European Strategy for Particle Physics

PARALLEL 8 / **DARK MATTER/DARK SECTOR**

Ultralight Dark Matter and Dark Sector

Julia K. Vogel (TU Dortmund), Aaron Chou (Fermilab)
For the ESPP 2026 WG on Dark Matter and Dark Sector

Special thanks to Ciaran O'Hare (https://cajohare.github.io/AxionLimits/)

23-27 **JUNE** 2025 **Lido di Venezia**

Input documents relevant to ULDM ($m_\chi \lesssim 1$ eV)

General submissions

#54 Grenoble Axion Haloscopes: From BabyGrAHal to GrAHal for axion DM search in the 1-150μeV mass range

#37 Long-Baseline Atom Interferometry

#146 The International Axion Observatory (IAXO): case, status and plans.

#198 Einstein Telescope - The future European Gravitational Wave Observatory

#204 R&D on quantum sensors for particle physics: the DRD5 collaboration

#228 Quantum Technologies in High Energy Physics. The CERN Quantum Technology Initiative input to the ESPP

#260 Quantum Sensing for Dark Matter and Gravitational Waves

Networks, Institutes and Committees

#13 Laboratori Nazionali di Frascati of INFN

#27 Exploring the Dark Universe: A European Strategy for Axions and other WISPs Discovery (COST Cosmic WISPers)

#112 Enhancing European Cooperation in the Search for Dark Matter (DMInfraNet)

#235 Summary Report of the Physics Beyond Colliders Study at CERN

+ National Inputs (see Friday session)

Axions and Axion-Like Particles (ALPs)

- QCD axions strongly motivated from solving strong CP problem
- Simultaneously natural dark matter candidates
- Additionally interesting astrophysical hints exist

- Similar particles produced in many higher order theories (e.g. string theory)
  → Axion-like particles (ALPs)

First Experiments have been entering highly motivated regions

Discovery potential for full QCD band at reach within the coming decades
Multiple experiments running, more being developed

WISP – Dark Matter – Dark Sector

- Other candidates are theoretically interesting CDM
  - ALPs
  - Dark photons/Hidden photons
  - …

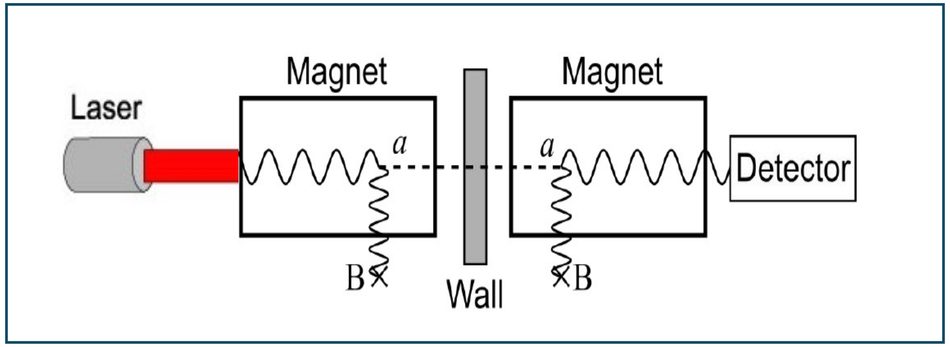
- Can mostly search for these particle in same experiments as axions (parallel mode)

Focus here on axions and ALPs with some DP

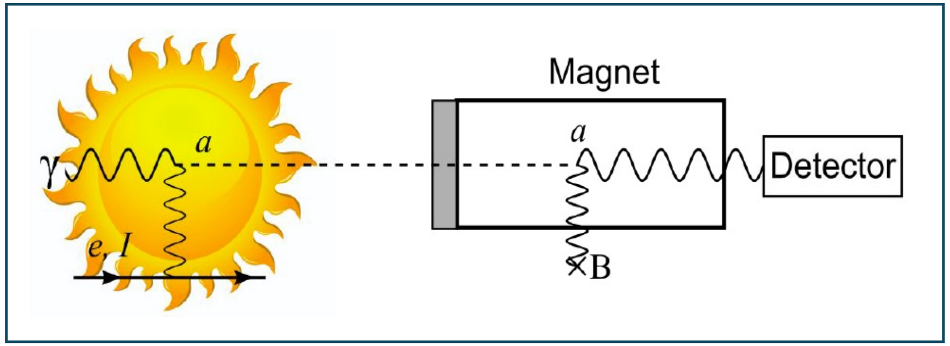
Similarly: focus first on axion-photon coupling here, but other couplings also of interest, while potentially more difficult to detect

Categories of Axion Search Experiments

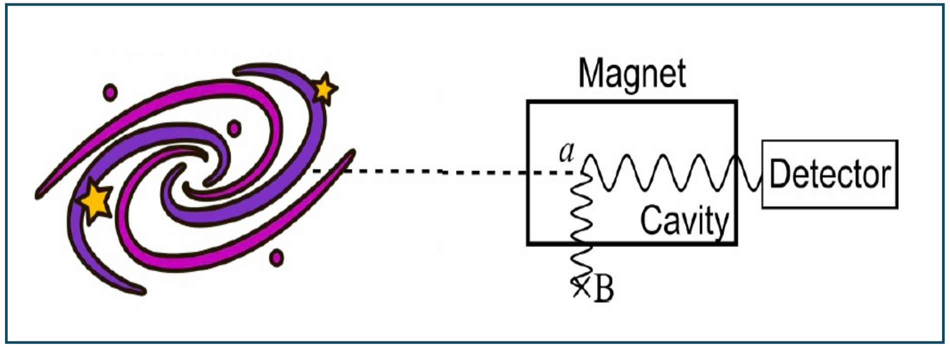
- ► Light-Shining-Through-Wall-Searches (no DM assumption)
  - Laboratory-based experiments producing and detecting axions



- ► Helioscopes (no DM assumption)
  - Laboratory-based solar searches

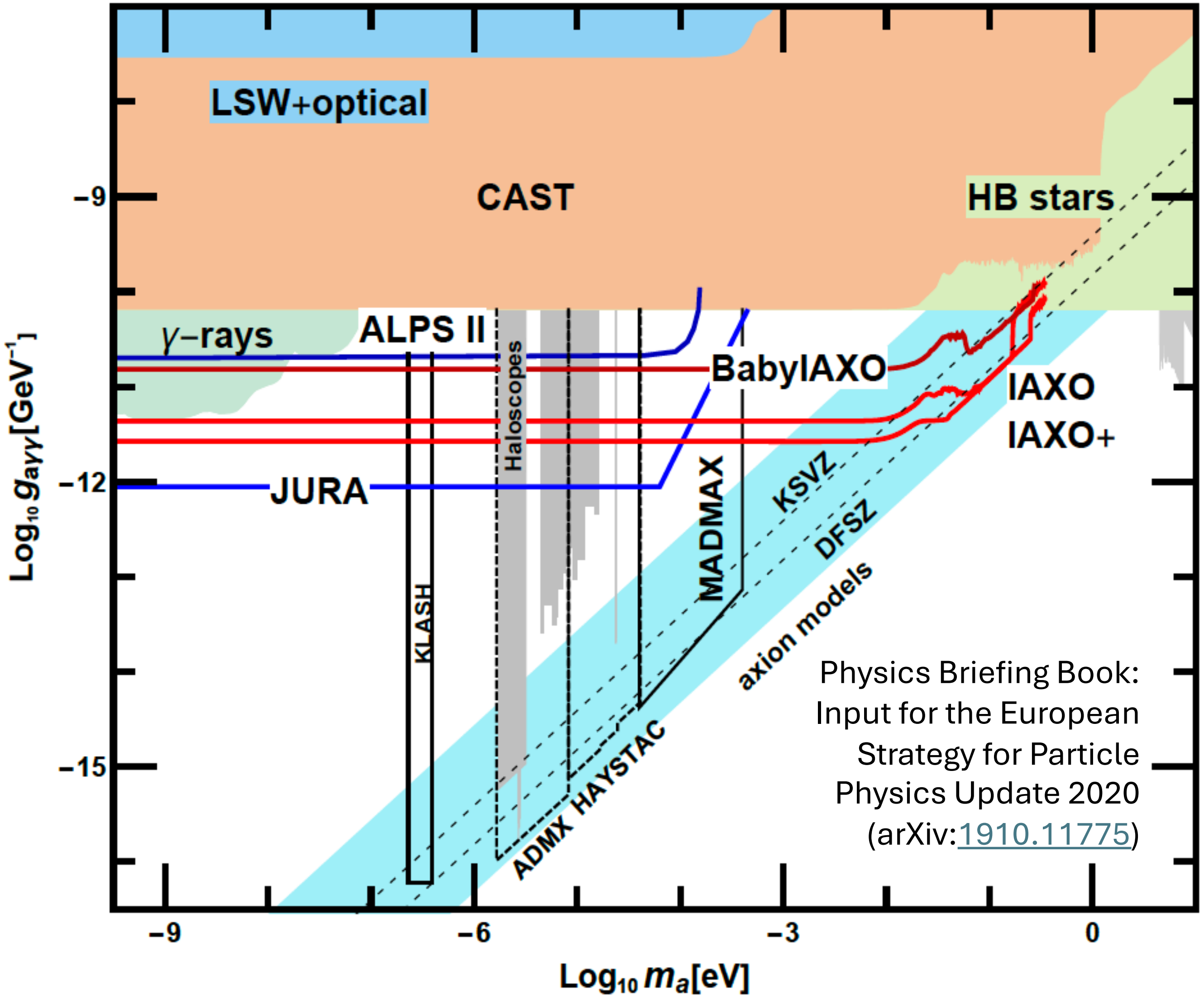


- ► Haloscopes
  - Microwave cavities
  - Dish antennas/dielectric and plasma haloscopes (higher m_a)
  - Lumped element detectors (lower m_a)



Previous prospects

► ESPP Update 2020



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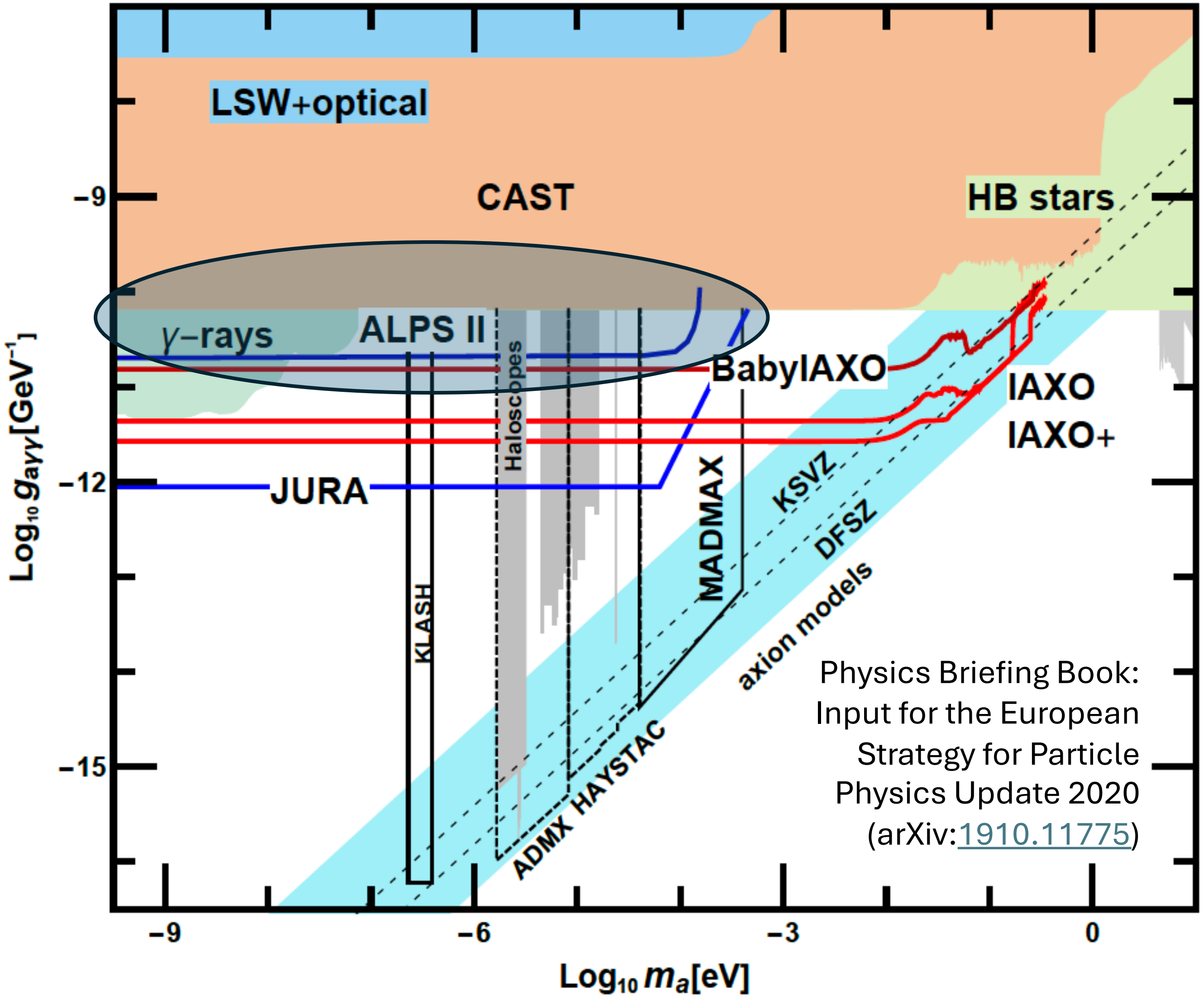
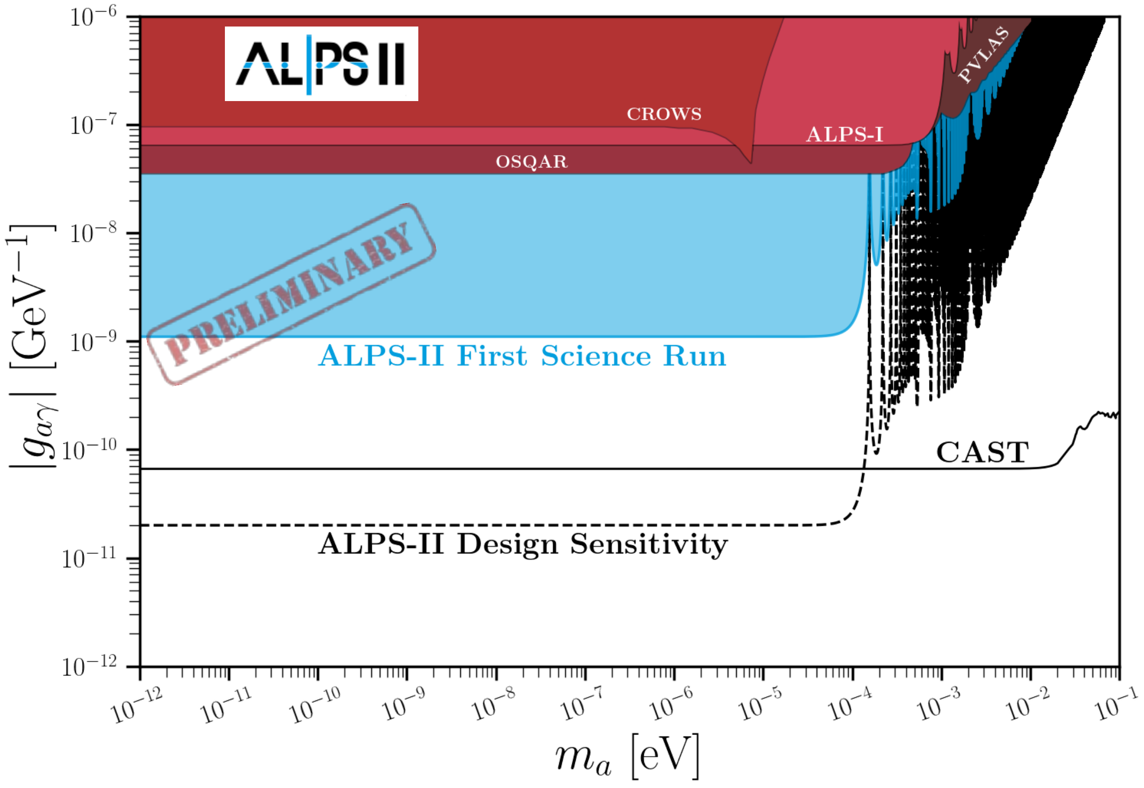
- ESPP Update 2020
- Where are we now?
  - ALPS II taking data





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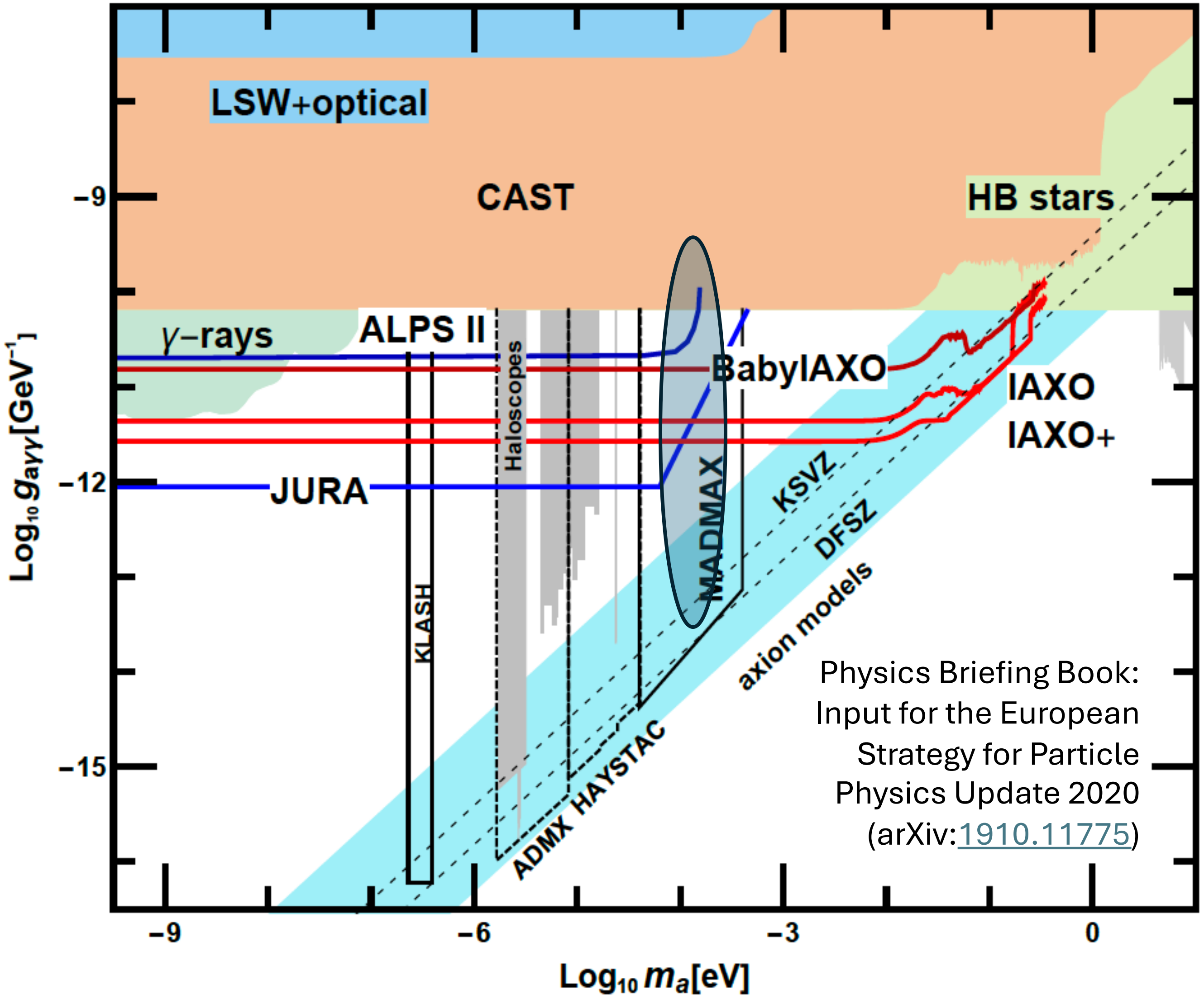

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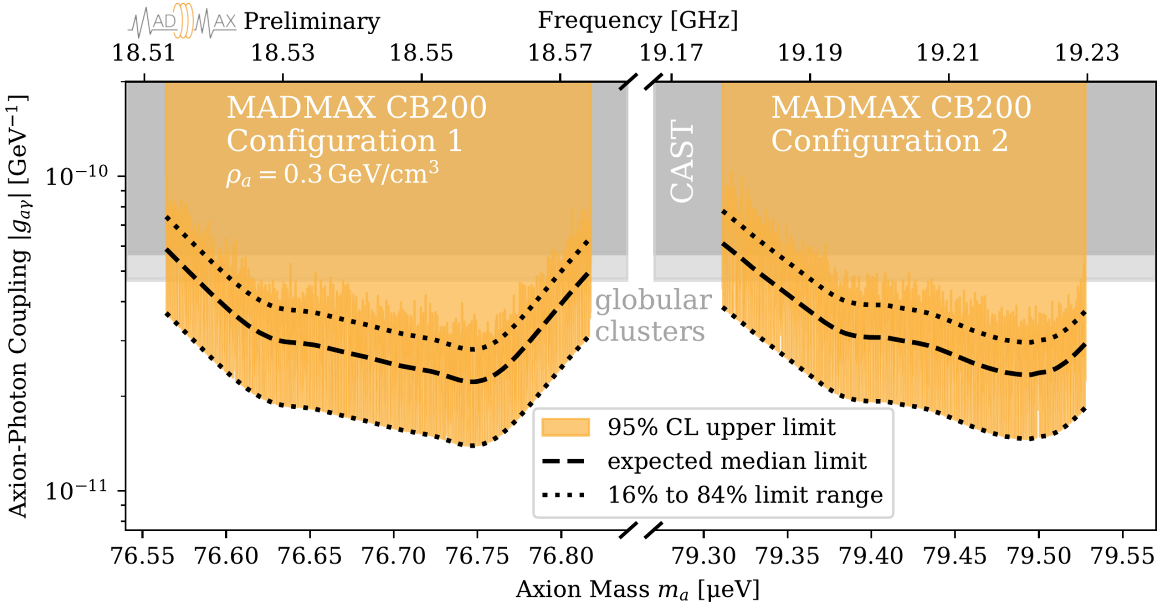
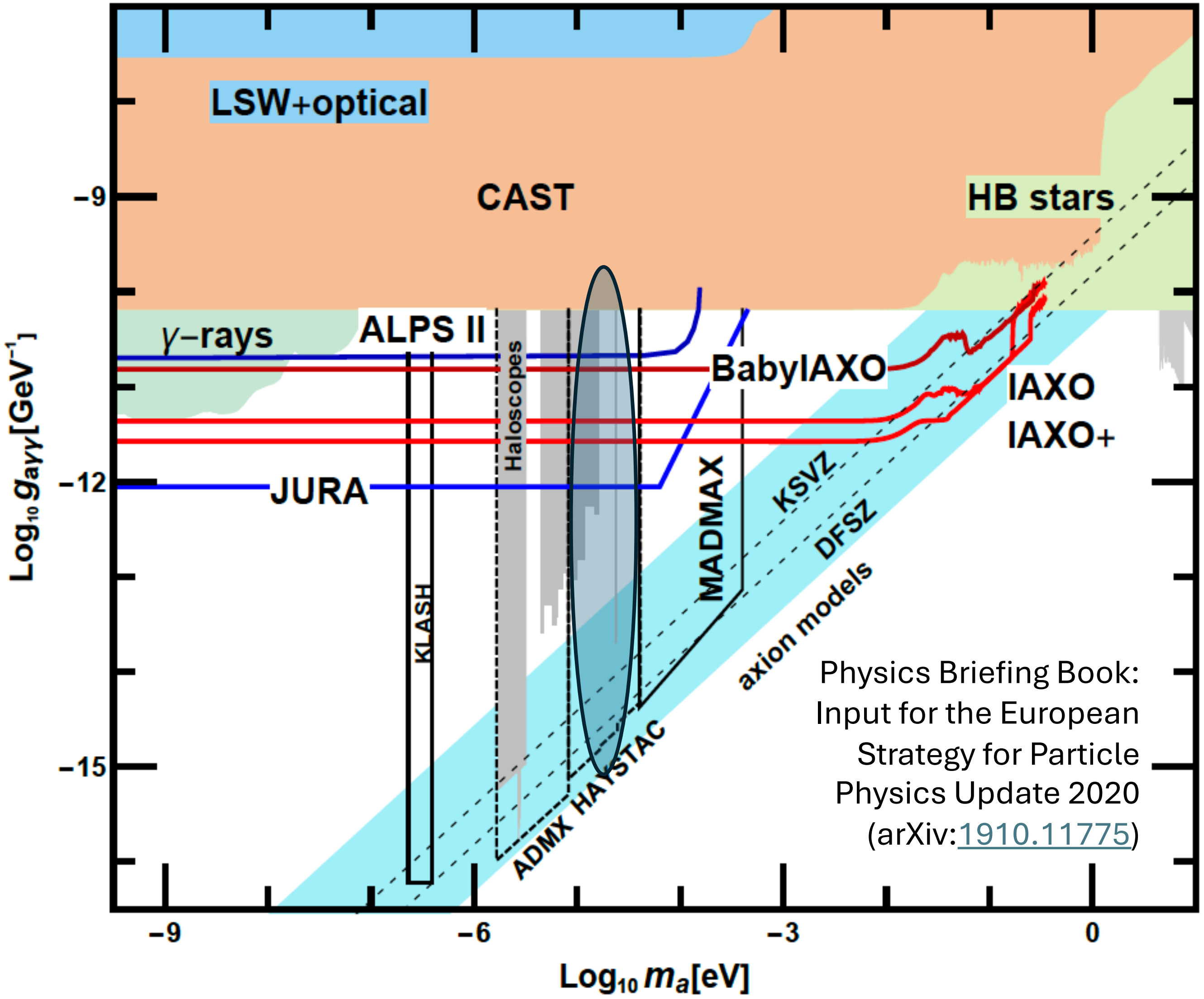
  - MADMAX prototype tests



MADMAX prototype setup with 3 disks & a mirror within 1.6 T magnetic dipole field (Morpurgo@CERN, t=14.5 d)

Ary dos Santos Garcia *et al.*, arXiv 2409.11777

Previous prospects



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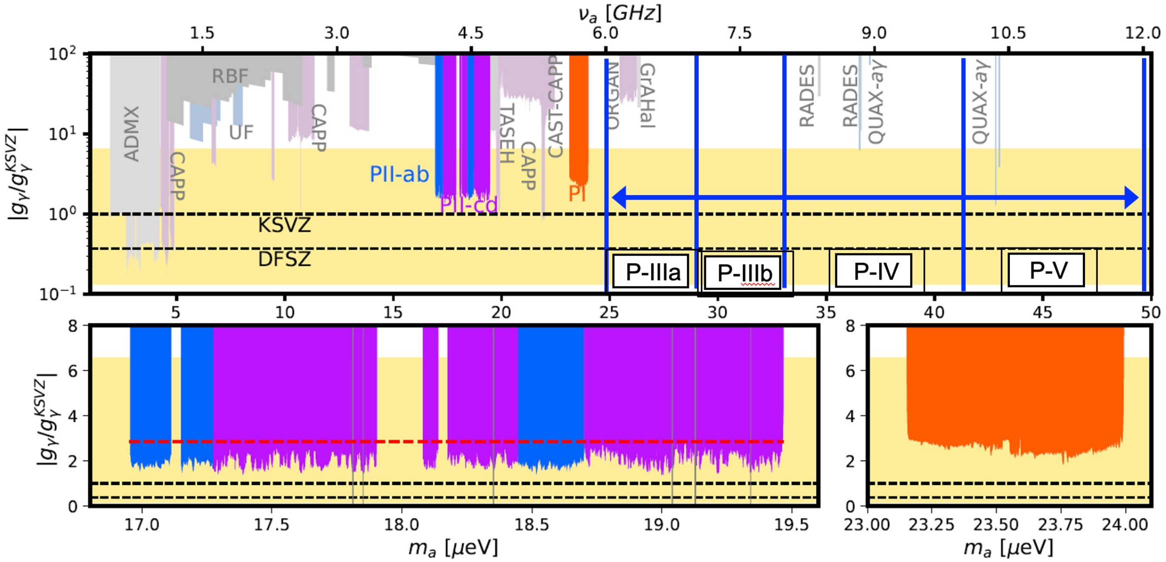
Haystac



PRL 134, 151006 (2025)

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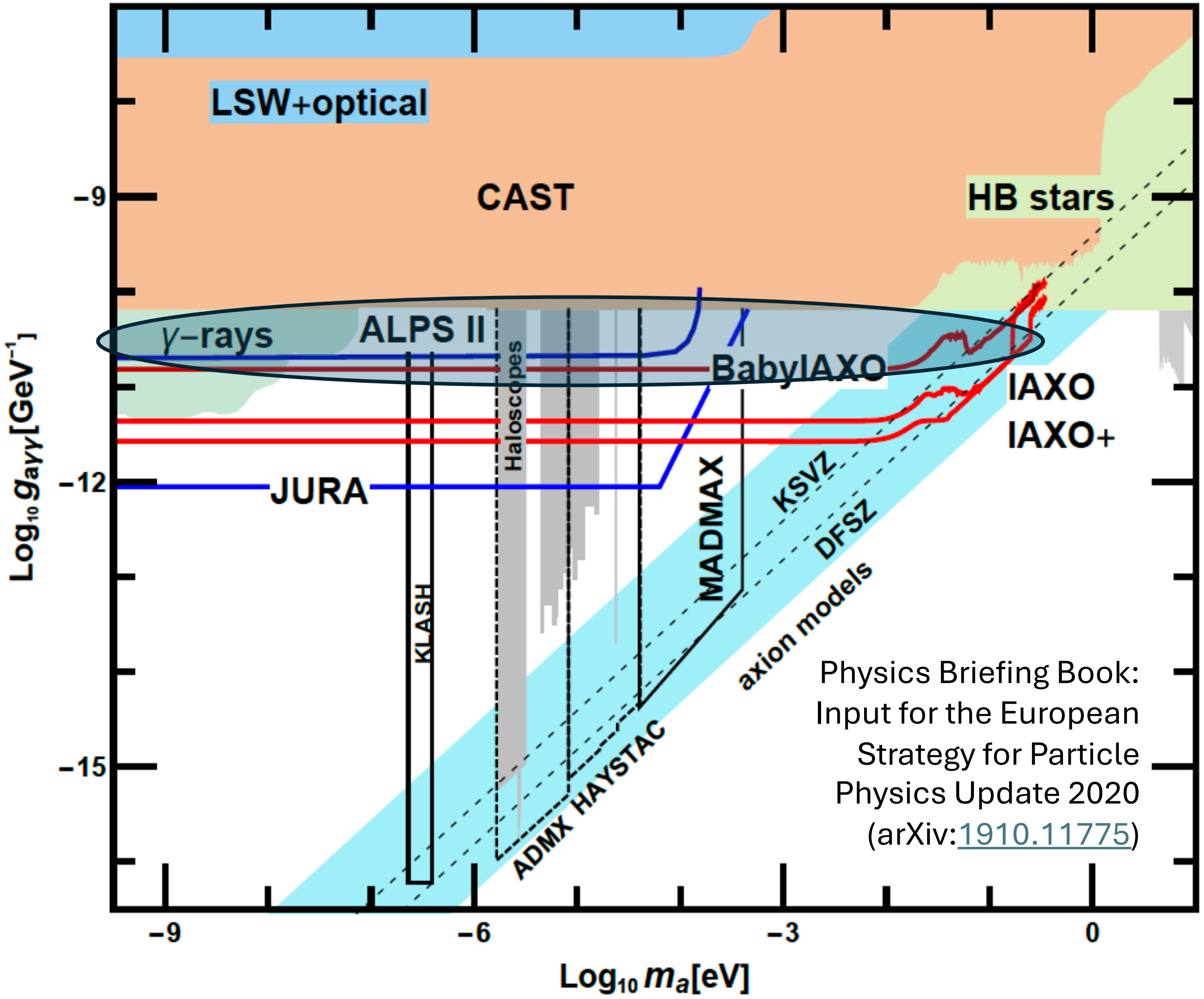

Physics Briefing Book: Input for the European Strategy for Particle Physics Update 2020 (arXiv:1910.11775)

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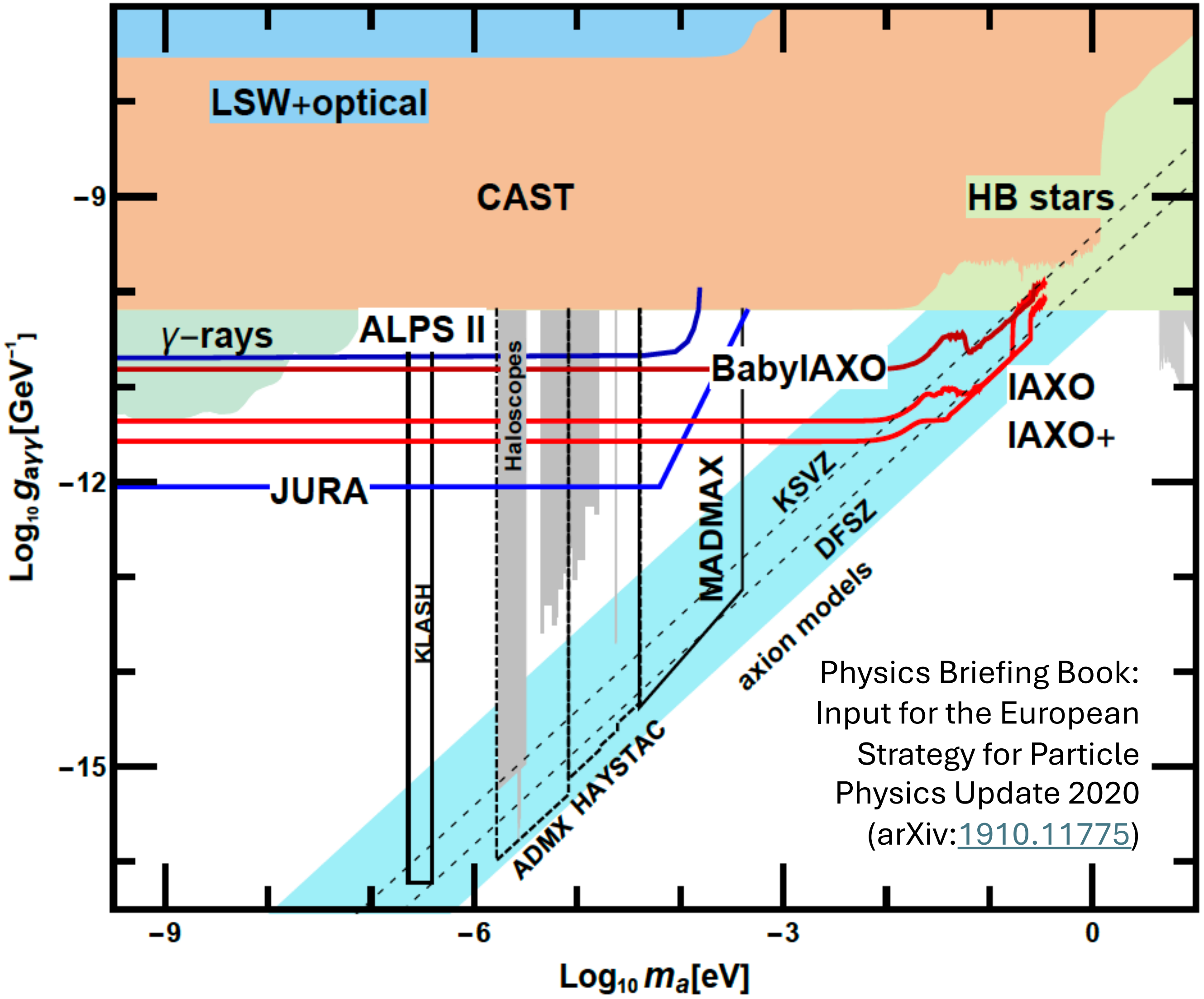
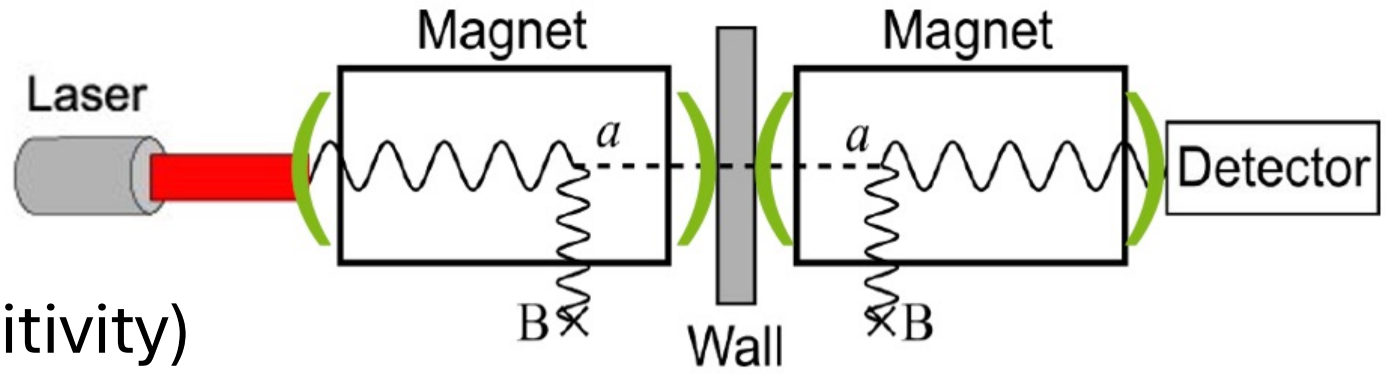


- ESPP Update 2020
- Where are we now?
  - ALPS II taking data
  - MADMAX prototype tests
  - HAYSTAC entering phase III
  - BabyIAXO being constructed @ DESY
- Existing experiments progressing
- Since 2020 more experiments proposed, especially to access still unexplored regions of QCD band

Purely Laboratory Searches: LSW

- Setups fully controlled: produce axions, detect axions

- Running experiments/under construction: ALPS II
(on the way to its design sensitivity)
  - Expected to explore untested regions



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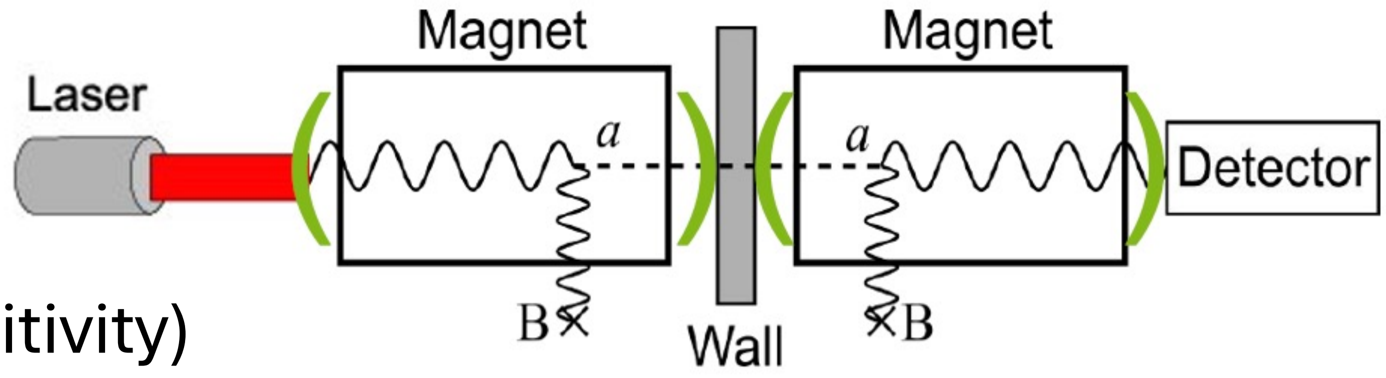

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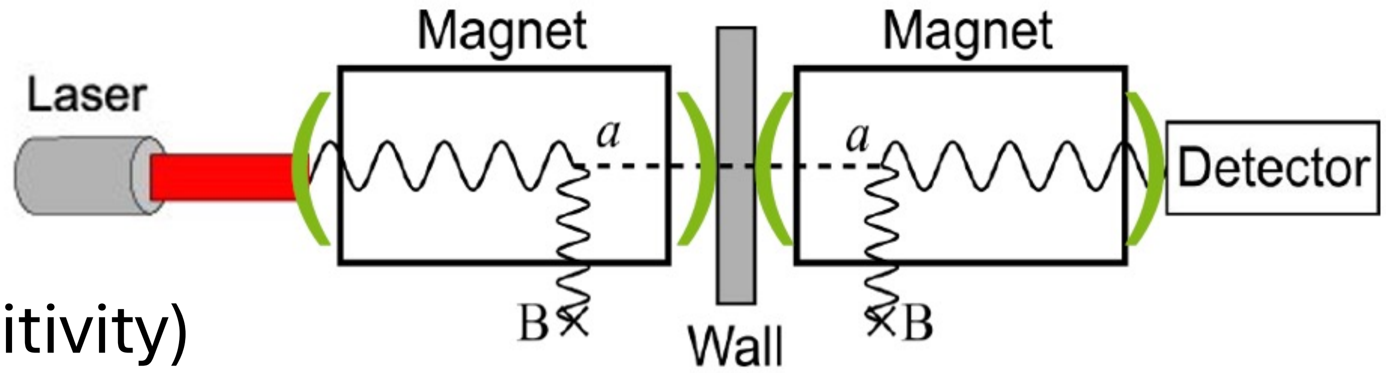

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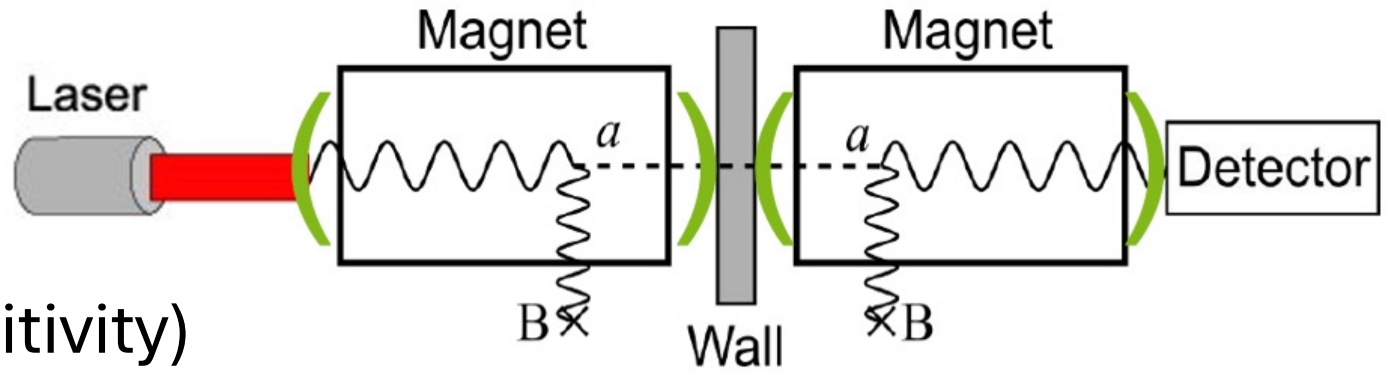

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- Longer-term: e.g. HyperLSW (in case of a haloscope detection)

https://inspirehep.net/literature/2805684

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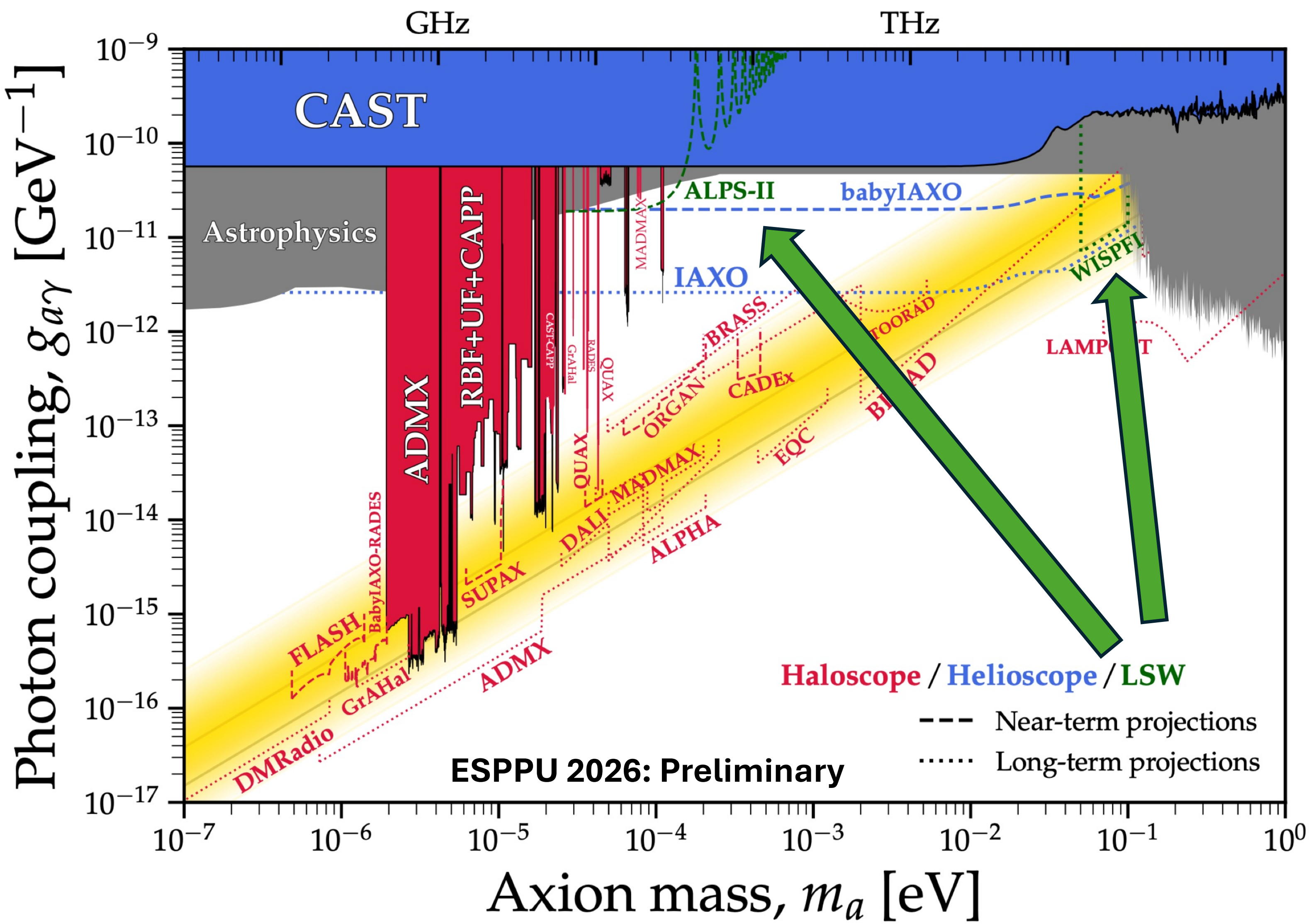
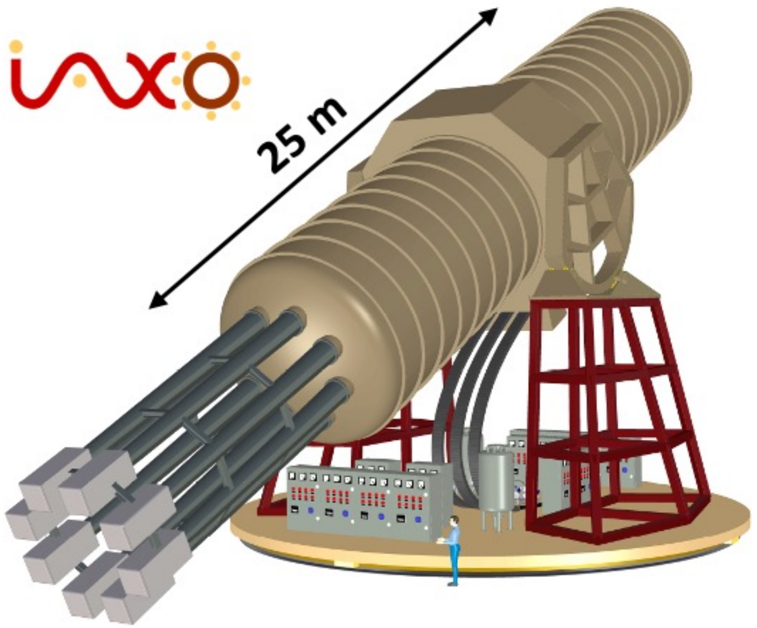


Solar Axion Searches: Helioscopes

- **Major international effort**: International Axion Observatory (IAXO)
- Intermediate stage BabyIAXO (helioscope in its own right)
- Goal: Probe QCD axions at high mass end (meV-eV)
  → Complementary to low mass searches +ALPs+test astrophysical hints+dark photons+...



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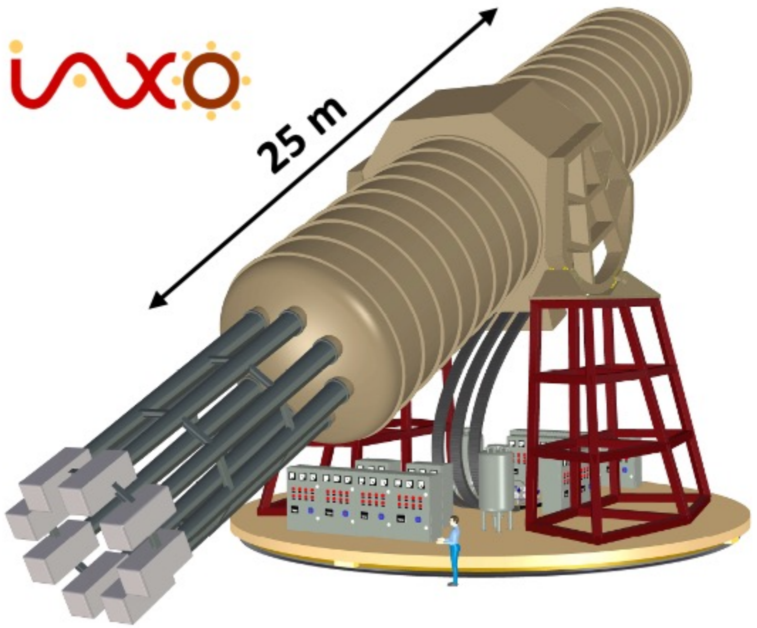
- BabyIAXO@DESY in construction phase
- Axion-photon, but can also study other couplings (a-e, a-N), also post-discovery capabilities



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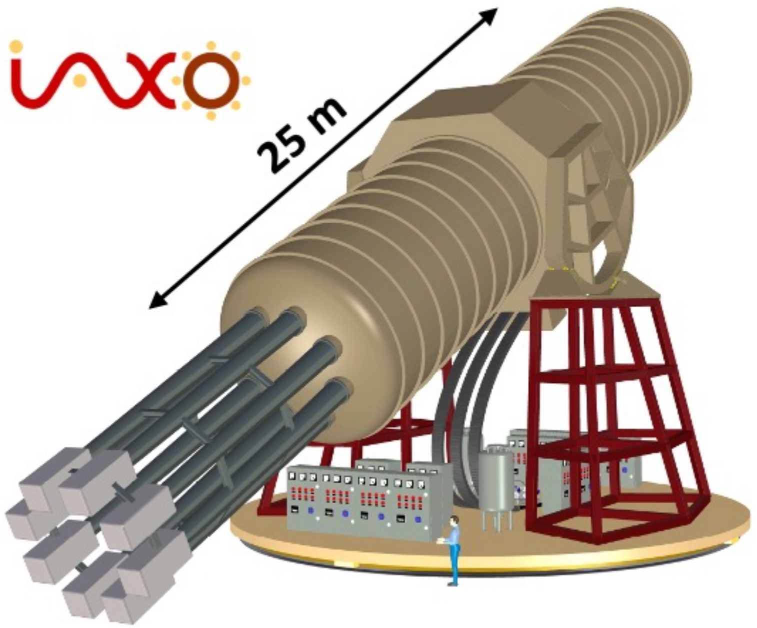
- BabyIAXO@DESY in construction phase
- Axion-photon, but can also study other couplings (a-e, a-N), also post-discovery capabilities
- Includes haloscope setup for DM searches and high-frequency GW studies (BabyIAXO-RADES)



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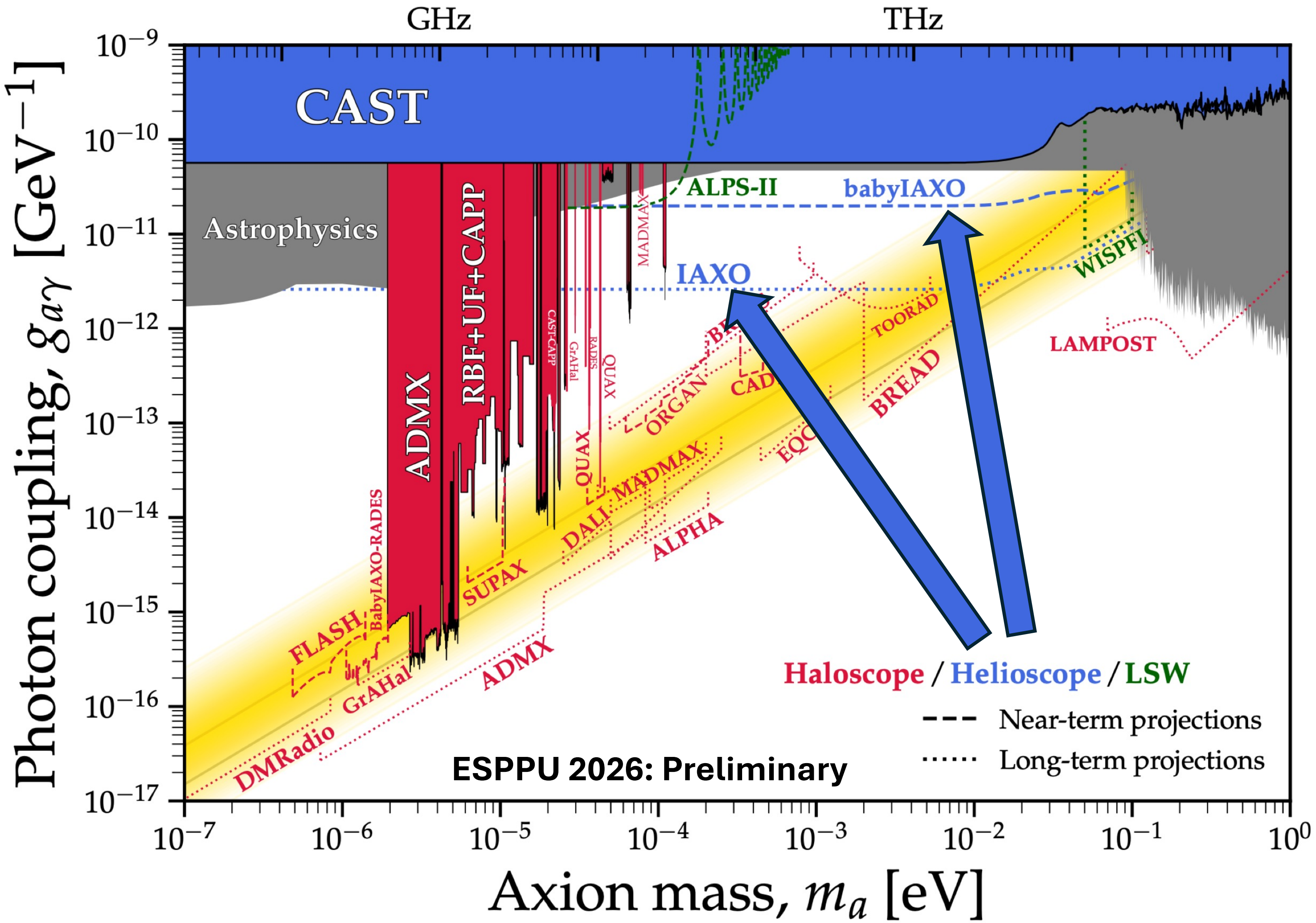

Dark Matter Searches: Haloscopes

- Resonant cavity haloscopes
  - Pioneered by ADMX, running and probing QCD band:
    ADMX, HAYSTAC, CAPP, QUAX
  - New setup being developed: RADES, GrAHal, SUPAX, CADEX, ORGAN, TASEH,PXS…

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- Expansion to higher masses:
  - Dielectric Haloscopes (MADMAX, DALI, LAMPOST, EQC…)
  - Dish Antennae (BRASS, BREAD)
  - Plasma Haloscopes (ALPHA/HAYSTAC)
  - Antiferromagnetic resonance (TOORAD) (Uses magnetic topological insulators to detect axion DM)

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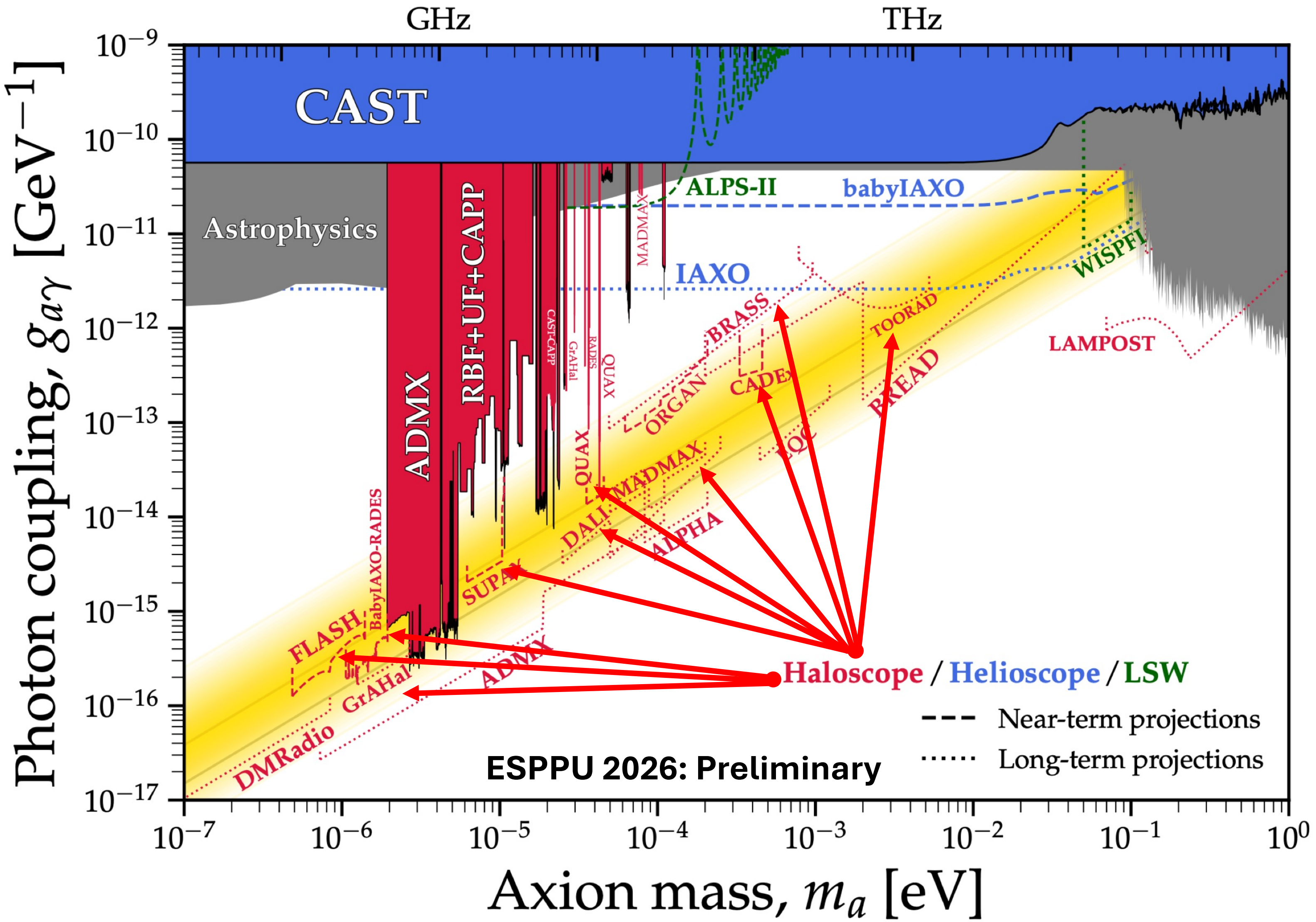
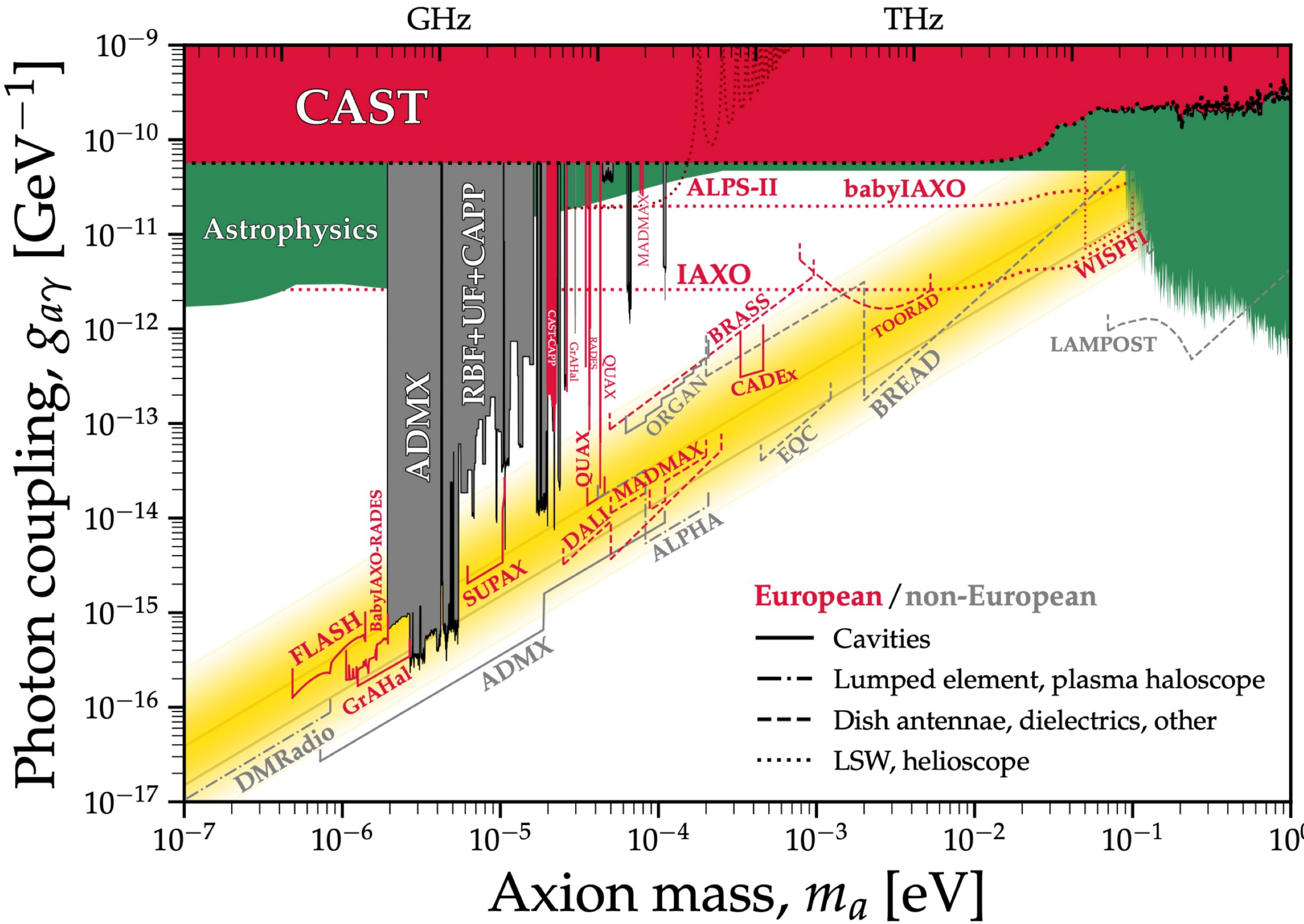
- Expansion to lower masses:
  - FLASH, BabyIAXO-RADES
  - Lumped element detectors (DMRadio, WISPLC,…)

Dark Matter Searches: Haloscopes



Axion Searches

- Large parts of QCD band can be studied in coming decades
- Significant European-leadership and/or involvement

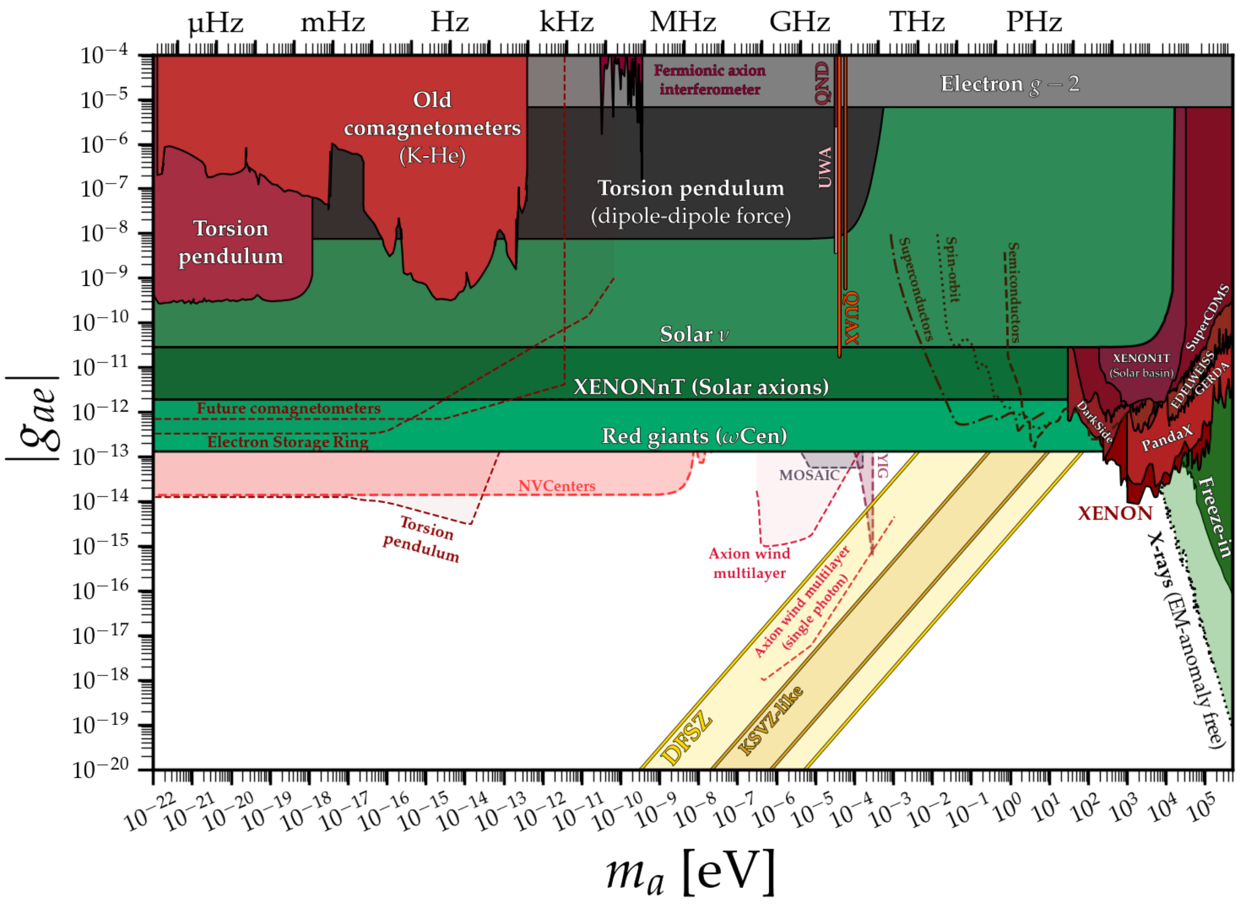


- Complementary experimental approaches are crucial to cover full viable axion parameter space
- Mixture of large-scale and smaller-scale experiments
- ALP searches in parallel

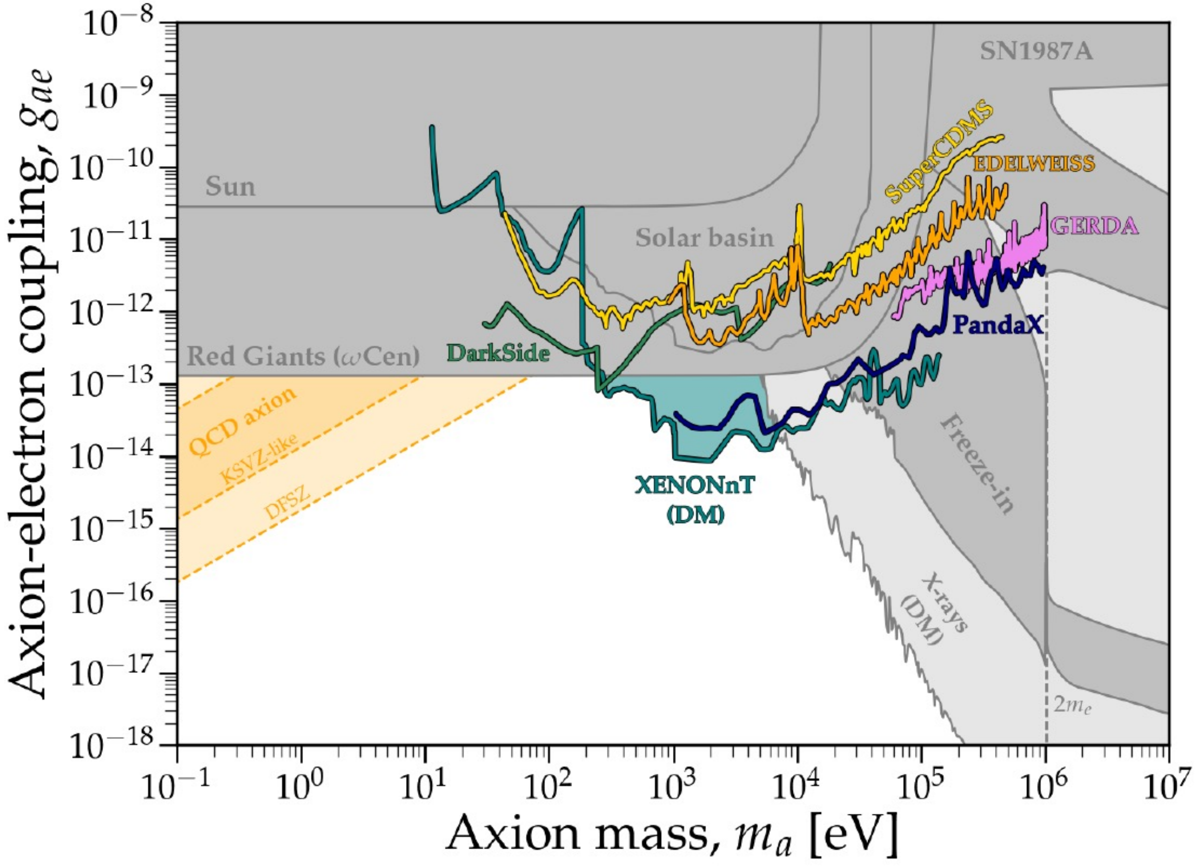
Beyond axion-photon searches

- Novel searches for other couplings
  - Axion-gluon, axion-electron, axion-nucleon
- Significant European engagement
  - QUAX (axion-induced spin precession in a ferromagnetic crystal (YIG))
  - CASPEr (NMR-based precision magnetometry)
  - Ariadne (axion-mediated spin-dependent forces)
  - SRF Heterodyne (superconducting resonators or hybrid NMR/quantum sensors, proposed)
  - …

Beyond axion-photon searches: g_{ae}

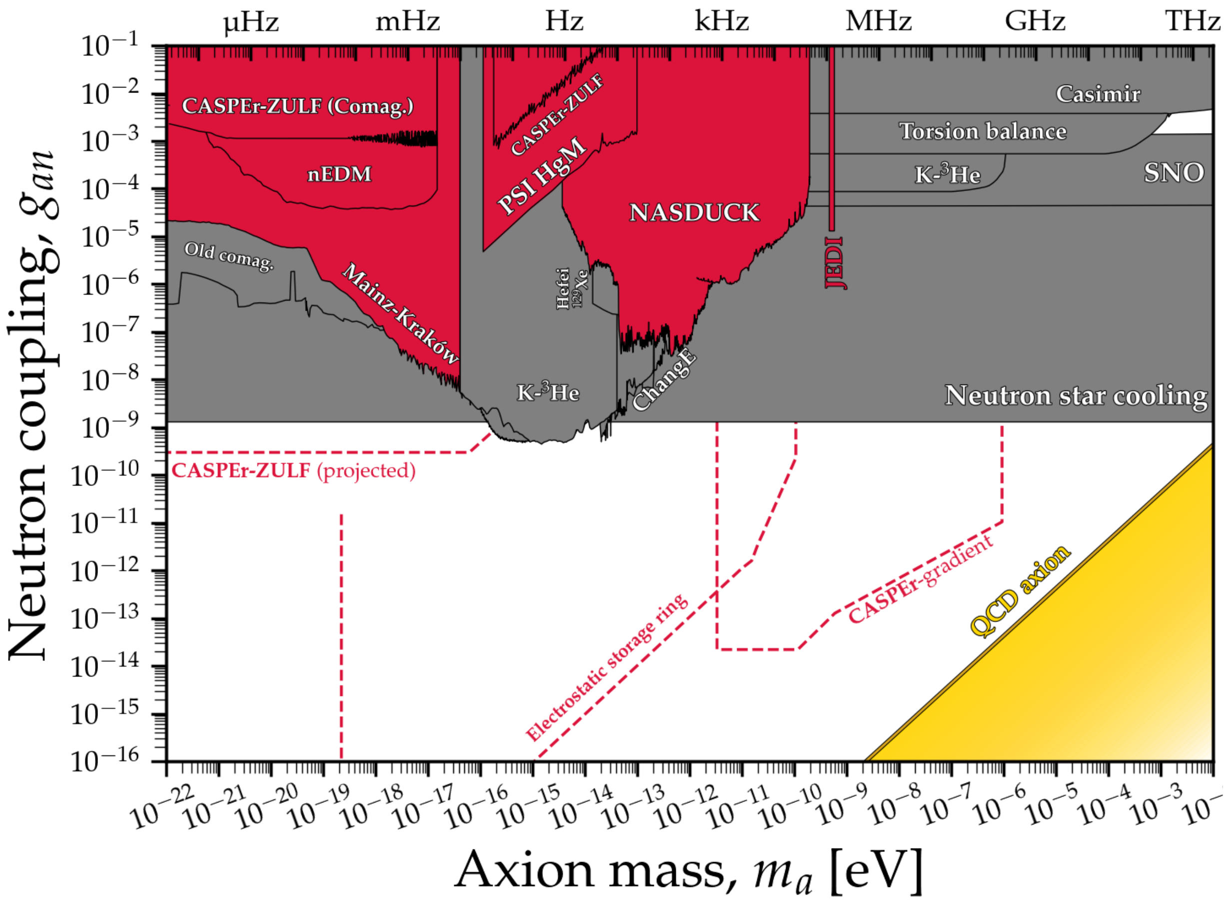


Full mass range

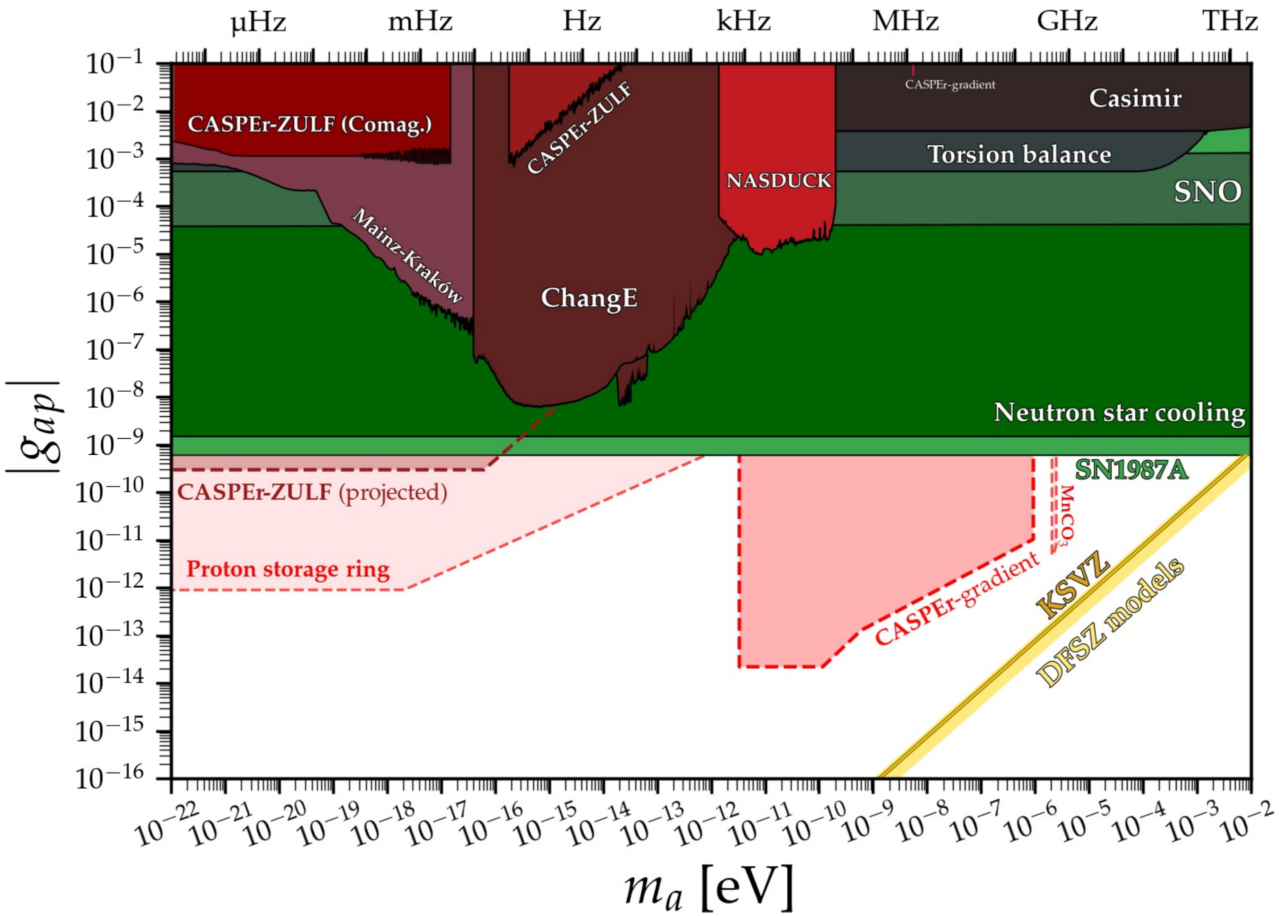


Zoom in on higher mass range

Beyond axion-photon searches: g_{aN}

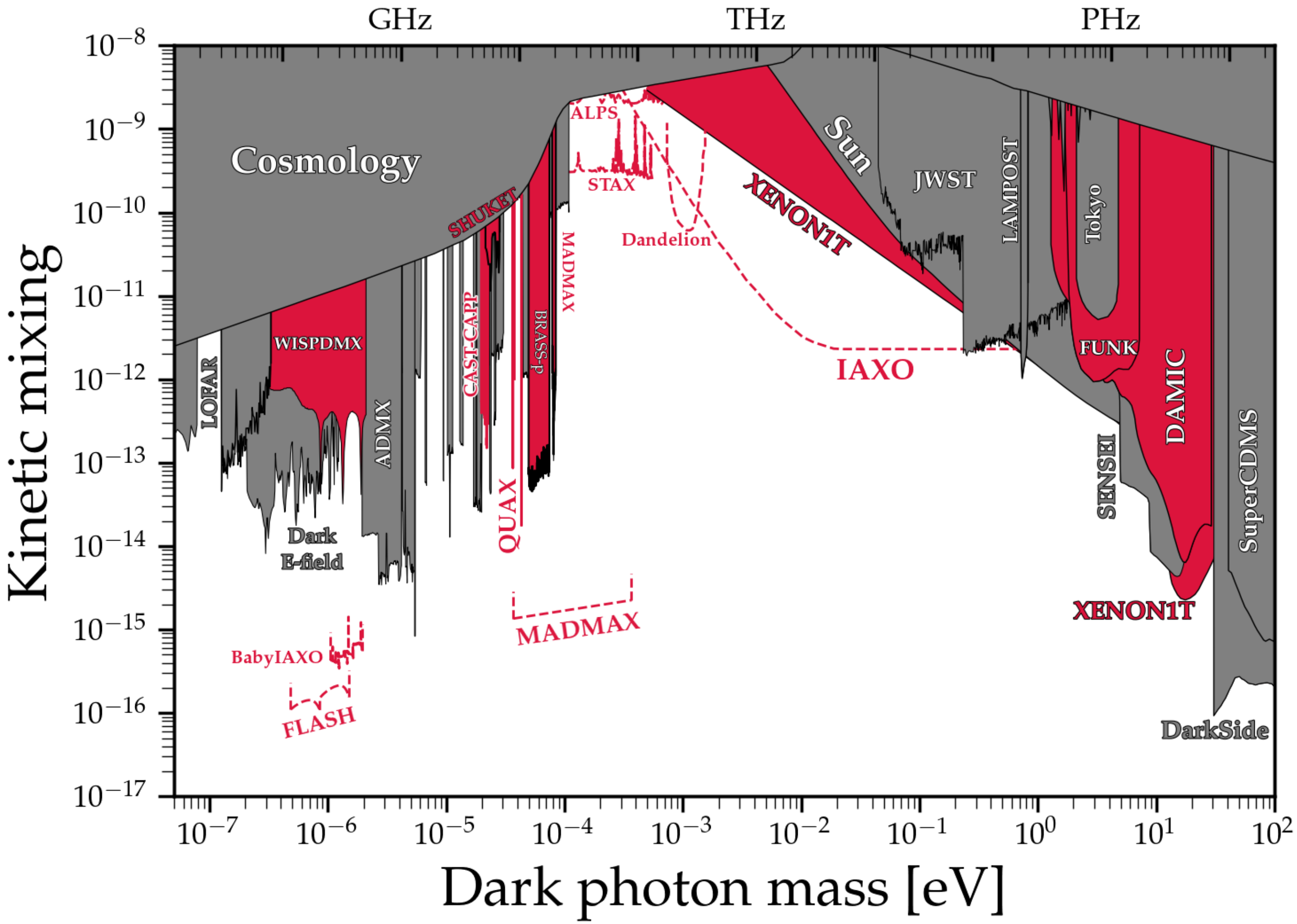


Axion-neutron coupling



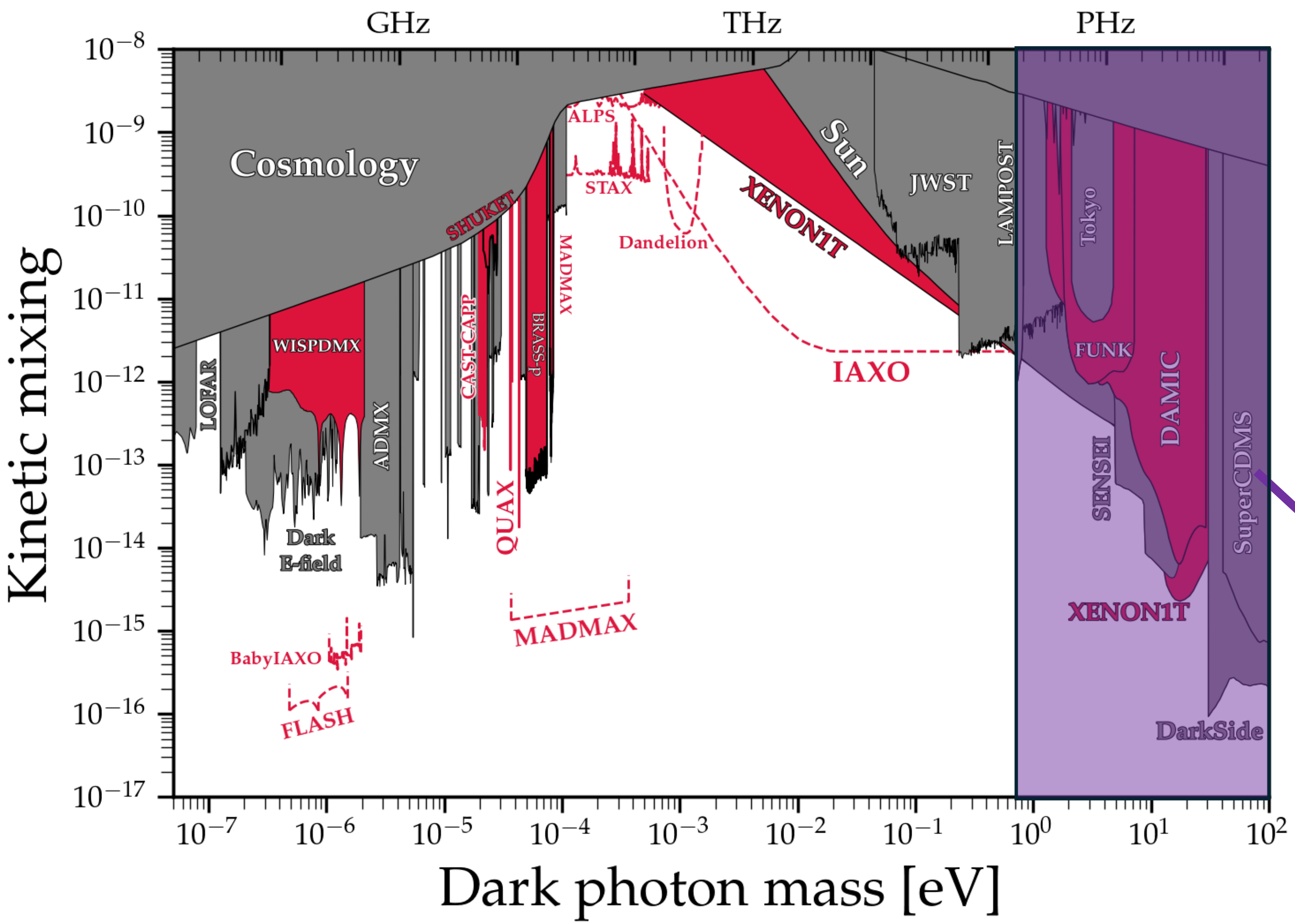
Axion-proton coupling

Other searches: Dark photon (DM & DS)



- Many axion experiments can also search for dark photons
- Furthermore, dedicated efforts ongoing
- Light dark photons could be DM

Other searches: Dark photon (DM & DS)



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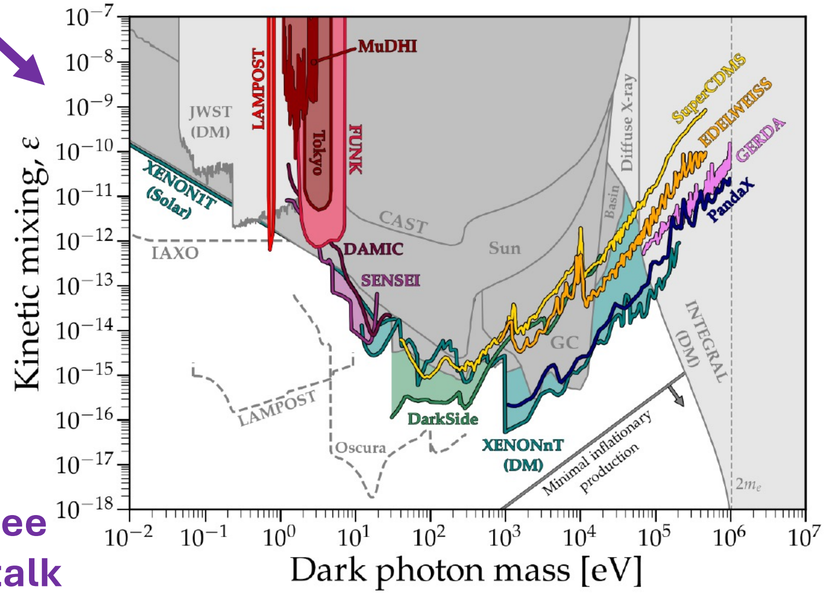

For higher masses see Paolo's & Monica's talk

Technologies that need to be (further) developed

- Magnets (large volume, high B-field)
- Detectors (low bgrd)
- Optics (different energies, couple large magnets to small detectors)
- Cryogenics and Vacuum technology
- Improved cavities
- Quantum sensing (interesting for all types of searches)

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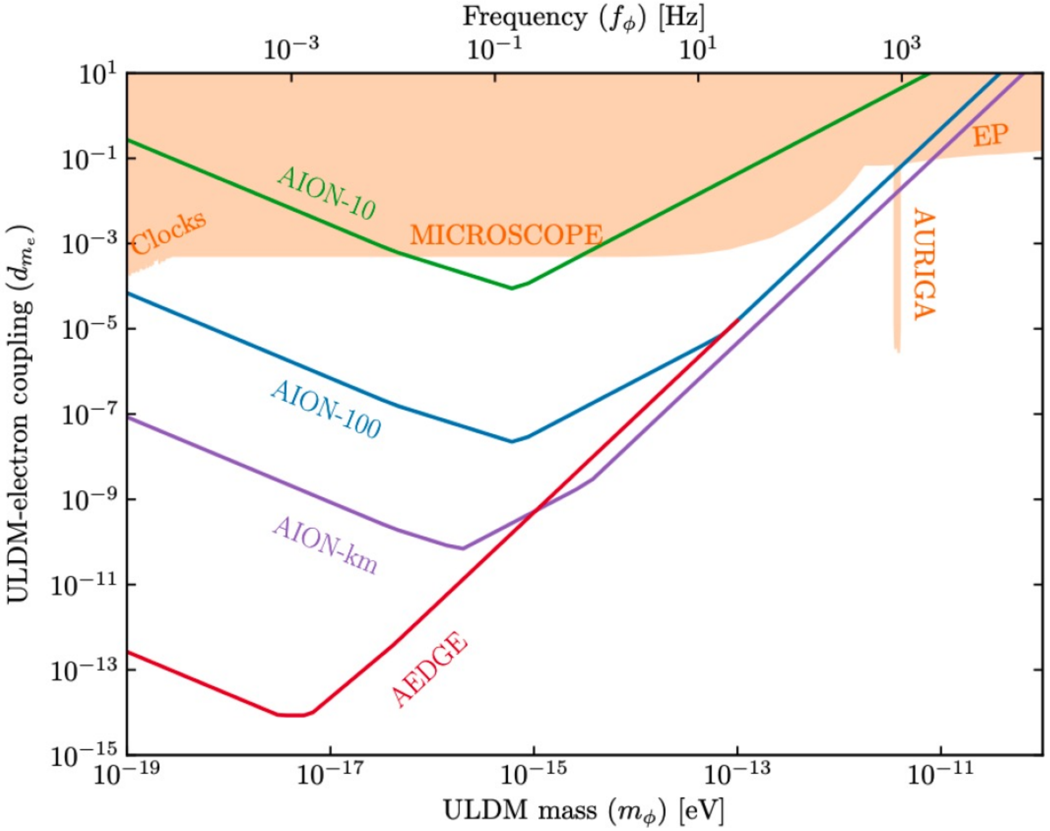
  Most crucial for
  - Haloscope approaches (e.g. RADES, SRF Heterodyne, Madmax,…)
  - Spin precession / NMR (e.g. CASPEr, Quax, GNOME,…)
  - Atomic Interferometer approaches (MAGIS, AION,…)
  - Close connection to GW searches (Mago, GravNet,…)

  → Lots of activity in this field (see e.g. #204,#228,#260)

New developments

- Atom interferometry (MAGIS/AION/MIGA/VLBAI/..., AEDGE in space) and similar techniques can search for ultralight scalar DM ←→ gravitational wave detection (intermediate frequencies ~ 10^{-1} – 1 Hz)

  → TVLBAI Proto-Collaboration: coordinated programme of IF with increasing baselines



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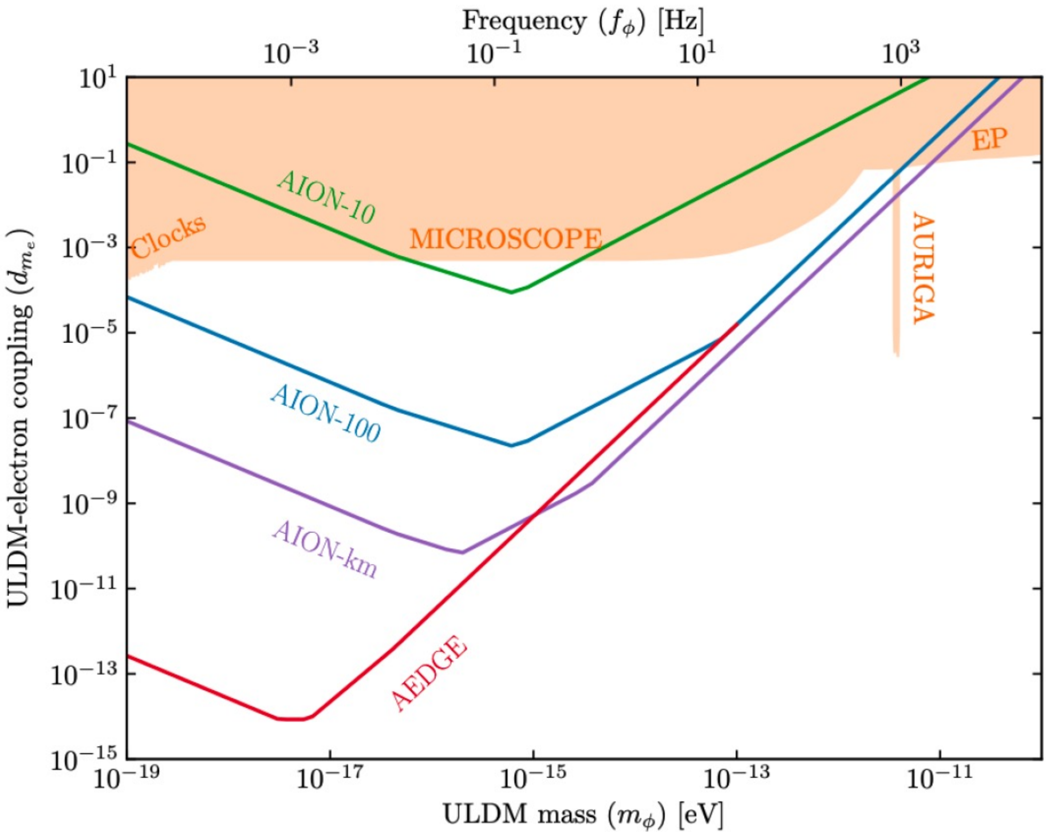
- Solid-State / Low-Temperature "Absorption" Detectors (e.g. QUAX-ae, SPHERES, HeLIUM)
- Oscillating EDMs at Storage Rings (e.g. JEDI)
- Electron Recoil Signals in Large-Scale Detectors like XLZD (Xenon/LZ/Darwin)



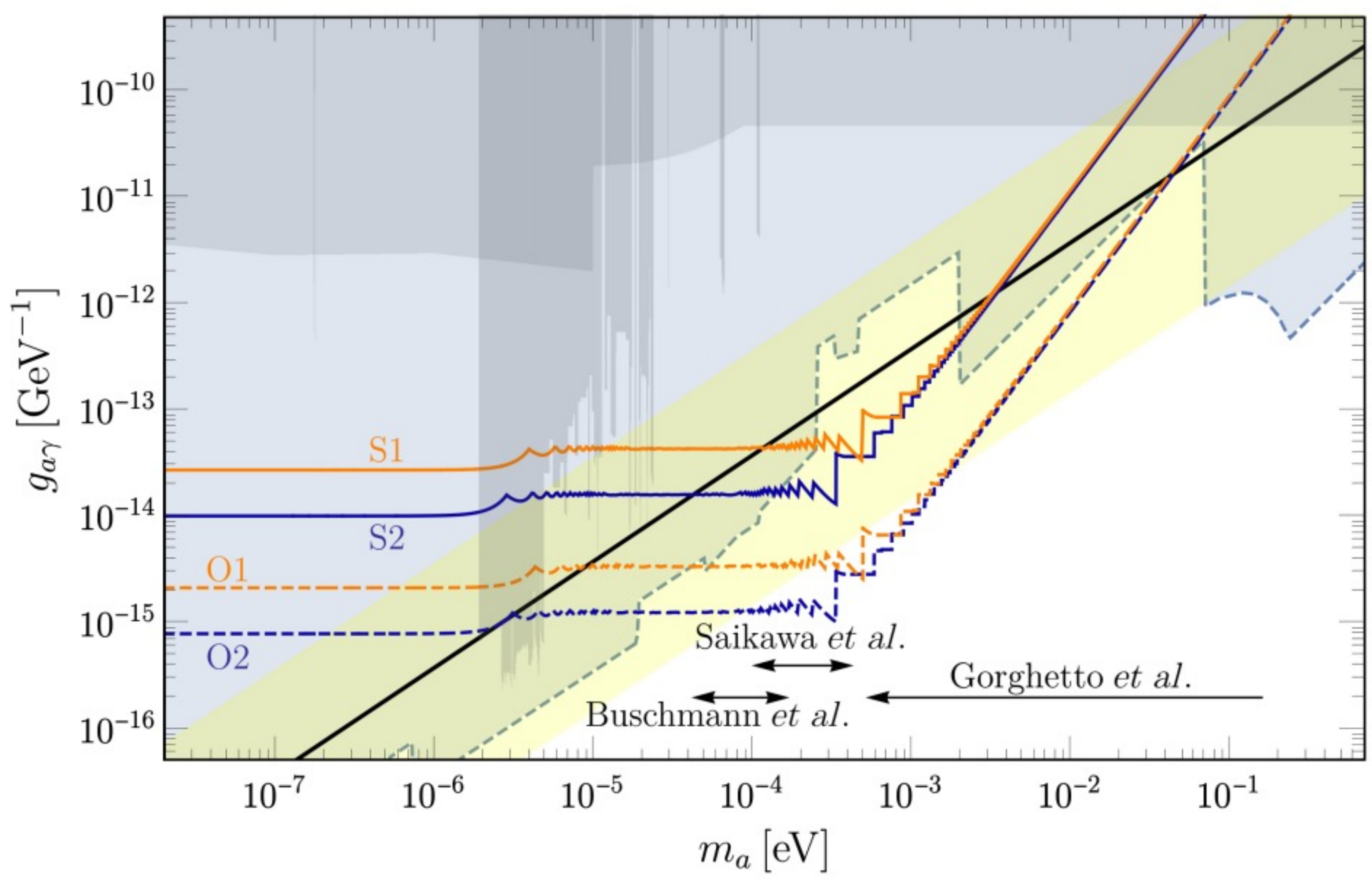
Cross-cutting topics

- X-ray Astronomy (IAXO, NuSTAR,...)
- Radio Astronomy (MADMAX, RADES,...)
- Gravitational waves (GravNet/SUPAX,...)
- NMR (CASPEr experiments)
- Condensed matter (QUAX)
- Quantum sensing (most experiments)
- EXP – TH – PHENO

Post discovery aspects/Outlook

HyperLSW in case of haloscope detection

- Alternating-magnet design can resonantly enhance LSW sensitivity
- Thus can potentially reach QCD axion band
- Study on how to achieve optimal sensitivity for given axion mass

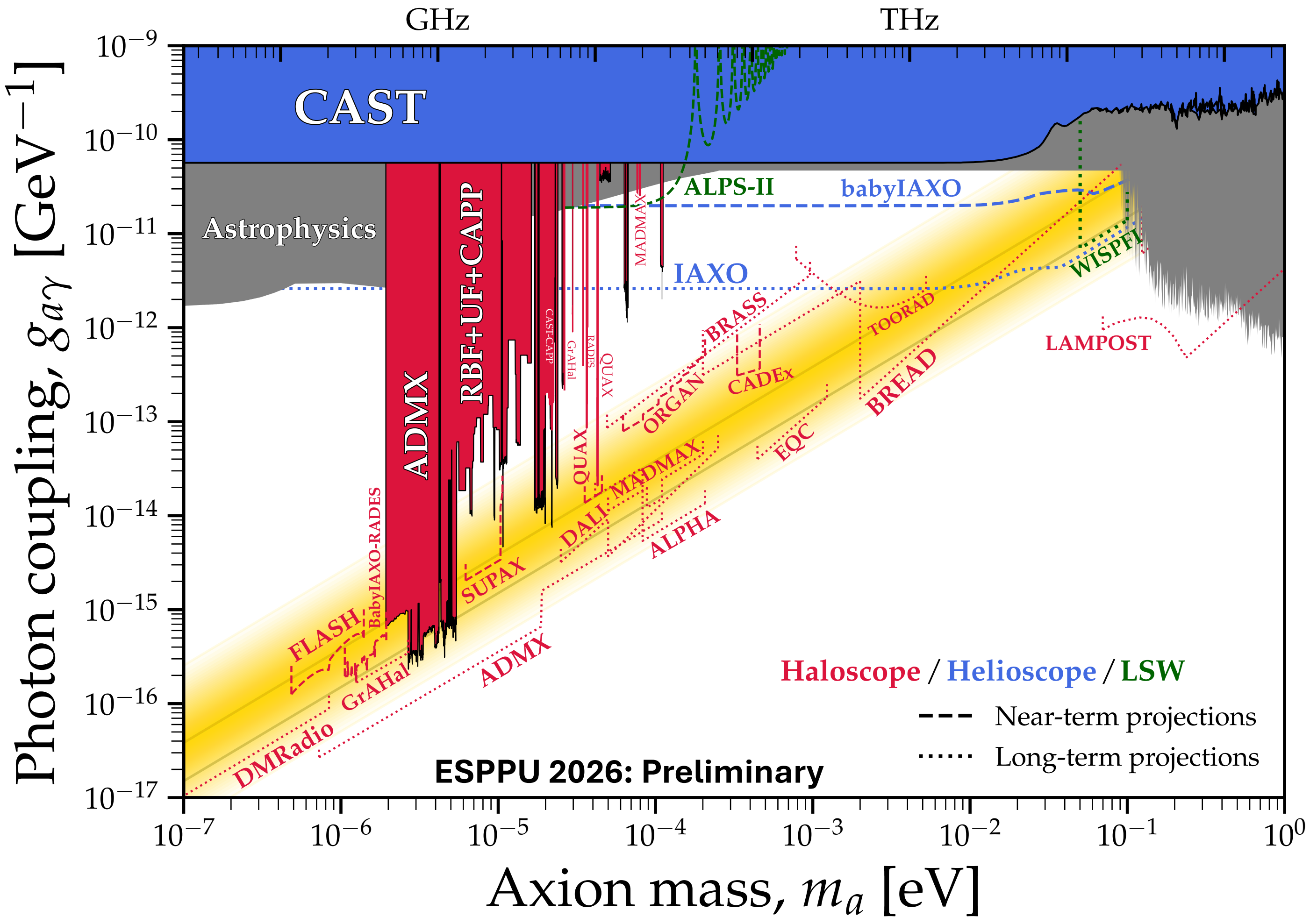


Magnets with a total of about 100 km length, 1m diameter

PRD 111, 015003 (2025)

Summary

- Large parameter space to cover for axions and ALPs
  → need for complementary approaches
  → QCD band coverage in reach
- Many small-scale experiment, but now need to scale-up to mid/large searches (MADMAX, IAXO,…)
- Study of other axion-couplings/DPs pursued
- Quantum sensing to push beyond SQL



Backup

Input documents including national input mentioning ULDM

General submissions

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#146 The International Axion Observatory (IAXO): case, status and plans.
#198 Einstein Telescope - The future European Gravitational Wave Observatory
#204 R&D on quantum sensors for particle physics: the DRD5 collaboration
#228 Quantum Technologies in High Energy Physics. The CERN Quantum Technology Initiative input to the ESPP
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Networks and Committees

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#235 Summary Report of the Physics Beyond Colliders Study at CERN

National input

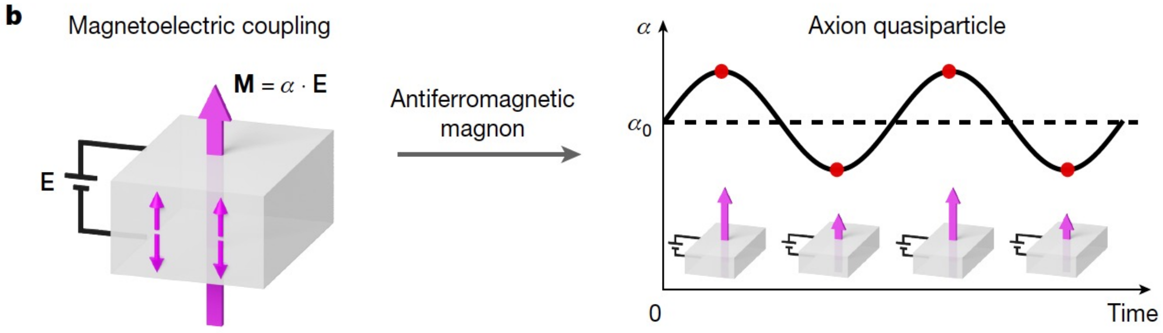
#13 Laboratori Nazionali di Frascati of INFN (INAF)
#15 French HEP community input to the European Strategy for Particle Physics
#22 Statement by the German Particle Physics Community as Input to the Update of the ESPP
#126 Input to ESPPU by the German Astroparticle Community
#147 Spanish national input to the European Strategy for Particle Physics

New Haloscopes

TOORAD (TOpolOgical Resonant Axion Detection)

Nature 641, 62–69 (2025)

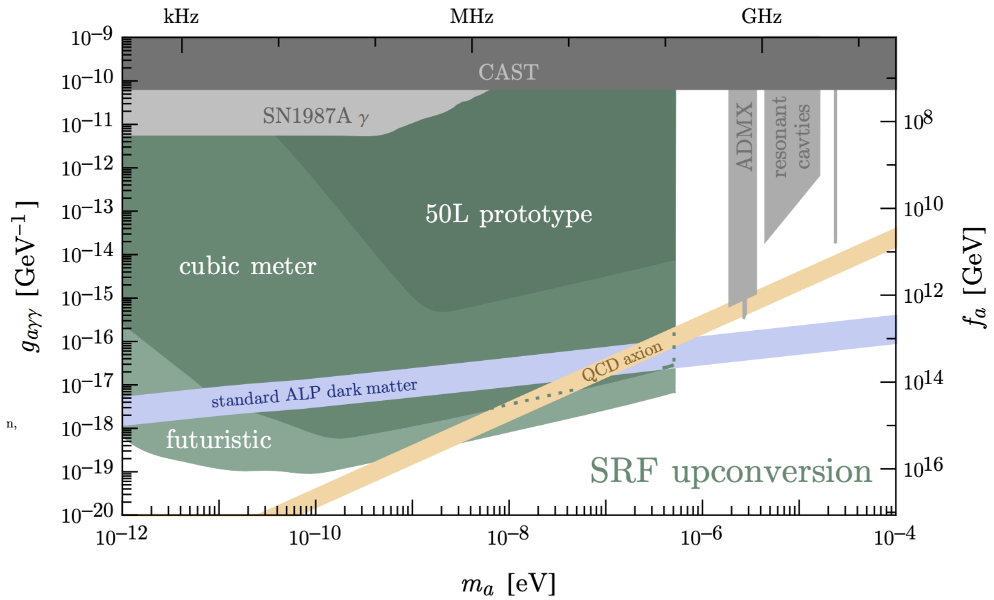
- Uses magnetic topological insulators to detect axion DM
- **Dynamical Axion quasiparticles (DAQ)** in materials like Fe-doped Bi_2Se_3 or $MnBi_2Te_4$ can convert into **THz photons** in B-field
- Targets ~**1 meV axion masses**
- **Volume-independent sensitivity** and **tunable resonance** via magnetic field
- Requires **efficient THz photon detectors** for readout



SRF Heterodyne

#228 Quantum Technologies in HEP. The CERN QTI input to the ESPP (JHEP 07 (2020) 088, PRD 104 (2021),11, L111701)
#260 Quantum Sensing for DM and Gravitational Waves

- New axion detection concept using SC RF cavities
- Like haloscopes, relies on a–γ conversion in a bgrd EM field, but here **oscillating (AC)** field at frequency f_0.
- Axion signal appears at $\mathbf{f_0 \pm m_a/2\pi}$, enabling detection independent of cavity size
- Decoupling of cavity geometry and m_a



Axion-electron: experiments

Future comagnetometers:
JHEP01(2020)167
Electron storage rings:
arXiv:2211.08439
Nitrogen-Vacancy Centers:
J. High Energ. Phys. 2025 (2025), 83
Torsion pendulum
Phys. Rev. Lett 115 (2015) 201801
Axion wind multilayer (SQL/single photon)
J. High Energ. Phys. 2024, 314 (2024)
MOSAIC
arXiv:2504.16160
YIG
Phys. Rev. D 101, 096013

Axion-nucleon: experiments

CASPEr-ZULF (Zero to Ultra-Low Field) (g_{ap}, g_{an})

- Uses **ultra-low magnetic fields** to detect axion-induced **nuclear spin precession**
- Sensitive to **oscillating EDMs** of nuclei caused by axion DM
- Searching for **axions in the neV to peV range**

CASPEr-gradient (g_{ap}, g_{an})

- Applies a **magnetic field gradient** across sample
- Designed to detect **axion wind effects** (spin precession from axion field gradient due to Earth's motion in DM halo)
- Targets **higher-mass axions** compared to ZULF, with complementary sensitivity

MnCO3 (g_{ap})

- Magnetically ordered material, well-aligned nucl./ electron spins, highly sensitive to axion-induced torques/precession signals
- Similar setups to **CASPEr**, enhanced coherence and magnetic response properties; axion wind or axion-induced EDM effects.

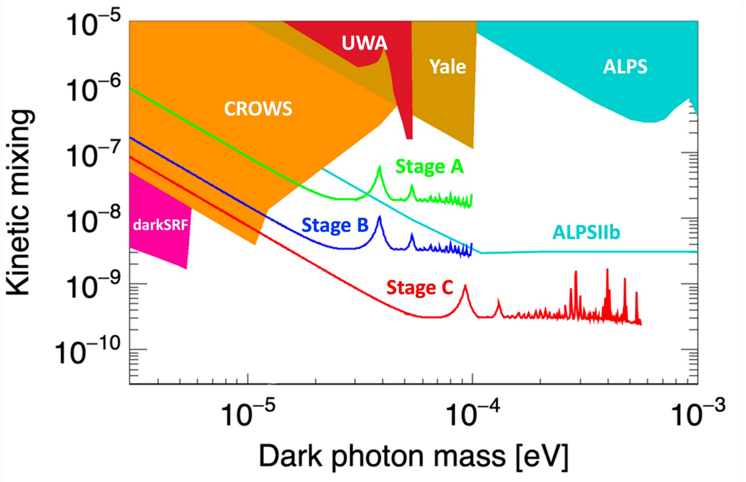
Dark Photon

STAX

arXiv: 2212.01139

LSW experiment operating in millimeter-wave (~30 GHz) range instead of optical or infrared frequencies

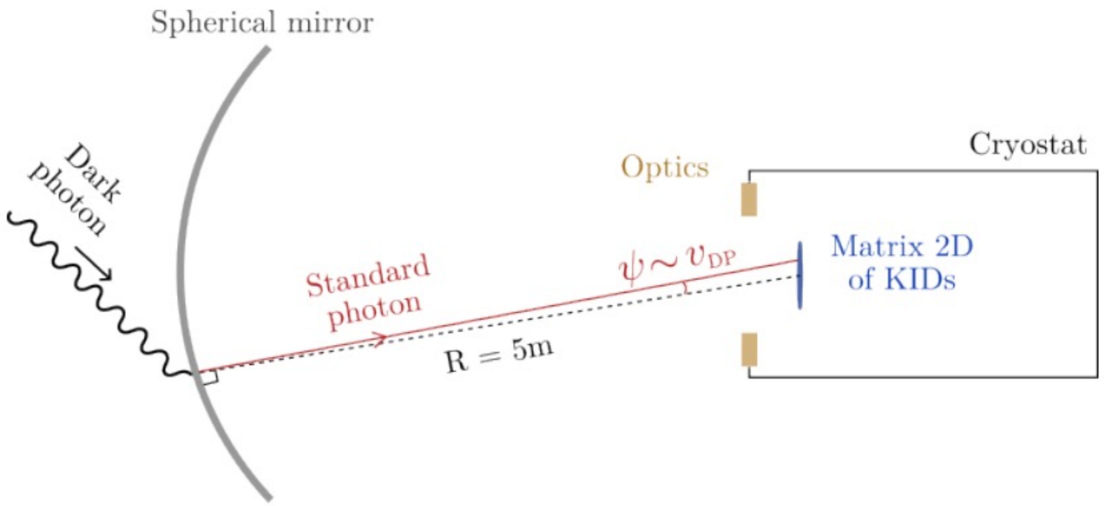
- Uses coherent wave detection rather than mainly photon counting
- Targets axion/dark photon mass range ~10^{-4} to 10^{-3} eV
- Employs advanced noise filtering and high temporal coherence techniques
- Plans to use high-power sources like phased-locked gyrotrons for improved sensitivity.



Dandelion

Dish antenna experiment searching for meV-mass dark photons

- Uses a spherical mirror and 418 cooled Kinetic Inductance Detectors to detect converted photons
- Mirror tilt moves the signal for continuous background monitoring
- Detects spatial (direction) and intensity (polarization) modulations of the signal.



Atomic interferometers