Exploring the dark universe:
The experimental quest for axions & ALPs

Julia K. Vogel

DPG Spring Meeting 2025

Göttingen, 31.03.– 04.04.2025

Outline

1. Why Axions?
2. Detection of Axions
   - Light-Shining-Through-Wall Searches
   - Helioscopes
   - Haloscopes
   - Other Approaches
3. Conclusions

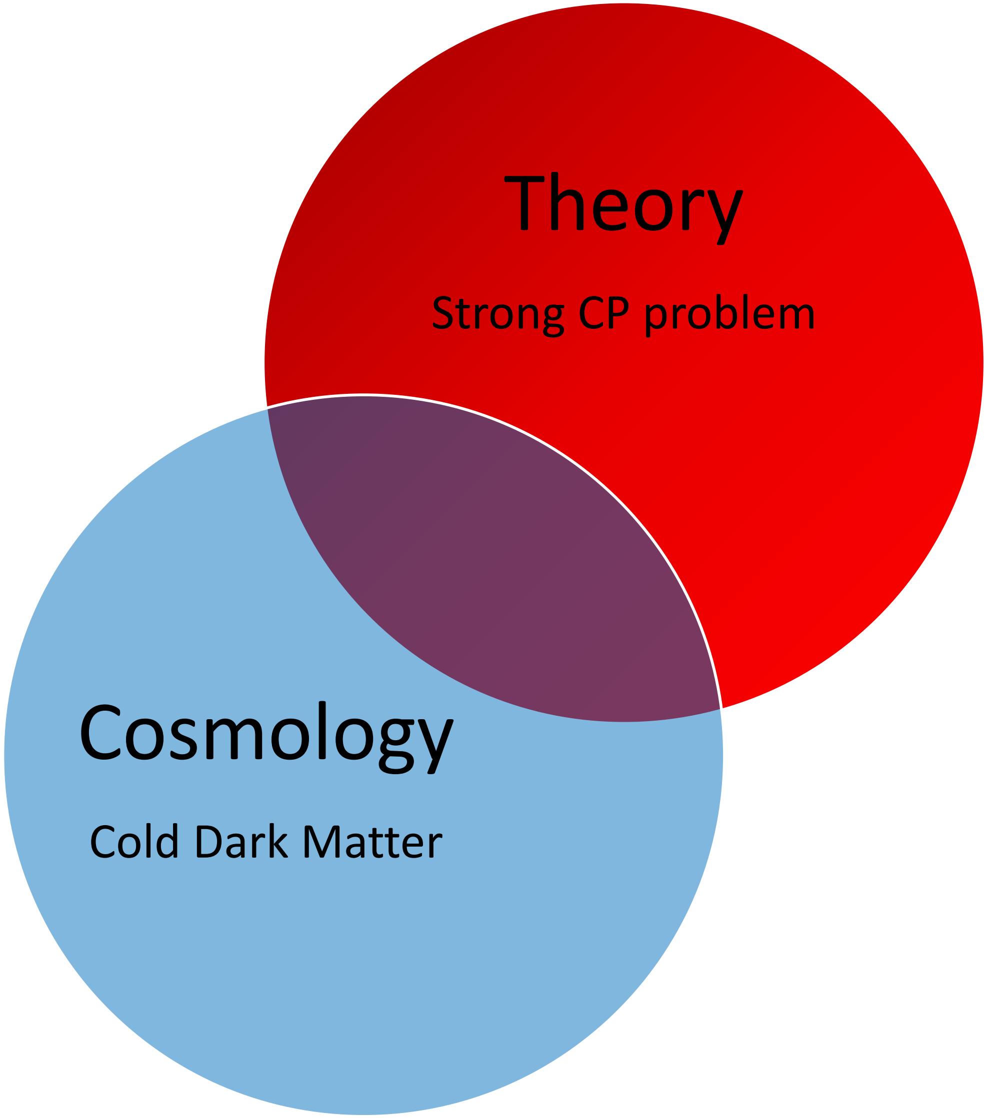
Why Axions?

Theory

Strong CP problem

CP =Charge-Parity

Why Axions?



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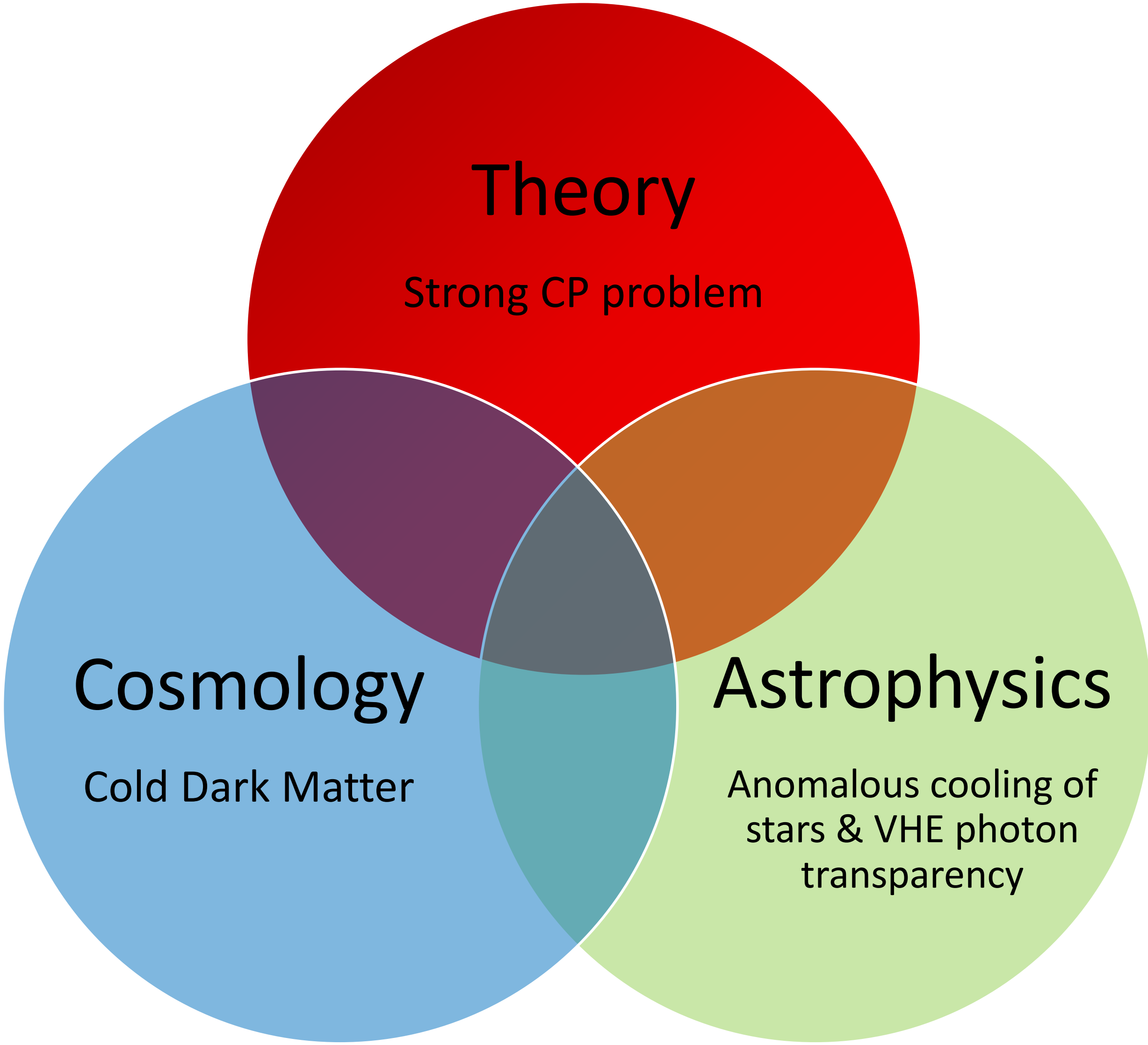
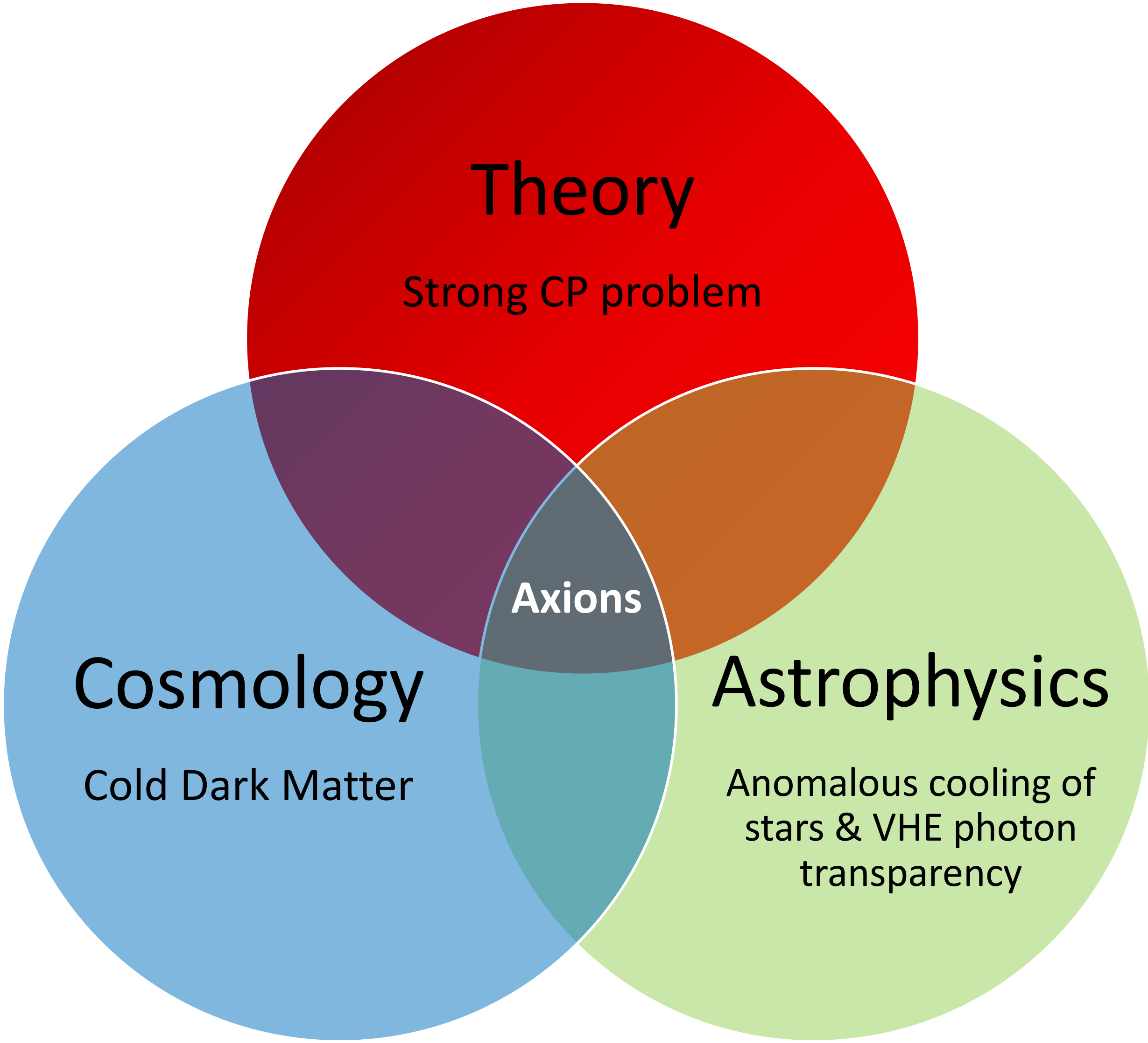


CP =Charge-Parity
VHE= Very high energy

Why Axions?



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Why Axions? The Strong CP Problem

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Pseudo Goldstone-Boson of spontaneous symmetry breaking of PQ at yet unknown scale f_a

Why Axions?

The Strong CP Problem

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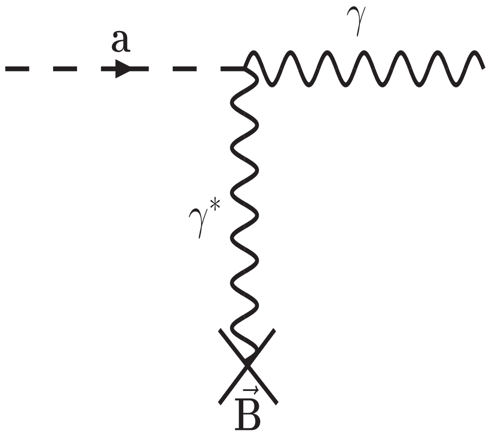
- **Properties of this potential DM candidate**
  - Extremely weakly-coupled fundamental pseudo-scalar
  - Generic coupling to two photons
  - Mass unknown $m_a \propto g_{a\gamma}$,
  - Astrophysics: $g_{a\gamma} < 10^{-10}$ GeV^{-1}



Why Axions? The Strong CP Problem

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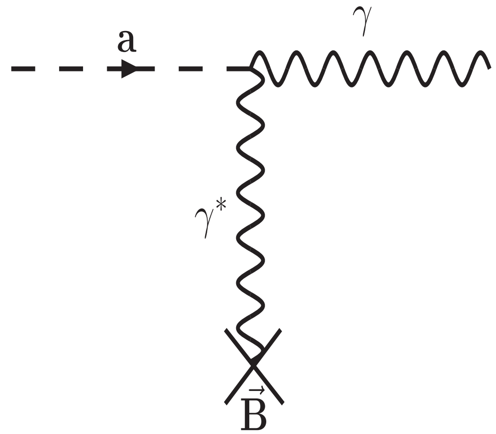

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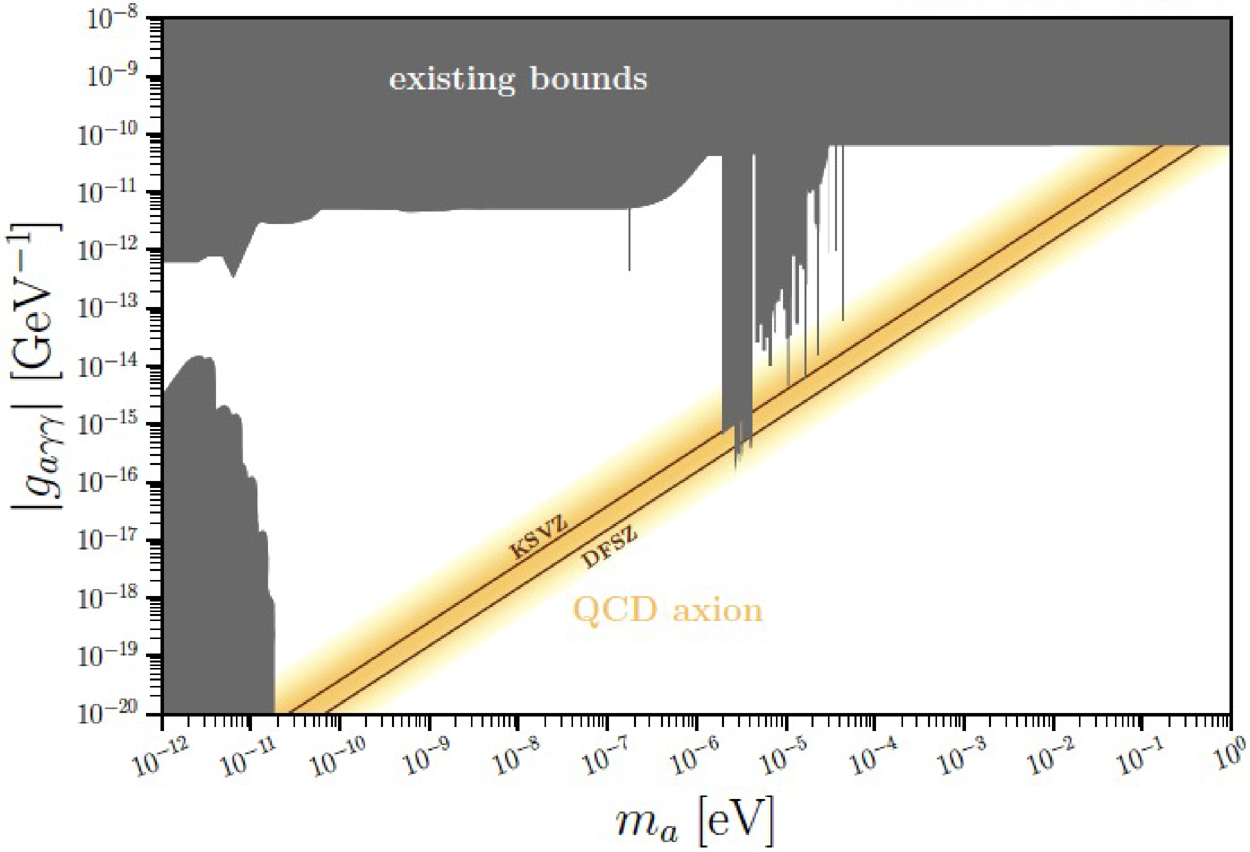
→ Dark matter candidate & solves strong CP

Solving the strong CP problem: the QCD Axion

- **KSVZ**: axions couple to BSM quarks only
- **DFSZ**: axions couple to fermions

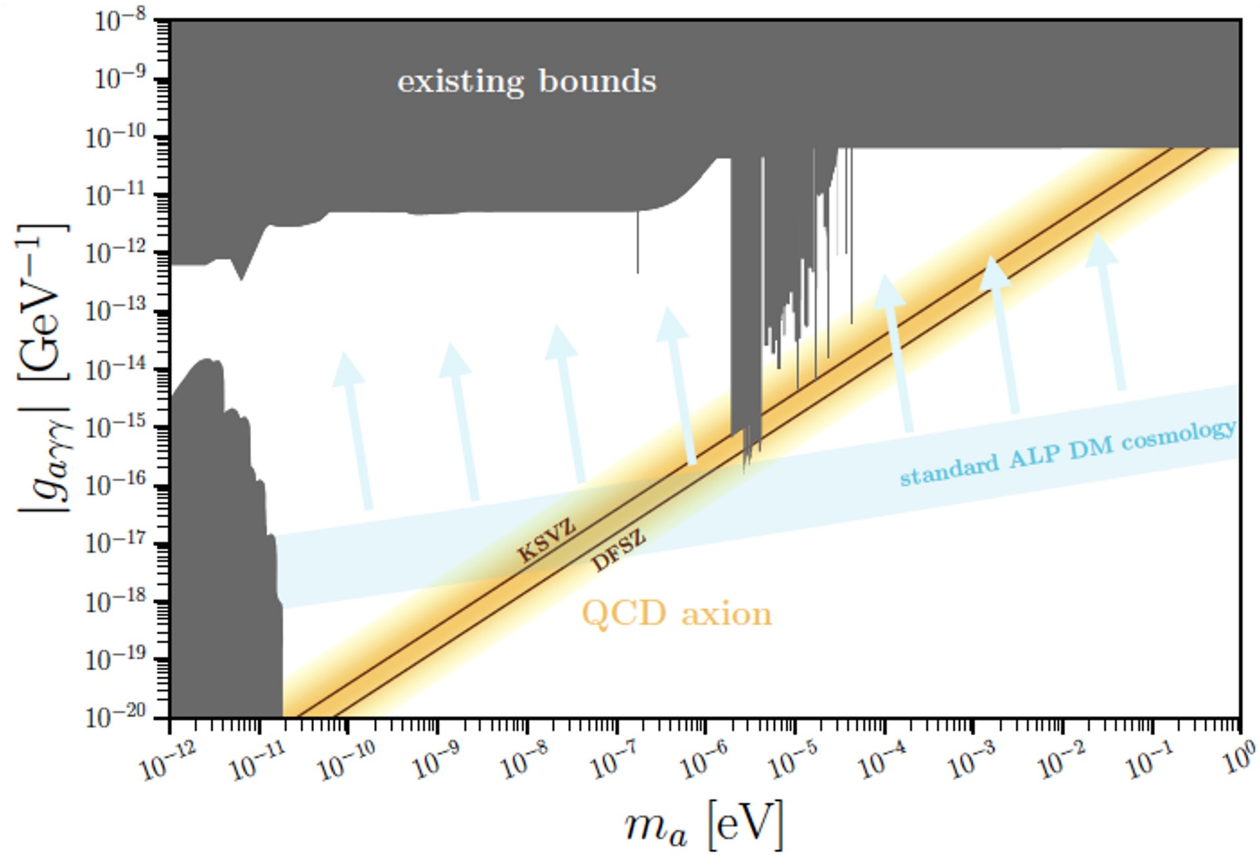
A. Berlin et al.



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.



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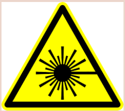
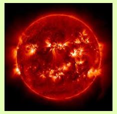
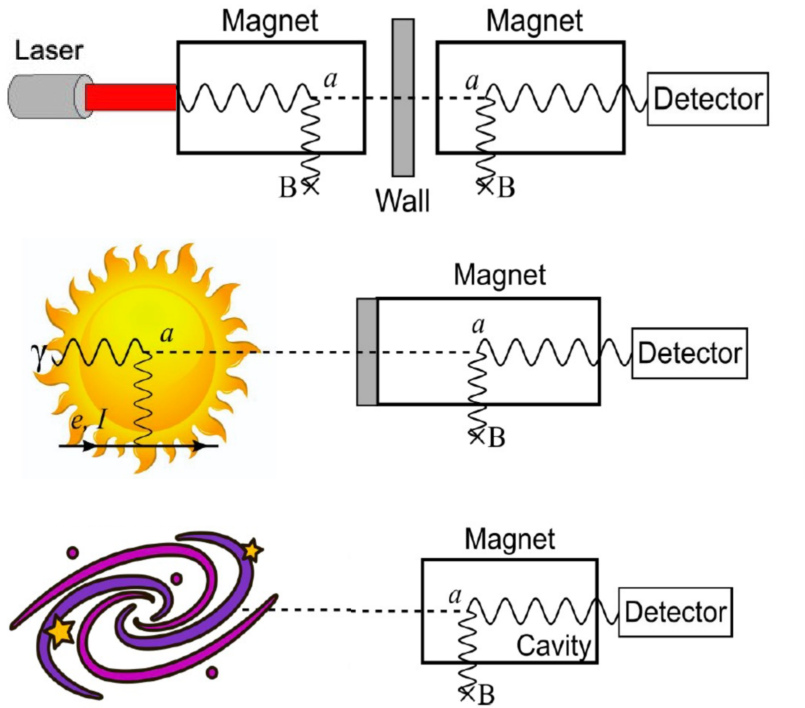
Detection of Axions

Source	Experiments	Model & cosmology dependency
Lab axions 	Light-Shining-Through-Wall (LSTW) Experiments	Very low
Solar axions 	Helioscopes	Low
Relic axions 	Haloscopes	High

Detection Principles for axions and ALPs



Large complementarity between different experimental approaches!

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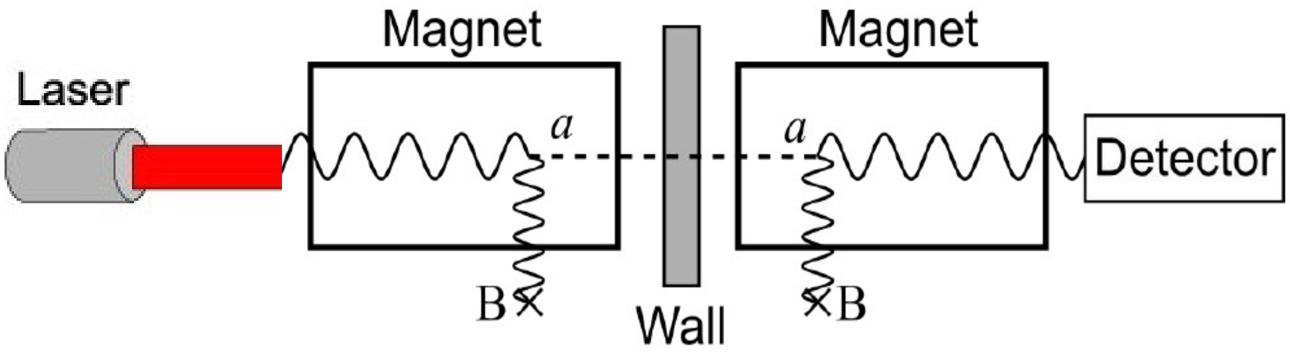
Detection of Axions I LSTW Experiments (no DM requirement)

- LIGHT-SHINING-THROUGH-WALL EXPERIMENTS: pure laboratory searches



ALPS, OSQAR,

Anselm 85;
Van Bibber *et al* 1987 *PRL* **59** 759

Concept: Axions mixing with photons in external electromagnetic field

- Conversion probability for a photon with energy w converts into axion after having traversed a distance L_B in magnetic field of strength B:

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

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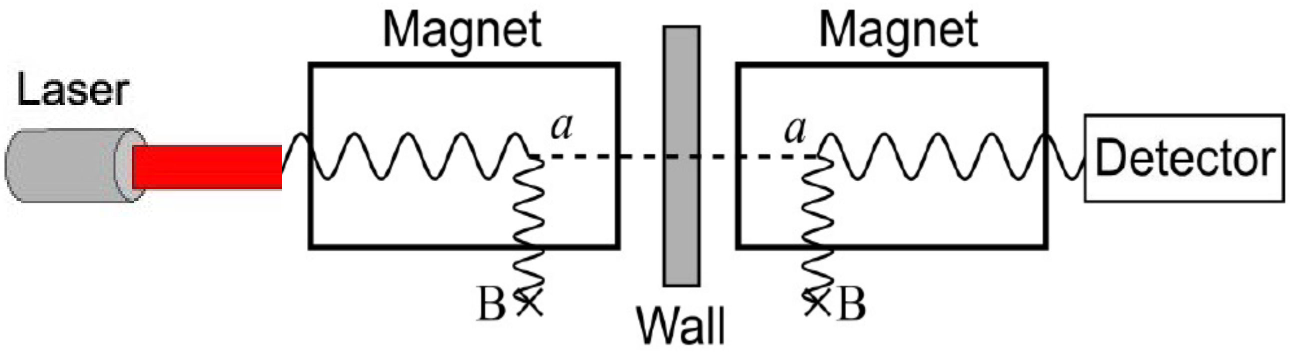

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- For small axion masses: $m_a \approx \text{meV}((\omega/\text{eV})(\text{m}/L_B))^{1/2}$:

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

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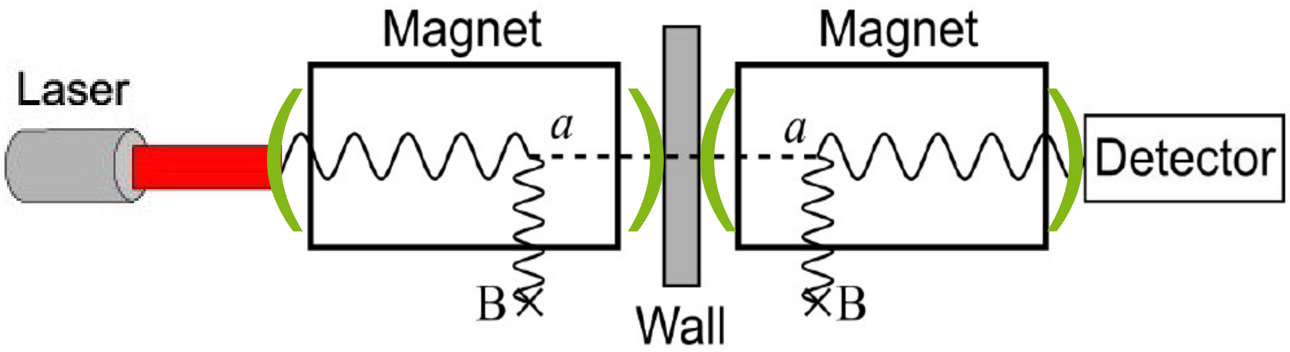

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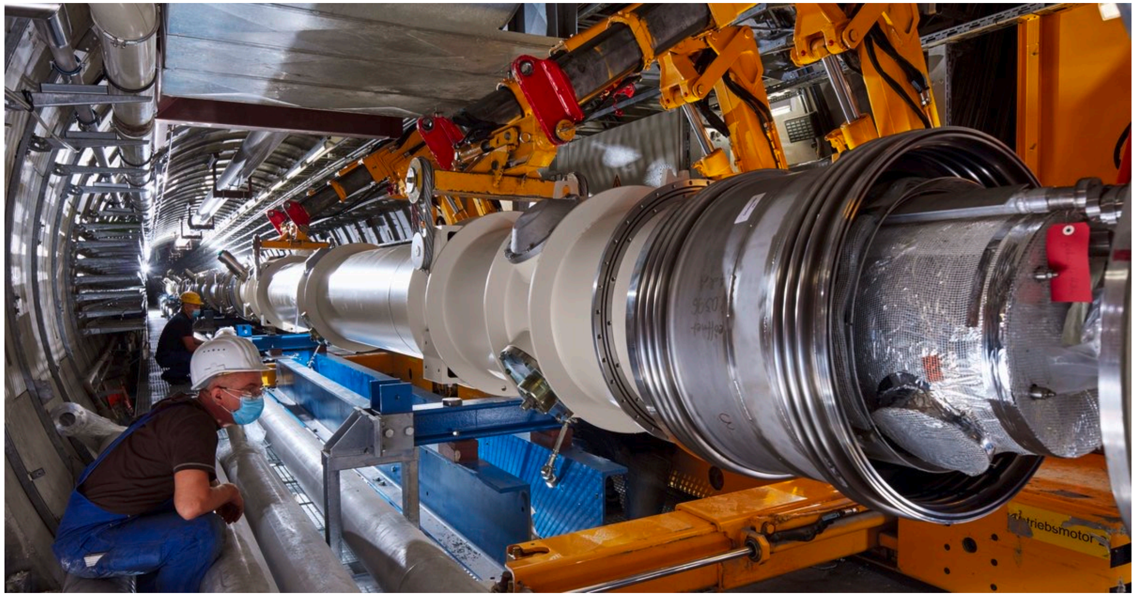
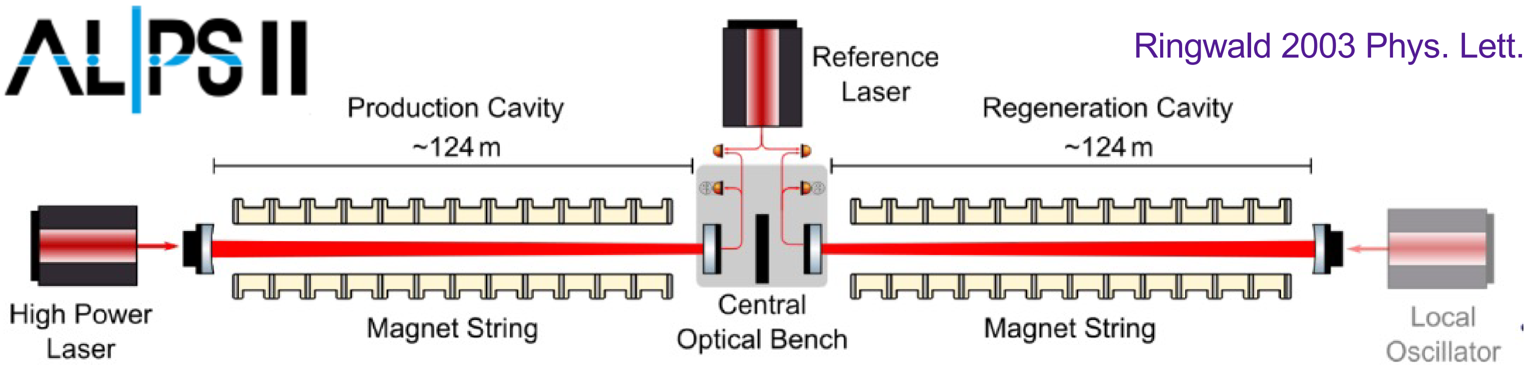
Detection of Axions I LSTW Experiments (no DM requirement)

▸ LIGHT-SHINING-THROUGH-WALL EXPERIMENTS: pure laboratory searches

- ALPS-II
  - 12 + 12 straightened HERA magnets
  - Optical cavities both at production and regeneration sites
  - Sensitivity 3000×ALPS

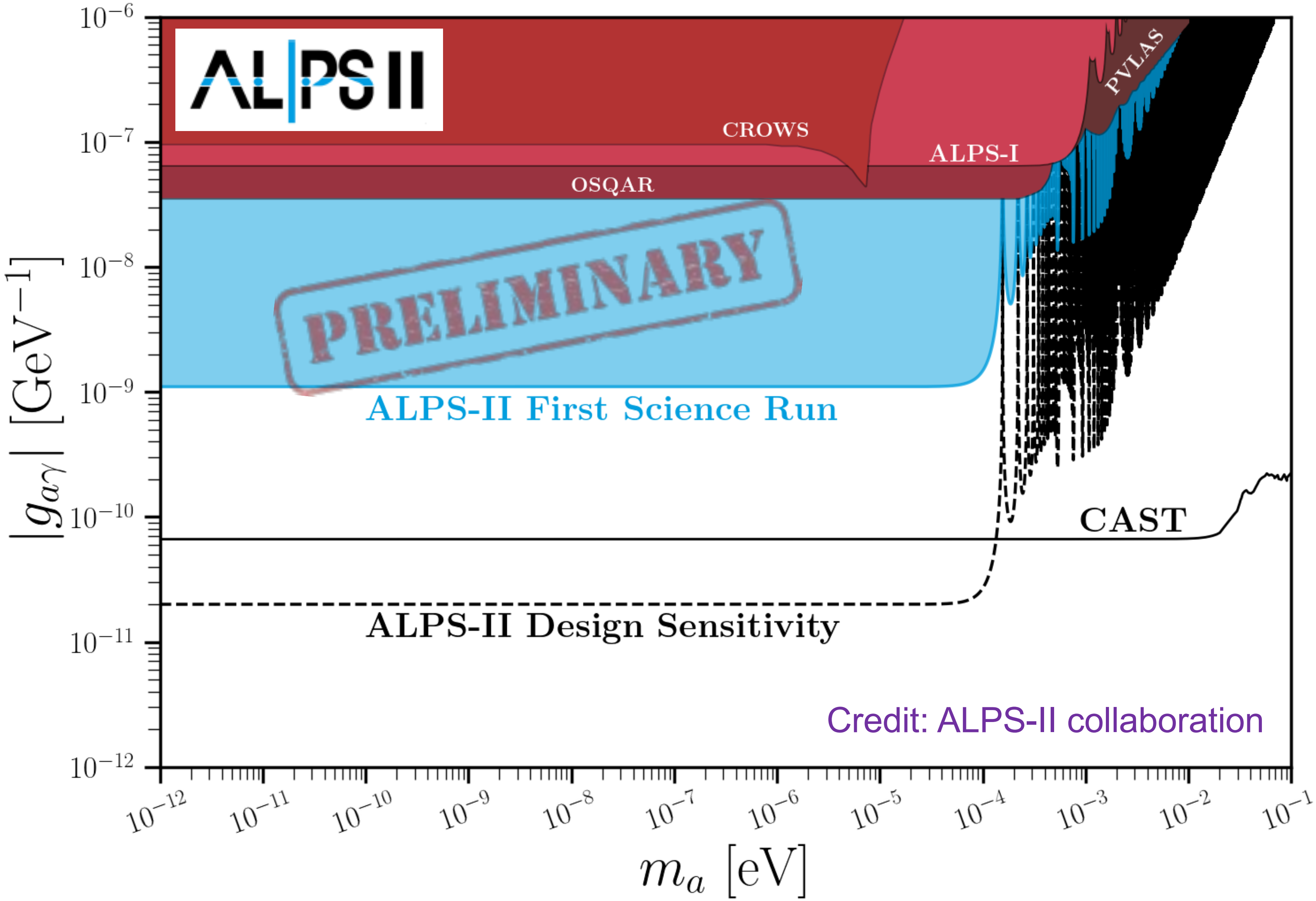




Ringwald 2003 Phys. Lett. B 569 51

ALPS-II@Göttingen2025: T65.1, T89.6

Detection of Axions I LSTW Experiments (no DM requirement)



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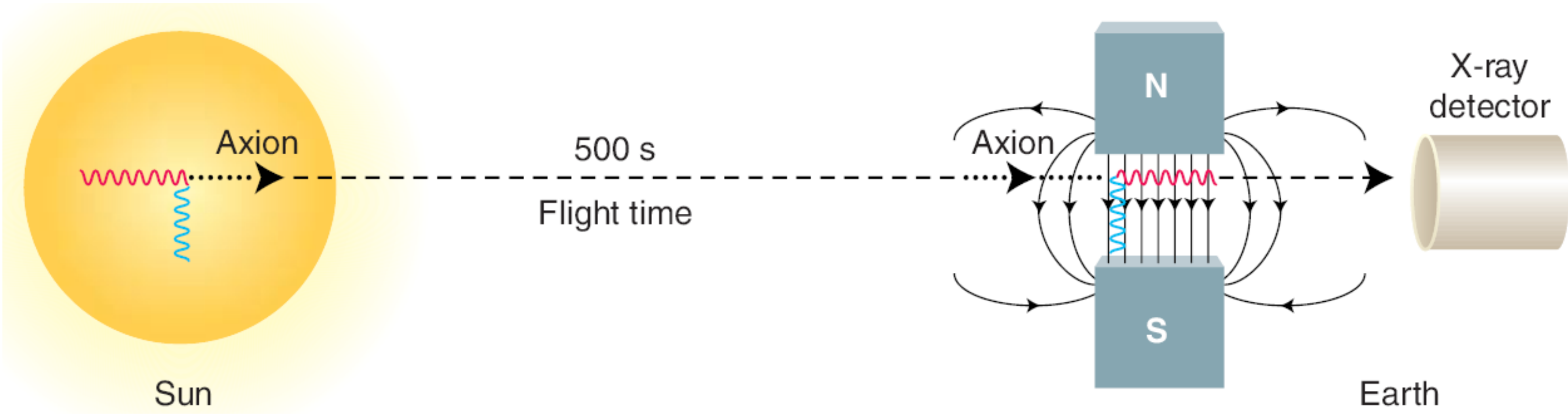
▸ AXION HELIOSCOPES: laboratory axion searches looking for solar axions



SUMICO, CAST, IAXO

P. Sikivie 1983 PRL 51 1415
van Bibber et al 1989 PRD 39 2089

Concept: **Axions produced in strong electromagnetic fields of the solar core and reconversion into x-ray (keV) photons in transverse laboratory B-field**

- Use gas to expand axion mass search range
- Helioscope Figure of Merit $\propto B^2L^2A$ (Magnet is key!!)
- To use large-scale magnets in combination with small ultralow-bgrd detectors: x-ray optics crucial connecting piece

- AXION HELIOSCOPES: laboratory axion searches looking for solar axions

B = 9.5 T
L = 9 m

Anastassopoulos et al. *Nature Phys.* ***13*** *(2017) 584-590*
Altenmüller et al. *PRL* **133** *(2024)*, 221005

- AXION HELIOSCOPES: laboratory axion searches looking for solar axions

B = 9.5 T
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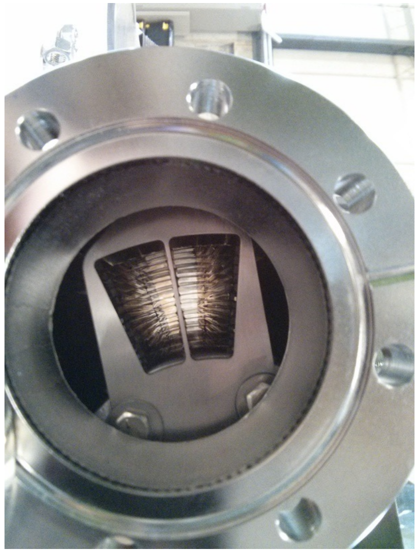
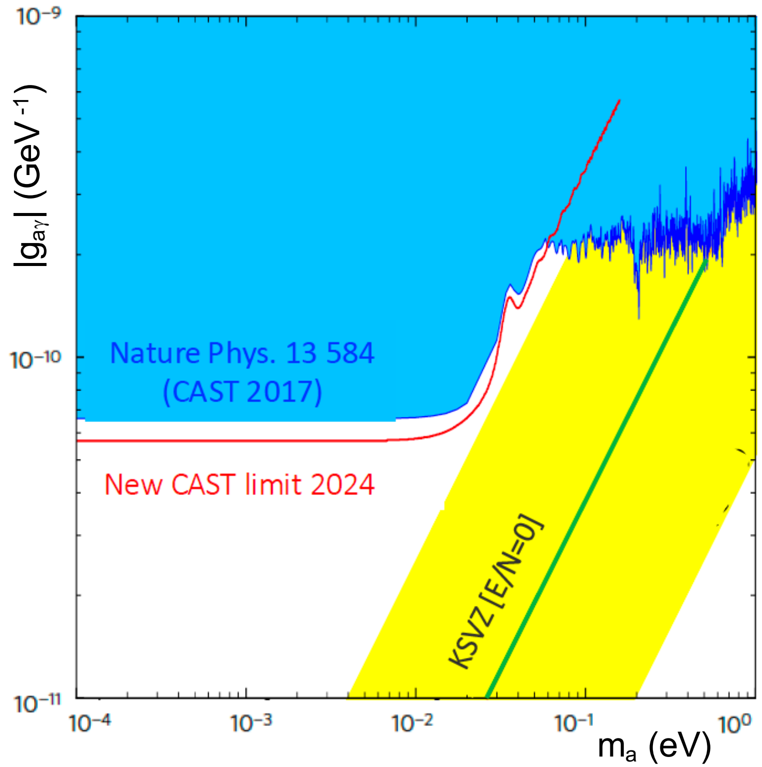
Benchmark limits for axion-photon coupling by the CERN Axion Solar Telescope (CAST) with next-gen experiment pathfinder





$g_{a\gamma} < 0.58 \times 10^{-10}$ GeV^{-1} (95% CL)

Anastassopoulos et al. *Nature Phys.* ***13*** *(2017)* 584-590
Altenmüller et al. *PRL* **133** *(2024)*, 221005

Helioscopes (no DM requirement)

CAST @ CERN

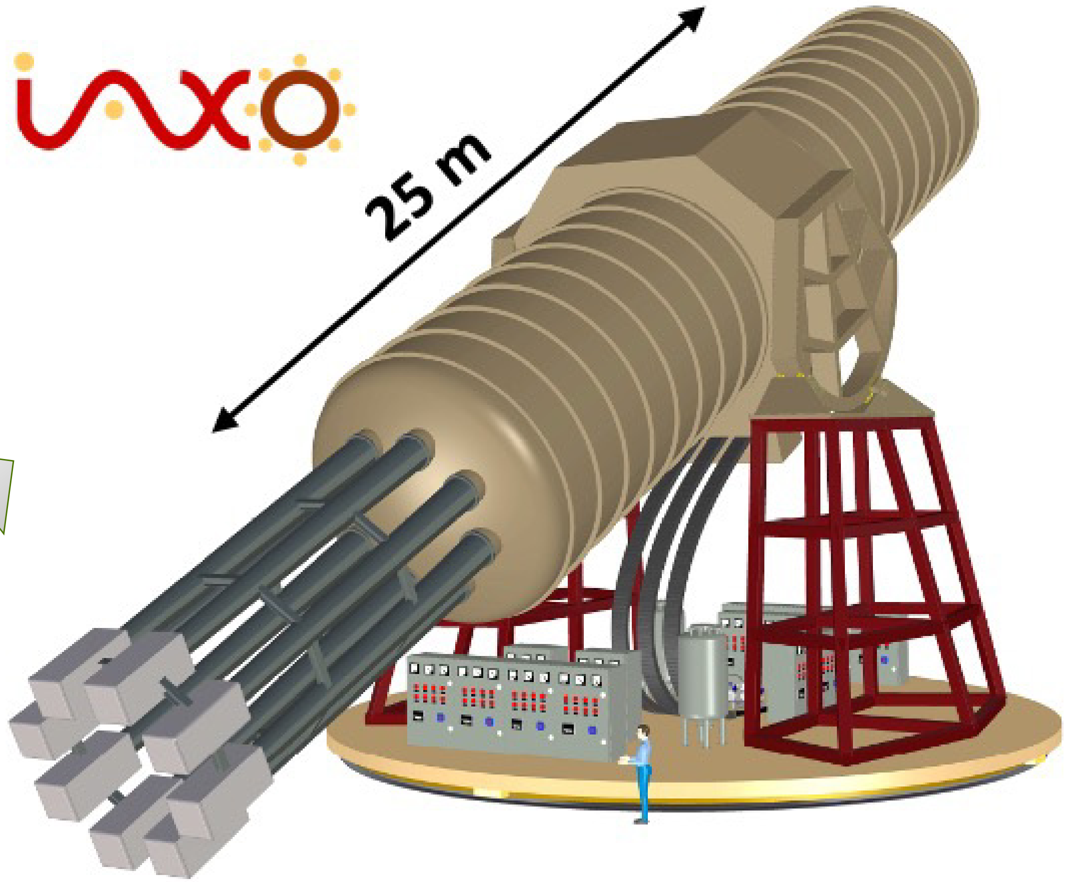
$g_{a\gamma} \lesssim 0.58 \times 10^{-10}$ GeV^{-1}

BabyIAXO @ DESY

$g_{a\gamma} \lesssim$ few 10^{-11} GeV^{-1} (expected)

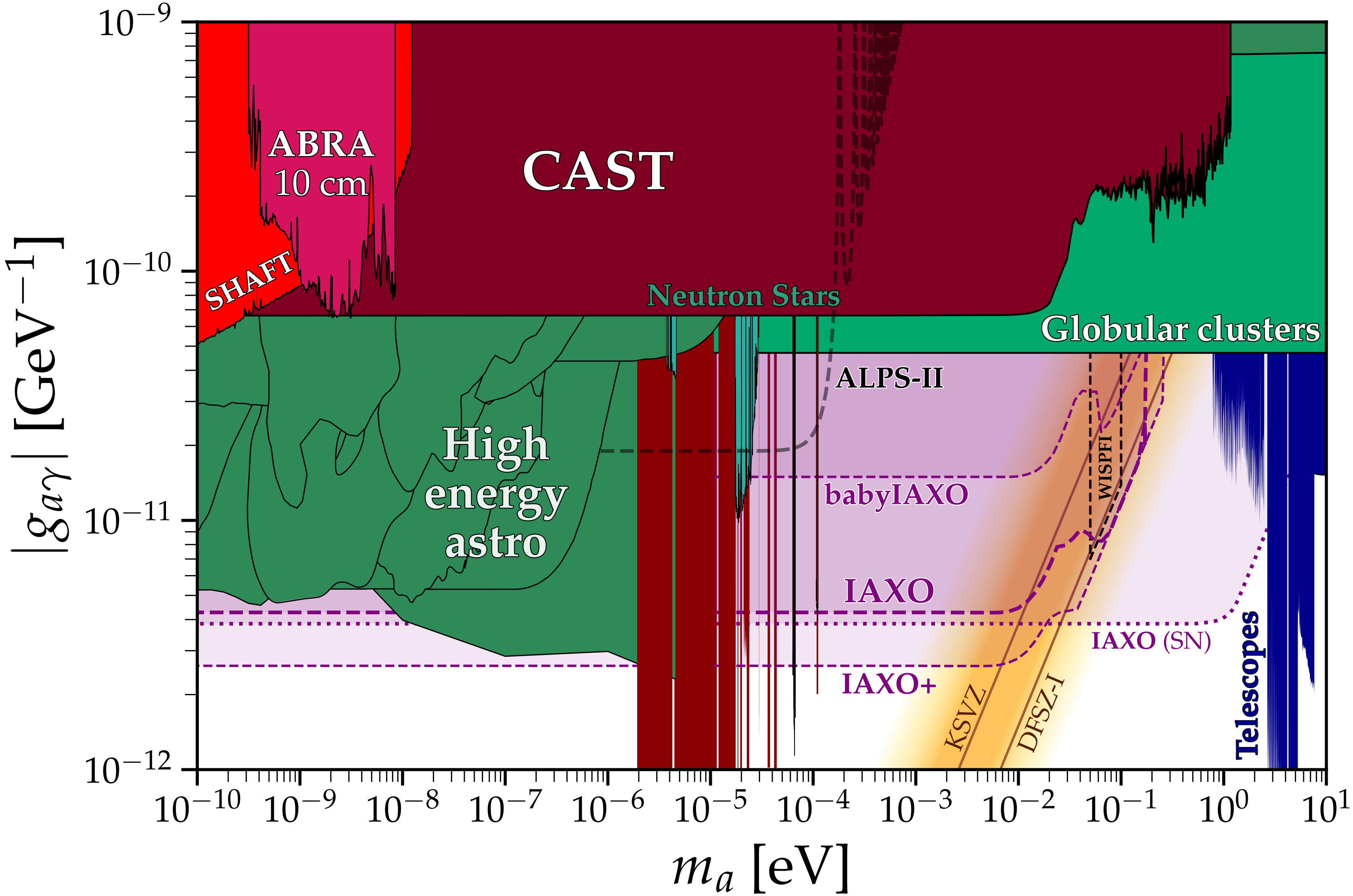
International Axion Observatory

IAXO



$g_{a\gamma} \lesssim$ few 10^{-12} GeV^{-1} (expected)

IAXO@Göttingen2025: T26.1, T26.2, T26.3, T26.6 , T47.6, T47.7, T65.1
RADES@Göttingen2025: T89.2


$|g_{a\gamma}|$ [GeV^{-1}]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
ABRA 10 cm
CAST
SHAFT
Neutron Stars
Globular clusters
ALPS-II
High energy astro
babyIAXO
WISPFI
IAXO
IAXO (SN)
IAXO+
KSVZ
DFSZ-I
Telescopes
10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1}
m_a [eV]

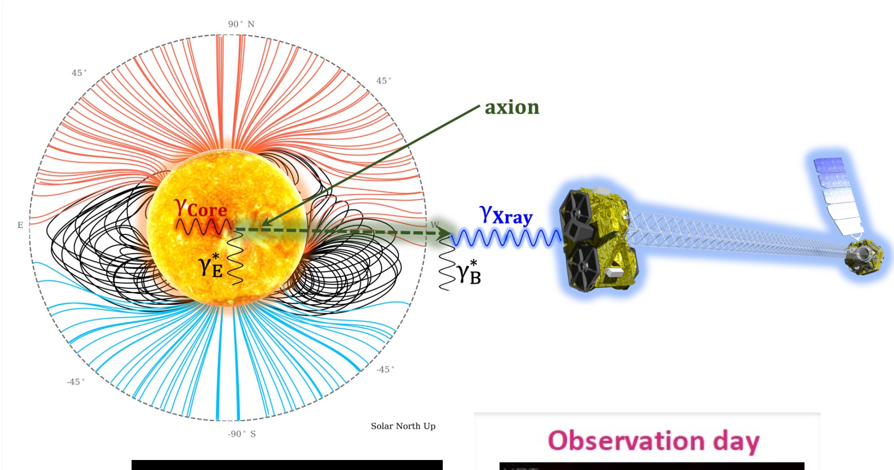
Detection of Axions II

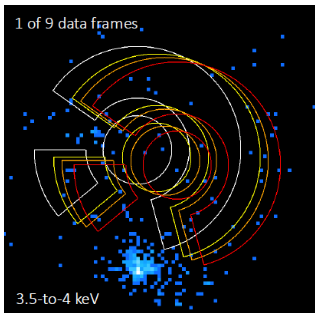
Helioscopes (no DM requirement)

- 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





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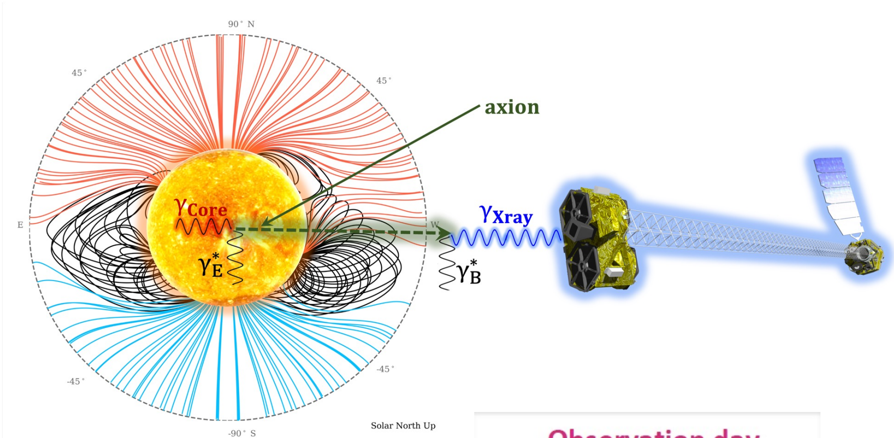

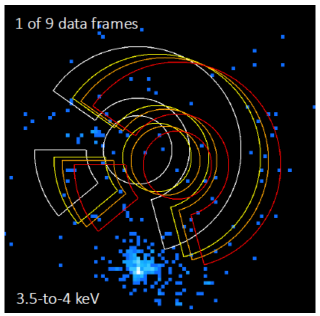

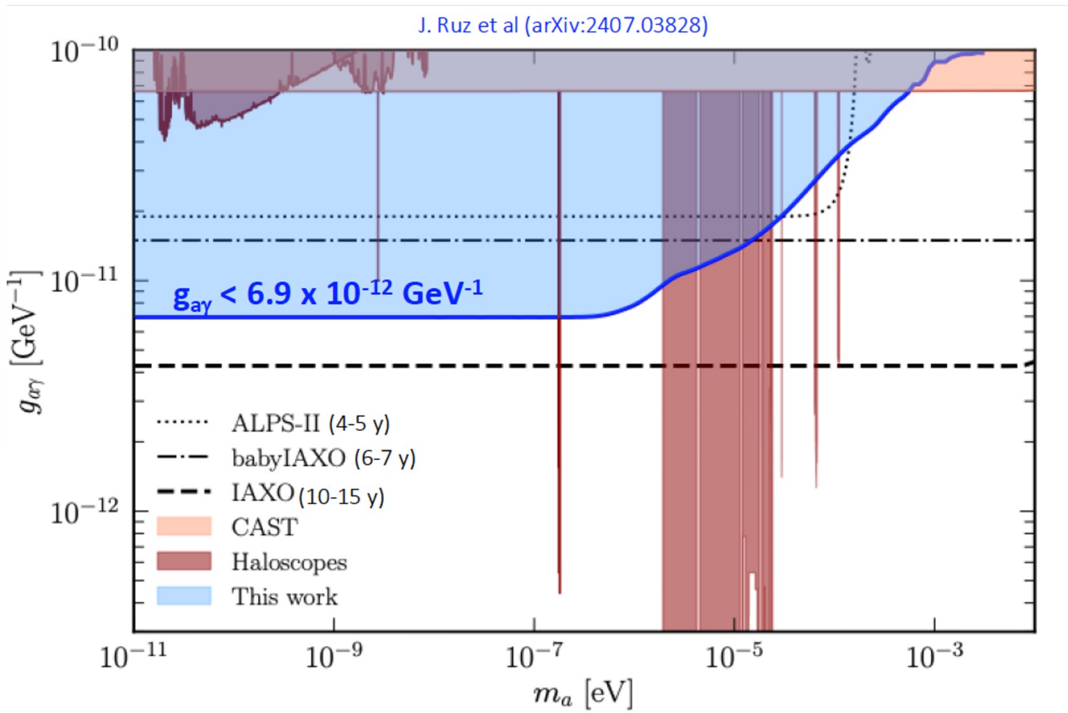

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- HALOSCOPES: Laboratory searches looking for galactic axions

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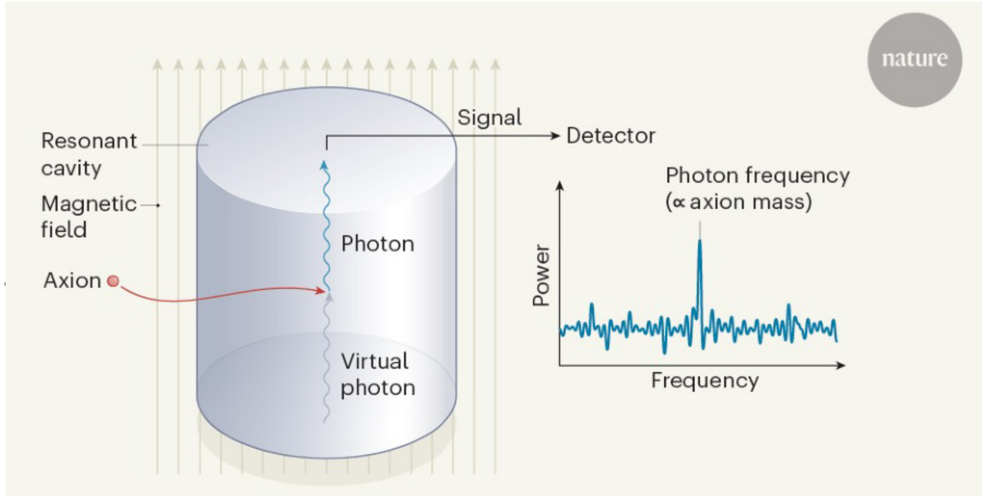

Concept:

DM axion converts into photon in microwave cavity placed inside magnetic field

- If axion mass matches resonance frequency of cavity

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

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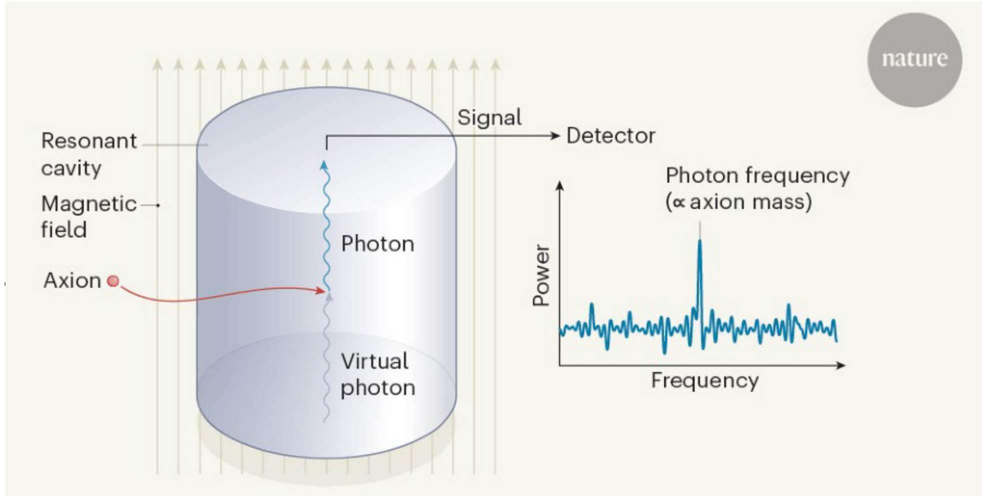

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- Need to tune resonance frequency to scan axion mass range
- Figure of merit

$$FOM \propto \frac{B^4 V^2 C^2 Q}{T_{SYS}} \qquad Q \sim 10^5$$

- HALOSCOPES: Laboratory searches looking for galactic axions

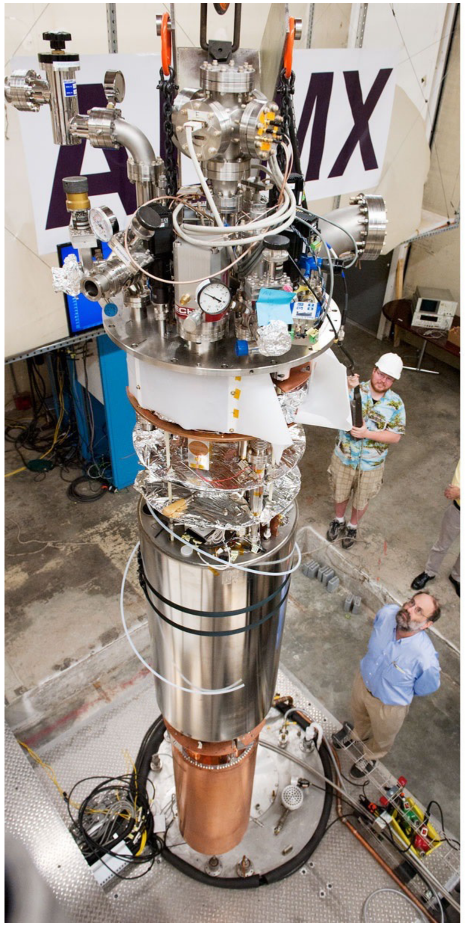
MICROWAVE CAVITIES

Currently active :

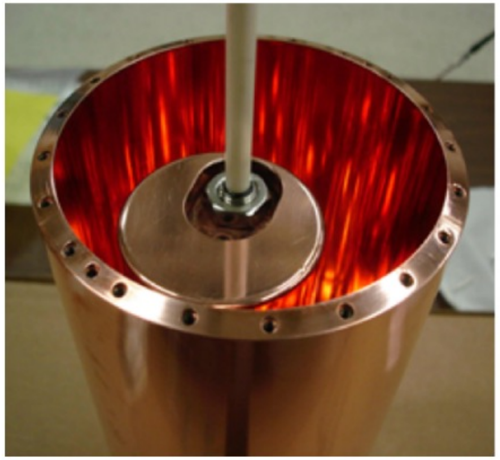
ADMX, HAYSTAC,
CAPP, GrAHal,
ORGAN, QUAX,
CAST-CAPP, **RADES,…**

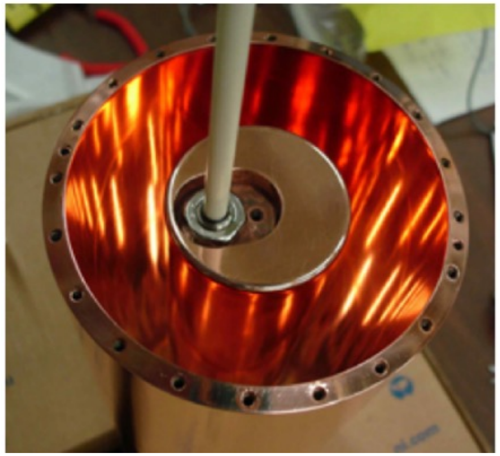
RADES@Göttingen2025: T89.2

ADMX



HAYSTAC





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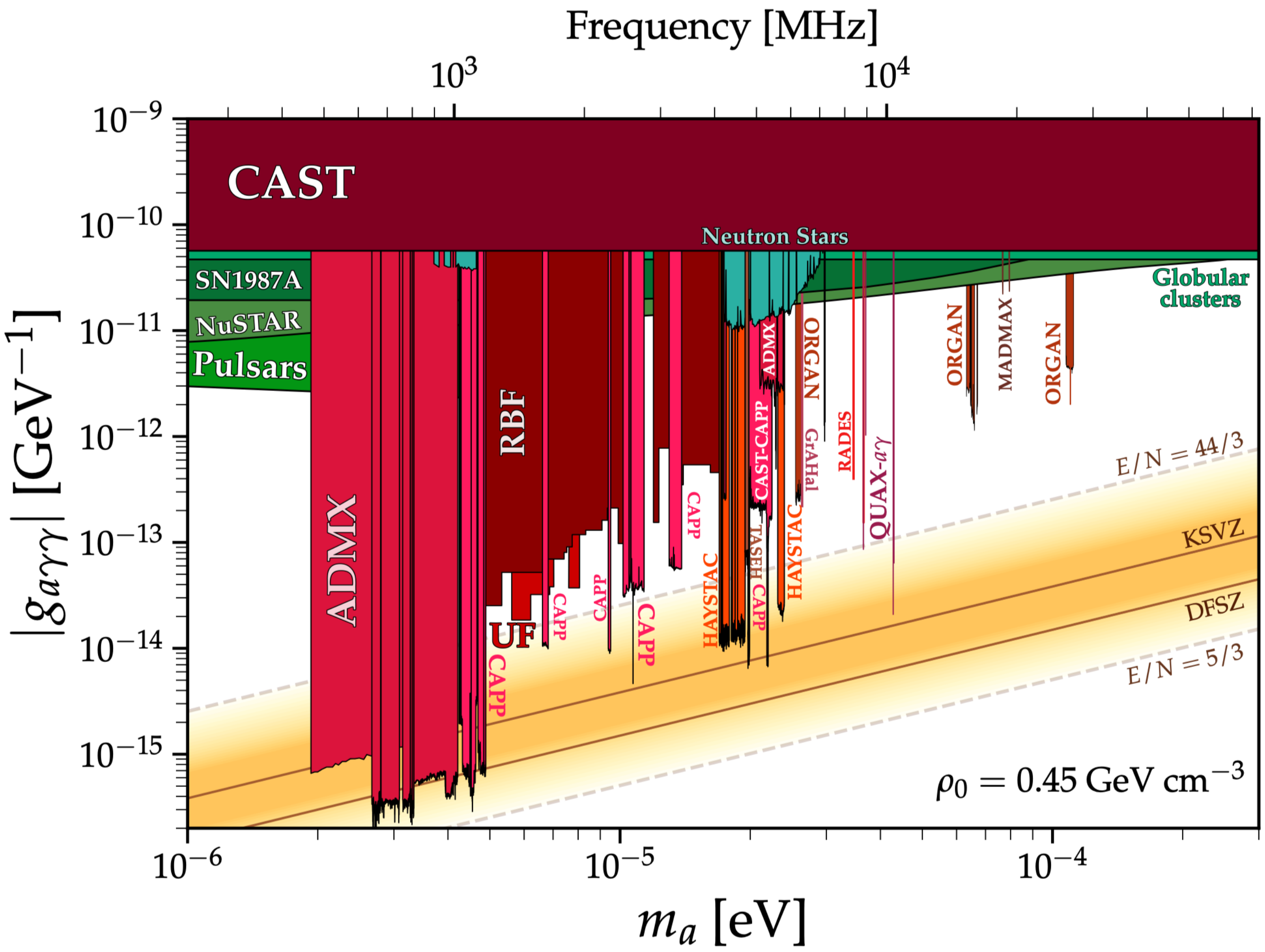
Currently active :

ADMX, HAYSTAC, CAPP, GrAHal, ORGAN, QUAX, CAST-CAPP, RADES,…

Vacuum Realignment

$m_a \backsim O(10\ \mu eV)$

$\nu \backsim O(GHz)$



Adapted from https://cajohare.github.io/AxionLimits/
(Shoutout to Ciaran O'Hare, the hero of axion plot unification)

- HALOSCOPES: Laboratory searches looking for galactic axions

MICROWAVE CAVITIES

Haystac

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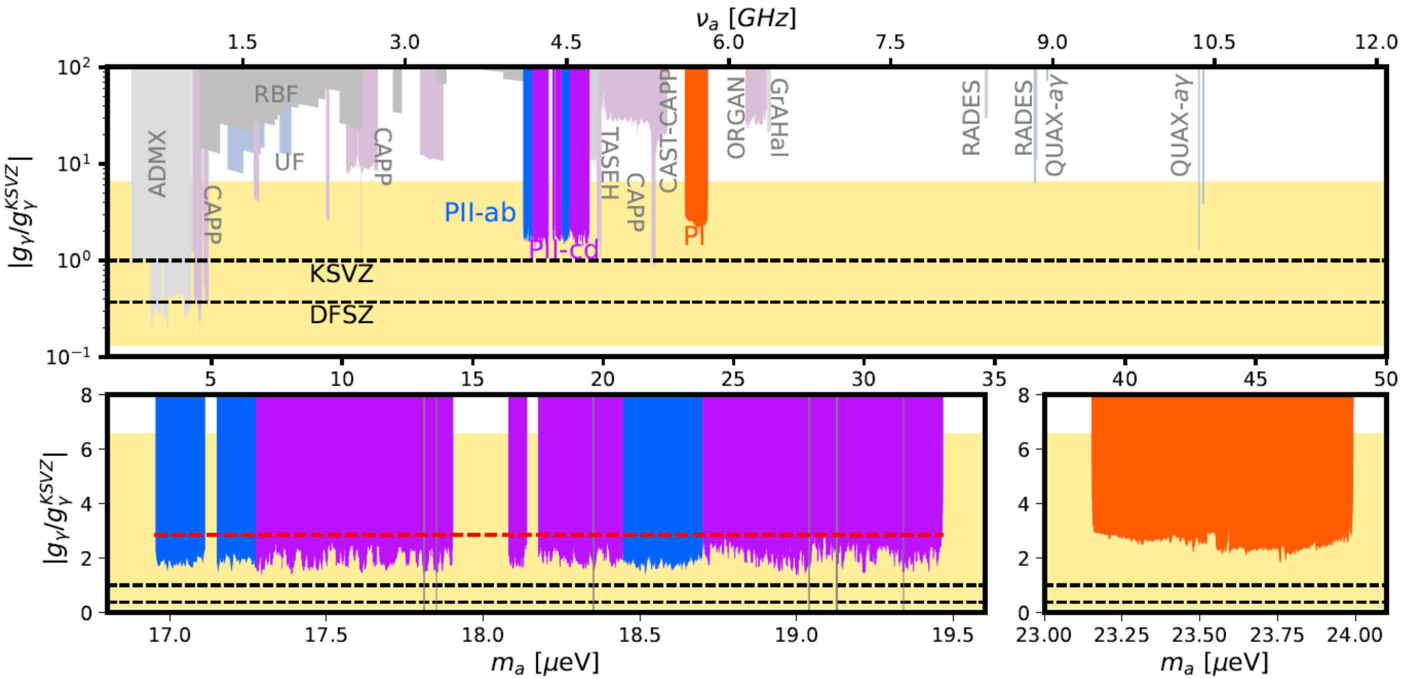

Most recent HAYSTAC results

arXiv:2409.08998 (2024), accepted for publication in PRL

▶ HALOSCOPES: Laboratory searches looking for galactic axions

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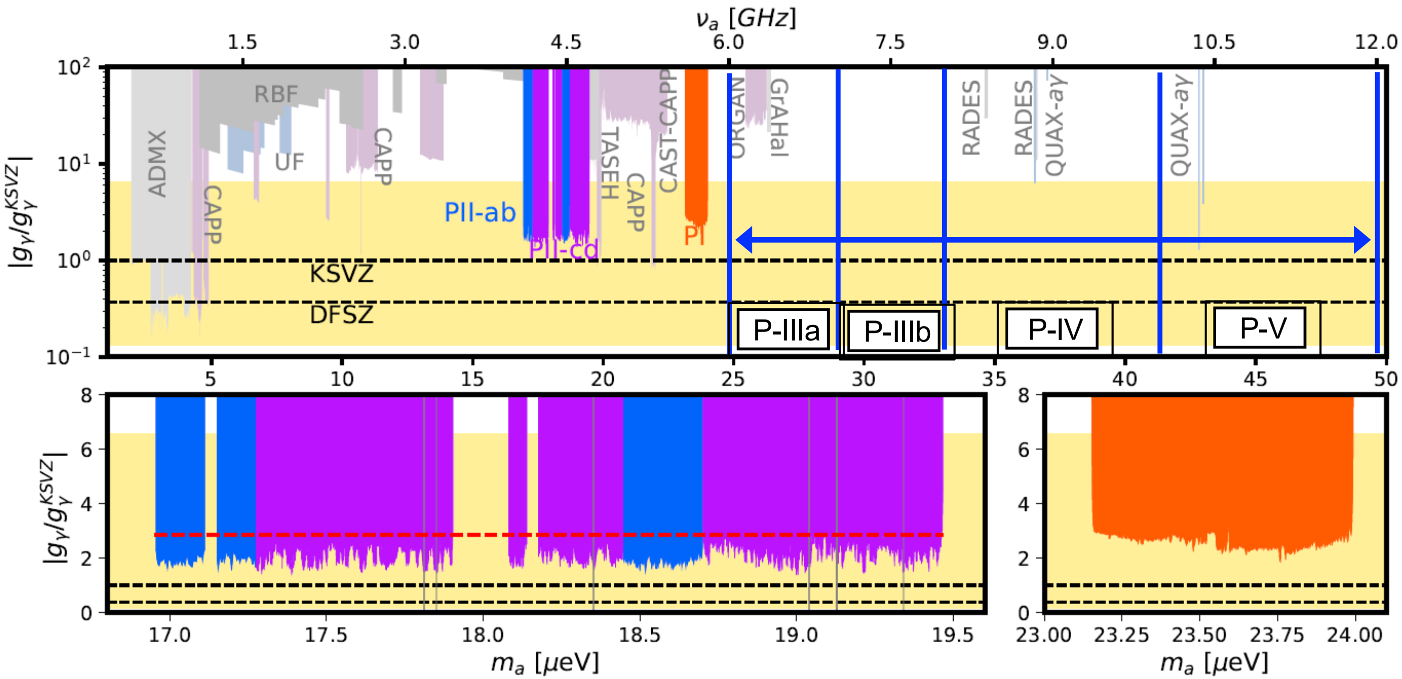


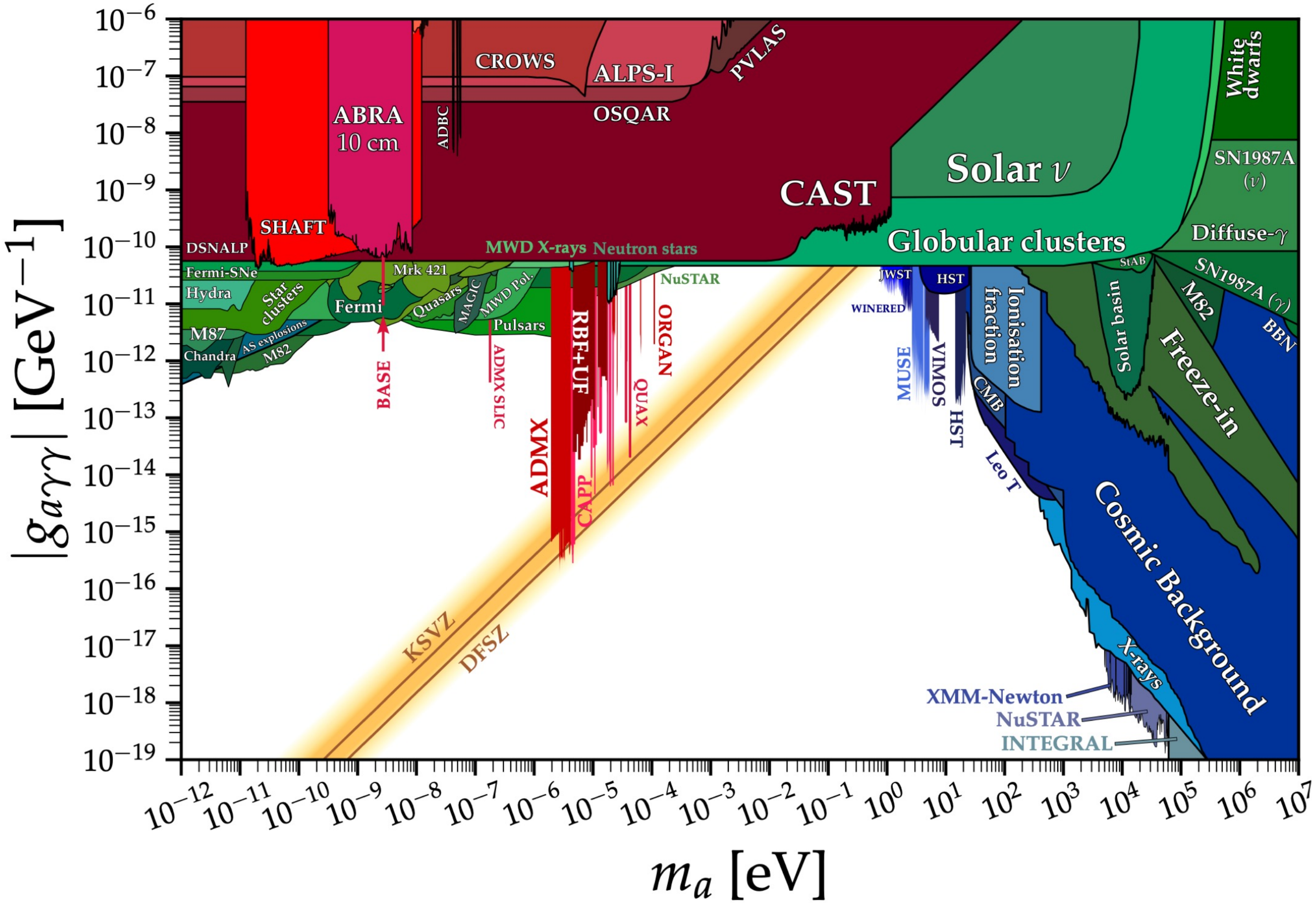
Most recent HAYSTAC results

Future upgrades in preparation

arXiv:2409.08998 (2024), accepted for publication in PRL

▶ HALOSCOPES: Laboratory searches looking for galactic axions

How to go to higher masses to search for **post-inflation** axions?



https://cajohare.github.io/AxionLimits/

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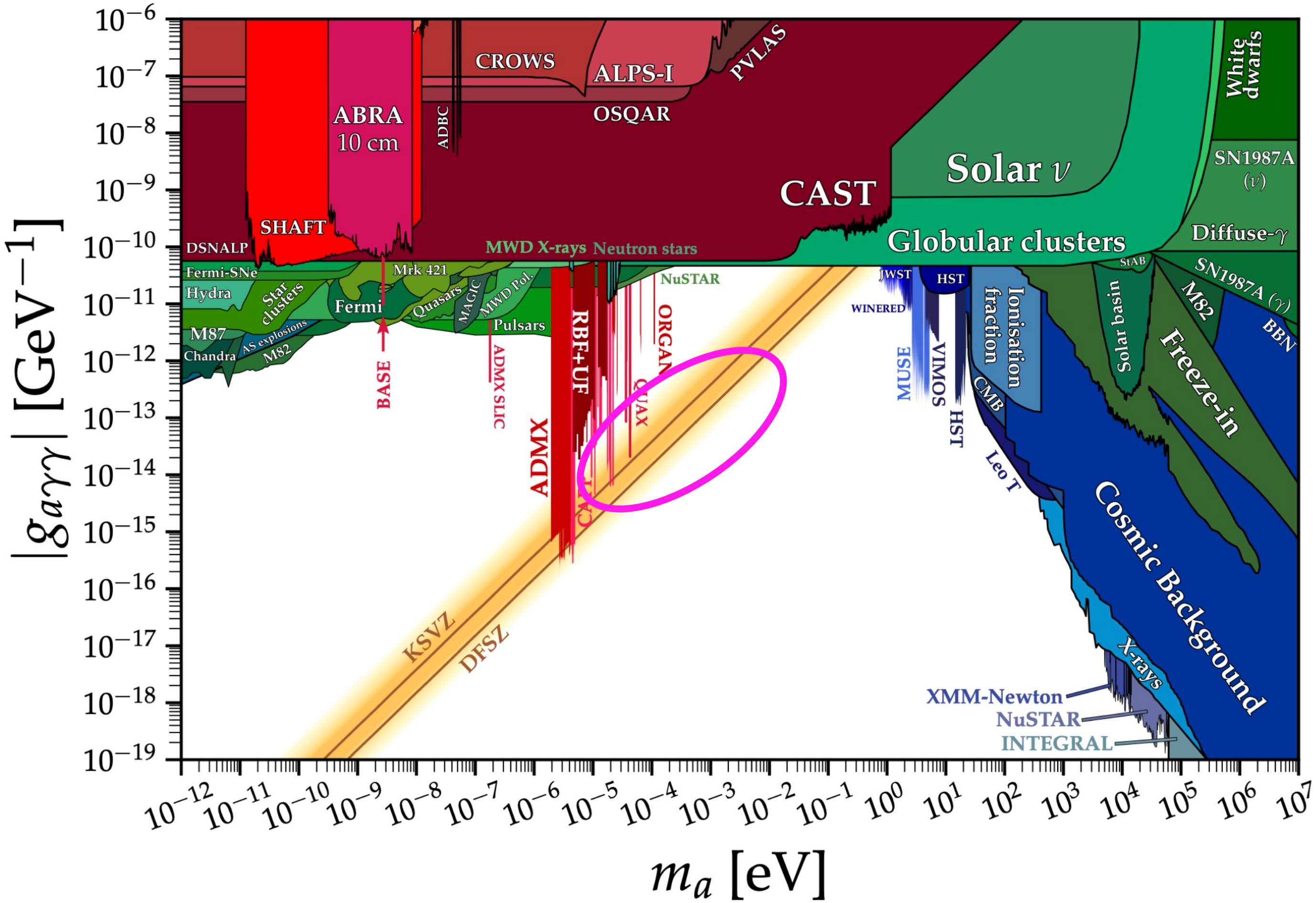
Higher frequencies, (i.e. higher m_a) requires **smaller** cavities and scans get **slower**!



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Dish Antennas & Plasma Haloscopes!

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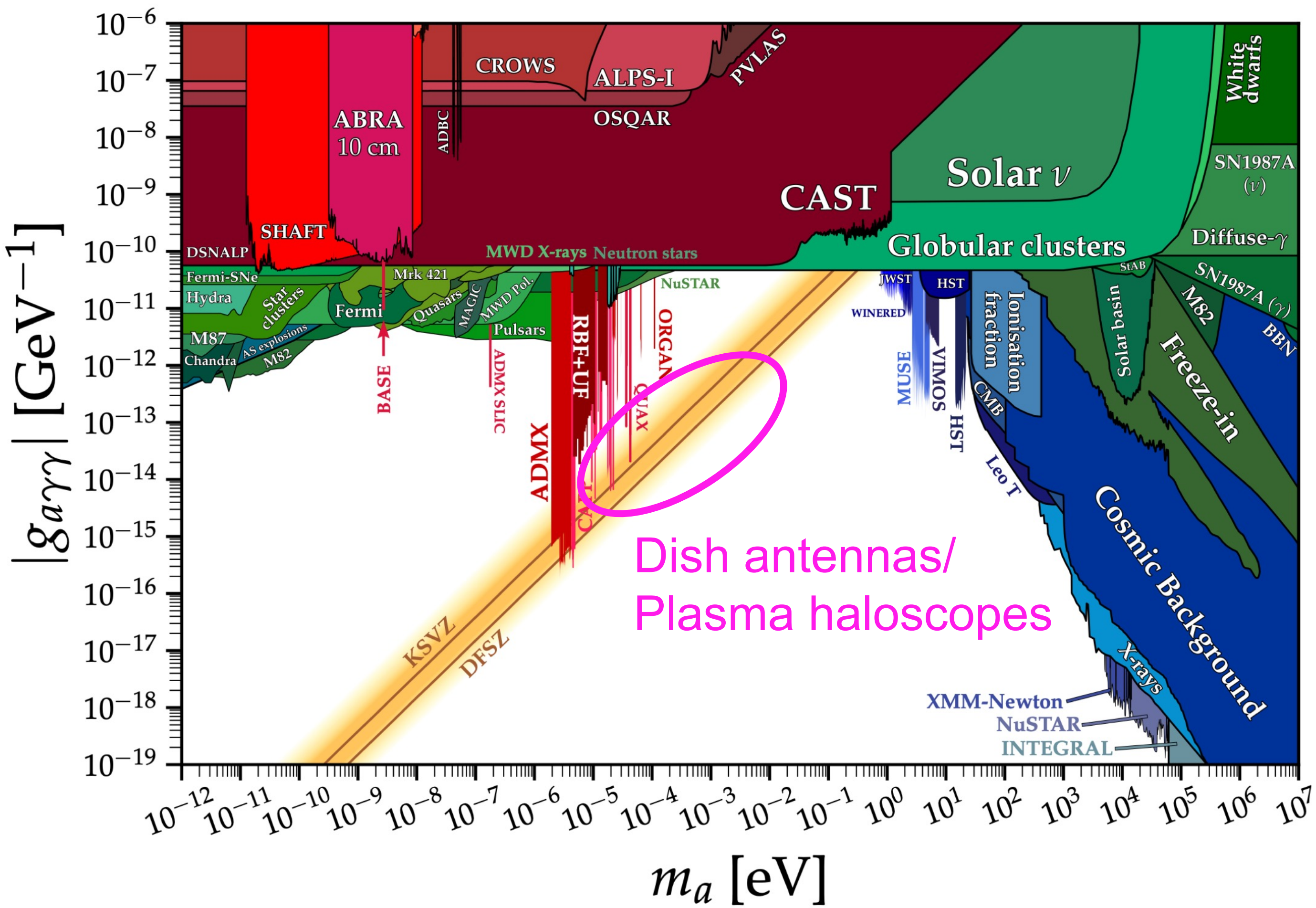
$\nu \quad \backsim O(10\text{-}100\ GHz)$

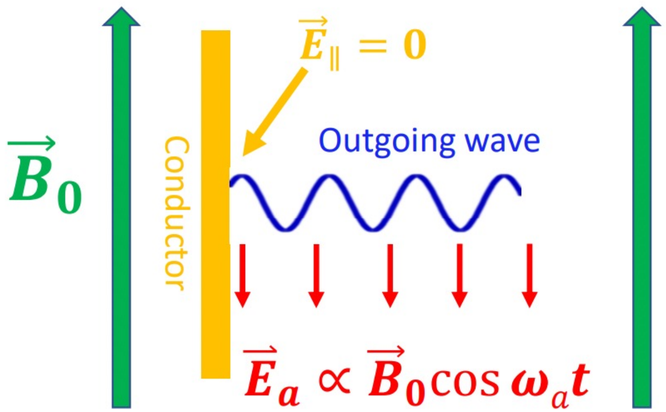


https://cajohare.github.io/AxionLimits/

Horns *et al* JCAP04(2013)016

▶ HALOSCOPES: DISH ANTENNAS

$P/A \propto B^2$

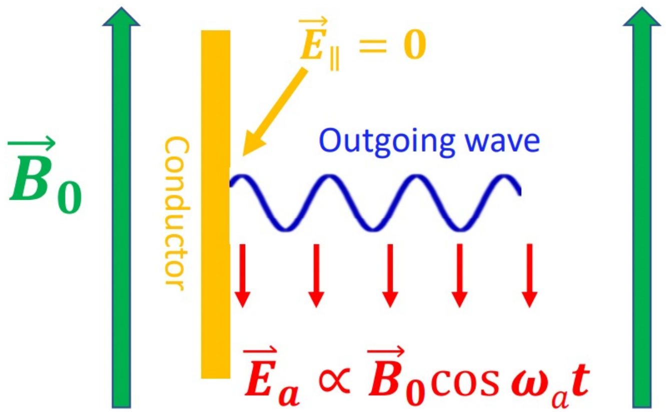


Concept: Axion induced radiation from a magnetized metal slab

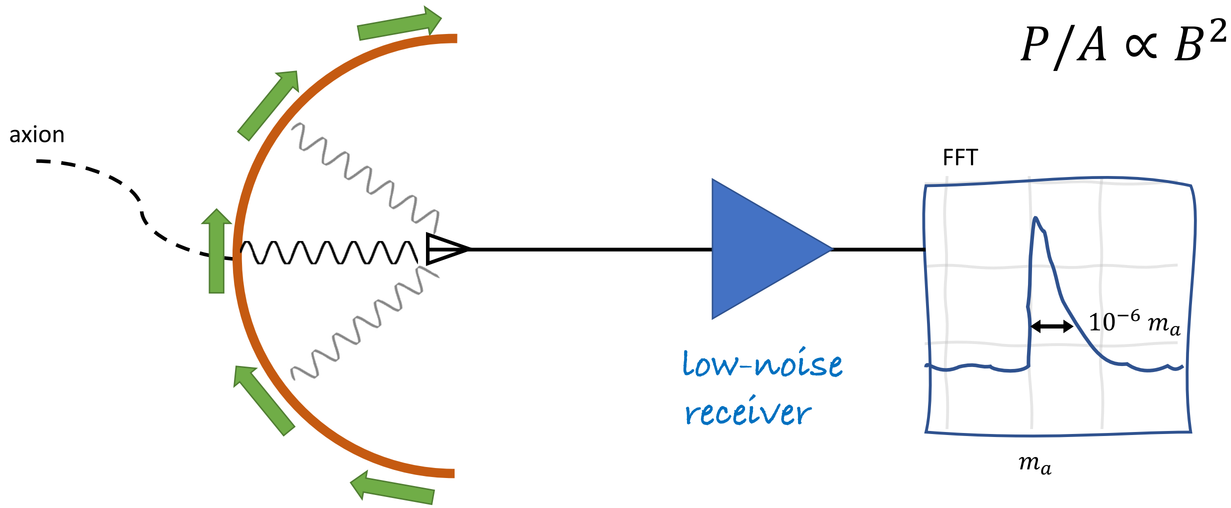
- DM axions interact with a static magnetic field
  → producing oscillating parallel E-field.
  Conducting surface in this field emits plane wave ⊥ surface with $\upsilon \propto m_a$
- Radiated power is low, however, no tuning required!

Horns *et al* JCAP04(2013)016

▶ HALOSCOPES: DISH ANTENNAS



$P/A \propto B^2$



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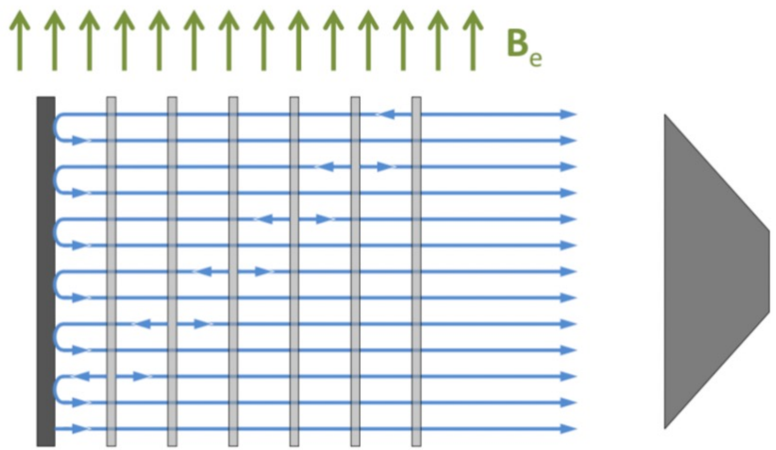
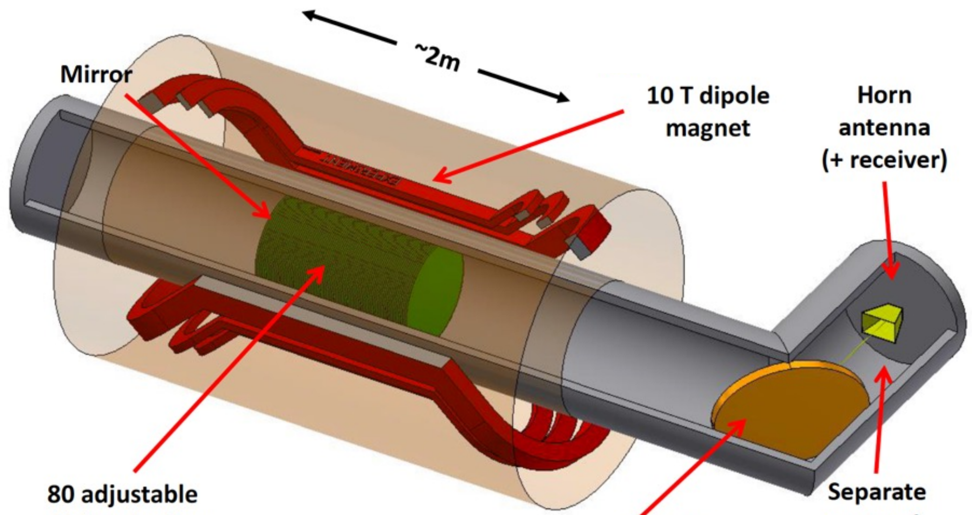




Enhanced Concept: Boosted dish antenna aka open dielectric resonator

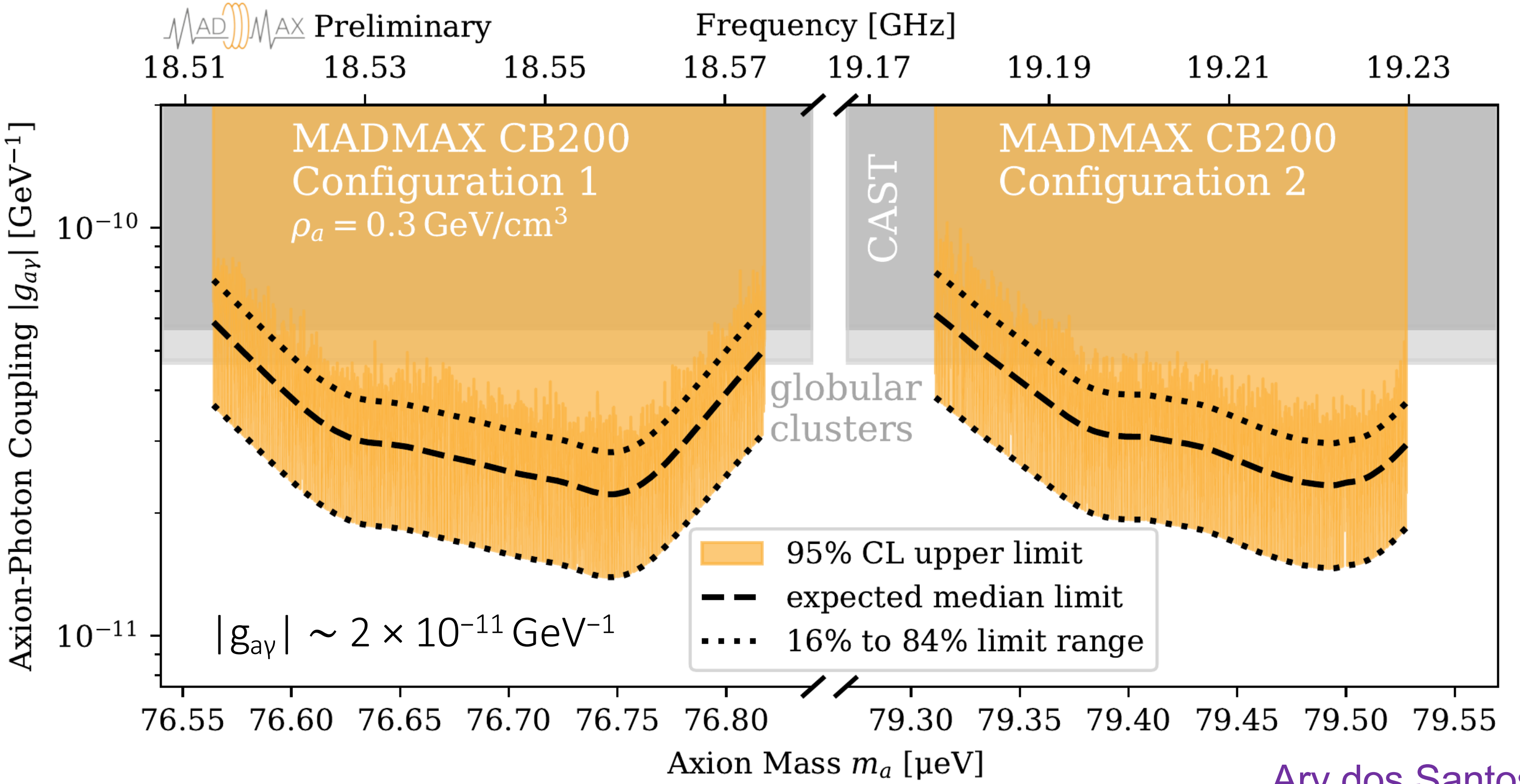
- Stack of dielectric plates as booster inside a magnetic field
- Tuned to the radiofrequencies (m_a around 100 μeV)
- Can enhance measured power by several 10^4, but tradeoff bandwidth/“boost factor”

MADMAX@Göttingen2025: T26.4, T26.5, T65.1, T89.1, T89.5

Detection of Axions III

Haloscopes (DM requirement)

▸ HALOSCOPES: DISH ANTENNAS

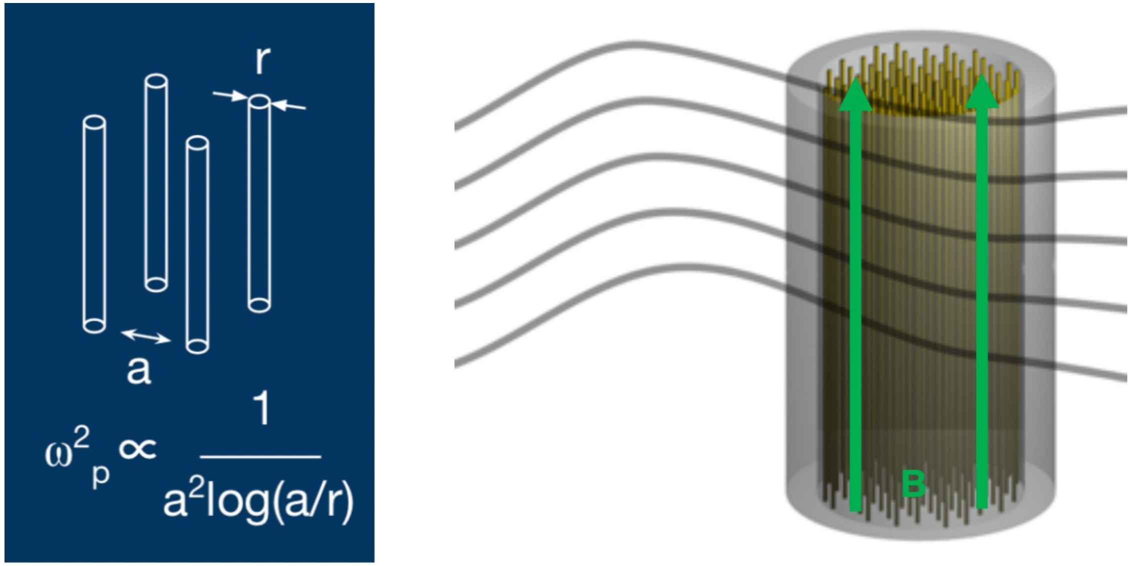


Ary dos Santos Garcia *et al.*, arXiv 2409.11777

MADMAX prototype setup with 3 disks and a mirror within the magnetic dipole field provided by the 1.6 T Morpurgo magnet at CERN (14.5 days of data)

MADMAX@Göttingen2025: T26.4, T26.5, T65.1, T89.1, T89.5

▶ HALOSCOPES: PLASMA HALOSCOPES

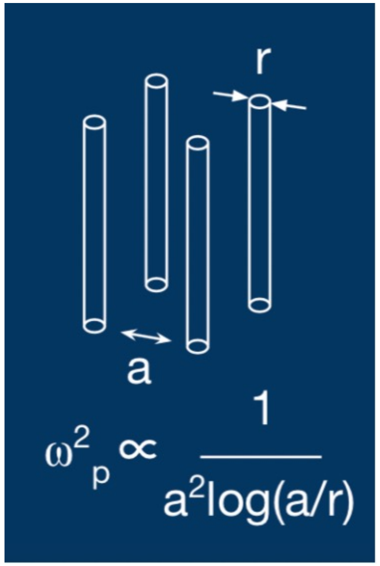


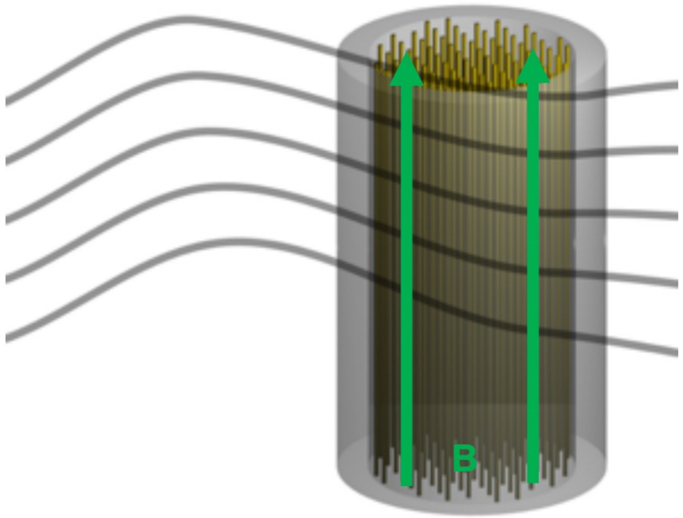
Concept: Oscillating DM axions induce plasmon excitations in magnetized plasma

- 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

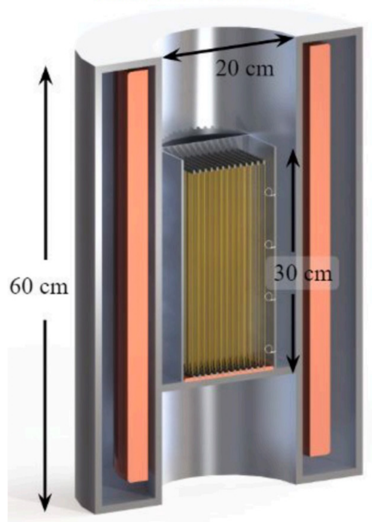
Lawson et al., PRL 123 (2019) 141802

▶ HALOSCOPES: PLASMA HALOSCOPES





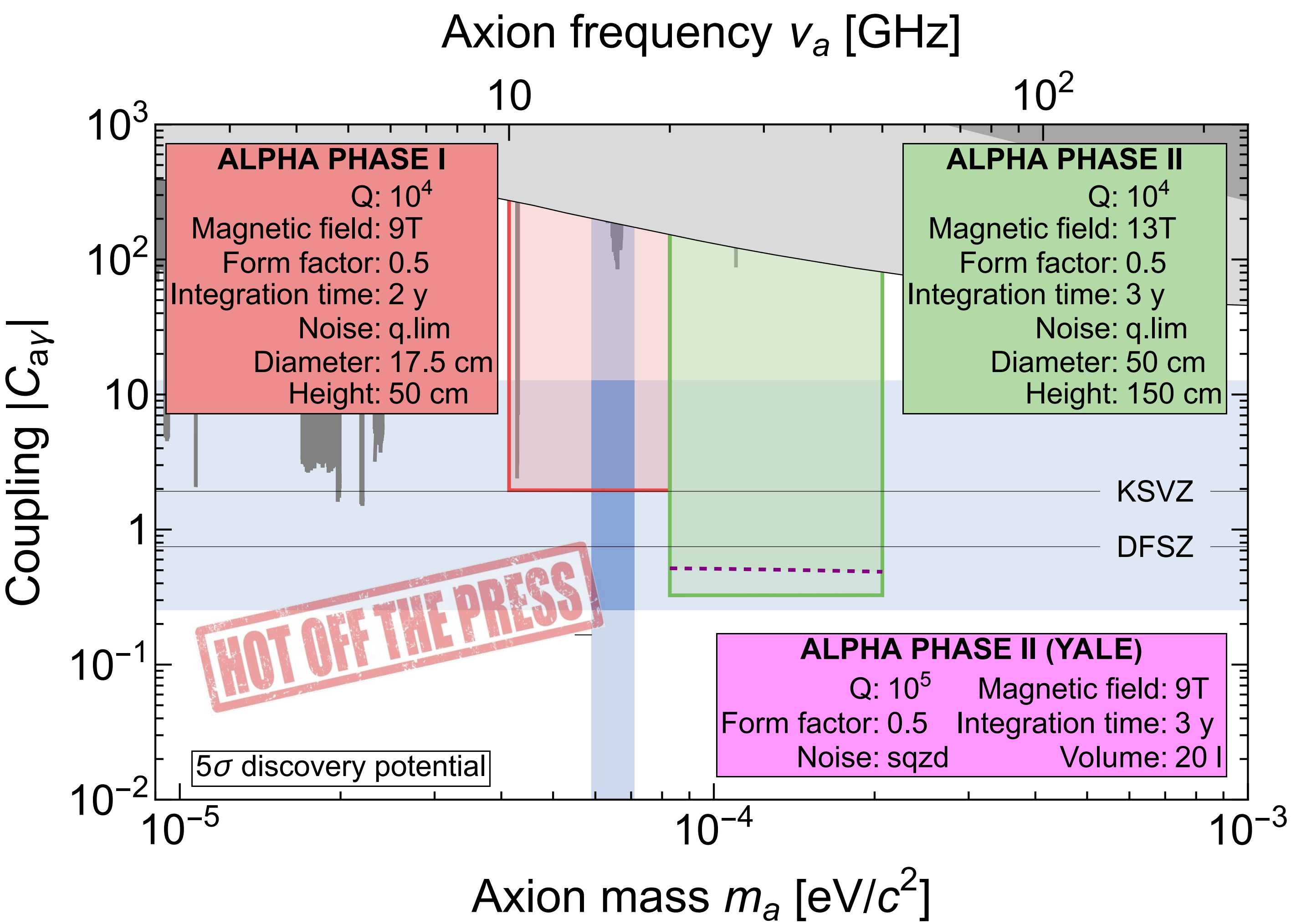
ALPHA Pathfinder



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



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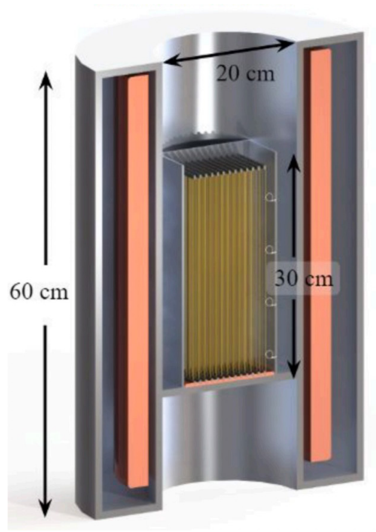
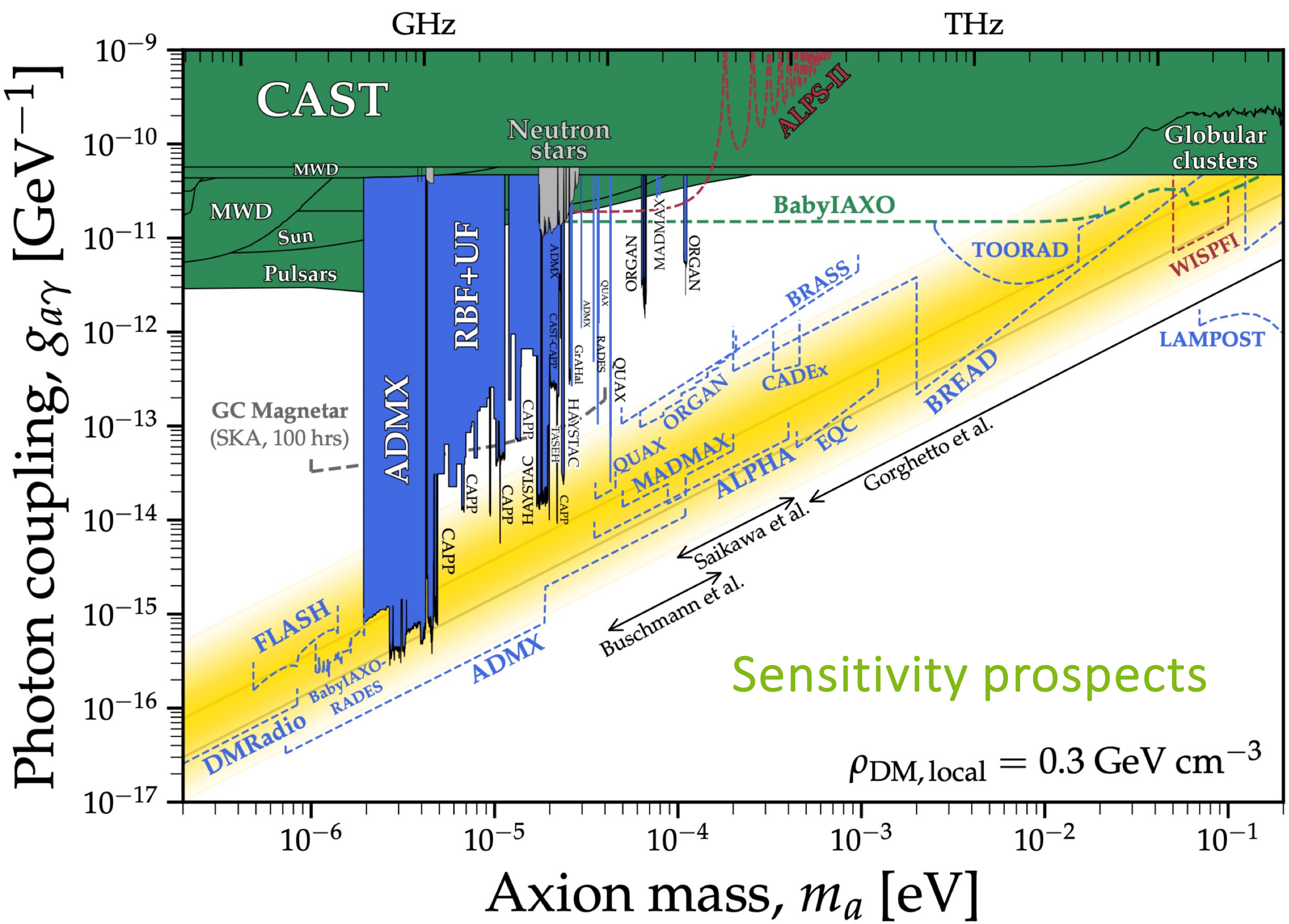


Credit:
K. Van Bibber and the ALPHA collaboration

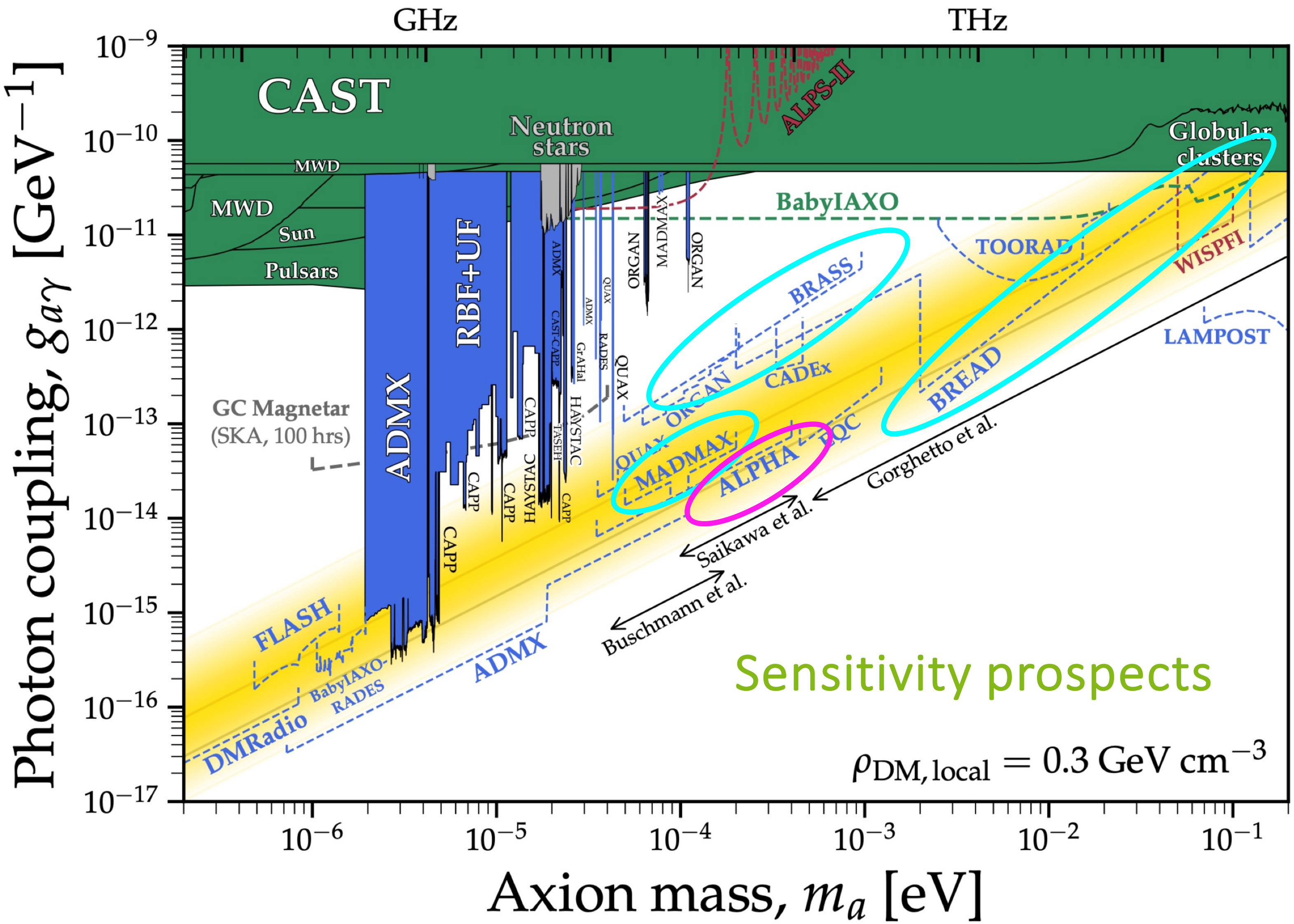
Detection of Axions III
Haloscopes (DM requirement)



https://cajohare.github.io/AxionLimits/

Detection of Axions III

Haloscopes (DM requirement)



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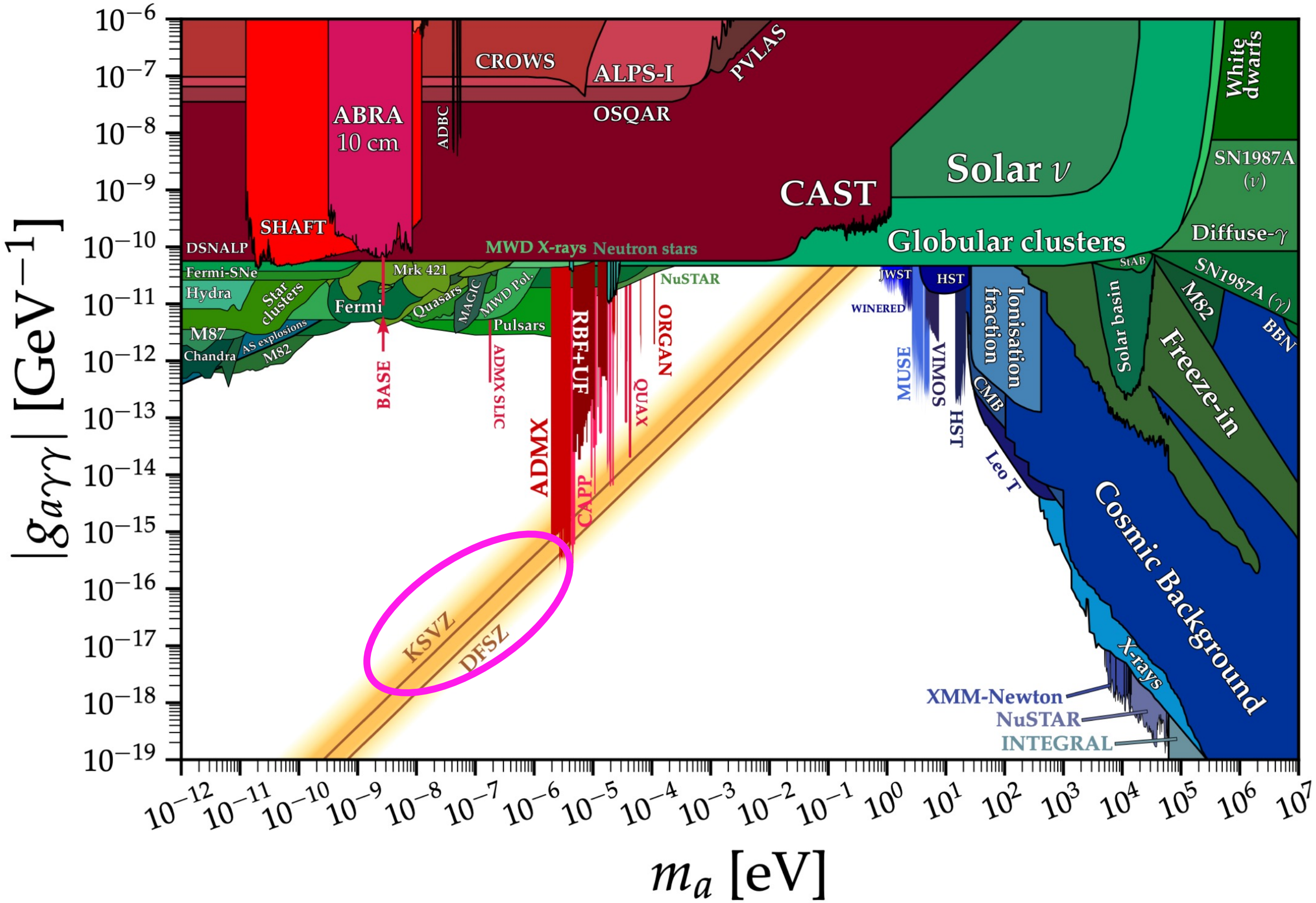
- HALOSCOPES: Laboratory searches looking for galactic axions

How to go to lower masses to search for GUT-scale axions?

Lower frequencies, (i.e. smaller m_a) requires increasingly **large** cavities



RADES@Göttingen2025: T89.2 https://cajohare.github.io/AxionLimits/

Detection of Axions III

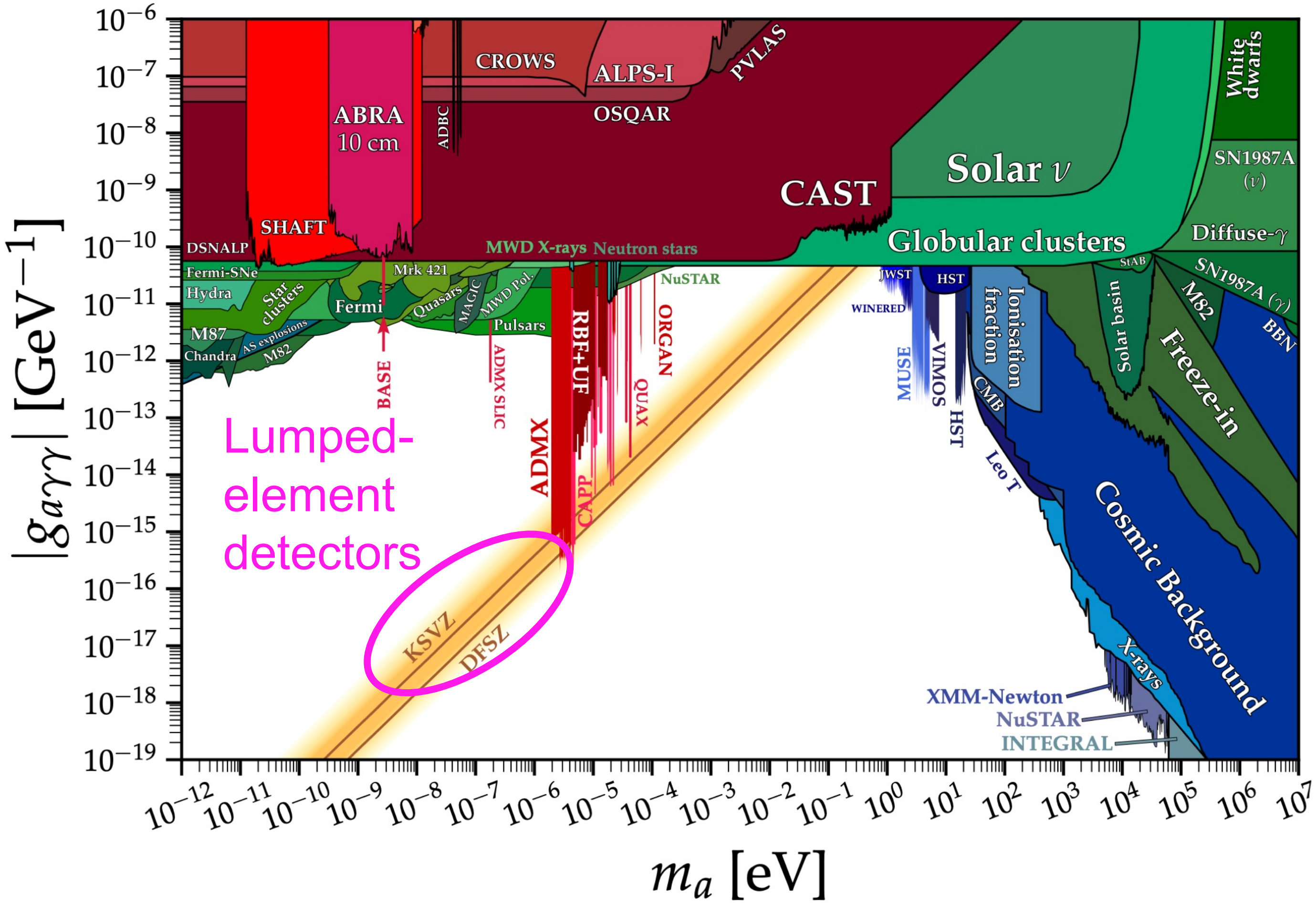
▶ HALOSCOPES: Laboratory searches looking for galactic axions

How to go to lower masses to search for GUT-scale axions?

Lower frequencies, (i.e. smaller m_a) requires increasingly **large** cavities

Lumped Element Detectors!

$m_a \backsim O(\text{neV})$
$\nu \backsim O(\text{kHz-GHz})$



https://cajohare.github.io/AxionLimits/

▶ HALOSCOPES: LUMPED-ELEMENT DETECTORS

Pilot experiments:

ABRACADABRA

ADMX SLIC

SHAFT

Next Generation:

WISPLC

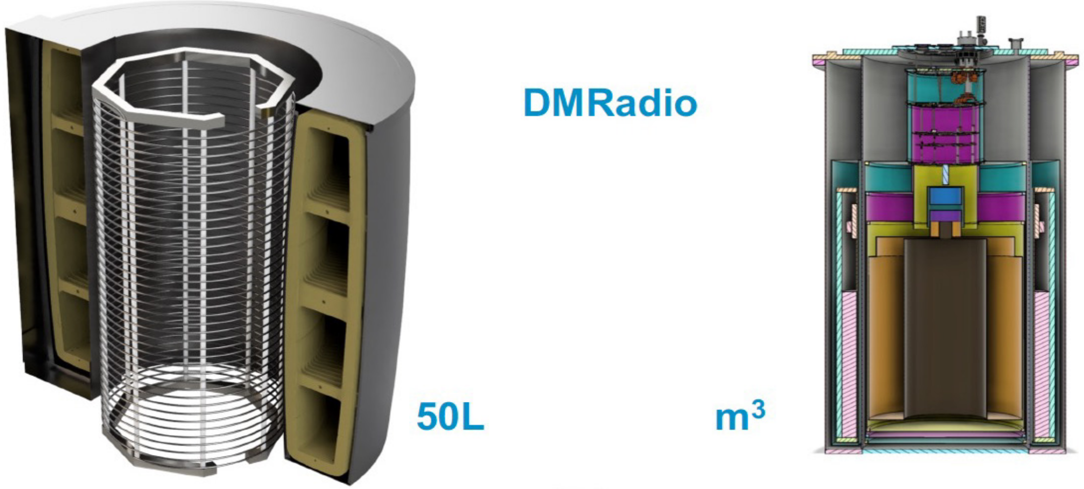
DMRadio

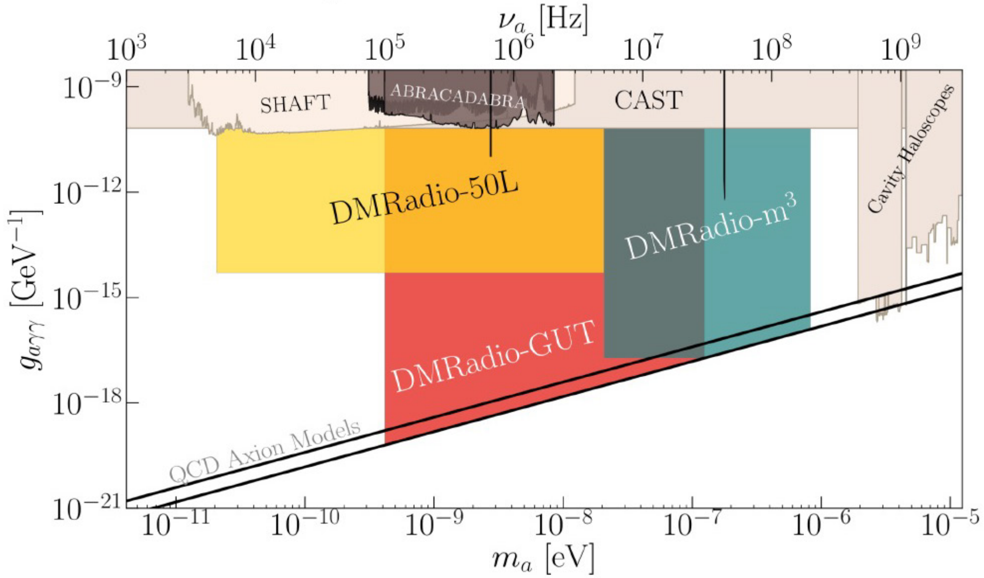
– DMRadio-50L
– DMRadio-m³

  (improvements in Q, V, B)

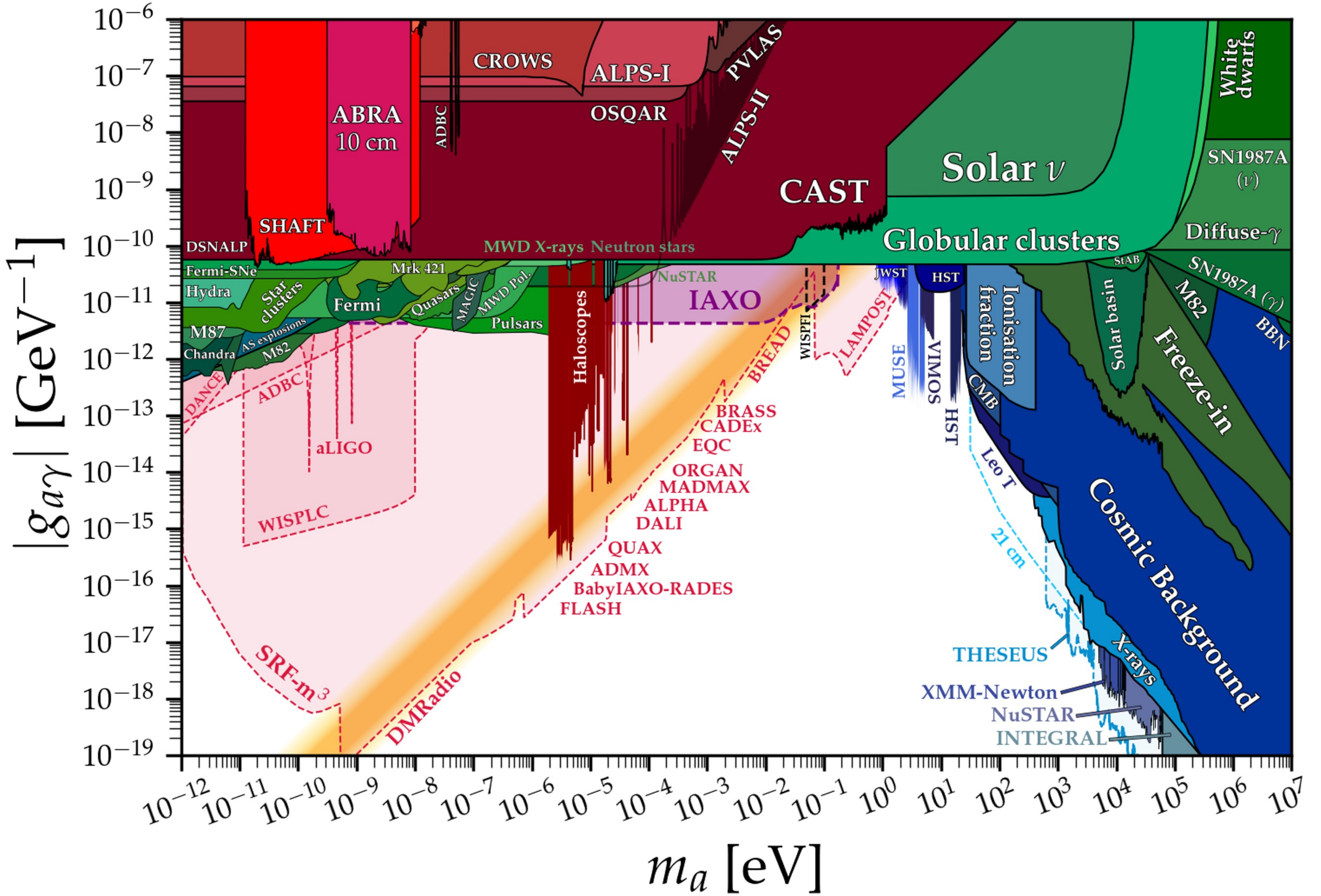
– DMRadio-GUT

  (ambitious next-next gen)





Detection of Axions III



https://cajohare.github.io/AxionLimits/

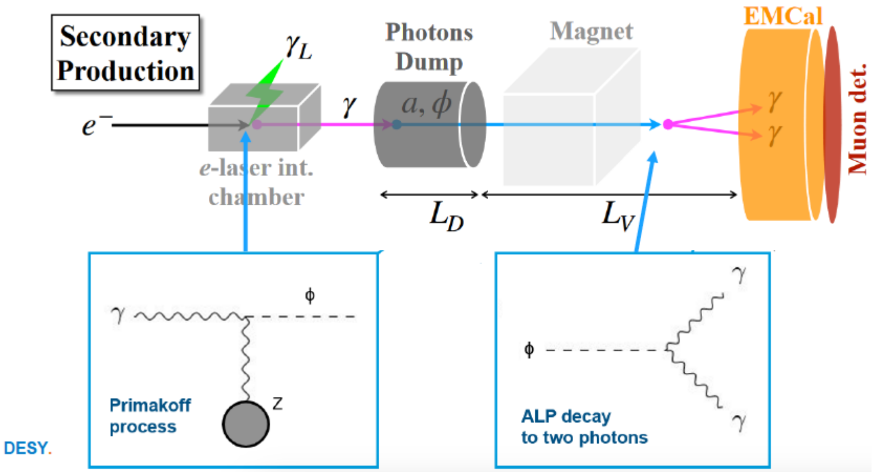
Outline

1. Why Axions?
2. **Detection of Axions**
   - Light-Shining-Through-Wall Searches
   - Helioscopes
   - Haloscopes
   - **Other Approaches**
3. Conclusions

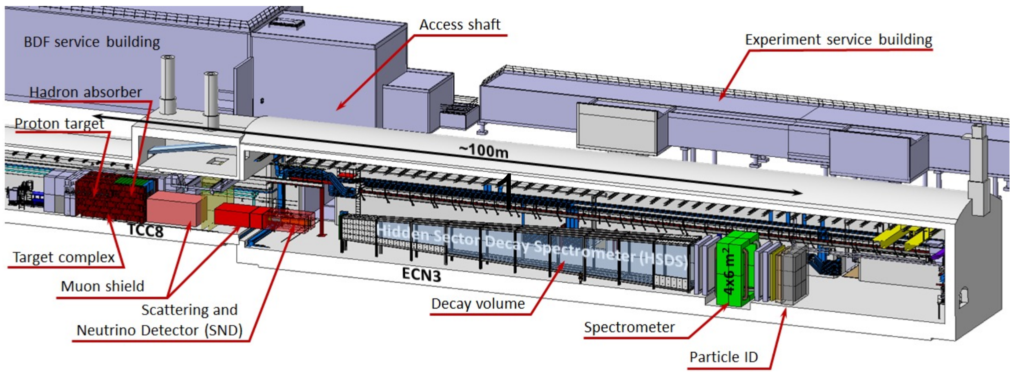
Detection of Axions IV

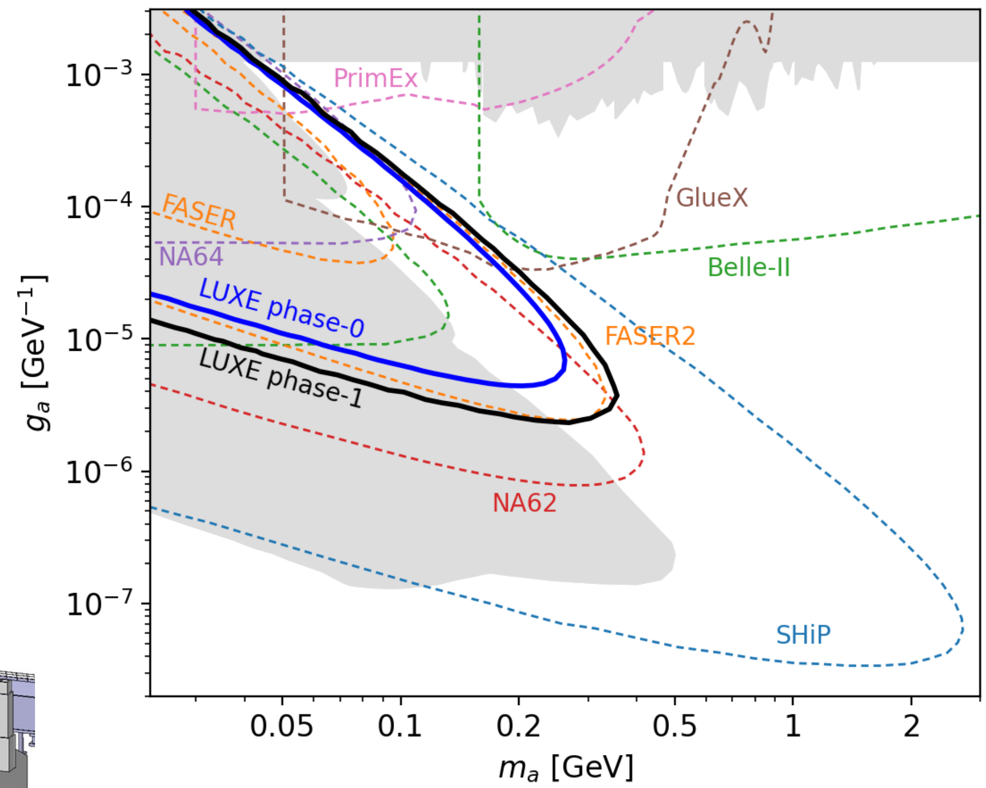
- Axions experiment using intense lasers (LUXE) or beam dump (SHiP)

LUXE@DESY



SHiP@CERN





SHiP@Göttingen2025: T23.3

Conclusions

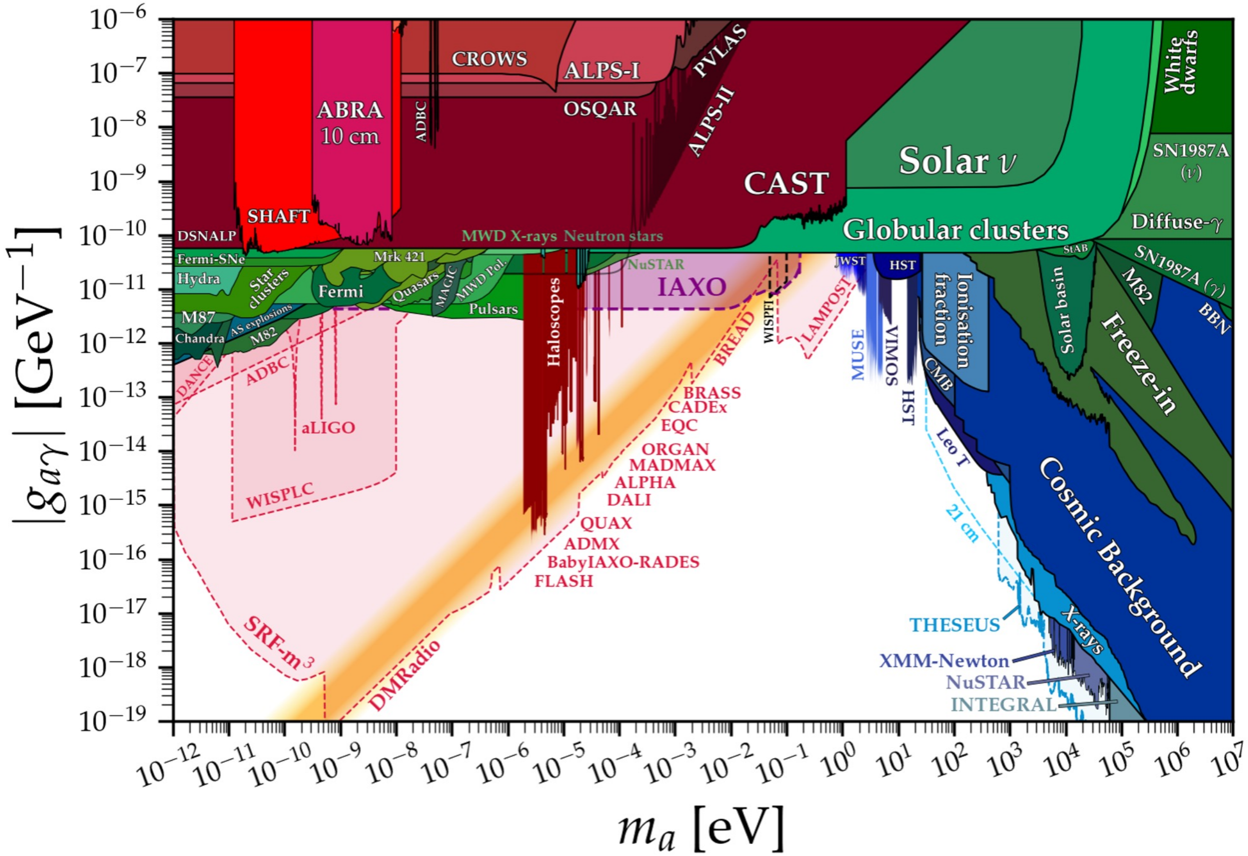
- Axions can solve strong CP & are simultaneously good DM candidates
- Axions/ALPs can be searched for in a variety of laboratory experiments: Haloscopes, Helioscopes, LSTW experiments,…
- Complementary searches are essential to cover all viable parameter space
- But wait, there is more:

  - More experiments

  - More couplings

  - More physics:

    DP, scalars,…



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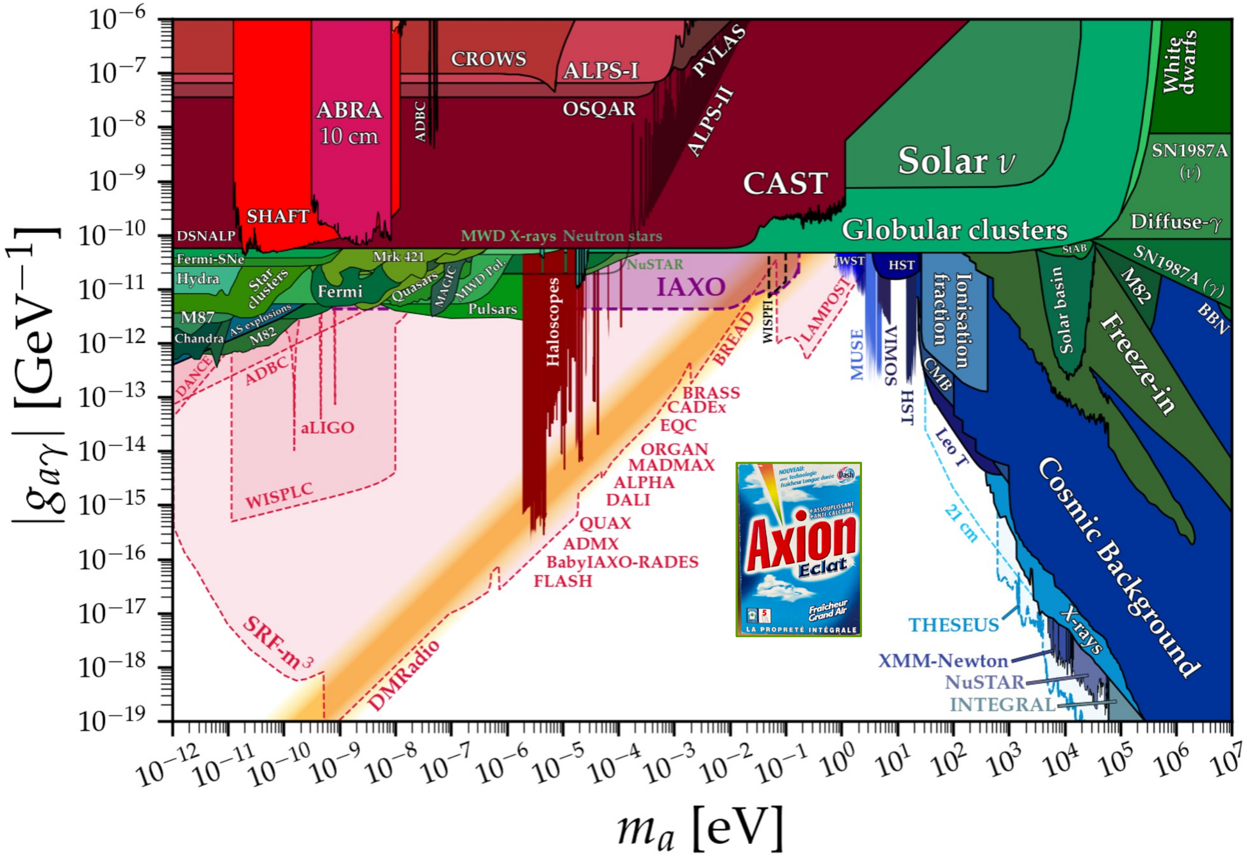


The (axion) future is bright!

Backup

Why is the electric dipole moment of the neutron (nEDM) so small?

- QCD Lagragian contains a CP violating term (with q-parameter of QCD vacuum)

$$\mathcal{L}_{\not{CP}} = \overline{\theta}\frac{\alpha_s}{8\pi}G^a_{\mu\nu}\widetilde{G}^{\mu\nu}_a$$

- Observational Consequences: Prediction of electric dipole moments (EDM) to hadrons, most importantly, to neutrons

Crewther,Di Vecchia,Veneziano,Witten 1979; Pospelov,Ritz 2000

$$d_n \sim 10^{-16}\ \bar{\theta}\ e\,\mathrm{cm}$$

- Latest measurements of the nEDM

Abel et al. 2020

$$|d_n| < 1.8 \times 10^{-26}\, e\,\mathrm{cm}$$

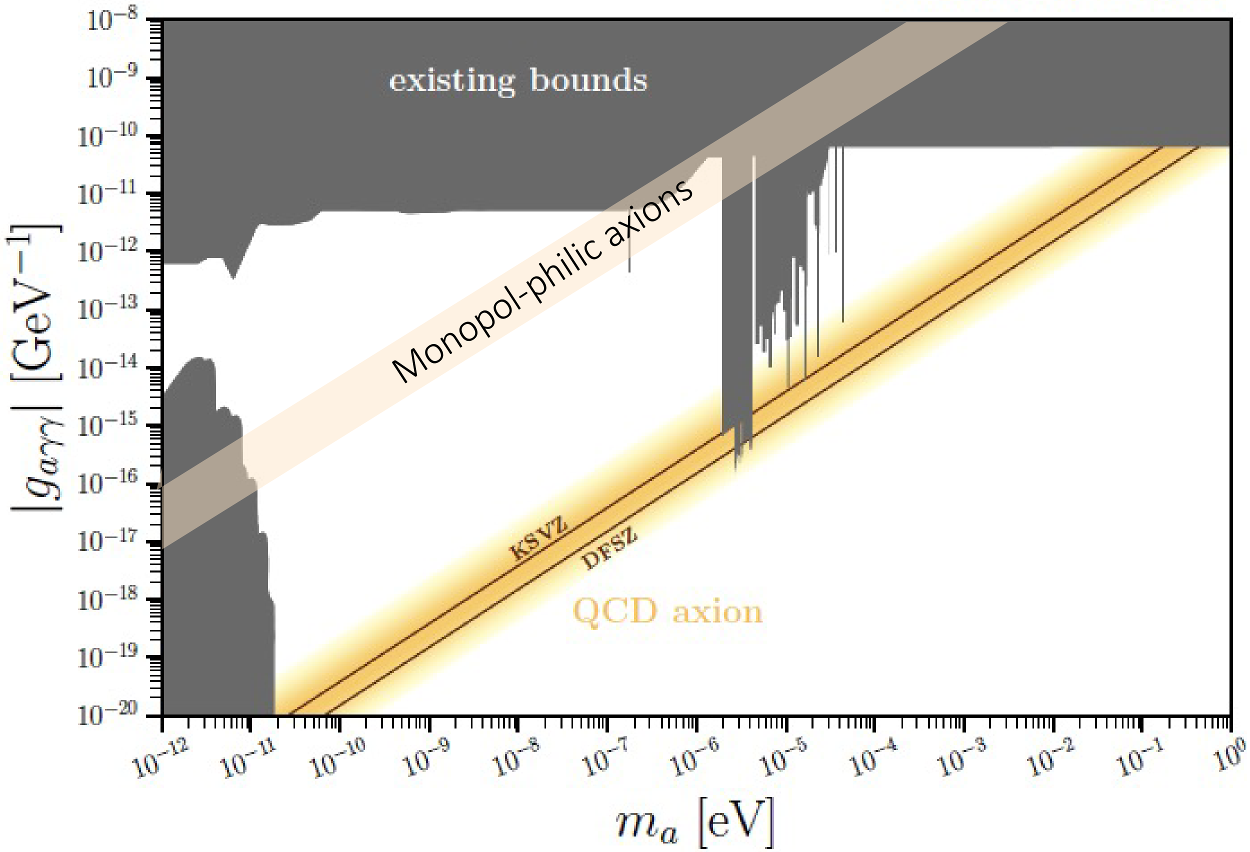
- Therefore expect $|\overline{\theta}| \lesssim 10^{-10}$

STRONG CP PROBLEM or WHY IS THETA SO SMALL?

Solving the strong CP problem: the QCD Axion

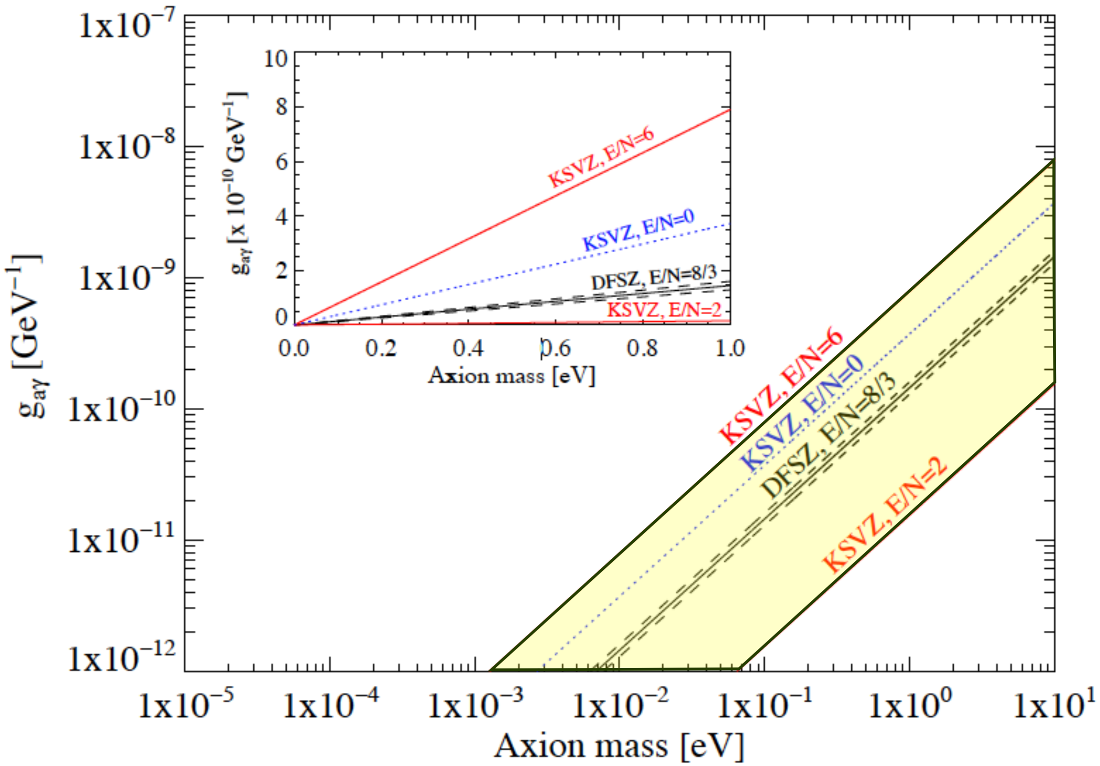
- **KSVZ**: axions couple to BSM quarks only
- **DFSZ**: axions couple to fermions
- Additionally, more recent models, e.g. Sokolov & Ringwald, JHEP 2021, 123 (2021)

A. Berlin et al.



Coupling of axions to photons exploited by many experiments

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



Traditional benchmark models

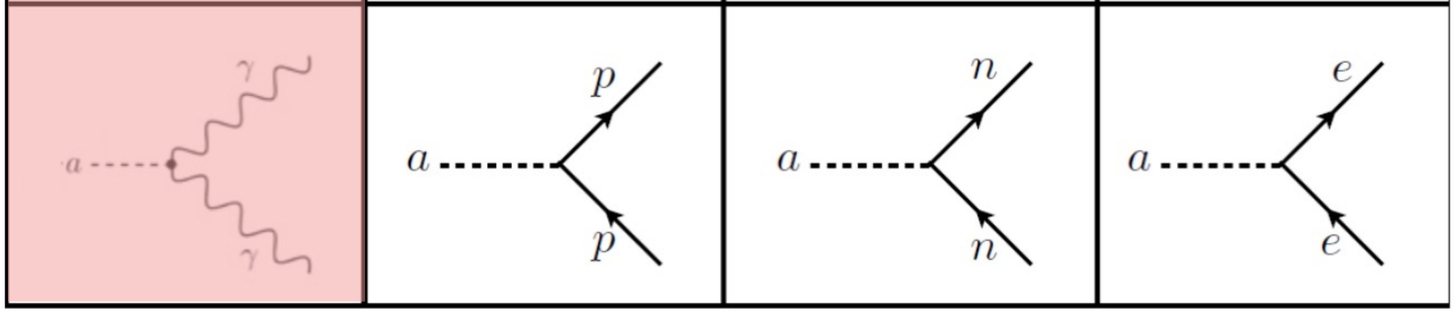
- **KSVZ**: axions couple to BSM quarks only
- **DFSZ**: axions couple to fermions

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

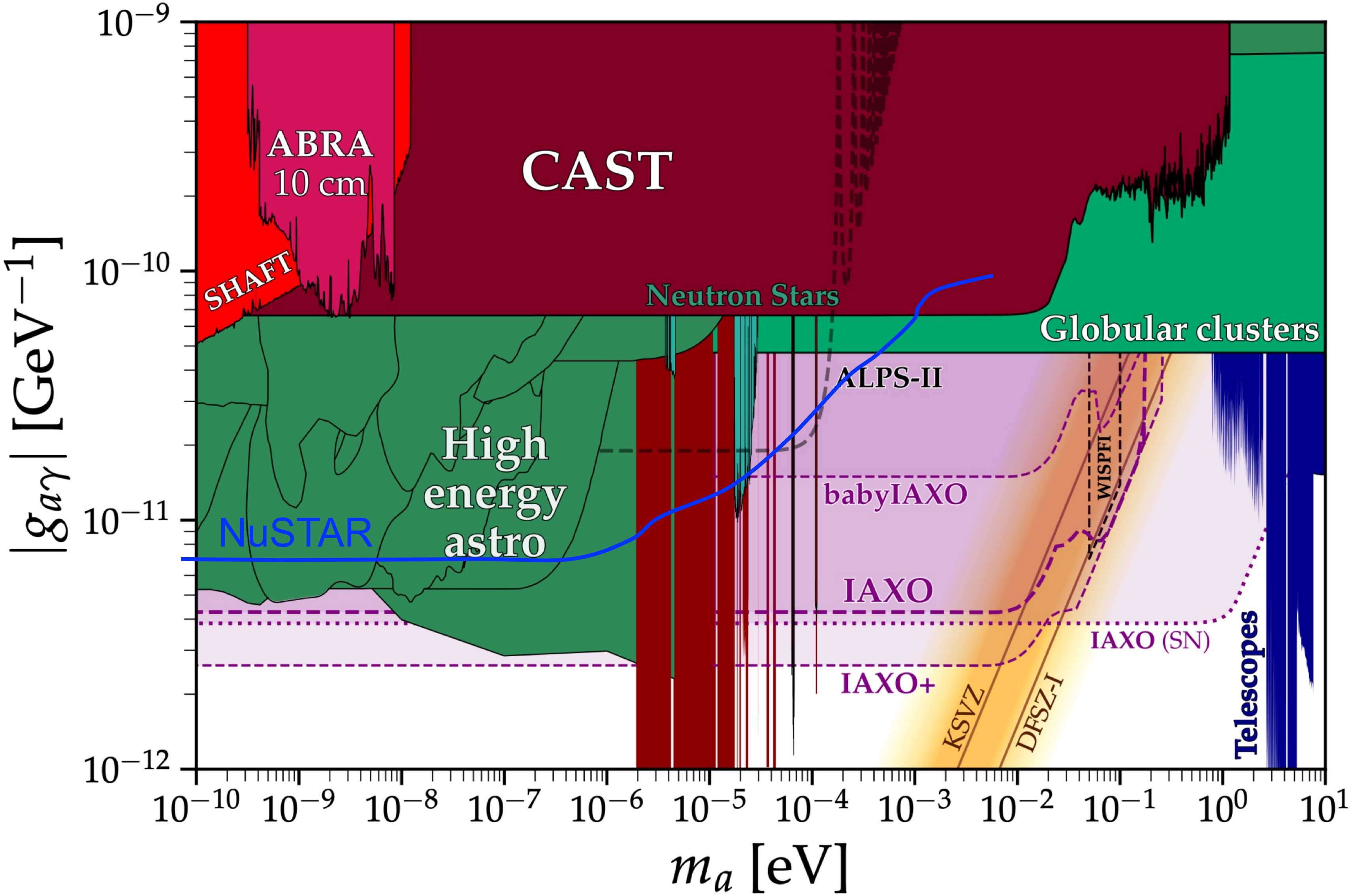


$$g_{a\gamma} = \frac{C_{a\gamma}\alpha}{2\pi f_a} \qquad g_{ap} = C_{ap}\frac{m_p}{f_a} \qquad g_{ap} = C_{an}\frac{m_n}{f_a} \qquad g_{ap} = C_{ae}\frac{m_e}{f_a}$$

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

Detection of Axions II

Helioscopes (no DM requirement)



NuSTAR@Göttingen2025: T89.4

▶ HALOSCOPES: DISH ANTENNAS

Horns *et al* JCAP04(2013)016
F. Bajjali et al., JCAP 08 (2023), 077

$P/A \propto B^2$

BRASS@ U. Hamburg

- Consists of plane permanently magnetized conversion panel

$$B = 0.8\,\mathrm{T}$$
$$A = 4.7\,\mathrm{m}^2$$

- Spherical reflector

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!
- BRASS@ U. Hamburg

Detection of Axions III

▶ HALOSCOPES: DISH ANTENNAS

Horns *et al* JCAP04(2013)016
Liu et al., PRL 128 (2022) 131801

$P/A \propto B^2$

BREAD@ Fermilab

- Cylindric parabolic conversion panel allows use of solenoidal magnetic field

$$B \sim 10\,\mathrm{T}$$

$$\mathcal{A} \sim 10\,\mathrm{m}^2$$

Concept: Axion induced radiation from a magnetized metal slab

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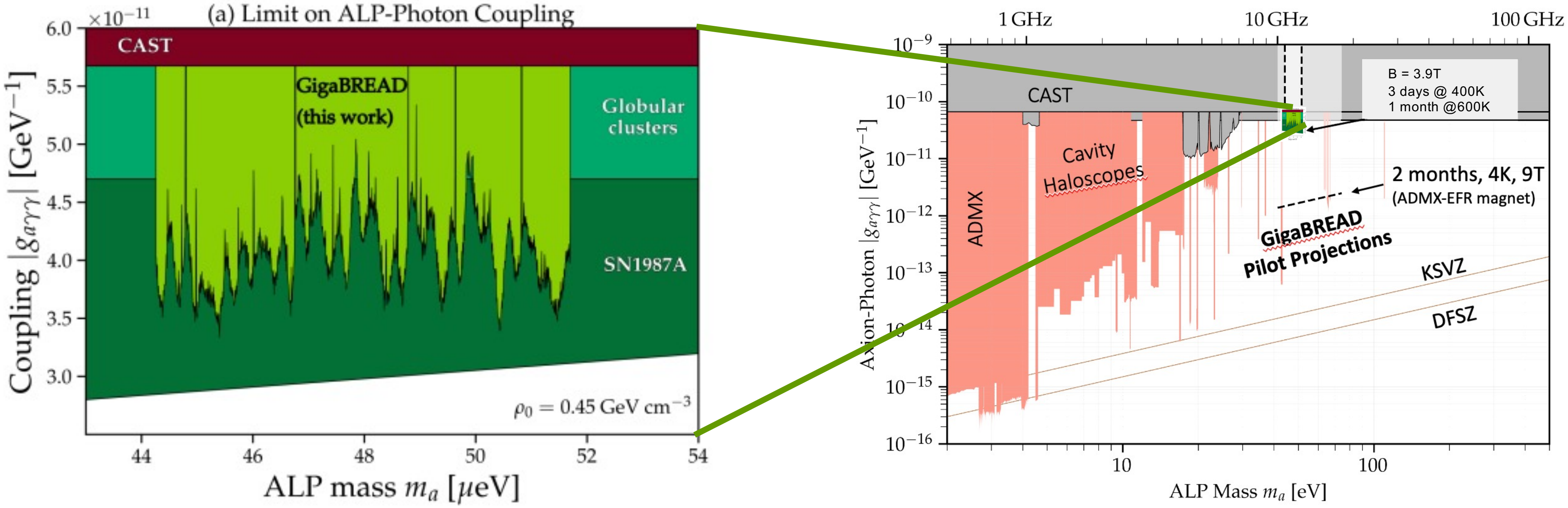
- BRASS@ U. Hamburg, BREAD@ Fermilab

▶ HALOSCOPES: DISH ANTENNAS

Hoshino *et al.*, arXiv 2501.17119



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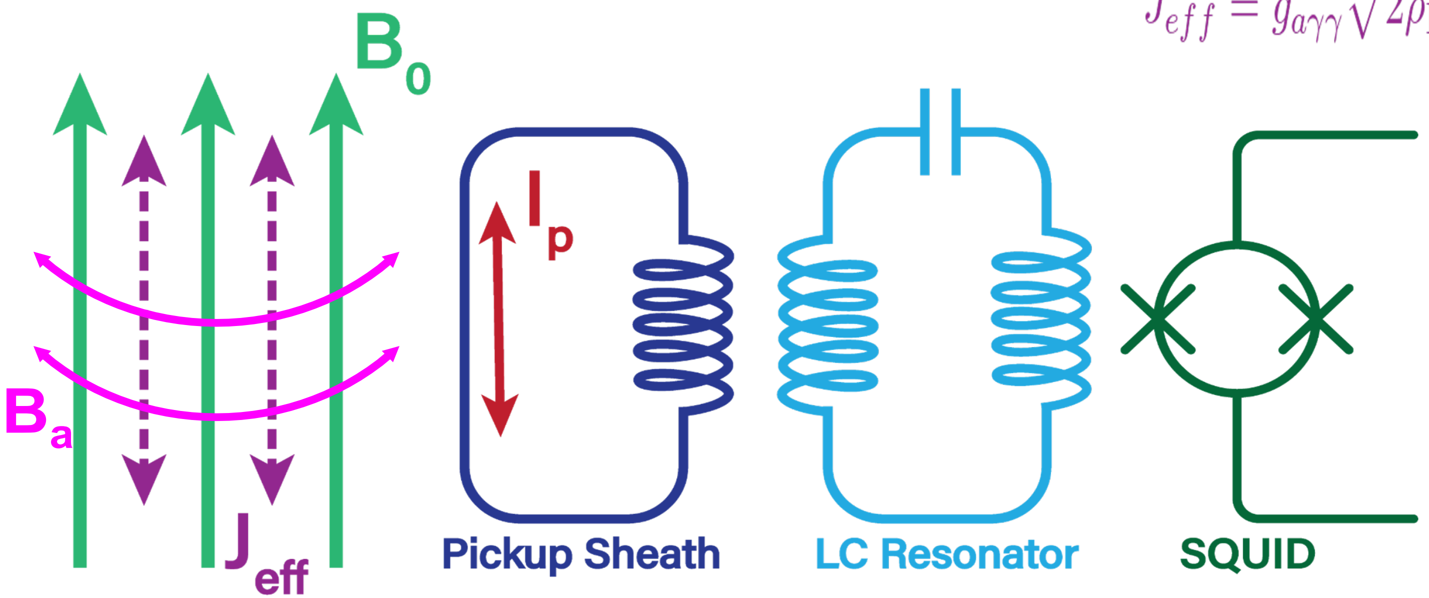
- BRASS@ U. Hamburg, BREAD@ Fermilab

▶ HALOSCOPES: LUMPED-ELEMENT DETECTORS

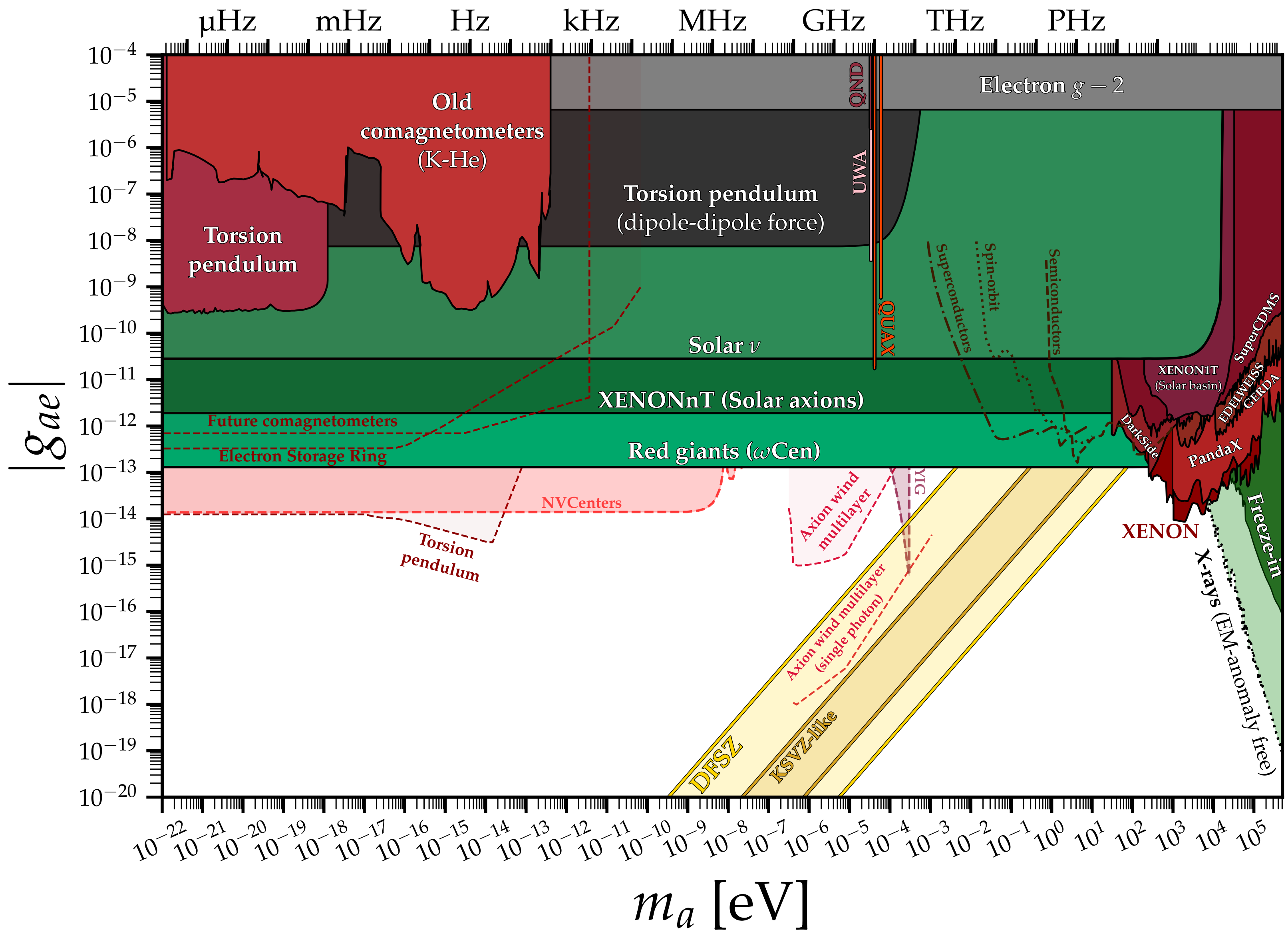
$$\vec{J}_{eff} = g_{a\gamma\gamma}\sqrt{2\rho_{\rm DM}}\cos(m_a t)\vec{B}_0$$



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

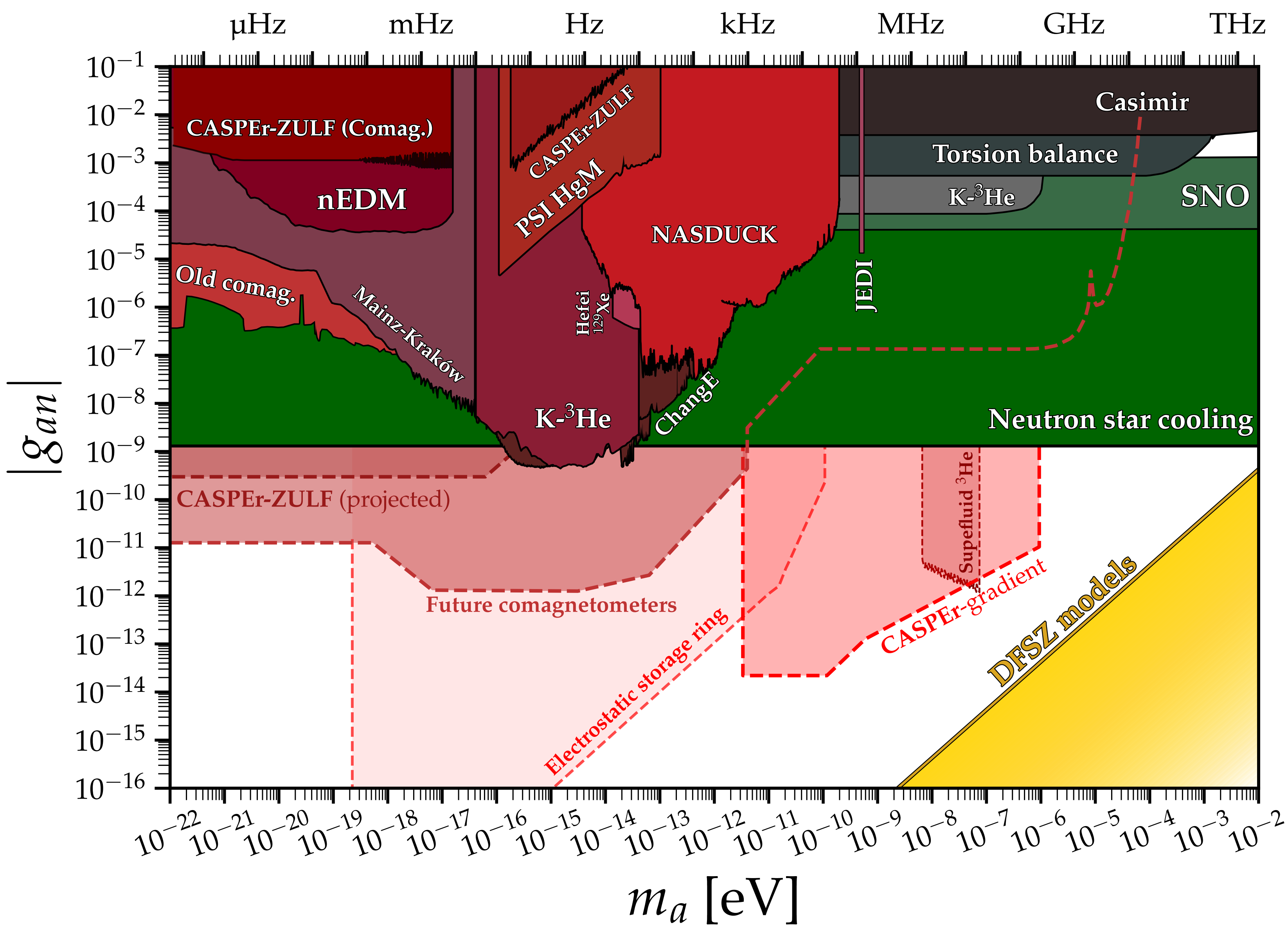
- J_{eff} in turn generates oscillating magnetic flux B_a (azimuthal)
- Can use pickup structure to read this
- Couple LC resonator inductively and use SQUID readout scheme

Detection of Axions



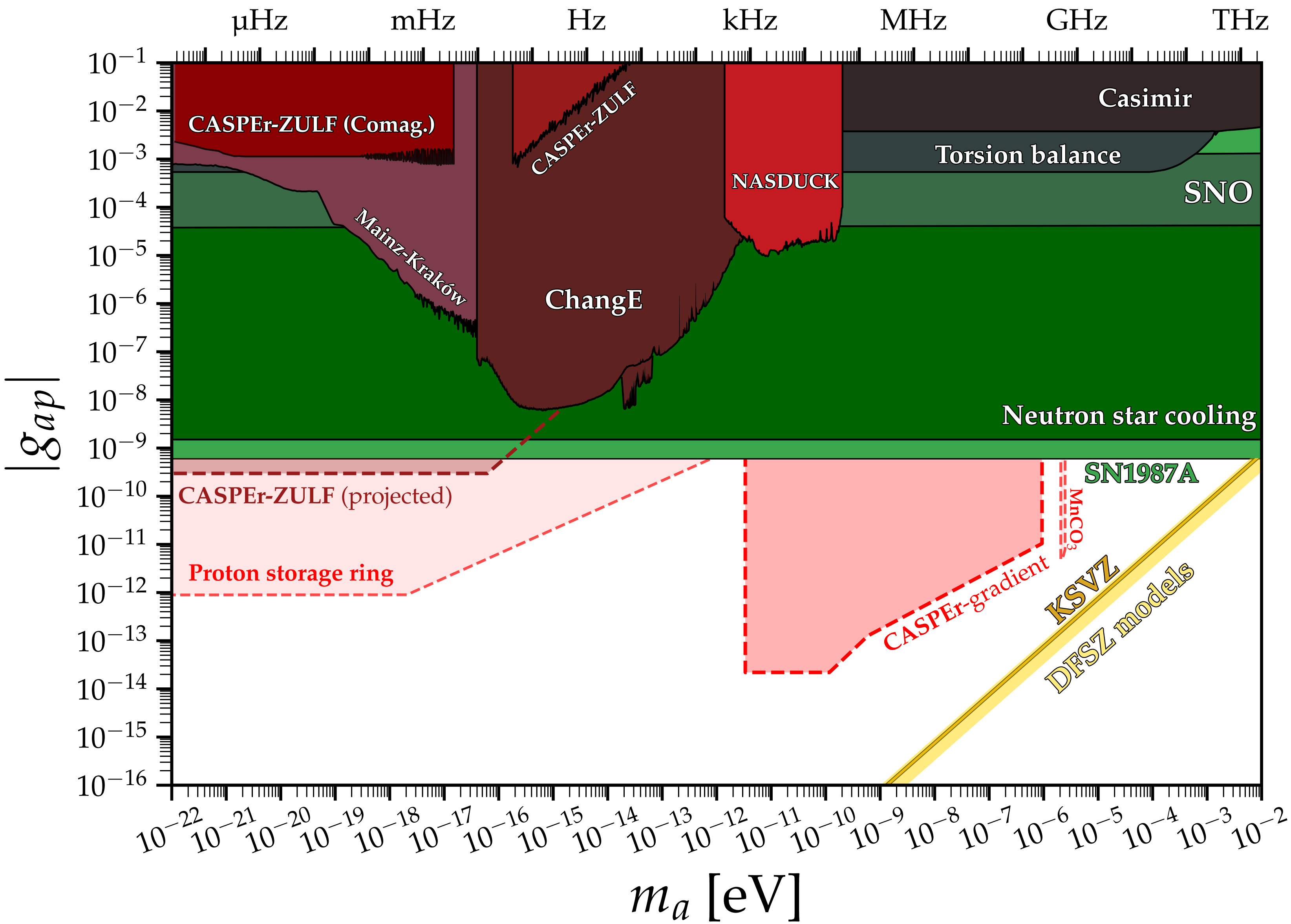
tu dortmund university

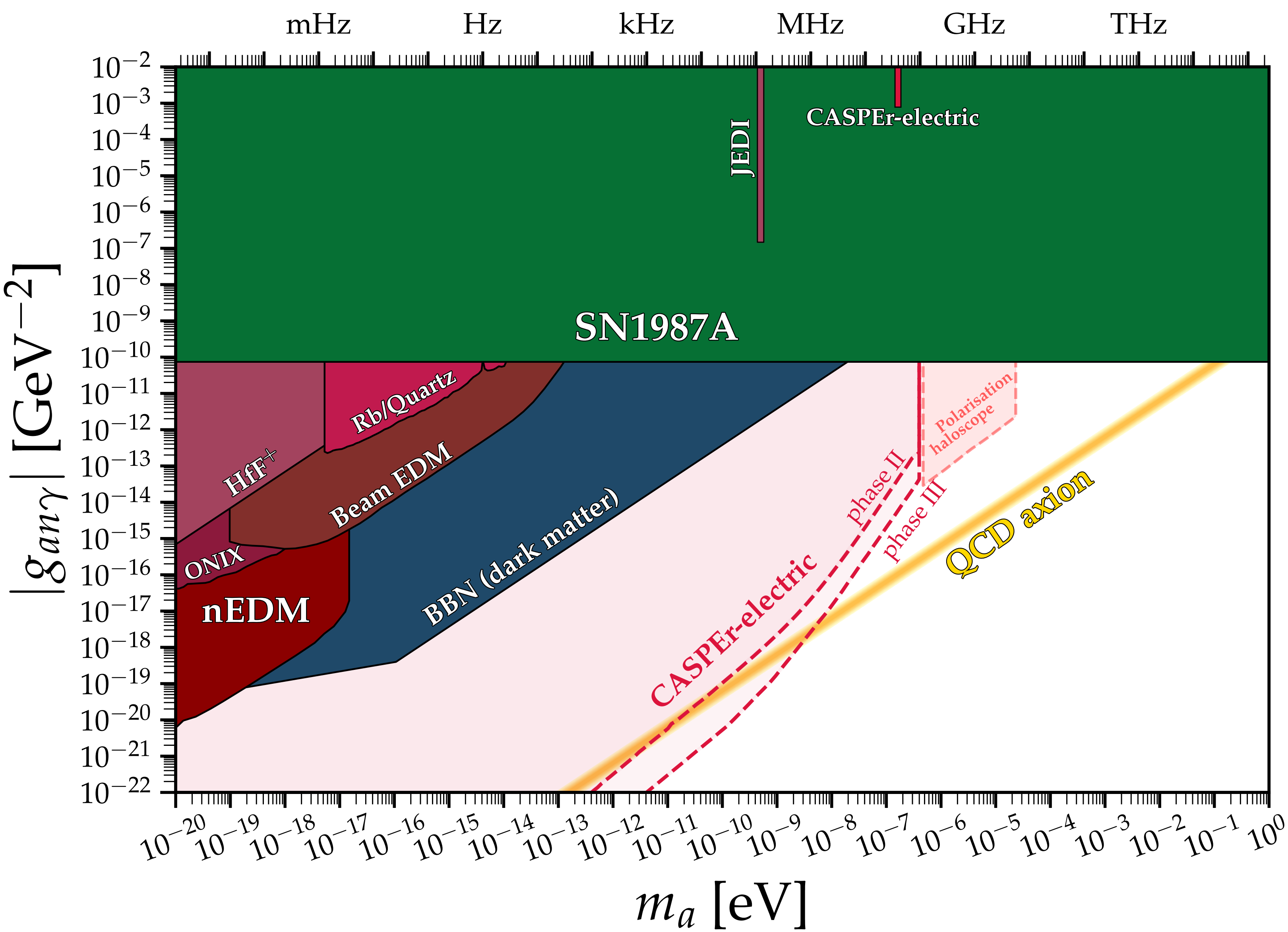
Other couplings



tu dortmund university

Detection of Axions




mHz
Hz
kHz
MHz
GHz
THz
10^{-2}
10^{-3}
10^{-4}
10^{-5}
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10^{-8}
10^{-9}
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10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
$|g_{an\gamma}|$ [GeV^{-2}]
JEDI
CASPEr-electric
SN1987A
Rb/Quartz
HfF+
Beam EDM
ONIX
nEDM
BBN (dark matter)
Polarisation haloscope
phase II
phase III
QCD axion
CASPEr-electric
10^{-20}
10^{-19}
10^{-18}
10^{-17}
10^{-16}
10^{-15}
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10^{-13}
10^{-12}
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10^{-8}
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10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
m_a [eV]

Full panorama