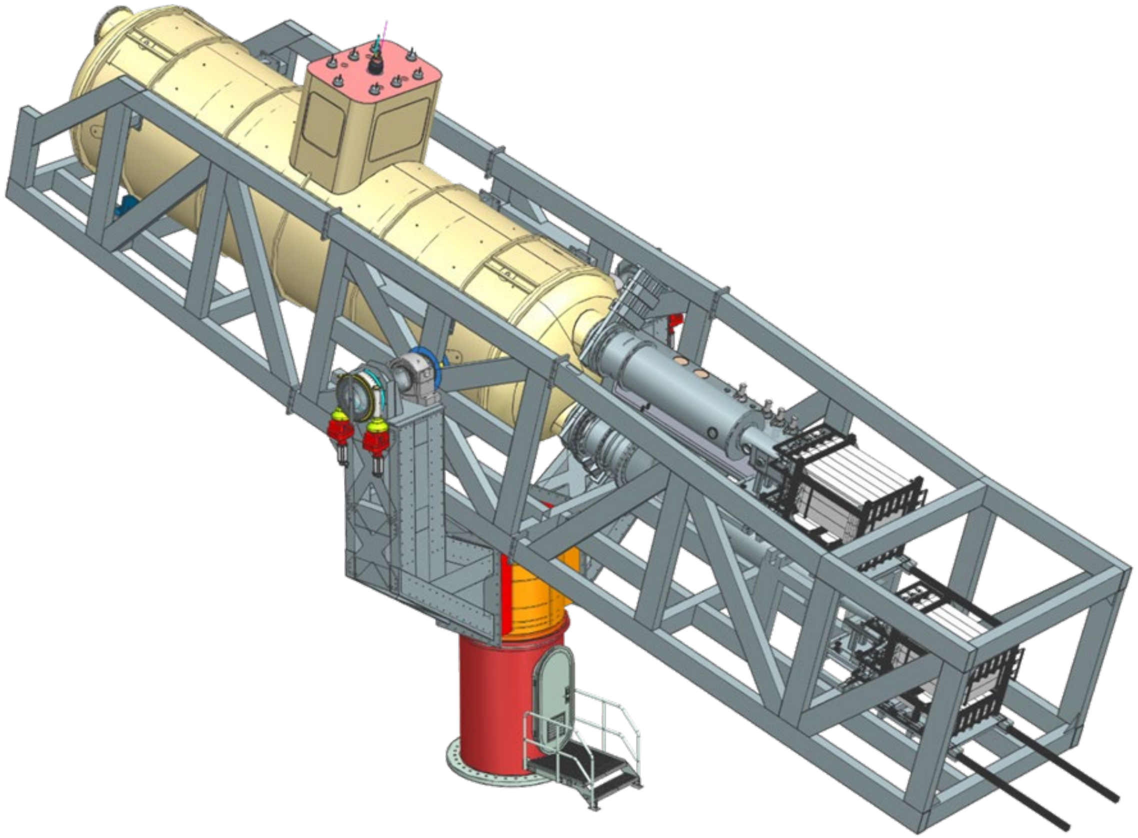
Axion searches with BabyIAXO



Gloria Luzón
on behalf of the IAXO Collaboration

November 3, 2025

TeVPA 2025, Valencia, Spain

Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

Outlook

- What are axions?
- Why and how to search for them
- Experimental efforts and astrophysical limits
- Solar axion searches: helioscopes
  - Production in the Sun and detection working principle
  - Cast: state of the art
  - The International Axion Observatory (IAXO)
  - BabyIAXO: the intermediate stage
- The (Baby)IAXO physics case
- Conclusions

What are axions?

- Hypothetical particles proposed to solve the strong CP problem.
  - CP violation expected in QCD, but not observed experimentally (θ , nEDM)

$$|\theta| < 1.3 \times 10^{-10} \quad \Longrightarrow \quad \mathcal{L}_{\cancel{CP}} = \theta \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \widetilde{G}^{\mu\nu}_a$$

  - Peccei-Quinn mechanism (1977): Problem solved dynamically →A new global U(1) symmetry, θ turn into a dynamical variable, relaxes to zero

$$\Downarrow$$

  - Axion: a pseudo Goldstone-Boson of spontaneous symmetry breaking of PQ at yet unknown scale f_a

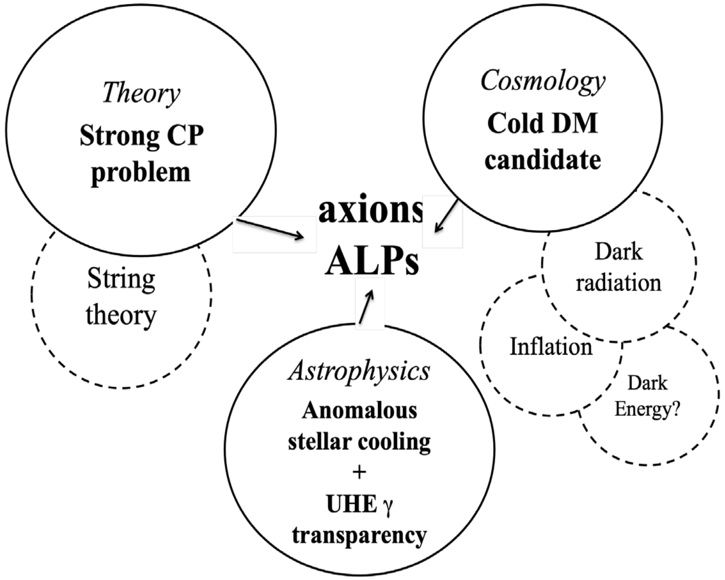
$$\boxed{m_a \approx 0.6\, eV \times \frac{10^7 GeV}{f_a}}$$

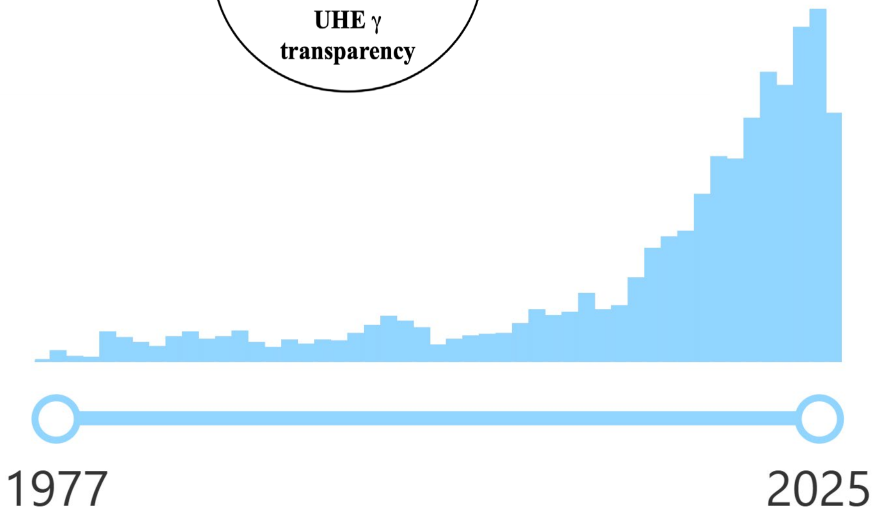
- Strong candidates for dark matter

Why axions

*Plenary talk by Javier Redondo

- Most compelling solution to the Strong CP problem of the SM
- Axion-like particles (ALPs) predicted by many extensions of the SM (e.g. string theory)
- Axions, like WIMPs, may solve the DM problem for free. (i.e. not ad hoc solution to DM)
- Astrophysical hints for axion/ALPs?
- Relevant axion/ALP parameter space at reach of current and near-future experiments
- Rapidly increasing interest & experimental efforts devoted to axions





How to search for them: axion-photon coupling

- Generic two photons interaction $L_{a\gamma\gamma} = g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$

$$g_{a\gamma\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - 1.92(4)\right) = \left(0.203(3)\frac{E}{N} - 0.39(1)\right)\frac{m_a}{\mathrm{GeV}^2}$$

$$\boxed{g_{a\gamma\gamma} \sim m_a}$$

✓DFSZ Model → E/N=8/3
✓Hadronic Models→ E/N =0 - 2 KSVZ

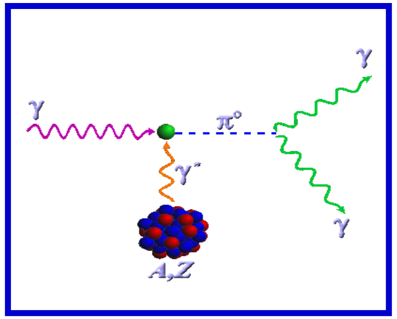
- \+ Axioelectric interactions → only for non hadronic models

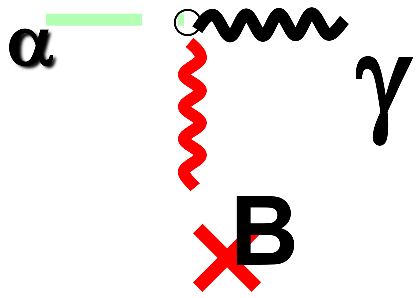
$$\mathcal{L}_{aff} = \frac{C_f}{2f_a}\partial_\mu a \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$

- **ALPS → BSM interactions** $\boxed{g_{a\gamma\gamma} \not\sim m_a}$

Primakoff effect(1951)

Behind most of the current experimental efforts



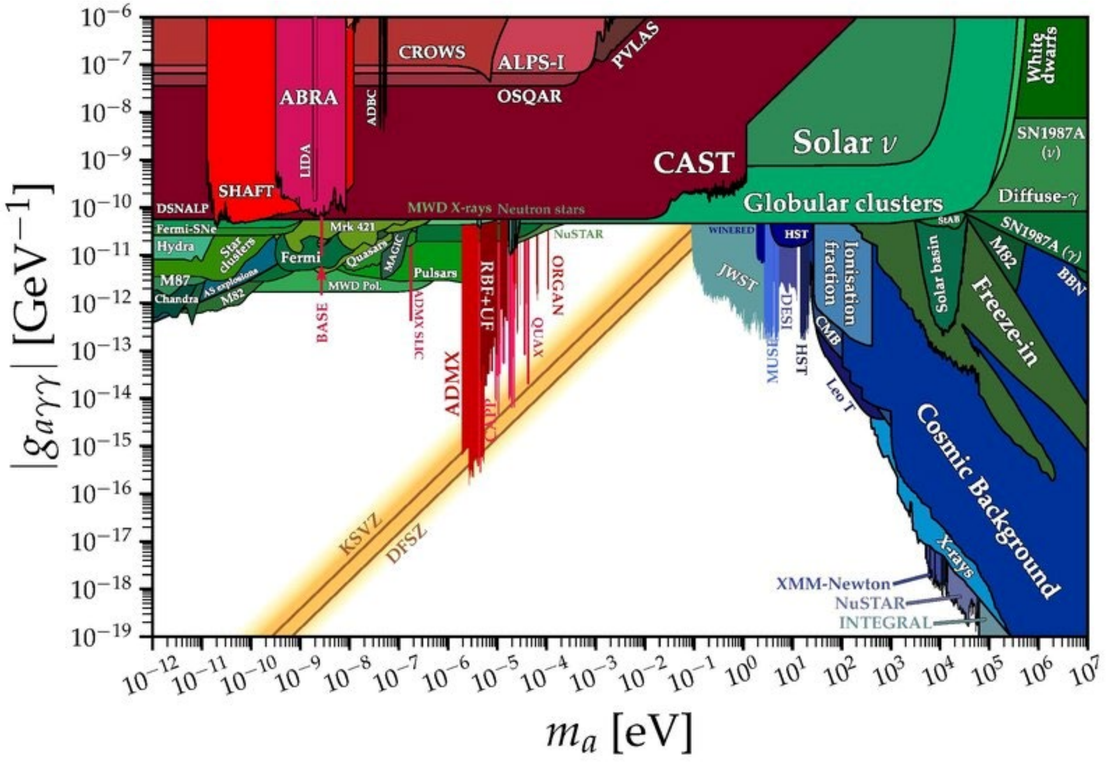


Axion production in intense EM fields

Experimental efforts and astrophysical/cosmological limits

Source		Experiments	Model & Cosmology dependency
Relic axions		ADMX, HAYSTAC, CASPEr, CAPP, MADMAX, QUAX, **RADES*-DARKQUANTUM****, ORGAN, …	High
Lab axions		ALPS, OSQAR, CROWS, ARIADNE,…	Very low
Solar axions		SUMICO, CAST, **(Baby)IAXO**	Low

*Talk by Cristian Cogollos
**Laura Segui's Poster

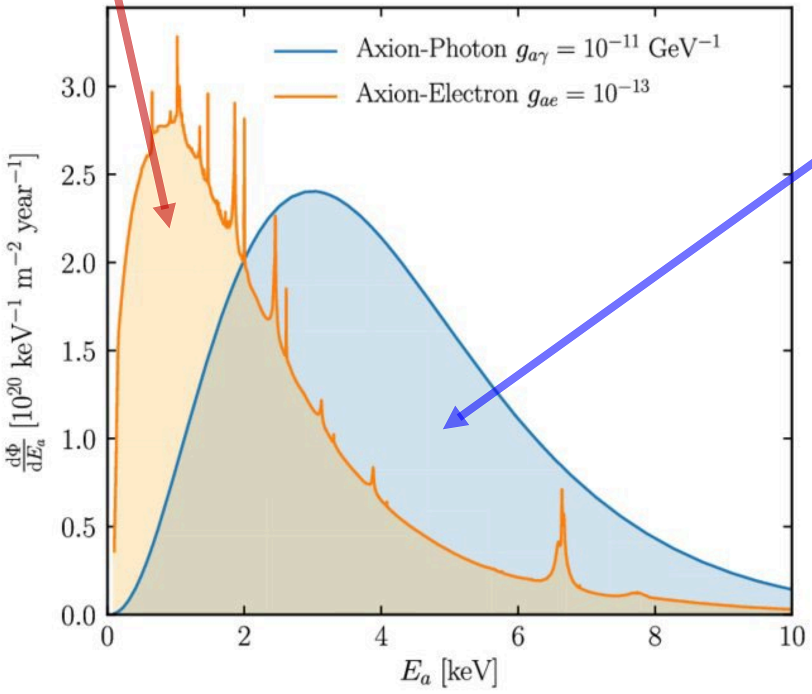


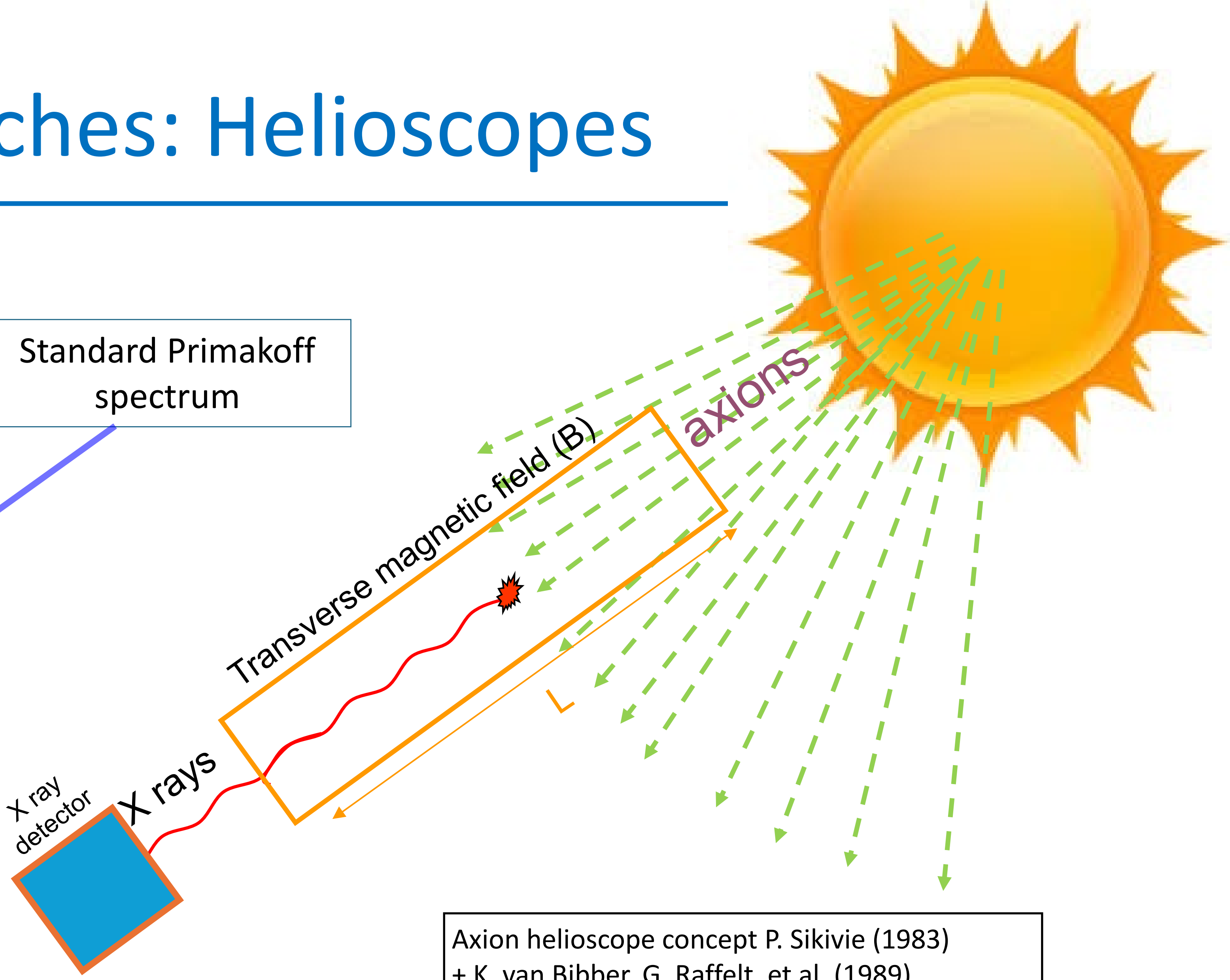
Earth based experiments. Astro/cosmo: no DM asumption and some asumptions. Band expectation for the QCD axion.

Solar axion searches: Helioscopes

Non-hadronic "ABC"
Solar axion flux

Standard Primakoff
spectrum





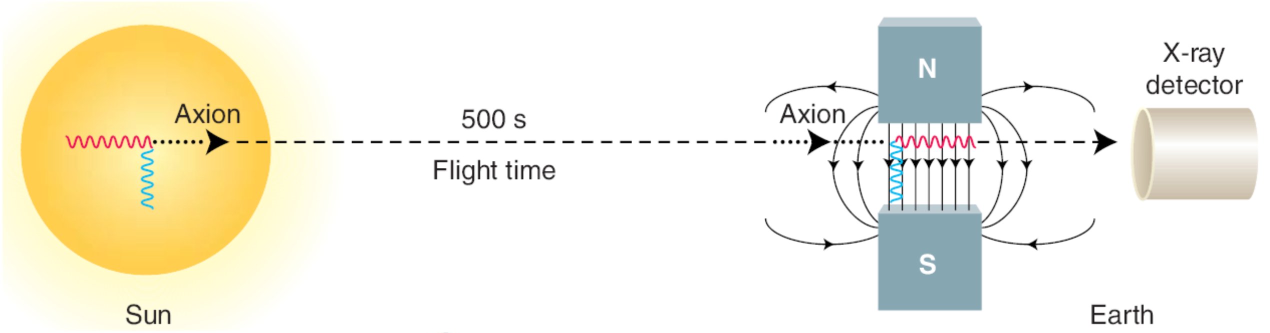
Axion helioscope concept P. Sikivie (1983)
+ K. van Bibber, G. Raffelt, et al. (1989)
(use of buffer gas)

Helioscopes: detection working principle

- First axion helioscope proposed by P. Sikivie

P. Sikivie 1983 PRL 51 1415

Reconversions of axions into x-ray photons possible in strong laboratory magnetic field



$$P_{a\to\gamma} = \left(\frac{BLg_{a\gamma\gamma}}{2}\right)^2 \qquad \frac{qL}{2} < \pi \qquad q = \frac{m_a^2}{2E_a}$$

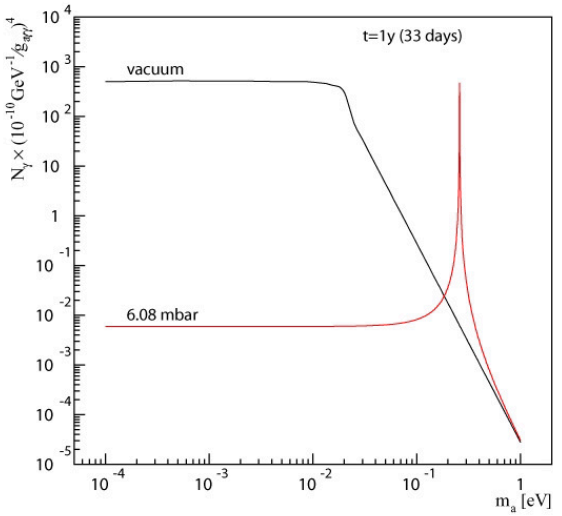
- Idea refined by K. van Bibber et al.

Van Bibber et al 1989 Phys. Rev. D 39 2089

Buffer gas to restore coherence over long magnetic field and access higher axion masses

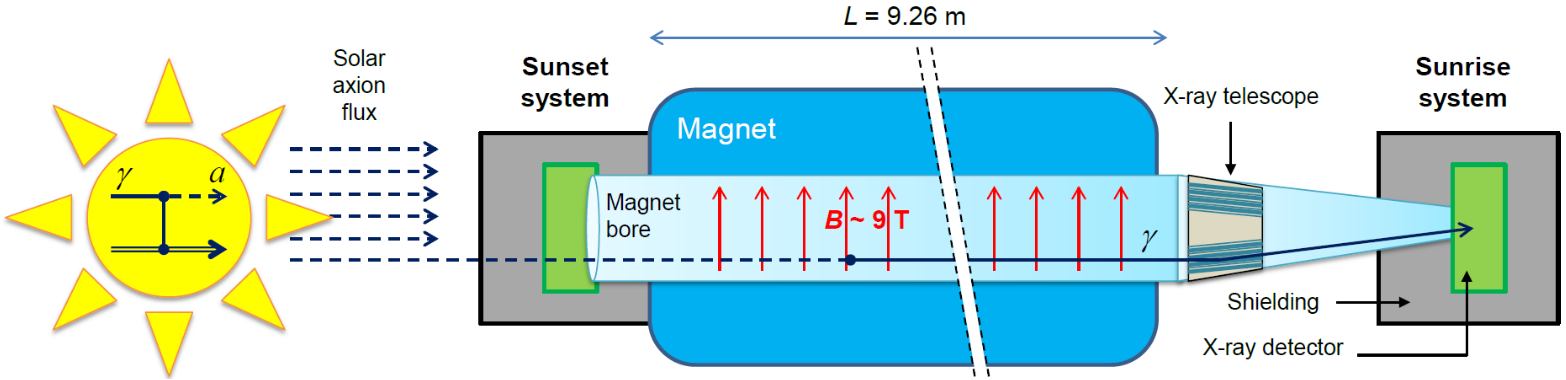
$$P_{a\to\gamma} = \left(\frac{Bg_{a\gamma\gamma}}{2}\right)^2 \frac{1}{q^2+\Gamma^2/4}\left[1+e^{-\Gamma L}-2e^{-\Gamma L/2}\cos(qL)\right] \qquad q = \left|\frac{m_\gamma^2 - m_a^2}{2E_a}\right|$$

CAST



CAST: state-of-the-art

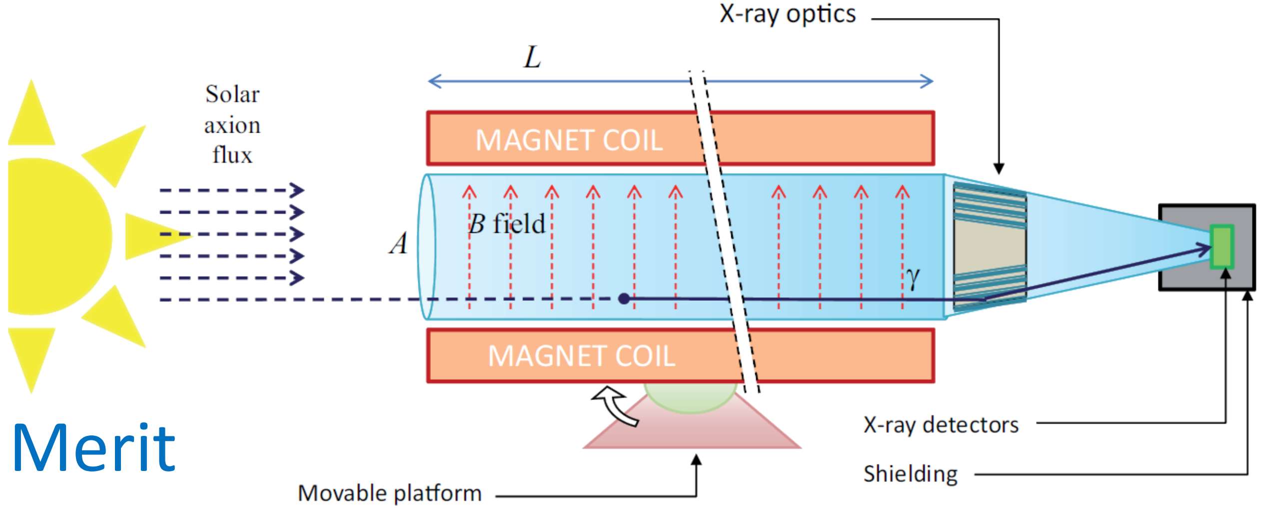
First helioscope using low background techniques & x-ray focusing



CAST First Results: **PRL 94 (2005)121301** Vacuum
CAST phase I final results: **JCAP (2007) 010** ^{4}He
CAST phase II latest results: **JCAP (2009) 008** ^{3}He
CAST phase III:**Nature Physics 13 (2017) 584** Vacuum

IAXO (International Axion Observatory) concept

Enhanced axion helioscope:
Irastorza et al 2011
JCAP 1106, 013



Helioscope Figure of Merit

Measure of sensitivity to axion-photon interaction:

$$g_{a\gamma}^{4} \propto \underbrace{(BL)^{-2} A^{-1}}_{\text{magnet}} \times \underbrace{t^{-1/2}}_{\text{exposure}} \times \underbrace{s^{1/2} \varepsilon_0^{-1}}_{\text{optics}} \times \underbrace{b^{1/2} \varepsilon^{-1}}_{\text{detectors}}$$

magnet
B = magnetic field
L = magnet length
A = cross-sectional area

exposure
t = time

optics
s = spot size
ε_0 = efficiency

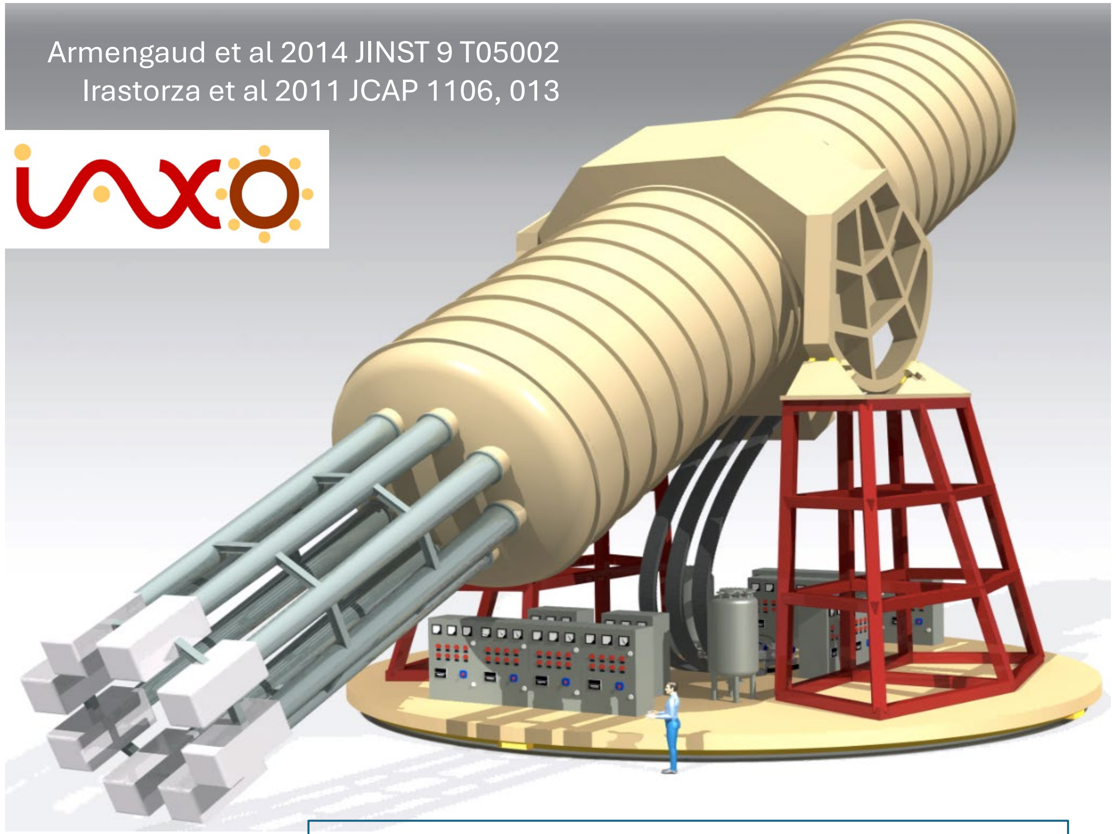
detectors
b = background
ε = efficiency

The smaller $g_{a\gamma}$, the better!

Expect improvement for next generation (International Axion Observatory):
1−1.5 orders of magnitude in sensitivity to $g_{a\gamma}$ (4+ orders of magnitude better S/N than CAST

IAXO: Cutting-Edge experiment

- Next generation "axion helioscope" after CAST→ mature technology
- Purpose-built large-scale magnet
  - >300 times larger FOM than CAST magnet
  - Toroidal geometry, up to 5.4 T
  - 8 conversion bores of 60 cm Ø, ~25 m long
- Detection systems (XRT+detectors)
  - Scaled-up versions based on experience in CAST
  - Low-background techniques for detectors
  - Optics based on slumped-glass technique used in NuStar
- ~50% Sun-tracking time
- Large magnetic volume available for additional "axion" physics (e.g. DM setups)

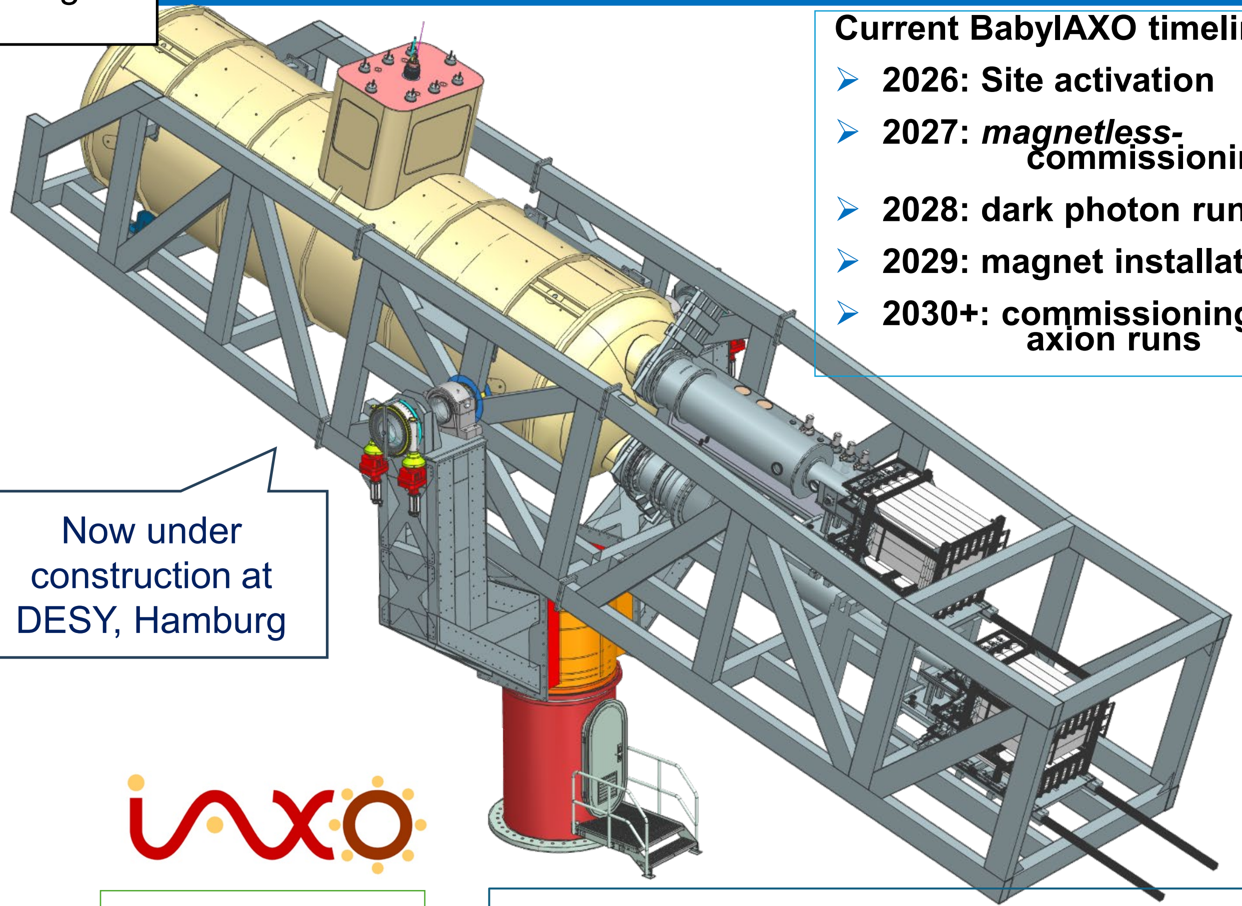


$g_{a\gamma} \lesssim$ few 10^{-12} GeV^{-1} (expected)

$g_{a\gamma} \lesssim 5.7 \times 10^{-11}$ GeV^{-1}

BabyIAXO: An intermediate experimental stage

BabyIAXO conceptual design
JHEP 05 (2021) 137



Current BabyIAXO timeline:
- **2026: Site activation**
- **2027: *magnetless*-commissioning**
- **2028: dark photon run**
- **2029: magnet installation**
- **2030+: commissioning + axion runs**

- A technological prototype of IAXO
  - Two bores of dimensions similar to final IAXO bores → detection lines representative of final ones.
  - Magnet will test design options of final IAXO magnet→upscalable
  - X-ray optics/detectors close to final IAXO configuration (focal length, performance)
  - Test & improve all systems. Risk mitigation for full IAXO

Now under construction at DESY, Hamburg

- Relevant physics outcome

  (~100 times larger FOM than CAST)

European Research Council
Established by the European Commission

ERC-AvG 2017 IAXO+

~100x CAST SNR

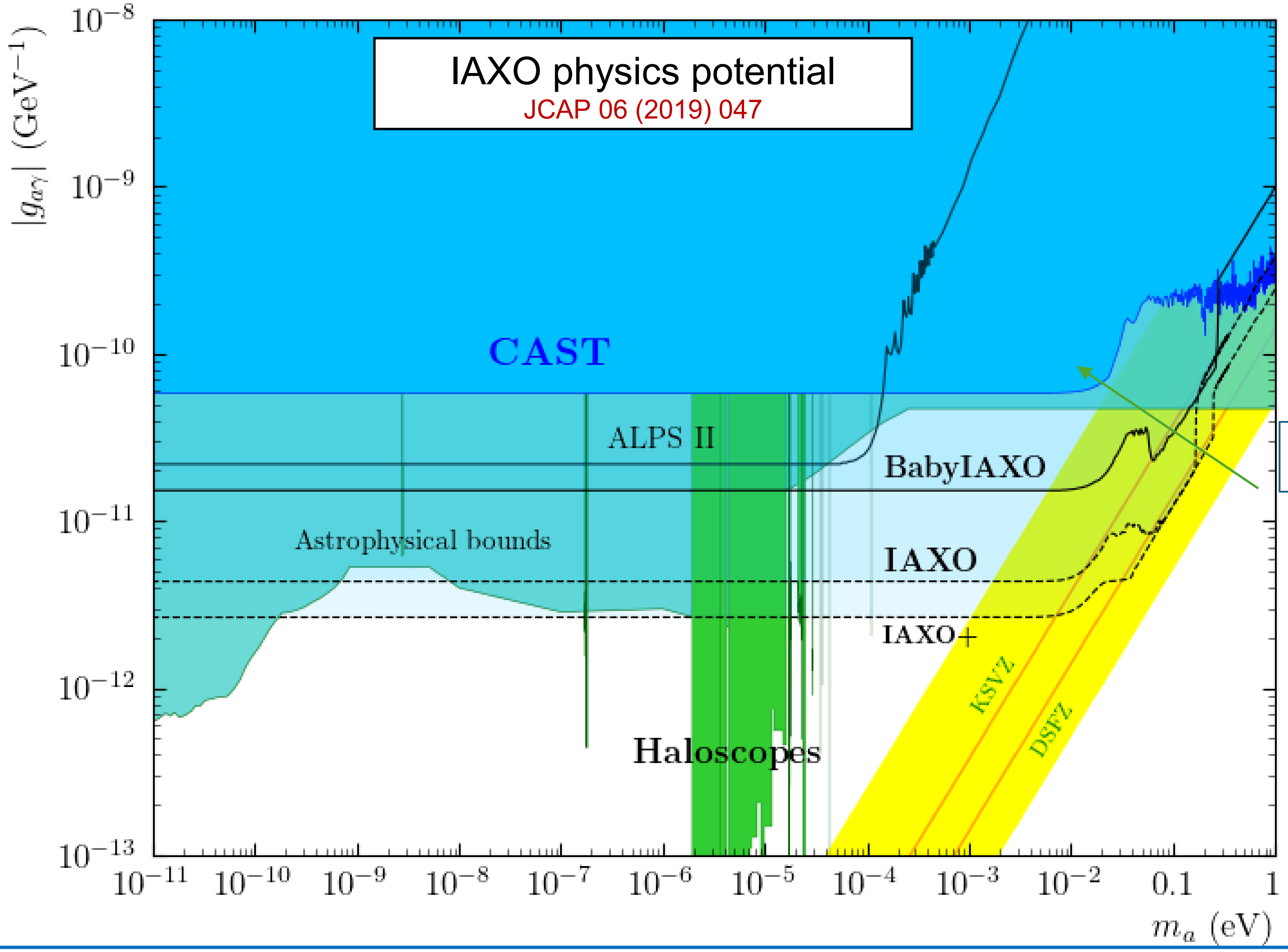
$g_{a\gamma} \lesssim$ few 10^{-11} GeV^{-1} (expected)

CAST

$g_{a\gamma} \lesssim 5.7 \times 10^{-11}$ GeV^{-1}

(Baby)IAXO physics case

Unexplored ALP space



QCD axion models

IAXO+: enhanced scenario with x10 (x4) higher FOM (MFOM) with respect LoI

BabyIAXO: a generic axion (ALP) facility

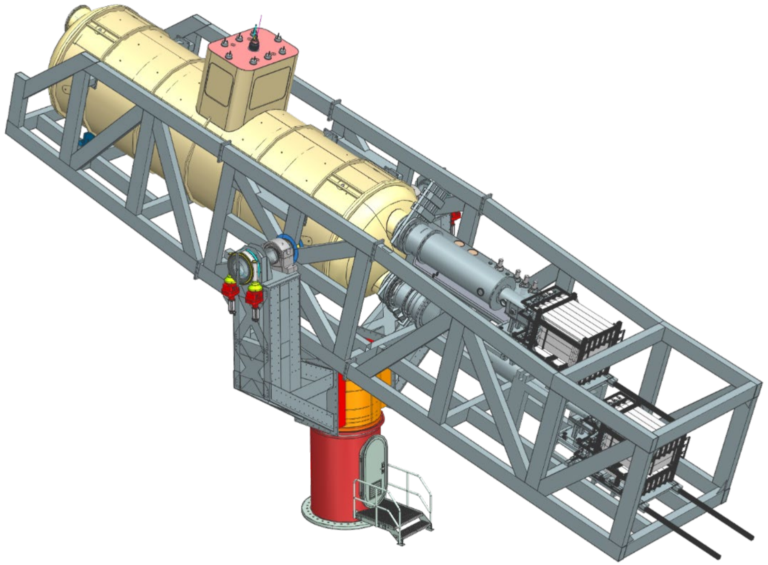
- A great infrastructure to target other physics goals beyond Primakoff solar axions:

Axions from close-by supernovae

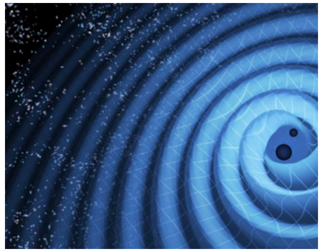
DM axions: haloscope setups within BIAXO

Non-Primakoff solar axions (a-e, a-N, …)

Post-discovery "precision" physics (solar B and T, axion mass and model)



Other WISPs: hidden (dark) photons, chameleons …And also high-frequency gravitational waves!!



Conclusions

- Axions = DM candidates simultaneously solving strong CP
- Complementary experimental efforts: haloscopes, helioscopes , LSTW, …
- Solar axion searches probe large regions of axion (ALP) parameter space
- Current best limit on solar axion (CAST): $g_{a\gamma} < 6.6 \times 10^{-11}$ GeV^{-1}
- BabyIAXO (IAXO) targets axion discovery: few 10^{-11} (10^{-12}) GeV^{-1} in g_{ag}
- Intriguing IAXO physics cases beyond axion-photon (g_{ae}, g_{aN}, QCD, ALPs, astrophysical hints, dark photons, dark energy…)

IAXO Collaboration

~125 scientists from 19 full member institutions + 6 associate institutions.

22nd Collaboration meeting

Full members: Kirchhoff Institute for Physics, Heidelberg U. (Germany) | IRFU-CEA (France) | CAPA-UNIZAR (Spain) | INAF-Brera (Italy) | CERN (*) (Switzerland) | ICCUB-Barcelona (Spain) | Siegen University (Germany) | Barry University (USA) | TU Dortmund (Germany) | University of Bonn (Germany) | DESY (Germany) | LLNL (USA) | University of Cape Town (S. Africa) | Technical University Munich (TUM) (Germany) | CEFCA-Teruel (Spain) | U. Polytechnical of Cartagena (Spain) | U. of Hamburg (Germany) | MPE/PANTER (Germany) | U. Columbia (USA) |

Associate members: DTU (Denmark) | SOLEIL (France) | IJCLab (France) | LIST-CEA (France) | ITA-Zaragoza (Spain) | IFIC-Valencia (Spain) | ESA (*) | NASA (*)

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