The Quest for the Axion

Andreas Ringwald
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Haus Saron
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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES
CLUSTER OF EXCELLENCE QUANTUM UNIVERSE
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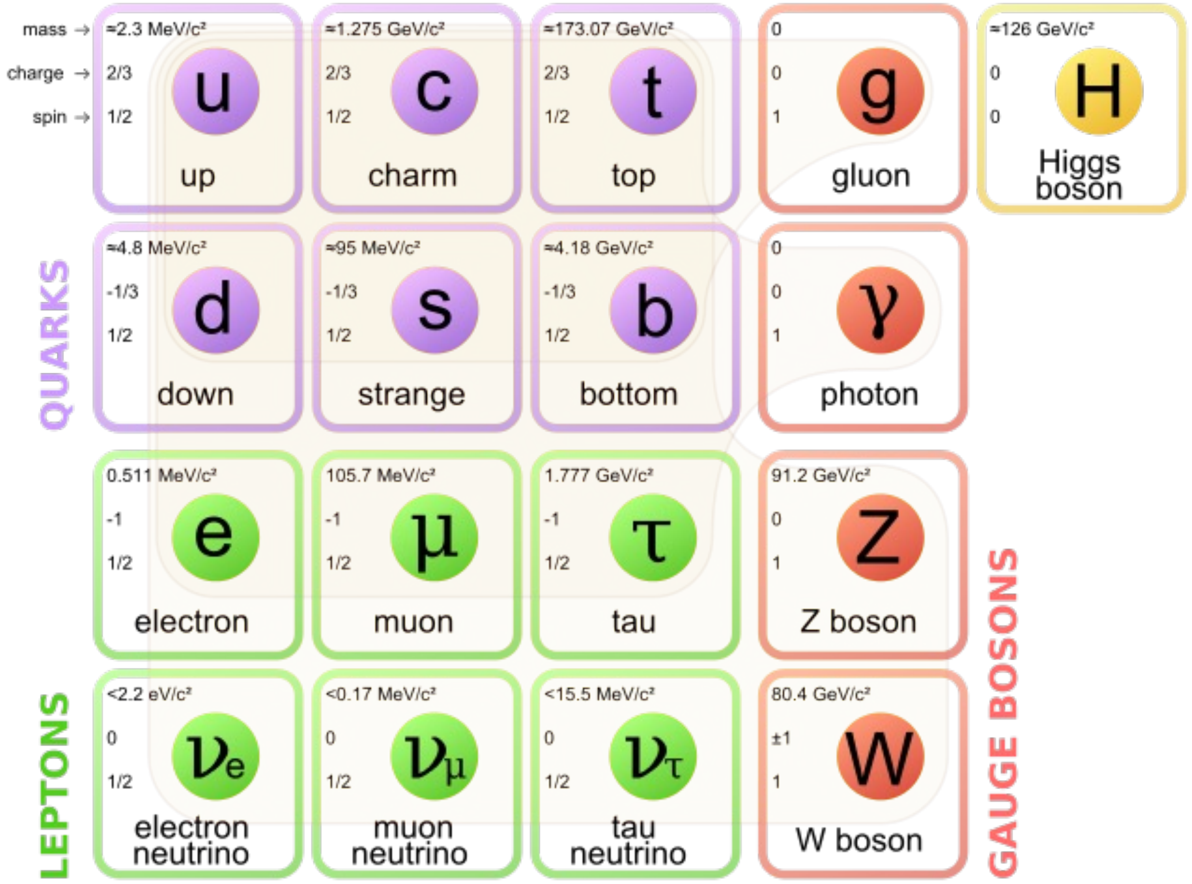
DESY.

The Axion

Solving two puzzles in one go

- Standard Model (SM)



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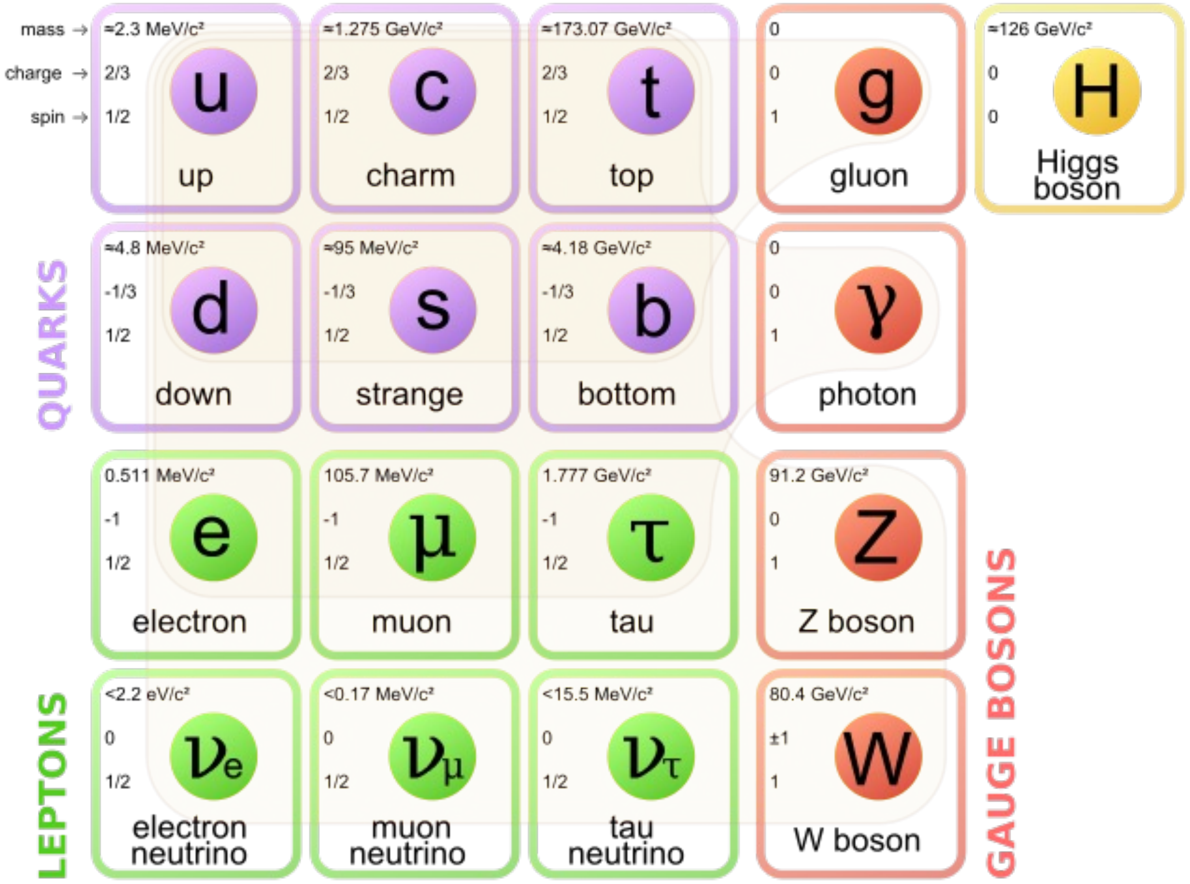

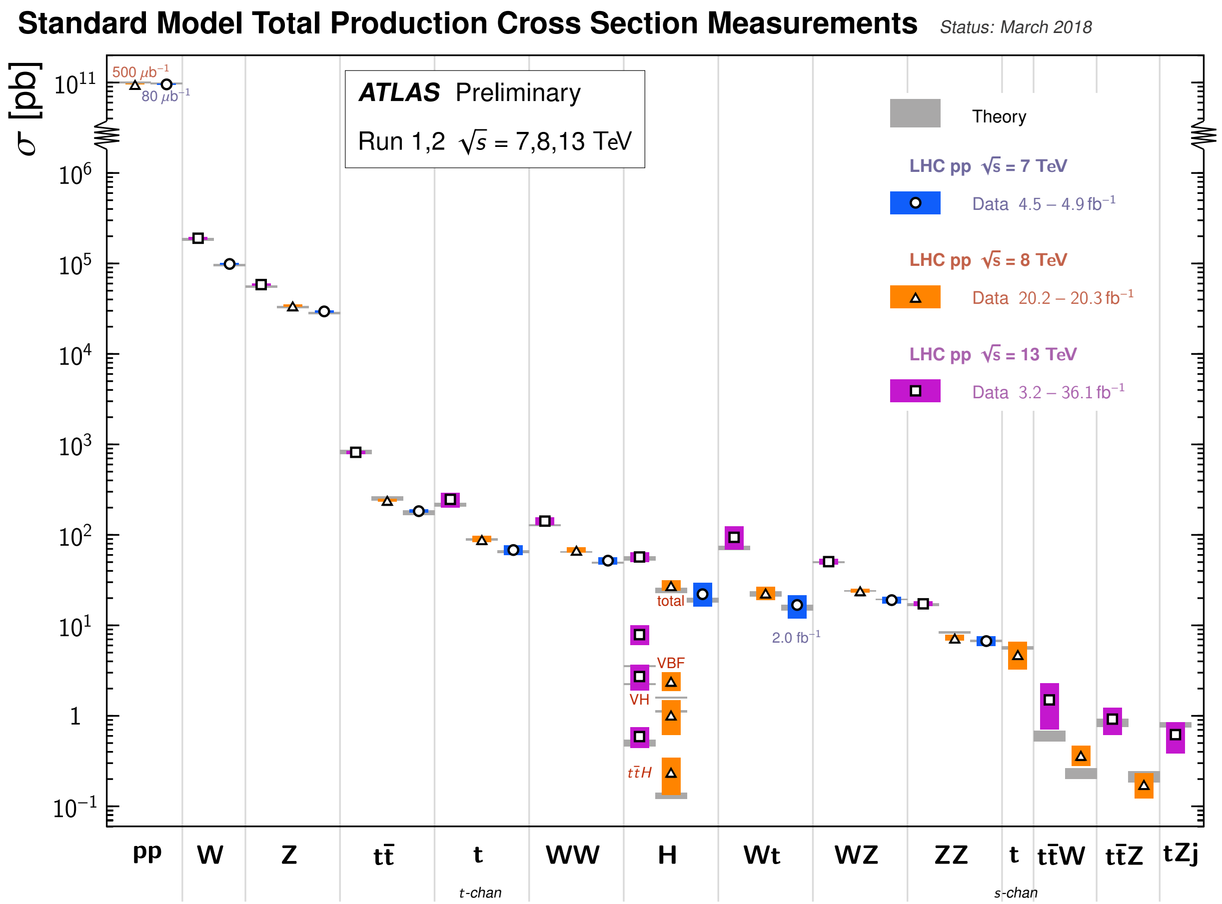

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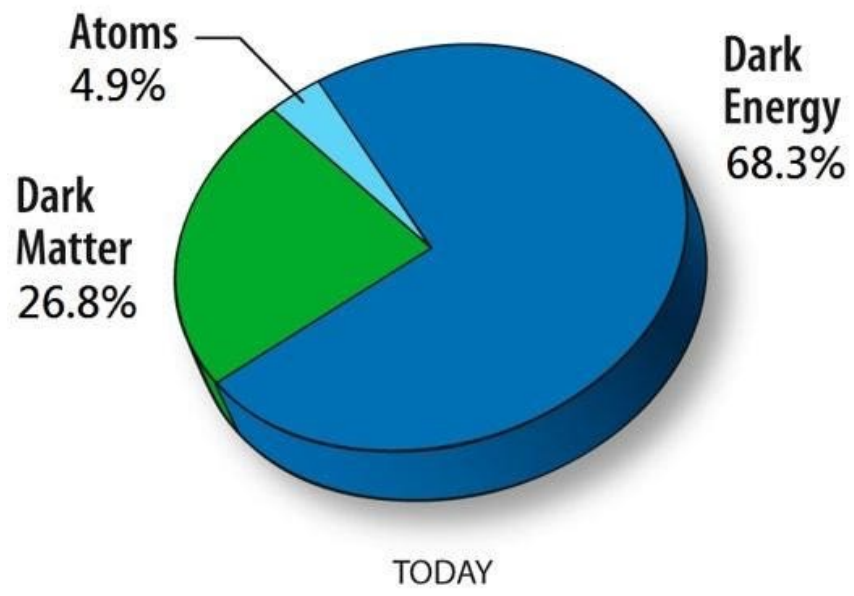

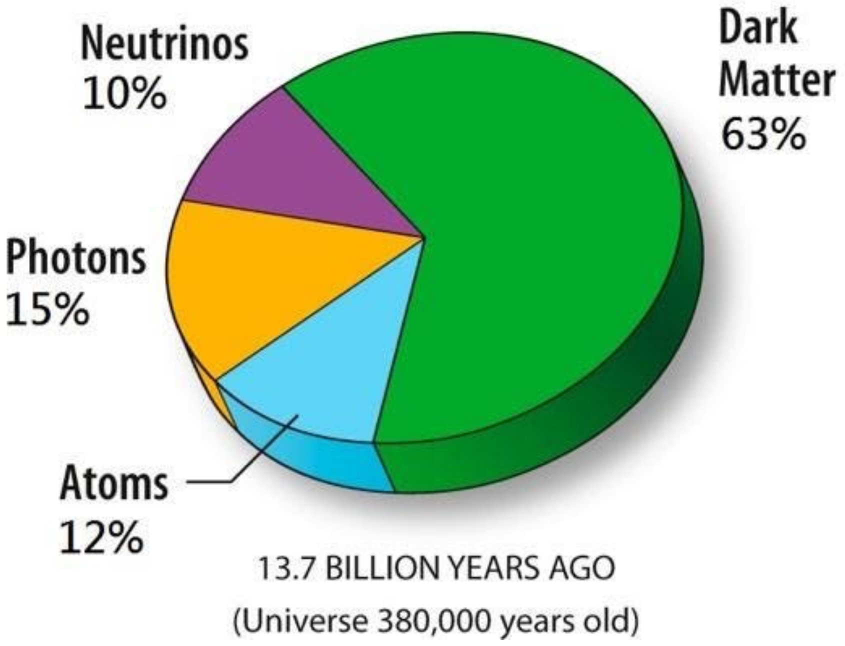

[E. Siegel, Forbes 2018]

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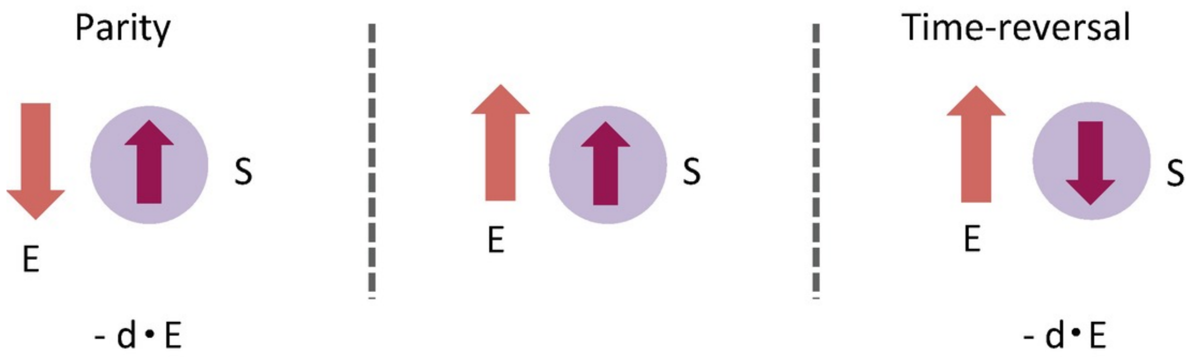

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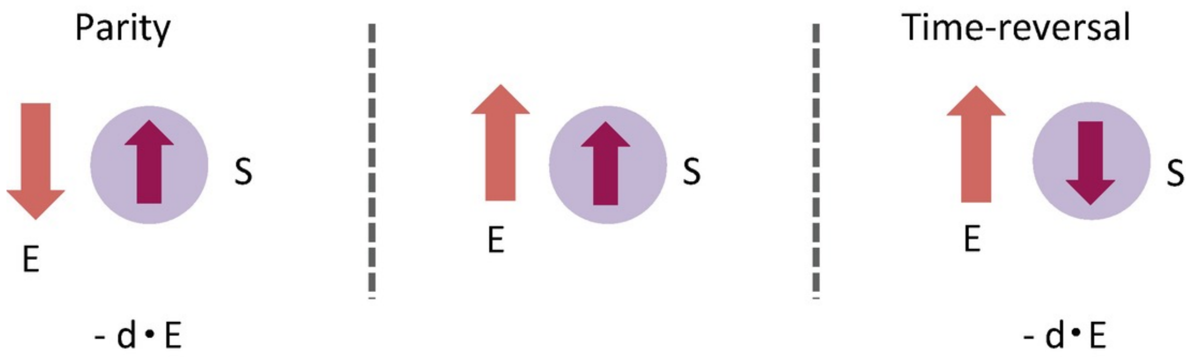

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QCD Lagrangian contains a term which violates P and T:

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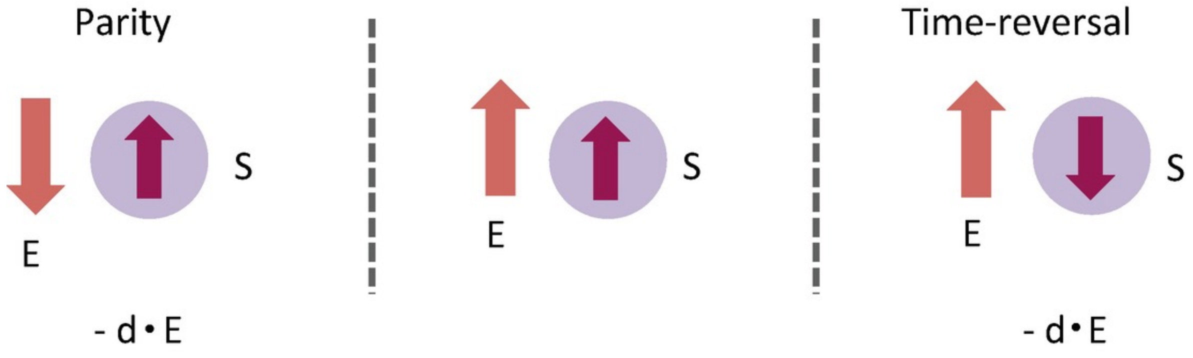

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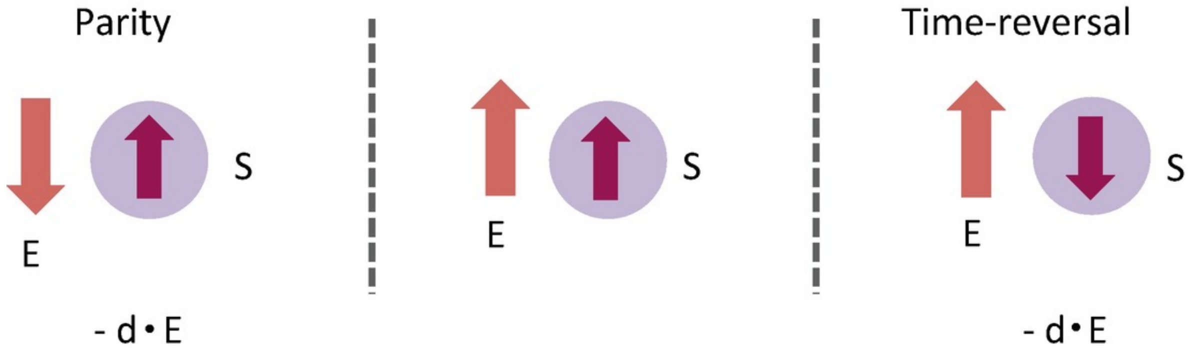

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[Crewther,Di Vecchia,Veneziano,Witten 79;...; Pospelov,Ritz 00]

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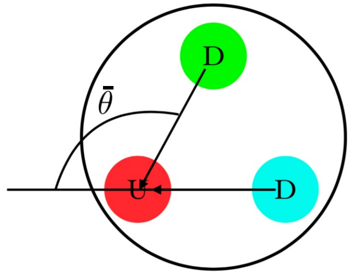

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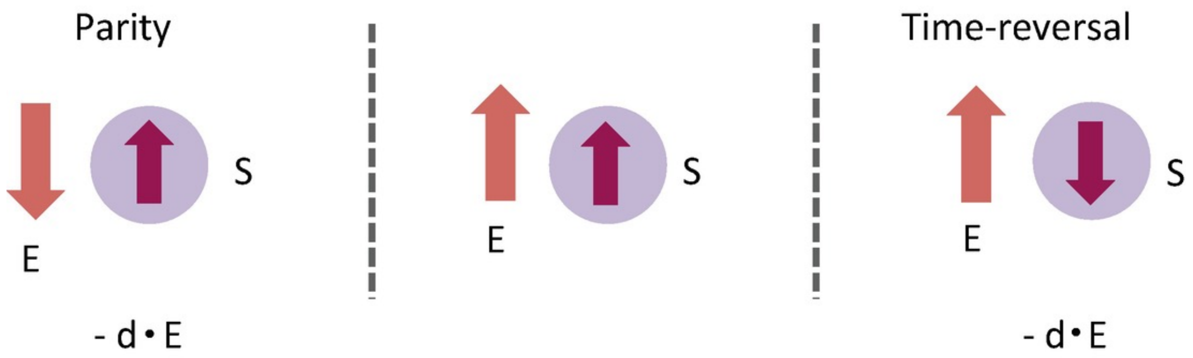

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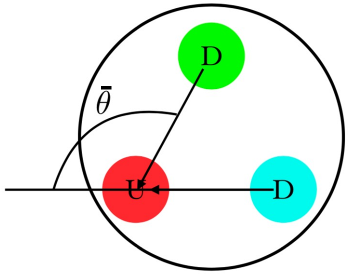

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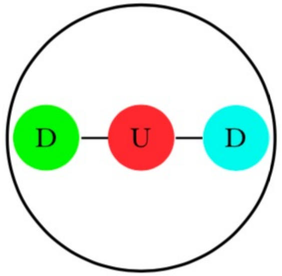

- Comparison with experiment: $\Rightarrow |\bar{\theta}| \lesssim 10^{-10}$

Strong CP Puzzle

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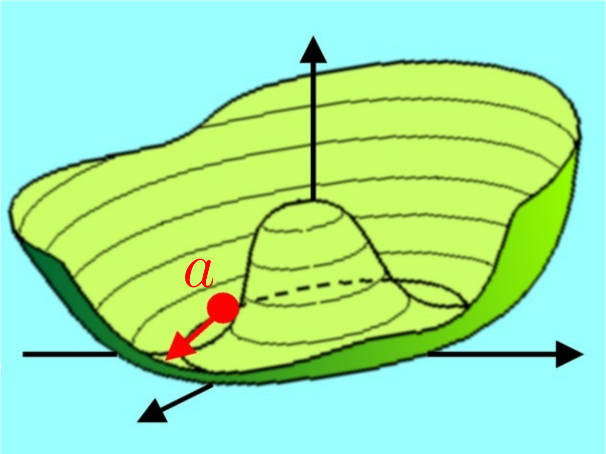
- Extension of the SM by a complex scalar field featuring a spontaneously broken global U(1) symmetry under which colored fermions (SM or BSM ones) have an axial charge assignment solves both puzzles in one go



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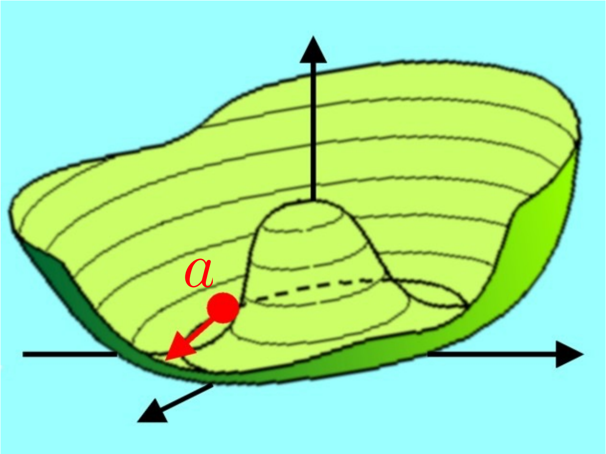
  - Pseudo-Goldstone boson field $a(x)$ arising from PQ symmetry breaking – axion field – acts as a space-time dependent theta parameter, $\theta(x) = a(x)/f_a;\ f_a = v_{\rm PQ}/N_{\mathcal{Q}}$, QCD dynamics leads to $\langle\theta\rangle = 0$ and thus explains tiny neutron EDM

[Peccei,Quinn `77; Weinberg `78; Wilczek `78]



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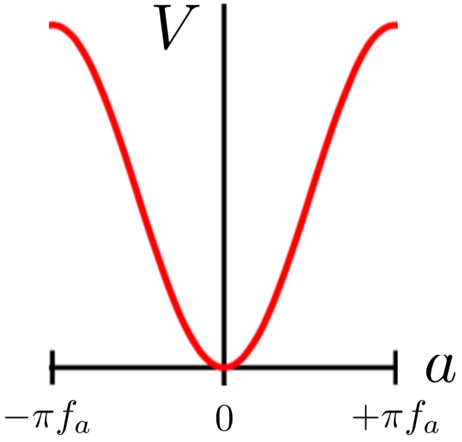

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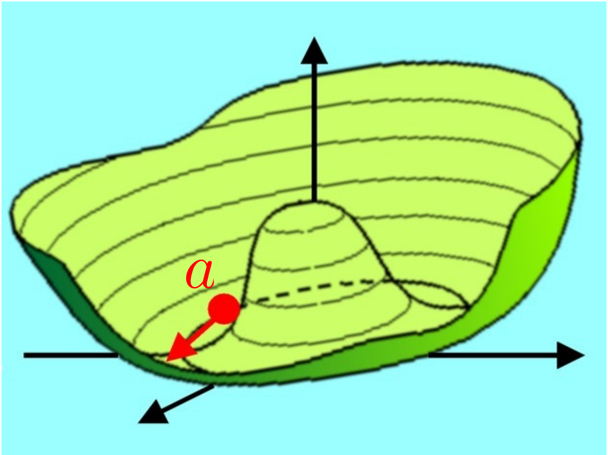
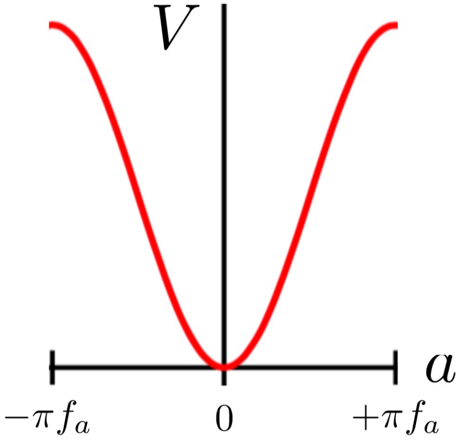
  - For large enough PQ symmetry breaking scale, it may be the main constituent of DM [Preskill,Wise,Wilczek `83; Abbott,Sikivie `83; Dine,Fischler `83]





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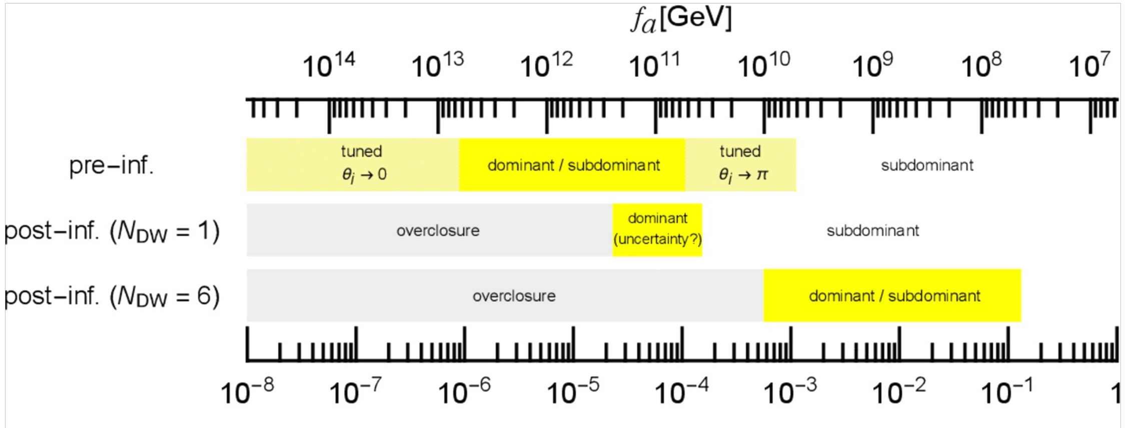

[Saikawa, https://arxiv.org/abs/1709.07091]

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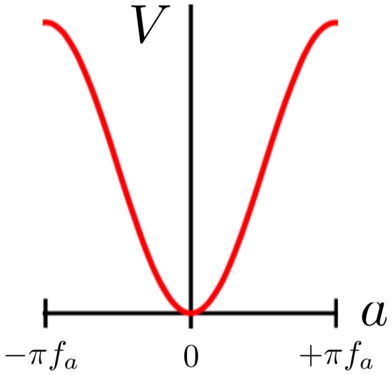

$$m_a = \sqrt{V''} \approx \frac{\sqrt{z}}{1+z}\,\frac{m_\pi f_\pi}{f_a} \approx 6\ \mu\text{eV}\left(\frac{10^{12}\,\text{GeV}}{f_a}\right)$$

$$z \equiv m_u/m_d$$

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$$\mathcal{L} \supset \frac{1}{2}\,\partial_\mu a\,\partial^\mu a - \frac{1}{2} m_a^2 a^2 + C_{a\gamma}\frac{\alpha}{8\pi}\frac{a}{f_a}\,F_{\mu\nu}\tilde{F}^{\mu\nu}$$

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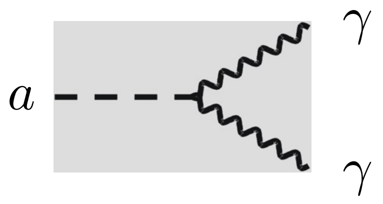

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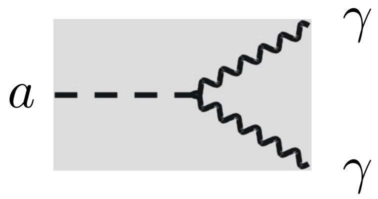

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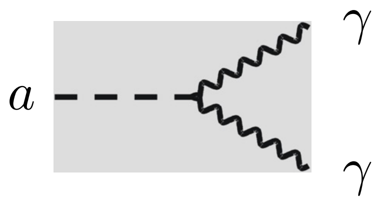

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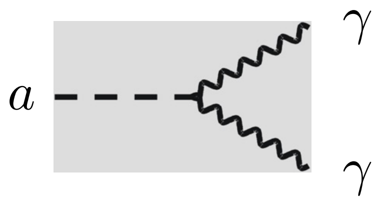

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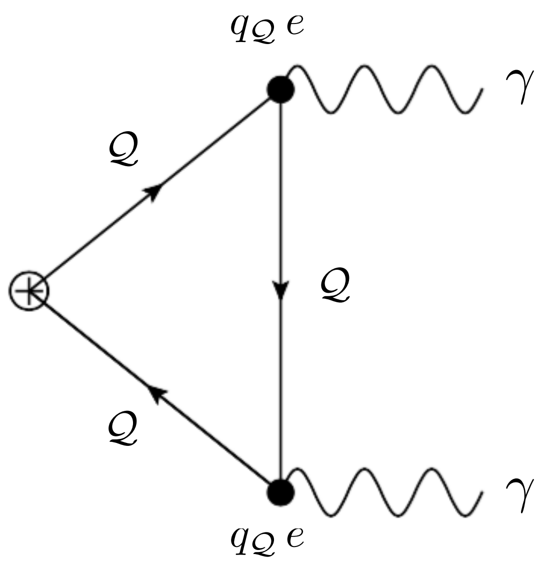
  - Wilson coefficient: $C_{a\gamma} = \frac{E_{\mathcal{Q}}}{N_{\mathcal{Q}}} - \frac{2}{3}\frac{4+z}{1+z}$ [Kaplan 85;Srednicki `85] $z \equiv m_u/m_d \approx 1/2$
    - For one exotic quark flavor $\mathcal{Q}$ with electric charge $q_{\mathcal{Q}}$: $N_{\mathcal{Q}} = 1,\; E_{\mathcal{Q}} = 6\, q_{\mathcal{Q}}^2$



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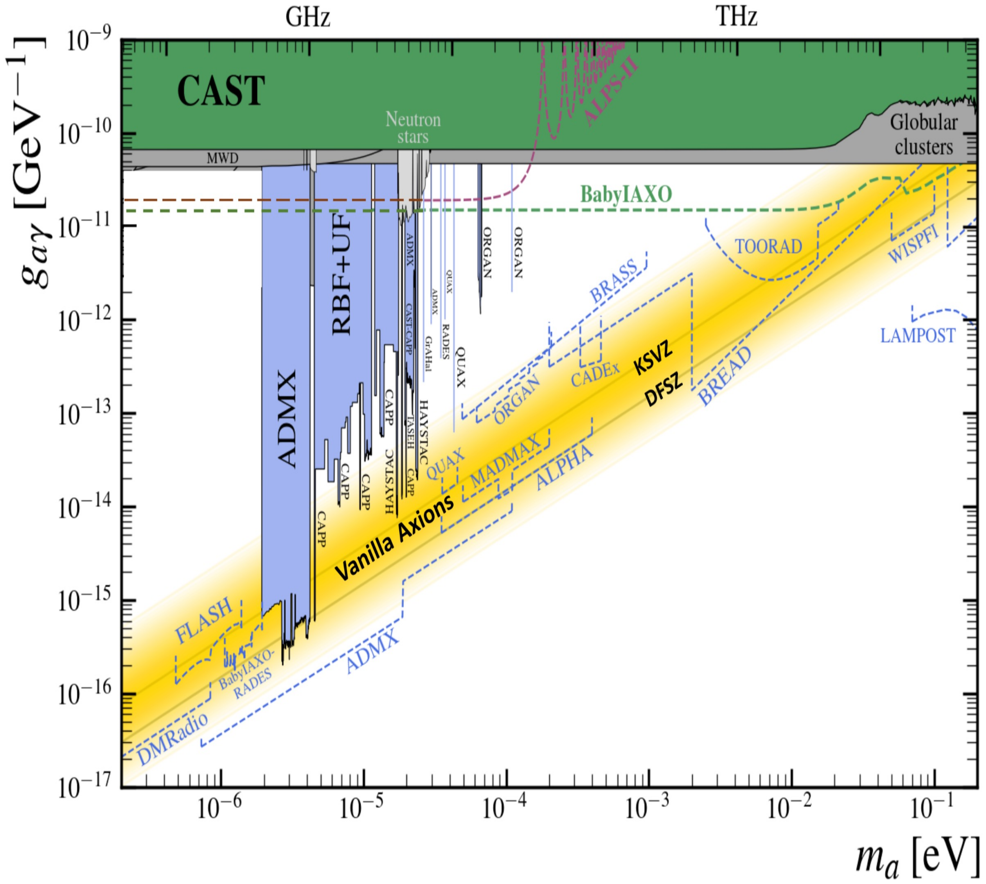

adapted from [https://github.com/cajohare/AxionLimits]

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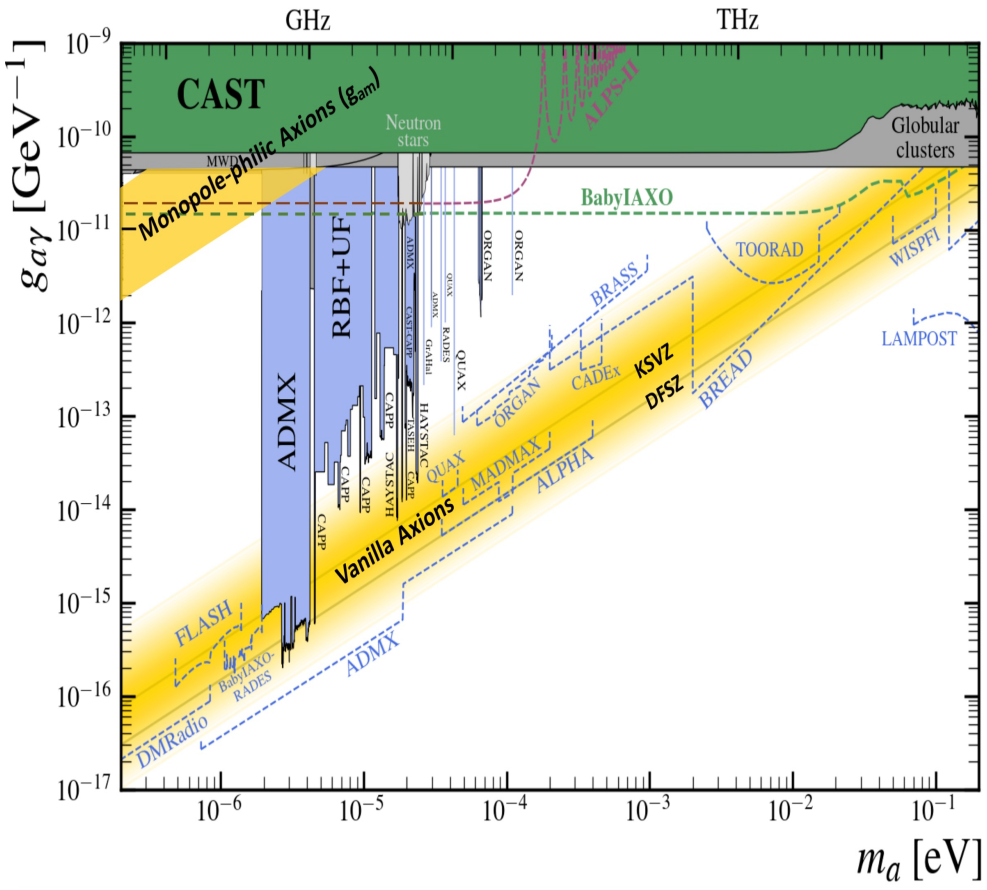
[Sokolov,AR 21, 22, 23]



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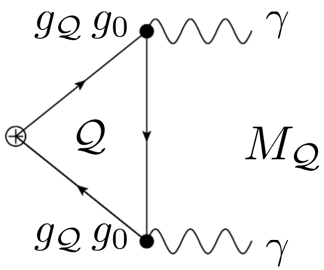
  - Induced photon coupling:

$$g_{am} \simeq \frac{\alpha_m}{2\pi f_\pi} \frac{m_a}{m_\pi} \frac{1+z}{\sqrt{z}} \frac{M_\mathcal{Q}}{N_\mathcal{Q}}$$

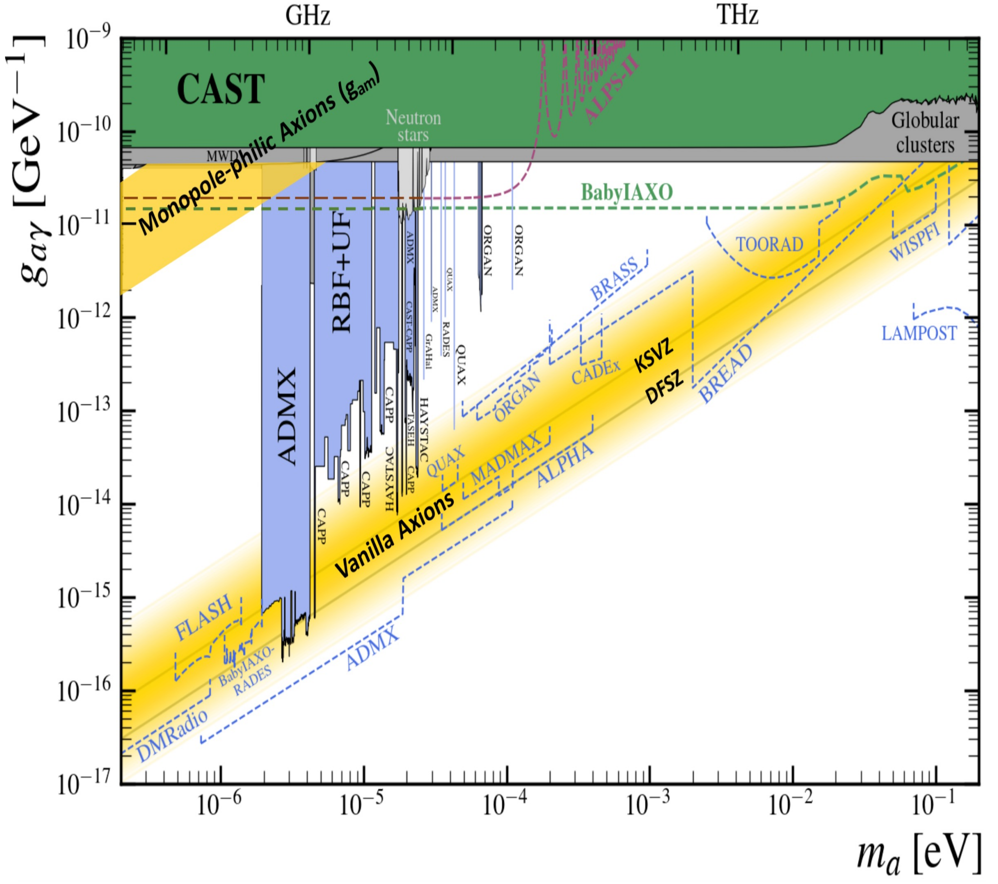


$$M_\mathcal{Q} = 6\, g_\mathcal{Q}^2$$

strongly enhanced due to charge quantisation ($e\, g_0 = 6\pi\, n$):

$$\alpha_m \equiv \frac{g_0^2}{4\pi} = \frac{9\pi}{e^2} = \frac{9}{4}\alpha^{-1} \quad \Rightarrow \quad \frac{g_{am}}{g_{a\gamma}} = \left(\frac{3\, g_\mathcal{Q}}{2\, q_\mathcal{Q}} \right)^2 \alpha^{-2} \sim 10^5$$

[Dirac 1931, Schwinger 1966, Zwanziger 1968]



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Axion Experiments Not Relying on Axion Dark Matter

Axion – photon conversion in electromagnetic fields

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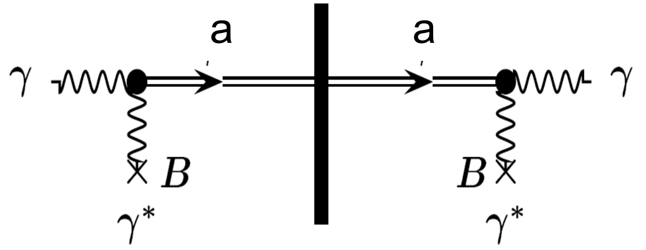

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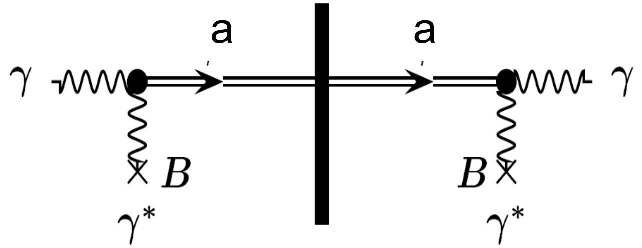
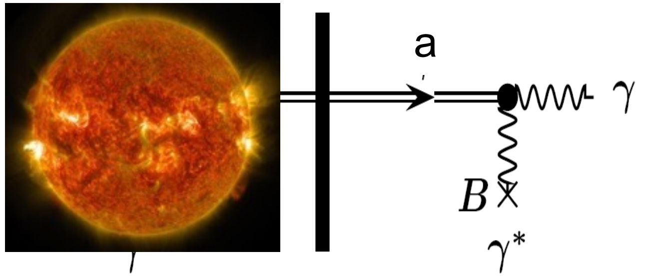


- **Helioscope** CAST, BabyIAXO, IAXO
  - laboratory search for solar axions



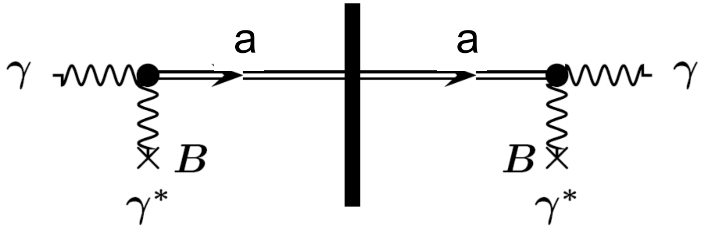
adapted from [Lindner]

Light-Shining-through-a-Wall Searches

Searching for home-made axions

- In an external electromagnetic field, axion experiences mixing with photon
- Light shining through a wall concept:

[Anselm 85; van Bibber 87]



- Probability, that photon with energy ω converts in axion after having traversed a distance L_B in magnetic field of strength B:

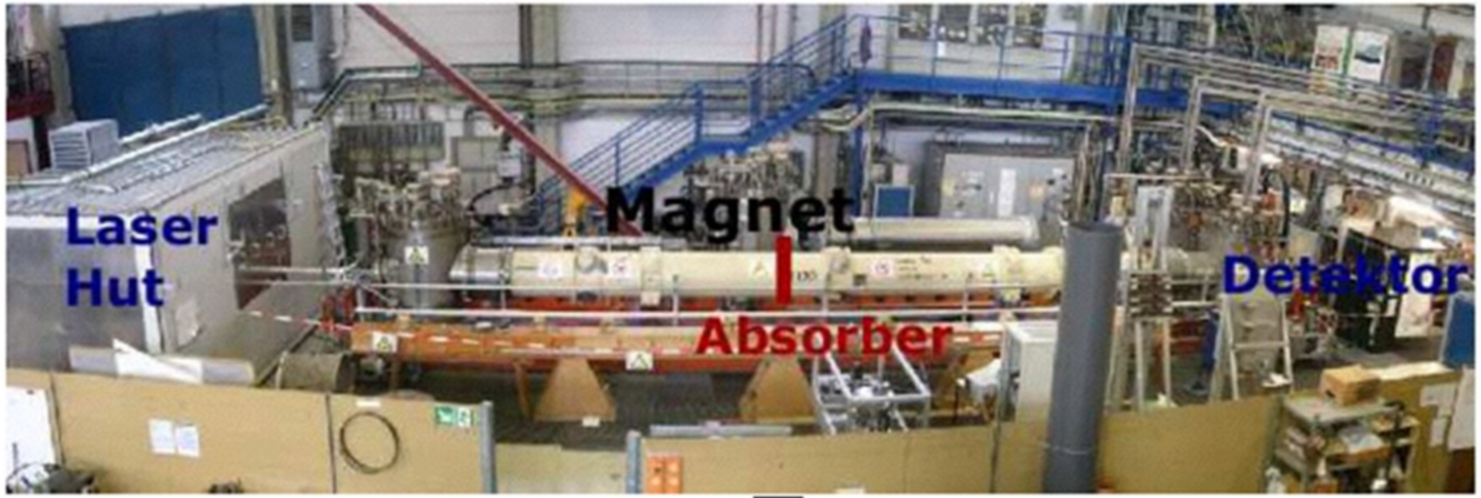
$$P(\gamma \leftrightarrow a) \simeq 4 \frac{(g_{a\gamma} \omega B)^2}{m_a^4} \sin^2 \left(\frac{m_a^2}{4\omega} L_B \right)$$

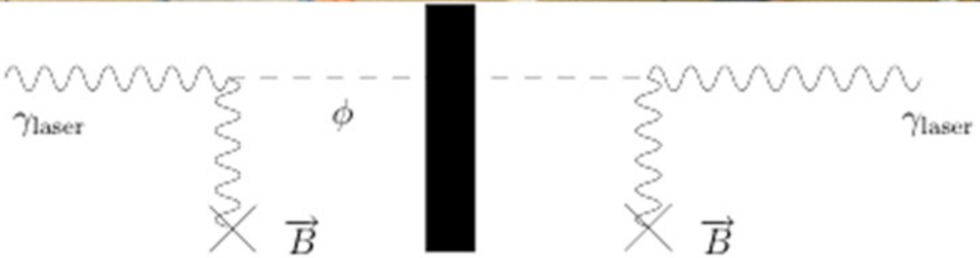
- For very light axion, $m_a \ll (2\pi\omega/L_B)^{1/2} \approx \mathrm{meV}((\omega/\mathrm{eV})(\mathrm{m}/L_B))^{1/2}$:

$$P(\gamma \to a \to \gamma) \simeq \frac{1}{16} (g_{a\gamma} B L_B)^4$$

Light-Shining-through-a-Wall Searches

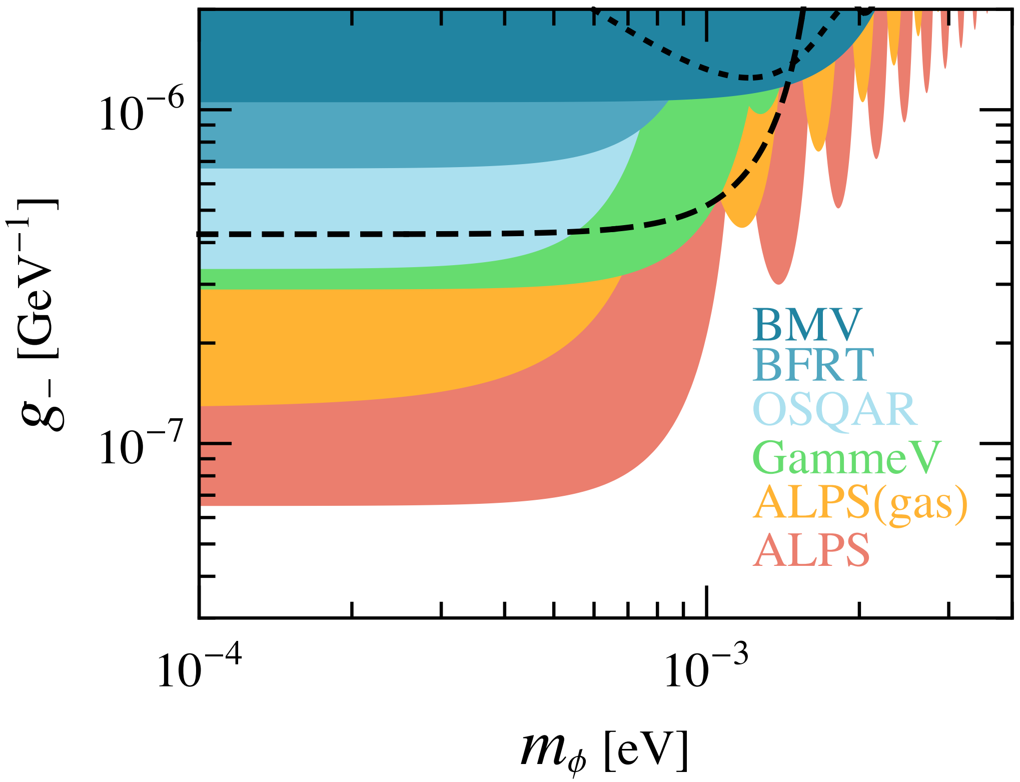
- ALPS I @ DESY (in collaboration with AEI Hannover and U Hamburg) exploited one HERA dipole:



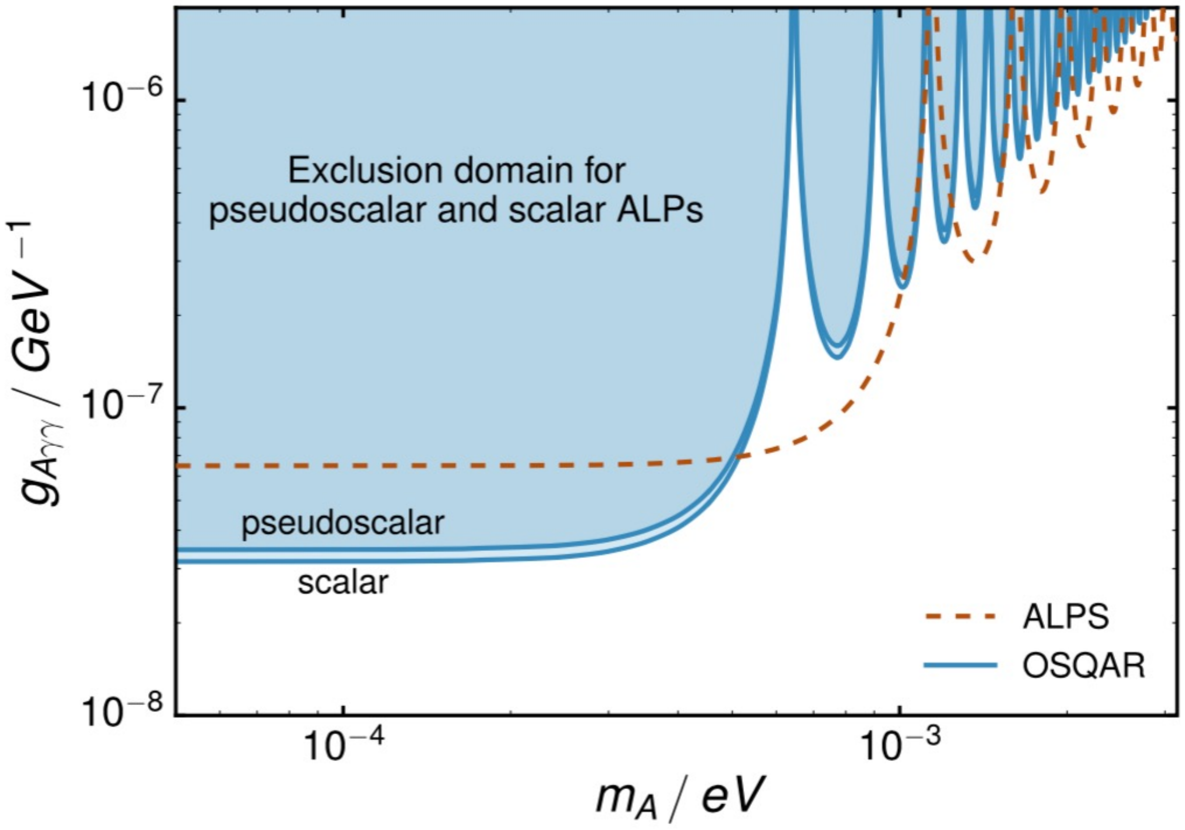


Light-Shining-through-a-Wall Searches

- ALPS I and OSQAR @ CERN have established the currently best pure laboratory limits on low mass ALPs:



[Ehret et al., Phys. Lett. B 689 (2010) 149]



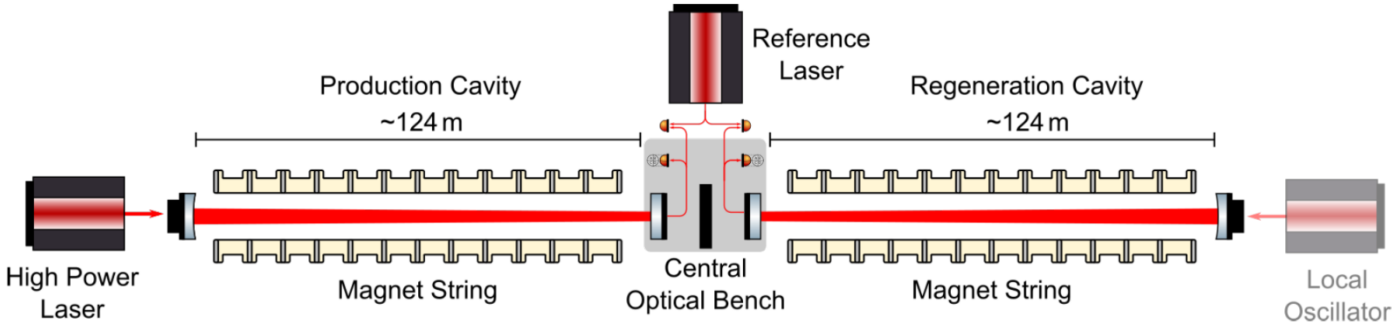
[Ballou et al., Phys.Rev.D 92 (2015) 9, 092002]

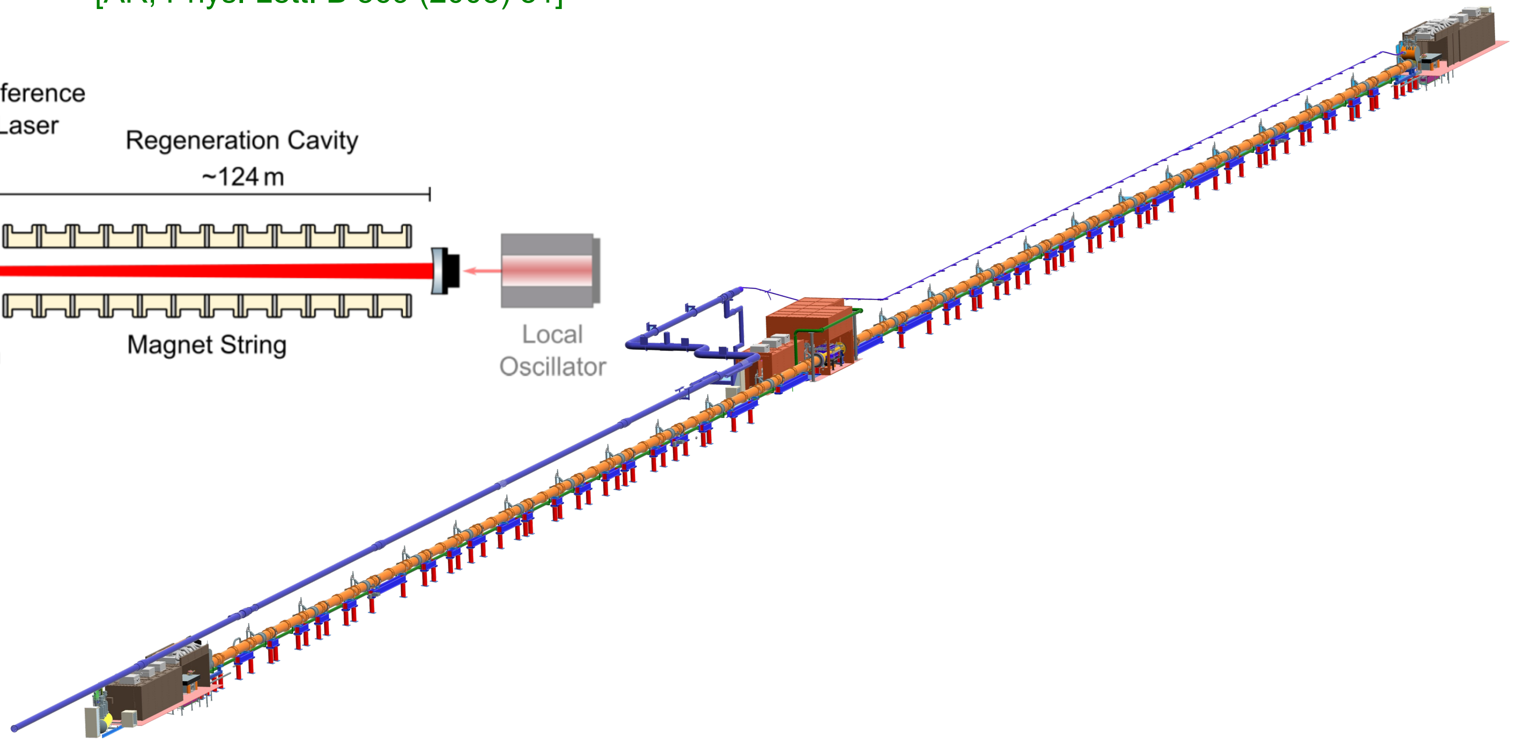
Light-Shining-through-a-Wall Searches

- ALPS II @ DESY (in coll. with U Cardiff, U Florida, U Hamburg, U Hannover, U Mainz, U Southern Denmark)

[Bähre et al (ALPS II TDR) 13]

  - Increase sensitivity in photon coupling by a factor of more than 10^3 by exploiting
    - 12 + 12 straightened HERA magnets [AR, Phys. Lett. B 569 (2003) 51]





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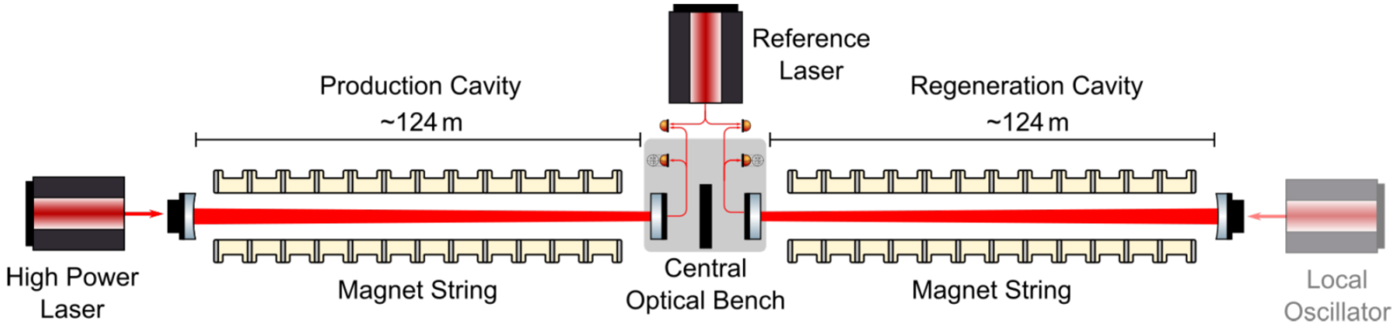

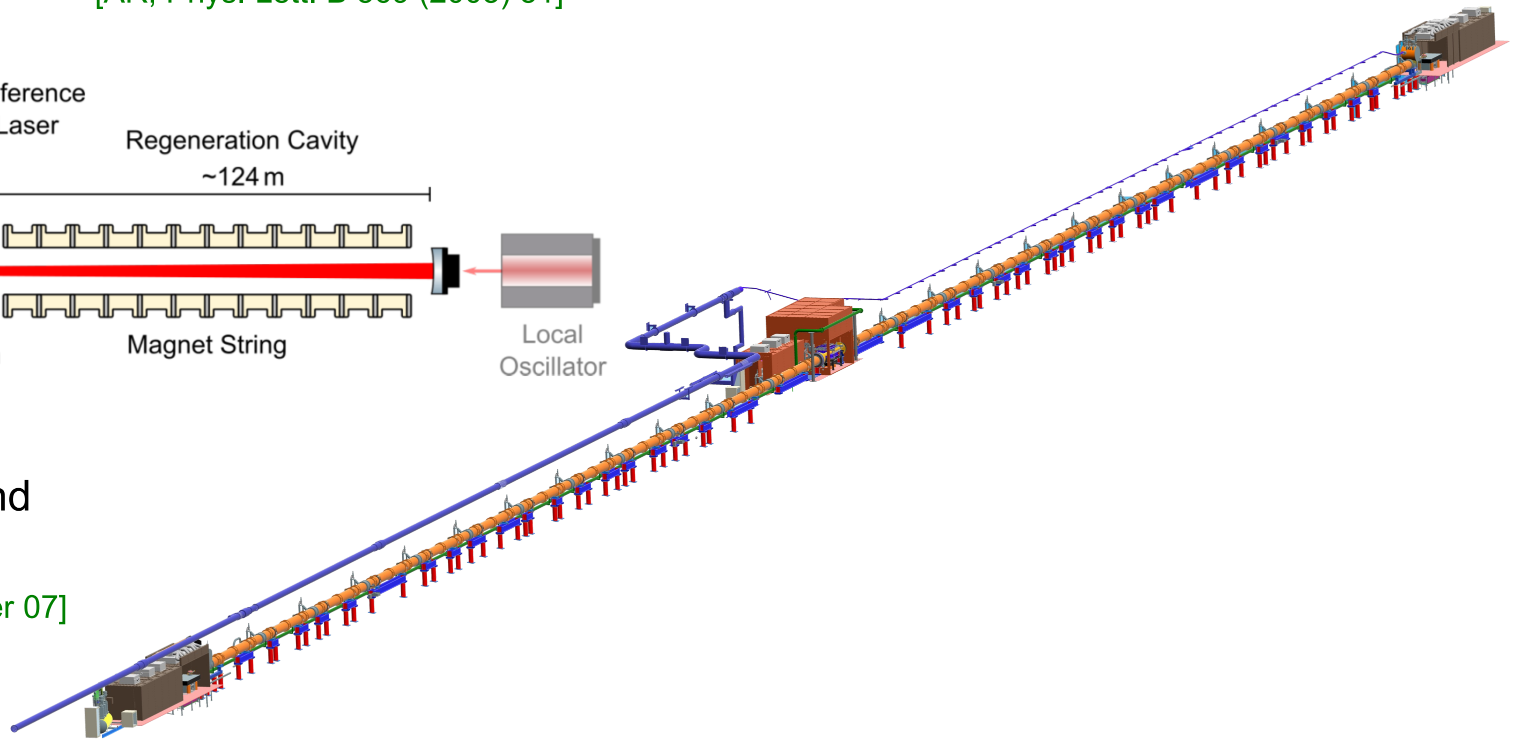

    - Optical cavities both at production and regeneration sites

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

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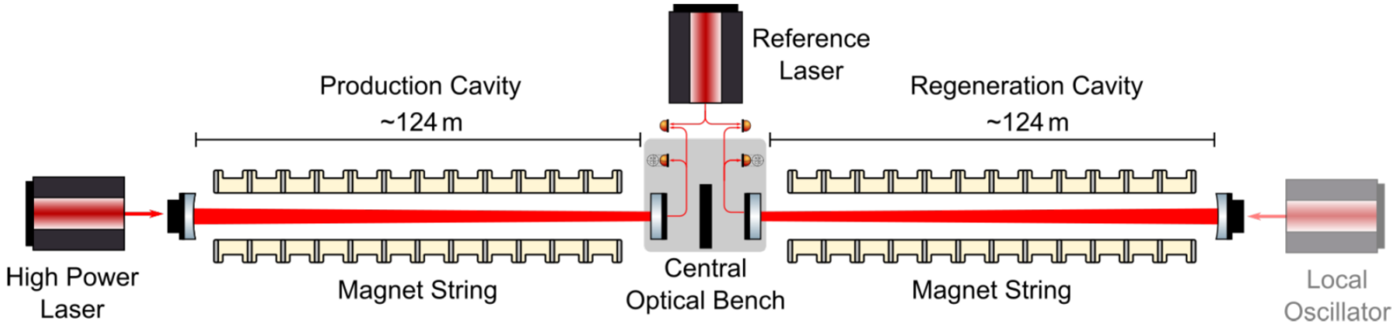

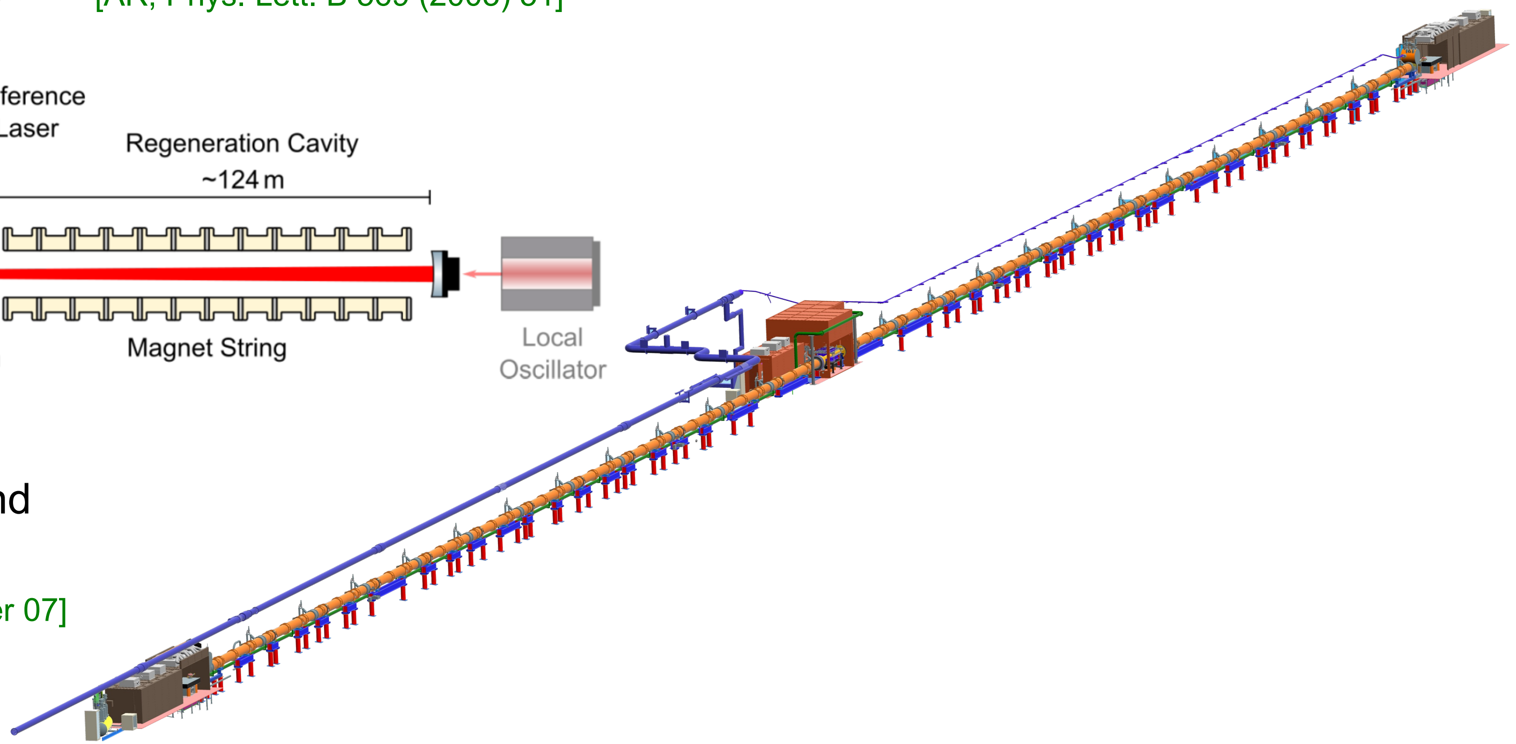

    - Optical cavities both at production and regeneration sites

[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 coll. with U Cardiff, U Florida, U Hamburg, U Hannover, U Mainz, U Southern Denmark)
  - Progress:
    - All 24 magnets installed, aligned and tested

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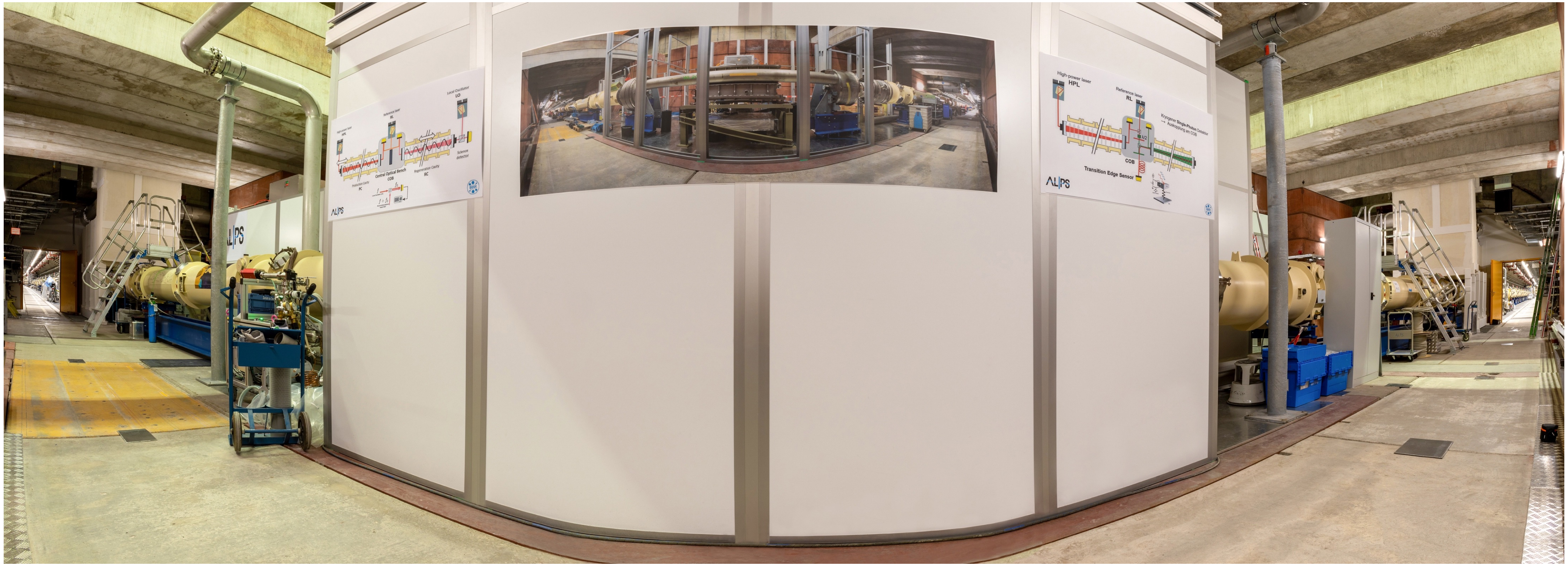

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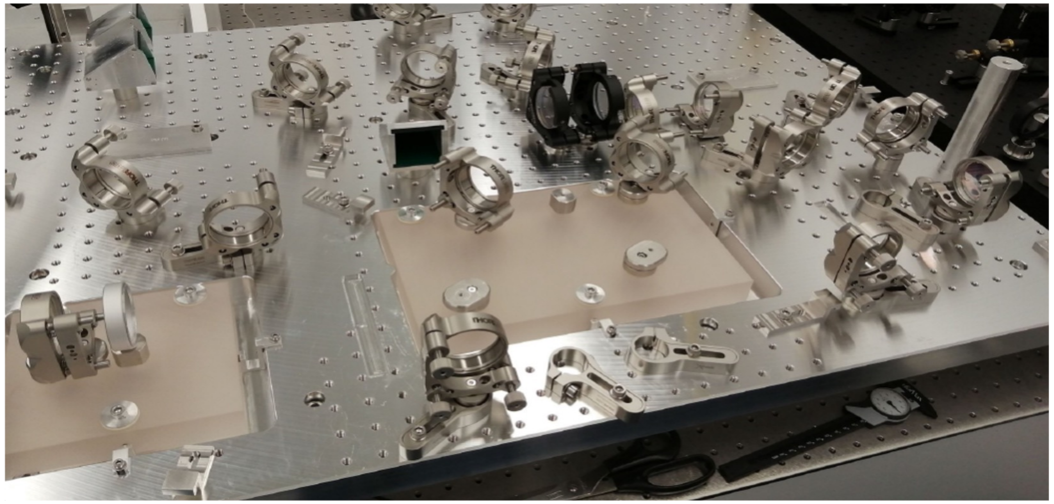

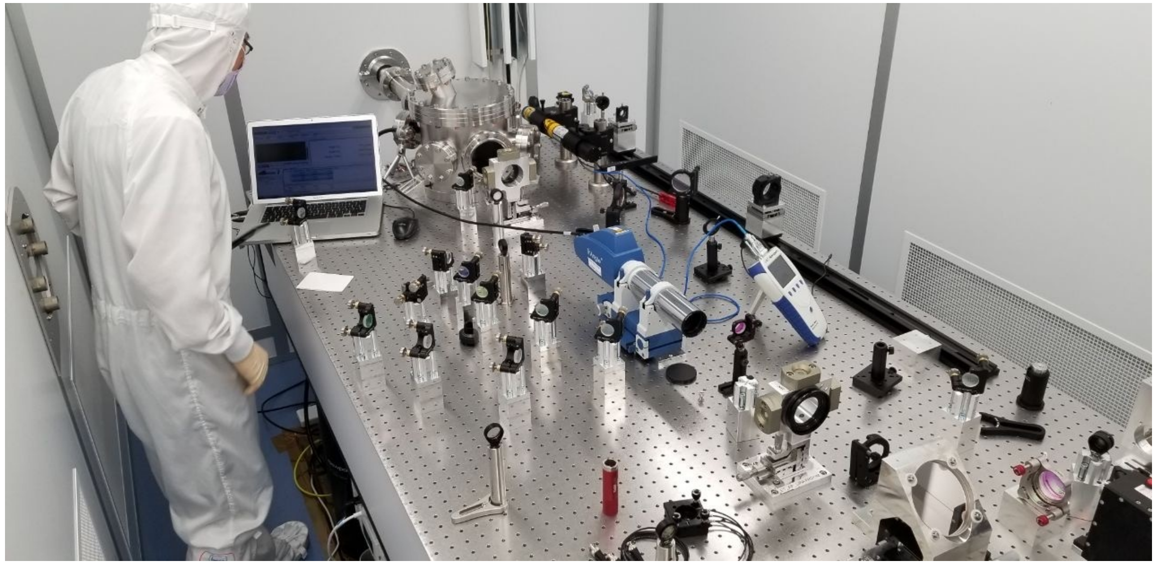

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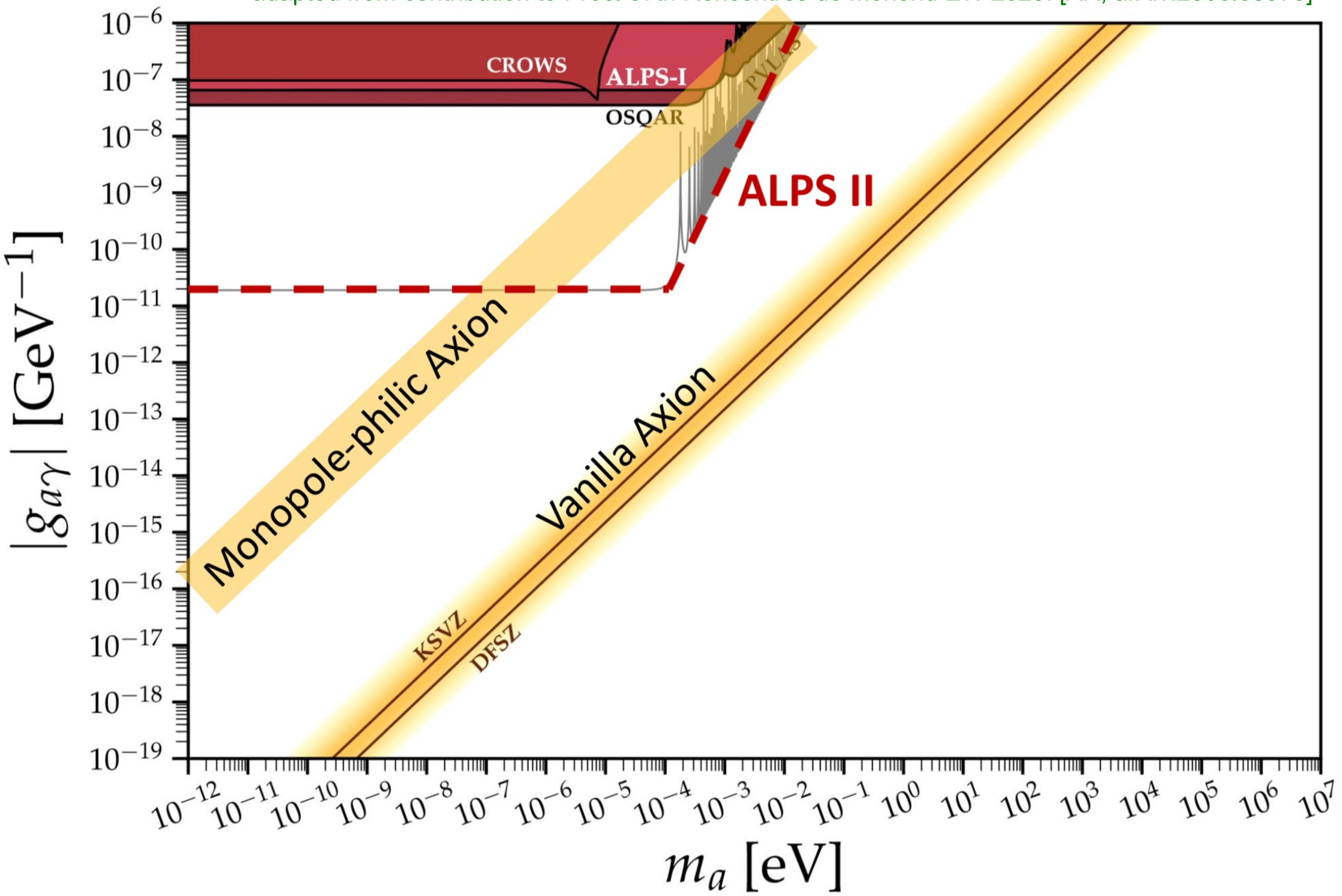
    - All 24 magnets installed, aligned and tested
    - Cleanrooms at end stations and center are operational
    - Commissioning of optical system finished
    - Data taking has started in May 2023

Light-Shining-through-a-Wall Searches

- ALPS II designed to improve sensitivity compared to ALPS I by a factor of ~ 3000

adapted from contribution to Proc. 57th Rencontres de Moriond EW 2023: [AR, arXiv:2306.08978]



Light-Shining-through-a-Wall Searches

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  - exploring uncharted territory in parameter space, beyond astrophysical constraints

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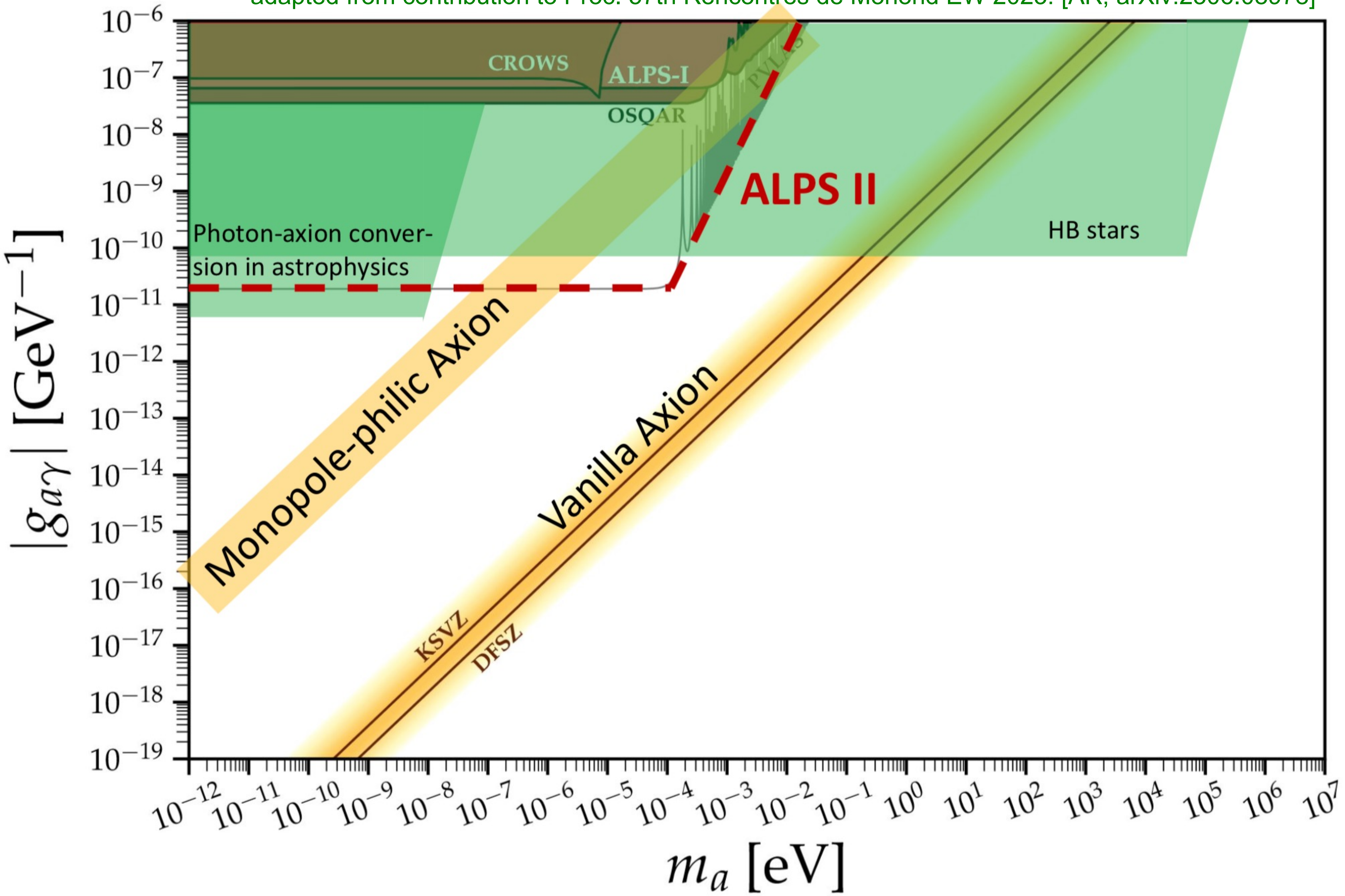

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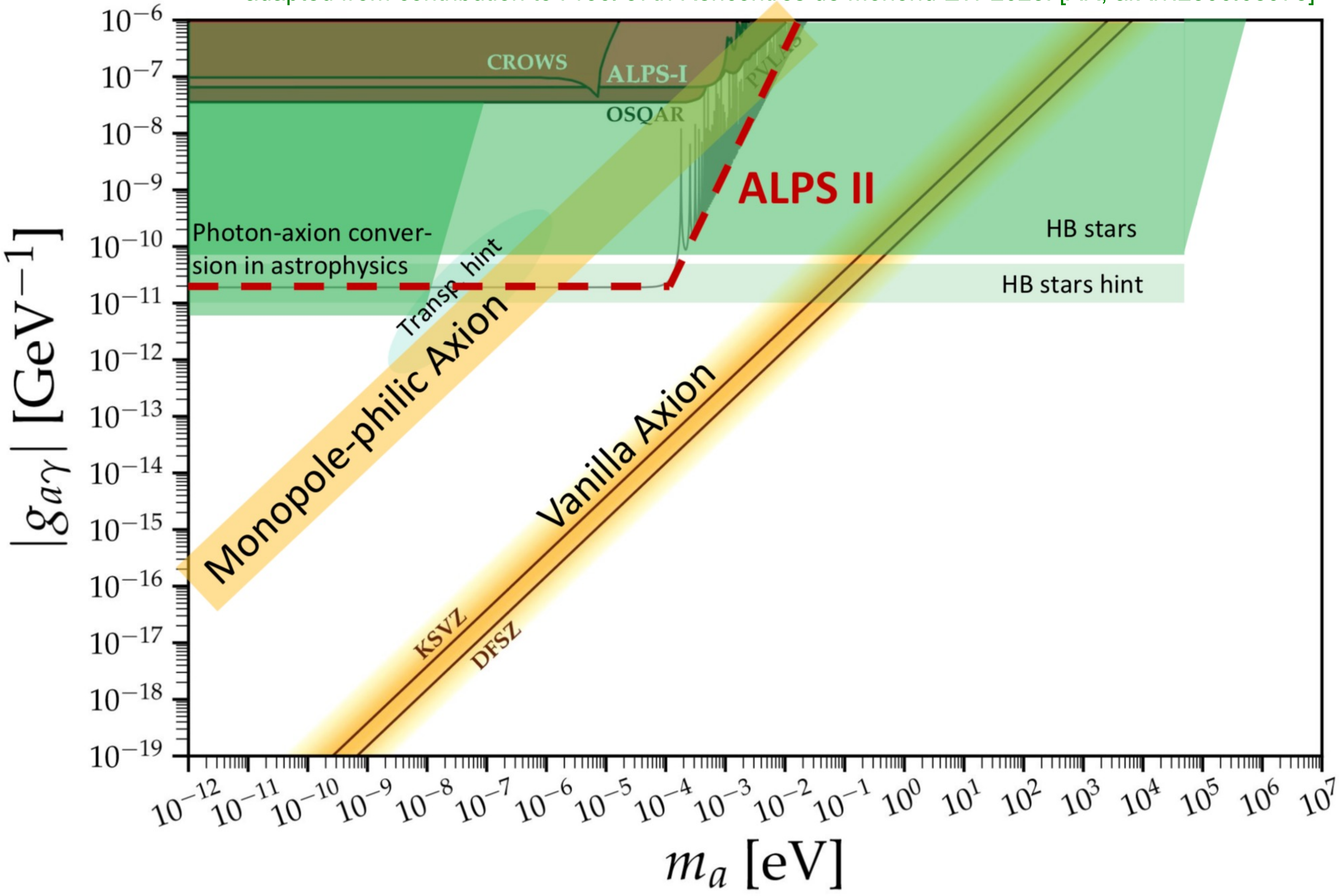

Light-Shining-through-a-Wall Searches

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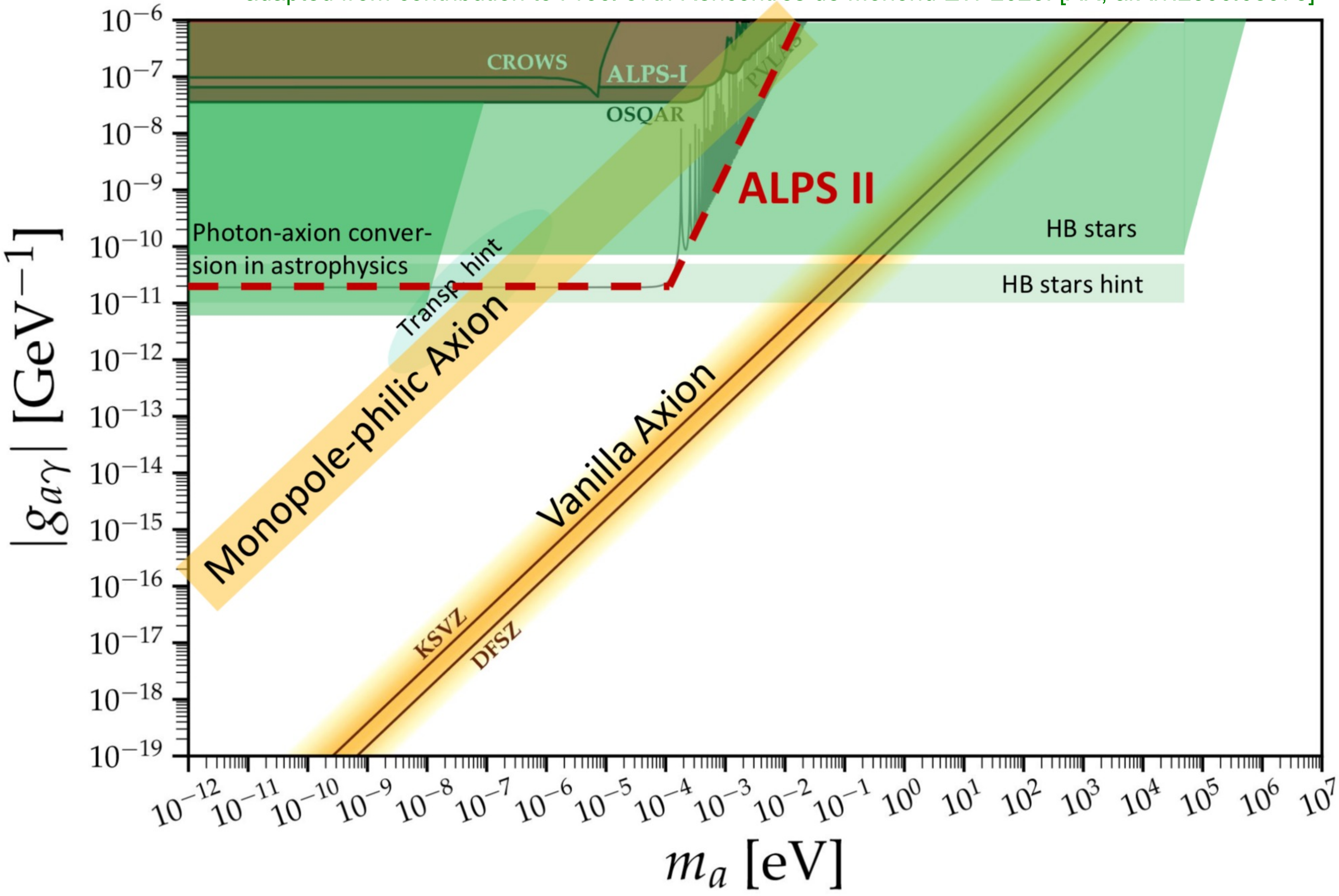
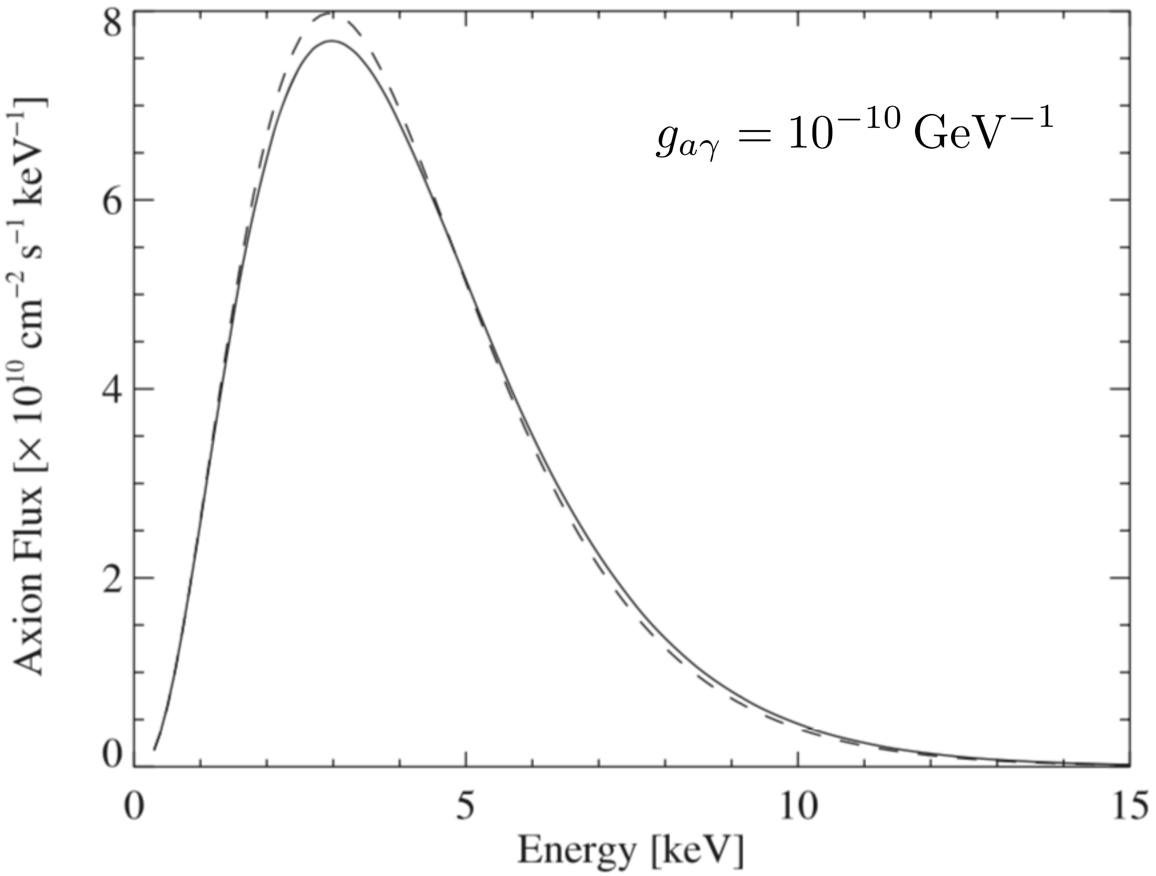
  - exploring uncharted territory in parameter space, beyond astrophysical constraints
  - checking axion explanation of astrophysical anomalies
- Full sensitivity expected to be reached in 2025

adapted from contribution to Proc. 57th Rencontres de Moriond EW 2023: [AR, arXiv:2306.08978]

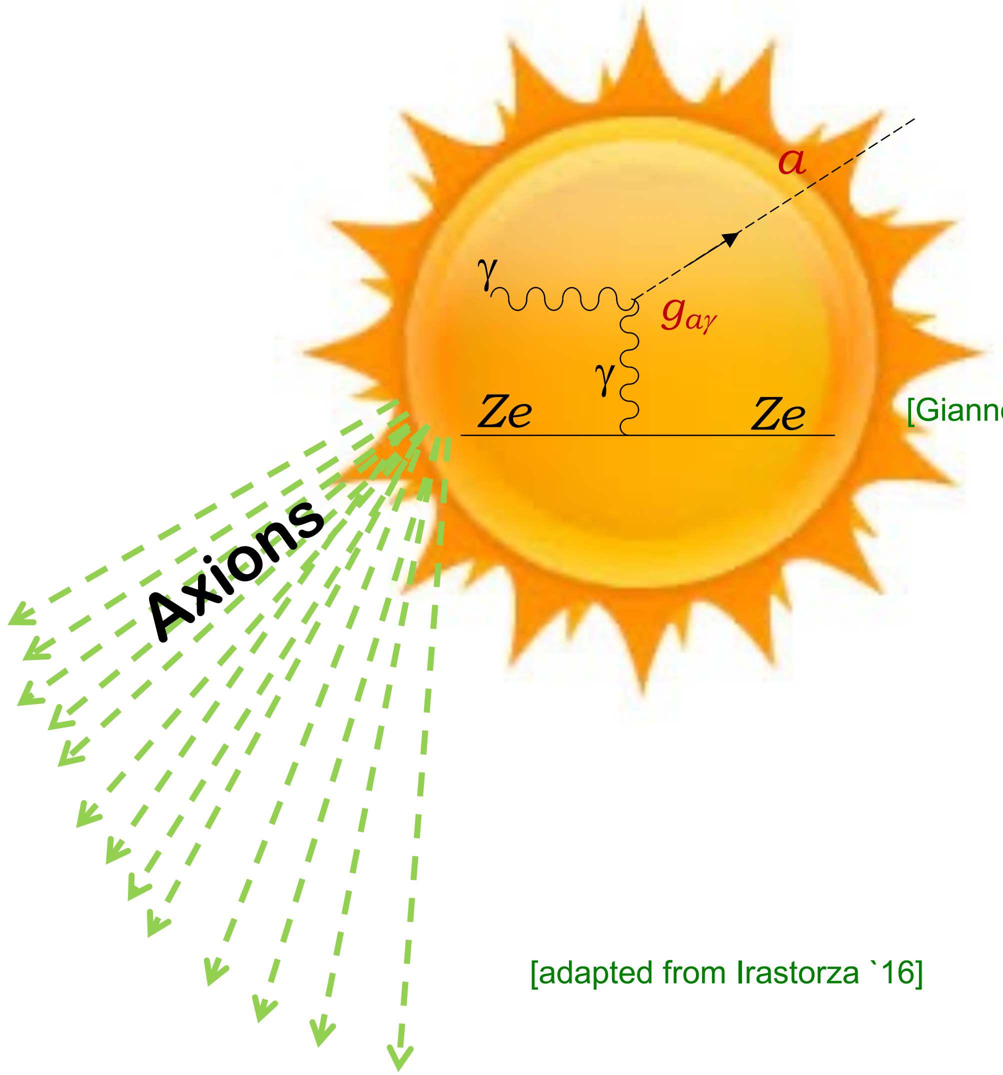


Helioscope Searches

- Flux of solar axions produced by Primakoff process in core:



[Adriamonje et al. `07]



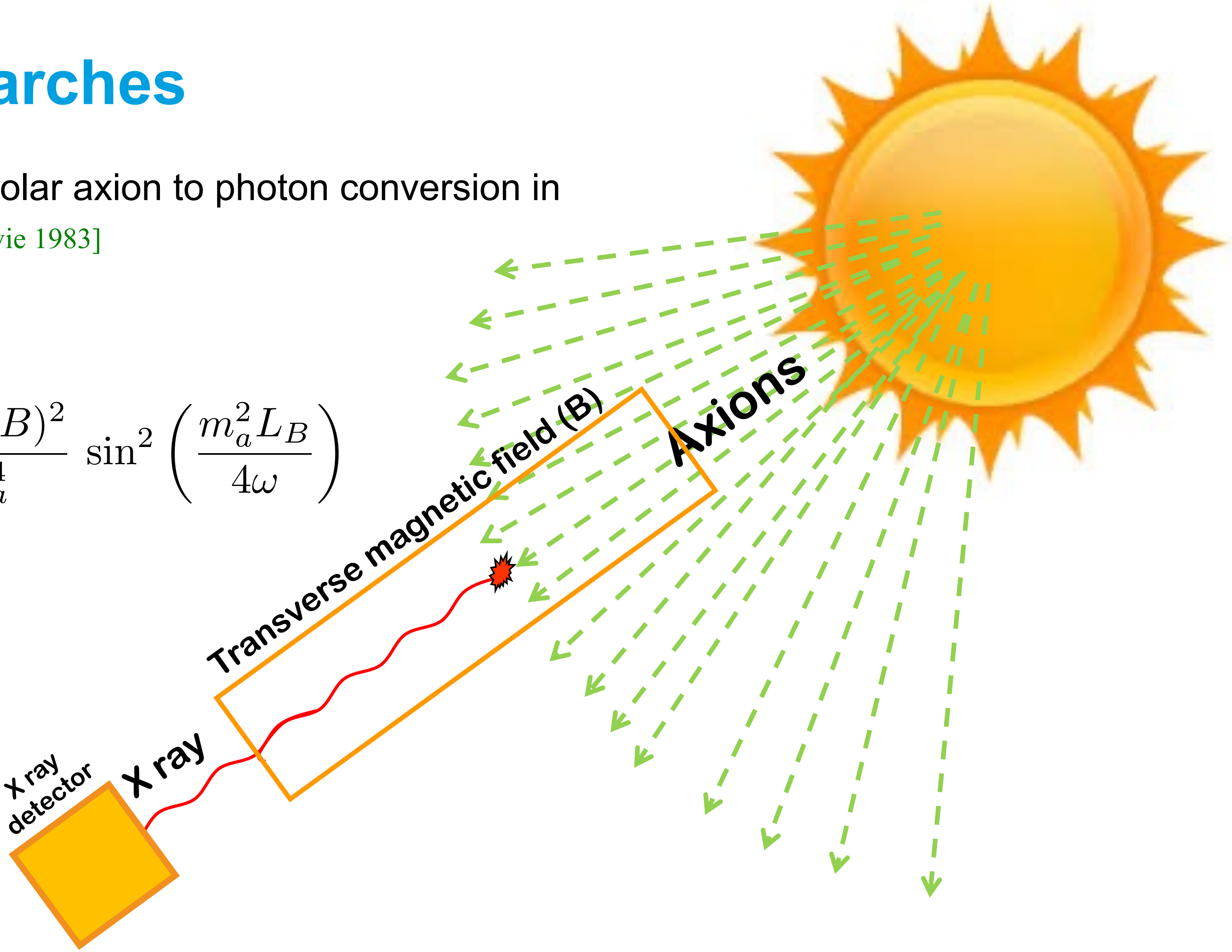
[Giannotti `16]

[adapted from Irastorza `16]

Helioscope Searches

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

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



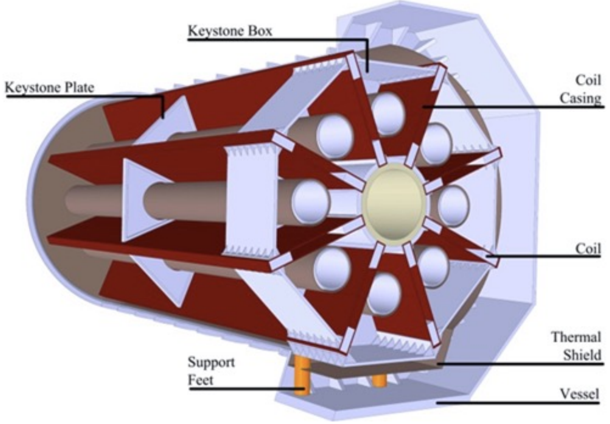
[adapted from Irastorza `16]

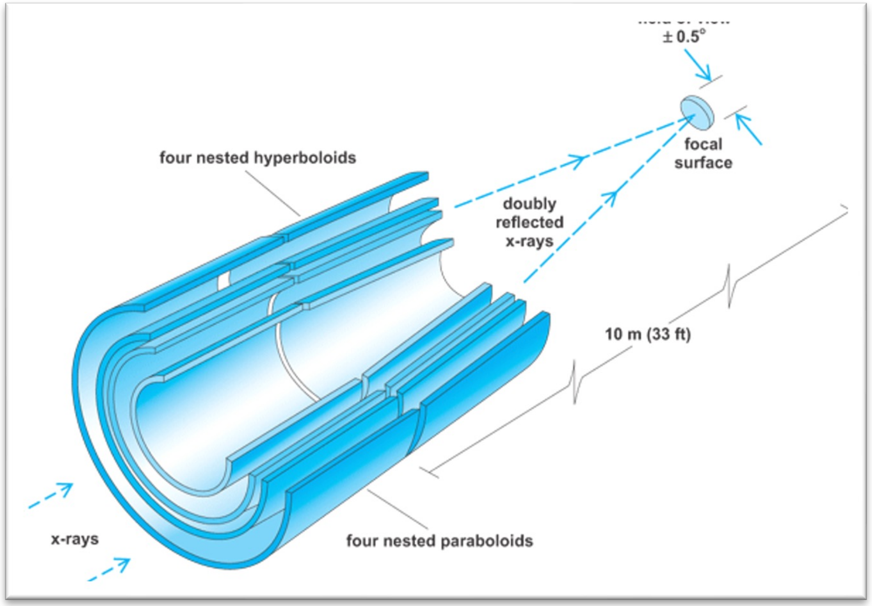
Helioscope Searches

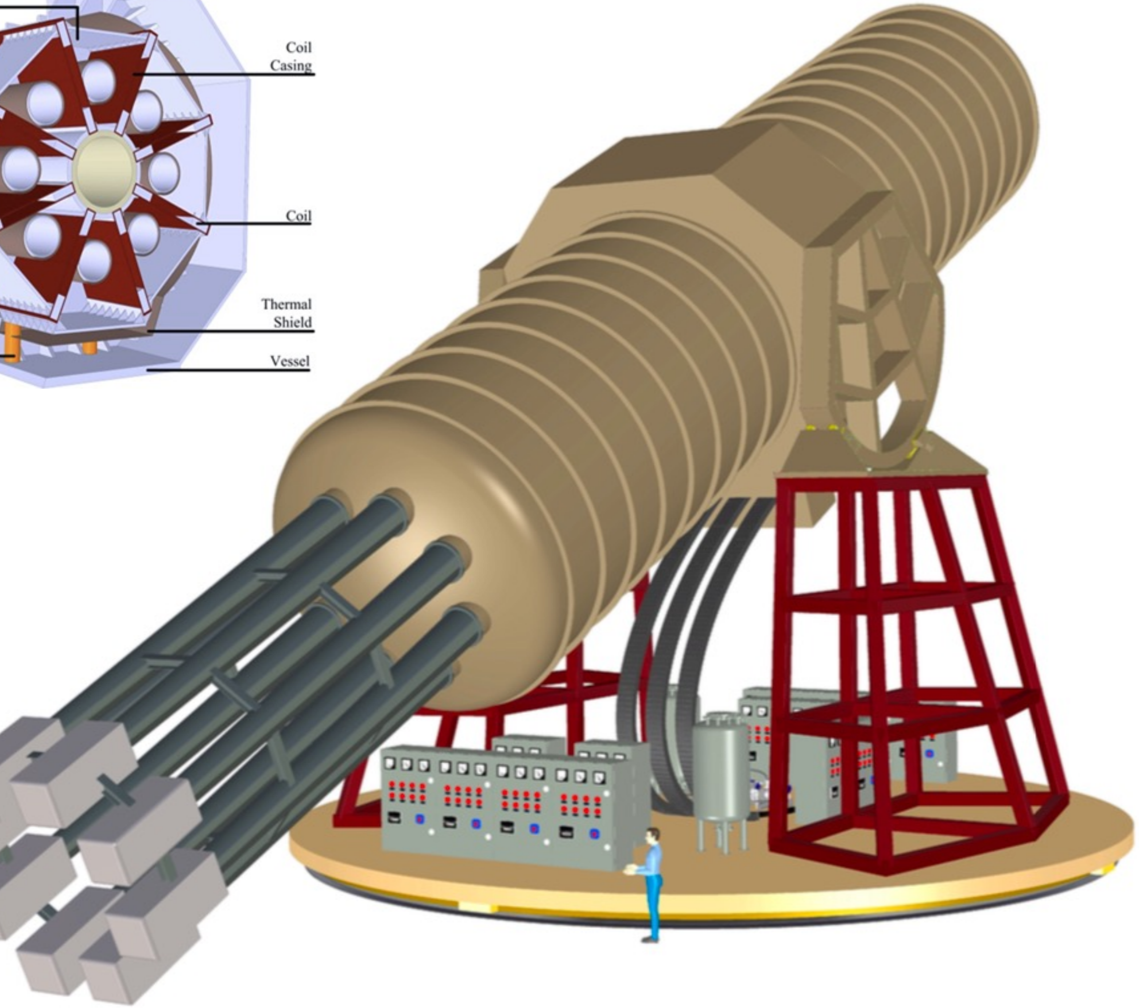
- Most sensitive until now: CERN Axion Solar Telescope (CAST)
  - Superconducting LHC dipole magnet
  - X-ray detectors
  - Use of buffer gas to extend sensitivity to higher masses (axion band)

Helioscope Searches

- International Axion Observatory (IAXO) [IAXO CDR: JINST 9 (2014) T05002 (arXiv:1401.3233)]
  - Large toroidal 8-coil magnet L = ~20 m
  - 8 bores: 600 mm diameter each
  - 8 X-ray telescopes + 8 detection systems
  - Rotating platform with services







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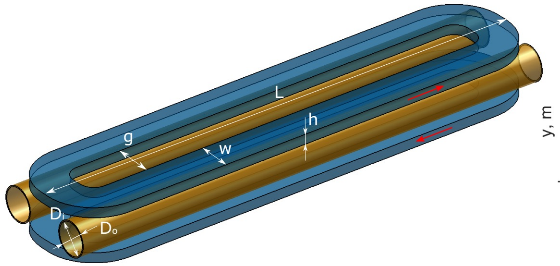
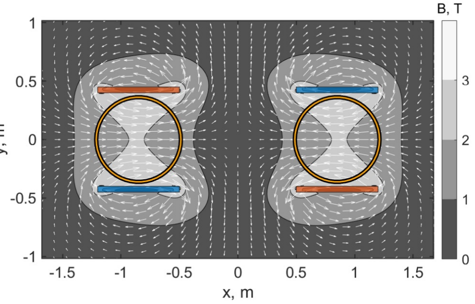
  - Rotating platform with services
- Proposed site: DESY

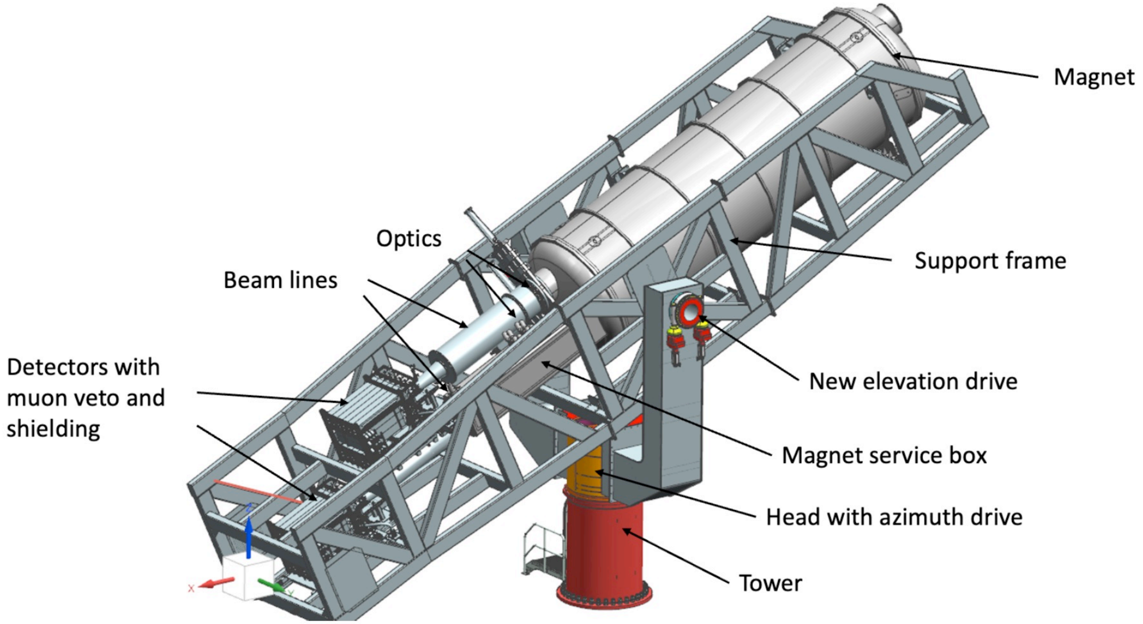
[IAXO CDR: JINST 9 (2014) T05002 (arXiv:1401.3233)]

Helioscope Searches

- Prototype for IAXO: BabyIAXO
  - Two bores of dimensions similar to final IAXO bores
  - Detection lines representative of final ones
  - Test & improve all systems
- Magnet technical design ongoing at CERN







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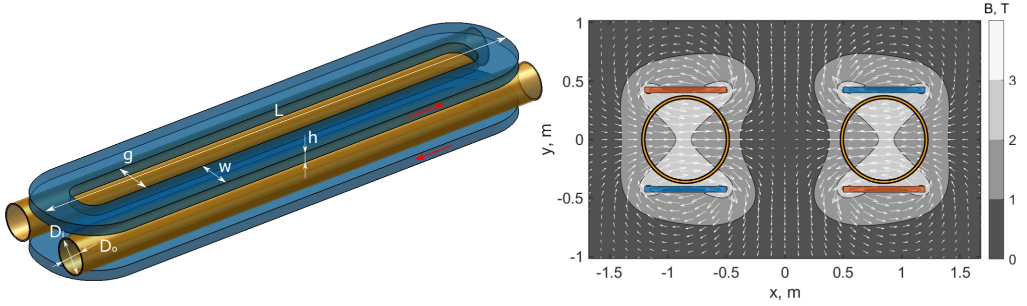

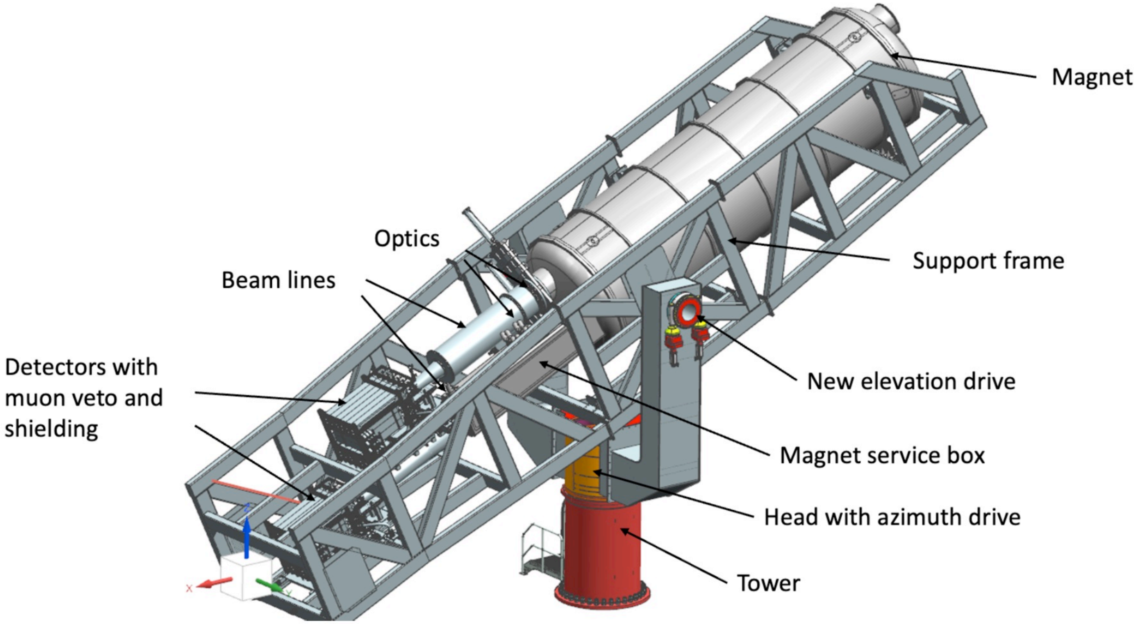

- Construction site: DESY
- Funded by CERN, DESY and Irastorza: ERC-AvG 2017 IAXO+

Irastorza: ERC-SynG 2023 DarkQuantum

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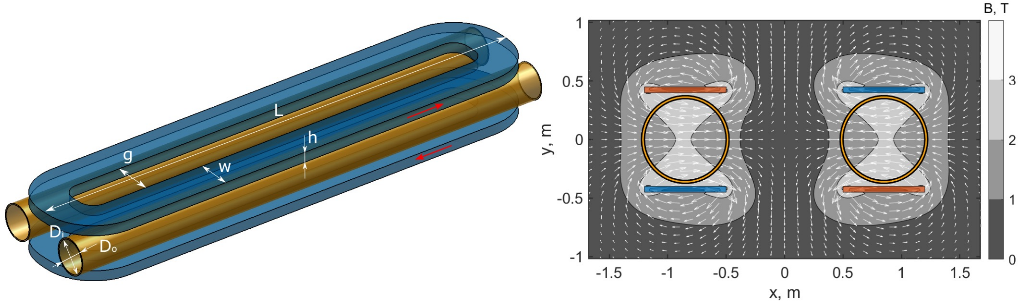

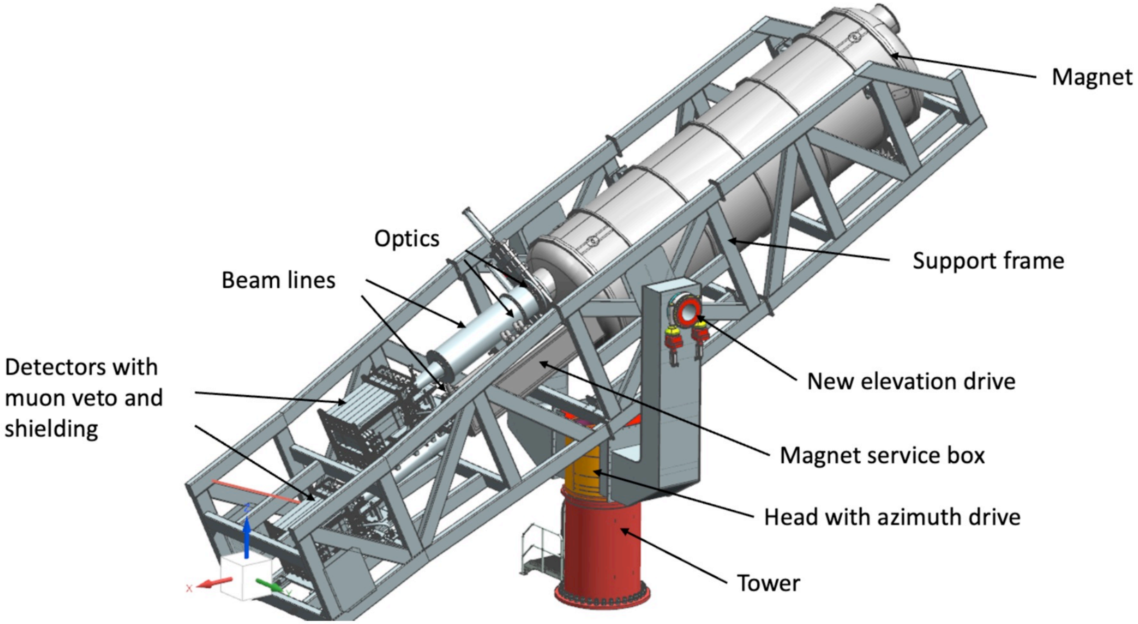

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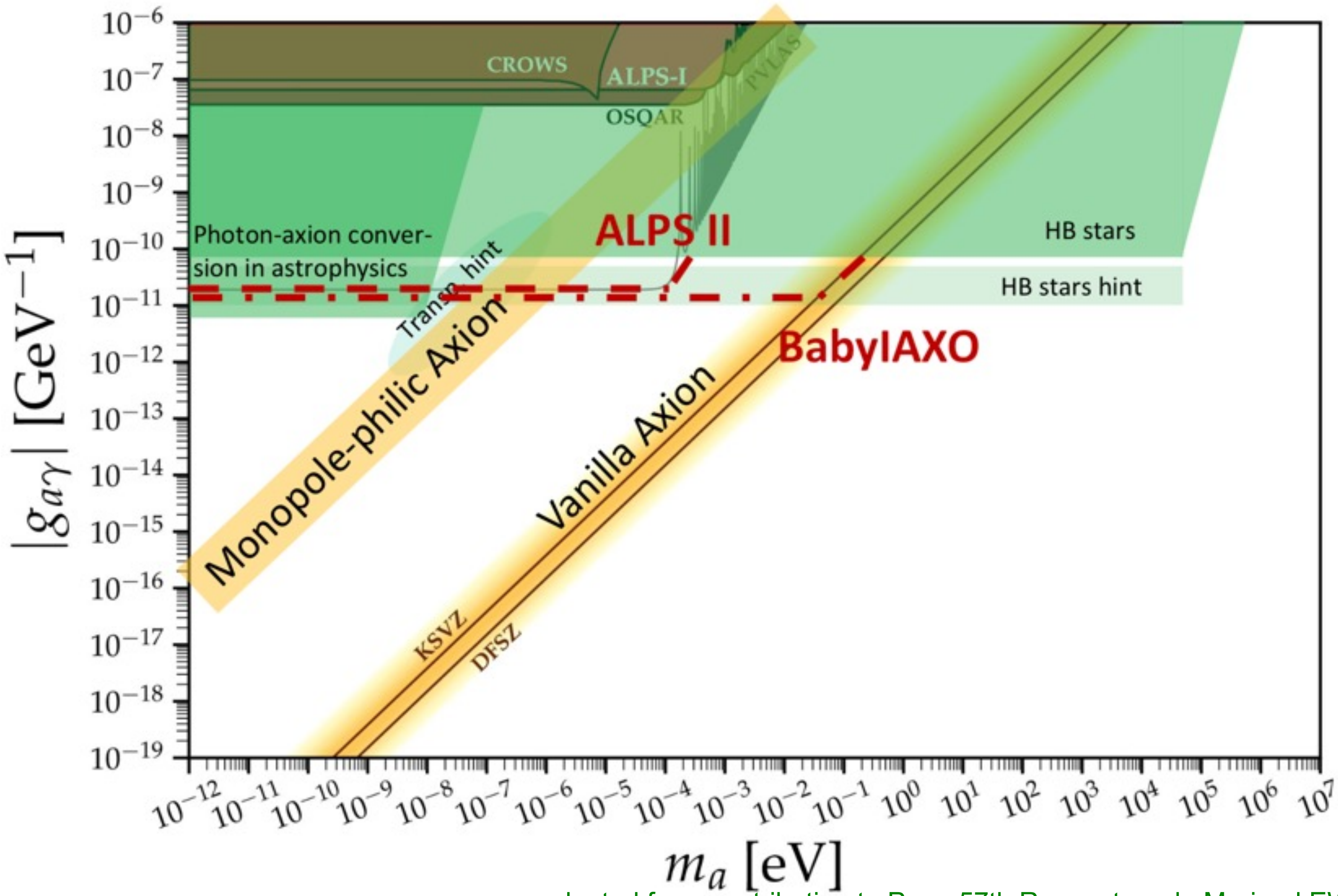
- Preparations have already started in 2020
- Start of data taking envisaged for 2028

Helioscope Searches

- BabyIAXO at low masses sensitivity similar to ALPS II, but probes also meV mass QCD axion:



adapted from contribution to Proc. 57th Rencontres de Moriond EW 2023: [AR, arXiv:2306.08978]

Axion Dark Matter

Standard production mechanisms

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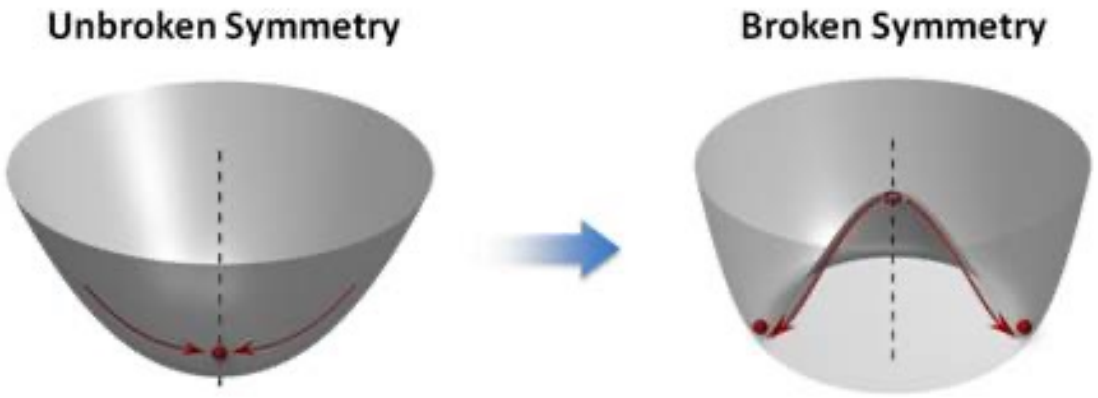
Standard production mechanisms

- Axion comes to existence as soon as Peccei-Quinn (PQ) symmetry is spontaneously broken



[Peking University]

Axion Dark Matter

Standard production mechanisms

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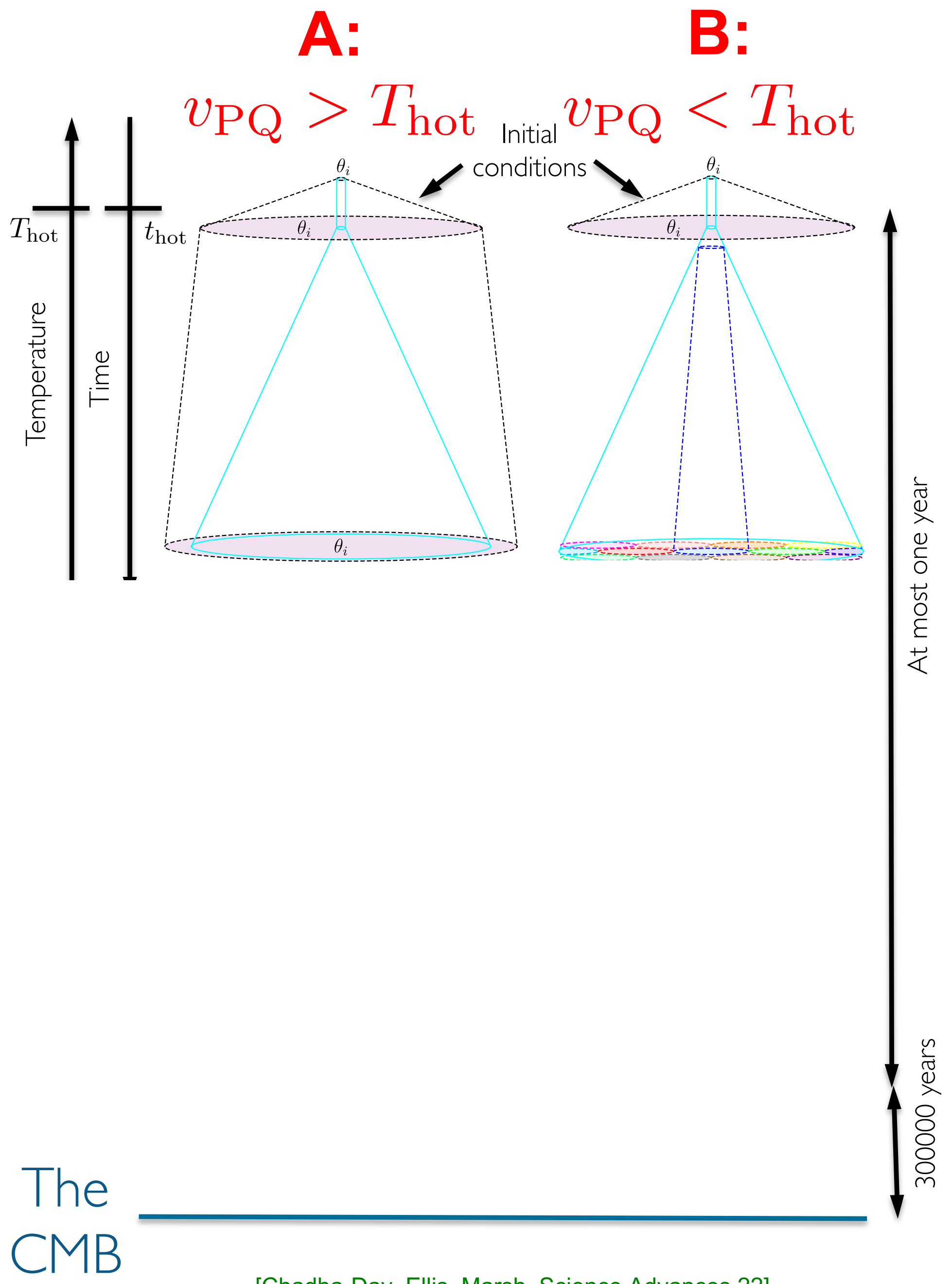
- Dynamics and resulting DM density depends on whether PQ breaking scale $v_{\rm PQ}$ is larger or smaller than the temperature of the universe at the onset of the hot phase, $T_{\rm hot}$



[Chadha-Day, Ellis, Marsh, Science Advances 22]

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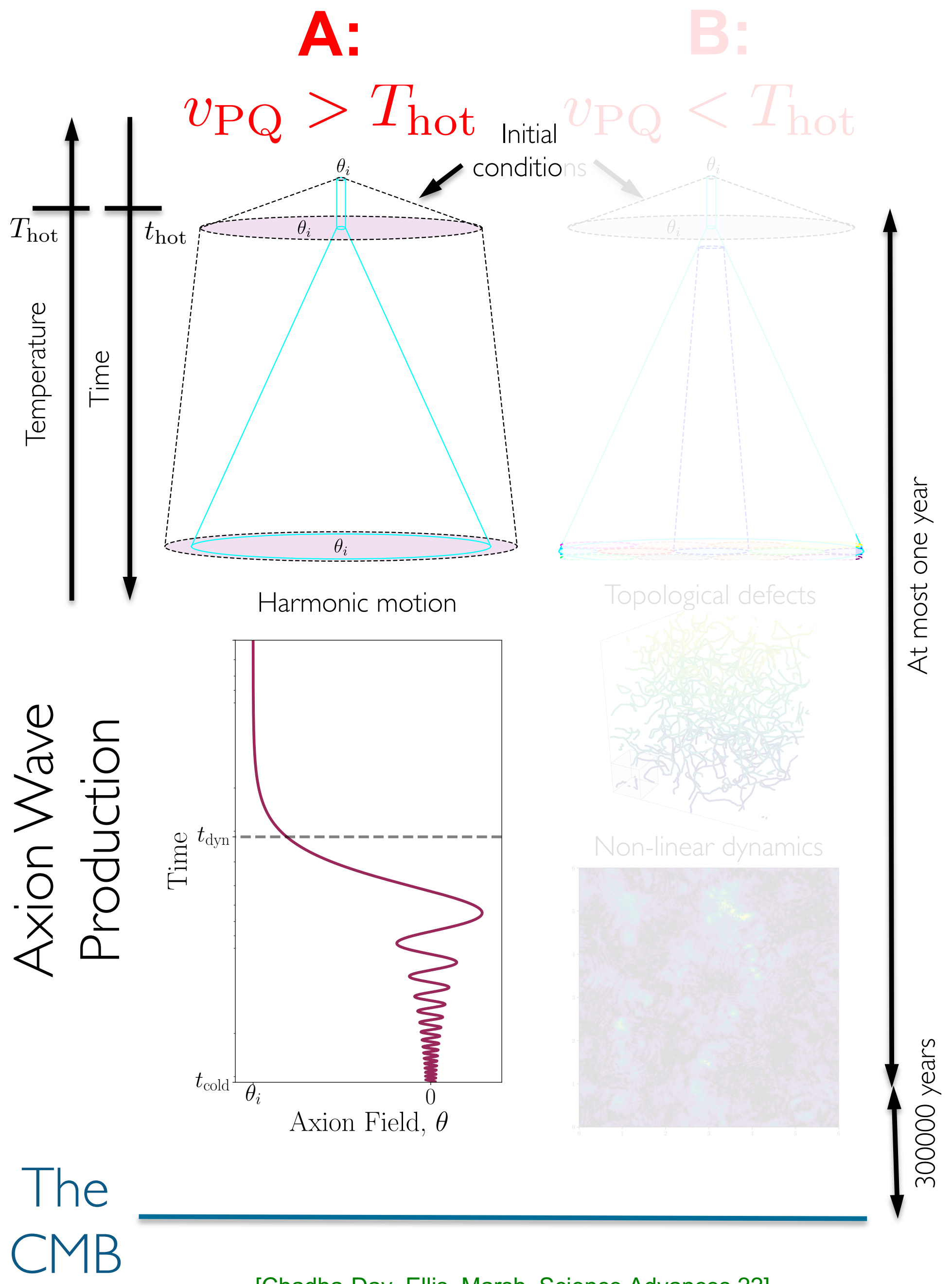
  - Scenario A ("pre-inflationary PQ breaking"):
    - axion DM production by realignment mechanism

[Preskill,Wise,Wilczek 83; Abbott,Sikivie 83; Dine,Fischler 83,....]



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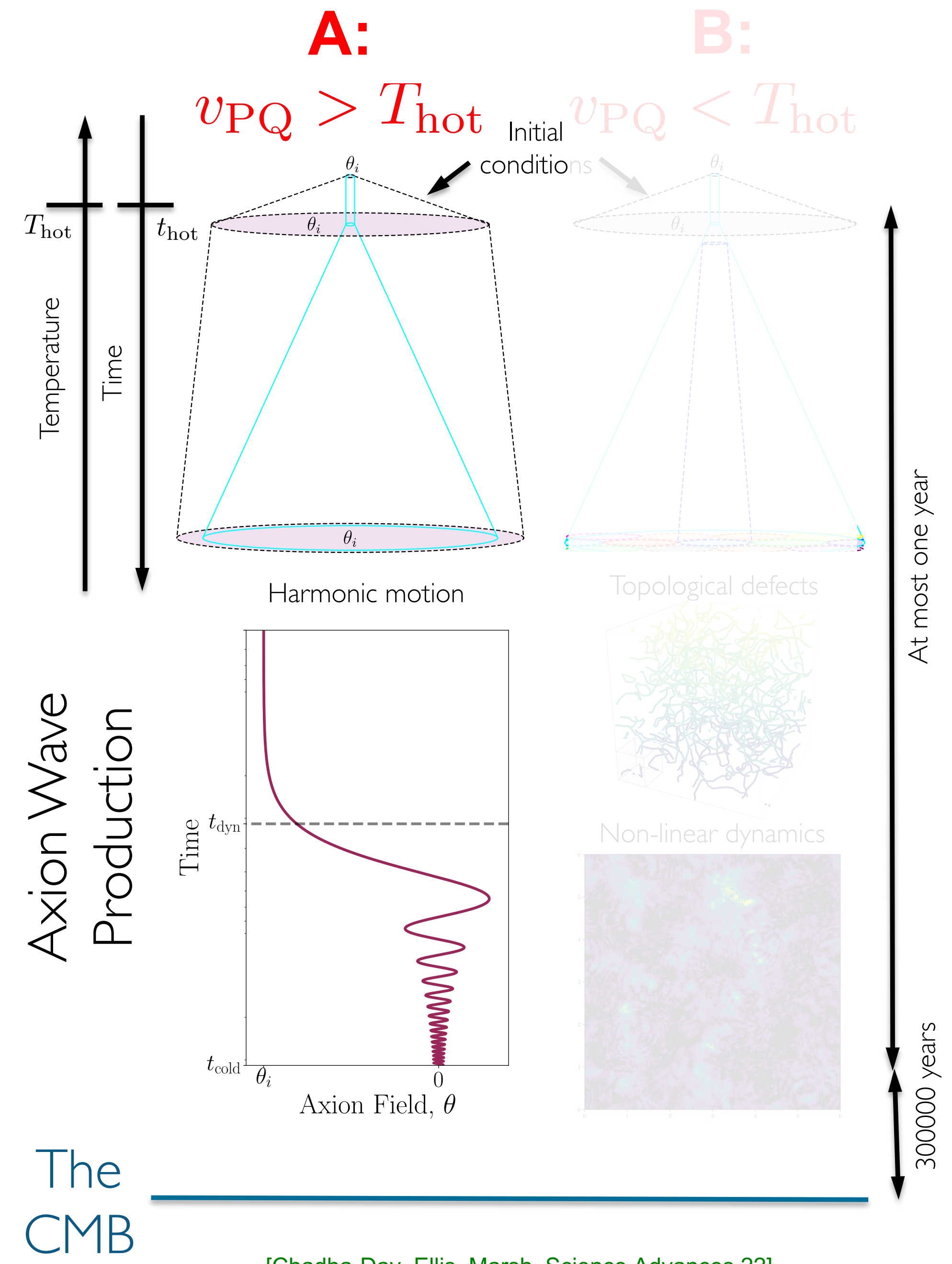
      [Preskill,Wise,Wilczek 83; Abbott,Sikivie 83; Dine,Fischler 83,....]
      - DM axion mass not fixed by DM abundance:

$$\Omega_a h^2 \approx 0.12 \left(\frac{6\ \mu\text{eV}}{m_a}\right)^{1.165} \theta_i^2\,, \qquad \theta_i \equiv a(t_{\rm hot})/f_a$$

[Borsanyi et al. `16]



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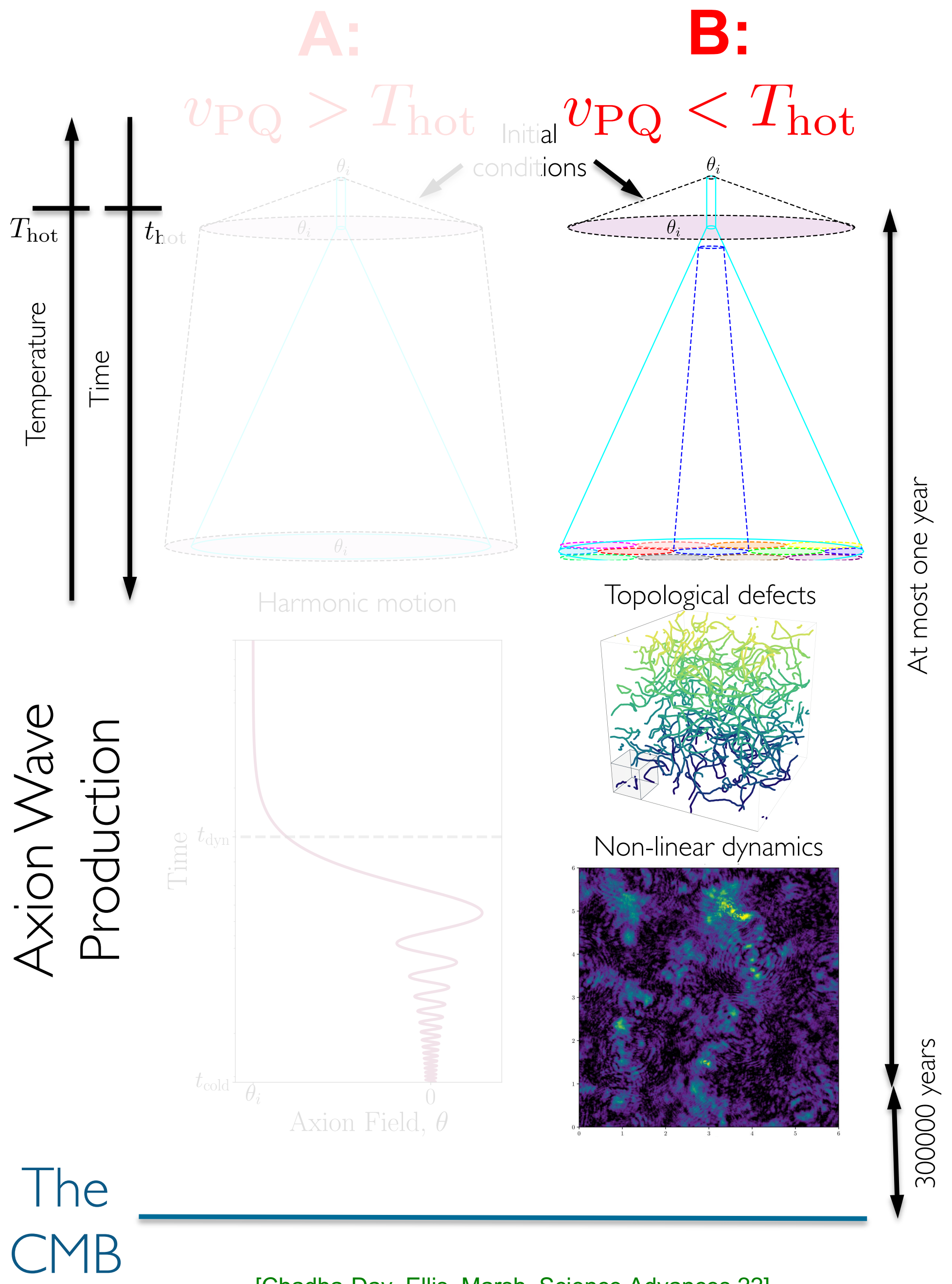
  - Scenario B ("post-inflationary PQ breaking"):
    - axion DM production by realignment mechanism and decay of topological defects (strings and domain walls)



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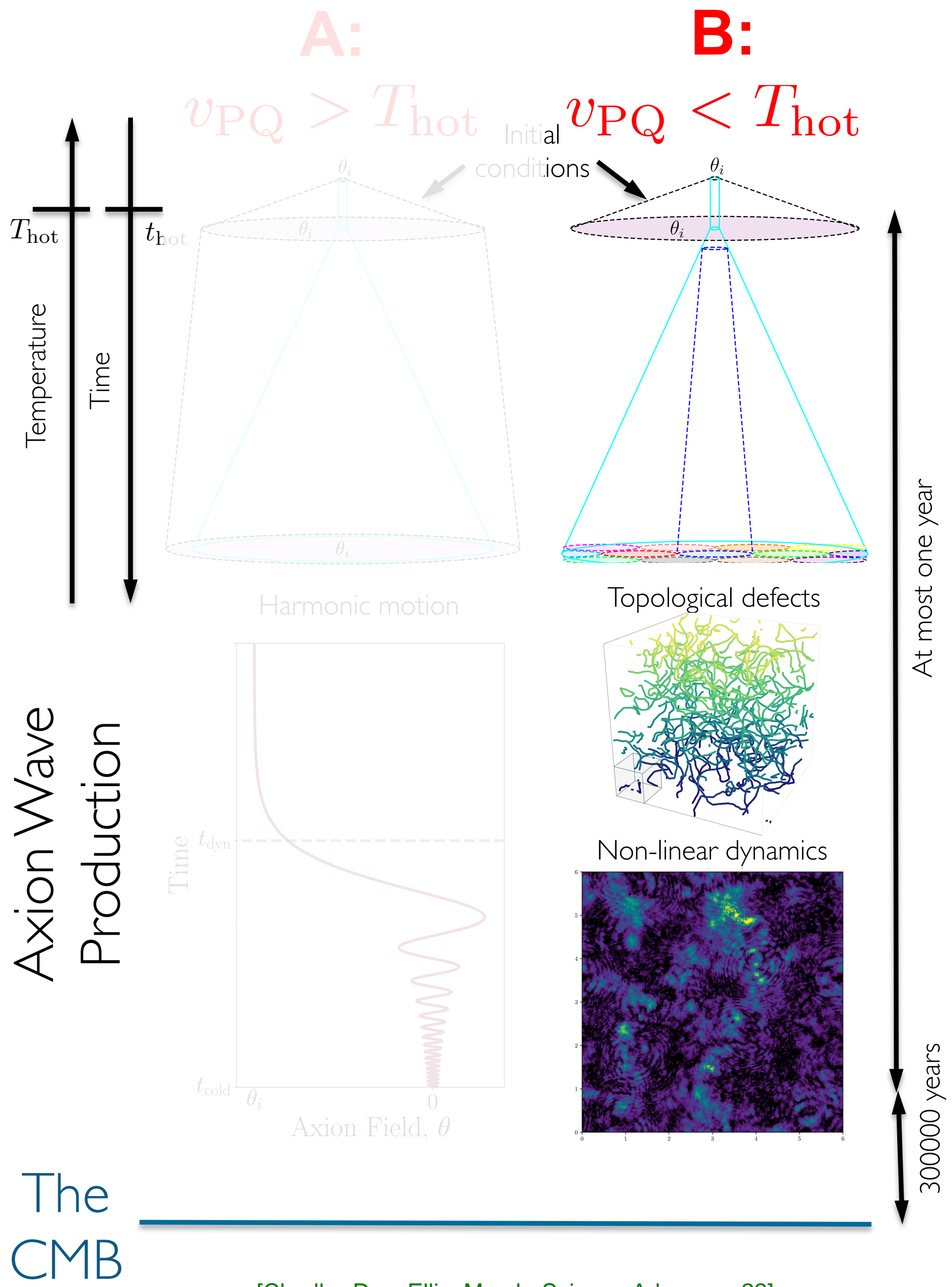
  - Scenario B ("post-inflationary PQ breaking"):
    - axion DM production by realignment mechanism and decay of topological defects (strings and domain walls)
      - required axion mass to explain 100% of DM abundance:

[Hiramatsu et al. 11,12,13; Kawasaki,Saikawa,Segikuchi 15; AR,Saikawa `16; Borsanyi et al. `16; Klaer,Moore `17; Gorghetto,Hardy,Villadoro `18; Buschmann et al. 19; Hindmarsh 19; Gorghetto,Hardy,Villadoro '20; Buschmann et al. 21;Beyer,Sarkar 23; Saikawa et al. 24; ...]

$$m_a \approx 26\ \mu\text{eV} - 0.5\ \text{meV},\ \text{for}\ N_{\rm DW} = N_{\mathcal{Q}} = 1$$

$$m_a \gtrsim \text{meV},\ \text{for}\ N_{\rm DW} = N_{\mathcal{Q}} > 1$$

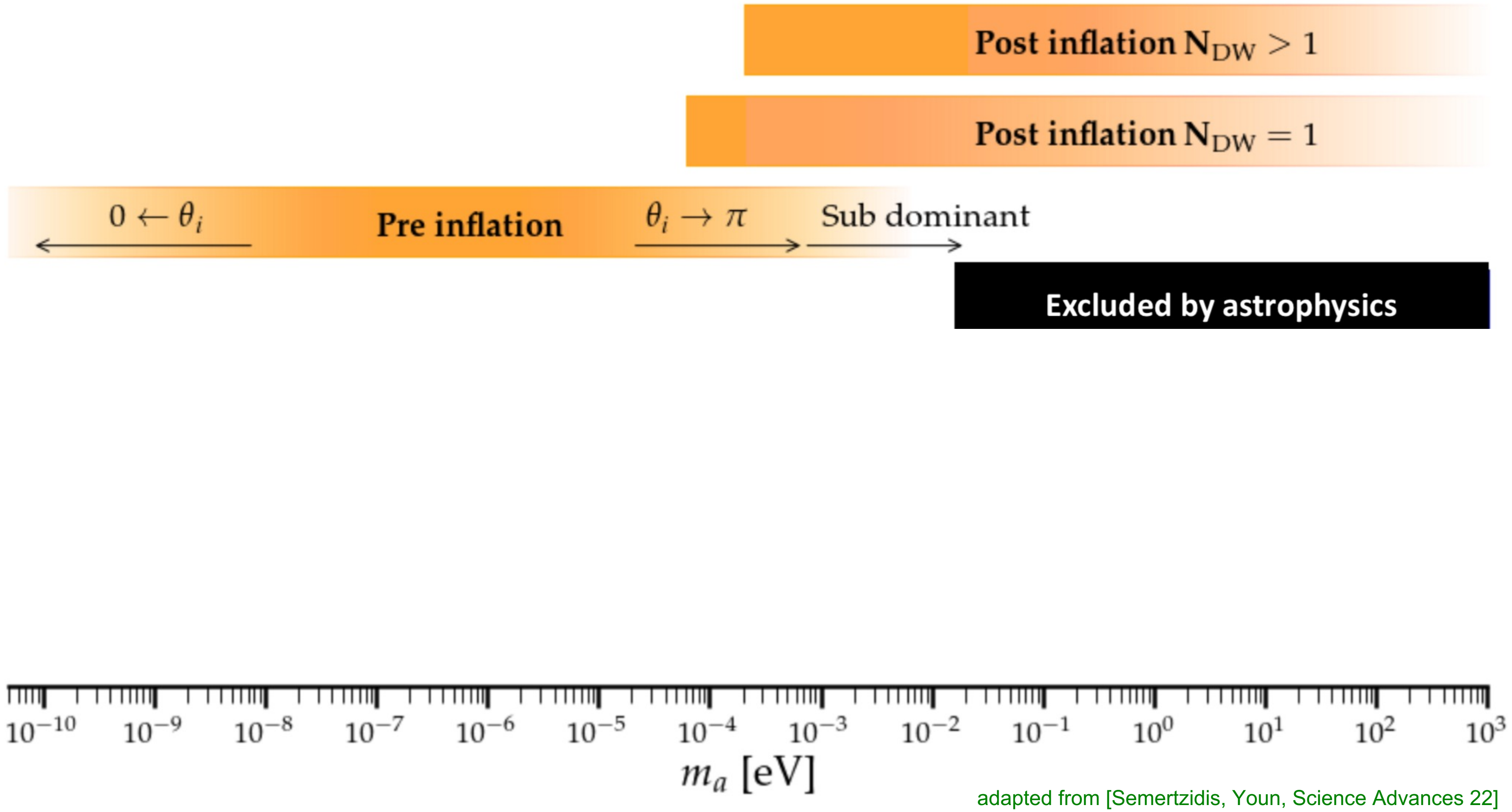


[Chadha-Day, Ellis, Marsh, Science Advances 22]

Axion Dark Matter Experiments

Variety of experimental techniques

- Huge possible mass range:

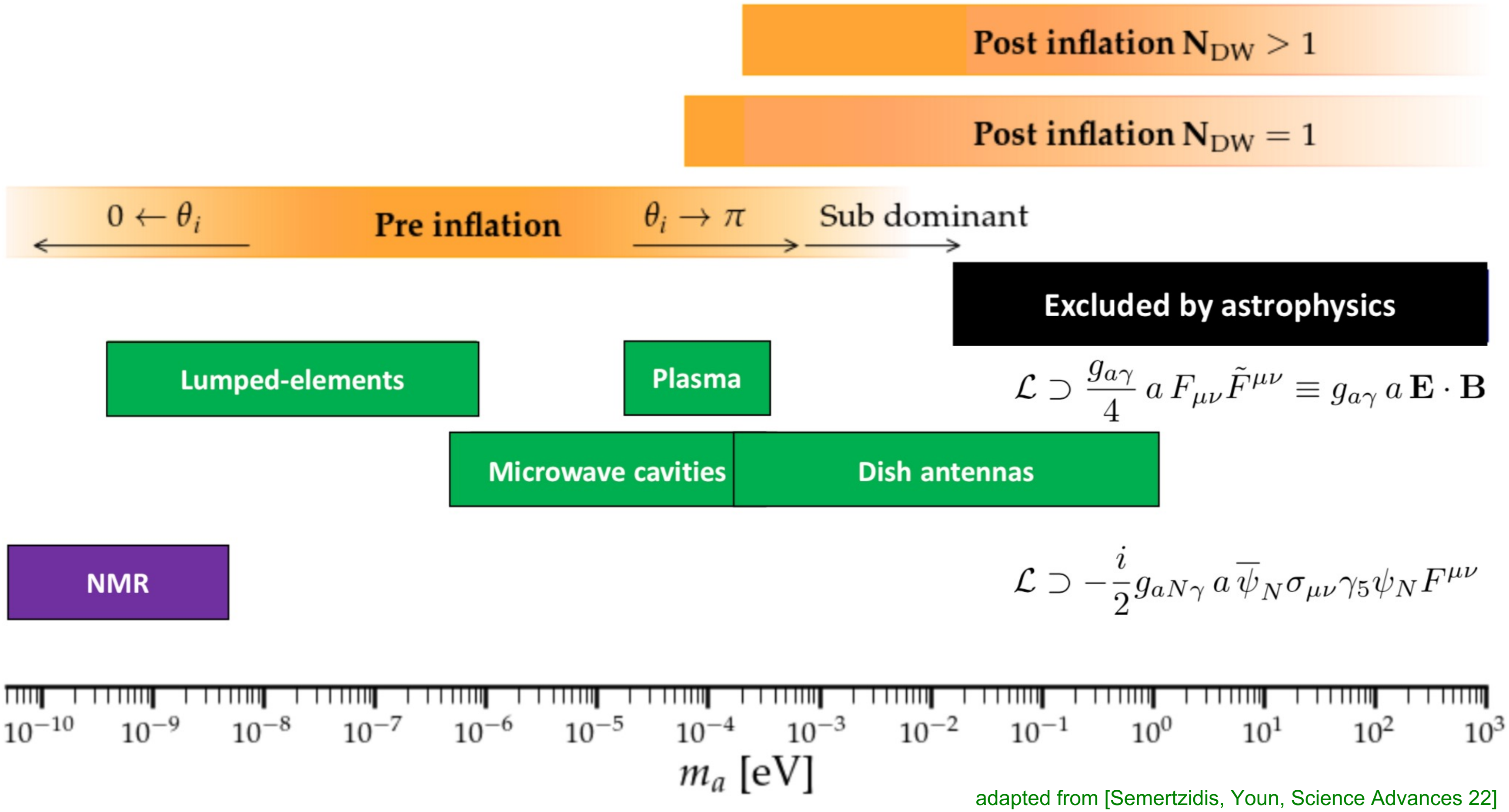


adapted from [Semertzidis, Youn, Science Advances 22]

Axion Dark Matter Experiments

Variety of experimental techniques

- Huge possible mass range requires various experimental techniques to search for axion dark matter via different axion couplings:



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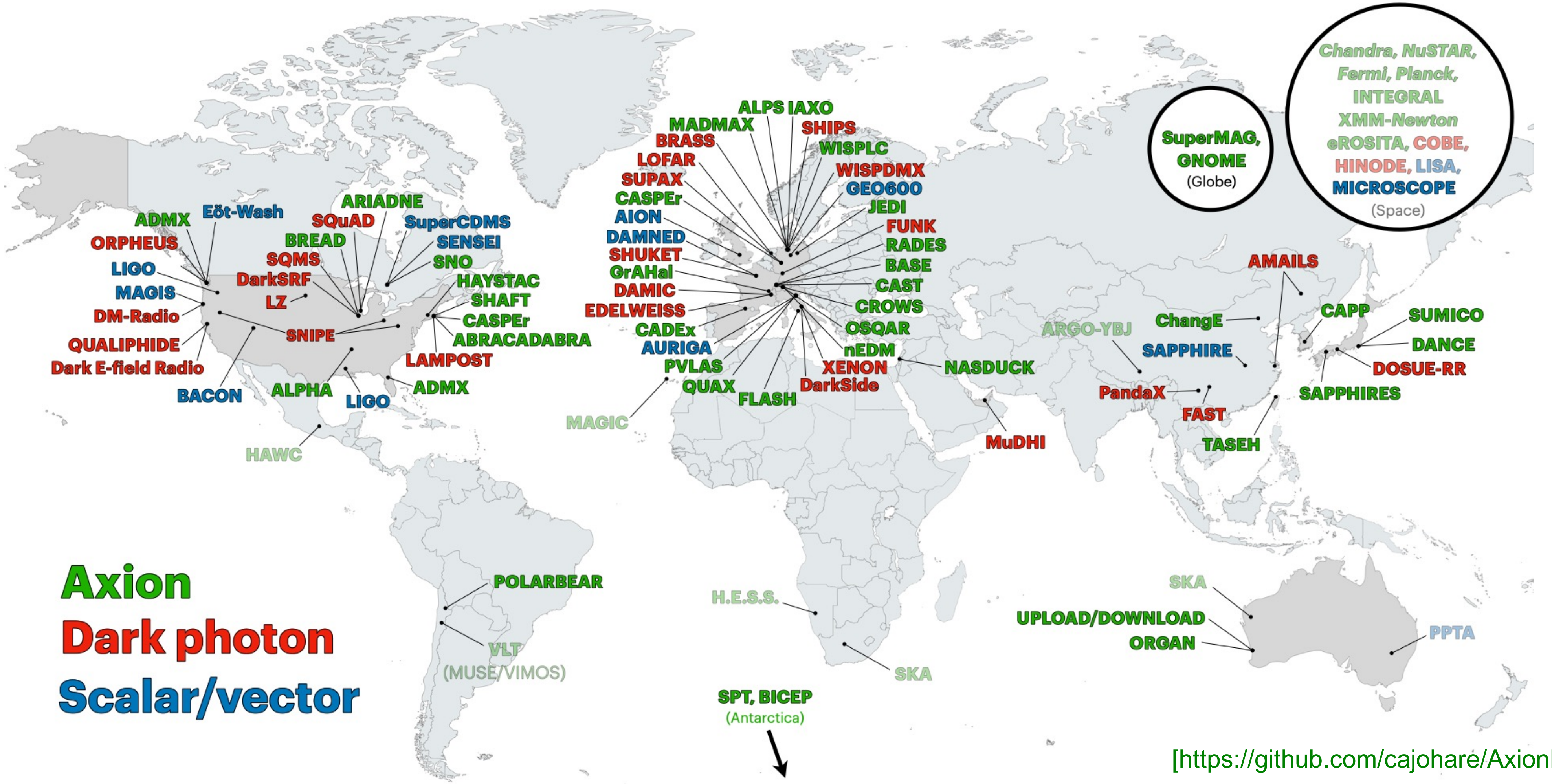
Axion Dark Matter Experiments

Enormous number of axion dark matter experiments worldwide

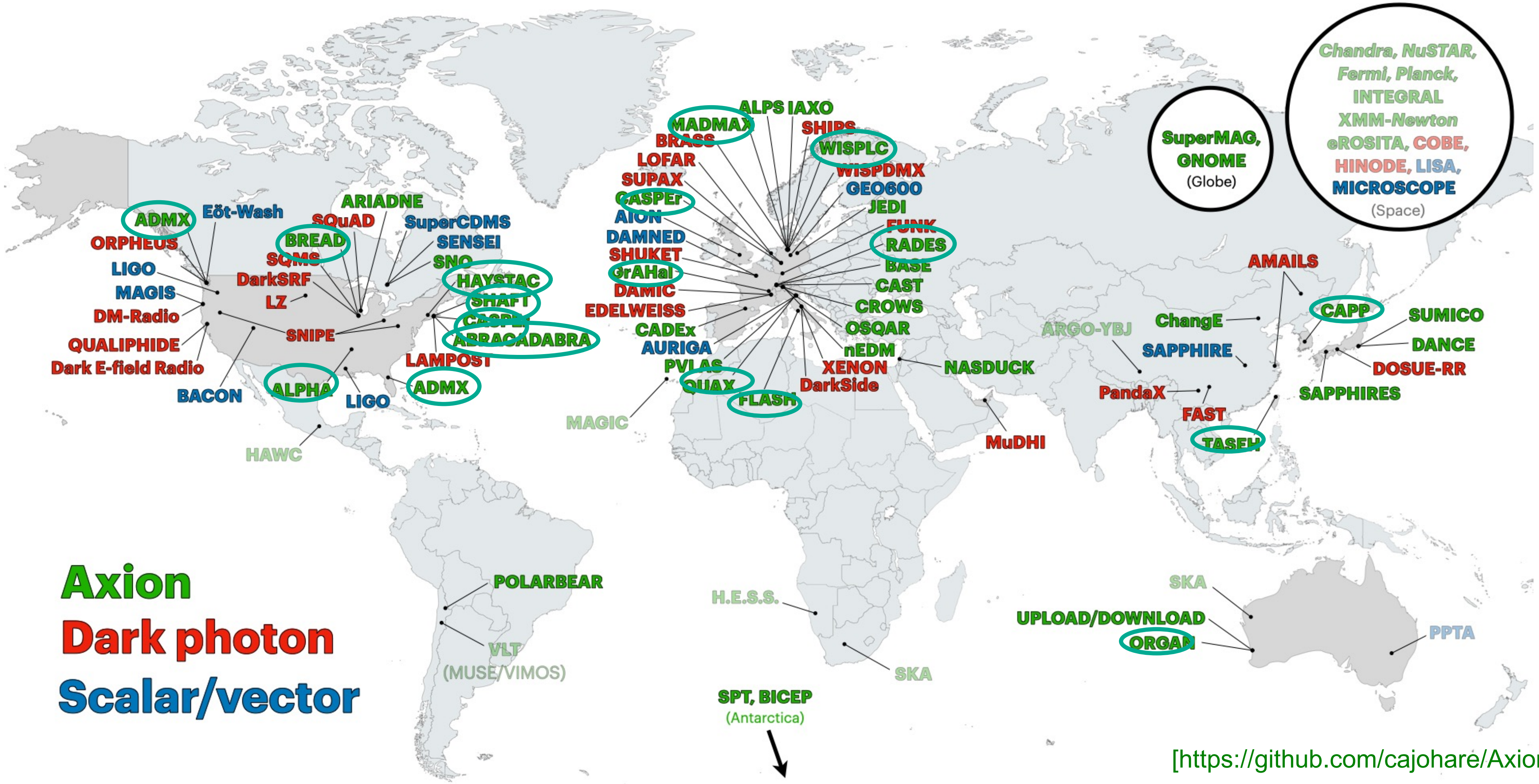


[https://github.com/cajohare/AxionLimits]

Axion Dark Matter Experiments

Enormous number of axion dark matter experiments worldwide

Can only talk about a subset of them …



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Axion Dark Matter Experiments

Wavy dark matter

- Axion DM experiments rely on the assumption that the dark matter halo of the Milky Way is comprised of axions
- The velocity dispersion of halo dark-matter axions is given by the galactic virial velocity, implying a macroscopic de Broglie wave length,

$$\lambda_{\rm dB} = 2\pi/(m_a v_a) \simeq {\rm km}\,(\mu{\rm eV}/m_a)(10^{-3}\,c/v_a)$$

- Correspondingly, halo dark-matter axions behave as an approximately spatially homogeneous and monochromatic classical oscillating field,

$$a(t) \simeq \sqrt{2\rho_a}\cos(m_a t)/m_a$$

- When presenting (projected) limits on halo dark-matter axion couplings it is assumed that

$$\rho_a = \rho_{\rm DM}^{\rm halo} \approx 0.45\,{\rm GeV\,cm}^{-3}$$

  - Large density variations in the initial state of the axion field in the post-inflationary scenario lead to the formation of compact dark matter objects known as “miniclusters”. These objects lead to an increased theoretical uncertainty in the local axion density for dark matter detection in the laboratory.

Haloscopes

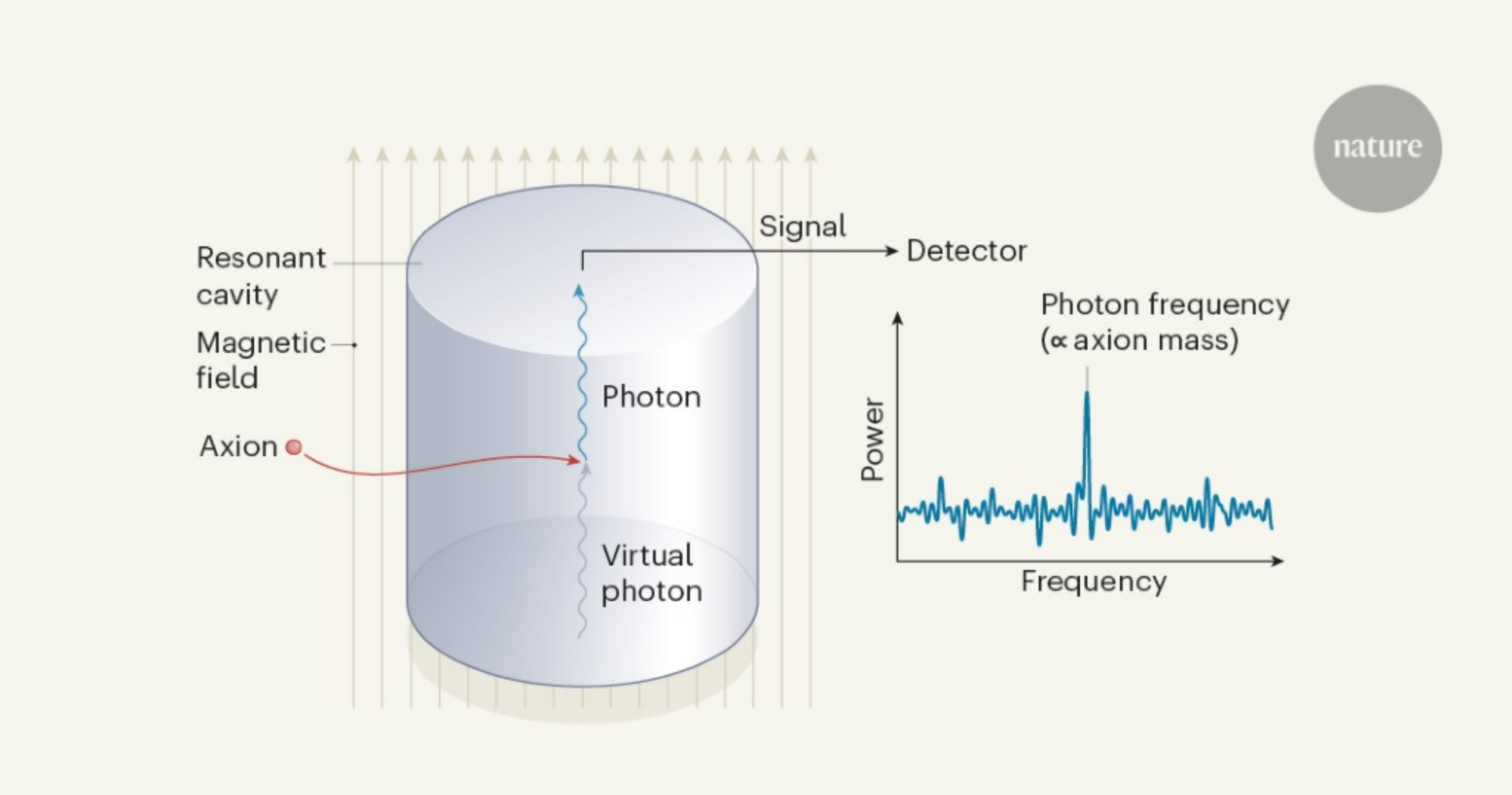
$$\mathcal{L} \supset \frac{g_{a\gamma}}{4}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} \equiv g_{a\gamma}\, a\, \mathbf{E}\cdot\mathbf{B}$$

Haloscopes

Microwave cavities

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

- **Concept:** In microwave cavity placed in magnetic field, DM axion converts into photon [Sikivie 83]



[Irastorza, Nature '21]

- If axion mass matches resonance frequency of cavity,

$$m_a = 2\pi\nu_{\rm res} \sim 4\,\mu{\rm eV}\left(\frac{\nu_{\rm res}}{\rm GHz}\right)$$

power output

$$P_{\rm out} \sim g_{a\gamma}^2\,\rho_{\rm a}\,B_0^2\,V\,Q$$

enhanced by quality factor

$$Q \sim 10^5$$

- Need to scan by tuning resonance frequency

Haloscopes

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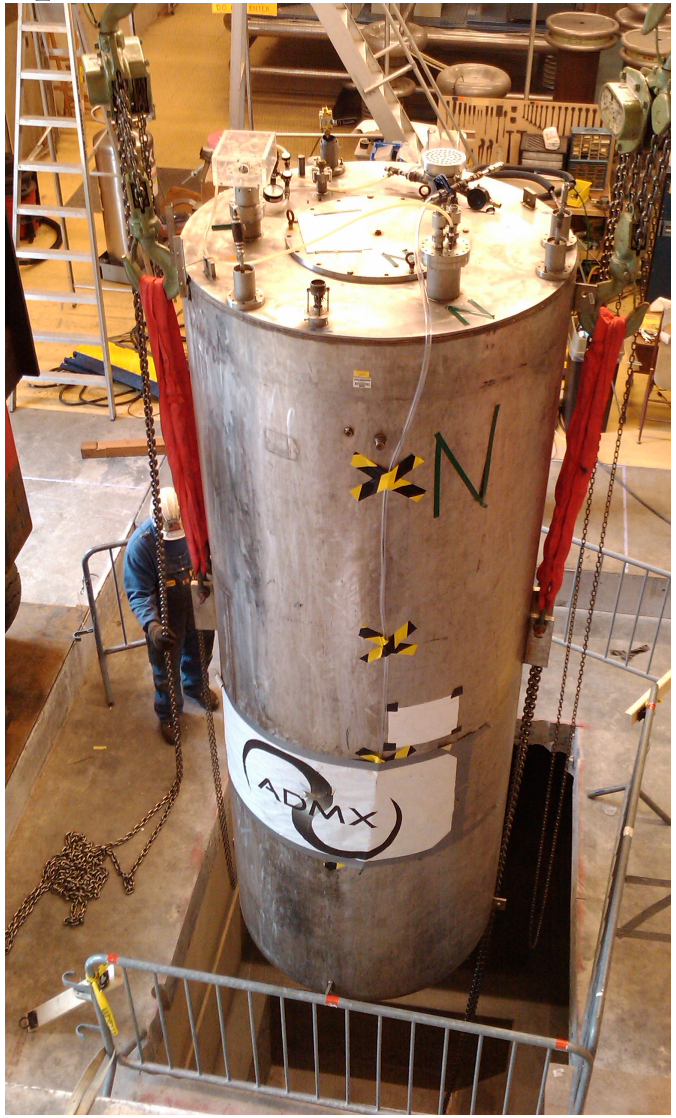
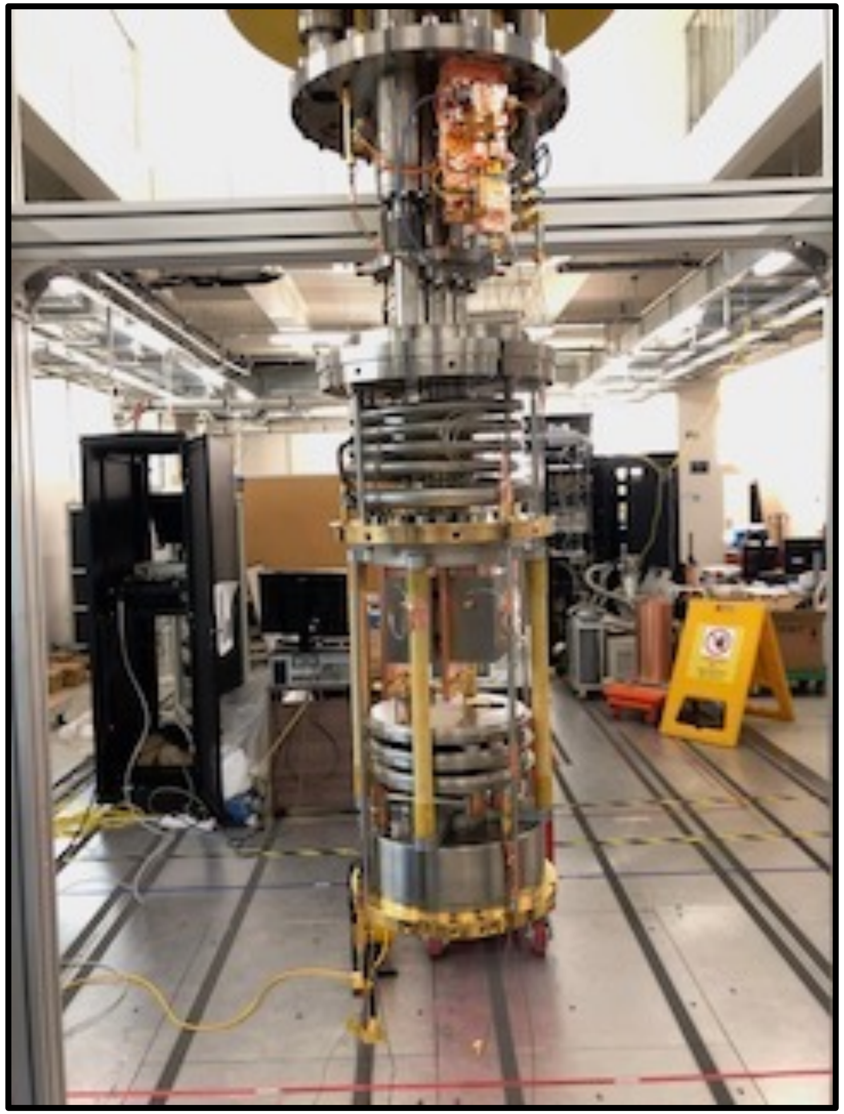
Microwave cavities

- **Currently running:**
  - ADMX
  - CAPP
  - CAST-CAPP
  - GrAHal
  - HAYSTAC
  - ORGAN
  - QUAX
  - RADES
  - TASEH



ADMX



CAPP

Haloscopes

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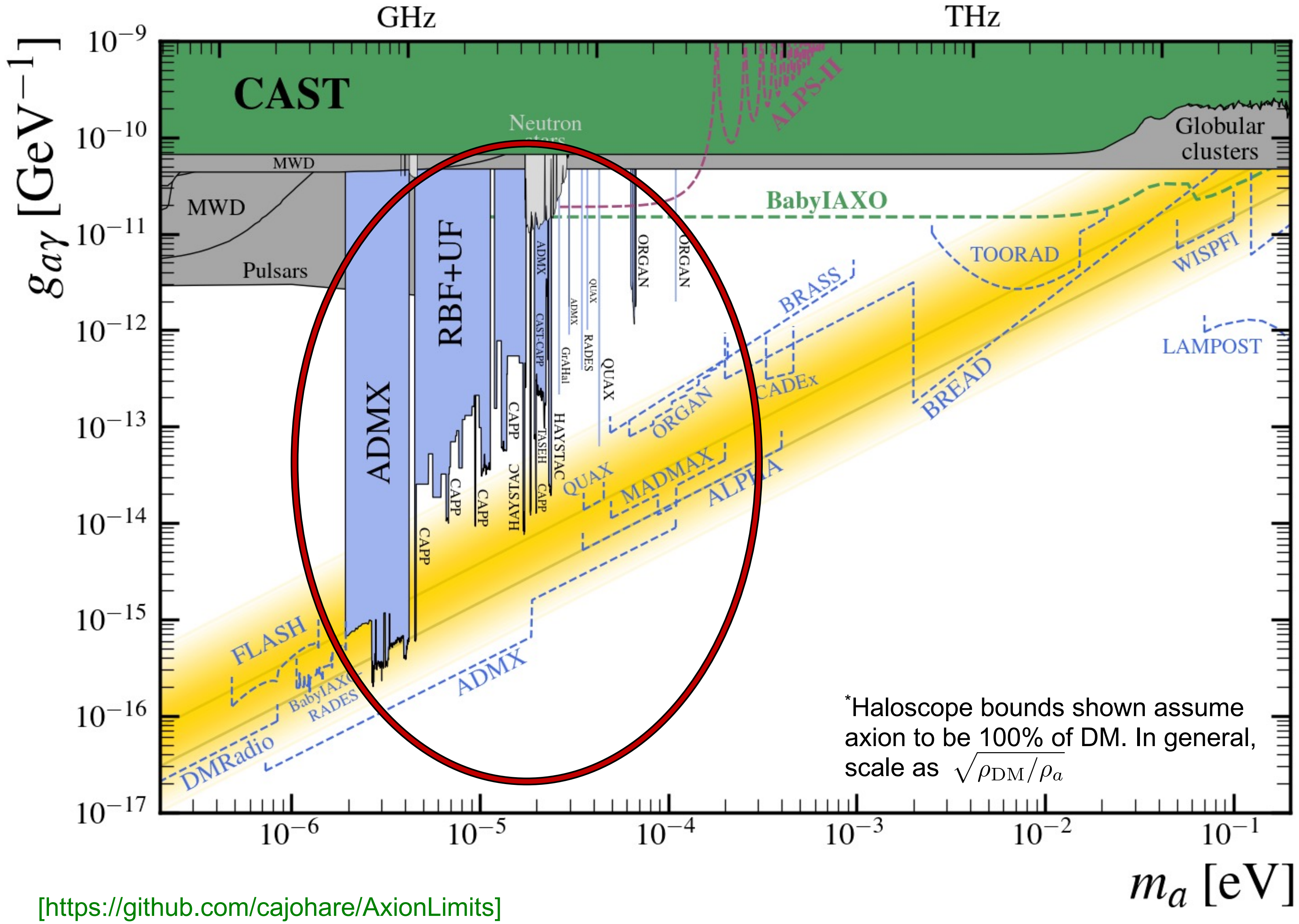

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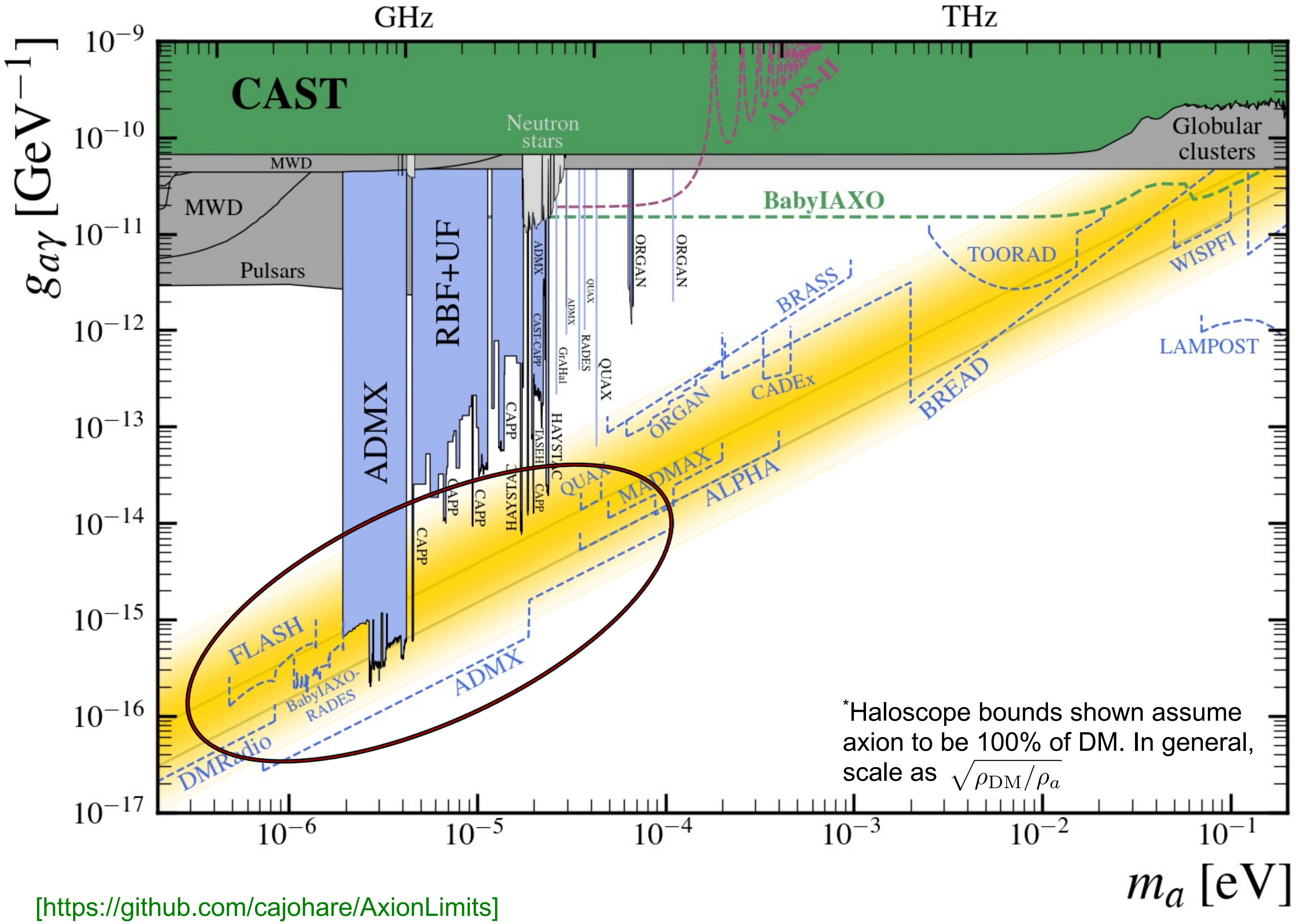
- **More experiments proposed**
- Within next decade, microwave cavities will dig deep into vanilla axion band in mass range

$$\mu\text{eV} \lesssim m_a \lesssim 100\,\mu\text{eV}$$



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Haloscopes

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Dish antennas

- **Dish antenna concept**:

  [Horns,Jaeckel,Lindner,Lobanov,Redondo,AR 13]

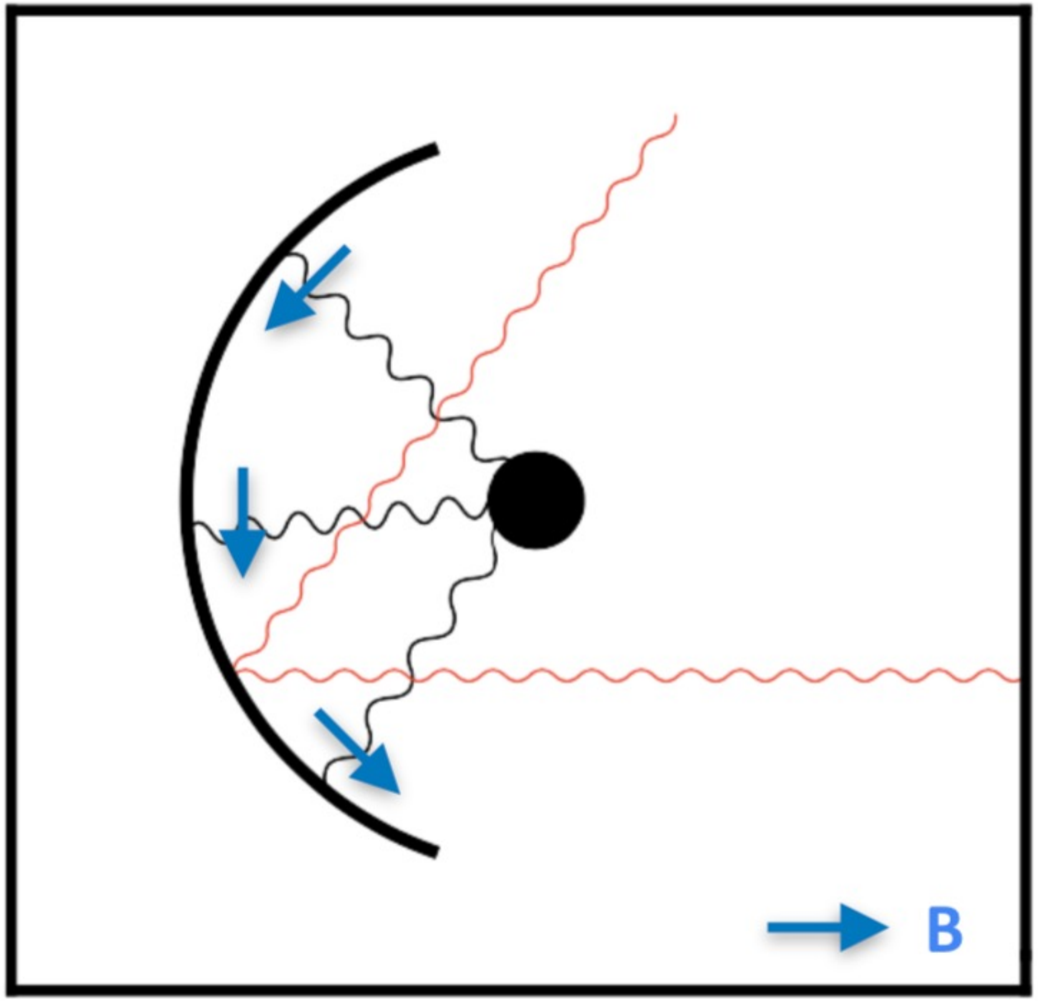
  - Oscillating axion DM in a background magnetic field carries a small electric field component,

    $$\mathbf{E}_a(t) = -g_{a\gamma}\mathbf{B}\, a(t)$$

  - Metallic mirror placed in a magnet field pointing parallel to the mirror surface will emit a nearly monochromatic EM wave perpendicular to the mirror surface with a frequency $\nu = m_a/(2\pi)$ and a cycle-averaged power per unit area:

    $$\mathcal{P}_\gamma/\mathcal{A} = |\mathbf{E}_a|^2/2$$

  - Broadband! No tuning necessary!



Haloscopes

Dish antennas

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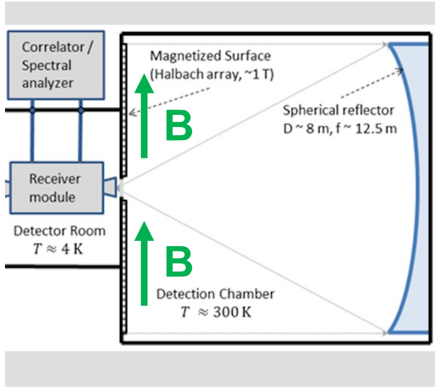
- **BRASS** @ U Hamburg

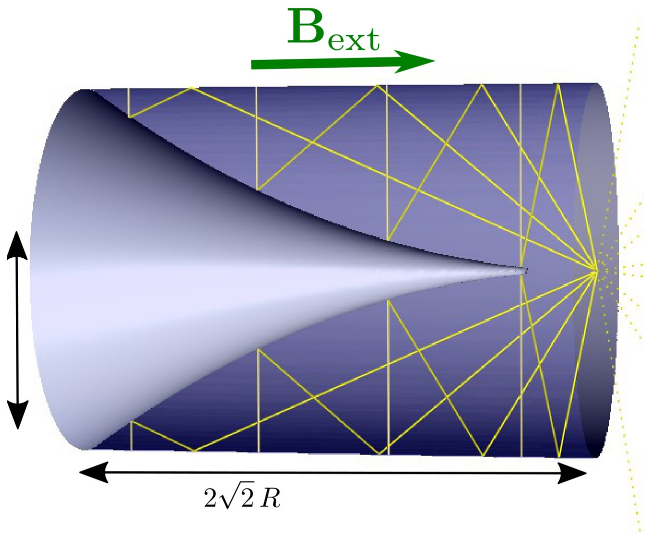


- Plane permanently magnetized conversion panel
  $B = 0.8\,\mathrm{T}$
  $\mathcal{A} = 4.7\,\mathrm{m}^2$
- Spherical reflector

[Bajjali et al., `23]

BRASS

- **BREAD** @ Fermilab



- Cylindric parabolic conversion panel allows use of solenoidal magnetic field
  $B \sim 10\,\mathrm{T}$
  $\mathcal{A} \sim 10\,\mathrm{m}^2$

[Liu et al., 22]

BREAD

Haloscopes

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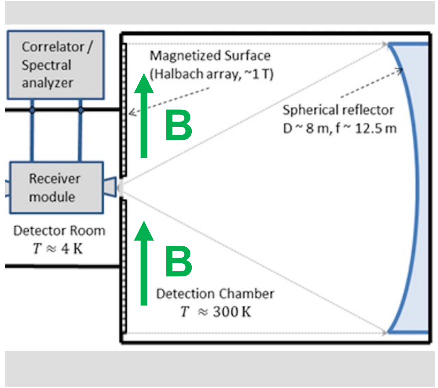

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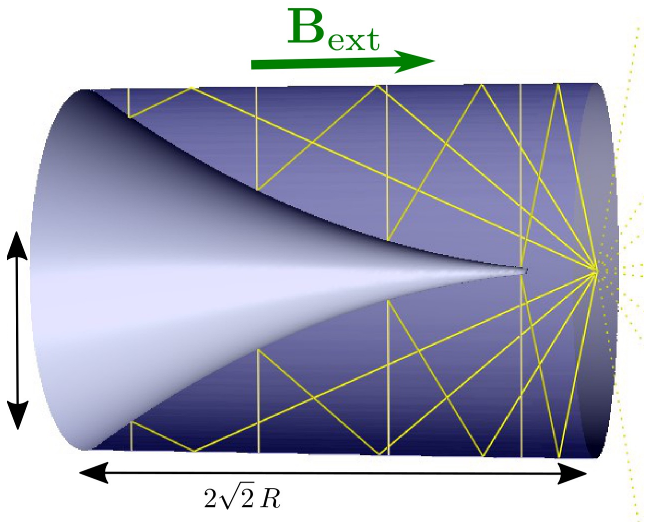

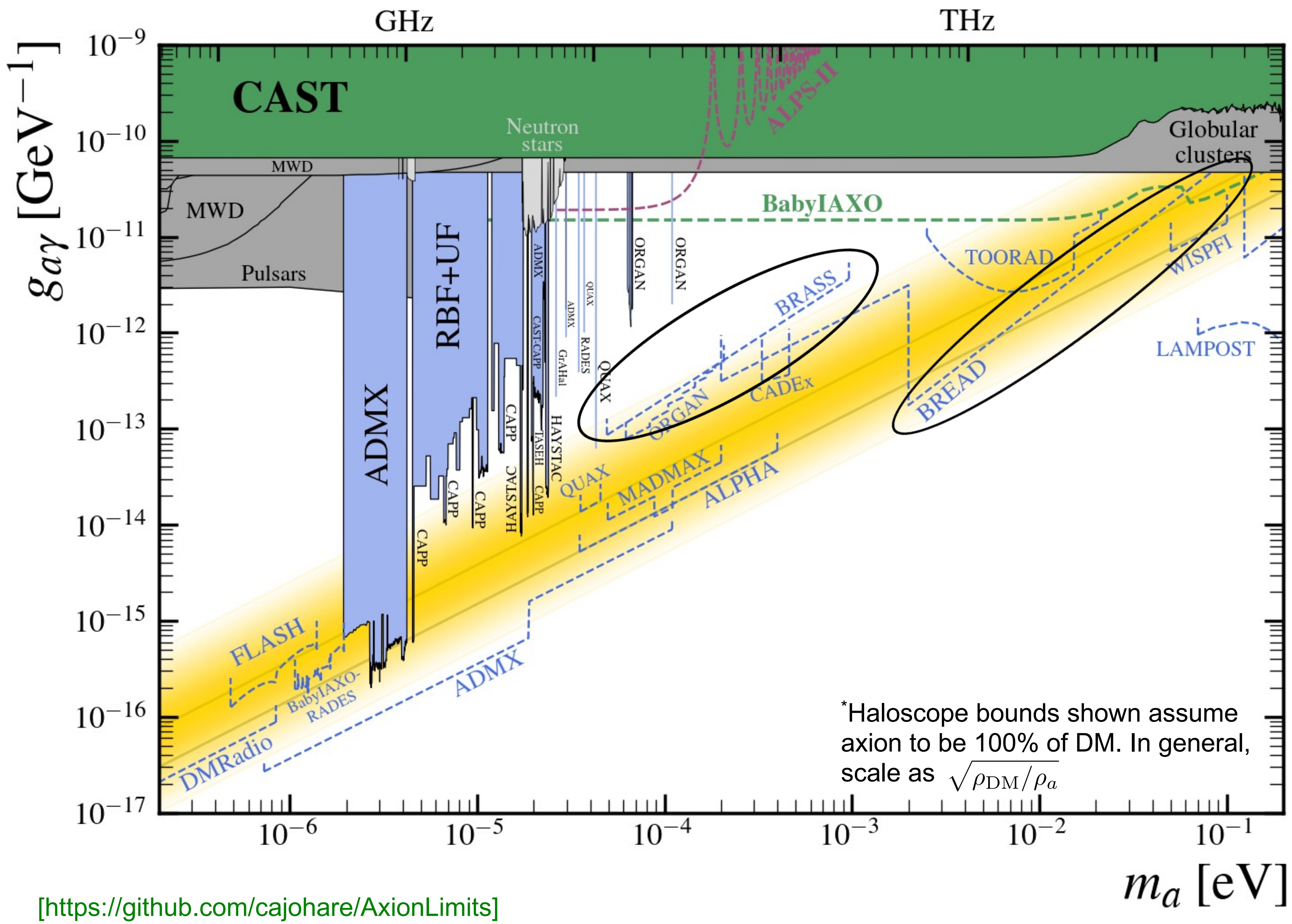

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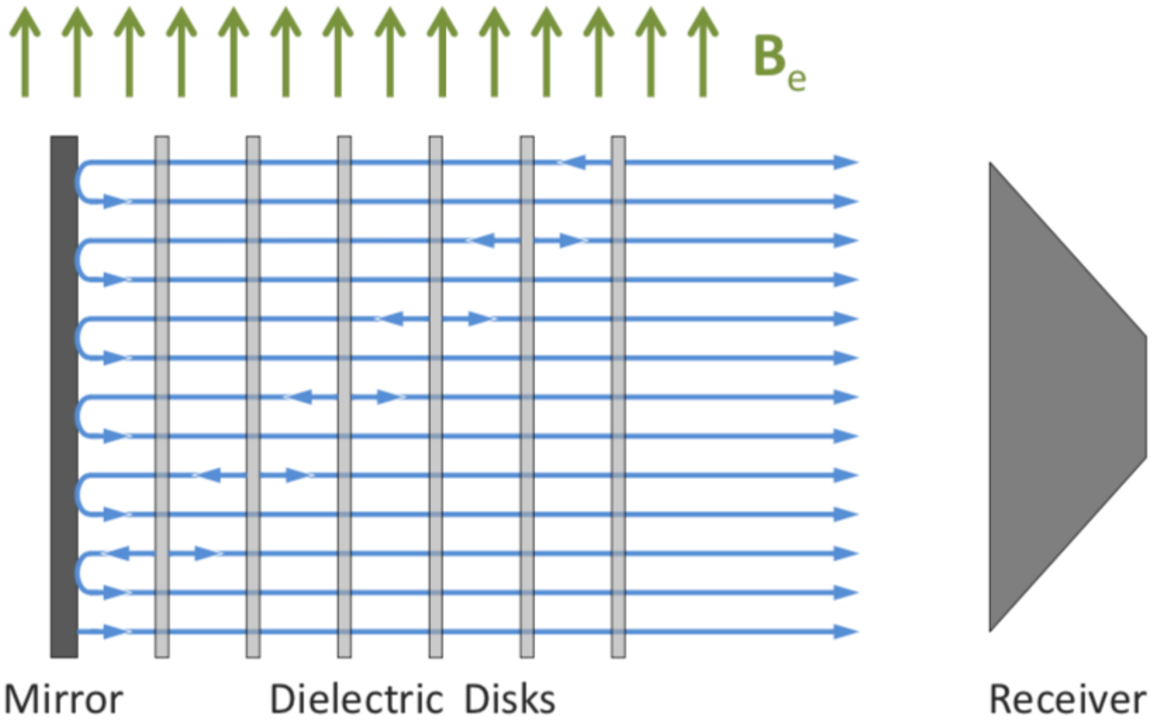
Dish antennas

- **Boosted dish antenna** aka **open dielectric resonator concept:**
  - Add stack of dielectric disks with $\sim \lambda/2$ spacing in front of mirror (all immersed in magnetic field) [Jaeckel,Redondo 13]
  - Constructive interference of photon part of wave function [Millar,Raffelt,Redondo,Steffen 16]

[Baryakhtar,Huang,Lasenby18]



[Caldwell et al. `16]

Haloscopes

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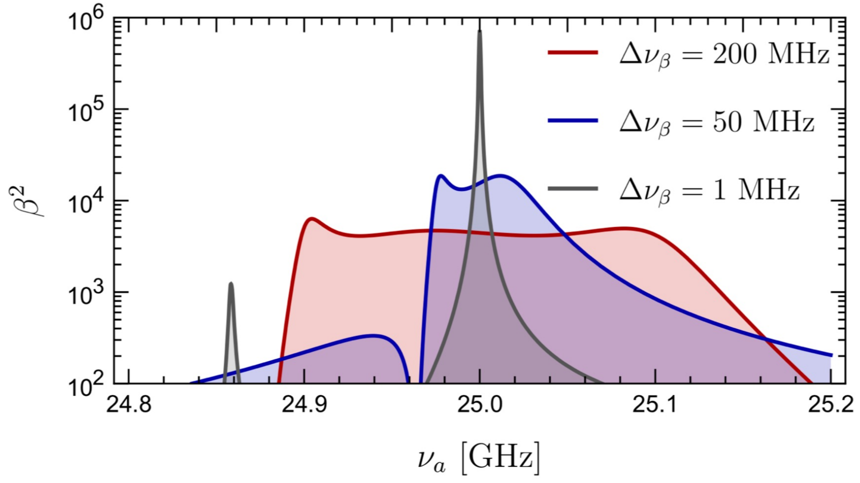
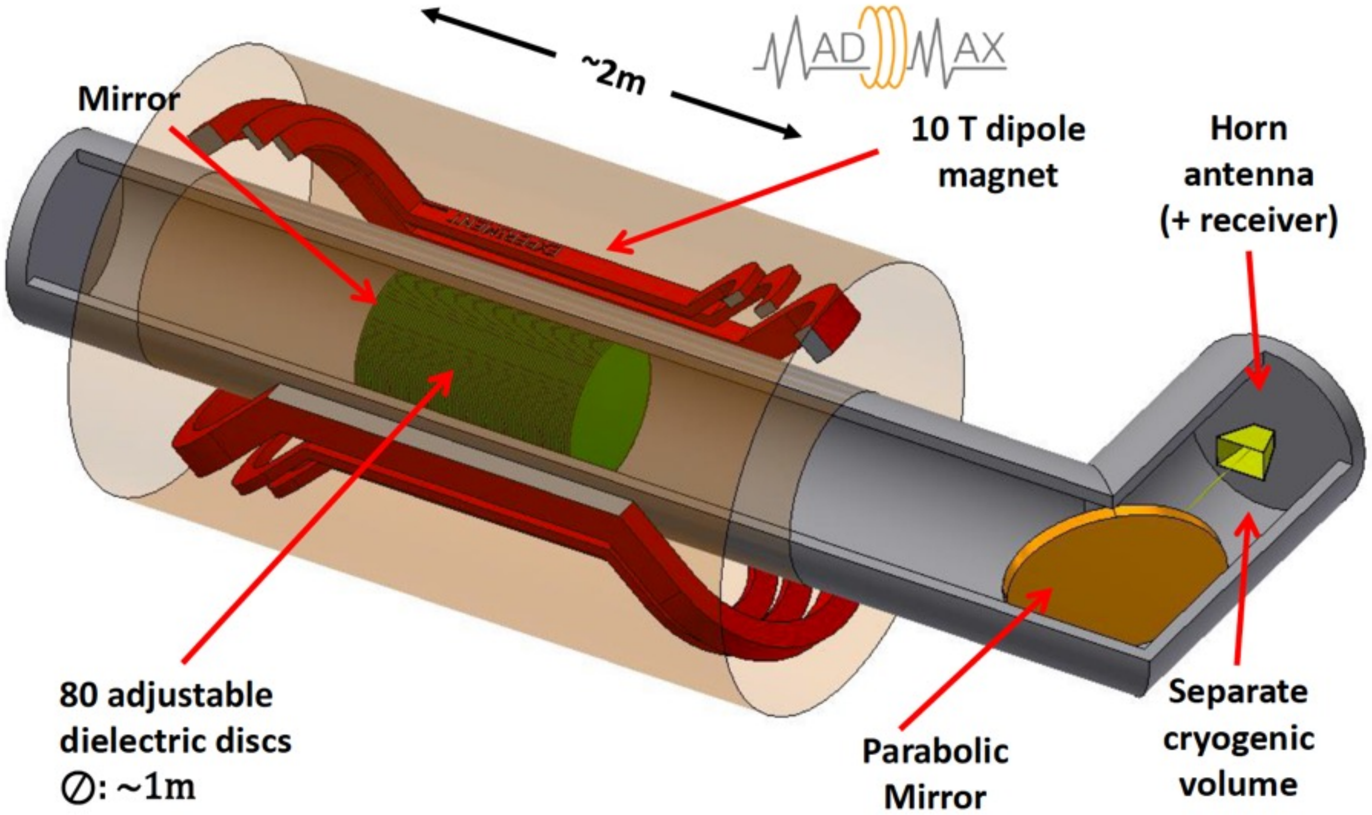
Dish antennas

MADMAX @ DESY

- Conceptional design [Bruns et al. 19]
  - 10 T magnet
  - Large number of adjustable dielectric disks
    - Tunable frequency and bandwidth





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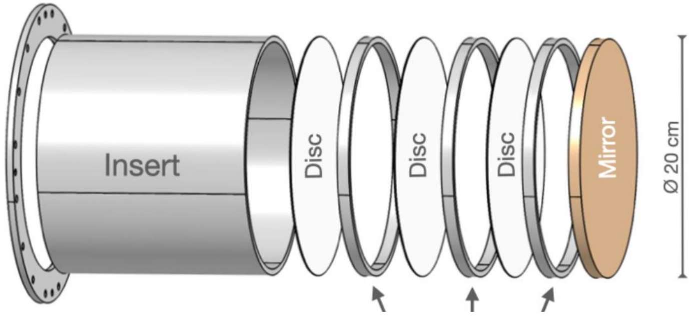
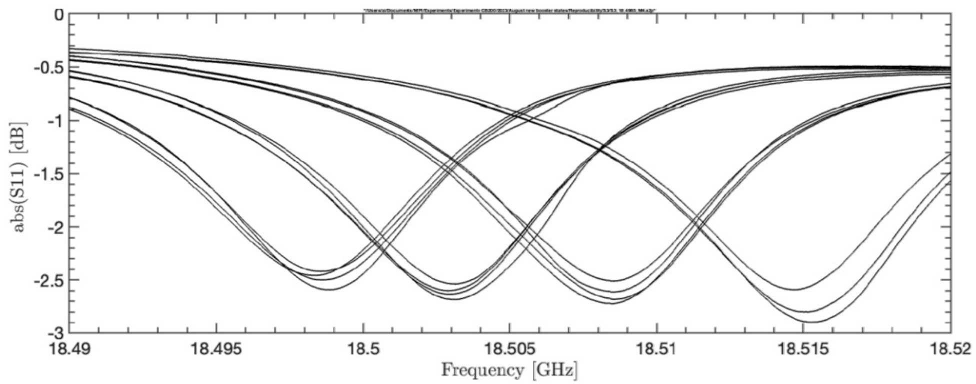
- Prototype tests and science runs exploiting MORPURGO magnet at CERN are going on



Expected sensitivity: $g_{a\gamma} < 4\cdot10^{-11}$ GeV^{-1}



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  - 10 T magnet
  - Large number of adjustable dielectric disks
    - Tunable frequency and bandwidth
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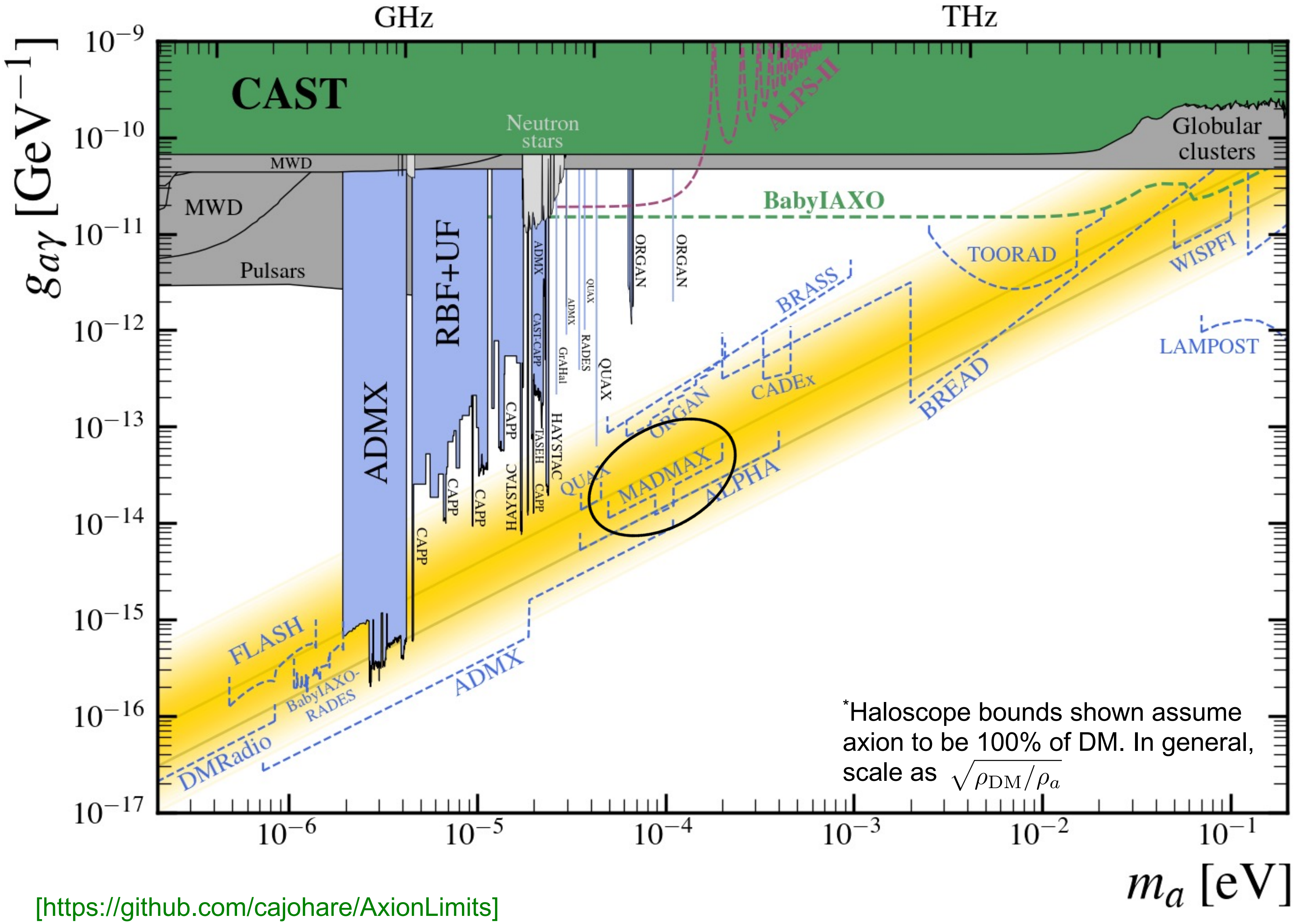
- **Full MADMAX expected to start data taking in 2030**



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Plasma haloscope

- **Plasma haloscope concept**:
  [Lawson, Millar, Pancaldi, Vitagliano, Wilczek, 19]
  - In a magnetized plasma, oscillating axion DM induces plasmon excitations,
    $$\mathbf{E} = -g_{a\gamma}\mathbf{B}_{\rm e} a \left(1 - \frac{\omega_p^2}{\omega_a^2 - i\omega_a\Gamma}\right)^{-1}$$
    - resonant enhancement, when plasma frequency matches axion mass,
      $$\omega_p = \omega_a \approx m_a$$
    - limited by losses (Γ)

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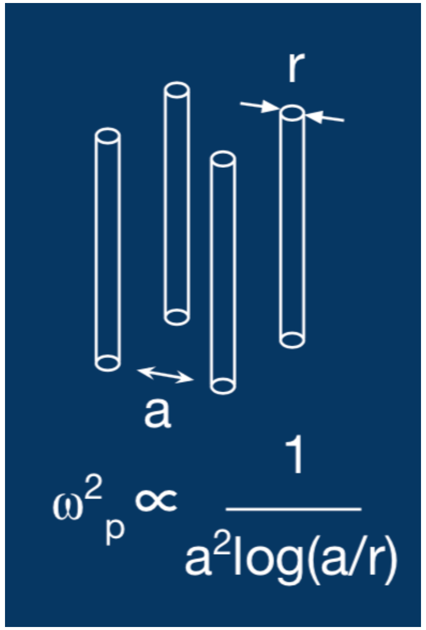
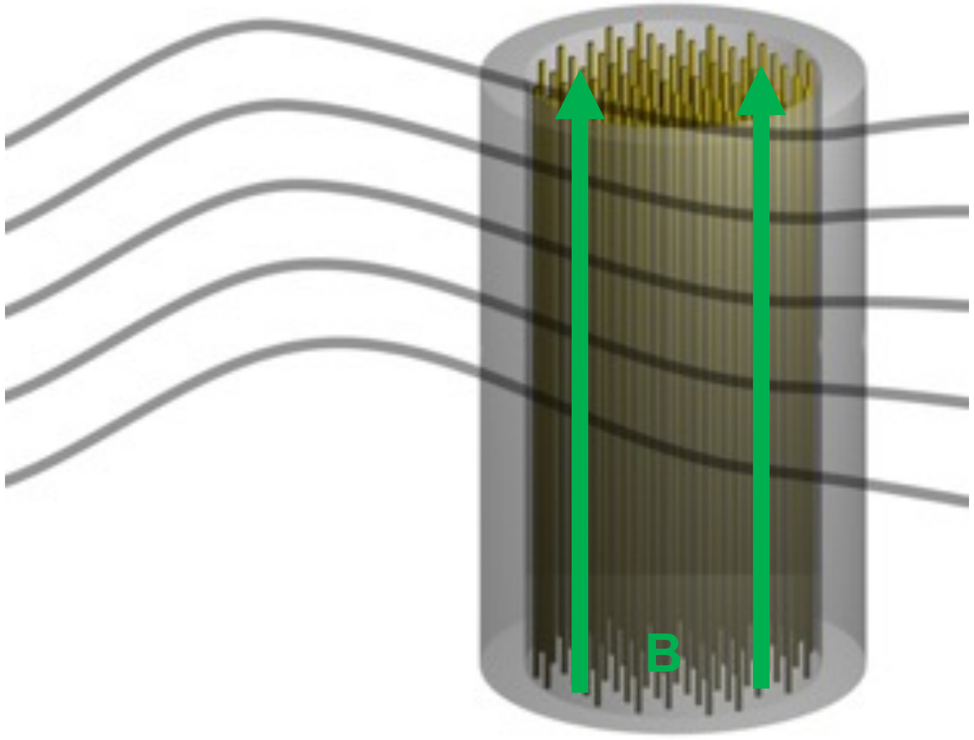
    - limited by losses (Γ)
  - A plasma with tunable plasma frequency in the GHz range can be realised by a wire array with variable interwire spacing ("wire metamaterial")





adapted from [Dunne, LBNL Instr. Sem. Feb 22]

Haloscopes

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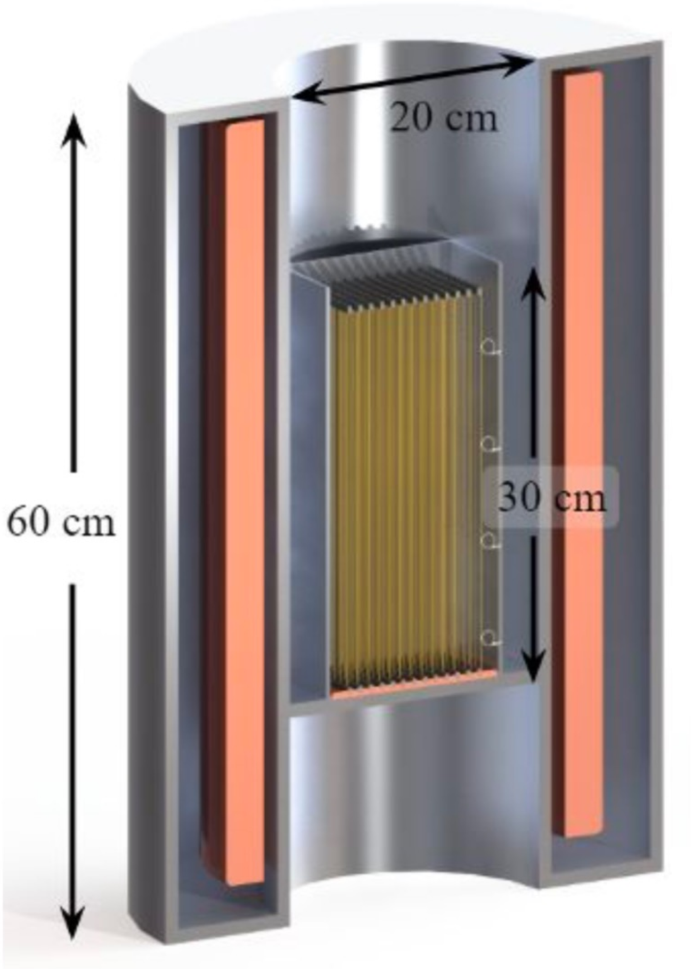
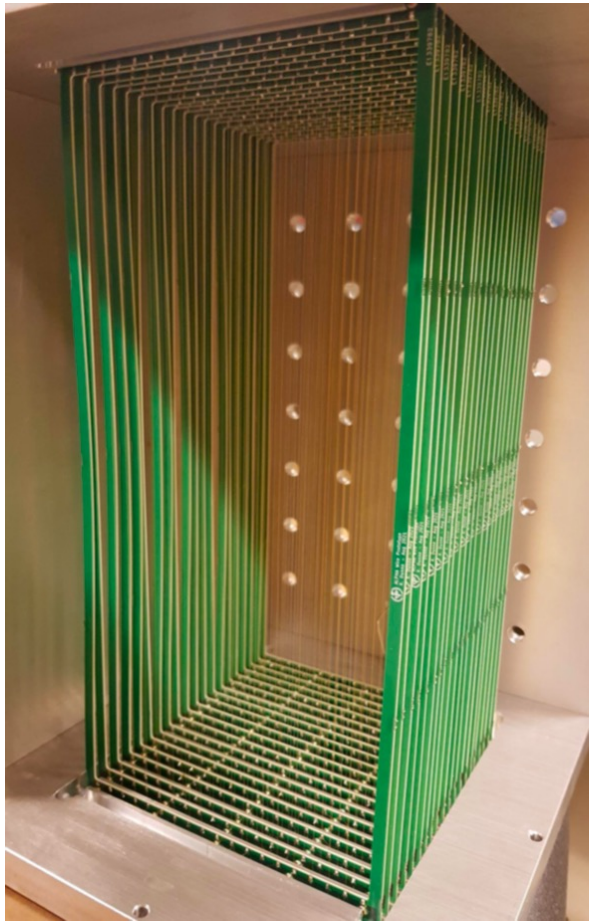
Plasma haloscope

ALPHA

- Goal: building tunable, cryogenic plasma haloscope
- ALPHA Pathfinder
  - 20 cm bore 8T solenoid
  - several wire material prototy-pes constructed
  - tuning with low power piezo-electric translation
  - sensitive to mass range around 10–20 GHz
  - data run expected ~2026

ALPHA Pathfinder





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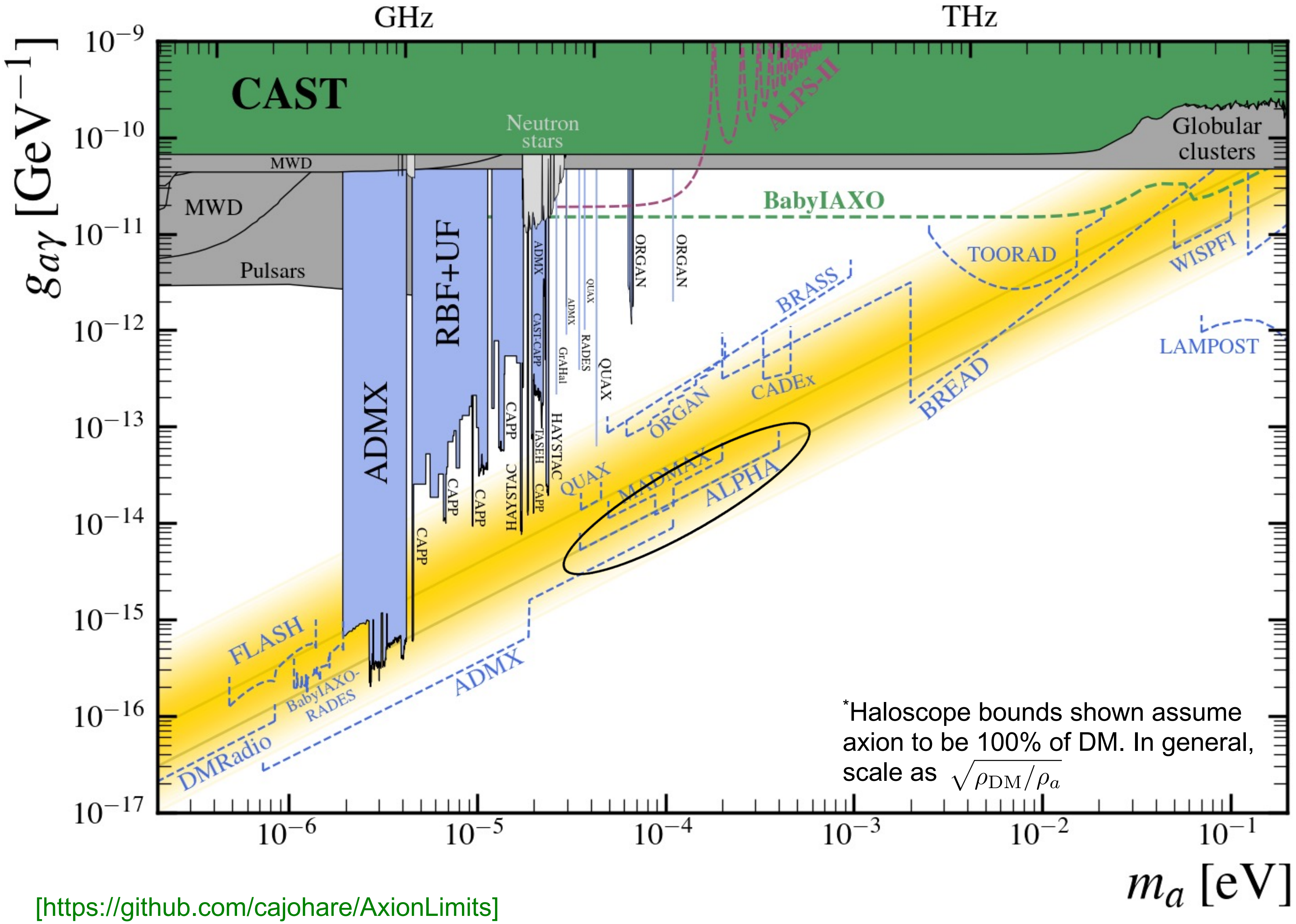
- **Full ALPHA designed to dig deep into axion band**



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Lumped-element detectors

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

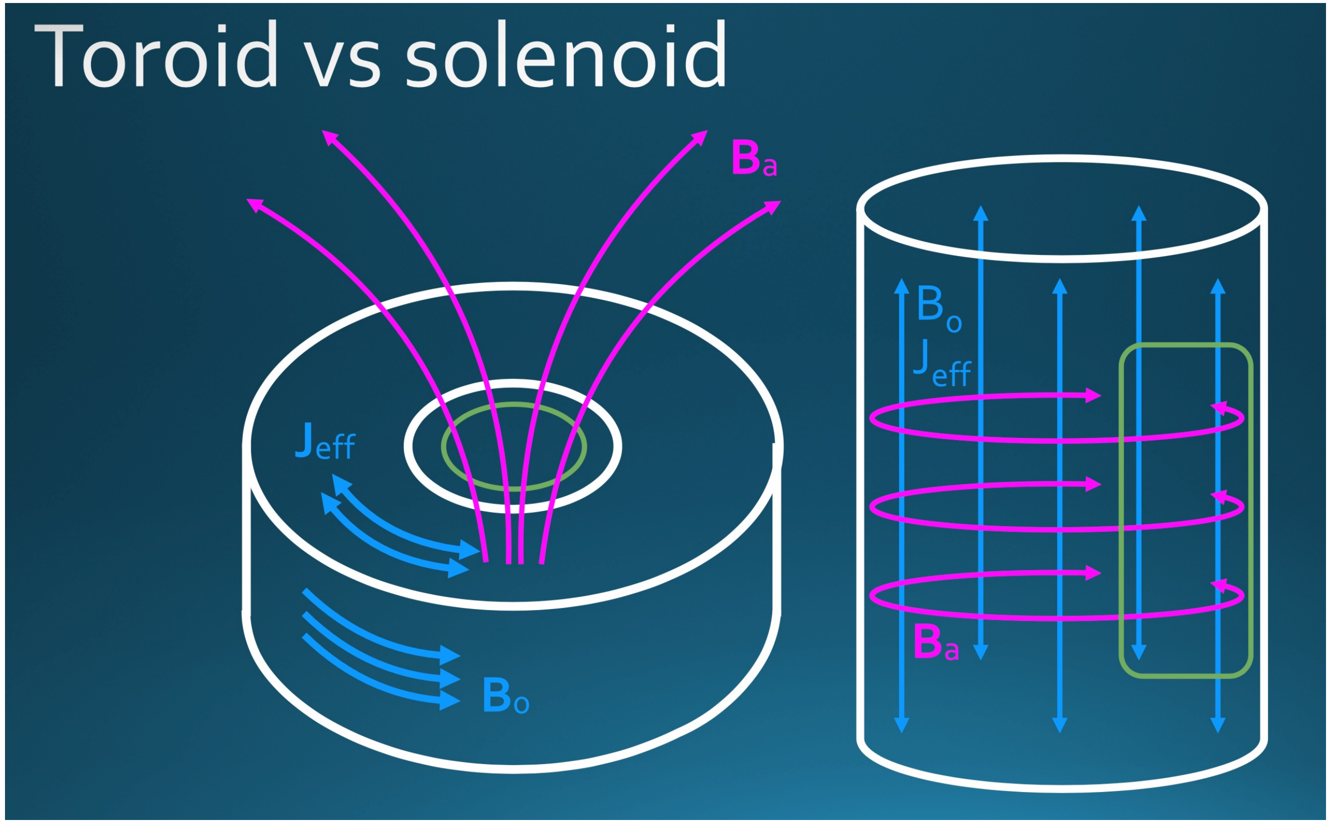
- **Concept:**
  - In the presence of a magnetic field B_0
    - axion DM field induces oscillating effective dis-placement current

      $$\mathbf{j}_a = -g_{a\gamma}\mathbf{B}_0\,\dot{a}$$

    - which in turn generates an oscillating magnetic field $\mathbf{B}_a$, such that

      $$\nabla\times\mathbf{B}_a = \mathbf{j}_a$$

    - The induced field can be
      - turned into an alternating current in a pickup loop,
      - resonantly amplified in a tunable LC circuit, and
      - finally detected via a SQUID



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

[Salemi '21]

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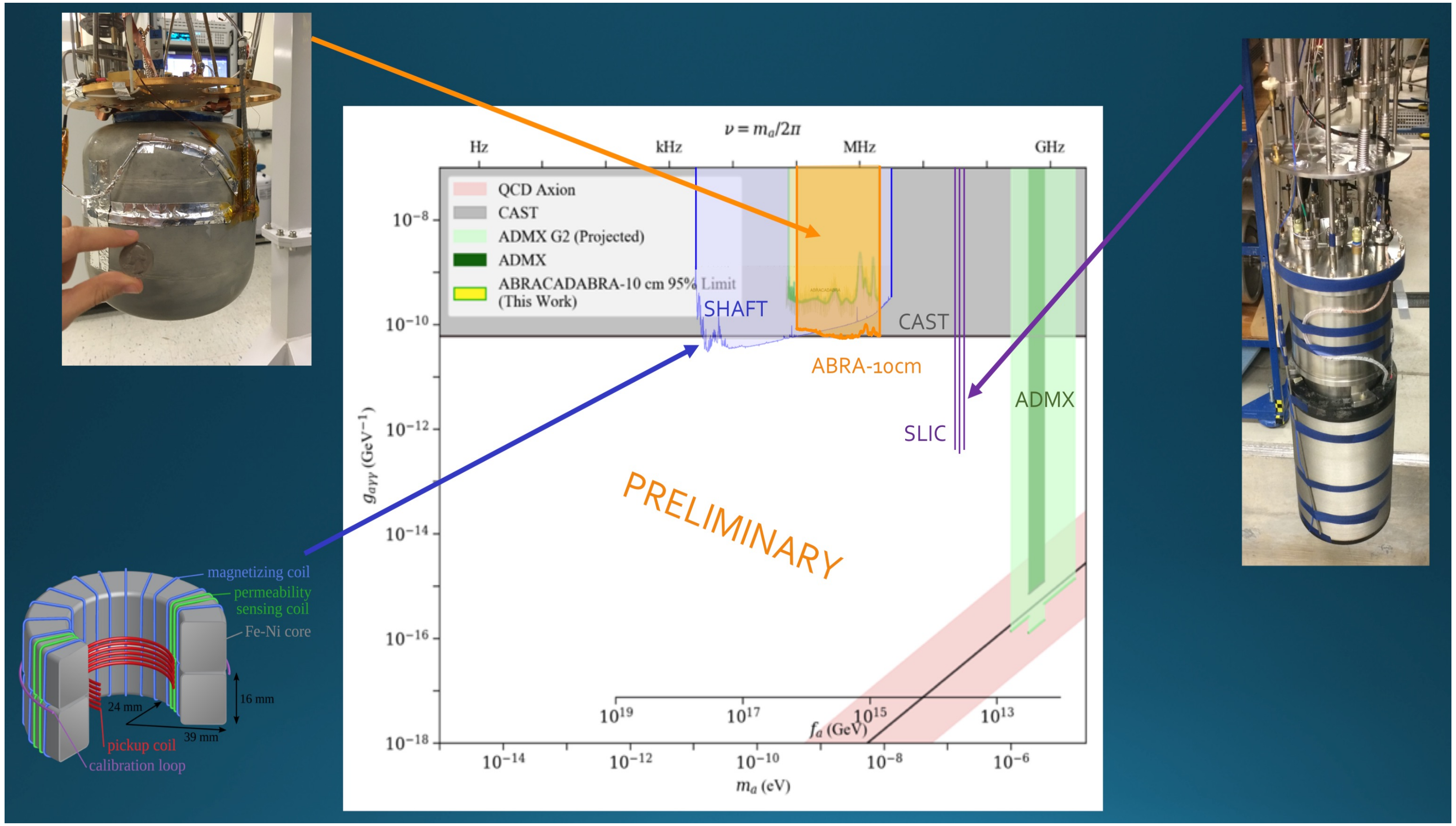
Lumped-element detectors

- **Pilot experiments:**
  - ABRACADABRA [Ouellet et al. 19]
  - ADMX SLIC [Crisosto et al. 20]
  - SHAFT [Gramolin et al. 21]



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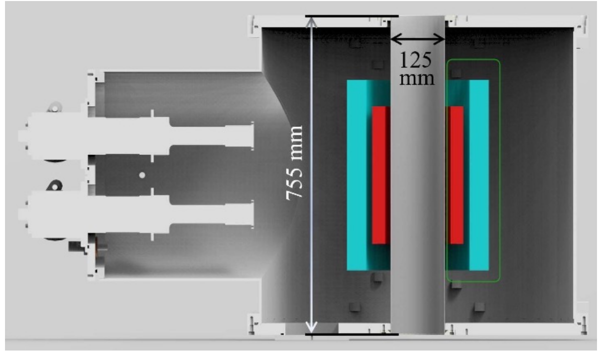
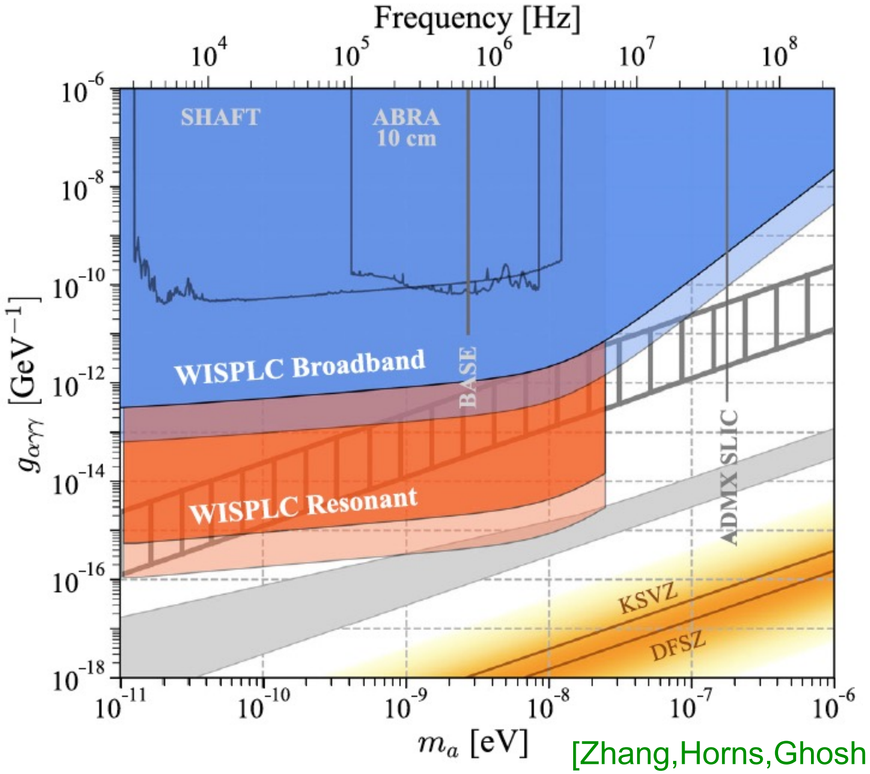


WISPLC



[Zhang,Horns,Ghosh 22]

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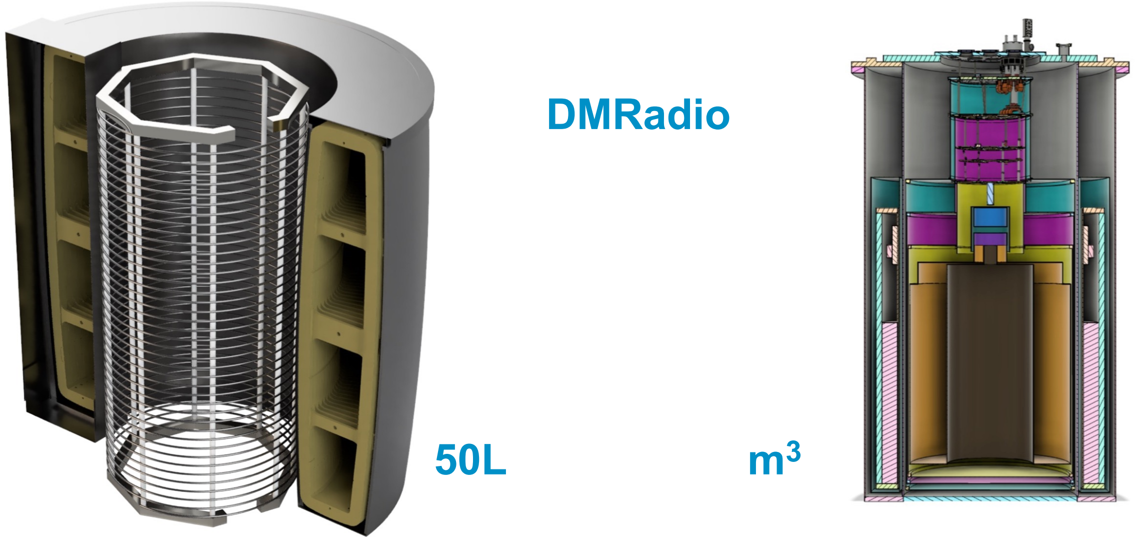

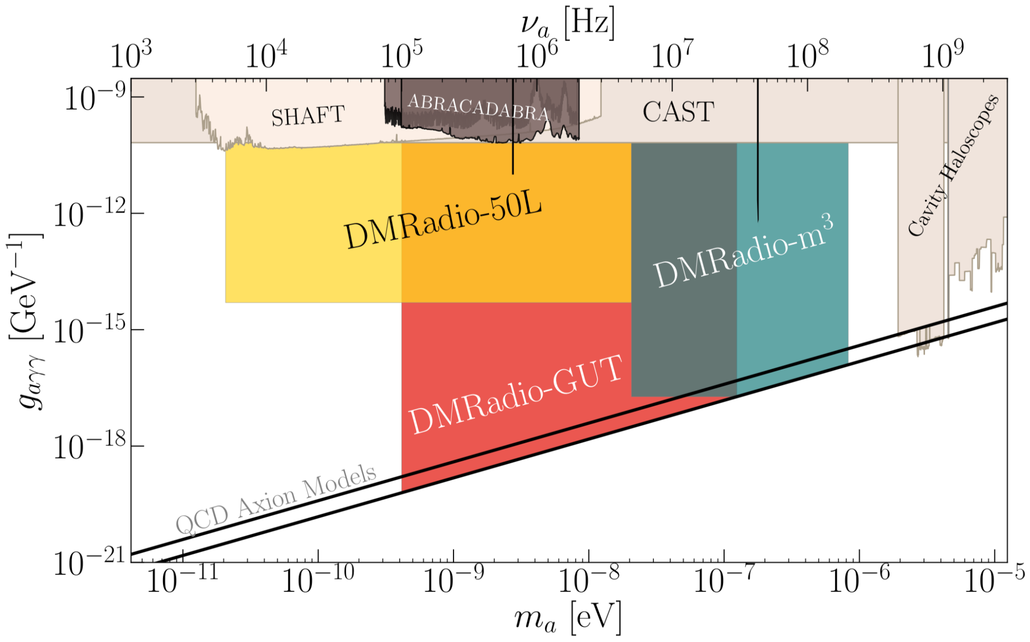

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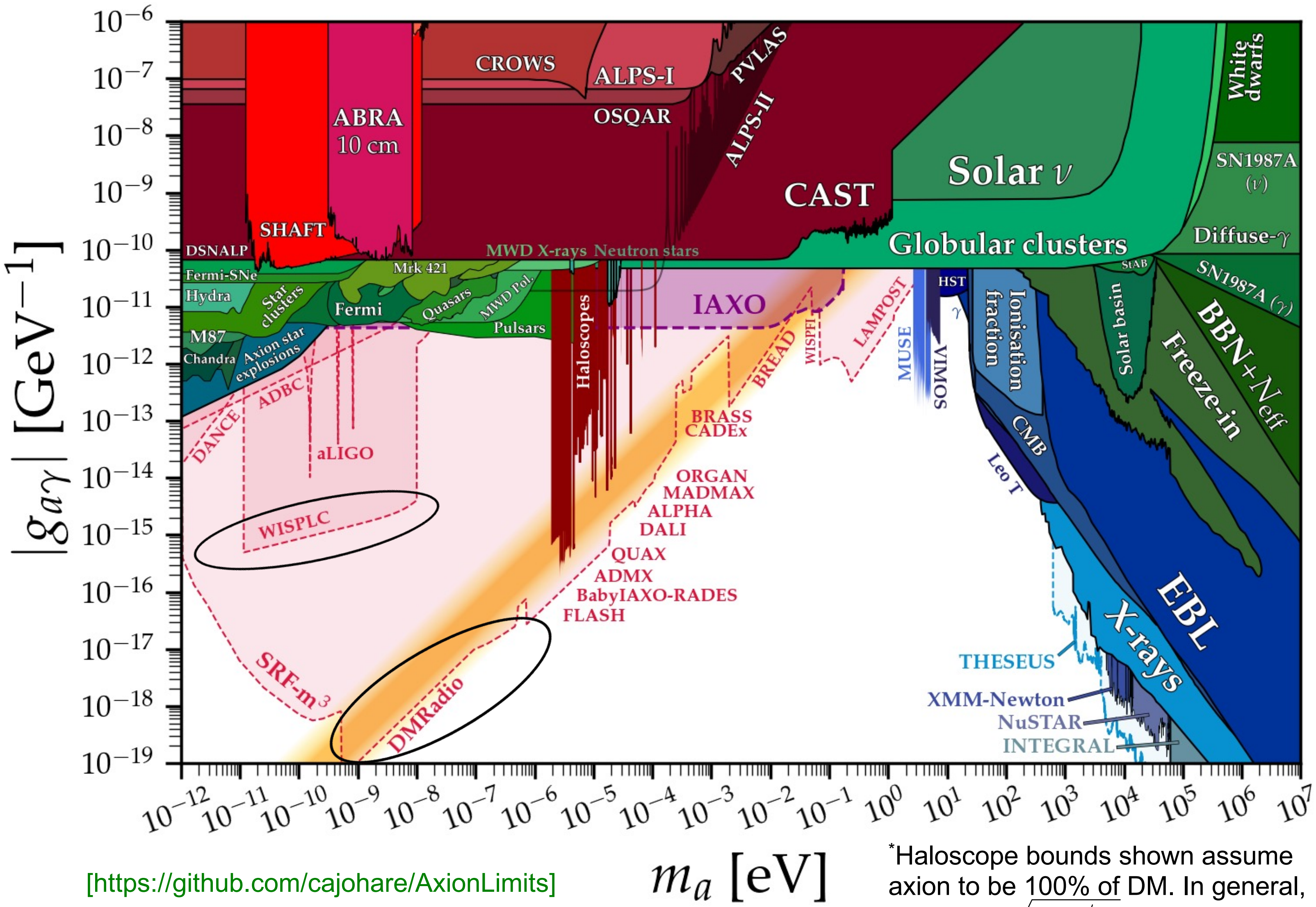
- **Digging deep into unexplored territory at low mass**



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*Haloscope bounds shown assume axion to be 100% of DM. In general, scale as $\sqrt{\rho_{\rm DM}/\rho_a}$

NMR Experiments

Searches for oscillating NEDMs

$$\mathcal{L} \supset -\frac{i}{2}\frac{eC_{\rm NEDM}}{f_a}\, a\,\overline{\psi}_N \sigma_{\mu\nu}\gamma_5 \psi_N F^{\mu\nu} \equiv -\frac{i}{2} g_{aN\gamma}\, a\,\overline{\psi}_N \sigma_{\mu\nu}\gamma_5 \psi_N F^{\mu\nu}$$

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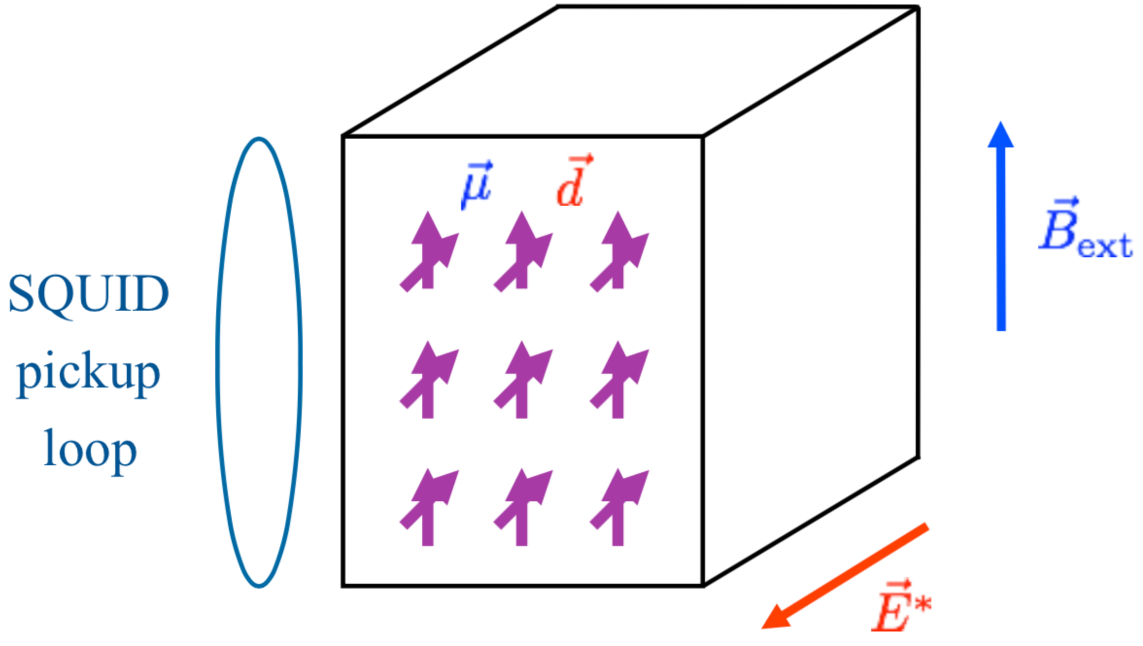
Searches for oscillating NEDMs

- **Concept:**
  - Axion DM field induces oscillating NEDMs:

    $$d_N(t) = g_{aN\gamma}\sqrt{2\rho_a}\cos(m_a t)/m_a$$

  - Place a ferroelectric crystal (permanent electric polarisation fields $\vec{E}^*$) in external $\vec{B}_{\rm ext} \perp E^*$
  - Nuclear spins are polarised along $\vec{B}_{\rm ext}$ and precess at Larmor frequency $\omega_L = 2\mu_N B_{\rm ext}$
  - Interaction $\epsilon_S \vec{d}_N(t)\cdot\vec{E}^*$ of DM induced NEDM with the $\vec{E}^*$-field leads to resonant increase of transverse magnetisation of sample when $\omega_L = m_a$

[Graham,Rajendran 13; Budker et al. 14]



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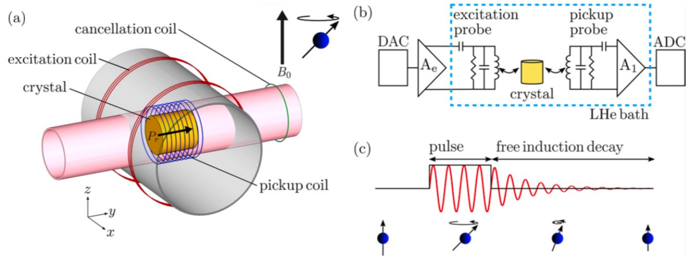
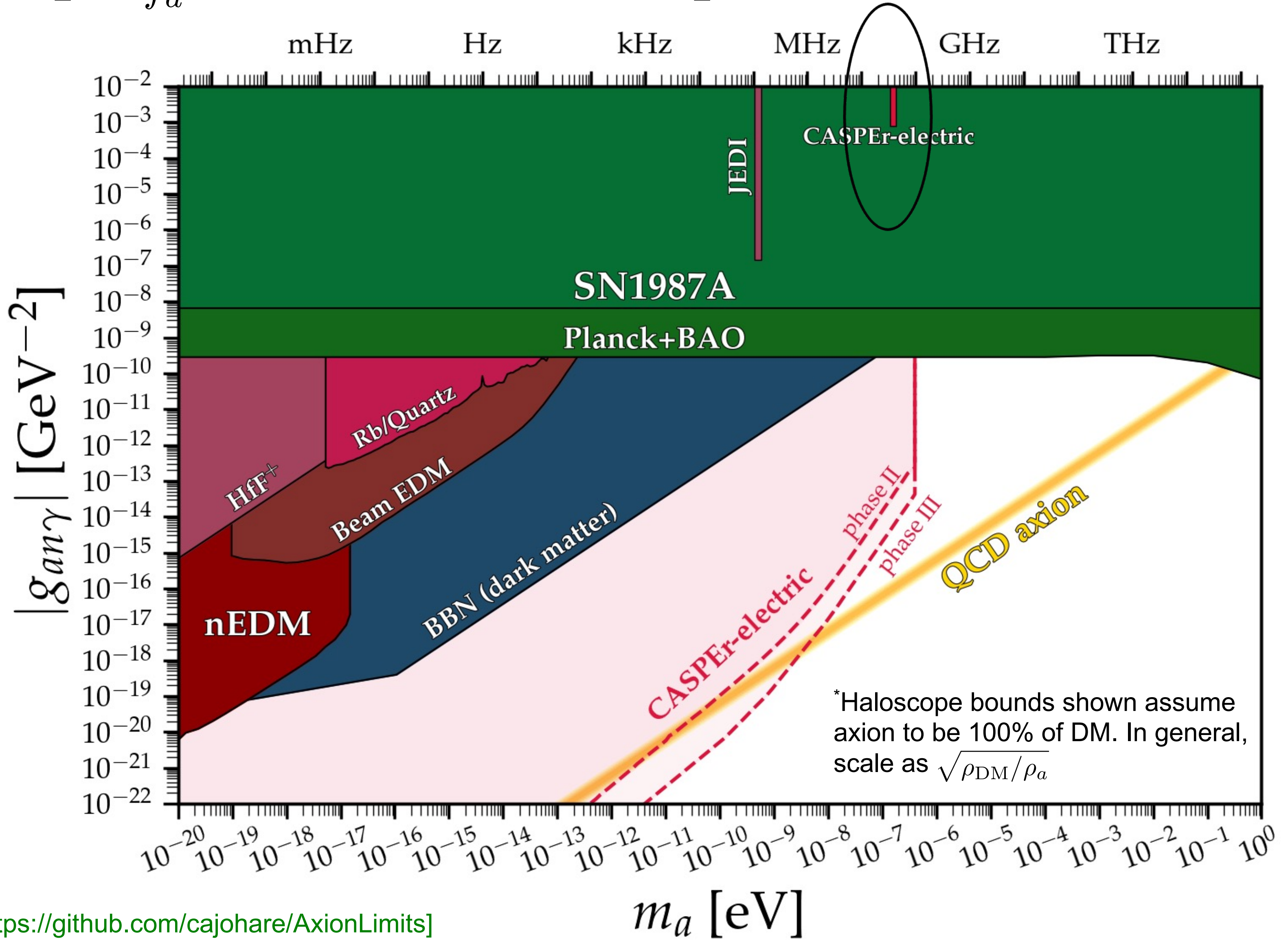
- CASPEr-Electric in Boston
  - **Initial pathfinder experiment deep in the excluded region**



[Aybas et al., 2101.01241]



[https://github.com/cajohare/AxionLimits]

NMR Experiments

Searches for oscillating NEDMs

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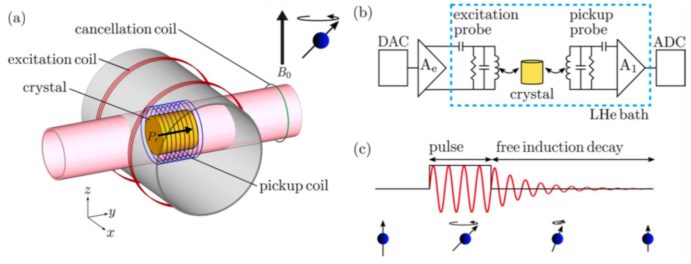

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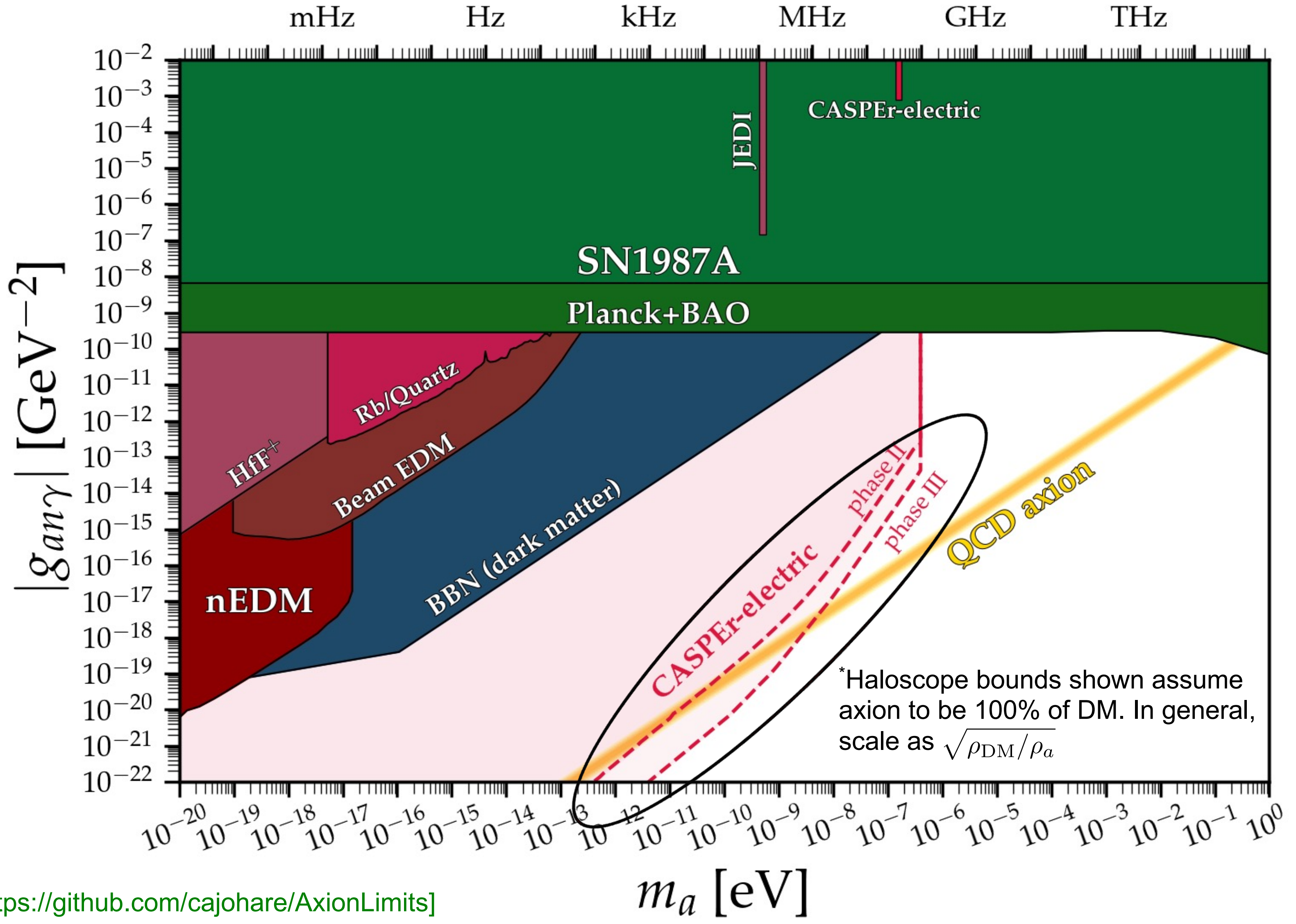
  - **Full experiment designed to reach QCD axion band**



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NMR Experiments

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Searches for oscillating NEDMs

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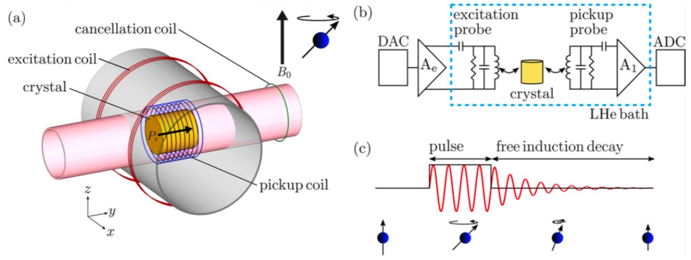
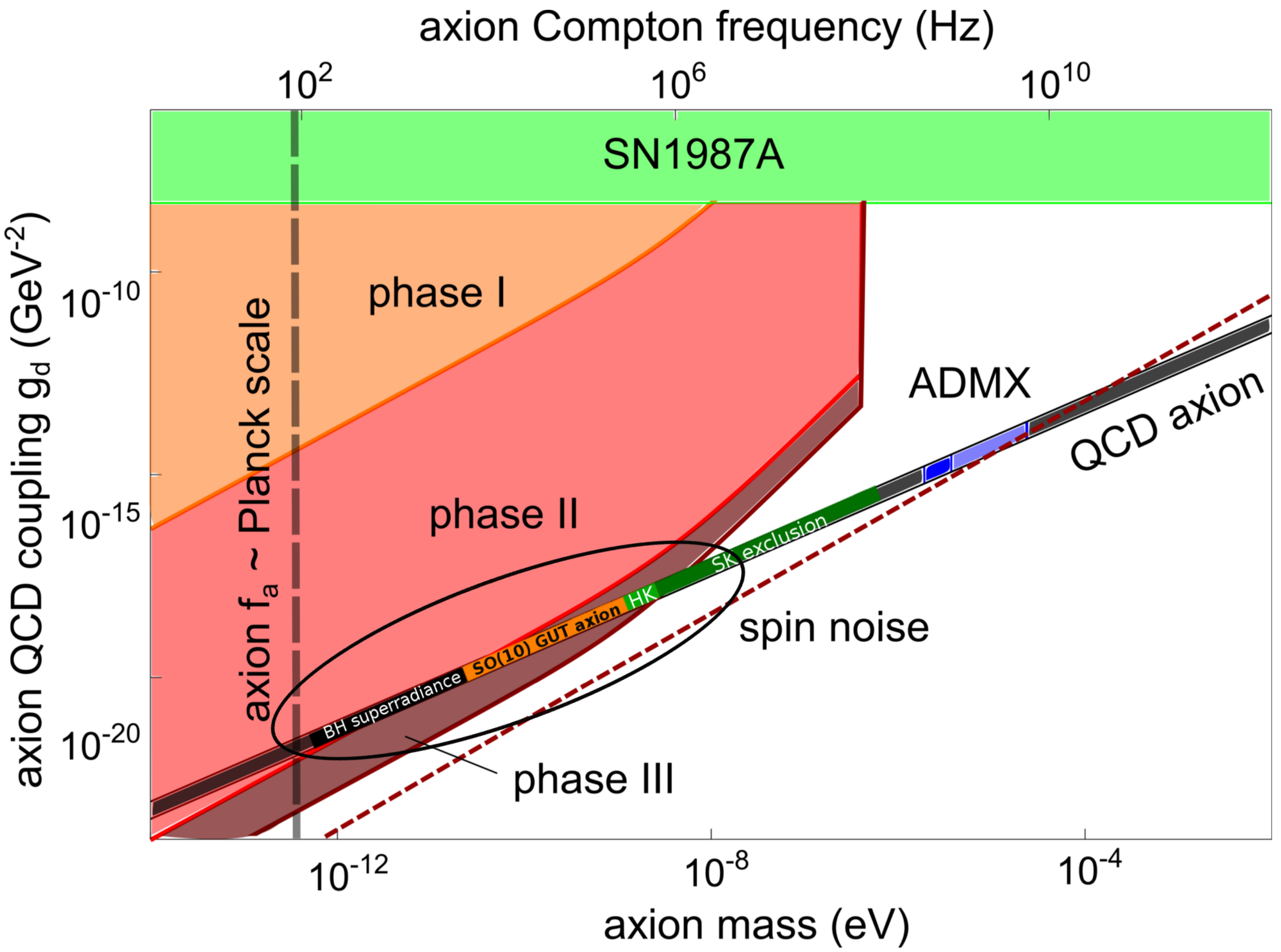


[Aybas et al., 2101.01241]

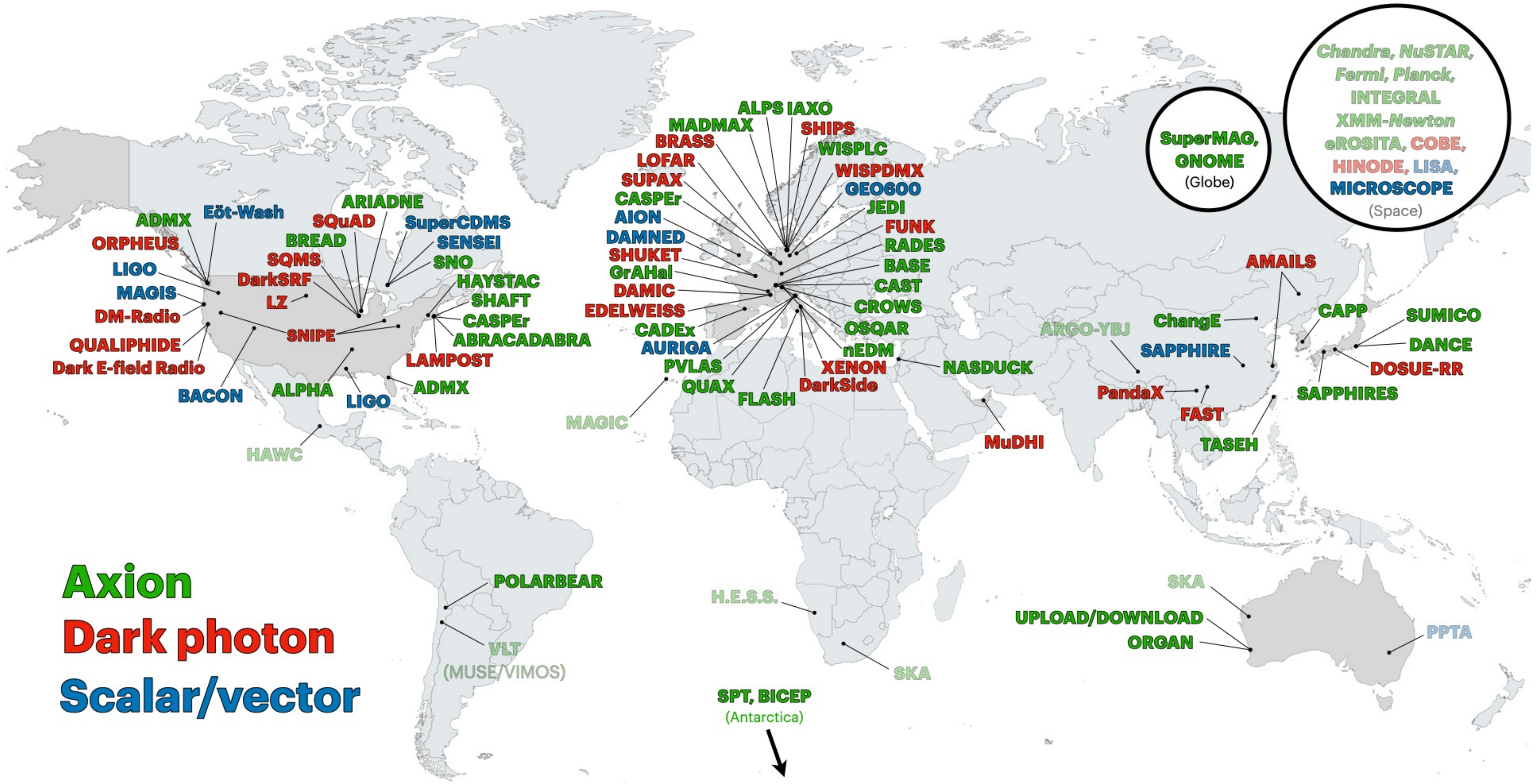
  - **Full experiment designed to reach QCD axion band in mass region predicted by SO(10) x $U(1)_{PQ}$ GUT**



[Ernst, Di Luzio, AR, Tamarit, arXiv:1811.11860]

Summary

- World-wide big experimental activity on axion searches exploiting different techniques and couplings:



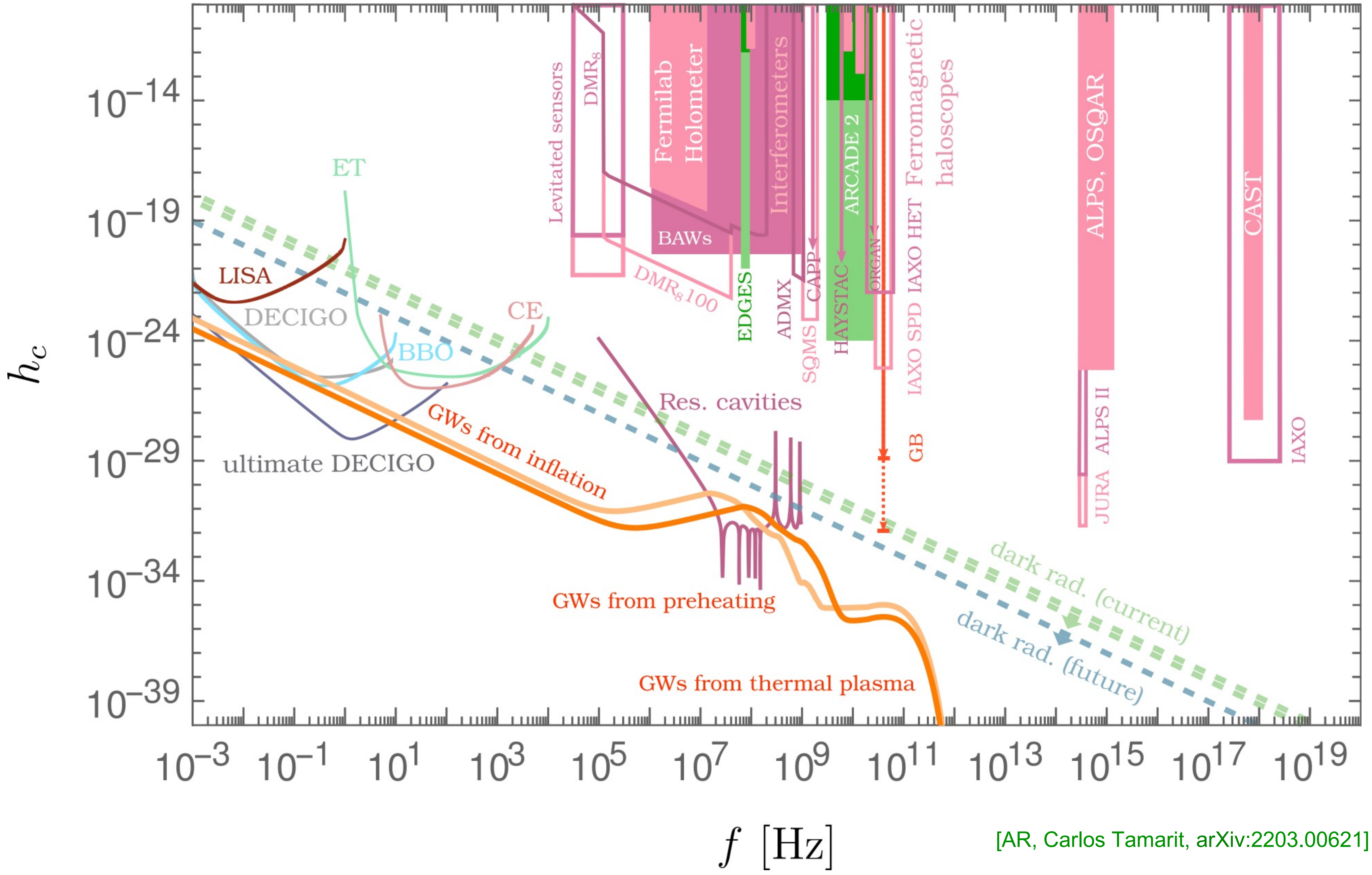
- Many new experimental techniques developed ... often in very tight collaborations between phenomenologically oriented theorists and theoretically interested experimentalists

Stay tuned!

Searches for High-Frequency Gravitational Waves

Axion haloscopes, LSW experiments, and helioscopes as HF-GW detectors

[Ejlli et al., 1908.00232]
[AR et al., 2011.04731]
[Berlin et al., 2112.11465]
[Domcke et al., 2202.00695]
[Franciolini et al., 2205.02153]
[Berlin et al., 2303.01518]
[Domcke et al., 2306.03125]



[AR, Carlos Tamarit, arXiv:2203.00621]

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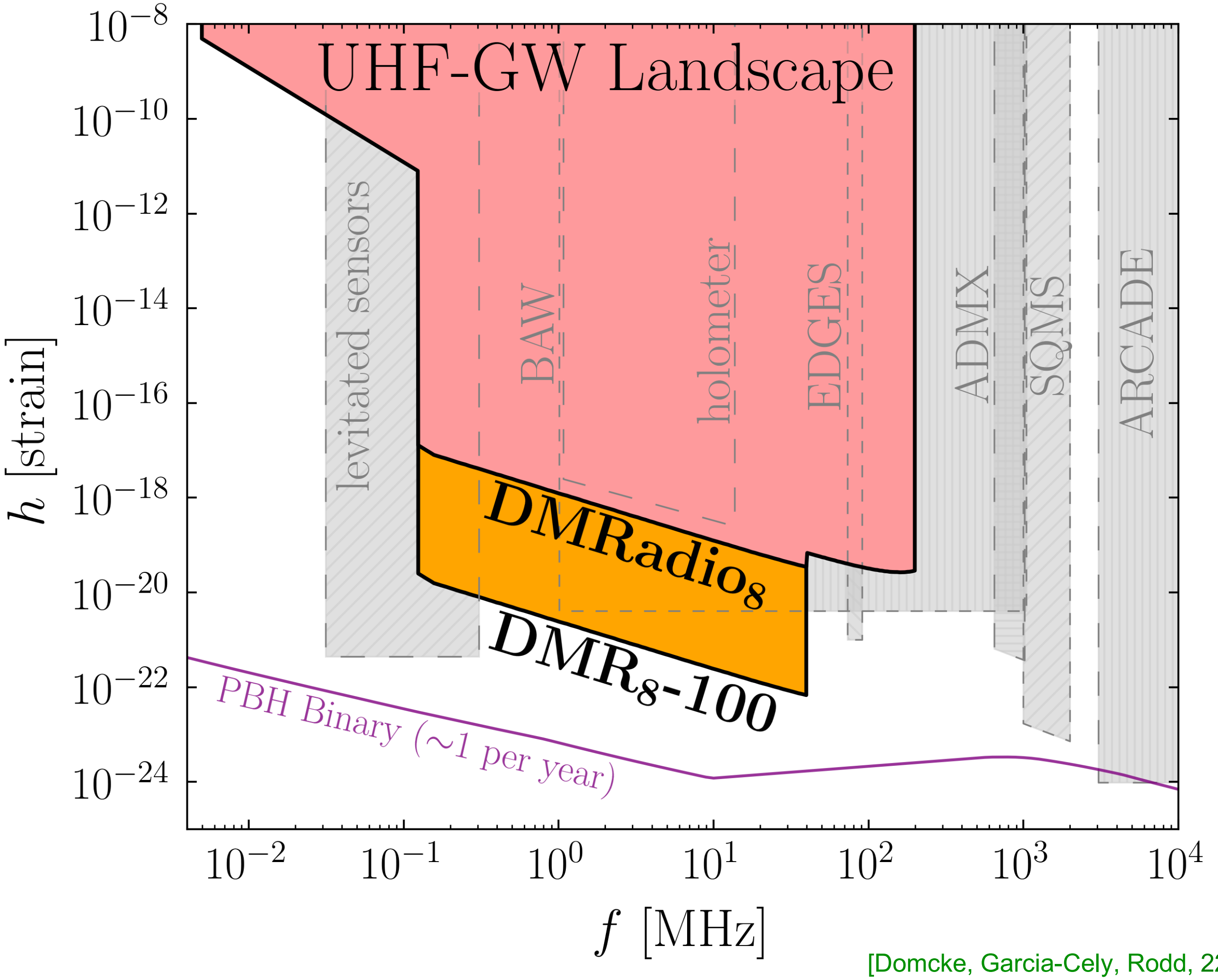

[Domcke, Garcia-Cely, Rodd, 2202.00695]