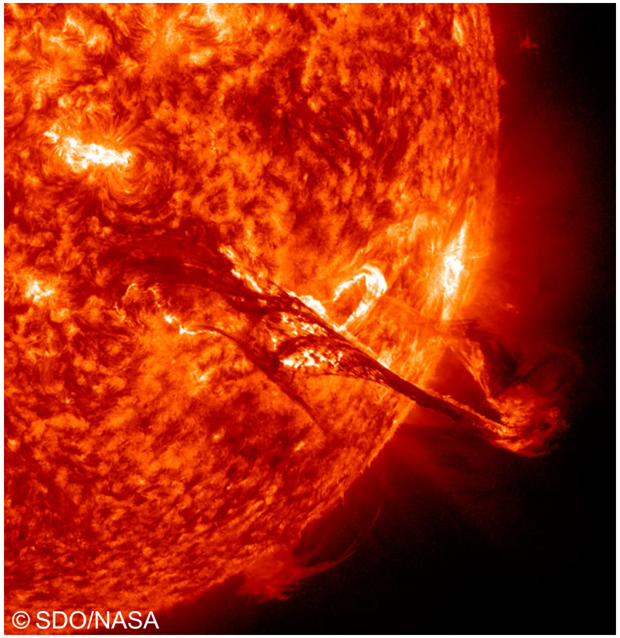
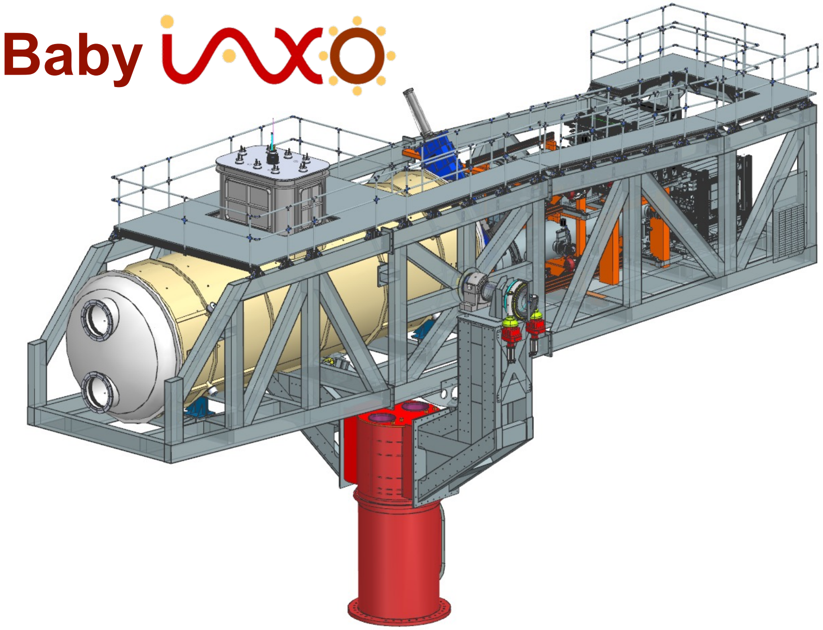
The Dark Side of the Sun:
The Quest for Solar Axions with Helioscopes





Julia K. Vogel

AXIONS IN STOCKHOLM, NORDITA, 30TH JUNE – 4TH JULY 2025

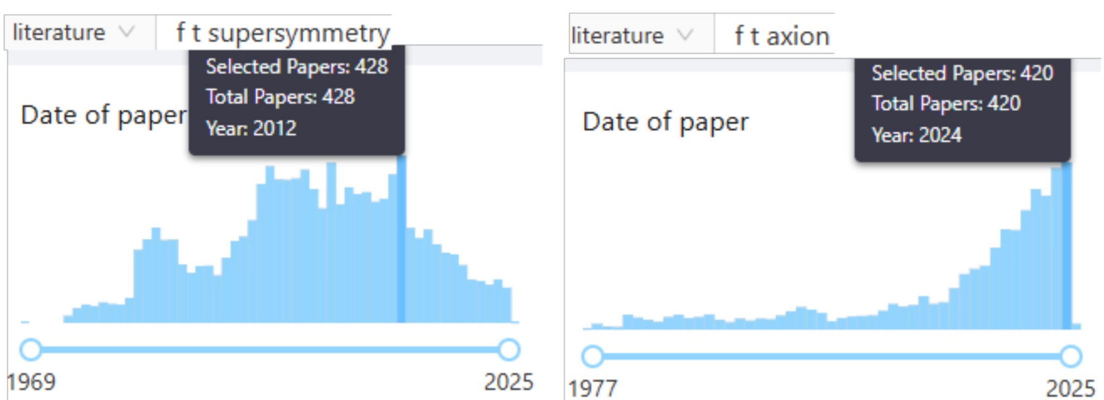
Outline

1. Axions and how to detect them
2. Solar Axion Searches
3. Current and future Axion Helioscopes
4. Outlook for helioscopes

Axions and how to detect them

- Axions featured prominently in ESPP Open Symposium, e.g. in TH & EXP Opening Talks (Eric Laenen, F. Gianotti)
- Mixture of small scale and larger scale experiments

Axions



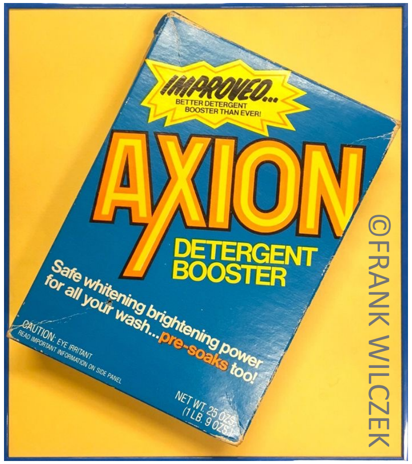
Axion physics is a beautiful combination of cosmology, particle, nuclear and astroparticle physics, with experiments large and small

When should we stop looking for DM (incl. axions)?

"We must be relentless in the search for dark matter because we know it is there"

M.Mccullough

Axions and how to detect them



- **Strong CP problem**

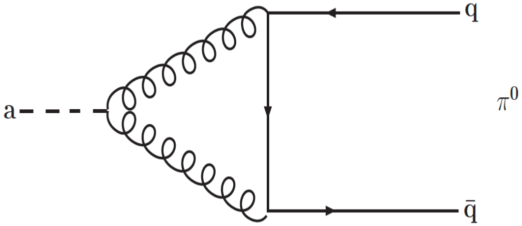
  CP violation expected in QCD, but not observed experimentally (θ, nEDM)

- **Peccei-Quinn solution** Peccei & Quinn, PRL 38 (1977) 1440.

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

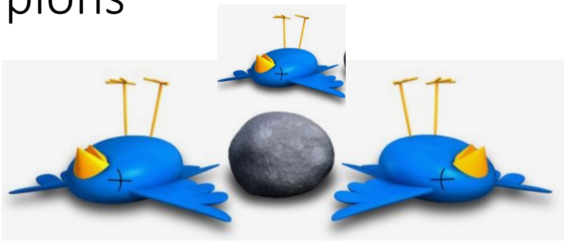
- **Axion** Weinberg, PRL 40 (1978) 223; Wilczek, PRL 40 (1978) 279

  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 due to coupling to pions
  - Mass unknown $m_a \propto g_{a\gamma}$,
  - Astrophysics: $g_{a\gamma} < 10^{-10}$ GeV^{-1}

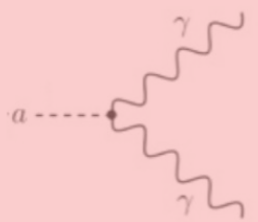
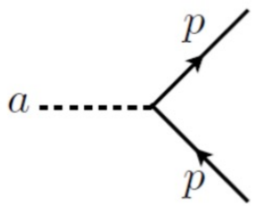
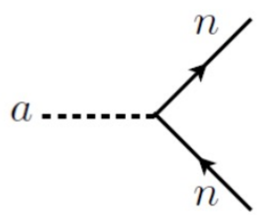
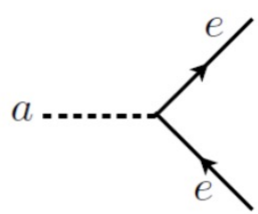
  → Dark matter candidate & solves strong CP



Axions and how to detect them

Coupling of **axions** to photons exploited by many experiments

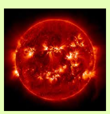
- Relatively “simple” and generic for all axion models
- Model-dependencies exist however

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

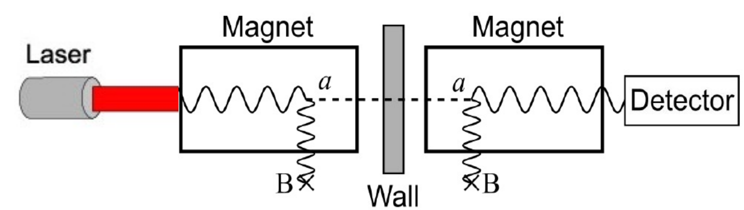
$g_{a\gamma} = \frac{C_{a\gamma}\alpha}{2\pi f_a}$ $\quad g_{ap} = C_{ap}\frac{m_p}{f_a}$ $\quad g_{ap} = C_{an}\frac{m_n}{f_a}$ $\quad g_{ap} = C_{ae}\frac{m_e}{f_a}$

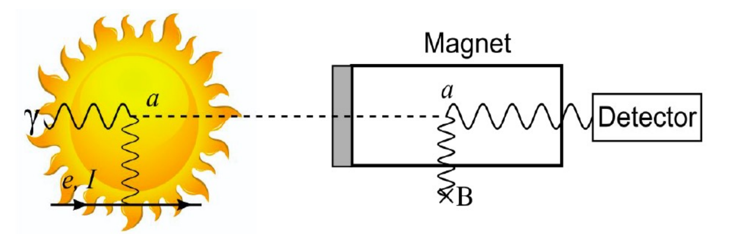
$$\mathcal{L} \supset \frac{g_{a\gamma\gamma}}{4}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} \equiv g_{a\gamma\gamma}\, a\, \mathbf{E}\cdot\mathbf{B}$$

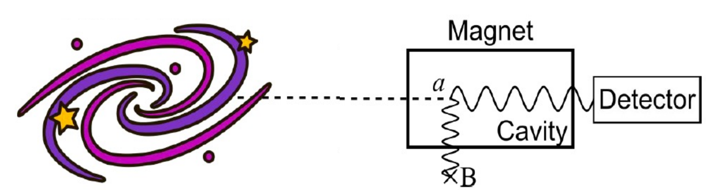
Axions and how to detect them

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

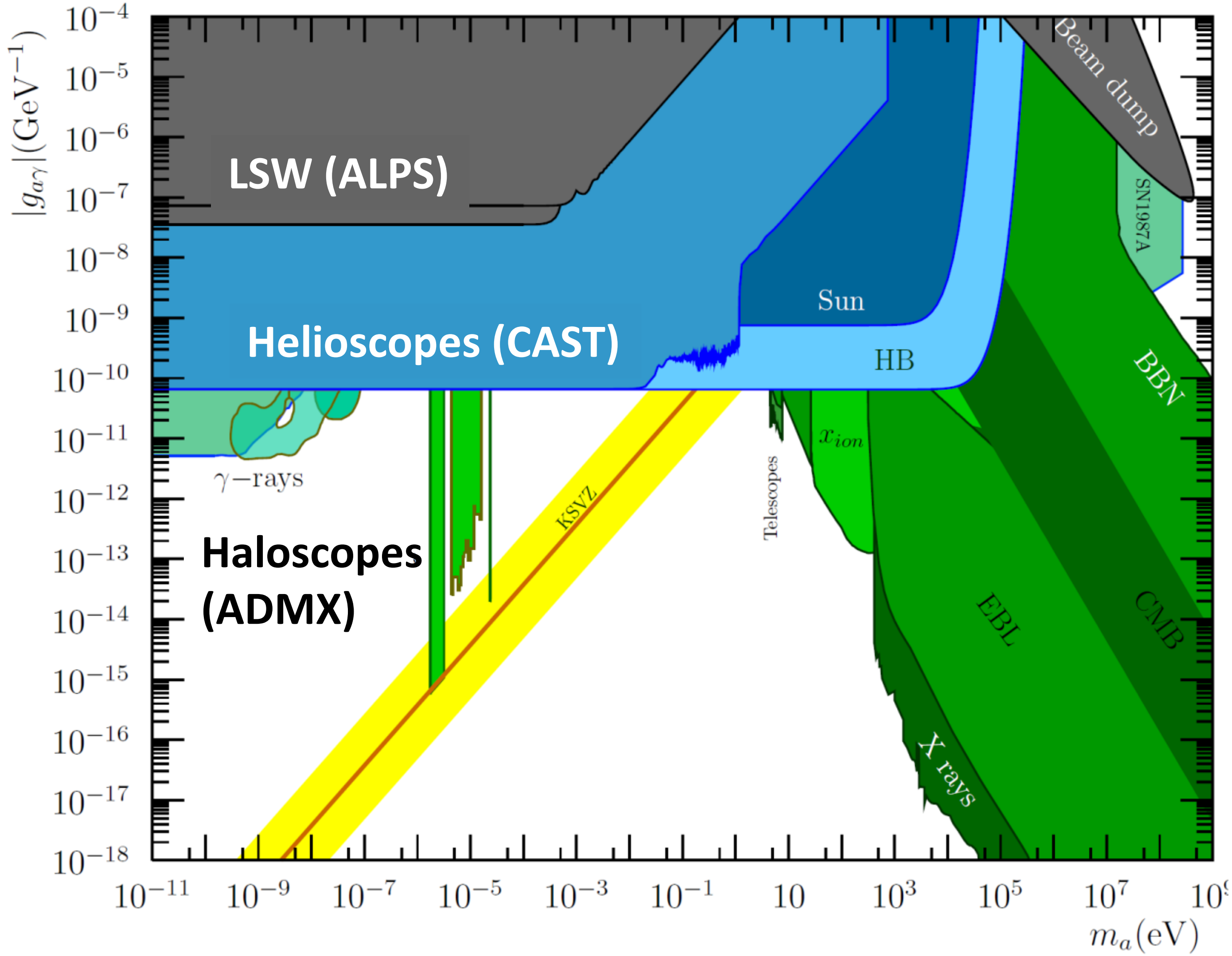






Large complementarity between different experimental approaches!

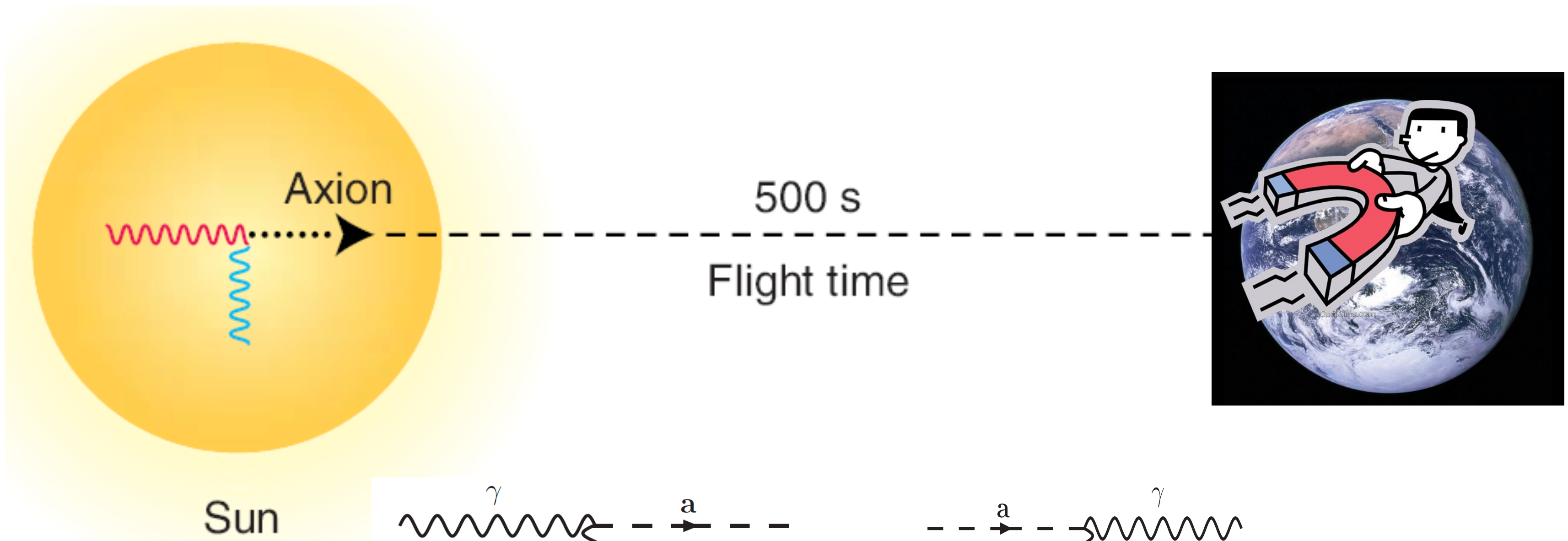
Axions and how to detect them

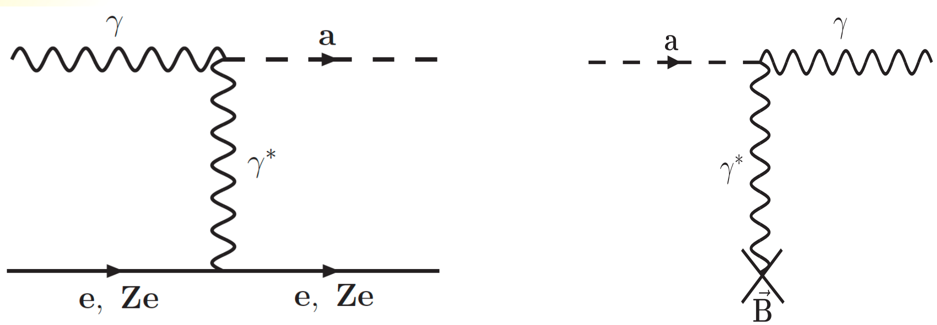


Outline

1. Axions and how to detect them
2. **Solar Axion Searches**
3. Current and future Axion Helioscopes
4. Outlook for helioscopes

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





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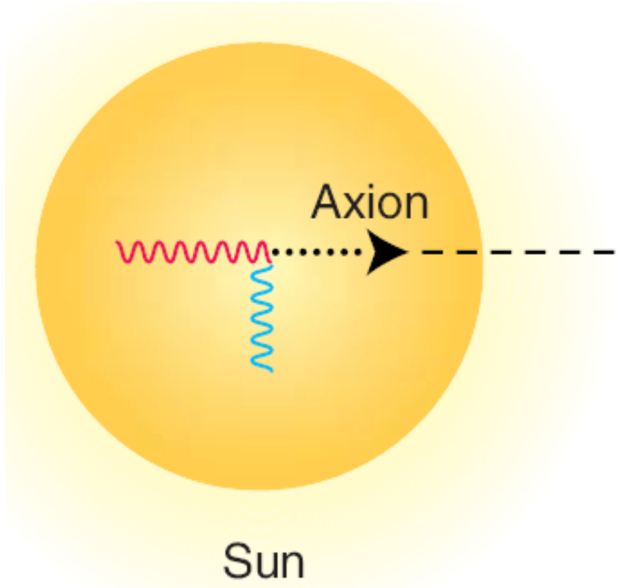

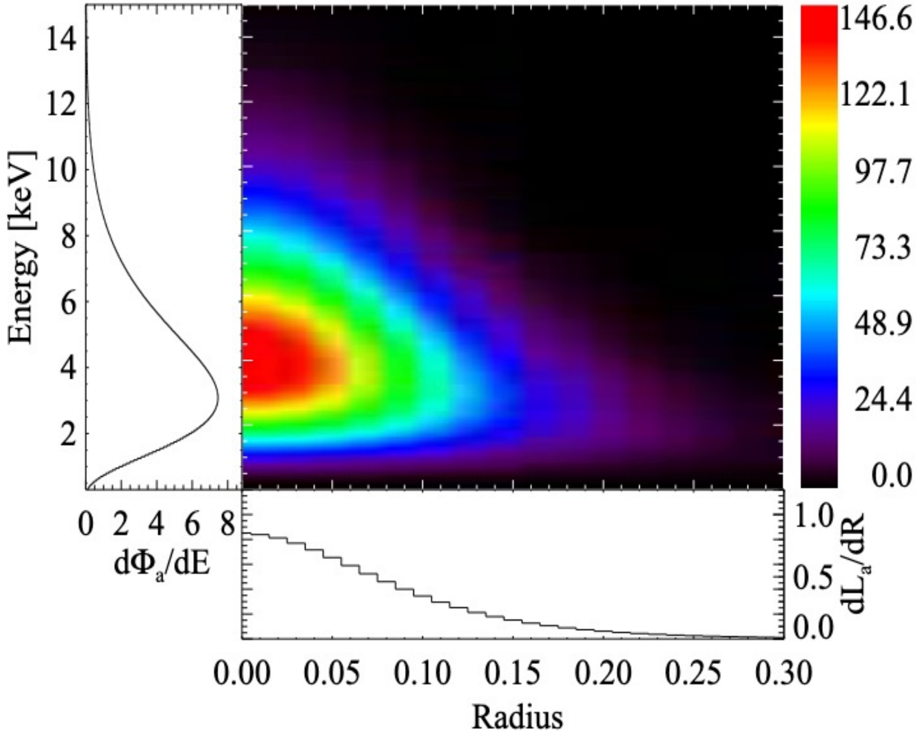

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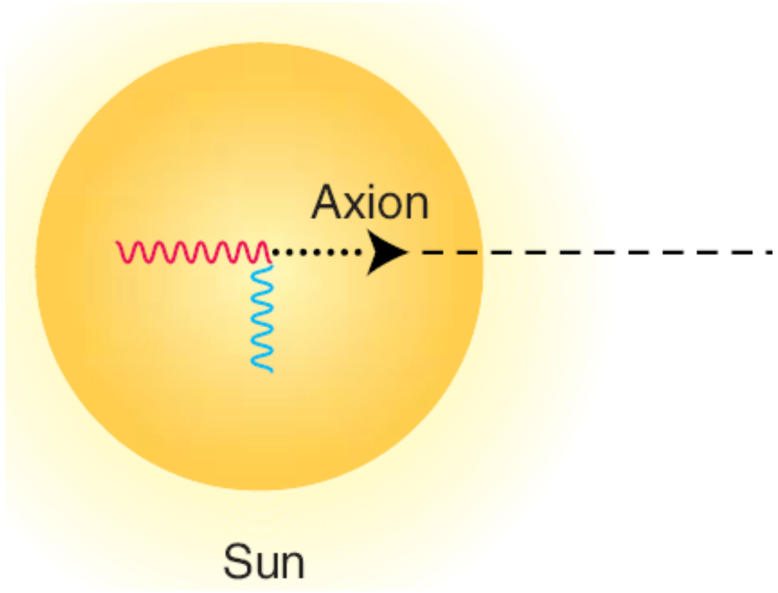
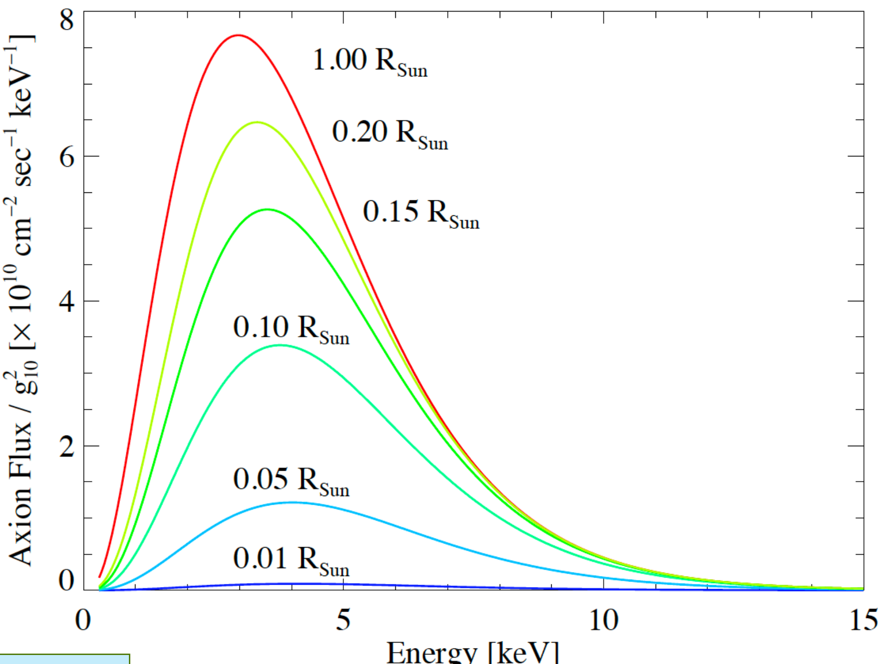




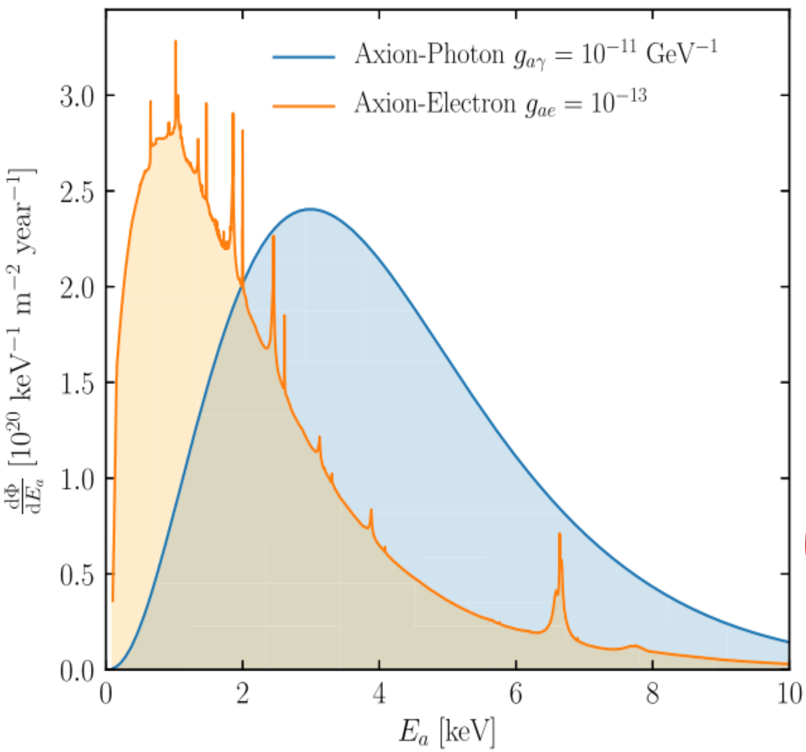
$$\frac{d\Phi_a}{dE} = 6.02 \times 10^{10} \left(\frac{g_{a\gamma}}{10^{-10}\mathrm{GeV}^{-1}} \right)^2 E^{2.481} e^{-E/1.205} \frac{1}{\mathrm{cm}^2\ \mathrm{s}\ \mathrm{keV}}$$

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

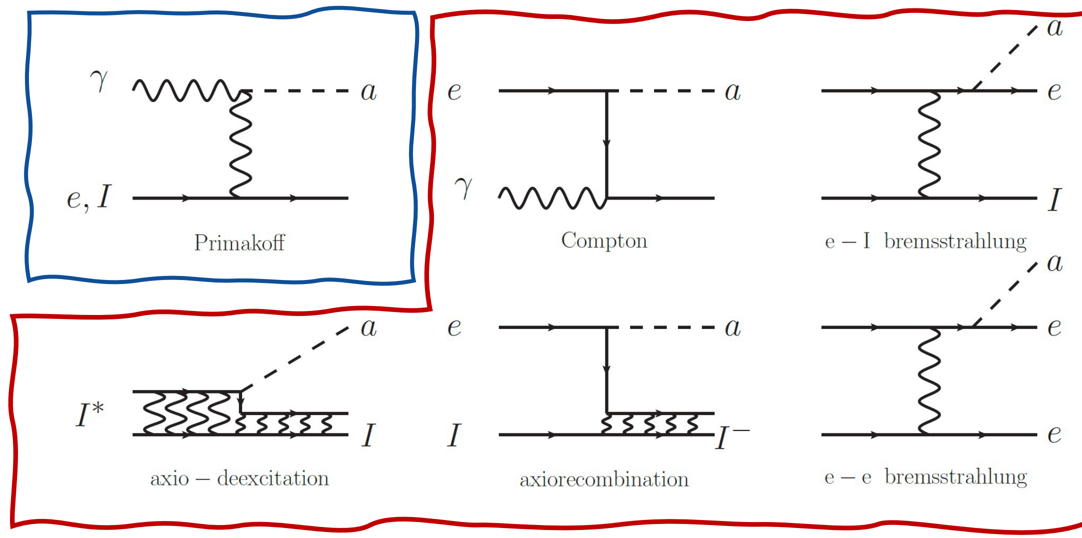
Van Bibber et al 1989 Phys. Rev. D 39 2089

Non-minimal axion models

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



Primakoff axions



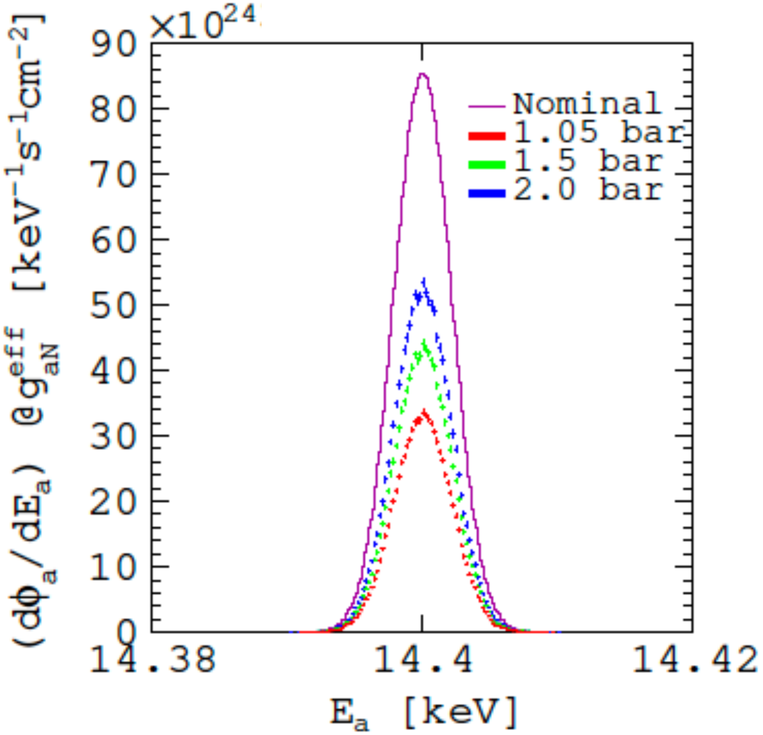
Non-hadronic or "ABC" axions (if the axion couples to electrons (g_{ae}))

Redondo, JCAP12(2013)008
Dafni et al., PRD **99**, 035037(2019)

Solar Axion Searches

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

- keV axions emitted in the M1 transition of Fe-57 nuclei (14.4 keV) and Tm-169 (8.4keV)
- 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 has couples via g_{aN} ,
  it is most likely a QCD axion



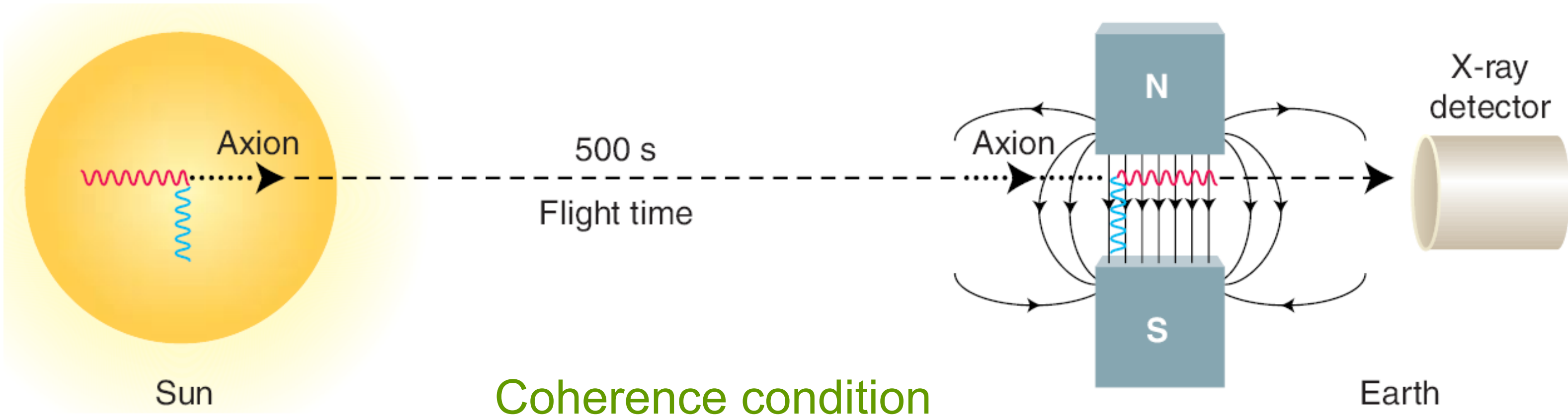
$$\Phi_a = 5.06 \times 10^{23}\ (g_{aN}^{\mathrm{eff}})^2\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

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
Candon et al. arXiv:2504.21107

P. Sikivie 1983 PRL 51 1415

First axion helioscope proposed by P. Sikivie

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



Coherence condition

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

VACUUM

Idea refined by K. van Bibber et al.

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

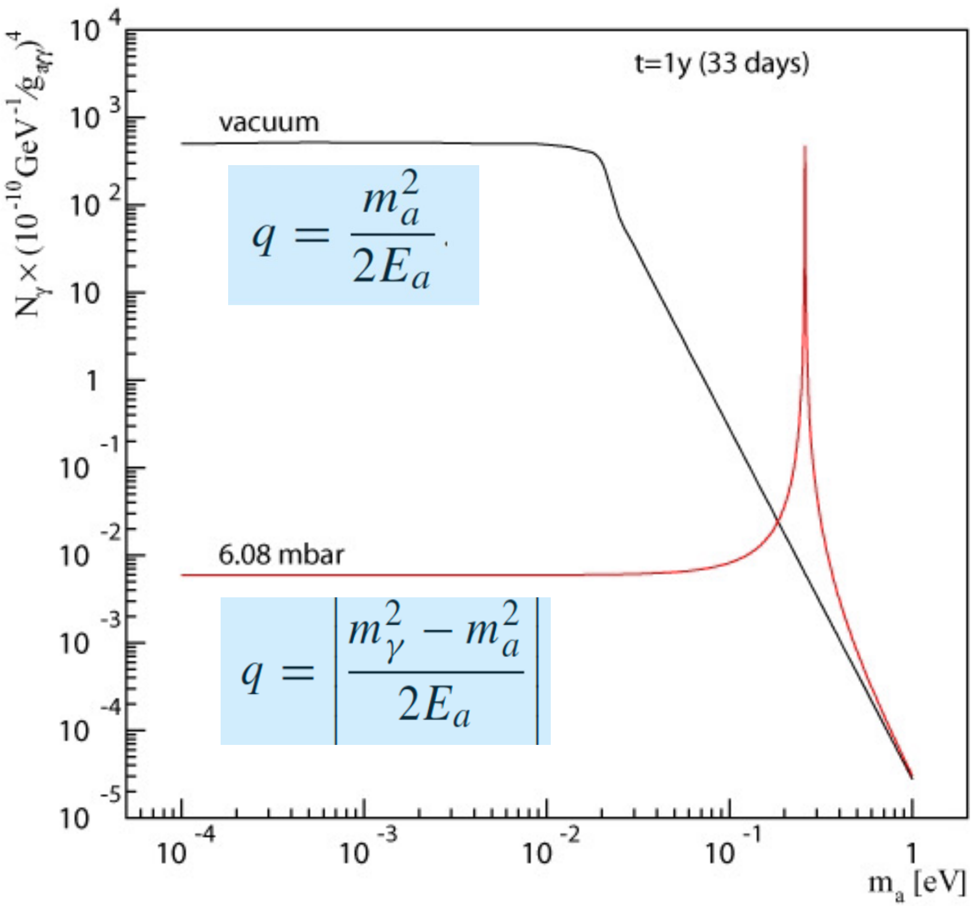
Buffer gas to restore coherence over long magnetic field and access higher axion masses

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

GAS

$$\boxed{\frac{qL}{2} < \pi}$$

Coherence condition



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

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

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

Can scan along the mass range by changing the density of the gas

$$m_\gamma \approx \sqrt{\frac{4\pi\alpha N_e}{m_e}}$$

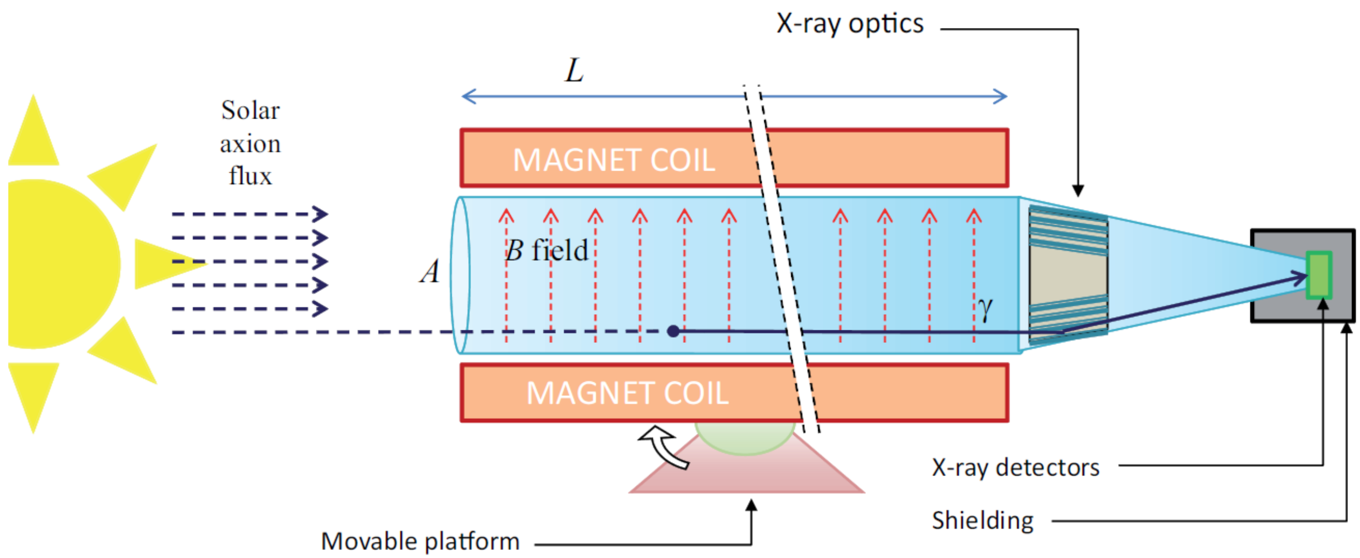
$$= 28.9\sqrt{\frac{Z}{A}\rho} \quad \mathrm{eV}$$

N_e = number of electrons/cm^3

ρ: gas density (g/cm^3)

Helioscope Figure of Merit

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



Measure of sensitivity to axion-photon interaction:

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

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 next gen improvement: 1−1.5 OoM in sensitivity to $g_{a\gamma}$ (factor 10k-20k in S/N)

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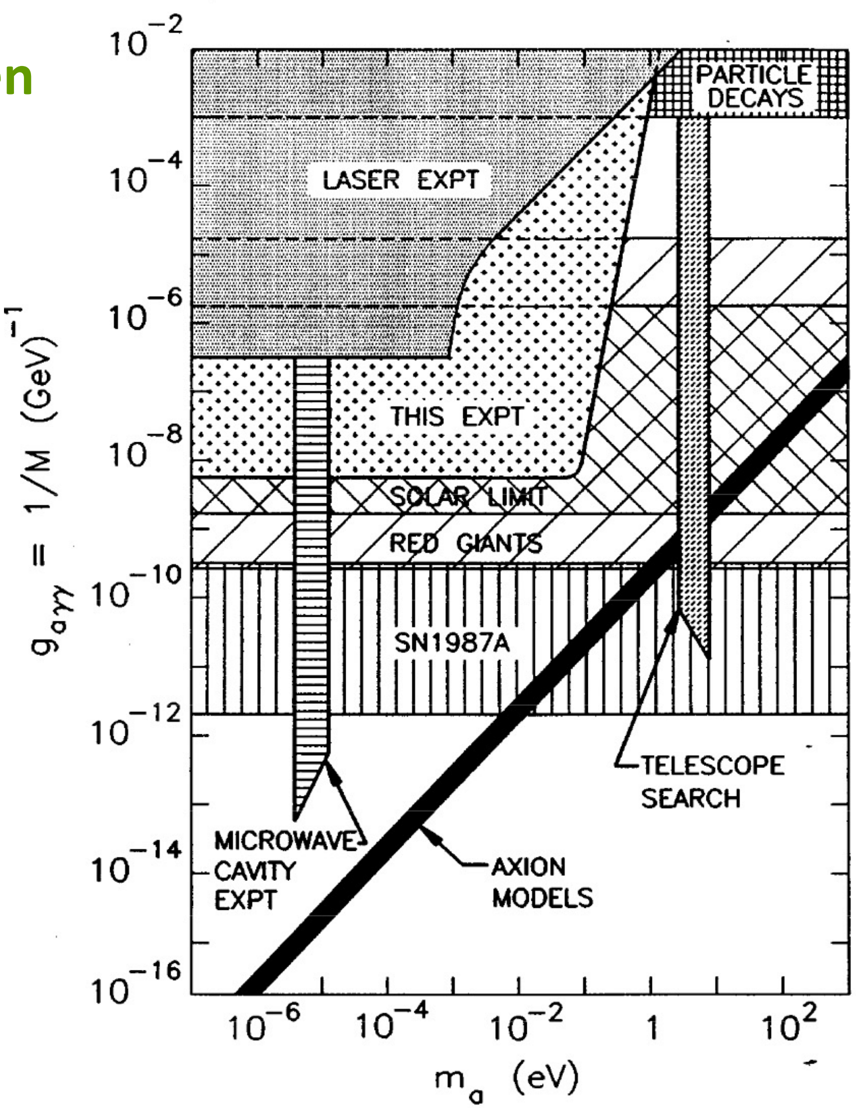
1st generation helioscope: Brookhaven

- First Axion Helioscope
- Merely a few hours of data

Lazarus et at. PRL 69 2333 (1992)



Current & Future Experiments

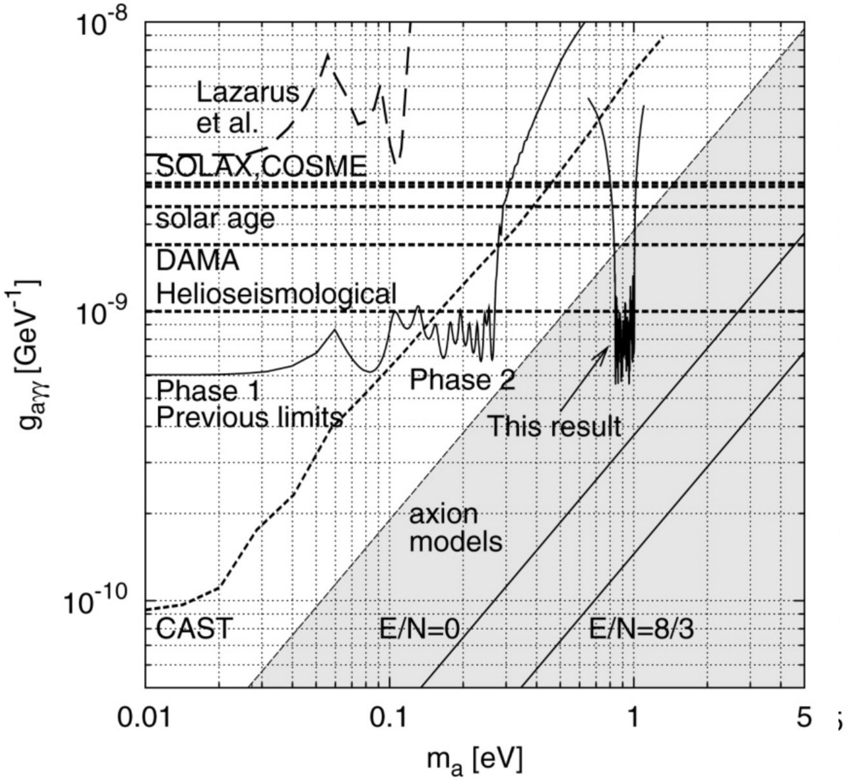
1st generation helioscope: Brookhaven

- First Axion Helioscope
- Merely a few hours of data

Lazarus et at. PRL 69 2333 (1992)

2nd generation: Tokyo Helioscope (SUMICO)

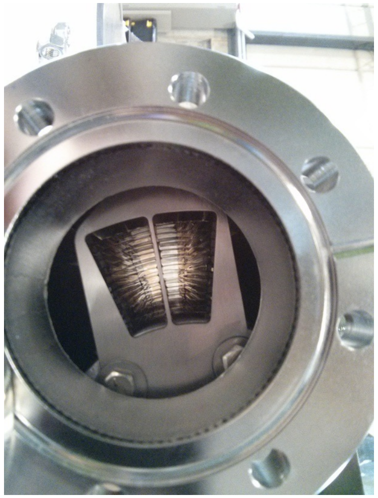
- 2.3 m long, 4 T magnet

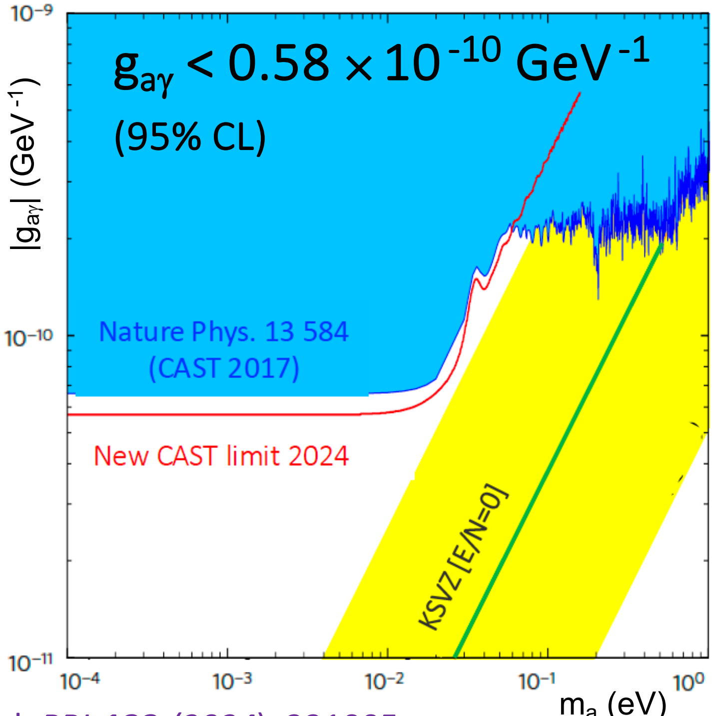


- CERN AXION SOLAR TELESCOPE

B = 9.5 T
L = 9 m

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





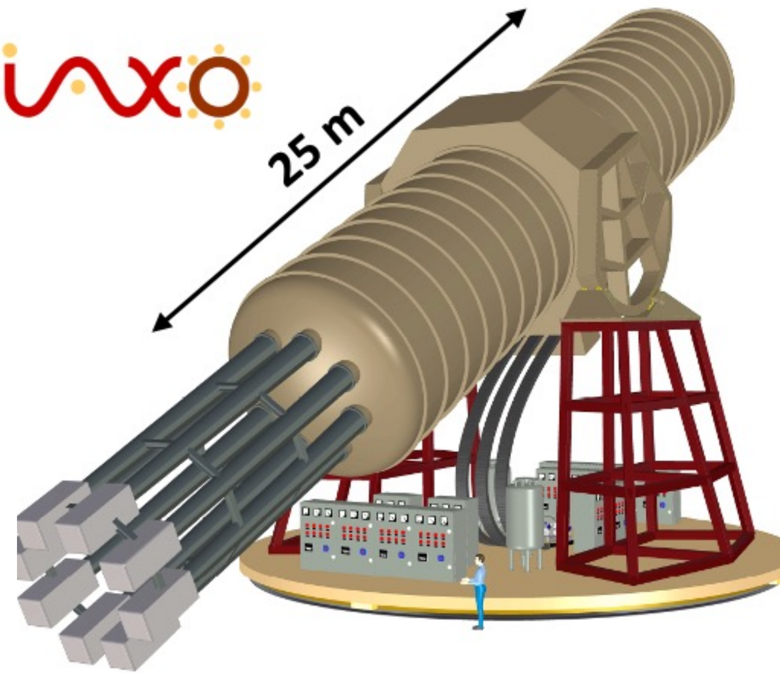
Anastassopoulos et al. *Nature Phys.* ***13*** *(2017) 584-590,* Altenmüller et al. *PRL* **133** *(2024)*, 221005

Current & Future Experiments Next-gen : IAXO/BabyIAXO

CAST @ CERN

BabyIAXO @ DESY

IAXO



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

B = 9.5 T
L = 9 m
A = 0.003 m^2

Completed

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

B = 5.4 T
L = 10 m
A = 0.77 m^2

Entering construction

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

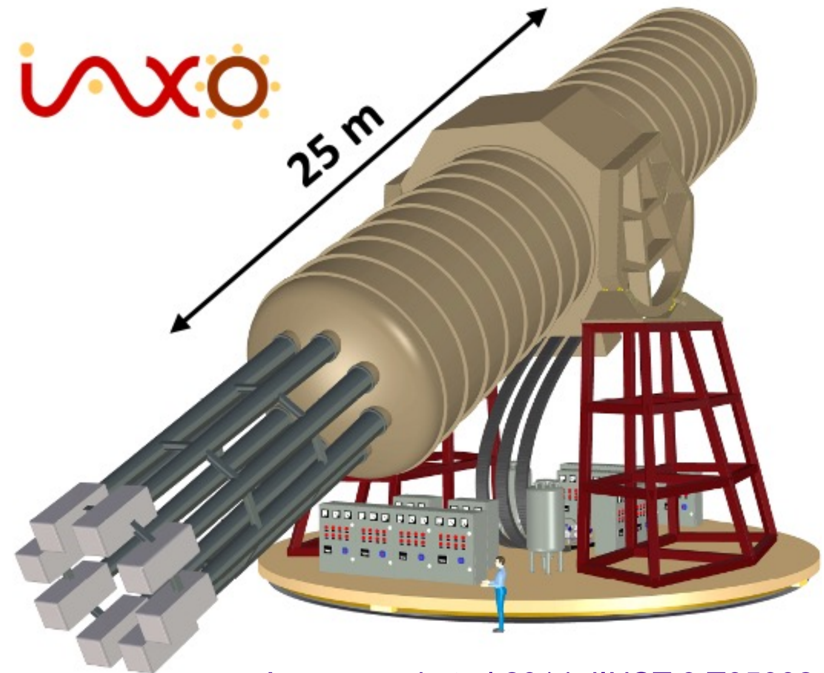
→ Factor 10k-20k in S/N

B = 5.4 T
L = 25 m
A = 2.26 m^2

Mid/Late 2030's

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

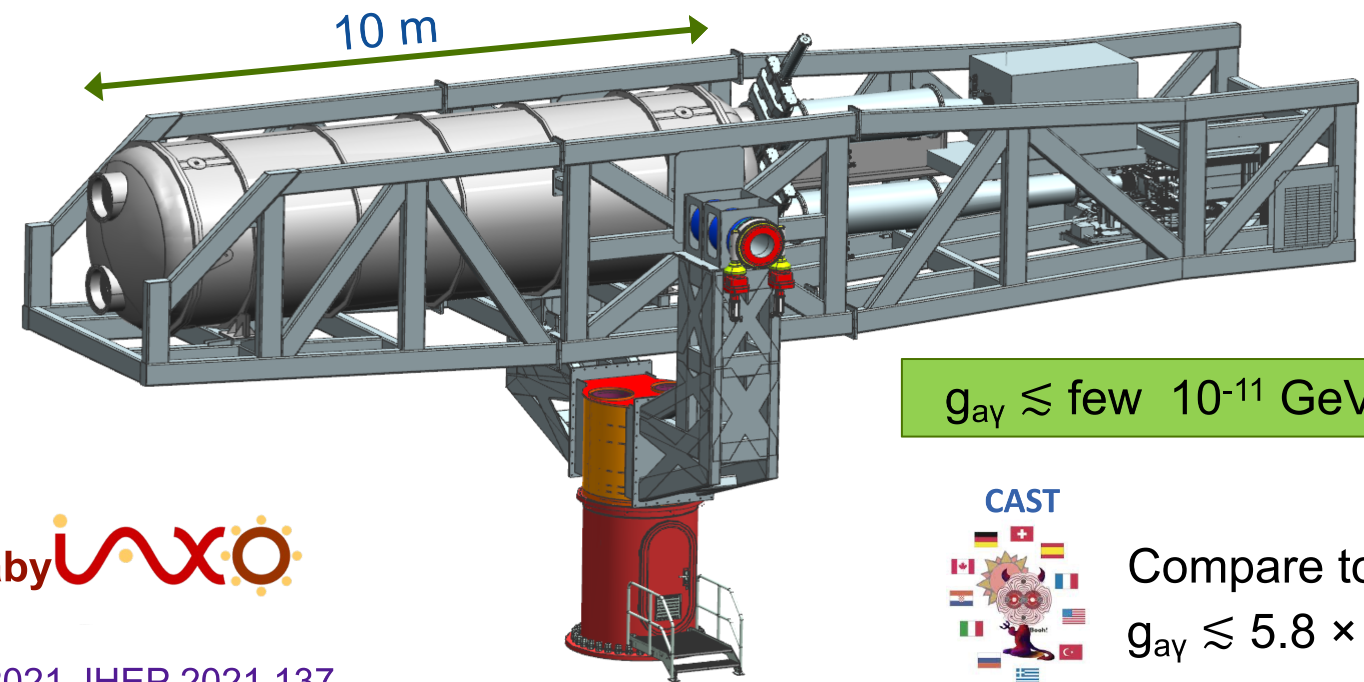
$g_{a\gamma} \lesssim$ few 10^{-12} GeV^{-1} (expected)

CAST

Compare to
$g_{a\gamma} \lesssim 5.8 \times 10^{-11}$ GeV^{-1}

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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BabyIAXO

CAST

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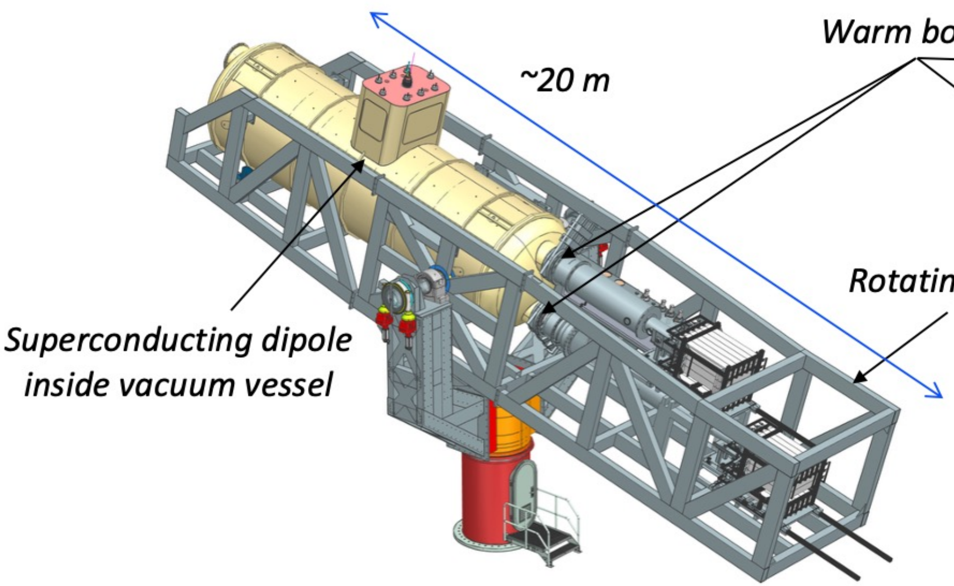
Abeln et al 2021 JHEP 2021 137

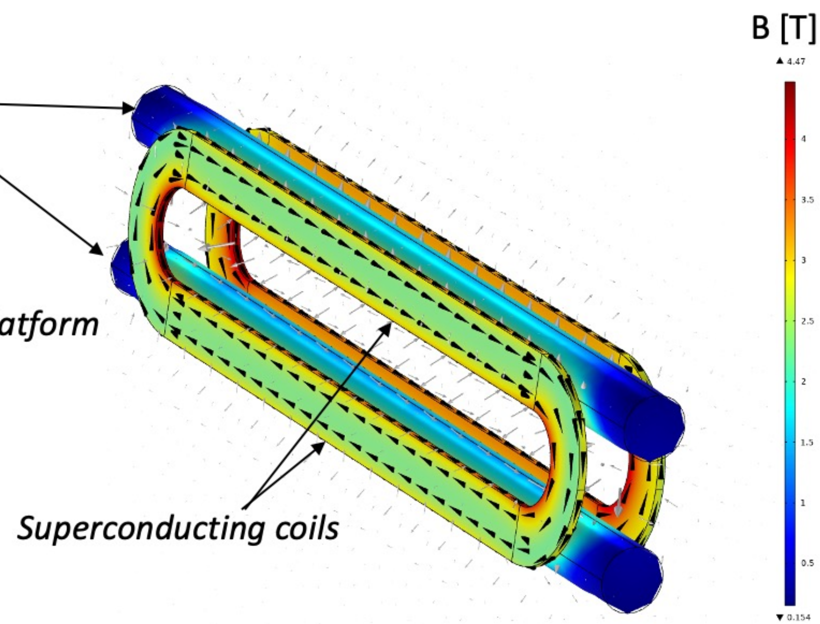
Baby IAXO MAGNET

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

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



BabyIAXO experiment, to be hosted at DESY



Magnet 3D coil geometry, current direction, and resulting magnetic field

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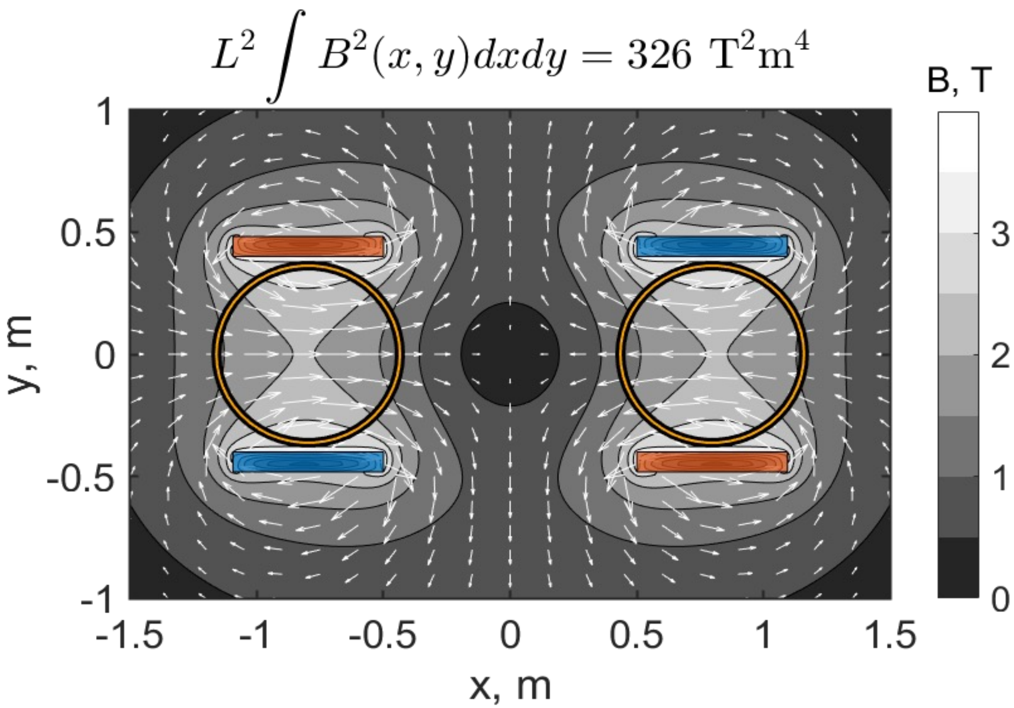

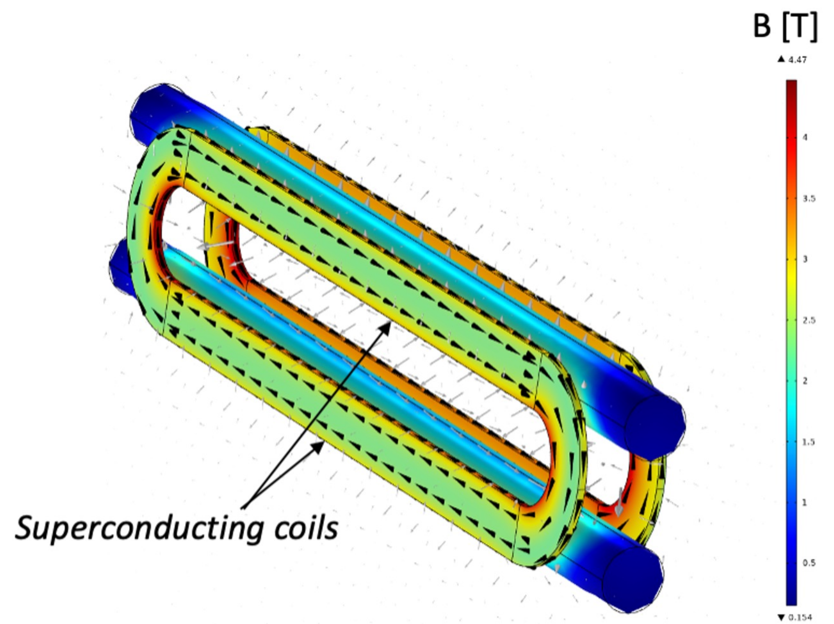

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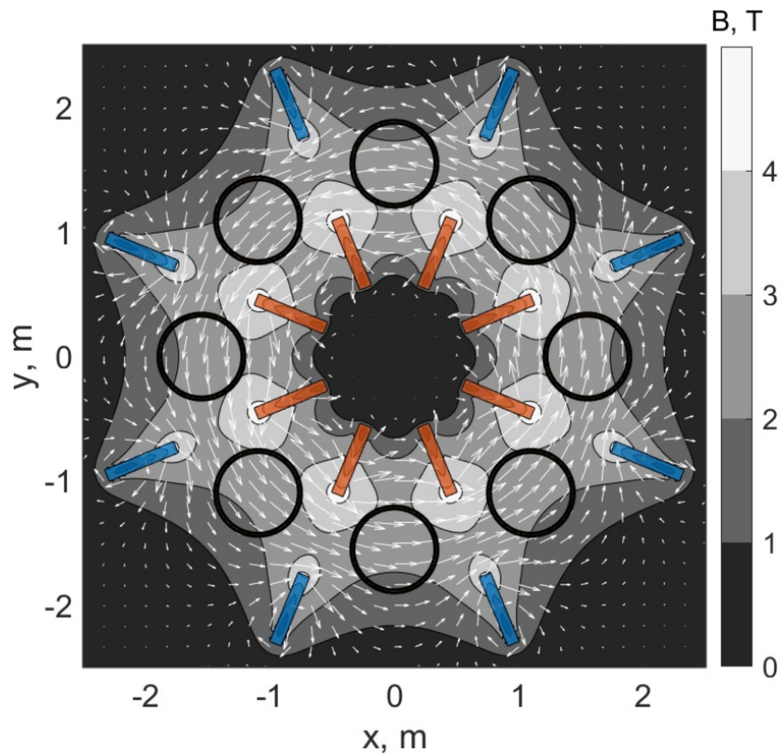
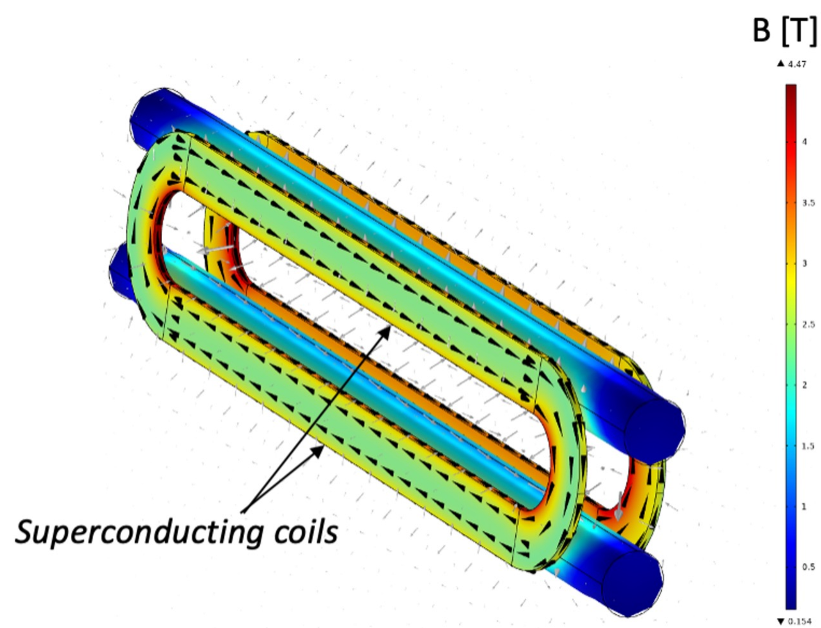




Magnet 3D coil geometry, current direction, and resulting magnetic field

Current & Future Experiments

Baby IAXO TELESCOPES

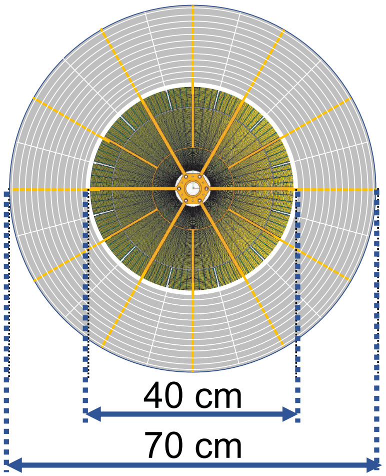
NEED: Maximized throughput efficiency (40-60%),
Small focal spot (r < 2.5 mm),
Cost-effective way (need 8 for IAXO)

- Baseline 1-10 keV (prototyping and R&D)
  - Existing XMM flight-spare telescope
  - Custom IAXO optic (NuSTAR/BRAVO)
- Beyond baseline
  - 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

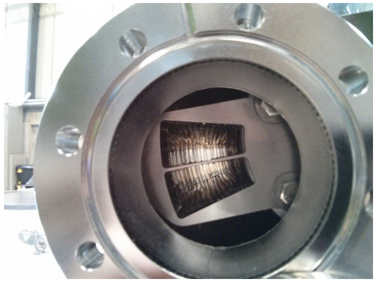
esa NASA

Custom optics
Hot and cold slumped glass

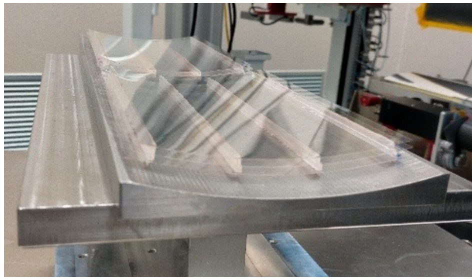


XMM Flight spare
Replicated optics

NuSTAR Pathfinder



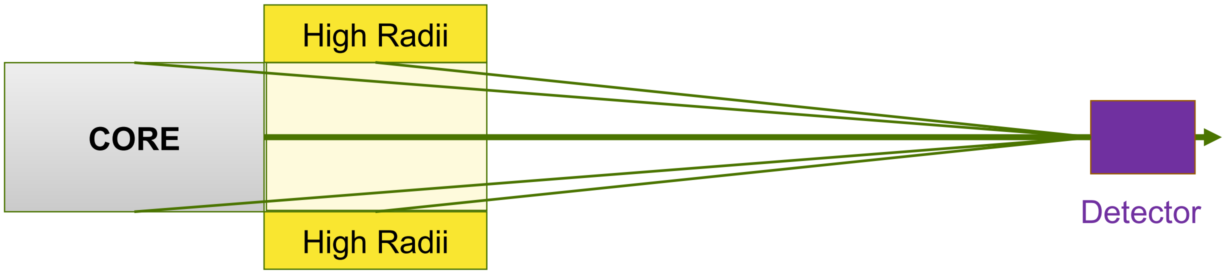
BRAVO Pathfinder

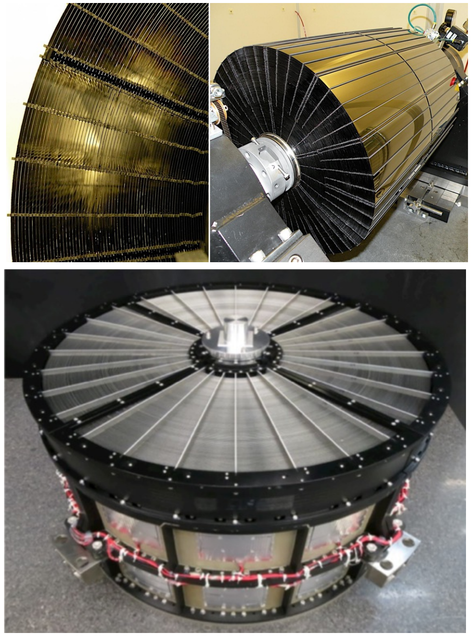


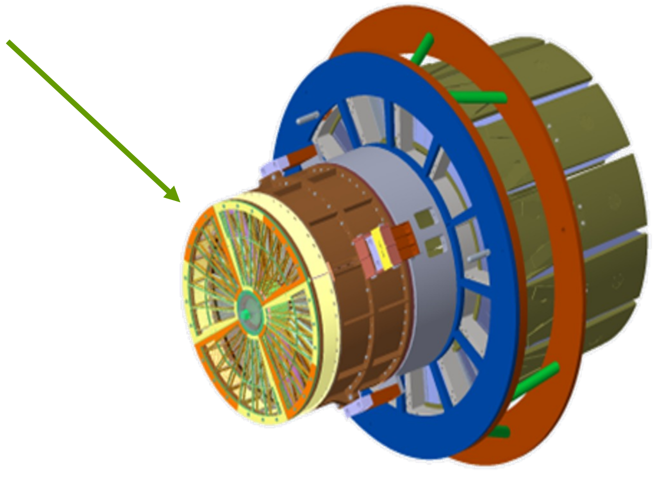
Henriksen et al 2021 AO 60, 22; Irastorza et al 2015 JCAP 12, 008

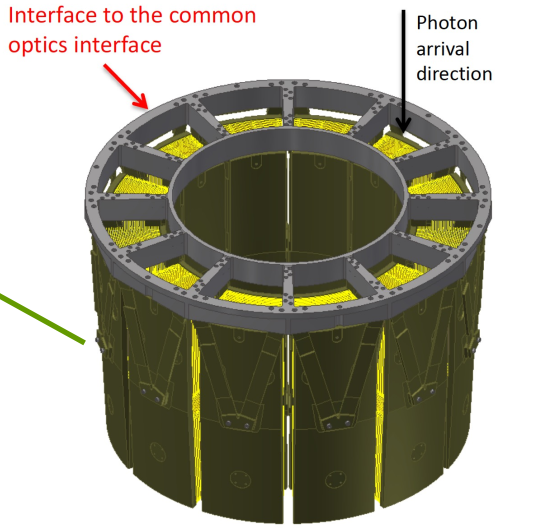
Baby IAXO TELESCOPES

Custom-built telescope









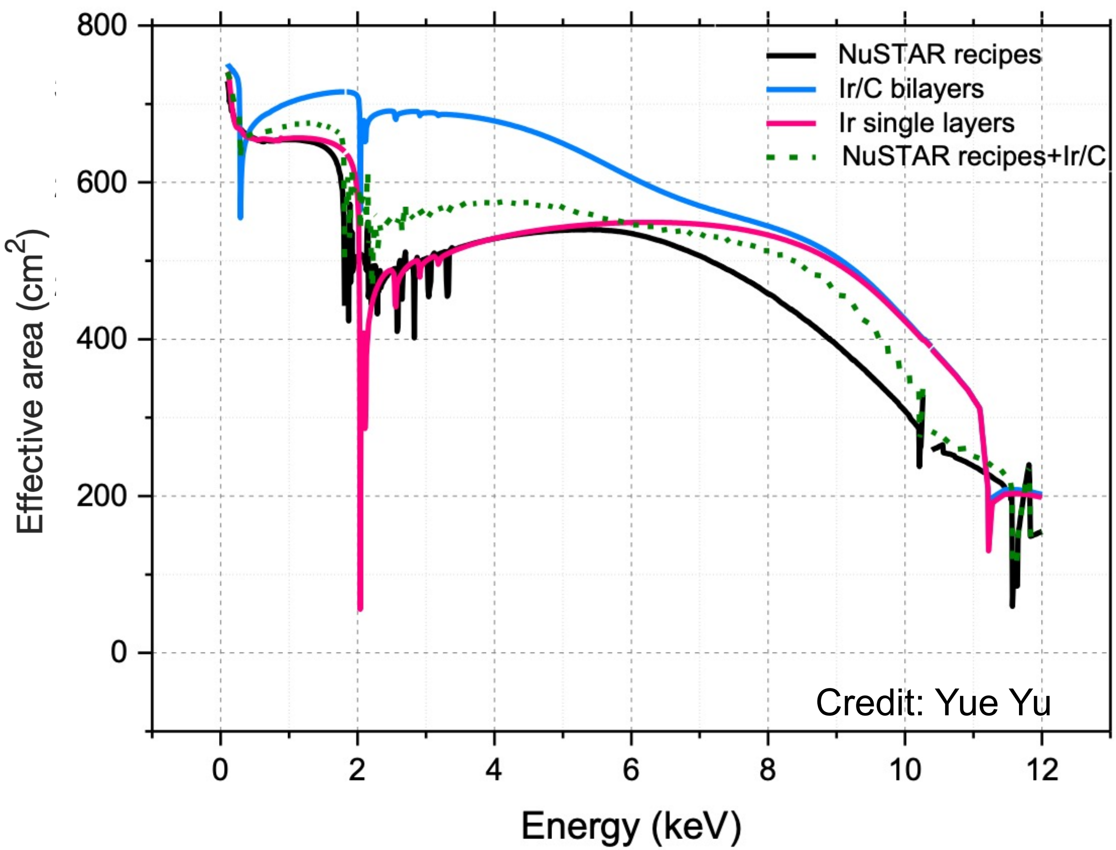
Core optic (NuSTAR/XRISM)

High radii (BRAVO-SUN)

Baby IAXO TELESCOPES

Custom-built telescope

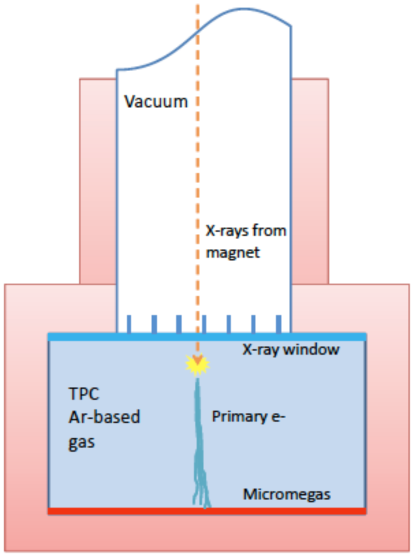
- Optimization to re-use as much existing NuSTAR glass as possible
- Compromise solution only degrades overall efficiency of the combined optics by less than 10%



BabyIAXO DETECTORS

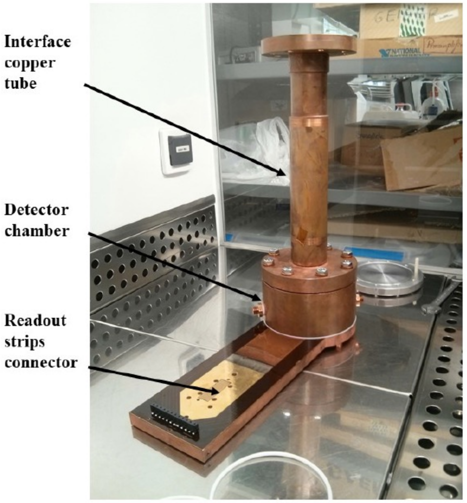
NEED (Baseline 1-10 keV)

- **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 baseline option to reach required low background
Additional technologies considered /active R&D efforts

Current & Future Experiments

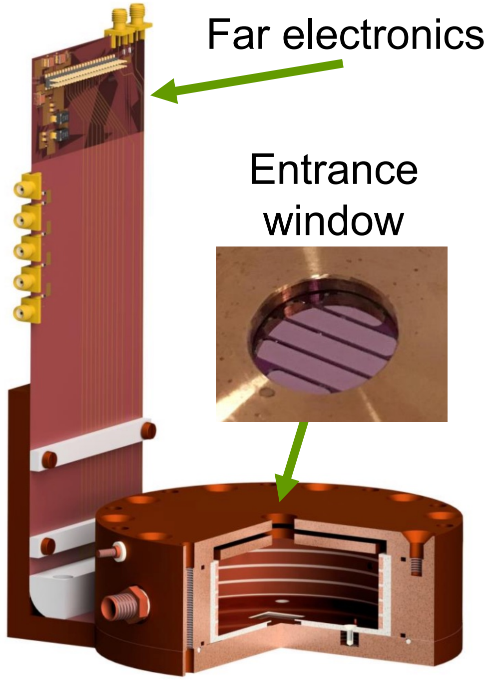
BabyIAXO Detectors

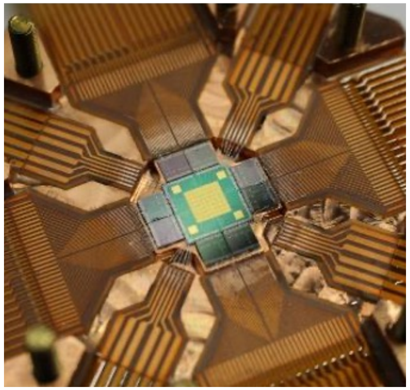
BabyIAXO DETECTOR

See poster by Lucinda Schönfeld

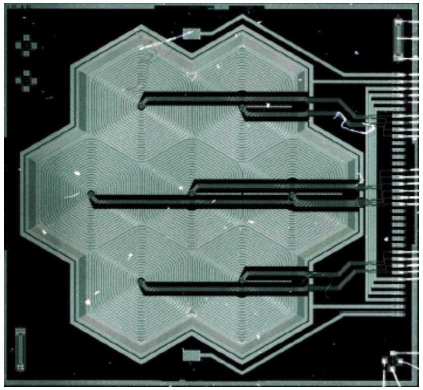
WANT (Beyond baseline)

- Pursuing a variety of detector technologies
  - Gaseous (Time Projection Chamber): MM, GridPix
  - Semiconductor: Silicon Drift Detectors (SDD)
  - Cryogenic: Metallic Magnetic Calorimeters (MMC), Transition Edge Sensors (TES)

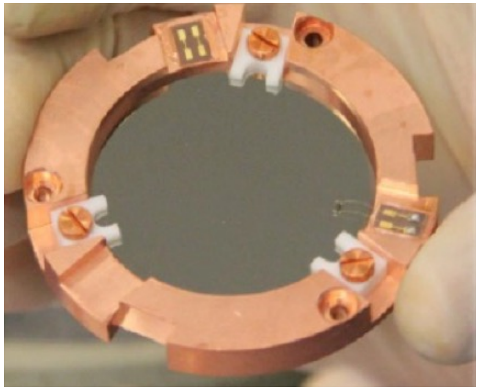




MMC

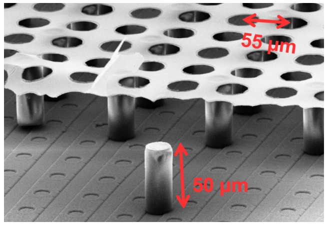


SDD



TES

Aluminum grid above Timepix3 readout chip



GridPix

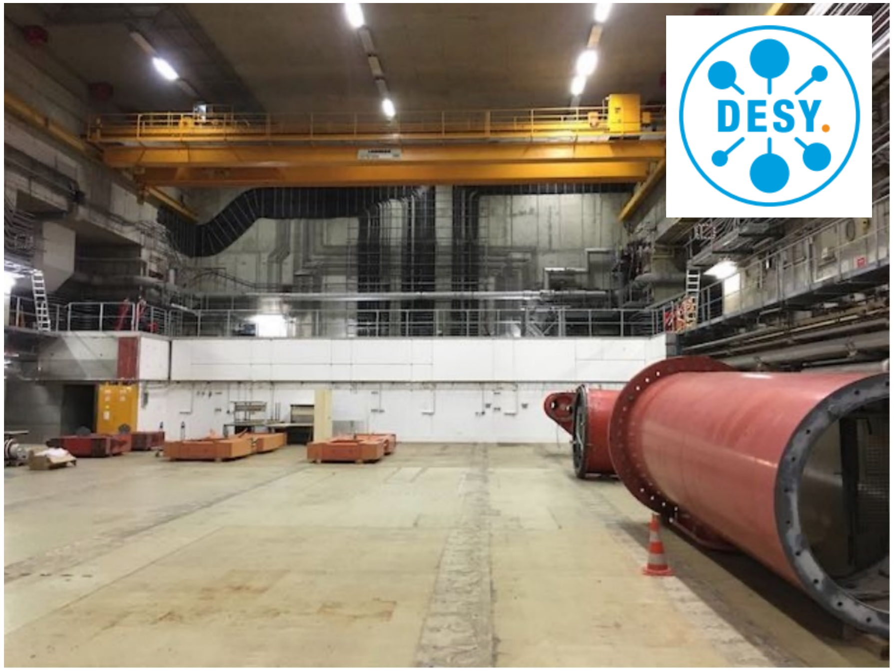
BabyIAXO Location

BabyIAXO @DESY

- DESY HERA hall as BIAXO 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 BIAXO without magnet before baseline science run



Current & Future Experiments

Next-gen sensitivities

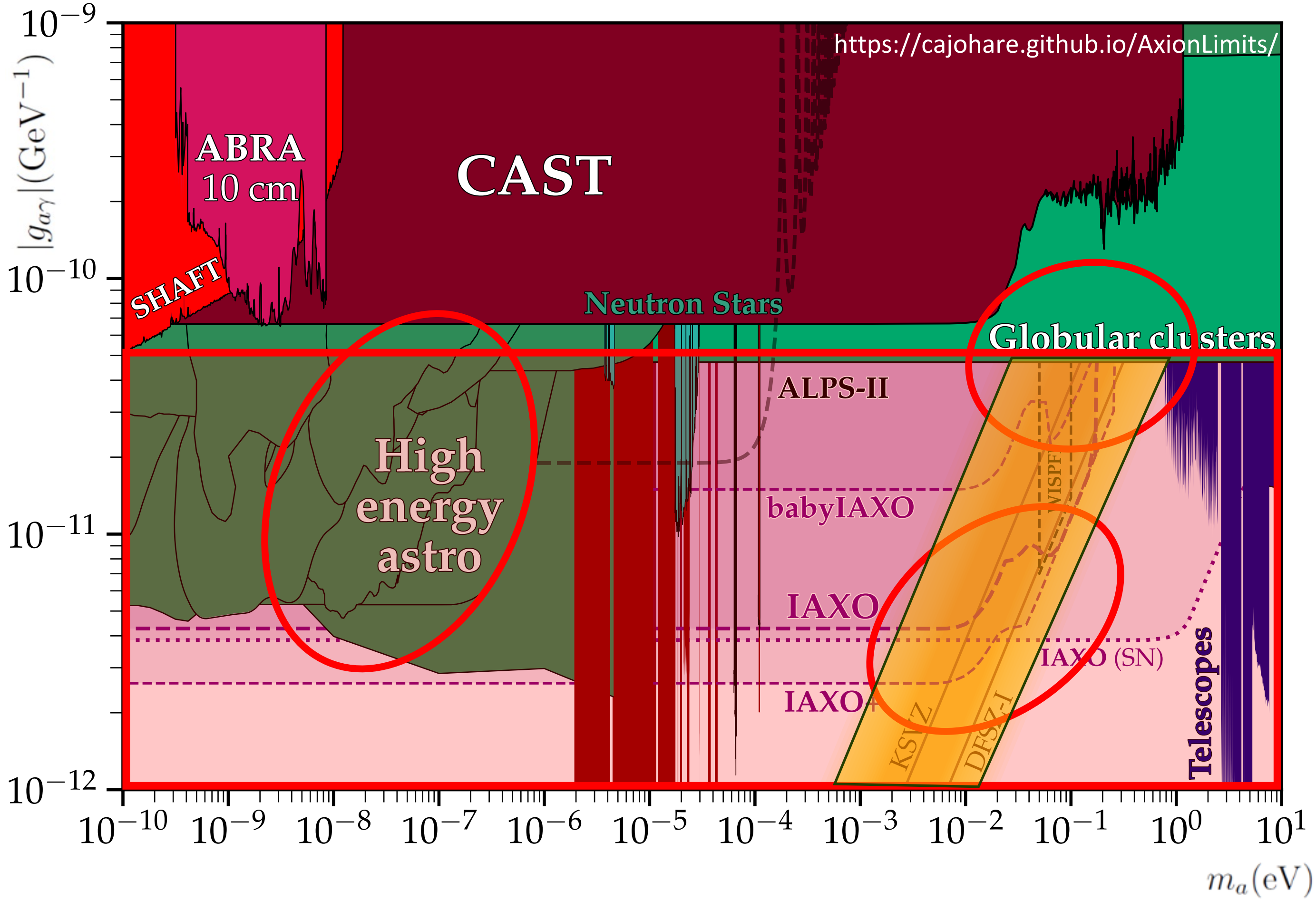


Figure of Merit:

- BIAXO: ~ 10 × $\mathrm{MFOM}_{\mathrm{CAST}}$
- IAXO : > 300 × $\mathrm{MFOM}_{\mathrm{CAST}}$

Science case

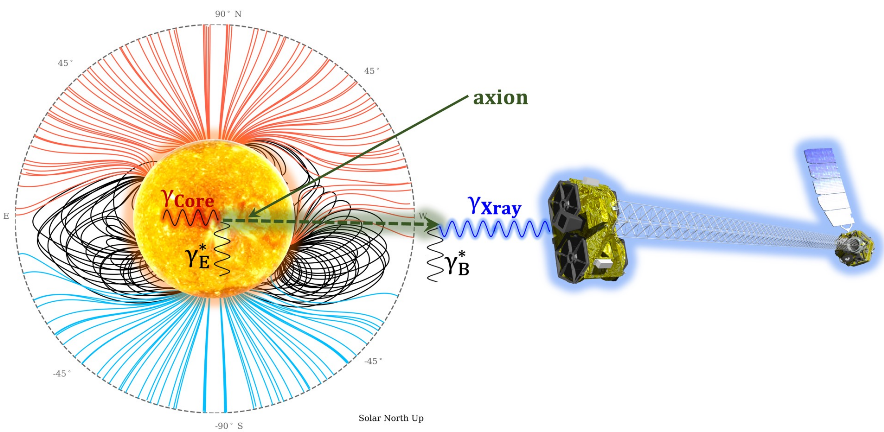
- QCD axions incl. DM candidates
- "ALP miracle" region: DM & Inflation solved
- Astrophysical hints: Anomalous stellar cooling
- Astrophysical hints: Transparency to UHE photons
- ALP dark matter

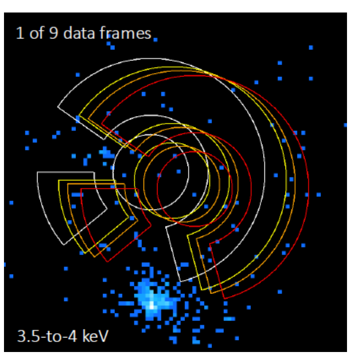
+ Beyond baseline program e.g. RADES, a-e, a-n, DP,...

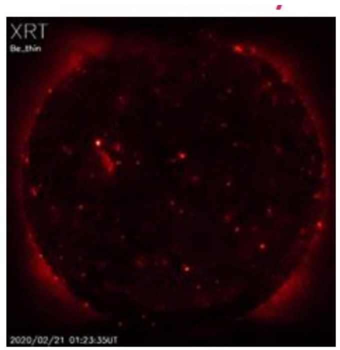
Armengaud et al 2019, JCAP 1906, 047

Novel Approach using satellites

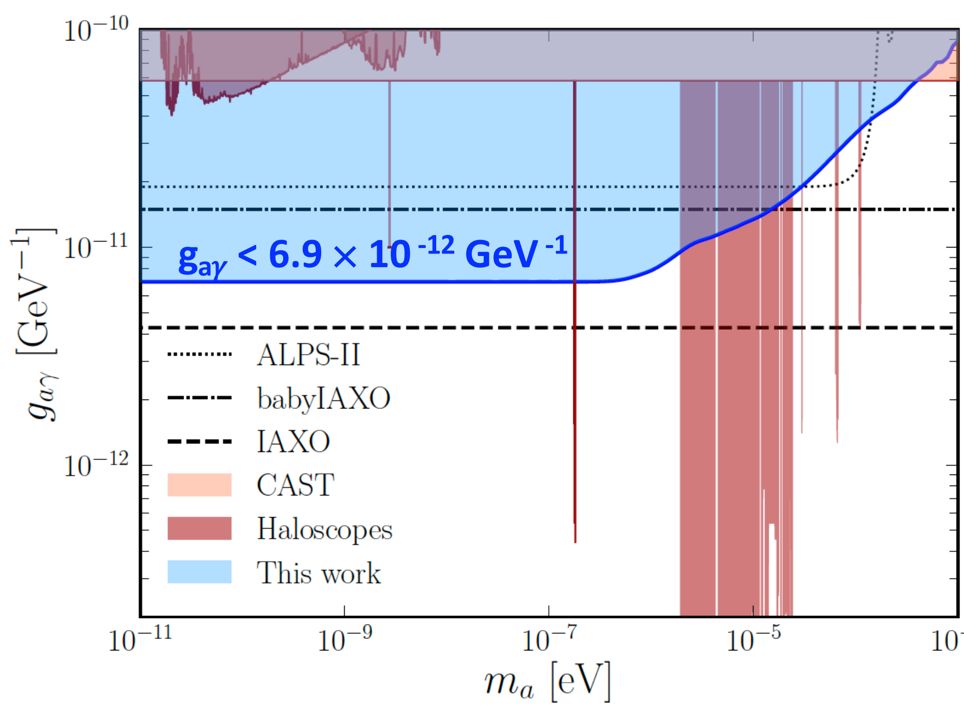
Concept: Utilize outer solar magnetic field for reconversion of axions into x-ray photons and use X-ray astronomy mission to detect them







J. Ruz et al., arXiv:2407.03828



Outline

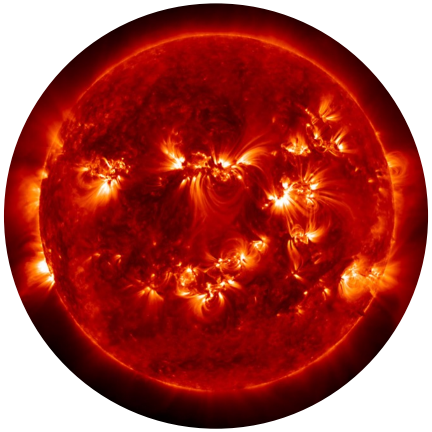
1. Axions and how to detect them
2. Solar Axion Searches
3. Current and future Axion Helioscopes
4. **Outlook for helioscopes**

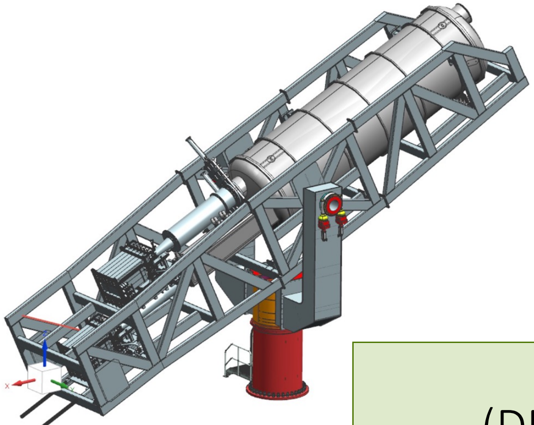
Armengaud et al 2019, JCAP 1906, 047

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	Post-discovery "precision" physics	SN Axions	Haloscope meets Helioscope



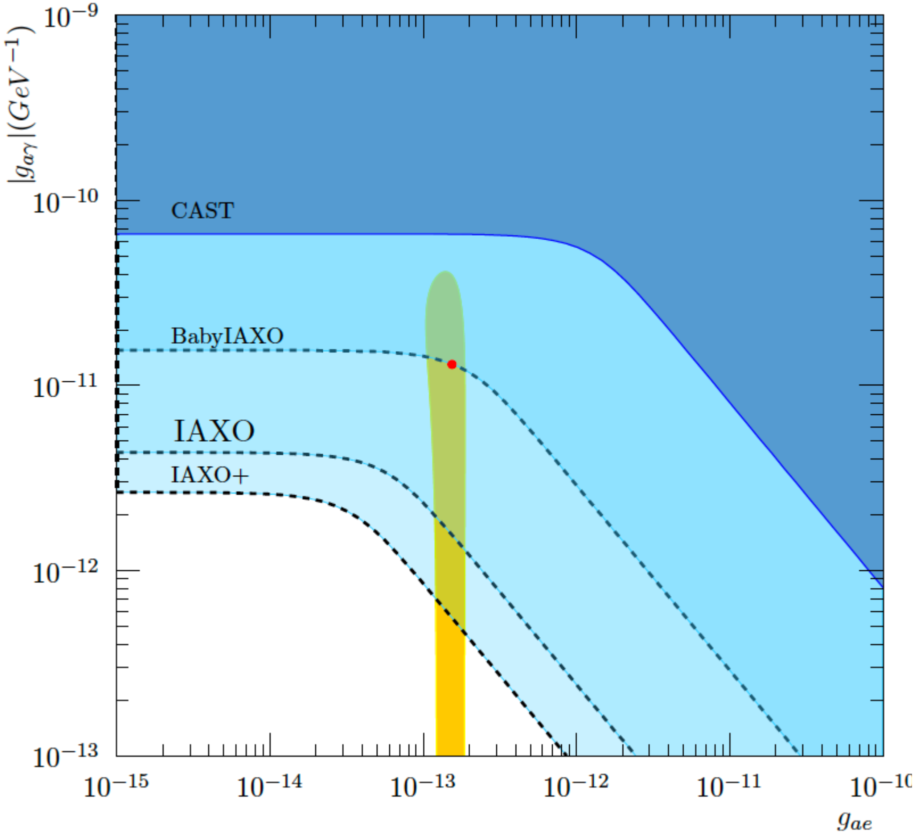


...and more
(DP, high-frequency gravitational waves,...)

Outlook for helioscopes

Parameter space showing the sensitivity of the experiments in the $g_{a\gamma}$- g_{ae} plane

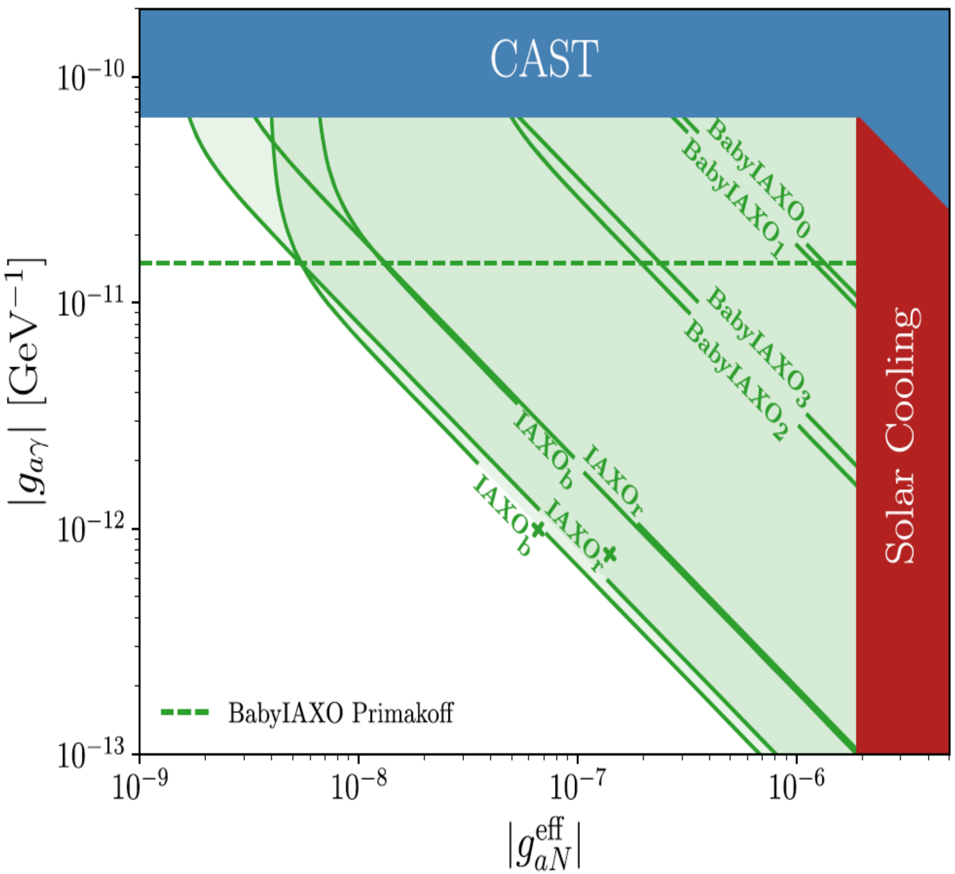
- Axion mass $m_a \simeq 1meV$



JCAP06(2019)047

Parameter space showing the sensitivity of the experiments in the $g_{a\gamma}$- g_{aN} plane

- Axion mass $m_a \simeq 20meV$

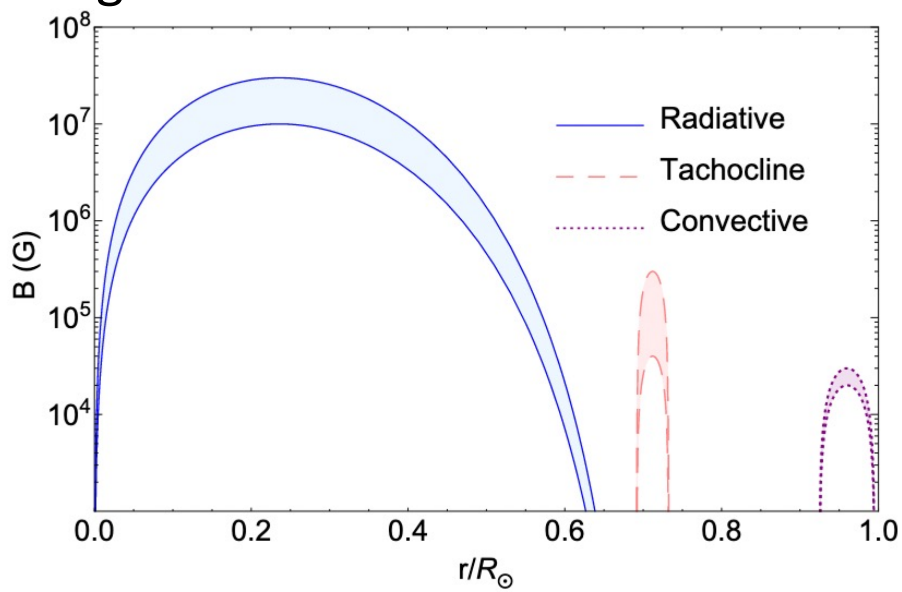


Eur. Phys. J. C 82, 120 (2022)

Non-Primakoff solar axions

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

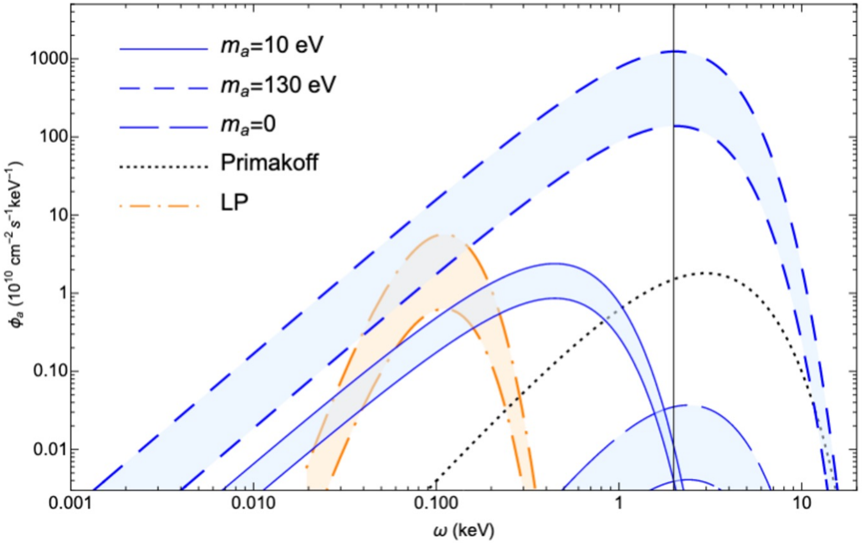
  → **needs more specialized detection systems** (XRTs, detectors)
- Solar ALP production via conversion in large-scale B-fields of longitudinal plasmons
  - Solar B-field dependence (field not well known but can be constrained)



Guarini et al. Phys. Rev. D **102**, 123024 (2020)

Non-Primakoff solar axions

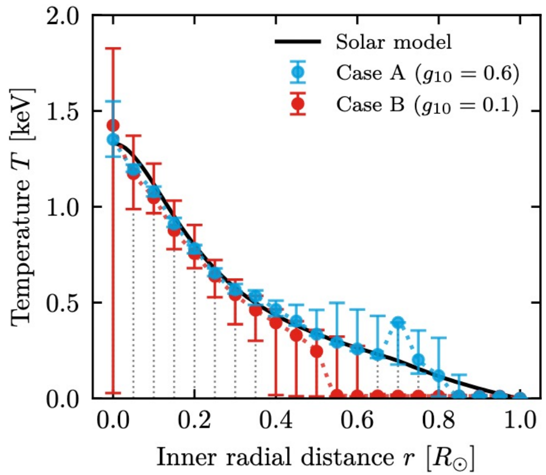
- ABC axions via axion-electron coupling or solar axions via axion-nucleon coupling as mentioned before:
  → **needs more specialized detection systems** (XRTs, detectors)
- Solar ALP production via conversion in large-scale B-fields of longitudinal plasmons
  - Solar B-field dependence (field not well 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



Hoof et al. JCAP 09 (2021) 006, Guarini et al. Phys. Rev. D **102**, 123024

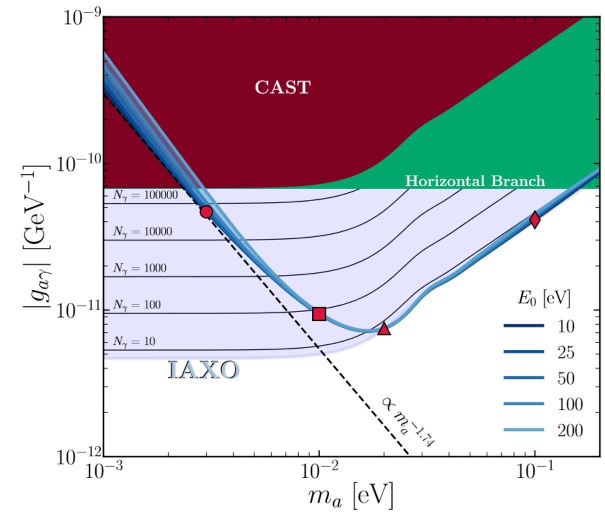
Post-discovery: Axion properties and applications

- Helioscopes as solar magneto-meters
- 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}, $g_{a\gamma}$)

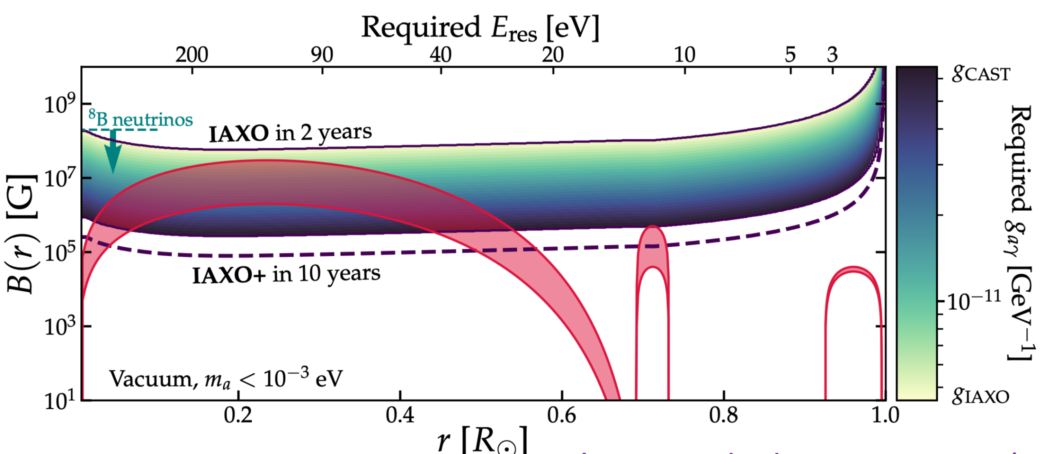


Hoof et al. JCAP10(2023)024

Dafni et al. Phys. Rev. D **99**, 035037(2019)

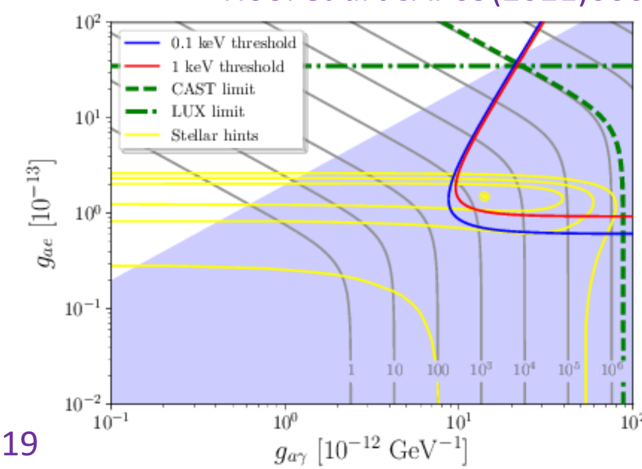


Jaeckel & Thormaehlen, JCAP 03(2019) 039



O'Hare et al. Phys. Rev. D **102** (2020) 043019

Hoof *et al* JCAP09(2021)006

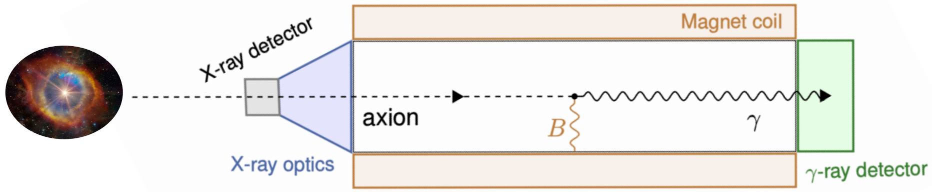


Outlook for helioscopes

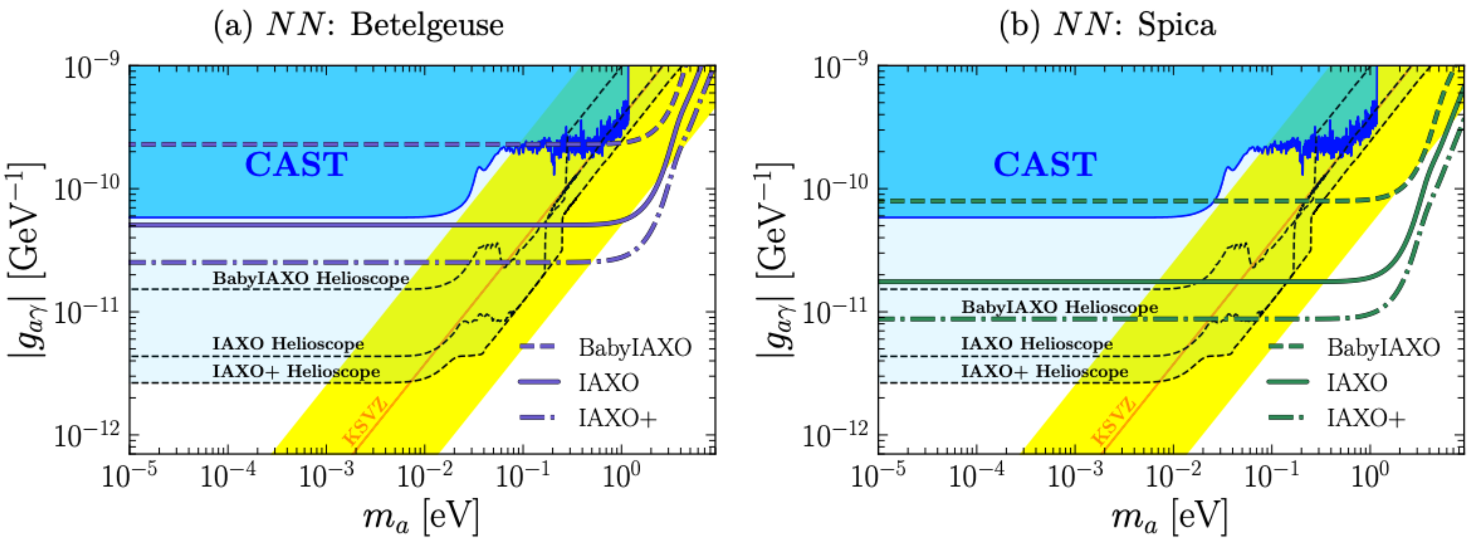
Axion from galactic supernova

Ge et al. JCAP11(2020)059
Carenza et al. 2502.19476

- If sufficiently close-by galactic SN, SN axions could be detectable at (Baby)IAXO.
- SN axions have O(100MeV) energies



- **Requires** IAXO to have large **HE γ-ray detector**, covering all magnet bore, sufficient pointing accuracy, alert system in place
- Can be implemented complementary to baseline BabyIAXO setup (opposite magnet side)

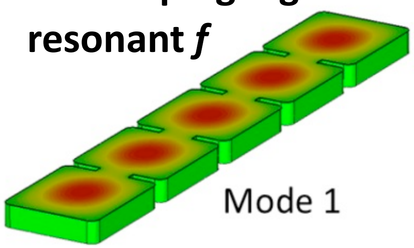


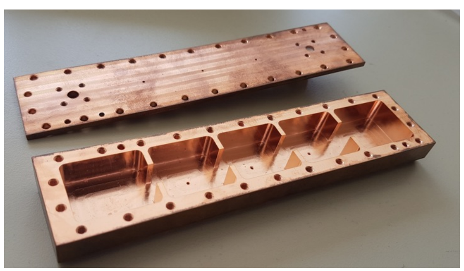
Betelgeuse: 222 pc
Spica: 77 pc
$g_{aN}= 10^{-9}$ and
no pion scattering

RADES

Exploratory project towards a later stage of CAST experiment: helioscope magnets for haloscope searches, with interesting results up to now

New geometry concepts to scale in V but keeping high resonant *f*



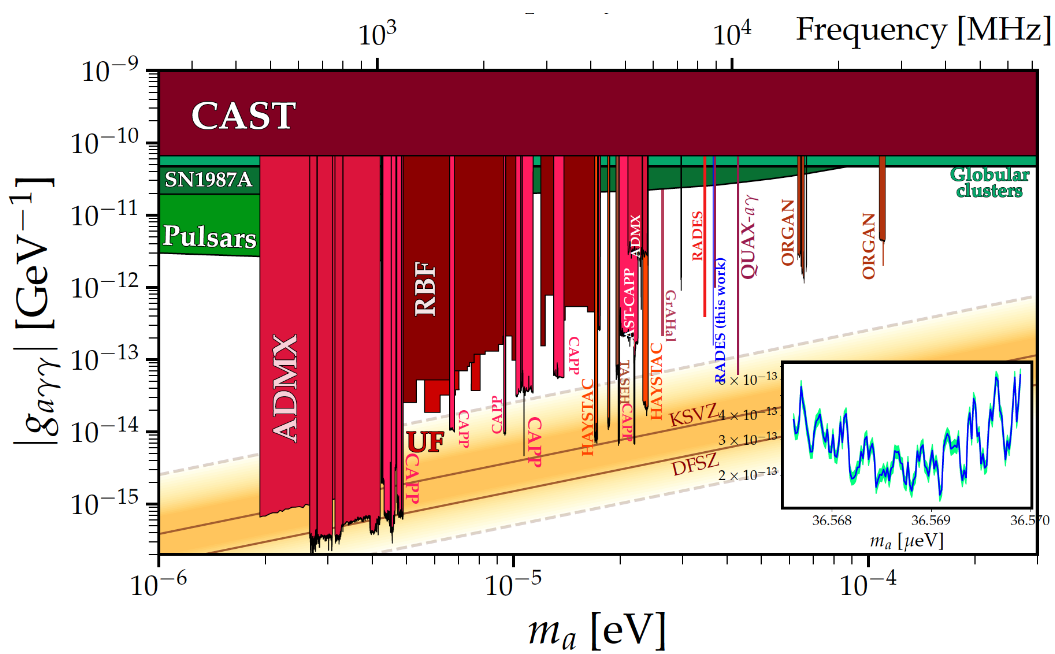


JCAP 05 (2018) 040
JHEP 07 (2020) 084

HTS coatings to improve Q factor

IEEE Trans. Appl. Super-cond. 32 (2022) 45

Physics results @ 34.67 μeV and 36.57 μeV

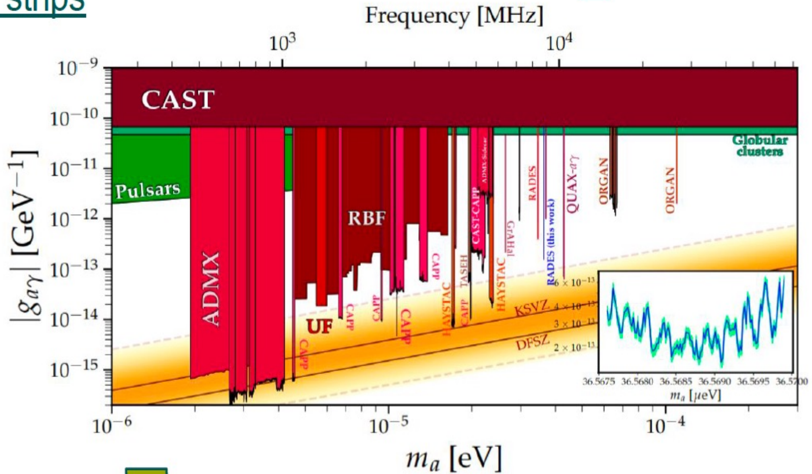


JHEP 10 (2021) 075, JHEP04(2025)113

Haloscope meets Helioscope

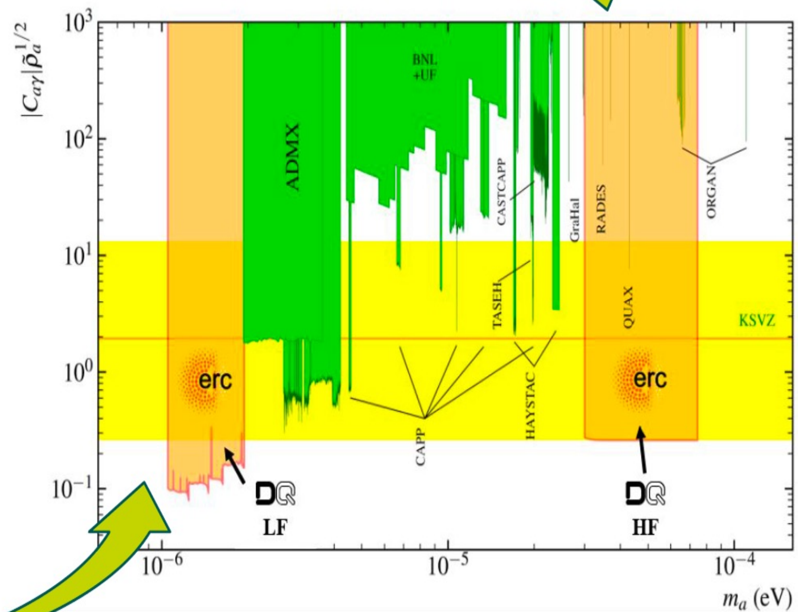
Credit: Babette Döbrich

2024: RADES searches in 2 narrow strips



High-frequency search

Scan time 800 days (multiple cavities)



Low-frequency search

Using babyIAXO bore (large cavities)

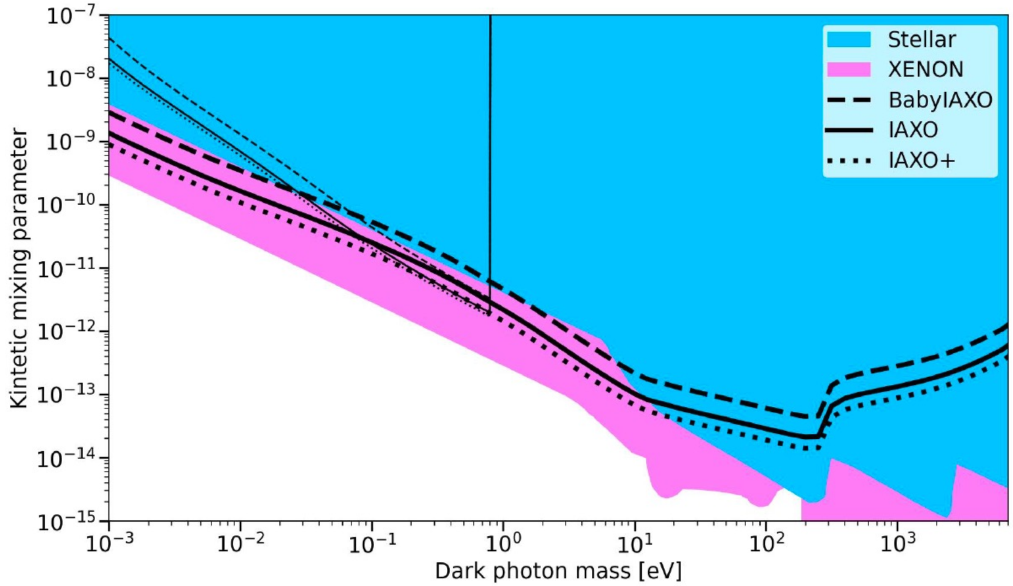
ERC-SYG Dark Quantum: cryogenics & quantum-limited readout: Irastorza, Wernsdorfer, Kontos, Paraoanu + partners
QRADES project in Quantera

Using conventional dilfridges (small cavities)

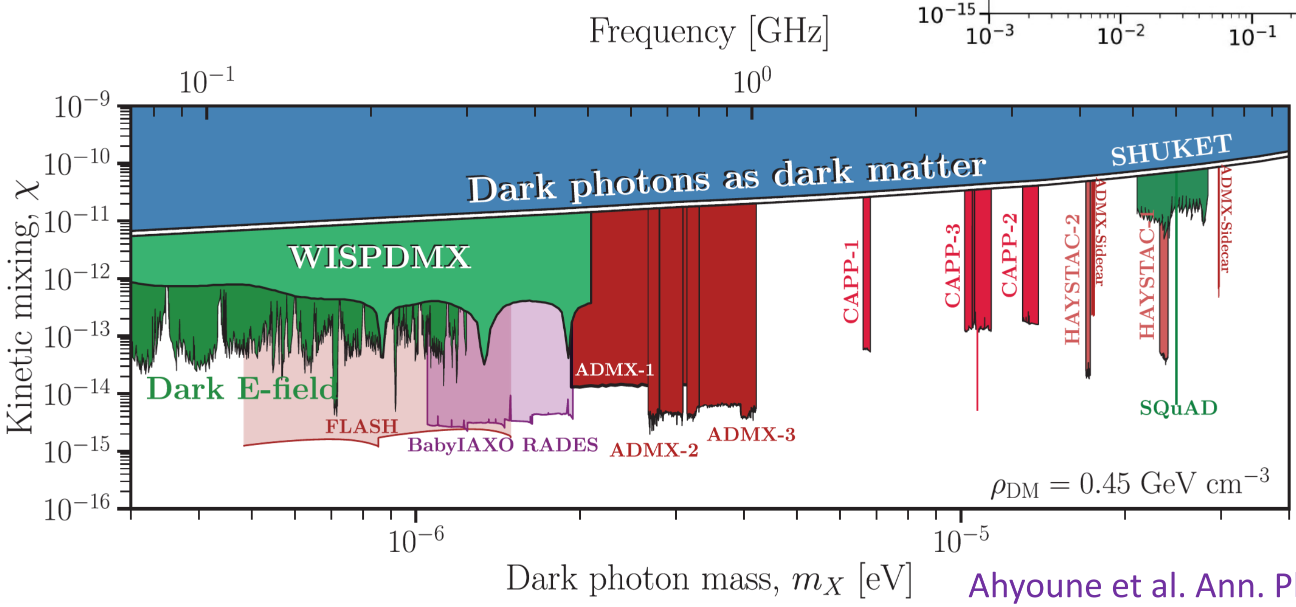
Outlook for helioscopes

Hidden photons at (Baby)IAXO

- Hidden photon search (solar/DS and DM) potentially possible
- Can use same setup as for axion search but without B-field



T. O'Shea et al JCAP06(2024)070



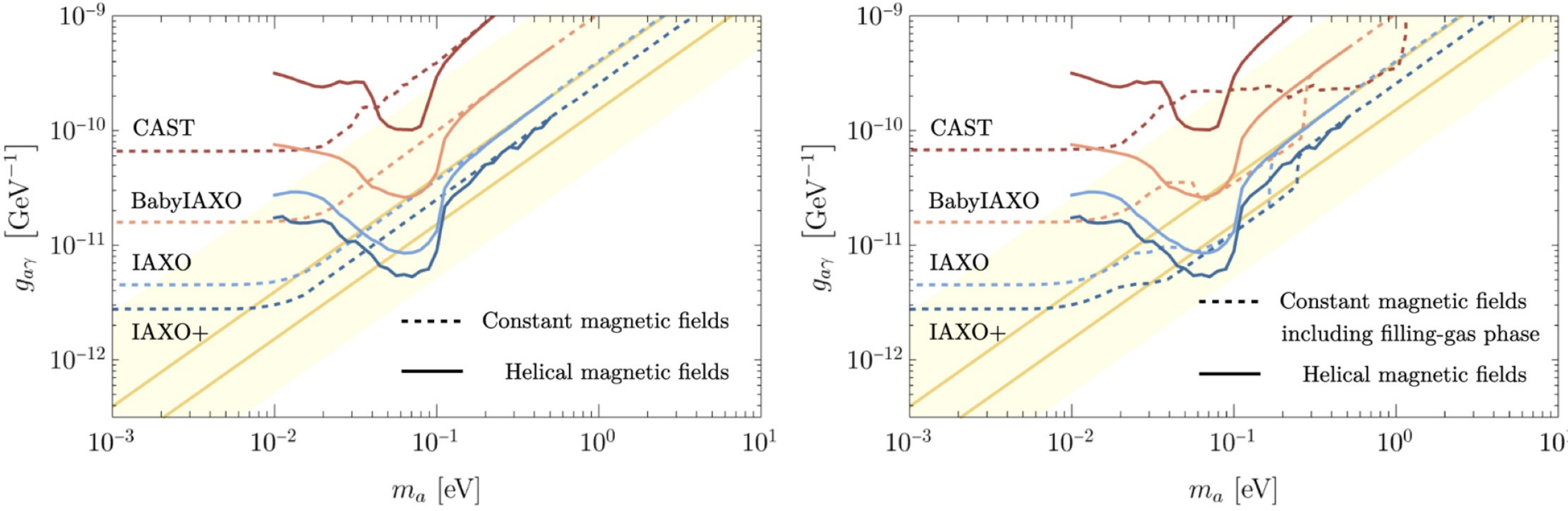
Ahyoune et al. Ann. Phys. (Berlin) 2023, 535, 2300326

Potential improvements with lower energy threshold for IAXO and/or BabyIAXO

Outlook for helioscopes

Potential improvements

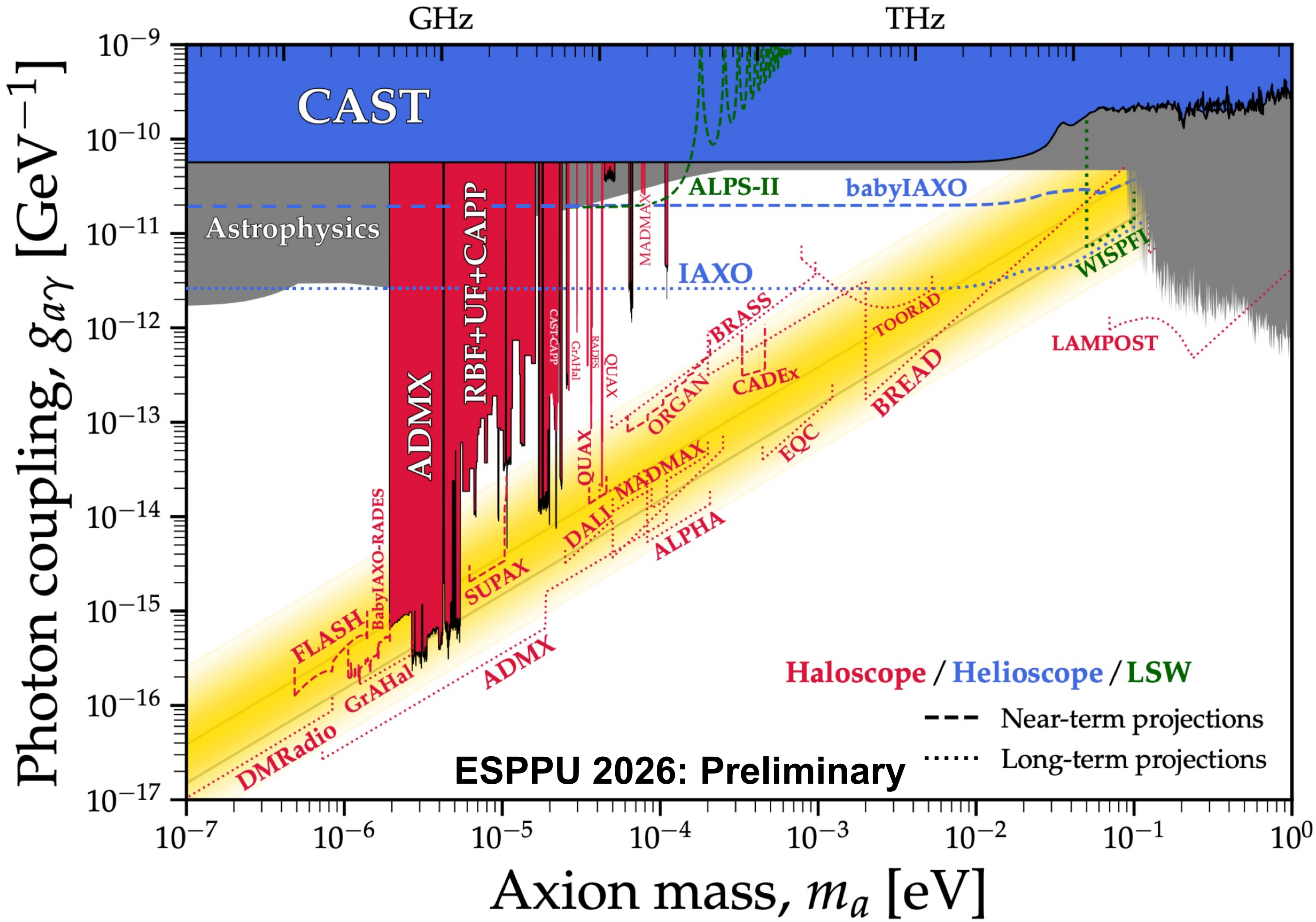
- Utilizing a helical magnet profile to enhance axion-photon conversion via axion-magnetic resonance (AMR) → maintain phase matching



Seong et al., JHEP 03 (2025) 071

Outlook for axions

But let's be relentless first and find the axion…



Summary

- Axions can solve strong CP & the dark matter problem
- Axions could be found with various experiments, complementary searches crucial including big and small efforts
- Helioscope searches (like IAXO) do NOT assume axions are DM
- Next-gen experiments expected to have discovery potential in relevant regions with lots of interesting science beyond vanilla axions

The (axion) future is bright!
Let's be relentless!

AXIONS IN STOCKHOLM

NORDITA, STOCKHOLM, SWEDEN
23 JUNE — 11 JULY 2025

THANK YOU!