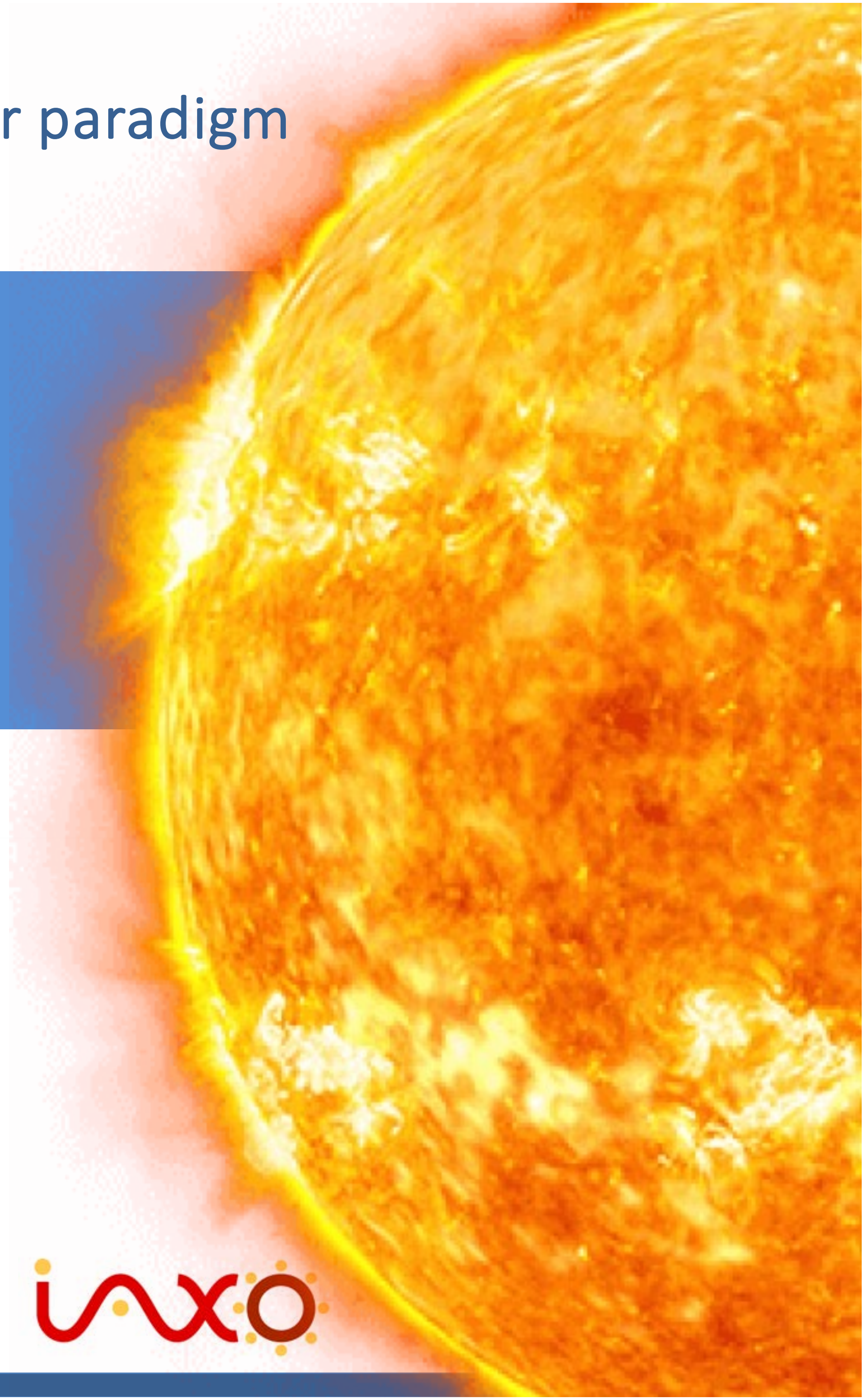
Axions beyond the dark matter paradigm

BabyIAXO



Jaime Ruz

January 29-31, 2024

Hamburg, Germany

DESY

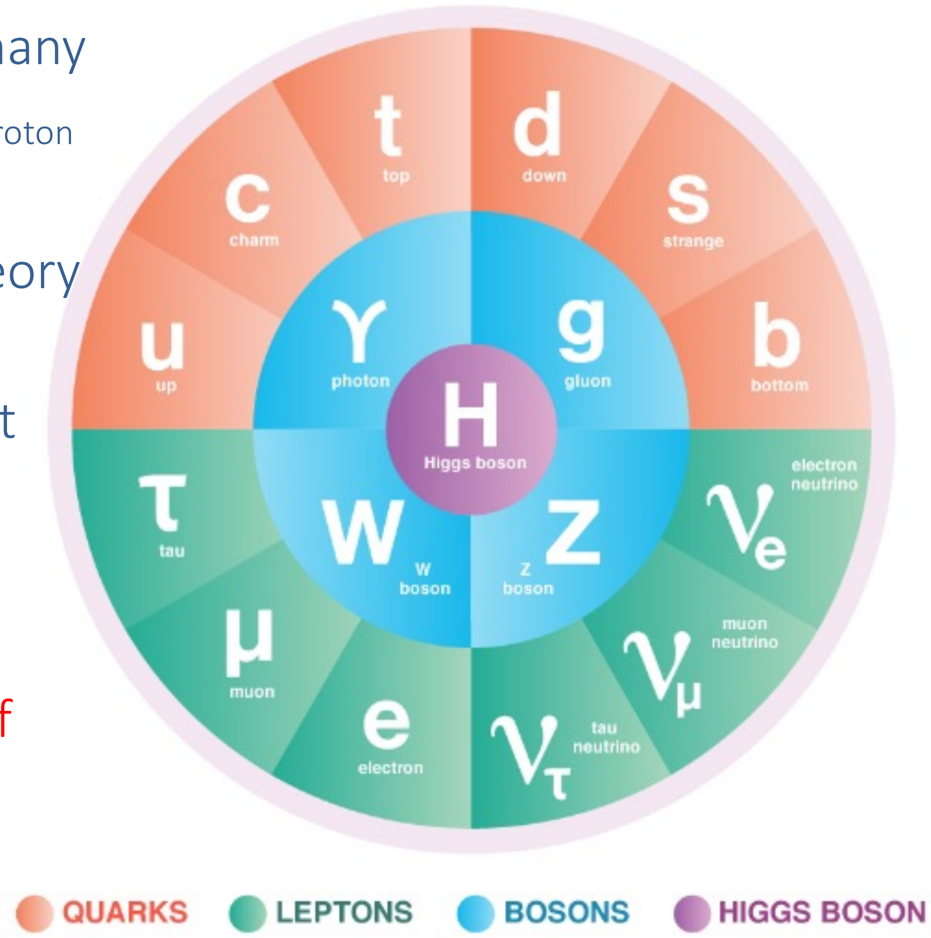
Outline

1. Standard Model, Strong CP and Dark Matter
2. The Axion
3. Detection of Axions. Solar Axion Searches
4. IAXO and BabyIAXO
5. Conclusions

Standard Model, strong CP

STANDARD MODEL (SM) OF PARTICLE PHYSICS

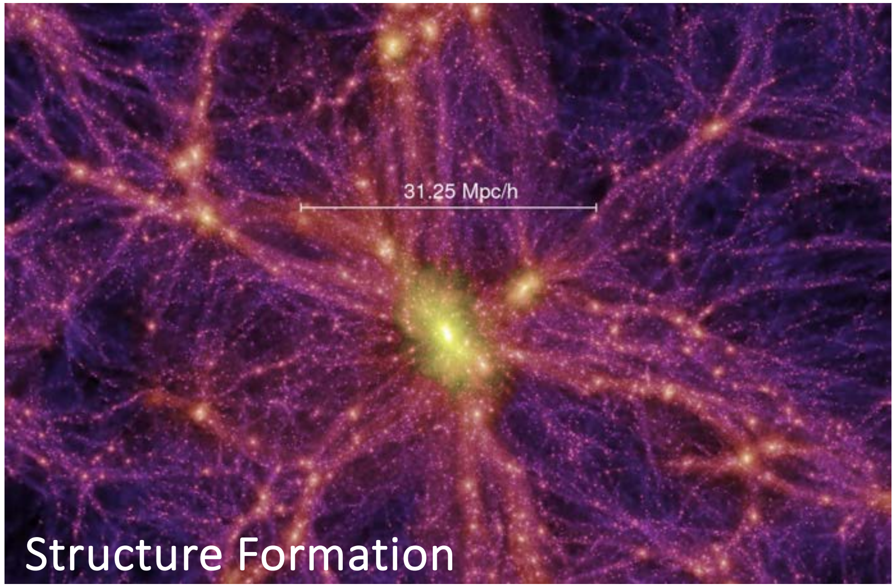
- ✓ Extremely successful theory describing many observations up to energies of ~1000 m_{proton}
- ✓ Merely an effective theory that could be considered the low energy limit of a Theory of Everything
- ✓ Expect observation of new phenomena at higher energies (e.g. LHC at CERN)
- ✓ SM cannot explain:
  - What is the nature of dark matter?
  - Why is the electric dipole moment of the neutron so small?



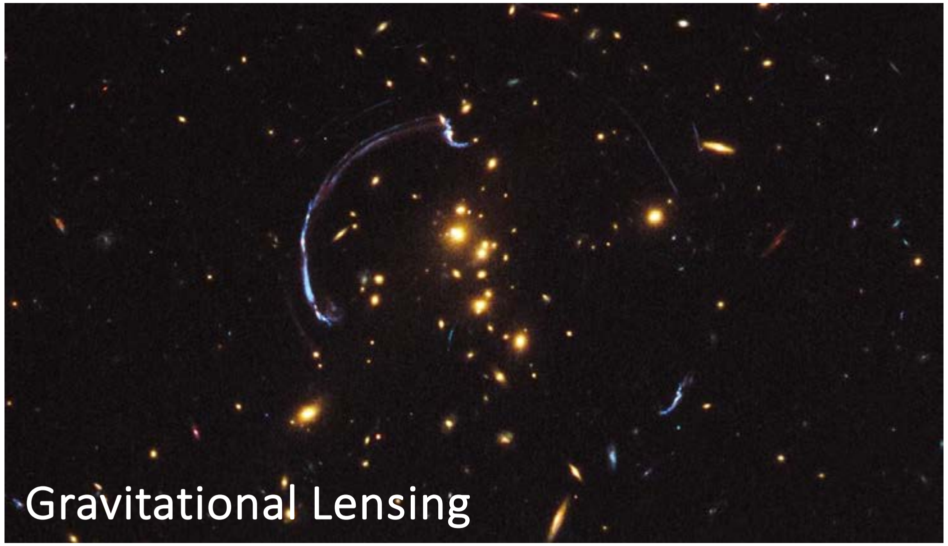
Dark Matter

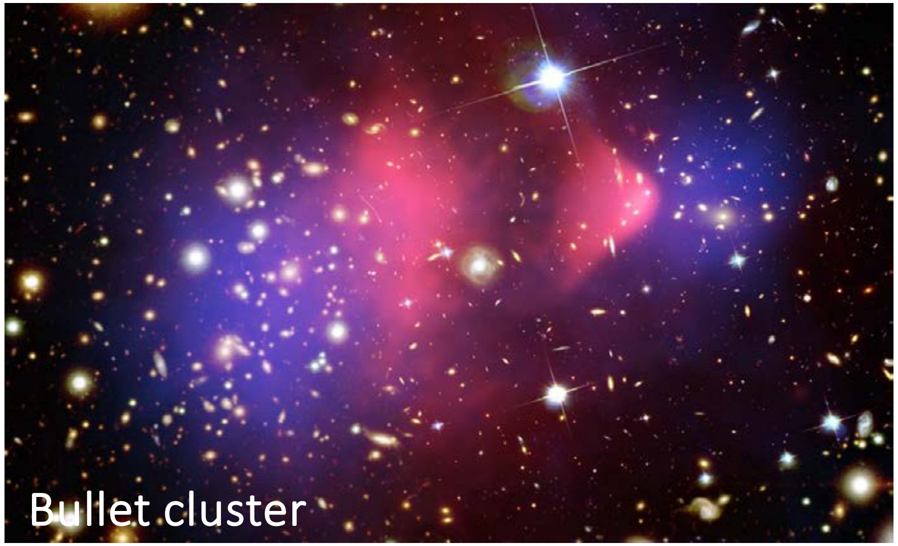
EVIDENCE FOR DARK MATTER

- ✓ Galaxy rotation curves
- ✓ Cosmic Microwave Background (CMB)
- ✓ Structure formation
- ✓ Gravitational lensing
- ✓ Bullet Cluster



Structure Formation


Gravitational Lensing


Bullet cluster

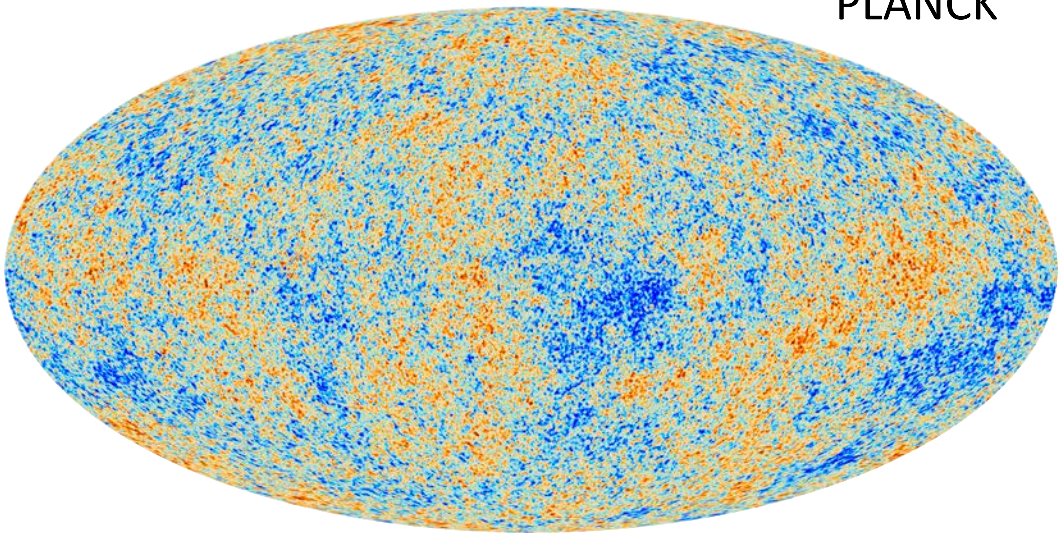
DARK MATTER PROBLEM: WE KNOW IT EXISTS BUT WHAT IS ITS NATURE?

Dark Matter

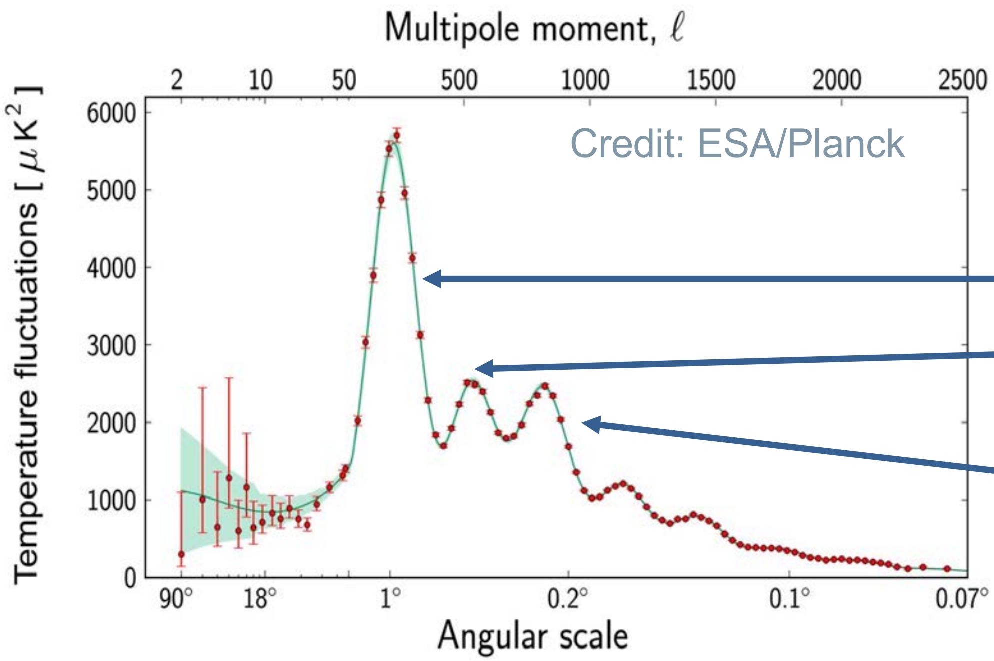
EVIDENCE FOR DARK MATTER

- ✓ Galaxy rotation curves
- ✓ Cosmic Microwave Background (CMB)

PLANCK



PLANCK power spectrum of the CMB radiation temperature anisotropy



Location and height of peaks determines cosmological parameters

Flat universe

Baryonic matter ~5% of the total mass/energy of the universe

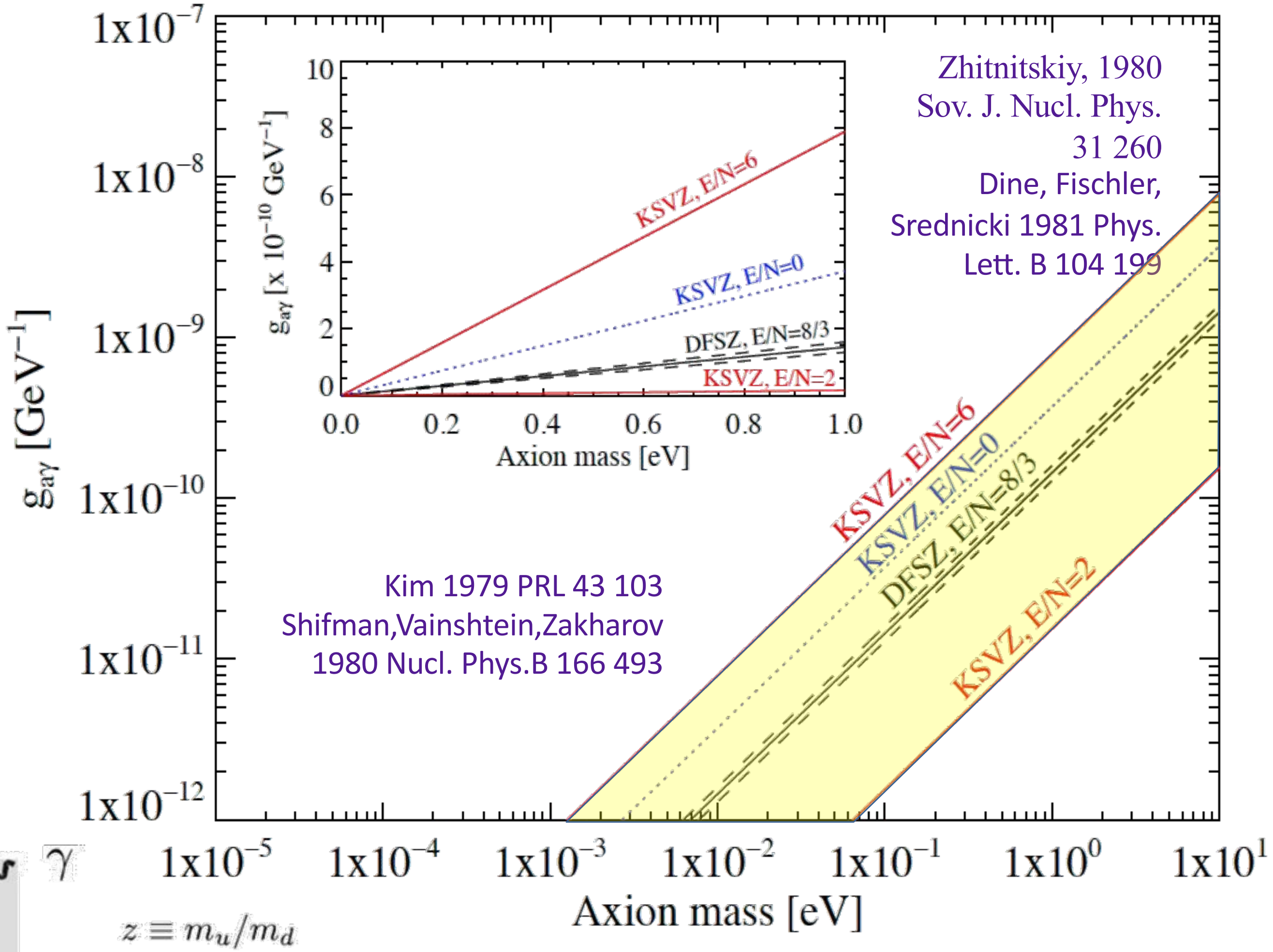
Amount of **dark matter** ~27%

The Axion

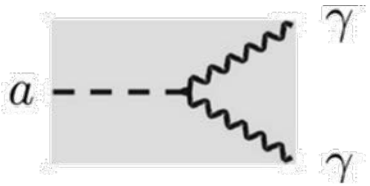

Standard Model
AXION
HYPOTHETICAL ELEMENTARY PARTICLE
PROMISES TO
"CLEAN UP"
YOUR STRONG
CP PROBLEM!

The Axion

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



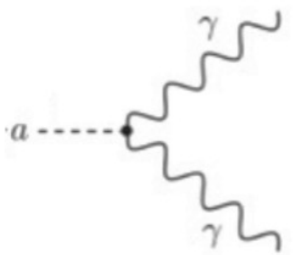
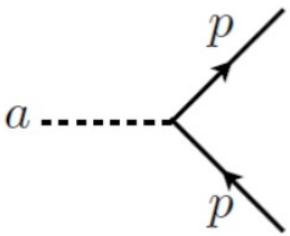
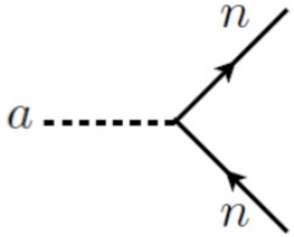
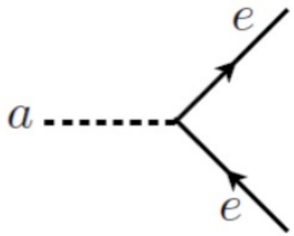
$$g_{a\gamma} \simeq \frac{\alpha}{2\pi f_\pi}\frac{m_a}{m_\pi}\frac{1+z}{\sqrt{z}}\left(\frac{E_Q}{N_Q} - \frac{2}{3}\frac{4+z}{1+z}\right)$$



$z \equiv m_u/m_d$

AXION COUPLINGS

- ✓ Axions interact with photons (generic) and with regular matter (model dependent)

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

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

- ✓ Due to its properties axions are favored dark matter candidates (next to WIMPs)

Detection of Axions

Source		Experiments	Model & cosmology dependency
Relic axions		Haloscopes	High (assumes axions are all of the DM)
Lab axions		Light-Shining-Through-Wall Experiments	Very low
Solar axions		Helioscopes	Low

Large complementarity between different experimental approaches!

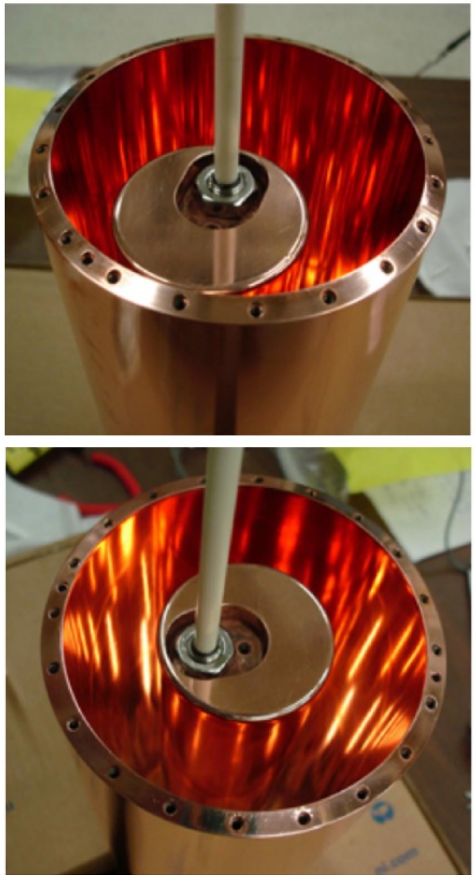
Detection of Axions

Haloscopes

EXPERIMENTS <u>RELYING</u> ON AXIONS BEING DARK MATTER

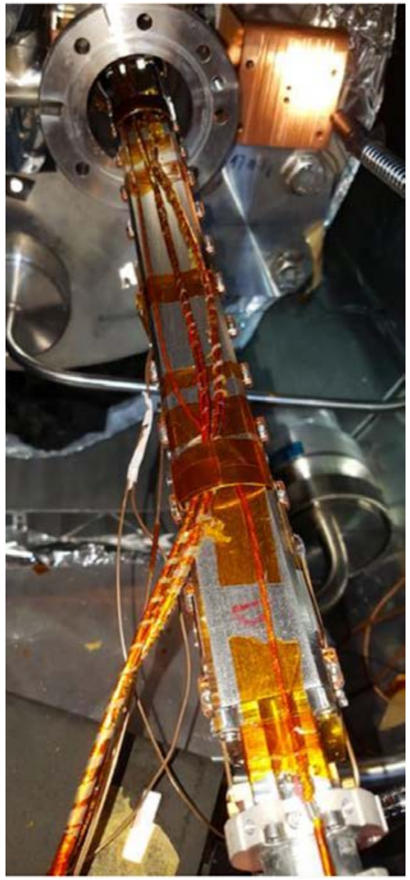
ADMX

HAYSTAC



RADES

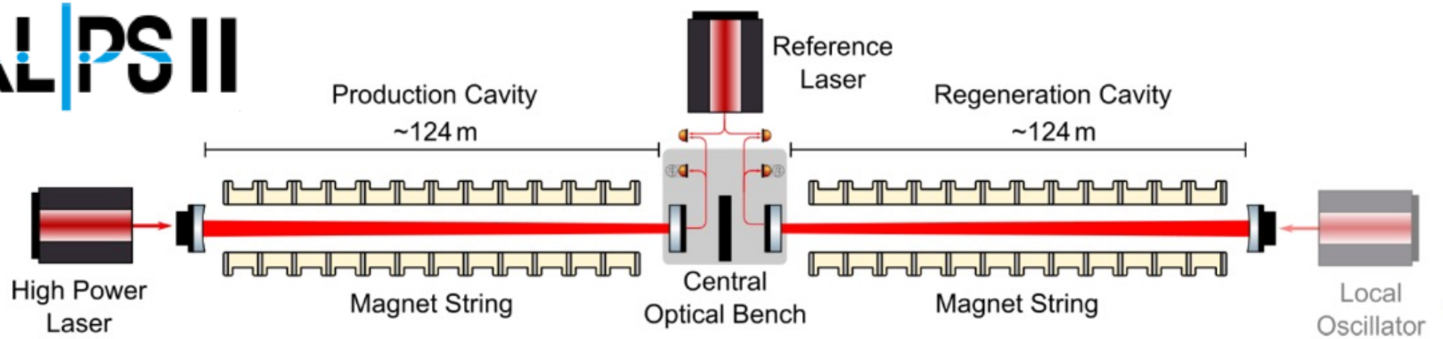
CAST-CAPP



M. Maroudas et al 2022 Nature Com. 13 1 1-9
Alvarez et al 2021 JHEP 2021 75

EXPERIMENTS NOT RELYING ON AXIONS BEING DARK MATTER

- LIGHT-SHINING-THROUGH-WALL EXPERIMENTS: pure laboratory searches
  - ✓ ALPS
    Most basic layout of a LSTW experiment
  - ✓ ALPS-II
    - 12 + 12 straightened HERA magnets
    - Optical cavities both at production and regeneration sites
    - Sensitivity 3000×ALPS



Ringwald 2003 Phys. Lett. B 569 51

Detection of Axions
Helioscopes

EXPERIMENTS NOT RELYING ON AXIONS BEING DARK MATTER

➢ AXION HELIOSCOPES: laboratory axion searches looking for solar axions

CERN AXION SOLAR TELESCOPE (CAST)

- Most powerful axion helioscope to date
- Superconducting prototype LHC dipole magnet
- X-ray focusing devices and ultralow-background detectors
- Use of buffer gas to extend sensitivity to higher masses (axion band)

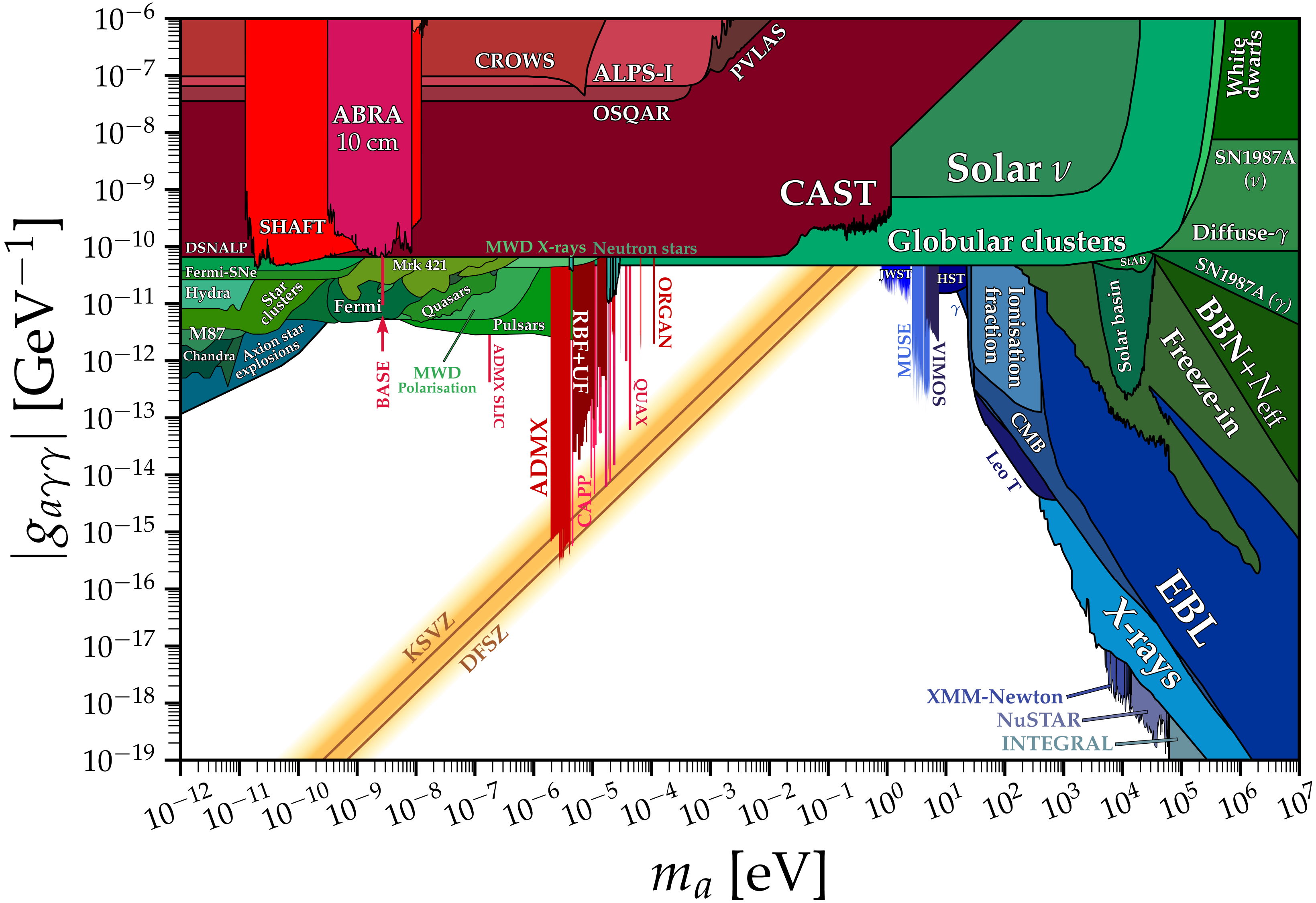
CAST Collaboration 2017 Nature Phys. 13 584-590
Arik et al 2015 PRD 92 021101
Arik et al 2014 PRL 112 091302
Barth et al 2013 JCAP 1305 010
Arik et al2011 PRL107 261302
Zioutas et al 2009 JCAP 0902 008
Zioutas et al 2007 JCAP 0704 010

STATE-OFF-THE-ART … SO FAR …

Detection of Axions

State-of-the-art

Adapted from https://github.com/cajohare/AxionLimits

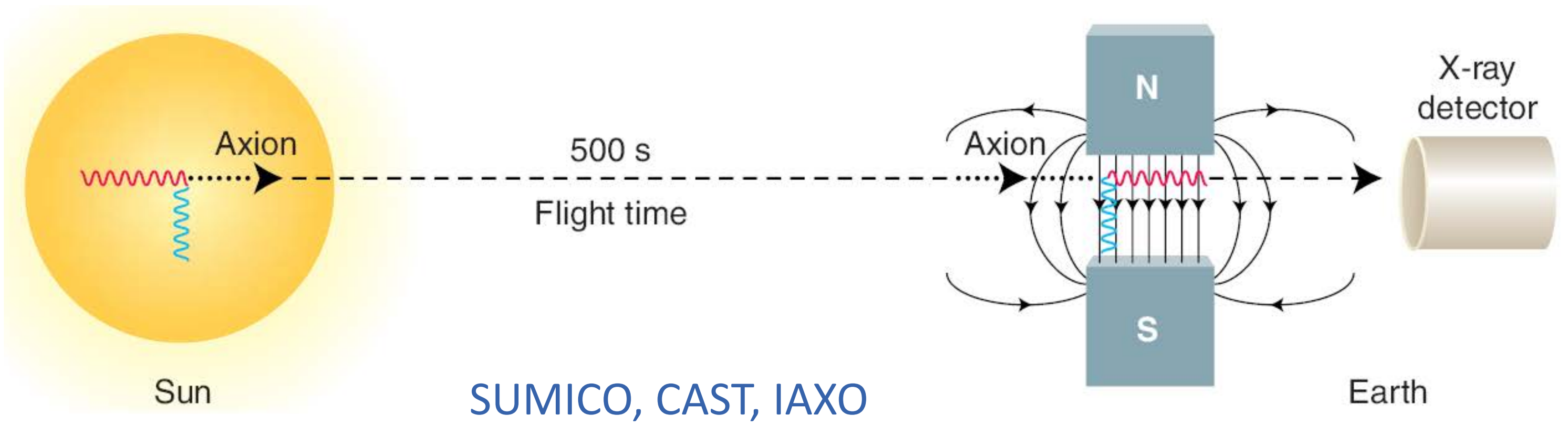


Solar Axion Searches

EXPERIMENTS NOT RELYING ON AXIONS BEING DARK MATTER

- AXION HELIOSCOPES: laboratory axion searches looking for solar axions

P. Sikivie 1983 PRL 51 1415



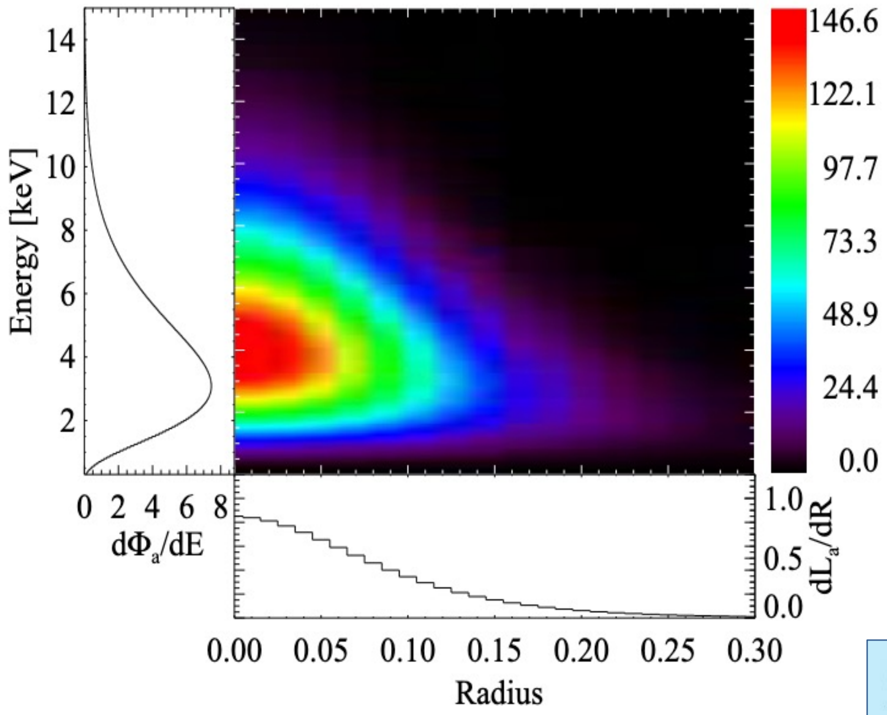
SUMICO, CAST, IAXO

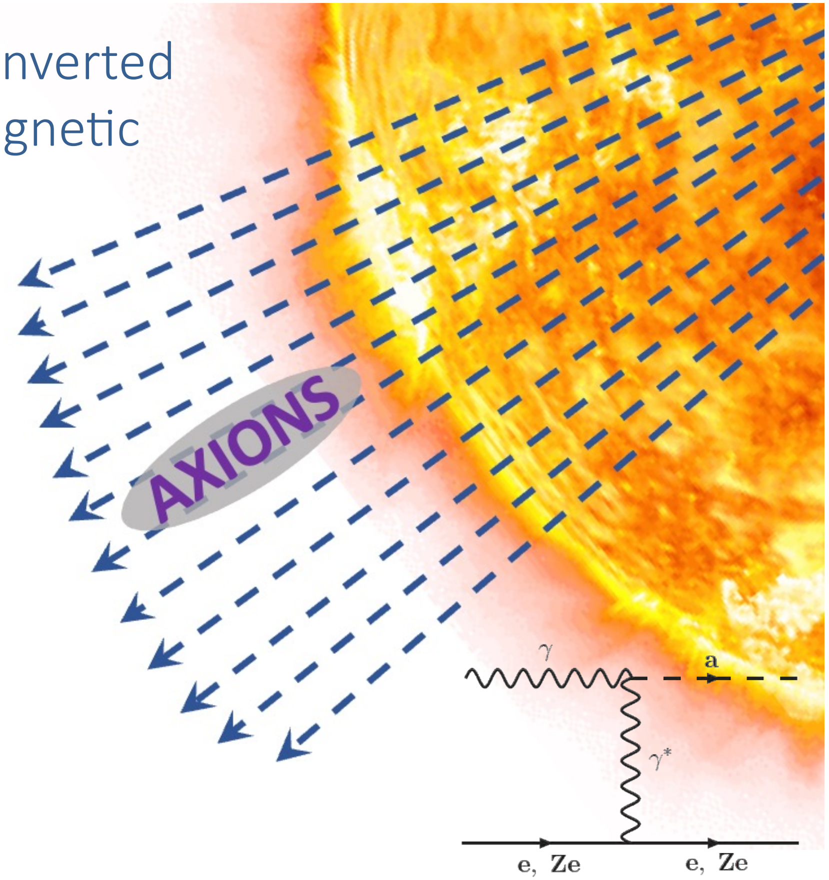
Concept:

- Axions produced in strong electromagnetic fields of the core of the Sun
- Solar axion conversion into x-ray (keV) photons in transverse laboratory B-field

Solar Axion Searches

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





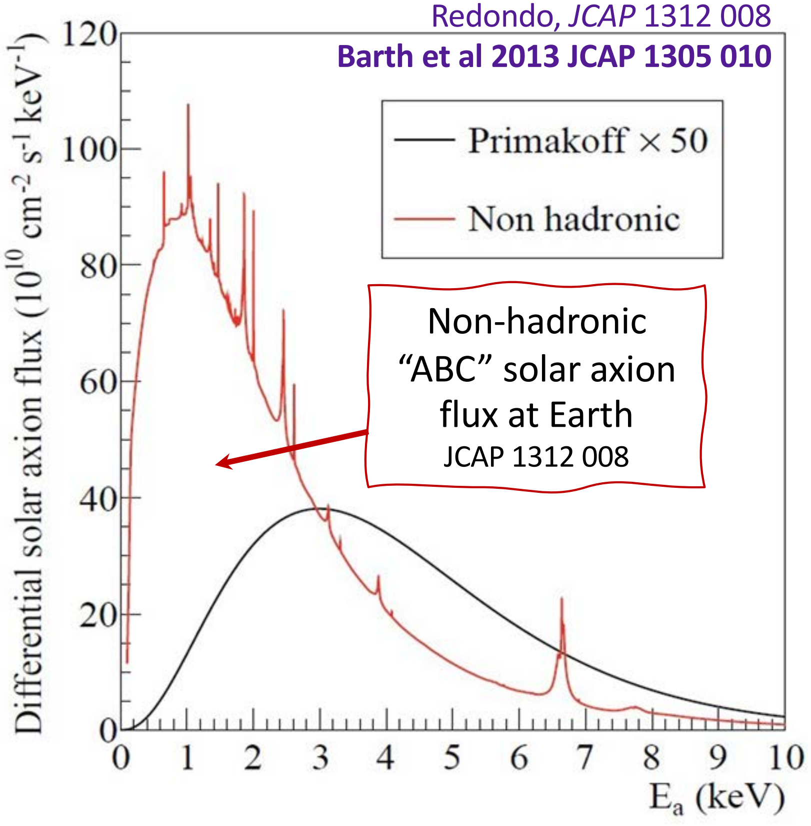
$$\frac{d\Phi_a}{dE} = 6.02 \times 10^{10} \left(\frac{g_{a\gamma}}{10^{-10}\mathrm{GeV}^{-1}}\right)^2 E^{2.481} e^{-E/1.205} \frac{1}{\mathrm{cm}^2\ \mathrm{s\ keV}}$$

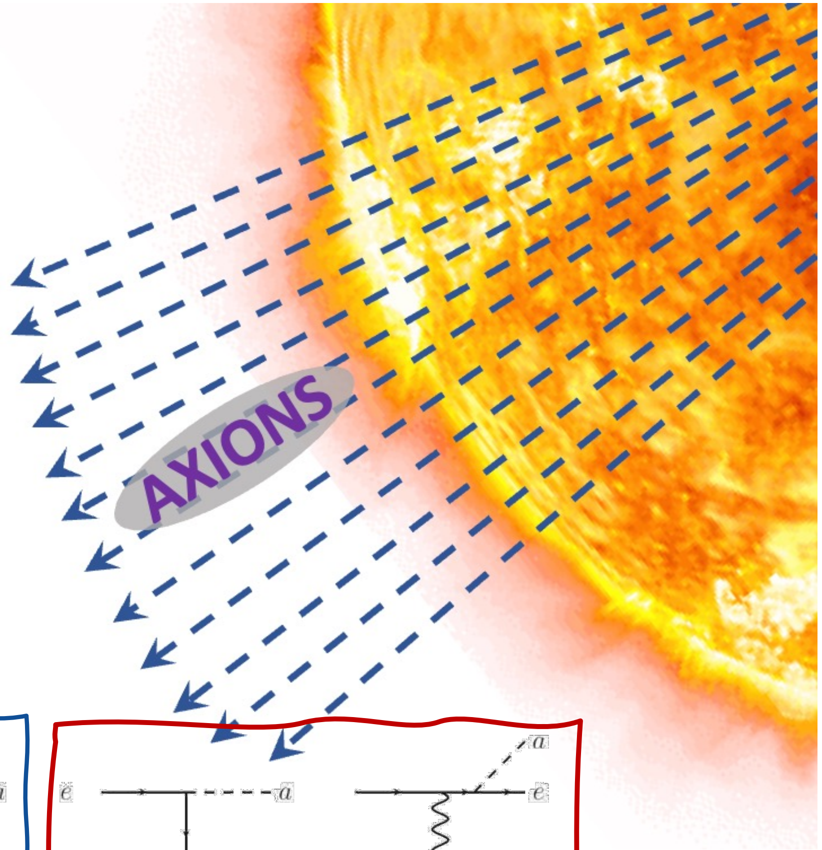
Hadronic axions (if the axion couples predominantly to photons (g_{ag}))

Baby IAXO

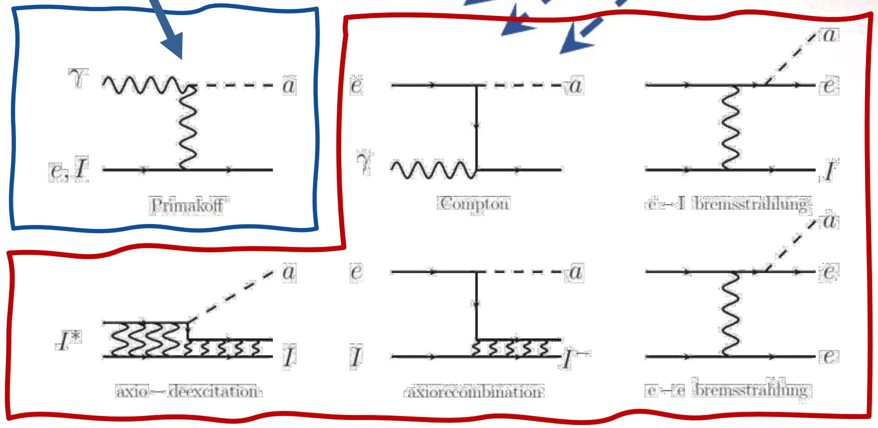
Solar Axion Searches

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





Primakoff axions

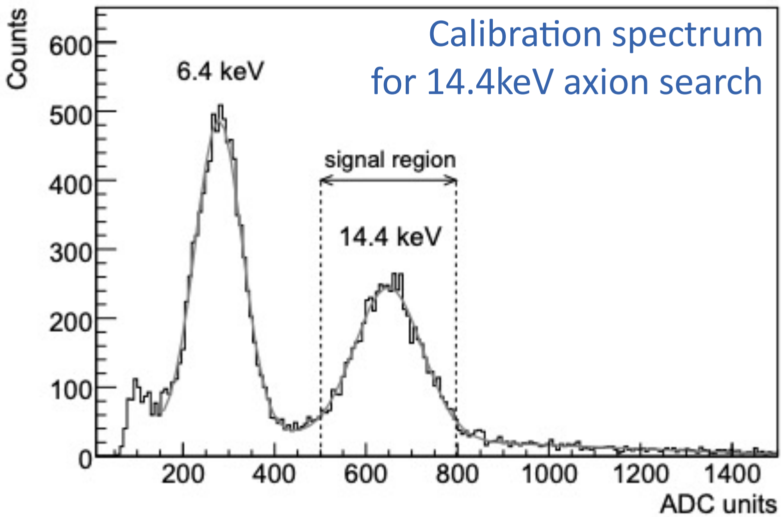


Non-hadronic or "ABC" axions (if the axion couples to electrons (g_{ae}))

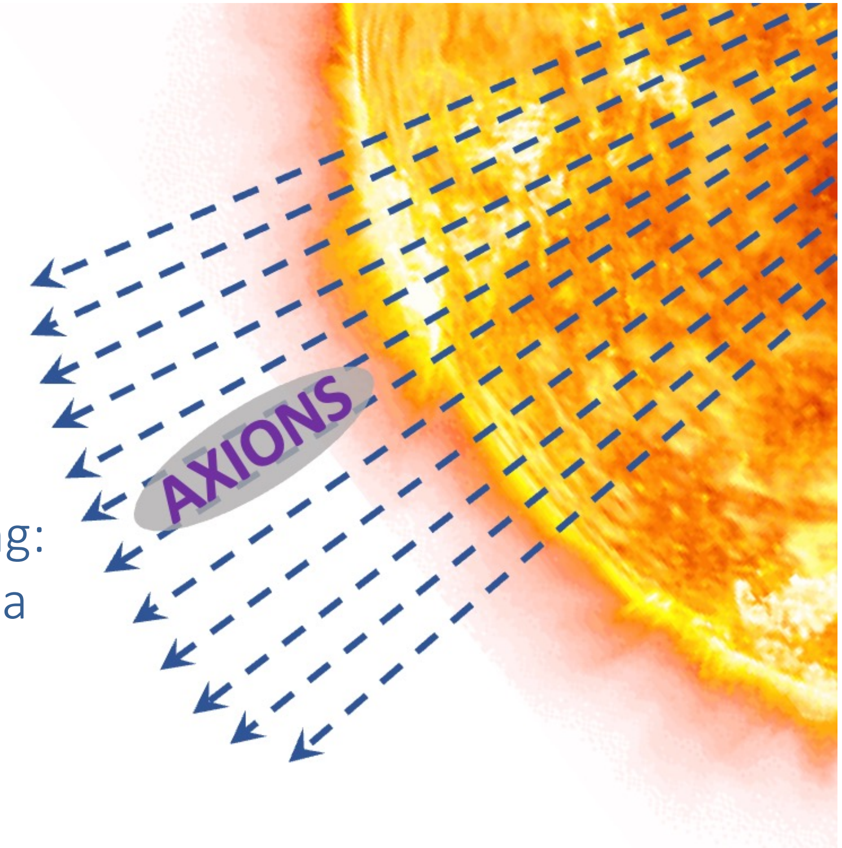
Baby IAXO

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;g)^{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



Calibration spectrum
for 14.4keV axion search



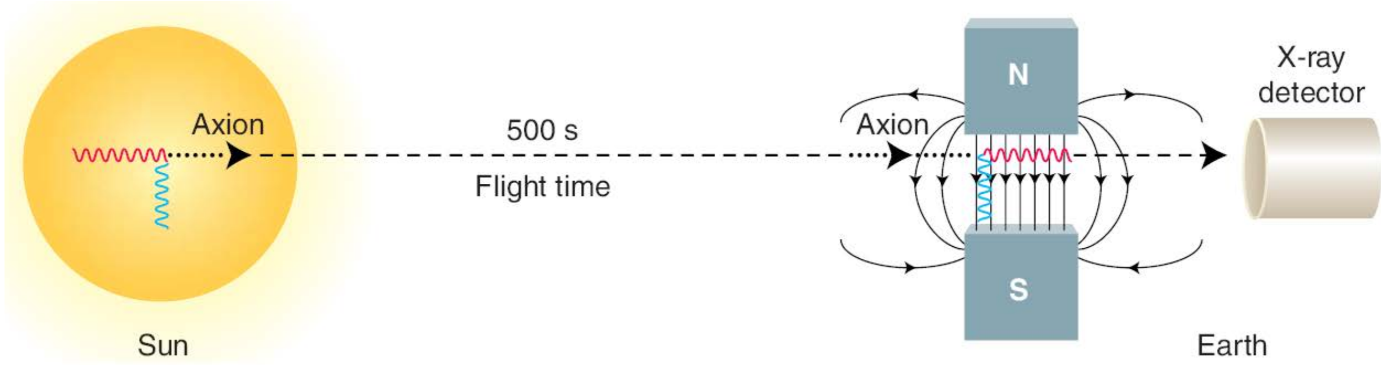
$$\Phi_a = 5.06 \times 10^{23} \, (g_{aN}^{\rm eff})^2 \, {\rm cm}^{-2}{\rm s}^{-1}$$

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

- 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

- 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

Baby IAXO

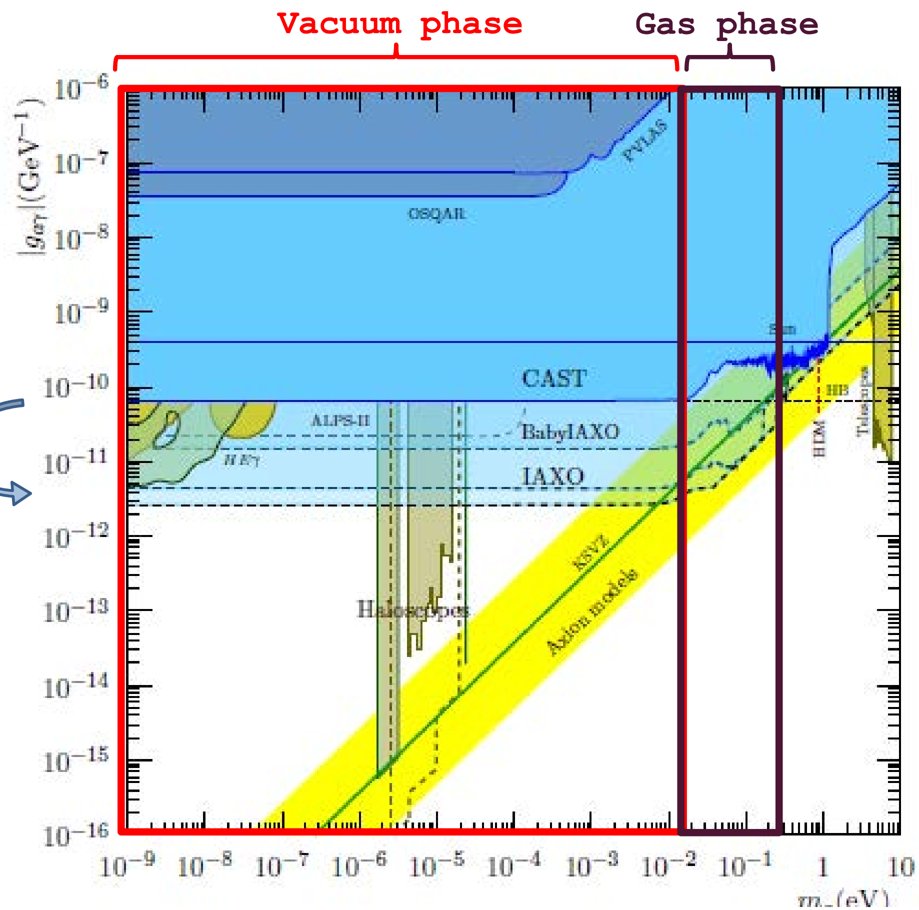
Solar Axion Searches

Detection Helioscope

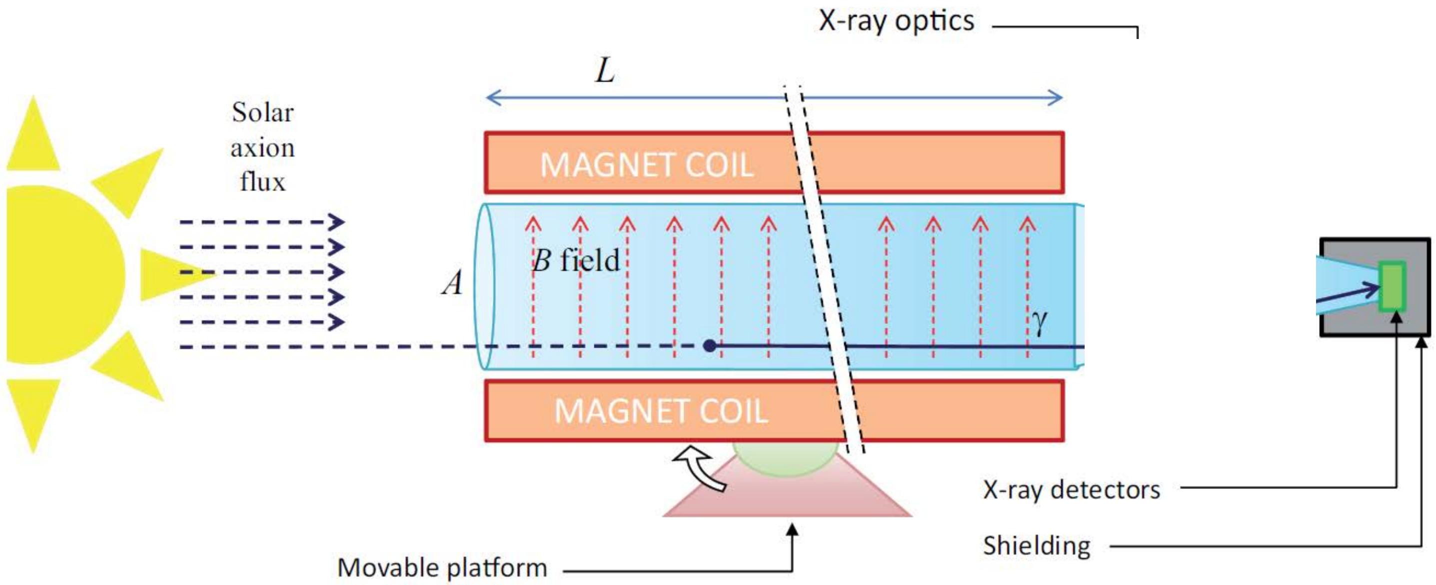
- Vacuum Phase:
  - Coherence condition valid for $m_a \lesssim 0.02$ eV
- Gas Phase:
  - Extends coherence condition valid from $0.02 \text{ eV} \lesssim m_a \lesssim 0.26$ eV

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

- Experimental conditions for BabyIAXO:
  - P_{max}(helium-4) $\simeq$ 1bar
  - T(average) $\simeq$ 295K



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



Measure of sensitivity to axion-photon interaction:

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

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

exposure
- t = time

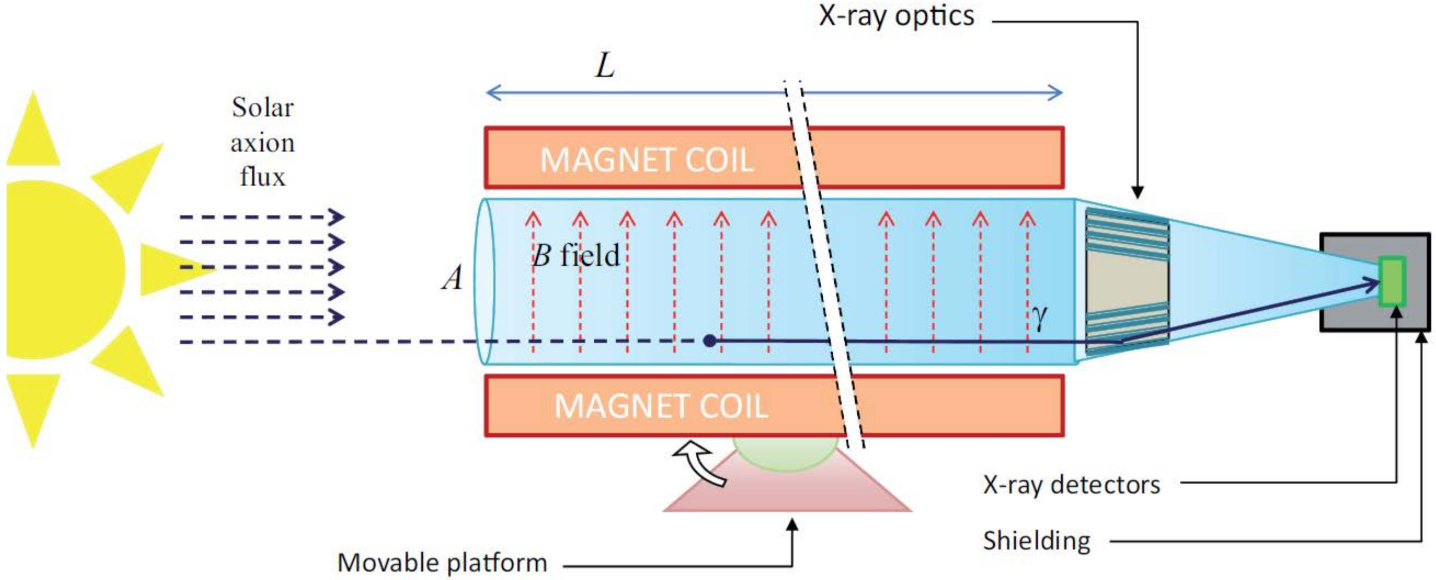
detectors
- b = background
- ε = efficiency

The smaller g_{ag} the better!

Baby IAXO

Helioscope Figure of Merit

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



Measure of sensitivity to axion-photon interaction:

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

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_{ag} 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

Next-gen experiments

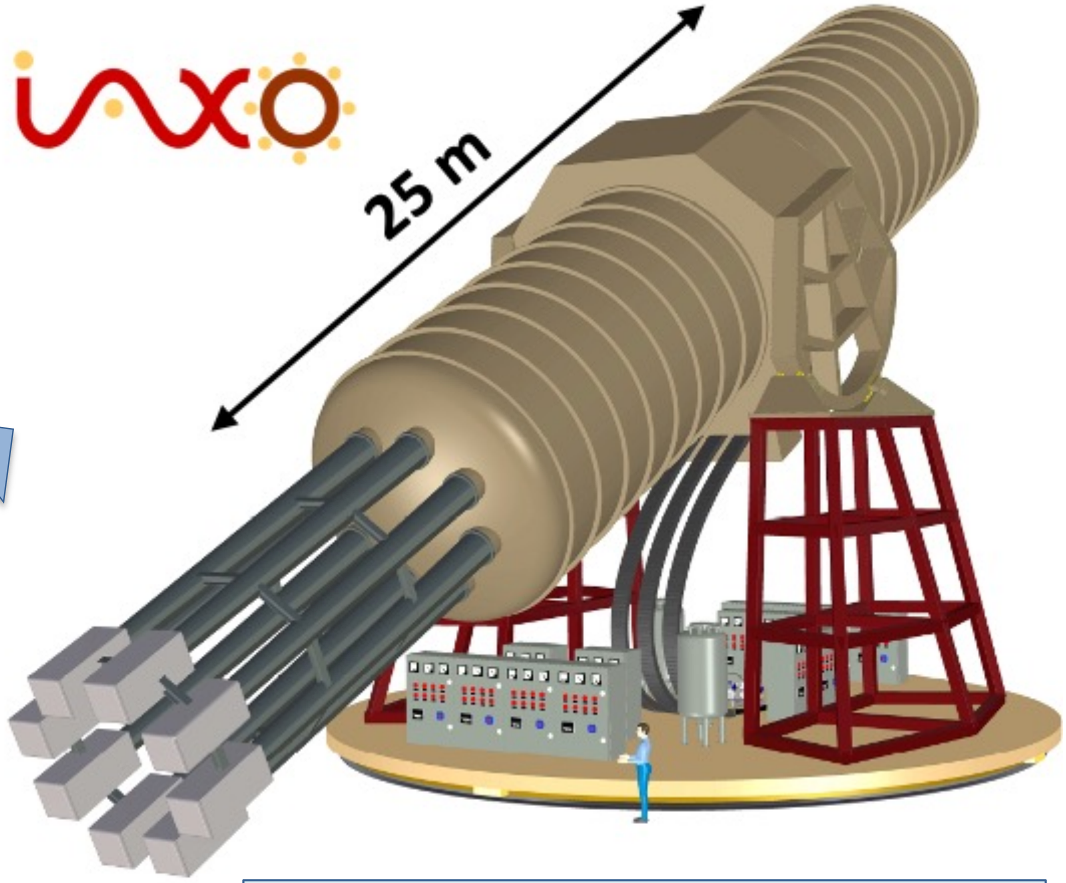
CAST

$g_{a\gamma} \lesssim 0.66 \times 10^{-10}$ GeV^{-1}

Baby IAXO

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

IAXO



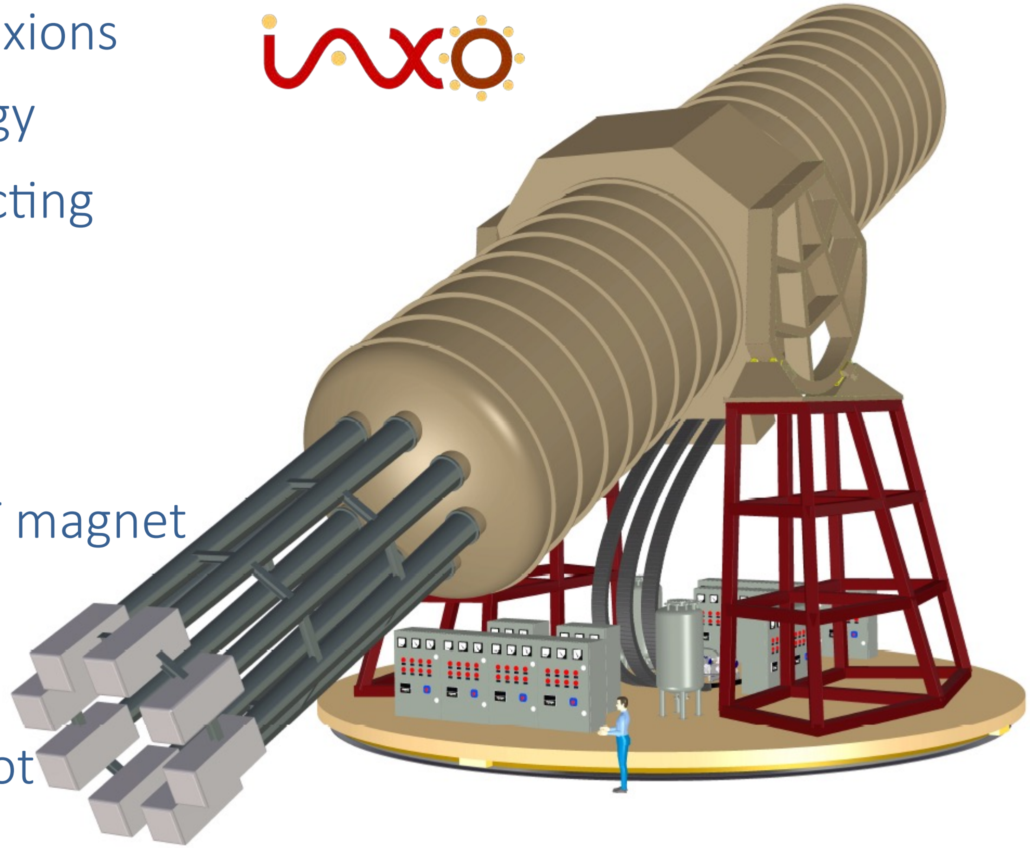
$g_{a\gamma} \lesssim$ few 10^{-12} GeV^{-1} (expected)

Baby IAXO

Solar Axion Searches

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
  - 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 bgrd detectors
- ✓ 50% of Sun-tracking time.



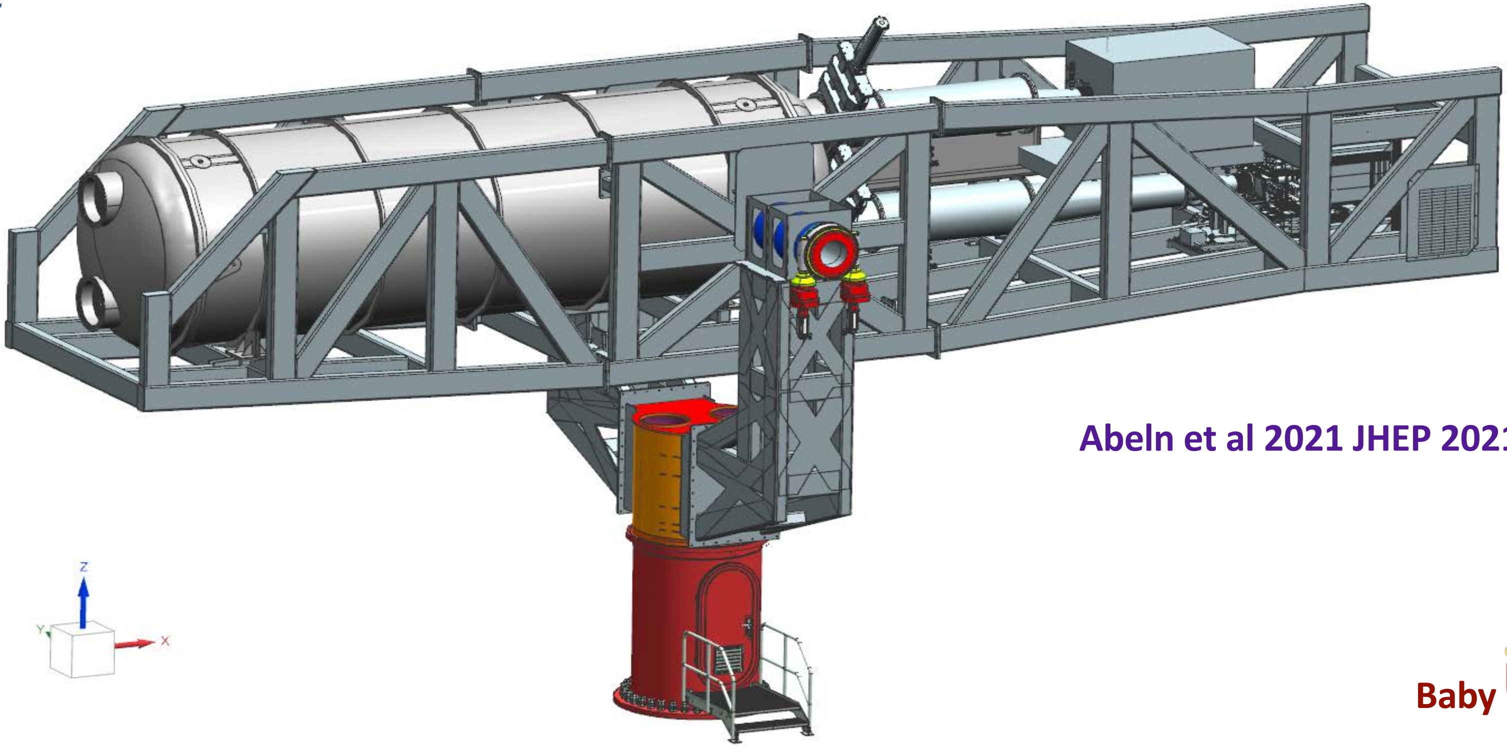
Armengaud et al 2014 JINST 9 T05002
Irastorza et al 2011 JCAP 1106, 013

Baby IAXO

Solar Axion Searches

BABYIAXO =INTERMEDIATE EXPERIMENTAL STAGE BBEFORE 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, perfor



Abeln et al 2021 JHEP 2021 137

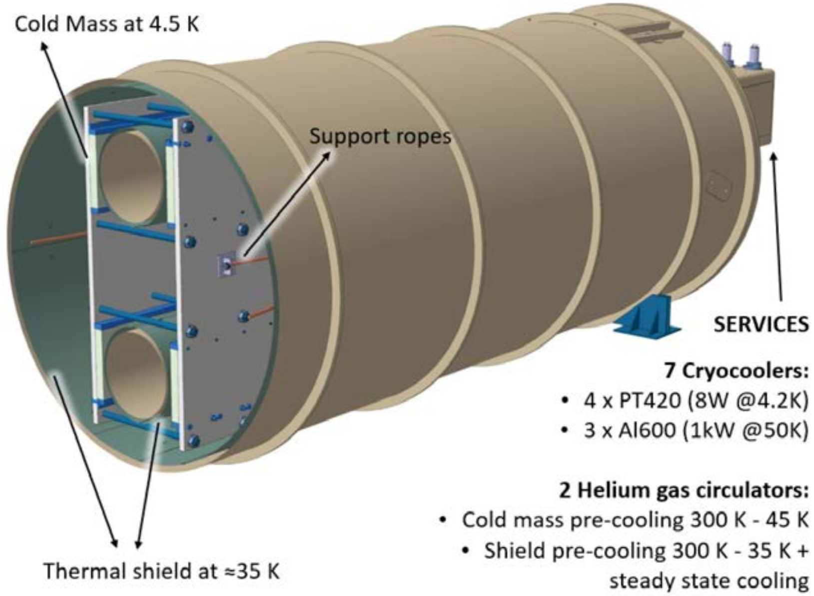
Solar Axion Searches

Solar Axion Searches

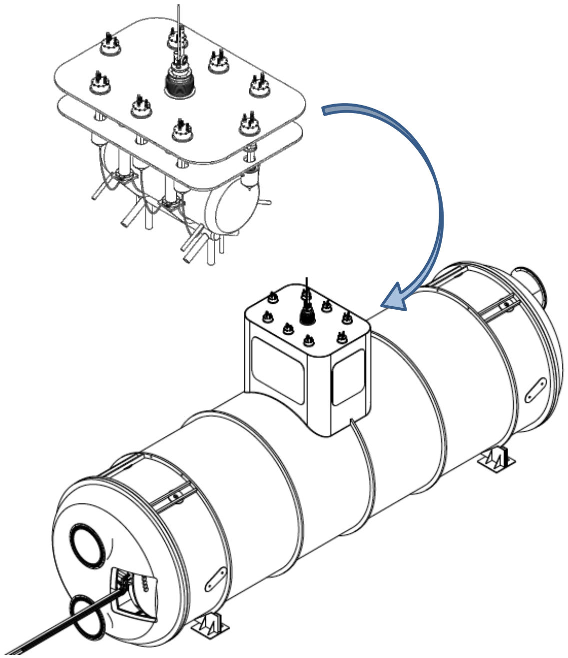
BabyIAXO

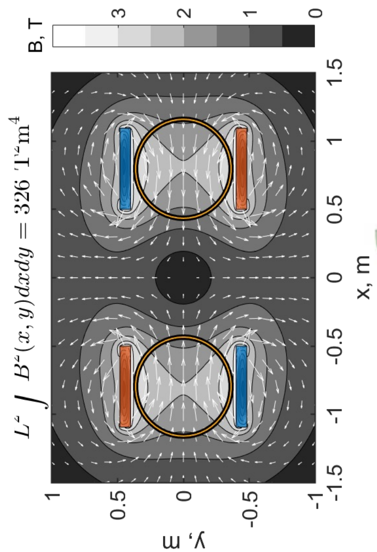
Solar Axion Searches

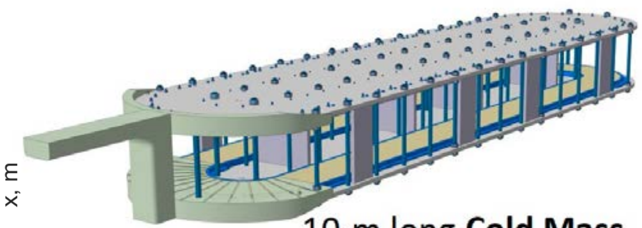
- ✓ BabyIAXO magnet to be operated at T ≤ 5 K featuring Nb-Ti-based superconducting coils with about 2 T in the bore
  - Nb-Ti is most affordable superconductor
  - It is also mechanically ductile and robust
  - Well studied work-horse conductor for most existing superconducting magnets



Contract for cable development recently signed





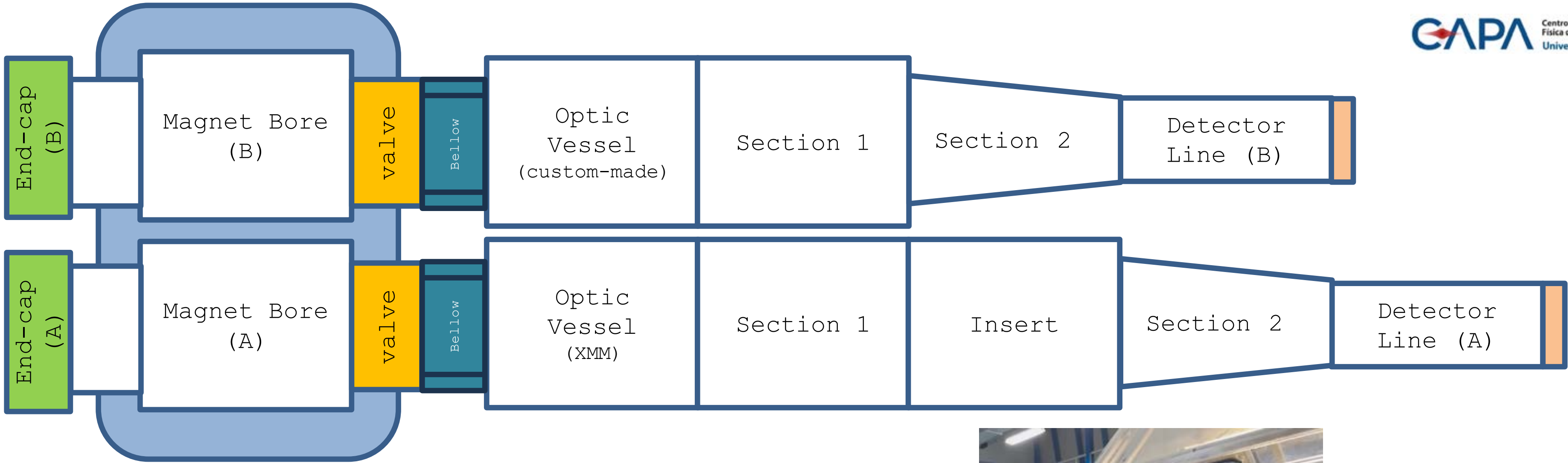


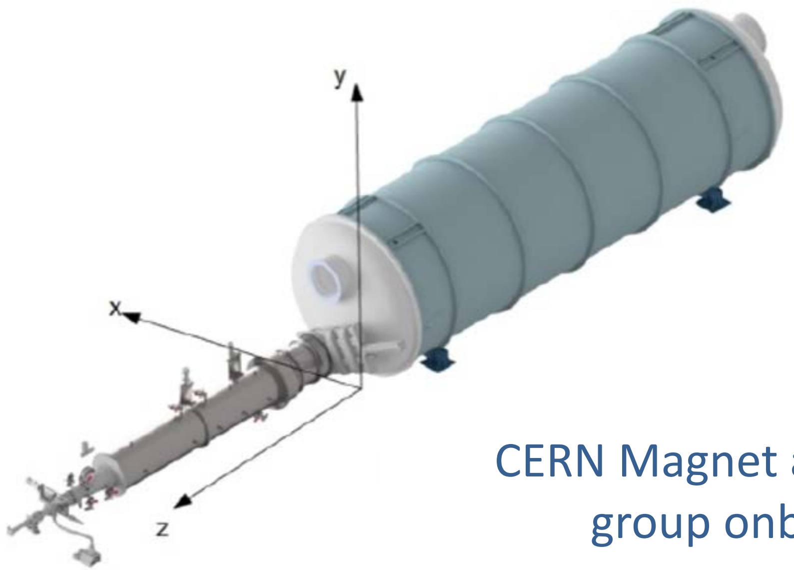
10-m long **Cold Mass**

Baby IAXO

Solar Axion Searches

BabyIAXO beam line





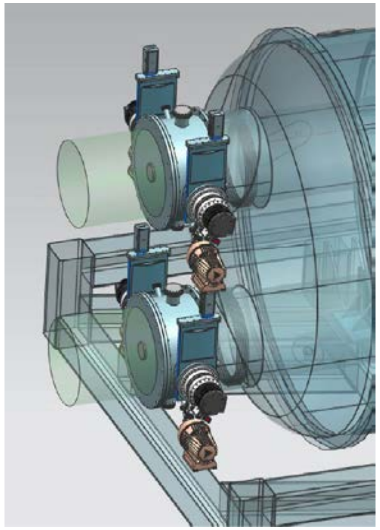
CERN Magnet and Cable group onboard

Ordering 2km of cable strand for winding tests

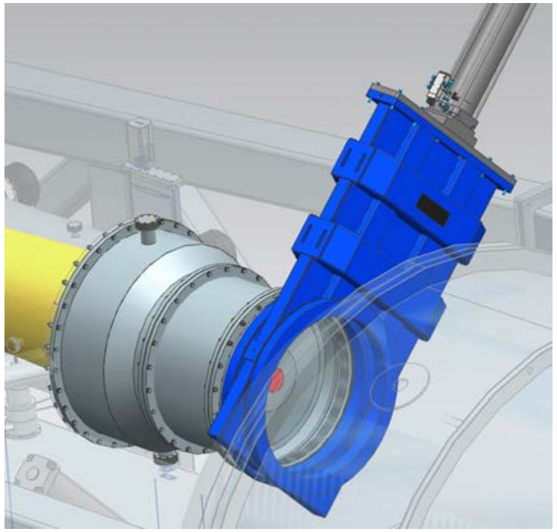
Baby IAXO

Solar Axion Searches

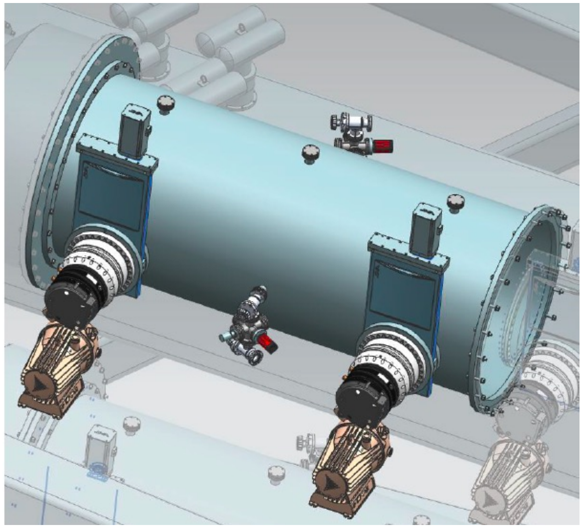
BabyIAXO beam line



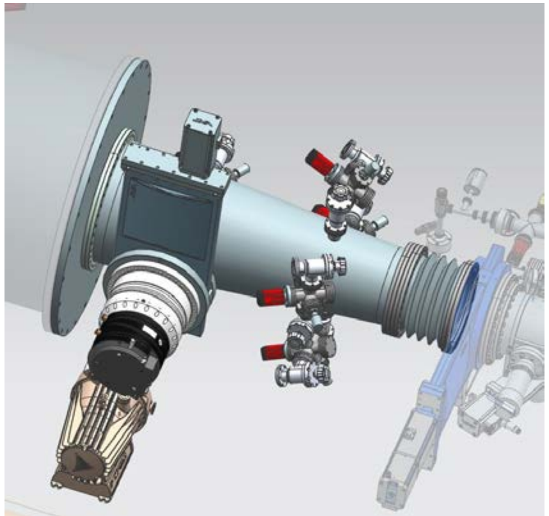
Magnet End-cap



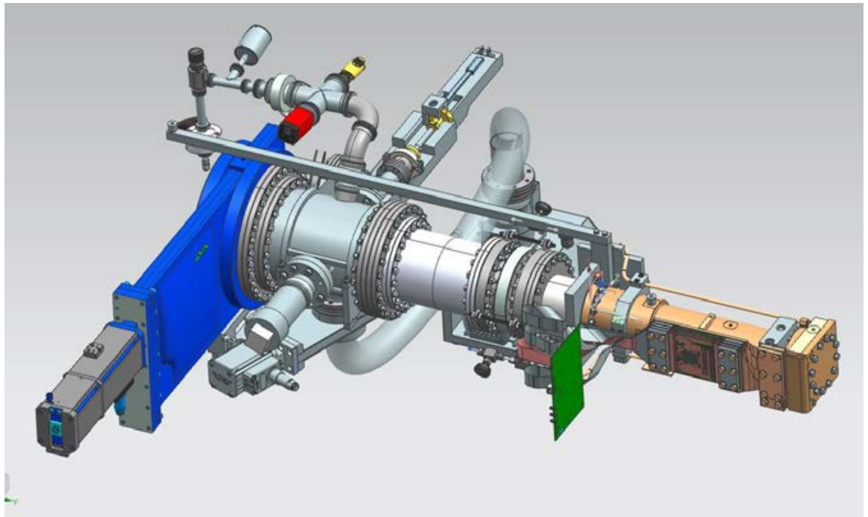
Magnet Telescope Vessel



Beam line Section 1



Beam line Section 2

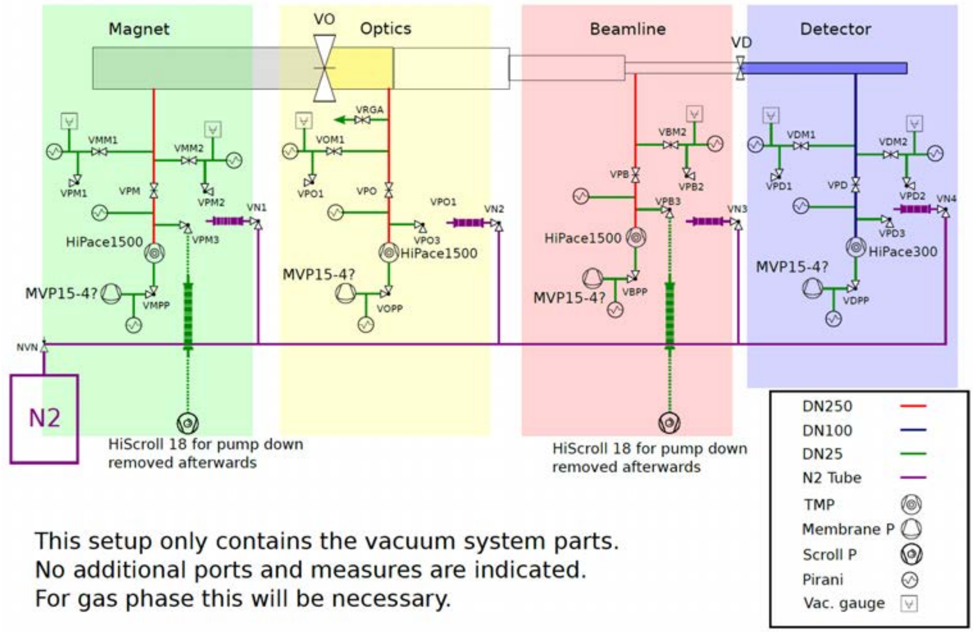


Detector line

BabyiIAXOS's vacuum & gas system Beam Line design Technical Design Review (TDR)

- **Successful Internal TDR Review. October 27th, 2023**
- **Successful External TDR Review. Novermber 8th, 2023**
  - ✓ Expecting minor comments by the end of this month

Status:
in contact with providers and manufacturers for quotes



Solar Axion Searches

BabyIAXO OPTIC APPROACH:

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

- ✓ NEED: Maximized throughput efficiency (40-60%),
  Small focal spot area (r < 2.5 mm),

- ✓ Baseline option (1-10 keV) (prototyping and R&D)
  - Bore 1: Existing XMM flight-spare telescope (replicated optics)
  - Bore 2: Custom IAXO optic (single- or multilayer-coated, segmented-glass or Al-foil Wolter-I, NuSTAR/XRISM/ATHENA)

- ✓ Beyond baseline (funding request pending)
  - Lower threshold of 0.3 keV or better
  - Add sensitivity at 14.4 keV

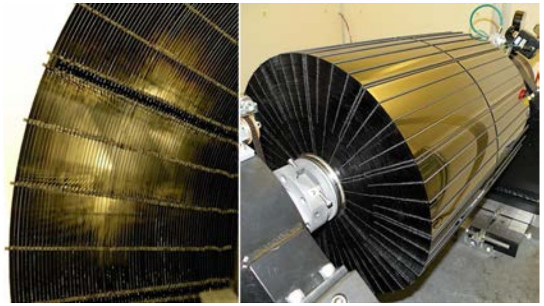
Baby IAXO

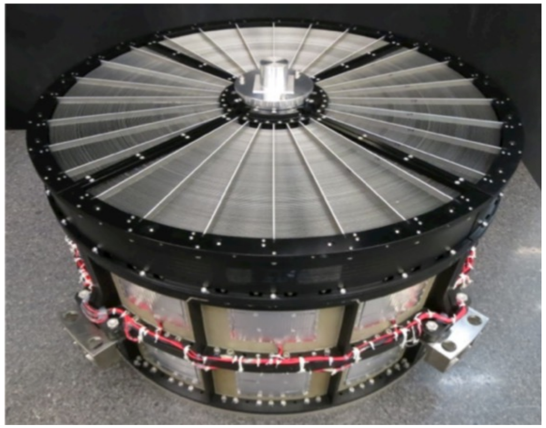
Leveraging decades of research by NASA and ESA for space instrumentation: minimal risk and superior performance

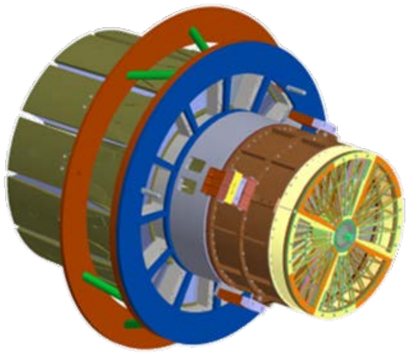
Solar Axion Searches

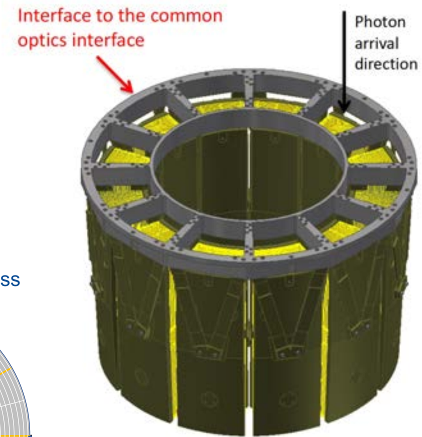
BabyIAXO Custom

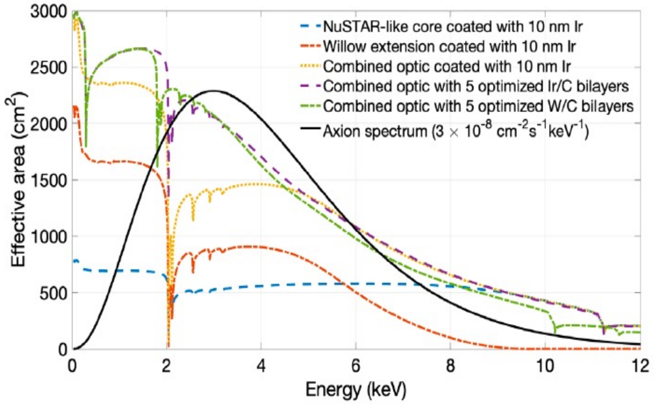
- ✓ IAXO-NuSTAR PATHFINDER @ CAST
- ✓ IAXO-CSGO/ATHENA PATHFINDER @ PANTER
- ✓ R&D for coating flat and curved substrates

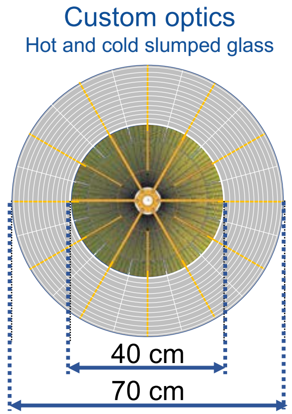










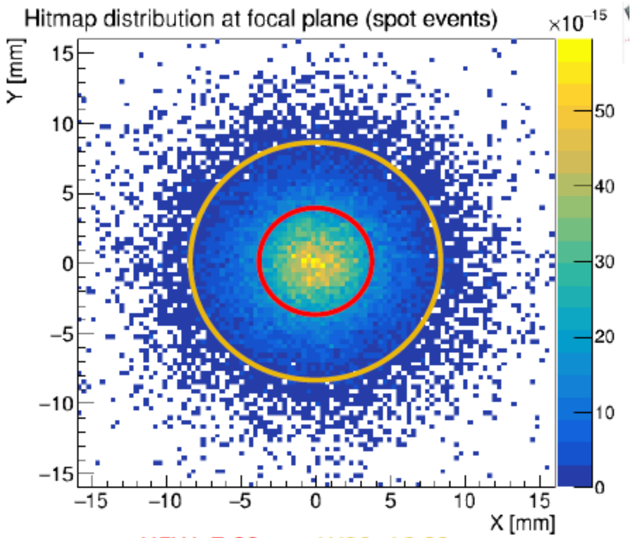


- CAD Design. Custom-optic beam line and cone of light.

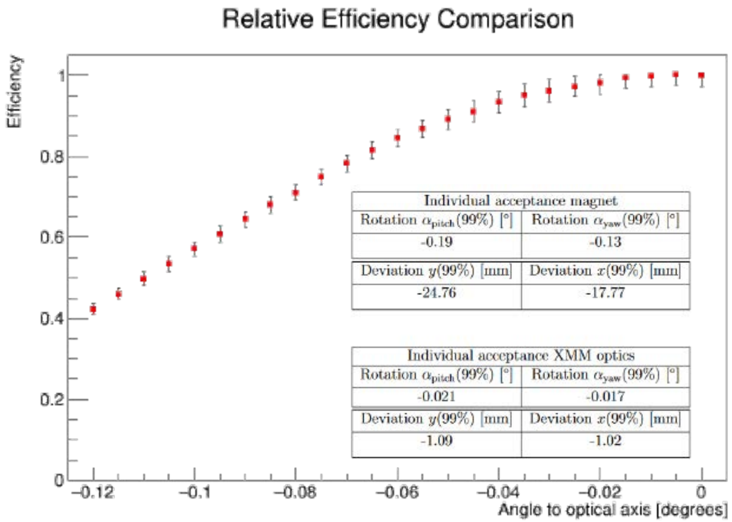
BabyIAXO Acceptance

- Run with 100 000 events
- Solar flux: Primakoff
- Vacuum stage
- Optics: XMM optics
- No detector window
- Results here done with REST v2.3.15

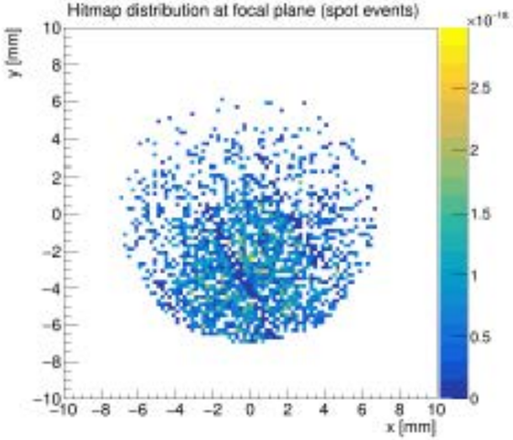
Rare Event Searches Toolkit software

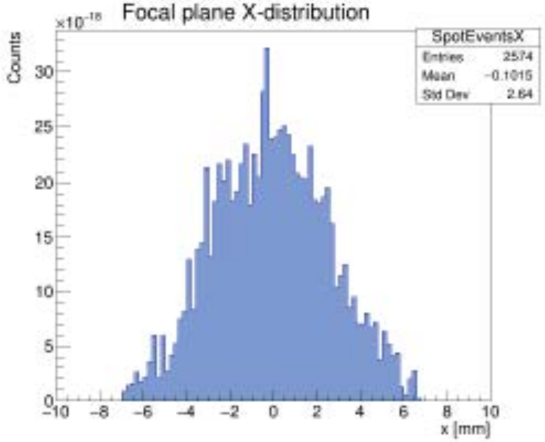


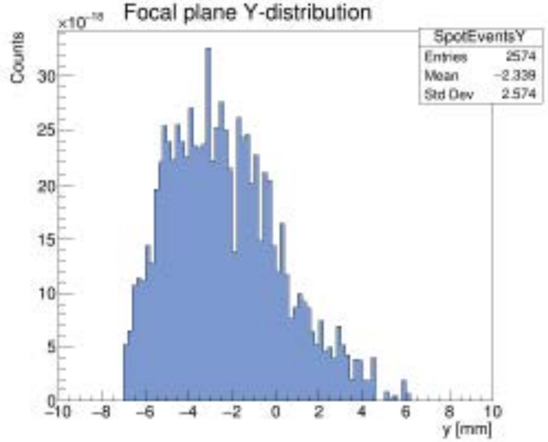
HEW=7.83mm W90=16.83mm
HEW=3.59′ W90=7.714′



Magnet and optics rotation





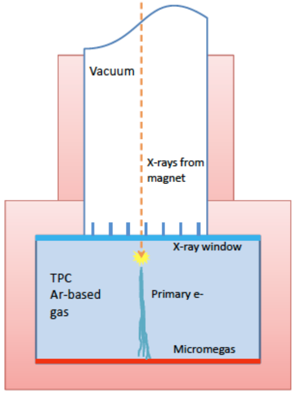


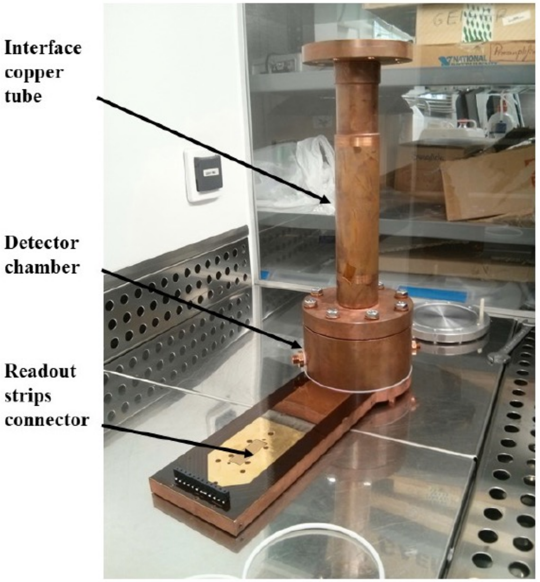
NEED (Baseline 1-10 keV):

- ✓ 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} (in CAST 2014 result) and
    - 10^{-7} cts keV^{-1} cm^{-2} s^{-1} measured underground at the Canfranc Laboratory (LSC)
- ✓ High detection efficiency

WANT:

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





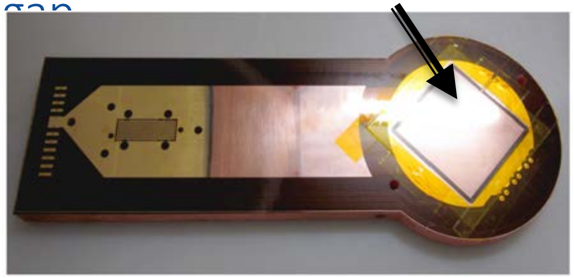
Micromegas best option to reach required low background Additional technologies considered and undergoing active R&D efforts (GridPix, MMC, TES, SDD)

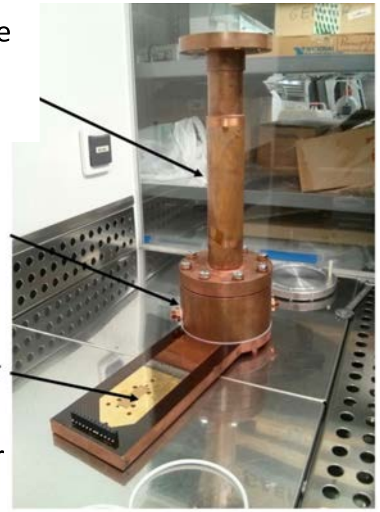
BabyIAXO Detectors

Microbulk Micromegas detectors

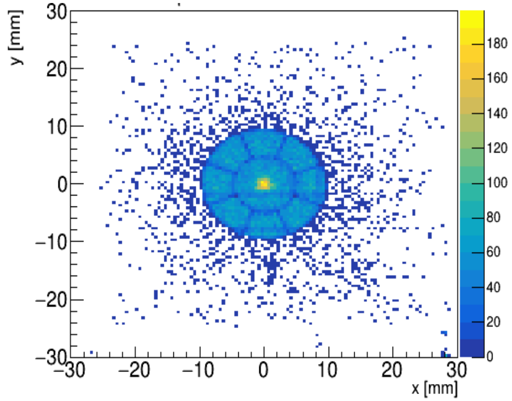
- ✓ Very homogeneous amplification gap uniform gain
- ✓ Intrinsically radiopure
- ✓ Good energy and spatial resolution
- ✓ Pixelized readout gives topological information
- ✓ Signal reaches the active volume through a mylar window
- ✓ X-rays ionize the gas in the conversion region and the produced signal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

Micromegas readout





Calibration intensity map



X-ray window

Rare Event Searches Toolkit software

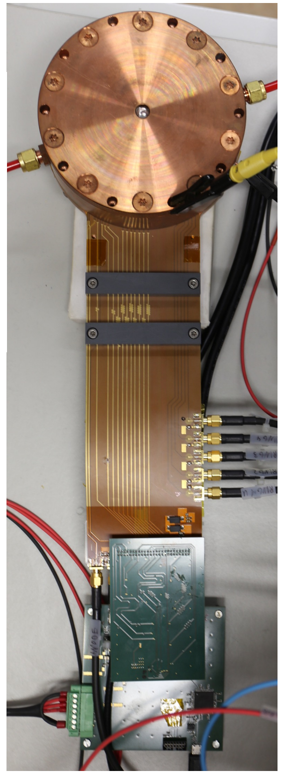
Baby IAXO

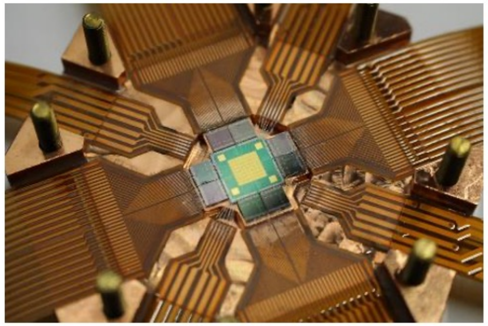
Solar Axion Searches

BabyIAXO Detectors

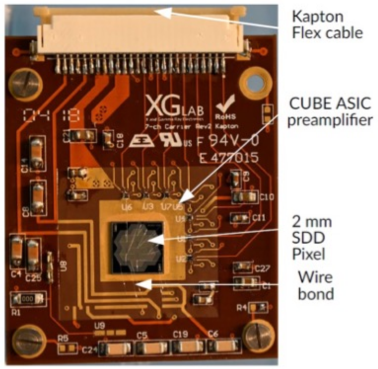
Beyond baseline, “high-precision” detectors
- ✓ Better threshold & energy resolution
- ✓ Design and material optimization ongoing in all fronts
- ✓ Background studies with different shielding configuration:
- ✓ DALPS project (French ANR)ß

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

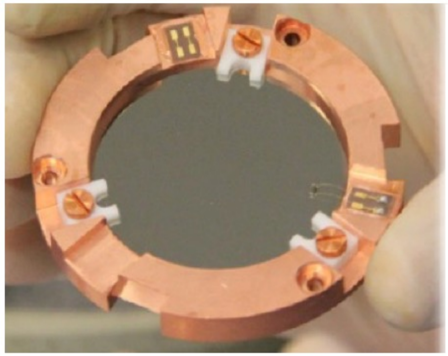




MMC: Metallic Magnetic calorimeters



SDD: Silicon Drift Detectors

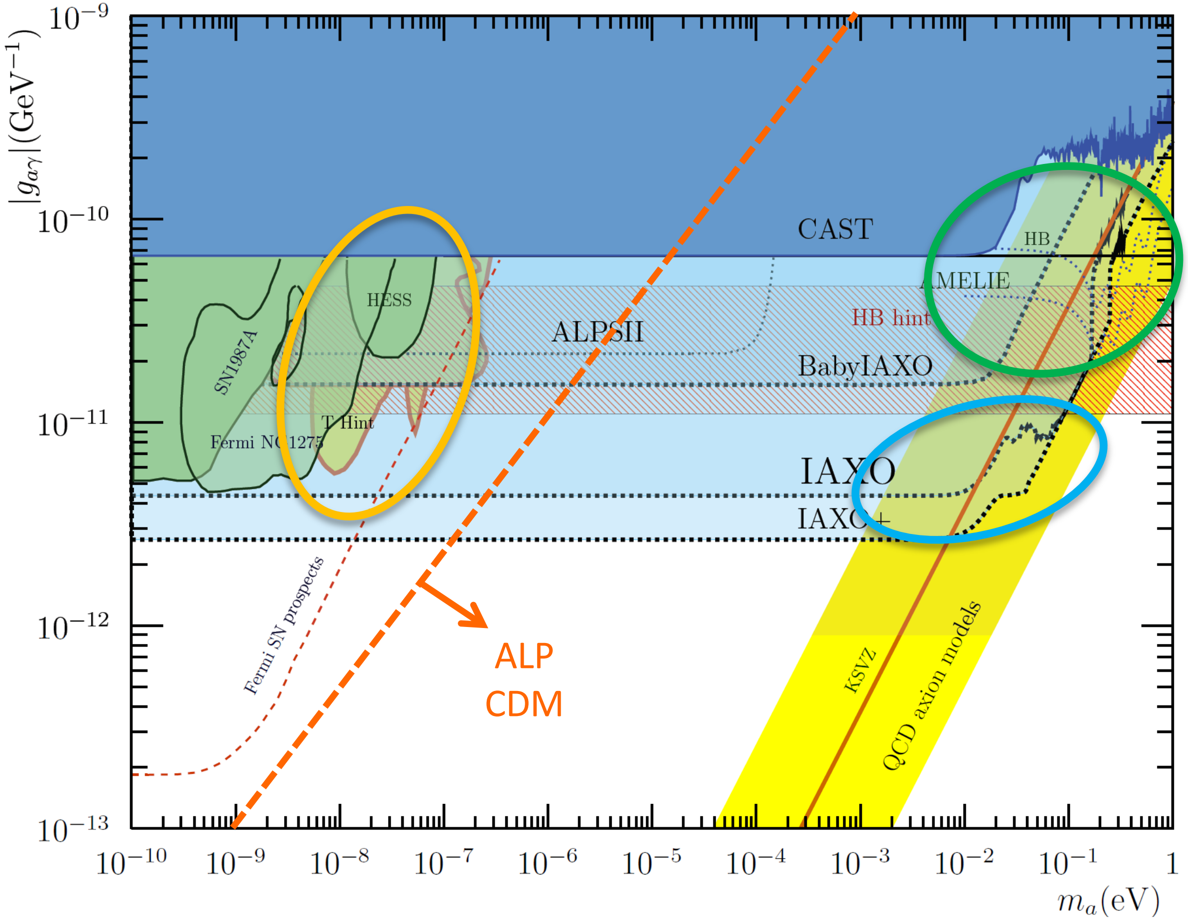


TES: Transition Edge senstors

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

Solar Axion Searches



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)

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

Armengaud et al 2019, JCAP 1906, 047

Armengaud et al 2019, JCAP 1906, 047

IAXO as a generic axion(-like) detection facility

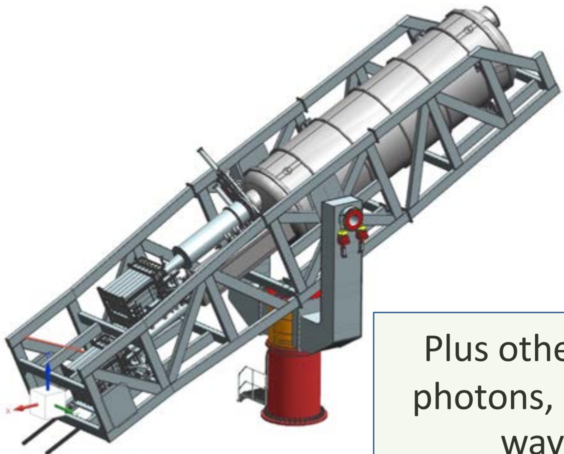
- (Baby)IAXO constitutes a great infrastructure that can be used to target other physics goals beyond Primakoff solar axions:

Other (non-Primakoff) solar axion production mechanisms (a-e, a-N, …)

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

Axions from close-by supernova explosions

Dark Matter axions: haloscope setups inside the BabyIAXO bores

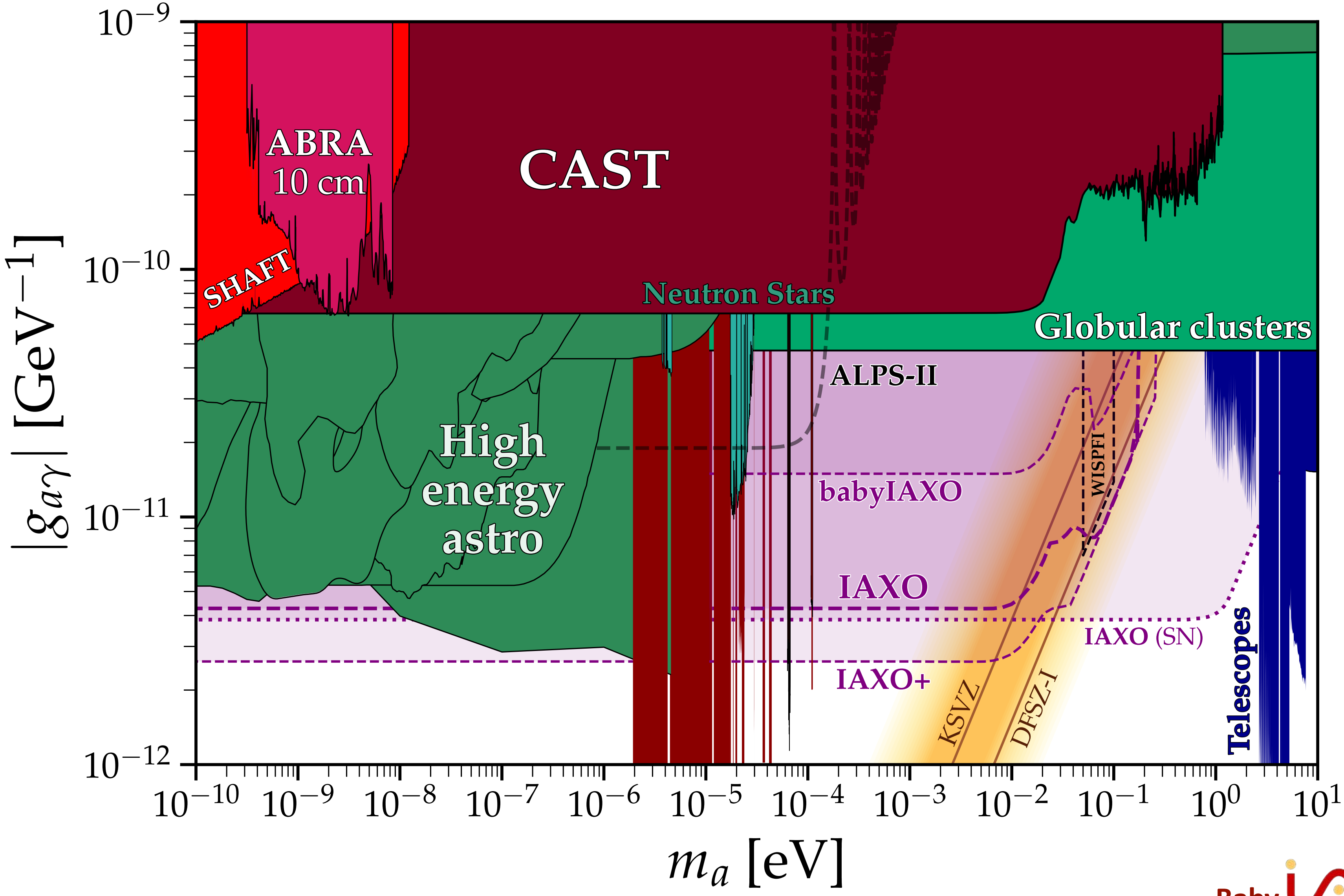


Plus other WISPs, such as hidden (dark) photons, chame-leons, etc., gravitational wave searches and NS studies

Goal sensitivity

Helioscopes

Adapted from https://github.com/cajohare/AxionLimits

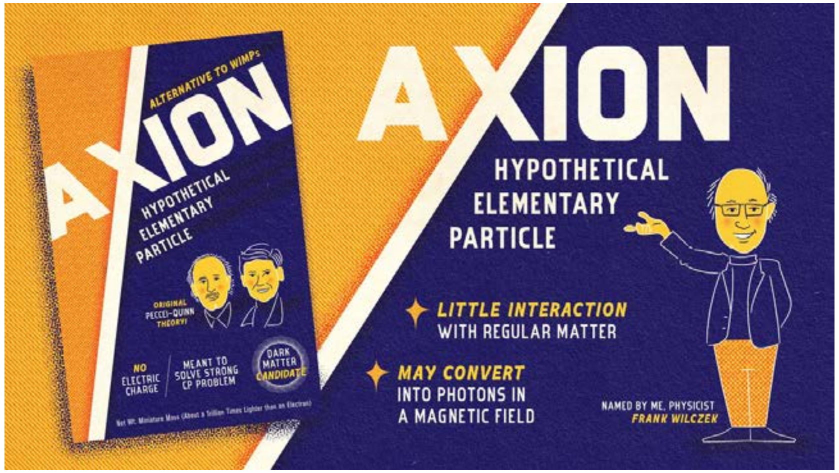


Baby IAXO

Conclusions

- ✓ Axions are well motivated dark matter candidates simultaneously solving strong CP
- ✓ Axions (and axion-like particles) can be searched for in a variety of laboratory experiments: Haloscopes, Helioscopes and LSTW experiments
- ✓ Solar axion searches probe large regions of well-motivated axion parameter space
- ✓ BabyIAXO (IAXO) targets axion discovery with sensitivities down to a few 10^{-11} (10^{-12}) GeV^{-1} in $g_{a\gamma}$
- ✓ Intriguing IAXO physics cases beyond axion-photon (g_{ae}, g_{aN}, QCD, ALPs, astrophysical hints, dark photons, dark energy…)

THANK YOU FOR YOUR ATTENTION!



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)

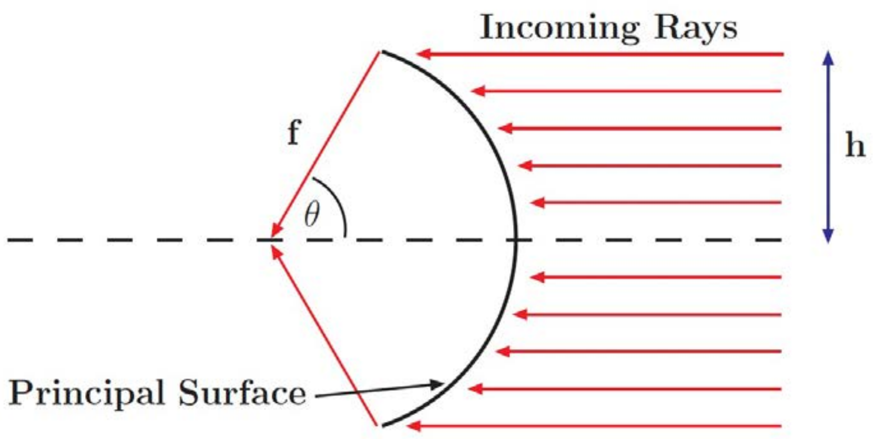
Backup

Solar Axion Searches

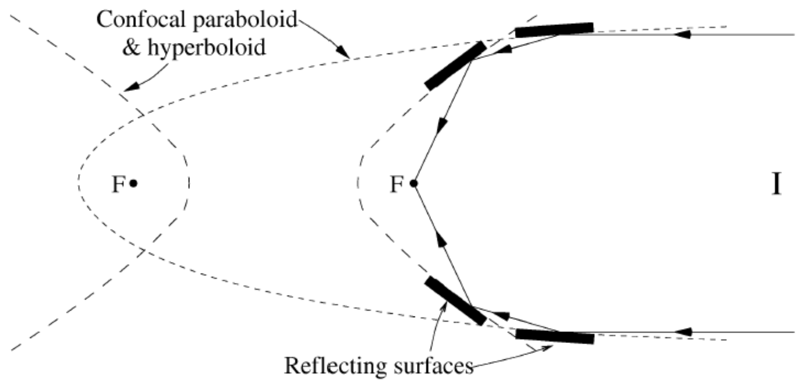
Intro to Wolter optics

- 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 (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

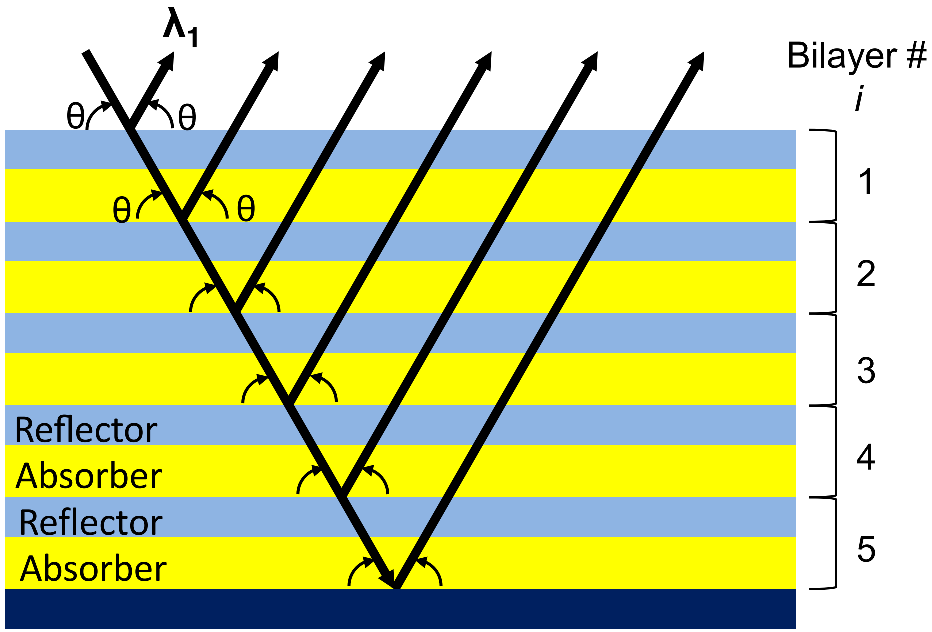


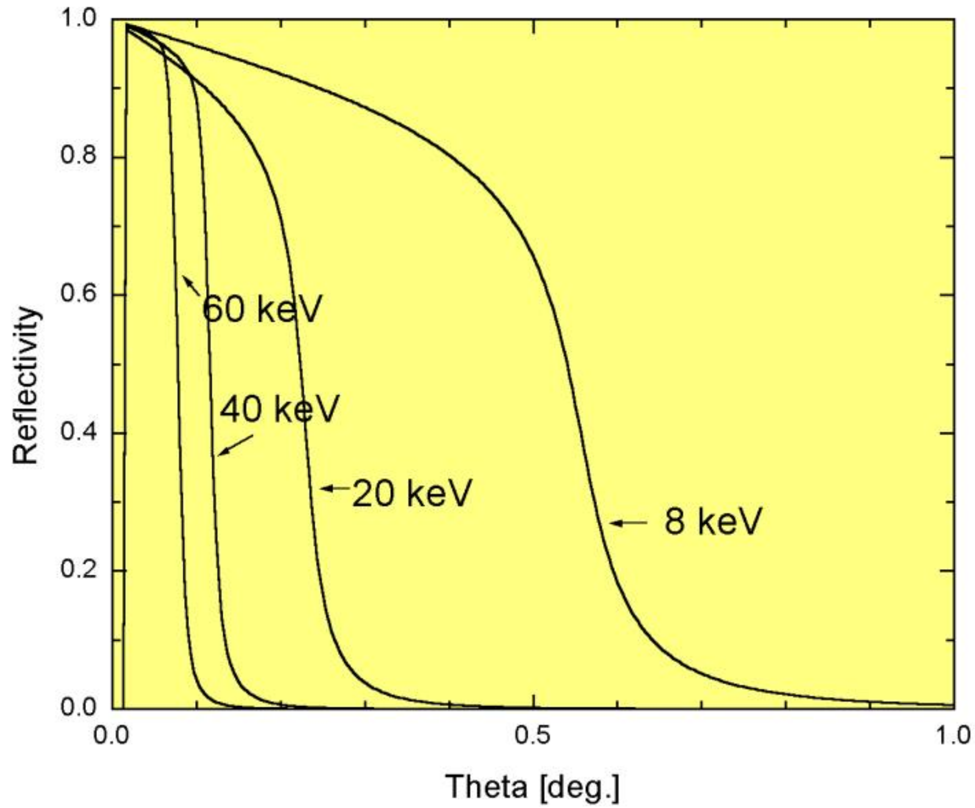
H. Wolter 1952 *Phys. Ann.* **6** 94.

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

- Reflectivity (from total external reflection) for metallic (Au, Pt, Ir) coatings high up to critical angle (θ_c) which depends on photon energy and mirror material
- For larger x-ray energies (> 10-15 keV): metallic coatings no longer efficient enough (shallow angles, single reflection)
- Multilayer coatings to extend energy range (or optimize response <10 keV) by making use of Bragg's law:

$$\lambda m = 2d \sin\theta$$



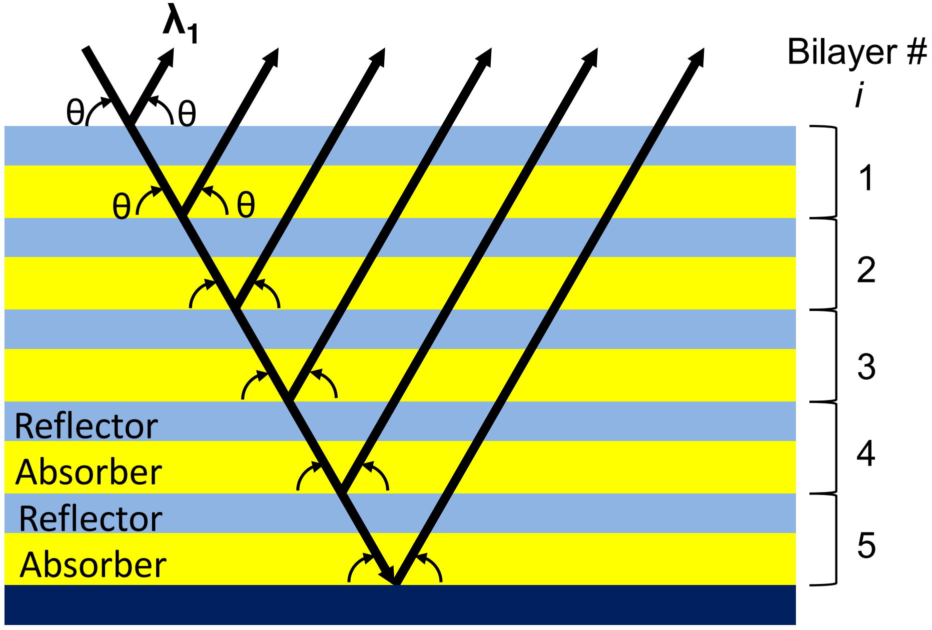


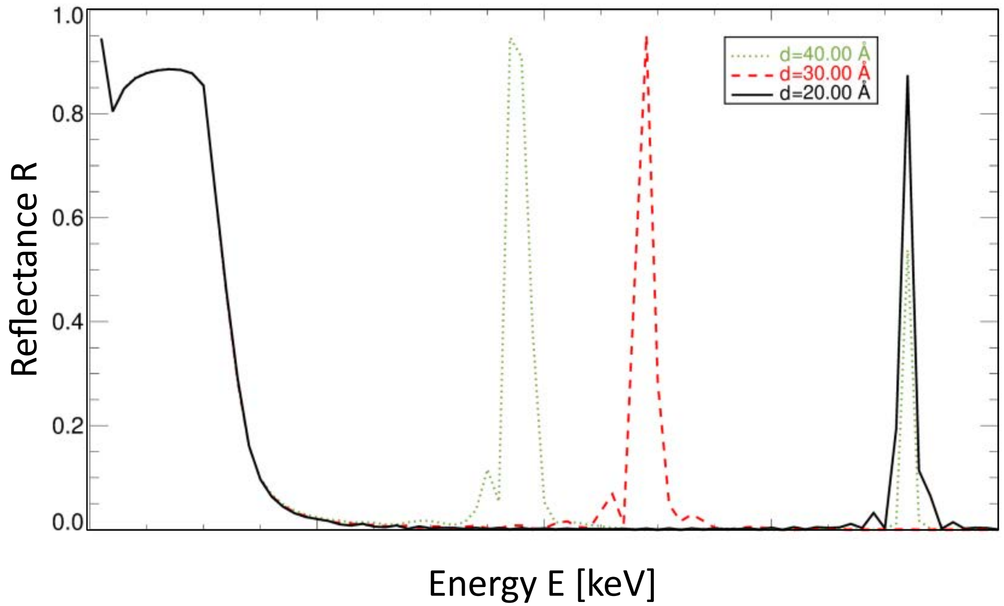
Intro to X-ray Coatings

- Reflectivity (from total external reflection) for metallic (Au, Pt, Ir) coatings high up to critical angle (θ_c) which depends on photon energy and mirror material
- For larger x-ray energies (> 10-15 keV): metallic coatings no longer efficient enough (shallow angles, single reflection)
- Multilayer coatings to extend energy range (or optimize response <10 keV) by making use of Bragg's law:

$$\lambda m = 2d \sin\theta$$

- Tuning the period (with const-d throughout the stack) to maximize reflectivity for specific E
  Larger energies require smaller periods—current practical limit is d = 1.5 nm



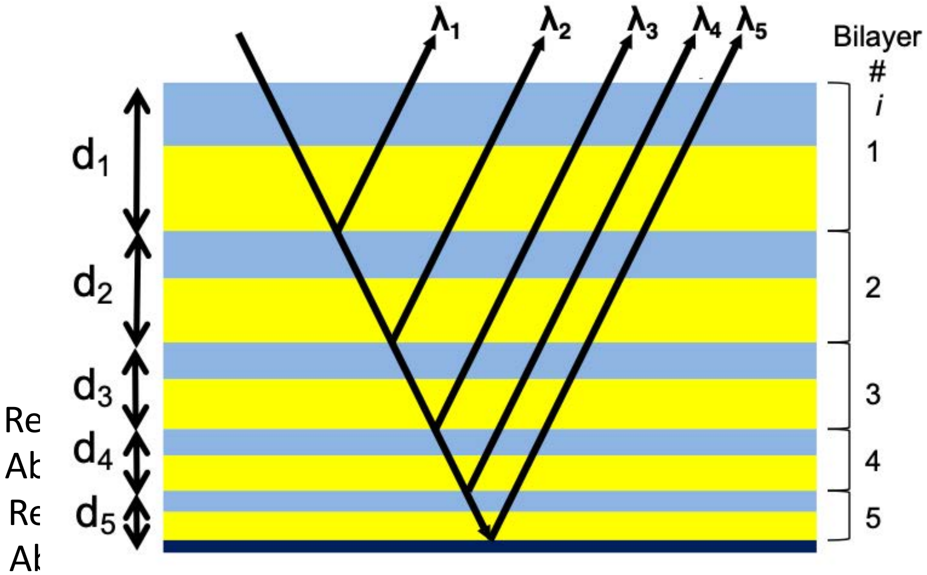


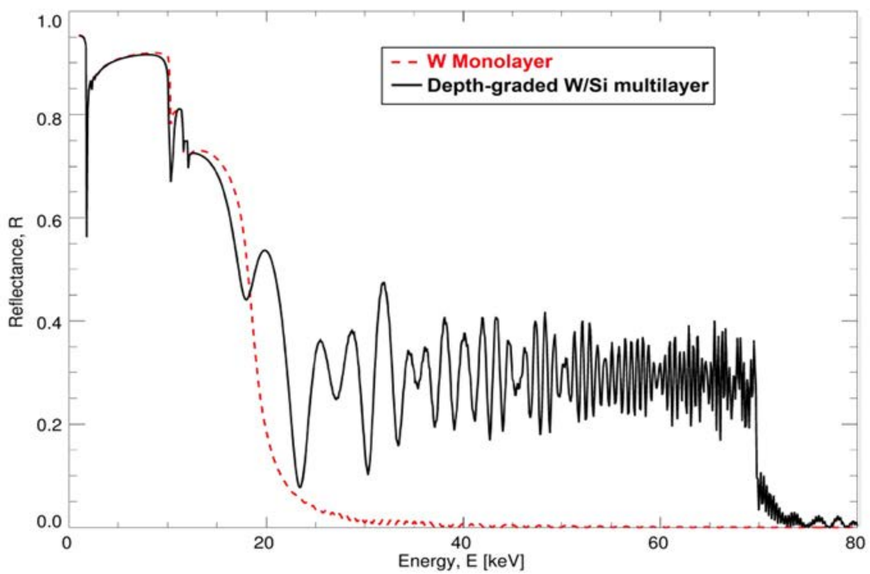
Solar Axion Searches

- Reflectivity (from total external reflection) for metallic (Au, Pt, Ir) coatings high up to critical angle (θ_c) which depends on photon energy and mirror material
- For larger x-ray energies (> 10-15 keV): metallic coatings no longer efficient enough (shallow angles, single reflection)
- Multilayer coatings to extend energy range (or optimize response <10 keV) by making use of Bragg's law:

$$\lambda m = 2d \sin\theta$$

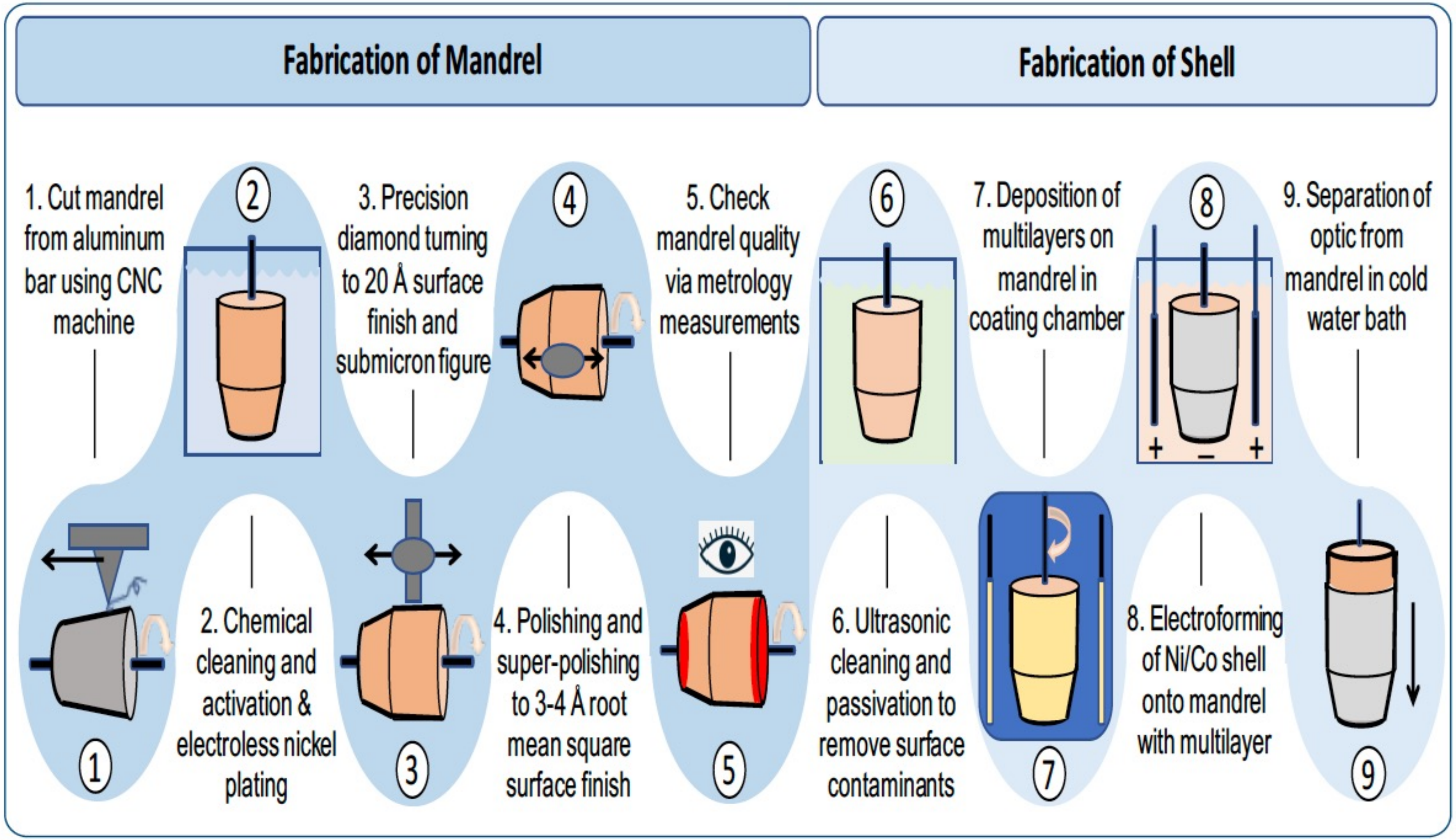
- Other options like depth-graded d-spacing, aperiodic multilayers etc for increased flexibility, but extend energy width or tailored response is at the cost of high reflectivity





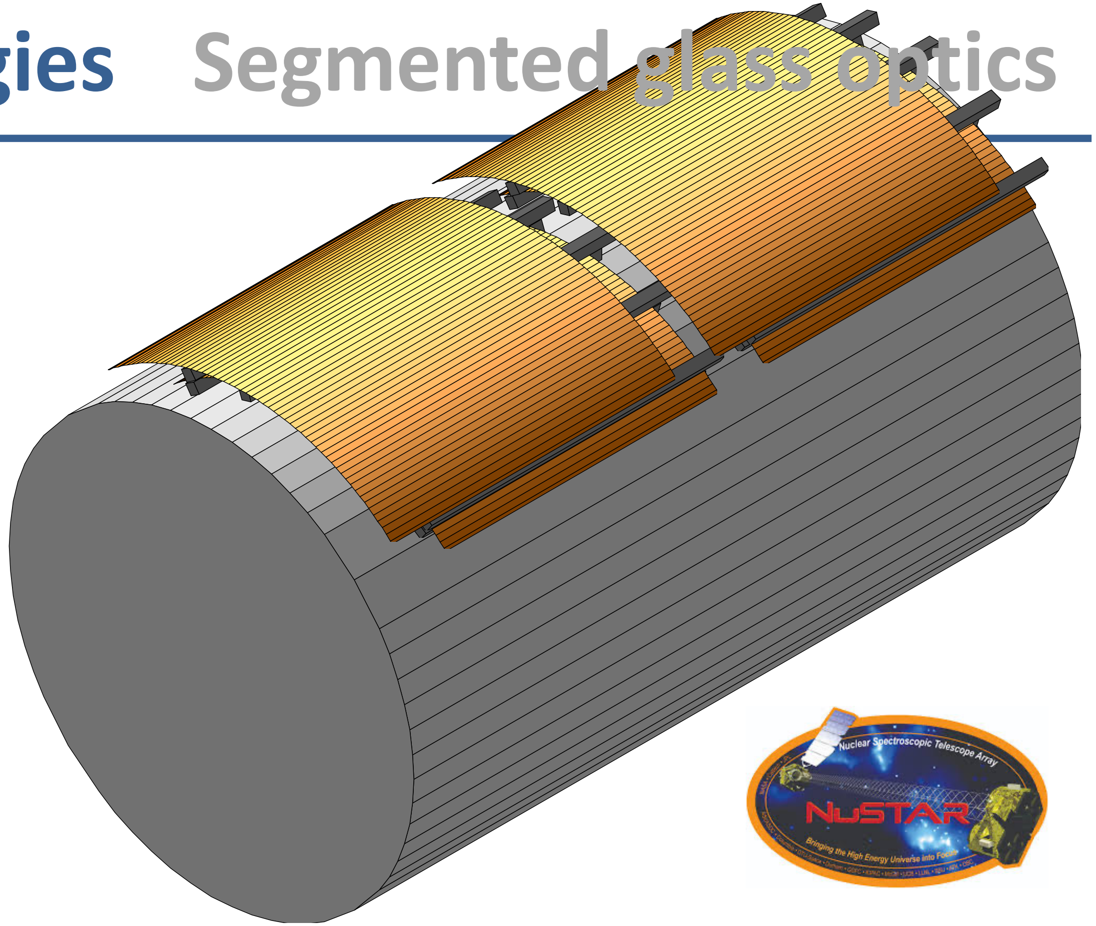
Multiparameter optimization that depends on science goals and priorities

X-Ray optics technologies

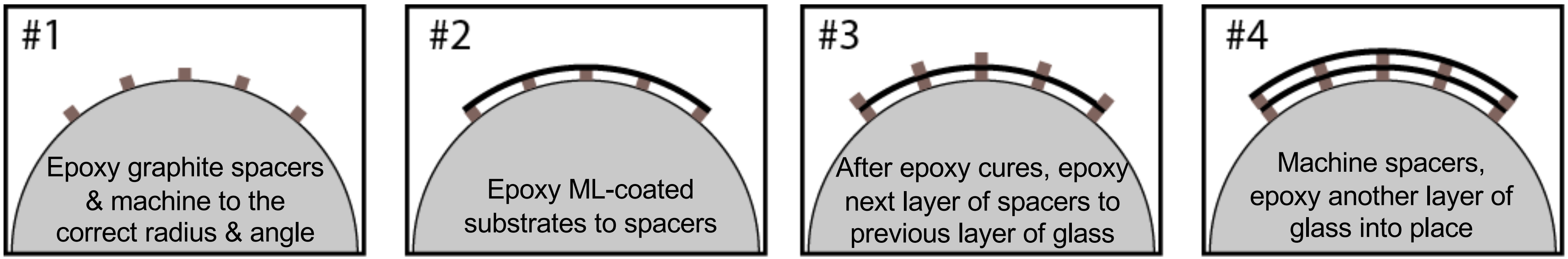


X-Ray optics technologies Segmented glass optics

- 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

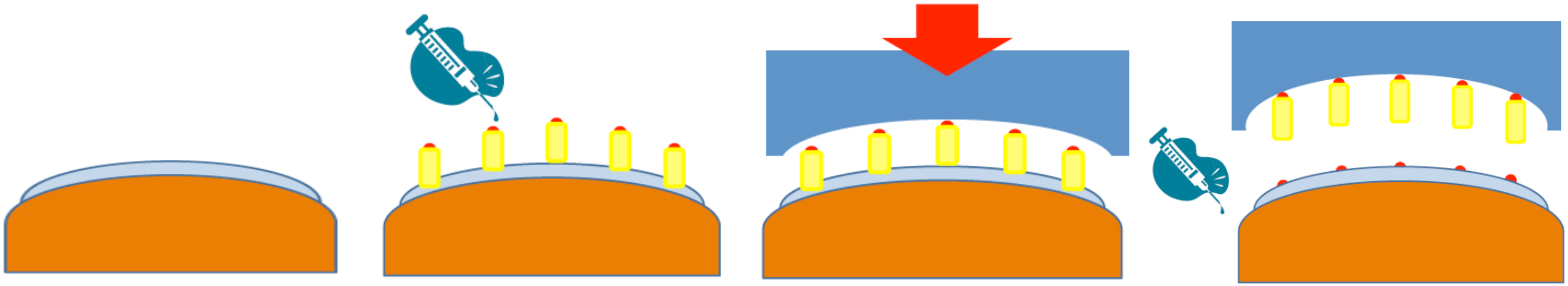


*JE Koglin et al. Proc. SPIE, **4851:607** (2003)*



X-Ray optics technologies Segmented glass optics

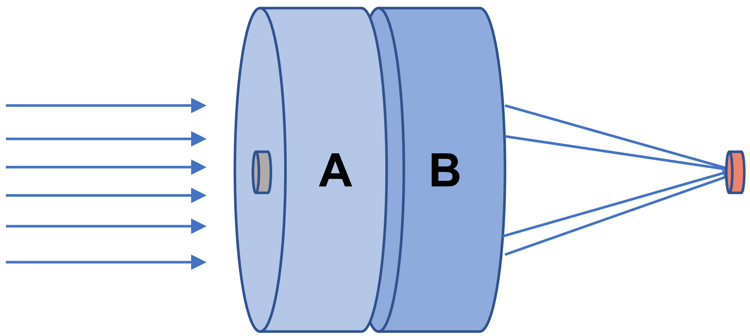
- Cold-slumped glass technology has been developed in recent years by IAXO collaborators
  - Glass plate assumes shape of mould
  - Glass shape is fixed with ribs
  - Mould can be taken as reference

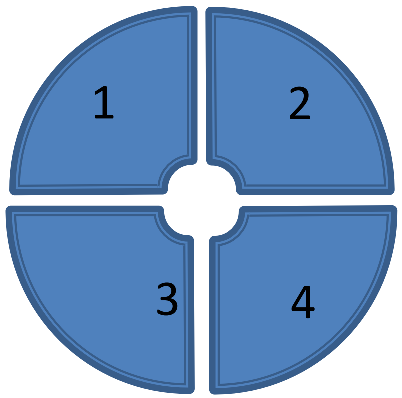


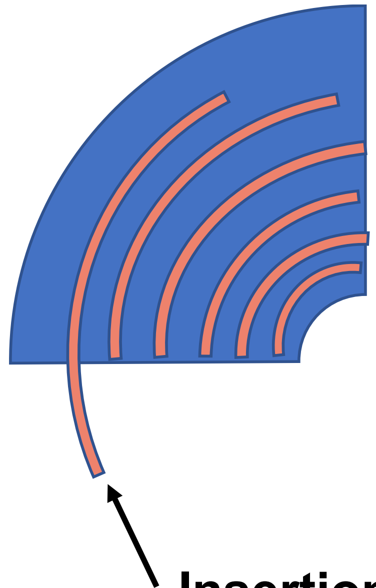
- Can be used to extend optics to cover large diameters (in BabyIAXO case 70 cm)

X-Ray optics technologies   Aluminum Foil Optics

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





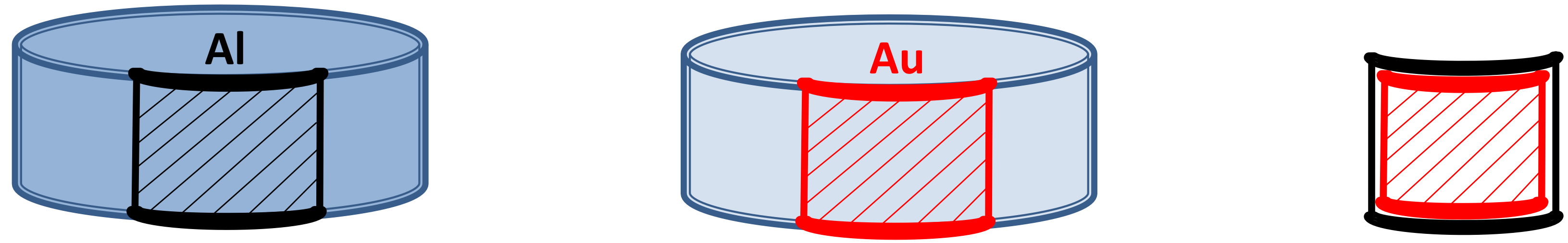


- Each bounce (A and B) consist of four highly nested cylinder quarters
  - ✓ Quarter independent assembly (220 shells)
  - ✓ Optic aperture from 10 to 45 cm diameter
  - ✓ Shells are inserted from the side of each quarter using a precise guidance tooling
  - ✓ Each cylinder is independently co-aligned (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

X-Ray optics technologies

Fabrication of Astro-H optics

Forming Mandrel (substrate) | Replication Mandrel (Coating) | Bonding

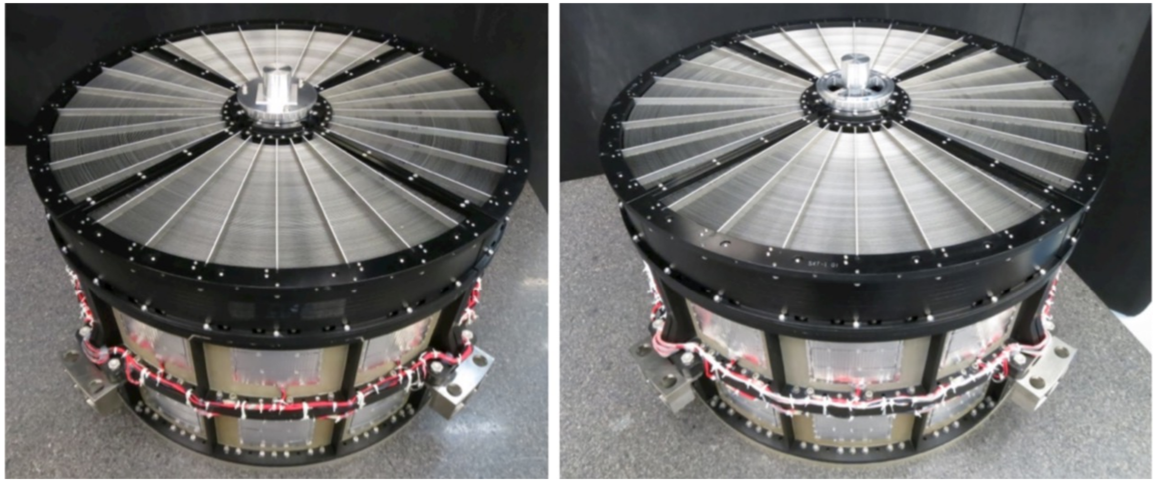


- Each shell is made at NASA Goddard from a 100 µm thick Aluminum sheet (Al sheet laser pre-cut as conic approximation to a Wolter-1 type optic)
- Stainless-steel mandrels then used to give the desired shape to the Al substrates
  - ✓ Aluminum sheets placed on mandrels and baked to preform the desired 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

X-Ray optics technologies Aluminum Foil Optics

Specifications of Astro-H optics

→ Good match for (Baby)IAXO



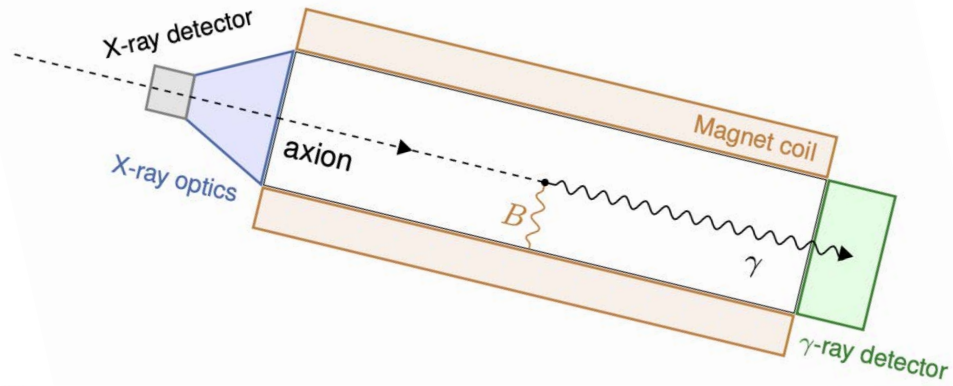
Astro-H's Soft X-ray Telescopes (SXTs) without thermal shield installed

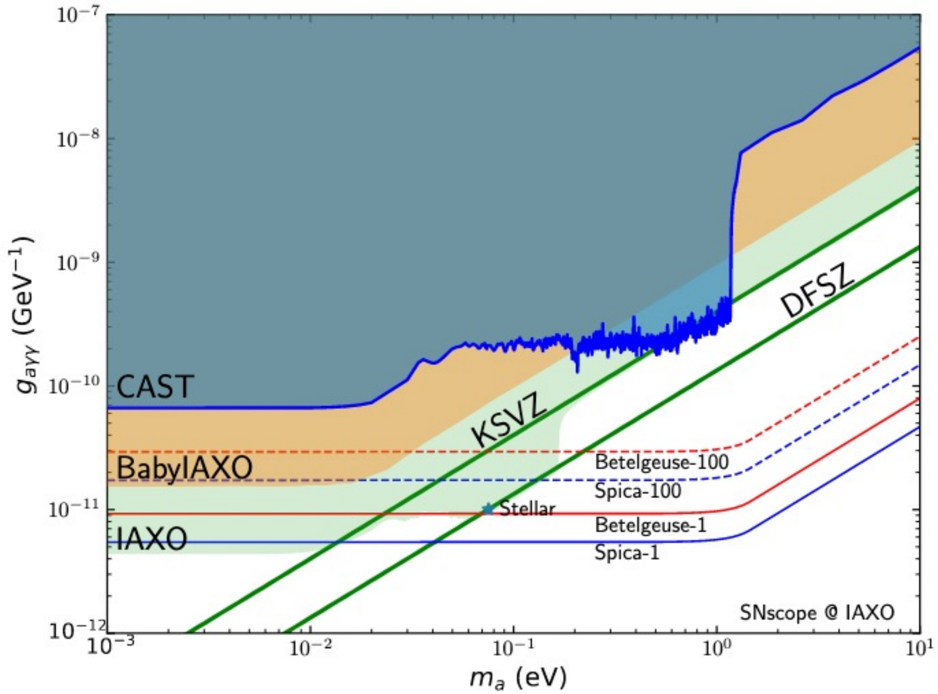
Design parameter	ASTRO-H SXT
Number of telescopes	1/1 (SXT-I/SXT-S)
Focal length	5.6 m
Effective diameter	116 to 450 mm
Grazing angle range	0.15 to 0.57 deg
Number of nesting	203
Foil length	101.6 mm
Reflector layer thickness	
Reflecting surface	Au (0.2 μm)
Coupling layer	Epoxy (12 μm)
Reflector substrate	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

Axion from galactic supernova

Ge et al. 2008.03924

- 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 g-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.

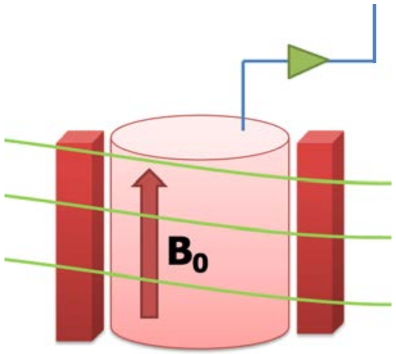


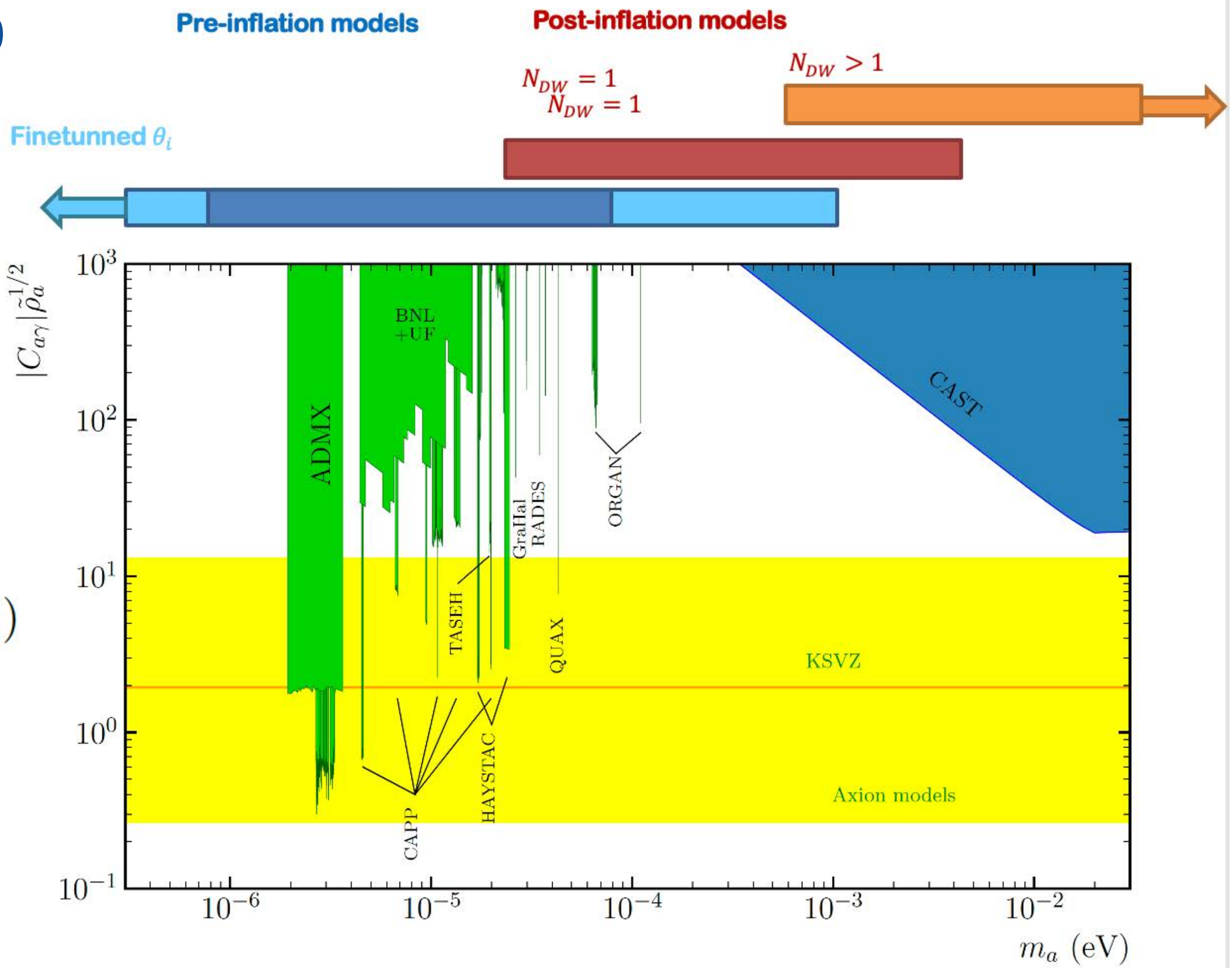


Detecting DM axions: Haloscopes for BabyIAXO

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

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

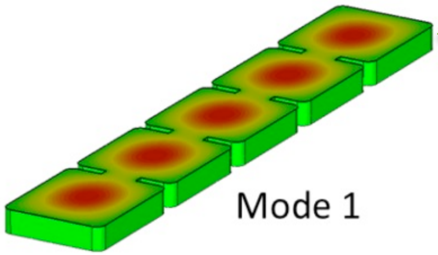




RADES

- 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

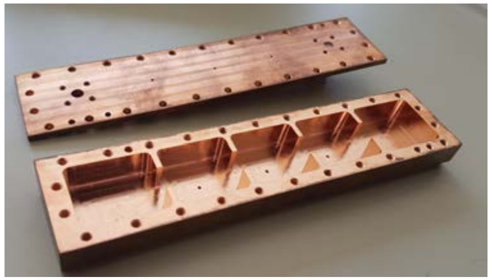
ERC-StG 2018
B. Dobrich, CERN

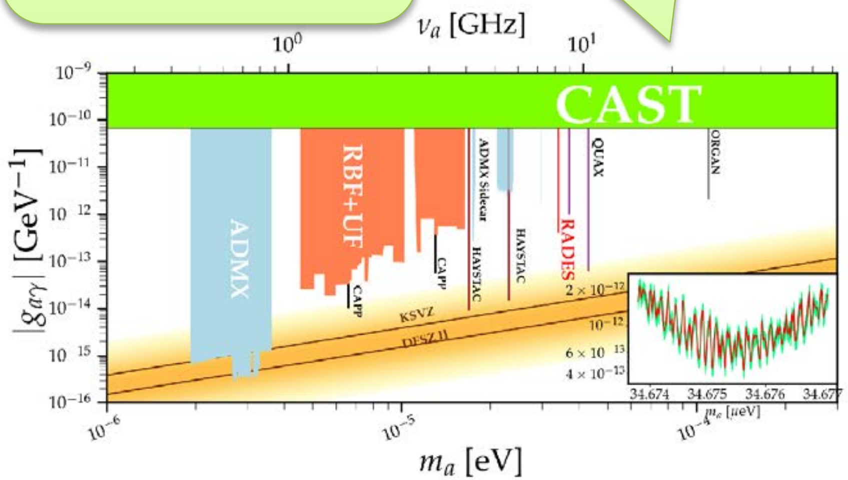


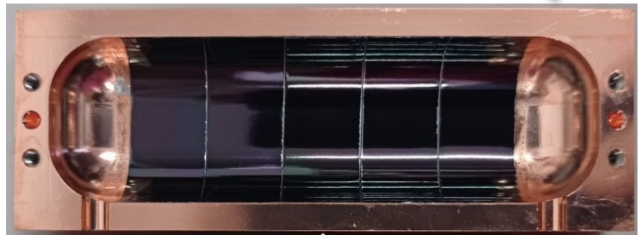
New geometry concepts to scale in V but keeping high resonant *f*

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

Inner HTS coatings to improve Q factor







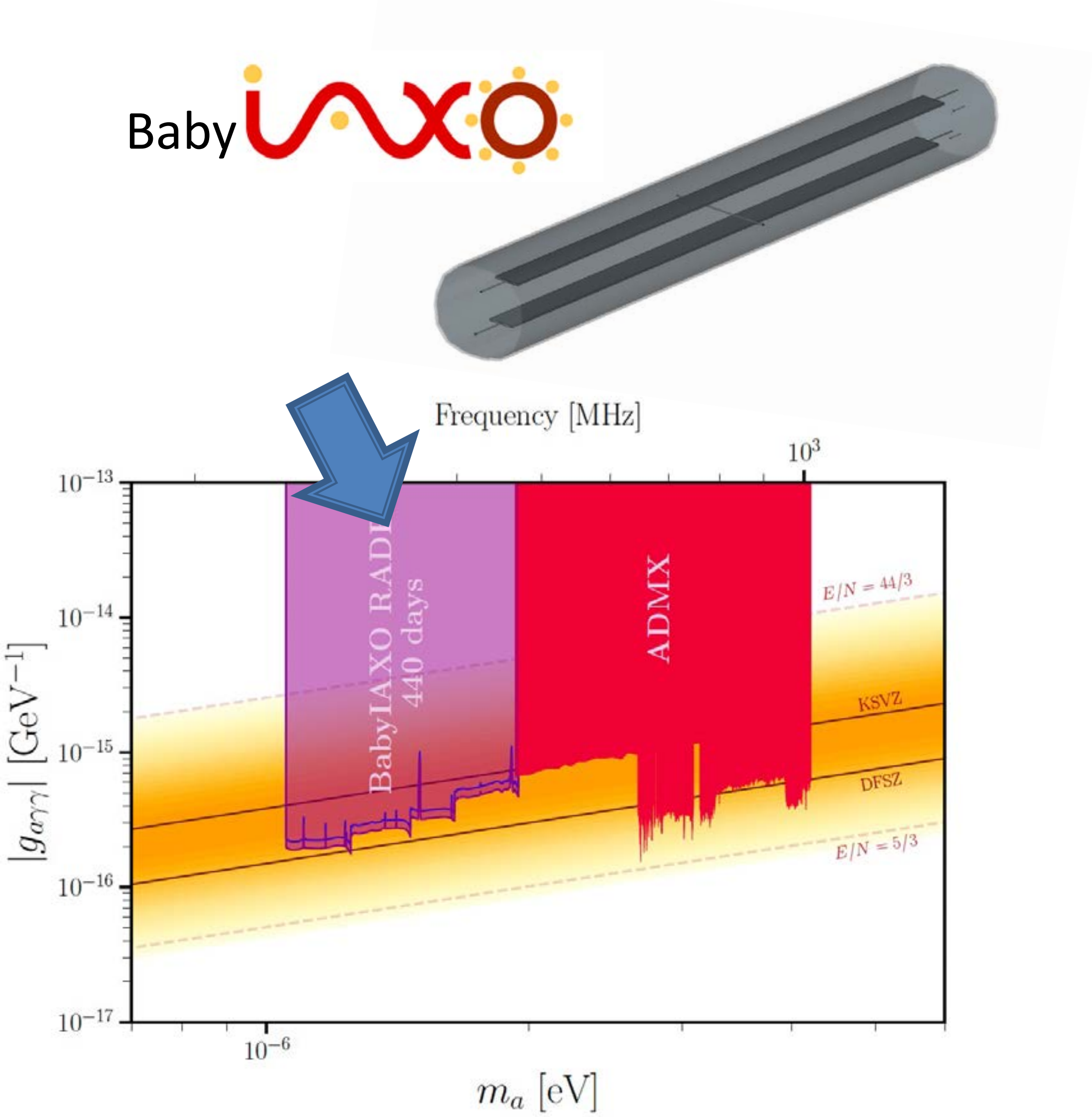
JCAP 05 (2018) 040
JHEP 07 (2020) 084

JHEP 10 (2021) 075

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

Beyond baseline physics

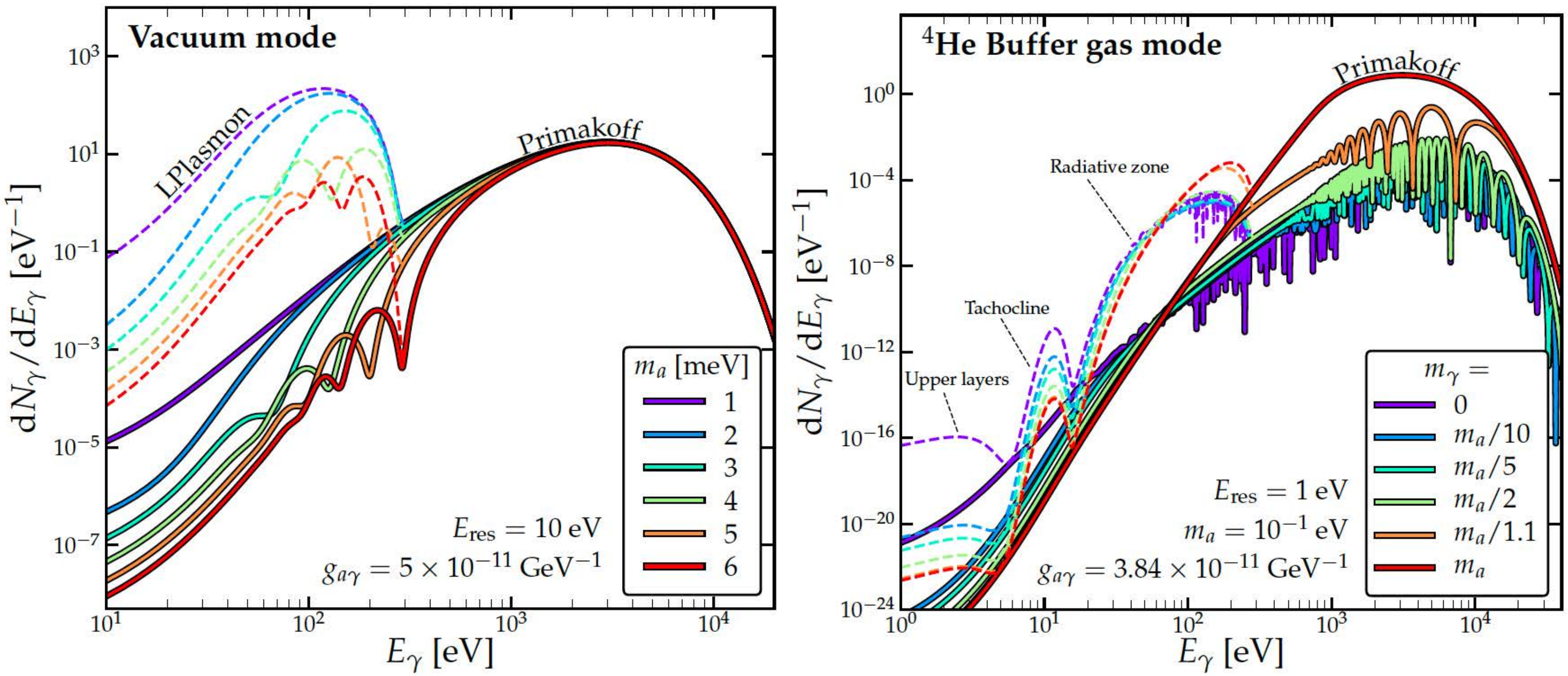
- Use of (Baby)IAXO large magnetic volume for axion DM setups
- Very competitive prospects for 1-2 meV axion searches.
  - 4 x 5m long cavities with tuning slabs
  - Low noise (standard) amplification + DAQ
  - Bores cooled down to 4-5 K
  - Sensitivity to KSVZ in < 2 year data acquisition
- Other implementations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



Ahyoune et al. (RADES Collaboration) arxiv:2306.17243

IAXO Physics

Beyond baseline physics



O'Hare et al. 2006.10415

IAXO Physics

Beyond baseline physics

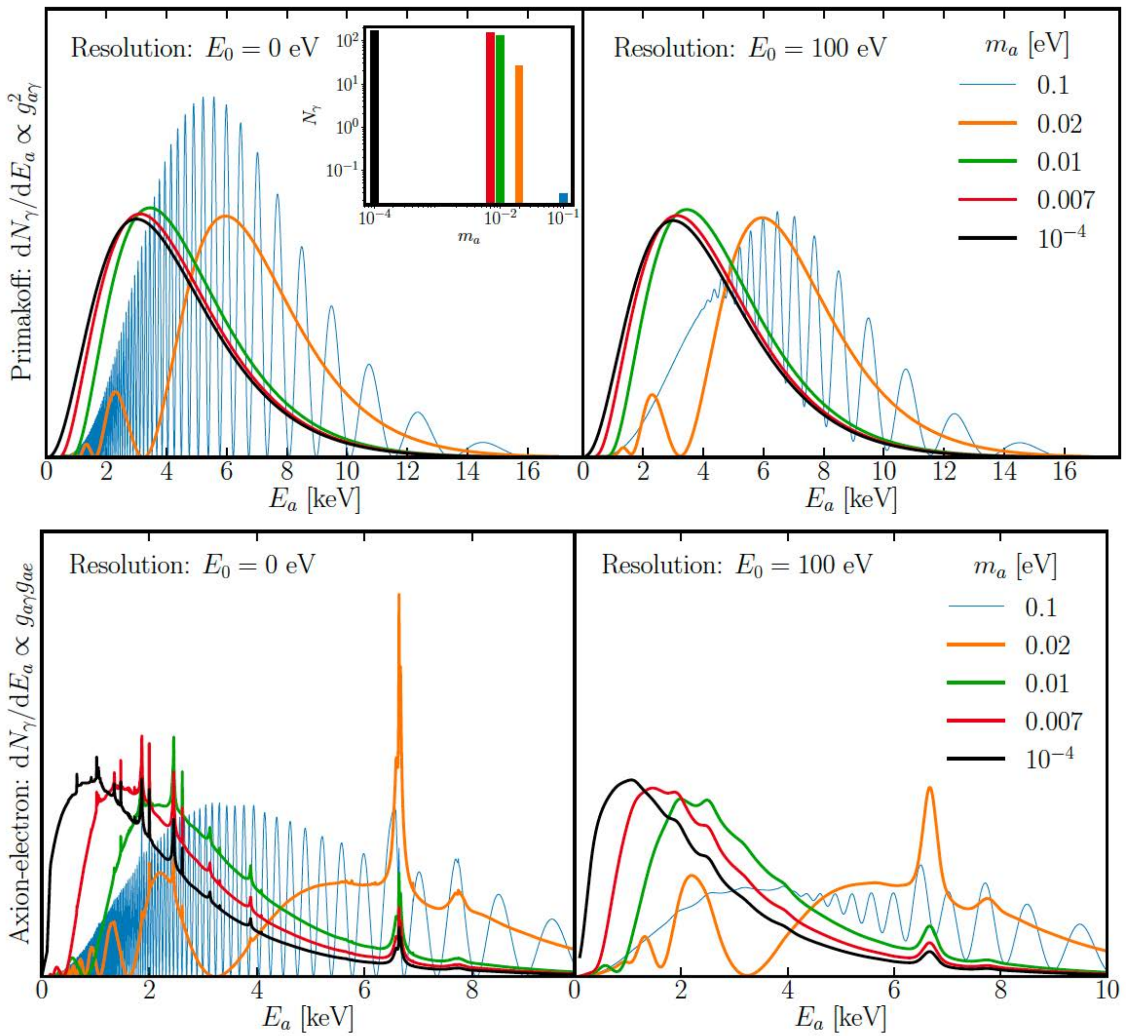


FIG. 3. Differential x-ray spectra as a function of energy due to solar axion conversion inside a 20 m long 2.5 T magnet. We display spectra for different values of the axion mass m_a as well as for both the solar Primakoff (**top**) and axion-electron (**bottom**) fluxes. The left-hand panels in both 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