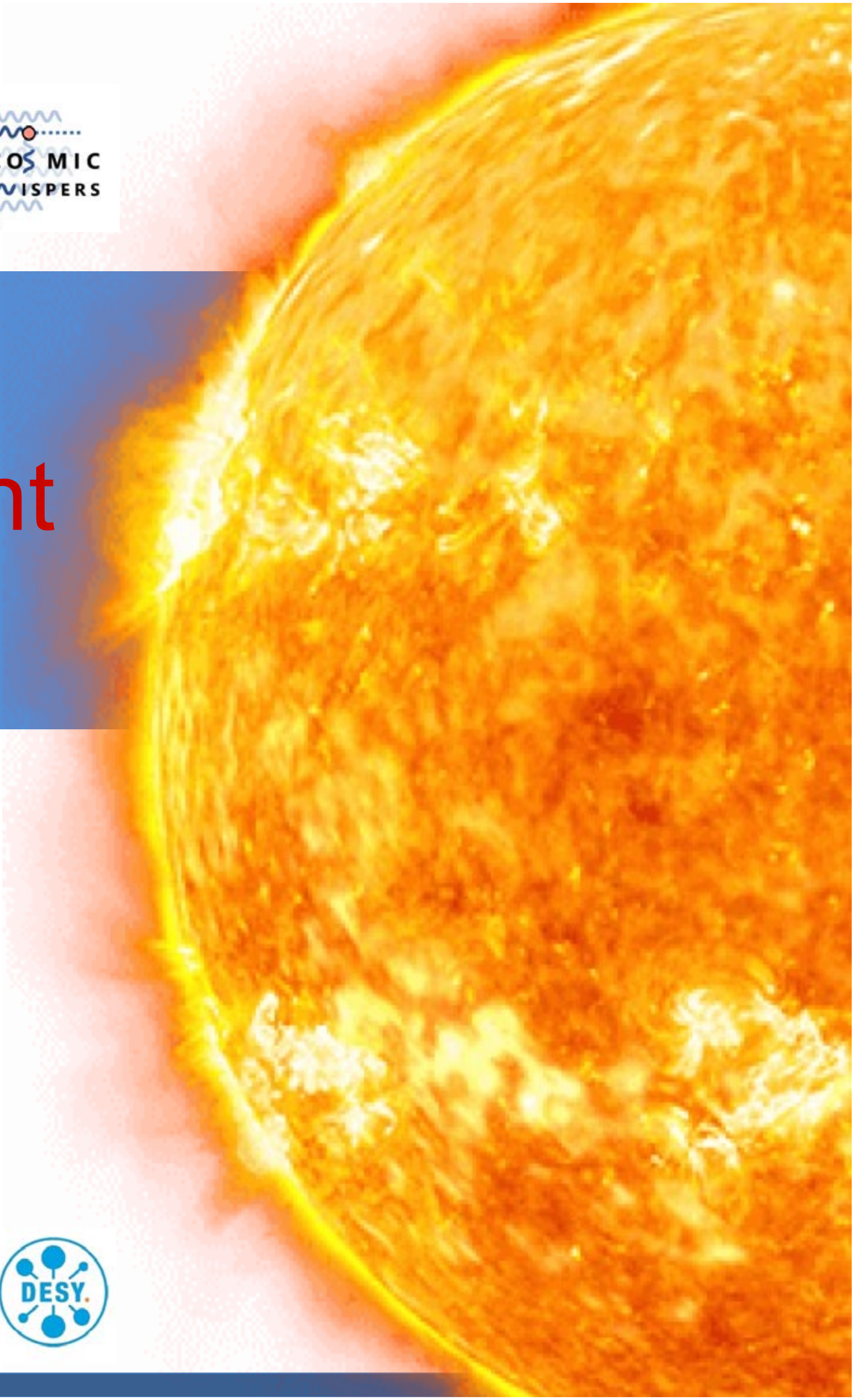
cost
EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

Funded by the European Union

COSMIC WISPERS
CA21106



The IAXO experiment

Jaime Ruz on behalf of the IAXO Collaboration

February 1-2, 2024

Hamburg, Germany

CAPA Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

DESY.

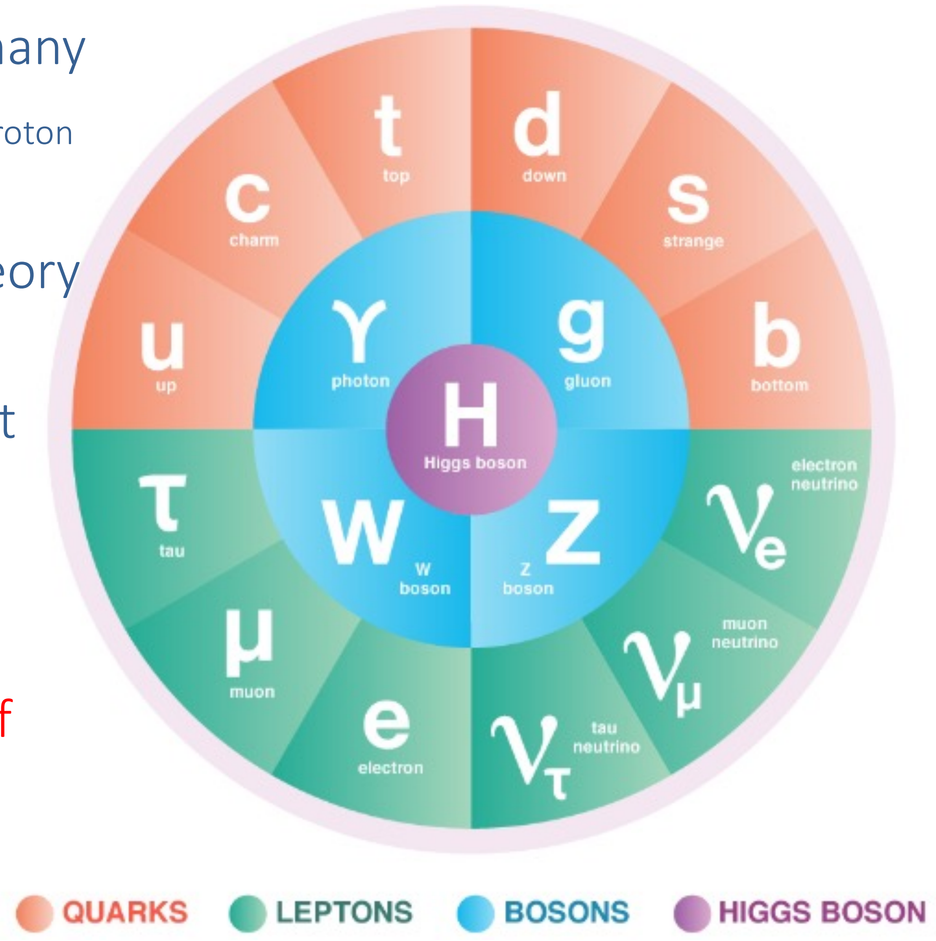
Outline

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

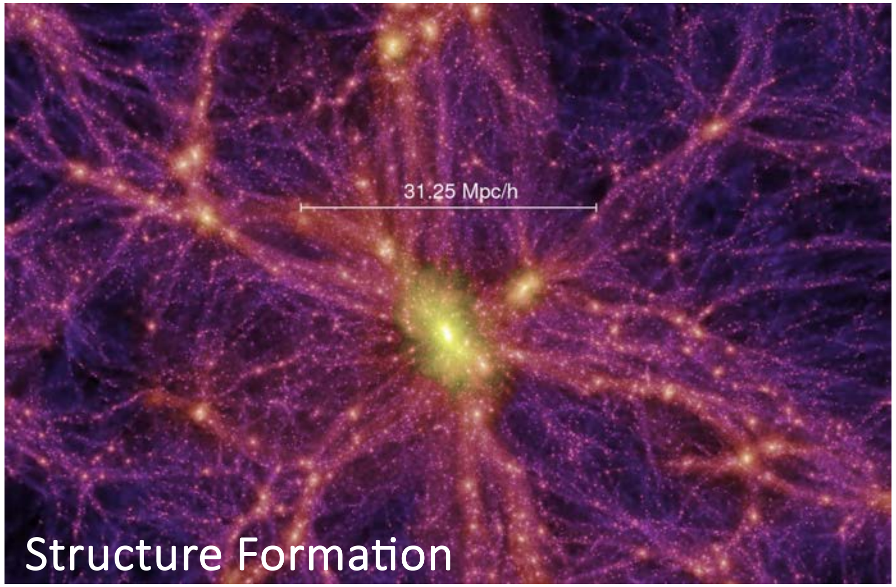
- ✓ Extremely successful theory describing many observations up to energies of ~1000 m_{proton}
- ✓ Merely an effective theory that could be considered the low energy limit of a Theory of Everything
- ✓ Expect observation of new phenomena at higher energies (e.g. LHC at CERN)
- ✓ SM cannot explain:
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

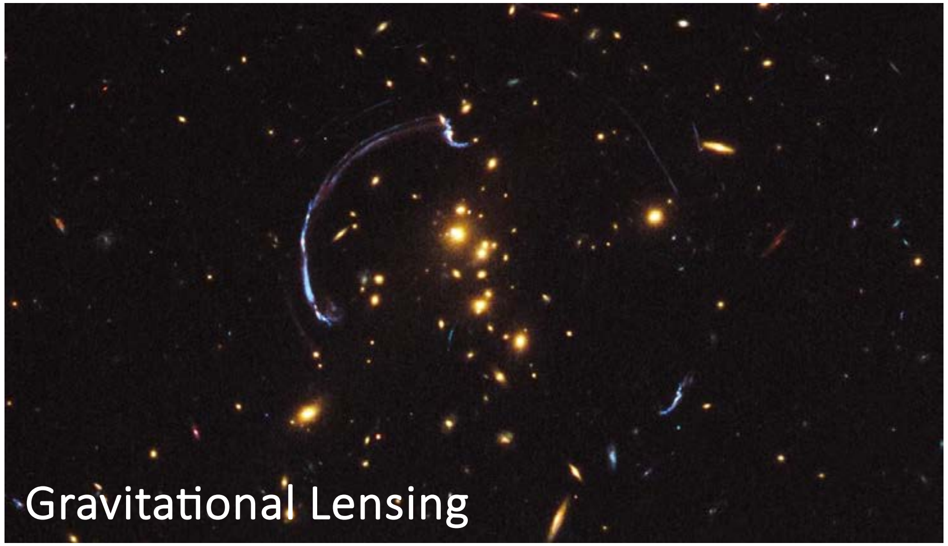


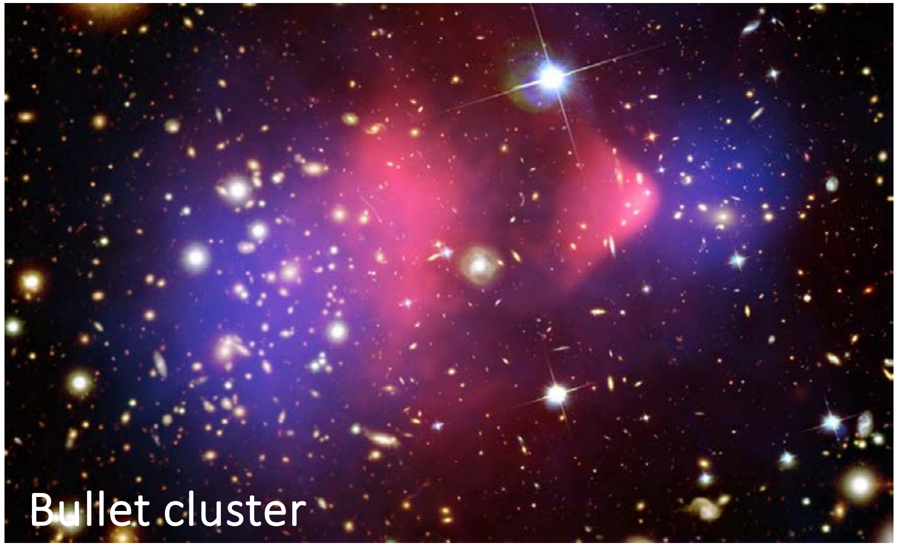
Dark Matter

EVIDENCE FOR DARK MATTER

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







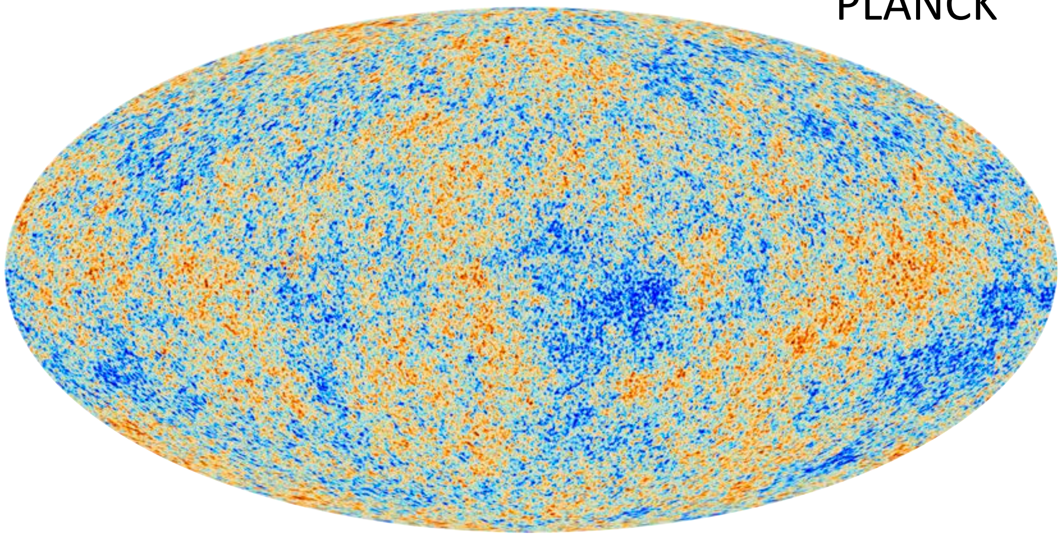
DARK MATTER PROBLEM: WE KNOW IT EXISTS BUT WHAT IS ITS NATURE?

Dark Matter

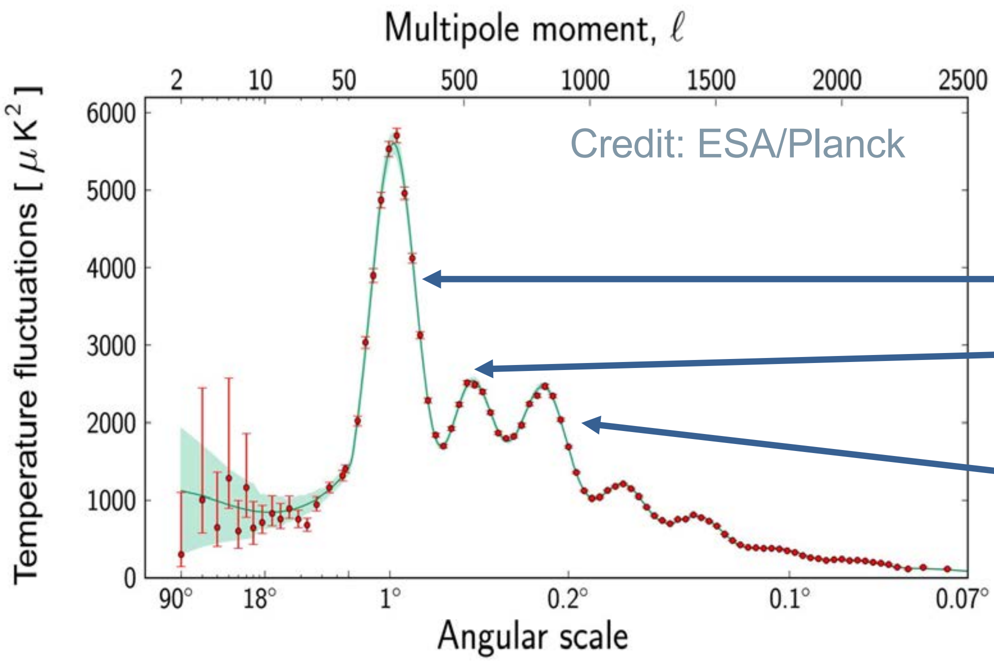
EVIDENCE FOR DARK MATTER

- ✓ 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%

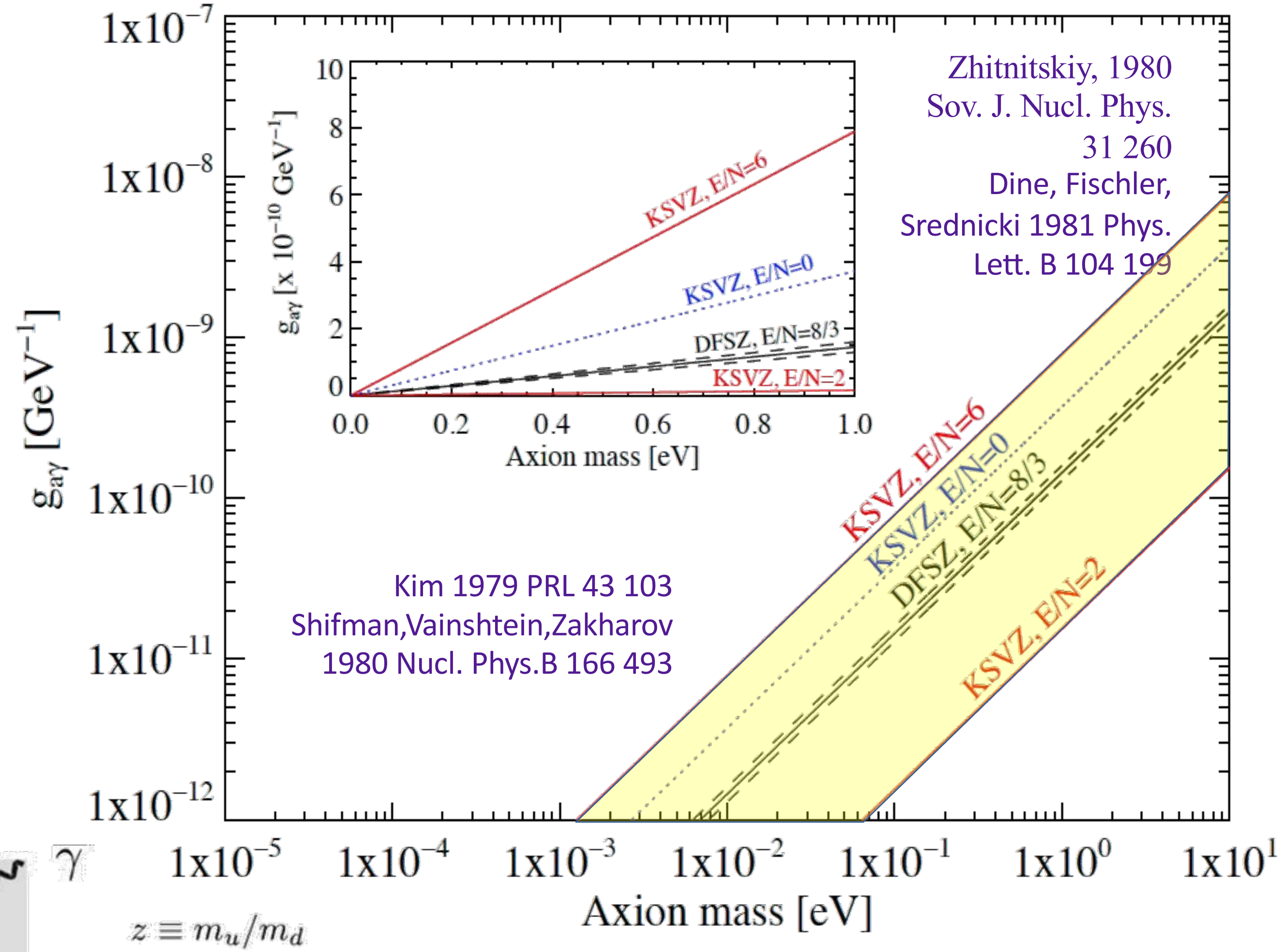
The Axion


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

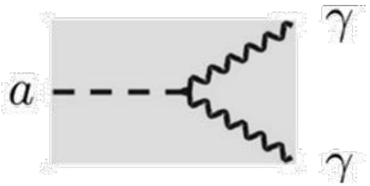
The Axion

Properties

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



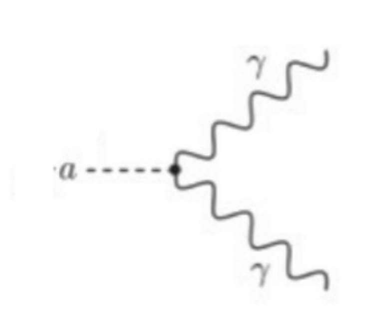
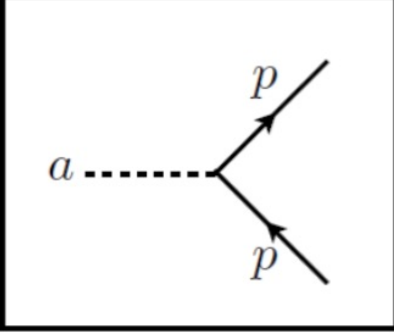
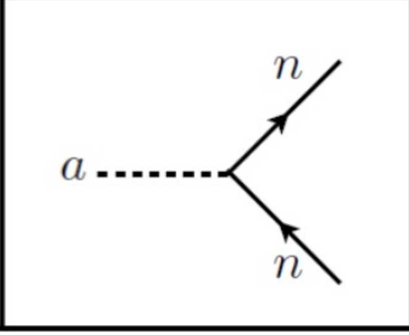
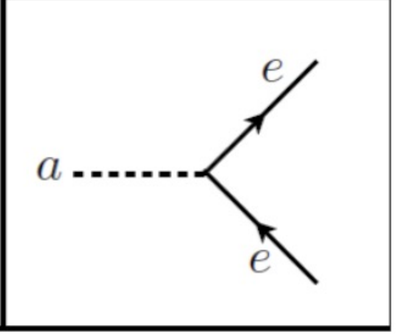
$$g_{a\gamma} \simeq \frac{\alpha}{2\pi f_\pi}\frac{m_a}{m_\pi}\frac{1+z}{\sqrt{z}}\left(\frac{E_Q}{N_Q} - \frac{2}{3}\frac{4+z}{1+z}\right)$$



$z \equiv m_u/m_d$

AXION COUPLINGS

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

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

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

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

Detection of Axions

Detection techniques

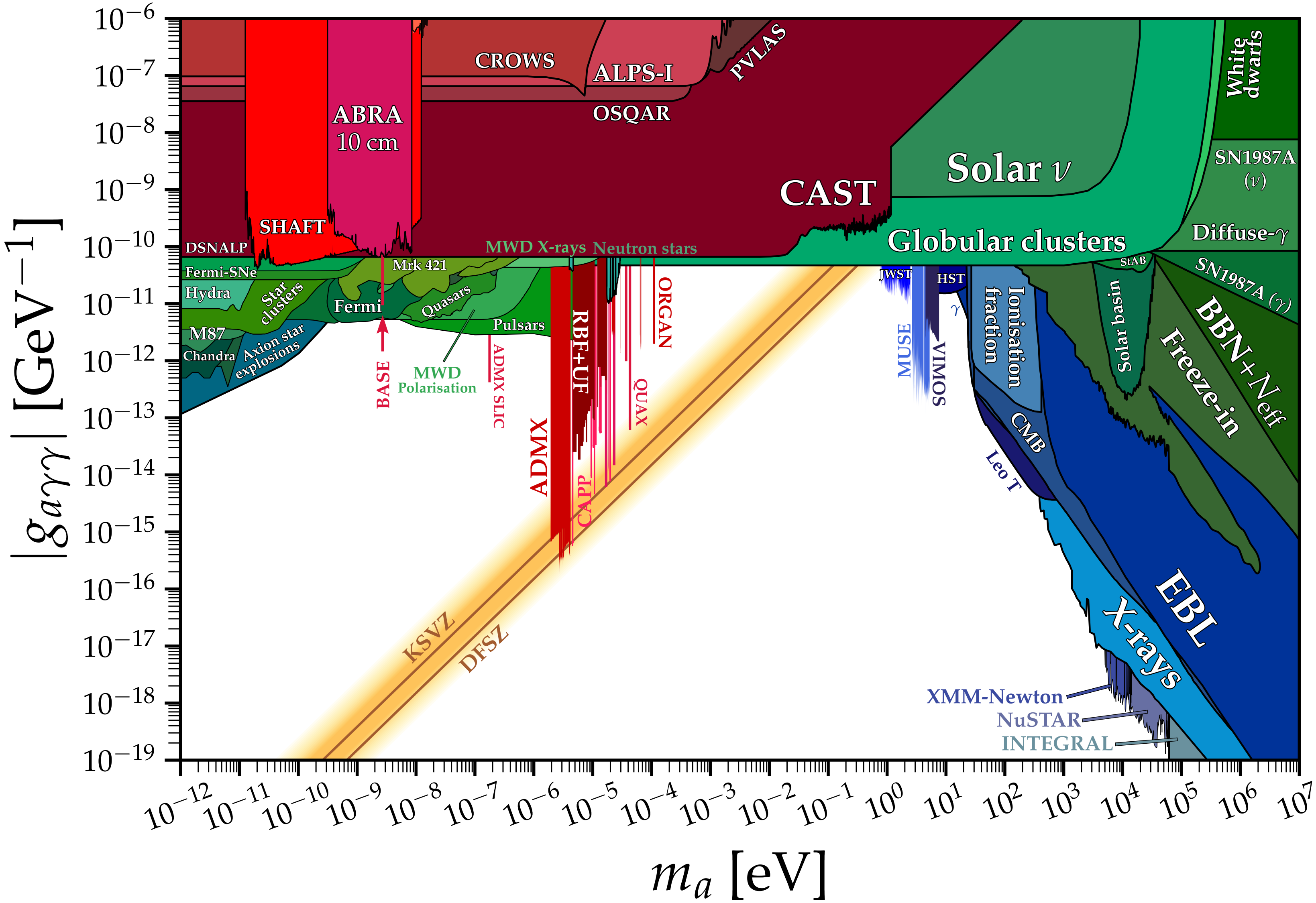
Source	Experiments	Model & cosmology dependency
Relic axions 	Haloscopes	High (assumes axions are all of the DM)
Lab axions 	Light-Shining-Through-Wall Experiments	Very low
Solar axions 	Helioscopes	Low

Large complementarity between different experimental approaches!

Detection of Axions

State-of-the-art

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

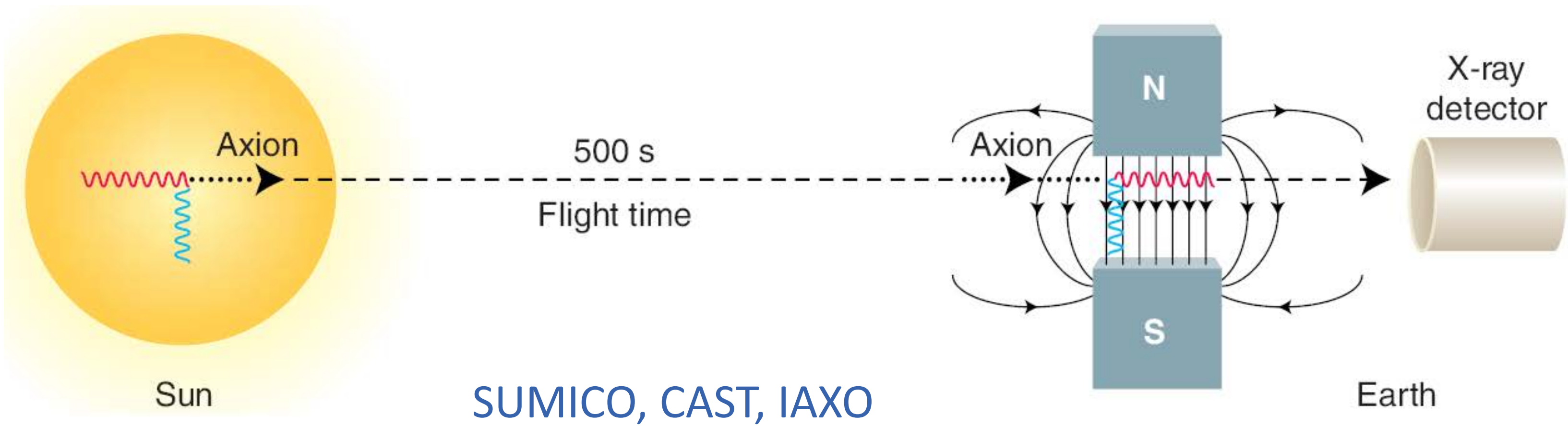


Solar Axion Searches

EXPERIMENTS NOT RELYING ON AXIONS BEING DARK MATTER

- AXION HELIOSCOPES: laboratory axion searches looking for solar axions

P. Sikivie 1983 PRL 51 1415



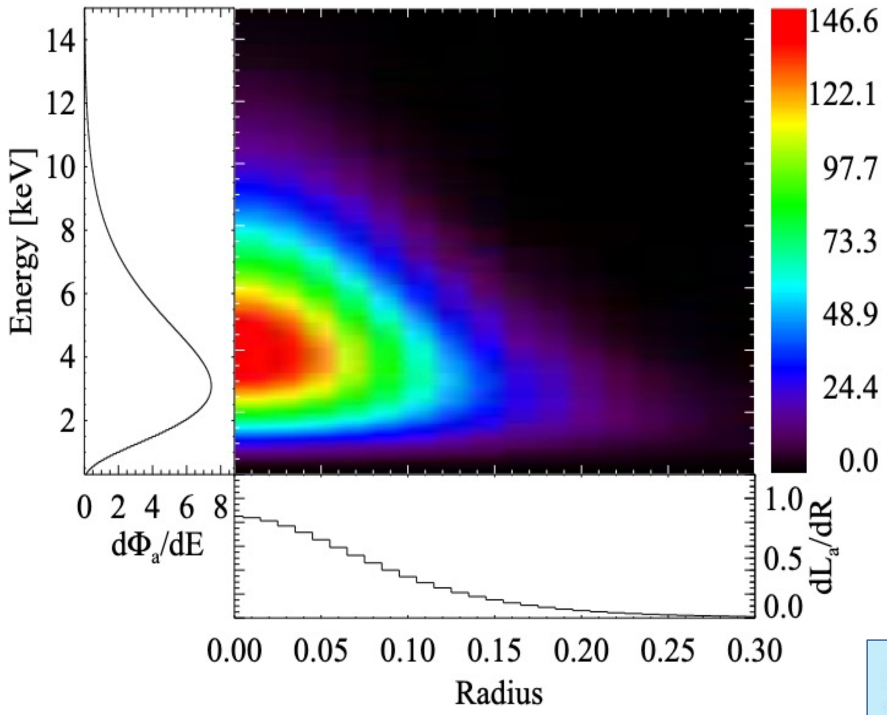
SUMICO, CAST, IAXO

Concept:

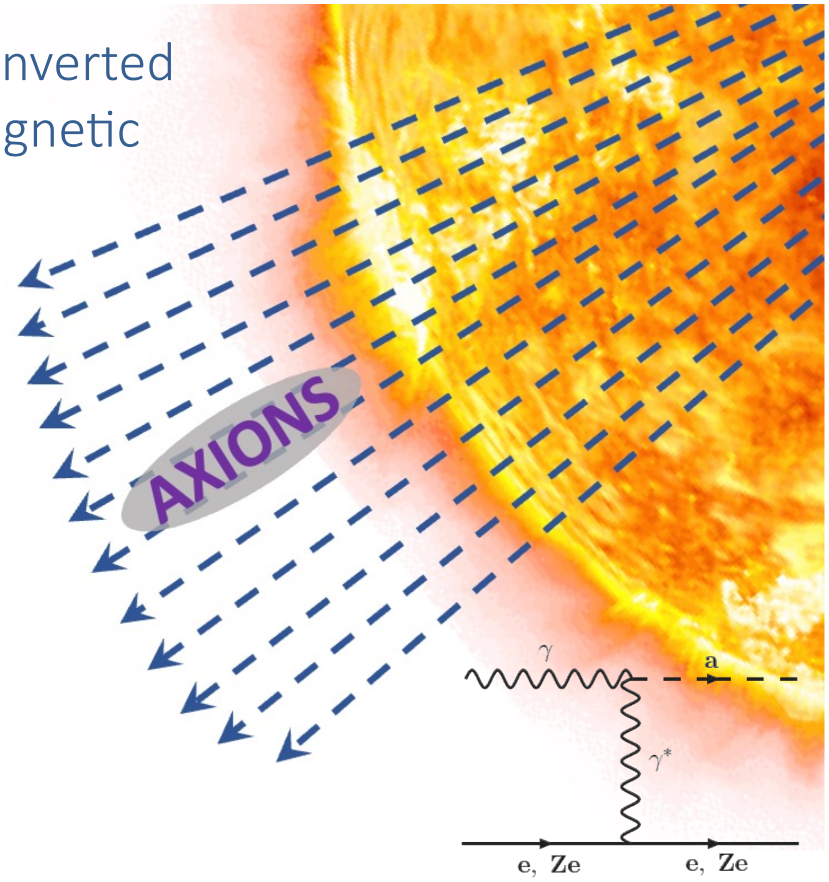
- Axions produced in strong electromagnetic fields of the core of the Sun
- Solar axion conversion into x-ray (keV) photons in transverse laboratory B-field

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.



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



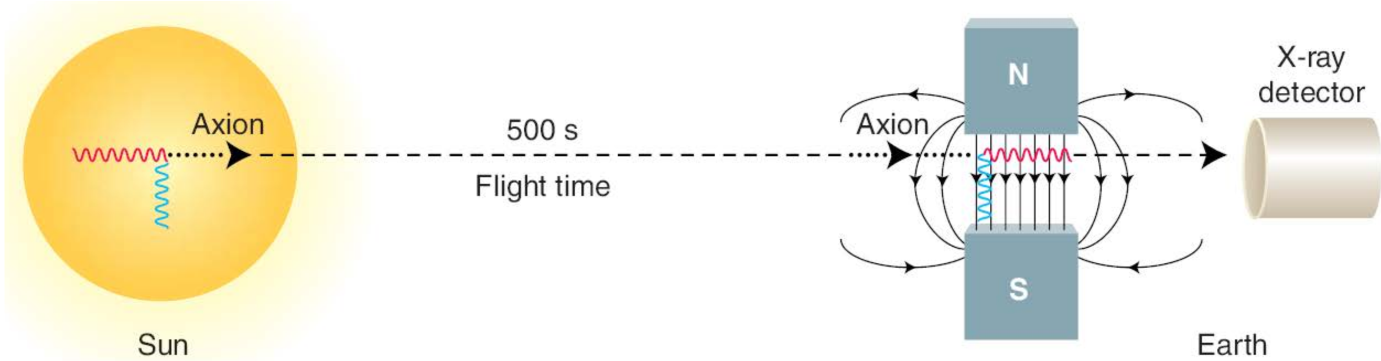
$$\frac{d\Phi_a}{dE} = 6.02 \times 10^{10} \left(\frac{g_{a\gamma}}{10^{-10}\mathrm{GeV}^{-1}} \right)^2 E^{2.481} e^{-E/1.205} \frac{1}{\mathrm{cm}^2 \ \mathrm{s\ keV}}$$

Solar Axion Searches

- First axion helioscope proposed by P. Sikivie

P. Sikivie 1983 PRL 51 1415

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



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

VACUUM

- Idea refined by K. van Bibber et al.

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

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

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

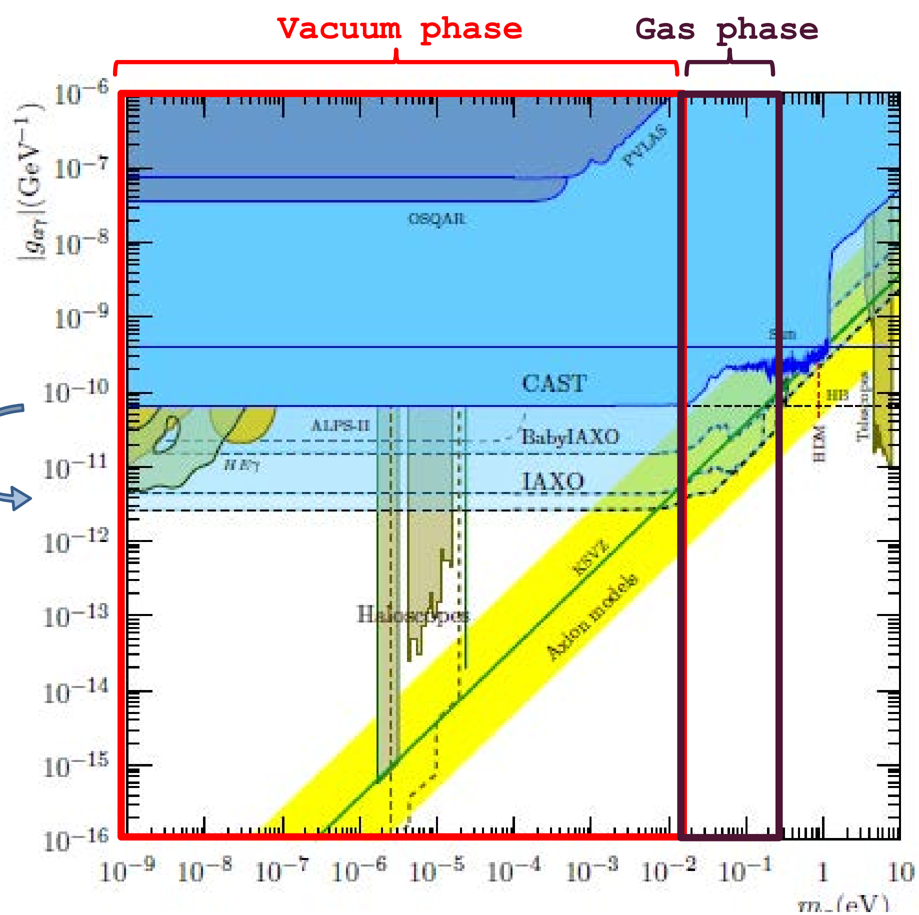
GAS

Solar Axion Searches

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

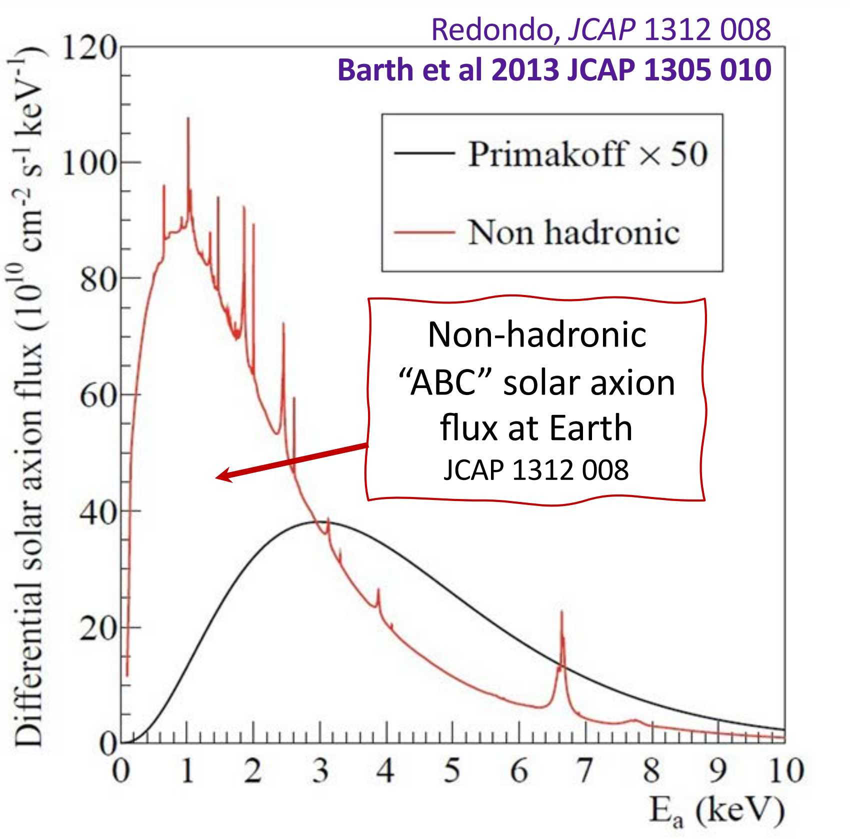
$$m_\gamma = 4.498716\sqrt{\frac{P_{He}[\text{atm}]}{T_{He}[\text{K}]}}\,\text{eV}.$$

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

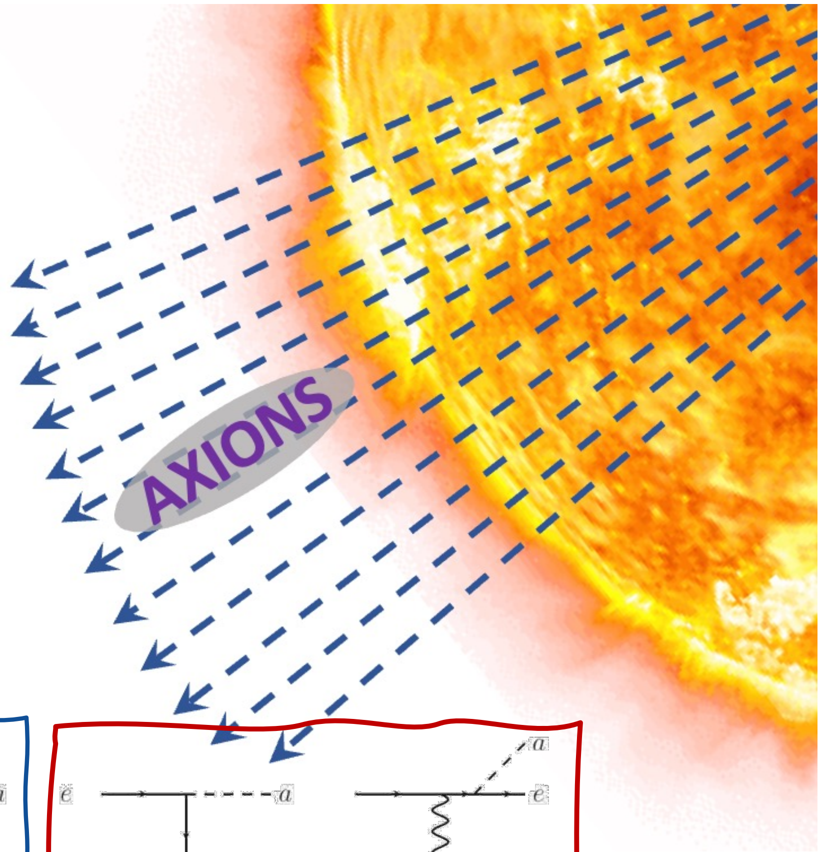


Solar Axion Searches

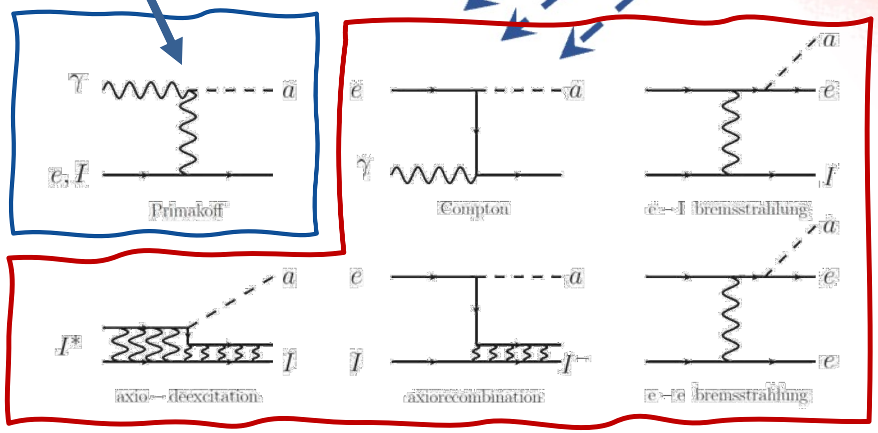
- Additionally to Primakoff: “ABC axions” which m be ✕100 more intense but model-dependent



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

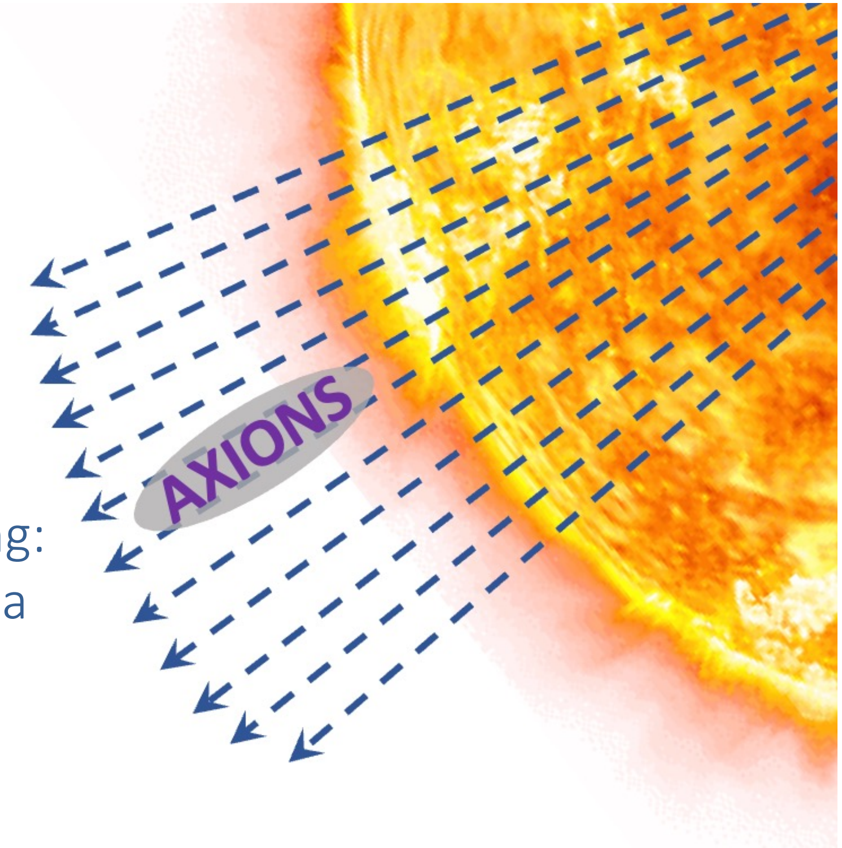


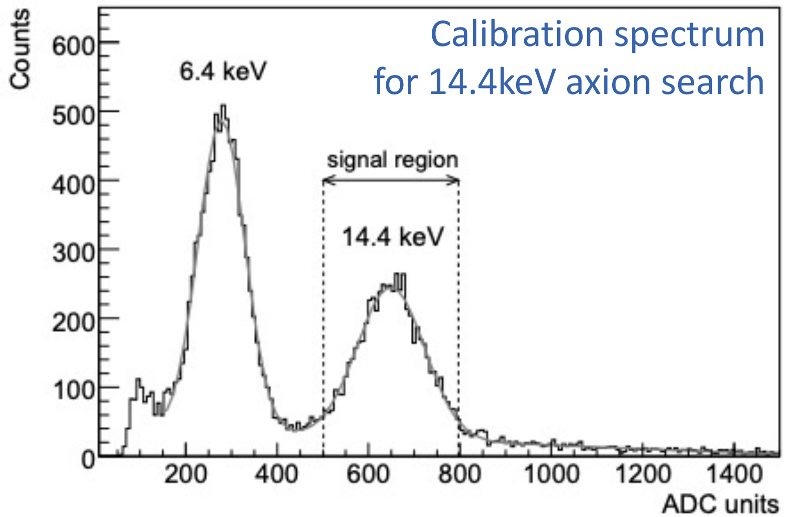
Primakoff axions



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

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

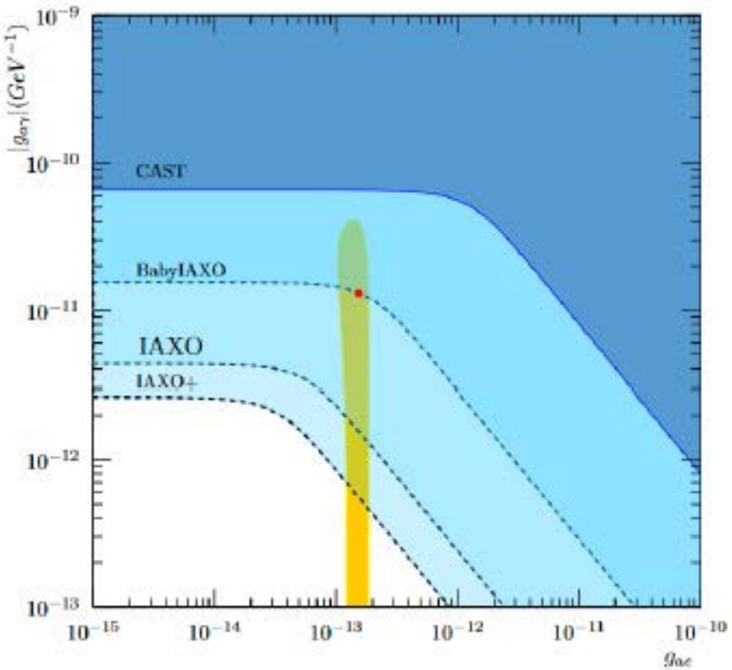
Di Luzio *et al* 2022 *Eur. Phys. J.* C 82:120
CAST collaboration *et al* 2009 *JCAP* 12 002
D. Miller *et al* 2010 JCAP 1003 032
Derbin *et al 2023 Jetp Lett.* **118**, 160

Solar Axion Searches

Detection Helioscope

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

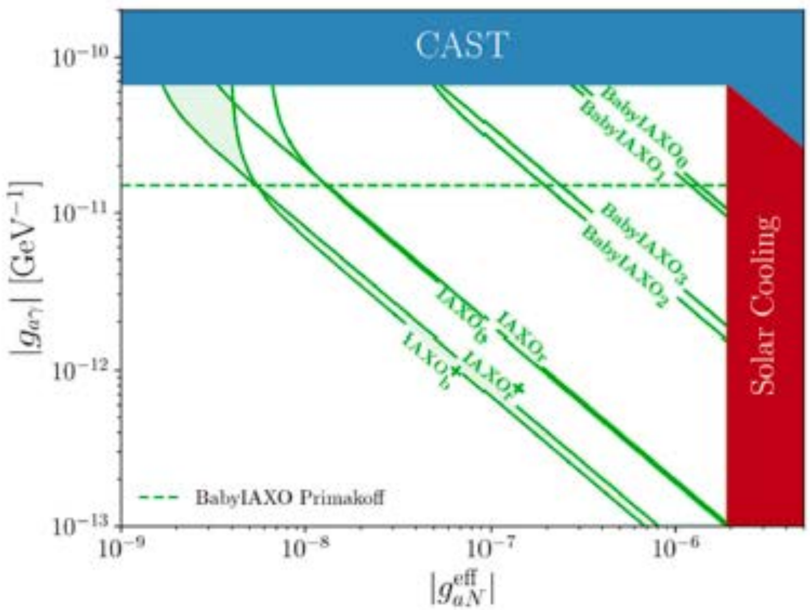
- Axion mass $m_a \simeq 1meV$



Physics potential of the International Axion Observatory (IAXO) JCAP06(2019)047

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

- Axion mass $m_a \simeq 20meV$

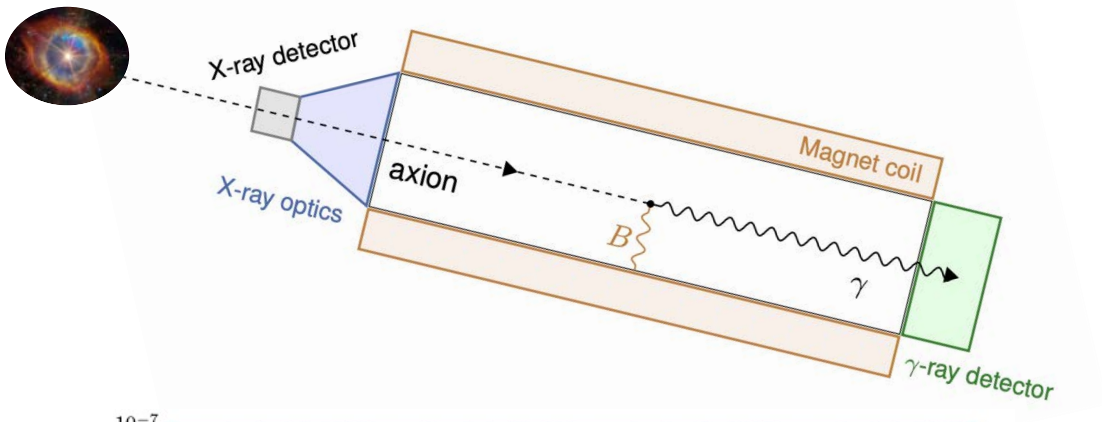


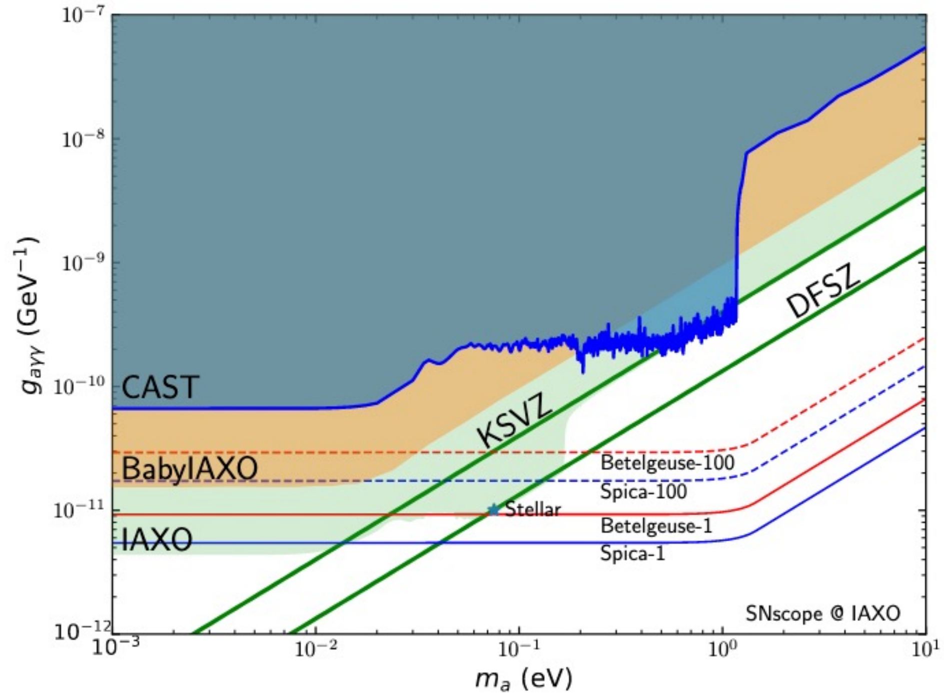
Probing the axion–nucleon coupling with the next generation of axion helioscopes Eur. Phys. J. C (2022) 82:120

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 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.

Ge et al. 2008.03924



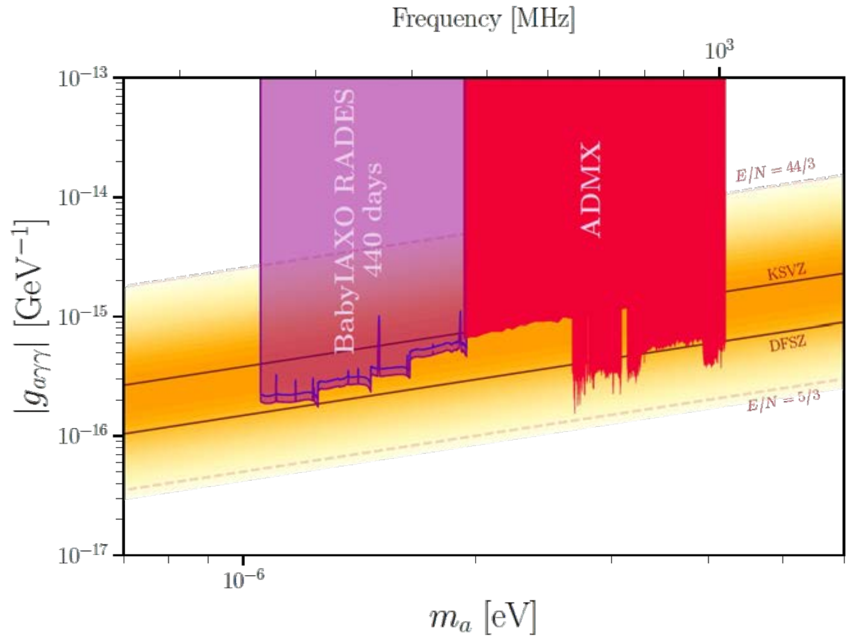


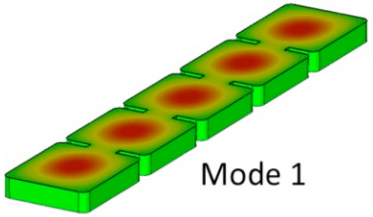
IAXO Physics

Beyond baseline physics

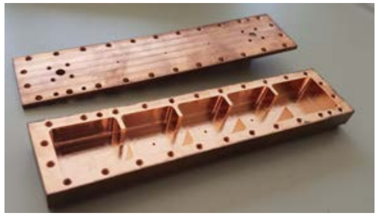
Ahyoune et al. (RADES Collaboration) arxiv:2306.17243

- Use of (Baby)IAXO large magnetic volume for axion DM setups
- Very competitive prospects for 1-2 meV axion searches.
- Other implementations are being discussed (need more work)





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



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

I. Irastorza (U. Zaragoza), T. Kontos (École Normale Supérieure de Paris), S. Paraoanu (Aalto University), W. Wernsdorfer (KIT)

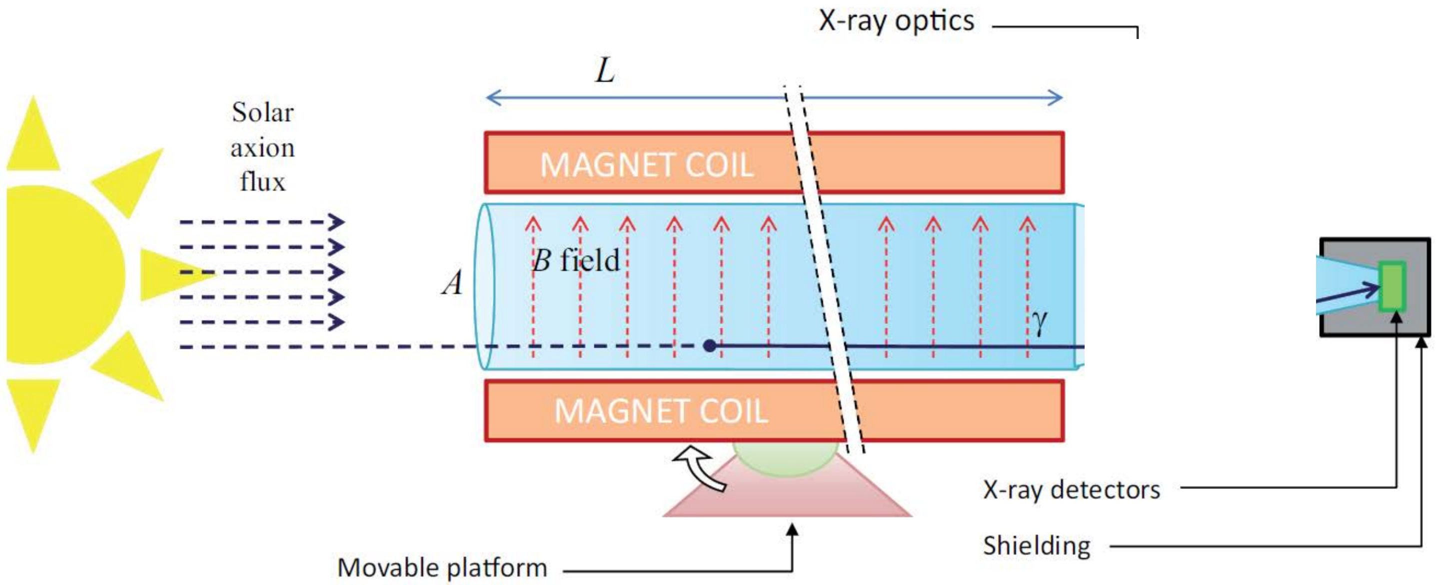
ERC-Synergy Grant DarkQuantum obtained !

- Develop quantum tech for axions
- Quantum-enhanced haloscope in BabyIAXO
- Connection with experts (cryo, quantum,...)
- Contribution to magnet

DarkQuantum

Solar Axion Searches

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



Measure of sensitivity to axion-photon interaction:

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

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

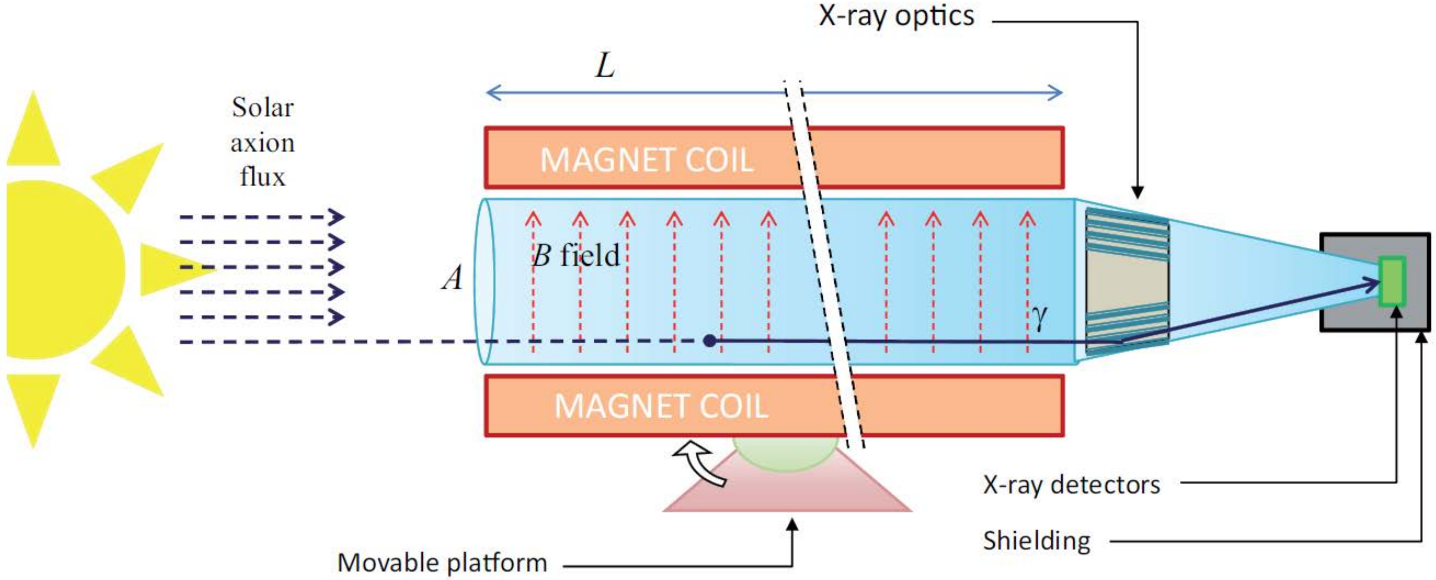
exposure
t = time

detectors
b = background
ε = efficiency

The smaller g_{ag} the better!

Solar Axion Searches

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



Measure of sensitivity to axion-photon interaction:

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

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

exposure
t = time

optics
s = spot size
ε_0= efficiency

detectors
b = background
ε = efficiency

The smaller g_{ag} the better!

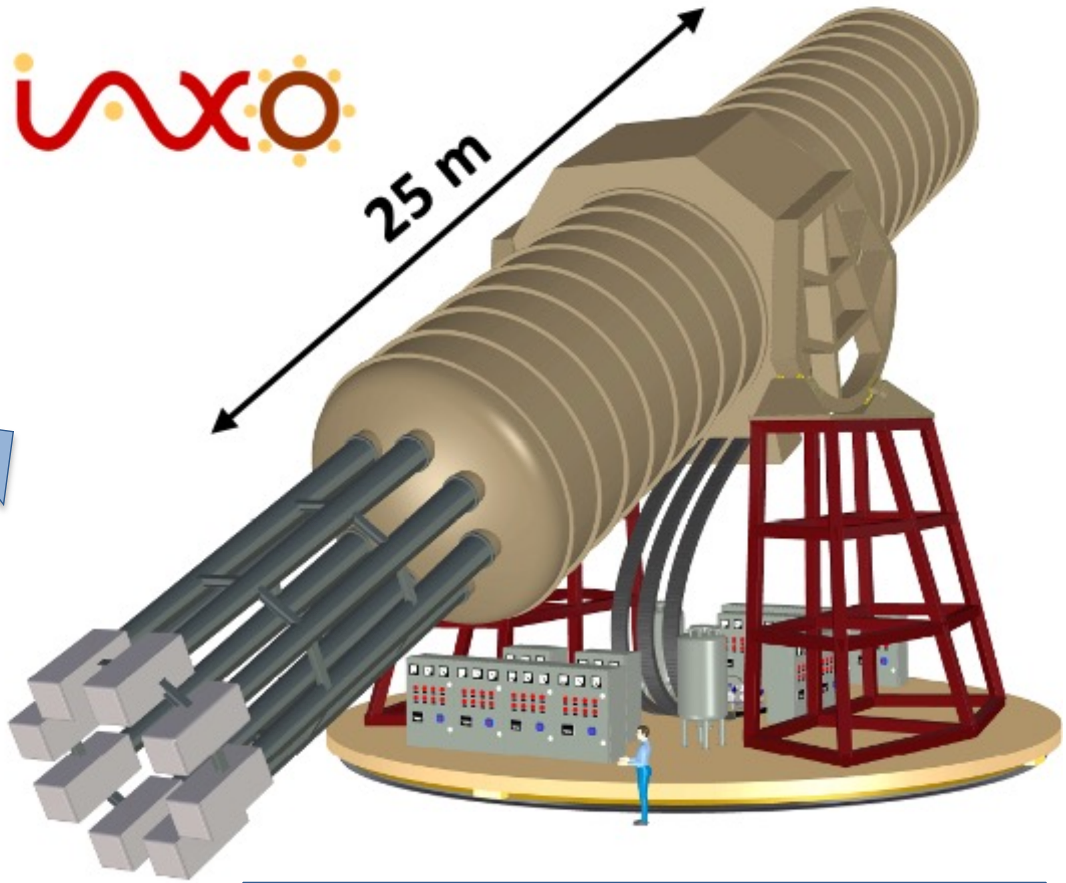
Expect improvement for next gen (International Axion Observatory):
1–1.5 orders of magnitude in sensitivity to $g_{a\gamma}$ (factor of 10000-20000 in S/N)

Solar Axion Searches

CAST

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

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

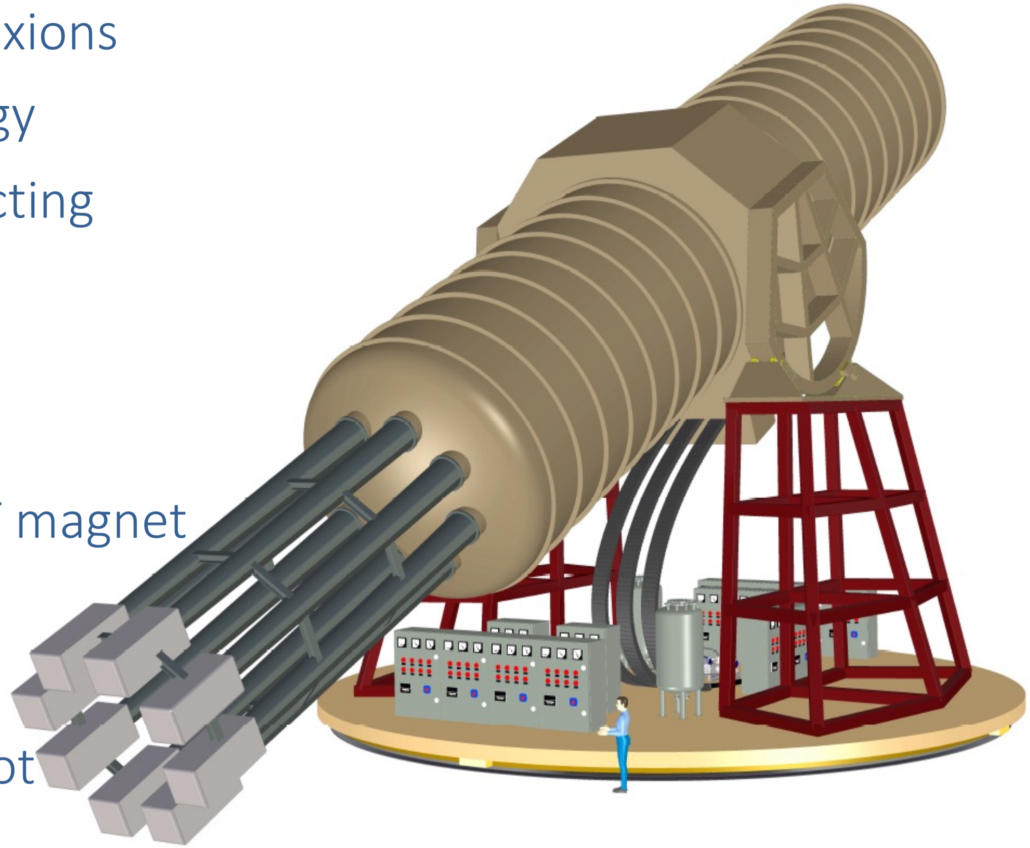


$g_{a\gamma} \lesssim \text{few}\ \ 10^{-12}\ \mathrm{GeV}^{-1}$ (expected)

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.

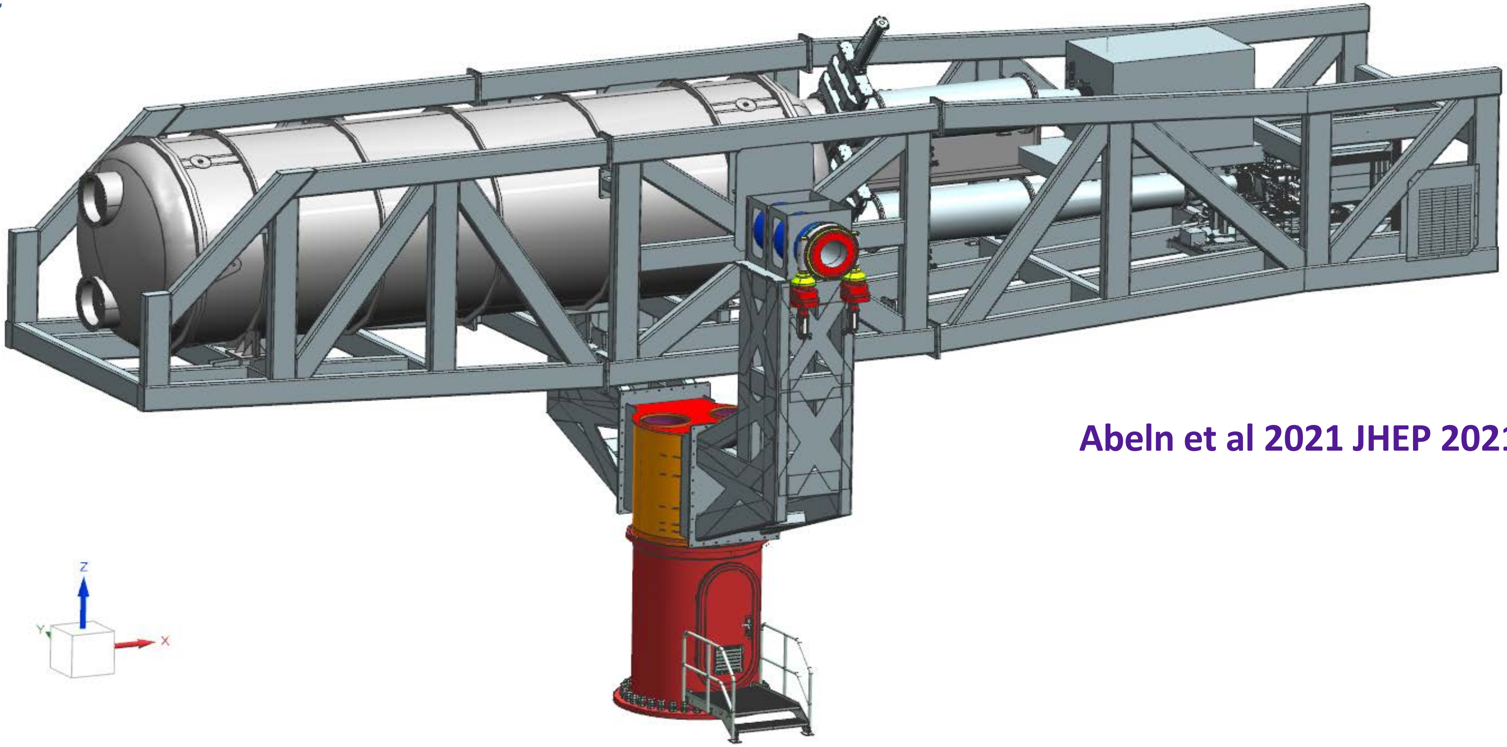


Armengaud et al 2014 JINST 9 T05002
Irastorza et al 2011 JCAP 1106, 013

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

Baby IAXO

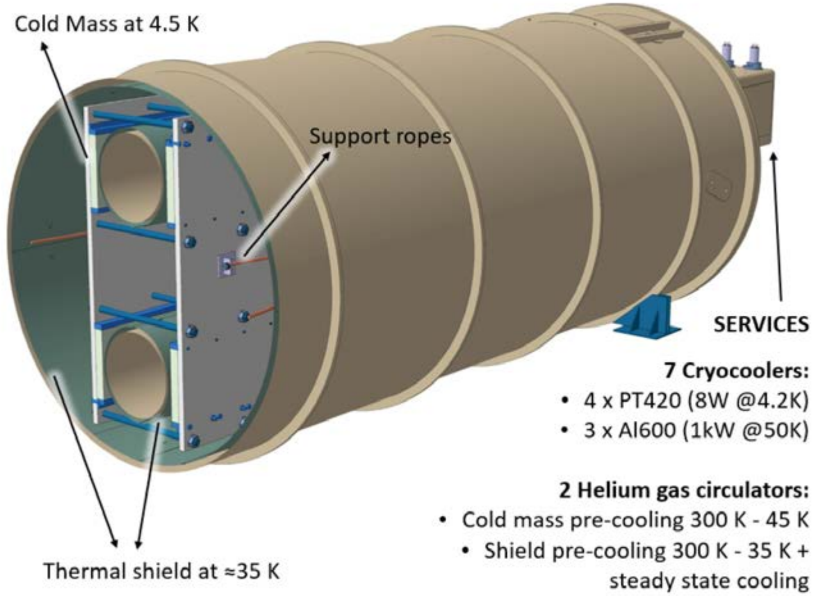
Solar Axion Searches

Baby IAXO

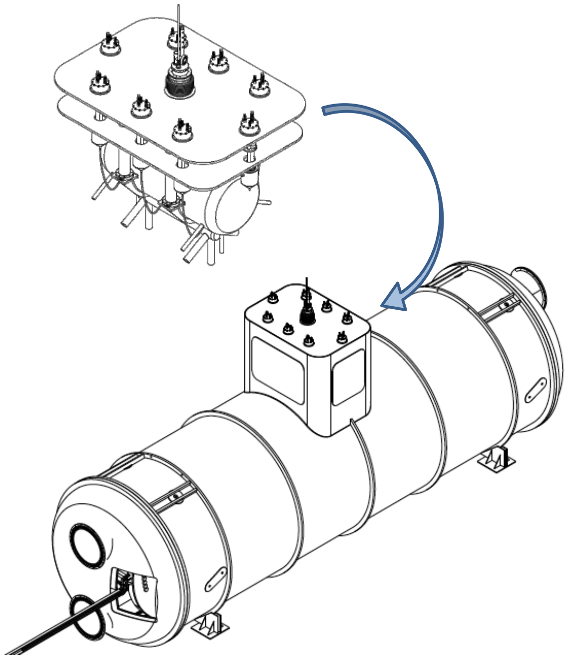
Solar Axion Searches

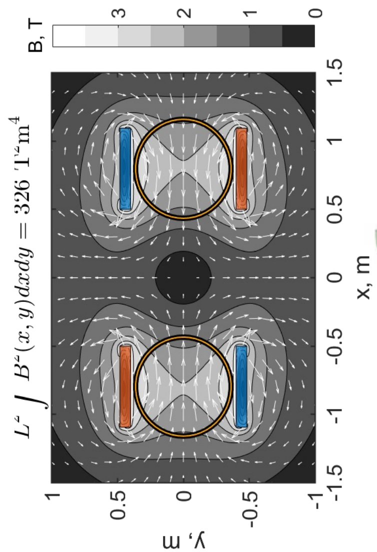
✓ BabyIAXO magnet to be operated at T ≤ 5 K featuring Nb-Ti-based superconducting coils with about 2 T in the bore

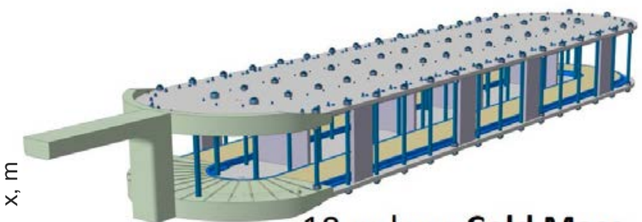
- Nb-Ti is most affordable superconductor
- It is also mechanically ductile and robust
- Well studied work-horse conductor for most existing superconducting magnets



Contract for cable development recently signed



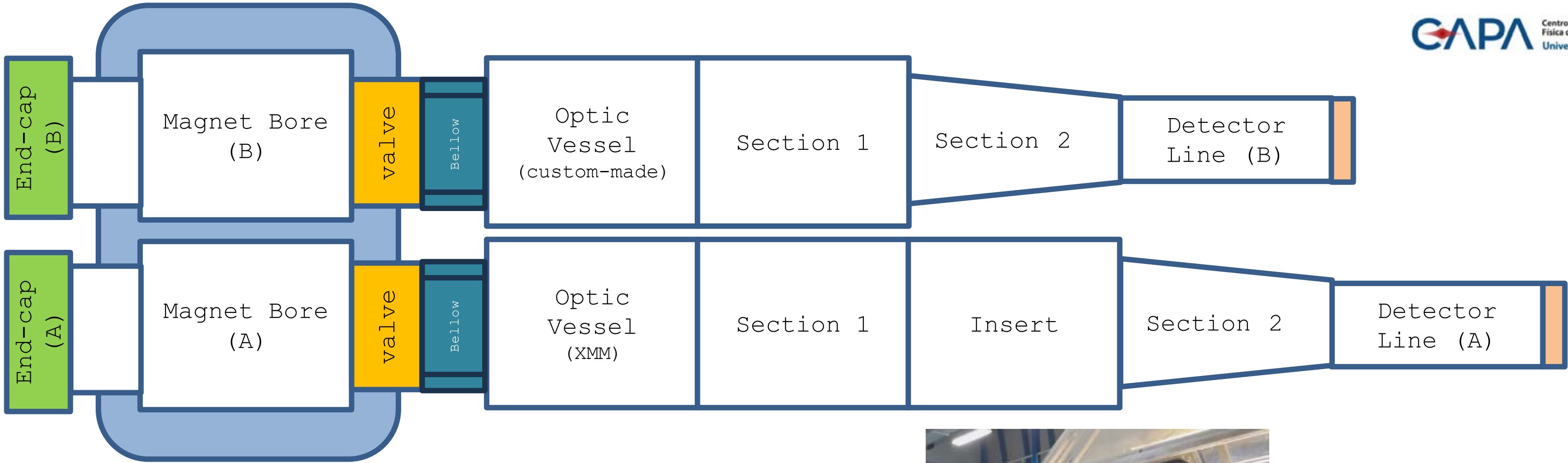


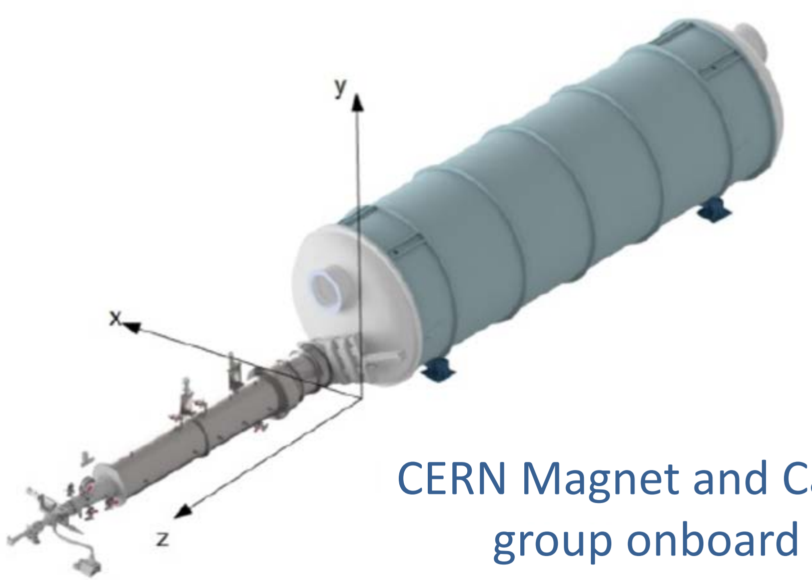


10-m long **Cold Mass**

MAGNET DEVELOPMENT

Solar Axion Searches



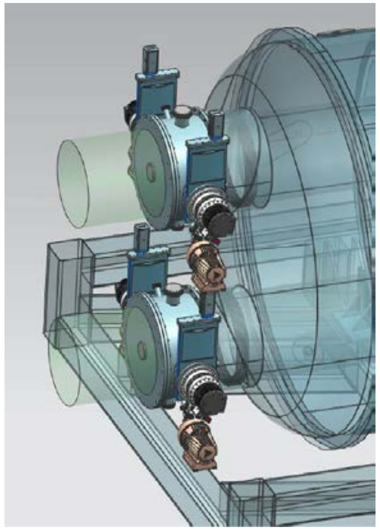


CERN Magnet and Cable group onboard

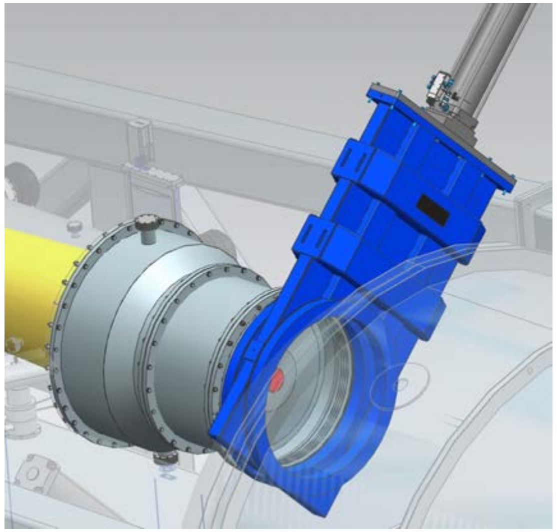
Ordering 2km of cable strand for winding tests

BEAM LINE

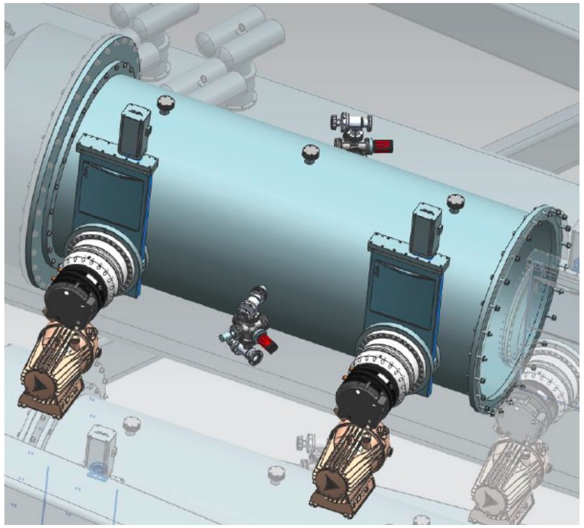
Solar Axion Searches



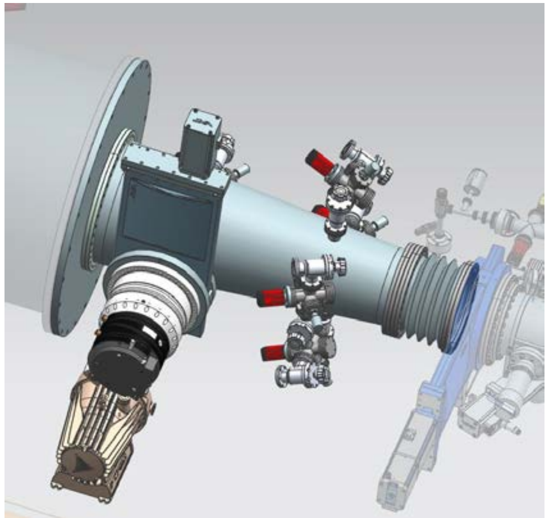
Magnet End-cap



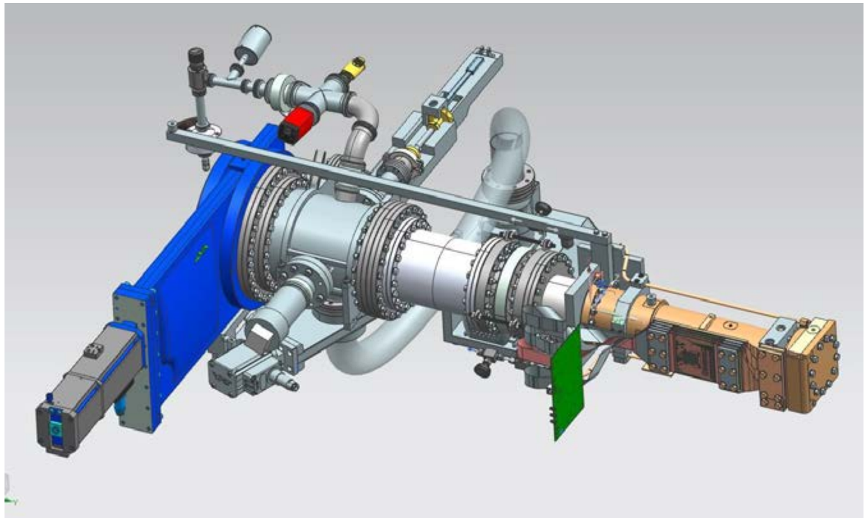
Magnet Telescope Vessel



Beam line Section 1



Beam line Section 2



Detector line

BEAM LINE

Solar Axion Searches

Baby IAXO

BabyIAXO OPTIC APPROACH:

✓ 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

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

X-ray Optics

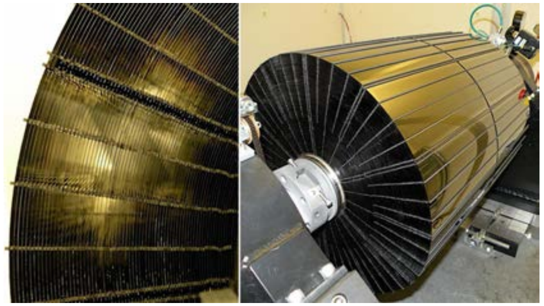
Leveraging decades of research by NASA and ESA for space instrumentation: minimal risk and superior performance

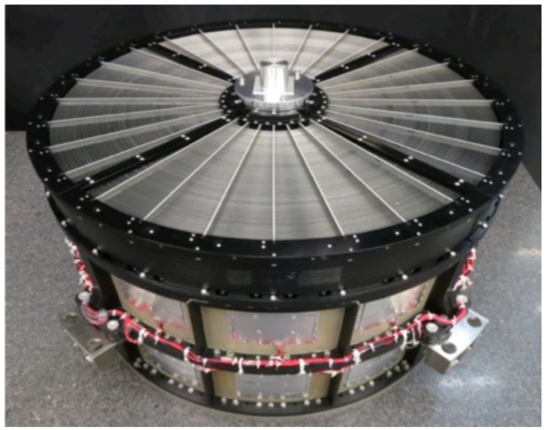
Solar Axion Searches

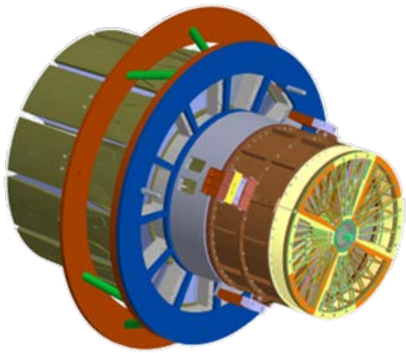
Baby IAXO

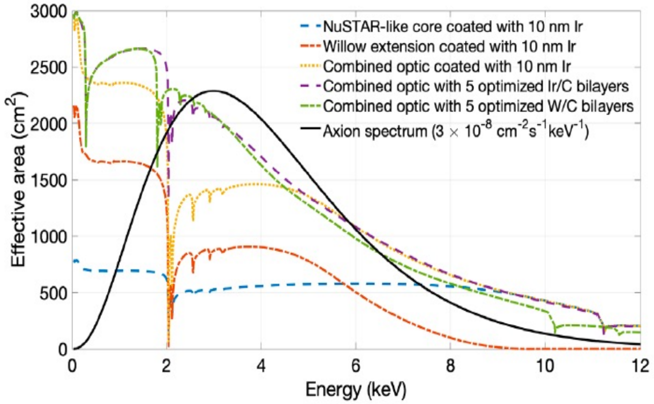
- ✓ IAXO-NuSTAR PATHFINDER @ CAST
- ✓ IAXO-CSGO/ATHENA PATHFINDER @ PANTER
- ✓ R&D for coating flat and curved substrates

NASA · MIT Massachusetts Institute of Technology · COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK · INAF ISTITUTO NAZIONALE DI ASTROFISICA · OSSERVATORIO ASTRONOMICO DI BRERA



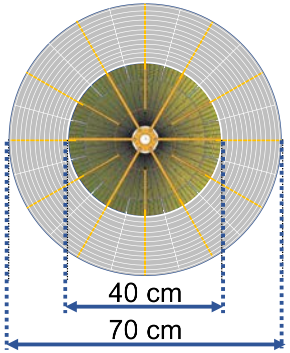


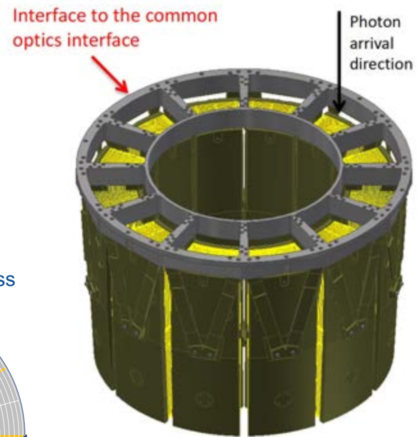




Custom optics

Hot and cold slumped glass





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

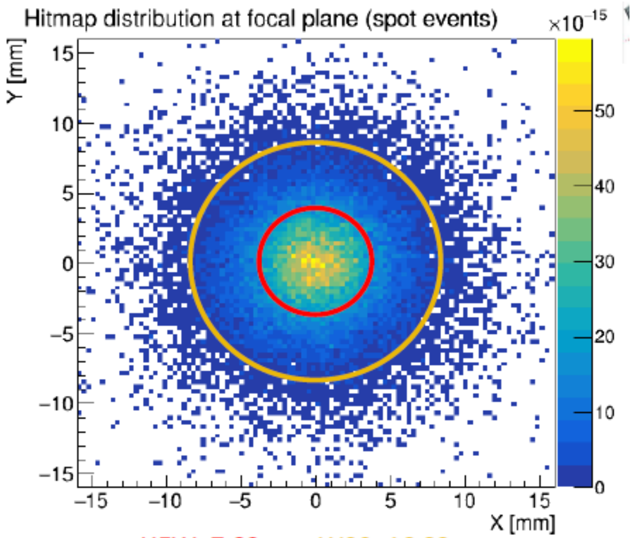
X-ray Optics

Solar Axion Searches

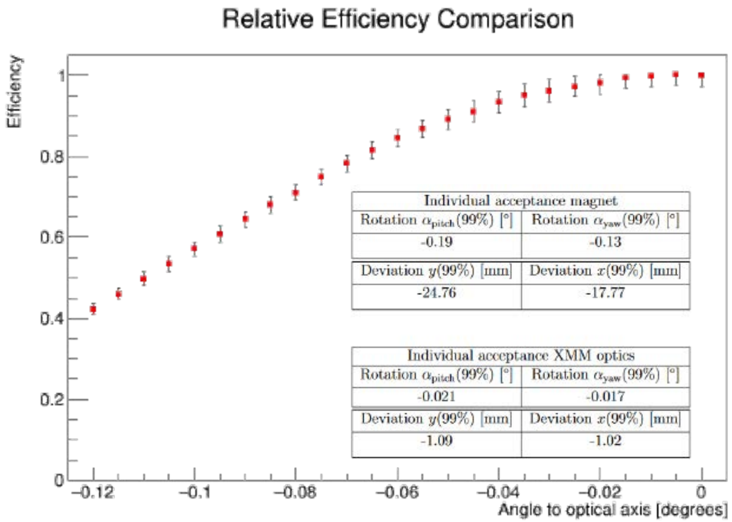
Baby IAXO

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

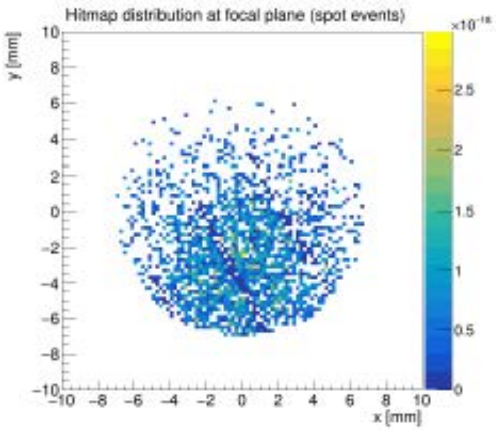
Rare Event Searches Toolkit software

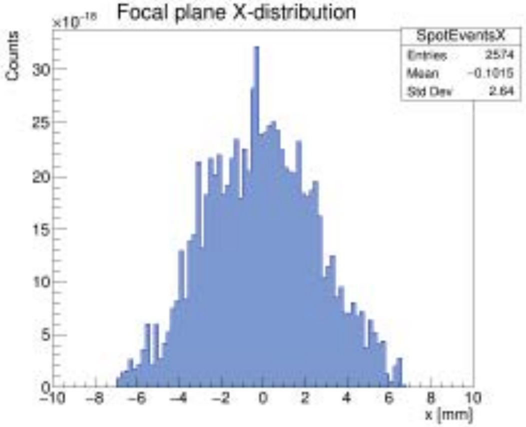


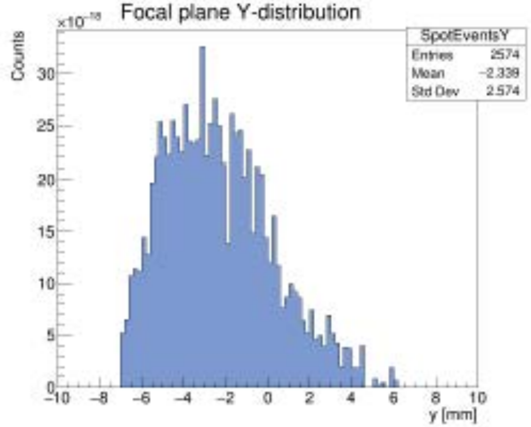
HEW=7.83mm W90=16.83mm
HEW=3.59’ W90=7.714’



Magnet and optics rotation







Acceptance Studies

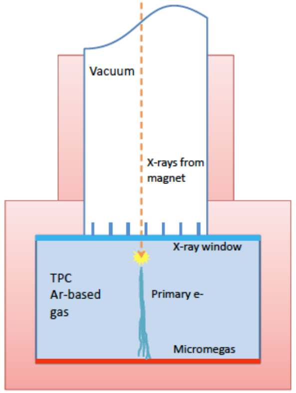
Solar Axion Searches

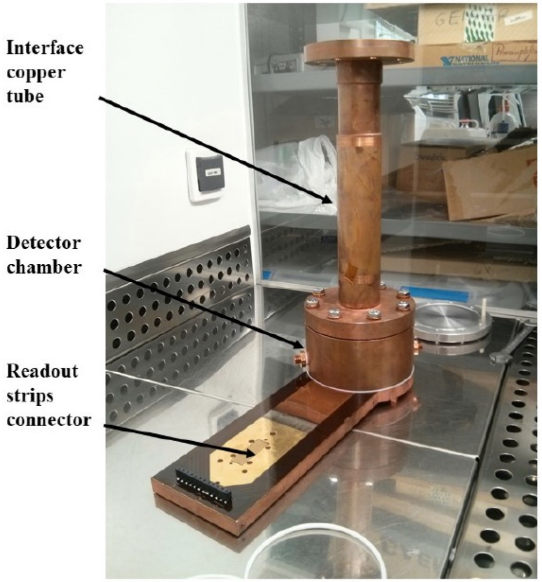
NEED (Baseline 1-10 keV):

- ✓ 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





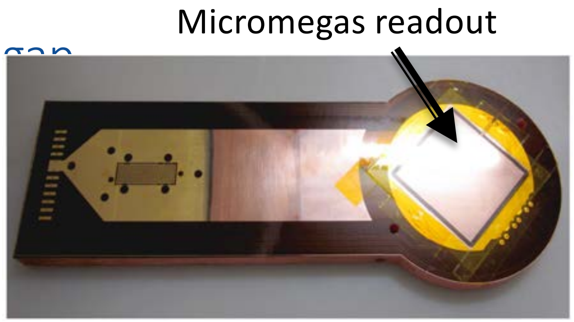
Detectors

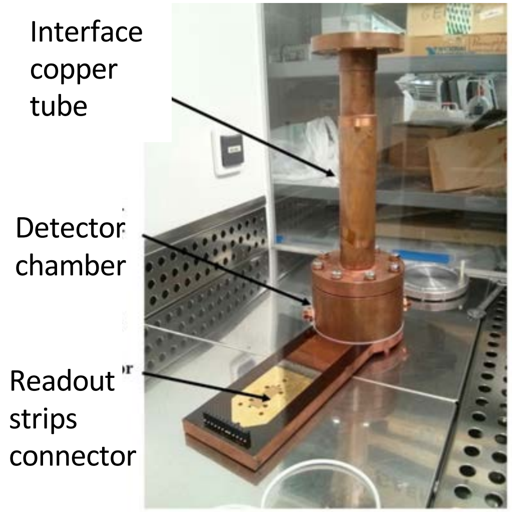
Micromegas best option to reach required low background Additional technologies considered and undergoing active R&D efforts (GridPix, MMC, TES, SDD)

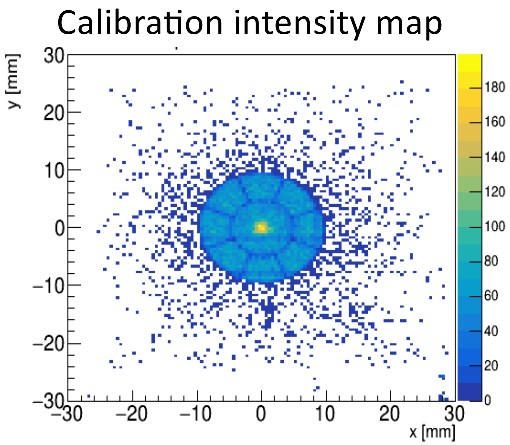
Solar Axion Searches

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).







X-ray window

Rare Event Searches Toolkit software

Detectors

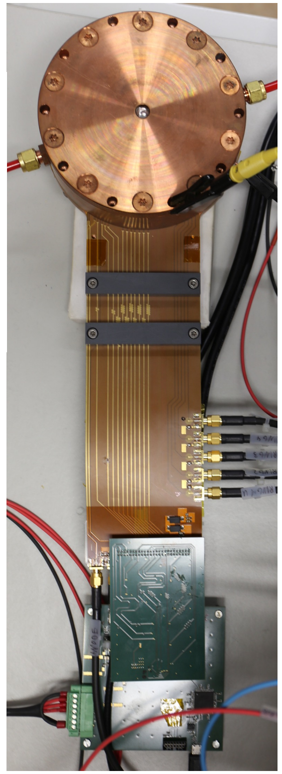
Solar Axion Searches

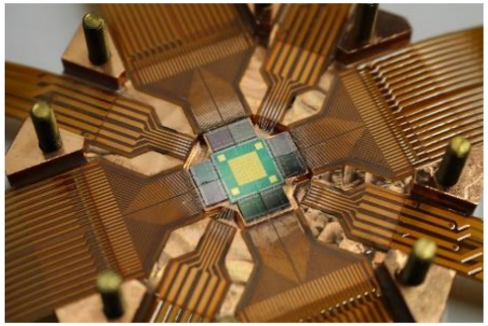
Baby IAXO

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

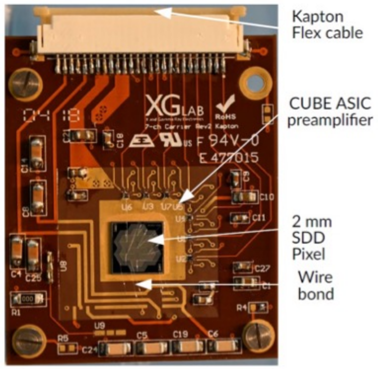
ERC-StG (2020)
M.Meyer
To understand bkg in TES

erc

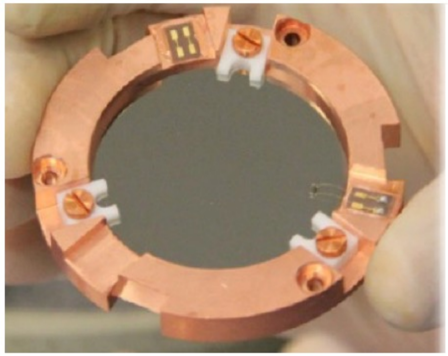




MMC: Metallic Magnetic calorimeters



SDD: Silicon Drift Detectors



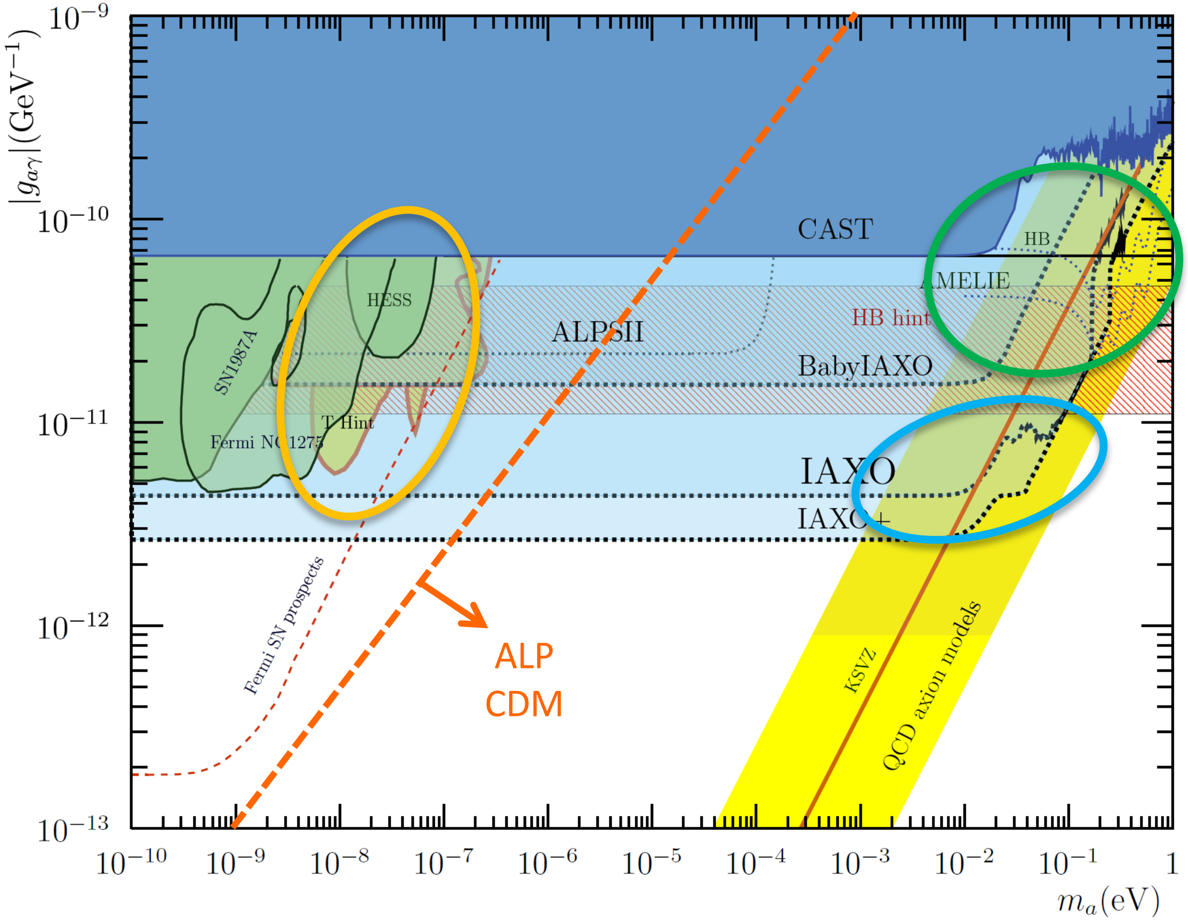
TES: Transition Edge senstors

Gridpix

Detectors

- ✓ 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

Sensitivities



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

Solar Axion Searches

Armengaud et al 2019, JCAP 1906, 047

IAXO as a generic axion(-like) detection facility

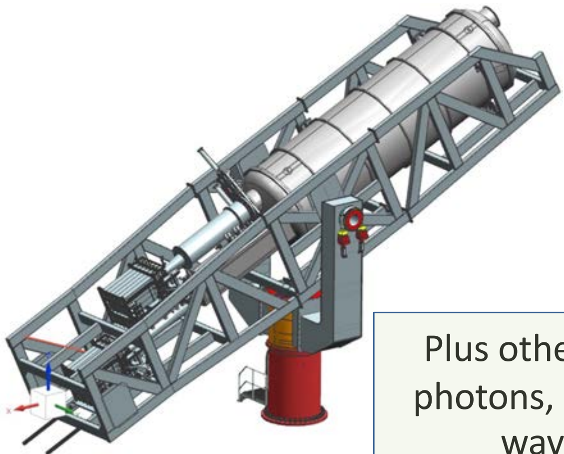
- (Baby)IAXO constitutes a great infrastructure that can be used to target other physics goals beyond Primakoff solar axions:

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



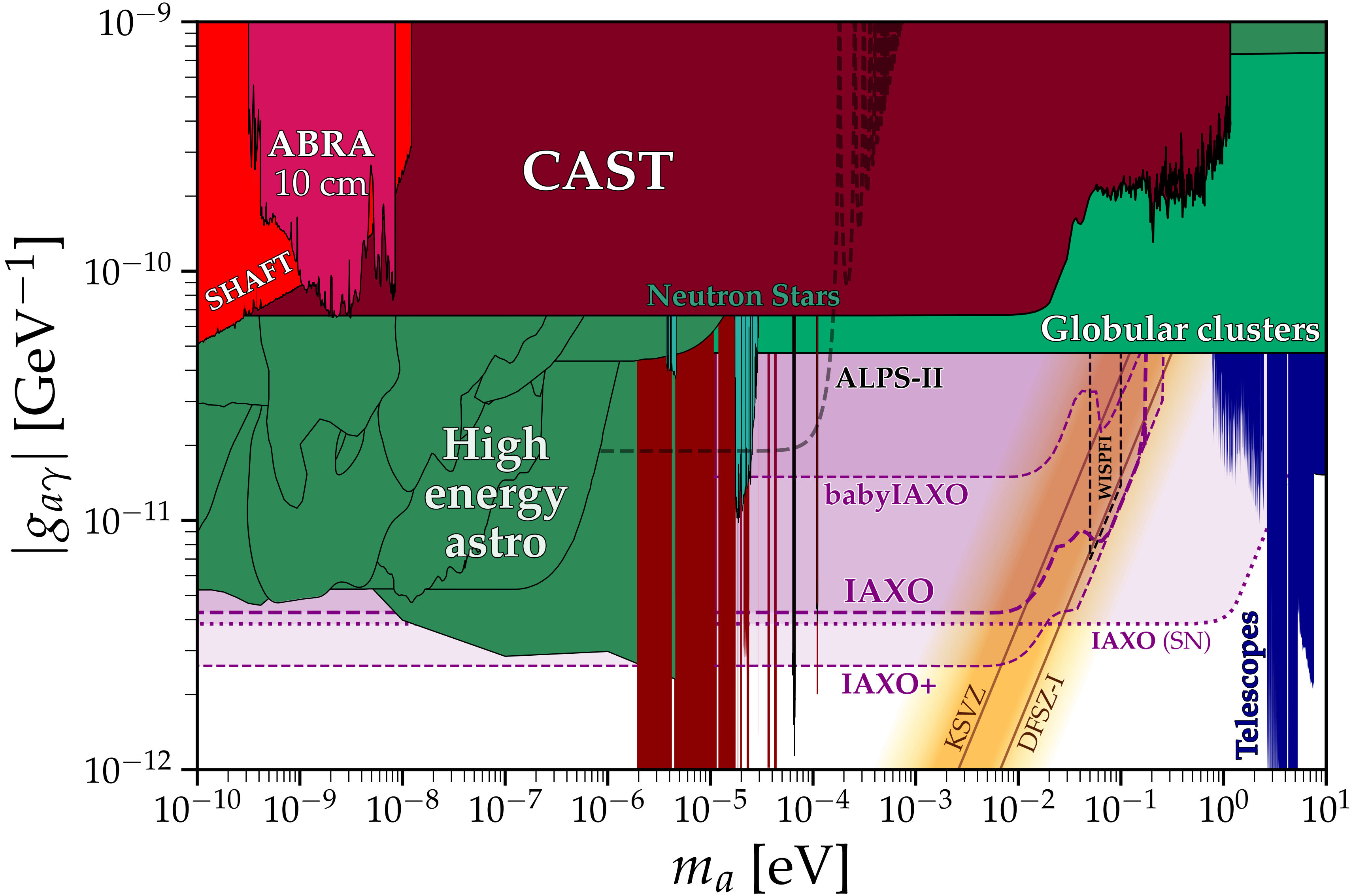
Plus other WISPs, such as hidden (dark) photons, chame-leons, etc., gravitational wave searches and NS studies

Beyond Base Line Science

IAXO & Baby IAXO

Sensitivities

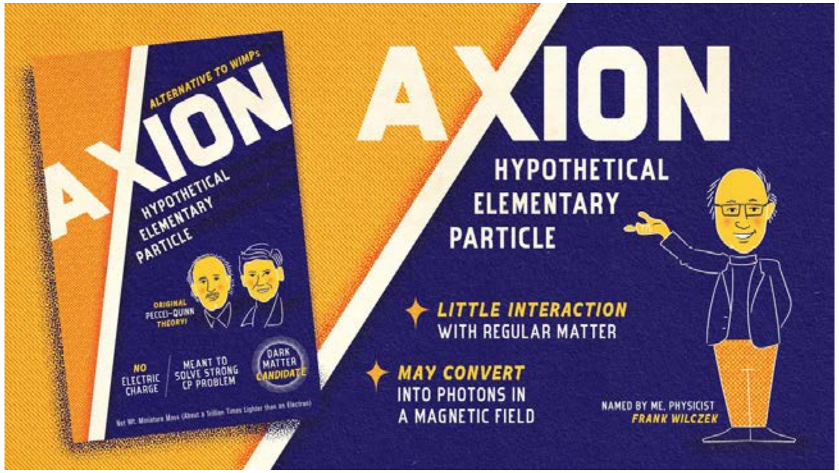
Adapted from https://github.com/cajohare/AxionLimits



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!



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