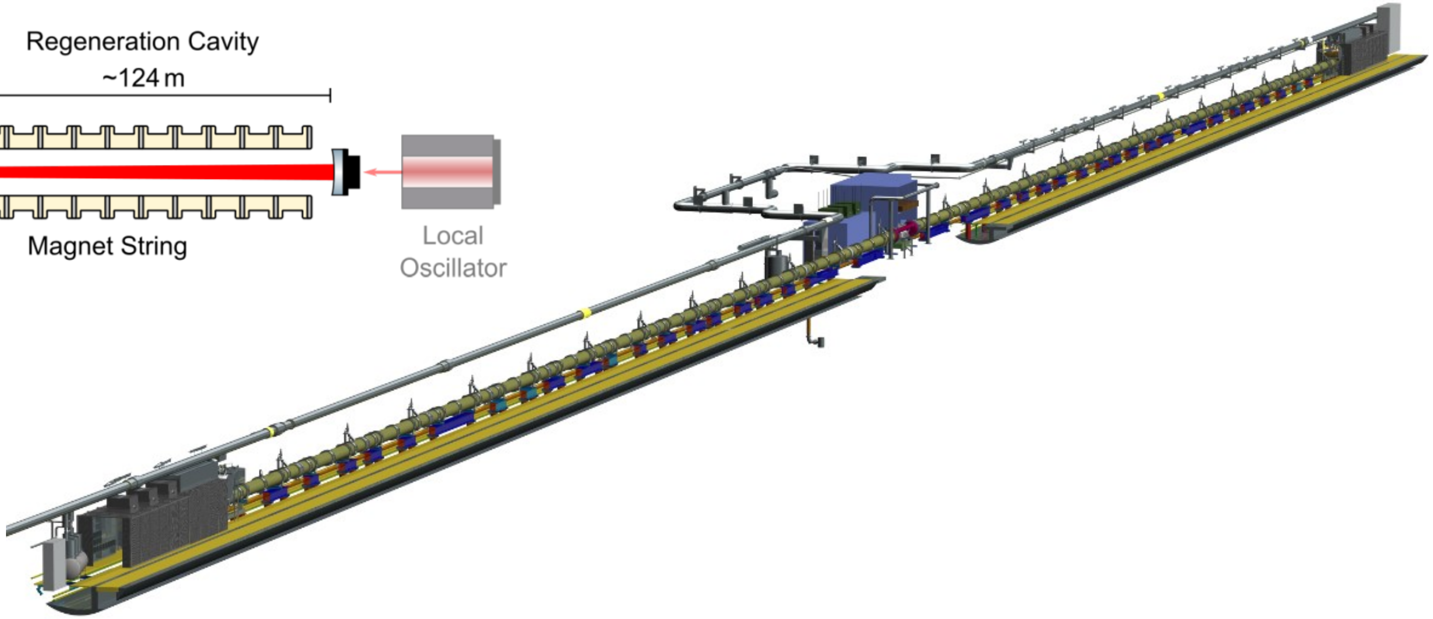

    - Optical cavities both at production and regeneration sites

[Hogeveen,Ziegenhagen 91;Sikivie,Tanner,van Bibber 07]

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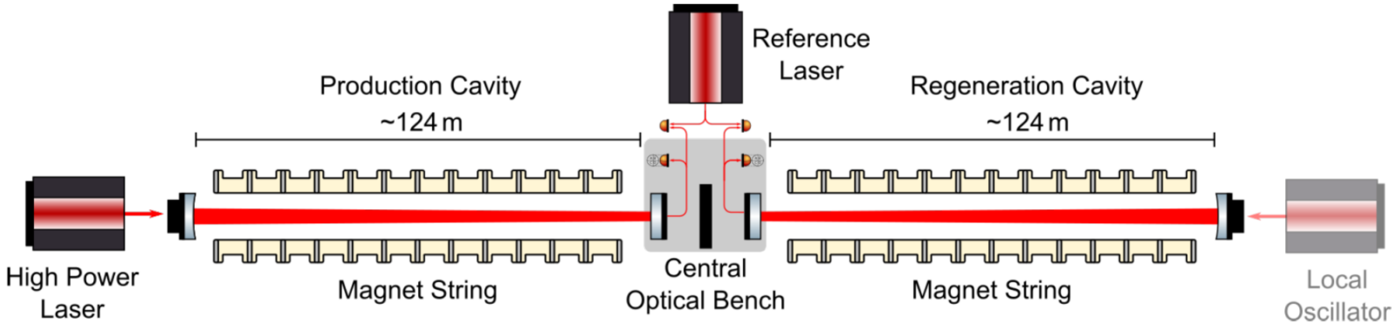
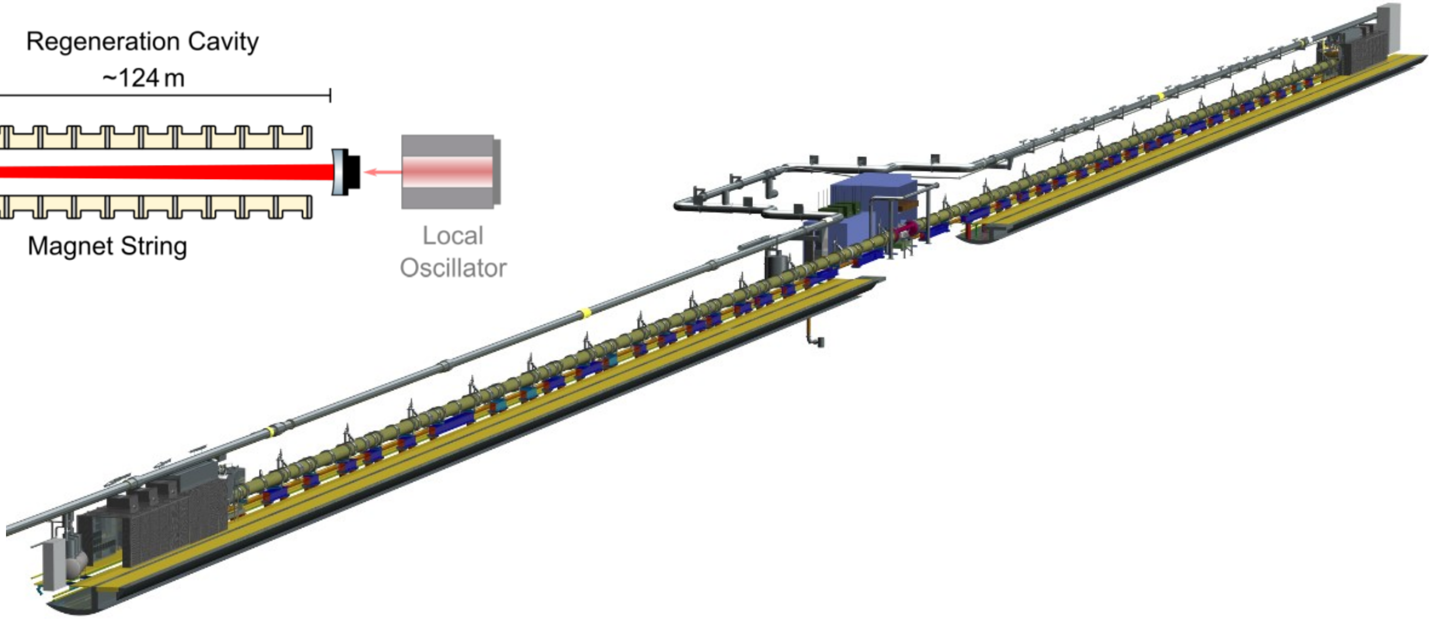
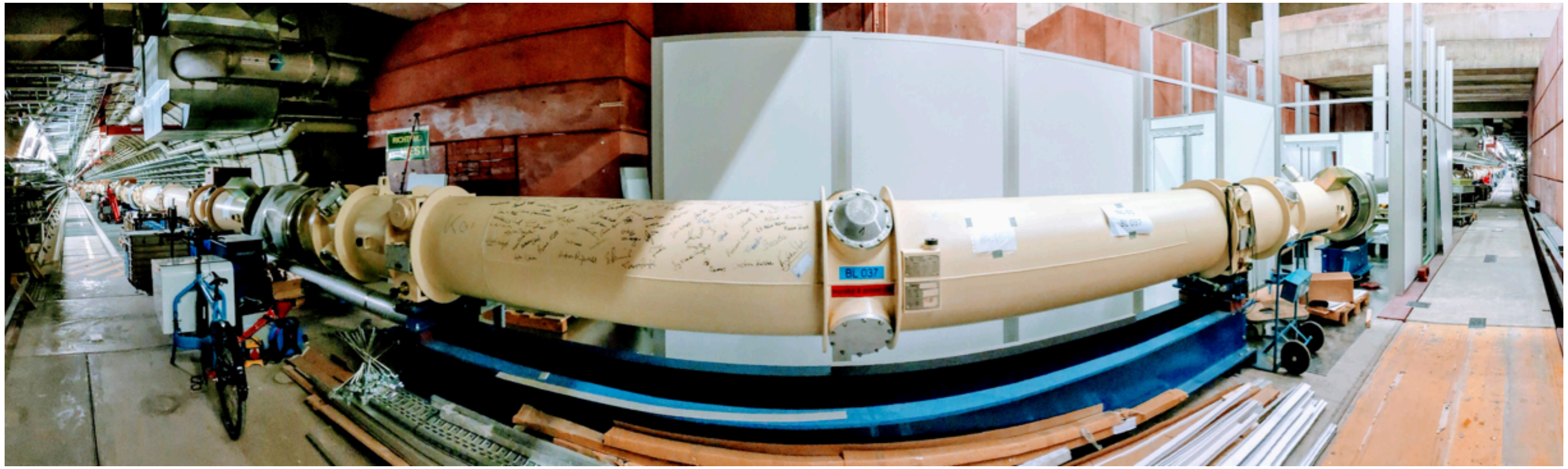


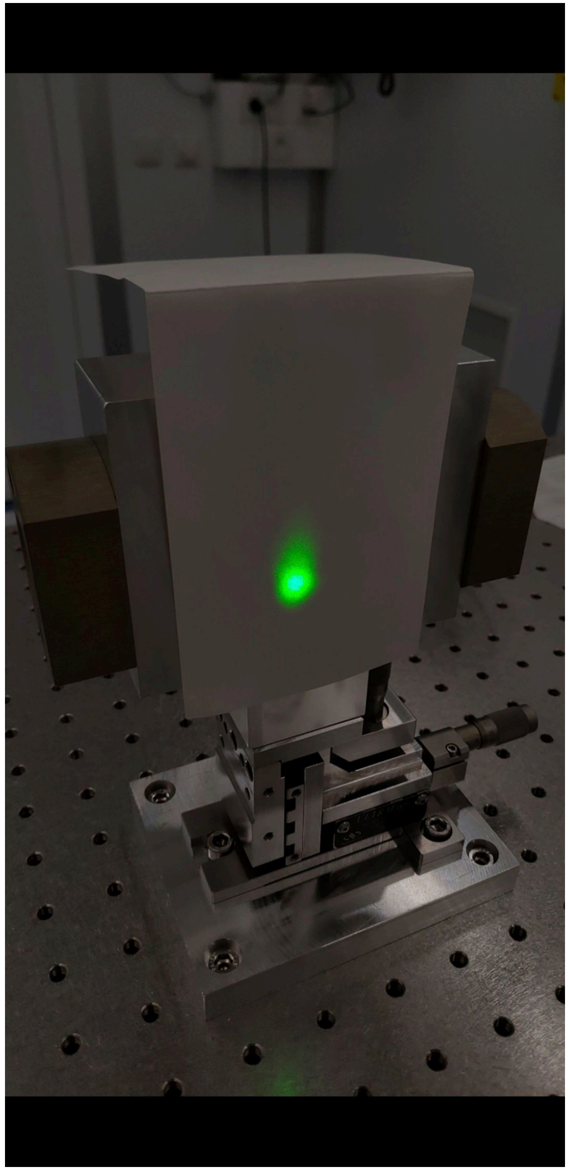


    - Optical cavities both at production and regeneration sites [Hogeveen,Ziegenhagen 91;Sikivie,Tanner,van Bibber 07]
    - Two detection techniques:
      - Heterodyne
      - Transition Edge Sensor (TES)

Light-Shining-through-a-Wall Searches

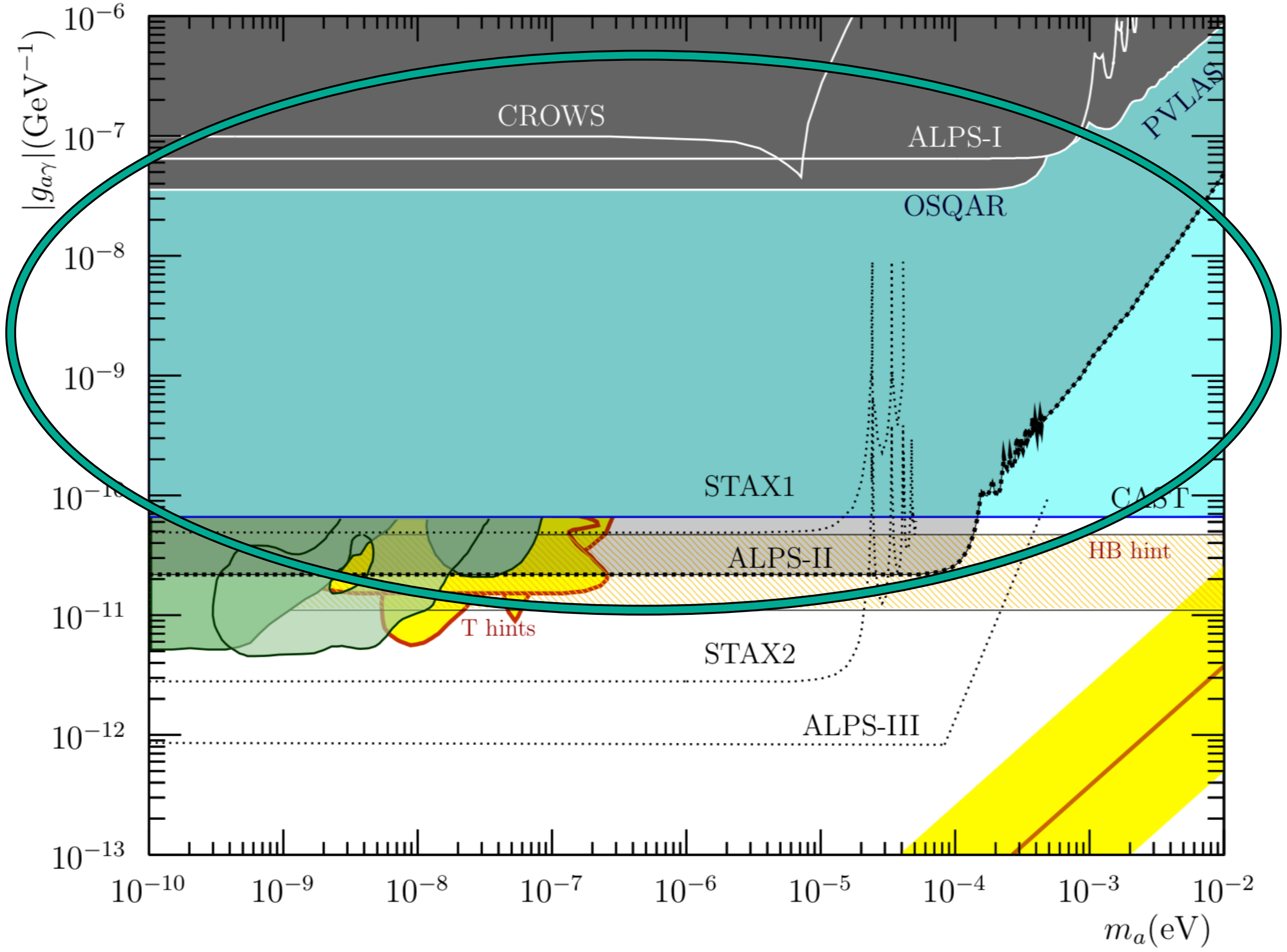
- ALPS II @ DESY (in collaboration with AEI Hannover, U Cardiff, U Florida, U Mainz)
  - Construction progressing:
    - All 24 magnets are installed and aligned
    - Cleanrooms at end stations are operational
    - Commissioning of the optical system has begun
      - Alignment laser through the beam tube accomplished
    - Test operation of magnets ongoing
  - First science run scheduled for Fall 2022





Light-Shining-through-a-Wall Searches

- ALPS II designed to beat astrophysical constraints and check astrophysical hints of axions:



[Irastorza, Redondo `18]

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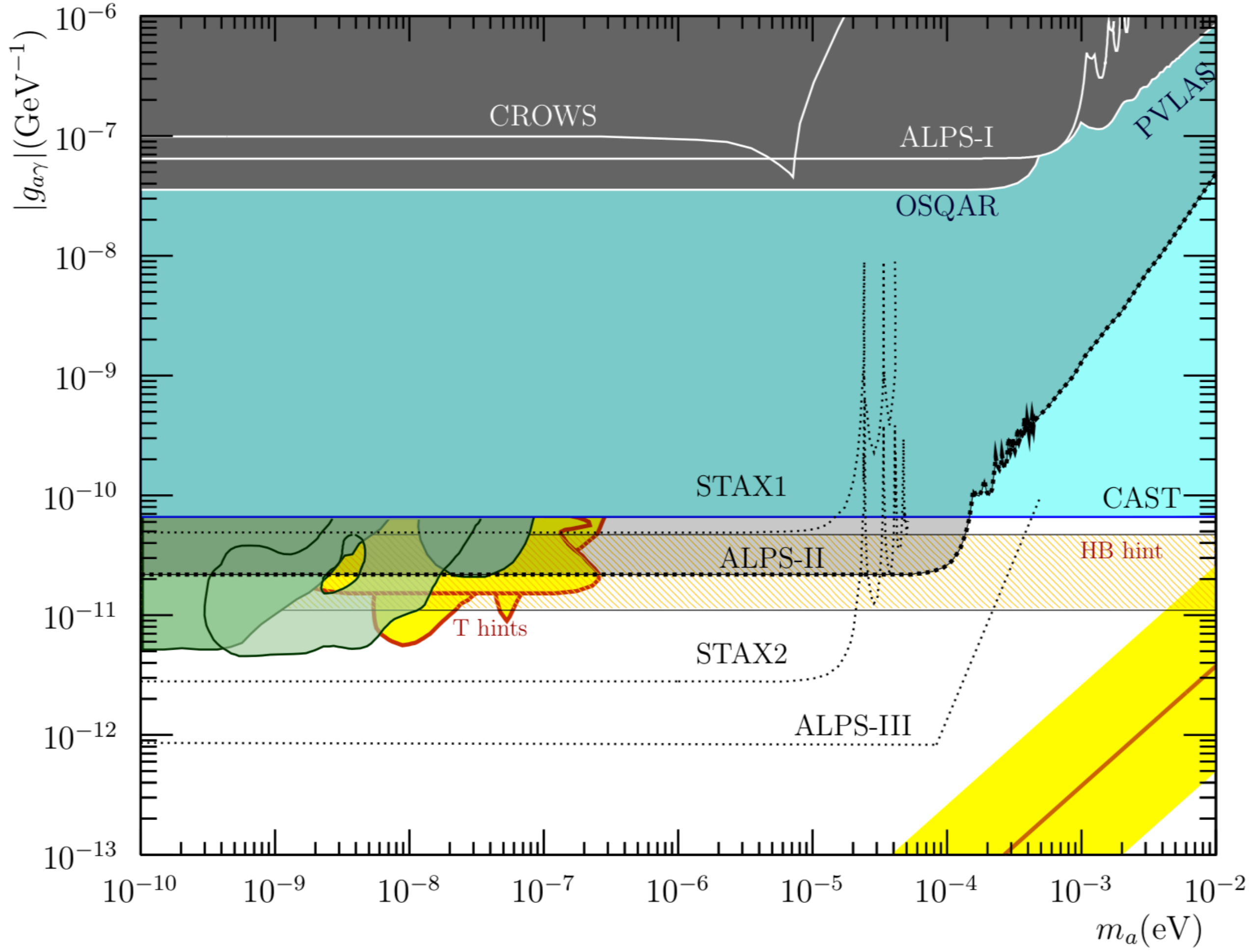

[Irastorza, Redondo `18]

- Proposed next generation LSW experiments

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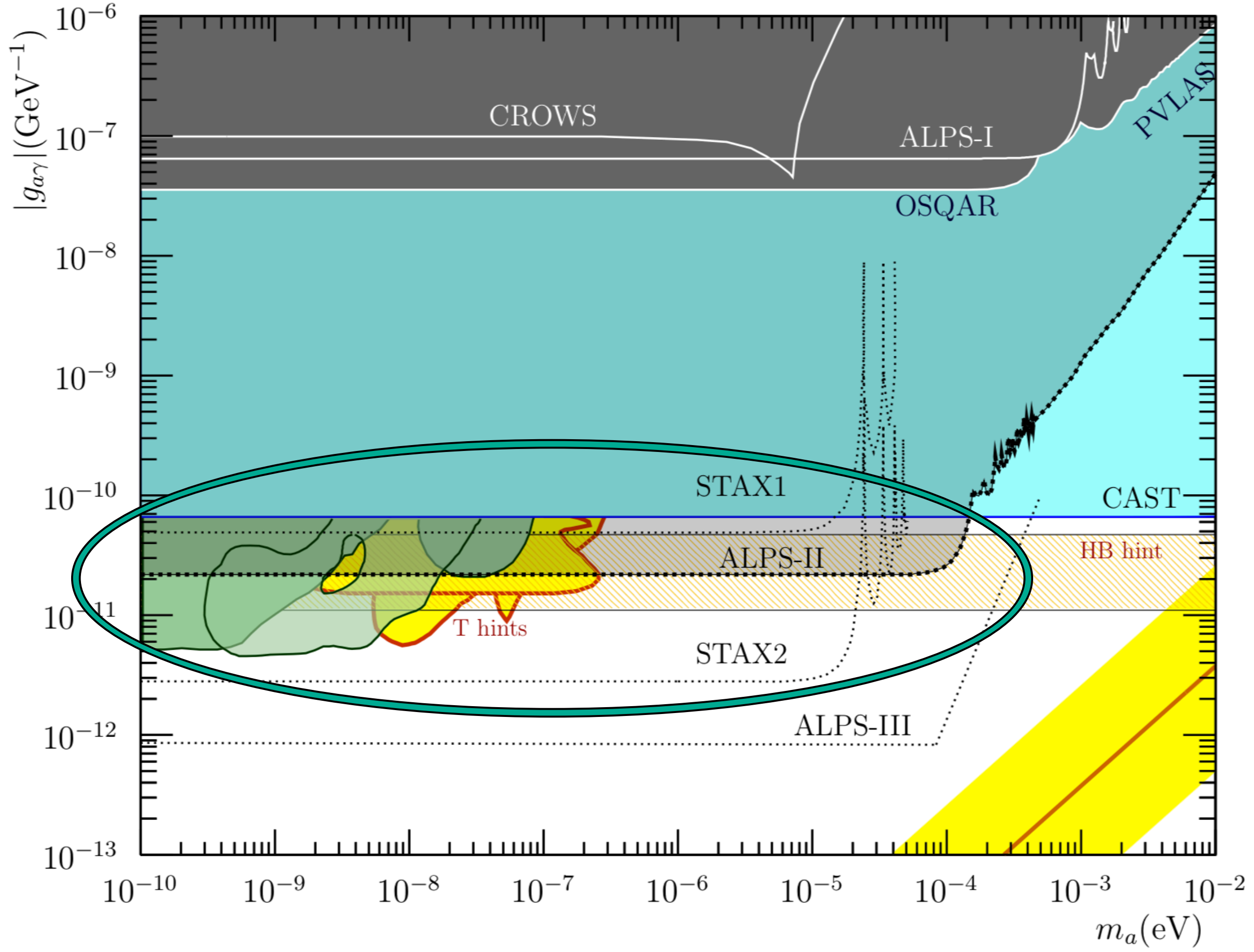

[Irastorza, Redondo `18]

- Proposed next generation LSW experiments
  - **STAX**: [Capparelli et al. `15]
    - Photon source: GHz gyrotron
    - Challenges of microwave range:
      - Resonant photon regeneration
      - Single photon detection (TES?)

[Miyazaki,Spagnolo `20]

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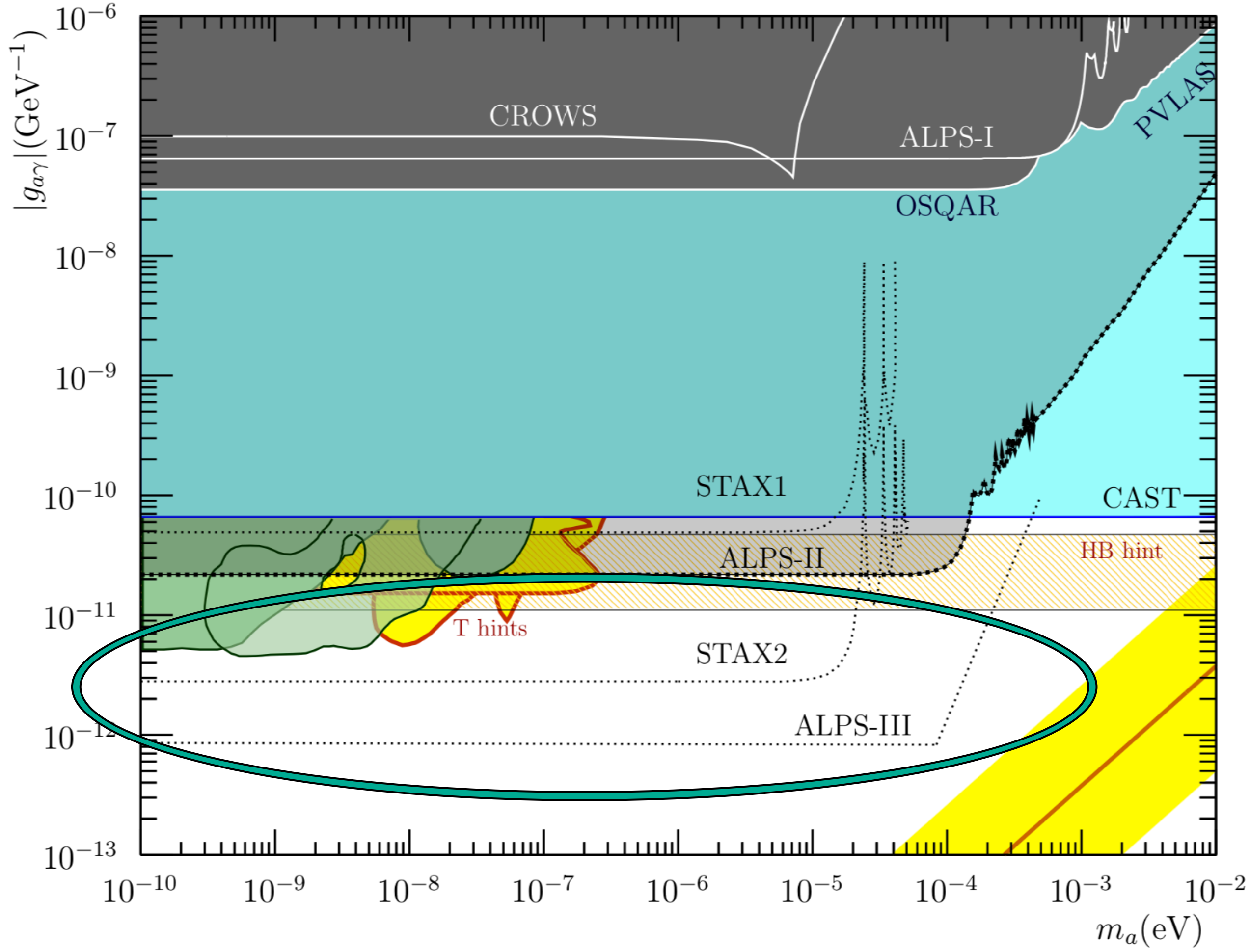

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      - Resonant photon regeneration
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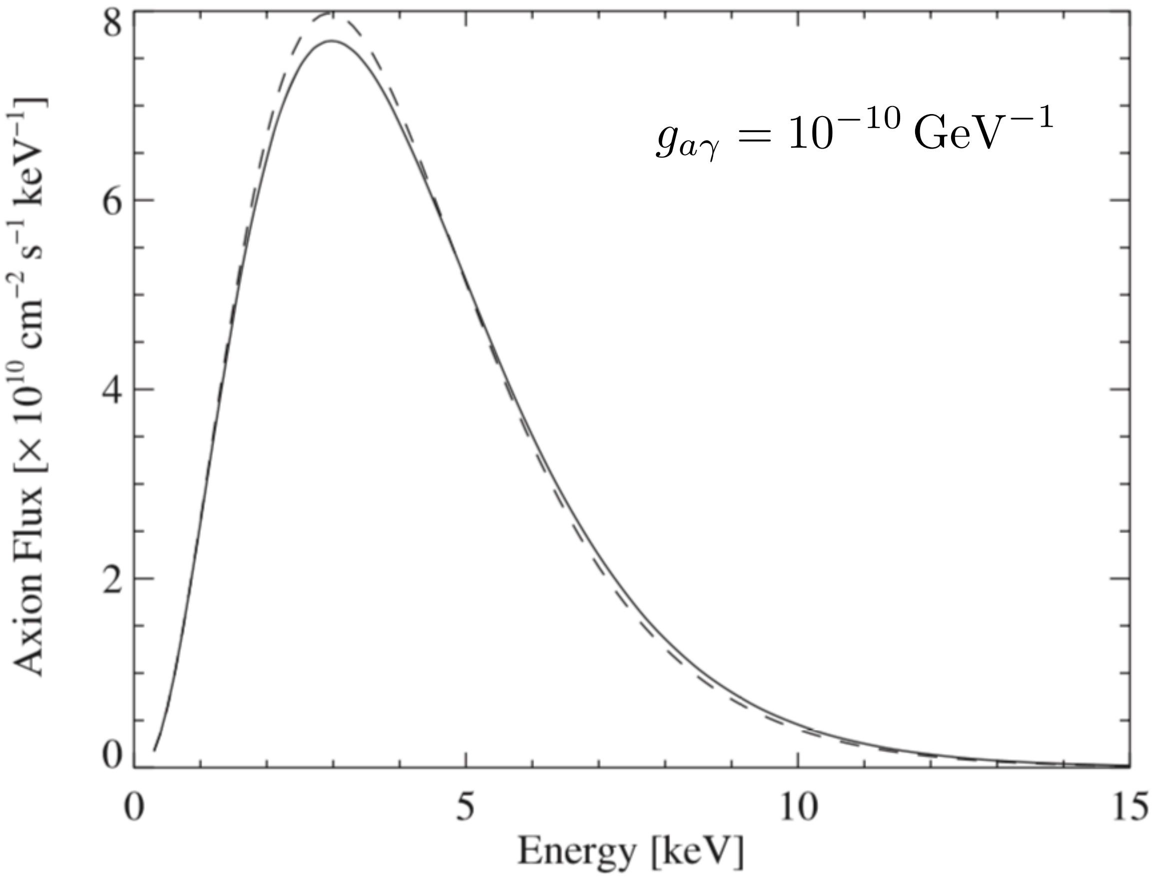
      [Miyazaki,Spagnolo `20]
  - **ALPS III** (aka JURA)

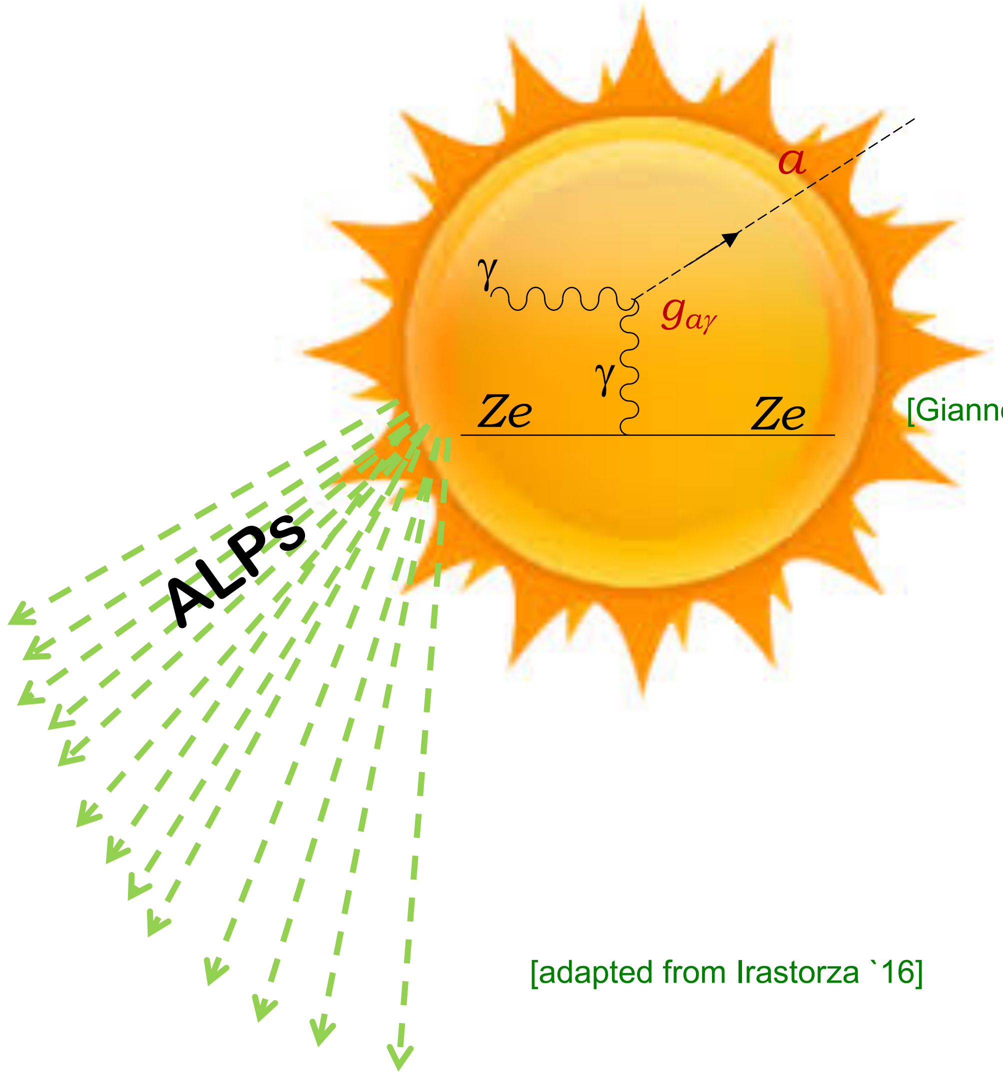
    [Lindner,Willke,Ten Kate `16]
    - 2 x 426 m long string of FCC-hh magnets (13 T)
    - MW scale optical resonator

Helioscope Searches

- Flux of solar axions/ALPs produced by two photon process in core:



[Adriamonje et al. `07]



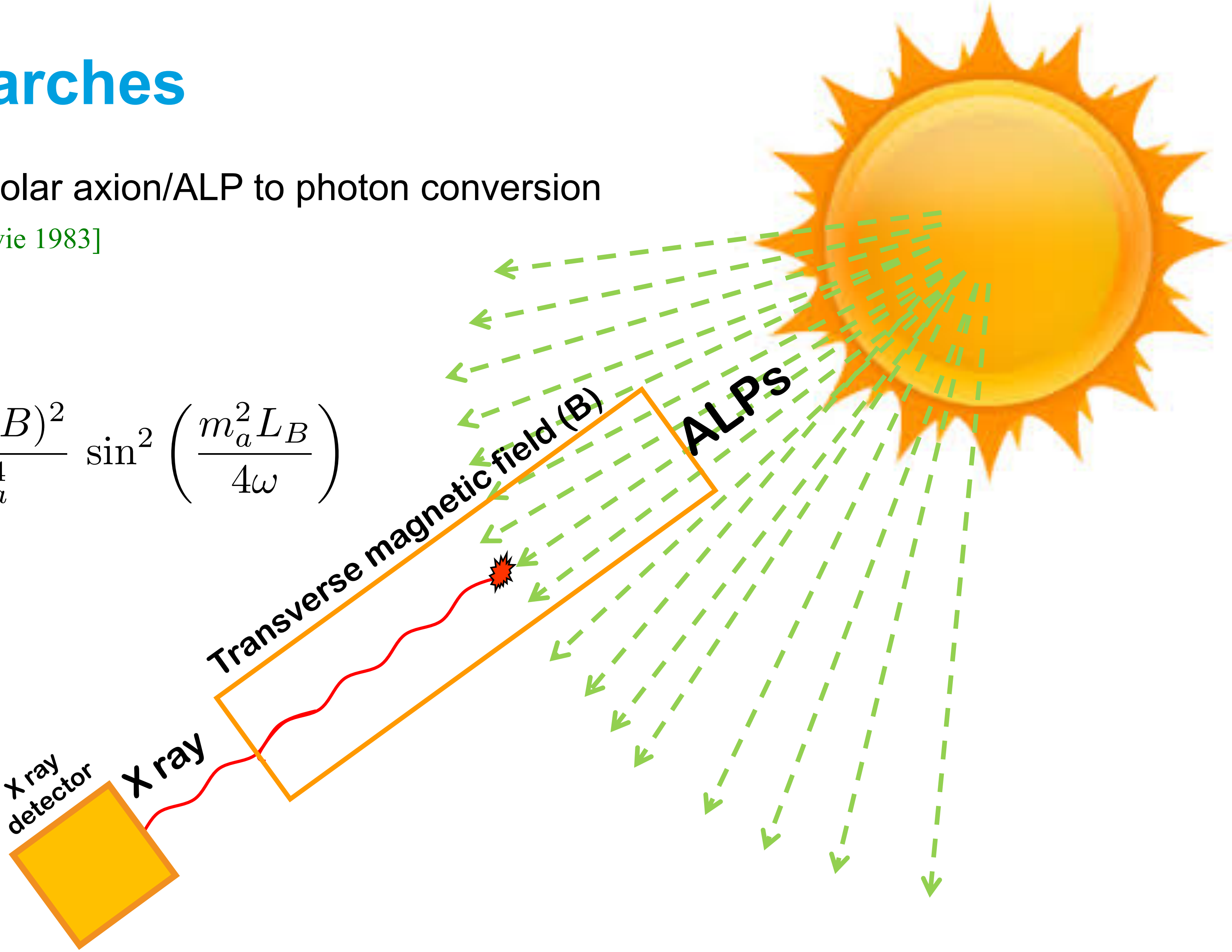
[Giannotti `16]

[adapted from Irastorza `16]

Helioscope Searches

- Helioscope concept: solar axion/ALP to photon conversion in magnetic field [Sikivie 1983]

$$P(a \to \gamma) \simeq 4\frac{(g_{a\gamma}\omega B)^2}{m_a^4}\sin^2\left(\frac{m_a^2 L_B}{4\omega}\right)$$



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Helioscope Searches

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  - Use of buffer gas to extend sensitivity to higher masses (axion band)

Helioscope Searches

- International Axion Observatory (IAXO) [IAXO CDR: JINST 9 (2014) T05002 (arXiv:1401.3233)]

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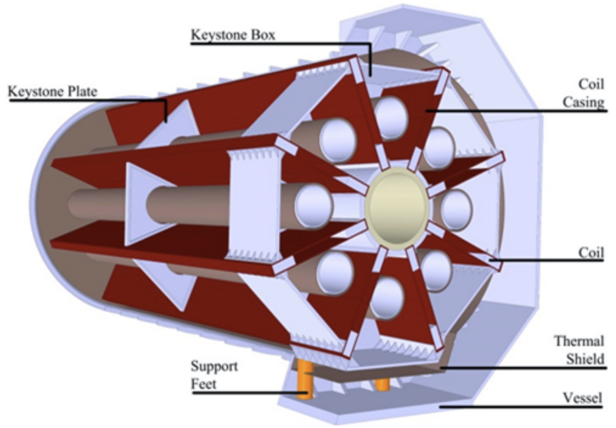

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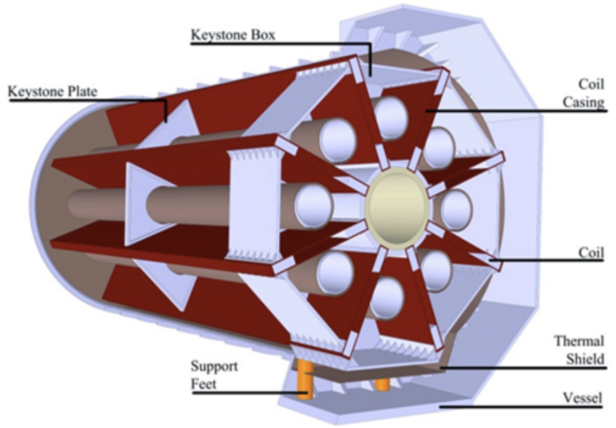

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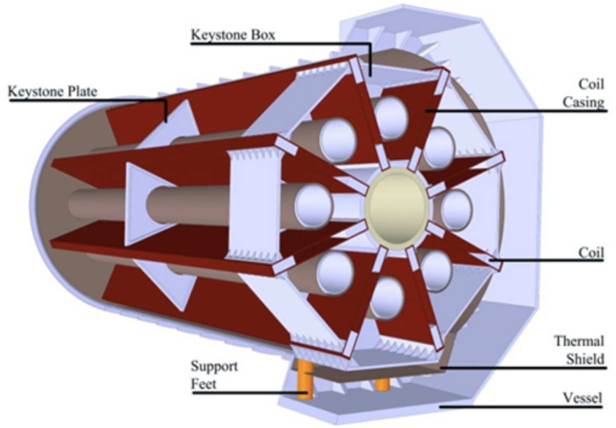

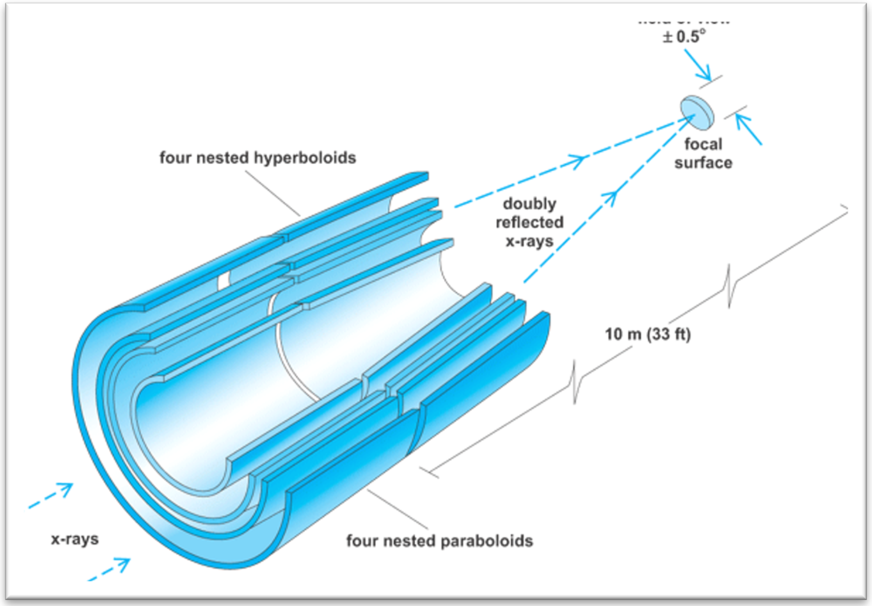

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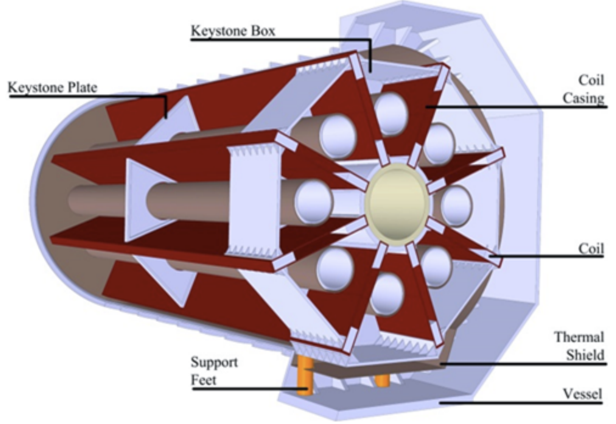

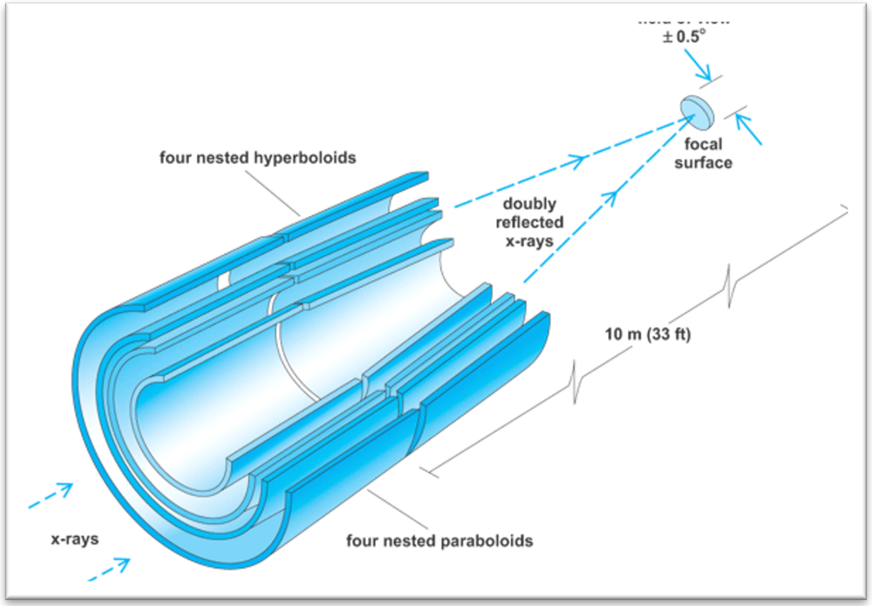

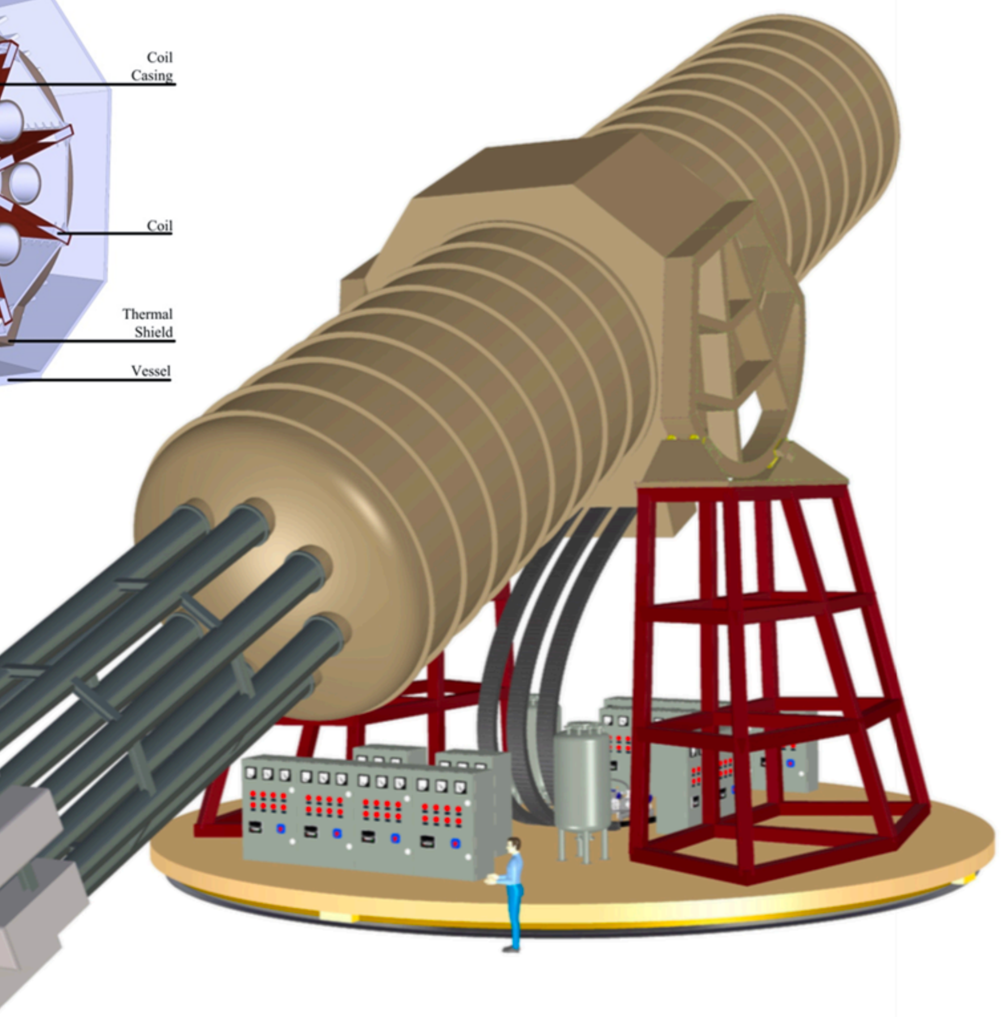

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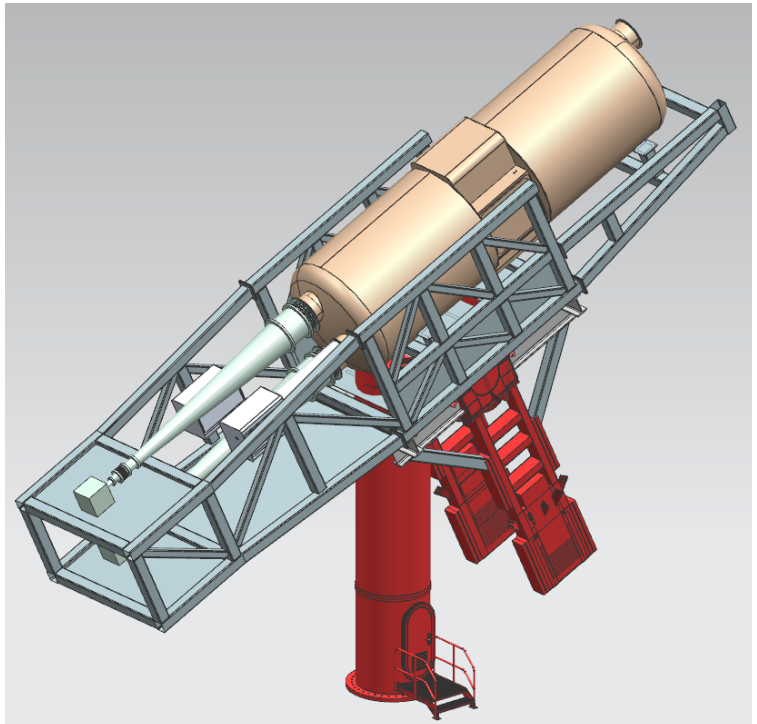

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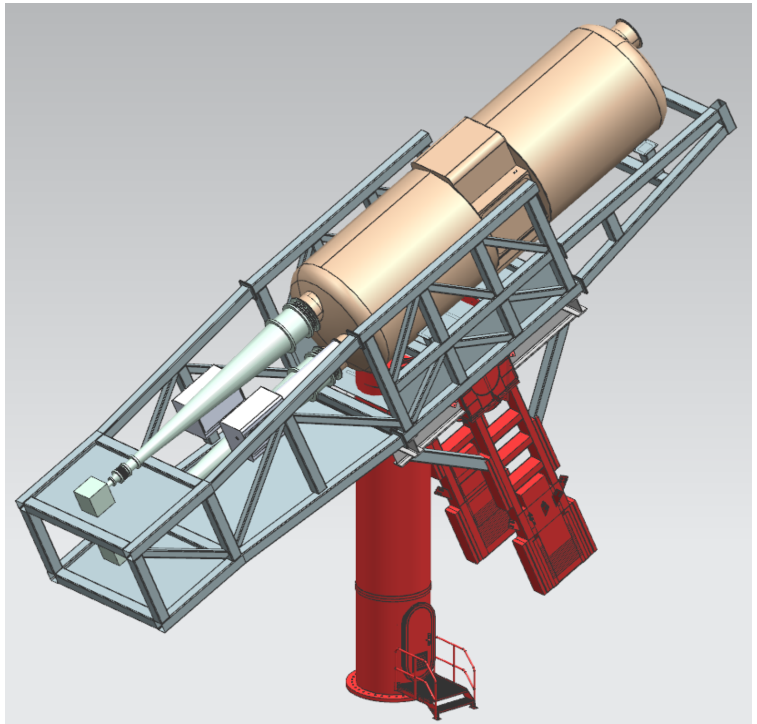

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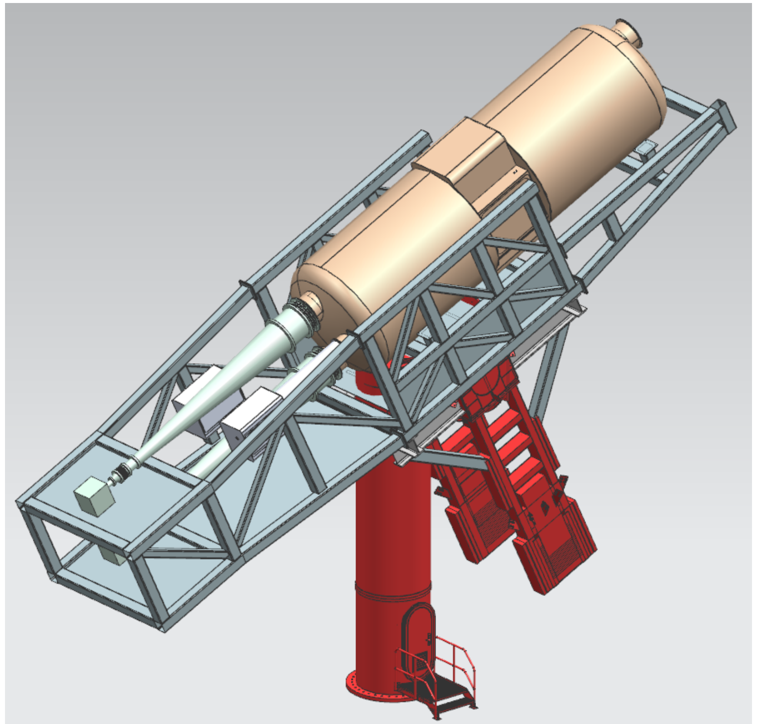

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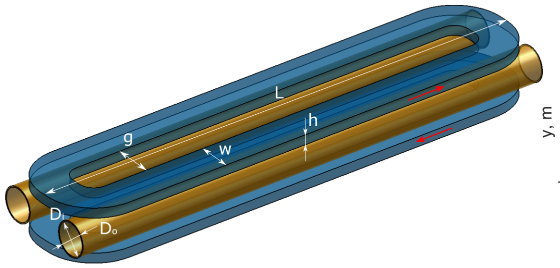

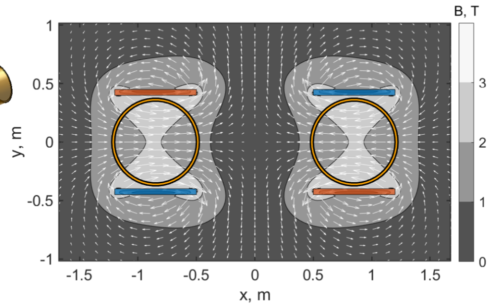

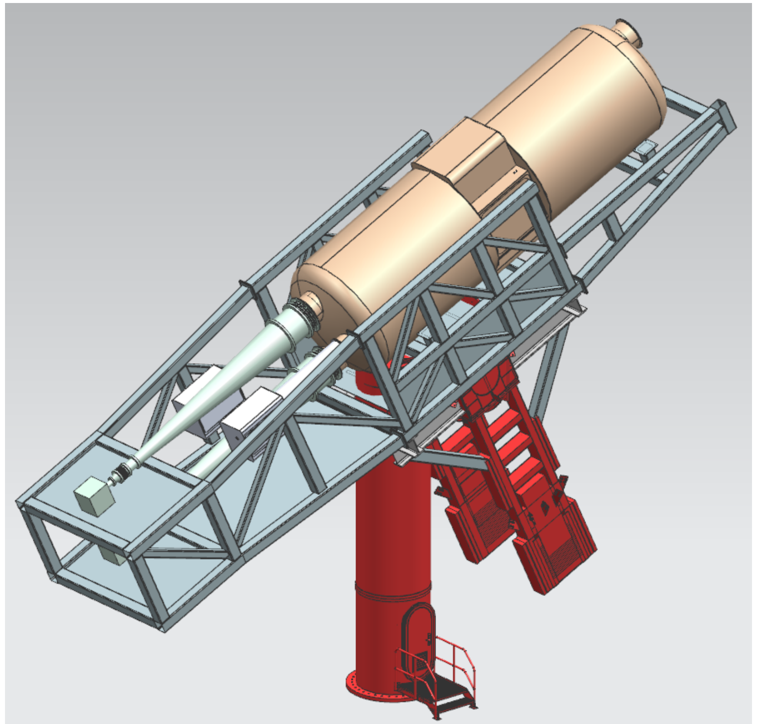

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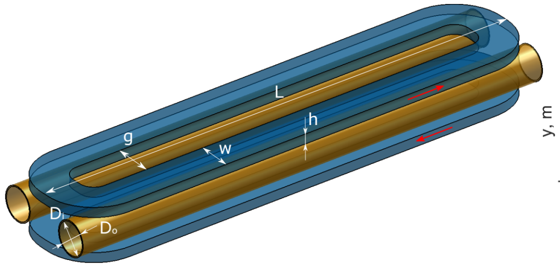

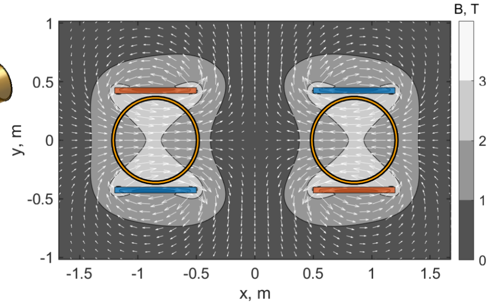

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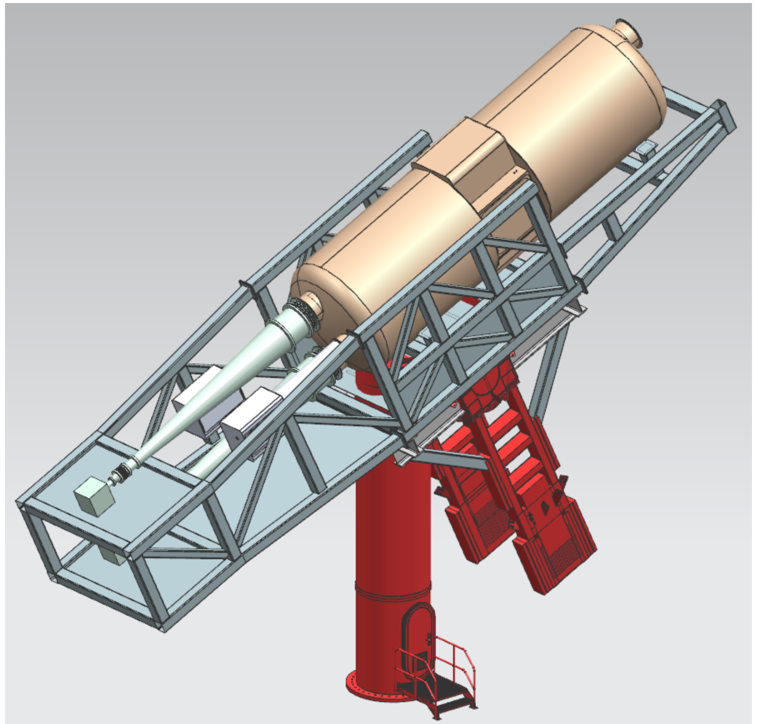

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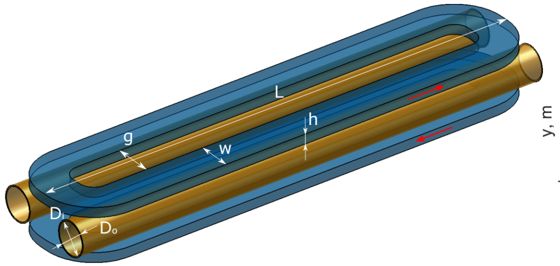

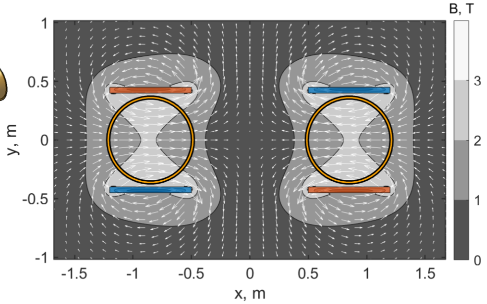

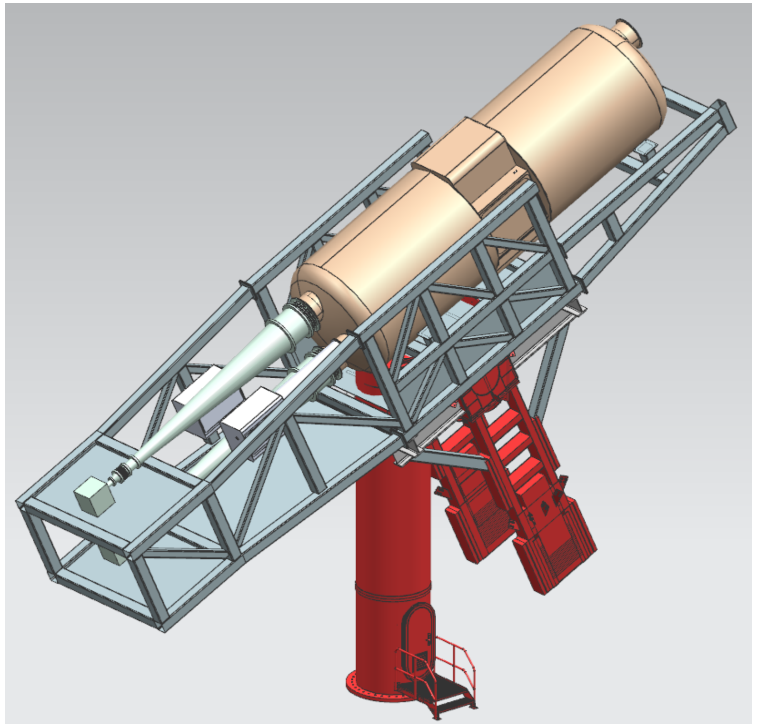

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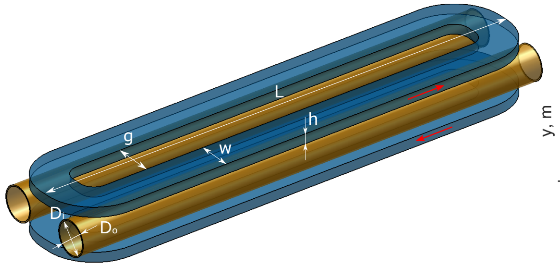

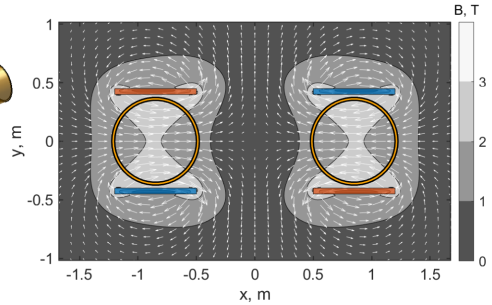

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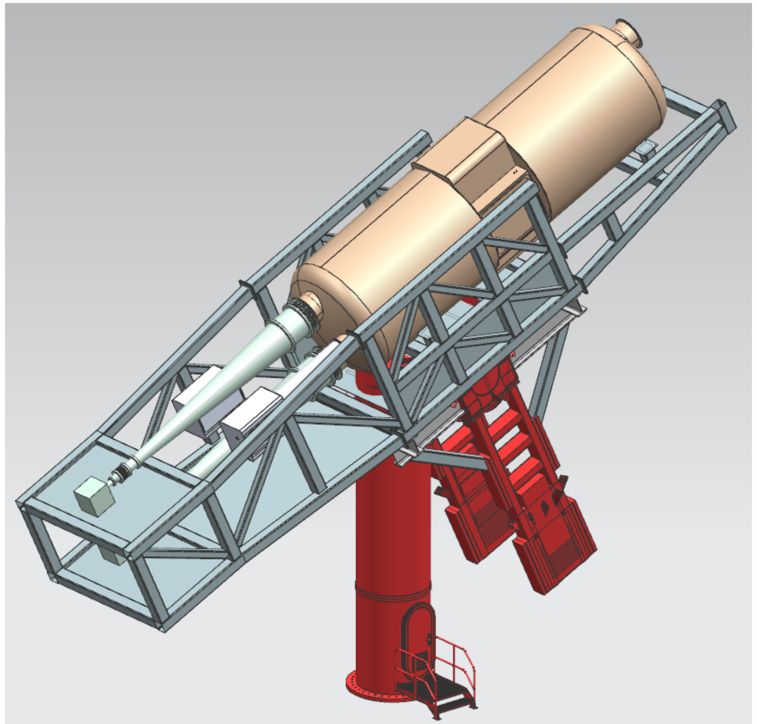

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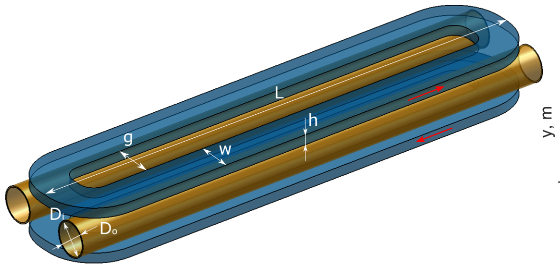

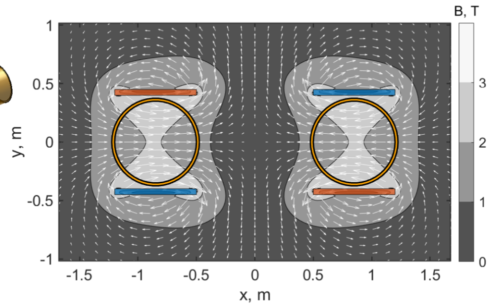

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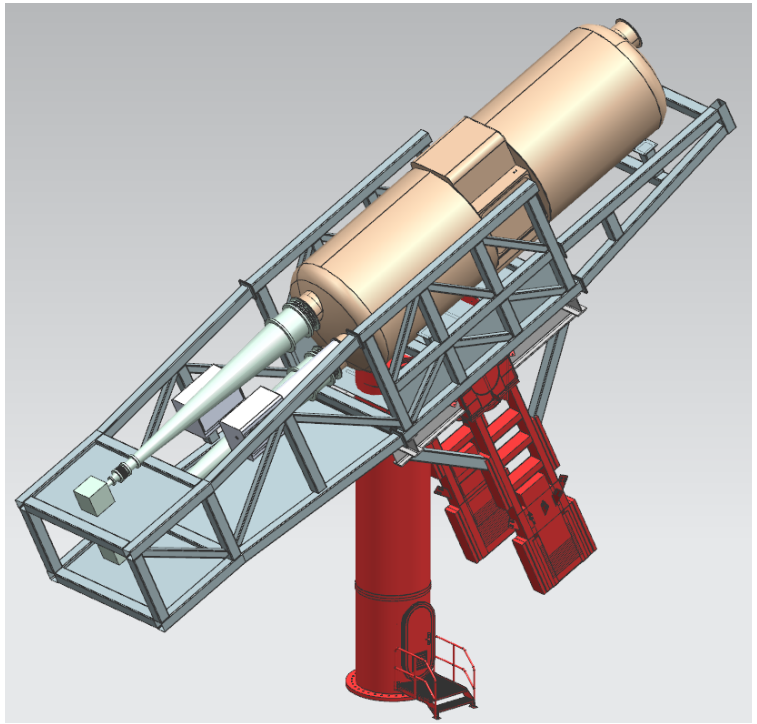
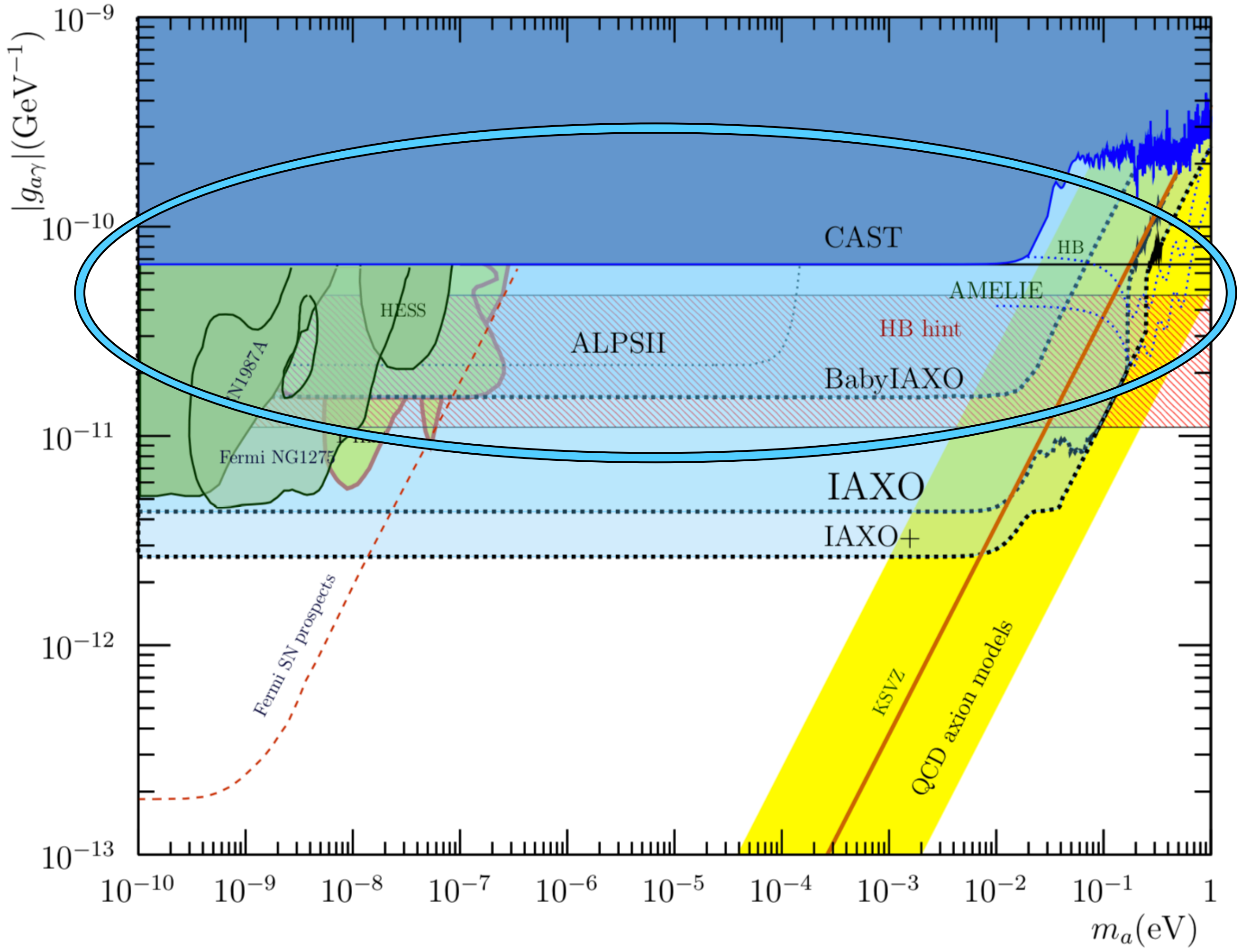


Helioscope Searches

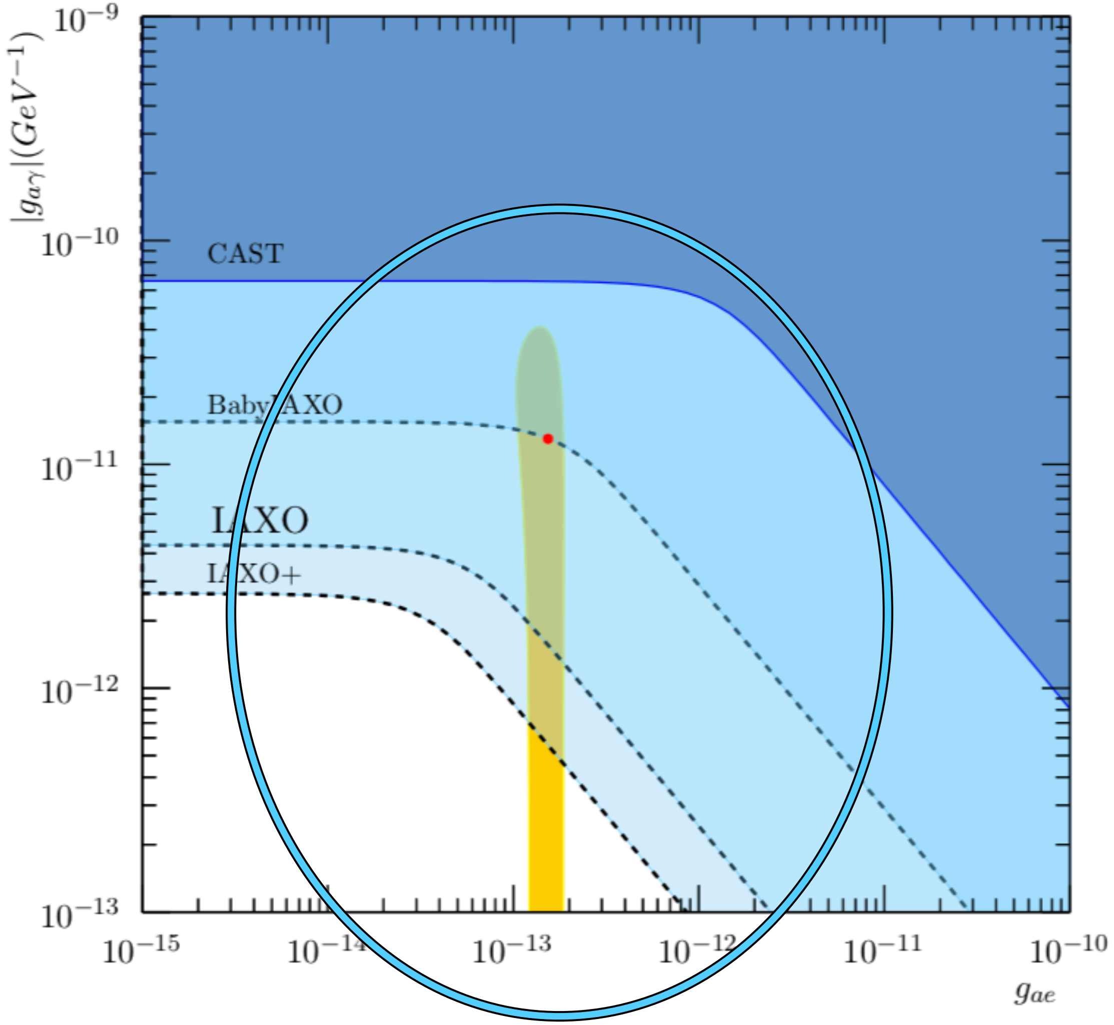
- (Baby)IAXO probes meV mass axion:



[Irastorza, Redondo, 18]

Helioscope Searches

- (Baby)IAXO also sensitive to electron coupling hinted at by stellar energy losses:

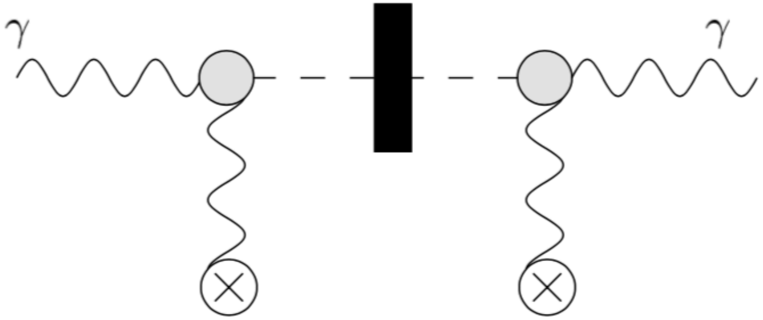


[Armengaud et al. 19]

Gravitational Wave Searches with ALPS & Co

Light Shining through Walls (LSW)

- **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



- In the Standard Model (SM), light-shining-through walls (LSW) occurs dominantly through magnetic conversion of gravitons:

$$P(\gamma \to g \to \gamma) \simeq (8\pi G)^2 (BL)^4 \equiv \frac{1}{M_P^4}(BL)^4$$

[Gertsenshtein 1962]

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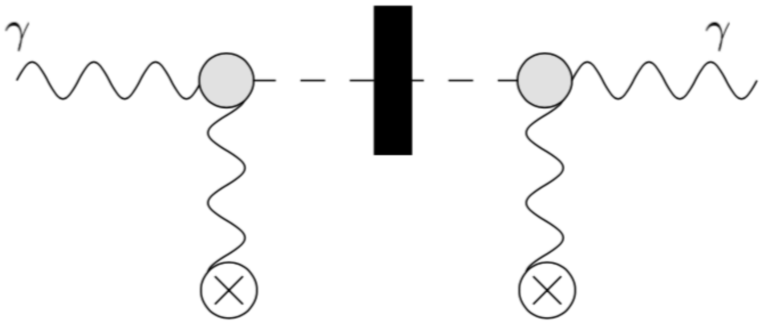

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[Gertsenshtein 1962]

- In a Peccei-Quinn extension of the SM, LSW can also proceed via magnetic conversion of axions or axion-like particles (ALPs):

$$P(\gamma \to a \to \gamma) \simeq \left[\frac{1}{4} g_{a\gamma}^2\right]^2 (BL)^4$$

[Sikivie 1983]

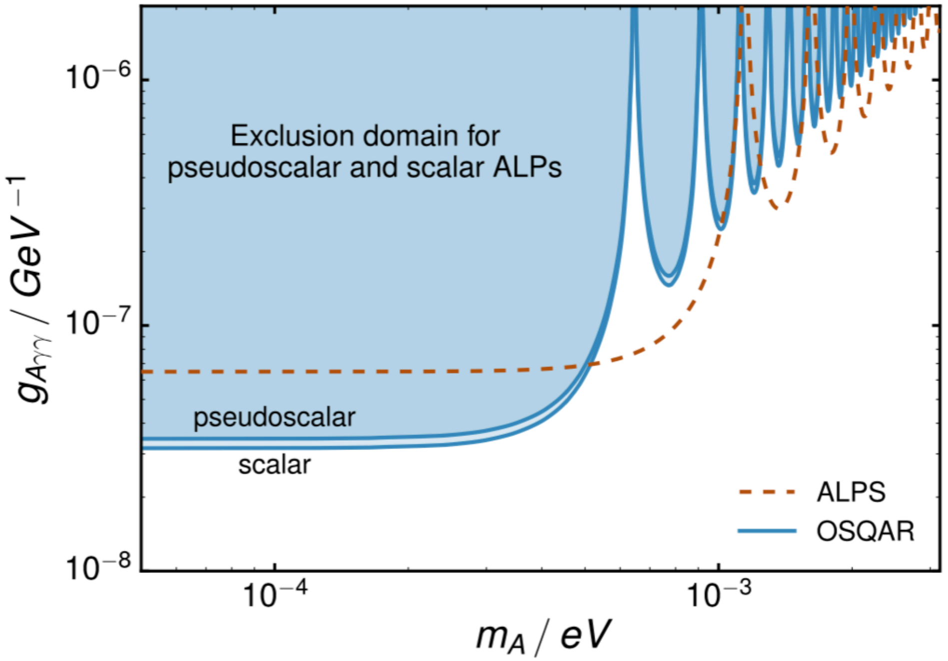
$$\mathcal{L} \supset -\frac{g_{a\gamma}}{4}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} \equiv g_{a\gamma}\, a\, \mathbf{E}\cdot\mathbf{B}$$

Gravitational Wave Searches with ALPS & Co

Light Shining through Walls (LSW)

- ALPS I and OSQAR @ CERN give currently best purely laboratory limit on the photon coupling of light ALPs:

[Ehret et al. 10; Ballou et al. 15]



[Ballou et al. 15]

- If interpreted in terms of photon conversion into gravitons and vice versa, this limit can be translated into a lower bound on the Planck mass:

$$M_P \,\widehat{=}\, \frac{2}{g_{a\gamma}} > 7 \times 10^7\,\mathrm{GeV}$$

  - Far away from actual value inferred from measurements of the Newton constant: $M_P \equiv 1/\sqrt{8\pi G} \simeq 2.4 \times 10^{18}\,\mathrm{GeV}$

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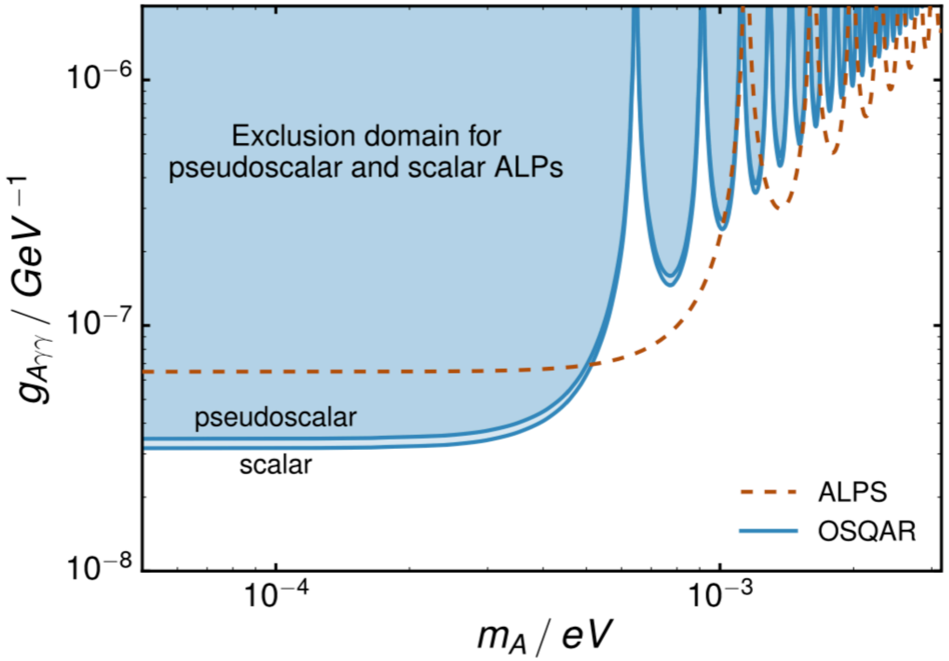

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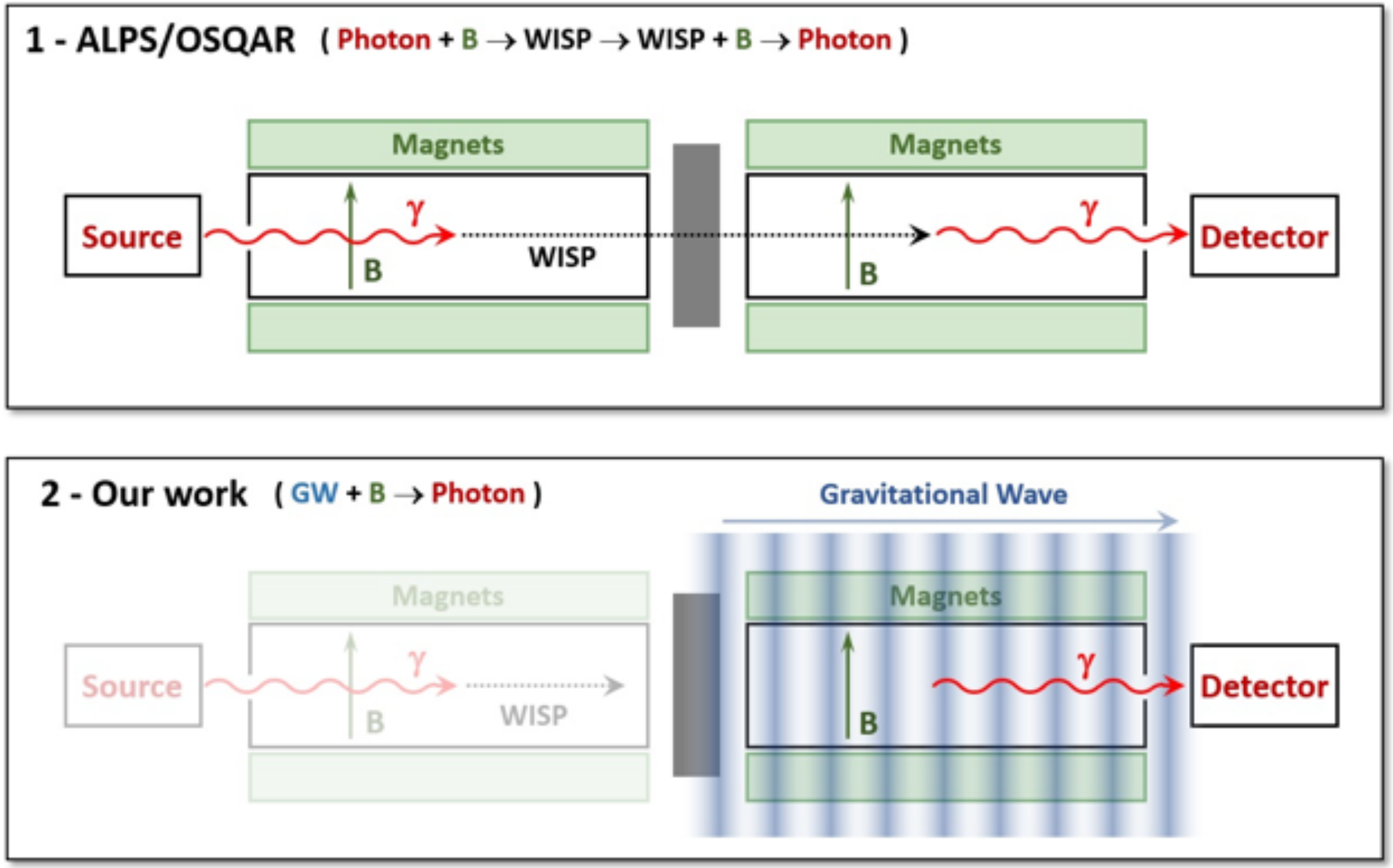
  - ALPS II prospects: $M_P \mathrel{\widehat{=}} \frac{2}{g_{a\gamma}} > 10^{11}\,\mathrm{GeV}$

Gravitational Wave Searches with ALPS & Co

Upper limits on stochastic GW background from LSW experiments and helioscopes

- LSW experiments (ALPS, OSQAR) and helioscopes (CAST, (Baby)IAXO are sensitive to any stochastic GW background due to graviton photon conversion:

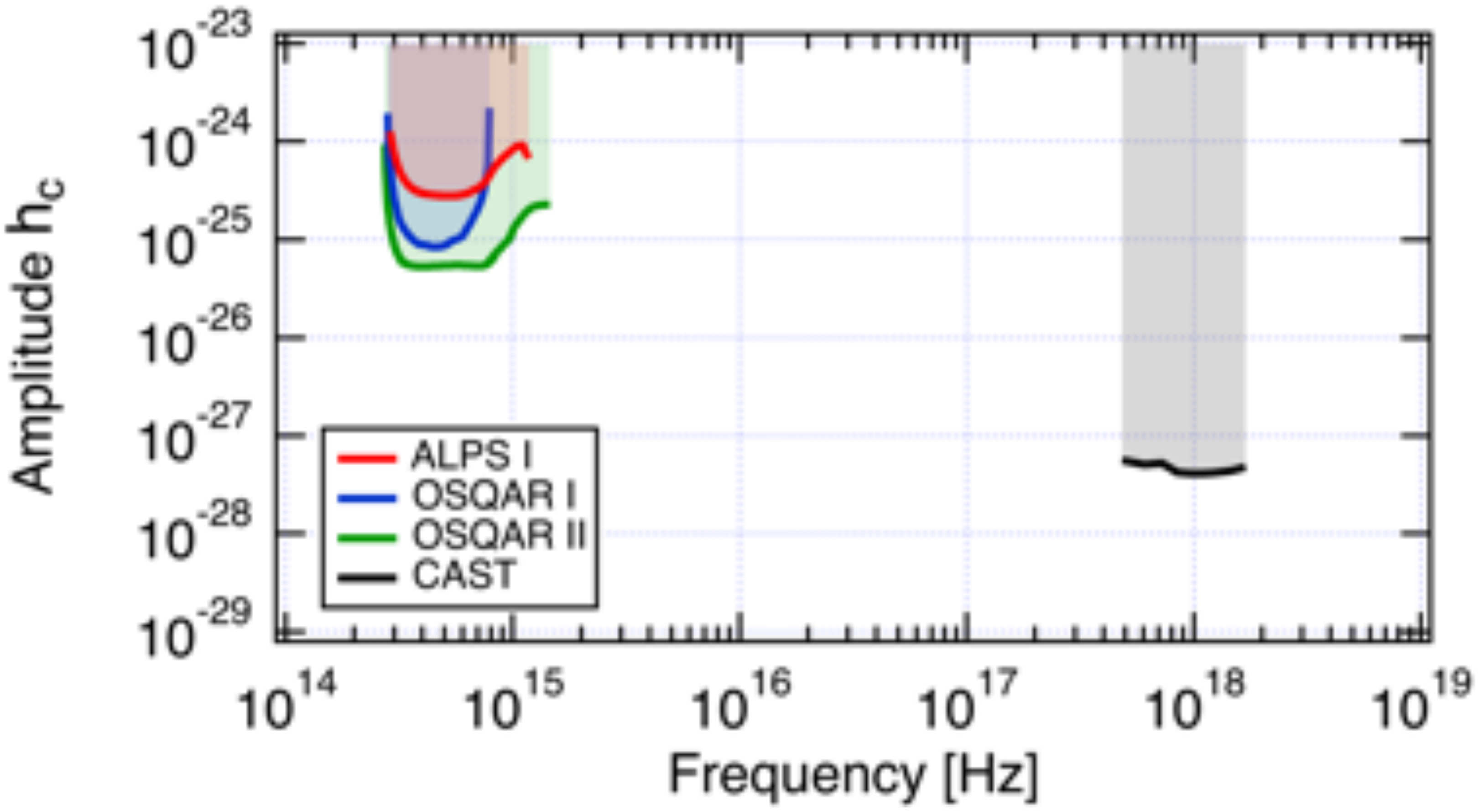


[Ejlli et al 2019]

Gravitational Wave Searches with ALPS & Co

Upper limits on stochastic GW background from LSW experiments and helioscopes

- 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:

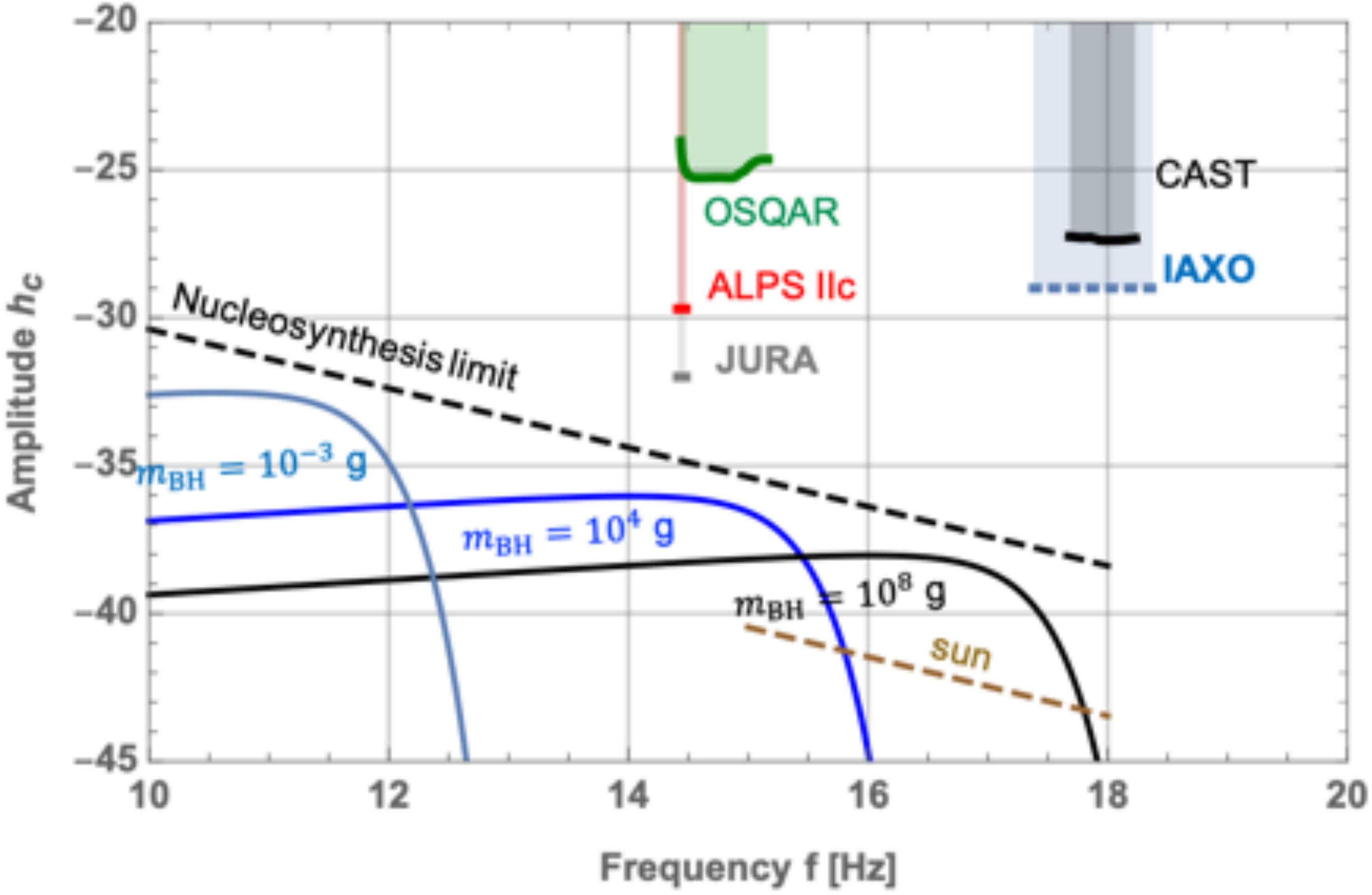


[Ejlli et al 2019]

Gravitational Wave Searches with ALPS & Co

Upper limits on stochastic GW background from LSW experiments and helioscopes

- Projected bounds from LSW experiments and helioscopes:



[Ejlli et al 2019]

GW Detection Opportunities beyond ALPS & Co?

- Currently, a community is forming which seriously considers the search for high-frequency gravitational waves:

CERN-TH-2020-185
HIP-2020-28/TH
DESY 20-195

arXiv:2011.12414v1 [gr-qc] 24 Nov 2020

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

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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 the MHz and 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.

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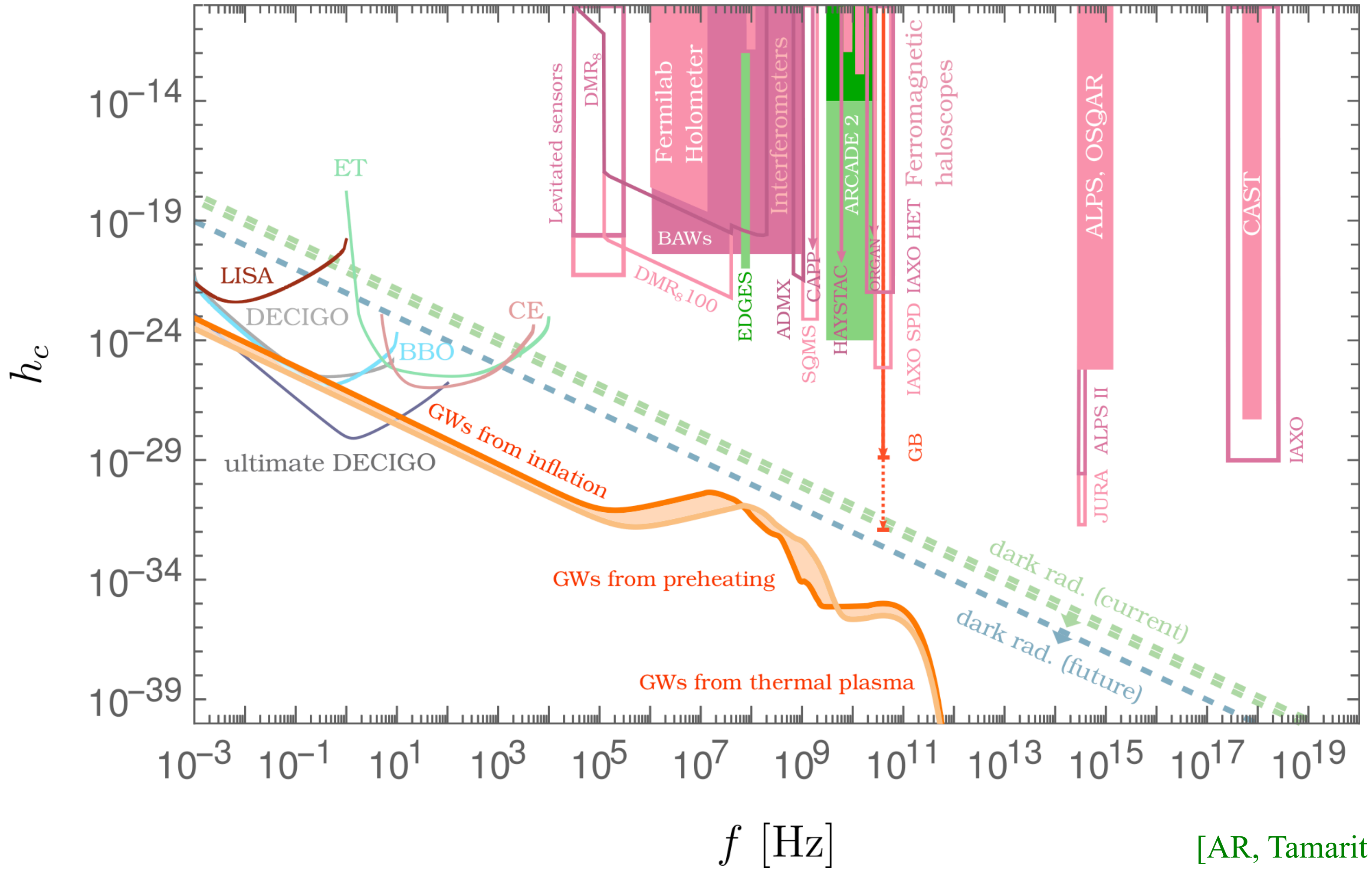
GW Detection Opportunities beyond ALPS & Co?

- Techniques developed for axion detection may well be suited for GW detection at high frequencies:



[AR, Tamarit in progress]