COSMIC WISPERS CA21106

cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

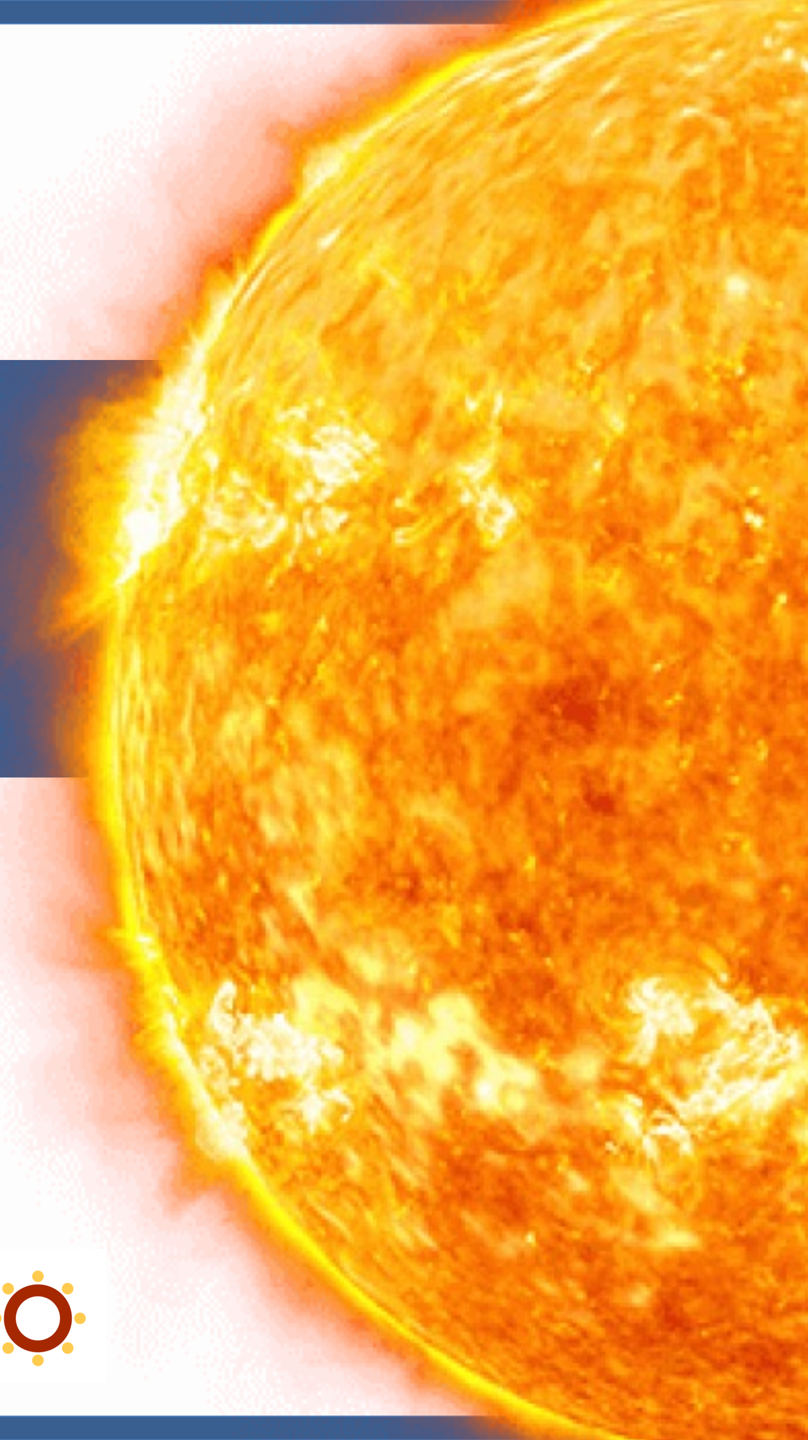
Experimental Landscape for Solar Axions and Other Light Particles

Julia K. Vogel

Axion++ 2023

Sept 25-28, 2023

LAPTh, Annecy, France

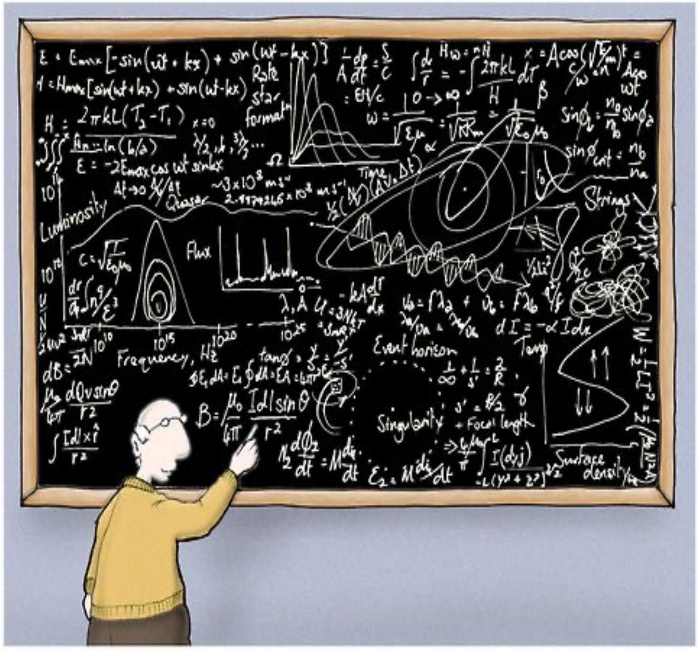


CAPA Centro de Astropartículas y Física de Altas Energías

Universidad Zaragoza 1542

Outline

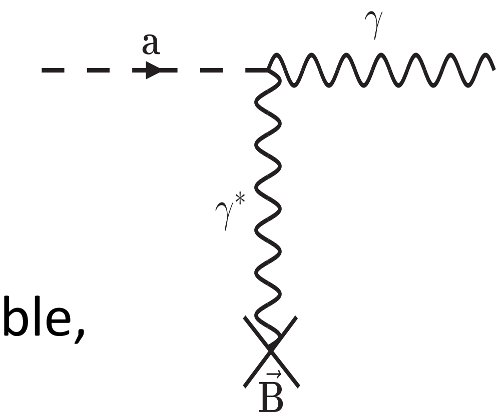
- Intro to Axions
- Solar Axion Detection
- Previous Helioscopes and State-of-the-Art
- Next-Gen: The International Axion Observatory (IAXO)
- Next-Gen: BabyIAXO
- Next-Gen: Physics Prospects
- Conclusions



Experimental axion physics made simple

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 into a dynamical variable, relaxes to zero
- **Axion**
  - Pseudo Goldstone-Boson results if this new symmetry is spontaneously broken 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**

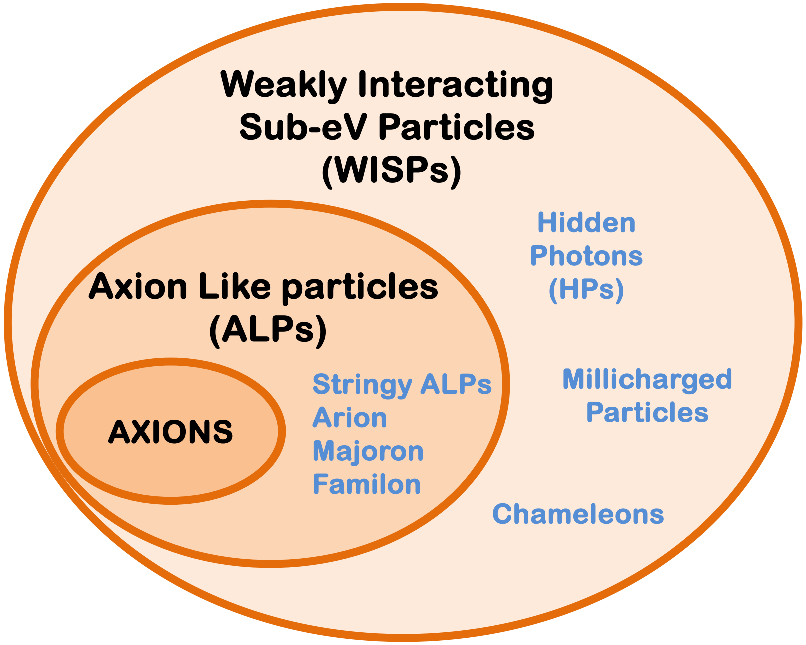
Recent experimental review:

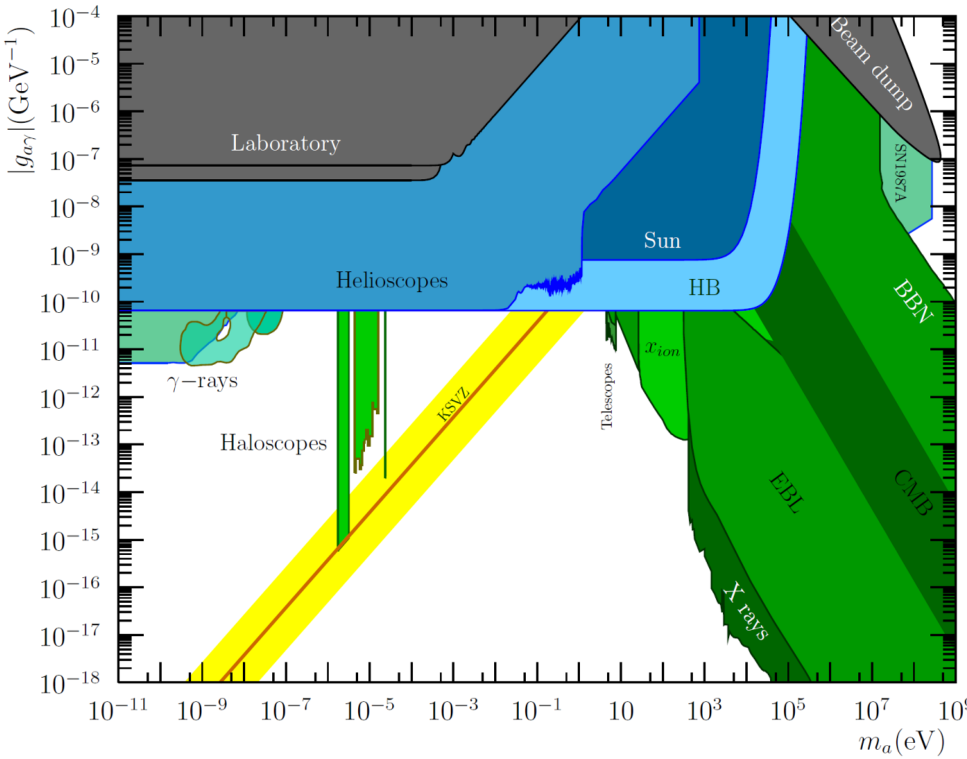
I. G. Irastorza & J. Redondo, PNPP 102, 89, 2018 (arXiv:1801.08127)
New experimental approaches in the search for axion-like particles

Beyond axions

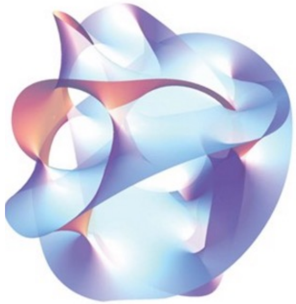
Many extensions of SM predict axion-like particles

Higher scale symmetry breaking



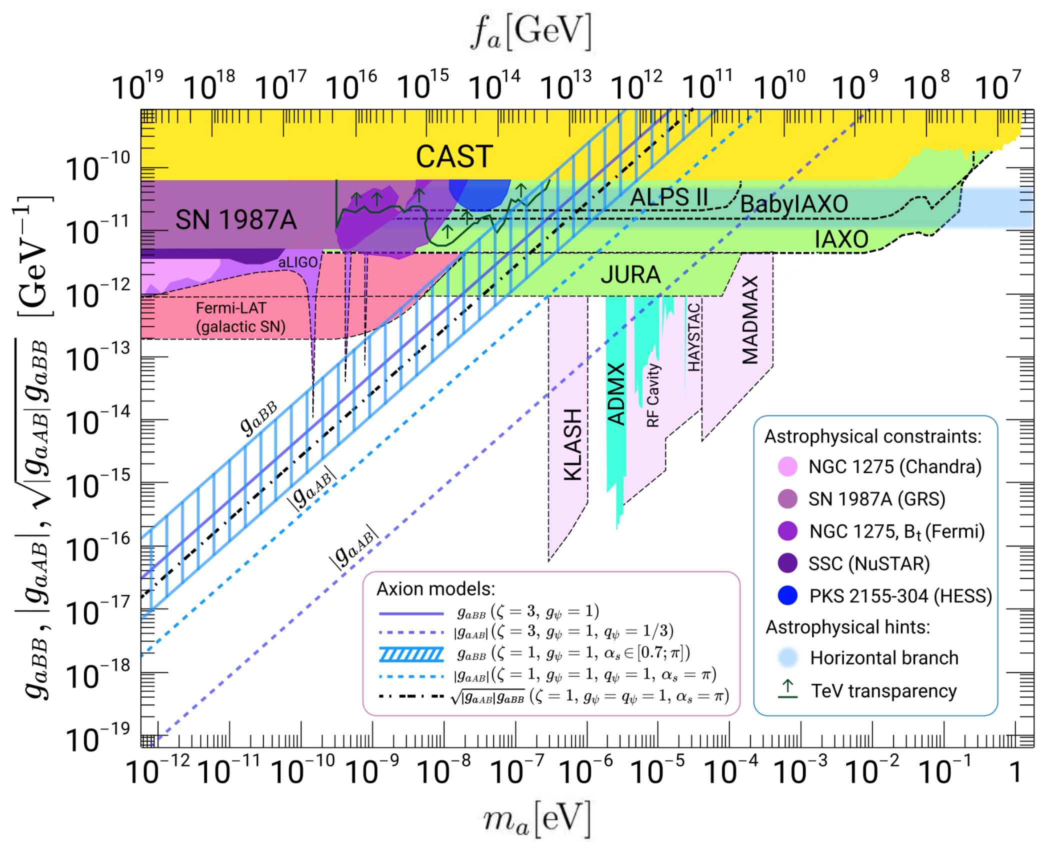


String theory predicts a multitude of axions



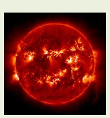
Axions beyond the “yellow band”

- Conventional QCD axion models generally live in the “yellow band” region (KSVZ, DSFZ benchmark models)
- Outside the band typically ALPs
- However, in recent years, a lot of activity in “model building”, leading to possible QCD axion models outside the conventional band
  - Usually populating parameter space towards larger coupling $g_{a\gamma}$.
  - Very interesting for experiments!

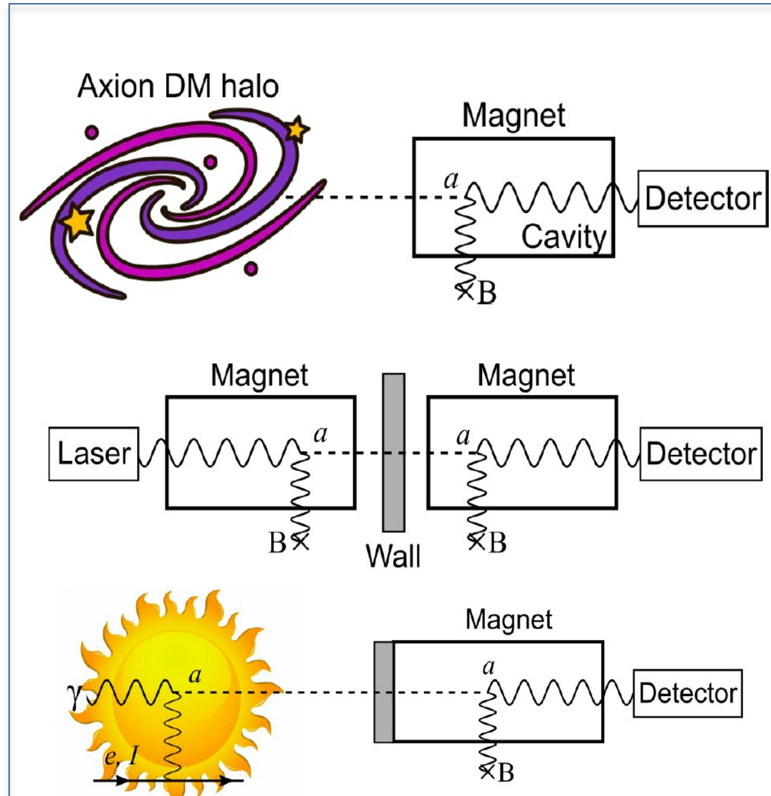


Example from Sokolov-Ringwald 2205.02605

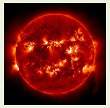
Axion Detection

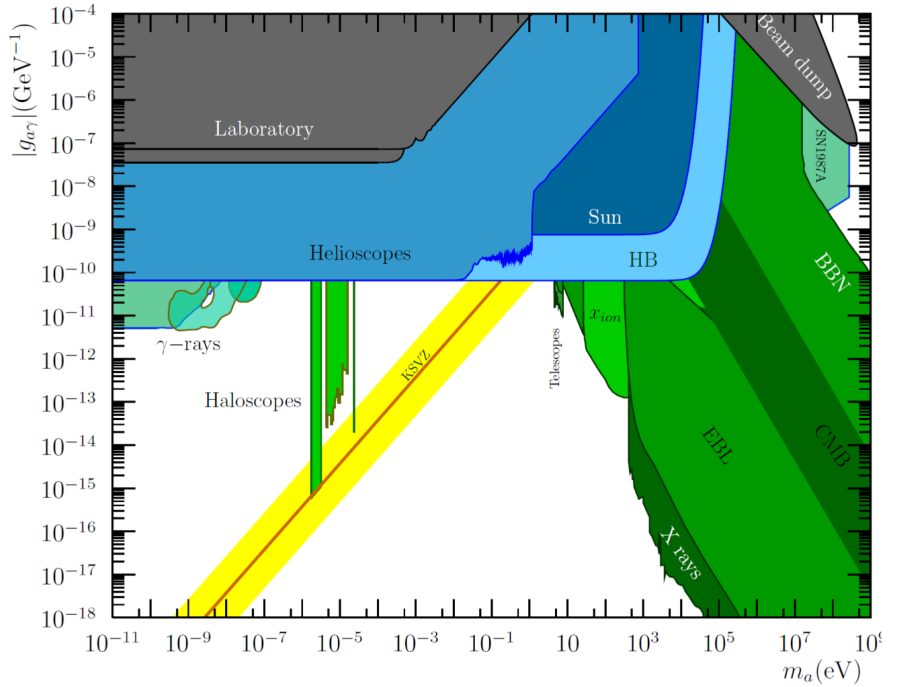
Source	Experiments	Model & cosmology dependency
Relic axions 	ADMX, HAYSTAC, CASPEr, CULTASK, CAST-CAPP, MADMAX, ORGAN, RADES, QUAX, GrAHal …	High
Lab axions 	ALPS, OSQAR, CROWS, ARIADNE,…	Very low
Solar axions 	SUMICO, CAST, (NuSTAR) IAXO & BabyIAXO	Low

Detection Principles for axions and ALPs



Axion Detection

Source	Experiments	Model & cosmology dependency
Relic axions 	ADMX, HAYSTAC, CASPEr, CULTASK, CAST-CAPP, MADMAX, ORGAN, RADES, QUAX, GrAHal …	High
Lab axions 	ALPS, OSQAR, CROWS, ARIADNE,…	Very low
Solar axions 	SUMICO, CAST, (NuSTAR) IAXO & BabyIAXO	Low



Large complementarity between different experimental approaches!

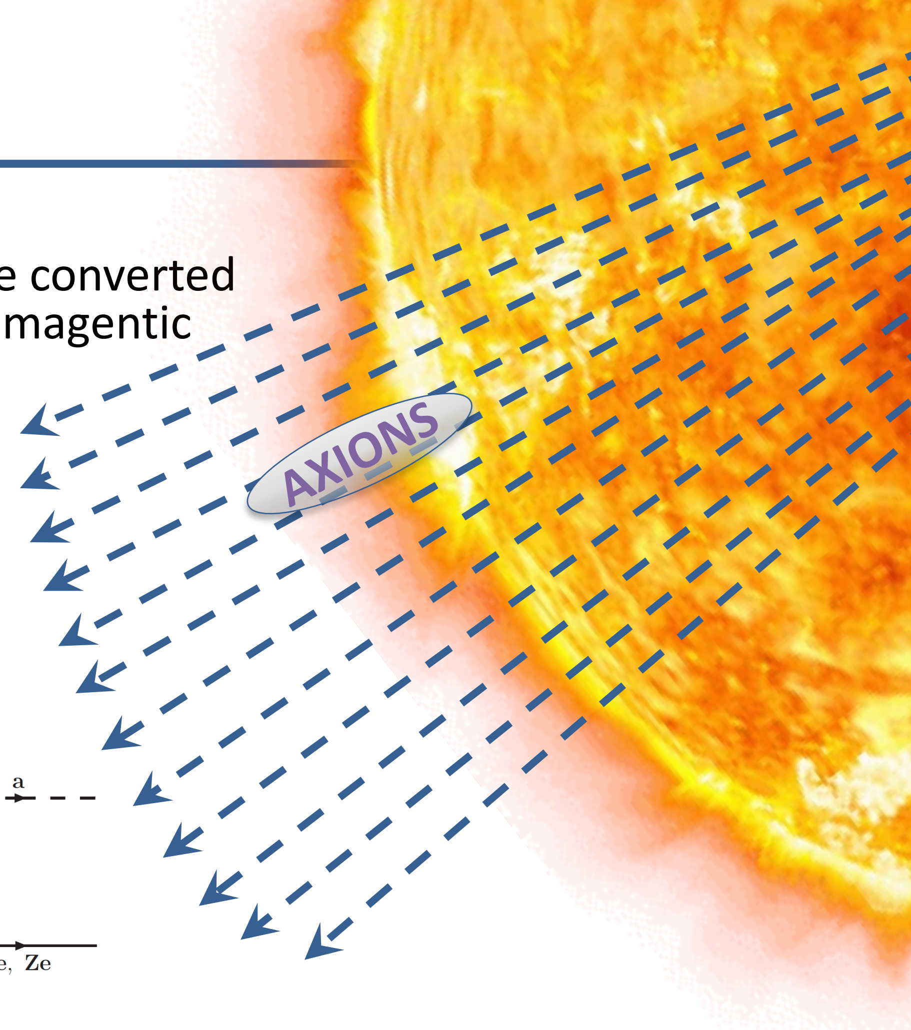
→ MADMAX: See Pascal’s talk
→ GrAHal: See Thierry’s talk

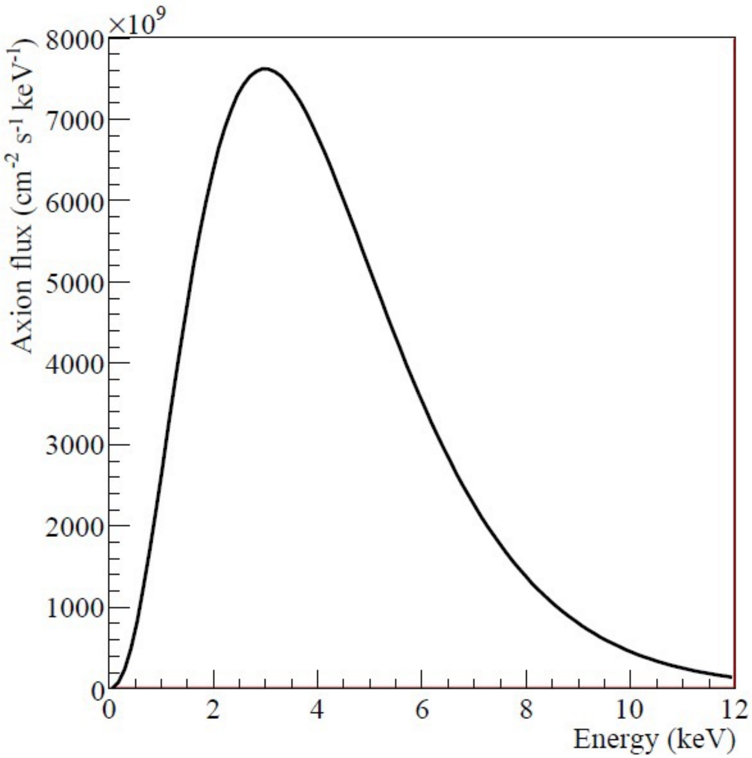
Intro to Axions

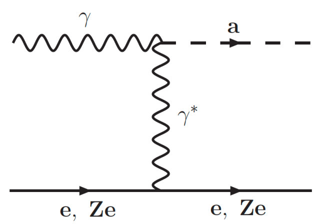
Solar Axion Detection

Standard Solar Axions

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







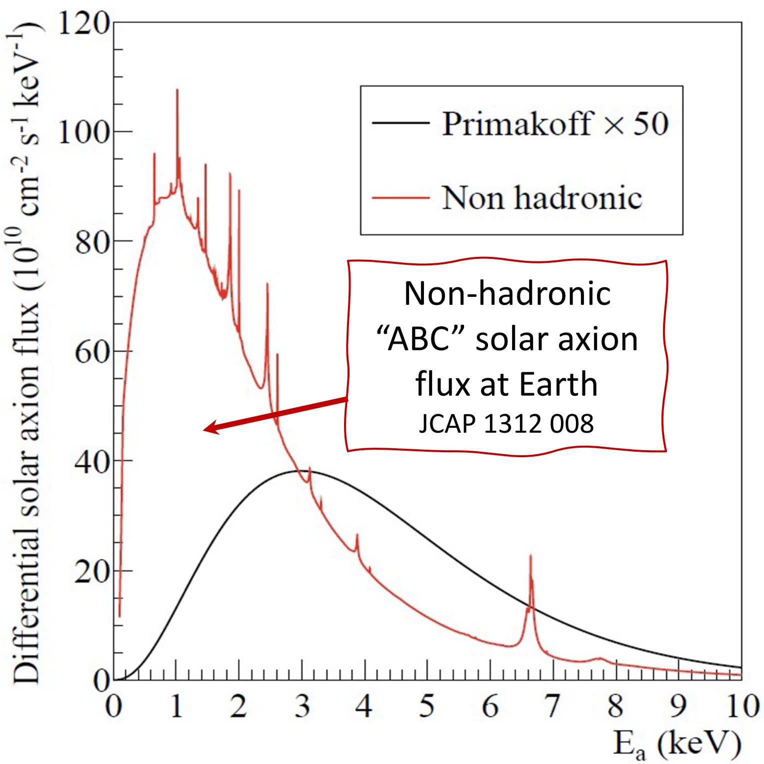
$$\frac{d\Phi_a}{dE} = 6.02 \times 10^{10} \left(\frac{g_{a\gamma}}{10^{-10}\mathrm{GeV}^{-1}}\right)^2 E^{2.481} e^{-E/1.205} \frac{1}{\mathrm{cm}^2\ \mathrm{s\ keV}}$$

$$g_{10} = g_{a\gamma}/10^{-10}\ \mathrm{GeV}^{-1}$$

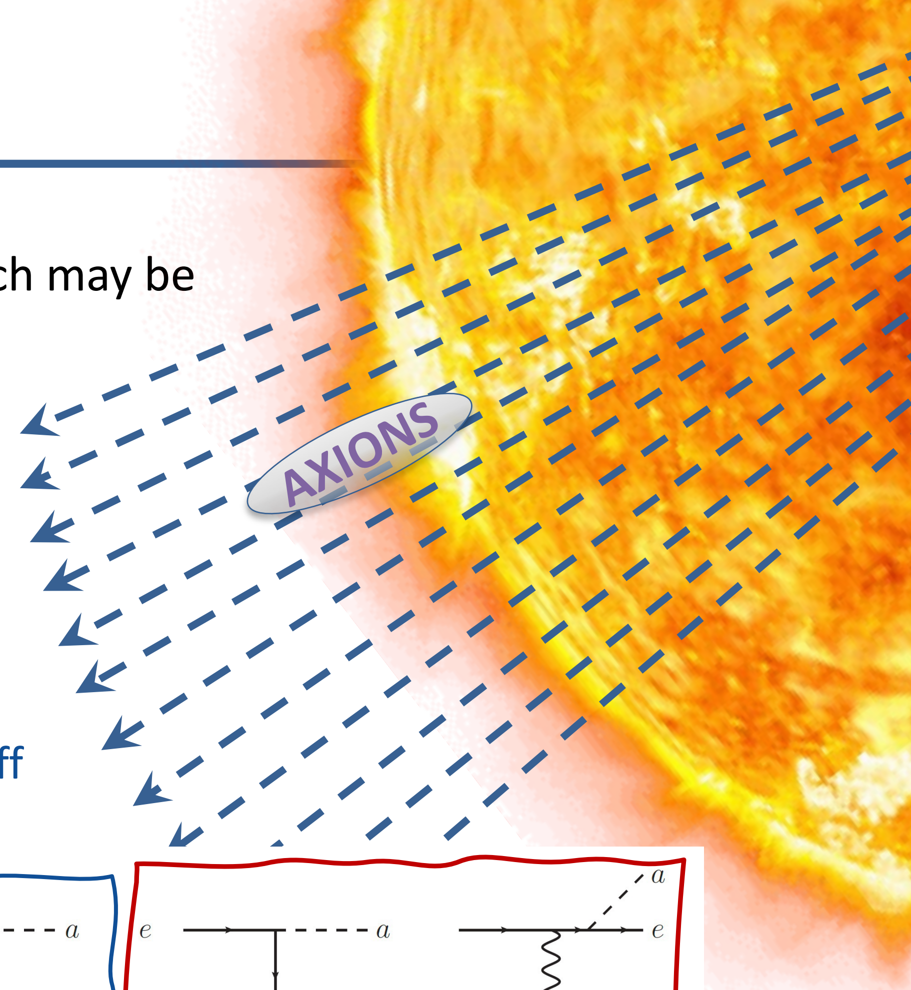
Van Bibber et al. *Phys.Rev. D* 39:2089 (1989)
CAST JCAP 04 (2007)010

Standard+ Solar Axions

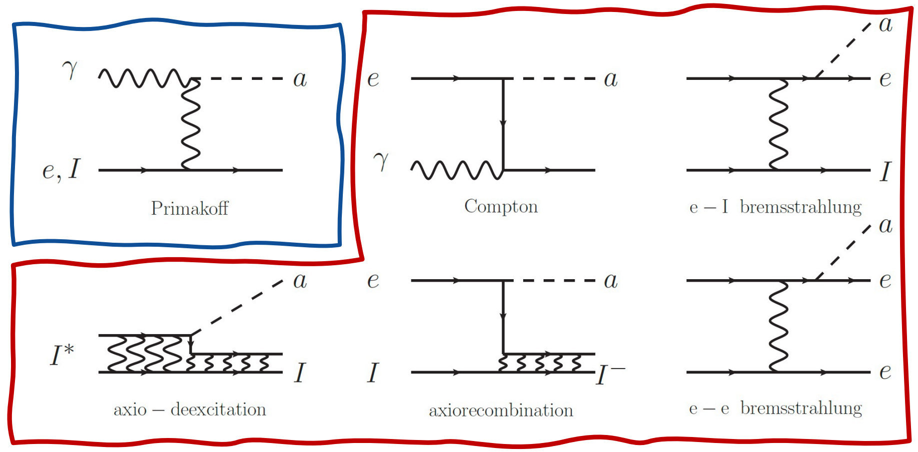
- Additionally to Primakoff: "ABC axions" which may be ×100 more intense but model-dependent



Redondo, *JCAP* 1312 008



Primakoff axions

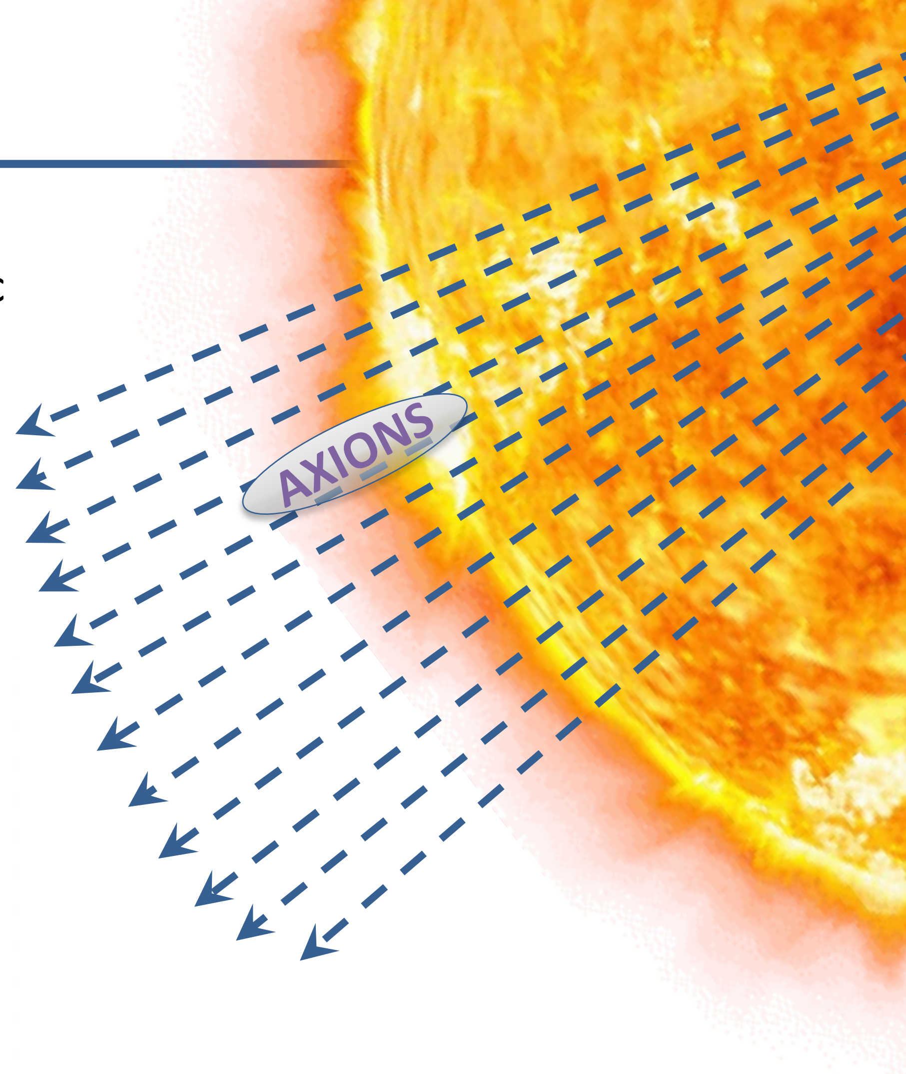


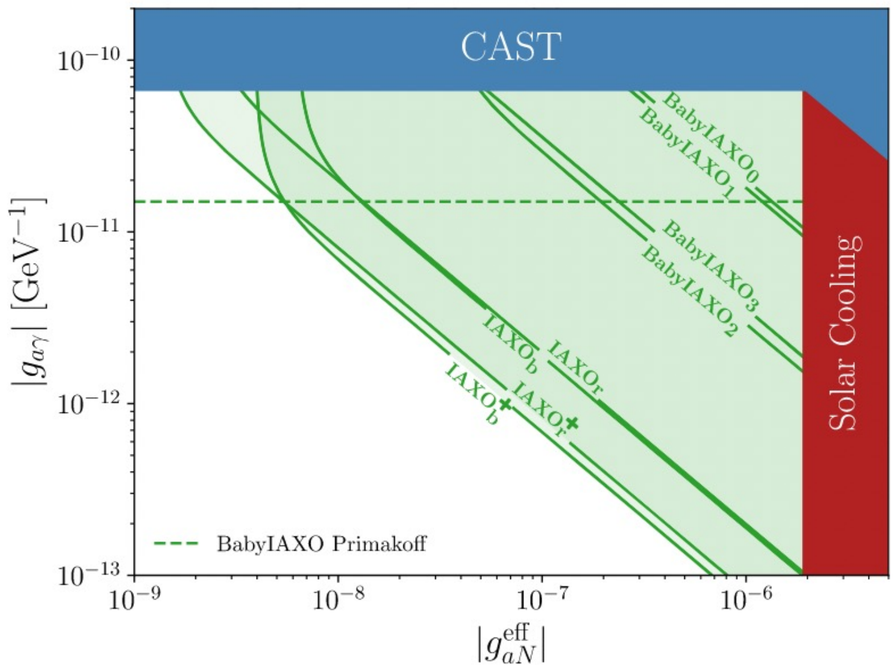
"ABC" or non-hadronic axions*

(*if the axion couples with electrons (g_{ae}))

More Solar Axions

- Via axion-nucleon couplings: monochromatic lines from nuclear transitions:
  - E.g. 14.4 keV axions emitted in the M1 transition of Fe-57 nuclei, MeV axions from ^{7}Li (0.478 MeV) and $D(p;\gamma)^{3}He$ (5.5 MeV) nuclear transitions or Tm-169





Di Lucio et al. *Eur. Phys. J.* C (2022) 82:120

Solar Axion Detection

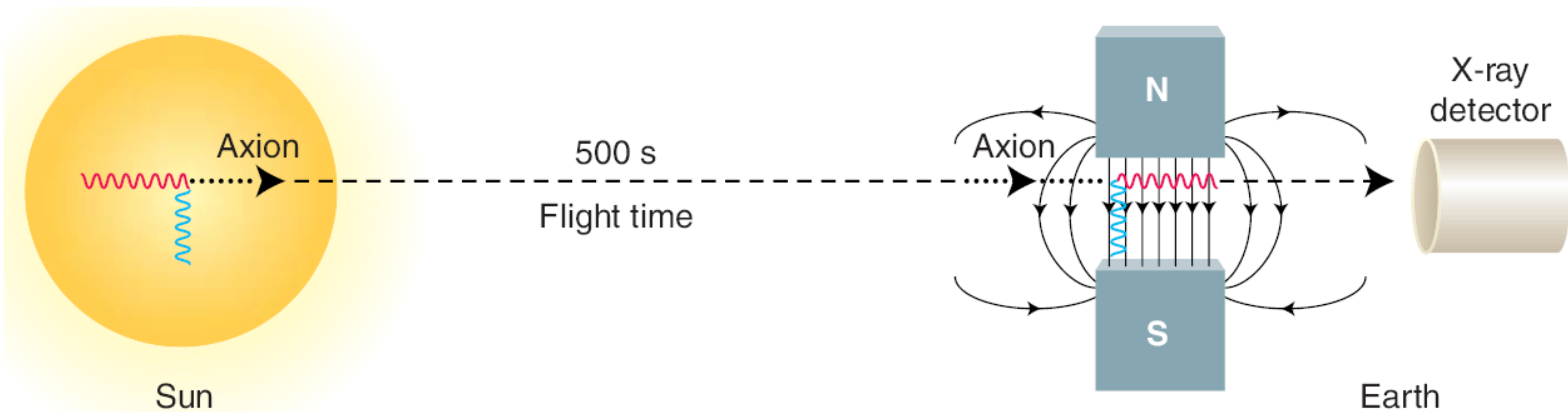
- First axion helioscope proposed by P. Sikivie

Sikivie *PRL* 51:1415 (1983)

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

Van Bibber et al. *Phys.Rev. D* 39:2089 (1989)

- Idea refined by K. van Bibber by using buffer gas to restore coherence over long magnetic field



$$P_{a\to\gamma} = \left(\frac{B g_{a\gamma\gamma}}{2}\right)^2 \frac{1}{q^2+\Gamma^2/4}\left[1+\mathrm{e}^{-\Gamma L} - 2\mathrm{e}^{-\Gamma L/2}\cos(qL)\right]$$

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

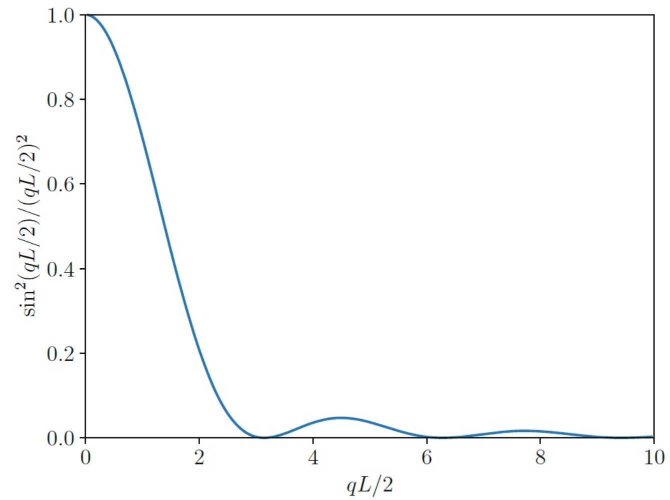
Solar Axion Detection

- In vacuum, conversion probability simplifies to:

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

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

Coherence condition
qL/2 << π



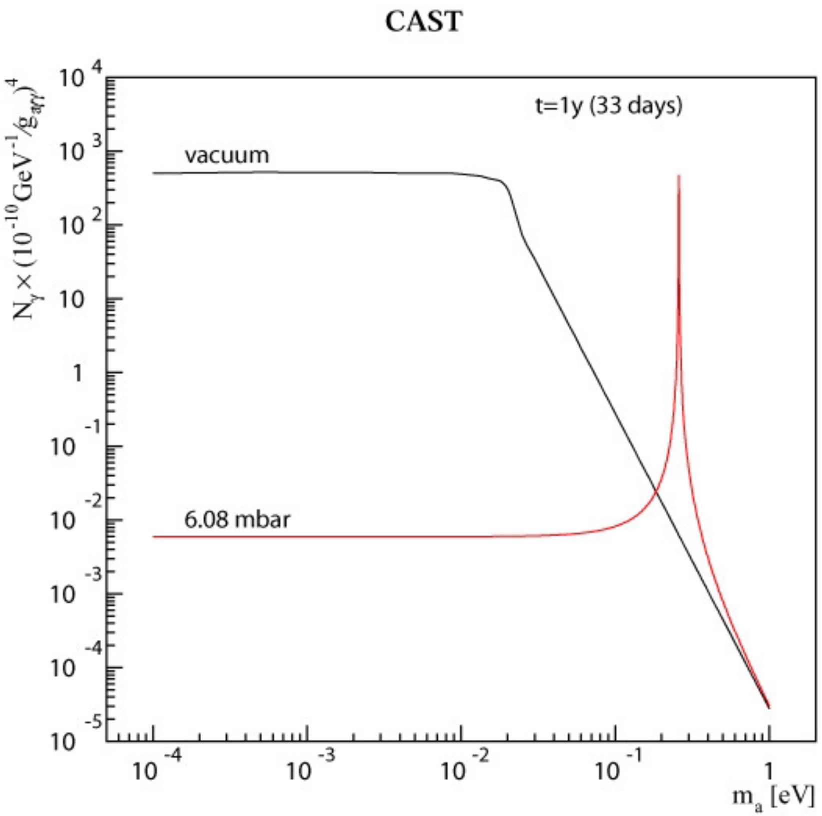
Solar Axion Detection

- In vacuum, conversion probability simplifies to:

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

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

Coherence condition
$qL/2 \ll \pi$



- With a buffer gas

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

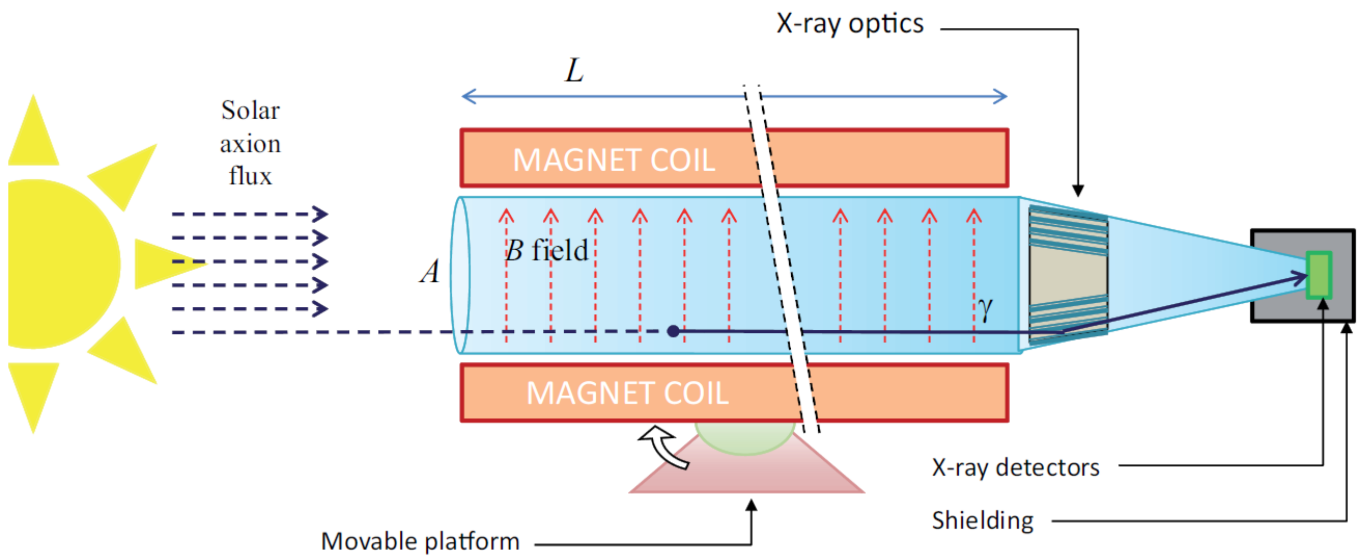
$$m_\gamma \approx \sqrt{\frac{4\pi\alpha N_e}{m_e}} = 28.9\sqrt{\frac{Z}{A}\rho} \quad \mathrm{eV}$$

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

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

Solar Axion Detection

Enhanced axion helioscope:
JCAP 1106, 013 (2011)



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

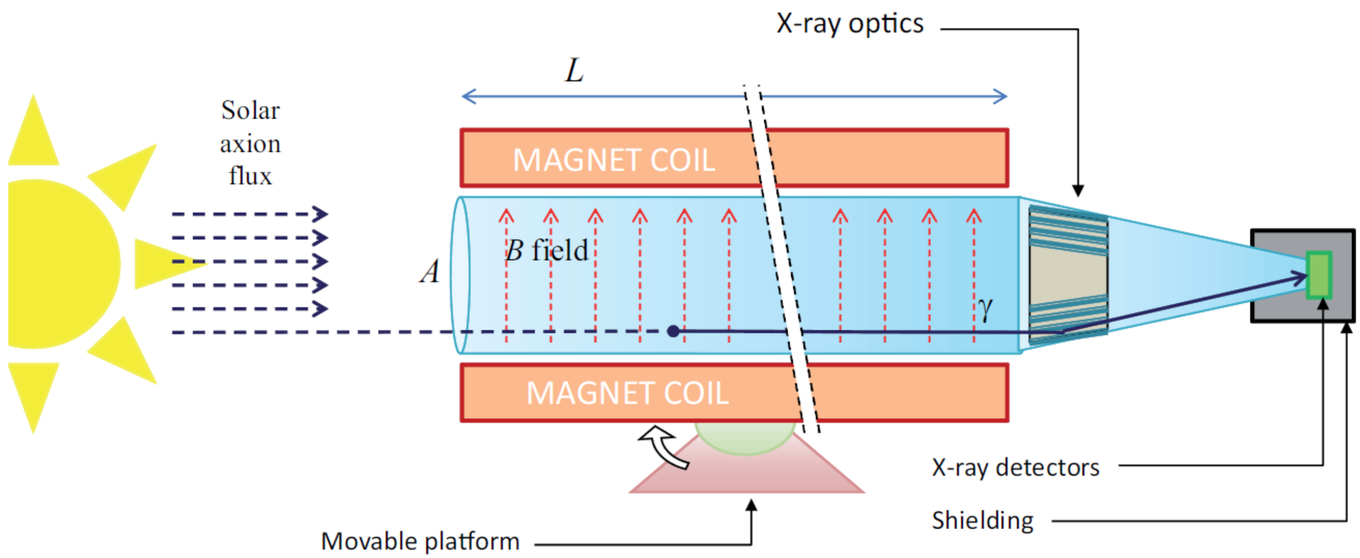
optics
- s = spot size
- ε_0 = efficiency

detectors
- b = background
- ε = efficiency

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

Solar Axion Detection

Enhanced axion helioscope: JCAP 1106, 013 (2011)



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

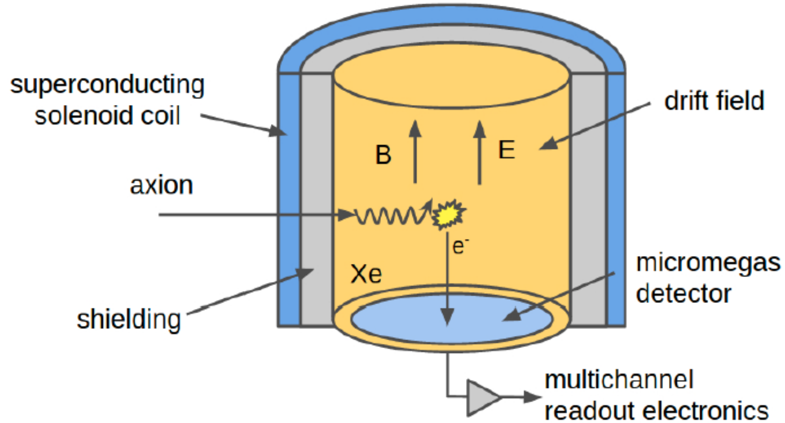
detectors
- b = background
- ε = efficiency

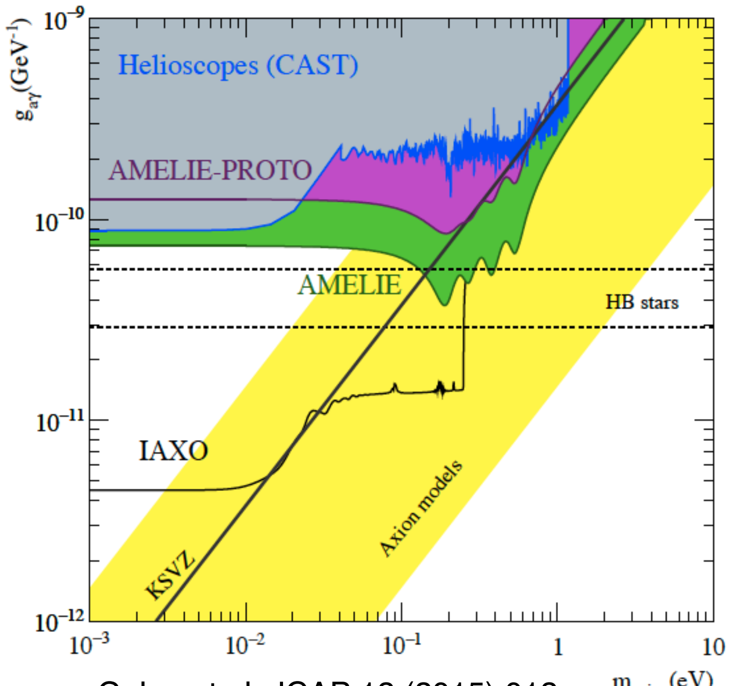
The smaller $g_{a\gamma}$ the better!

Typically factor 7 in $g_{a\gamma}$ between different generations, expect for next gen:
1–1.5 orders of magnitude in sensitivity to $g_{a\gamma}$ (factor of 10000-20000 in S/N)

Solar Axion Detection

- **Other Solar Axion Searches include:**
  - **Stationary Helioscopes**, such as the Axion Modulation hELIoscope Experiment (AMELIE): Stationary detector in magnetic field
    → modulation signal, able to complement helioscopes at high axion masses
  - **Crystalline detectors** (using Primakoff-Bragg conversion): SOLAX/COSME/DAMA & future experiments (e.g. CUORE) not competitive with helioscopes $m_a < 1$ eV
  - **Satellite experiments** e.g. Hinode, Nustar
  - **WIMP searches** like XENON1T





Galan et al, JCAP 12 (2015) 012

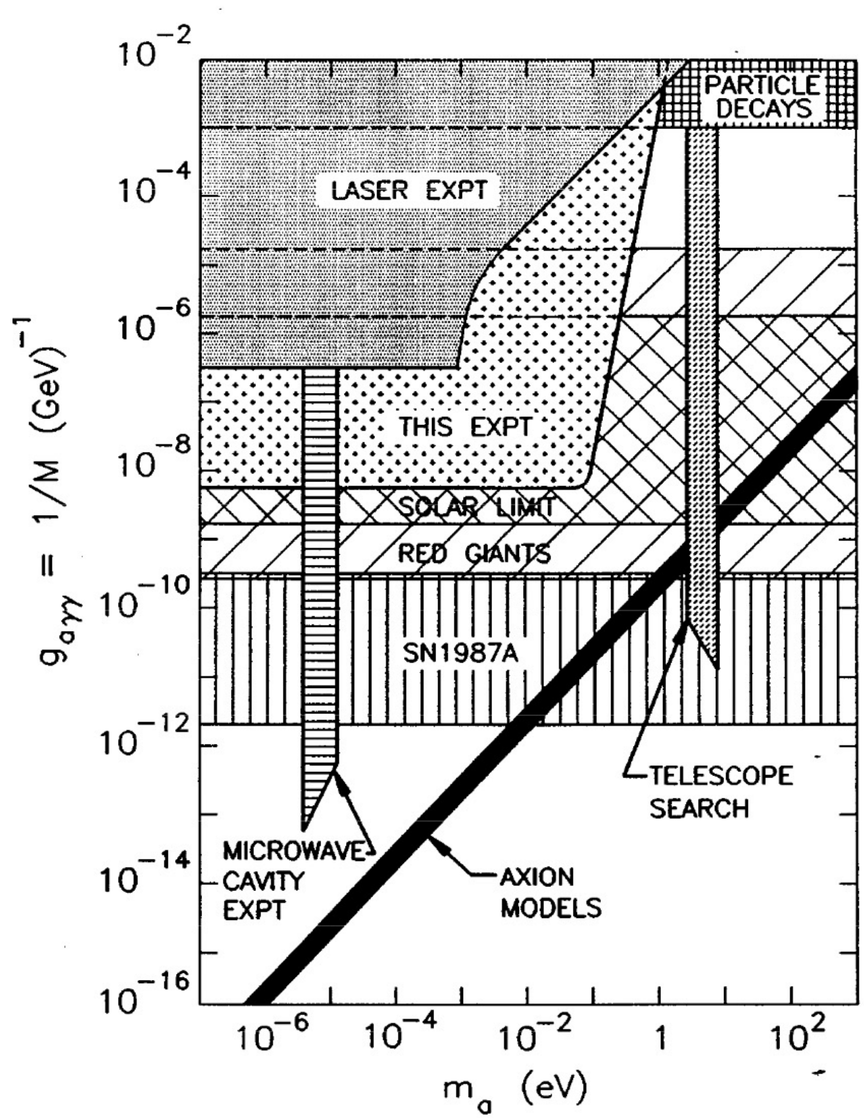
Intro to Axions

Solar Axion Detection

Previous Helioscopes and State-of-the-Art

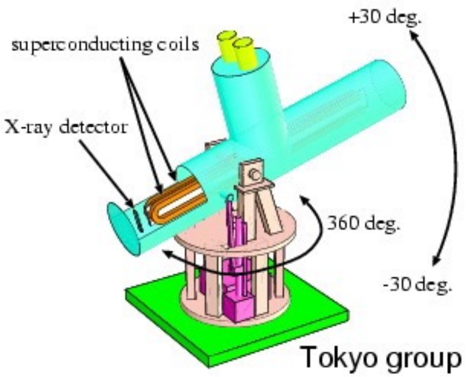
Previous Helioscopes

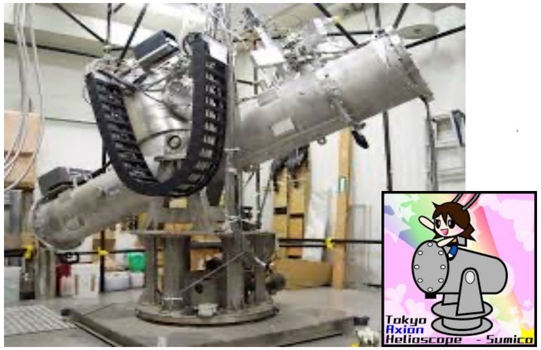
- **1st generation helioscope: Brookhaven**
  - Just a few hours of data
  - Lazarus et at. PRL 69 (92)

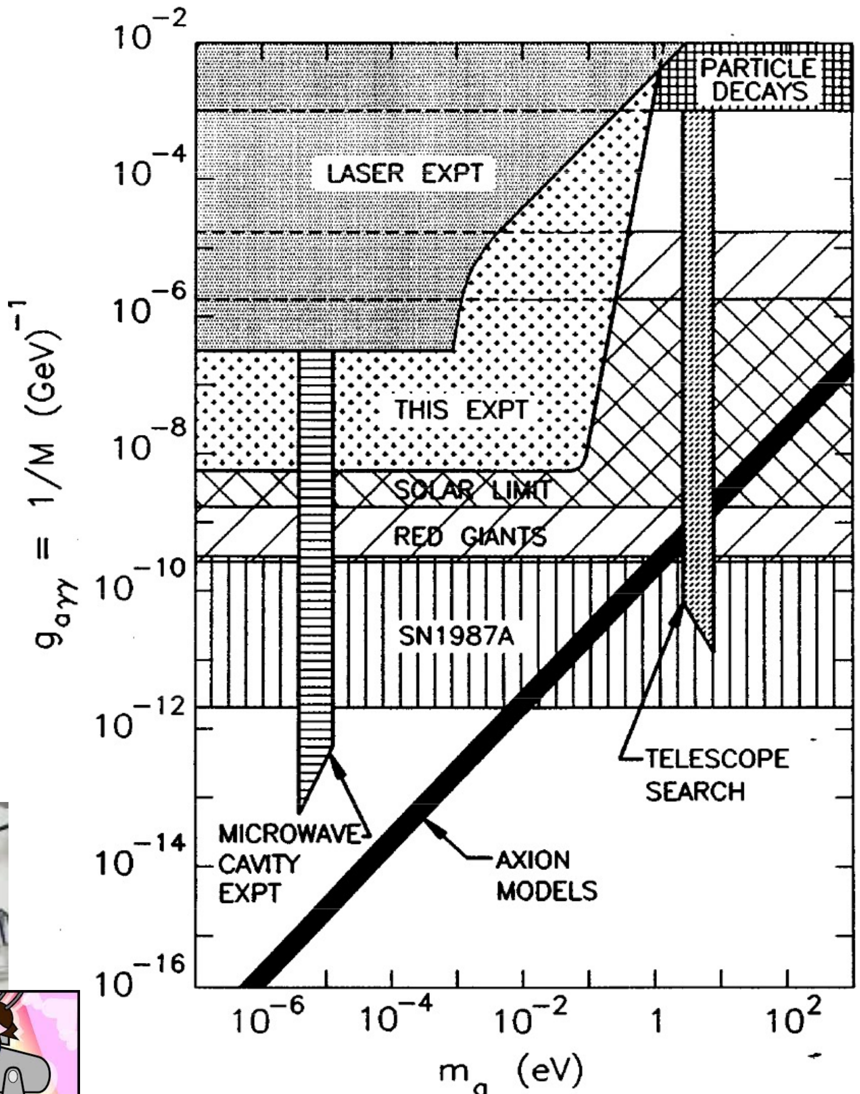


Previous Helioscopes

- **1st generation helioscope: Brookhaven**
  - Just a few hours of data (1.8m, 2.2T)
  - Lazarus et at. PRL 69 (92)
- **2nd generation: Tokyo Helioscope (SUMICO)**
  - 2.3 m long, 4 T magnet
  - $g_{a\gamma} < 6.0 \times 10^{-10}$ GeV^{-1}







Previous Helioscopes

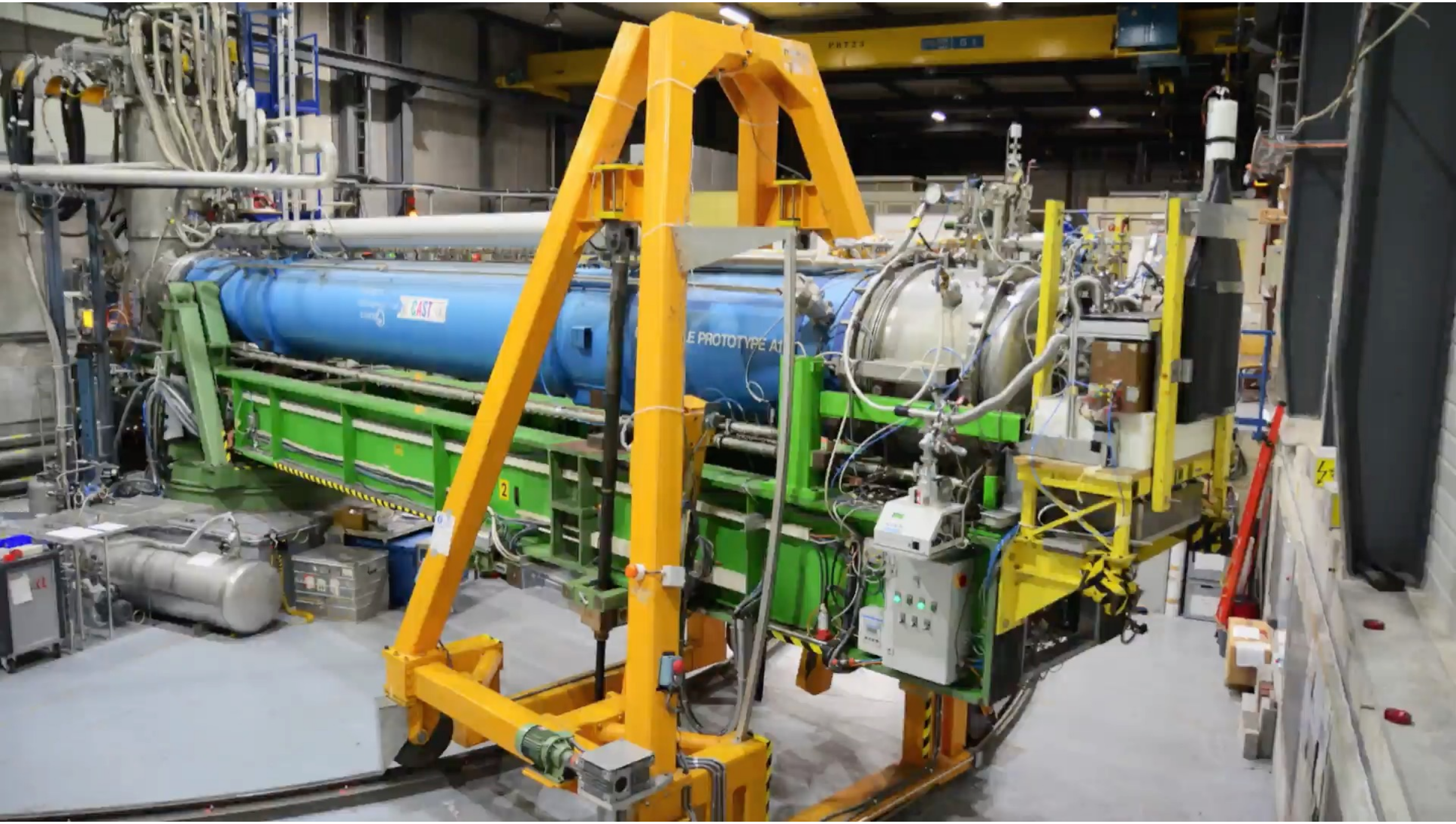
CERN Axion Solar Telescope

A powerful **axion helioscope** → more than 20 years of experience

- Decommissioned prototype **LHC dipole magnet**
  → Length = 10 m; Magnetic field = 9 T
- **X-ray focusing** and novel **low-bgrd** techniques
- **Solar tracking** possible during sunrise and sunset (2 x 1.5 h per day)
- **First data** in 2003/04 (Phase I, vacuum)
- **^{4}He/^{3}He runs** 2006-12 (Phase II, buffer gas)
- Then **improved vacuum run** (2013-15), RADES and CAPP cavities and exotic physics

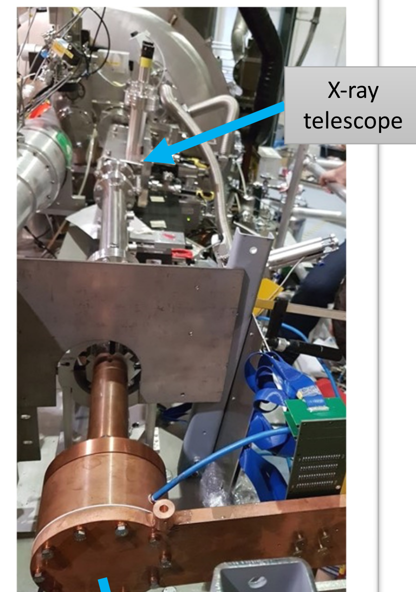
Nature Phys. ***13*** *(2017) 584-590*
JHEP 2021 75, (2021)
*Nature Com.*13, 1, 1-9 (2022)

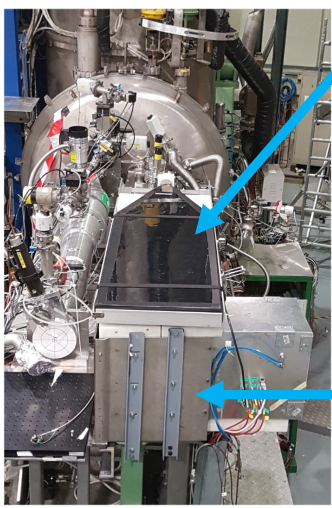
Previous Helioscopes



Previous Helioscopes

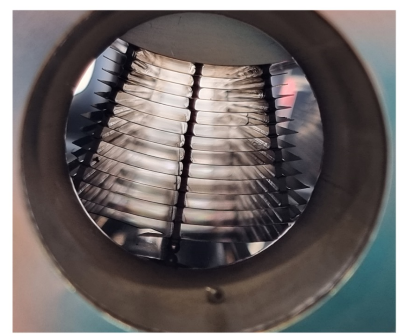
IAXO pathfinder system @ CAST





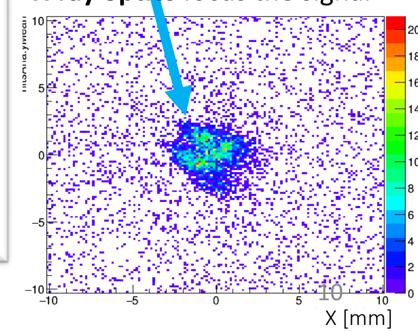
Active shielding:
plastic scintillator as a cosmic muon veto.

Passive shielding:
10 cm of lead around the detector.



X-ray optics

X-ray optics focus the signal



Previous Helioscopes

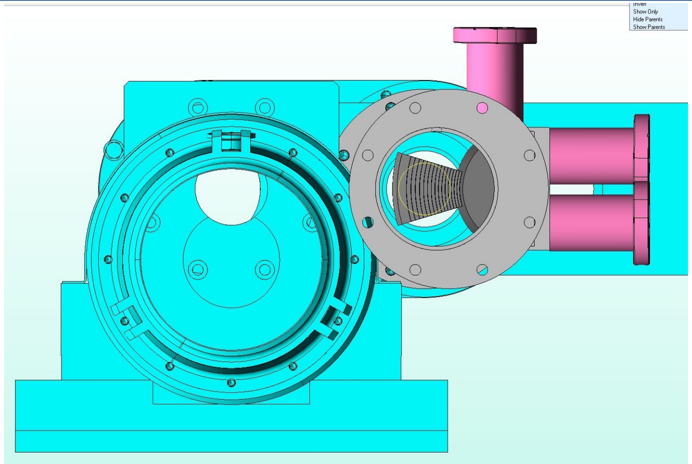
IAXO pathfinder @ CAST

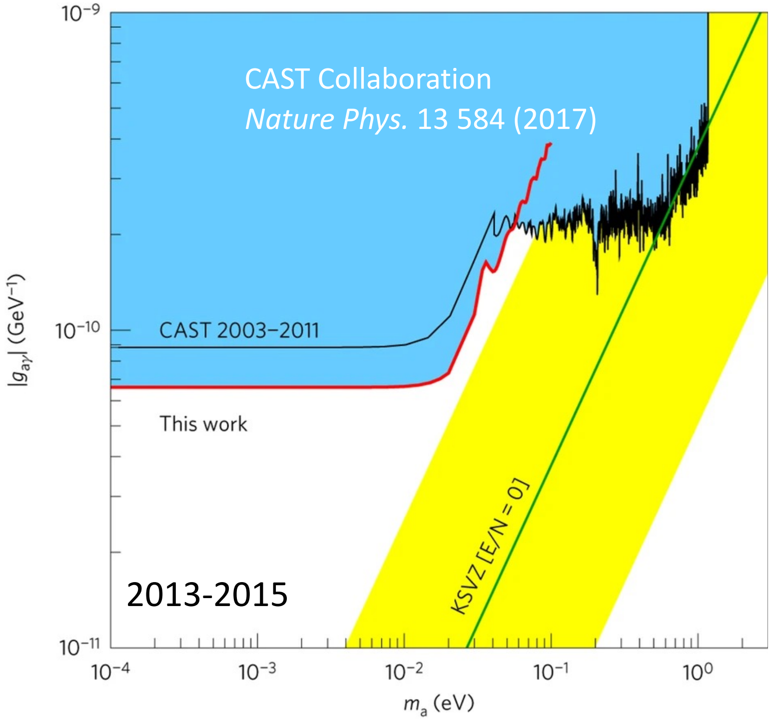
- Small x-ray optics
  Fabricated purposely using thermally-formed glass substrates (NuSTAR-like)

  +
- Micromegas low background detector
  Applied lessons learned from R&D: compactness, better shielding, radiopurity,…

- Best experimental limit on axion-photon coupling over broad axion mass range

$$g_{a\gamma} < 0.66 \times 10^{-10}\ \mathrm{GeV}^{-1}\ (95\%\ \mathrm{C.L.})$$





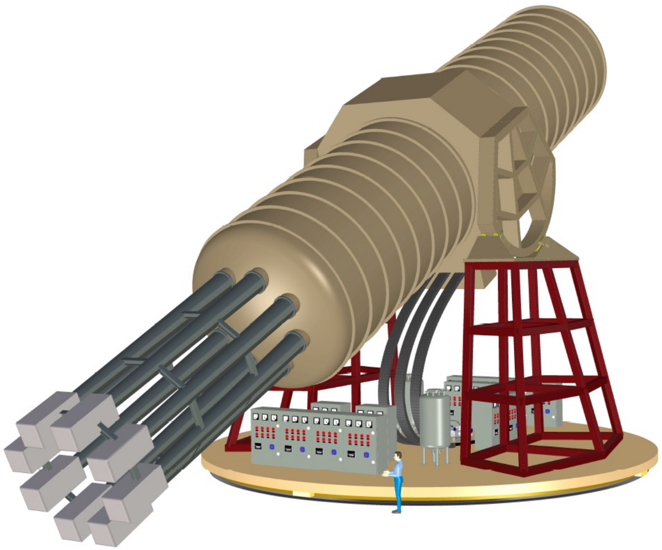
Anastassopoulos et al. *Nature Phys.* ***13*** *(2017) 584-590*

Intro to Axions

Solar Axion Detection

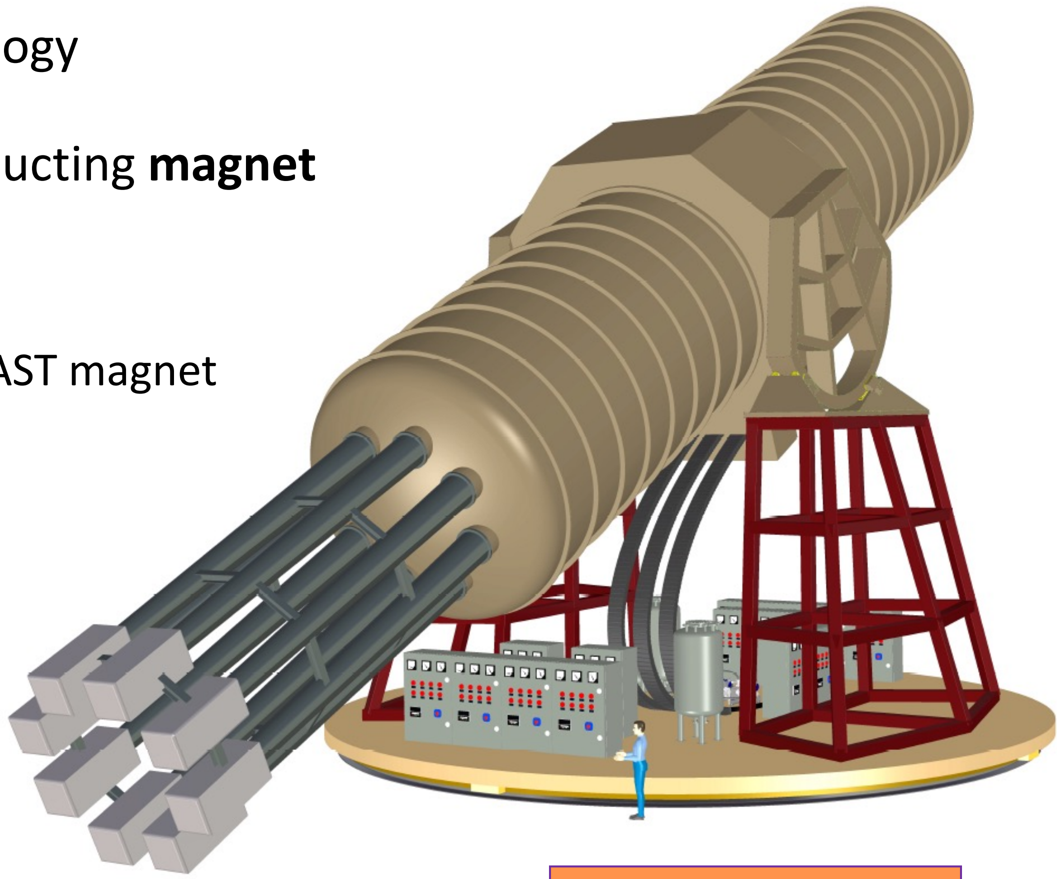
Previous Helioscopes and State-of-the-Art

Next-Gen: The International Axion Observatory (IAXO)



The International Axion Observatory (IAXO)

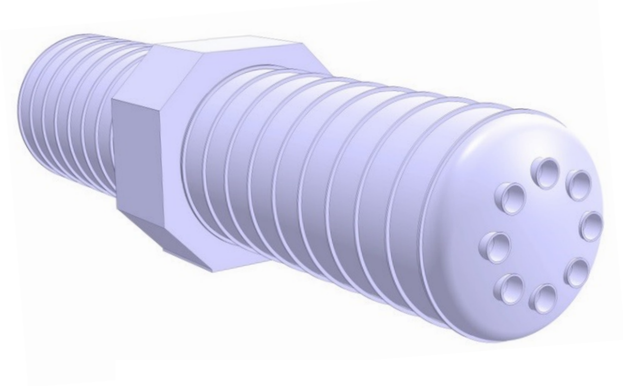
- Next generation helioscope for solar axions
- Mature and state-of-the-art technology
- Purpose-built large-scale superconducting **magnet**
    - Toroidal geometry
    - 20 meters long, up to 5.4 T.
    - >300 times larger FoM than CAST magnet
    - 8 conversion bores of 60 cm Ø
- 8 detection lines (**XRT+detectors**)
- X-ray optics with 0.2 cm^2 focal spot
- Ultra-low bgrd detectors
- 50% of Sun-tracking time.

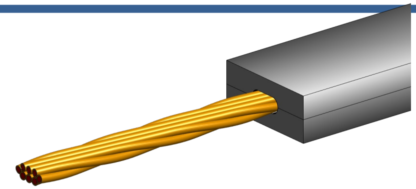


E. Armengaud *et al* 2014 *JINST* **9** T05002

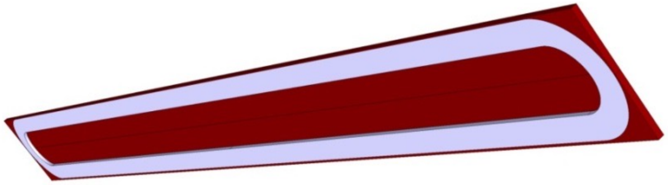
IAXO Magnet

- Core piece of IAXO: magnet

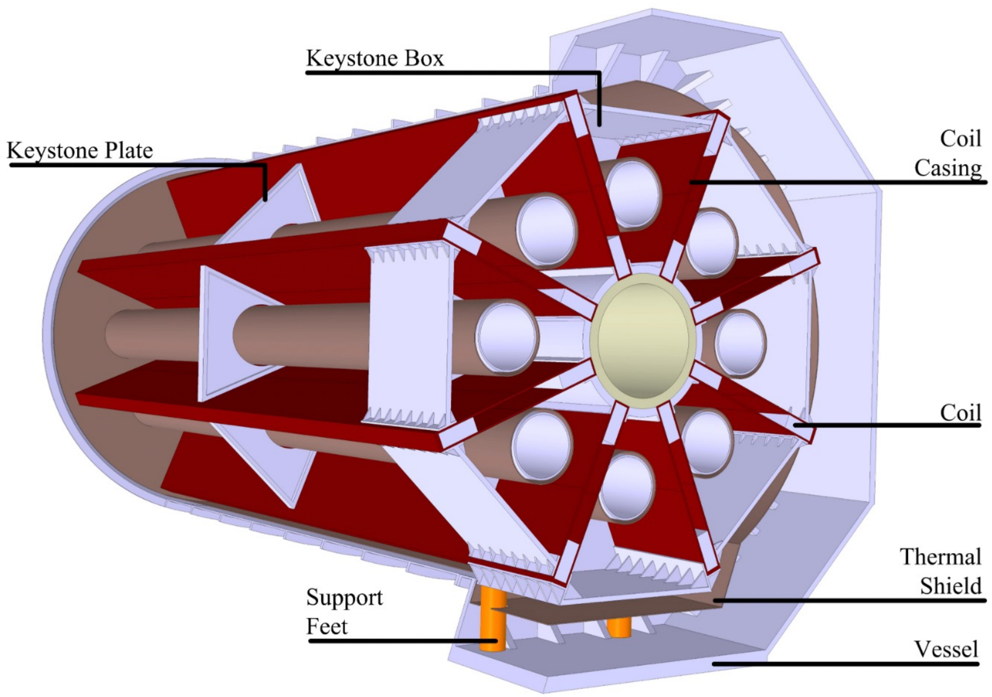


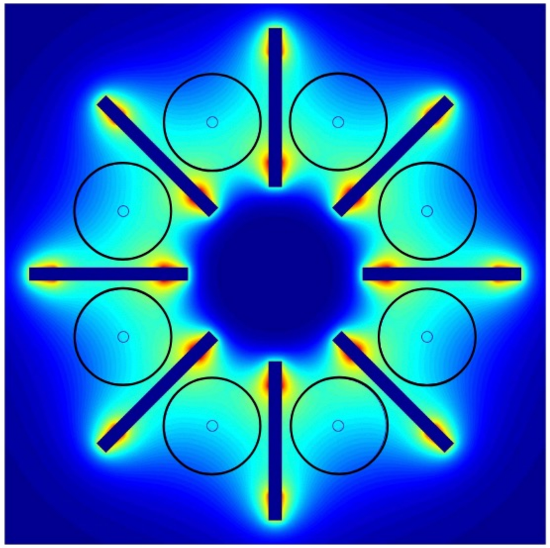


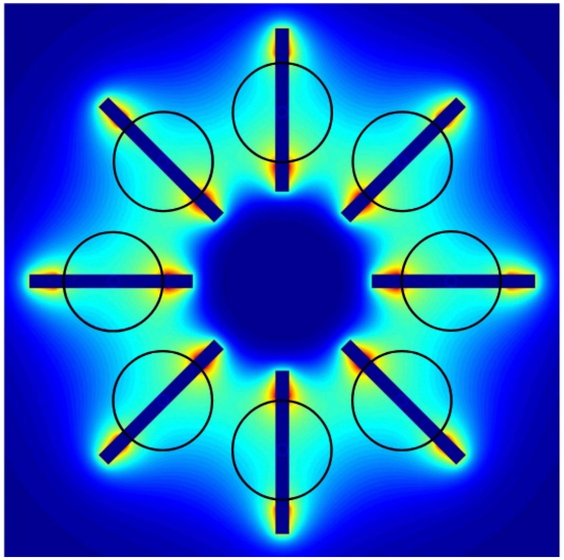
Al-stabilized Rutherford cable



IAXO racetrack coil







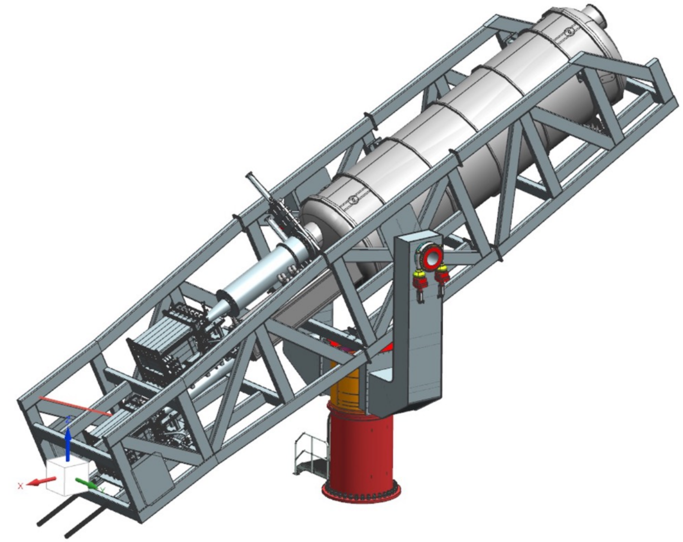
Intro to axions

Solar Axion Detection

Previous helioscopes and State-of-the-Art

Next-Gen: The International Axion Observatory (IAXO)

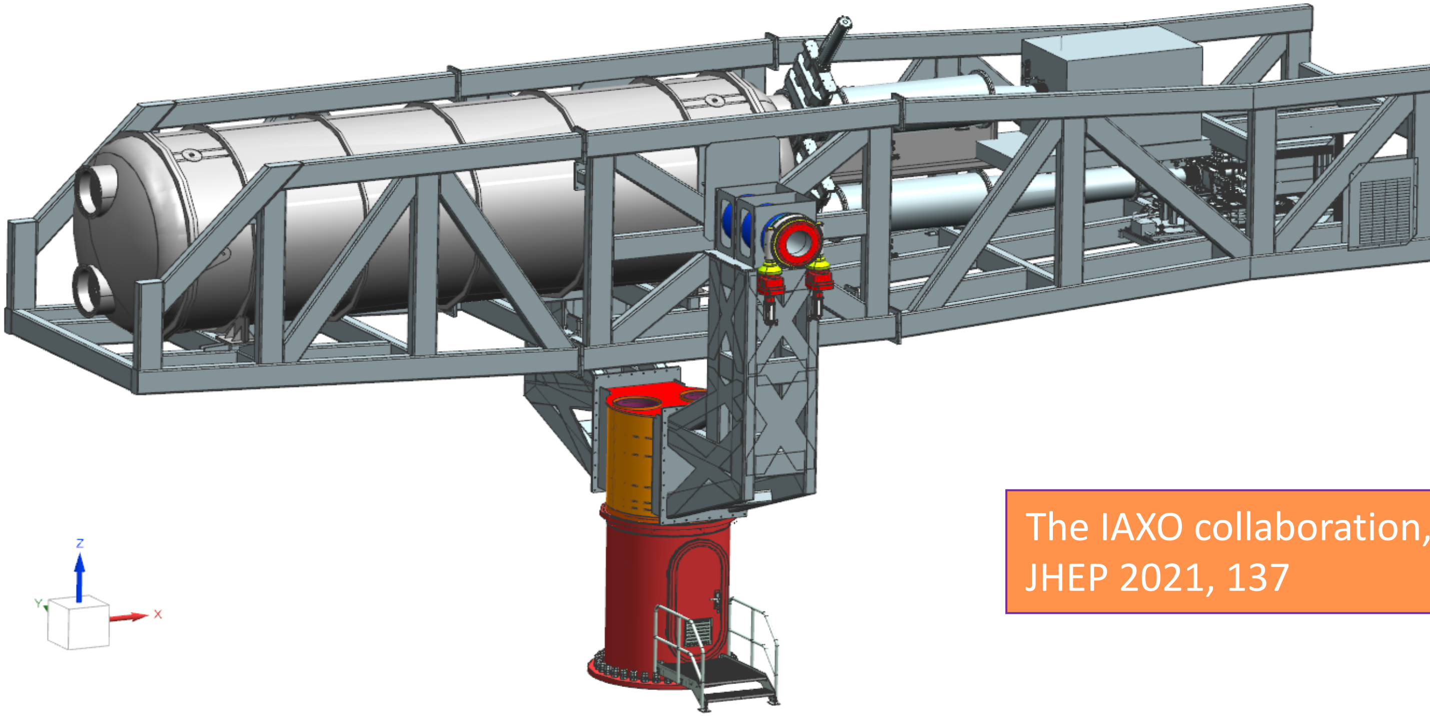
Next-Gen: BabyIAXO



BabyIAXO

BabyIAXO = Intermediate experimental stage before IAXO

- Technological prototype of IAXO with only two magnet bores (10 m, Ø 70 cm) to be installed at DESY.
- 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)



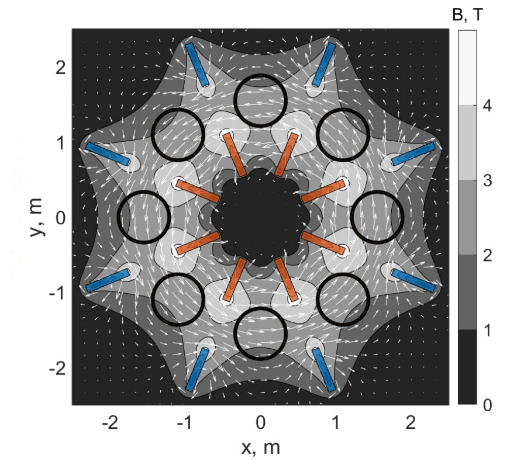
The IAXO collaboration, JHEP 2021, 137

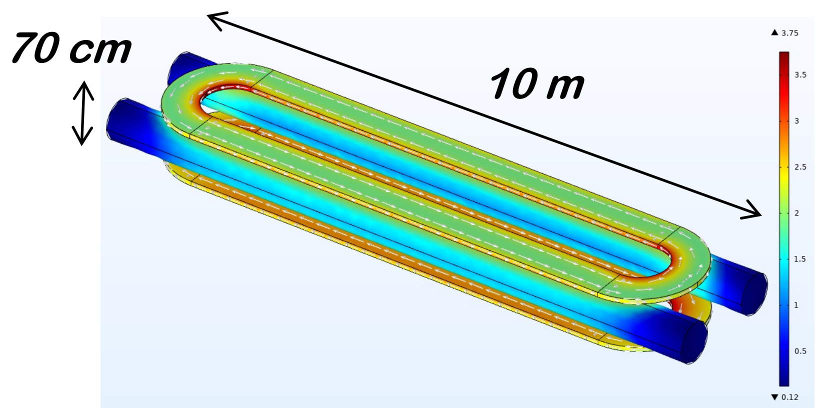
BabyIAXO magnet

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

“Common coil” configuration chosen

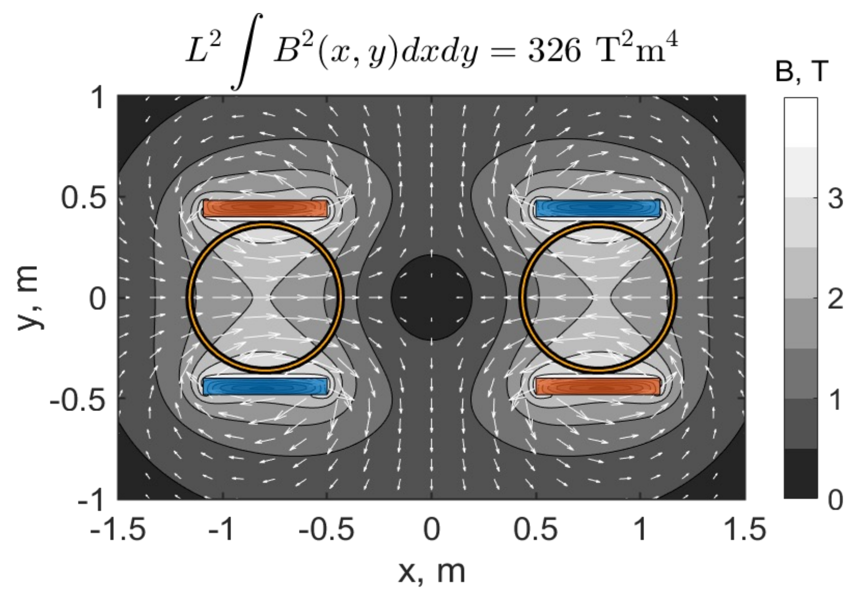
- Minimal construction risk preferred: move to construction asap
- Cost-effective: Best use of existing infrastructure/tooling @CERN
- Winding layout very close to current IAXO toroidal design: racetrack layout
- Some issues with production of Al-stabilized super-conductor cable





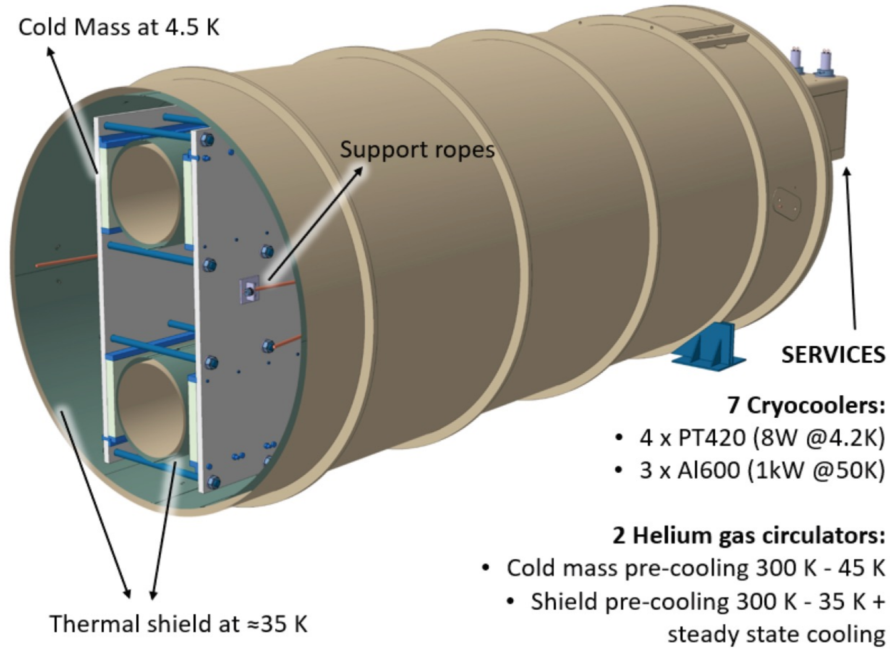
Common-coil dipole, with counter-flowing current in two superconducting race-track coils

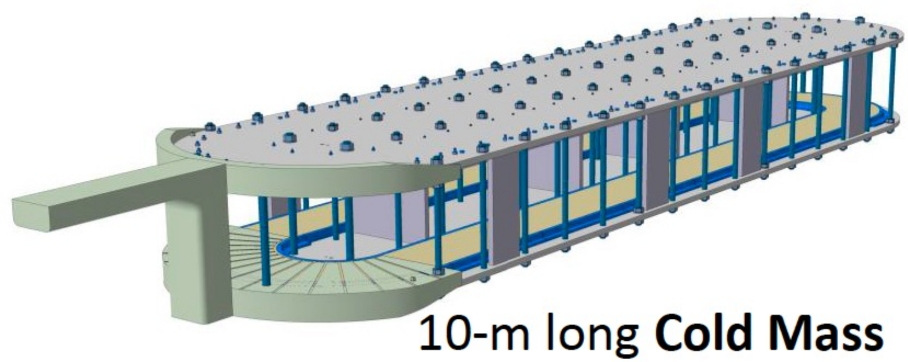
Magnetic field and load line of the conductor for BabyIAXO



BabyIAXO magnet

- BabyIAXO magnet to be operated at T ≤ 5 K featuring Nb-Ti-based superconducting coils with about 2 T in the bore
- Why Al-stabilized Nb/Ti-Cu conductor?
  - Nb-Ti is most affordable superconductor
  - It is also mechanically ductile and robust
  - Well studied work-horse conductor for most existing superconducting magnets
  - Cons: need low T and has limited B-field range
  - Al-stabilizer has very high thermal AND electrical conductivity (cooling and quenching), which also limits training quenches
- But: Supply issues, which causes some delays for experiments





BabyIAXO optics

- Astrophysics community has spent 50 years developing deep experience and design principles for X-ray optics

- These do not map directly to the needs for axion helioscopes like IAXO, but can still leverage

Astronomy
- Unknown source spectrum
- Unknown source size
- Desire wide FOV (up to 60′)
- Higher angular resolution always better
- Mass-constrained

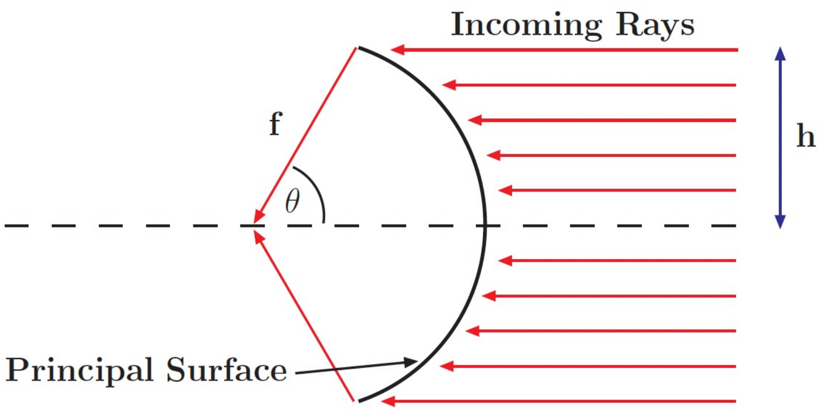
Solar axions
- Known source spectrum
- Known source size
- Modest FOV (10-20′)
- Modest angular resolution of a few arcmin is acceptable
- Not mass-constrained

- Segmented glass selected as baseline for (Baby)IAXO because of cost, collaboration's expertise and experimental constraints

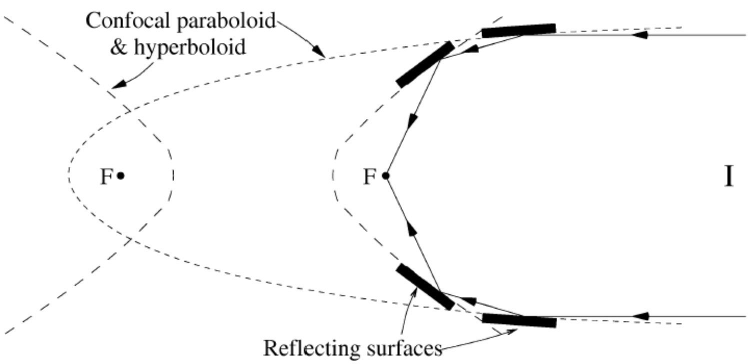
BabyIAXO optics

- X-ray optics are based on the principle of total external reflection (TER) below critical angle
  → Grazing incidence optics
- In order to obtain sharp image (same focal spot for different h) over field of view, Abbe sine condition need to be satisfied:

$$f = \frac{h}{\sin(\theta)}$$



- H. Wolter (*Phys Ann* **6**, 94, (1952)): Two conic surfaces of revolutions to nearly satisfy Abbe sine rule
- Three families of designs, one of which can be nested (Wolter I) and is widely used
- Wolter I has properties similar to a thin lens



Advantages of Wolter optic:
Imaging capability, improvement of signal-to-noise, enables reduction of background

BabyIAXO optics

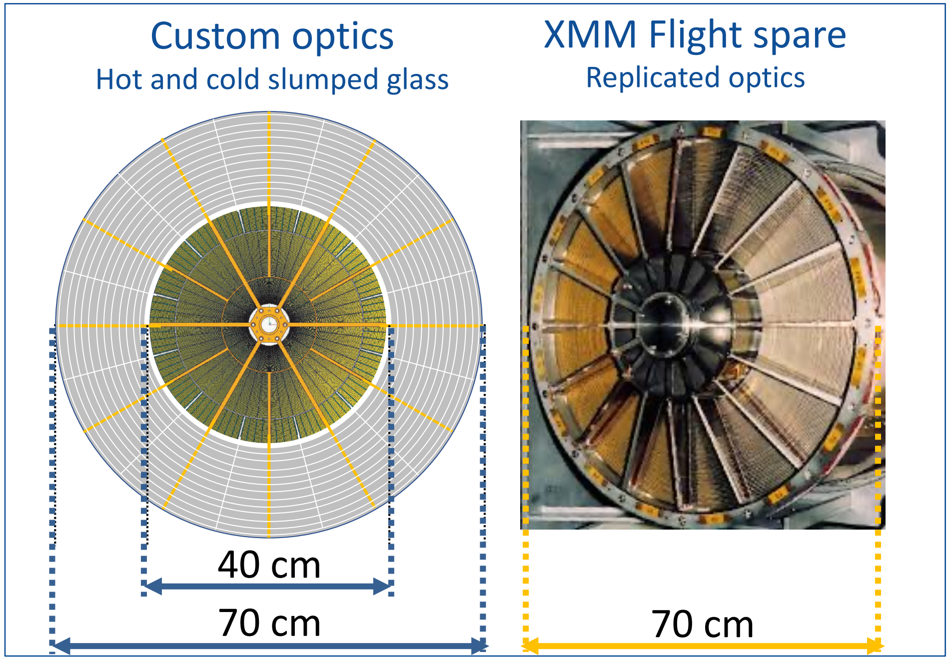
(Baby)IAXO needs

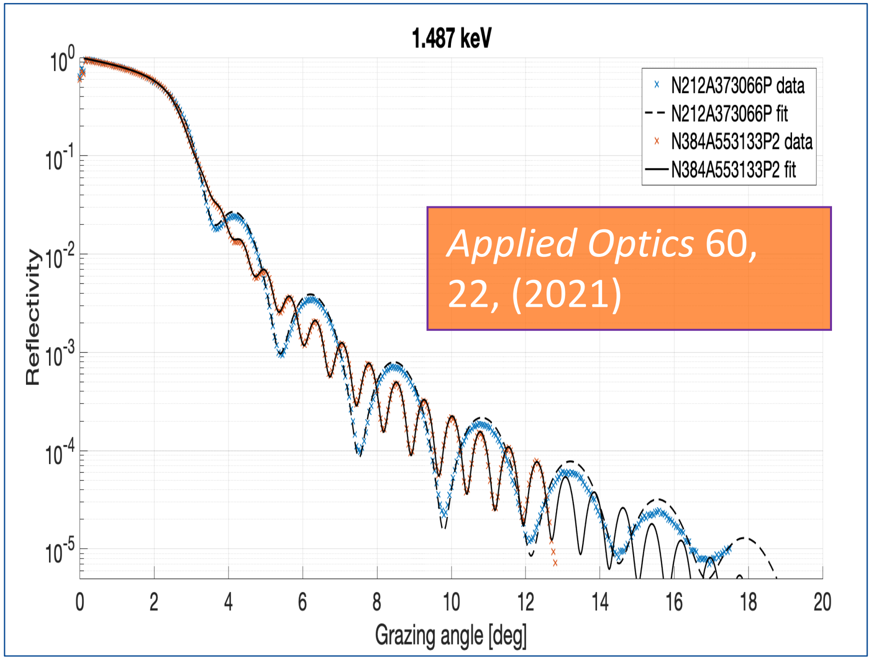
- **Maximized throughput efficiency (40-60%)**
  - Tuned to axion spectrum and detector response
  - Can be enhanced with multilayer coatings for ROI and low energy response
- **Minimized focal spot area (0.2 cm²/ r < 2.5 mm)**
  - Modest spatial resolution (arcmin level)
  - Moderate focal length
- **Cost effective** way to build 1 to 8 highly nested, high-efficiency optics

Segmented glass optics (or Al foil optics) ideal for (Baby)IAXO and have been used or are planned for NASA/ESA missions like NuSTAR, XRISM & Athena

BabyIAXO optics

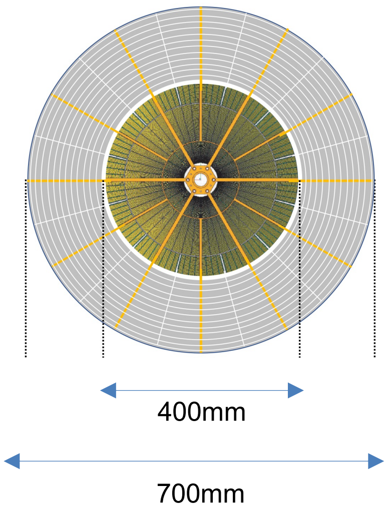
- **Baseline option**: One custom IAXO optic (multilayer-coated, segmented-glass or Al-foil Wolter-I) and flight spare XMM telescope
- Minimal risk to the project
  - Risk reduction for final IAXO segmented-glass optics
  - XMM optics specs very close to IAXO optics design
  - First coating test (10 & 30 nm Ir) on Nustar flight spare glass and Willow glass, great match of data and model

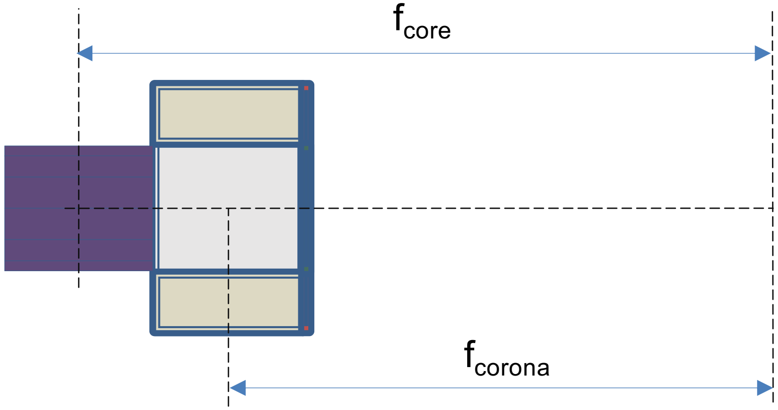




BabyIAXO optics

- **IAXO custom-made optics**

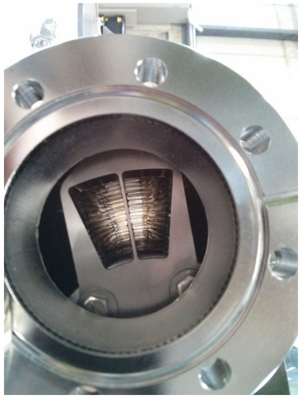




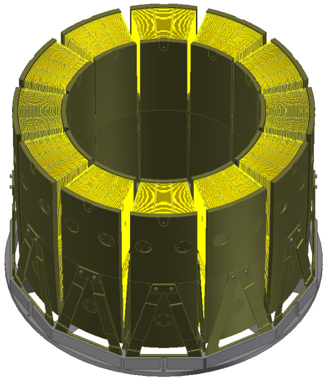
- Inner and outer part of telescope offset for simplified assembly
- Nustar-like pasthfinder was tested @ CAST
- First prototype for outer part of optic has just recently been tested

NuSTAR

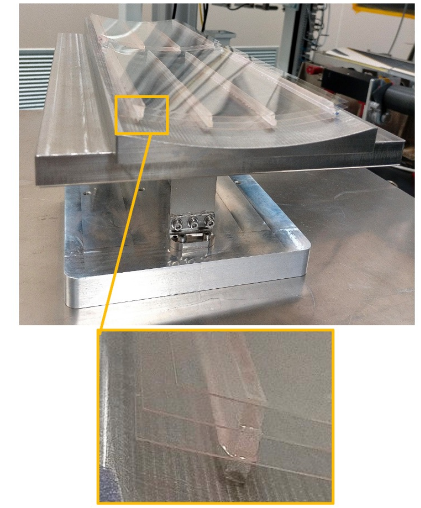
IAXO pathfinder (core)



CSGO



CSGO Pathfinder (corona)



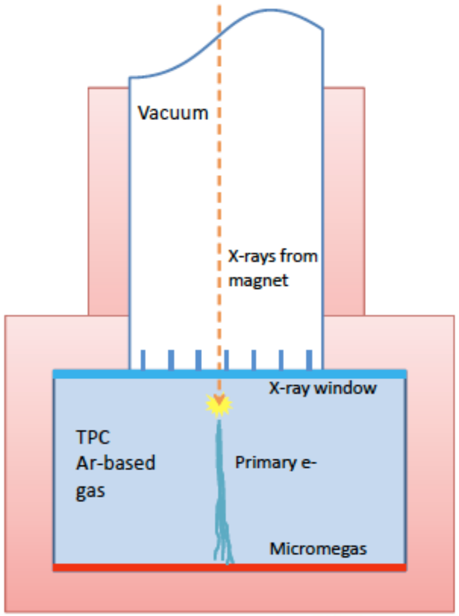
BabyIAXO detectors

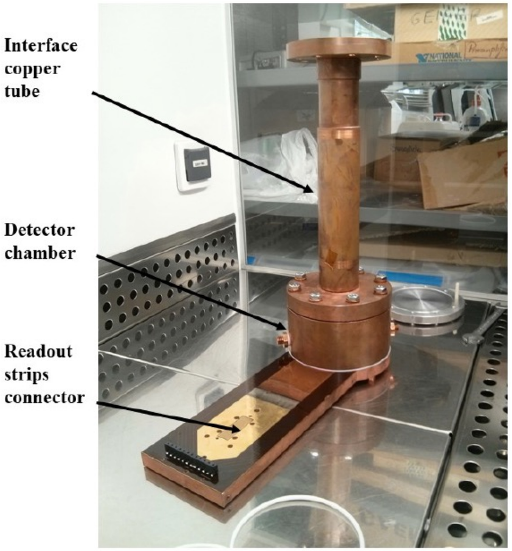
(Baby)IAXO needs

- **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} (in CAST 2014 result) and
  - 10^{-7} cts keV^{-1} cm^{-2} s^{-1} measured underground at LSC
- **High detection efficiency**
- **Want: Low E-threshold (< 1 keV) and good energy resolution**
  - Especially interesting for axion-electron measurements
  - Notably useful in case an axion signal is detected



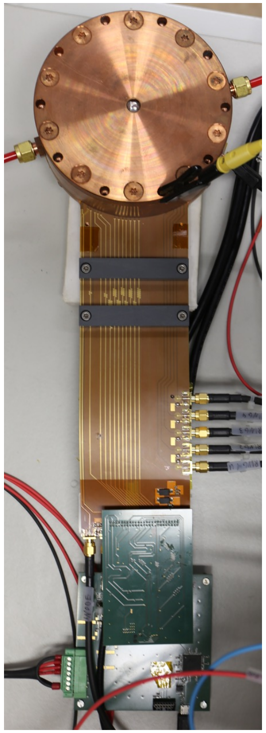


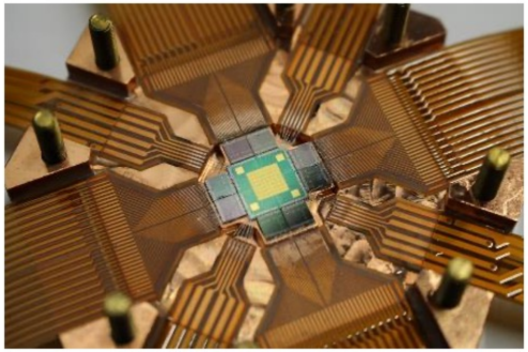
BASELINE: Micromegas technology best option to reach required low background levels
Additional technologies considered and undergoing active R&D efforts (GridPix, MMC, TES, SDD)

BabyIAXO detectors

- **Beyond baseline, "high precision" detectors**
  - **Better threshold & energy resolution**
  - **Design and material optimization ongoing in all fronts**
  - **Background studies with different shielding configurations**
  - **DALPS project (French ANR)**

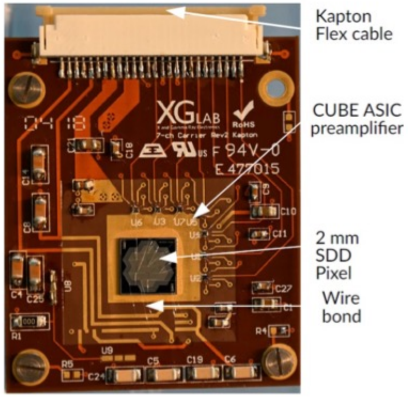
ERC-StG (2020)
M.Meyer
To understand bkg in TES



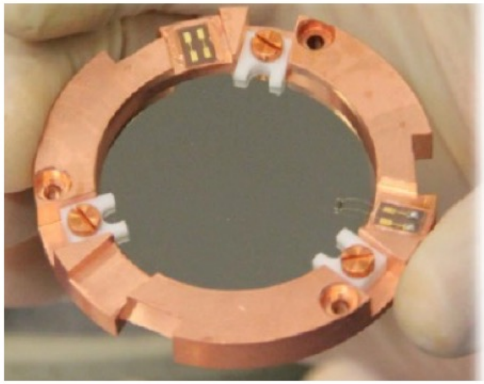


MMC: Metallic Magnetic calorimeters

→ See Loredana's talk today



SDD: Silicon Drift Detectors



TES: Transition Edge senstors

Gridpix

→ Currently multiple new IAXO MM prototypes running in different locations (incl. Canfranc Underground Lab) with continuous improvements being made

→ R&D ongoing for new detector technologies for high precision

BabyIAXO @ DESY

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

→ See Johanna's talk today

Rare Event Searches Toolkit software

Expect to commission BabyIAXO without magnet before baseline science run

Intro to Axions

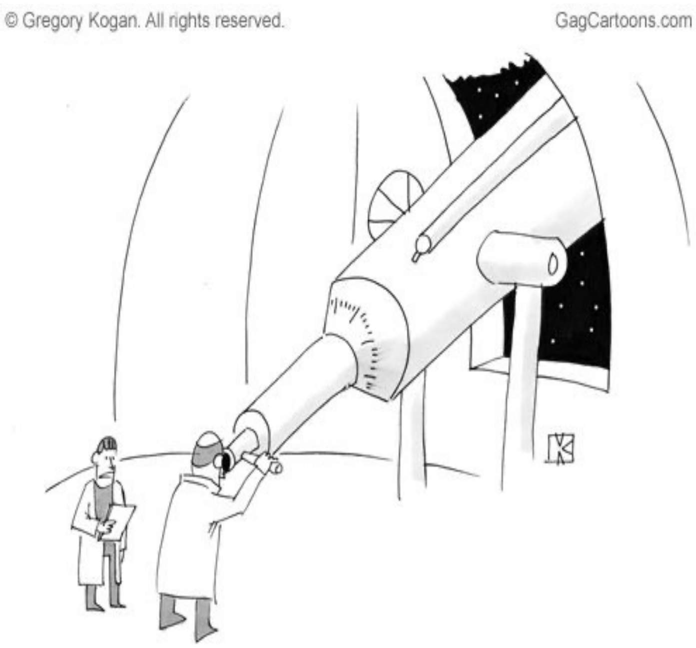
Solar Axion Detection

Previous Helioscopes and State-of-the-Art

Next-Gen: The International Axion Observatory (IAXO)

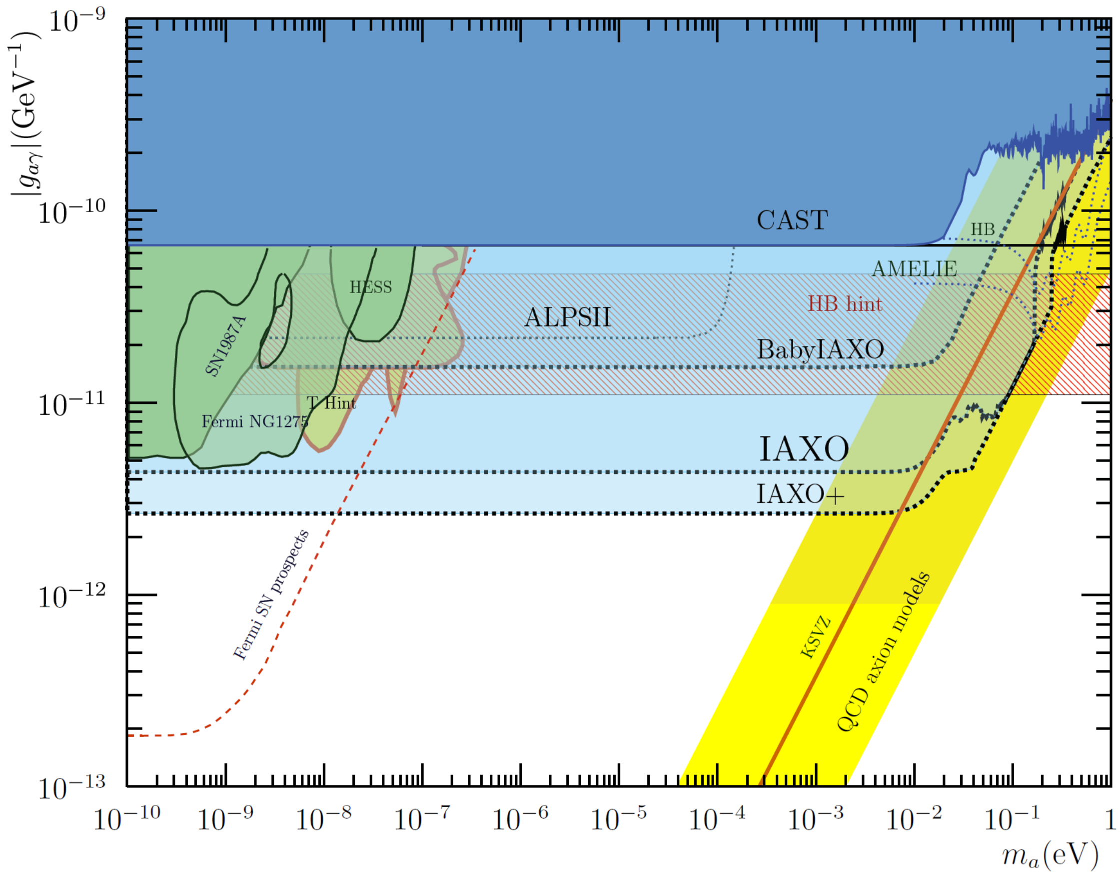
Next-Gen: BabyIAXO

Next-Gen: Physics Prospects



"That isn't dark matter, sir—you just forgot to take off the lens cap."

BabyIAXO and IAXO physics reach



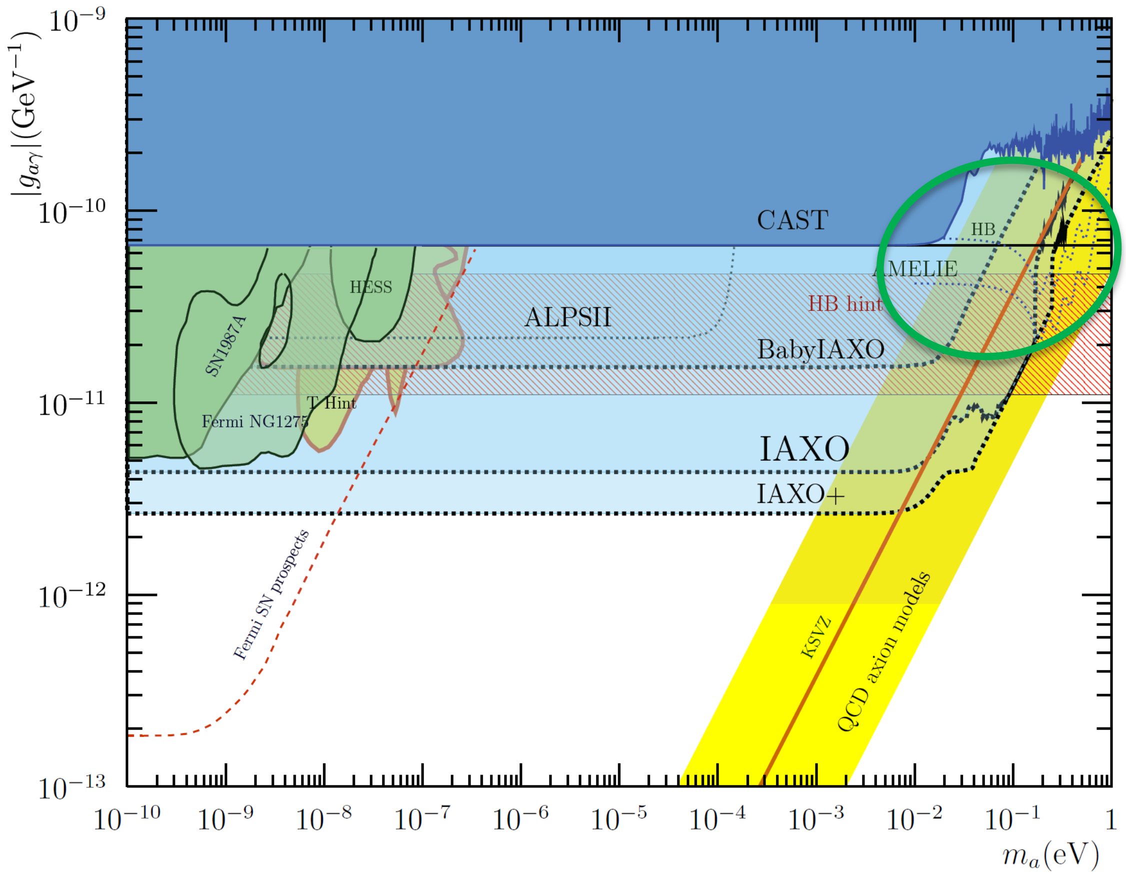
BabyIAXO prospects:
10 x $MFOM_{CAST}$ + optics and detector from conservative scenario of LoI

IAXO: > 300 x $MFOM_{CAST}$ +optics and detector improvements

IAXO+: Enhanced scenario with x 10 (x4) higher FOM (MFOM) with respect LoI

IAXO will probe large parts of QCD axion model space (KSVZ, DFSZ) including viable DM models

BabyIAXO and IAXO physics reach



BabyIAXO prospects:
10 x $MFOM_{CAST}$ + optics and detector from conservative scenario of LoI

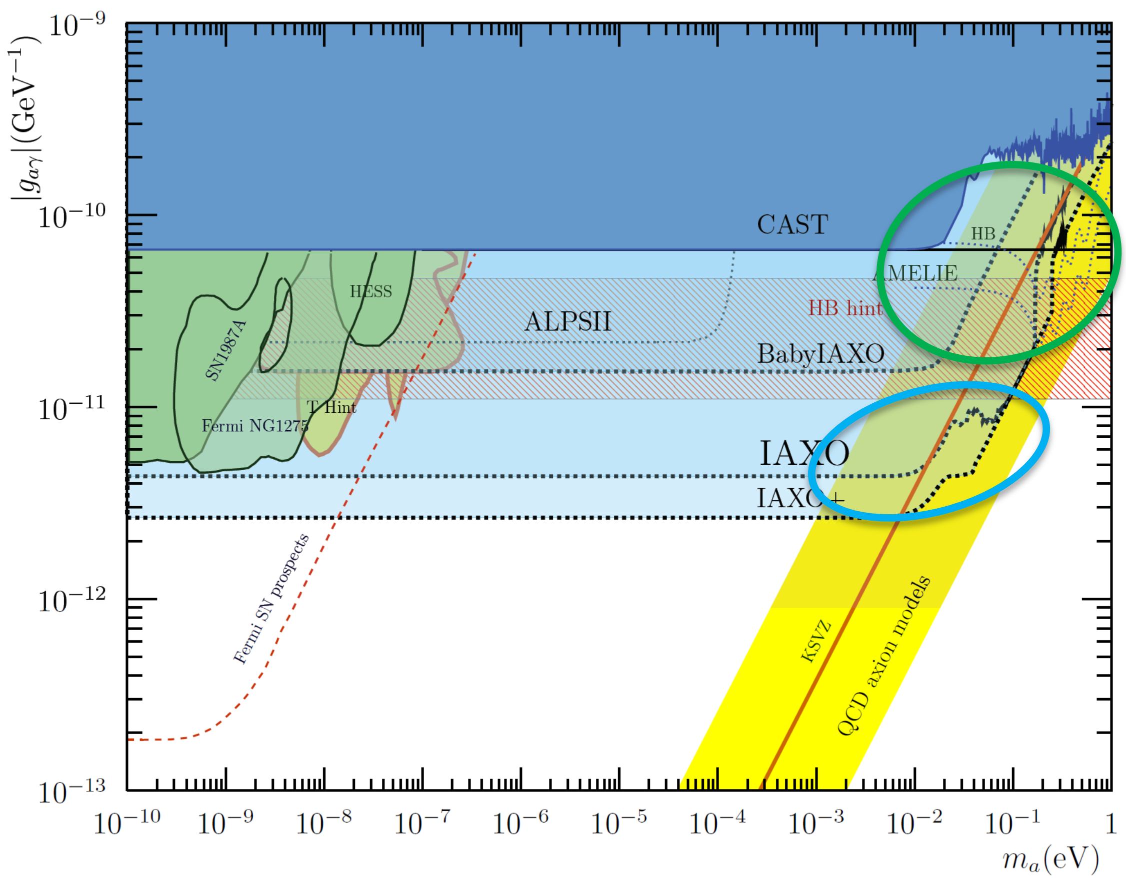
IAXO: > 300 x $MFOM_{CAST}$ +optics and detector improvements

IAXO+: Enhanced scenario with x 10 (x4) higher FOM (MFOM) with respect LoI

IAXO will probe large parts of QCD axion model space (KSVZ, DFSZ) including viable DM models

"ALP miracle" region: ALPs solving both DM & inflation (Daido et al. 2017 arXiv:1710.11107)

BabyIAXO and IAXO physics reach



BabyIAXO prospects:
10 x $\mathrm{MFOM}_{\mathrm{CAST}}$ + optics and detector from conservative scenario of LoI

IAXO: > 300 x $\mathrm{MFOM}_{\mathrm{CAST}}$ +optics and detector improvements

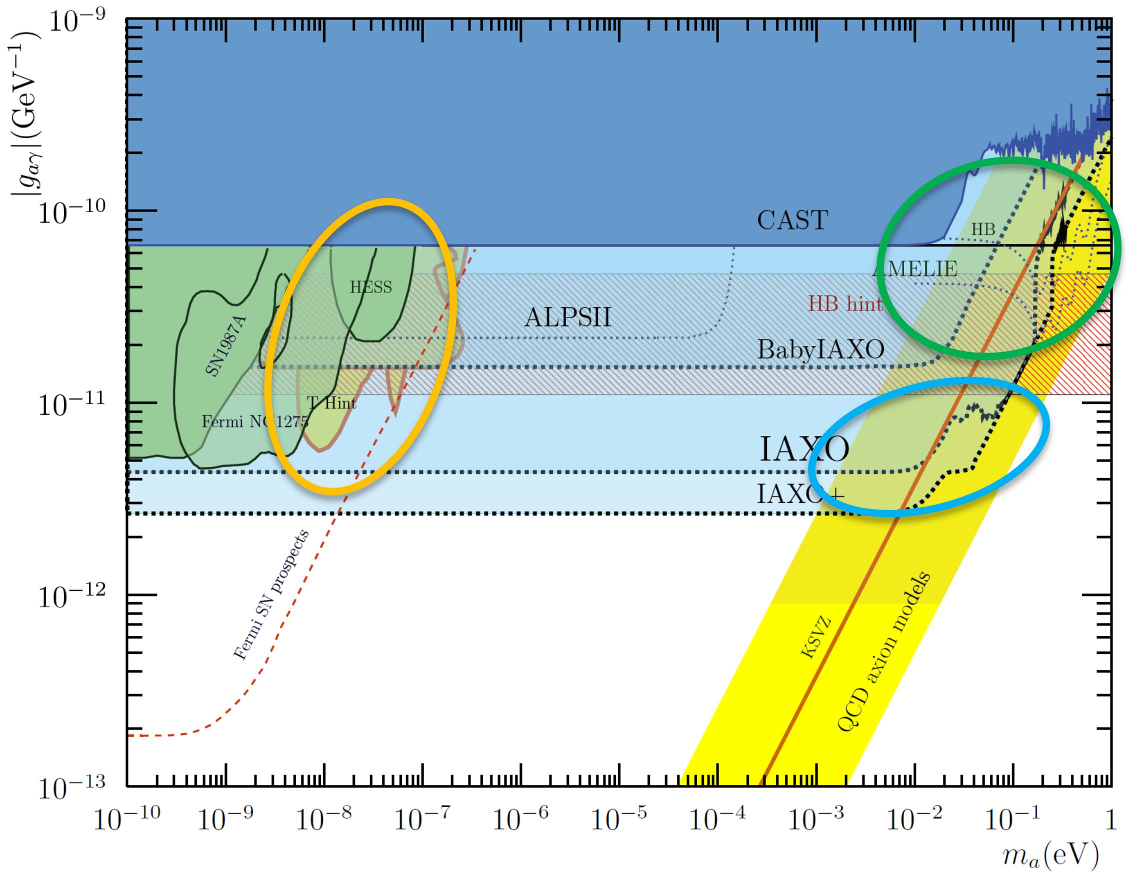
IAXO+: Enhanced scenario with x 10 (x4) higher FOM (MFOM) with respect LoI

IAXO will probe large parts of QCD axion model space (KSVZ, DFSZ) including viable DM models

"ALP miracle" region: ALPs solving both DM & inflation (Daido et al. 2017 arXiv:1710.11107)

Large fraction of the axion & ALP models invoked in the "stellar cooling anomaly" (g_{ae} particularly interesting for this)

BabyIAXO and IAXO physics reach



BabyIAXO prospects:
10 x $\mathrm{MFOM}_{\mathrm{CAST}}$ + optics and detector from conservative scenario of LoI

IAXO: > 300 x $\mathrm{MFOM}_{\mathrm{CAST}}$ +optics and detector improvements

IAXO+: Enhanced scenario with x 10 (x4) higher FOM (MFOM) with respect LoI

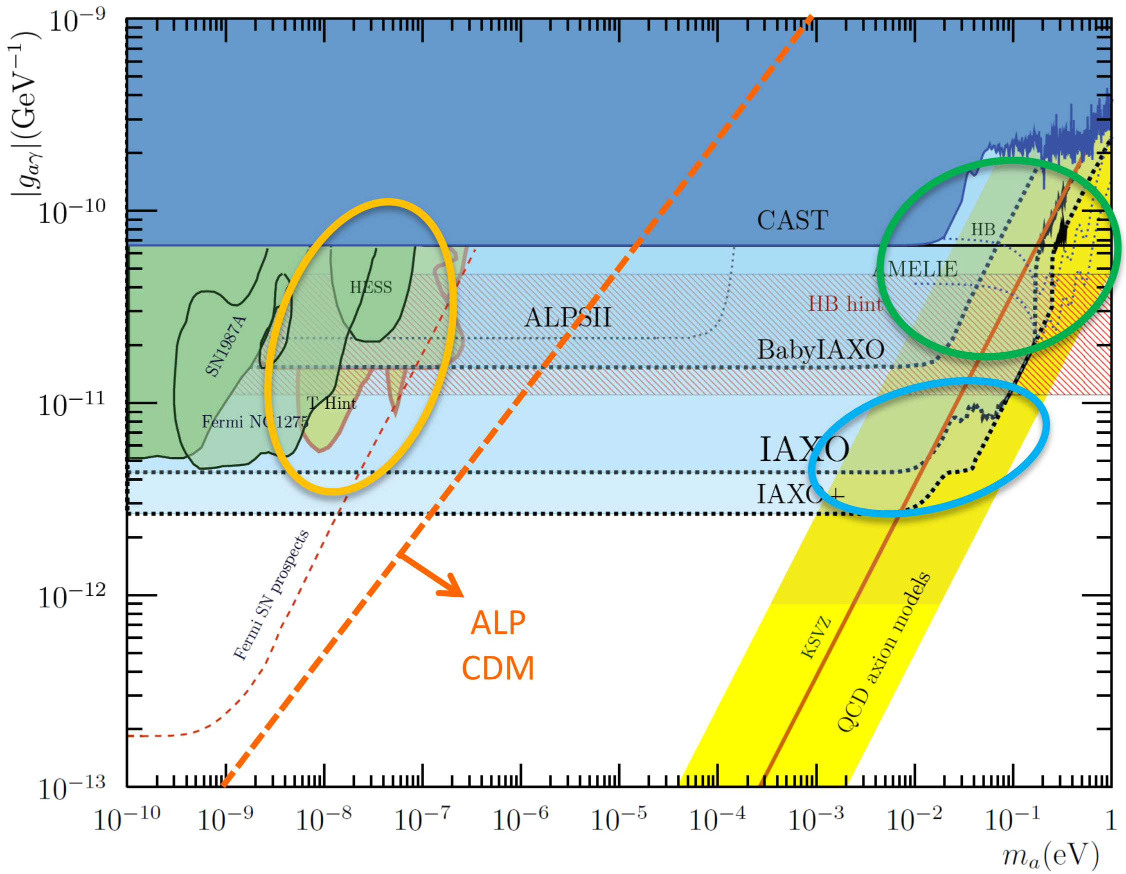
IAXO will probe large parts of QCD axion model space (KSVZ, DFSZ) including viable DM models

"ALP miracle" region: ALPs solving both DM & inflation (Daido et al. 2017 arXiv:1710.11107)

Large fraction of the axion & ALP models invoked in the "stellar cooling anomaly" (g_{ae} particularly interesting for this)

IAXO will fully explore ALP models invoked to solve the "transparency hint"

BabyIAXO and IAXO physics reach



BabyIAXO prospects:
10 x $\mathrm{MFOM}_{\mathrm{CAST}}$ + optics and detector from conservative scenario of LoI

IAXO: > 300 x $\mathrm{MFOM}_{\mathrm{CAST}}$ +optics and detector improvements

IAXO+: Enhanced scenario with x 10 (x4) higher FOM (MFOM) with respect LoI

IAXO will probe large parts of QCD axion model space (KSVZ, DFSZ) including viable DM models

“ALP miracle” region: ALPs solving both DM & inflation (Daido et al. 2017 arXiv:1710.11107)

Large fraction of the axion & ALP models invoked in the “stellar cooling anomaly” (g_{ae} particularly interesting for this)

IAXO will fully explore ALP models invoked to solve the “transparency hint”

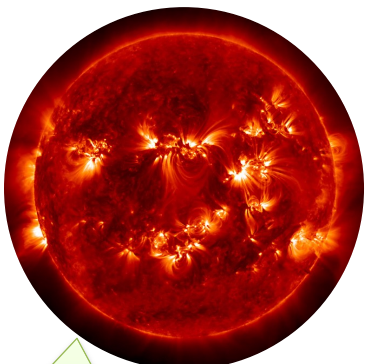
IAXO will also be able to probe large parameter space for CDM ALPs

IAXO Collaboration, *JCAP* 1906, 047, (2019)

BabyIAXO beyond the baseline

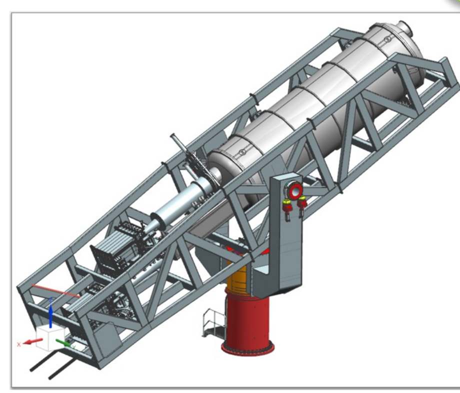
BabyIAXO as a generic axion(-like) detection facility

- BabyIAXO constitutes a great infrastructure that can be used to target other physics goals beyond Primakoff solar axions:



Other (non-Primakoff) solar axion production mechanisms

Axions from SN



Post-discovery "precision" physics

Dark Matter axions: haloscope setups inside the BabyIAXO bores

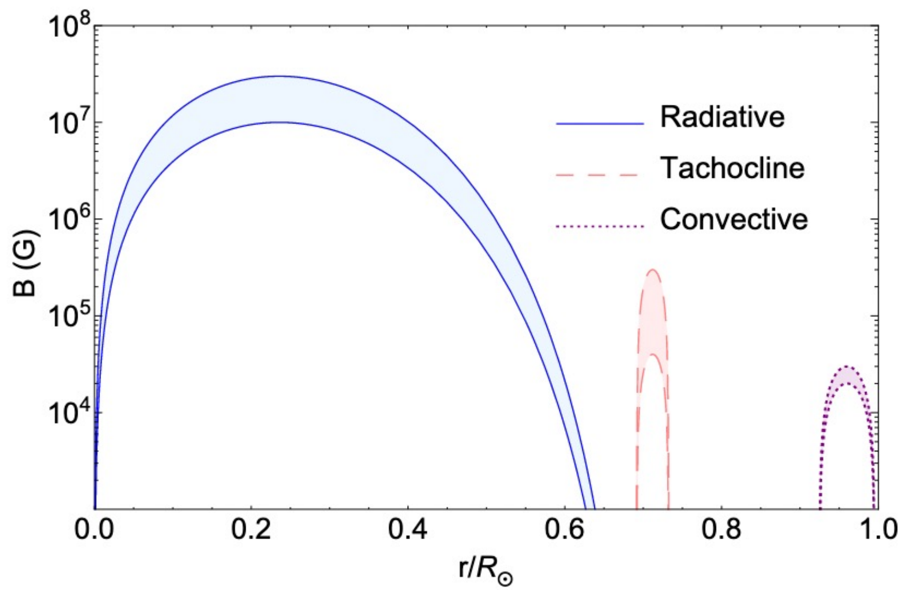
Other WISPs: hidden (dark) photons, chameleons, …

BabyIAXO beyond the baseline

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

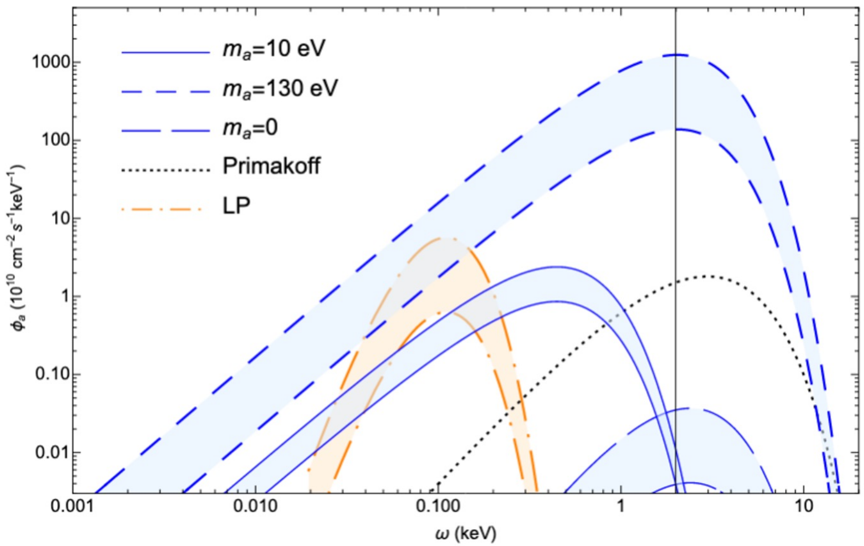


Guarini et al. 2010.06601

BabyIAXO beyond the baseline

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

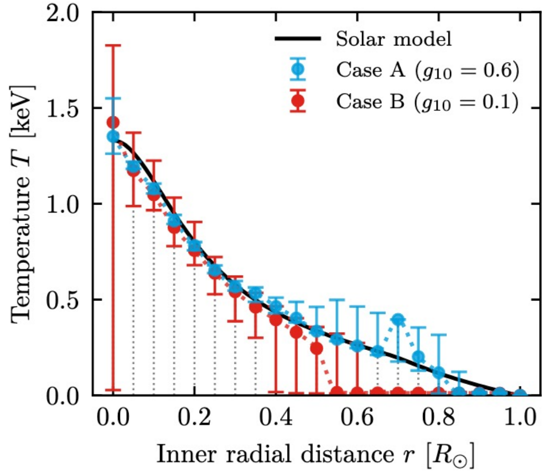


Guarini et al. 2010.06601

BabyIAXO beyond the baseline

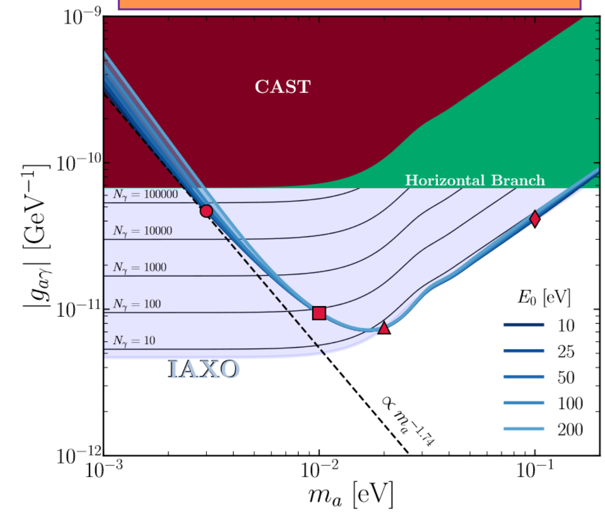
Post-discovery: Axion properties and applications

- 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}, $g_{a\gamma}$)

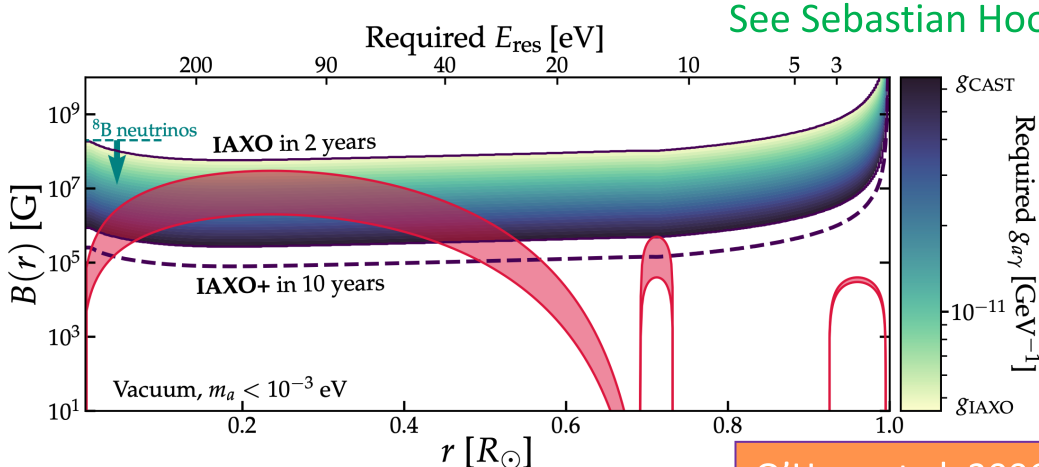


Hoof et al. 2306.00077

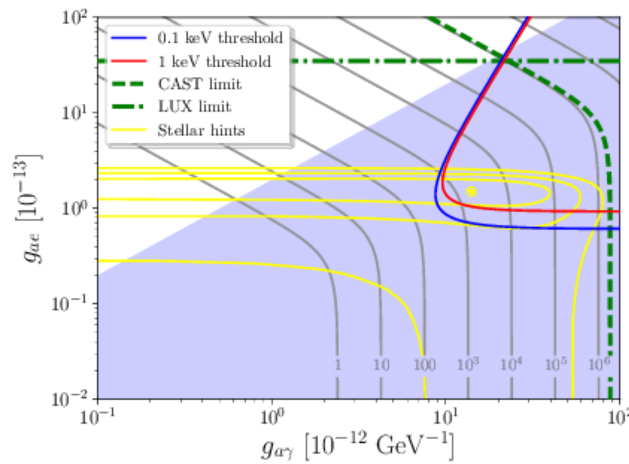
See Sebastian Hoof's talk tmrw



Dafni et al. 1811.09290



O'Hare et al. 2006.10415



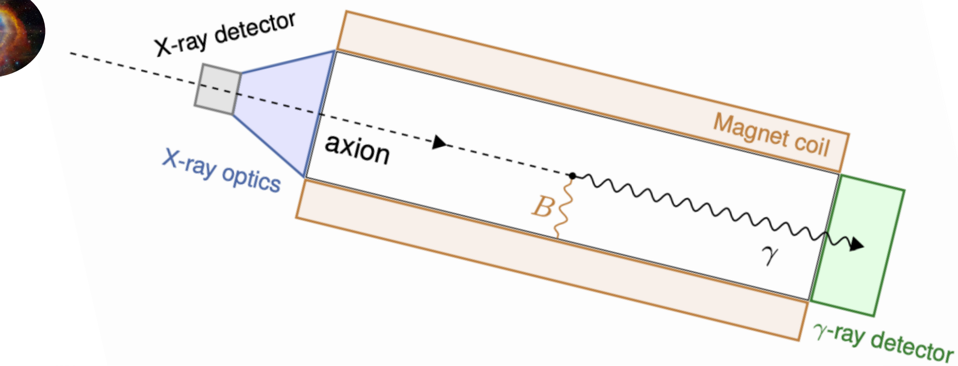
Jaeckel et al. 1811.09278

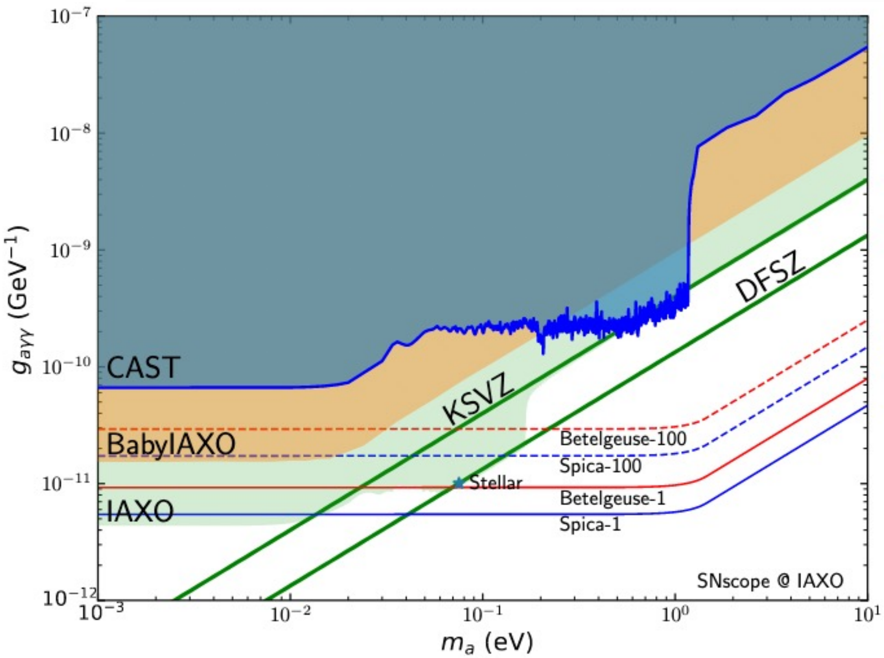
BabyIAXO beyond the baseline

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

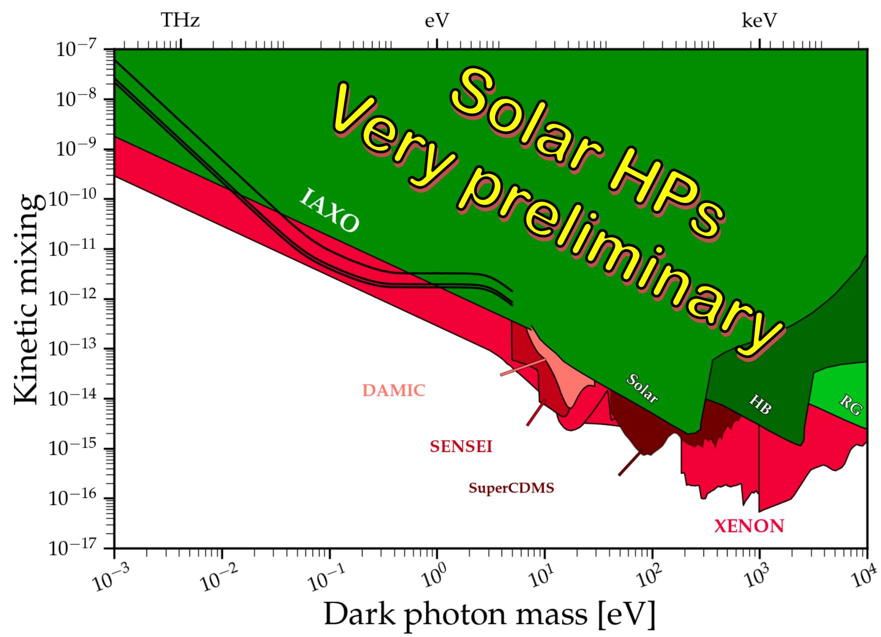


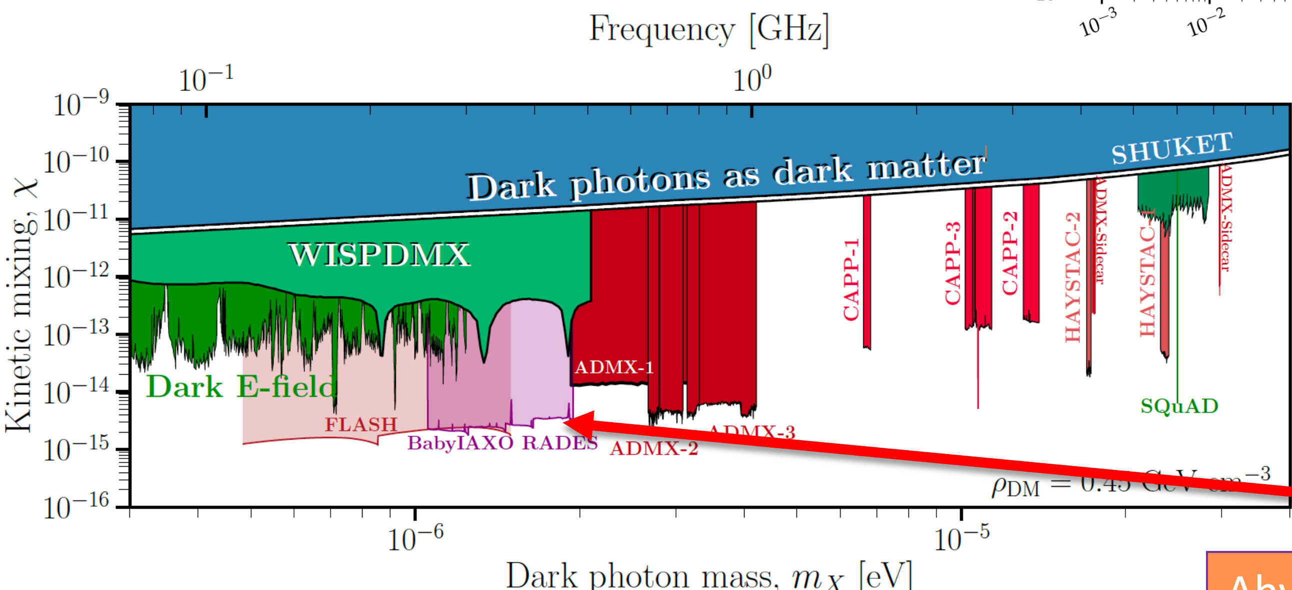


BabyIAXO beyond the baseline

Hidden photons at (Baby)IAXO

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





Paper in preparation (Calculations by T. O'Shea)

Calculations by C. Cogollos

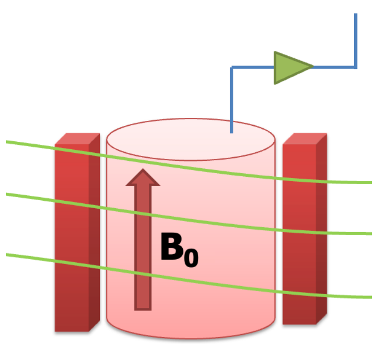
Ahyoune et al. arxiv: 2306.17243

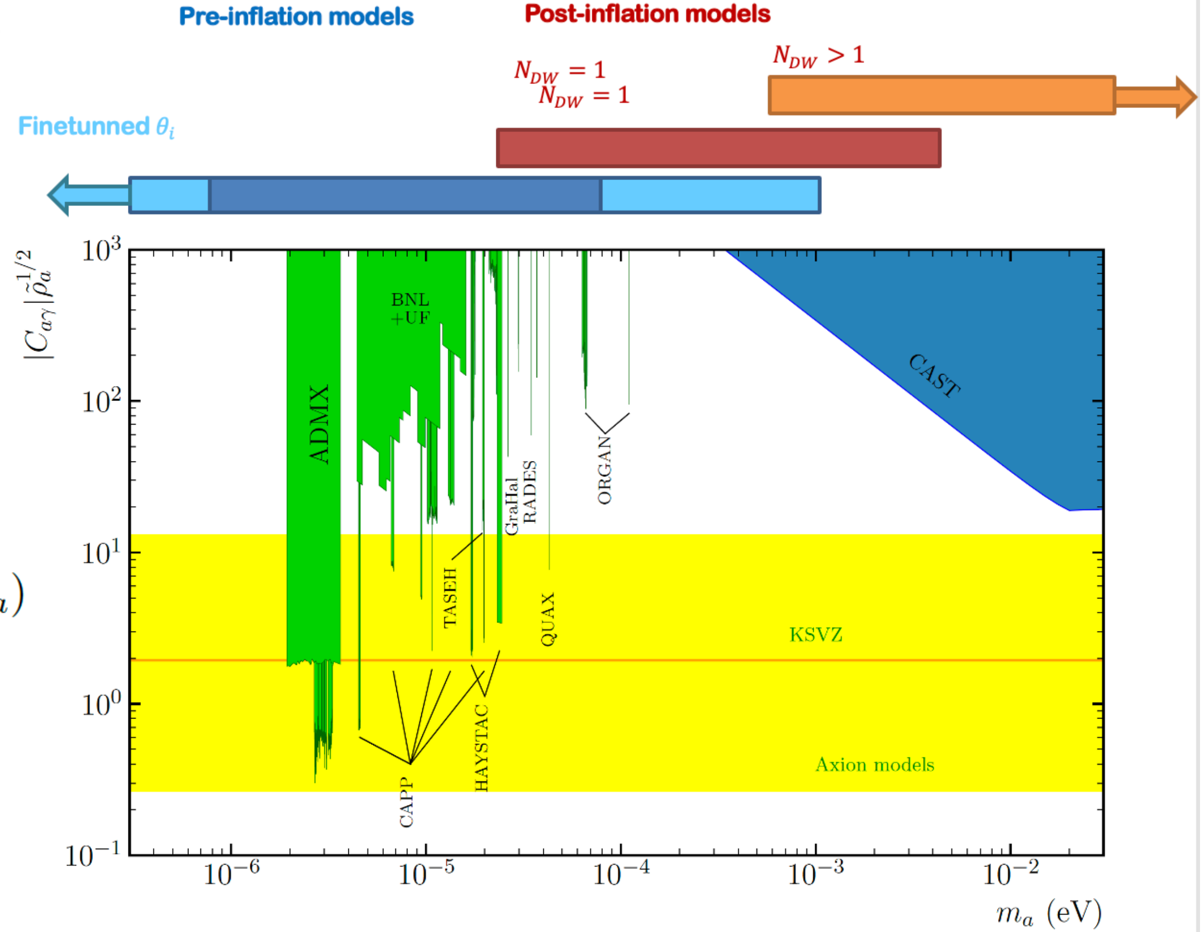
BabyIAXO beyond the baseline

Detecting DM axions: Haloscopes for BabyIAXO

- Assumption:
  DM is mostly axions
- Resonant cavities (Sikivie,1983):
  Primakoff conversion inside a “tunable” resonant cavity

$$P_d = \kappa g_{a\gamma}^2 \frac{\rho_{\rm DM}}{m_a} B_e^2 C V min(Q_l, Q_a)$$



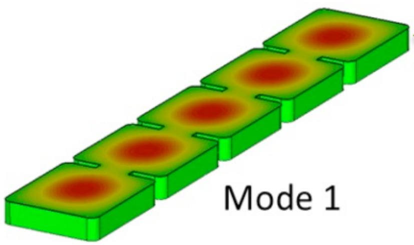


BabyIAXO beyond the baseline

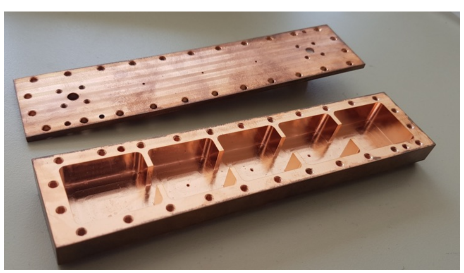
RADES

- Exploratory project towards a later stage of CAST experiment: helioscope magnets for haloscope searches
- Creation of “axion haloscope” community in Europe (with basically no previous trajectory)
- Very interesting results up to now

ERC-StG 2018
B. Dobrich, CERN

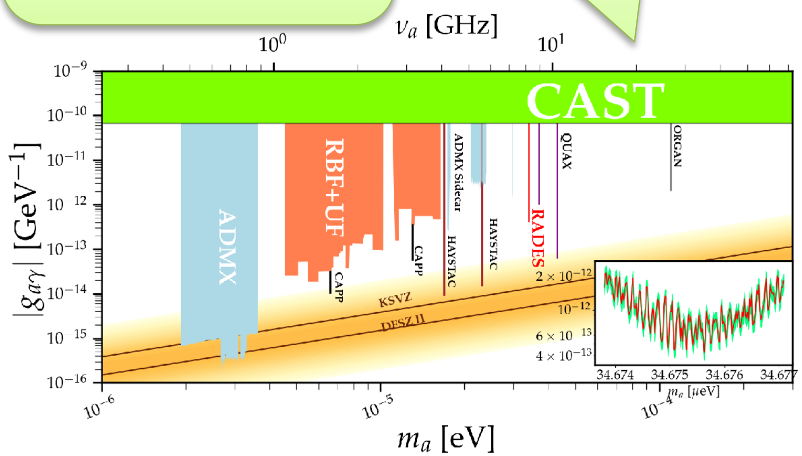


New geometry concepts to scale in V but keeping high resonant *f*



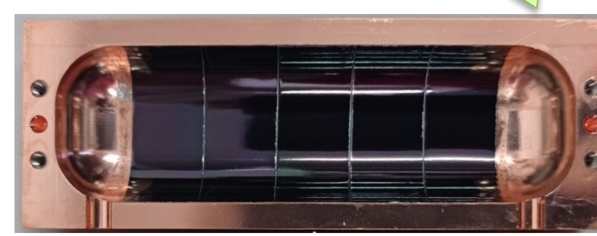
JCAP 05 (2018) 040
JHEP 07 (2020) 084

Physics result at single *f* point (34.67 μeV) in the CAST magnet



JHEP 10 (2021) 075

Inner HTS coatings to improve Q factor

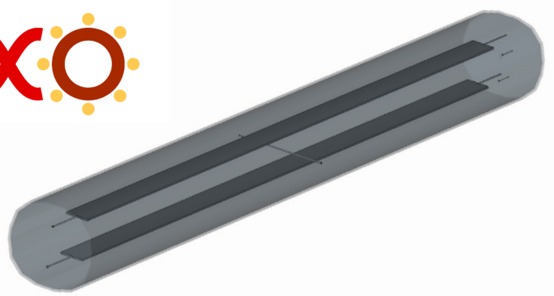


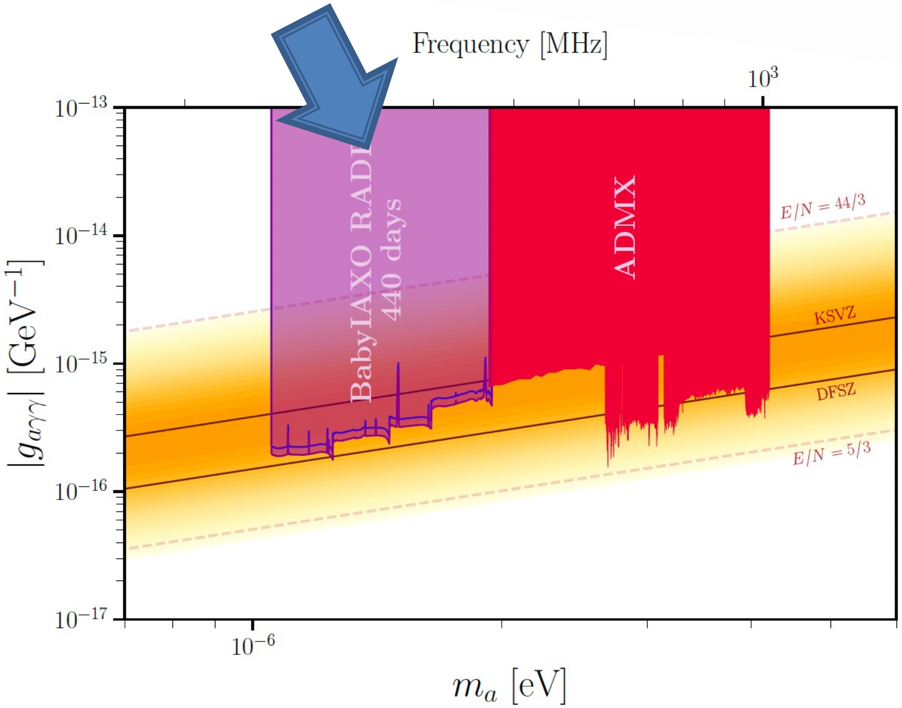
IEEE Trans. Appl. Supercond. 32 (2022) 45

BabyIAXO beyond the baseline

- 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?

Baby





Ahyoune et al. (RADES Collaboration) arxiv:2306.17243

BabyIAXO beyond the baseline

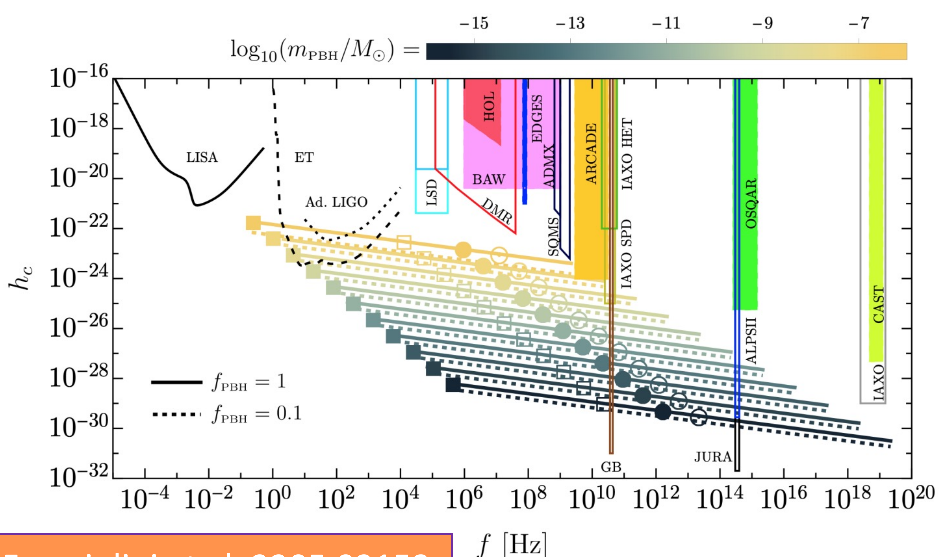
Other and more recent ideas to be studied by newly installed IAXO Physics group including:

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

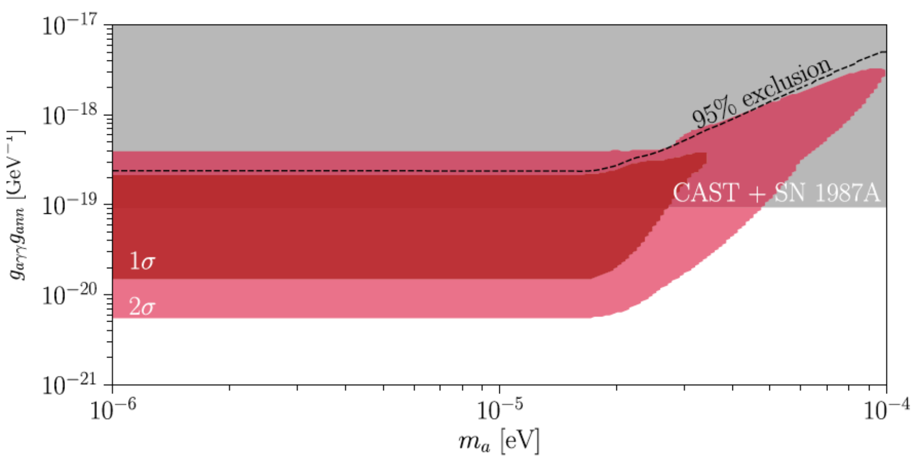
  → See Valerie's lecture

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

  → See Maurizio's lecture



Franciolini et al. 2205.02153



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

IAXO Collaboration

IAXO collaboration: ~125 scientists from 22 full member institutions + 5 associate institutions

Full members:

Kirchhoff Institute for Physics, Heidelberg U. (Germany) | IRFU-CEA (France) | CAPA-UNIZAR (Spain) | INAF-Brera (Italy) | CERN (Switzerland) | ICCUB-Barcelona (Spain) | Petersburg Nuclear Physics Institute (Russia, on hold) | Siegen University (Germany) | Barry University (USA) | Institute of Nuclear Research, Moscow (Russia , on hold) | University of Bonn (Germany) | DESY (Germany) | University of Mainz (Germany) | MIT (USA) | LLNL (USA) | University of Cape Town (S. Africa) | Moscow Institute of Physics and Technology (Russia , on hold) | Technical University Munich (TUM) (Germany) | CEFCA-Teruel (Spain) | U. Polytechnical of Cartagena (Spain) | U. of Hamburg (Germany) | MPE/PANTER (Germany)

Associate members:

DTU (Denmark) | U. Columbia (USA) | SOLEIL (France) | IJCLab (France) | LIST-CEA (France)

Outline

Intro to Axions

Solar Axion Detection

Previous Helioscopes and State-of-the-Art

Next-Gen: The International Axion Observatory (IAXO)

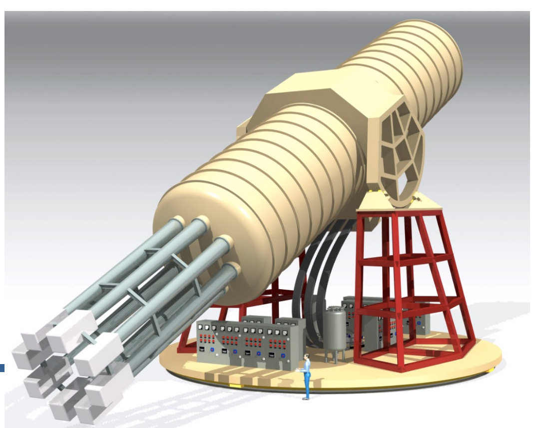
Next-Gen: BabyIAXO

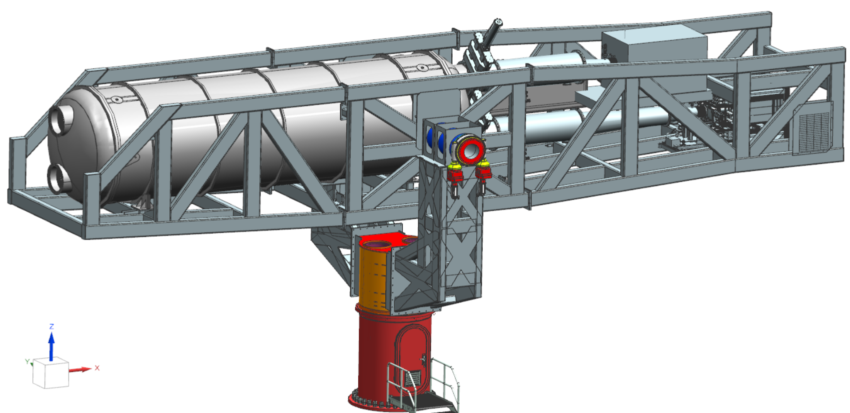
Next-Gen: Physics Prospects

Conclusions

Conclusions

- Helioscopes can search for axions and ALPs from the Sun over wide mass range
- Current best limit on Primakoff axions by CAST: $g_{a\gamma} < 0.66 \times 10^{-10}$ GeV^{-1} (95% C.L.)
- BabyIAXO envisioned to reach a few 10^{-11} GeV^{-1} in coupling of axion-to photons
- IAXO and IAXO+: Sensitivities of few 10^{-12} GeV^{-1} in coupling of axion-to photons (>1 order of magnitude improvement in $g_{a\gamma}$ or > 4 OM in S/N over CAST)
- Diverse Physics reach:
  QCD axions, ALPs, astrophysical hints, dark radiation, dark energy, …





THANK YOU FOR YOUR ATTENTION!
QUESTIONS?

jvogel@unizar.es

Exercise 1: Solar Axion Detection

Example: Calculate the axion mass range accessible to CAST (L = 10 m) for a typical pressure setting of p = 5.49 mbar at T = 1.8 K for an axion energy of E_a = 4.2 keV.

Use $q = \left| \frac{m_\gamma^2 - m_a^2}{2E_a} \right|$ & $\frac{qL}{2} < \pi$,

→ $$\sqrt{m_\gamma^2 - \frac{4\pi E_a}{L}} < m_a < \sqrt{m_\gamma^2 + \frac{4\pi E_a}{L}}.$$

Exercise 1: Solar Axion Detection

Example: Calculate the axion mass range accessible to CAST (L = 10 m) for a typical pressure setting of p = 5.49 mbar at T = 1.8 K for an axion energy of E_a = 4.2 keV.

Use $q = \left| \frac{m_\gamma^2 - m_a^2}{2E_a} \right|$ & $\frac{qL}{2} < \pi,$

→ $$\sqrt{m_\gamma^2 - \frac{4\pi E_a}{L}} < m_a < \sqrt{m_\gamma^2 + \frac{4\pi E_a}{L}}.$$

Exercise 1: Solar Axion Detection

Example: Calculate the axion mass range accessible to CAST (L = 10 m) for a typical pressure setting of p = 5.49 mbar at T = 1.8 K for an axion energy of E_a = 4.2 keV.

Use $q = \left| \frac{m_\gamma^2 - m_a^2}{2E_a} \right|$ & $\frac{qL}{2} < \pi$,

→ $$\sqrt{m_\gamma^2 - \frac{4\pi E_a}{L}} < m_a < \sqrt{m_\gamma^2 + \frac{4\pi E_a}{L}}.$$

$$\sqrt{0,02\frac{5,49}{1,8}\mathrm{eV}^2 - \frac{4\pi 4200\mathrm{eV}}{10\mathrm{m}}} < m_a < \sqrt{0,02\frac{5,49}{1,8}\mathrm{eV}^2 + \frac{4\pi 4200\mathrm{eV}}{10\mathrm{m}}}$$

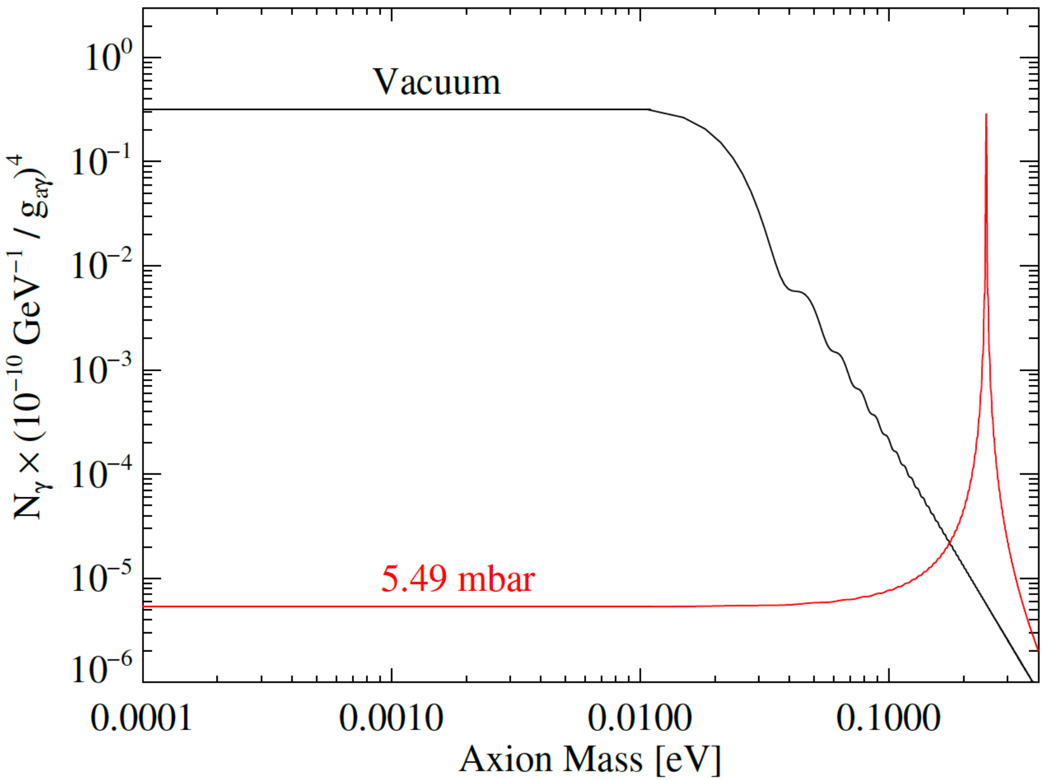
$$\sqrt{0,02\frac{5,49}{1,8}\mathrm{eV}^2 - \frac{4\pi 4200\mathrm{eV}\cdot 1,98\times 10^{-7}\ \mathrm{eV}}{10}} < m_a < \sqrt{0,02\frac{5,49}{1,8}\mathrm{eV}^2 + \frac{4\pi 4200\mathrm{eV}\cdot 1,98\times 10^{-7}\ \mathrm{eV}}{10}}$$

$$\sqrt{0,05995}\ \mathrm{eV} < m_a < \sqrt{0,06205}\ \mathrm{eV}$$

$$0,245\ \mathrm{eV} < m_a < 0,249\ \mathrm{eV}$$

Exercise 1: Solar Axion Detection

Example: Calculate the axion mass range accessible to CAST (L = 10 m) for a typical pressure setting of p = 5.49 mbar at T = 1.8 K for an axion energy of E_a = 4.2 keV.



$$0,245\ \text{eV} < m_a < 0,249\ \text{eV}$$

Exercise 2: BabyIAXO optics

Exercise: Why do we use X-ray optics?

Why don’t we care about excellent spatial resolution for discovery?

How big an “axion” focal spot are we talking about (example IAXO)?

Exercise 2: BabyIAXO optics

Exercise: Why do we use X-ray optics?

Why don't we care about excellent spatial resolution for discovery?

How big an "axion" focal spot are we talking about (example IAXO)?

Given that the region of the Sun from which most axions are expected has an extension of s_{object} = 3 arcmin and the imaging capability of a envisioned IAXO optic is s_{optic} = 2 arcmin, estimate the expected focal spot area (and its radius) for a focal length of 5 m.

Exercise 2: BabyIAXO optics

Exercise: Why do we use X-ray optics?

Why don't we care about excellent spatial resolution for discovery?

How big an "axion" focal spot are we talking about (example IAXO)?

Given that the region of the Sun from which most axions are expected has an extension of s_{object} = 3 arcmin and the imaging capability of a envisioned IAXO optic is s_{optic} = 2 arcmin, estimate the expected focal spot area (and its radius) for a focal length of 5 m.

Total angular spotsize:

$$\begin{aligned} s_{\text{total}} &= \sqrt{s_{\text{object}}^2 + s_{\text{optic}}^2} \\ &= \sqrt{(0,87 \text{ mrad})^2 + (0,58 \text{ mrad})^2} \\ &= 1,09 \text{ mrad} \end{aligned}$$

$$1 \text{ arcmin} = \frac{1}{60} \text{ deg} = \frac{2\pi}{60 \cdot 360} \text{ rad} = 2,909 \times 10^{-4} \text{ rad} = 0,29 \text{ mrad}$$

Exercise 2: BabyIAXO optics

Exercise: Why do we use X-ray optics?

Why don't we care about excellent spatial resolution for discovery?

How big an "axion" focal spot are we talking about (example IAXO)?

Given that the region of the Sun from which most axions are expected has an extension of s_{object} = 3 arcmin and the imaging capability of a envisioned IAXO optic is s_{optic} = 2 arcmin, estimate the expected focal spot area (and its radius) for a focal length of 5 m.

Total angular spotsize:

$$\begin{aligned} s_{\text{total}} &= \sqrt{s^2_{\text{object}} + s^2_{\text{optic}}} \\ &= \sqrt{(0,87\ \text{mrad})^2 + (0,58\ \text{mrad})^2} \\ &= 1,09\ \text{mrad} \end{aligned}$$

The spatial diameter of the imaged focal spot can be calculated as focal length $f \times s_{total}$ and therefore the focal spot area a is

$$a = \frac{\pi}{4}\left(s_{\text{total}} \times f\right)^2 = 0,23\ \text{cm}^2.$$

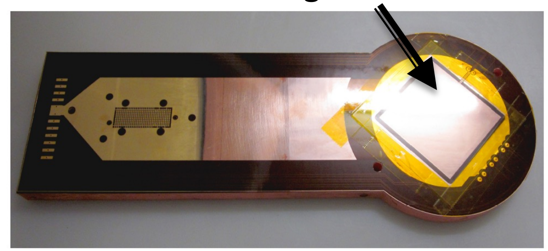
$$r = \frac{s_{\text{total}} \times f}{2} = 2,7\ \text{mm}.$$

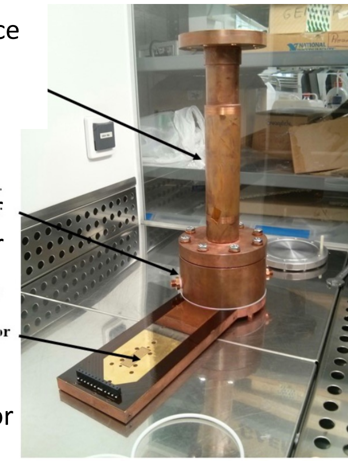
BabyIAXO detectors

Microbulk Micromegas detectors

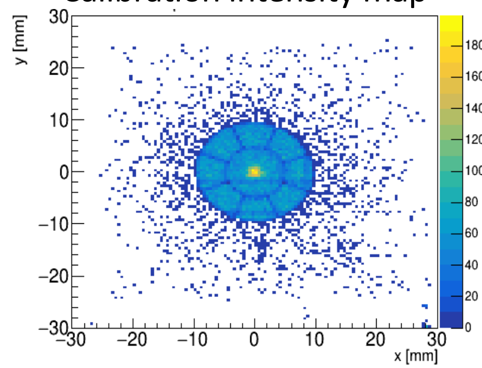
- Very homogeneous amplification gap, uniform gain
- Intrinsically radiopure
- Good energy and spatial resolution
- Pixelized readout gives topological information
- Signal reaches the active volume through a mylar window
- X-rays ionize the gas in the conversion region and the produced signal is read by the Micromegas
- Data is analyzed with the [REST-for-Physics framework](github.com/rest-for-physics) (github.com/rest-for-physics).

Micromegas readout





Calibration intensity map

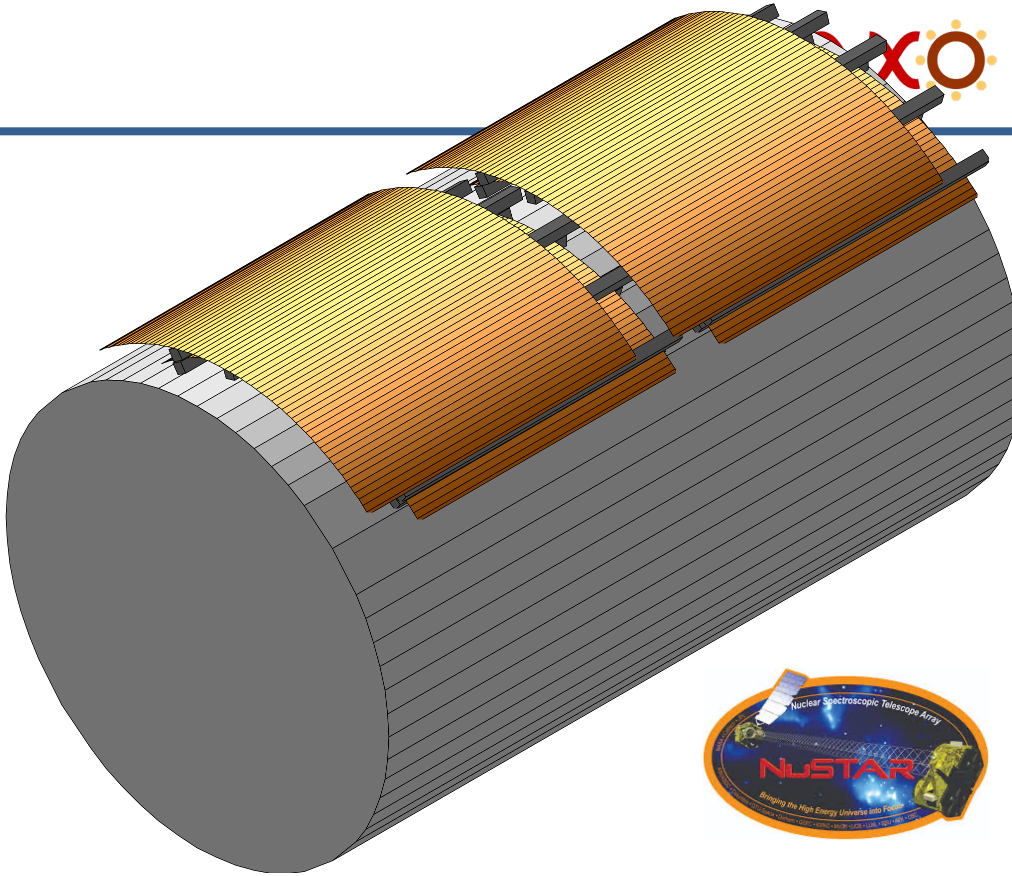


X-ray window

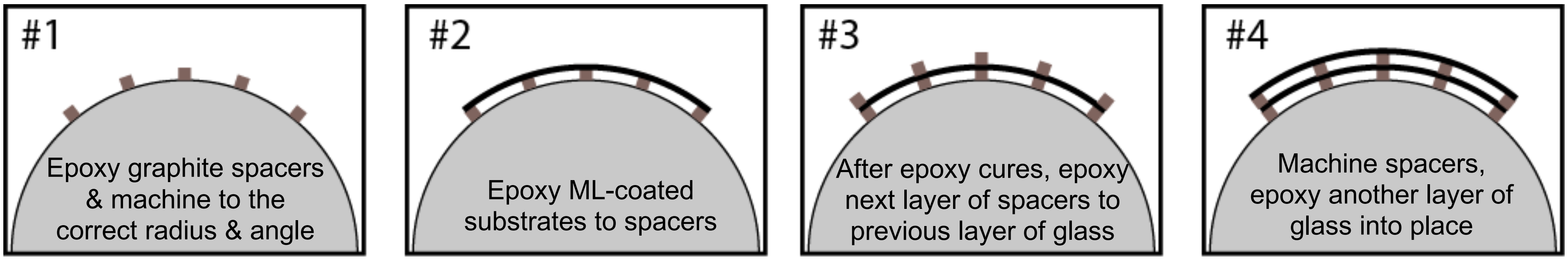
Rare Event Searches Toolkit **software**

BabyIAXO optics

- Segmented optics rely on several individual pieces of substrates to complete a single layer
- Selected as baseline technology for (B)IAXO, because
  - Mature technology/Expertise
  - Single/multilayer coatings can be deposited
  - Cost-effective
  - Modest imaging requirements for IAXO

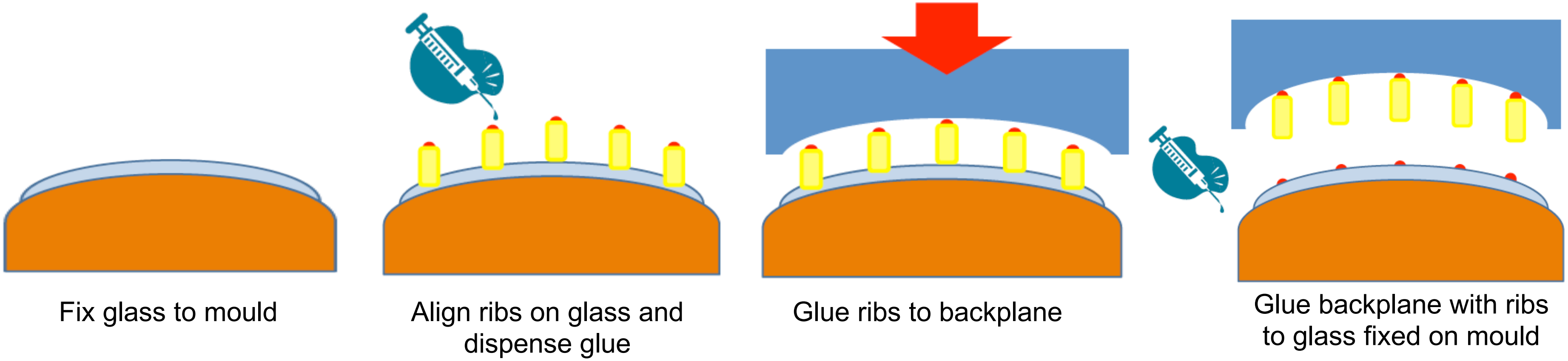


JE Koglin et al. Proc. SPIE, ***4851:607*** *(2003)*



BabyIAXO optics

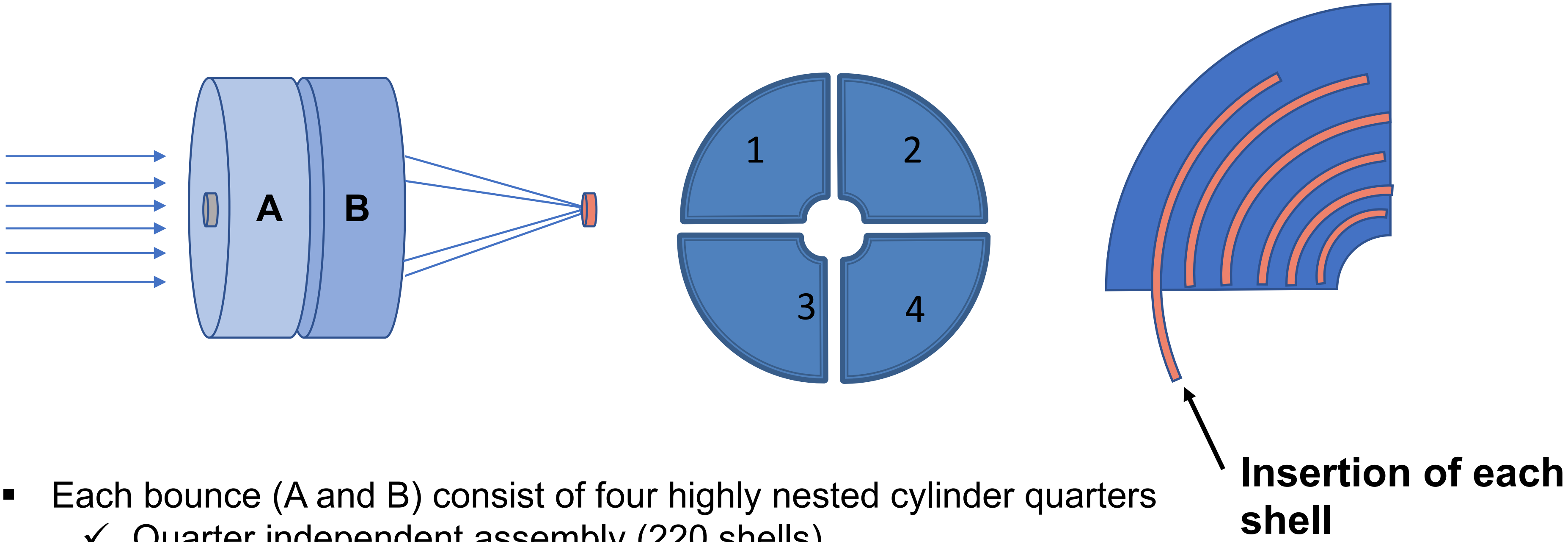
- Cold-slumped glass technology has been developed in recent years by IAXO collaborators
  - Glass plate assumes shape of mould
  - Glass shape is fixed with ribs
  - Mould can be taken as reference



- Can be used to extend optics to cover large diameters (in BabyIAXO case 70 cm)

Alternative approach: Aluminum foil optic

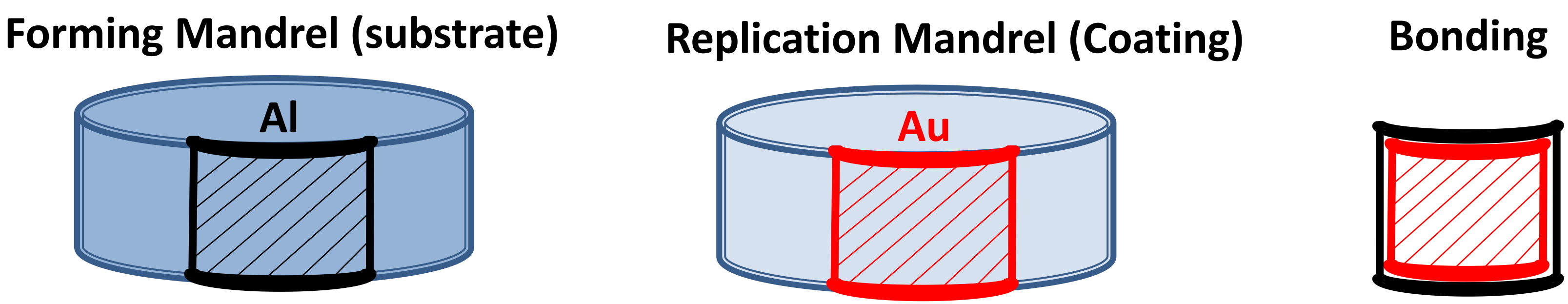
Principle of Astro-H optics: 2-bounce Wolter-1 type optics



- Each bounce (A and B) consist of four highly nested cylinder quarters
  - ✓ Quarter independent assembly (220 shells)
  - ✓ Optic aperture from 10 to 45 cm diameter
  - ✓ Shells are inserted from the side of each quarter using a precise guidance tooling
  - ✓ Each cylinder is independently co-aligned (4 sectors are forming a sharp image together)
- Both cylinders, A and B are combined and optically aligned for maximum throughput
- The complete optic is calibrated in a PANTER-like facility at NASA Goddard Space Flight Center

Alternative approach: Aluminum foil optic

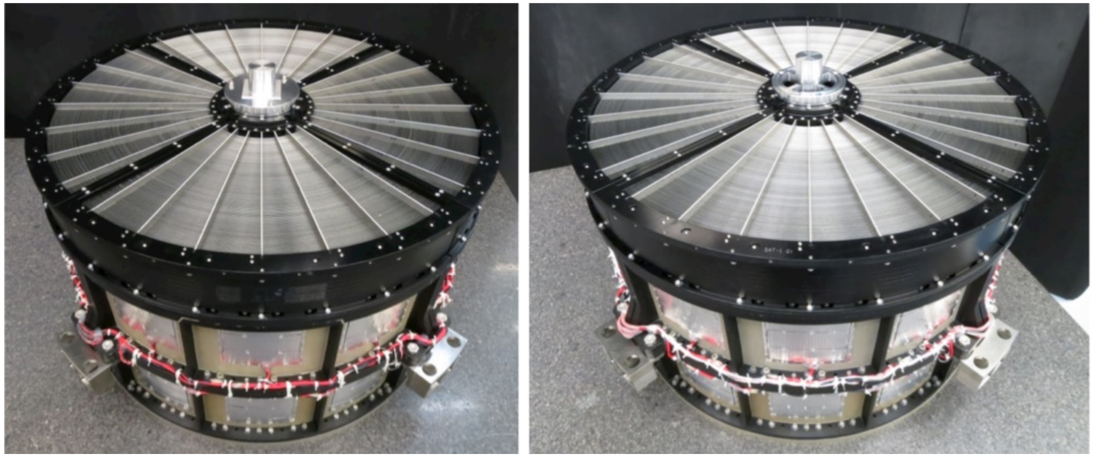
Fabrication of Astro-H optics



- Each shell is made at NASA Goddard from a 100 μm thick Aluminum sheet (Al sheet laser pre-cut as conic approximation to a Wolter-1 type optic)
- Stainless-steel mandrels then used to give the desired shape to the Al substrates
  - ✓ Aluminum sheets placed on mandrels and baked to preform the desired conic shells
- Gold is sputtered on high quality glass mandrels
  - ✓ The 0.2μm Au-coated glass is epoxied (~12 μm)
  - ✓ Carefully brought in contact with the Al shell
  - ✓ The epoxy is cured in oven to bond the gold substrate and the aluminum shell
  - ✓ The glass mandrel detaches from the gold and shell of the optic is ready to install
- This process allows for ~1arcmin Xray optics
- Higher radii optic shells can be made by using larger mandrels

Alternative approach: Aluminum foil optic

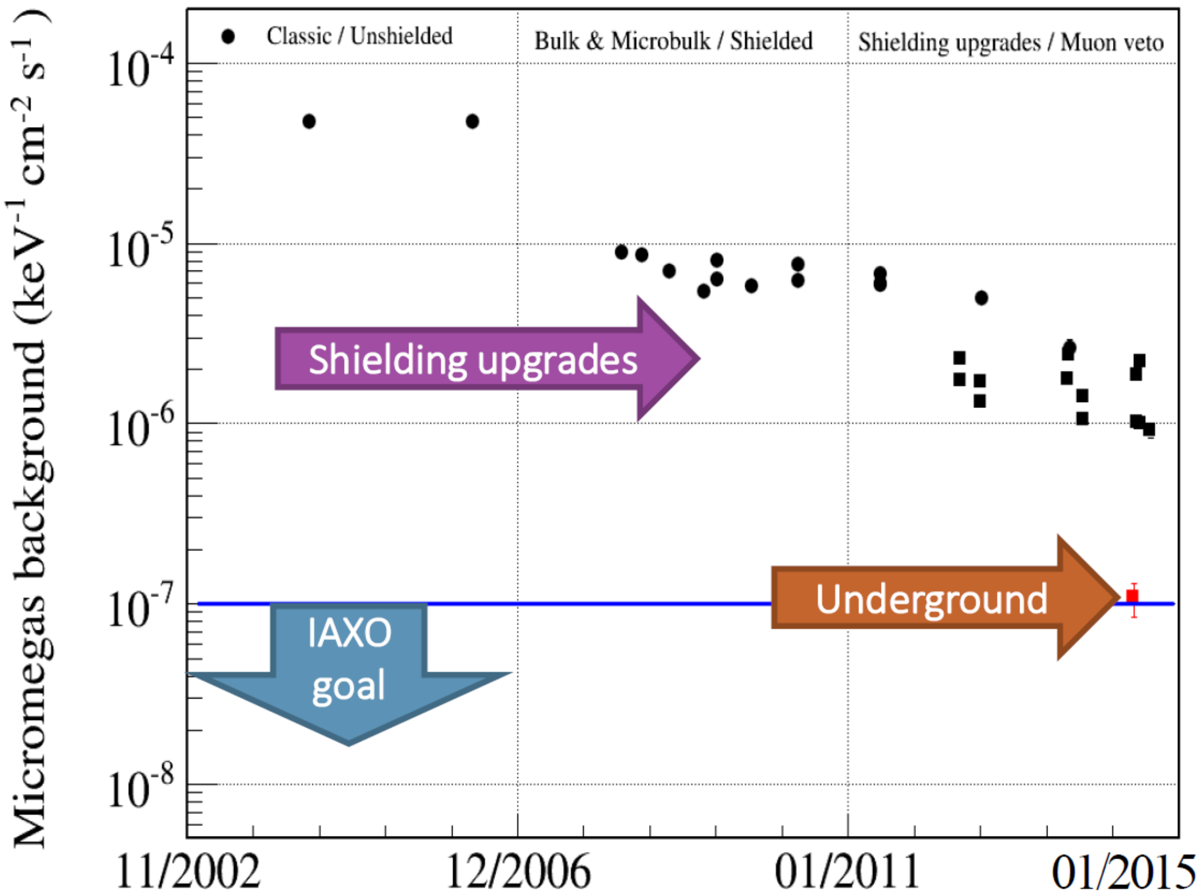
Specifications of Astro-H optics
→ Good match for (Baby)IAXO



Astro-H's Soft X-ray Telescopes (SXTs)
without thermal shield installed

Design parameter	ASTRO-H SXT
Number of telescopes	1/1 (SXT-I/SXT-S)
Focal length	5.6 m
Effective diameter	116 to 450 mm
Grazing angle range	0.15 to 0.57 deg
Number of nesting	203
Foil length	101.6 mm
Reflector layer thickness	
Reflecting surface	Au (0.2 μm)
Coupling layer	Epoxy (12 μm)
Reflector substrate	Al (152, 229, 305 μm)
Reflector thickness	
Inner	0.16 mm (No. 1–79)
Middle	0.24 mm (No. 80–153)
Outer	0.32 mm (No. 154–203)
Mass of a telescope	~43 kg

BabyIAXO detectors



Achieved result 2013-2015 CAST data taking in the IAXO pathfinder system:

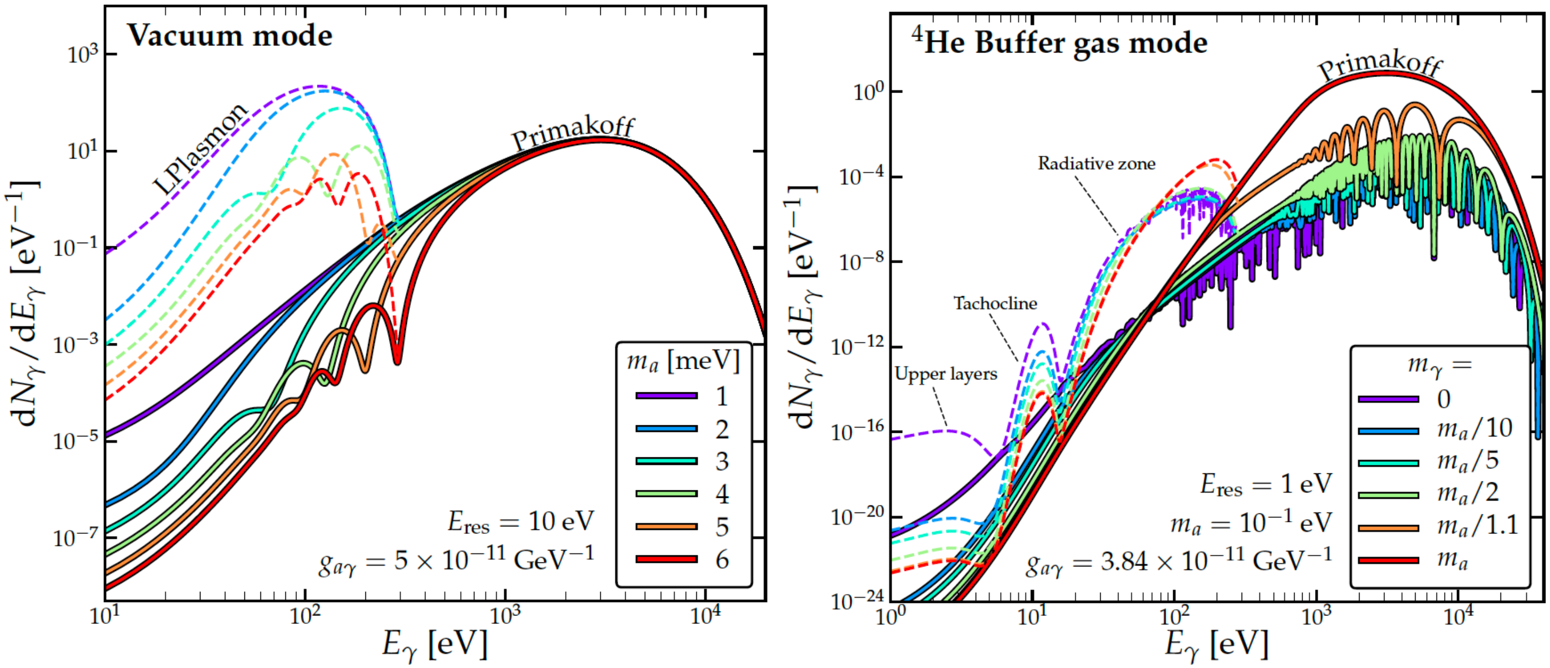
$<10^{-6}$ c/keV/cm^2/s (~0.2 c/h)

Old tests (2014) with a CAST replica detector at the LSC:

10^{-7} c/keV/cm^2/s

Current efforts focused to reduce cosmic-induced background

(B)IAXO beyond baseline



O’Hare et al. 2006.10415

(B)IAXO beyond baseline

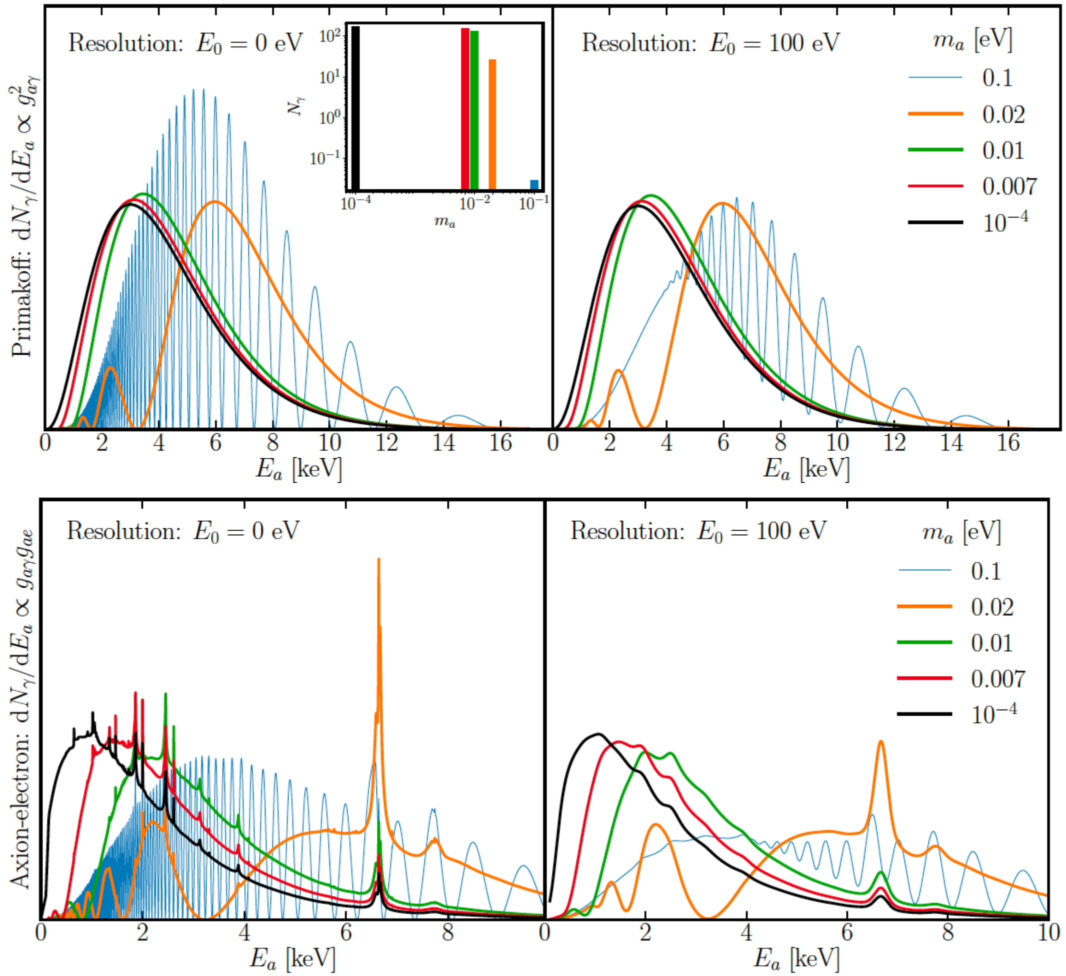
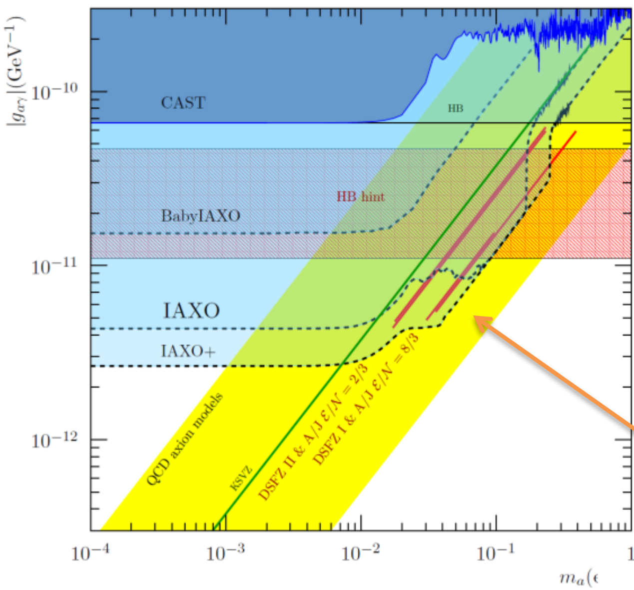


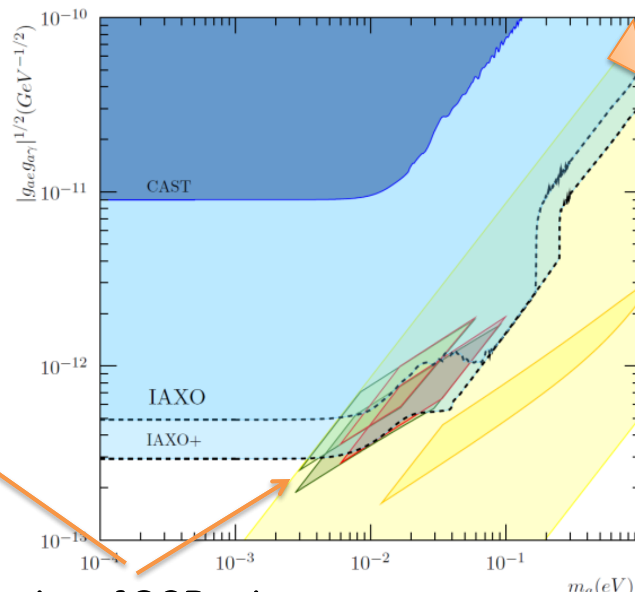
FIG. 3. Differential x-ray spectra as a function of energy due to solar axion conversion inside a 20 m long 2.5 T magnet. We display spectra for different values of the axion mass m_a as well as for both the solar Primakoff (**top**) and axion-electron (**bottom**) fluxes. The left-hand panels in both cases show the underlying spectra, whereas the right-hand panels show the spectra after being convolved with a Gaussian energy resolution of width $E_0 = 100$ eV. For comparison, we have normalised all spectra to one. Instead we display in the **inset**, the total integrated number of events N_γ as a function of the five masses, assuming $g_{a\gamma} = 10^{-11}$ GeV^{-1}.

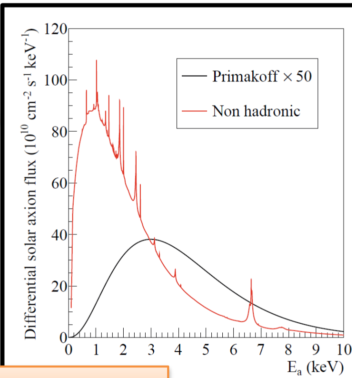
Dafni et al. 1811.09290

IAXO and BabyIAXO: Stellar cooling

- Multiple stellar anomalies (HB, RG, WD, NS,..). Overall 3σ effect.







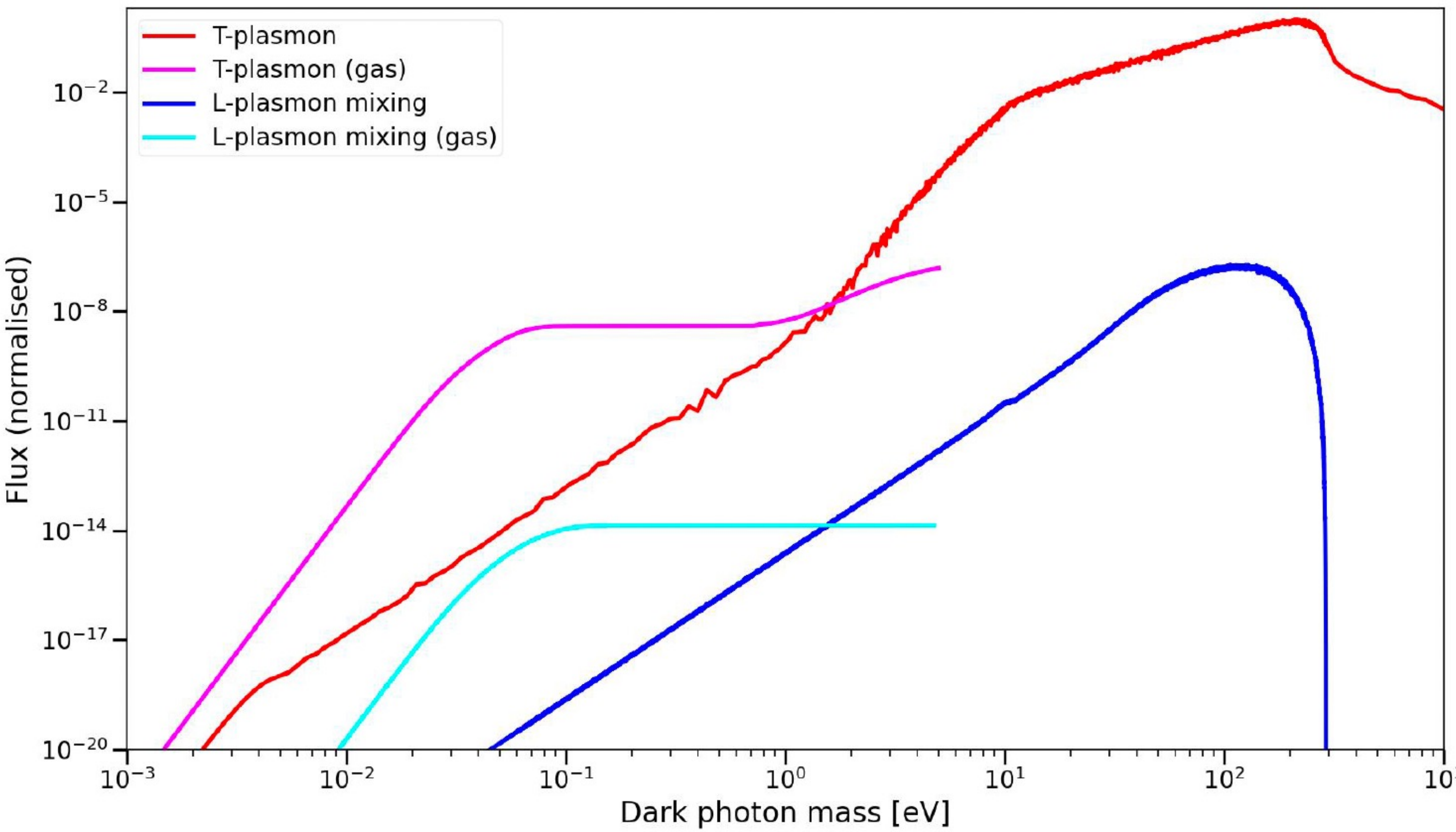
g_{ae} channel

Region of QCD axion models that solve the stellar anomaly

- IAXO will explore most of the relevant models (especially with IAXO+)
- Only experiment with such capability

M. Giannotti et al.
JCAP 1710 (2017) 010
arXiv:1708.02111

Solar Dark Photons



Post discover science