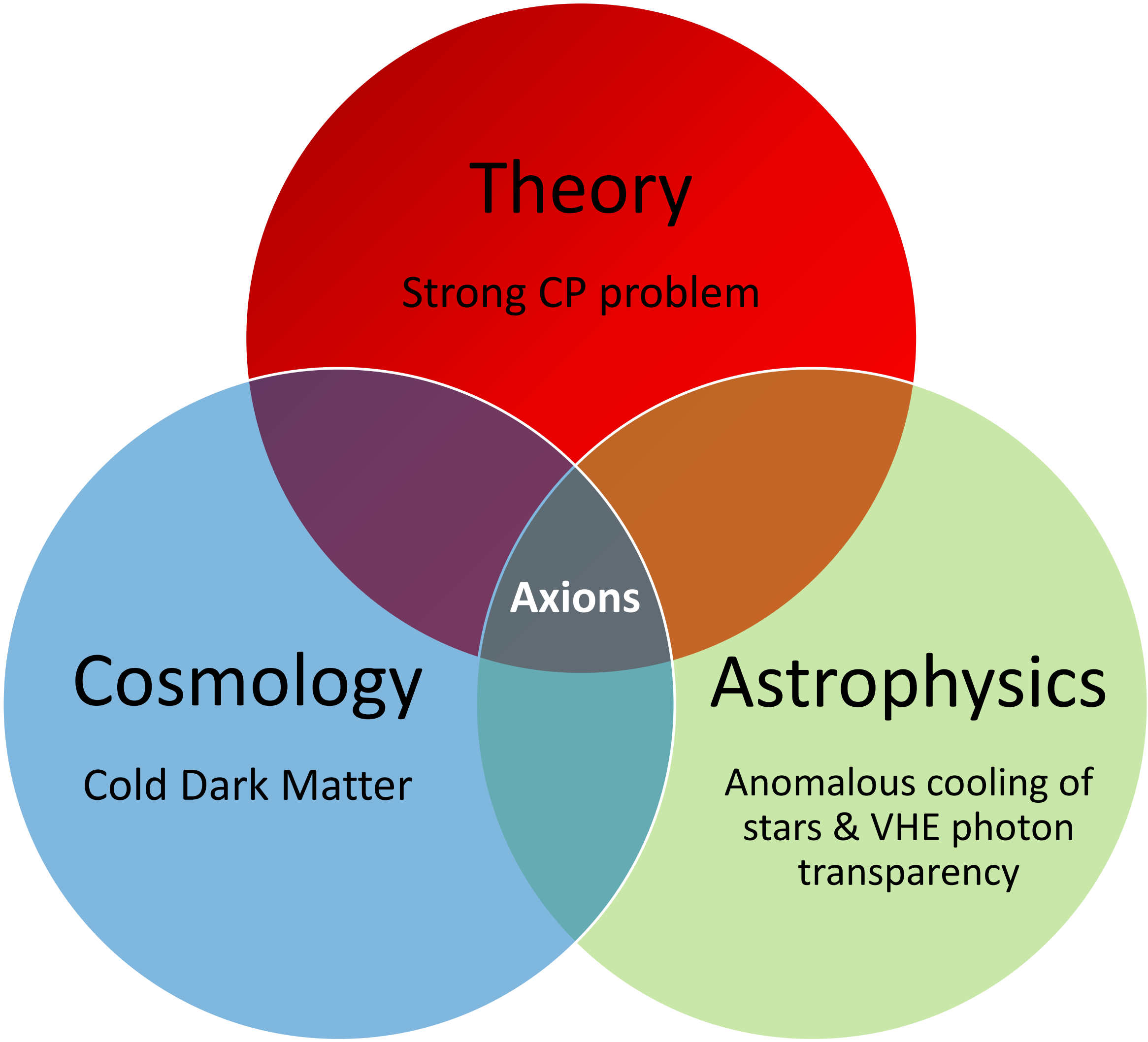
Searches for Axions and Axion-Like Particles (ALPs)

Julia K. Vogel (TU Dortmund)

ErUM-Pro Strategy Workshop

Special Thanks for input and comments:
Klaus Desch, Erika Garutti, Dieter Horns, Axel Lindner, Bela Majorovits, Marios Maroudas, Alexander Schmidt and others

Why Axions?

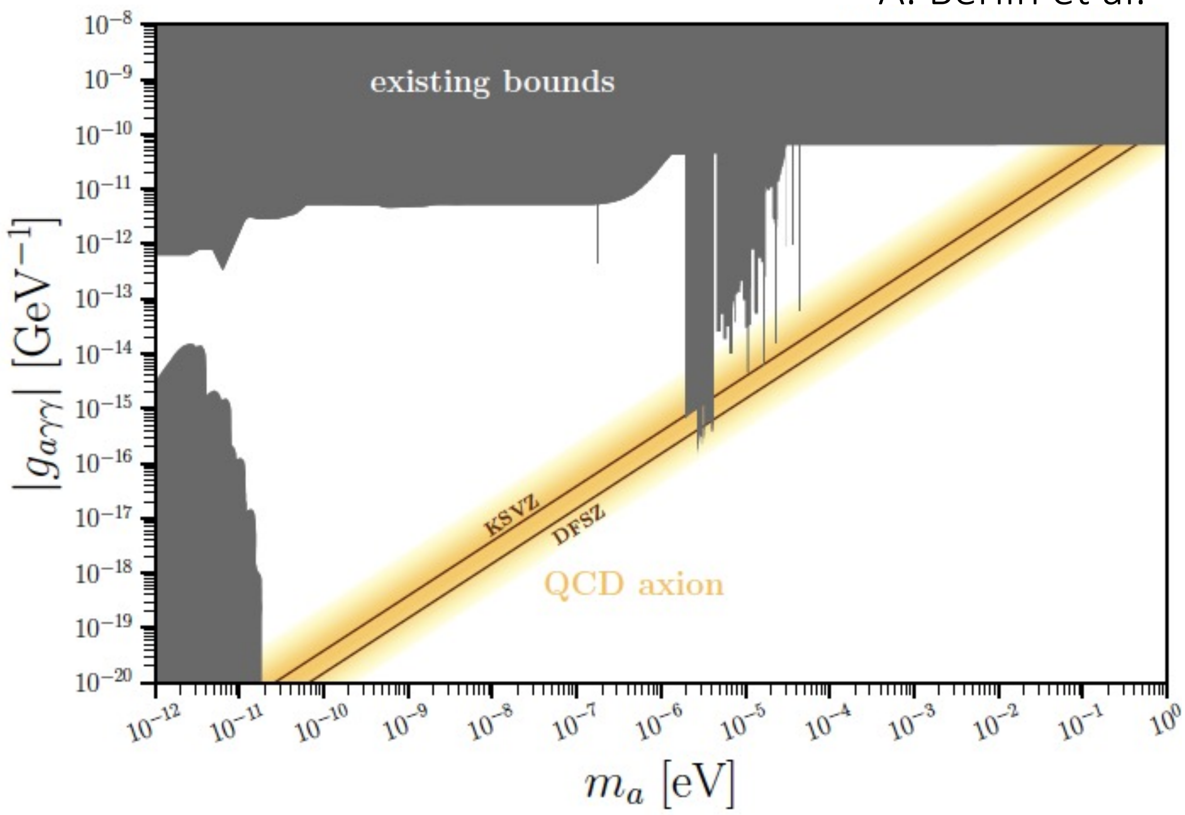


CP =Charge-Parity
VHE= Very high energy

Solving the strong CP problem: the QCD Axion

- **KSVZ**: axions couple to BSM quarks only (hadronic axions)
- **DFSZ**: axions couple to fermions (non-hadronic axions)

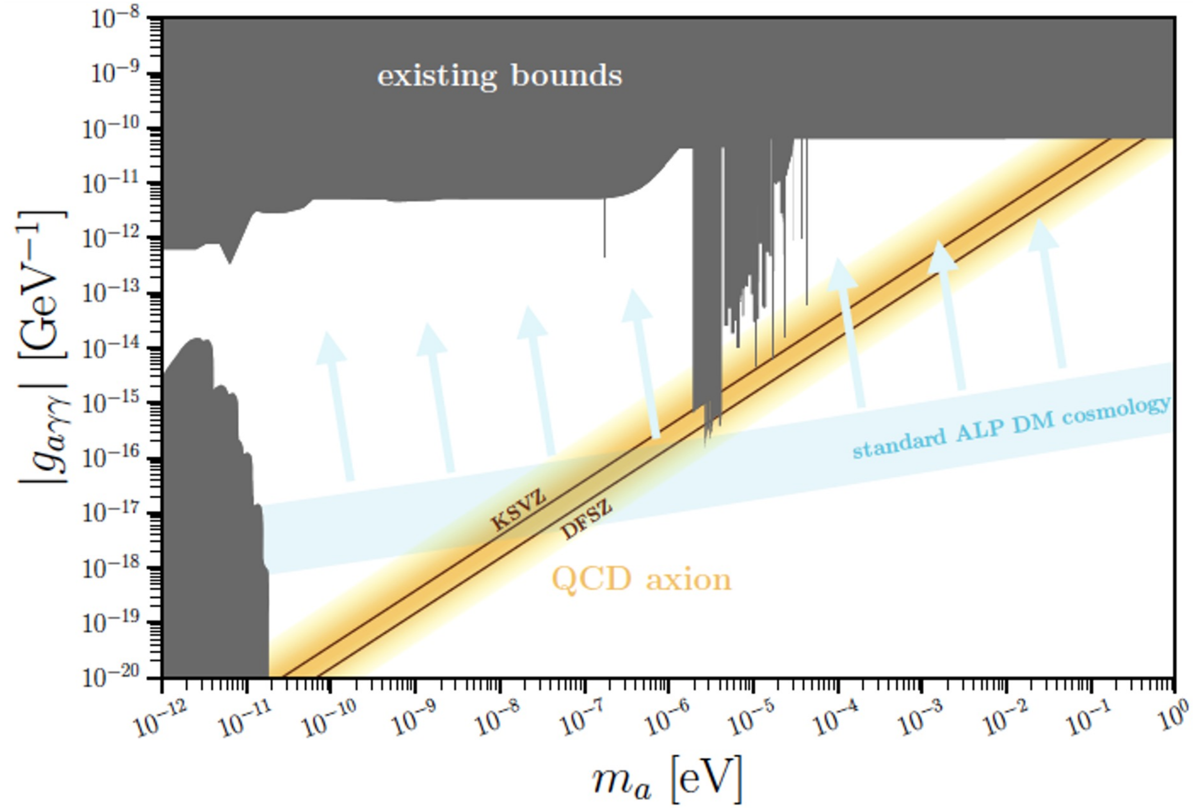
A. Berlin et al.



Going beyond QCD: Axion-like Particles (ALPs)

- Similar particles are produced in many higher order theories, e.g. string theory
- DM candidates, but not necessarily solving strong CP problem
- Out of convenience use “axions” to refer to QCD axions and ALPs
- Can often search for axion-like particles (ALPs) in same experiments as axions

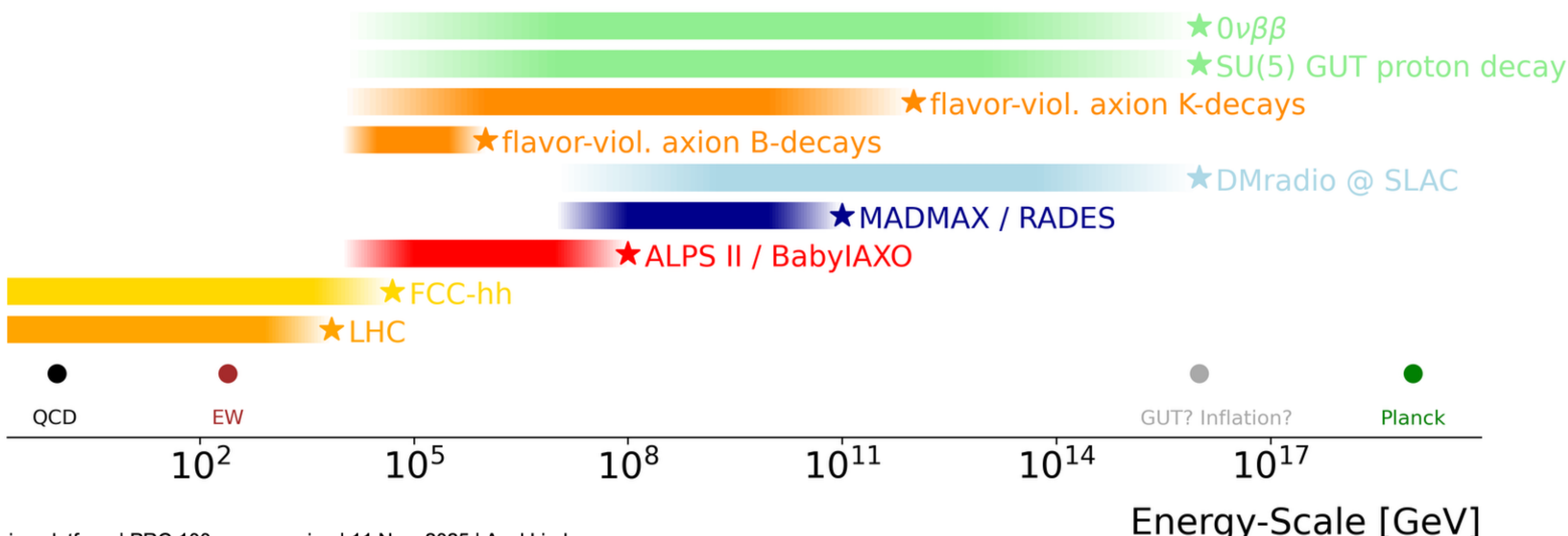
A. Berlin et al.



Model-independent and model-dependent BSM searches

Model-dependent approaches for highest energies

- (Nearly) "model-independent" axion searches.
- Assuming axion dark matter (very lightweight dark matter).
- Assuming flavor-violating axions. (https://arxiv.org/abs/1911.05018/, https://arxiv.org/abs/2503.22256)
- Examples for other approaches. (PDG, https://arxiv.org/pdf/1806.02780)



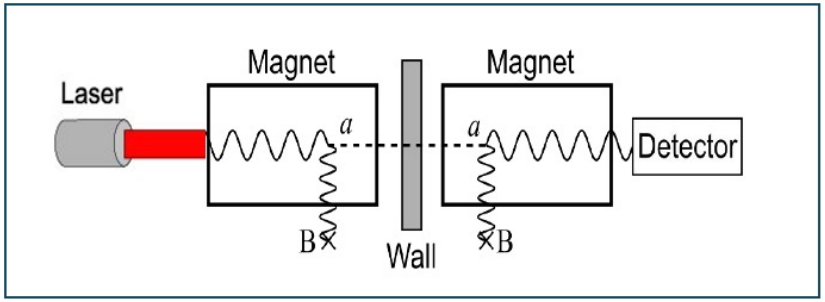
Axion platform | PRC 100 open session | 11 Nov. 2025 | Axel Lindner

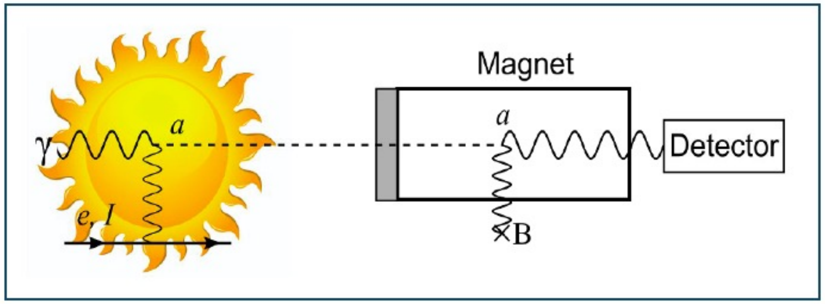
Axel Lindner@ Open Session of DESY PRC Nov 2025

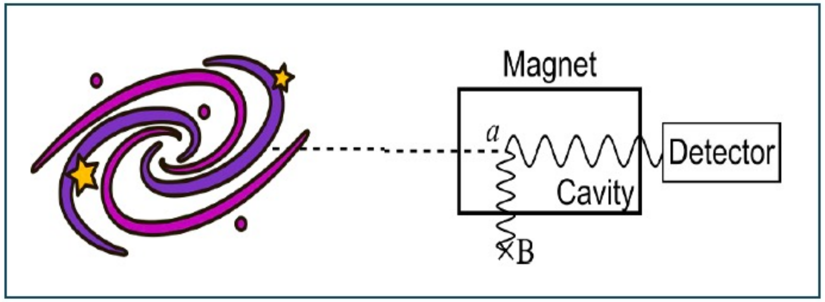
Detection of Axions

- Pure Laboratory Searches/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)

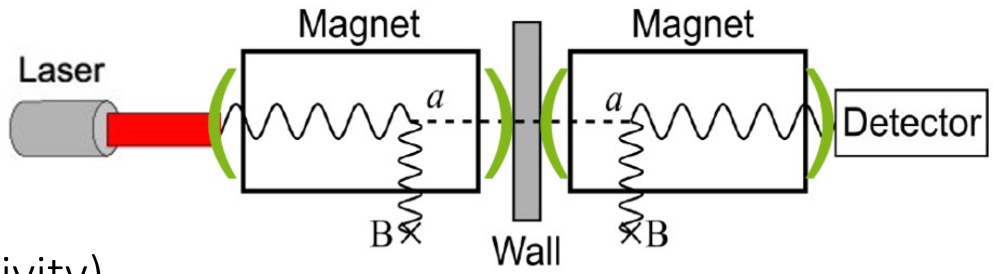
+ Novel, emerging ideas





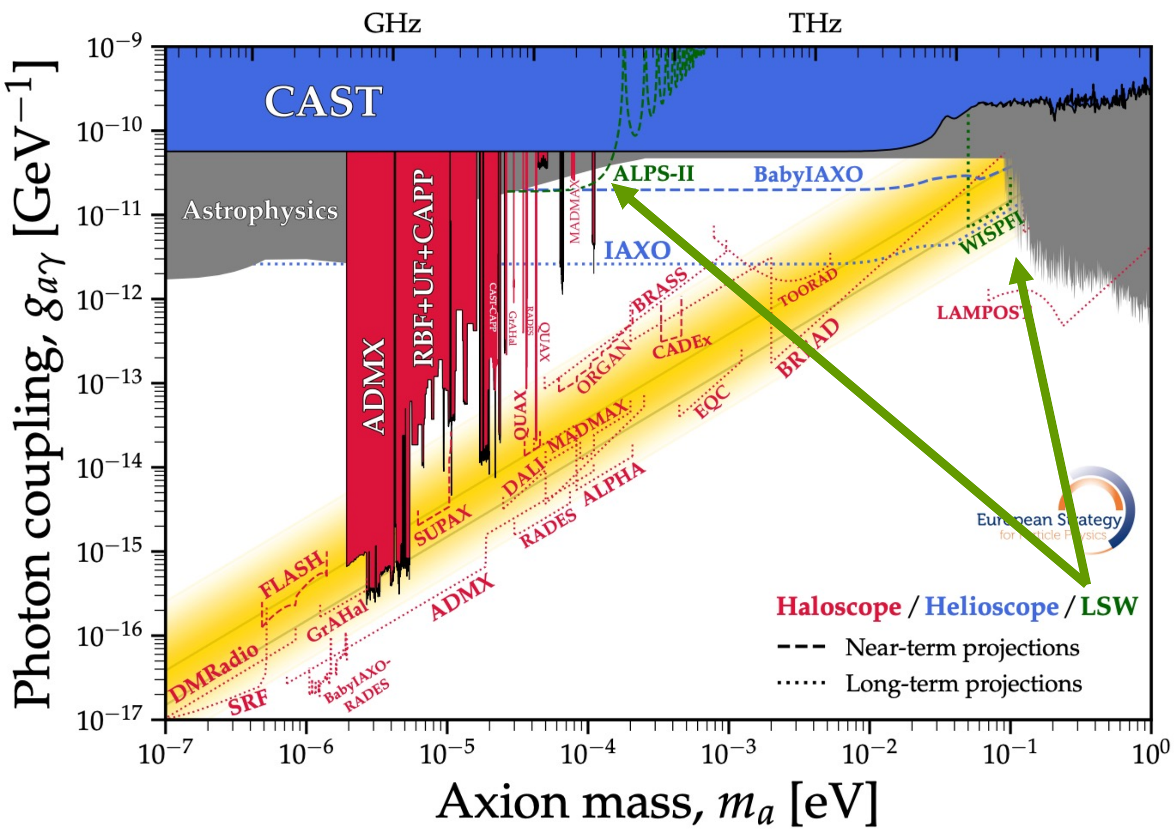


Detection of Axions I Lab Experiments (no DM requirement)



- Setups fully controlled: produce axions, detect axions
- Running experiments/under construction: ALPS II (on the way to full design sensitivity)
  - Expected to explore untested regions
- Newly proposed laboratory variation of LSW (meV-100 meV): WISPFI (fiber interferometer, prototype stage) and WINTER (WISP Interferometer, prototype table-top version under construction)
- Other couplings can be searched for in lab as well, e.g.: CASPEr (a-N)
- Longer-term: e.g. HyperLSW (in case of a haloscope detection)

Detection of Axions I   Lab Experiments (no DM requirement)



ALPS II (Future Plans)

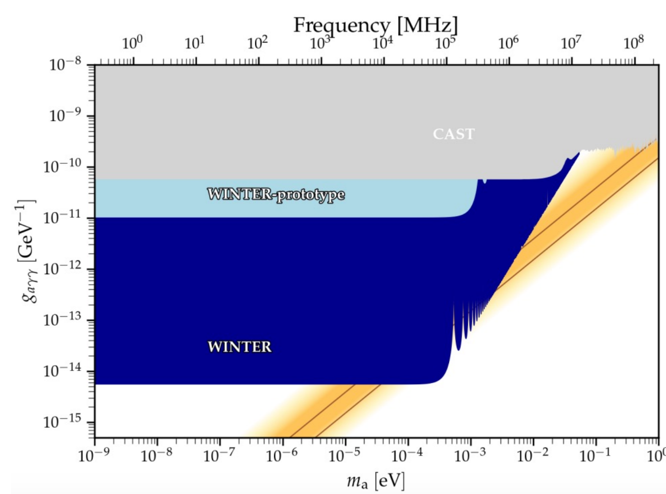
- Fully exploit new boson searches at ALPS II.
- First-time measurement of VMB (arXiv:2510.14064)
- High-frequency gravitational wave searches, interferometric DM searches

+ international collaborators

Future Plans for WISPFI and WINTER

Move from prototypes to full experiments

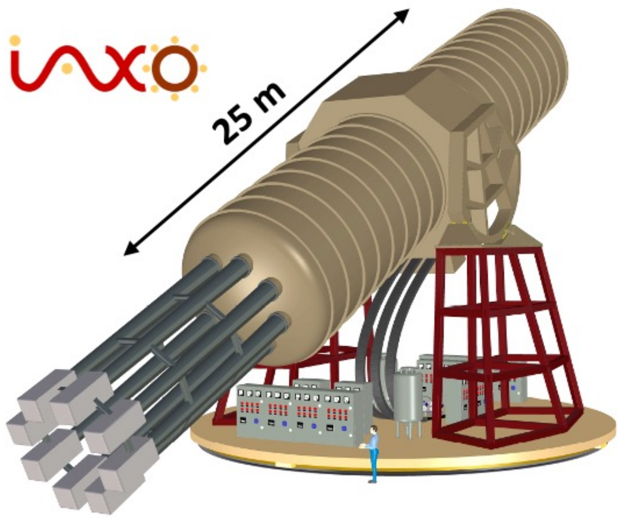
(https://agenda.infn.it/event/46273/contributions/269303, arXiv:2509.16725)

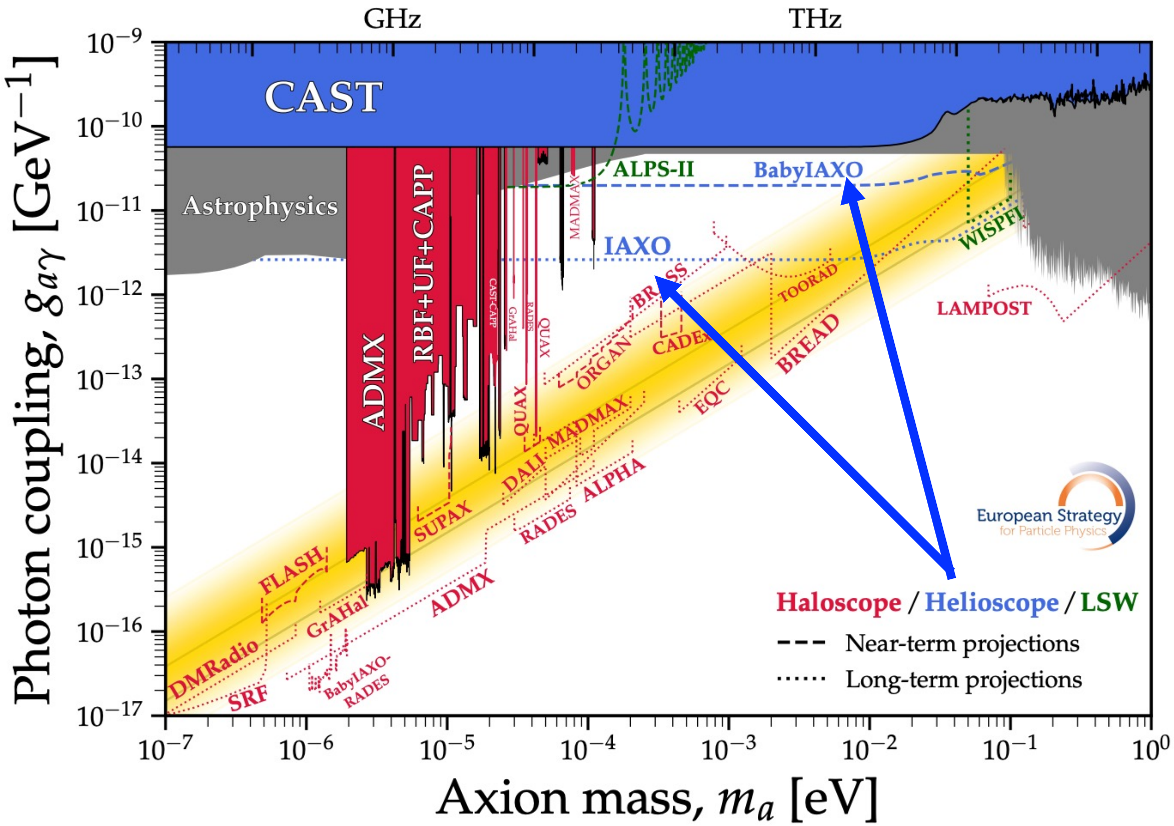


Detection of Axions II

Helioscopes (no DM requirement)

- 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+other couplings+ test astrophysical hints+dark photons+…
- BabyIAXO@DESY in construction phase
- Includes haloscope setup for DM searches and high-frequency GW studies (BabyIAXO-RADES)





BabyIAXO (Future Plans)

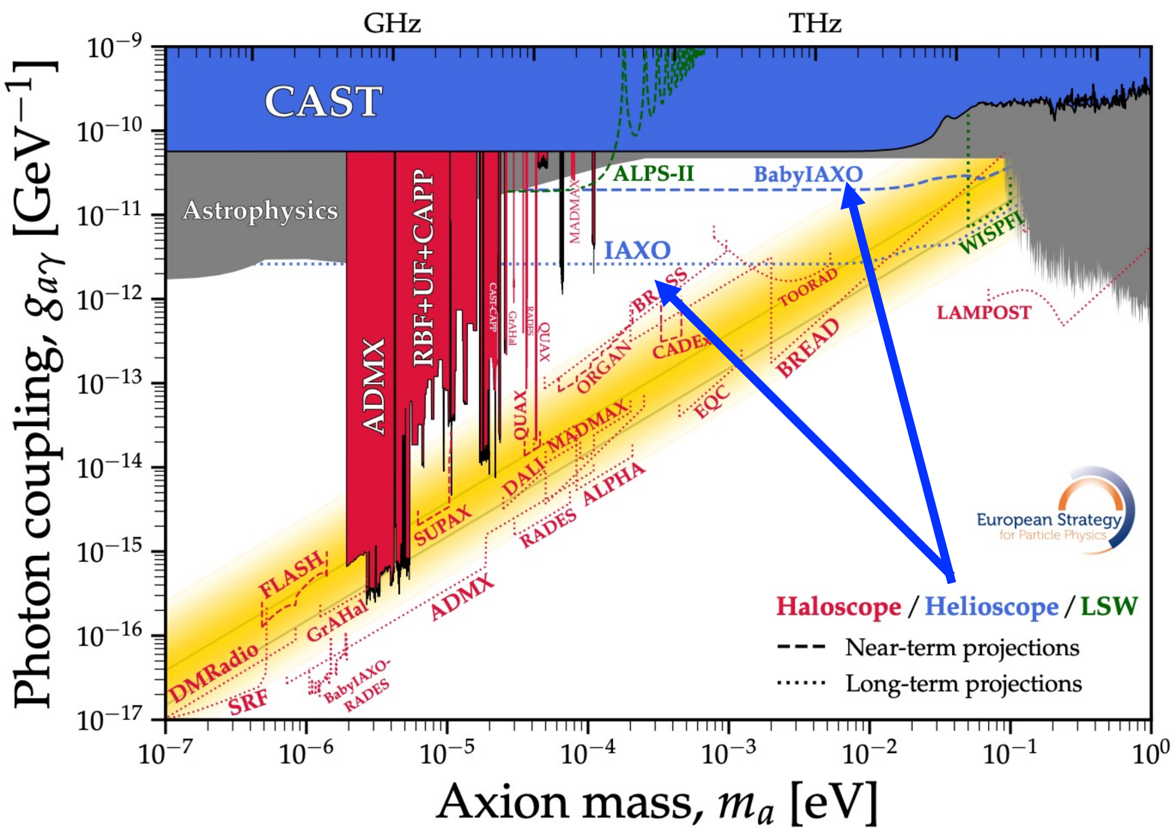
- "Dry run" (structure and drive system +instruments without magnet (end of 2027)
- Magnet delivery to DESY (early 2030)
- Start of first science run in 2031

IAXO will be beyond the 2027-2030 time frame

+ international collaborators

Detection of Axions II

Helioscopes (no DM requirement)



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Other Helioscope-Approaches

- Using satellite missions to observe Sun and other stars (e.g. NuSTAR)

Phys. Rev. Lett. 135, 141001

dortmund university

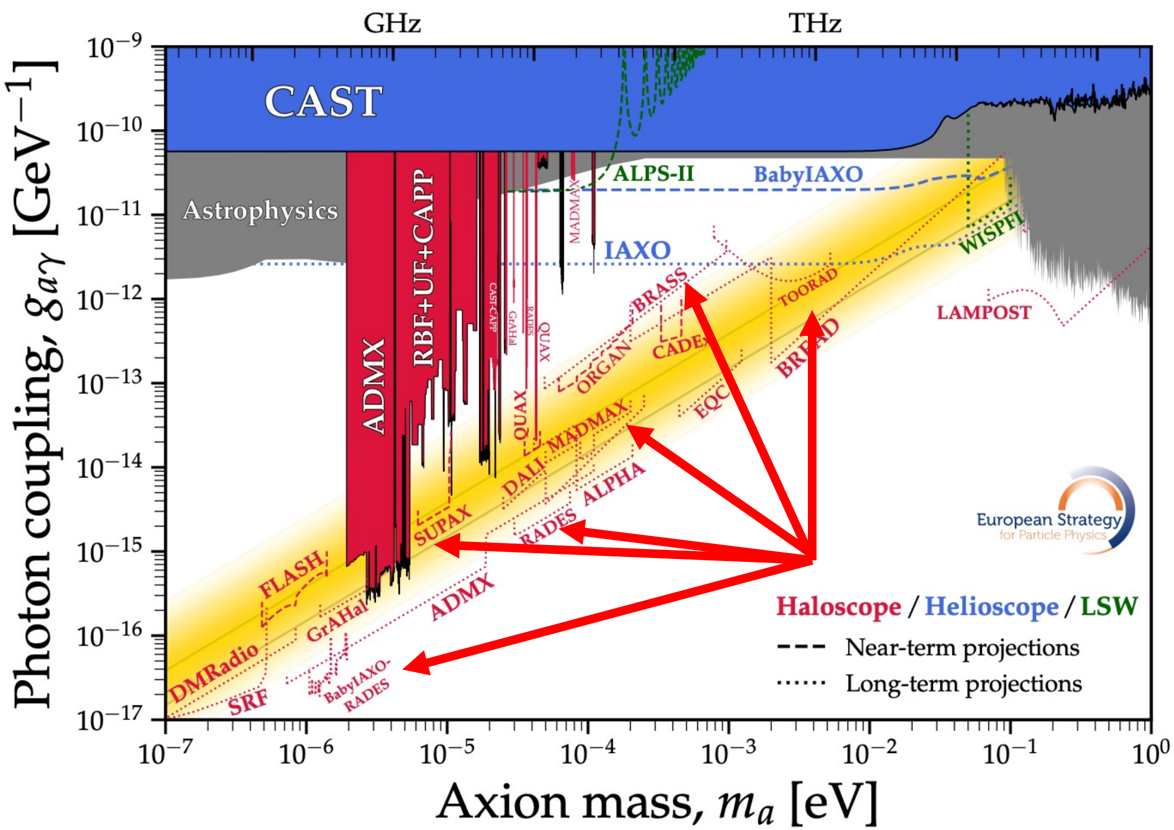
+ international collaborators ...

Detection of Axions III

- **Resonant cavity haloscopes**
  - Pioneered by ADMX, running and probing QCD band: ADMX, HAYSTAC, CAPP, QUAX
  - New setup being developed: RADES, SUPAX, GrAHal, CADEX, ORGAN, TASEH,PXS…
- **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)
  - ADAMOS (Axion Daily Modulation Searches), WISPCAV
- **Expansion to lower masses**
  - BabyIAXO-RADES, FLASH
  - Lumped element detectors (WISPLC, DMRadio, …)

+ others that I may have unintentionally forgotten…

Detection of Axions III — Haloscopes (DM requirement)



Future Plans MADMAX

- Continuation of prototype tests with CERN MORPURGO magnet
- Work towards quantum sensing of single photons (~100 GHz).
- Interim magnet could arrive at DESY's cryoplatform in 2030.

RADES/BIAXO-RADES

- Continue to develop Rades at HF and LF
- Data acquisition with 2nd LF prototype at CERN North Area (LoI SPSC)

Future Plans SUPAX

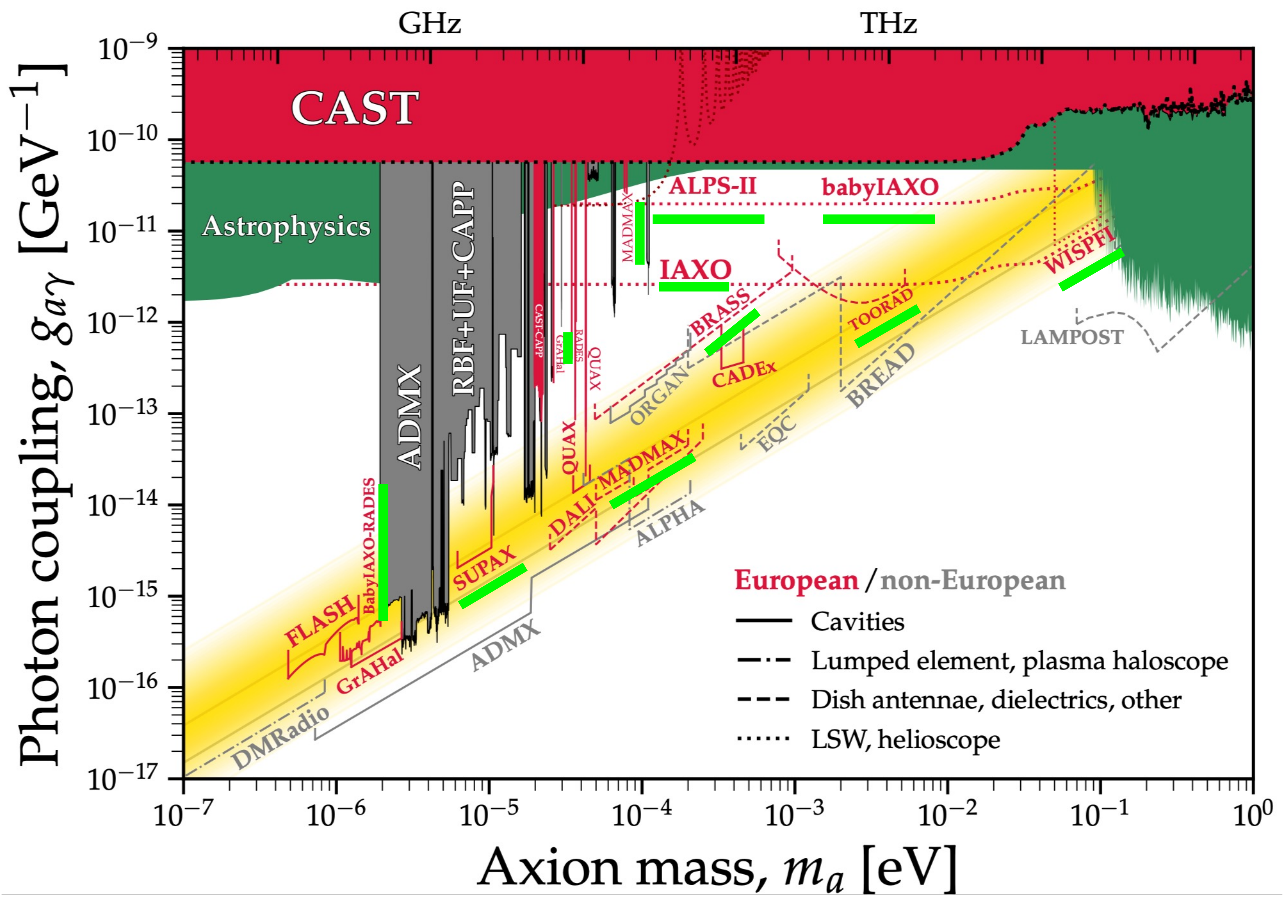
- Construct and operate the full SUPAX experiment

Future plans BRASS/ADAMOS/WISPCAV/WISPLC

- Various stages (simulation, prototype,...)

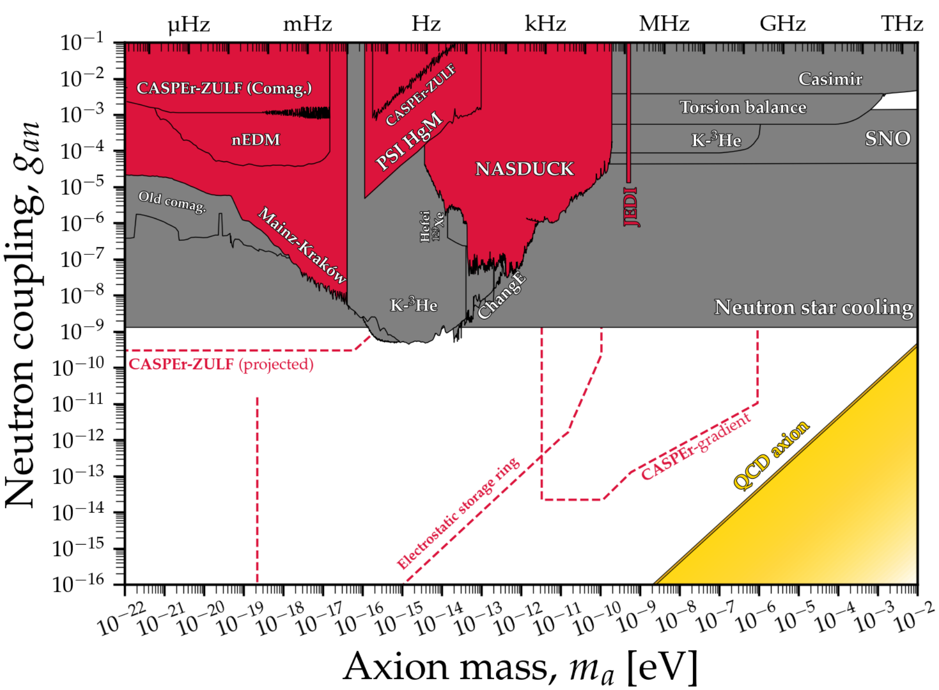
The coming decade and beyond

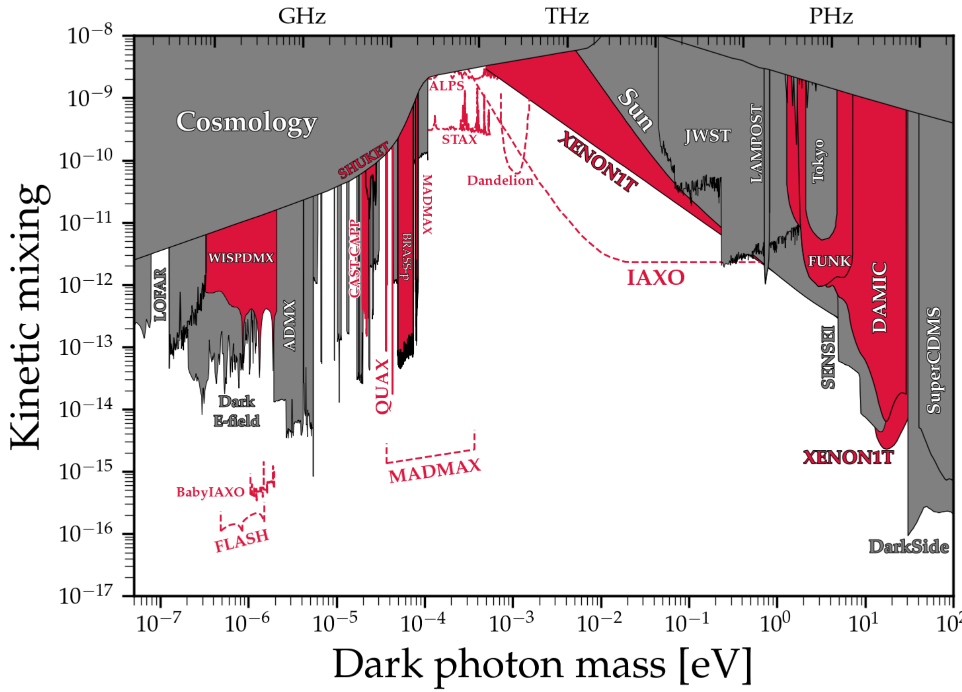
- Super exciting: Large parts of QCD band can be studied in coming decade(s)
- Significant German leadership and/or involvement
- Complementary experimental approaches crucial



- Mixture of large-scale and smaller-scale experiments
- ALP/dark photon/... searches in parallel

Beyond axion-photon & dark photon





- Other axion couplings interesting
- Potentially more difficult to detect
- Tendency to focus first on axion-photon coupling

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

Funding and near-term goals

- Experiments moving forward via Excellence Initiative, large infrastructure proposals, MP institute funding and international partners…
- German axion community is moving closer together (e.g. first joint RADES-MADMAX collaboration meeting)

→ Crucial to further grow closer

→ Maximize potential to use common infrastructures

→ Optimization of knowledge transfer

DESY's axion platform as new center for axions in Germany, large community interest to work together

Conclusions

- Axion/ALP physics case
  - Multifaceted, but also “simple”: one axion could clean up multiple problems
  - One of the best BSM scenario at reach of experiments in coming decade(s)

- Experiments in Germany
  - World-leading, very diverse in both approach and size, growing and growing together
  - Cutting-edge technologies being developed
  - Huge excitement amongst young (and not-so-young) physicists

We need to:

- (Finish) securing construction and especially operation phases.
- Secure participation of German university groups
- Grow into even tighter community
- Find the axion/ALP

Thank you!

Questions?

Technology & cross-cutting topics

Technology development

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

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

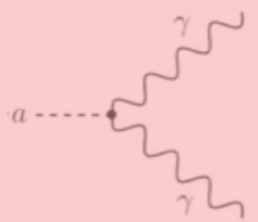
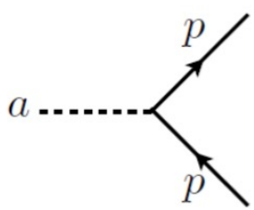
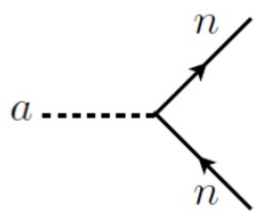
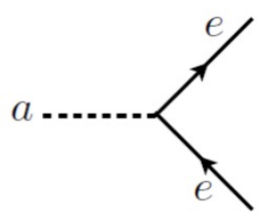
Cross-cutting topics

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

Axions

Coupling of axions to photons exploited by many experiments

- Relatively "simple" and generic for all axion models
- Model-dependencies exist however

2 photon	proton	neutron	electron
$\frac{\alpha C_{a\gamma}}{2\pi}\frac{a}{f_a}\frac{F_{\mu\nu}\tilde{F}^{\mu\nu}}{4}$ +	$C_{ap}m_p\frac{a}{f_a}[i\bar{p}\gamma_5 p]$ +	$C_{an}m_n\frac{a}{f_a}[i\bar{n}\gamma_5 n]$ +	$C_{ae}m_e\frac{a}{f_a}[i\bar{e}\gamma_5 e]$ +
			

$$g_{a\gamma} = \frac{C_{a\gamma}\alpha}{2\pi f_a} \qquad g_{ap} = C_{ap}\frac{m_p}{f_a} \qquad g_{ap} = C_{an}\frac{m_n}{f_a} \qquad g_{ap} = C_{ae}\frac{m_e}{f_a}$$

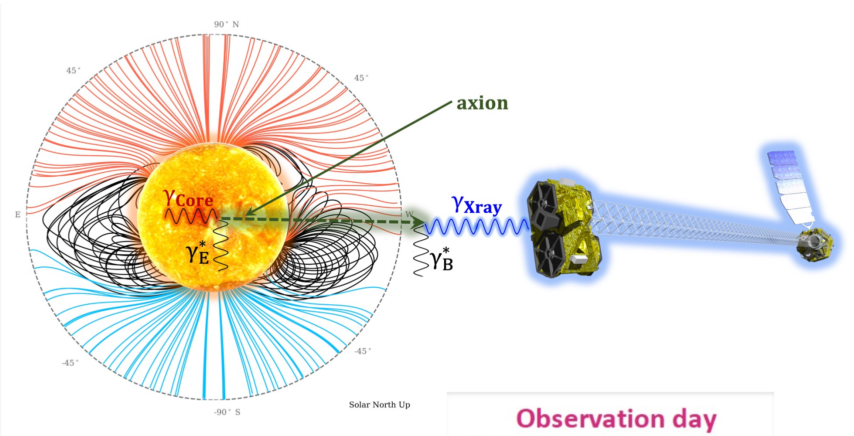
$$\mathcal{L}_{a\gamma} = -\frac{1}{4}g_{a\gamma}F_{\mu\nu}\tilde{F}^{\mu\nu}a = g_{a\gamma}\vec{E}\cdot\vec{B}a,$$

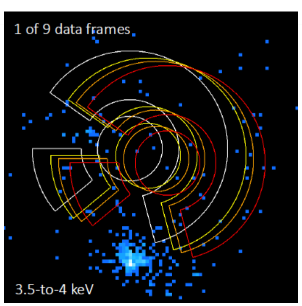
Helioscopes (no DM requirement)

- AXION HELIOSCOPES: laboratory axion searches looking for solar axions

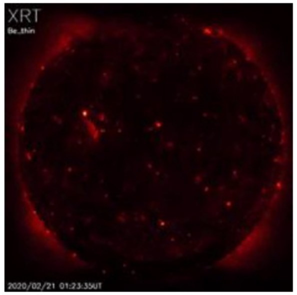
Novel Approach using satellites

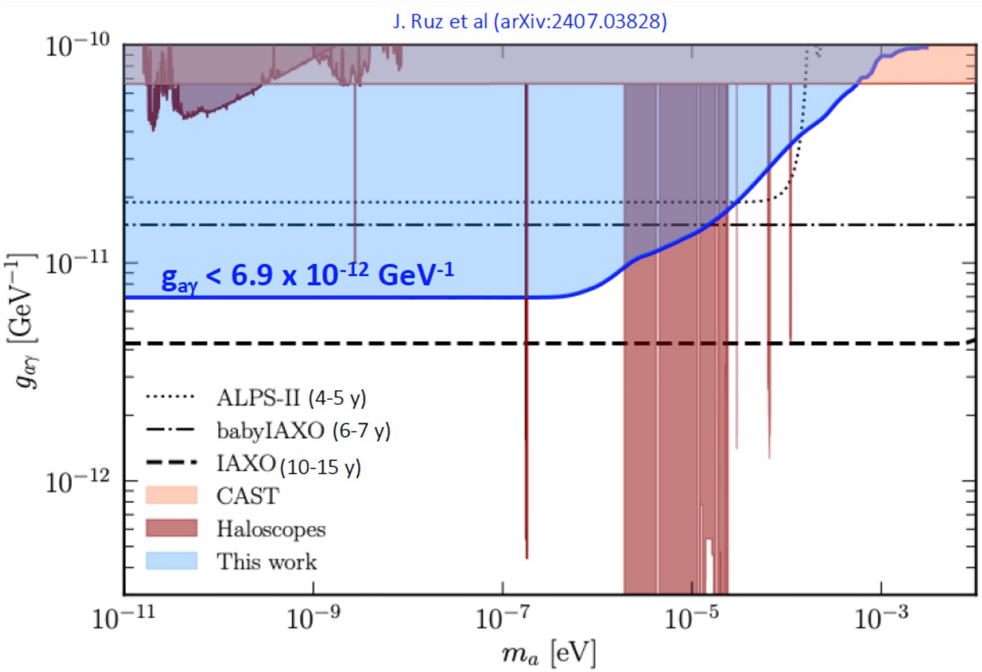
Concept: Utilize outer solar magnetic field for reconversion of axions into x-ray photons and use X-ray astronomy mission to detect them





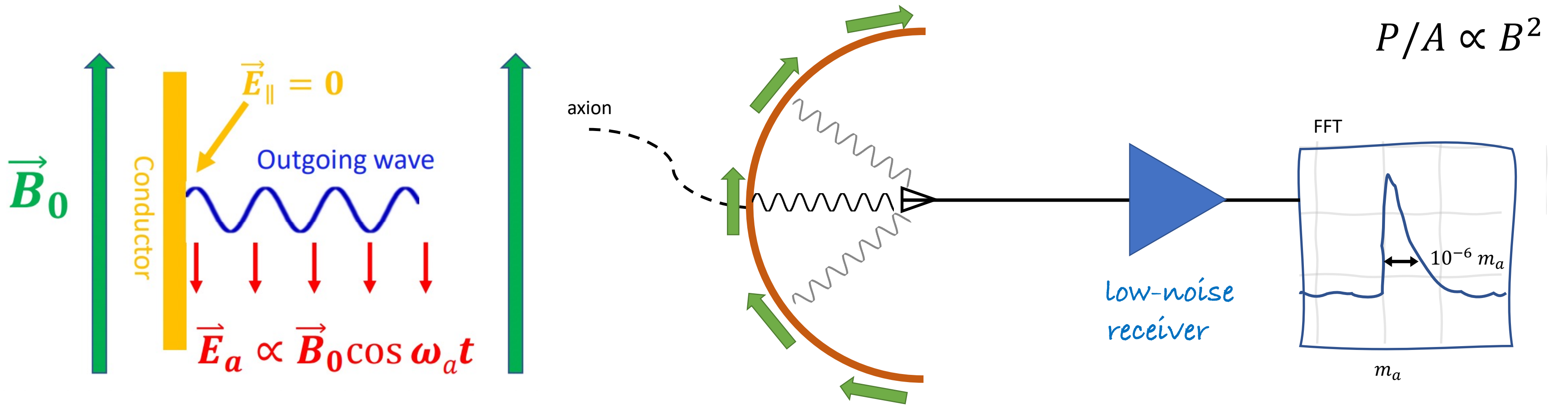
Observation day





Horns *et al* JCAP04(2013)016

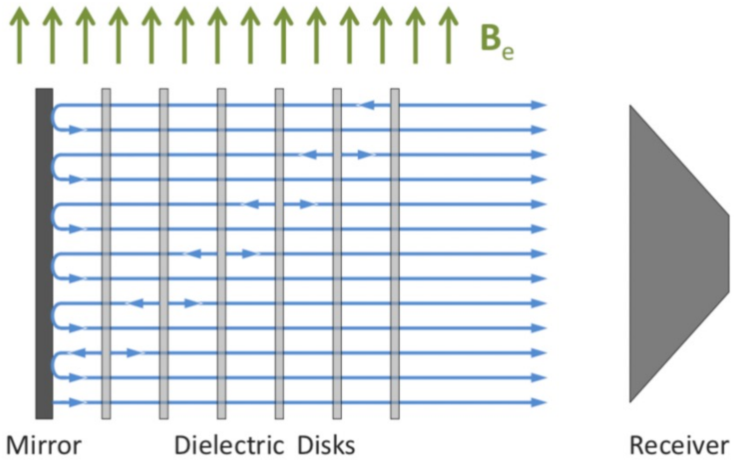
▶ HALOSCOPES: DISH ANTENNAS

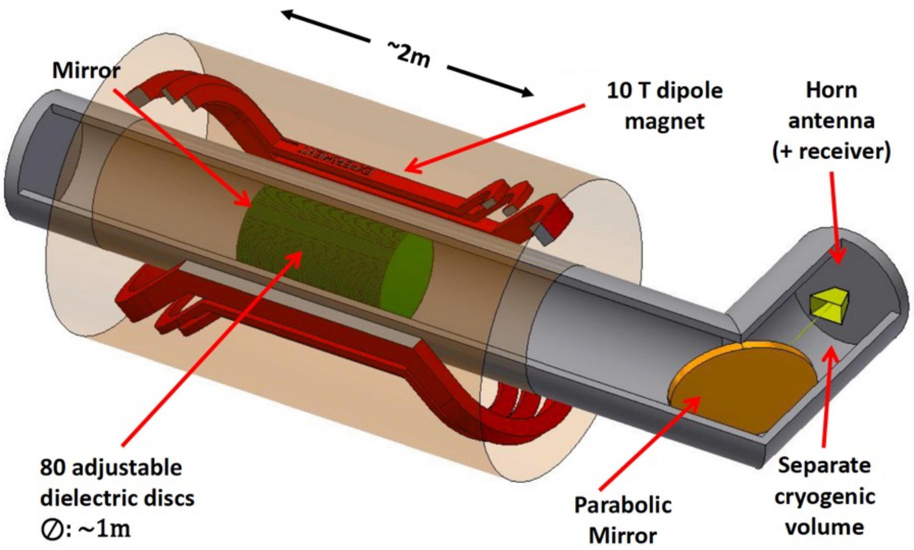


Concept: Axion induced radiation from a magnetized metal slab

- DM axions interact with a static magnetic field
  → producing oscillating parallel E-field.
  Conducting surface in this field emits plane wave ⊥ surface with $\upsilon \propto m_a$
- Radiated power is low, however, no tuning required!

▸ HALOSCOPES: DISH ANTENNAS

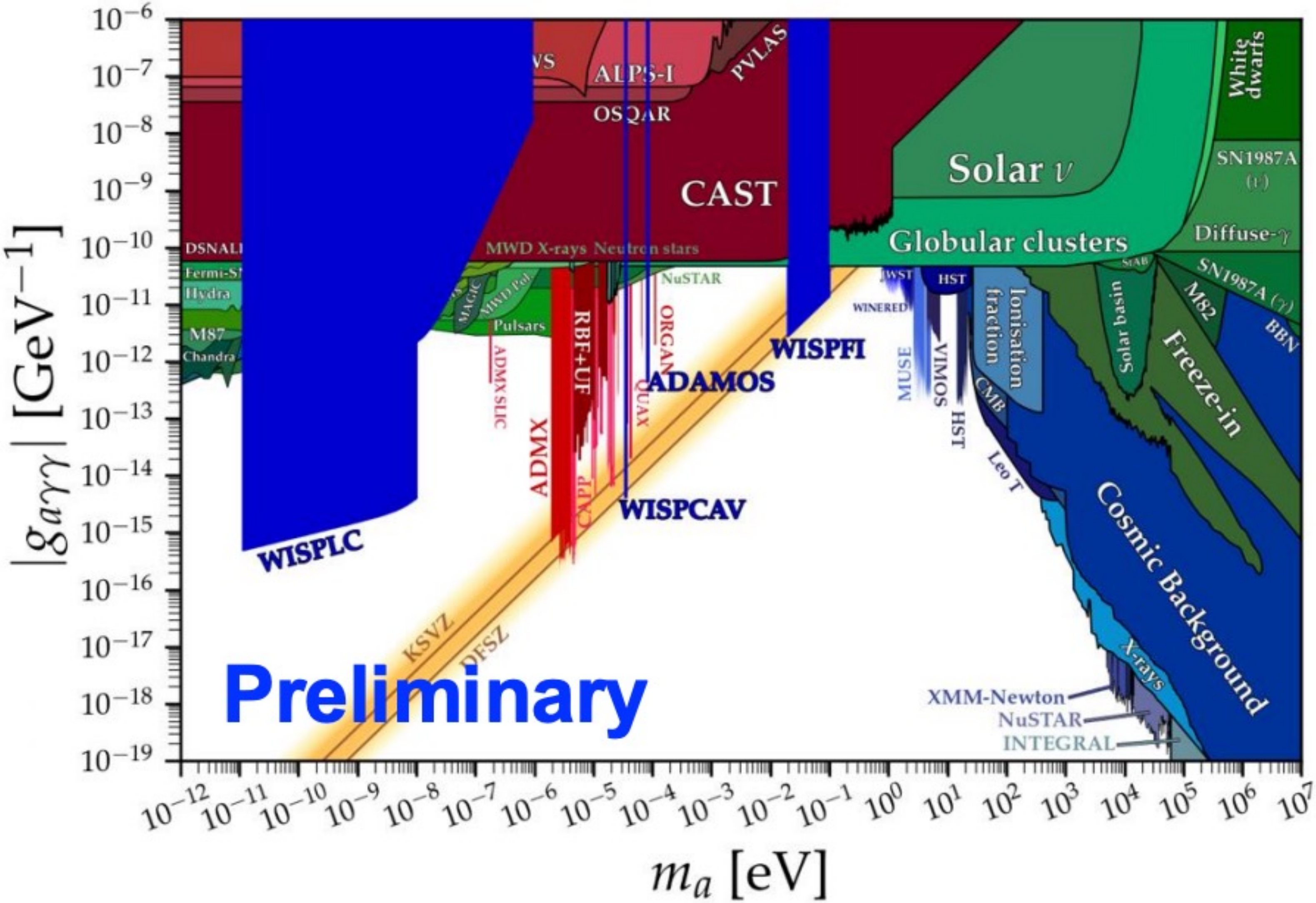




Enhanced Concept: Boosted dish antenna aka open dielectric resonator

- Stack of dielectric plates as booster inside a magnetic field
- Tuned to the radiofrequencies (m_a around 100 µeV)
- Can enhance measured power by several 10^4, but tradeoff bandwidth/"boost factor"

ADAMOS/WISPCAV/WISPFI/WISPLC



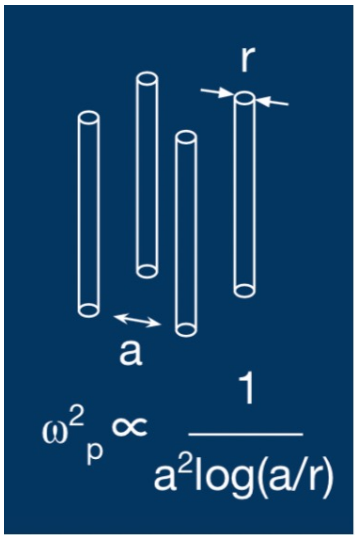
https://agenda.infn.it/event/46273/contributions/269303

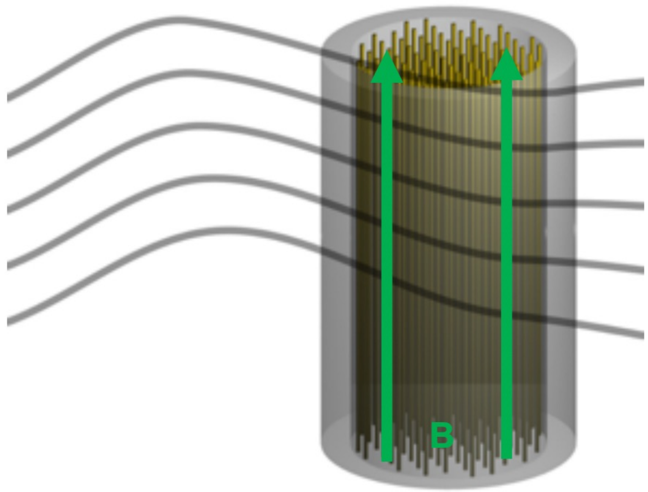
Detection of Axions III

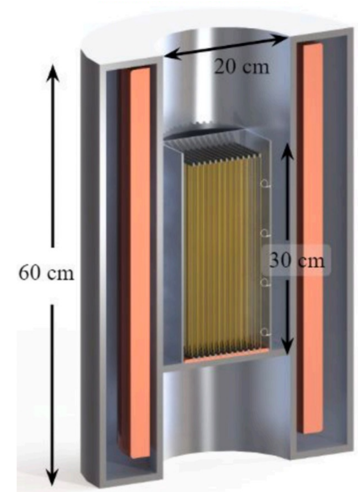
Haloscopes (DM requirement)

- HALOSCOPES: PLASMA HALOSCOPES

ALPHA Pathfinder





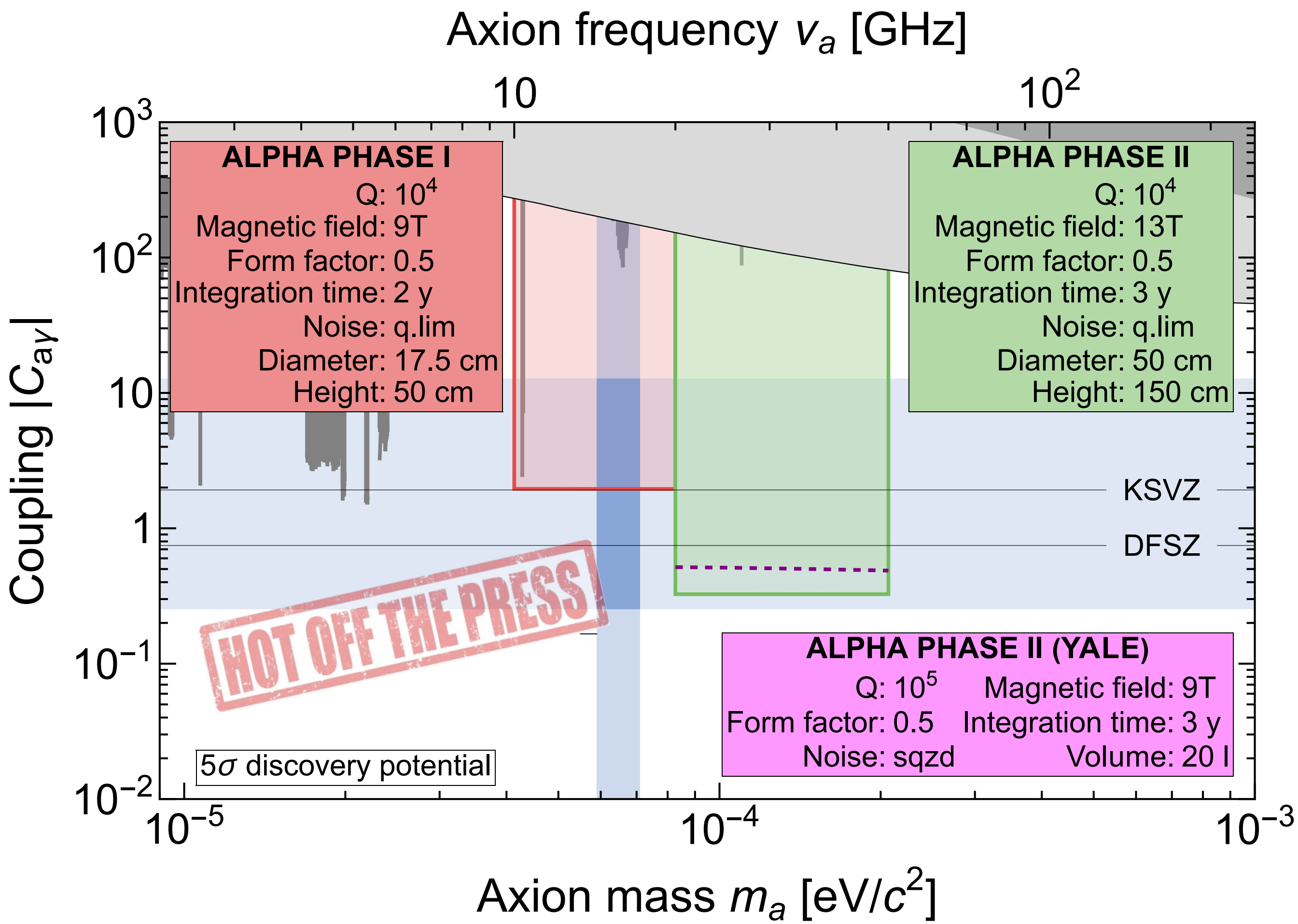


Concept: Oscillating DM axions induce plasmon excitations in magnetized plasma

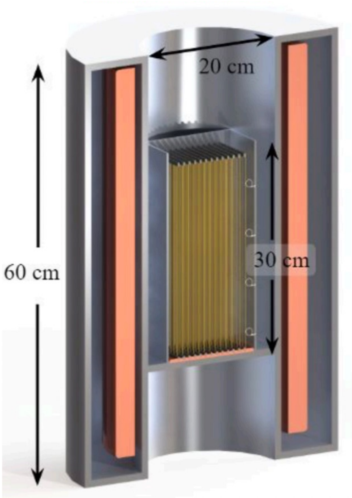
- Resonant enhancement when plasma frequency matches axion mass:
- Can create plasma with tunable plasma frequency in GHz range using wire metamaterial (wire array with variable interwire spacing)
- Tuning then possible via geometry, limited by losses
- ALPHA (@Yale & ORNL)

Lawson et al., PRL 123 (2019) 141802

Haloscopes (DM requirement)



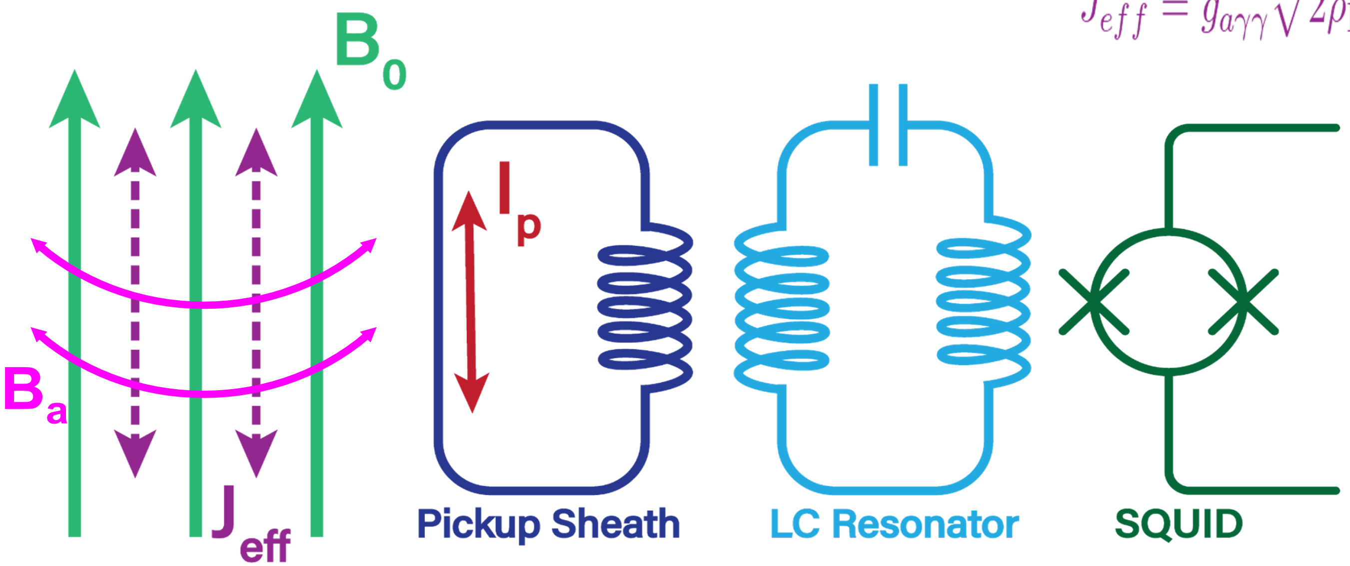
ALPHA Pathfinder



Credit:
K. Van Bibber and the ALPHA collaboration

▶ HALOSCOPES: LUMPED-ELEMENT DETECTORS

$\vec{J}_{eff} = g_{a\gamma\gamma}\sqrt{2\rho_{\mathrm{DM}}}\cos(m_a t)\vec{\mathrm{B}}_0$



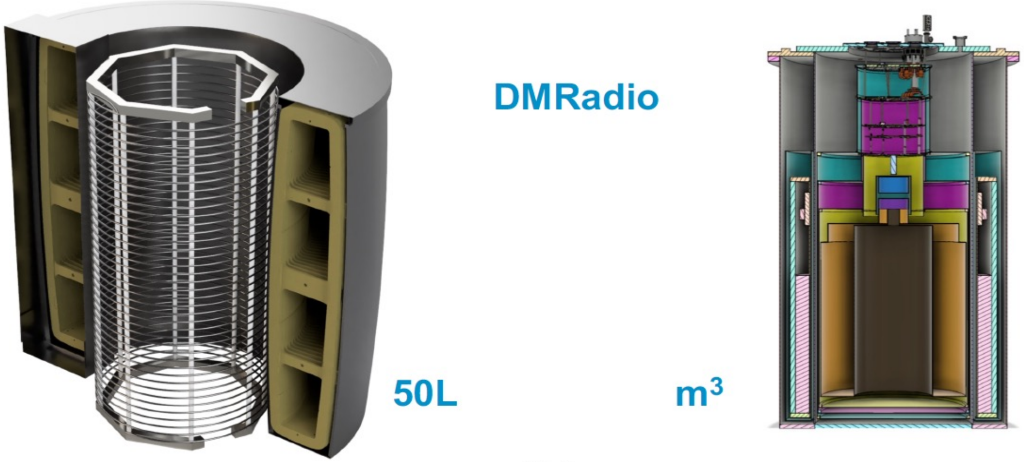
Concept: Axion generates oscillating effective current J_{eff} parallel to B_0 in toroidal or solenoidal magnet

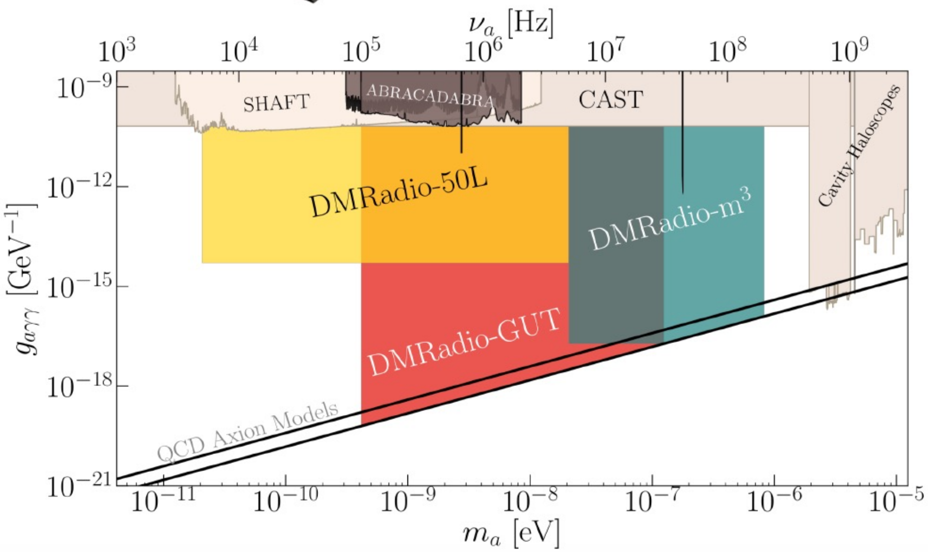
- J_{eff} in turn generates oscillating magnetic flux B_a (azimuthal)
- Can use pickup structure to read this
- Couple LC resonator inductively and use SQUID readout scheme

▶ HALOSCOPES: LUMPED-ELEMENT DETECTORS

Pilot experiments:
ABRACADABRA
ADMX SLIC
SHAFT

Next Generation:
WISPLC
DMRadio
- DMRadio-50L
- DMRadio-m^3
  (improvements in Q, V, B)
- DMRadio-GUT
  (ambitious next-next gen)



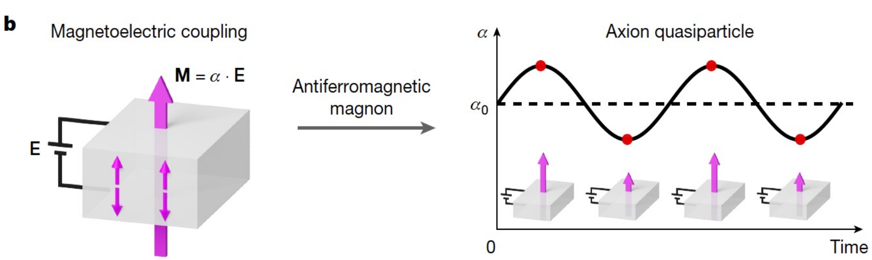


New Haloscopes

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

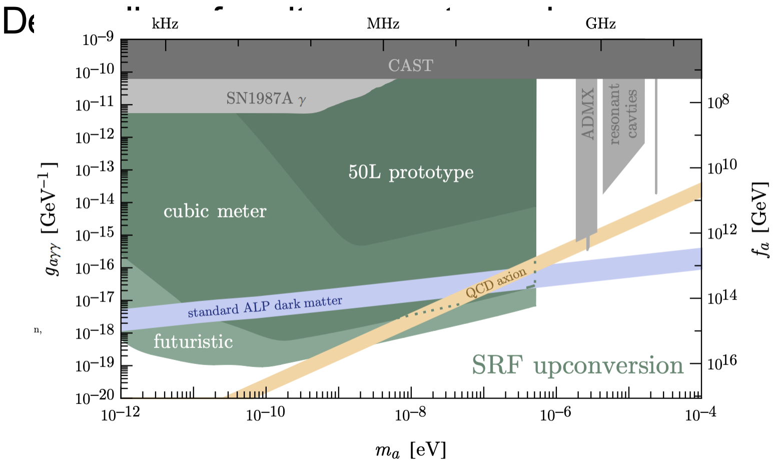


SRF Heterodyne

#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 **$f_0 \pm m_a/2\pi$**, enabling detection independent of cavity size
- De



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.

For reference see https://cajohare.github.io/AxionLimits/)

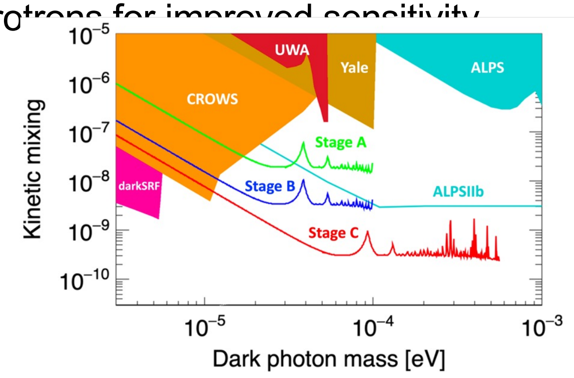
Dark Photon

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.