COSMIC WISPERS
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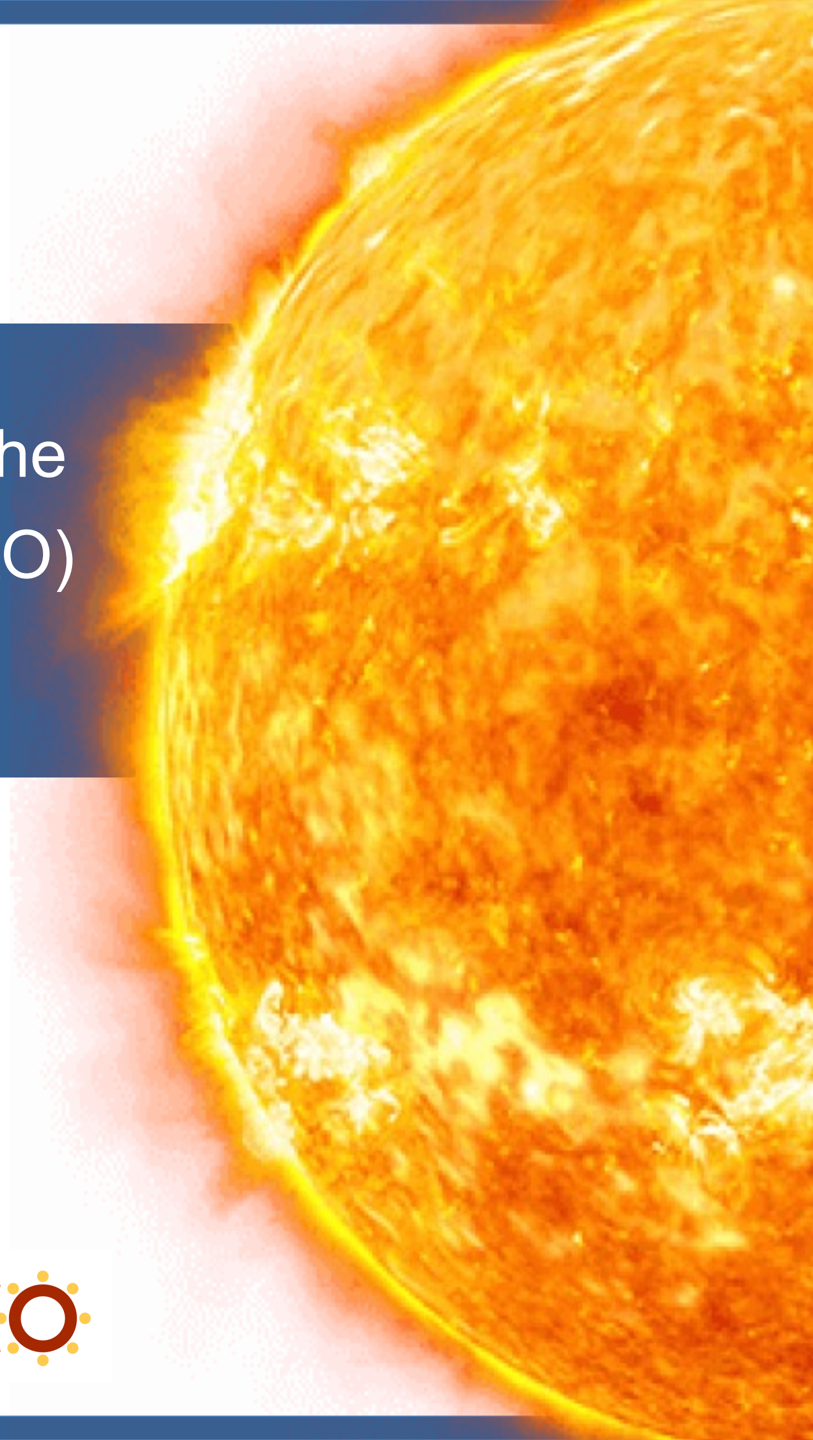
cost
EUROPEAN COOPERATION
IN SCIENCE & TECHNOLOGY



Searches for Axions and ALPs with the International Axion Observatory (IAXO) and (Baby)IAXO

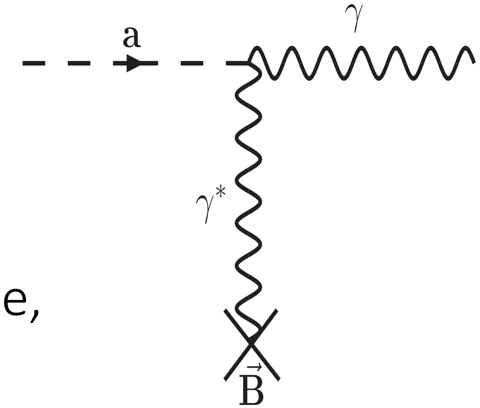
Julia K. Vogel
on behalf of the IAXO Collaboration
July 9, 2024
IDM 2024, L'Aquila, Italy

CAPA
Centro de Astropartículas y
Física de Altas Energías

1542
Universidad
Zaragoza

IAXO

What is an axion (in a nutshell)?



- **Strong CP problem**

  CP violation expected in QCD, but not observed experimentally (θ, nEDM)

- **Peccei-Quinn solution**

  New global U(1) symmetry, θ turn into a dynamical variable, relaxes to zero

- **Axion**

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

- **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}

  → **Dark matter candidate**

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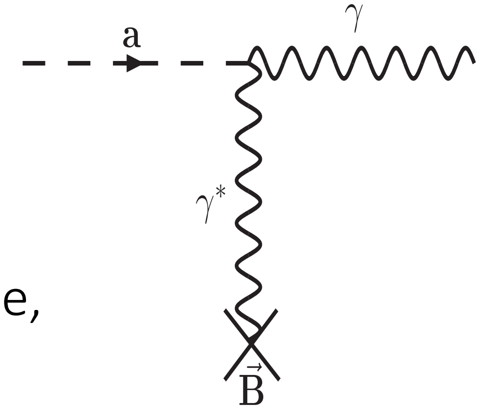

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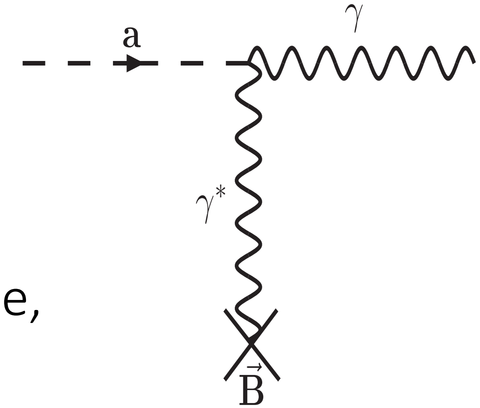

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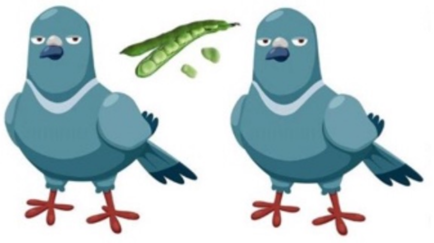
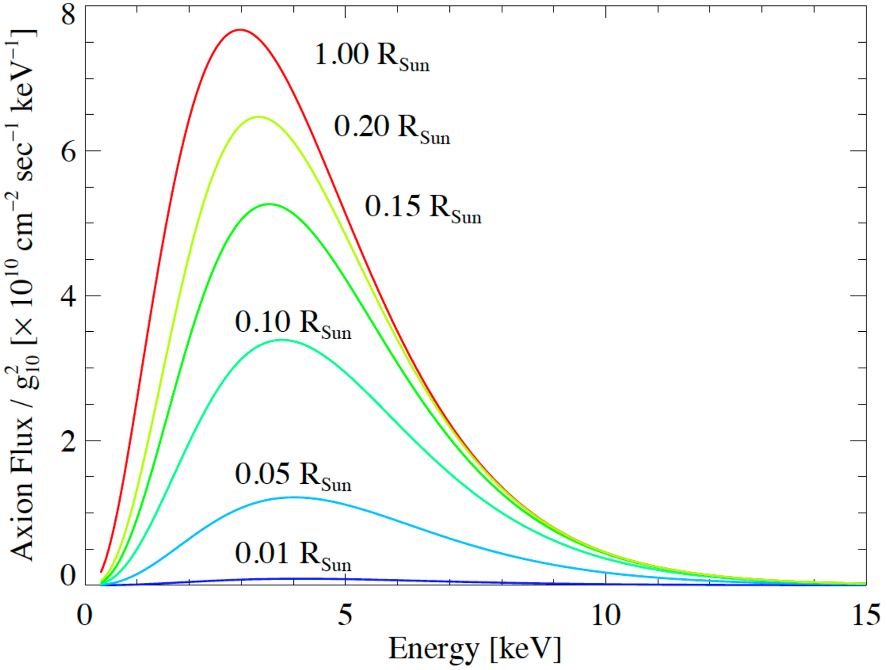


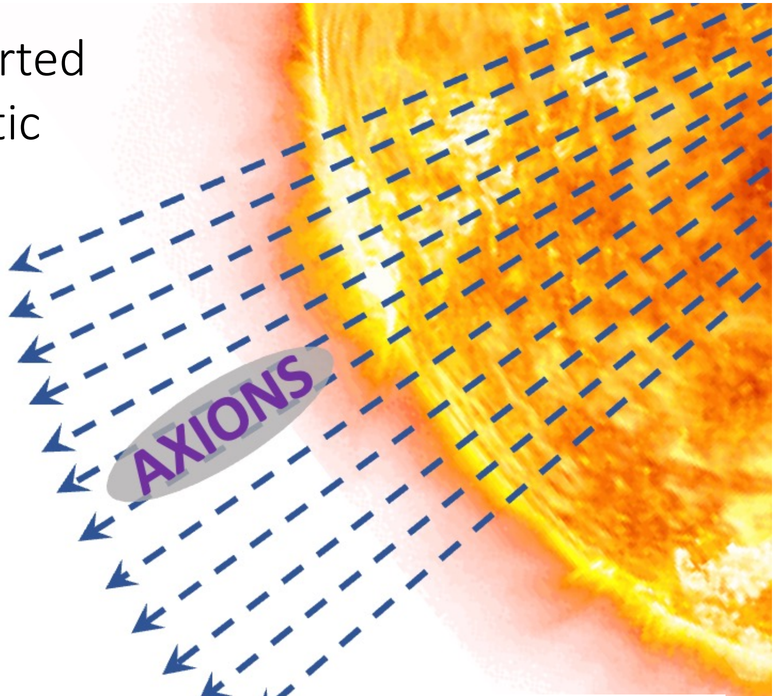
“Prendere due piccioni con una fava”

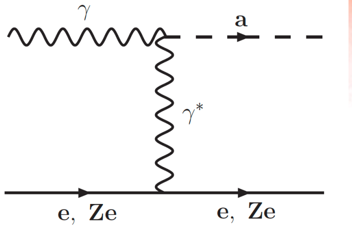
Solar Axion Searches

Minimal axion models

Blackbody photons (keV) in solar core can be converted into axions in the presence of strong electromagnetic fields in the plasma → Primakoff Effect







Hadronic axions (if the axion couples predominantly to photons ($g_{a\gamma}$))

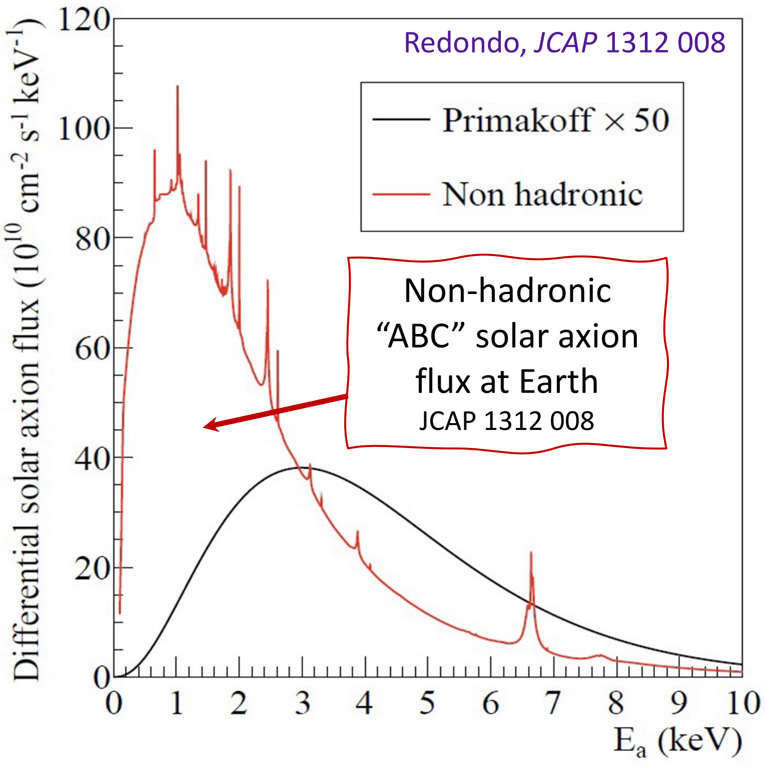
$$\frac{d\Phi_a}{dE} = 6.02 \times 10^{10} \left(\frac{g_{a\gamma}}{10^{-10}\text{GeV}^{-1}} \right)^2 E^{2.481} e^{-E/1.205} \frac{1}{\text{cm}^2 \text{ s keV}}$$

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

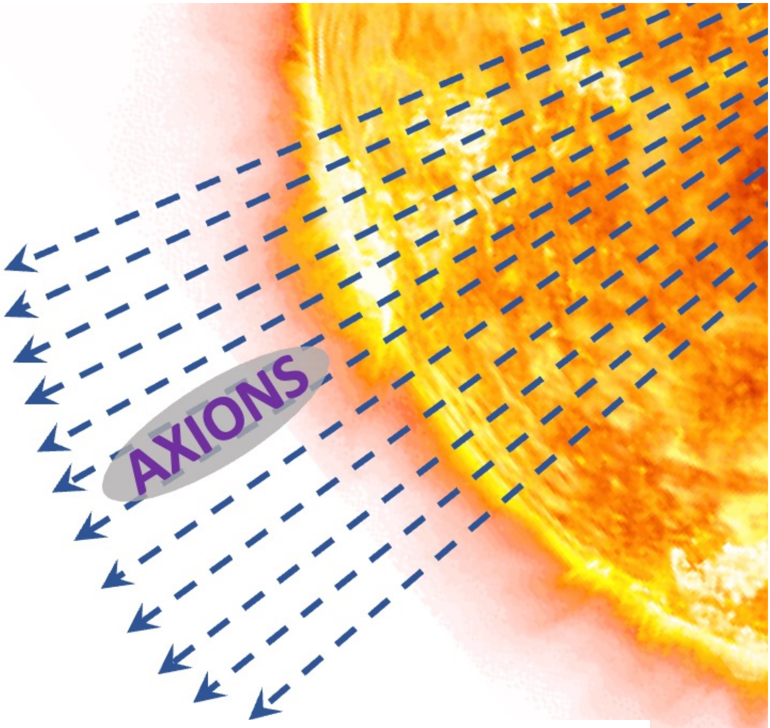
Solar Axion Searches

Non-minimal axion models

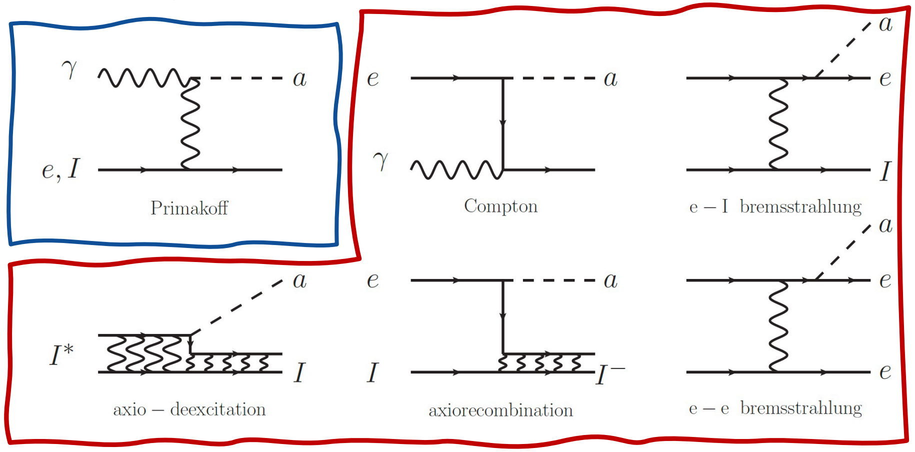
Additionally to Primakoff: “ABC axions” which may be ×100 more intense but model-dependent



Non-hadronic “ABC” solar axion flux at Earth
JCAP 1312 008



Primakoff axions



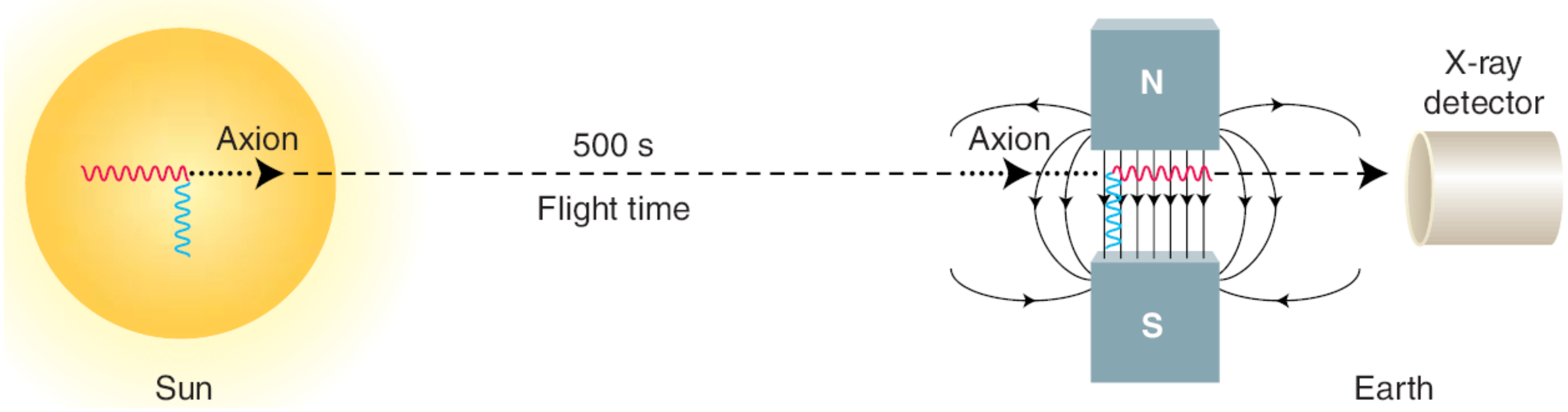
Non-hadronic or “ABC” axions (if the axion couples to electrons (g_{ae}))

Solar Axion Searches

- 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



$$P_{a\to\gamma} = \left(\frac{BLg_{a\gamma\gamma}}{2}\right)^2 \quad \text{for} \quad \frac{qL}{2} < \pi \quad \text{with} \quad q = \frac{m_a^2}{2E_a}.$$

VACUUM

Solar Axion Searches

Detection Helioscope

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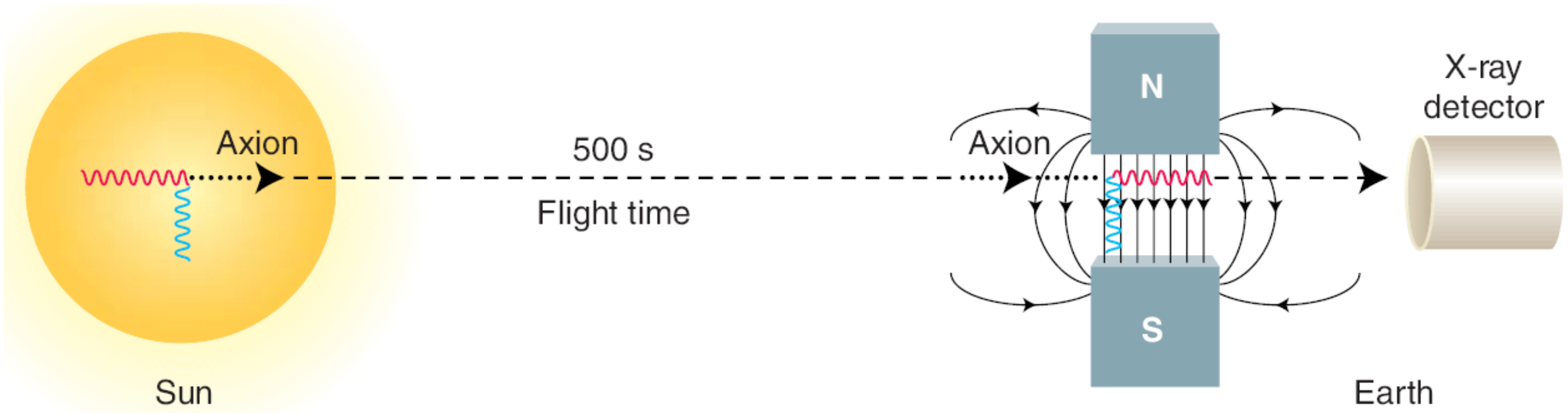


$$P_{a\to\gamma} = \left(\frac{BLg_{a\gamma\gamma}}{2}\right)^2$$ for $\frac{qL}{2} < \pi$ with $q = \frac{m_a^2}{2E_a}$ VACUUM

- Idea refined by K. van Bibber et al.

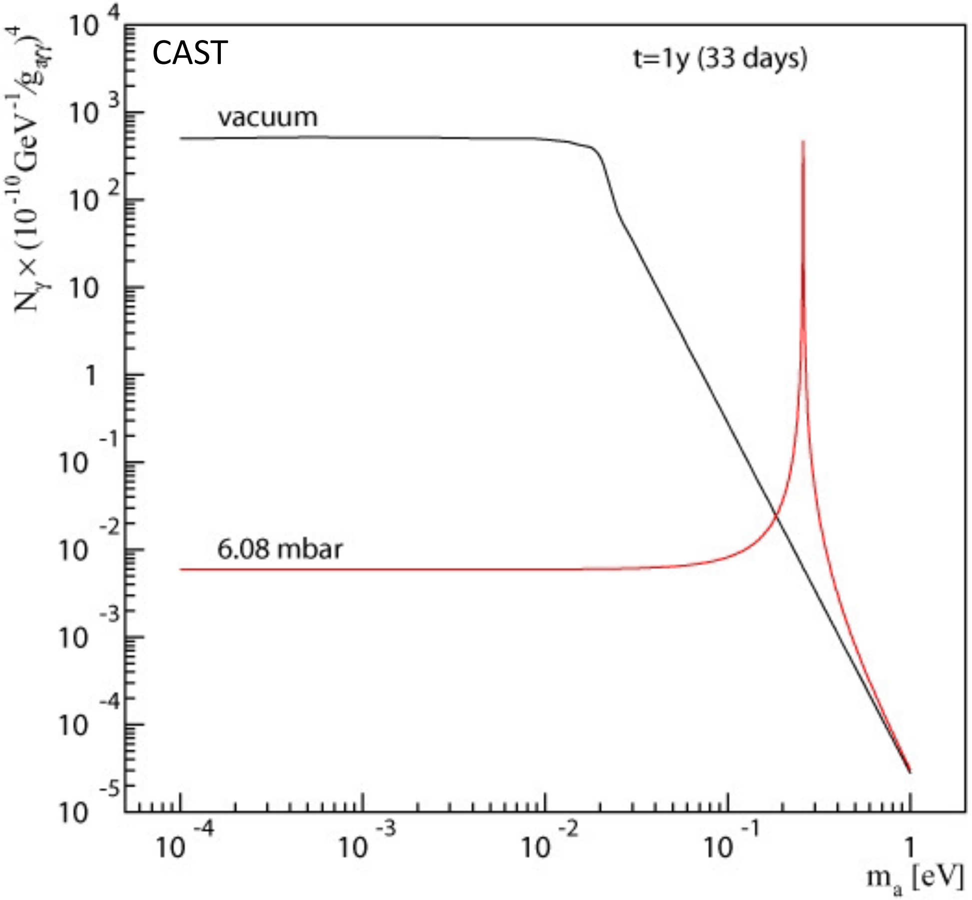
Van Bibber et al 1989 Phys. Rev. D 39 2089

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

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

Solar Axion Searches

Detection Helioscope

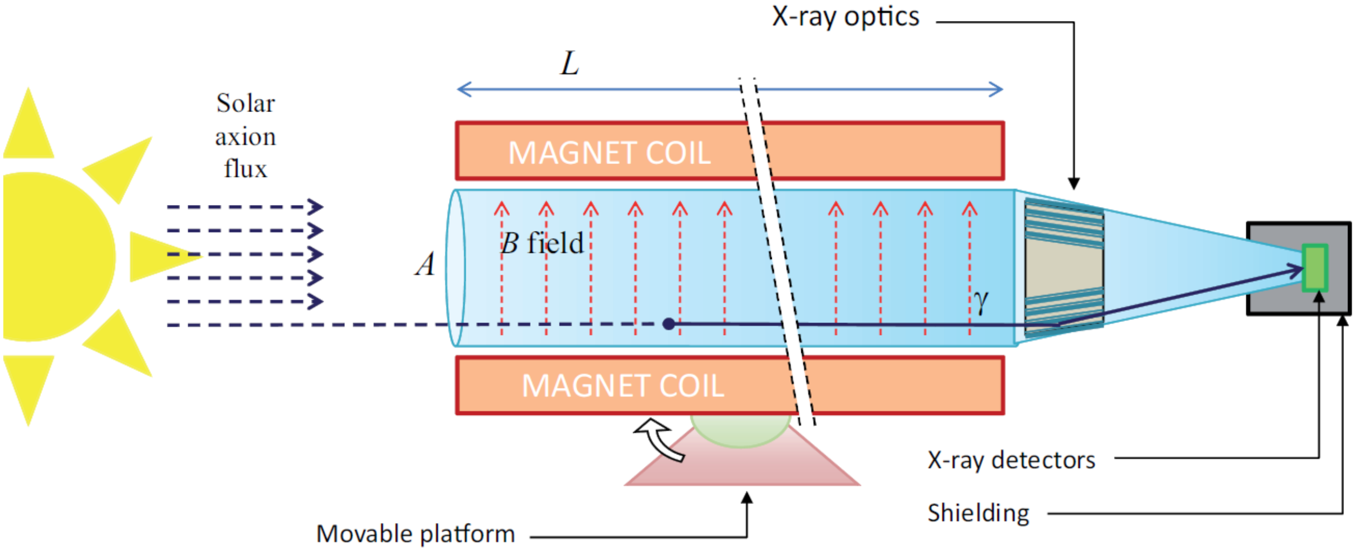


$$N_\gamma = \int \frac{d\Phi_a}{dE_a} P_{a\to\gamma}\, S\, t\, dE_a \quad \propto \quad g_{a\gamma}^4$$

Solar Axion Searches

Helioscope Figure of Merit

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



Measure of sensitivity to axion-photon interaction:

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

magnet

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

exposure

t = time

optics

s = spot size
ε_0 = efficiency

detectors

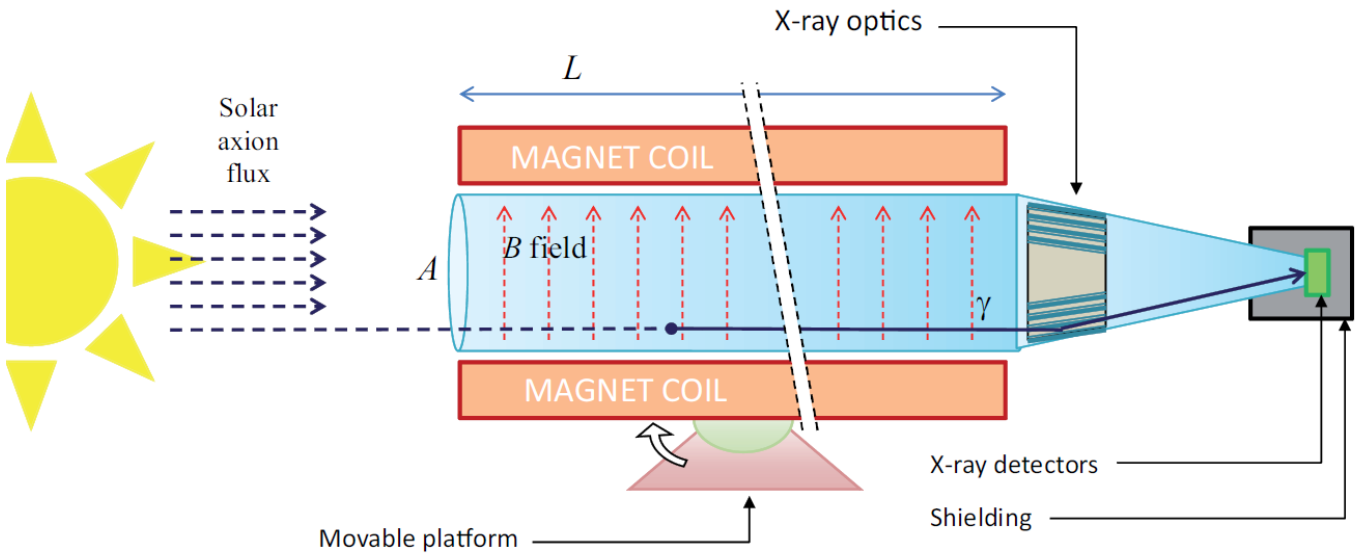
b = background
ε = efficiency

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

Solar Axion Searches

Helioscope Figure of Merit

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



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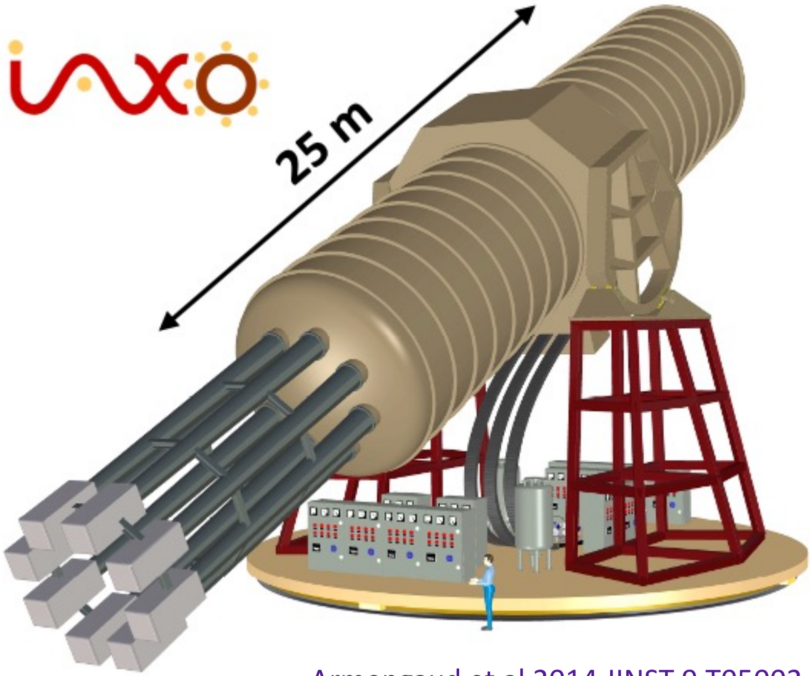
The smaller $g_{a\gamma}$ the better!

Expect improvement for next gen (International Axion Observatory):
1–1.5 orders of magnitude in sensitivity to $g_{a\gamma}$ (factor of 10000-20000 in S/N)

Solar Axion Searches

INTERNATIONAL AXION OBSERVATORY (IAXO)

- Next-gen helioscope for solar axions
- Mature and state-of-the-art technology
- Purpose-built large-scale superconducting magnet
  - Toroidal geometry
  - 25 meters long, up to 5.4 T
  - > 300 times larger FoM than CAST magnet
  - 8 conversion bores of 60 cm Ø
- 8 detection lines
  - X-ray optics with 0.2 cm² focal spot
  - Ultra-low background detectors
- 50% of Sun-tracking time.



Armengaud et al 2014 JINST 9 T05002
Irastorza et al 2011 JCAP 1106, 013

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

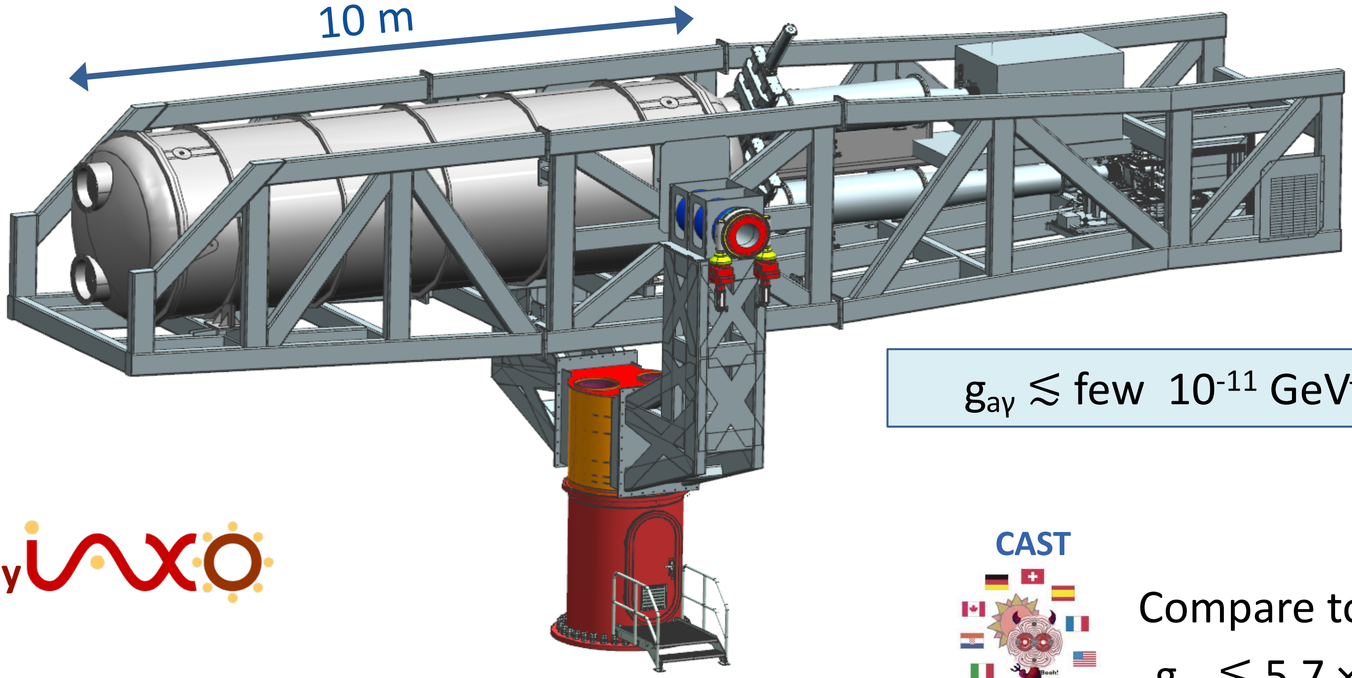
CAST

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

Solar Axion Searches

BABYIAXO =INTERMEDIATE EXPERIMENTAL STAGE BEFORE IAXO

- Technological prototype of IAXO with only two magnet bores (10 m, Ø 70 cm)
- Relevant physical outcome (~10 × CAST B^2L^2A)
- Magnet will be upscalable version for IAXO
- X-ray optics/detectors close to final IAXO configuration (focal length, performance)



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Abeln et al 2021 JHEP 2021 137

CAST

Compare to

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

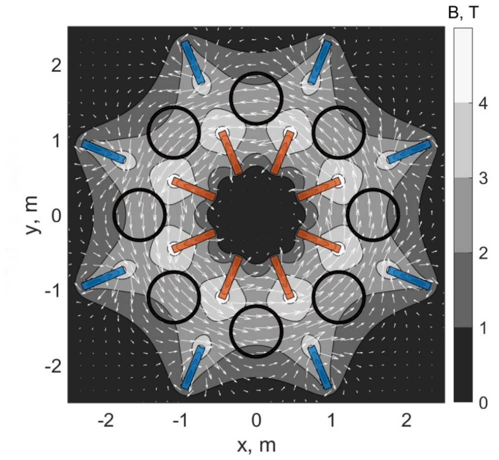
Solar Axion Searches

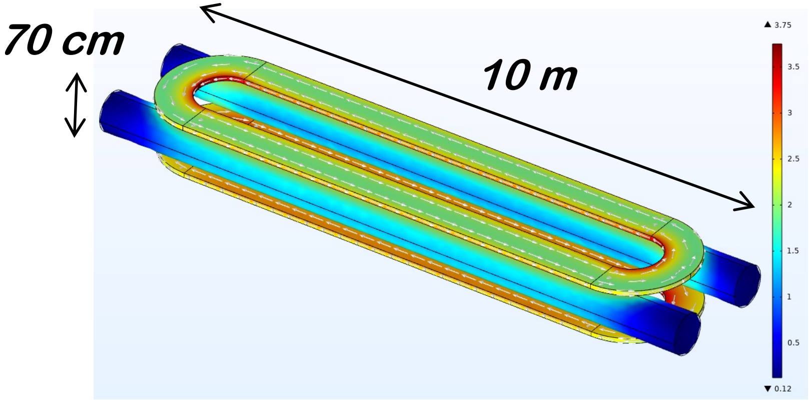
BabyIAXO Magnet

BabyIAXO MAGNET

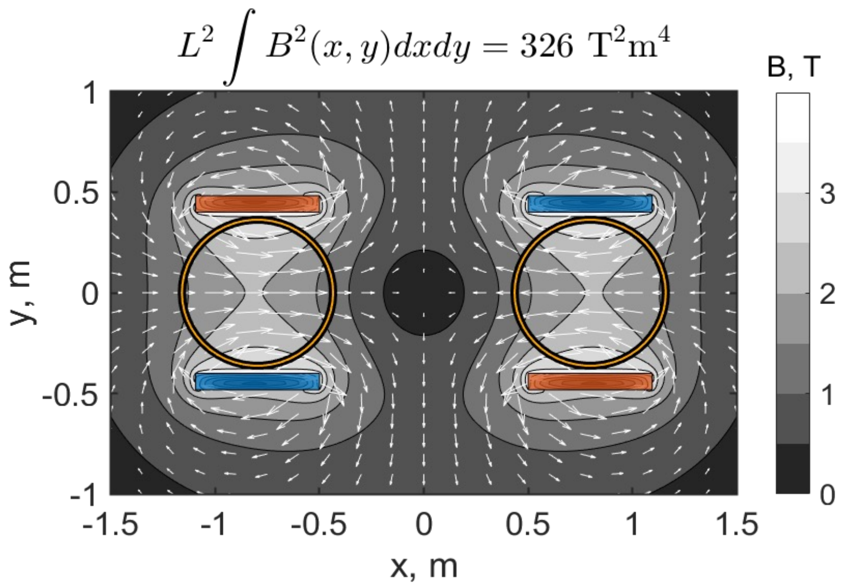
NEED: large magnetic field B & cross-sectional area A

- "Common coil" configuration
- Minimal construction risk and cost-effective
- Racetrack layout very close to IAXO toroidal design
- Some delays due to availability of Al-stabilized superconductor cable





Common-coil dipole, with counter-flowing current in two superconducting race-track coils



$$L^2 \int B^2(x,y)dxdy = 326\ \mathrm{T^2 m^4}$$

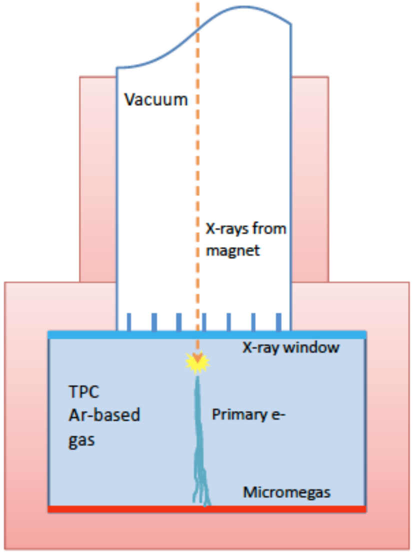
Magnetic field for BabyIAXO

BabyIAXO Detectors

BabyIAXO DETECTORS

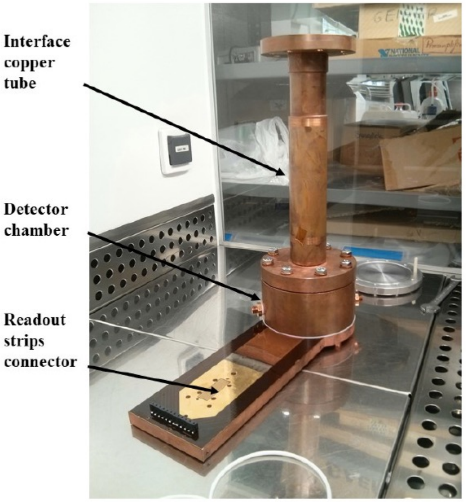
NEED (Baseline 1-10 keV)

- **Low background** (<10^{-7} – 10^{-8} cts keV^{-1} cm^{-2} s^{-1})
  - Less than 1 event per 6 months of data taking!
  - Already demonstrated 8×10^{-7} c keV^{-1} cm^{-2} s^{-1} and 10^{-7} cts keV^{-1} cm^{-2} s^{-1} above ground and at Canfranc, respectively
- **High detection efficiency**



WANT (Beyond baseline)

- **Low E-threshold** (< 1 keV) and improved **E-resolution**
  - Especially interesting for axion-electron measurements
  - Notably useful in case an axion signal is detected



Micromegas best option to reach required low background
Additional technologies considered /active R&D efforts
(GridPix, MMC, TES, SDD)

BabyIAXO Optics

BabyIAXO TELESCOPES

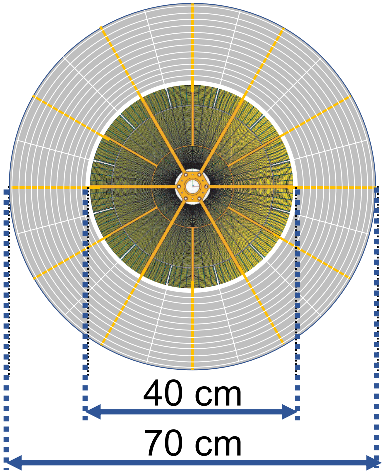
NEED: Maximized throughput efficiency (40-60%),
Small focal spot (r < 2.5 mm),
Cost-effective way (need 8 for IAXO)

- Baseline 1-10 keV (prototyping and R&D)
  - Existing XMM flight-spare telescope
  - Custom IAXO optic (NuSTAR/BRAVO)
- Beyond baseline (funding request pending)
  - Lower threshold of 0.3 keV or better
  - Add sensitivity at 14.4 keV

Leveraging decades of NASA/ESA research for space instrumentation:
minimal risk and superior performance

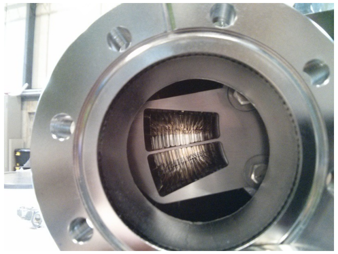
Henriksen et al 2021 AO 60, 22; Irastorza et al 2015 JCAP 12, 008

Custom optics
Hot and cold slumped glass

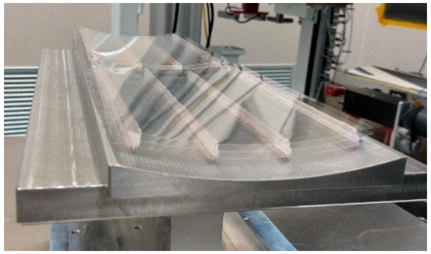


XMM Flight spare

NuSTAR Pathfinder



BRAVO Pathfinder



Solar Axion Searches

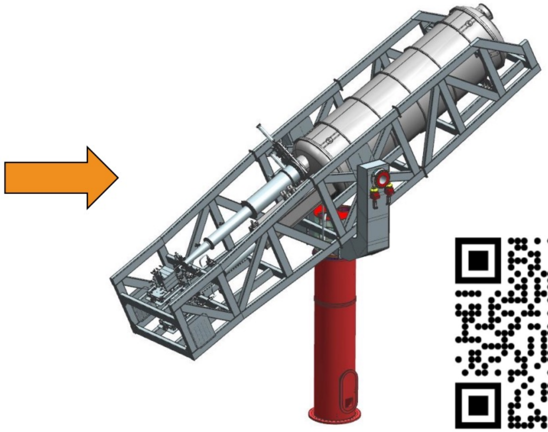
BabyIAXO Location

BabyIAXO @DESY

- DESY HERA hall as BabyIAXO site
- CTA Medium Sized Telescope (MST) support and drive system to be used for BIAXO
- End-to-end simulation of (B)IAXO experiment

Rare Event Searches Toolkit
software

Expect to commission BabyIAXO without magnet before baseline science run



Solar Axion Searches

Vacuum Phase

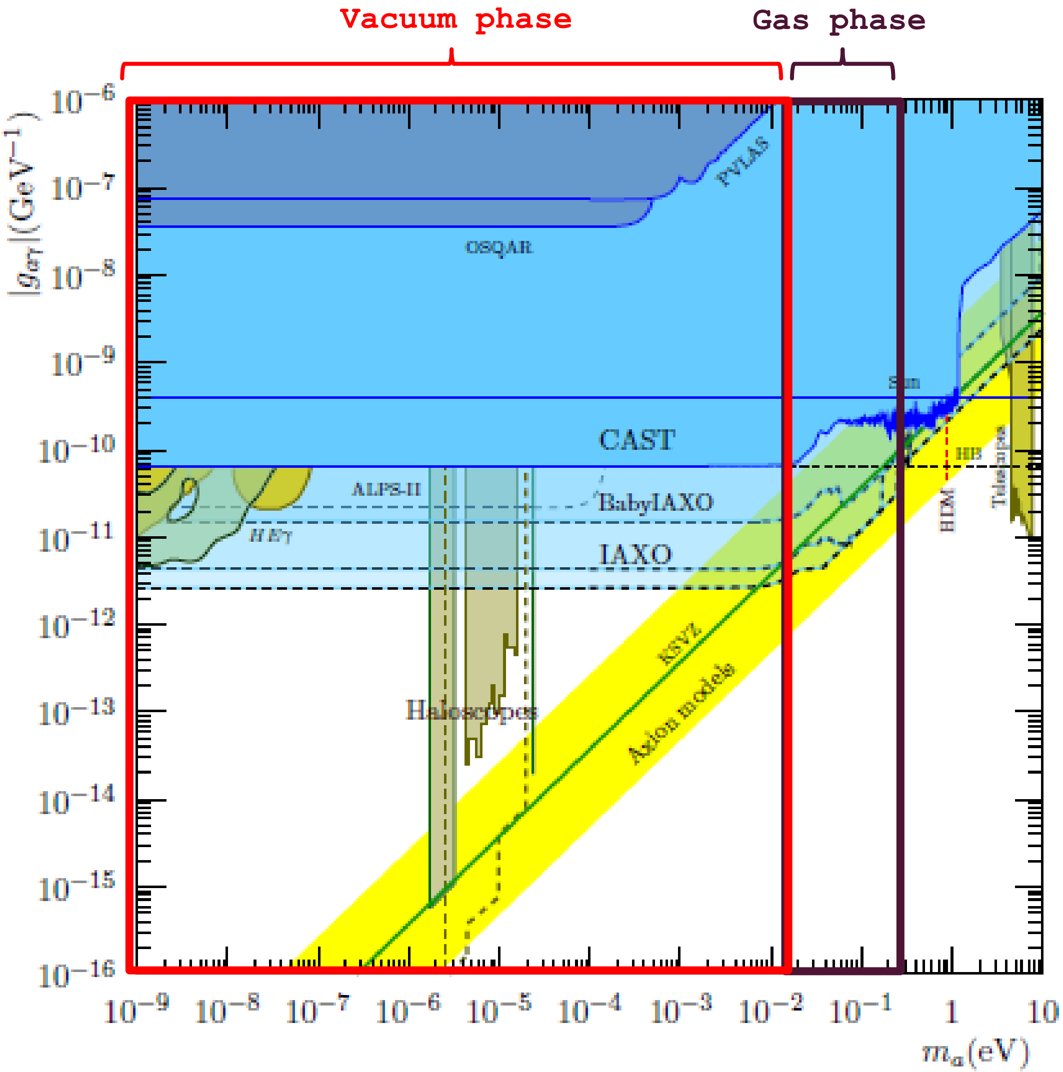
Coherence condition valid for $m_a \lesssim 0.02$ eV

Gas Phase

- Extends coherence condition valid from $0.02 \text{ eV} \lesssim m_a \lesssim 0.26$ eV

$$m_\gamma = 4.498716\sqrt{\frac{P_{He}[\text{atm}]}{T_{He}[\text{K}]}}\,\text{eV}.$$

- Experimental conditions BIAXO:
  - P_{max}(helium-4) ≃ 1bar
  - T(average) ≃ 295K



Solar Axion Searches IAXO Beyond Baseline

Armengaud et al 2019, JCAP 1906, 047

IAXO as a generic axion(-like) detection facility

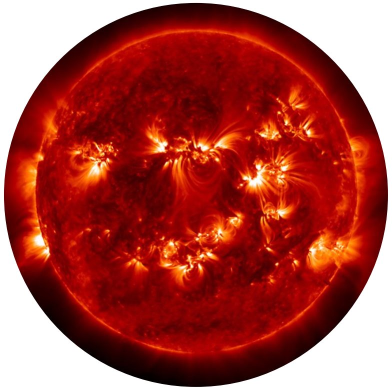
(Baby)IAXO constitutes a great infrastructure that can be used to target other physics goals beyond Primakoff solar axions

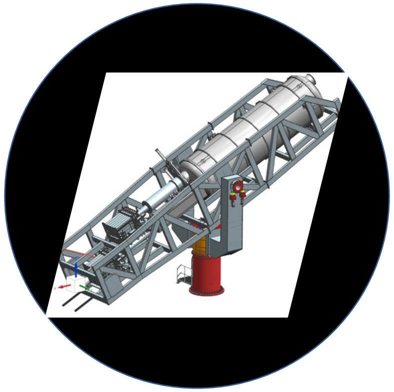
Non-Primakoff solar axions (a-e, a-N, …)

DM axions: haloscope setups within BIAXO

Axions from close-by supernovae

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





+ More (dark photons, chameleons, gravitational wave searches and NS studies)…

Conclusions

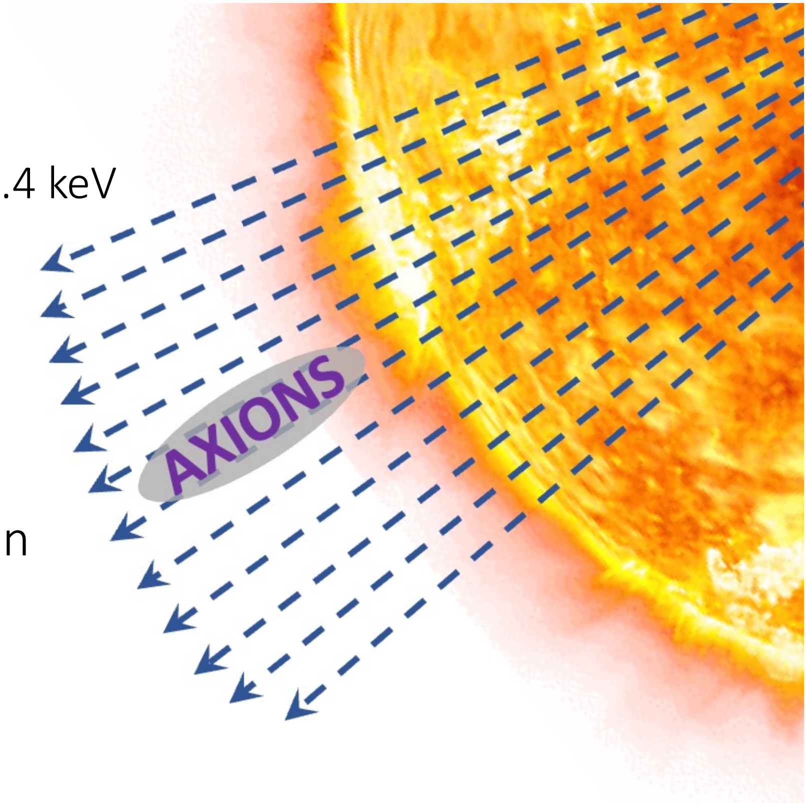
- Axions = DM candidates simultaneously solving strong CP
- Axions can be searched for with haloscopes, helioscopes and LSTW
- Solar axion searches probe large regions of axion parameter space
- Current best limit on solar axion (CAST): $g_{a\gamma} < 5.7 \times 10^{-11}$ GeV^{-1}
- BabyIAXO (IAXO) targets 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…)

BACKUP SLIDES

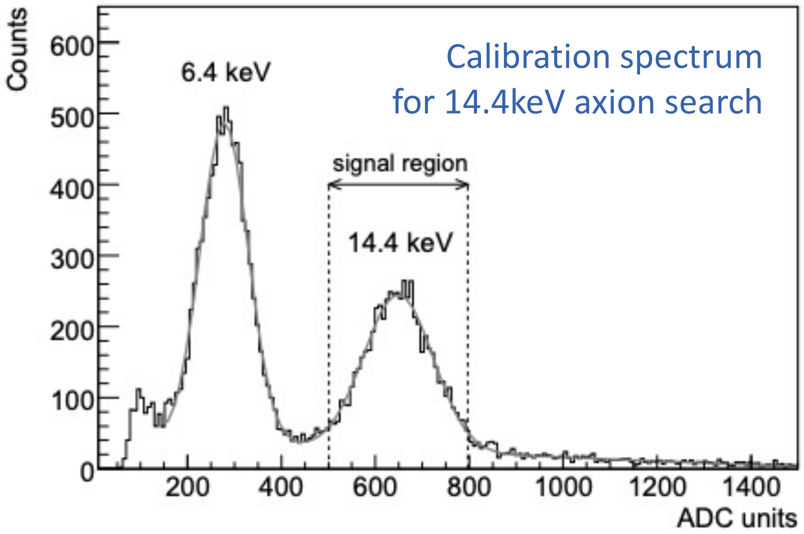
Solar Axion Searches

Via axion-nucleon couplings can also observe monochromatic lines from nuclear transitions

- **keV axions:** M1 transition of Fe-57 nuclei @14.4 keV and Tm-169 @8.4 keV
- **MeV axions:**
  From ^{7}Li (0.478 MeV) and D(p;γ)^{3}He (5.5 MeV)



Axions-nucleon coupling g_{aN} especially intriguing:
If the axion couples via g_{aN} , most likely a QCD axion



Calibration spectrum
for 14.4keV axion search

$$\Phi_a = 5.06 \times 10^{23} \, (g_{aN}^{\mathrm{eff}})^2 \ \mathrm{cm}^{-2}\mathrm{s}^{-1} .$$

Di Luzio *et al* 2022 *Eur. Phys. J.* C 82:120
CAST collaboration *et al* 2009 *JCAP* 12 002
D. Miller *et al* 2010 JCAP 1003 032
Derbin *et al 2023 Jetp Lett.* 118, 160

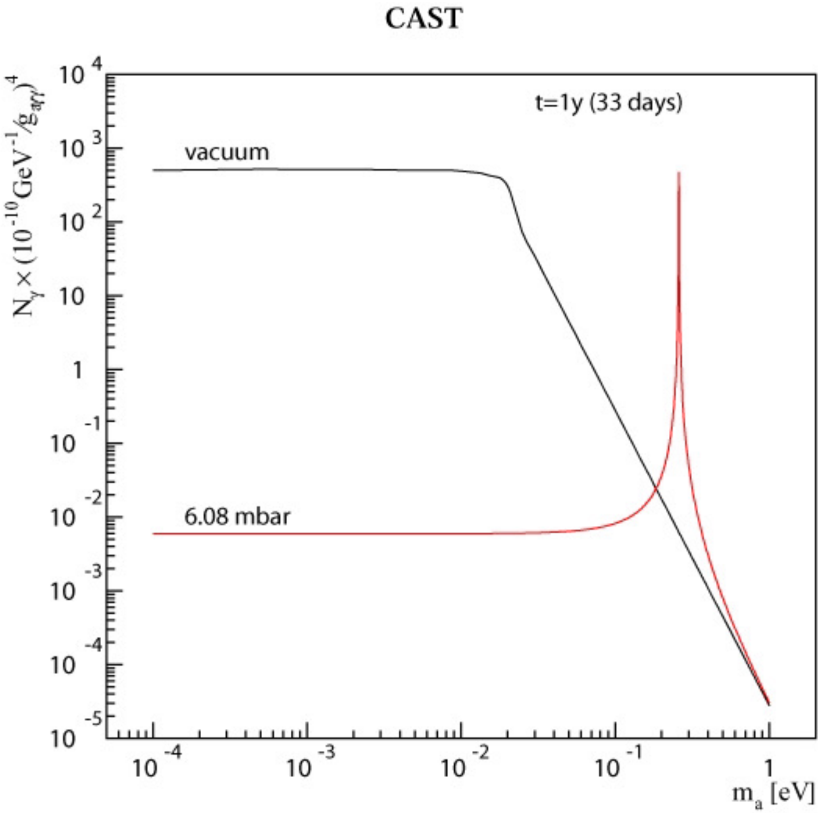
Solar Axion Detection   Coherence Condition

- In vacuum, conversion probability simplifies to:

$$P_{a\to\gamma} = \left(\frac{BLg_{a\gamma\gamma}}{2}\right)^2 \boxed{\left(\frac{\sin\left(\frac{qL}{2}\right)}{\left(\frac{qL}{2}\right)}\right)^2}$$

$$q = \frac{m_a^2}{2E_a}$$

Coherence condition
$qL/2 \ll \pi$



- With a buffer gas

$$q = \left|\frac{m_\gamma^2 - m_a^2}{2E_a}\right|$$

$$m_\gamma \approx \sqrt{\frac{4\pi\alpha N_e}{m_e}} = 28.9\sqrt{\frac{Z}{A}\rho} \quad \mathrm{eV}$$

$$N_\gamma = \int \frac{d\Phi_a}{dE_a} P_{a\to\gamma}\, S\, t\, dE_a \quad \propto \quad g_{a\gamma}^4$$

with N_e: number of electrons/cm^3 and ρ: gas density (g/cm3)

IAXO Physics

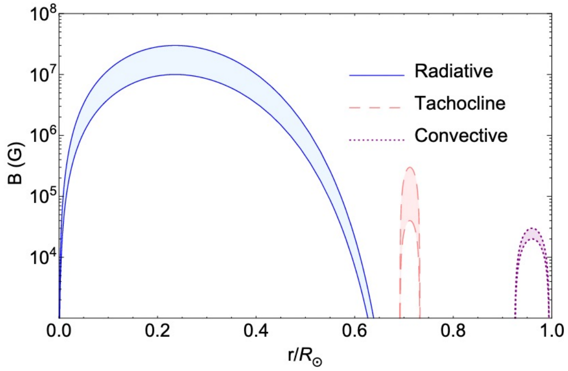
Beyond baseline physics

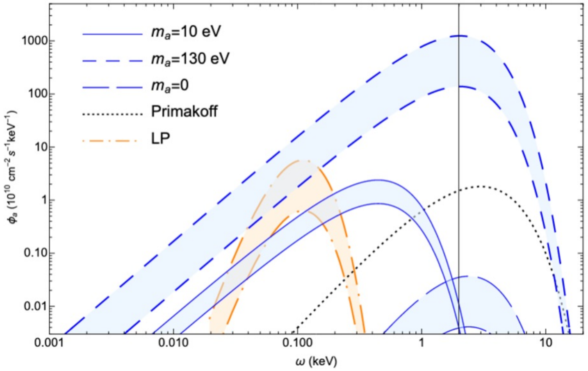
Non-Primakoff solar axions

- ABC axions via axion-electron coupling or solar axions via axion-nucleon coupling as mentioned before:

  → **needs more specialized detection systems** (XRTs, detectors)

- ALP production in large-scale B-fields in the Sun
  - Solar B-field dependence (field not well known but can be constrained)
  - ALP flux from longitudinal plasmon (LP)-ALP conversions peaks around 100 eV (could be detectable with **upgraded IAXO**)
  - Depends on axion-photon coupling
  - Transversal plasmon-ALP conversion depends also on axion mass



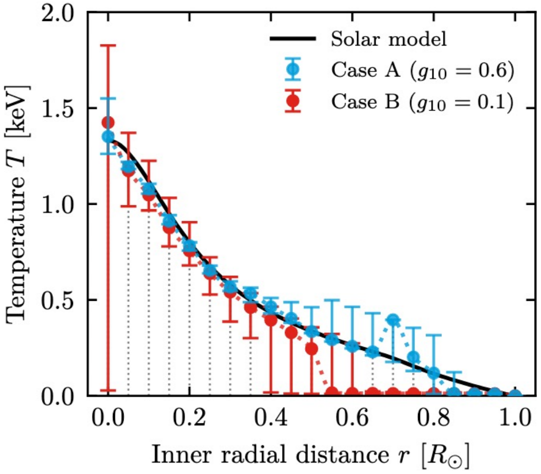


Guarini et al. 2010.06601

IAXO Physics Beyond baseline physics

Post-discovery: Axion properties and applications

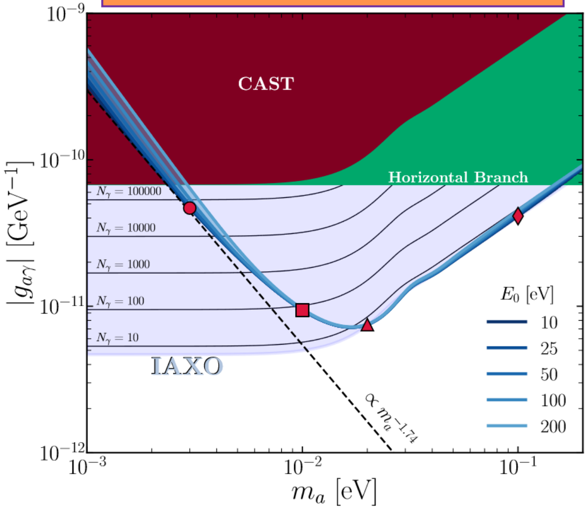
- Helioscopes as solar magnetometers
- Axions as solar thermometers
- Axion mass can be determined from spectral shape
- Detection of both ABC and Primakoff axion spectrum would allow distinguishing axion models (g_{ae}, $g_{a\gamma}$)



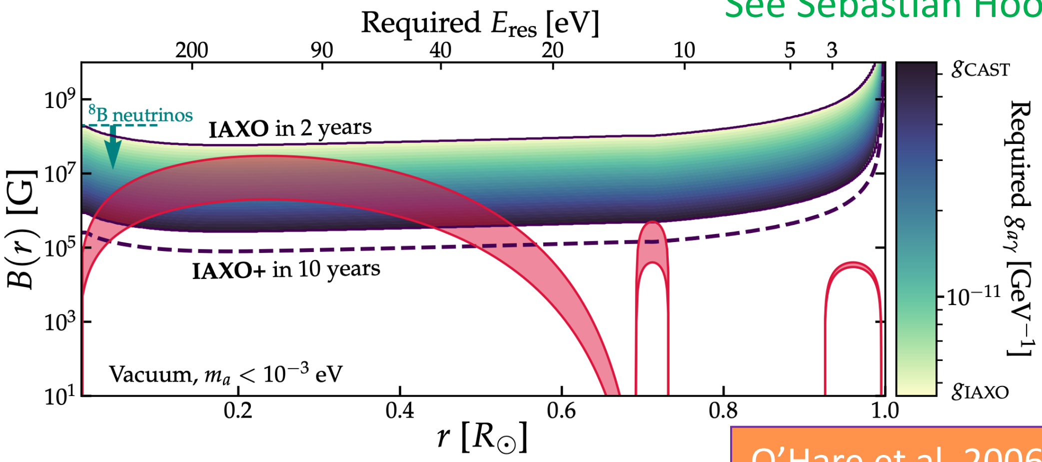
Hoof et al. 2306.00077

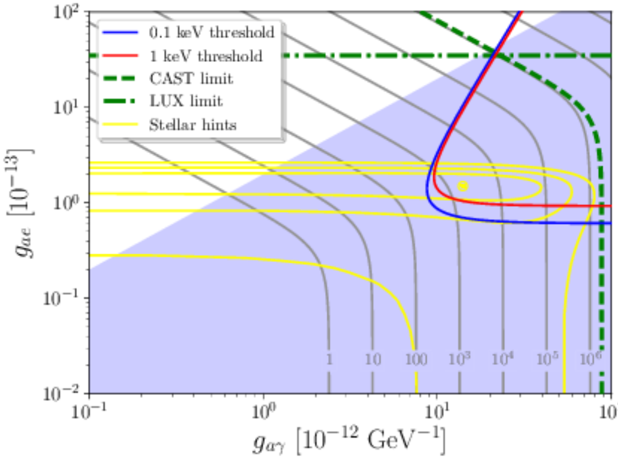
See Sebastian Hoof's talk tmrw

Dafni et al. 1811.09290



Jaeckel et al. 1811.09278





O'Hare et al. 2006.10415

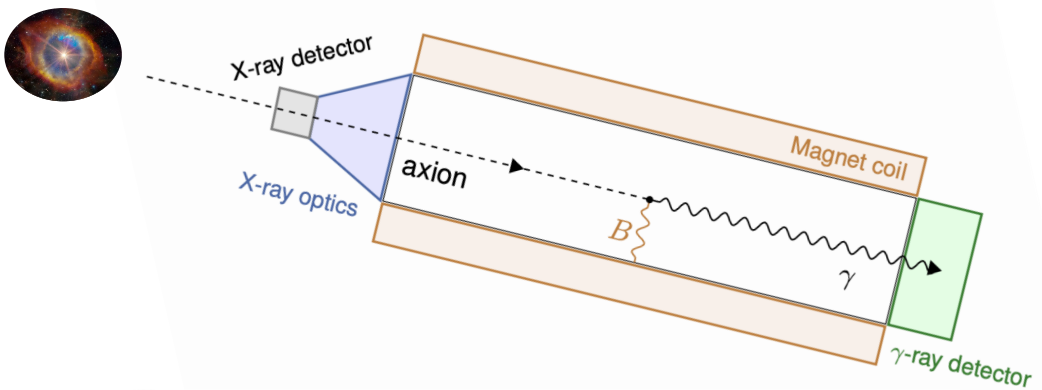
IAXO Physics

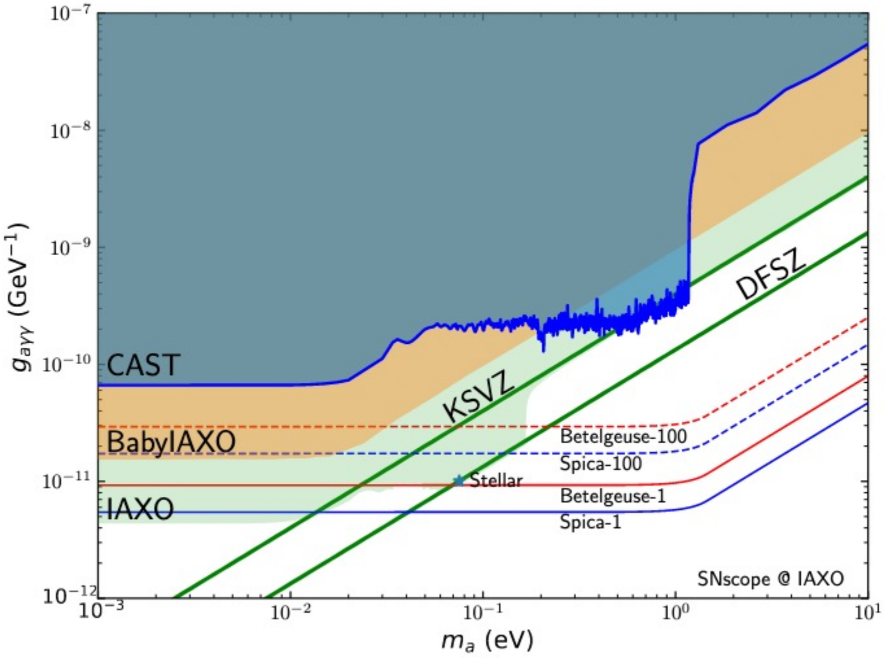
Beyond baseline physics

Axion from galactic supernova

- If a sufficiently close-by galactic SN explodes, SN axions could be detectable at (Baby)IAXO.
- SN axions have O(100MeV) energies
- **Requires** IAXO to be equipped with large **HE γ-ray detector**, covering all magnet bore, sufficient pointing accuracy, alert system in place
- Can be implemented complementary to baseline BabyIAXO setup by using opposite side of magnet.

Ge et al. 2008.03924



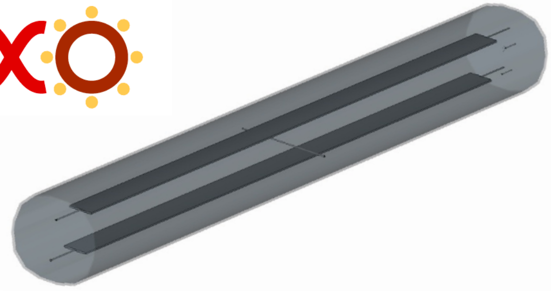


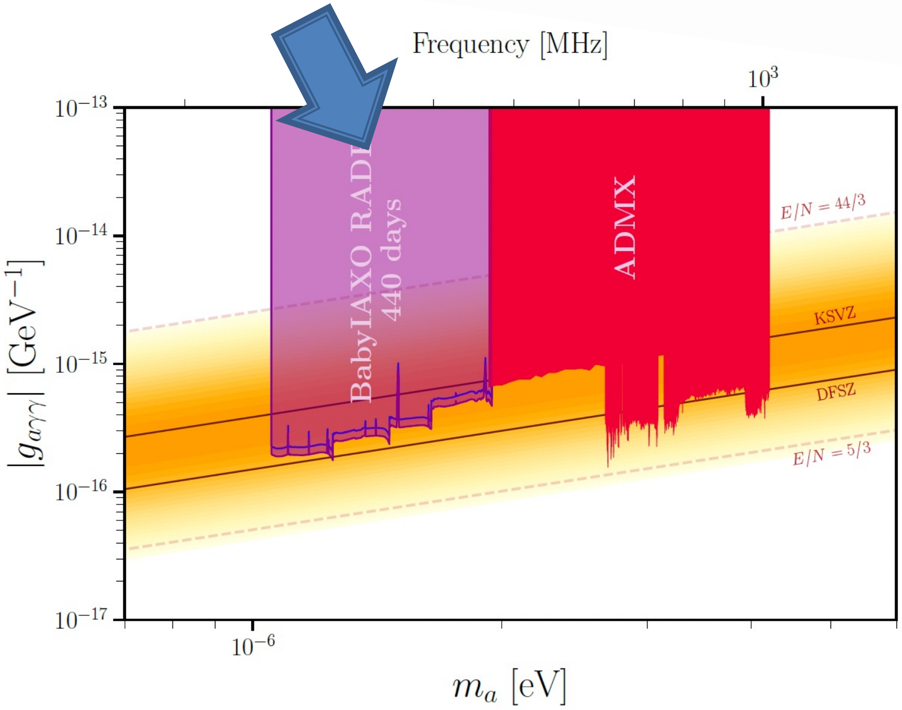
IAXO Physics

Beyond baseline physics

- Use of (Baby)IAXO large magnetic volume for axion DM setups
- Very competitive prospects for 1-2 μeV axion searches.
  - 4 x 5m long cavities with tuning slabs
  - Low noise (standard) amplification + DAQ
  - Bores cooled down to 4-5 K
  - Sensitivity to KSVZ in < 2 year data acquisition
- Other implementations are being discussed (need more work)
  - E.g. extension to much lower masses using BASE-like search inside BabyIAXO possible?

BabyIAXO





Ahyoune et al. (RADES Collaboration) arxiv:2306.17243

BabyIAXO beyond the baseline

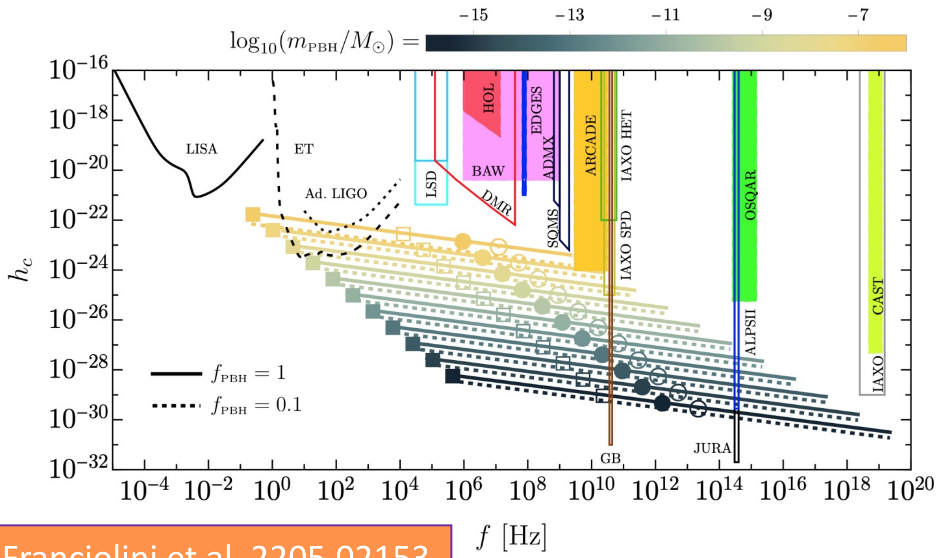
Other and more recent ideas to be studied by newly installed IAXO Physics group including:

- Gravitational waves: High frequency GWs are expected in non-standard scenarios, e.g. PBHs → future synergies with axion experiments?

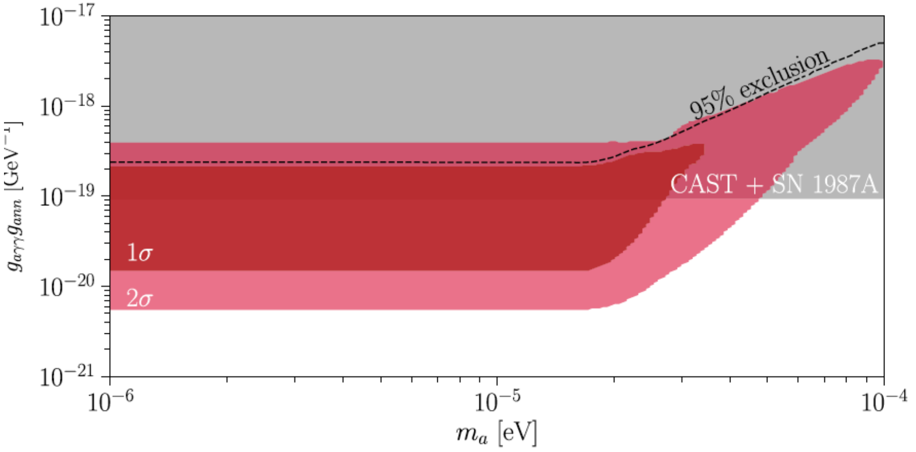
  → Valerie's lecture @Axion++ 2023

- Neutron stars as axion labs: searches of relevant parameter space with IAXO?

  → Maurizio's lecture @Axion++ 2023



Franciolini et al. 2205.02153



Plot from Ben Safdi's talk at GGI axion workshop 2023