Solar Axion Searches with Helioscopes

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INFL LNF, Frascati, Italy

Outline

Intro to axions

Solar Axion Detection

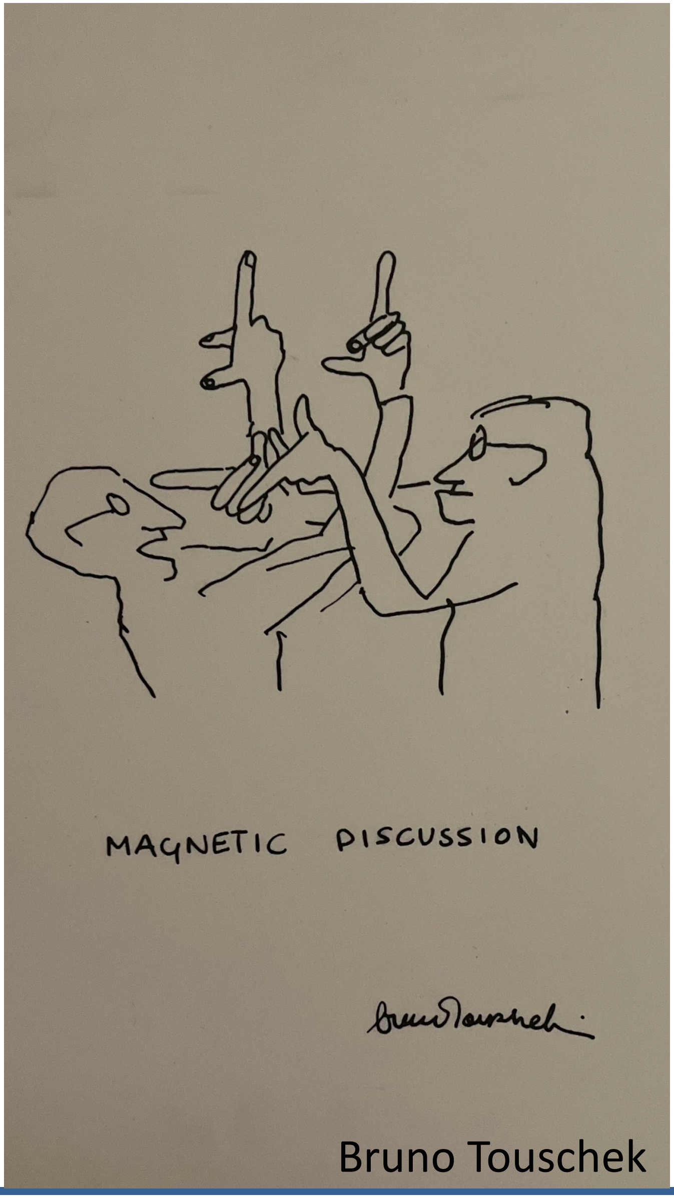
Previous helioscopes and State-of-the-Art

Next-Gen: The International Axion Observatory (IAXO)

Next-Gen: BabyIAXO

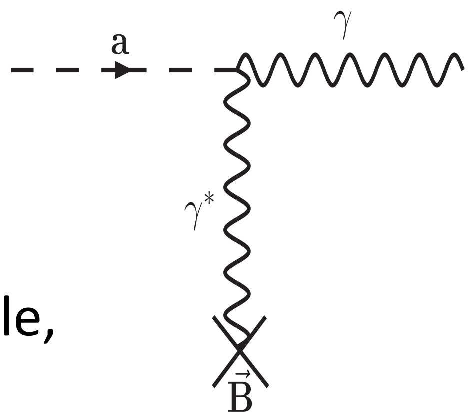
Next-Gen: Physics Prospects

Conclusions



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}

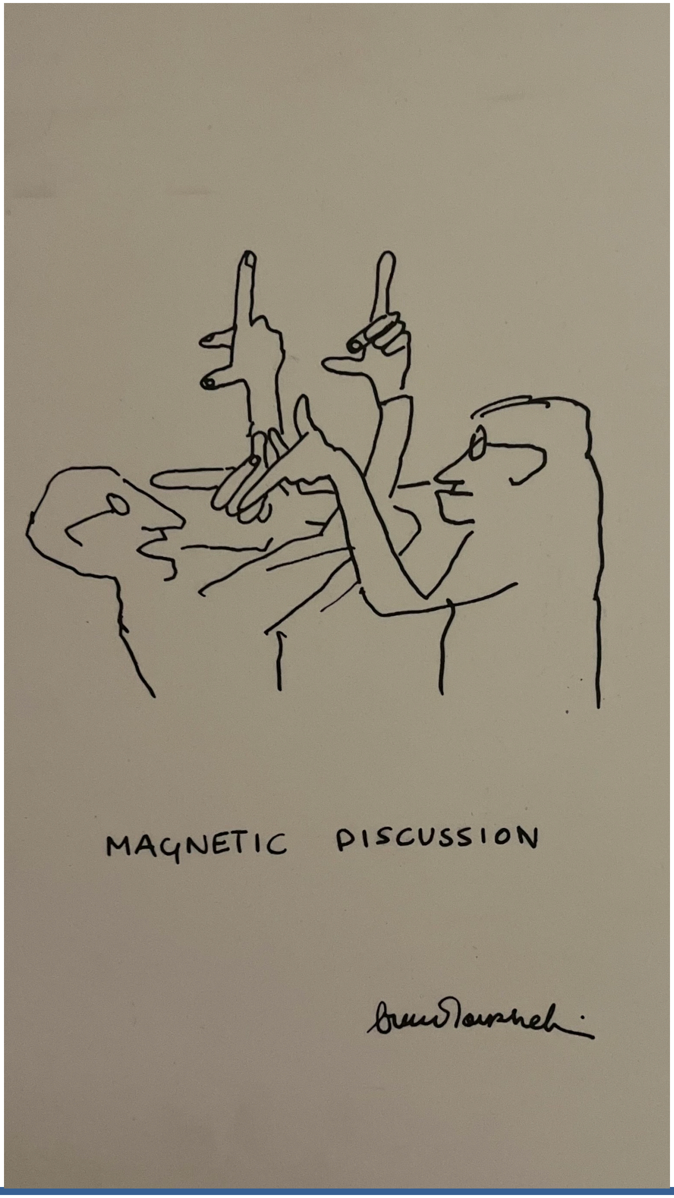
→ **Dark matter candidate**

Recent experimental review:

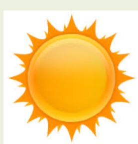
I. G. Irastorza & J. Redondo, PNPP 102, 89, 2018 (arXiv:1801.08127)
New experimental approaches in the search for axion-like particles

Intro to axions

Solar Axion Detection



Axion Detection

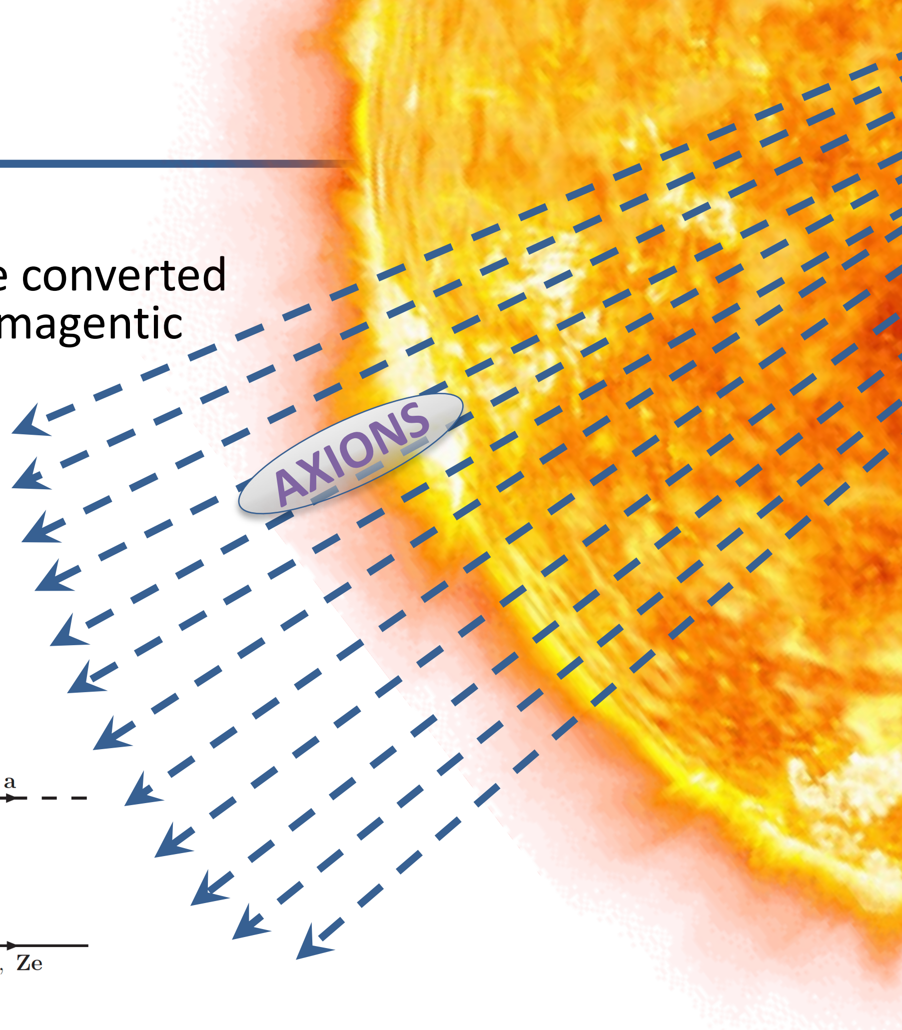
Source	Experiments	Model and cosmology dependency	Technology
Relic axions 	ADMX, HAYSTAC, CASPEr, CULTASK, CAST-CAPP, MADMAX, ORGAN, RADES, QUAX, …	High	New ideas emerging, Active R&D going on,…
Lab axions 	ALPS, OSQAR, CROWS, ARIADNE,…	Very low	
Solar axions 	SUMICO, CAST, (NuSTAR) IAXO & BabyIAXO	Low	Ready for large scale experiment

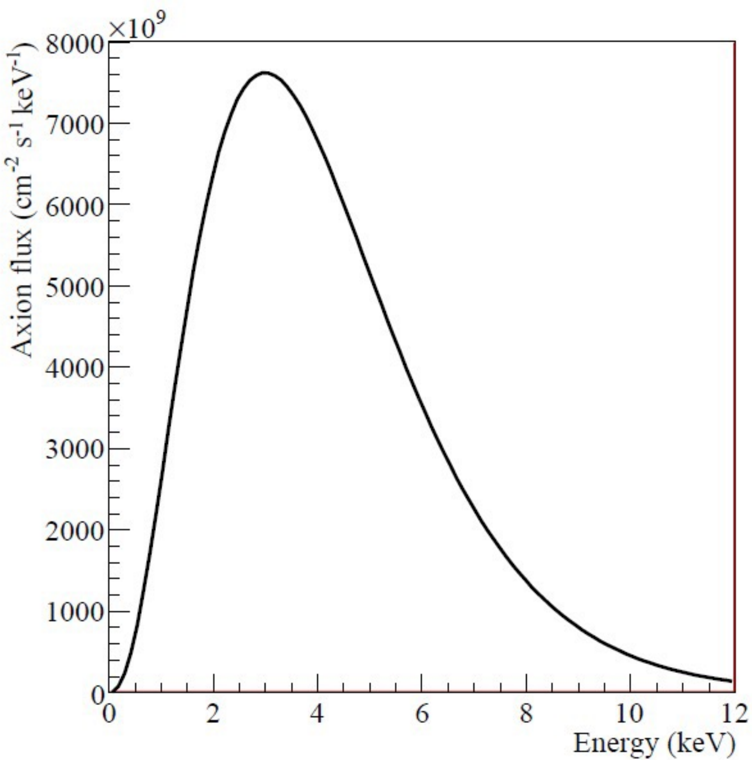
Helioscopes technique:

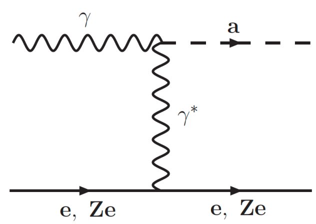
- Does not require axions to be dominant DM component
- Large complementarity with other strategies
- Technology mature enough for a large scale experiment (IAXO)

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







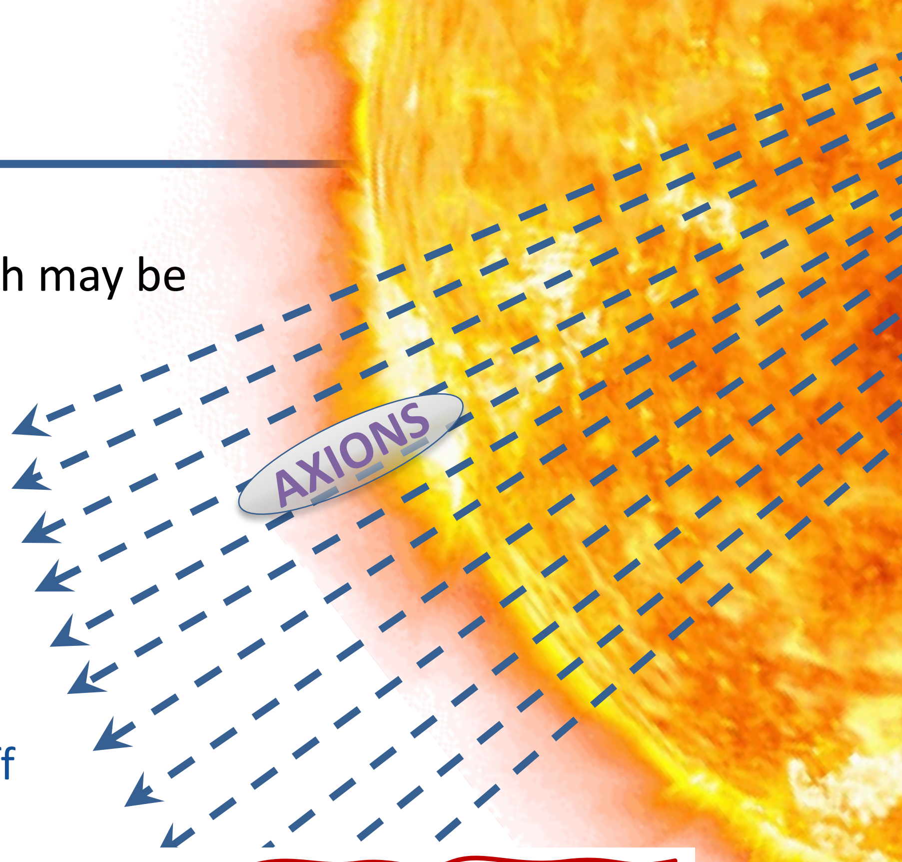
$$\frac{d\Phi_a}{dE} = 6.02 \times 10^{10} \left(\frac{g_{a\gamma}}{10^{-10}\mathrm{GeV}^{-1}}\right)^2 E^{2.481} e^{-E/1.205} \frac{1}{\mathrm{cm}^2\ \mathrm{s\ keV}}$$

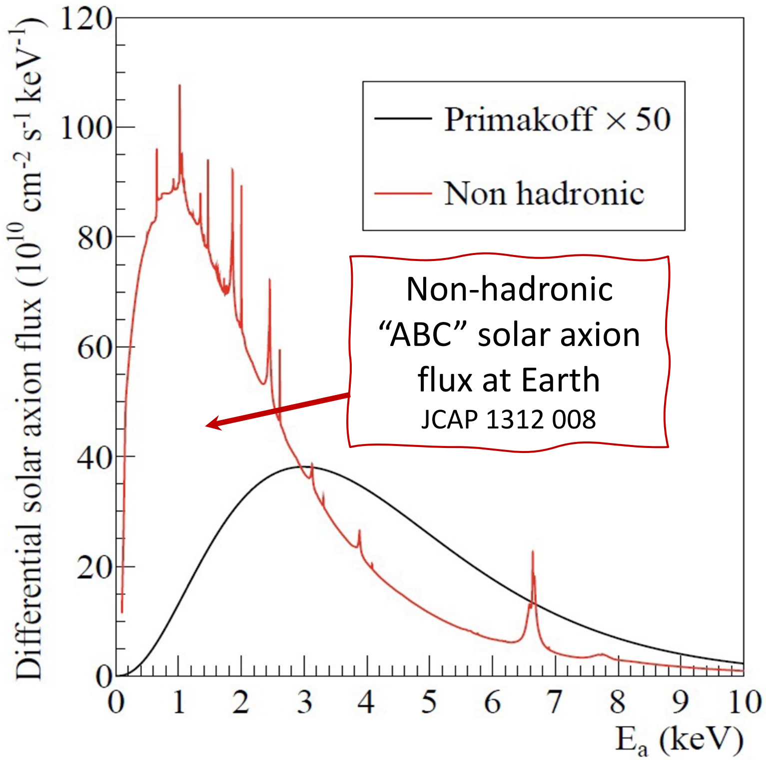
$$g_{10} = g_{a\gamma}/10^{-10}\ \mathrm{GeV}^{-1}$$

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

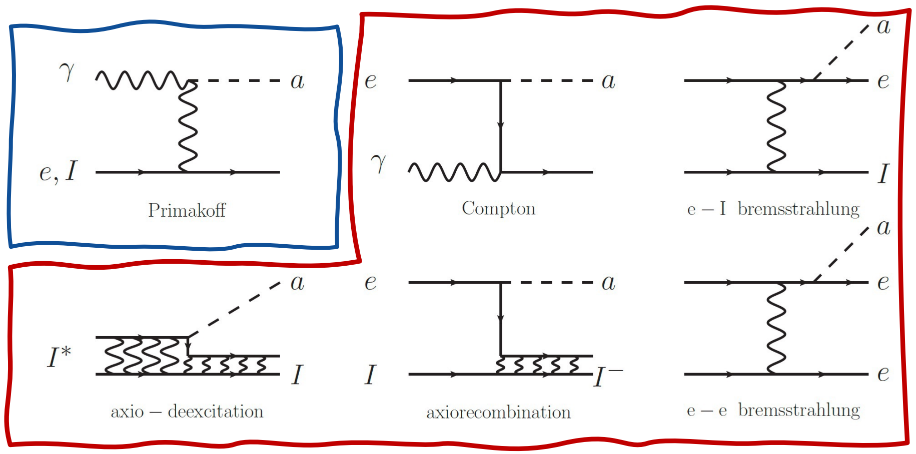
Standard^{+} Solar Axions

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





Primakoff axions



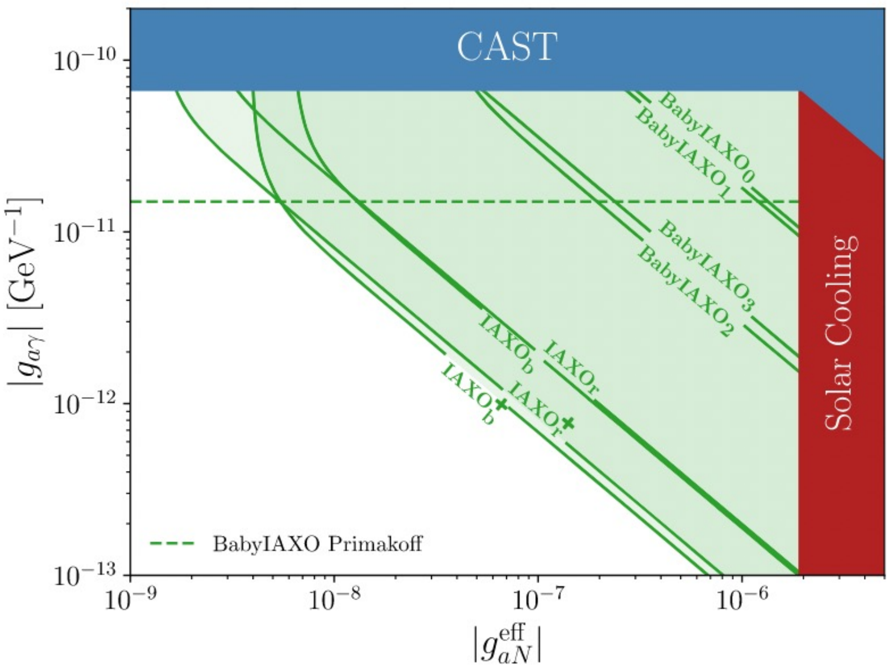
“ABC” or non-hadronic axions*

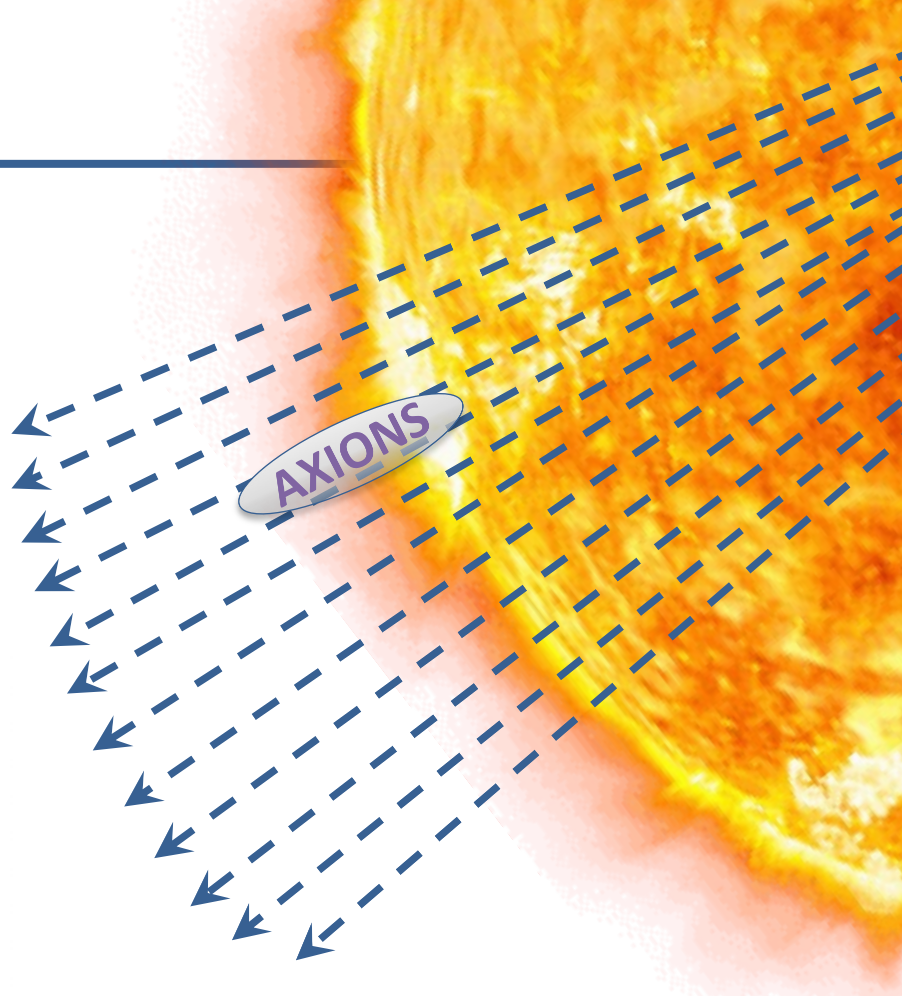
Redondo, *JCAP* 1312 008

(*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 and D(p;γ)^{3}He nuclear transitions or Tm-169





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

Solar Axion Detection

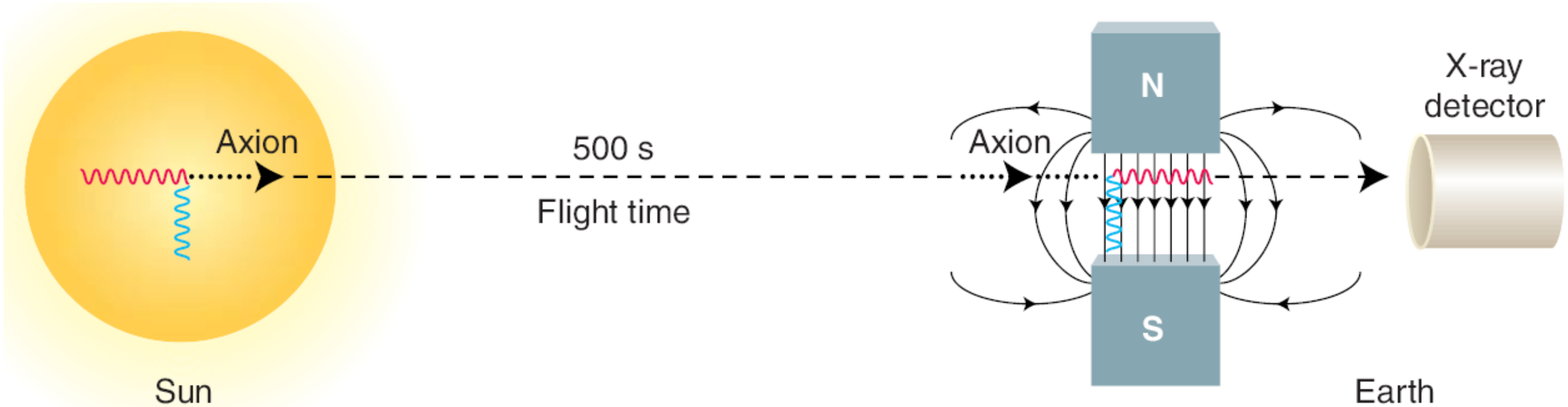
- First axion helioscope proposed by P. Sikivie

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



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

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

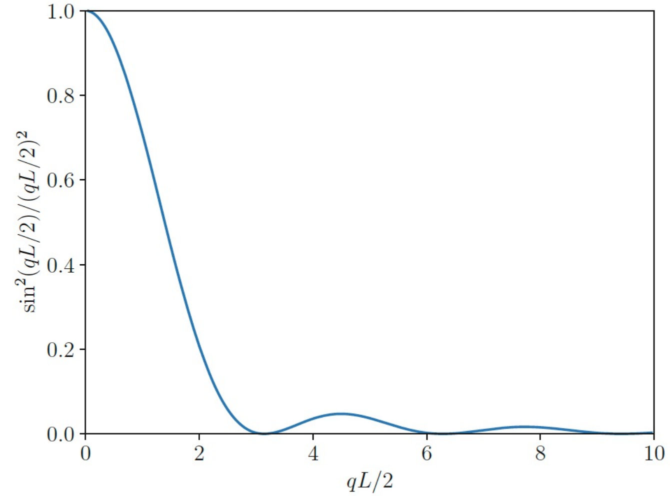
Solar Axion Detection

- 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 << 1



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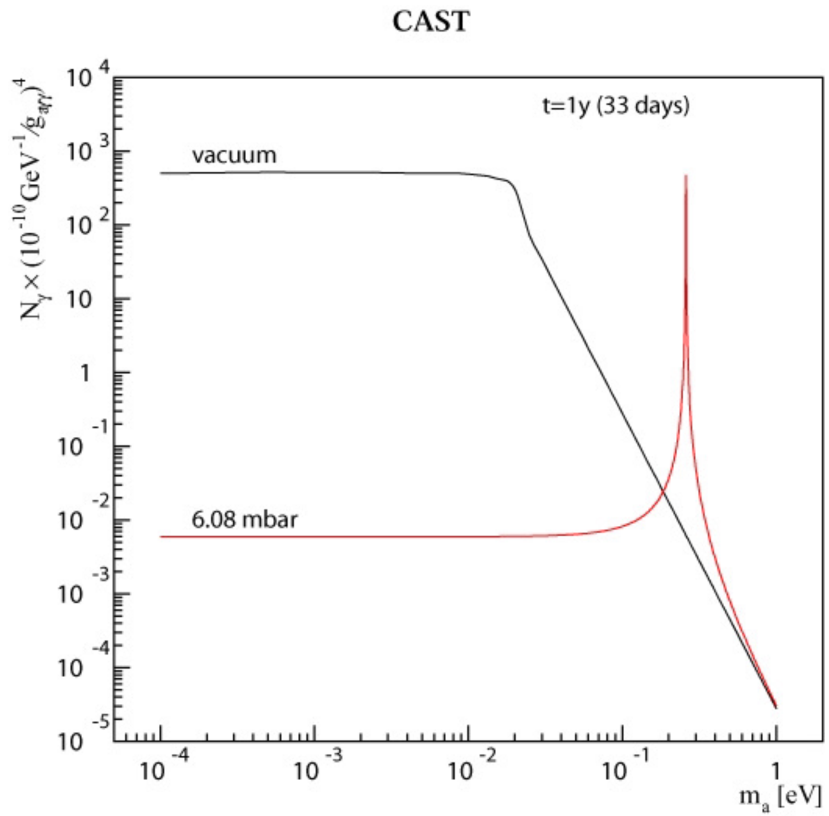


$$N_\gamma = \int \frac{d\Phi_a}{dE_a} P_{a\to\gamma} S\, t\, dE_a \quad \propto \quad g_{a\gamma}^4$$

- With a buffer gas

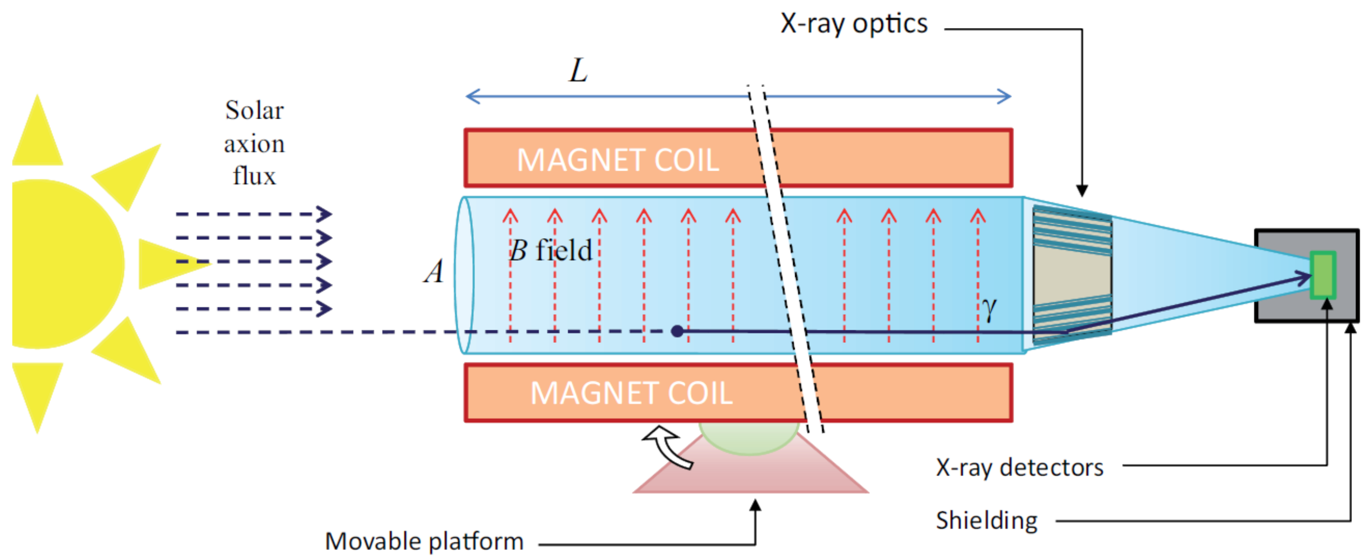
$$q = \left|\frac{m_\gamma^2 - m_a^2}{2E_a}\right|$$

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

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:

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

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

exposure
- t = time

optics
- s = spot size
- ε_0 = efficiency

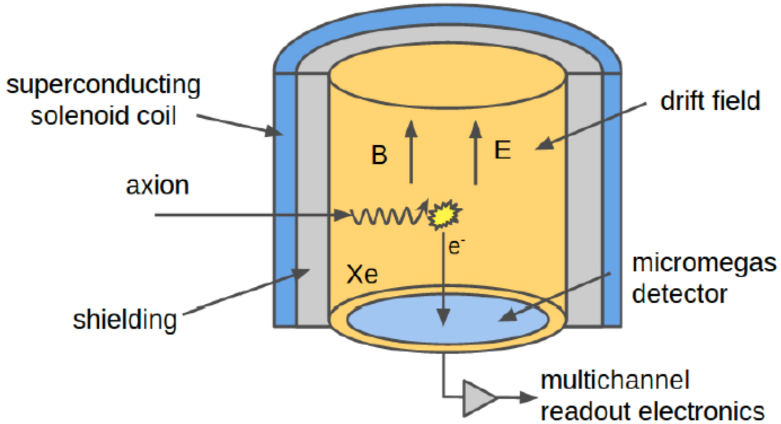
detectors
- b = background
- ε = efficiency

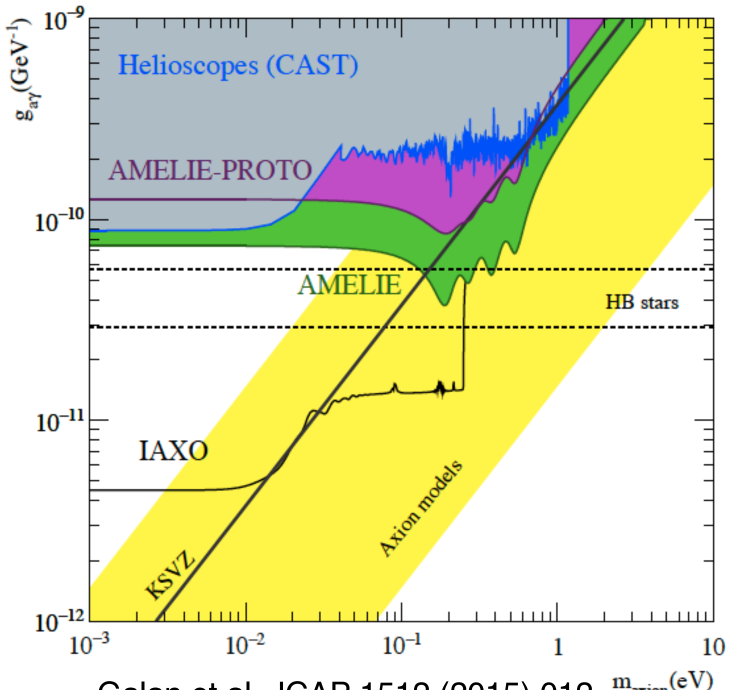
The smaller $g_{a\gamma}$ the better!

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
  - **Non-Primakoff-Effect Conversion** (axion-electron, axion-nucleon)



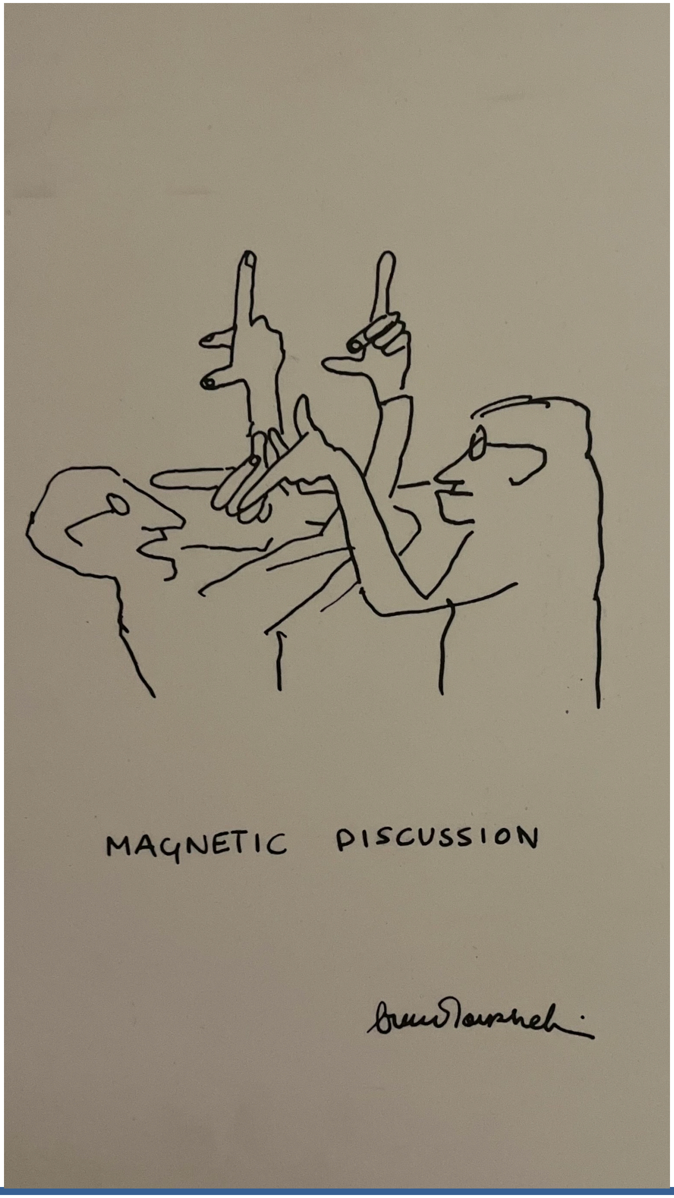


Galan et al, JCAP 1512 (2015) 012

Intro to axions

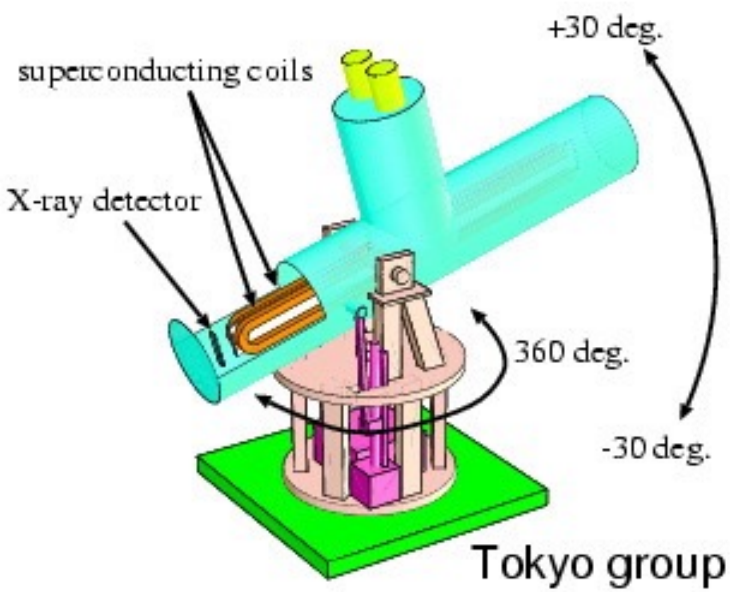
Solar Axion Detection

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)
- **2nd generation: Tokyo Helioscope (SUMICO)**
  - 2.3 m long, 4 T magnet



Previous Helioscopes

CERN Axion Solar Telescope

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

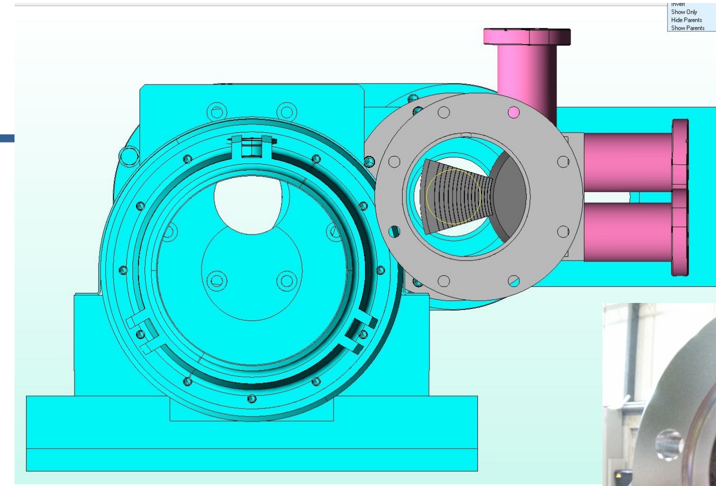
- Decommissioned prototype **LHC dipole magnet**
  → Length = 10 m; Magnetic field = 9 T
- **X-ray focusing** and novel **low-bgrd** techniques
- **Solar tracking** possible during sunrise and sunset (2 x 1.5 h per day)
- **First data** in 2003/04 (Phase I, vacuum)
- **$^4He/^3He$ runs** 2006-12 (Phase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

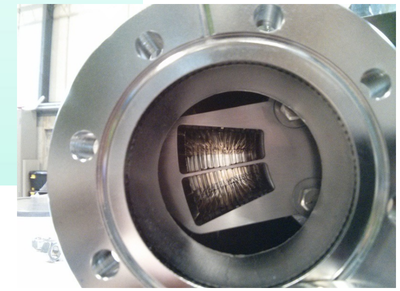
Nature Phys. ***13*** *(2017) 584-590*
JHEP 2021 75, (2021)
*Nature Com.*13, 1, 1-9 (2022)

Previous Helioscopes

CERN Axion Solar Telescope

2013-2015: IAXO pathfinder @ CAST

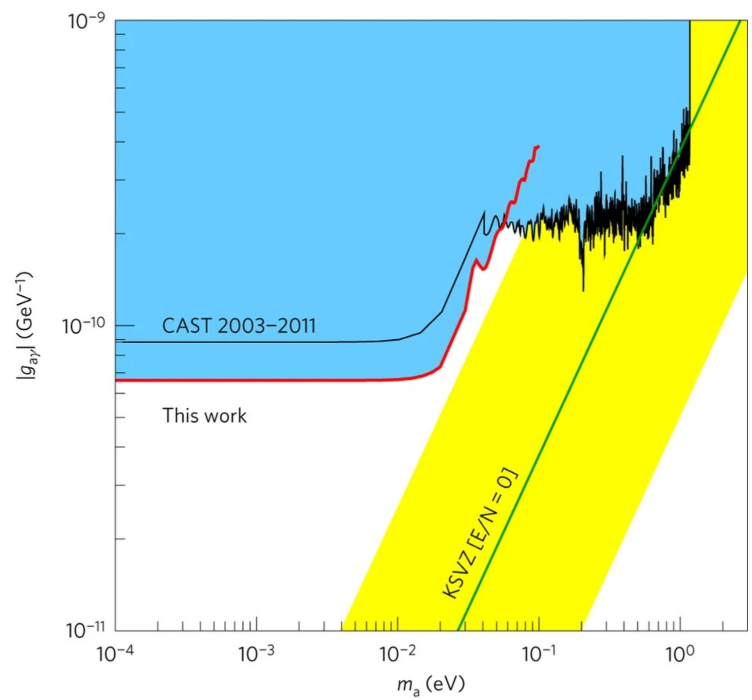




- Small x-ray optics
  Fabricated purposely using thermally-formed glass substrates (NuSTAR-like)
  +
- Micromegas low background detector
  Applied lessons learned from R&D: compactness, better shielding, radiopurity,…

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

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



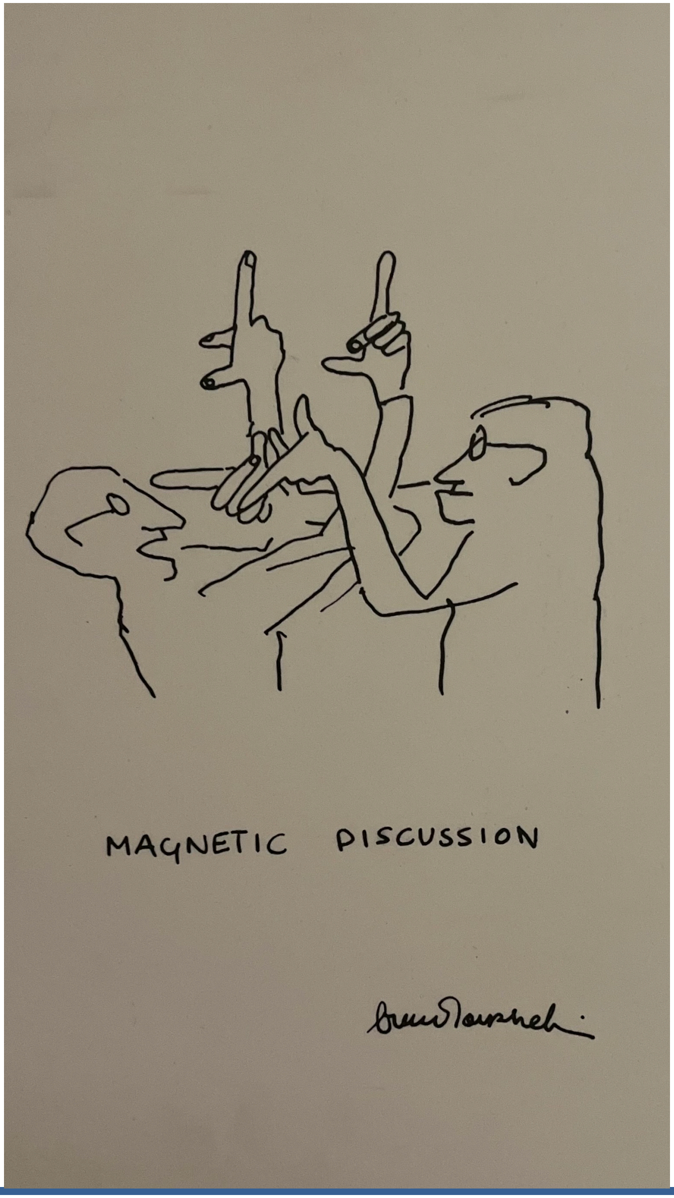
Anastassopoulos et al. *Nature Phys.* ***13*** *(2017) 584-590*

Intro to axions

Solar Axion Detection

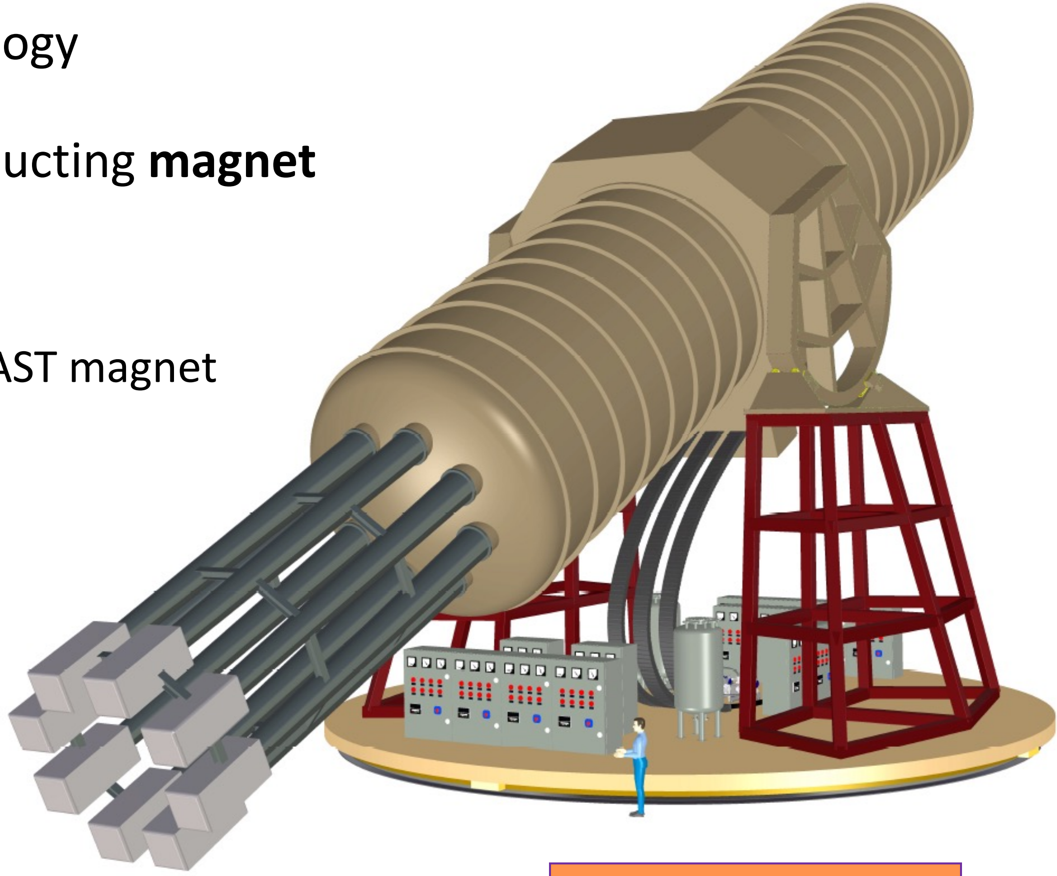
Previous helioscopes and State-of-the-Art

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

Intro to axions

Solar Axion Detection

Previous helioscopes and State-of-the-Art

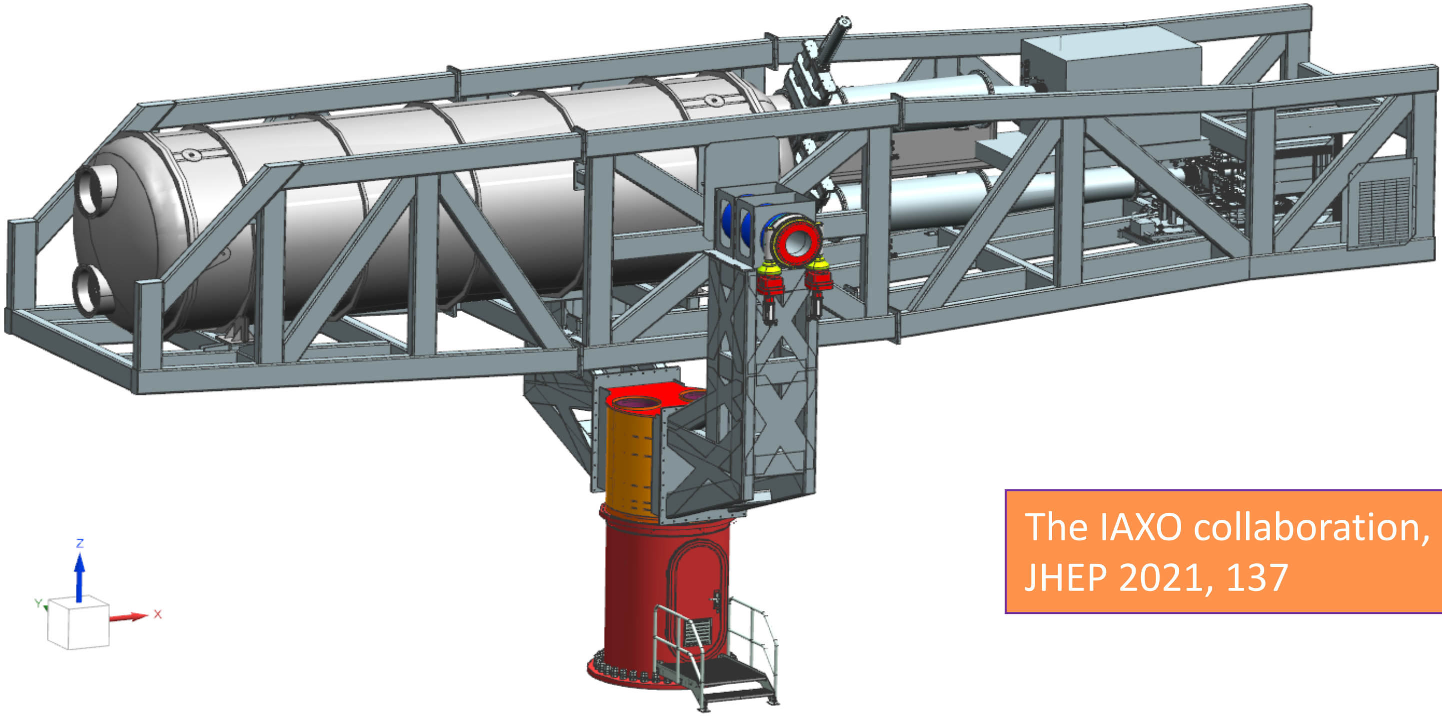
Next-Gen: The International Axion Observatory (IAXO)

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)



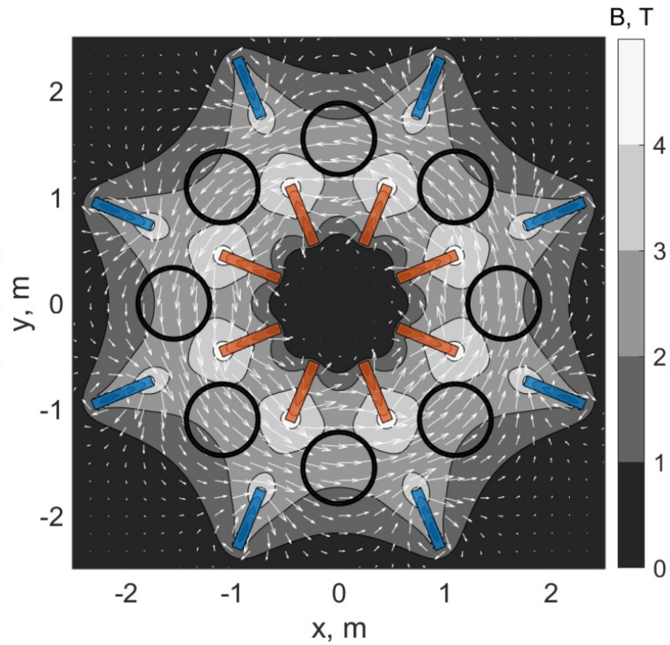
The IAXO collaboration, JHEP 2021, 137

BabyIAXO magnet

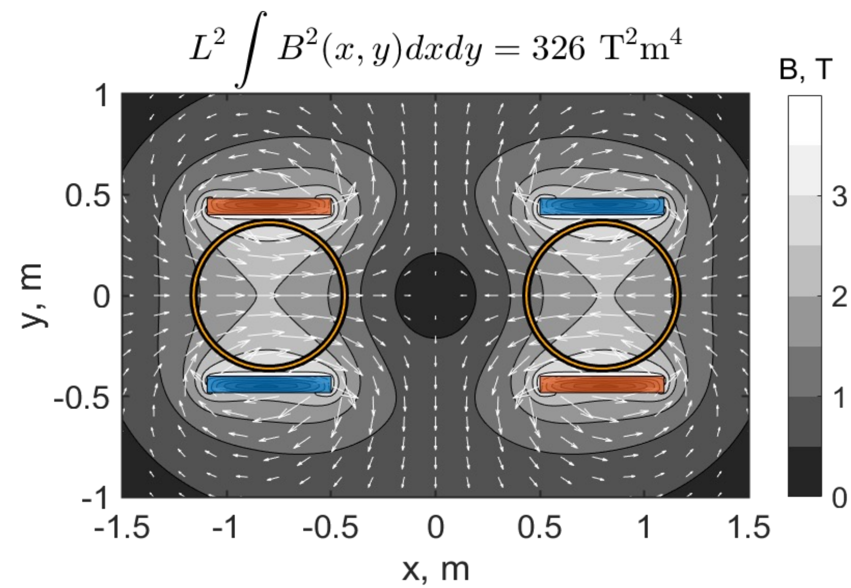
Need large magnetic field B & cross-sectional area A:

“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 superconductor cable



Magnetic field and load line of the conductor for BabyIAXO

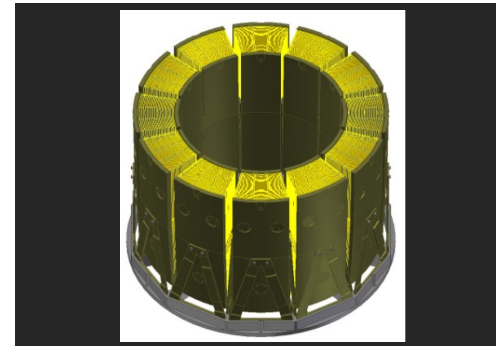


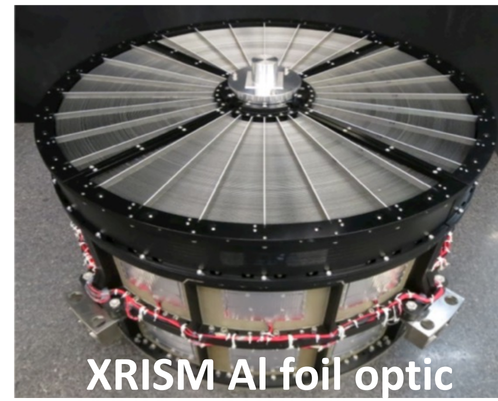
BabyIAXO optics

(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 cm^2/ 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

Al foil optics and/or segmented glass optics ideal for (Baby)IAXO and have been used/planned for NASA/ESA missions like NuSTAR, Astro-H and XRISM, Athena

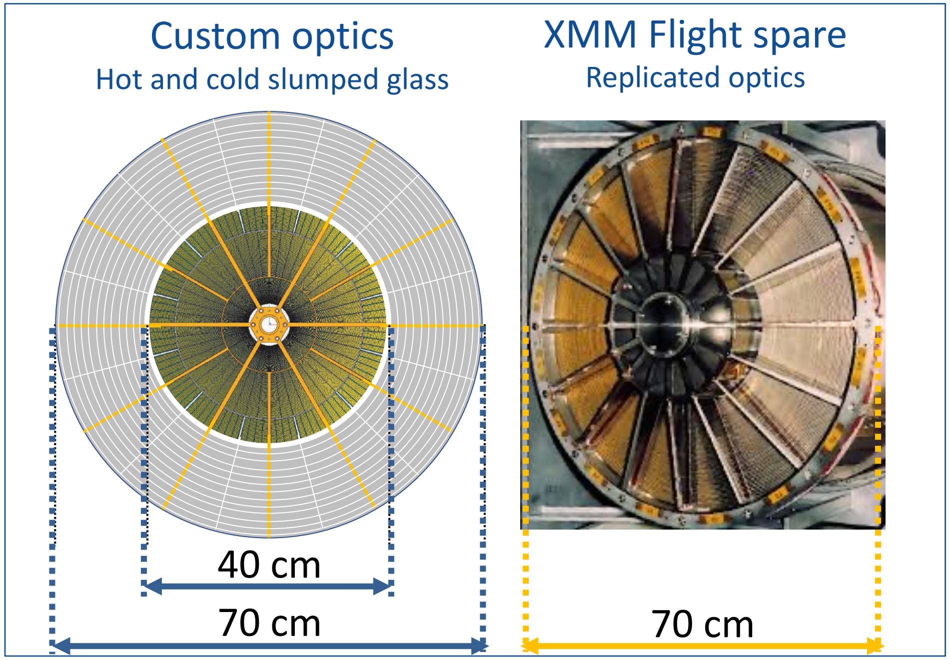

CSGO process (Athena)

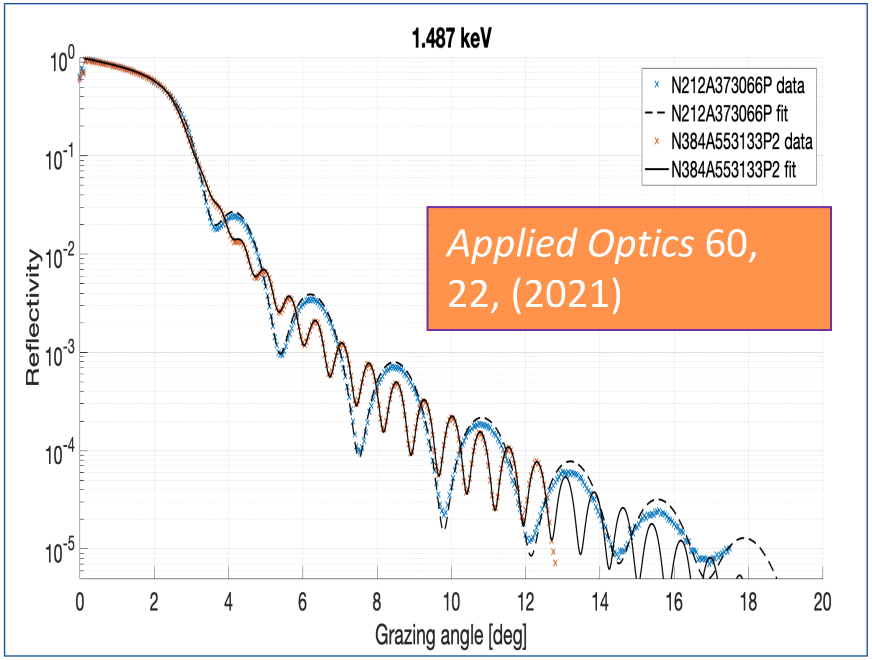

XRISM Al foil optic


NuSTAR segm. glass

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



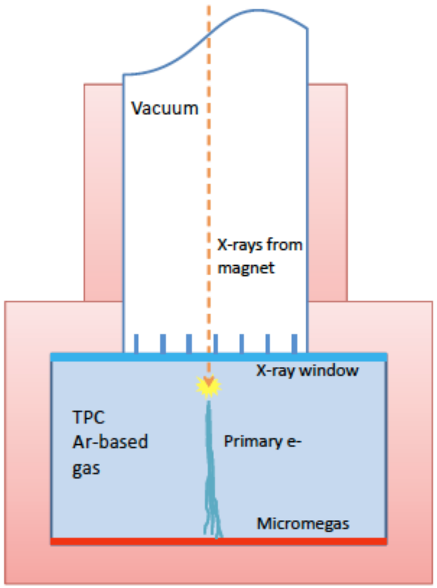


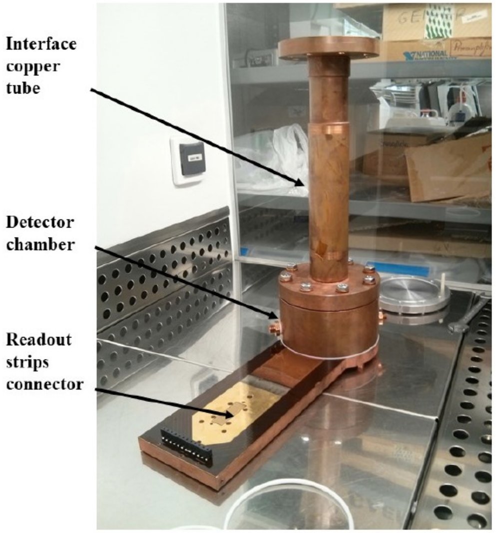
BabyIAXO detectors

(Baby)IAXO needs

- Low background (<10^{-7} – 10^{-8} cts keV^{-1} cm^{-2} s^{-1})
  - 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
- Desirable: Low energy threshold (< 1 keV) and good energy resolution
  - Especially interesting for axion-electron measurements
  - Notably useful in case an axion signal is detected

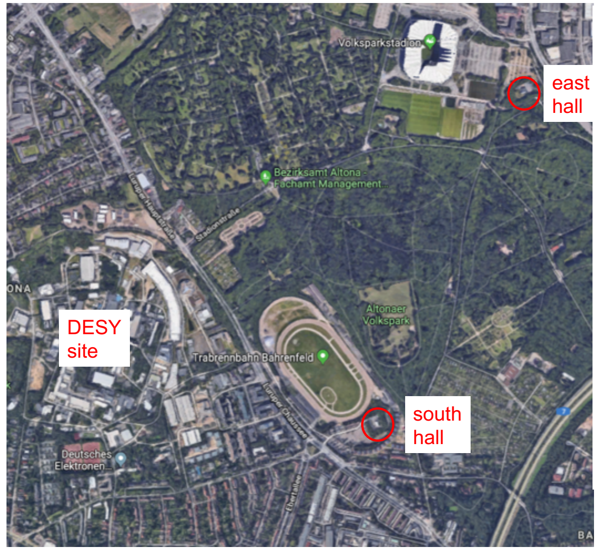
BASELINE: Micromegas technology best option to reach required low background levels
Additional technologies considered and undergoing active R&D efforts (GridPix, MMC, TES, SDD)

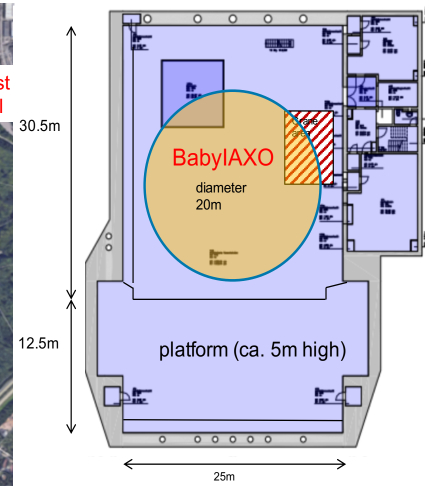


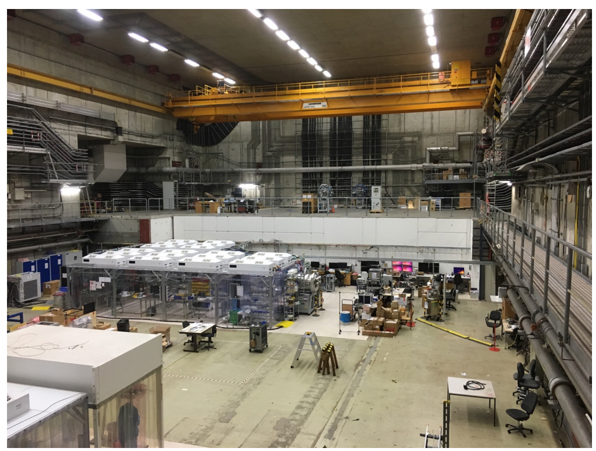


BabyIAXO @ DESY

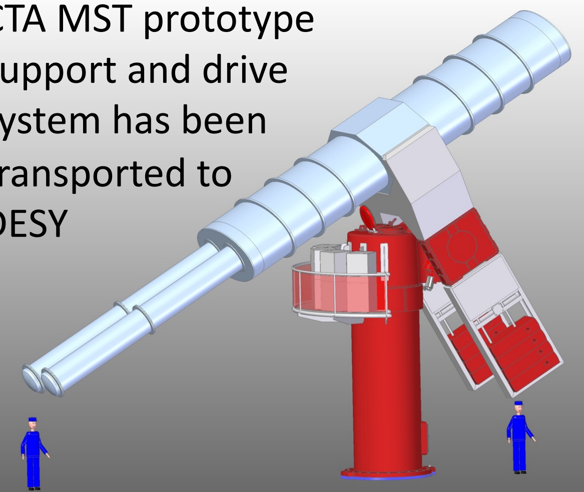
- DESY HERA halls as BabyIAXO site
- Infrastructure at DESY & expertise very well suited to host IAXO
- CTA Medium Sized Telescope (MST) support and drive system planned to be used for BabyIAXO







CTA MST prototype support and drive system has been transported to DESY



Expect BabyIAXO commissioning in 2027!

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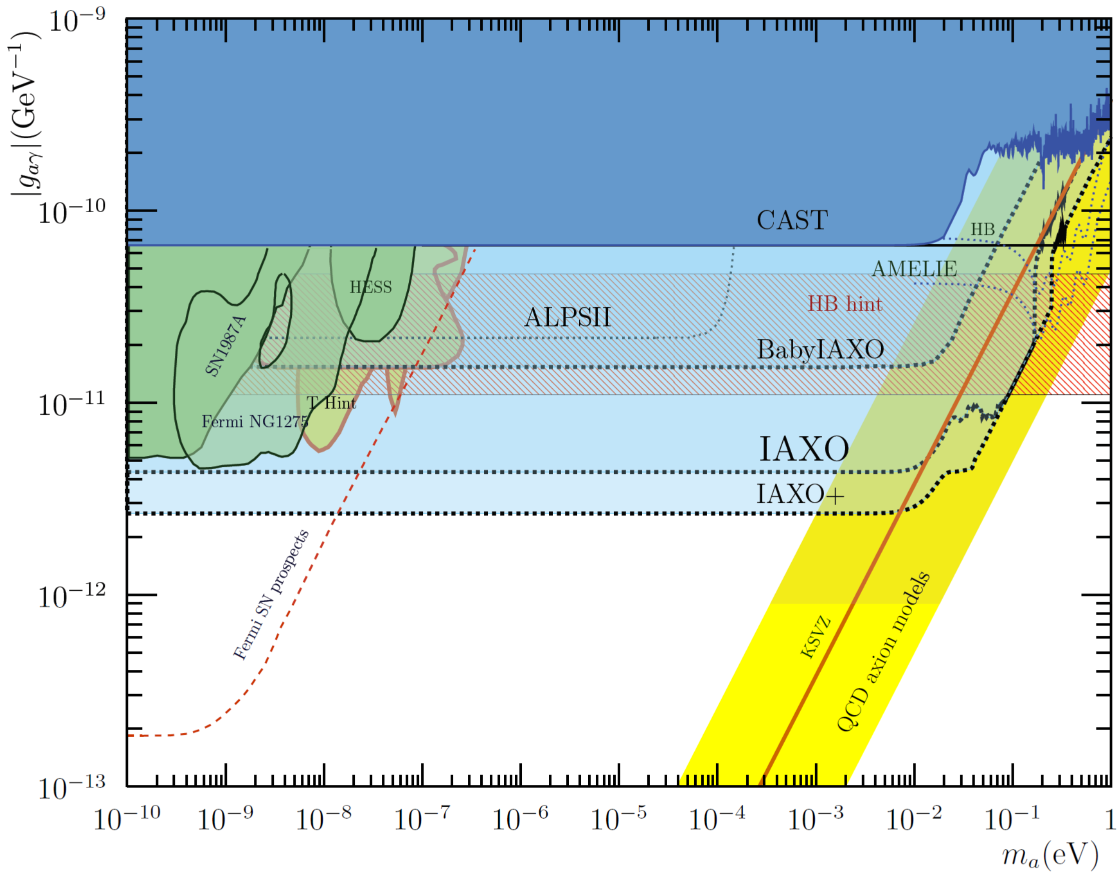
Next-Gen: The International Axion Observatory (IAXO)

Next-Gen: BabyIAXO

Next-Gen: Physics Prospects

BabyIAXO and IAXO physics reach



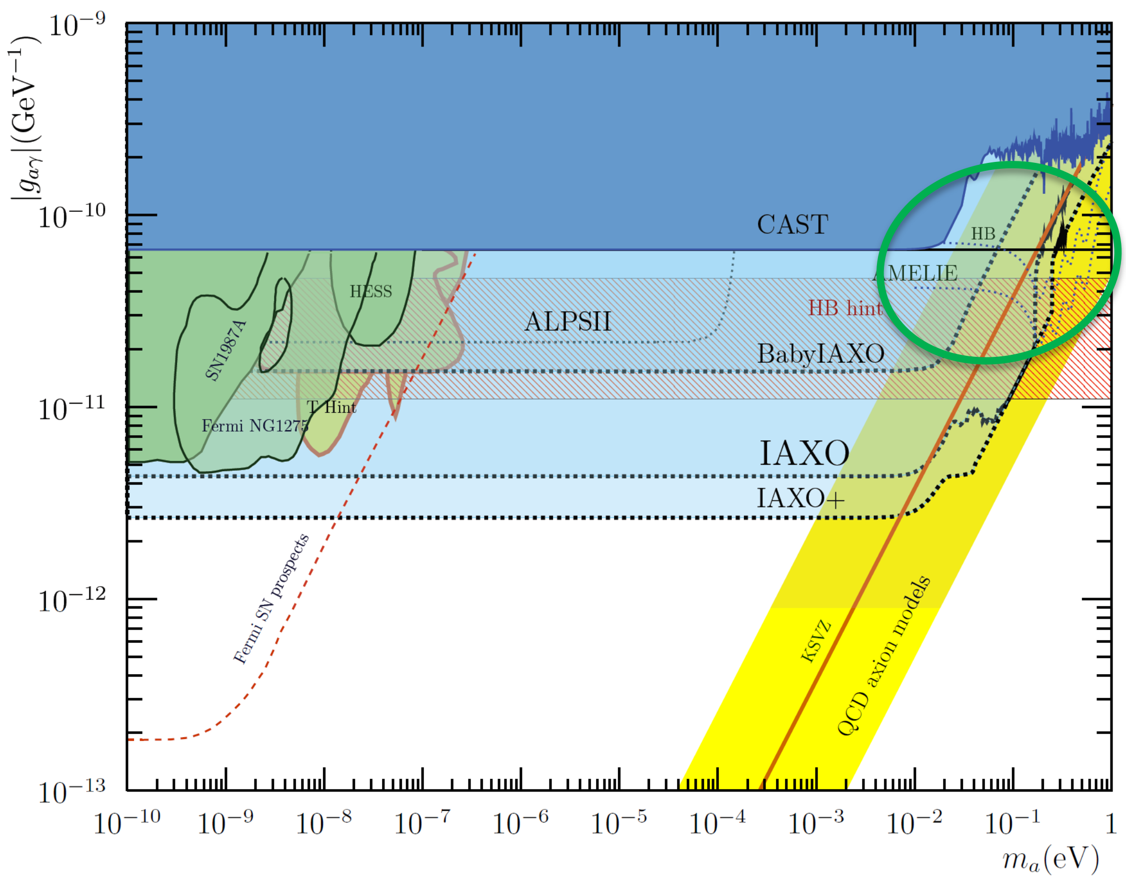
BabyIAXO prospects:
10 x $MFOM_{CAST}$ + optics and detector from conservative scenario of LoI

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



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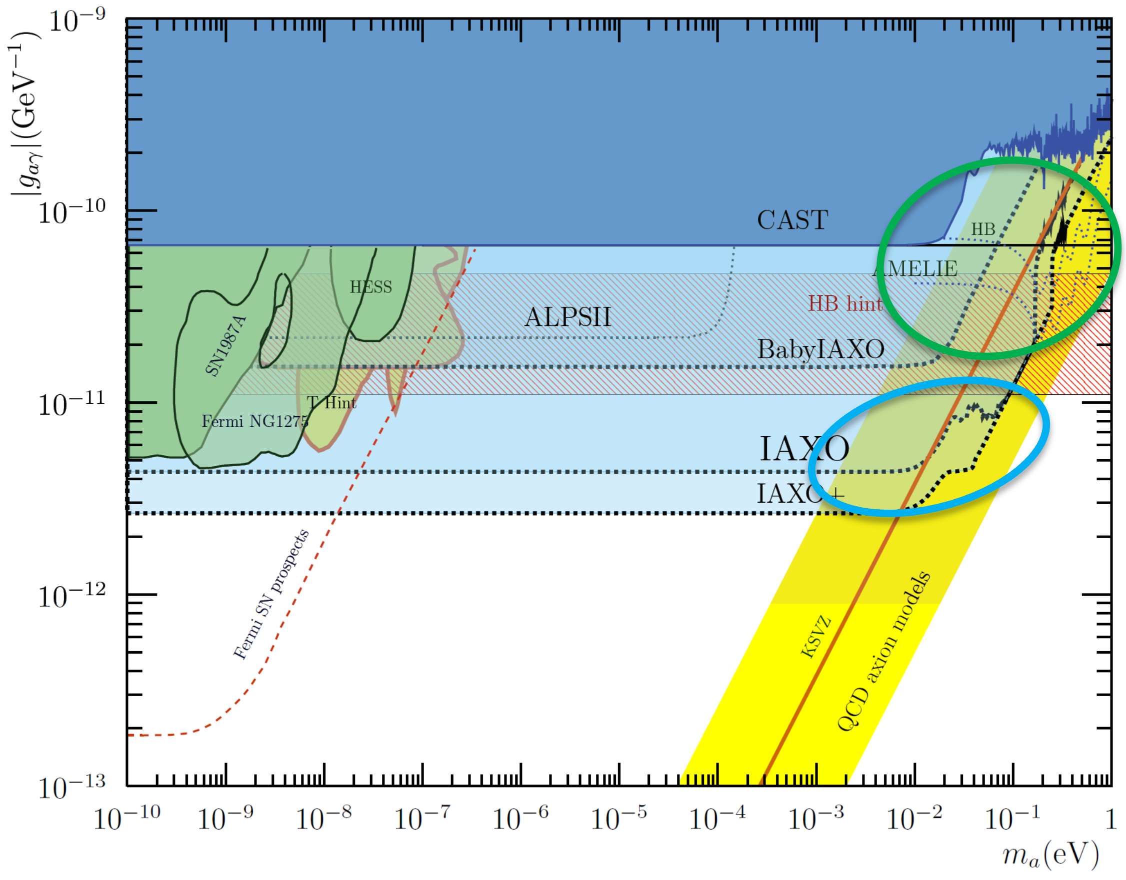
"ALP miracle" region: ALPs solving both DM & inflation (Daido et al. 2017 arXiv:1710.11107)

BabyIAXO and IAXO physics reach



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

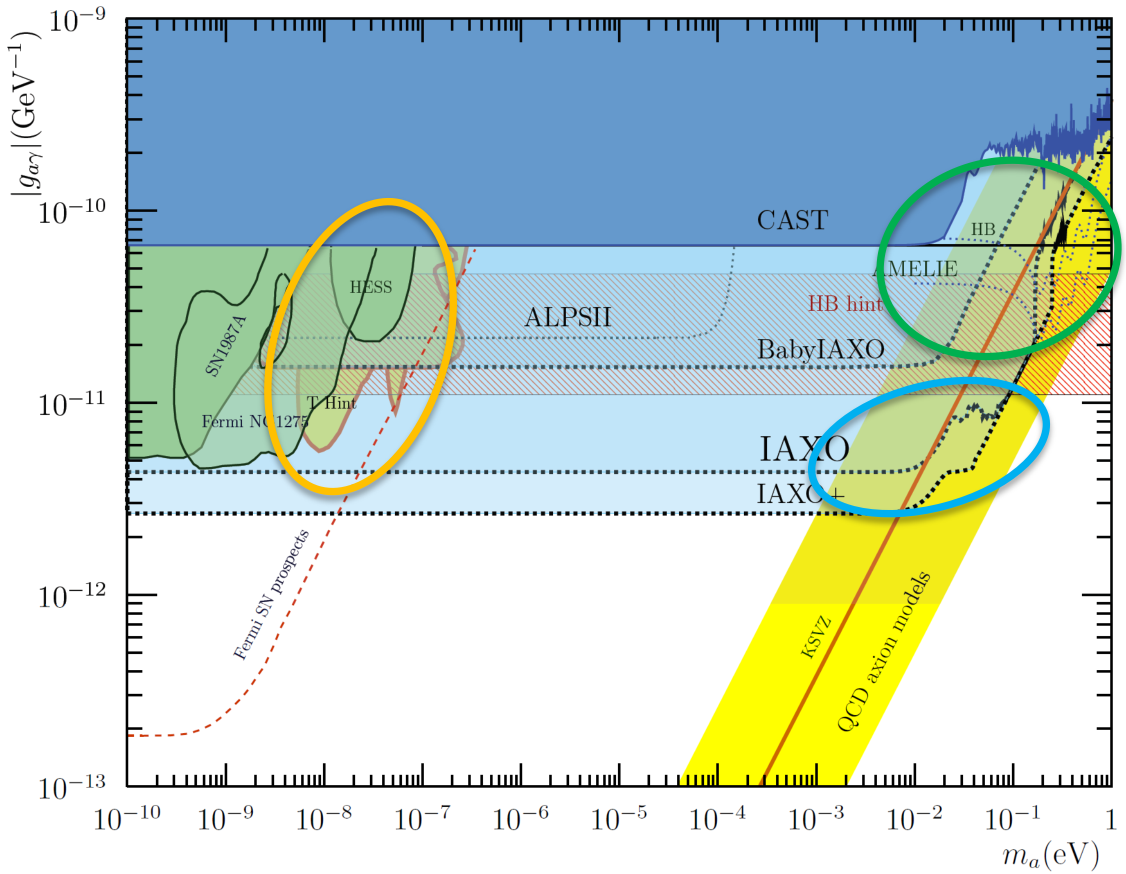
IAXO+: Enhanced scenario with x 10 (x4) higher FOM (MFOM) with respect LoI

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)

BabyIAXO and IAXO physics reach



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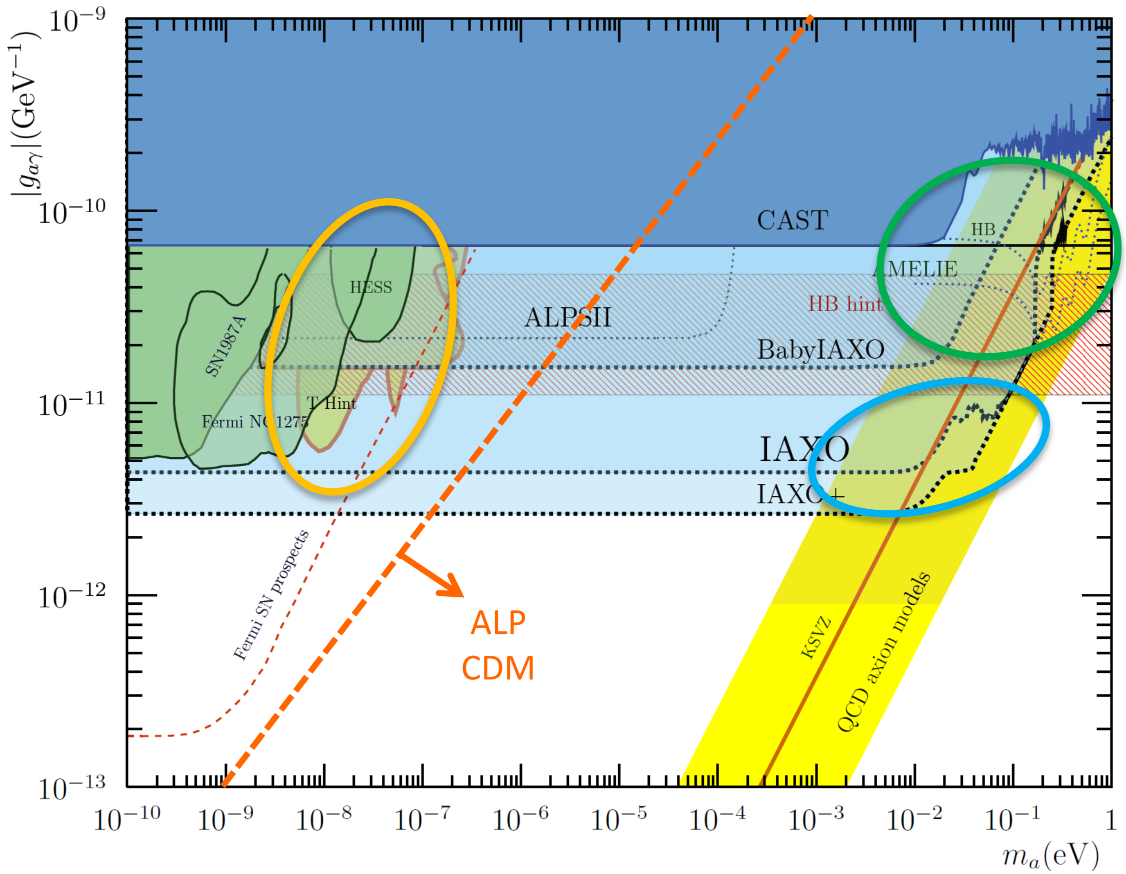

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Large fraction of the axion & ALP models invoked in the “stellar cooling anomaly” (g_{ae} particularly interesting for this)

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)

The IAXO collaboration

Petersburg Nuclear Physics Institute

DESY

IRFU CEA Saclay

INR RAS

Columbia U.

Lawrence Livermore National Laboratory

Universidad de Zaragoza

Johannes Gutenberg University, Mainz

Barry University

Centro de Estudios de Física del Cosmos de Aragón

Heidelberg University

Universitat de Barcelona

Siegen University

Universität Bonn

CSIC Barcelona

MPP Munich

Ruđer Bošković Institute, Zagreb

MPE/ Panter

CERN

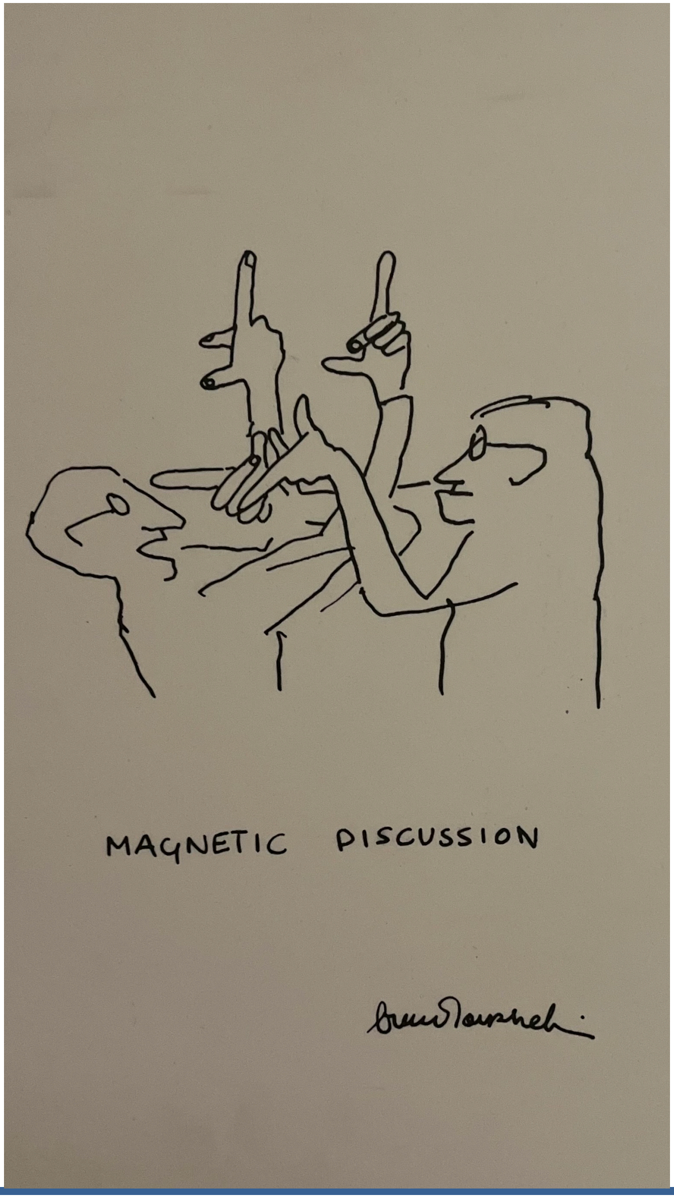
INAF Milano

University of Cape Town

Come to the dark side!

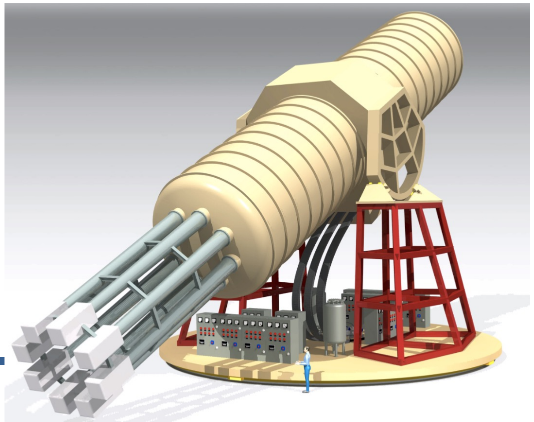
Outline

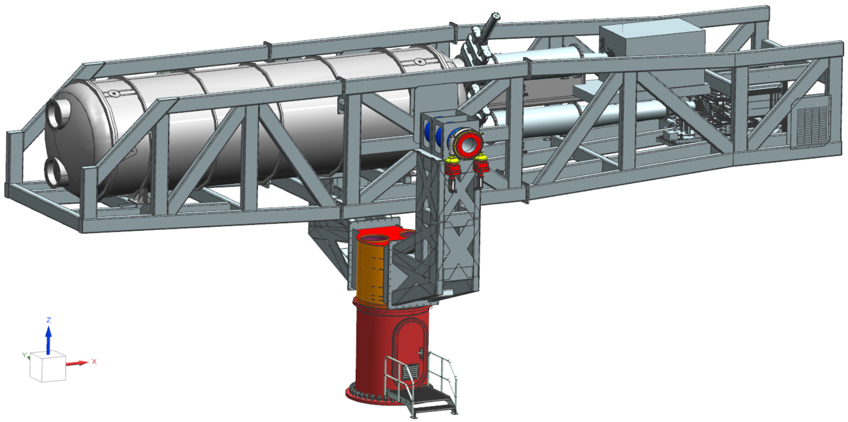
- Intro to axions
- Solar Axion Detection
- Previous helioscopes and State-of-the-Art
- Next-Gen: The International Axion Observatory (IAXO)
- Next-Gen: BabyIAXO
- Next-Gen: Physics Prospects
- Conclusions



Conclusions

- Axions and ALPs could solve the dark matter problem
- 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 × 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 $g_{a\gamma}$ [> 4 OM in S/N] over CAST)
- Diverse Physics reach:
  QCD axions, ALPs, astrophysical hints, dark radiation, dark energy, …



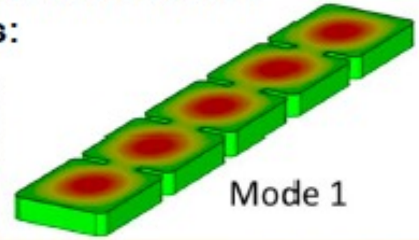


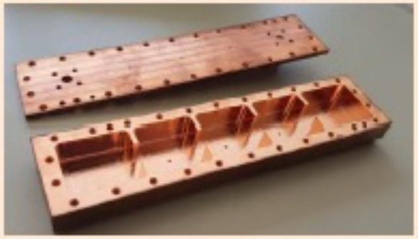
THANK YOU FOR YOUR ATTENTION!
QUESTIONS?

Additional IAXO Physics: Dark Matter Searches

- Use of (Baby)IAXO large magnetic volume for axion DM setups.
- RADES R&D exploring new concept to fill large V with high-frequency cavities.
  - Evolved from concept to serious experimental effort in the last ~3 years
  - Proof-of-concept at small scale successful tested in CAST
  - Technological connection with CERN
- Aim: to become the seed of a program to implement DM searches in BabyIAXO.

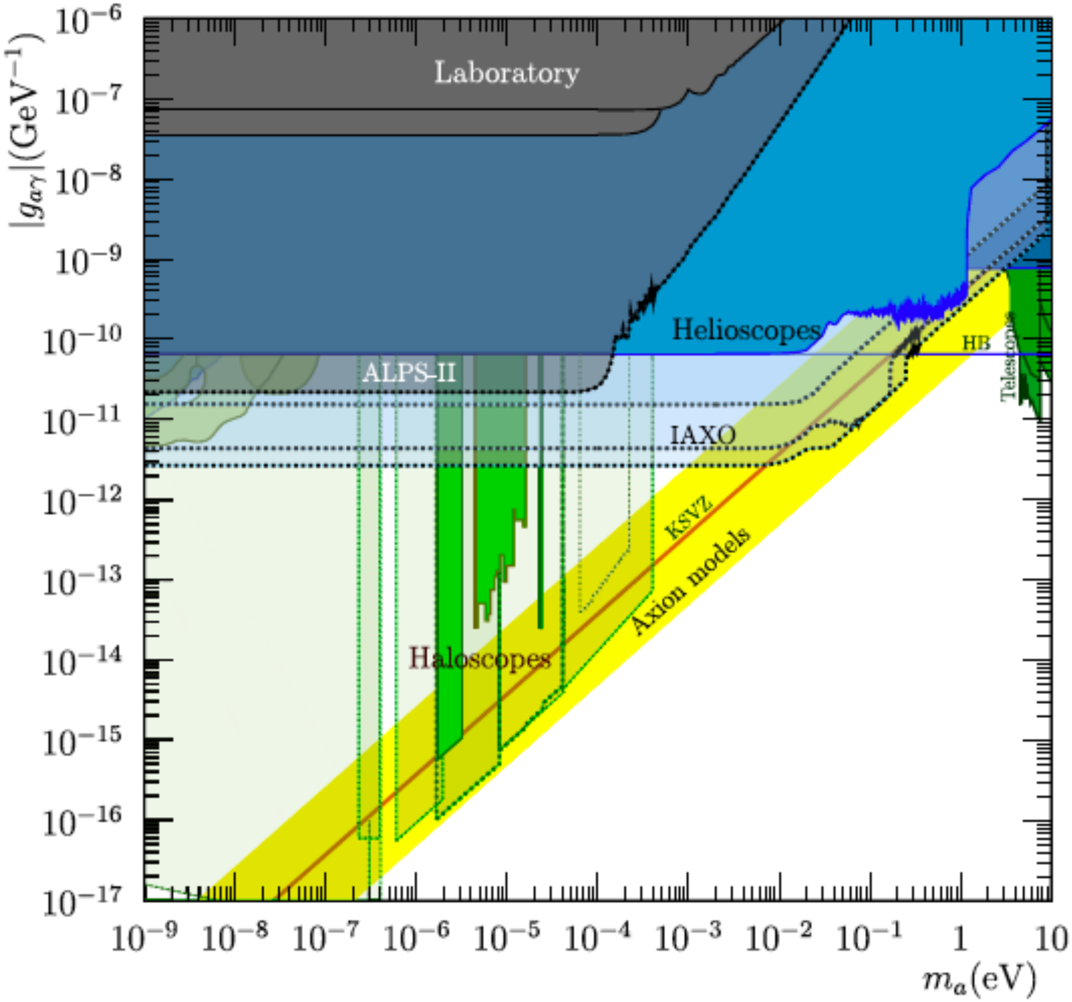
RADES concept: array of small cavities interconnected with irises:





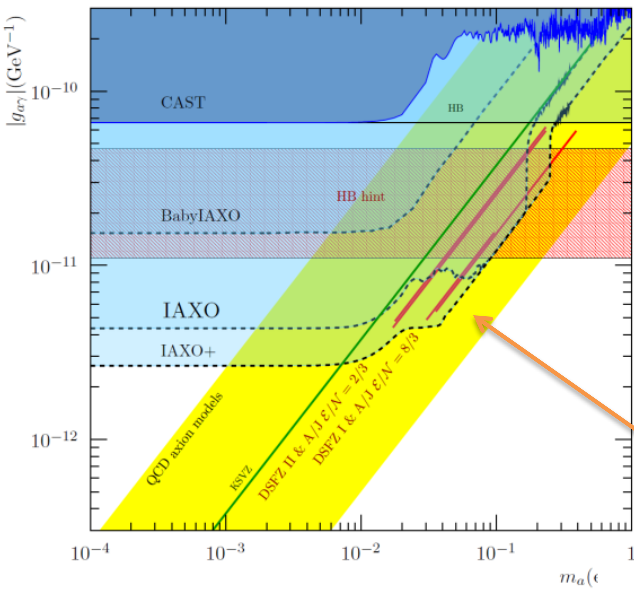
Part of ERC-StG (2018)
B. Döbrich/CERN

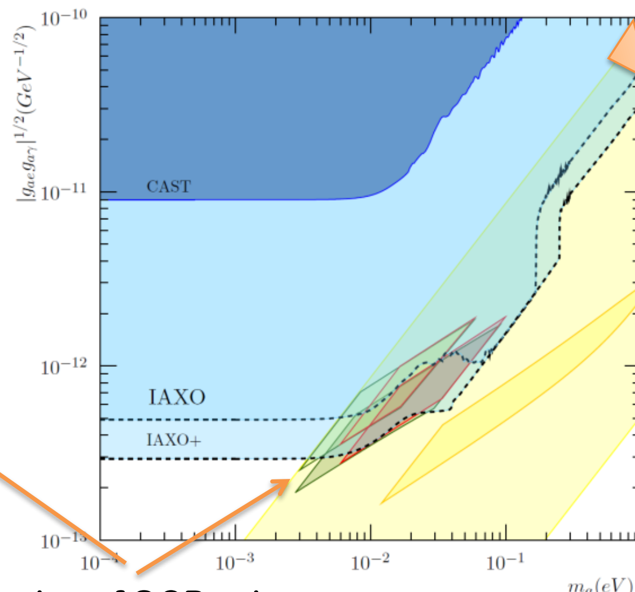
Axion experiments: status and prospects

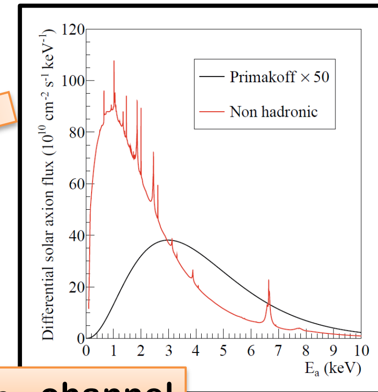


IAXO and BabyIAXO: Stellar cooling

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







g_{ae} channel

Region of QCD axion models that solve the stellar anomaly

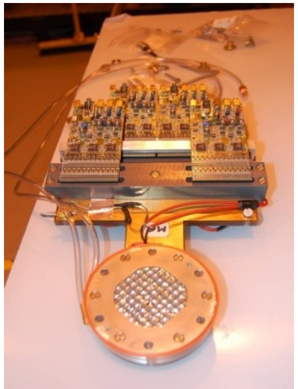
M. Giannotti et al.
JCAP 1710 (2017) 010
arXiv:1708.02111

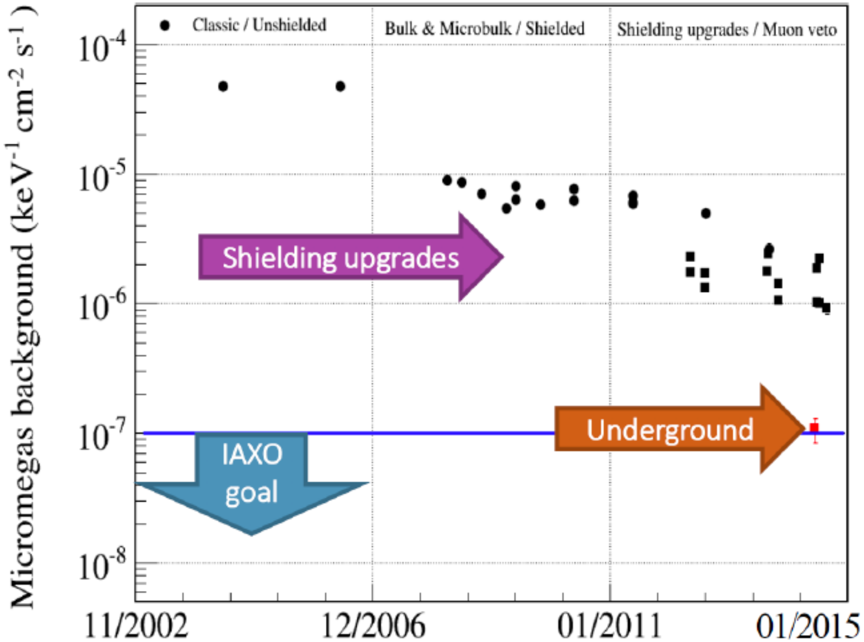
- **IAXO will explore most of the relevant models (especially with IAXO+)**
- **Only experiment with such capability**

BabyIAXO detectors

- Baseline option: 2 Micromegas (MM), in addition, R&D generic platform to improve and tests all other detection technologies: GridPix, Transition Edge Sensors (TES), Metallic Magnetic Calorimeters (MMC), Silicon Drift Detectors (SDD)
- MM progress:
  - BabyIAXO design being finalized, based on IAXO pathfinder system
  - Expect to produce prototypes in summer, passive lead shielding & muon veto TBD
  - Testing Xenon-based gas mixtures and high transmission windows
- R&D progress: focus on background reduction and simulation with first tests

Micromesh Gaseous Detector

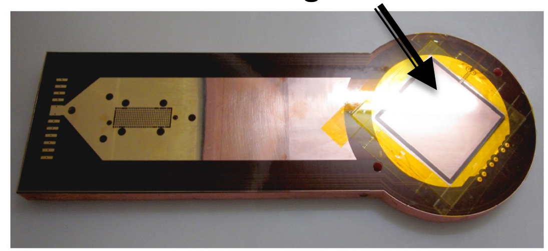


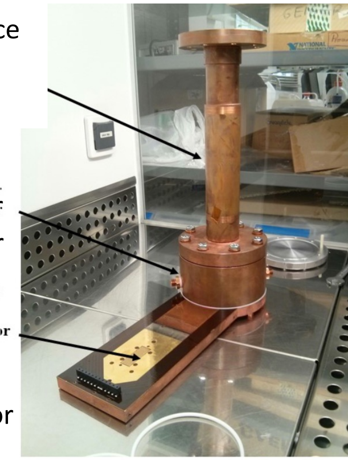


BabyIAXO detectors

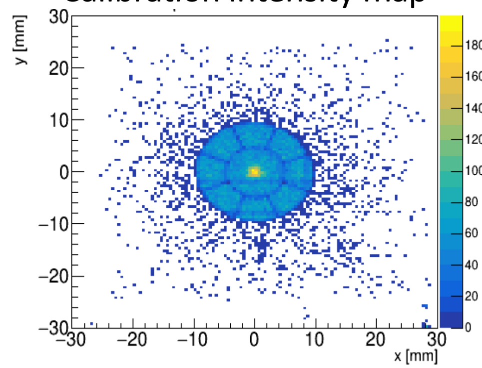
Microbulk Micromegas detectors

- 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).





Calibration intensity map



X-ray window

Rare Event Searches Toolkit **software**