Searches for axions and ALPs with helioscopes

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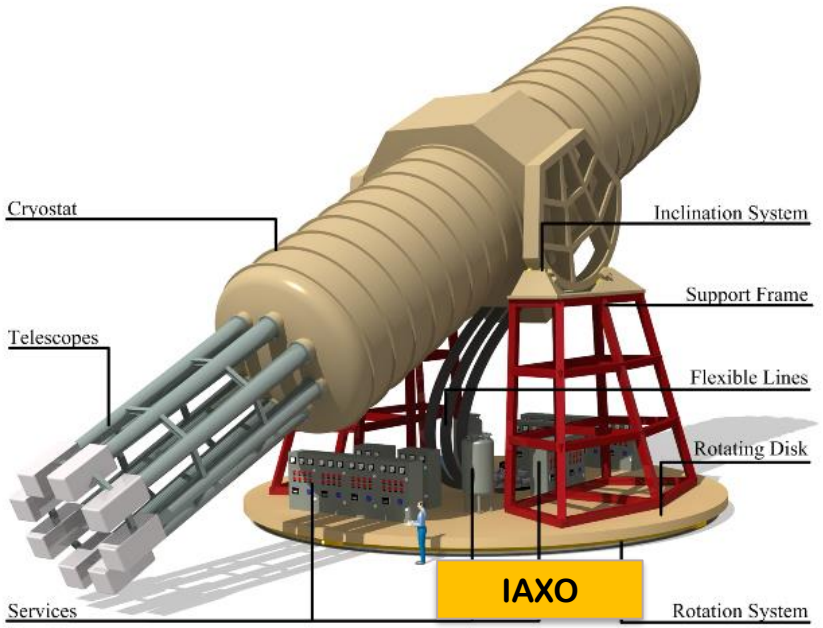
Open Symposium – Update of the European Strategy for Particle Physics
Granada, 14 May 2019

Based mainly on input to ESPP:
#27 The International Axion Observatory (IAXO): case, status and plans.
but also
#112 A European Strategy Towards Finding Axions and Other WISPs
#42 The Physics Beyond Colliders Study at CERN
#60 PBC technology subgroup report

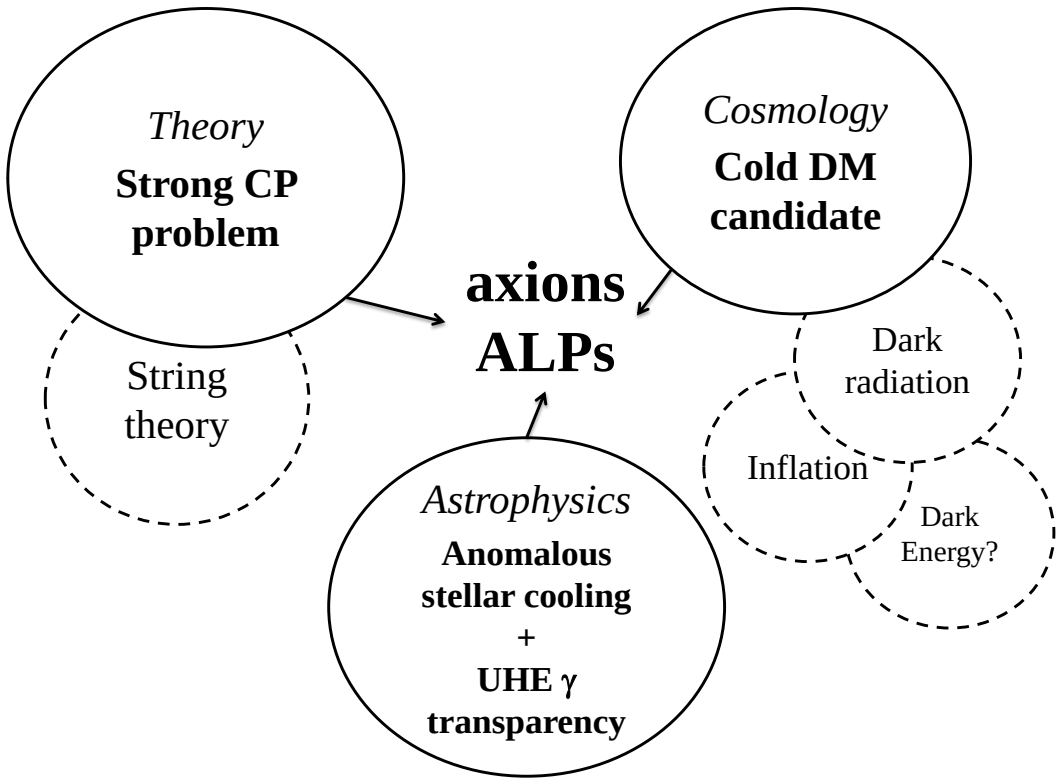


Axion motivation in a nutshell

- Most compelling solution to the **Strong CP problem** of the SM

- Axion-like particles (ALPs) **predicted by many extensions** of the SM (e.g. string theory)
- Axions, like WIMPs, may **solve the DM problem *for free***. (i.e. not *ad hoc* solution to DM)
- **Astrophysical hints** for axion/ALPs?
  - Transparency of the Universe to UHE gammas
  - Stellar anomalous cooling → $g_{a\gamma}$ ~ few 10^{-11} GeV^{-1} / m_a ~few meV ?

- Relevant axion/ALP parameter space at **reach of current and near-future experiments**



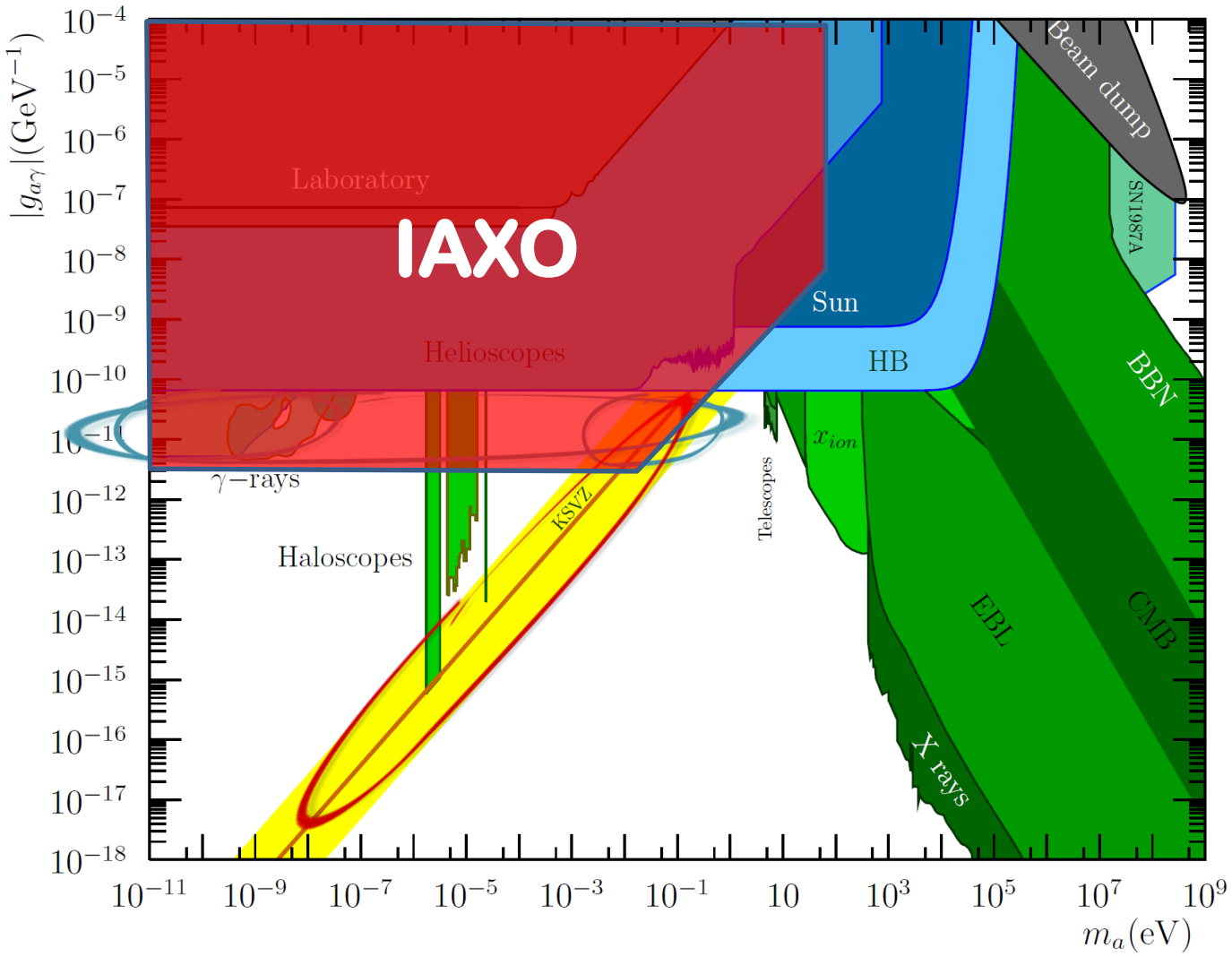
Axion/ALP searches motivation

"Focuses of interest" in the ALP parameter space

Theory
Astrophysics
Cosmology

IAXO addresses partially all of them

meV+ QCD axion region exclusive target of IAXO



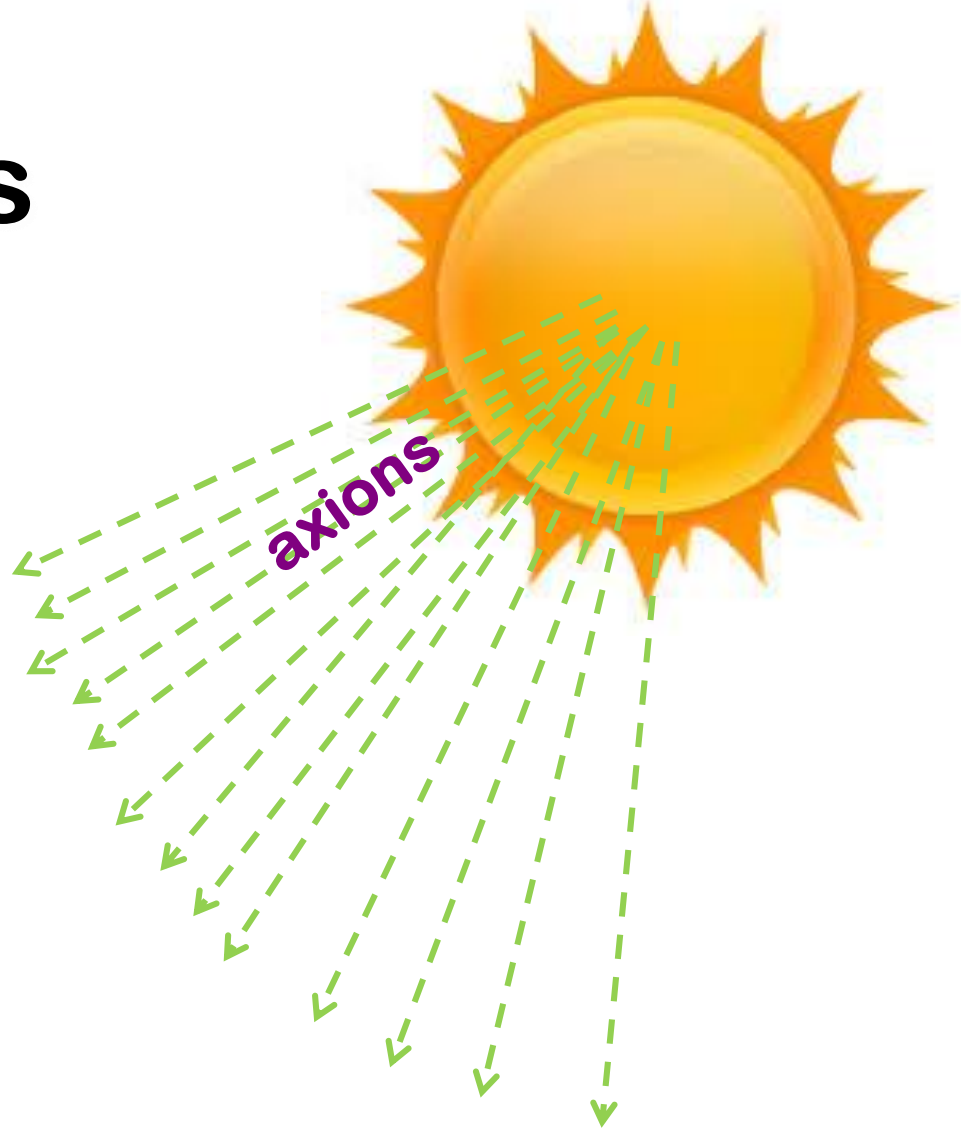
Detection of axions

Large complementarity among categories

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

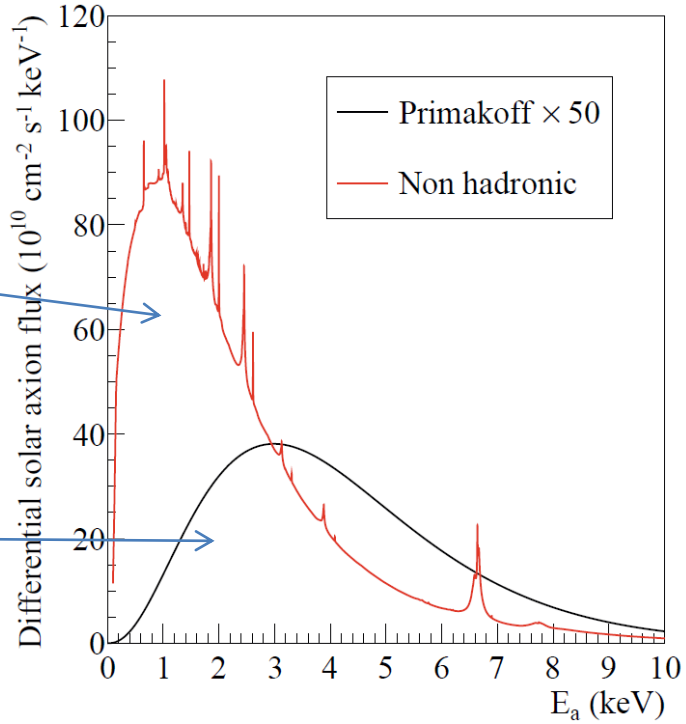
Solar Axions

- **Primakoff conversion of solar plasma photons** → generic prediction of most axion models
- In addition, g_{ae}-mediated axions (model dependent)



Non-hadronic "ABC" Solar axion flux at Earth *JCAP 1312 008* (only if axion couples to electron)

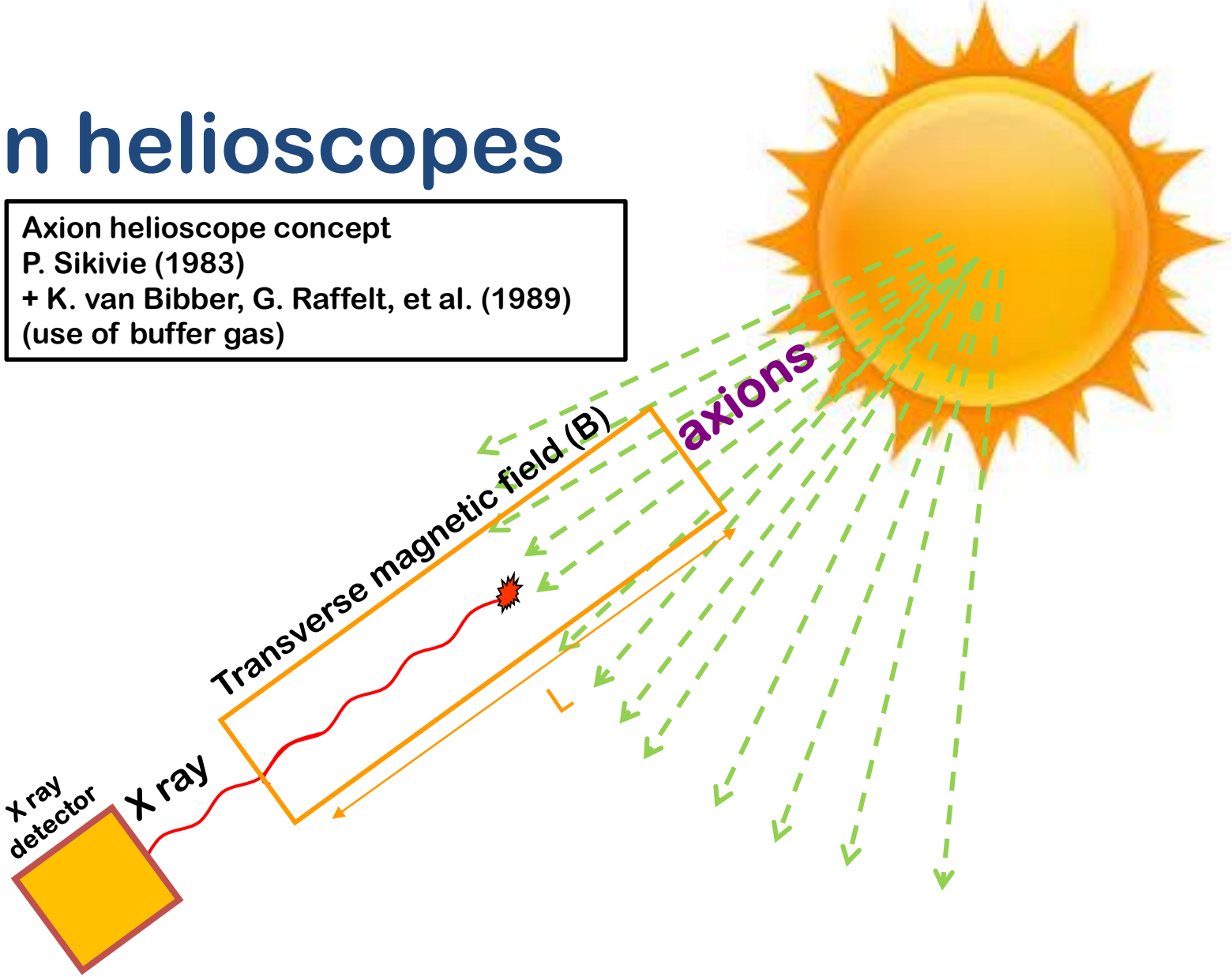
Standard Primakoff spectrum



Axion helioscopes

- **Previous helioscopes:**
  - First implementation at Brookhaven (just few hours of data) [Lazarus et at. PRL 69 (92)]
  - TOKYO Helioscope (SUMICO): 2.3 m long 4 T magnet

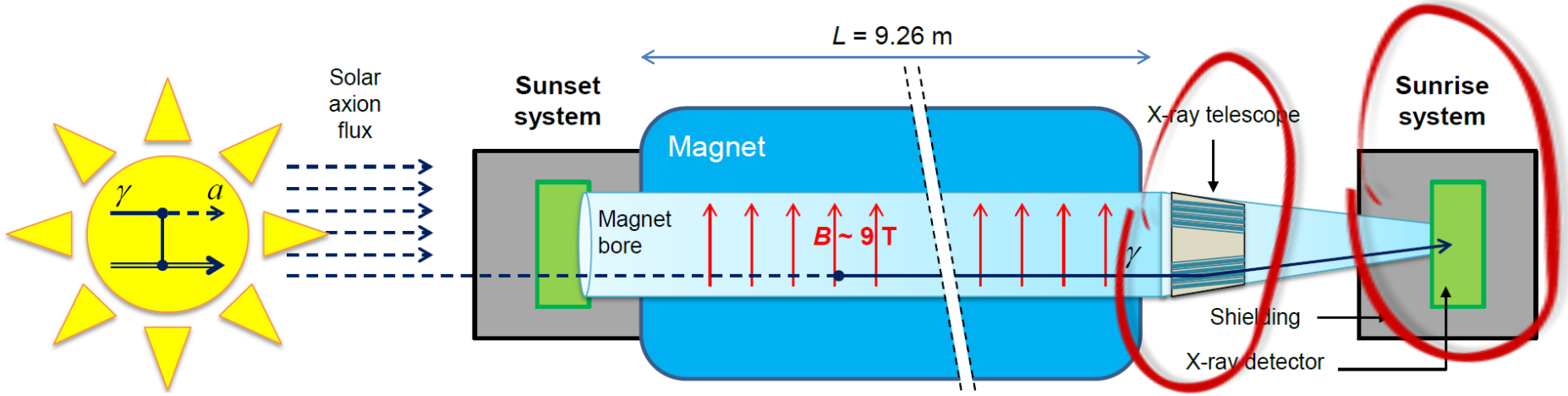
Axion helioscope concept
P. Sikivie (1983)
+ K. van Bibber, G. Raffelt, et al. (1989)
(use of buffer gas)



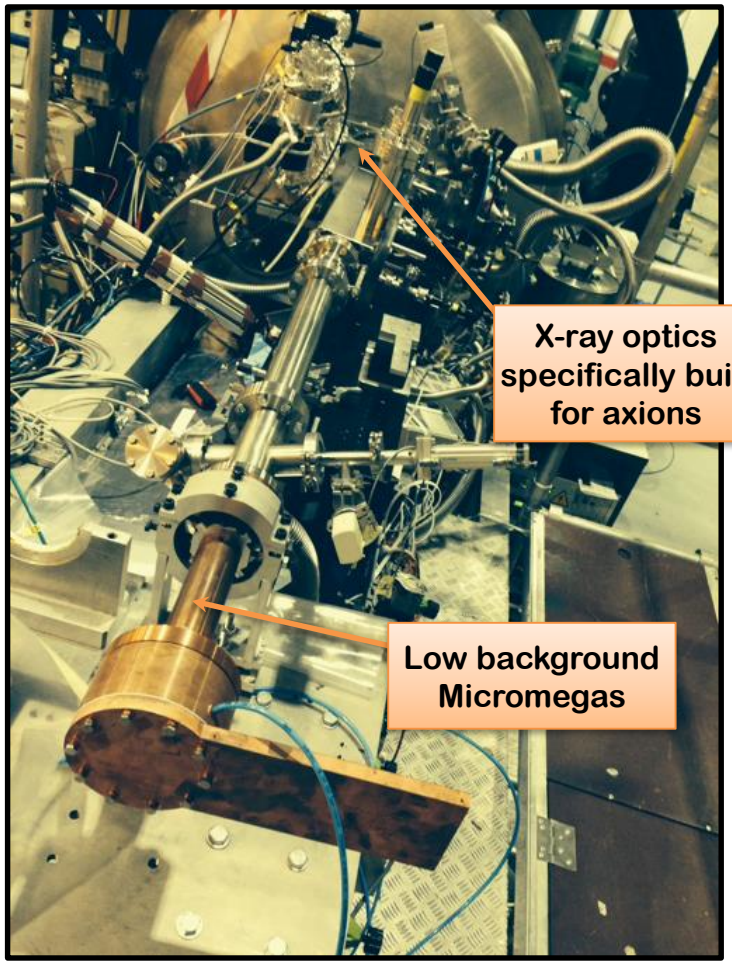
CAST: state-of-the-art

Current state-of-the-art:
CERN Axion Solar Telescope (CAST)

First helioscope using low background techniques & x-ray focusing



Latest CAST limit



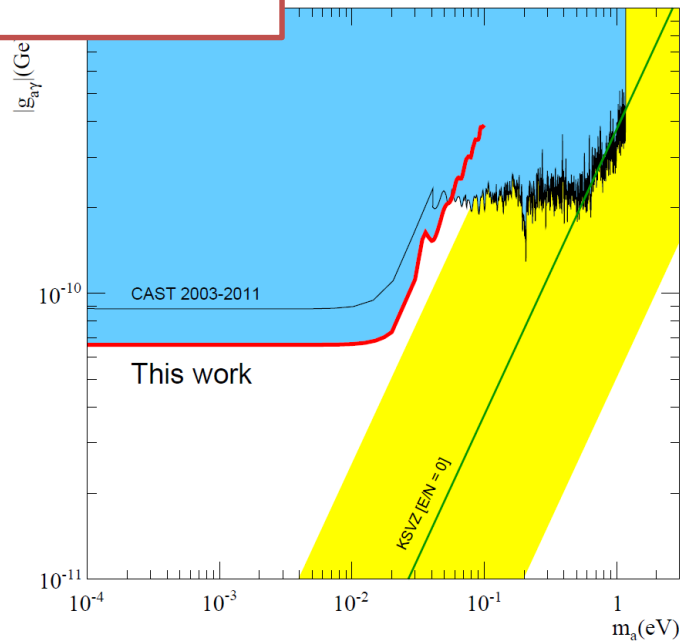
nature physics
ARTICLES
PUBLISHED ONLINE: 1 MAY 2017 | DOI: 10.1038/NPHYS4109
OPEN

New CAST limit on the axion-photon interaction

CAST Collaboration†

Hypothetical low-mass particles, such as axions, provide a compelling explanation for the dark matter in the universe. Such particles are expected to emerge abundantly from the hot interior of stars. To test this prediction, the CERN Axion Solar t directed towards the Sun. In the strong magnetic d by X-ray detectors. In the 2013–2015 run, thanks

$$g_{a\gamma} < 0.66 \times 10^{-10}\,\mathrm{GeV}^{-1} \text{ at } 95\%\ \mathrm{CL}$$

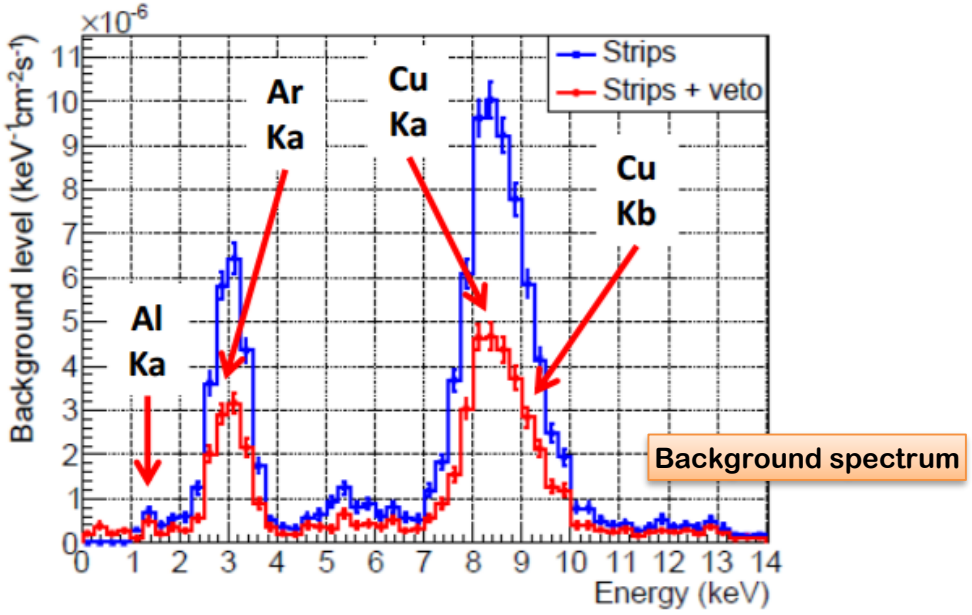


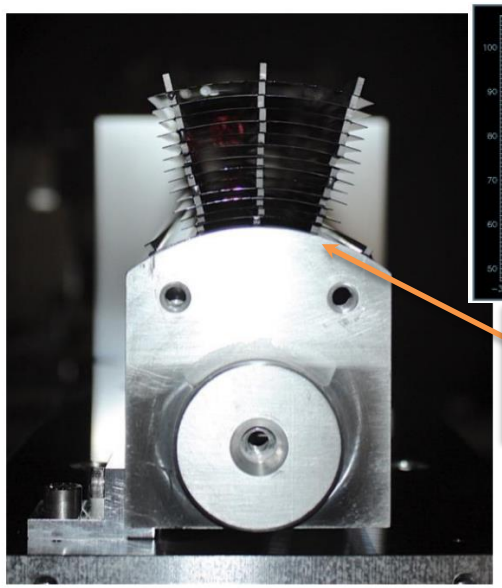
IAXO pathfinder system at CAST:
x-ray focusing + low background detector combined in same system
Small-scale version of IAXO baseline detection lines

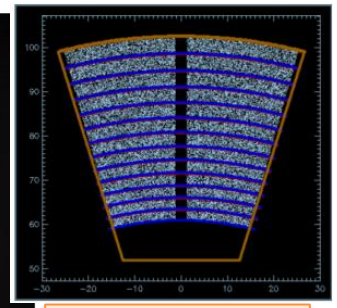
IAXO pathfinder system in CAST

Test MM detector + slumped-glass x-ray optics together

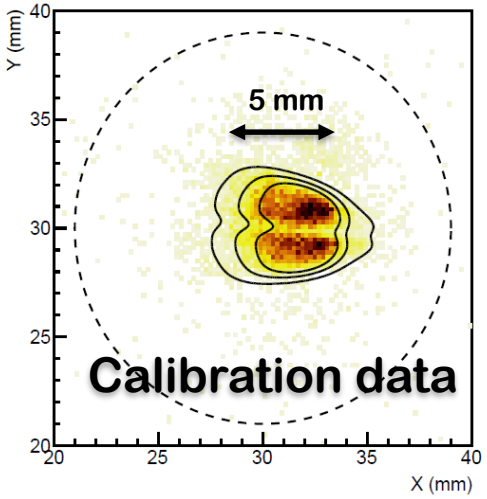
Detector: JCAP12 (2015)
Physics: Nature Phys. 13 (2017) 584-590

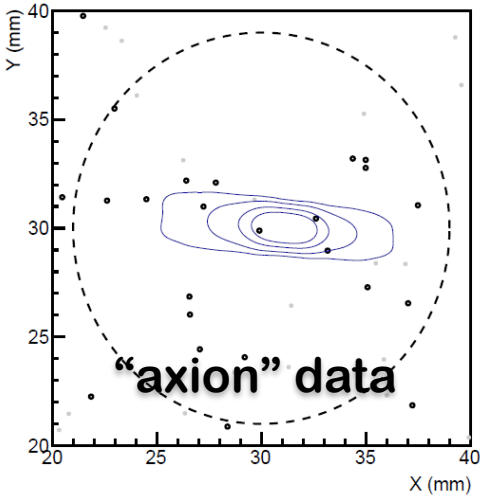




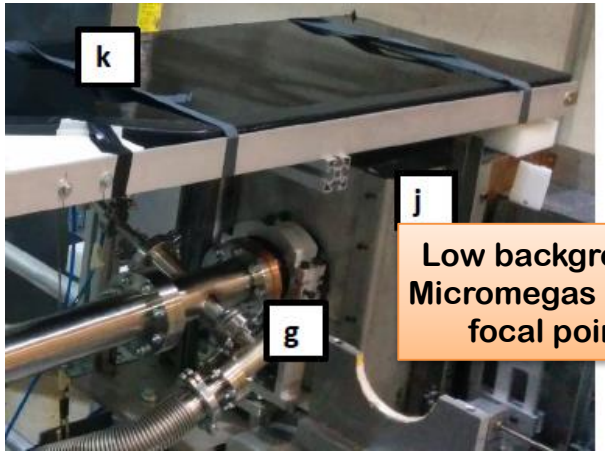


X-ray optics specifically built for axions



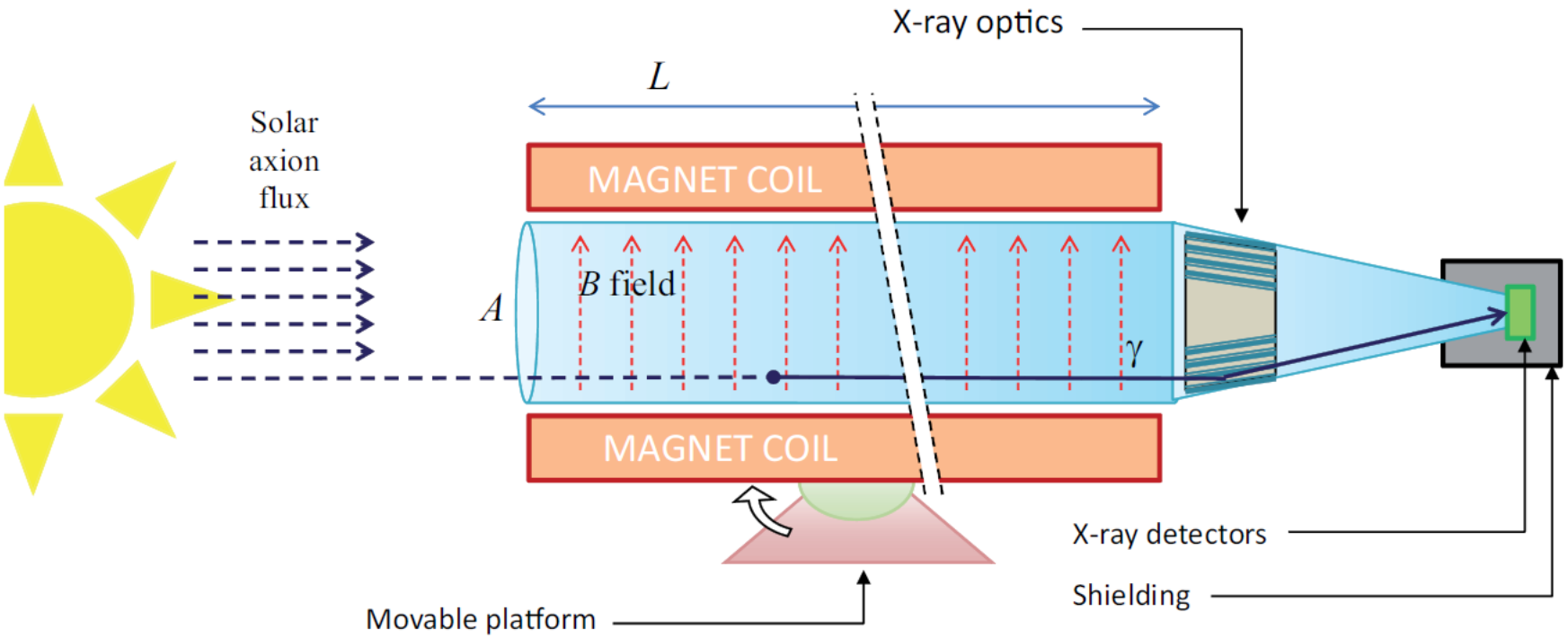


- Best SNR of any previous detector
- 290 tracking hour acquired (6.5 months operation)
- 3 counts observed in RoI (1 expected)



Low background Micromegas at the focal point

An enhanced axion helioscope



IAXO is conceived as a large-scale, but realistic, enhanced axion helioscope

>10^4 better SNR than CAST

Sensitive to g_{ag} ~ x20 lower than CAST

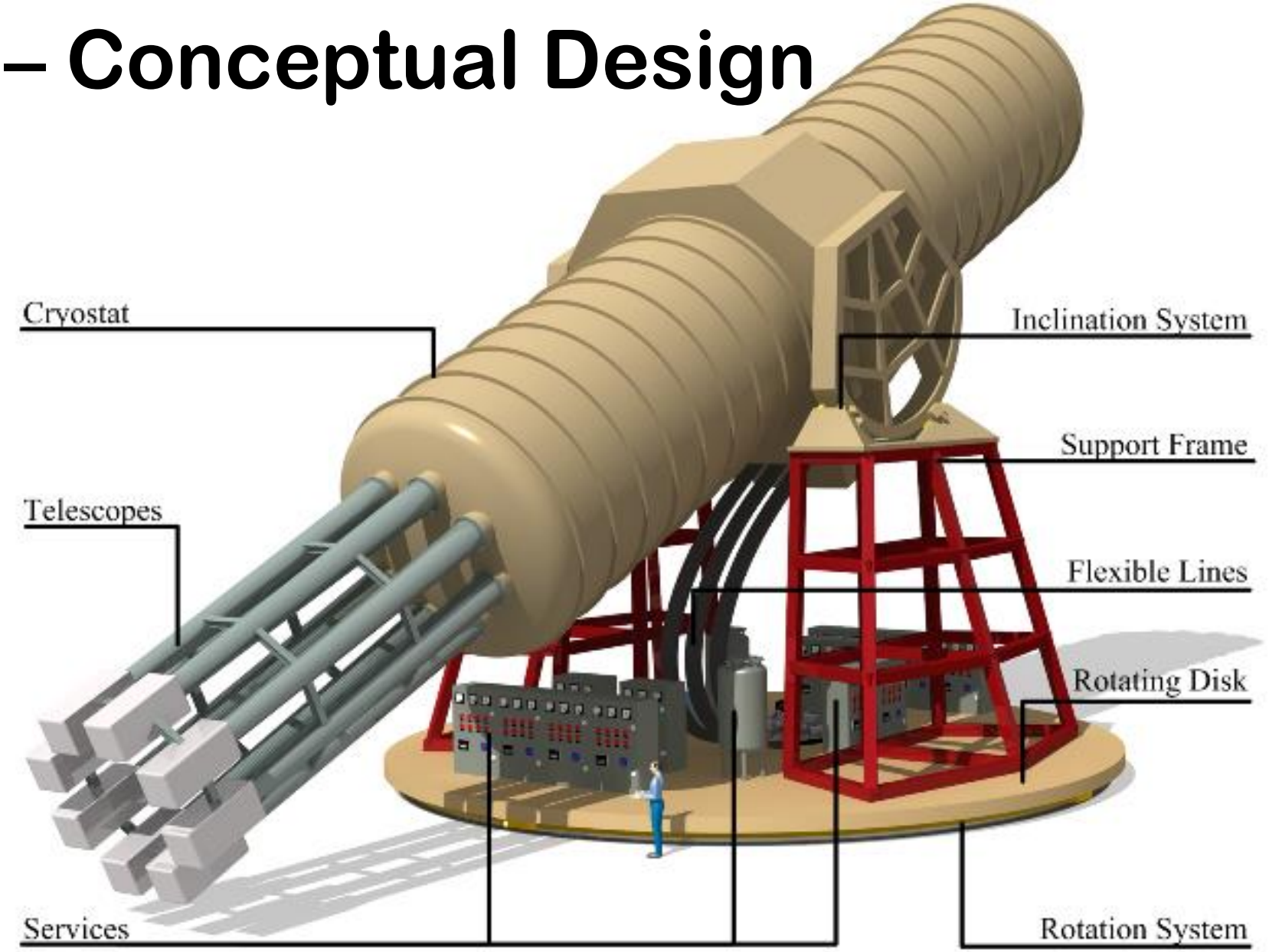
Enhanced axion helioscope:
JCAP 1106:013,2011

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

IAXO – Conceptual Design

- Large toroidal 8-coil magnet *L* =~20 m
- 8 bores: 600 mm diameter each
- 8 x-ray telescopes + 8 detection systems
- Rotating platform with services

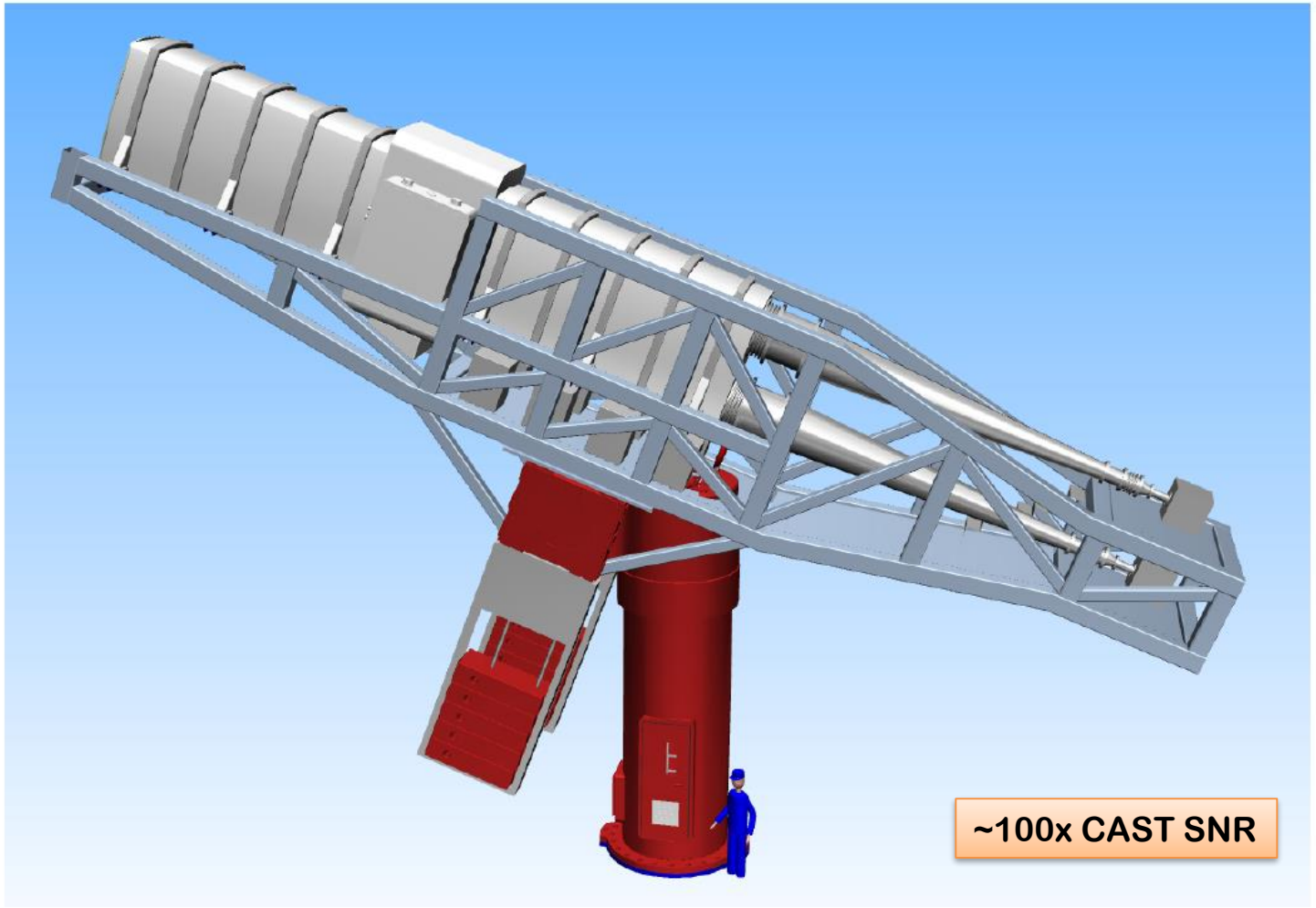
IAXO CDR: JINST 9 (2014) T05002 (arXiv:1401.3233)



BabyIAXO

- **Prototype:** Intermediate experimental stage before IAXO
  - Two bores of dimensions similar to final IAXO bores → detection lines representative of final ones.
  - Magnet will test design options of final IAXO magnet
  - Test & improve all systems. Risk mitigation for full IAXO
- **Physics:** will also produce relevant physics outcome

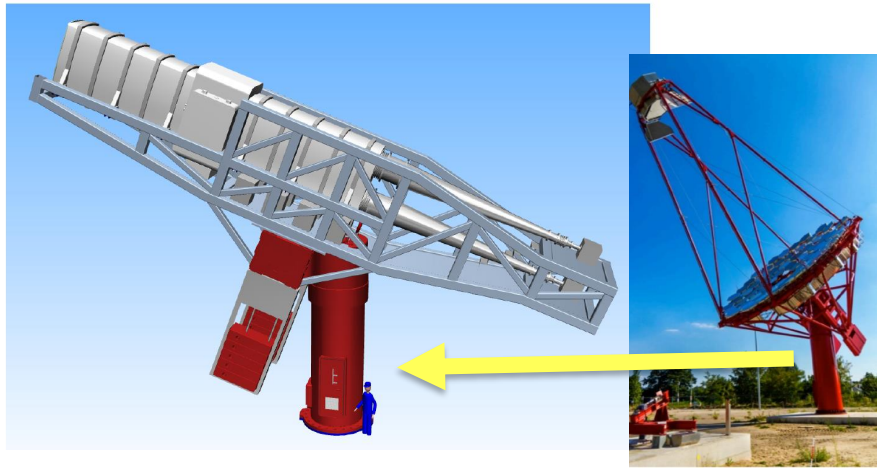
  (~100 times larger FOM than CAST)

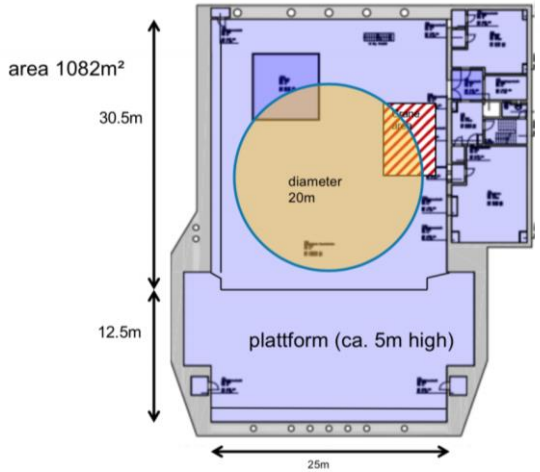


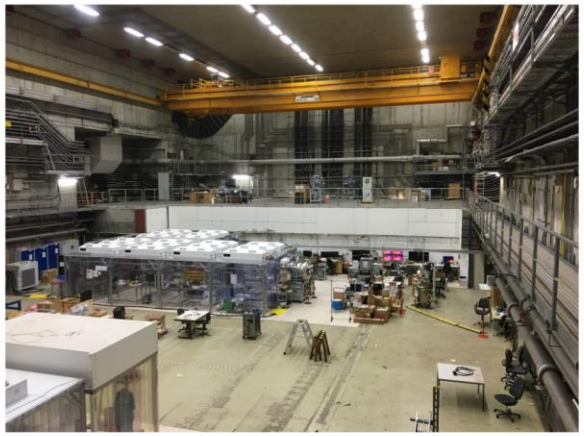
(Baby)IAXO @ DESY

- BabyIAXO under review by DESY PRC

- DESY in a ideal host for IAXO. Existing expertise/capabilities nicely complements those of collaboration.
- DESY “axion program” under consideration, ideal environment for BabyIAXO and IAXO
- Important connection with CERN (magnet expertise)

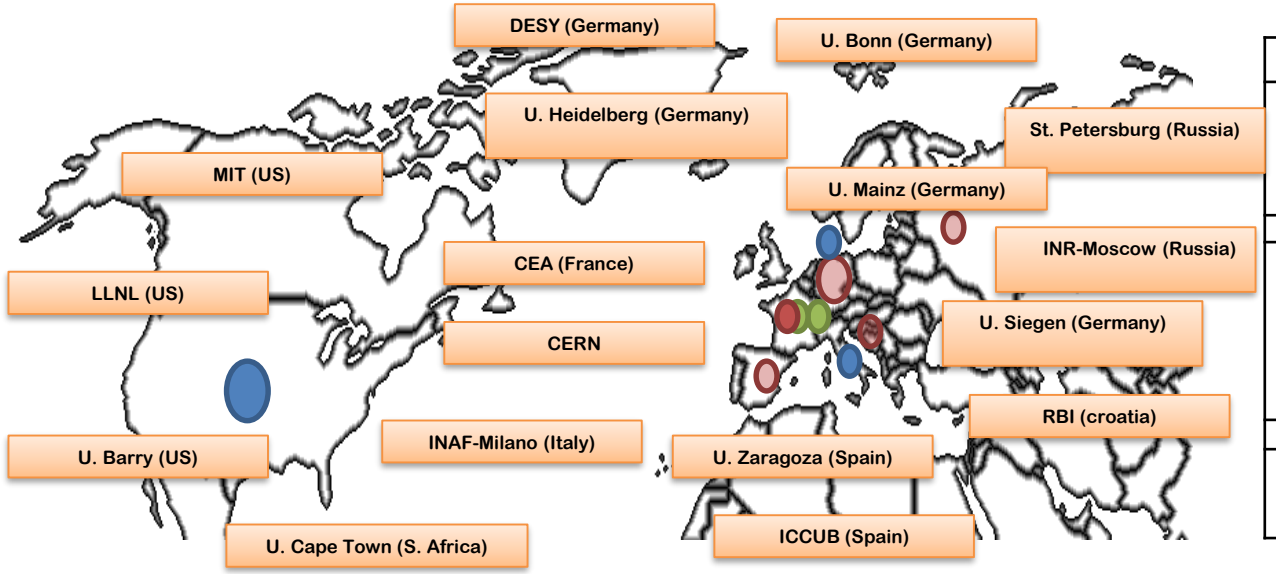






Collaboration & timeline

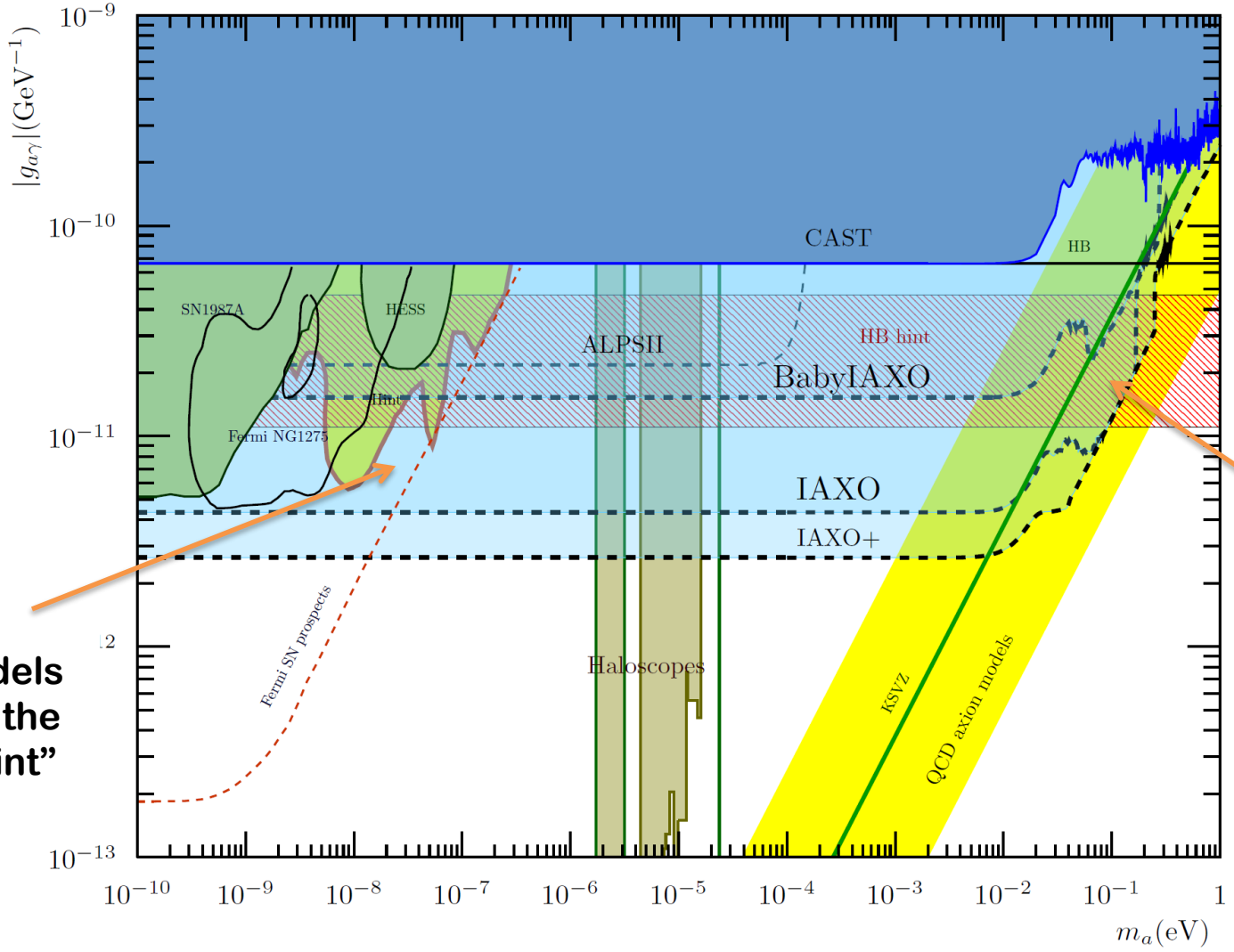
- **Large collaboration with needed experience**
  - 17 institutions from Germany, Spain, US, France, Russia, Italy, Croatia, S. Africa, CERN.
- **Know-how portfolio encompassing all needed expertise**
  - Involvement of large institutes like DESY (site), CERN (magnet)
- **Realistic timeline leading to BabyIAXO commissioning by 2023**



		2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029+
	Design											
	Construction											
	Commissioning											
Data taking	Vacuum phase											
Data taking	Upgrade to gas											
Data taking	Gas phase											
Data taking	Beyond-baseline											
IAXO	Design											
IAXO	Construction					Tentative						

BabyIAXO & IAXO physics reach

BabyIAXO & IAXO prospects:
Following current LoI designs



IAXO+: enhanced scenario with x10 (x4) higher FOM (MFOM) with respect to LoI

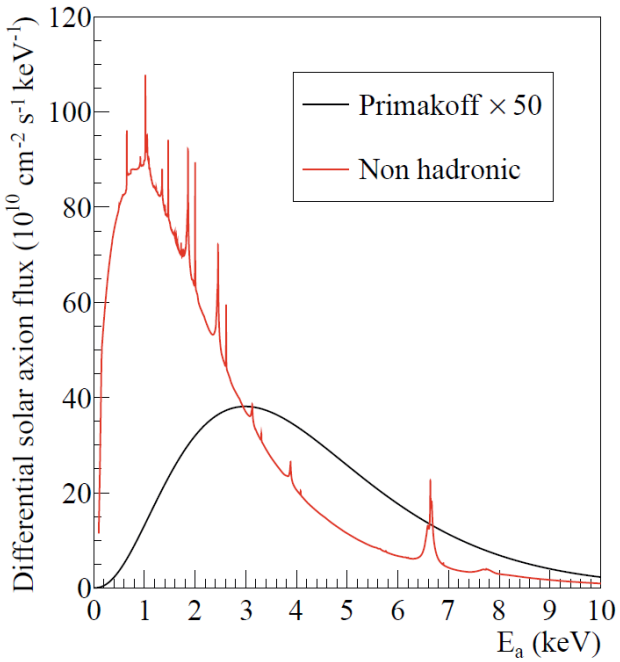
IAXO will fully explore ALP models invoked to solve the "transparency hint"

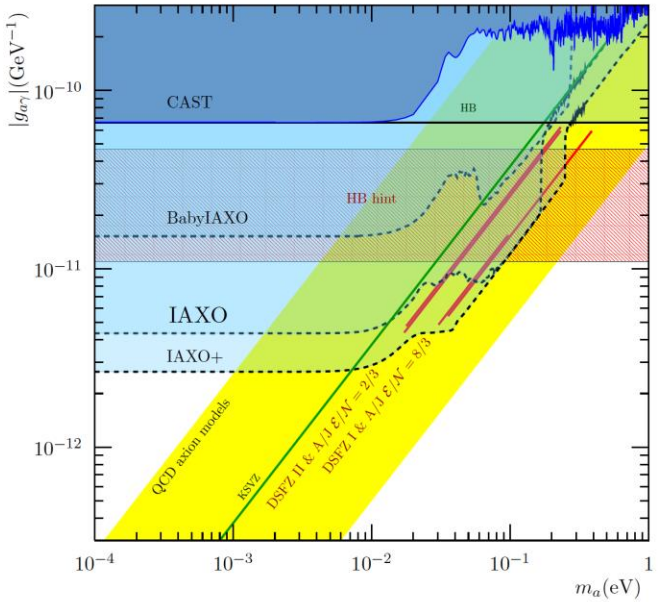
… as well as a large fraction of the axion & ALP models invoked in the "stellar cooling anomaly"
But for this the g_{ae} is particularly interesting

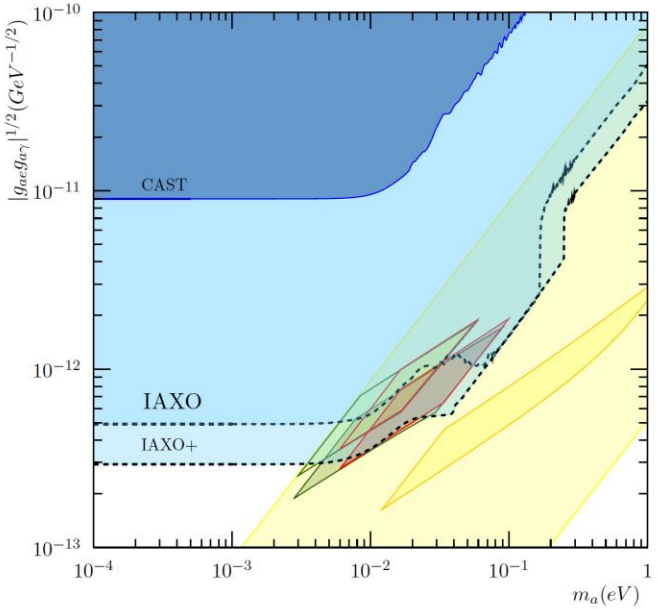
MFOM = Magnet FOM

IAXO & stellar cooling hints

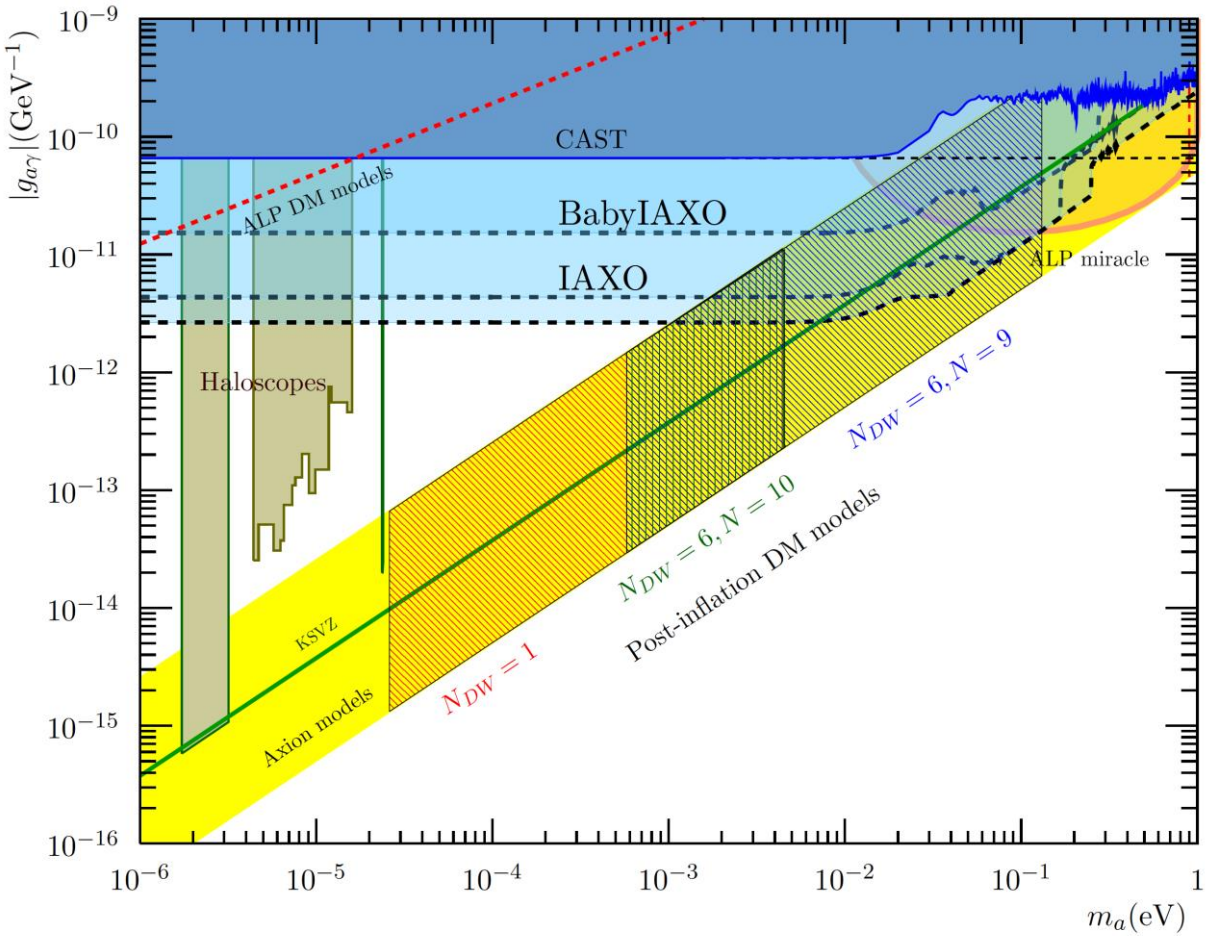
- **IAXO can detect "ABC" solar axions (i.e. non-hadronic, g_{ae}-mediated)**
- **Boost in sensitivity for models featuring g_{ae}- coupling.**
- **Will probe QCD axion models invoked to solve all stellar cooling anomalies**







IAXO & axion cosmology



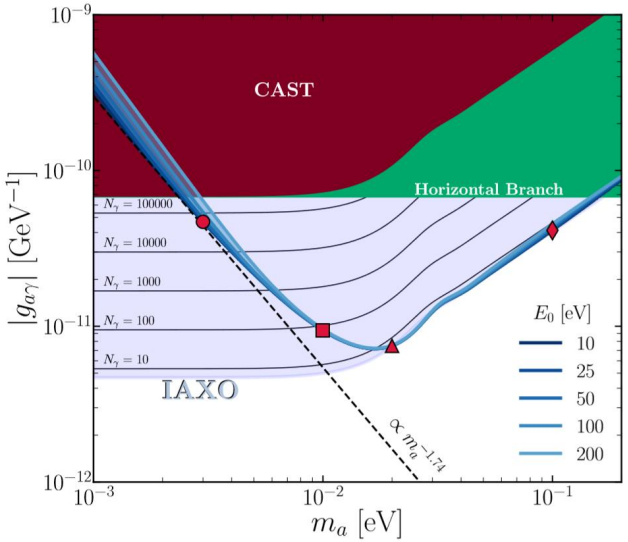
- **Axion post-inflation mass window overlaps with astro window**
  - **Uncertainty in topological defect decay is large (Gorghetto et al 2018)**
  - **NDW>1 models (Saikawa, Ringwald 2016)**

- **Also:**
  - **If axions only subdominant DM component, axion mass moves to higher values.**
  - **"ALP miracle" (ALP inflation + DM) models @ 0.01 to 1 eV**
  - **EDGES anomaly interpretation with DM axions at 0.01-1 eV range**

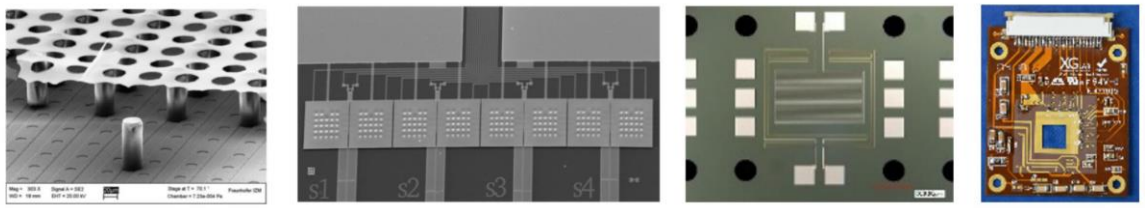
- **IAXO will probe interesting DM axion & ALP models**

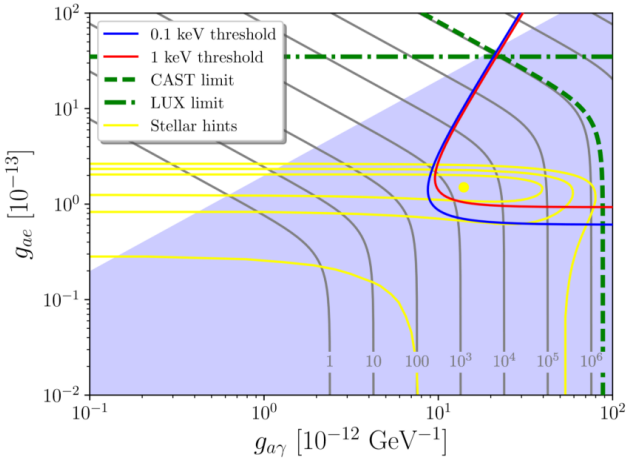
Post-discovery physics

- A positive signal in BabyIAXO will be seen >100x stronger in IAXO
- With sufficient statistics and precision detectors IAXO can determine axion model parameters:
  - Axion mass: "Weighing" the solar axion" [Dafni et al. arXiv:1811.09278]
  - Axion couplings: "Distinguishing axion models with IAXO" [Jaeckel et al. arXiv:1811.09278]



- IAXO collaboration is developing high-precision ("post-discovery") detectors (e.g. MMCs or TES)



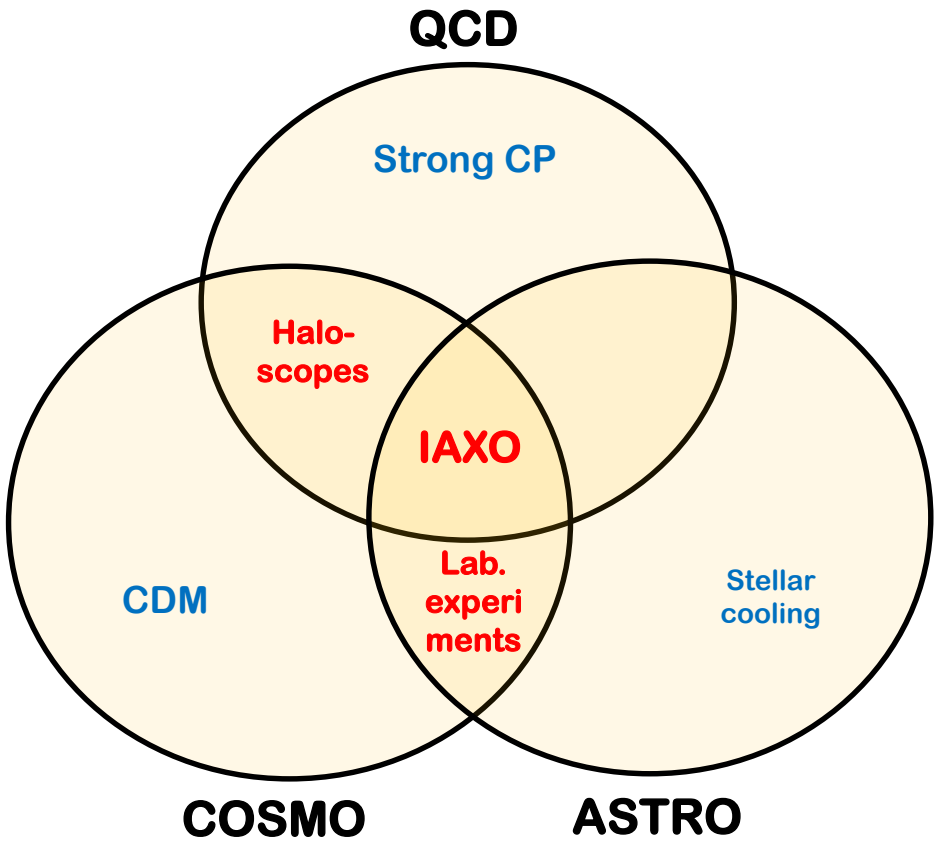


IAXO physics case – summary statements

IAXO will probe…

- Large generic unexplored ALP space
  - down to $g_{a\gamma}$ ~ few 10^{-12} GeV^{-1}
  - down to g_{ae} ~ few 10^{-13}
- QCD axion models in the meV to eV mass band.
- Astrophysically hinted regions
- Cosmologically interesting regions

- All this, independent of the axion-as-DM hypothesis.
- No other competing technique. IAXO is unique in the axion experimental landscape and very complementary.
- BabyIAXO relevant intermediate physics potential

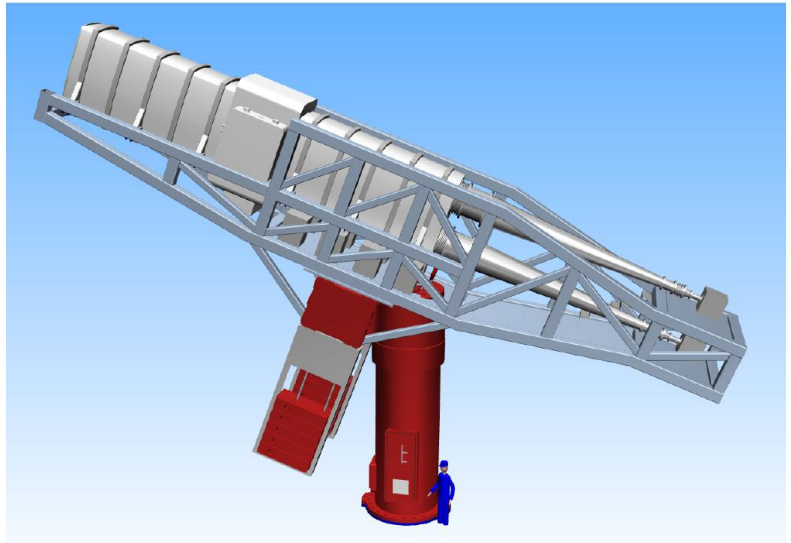


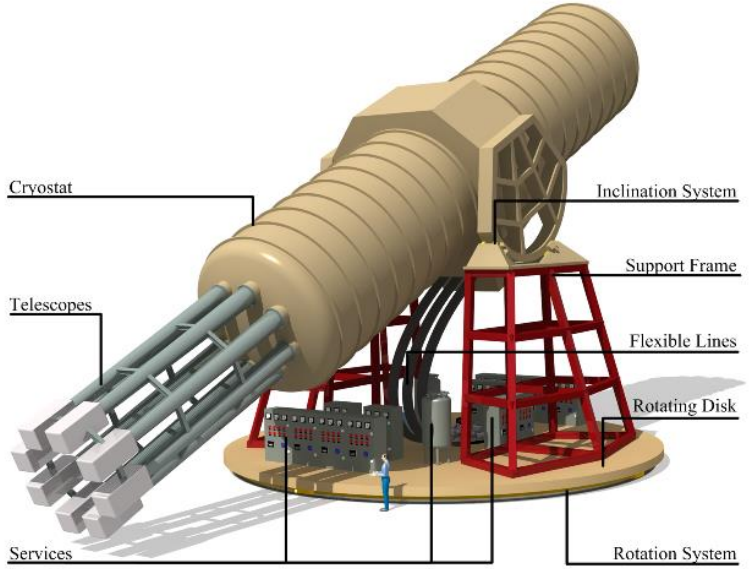
Review of Physics potential of IAXO
arXiv:1904.09155

Conclusions

- Helioscopes have a unique and complementary physics case in the "axion experimental landscape".

- Realistic path to physics in a few years:
- BabyIAXO is well on track" for implementation at DESY (in-depth review of project will take place next week!)
- The IAXO collaboration encompasses the needed know-hows and has already secured a substantial fraction of the resources.
- The project relies on the 15+ year experience with CAST + CERN expertise in large SC magnets.
- DESY in a ideal host for IAXO. Expertise/capabilities complementary to collaboration. IAXO part of the DESY "axion program" under consideration.

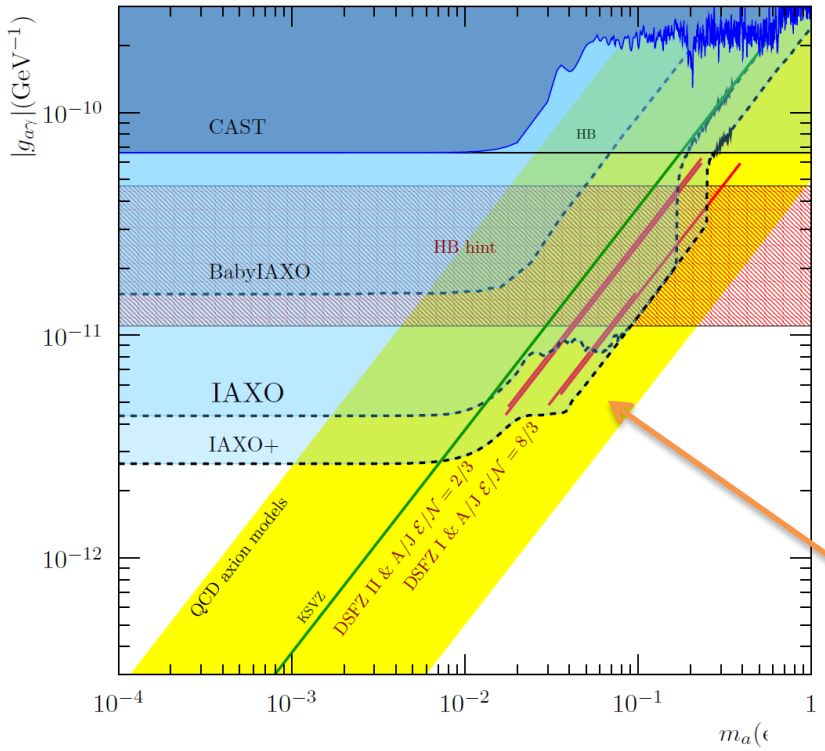


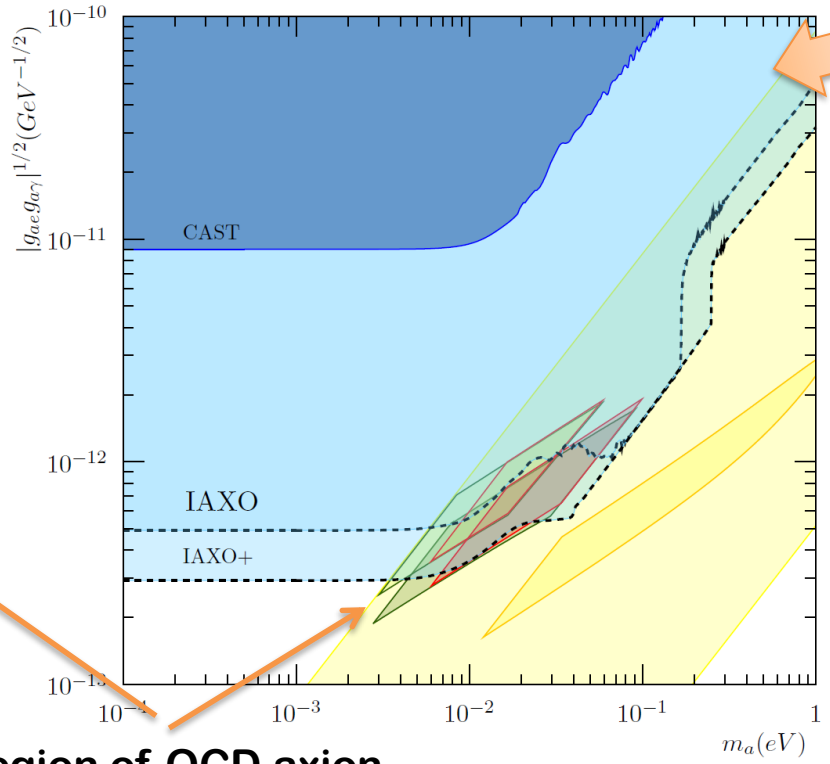


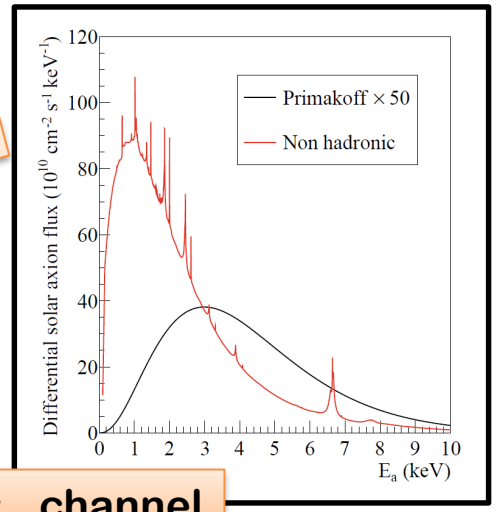
Backup slides

IAXO & stellar cooling

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







g_{ae} **channel**

Region of QCD axion models that solve the stellar anomaly

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

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

IAXO and CERN

[from PBC technology subgroup meetings]

- IAXO crucially relies on CERN's expertise on large-scale superconducting detector magnets. Both BabyIAXO and IAXO detector magnets are systems of a scale for which CERN's expertise and infrastructure is almost unique.
- The collaboration expects support and significant participation of CERN, in particular, but not exclusively, with knowledge and expert personnel to the Technical Design Report of magnets and related infrastructure, as well as the technical follow-up during construction, testing and commissioning, first of BabyIAXO and then for IAXO.
- CAST is still active at CERN hosting a number of small-scale prototypes for testing novel concepts or performing R&D. There is potential in further using CAST infrastructure for providing feedback during the preparatory phase of IAXO, for example, to improve the insight on detector backgrounds

Axions: theory motivation

- Axion: introduced to solve the **strong CP problem**

- In QCD, nothing prevents from introducing a term like:

$$\mathcal{L}_{CP} = \theta \frac{\alpha_s}{8\pi} G\tilde{G}$$

This term is **CP violating**.

$$\theta = \bar{\theta} + \arg\det M \ .$$

2 contributions of very different origin…

From non-observation of neutron electric dipole moment:

$$|\theta| < 1.3 \times 10^{-10}$$

- Why so small?

- High fine-tunning required for this to work in the SM

Axions: theory motivation

- **Peccei-Quinn solution to the strong CP problem**

- **New U(1) symmetry introduced in the SM: Peccei Quinn symmetry of scale f_a**
- **The AXION appears as the Nambu-Goldstone boson of the spontaneous breaking of the PQ symmetry**

"Axion lagrangian"

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 - \frac{\alpha_s}{8\pi f_a} a G\tilde{G}$$

θ absorbed in the definition of a

$\theta = a/f_a$ relaxes to zero…
CP conservation is preserved "dynamically"

The axion

- The PQ scenario solves the strong CP-problem. But a most interesting consequence is the appearance of this new particle, the *axion*.

(Weinberg, Wilcek)

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 - \frac{\alpha_s}{8\pi f_a} a G\tilde{G}$$

- **Basic properties:**
  - Pseudoscalar particle
  - Neutral
  - Gets very small mass through mixing with pions
  - Stable (for practical purposes).
  - Phenomenology driven by the PQ scale f_a. (couplings inversely proportional to f_a)

$$m_A = 5.70(7)\mu\text{eV}\left(\frac{10^{12}\text{GeV}}{f_A}\right)$$

Axion phenomenology

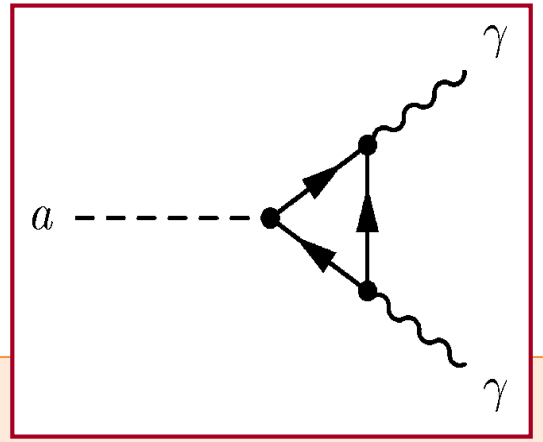
- Some phenomenology depends on the **"axion model"**, e.g.
  - KSVZ axions are "hadronic axions" (no coupling with leptons at tree level)
  - DFSZ axions couple to electrons

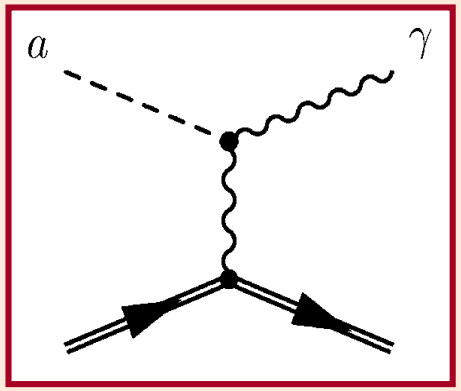
Gluon coupling	Mass	Photon coupling	Fermion couplings
$\frac{\alpha_s}{8\pi f_a} a G\tilde{G}$	$m_A = 5.70(7)\mu\text{eV} \times \left(\frac{10^{12}\text{GeV}}{f_A}\right)$	$g_{a\gamma\gamma}(\mathbf{E}\cdot\mathbf{B})a$ $g_{a\gamma\gamma} = \frac{\alpha_s}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$	Electron coupling Nucleon coupling ...
generic	*generic*	*generic but value model dependent*	*Model dependent*

Axion phenomenology

- **Axion-photon coupling** present in every model.

$$\mathcal{L}_{a\gamma} = g_{a\gamma\gamma}(\mathbf{E}\cdot\mathbf{B})a \qquad g_{a\gamma\gamma} = \frac{\alpha_s}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$$



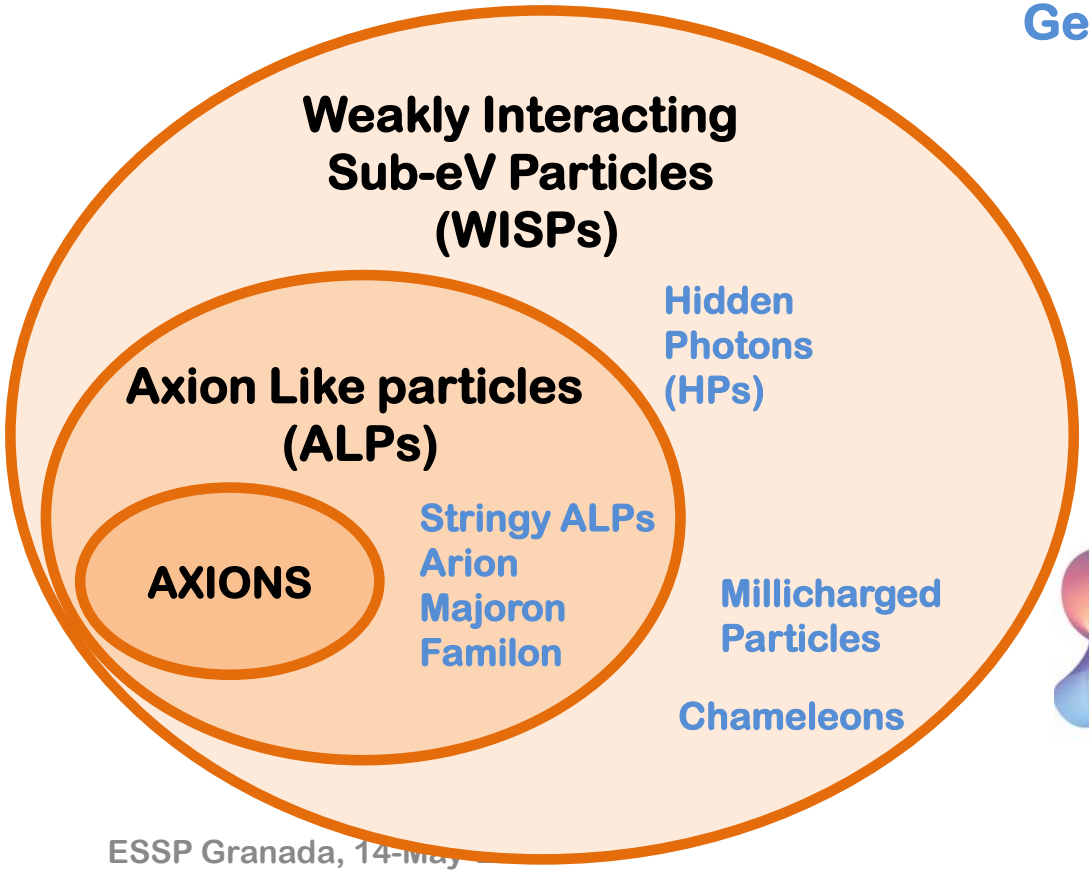


- **Axion-photon conversion** in the presence of an electromagnetic field (**Primakoff effect**)

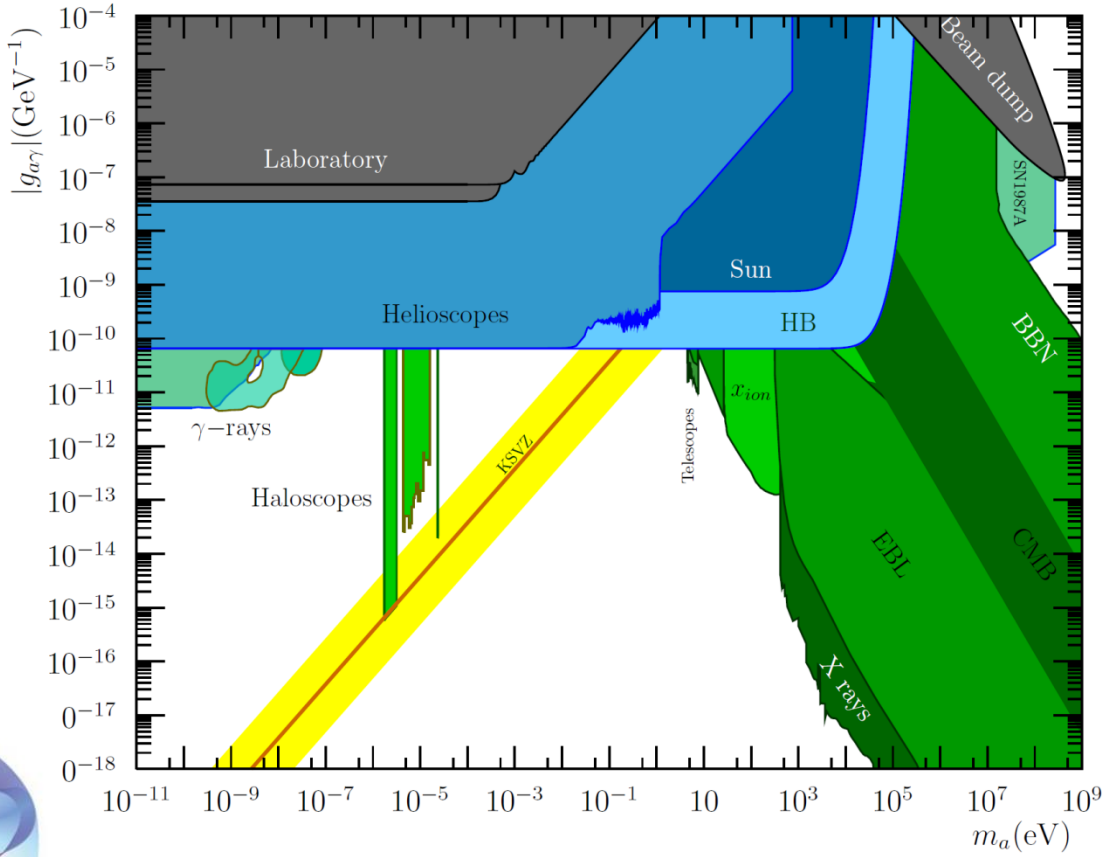
This is probably the most relevant of axion properties.
Most axion detection strategies are based on the axion-photon coupling

Beyond axions

- Many extensions of SM predict axion-like particles
  - Higher scale symmetry breaking

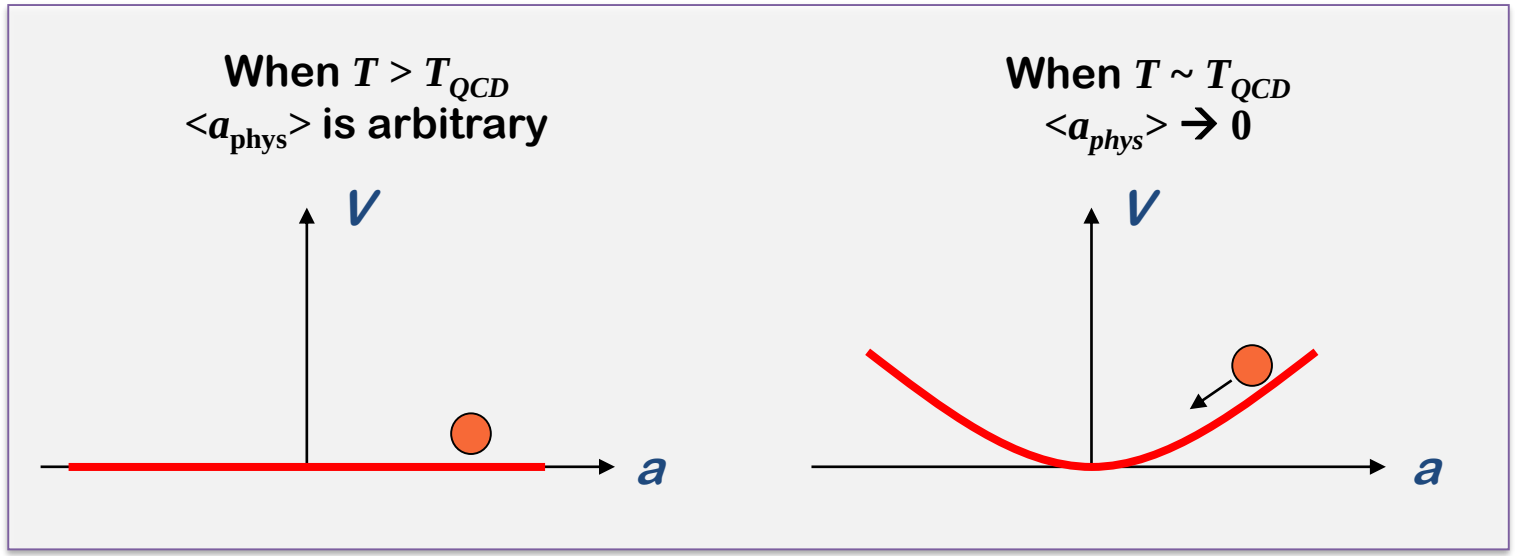


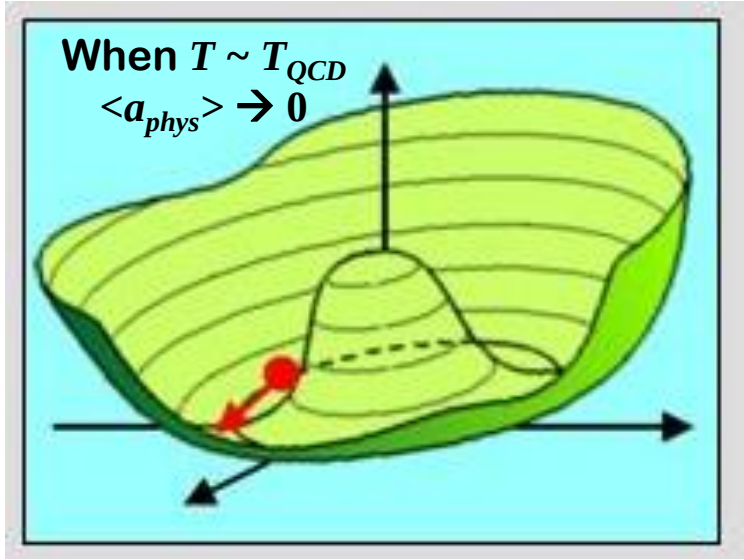
Generic ALPs parameter space →



String theory predicts a plenitude of ALPs

Cosmological axions: axion realignment



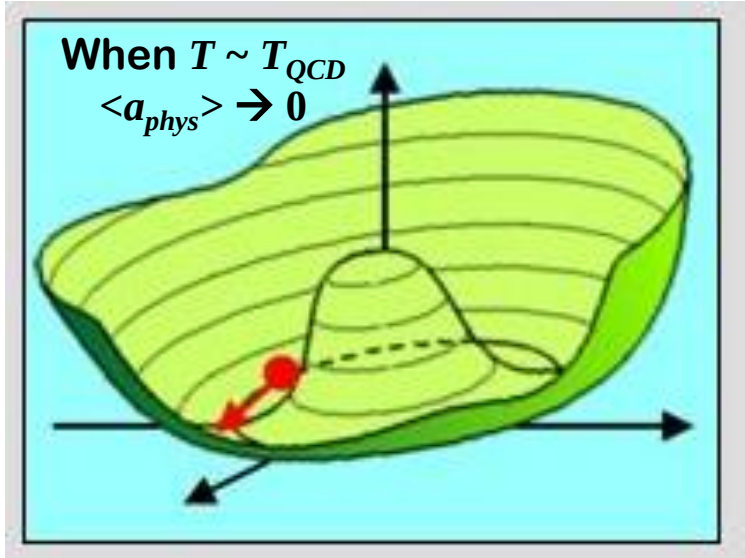


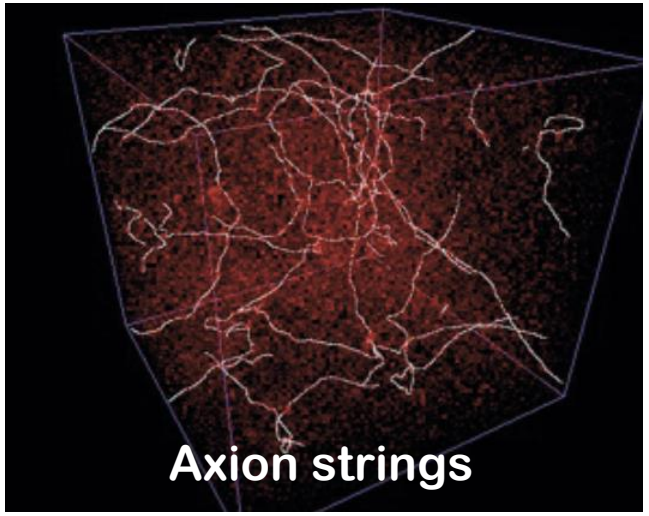
As the Universe cools down below T_{QCD}, space is filled with low energy axion field fluctuations → act as cold dark matter

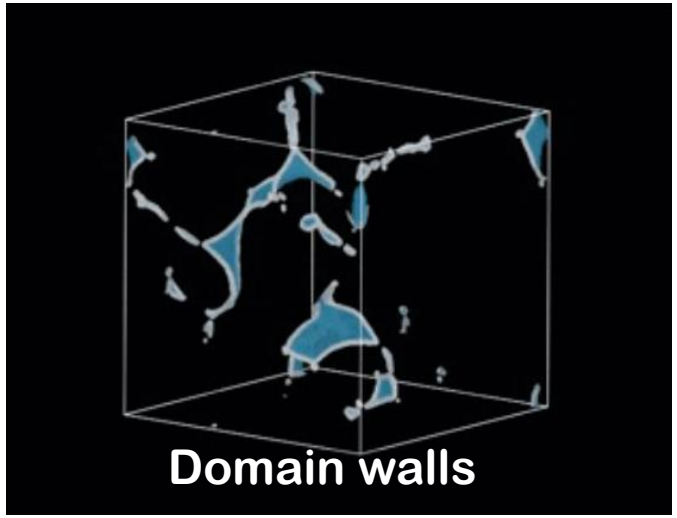
Their density depends on the initial value of $<a_{phys}>$ ("misalignment angle") which:

- Unique (but unknown) for all visible Universe in pre-inflation models
- Effectively averaged away in post-inflation models $\langle \theta_a^2 \rangle = \pi^2/3$

Cosmological axions: topological defects







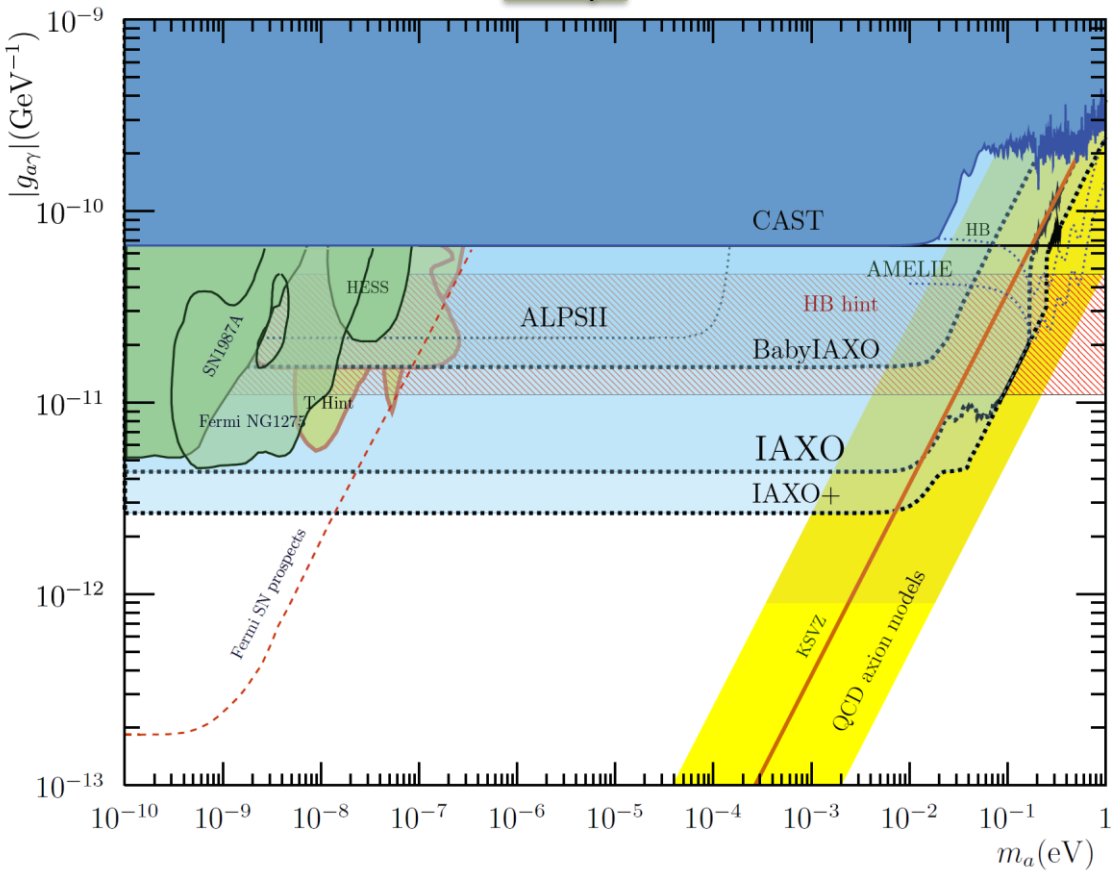
But inflation may "wipe out" topological defects… Did inflation happen before or after the creation of defects (PQ transition) ?

pre-inflation or post-inflation scenarios

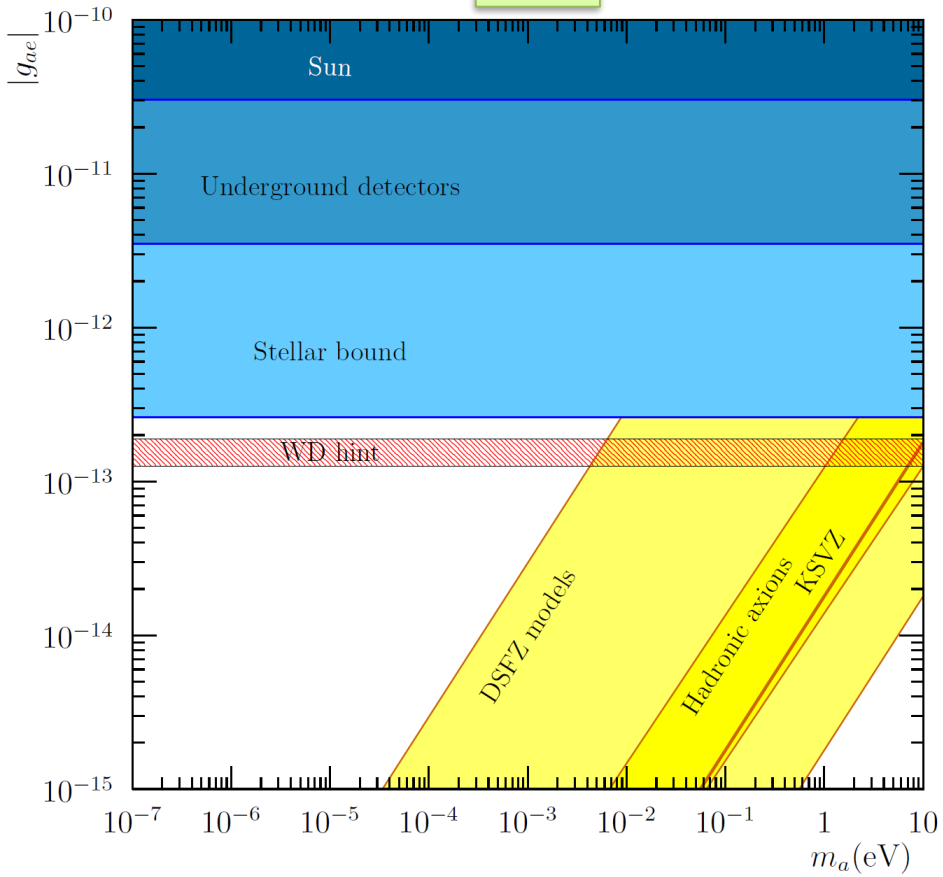
Computation of axion DM density from defect decay is complicated (→ big uncertainty)

Astrophysical hints for axions

$g_{a\gamma}$



g_{ae}

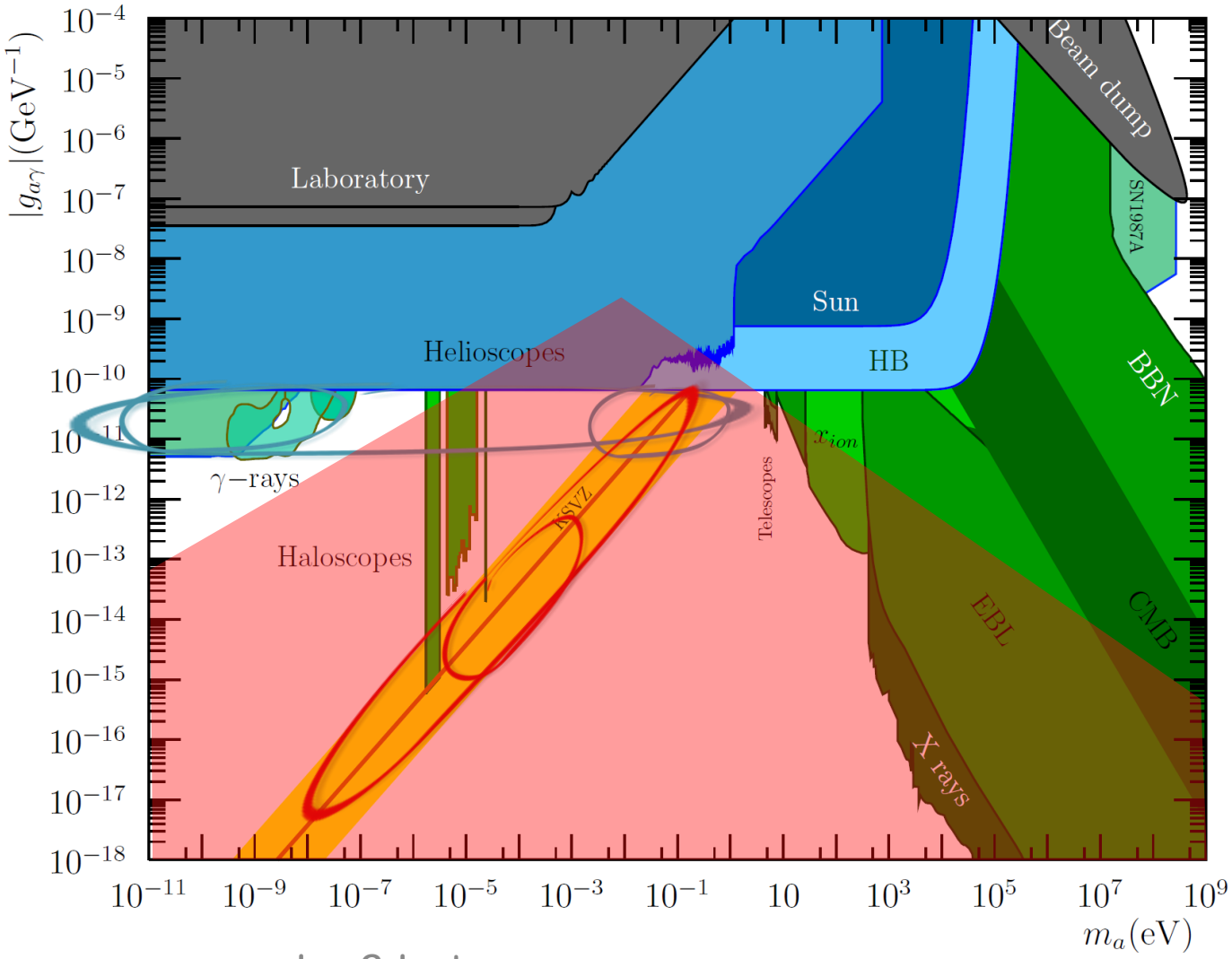


Axion/ALP searches motivation

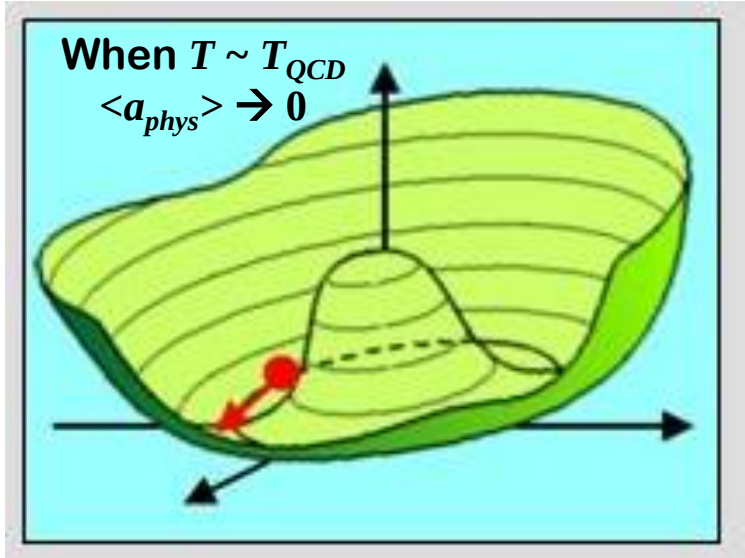
"Focuses of interest" in the ALP parameter space

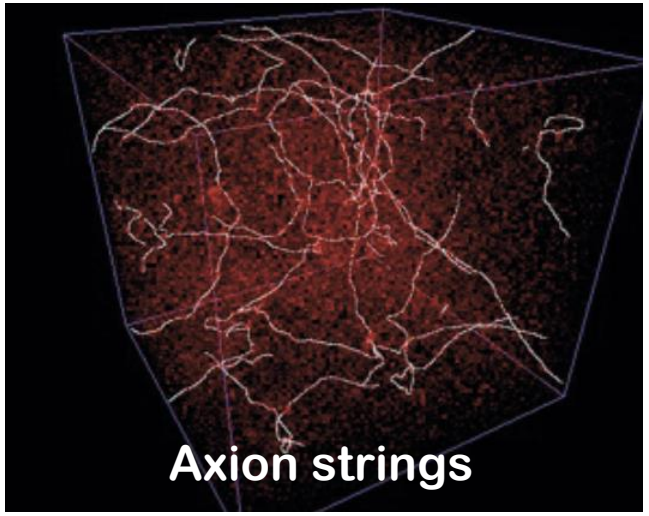
Theory
Astrophysics
Cosmology

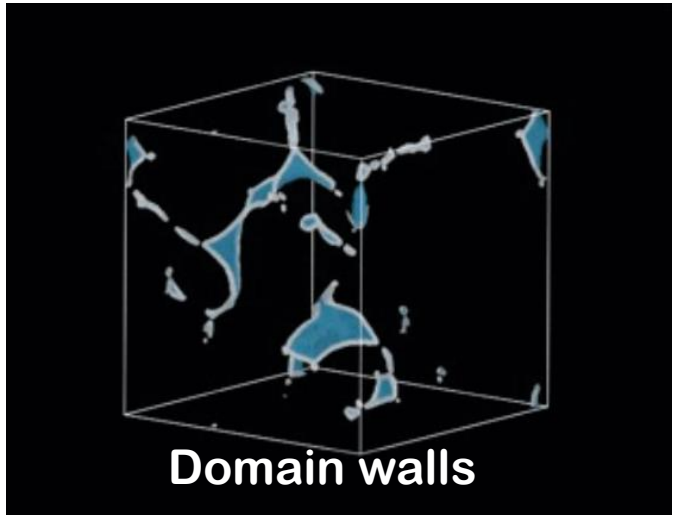
Generic ALP DM models



Cosmological axions







Axion realignment

(initial misalignment angle?)

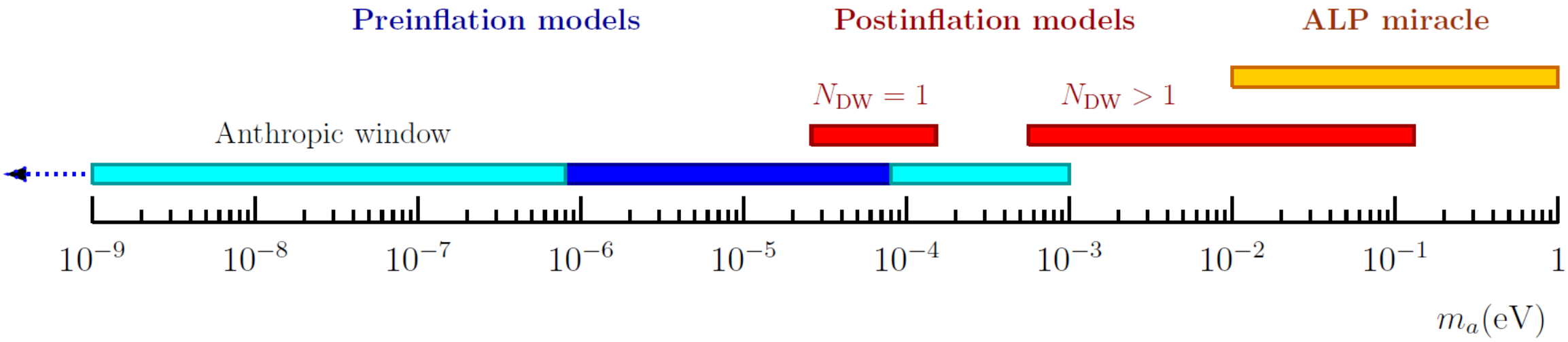
But also… topological defects

(inflation can wipe them out if it happens afterwards)

Note: thermal production of axions (as neutrinos) gives hot DM (upper limit ma~1 eV)

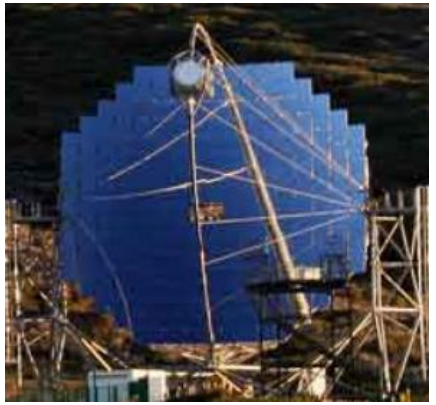
Axion DM density vs axion mass

- **Axions are good DM candidates → for which m_a do we get $\Omega_a \sim \Omega_{DM}$?**
  - **Pre-inflation models → only misalignment contribution, but initial angle unknown → very large m_a range possible (even very low m_a values with anthropic tuning)**
  - **Post-inflation models → misalignment becomes more predictive as initial angle gets averaged. BUT, topological defects are now important (source of uncertainty).**
- **In any case, for $\Omega_a < \Omega_{DM}$ → m_a increases as $m_a \sim \Omega_a^{-1}$**
- **Note: thermal production of axions (as neutrinos) gives hot DM (upper limit m_a~1 eV)**



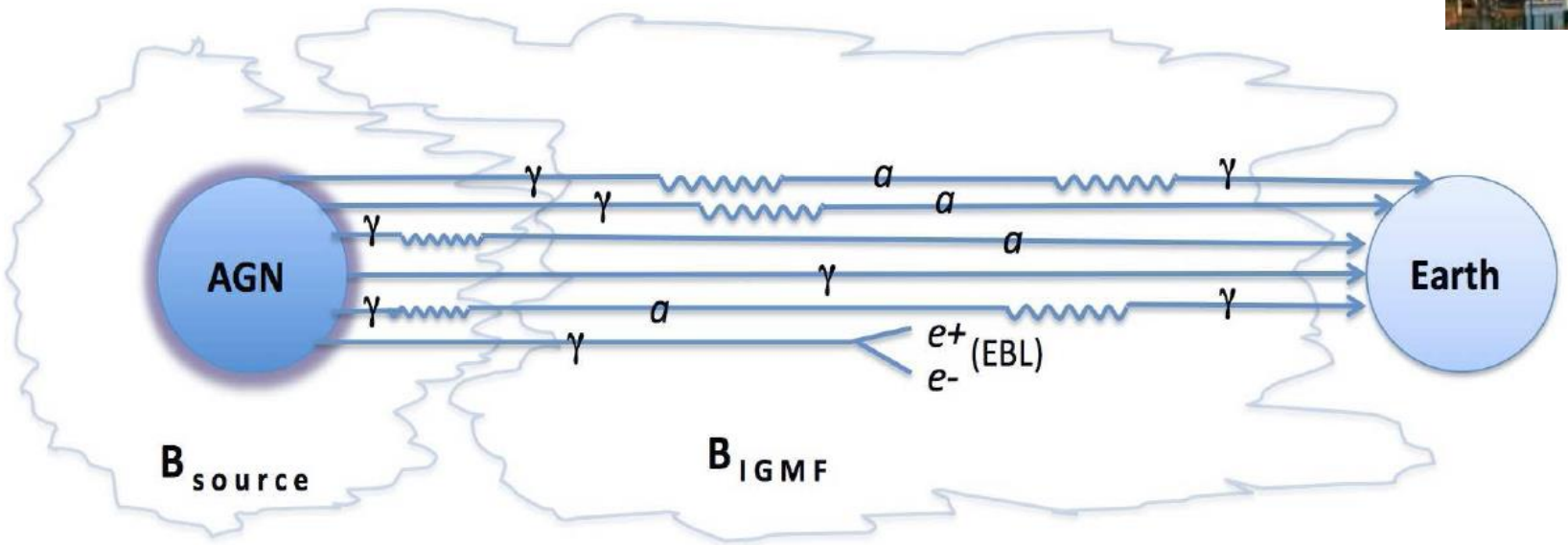
Astrophysical hints for axions

- **Gama ray telescopes like MAGIC or HESS observe HE photons from very distant sources…**



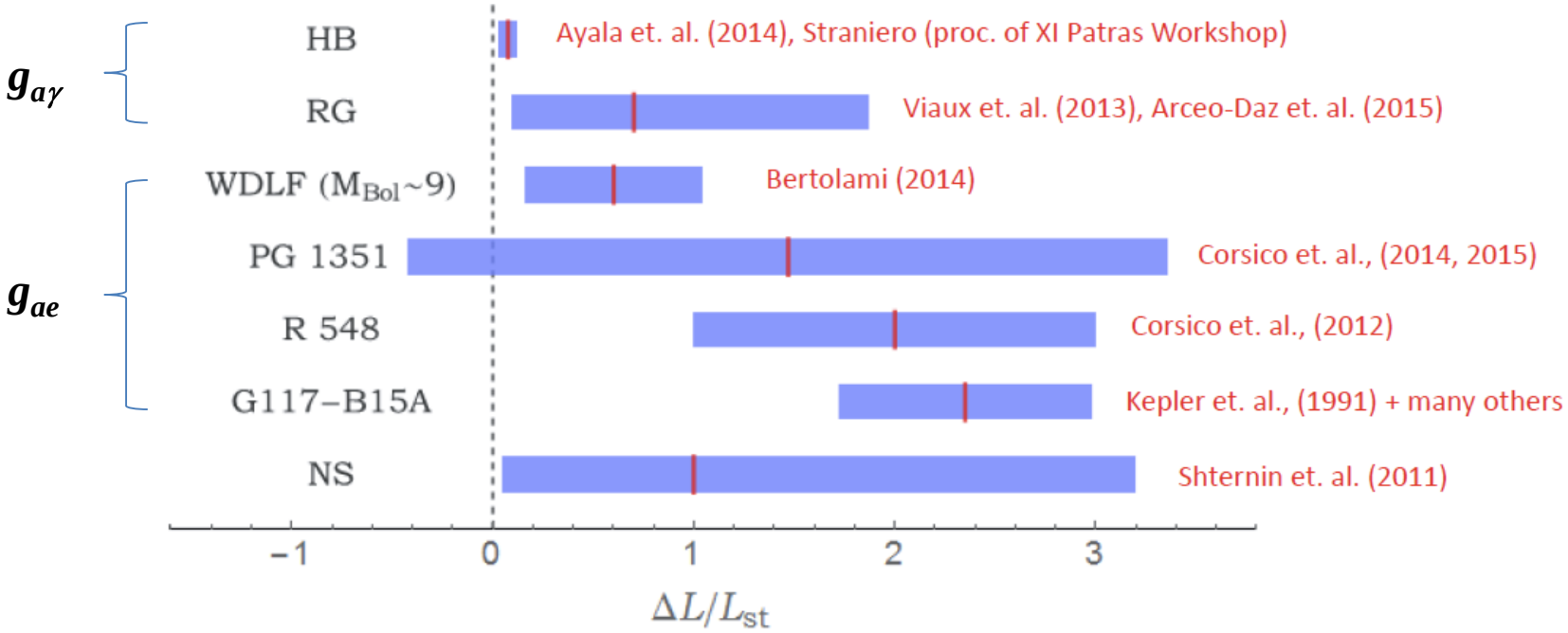
ALP:

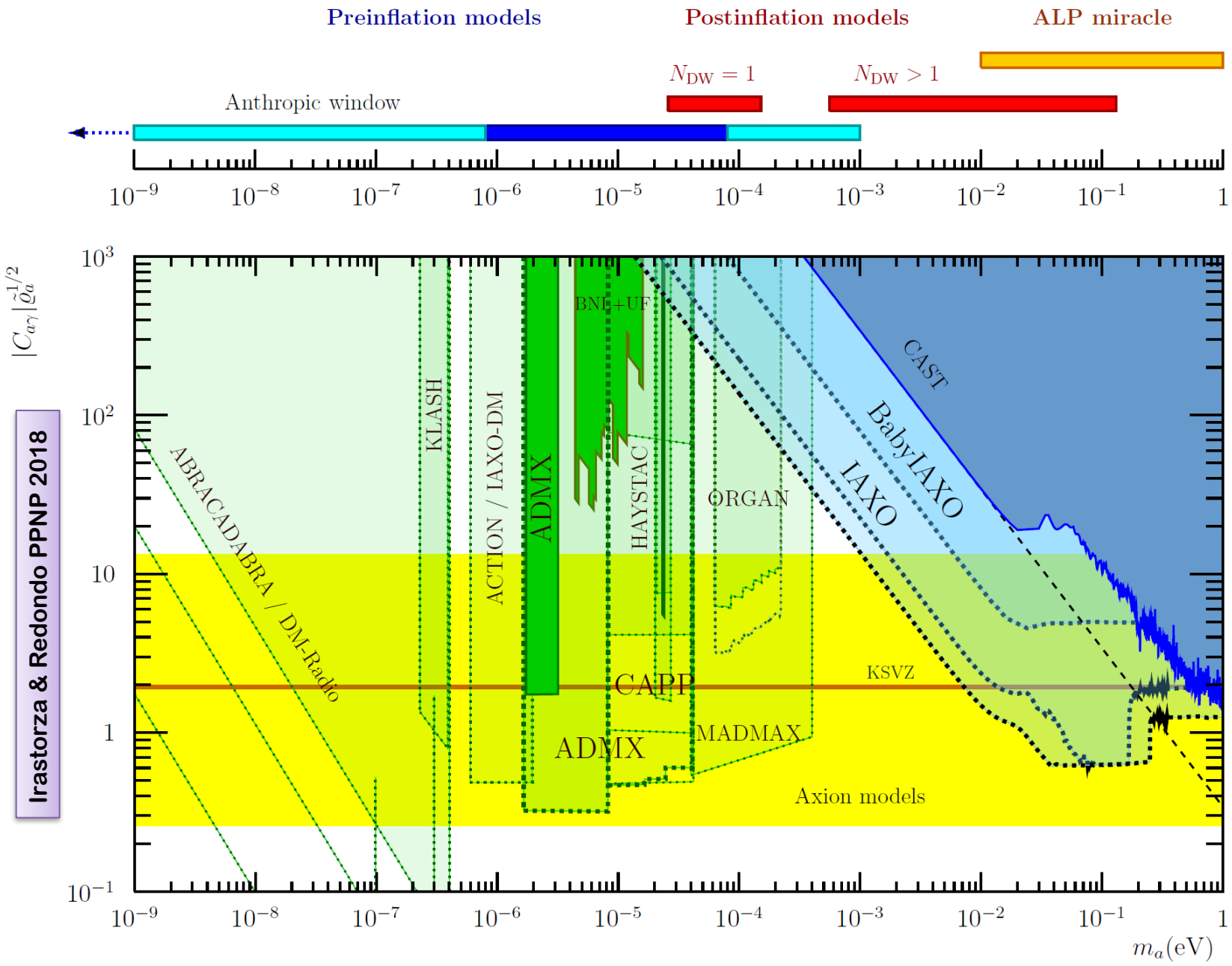
$$g_{a\gamma} \sim 10^{-12}\text{–}10^{-10}\ \mathrm{GeV}^{-1}$$
$$m_a \lesssim 10^{-(10-7)}\ \mathrm{eV}$$



Astrophysical hints for axions

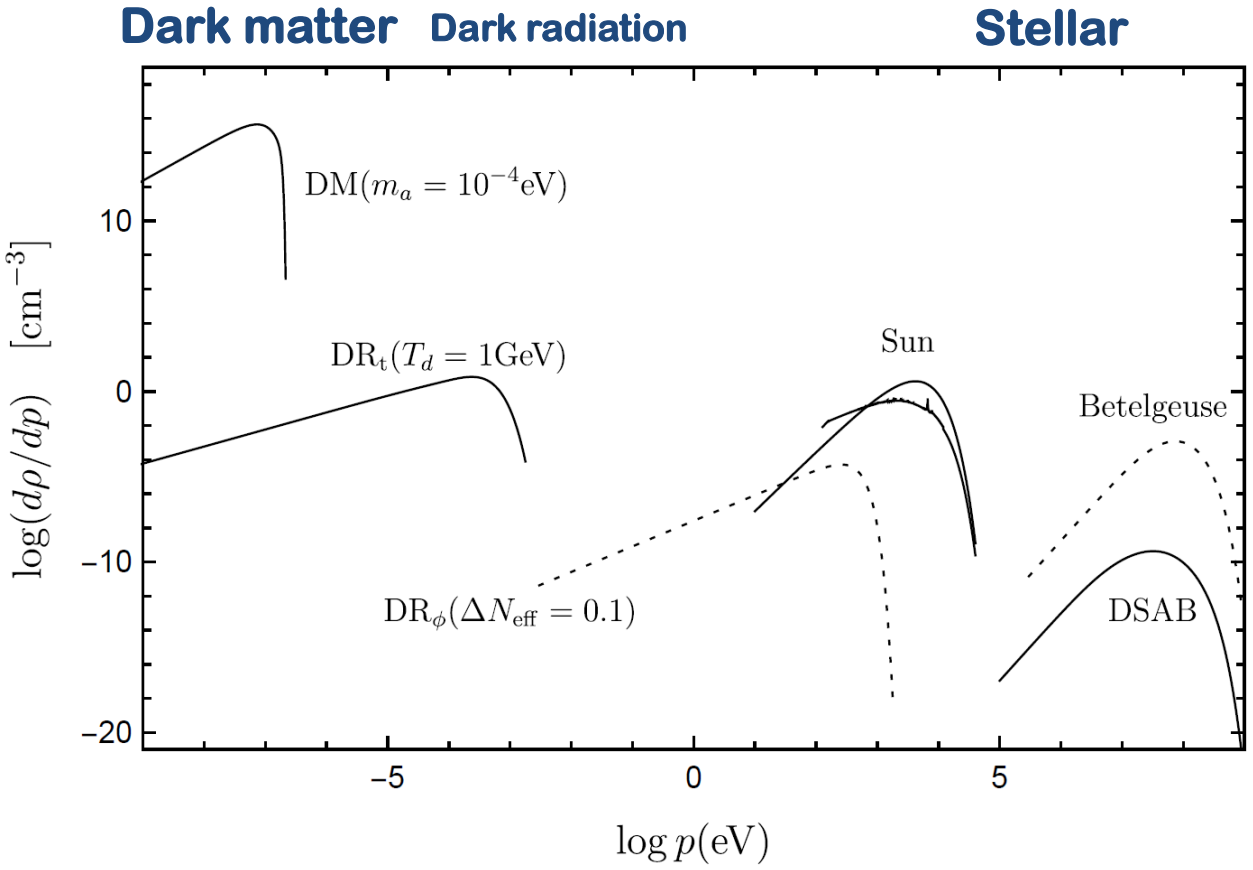
- Most stellar systems seem to cool down faster than expected.
- Presence of axions/ALPs offer a good joint explanation (Giannotti et al. JCAP05(2016)057 [arXiv:1512.08108])
- Parameters at reach of IAXO




Preinflation models
Postinflation models
ALP miracle
$N_{DW} = 1$
$N_{DW} > 1$
Anthropic window
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1
$|C_{a\gamma}|\varrho_a^{1/2}$
10^3 10^2 10 1 10^{-1}
Irastorza & Redondo PPNP 2018
ABRACADABRA / DM-Radio
KLASH
ACTION / IAXO-DM
ADMX
BNL+UF
HAYSTAC
ORGAN
CAST
BabyIAXO
IAXO
CAPP
KSVZ
MADMAX
ADMX
Axion models
m_a(eV)

Sources of axions

Natural sources



Laboratory sources

- Photon-ALP conversion in strong magnetic fields (axion-photon coupling)
- ALP fields from macroscopic bodies (fermionic couplings)

Most detection strategies rely on the axion-photon conversion

Axion detection strategies

Detection method	$g_{a\gamma}$	g_{ae}	g_{aN}	$g_{A\gamma n}$	$g_{a\gamma}g_{ae}$	$g_{a\gamma}g_{aN}$	$g_{ae}g_{aN}$	$g_N\bar{g}_N$	Model dependency
Light shining through wall	×								no
Polarization experiments	×								no
Spin-dependent 5th force			×				×	×	no
Helioscopes	×				×	×			Sun
Primakoff-Bragg in crystals	×				×				Sun
Underground ion. detectors	×	×	×			×	×		Sun*
Haloscopes	×								DM
Pick up coil & LC circuit	×								DM
Dish antenna & dielectric	×								DM
DM-induced EDM (NMR)			×	×					DM
Spin precession in cavity		×							DM
Atomic transitions		×	×						DM

Table 3: List of the axion detection methods discussed in the review, with indication of the axion couplings (or product of couplings) that they are sensitive to, as well as whether they rely on astrophysical (axions/ALPs are produced by the Sun) or cosmological (the dark matter is made of axions/ALPs) assumptions. *Also "DM" when searching for ALP DM signals, see section 6.2

ALP generic couplings

$$\mathcal{L}_{\mathrm{ALP-int.}} = -\frac{g_{a\gamma}}{4} F_{\mu\nu}\widetilde{F}^{\mu\nu} a - a\sum_f g_{af} i\bar{f}\gamma^5 f - aF_{\mu\nu}\sum_f \frac{\bar{g}_{a\gamma f}}{2} i\bar{f}\sigma^{\mu\nu}\gamma^5 f + \ldots$$

$$-\frac{\bar{g}_{a\gamma}}{4} F_{\mu\nu}F^{\mu\nu} a - a\sum_f \bar{g}_{af}\bar{f}f$$

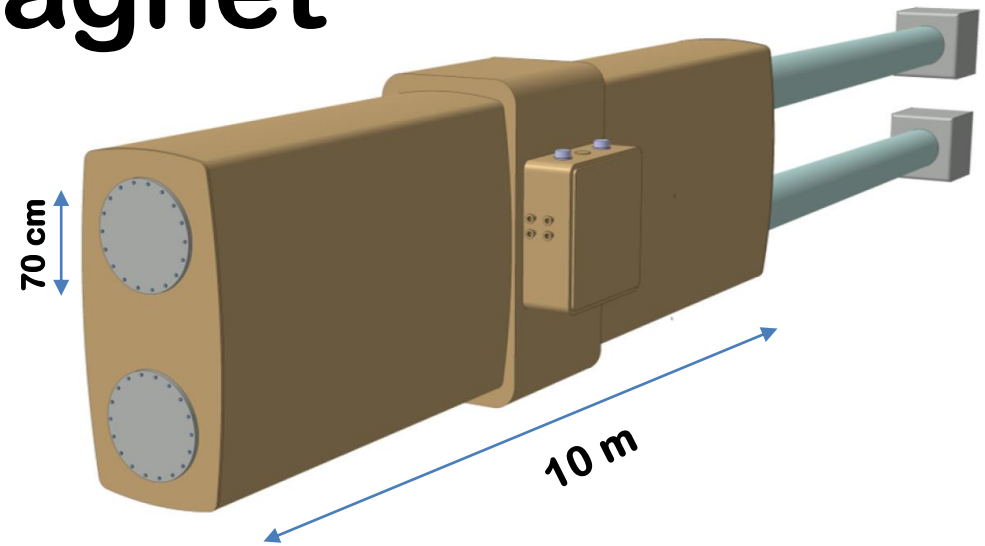
$$g_{Af} \equiv \frac{C_{Af} m_f}{f_A} = 1.75\times 10^{-13} C_{Af}\frac{m_f}{\mathrm{GeV}}\frac{m_A}{\mu\mathrm{eV}},$$

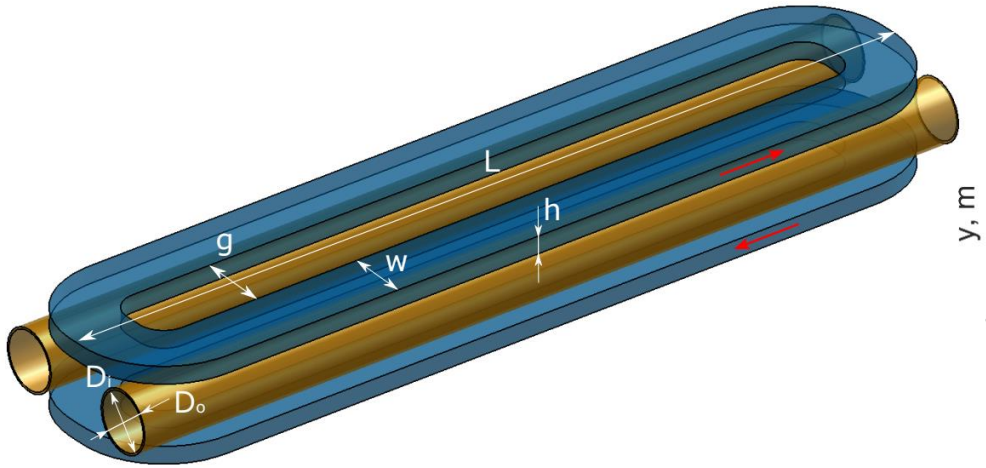
$$g_{A\gamma} \equiv \frac{\alpha}{2\pi}\frac{C_{A\gamma}}{f_A} = 2.0\times 10^{-16} C_{A\gamma}\frac{m_A}{\mu\mathrm{eV}}\,\mathrm{GeV}^{-1},$$

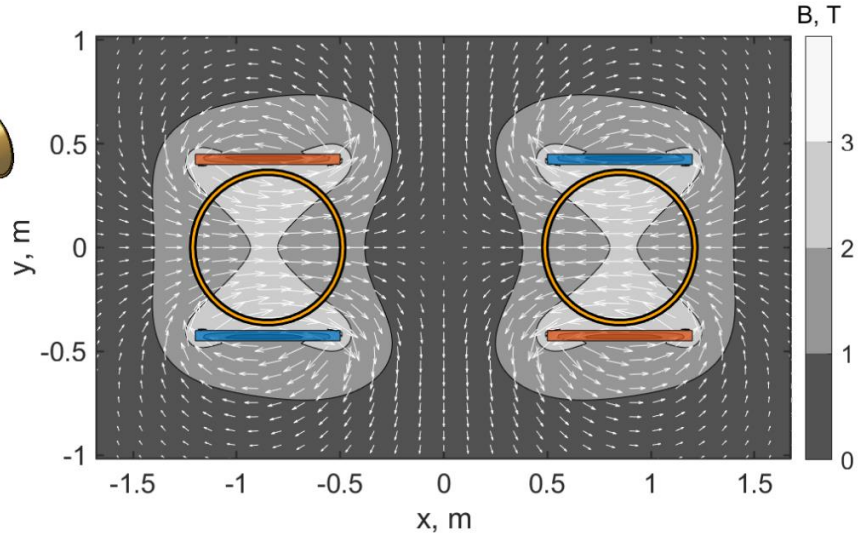
$$\bar{g}_{A\gamma n} \equiv \frac{\bar{C}_{A\gamma n}}{m_n f_A} = 6.4\times 10^{-16}\frac{m_A}{\mu\mathrm{eV}}\mathrm{GeV}^{-2},$$

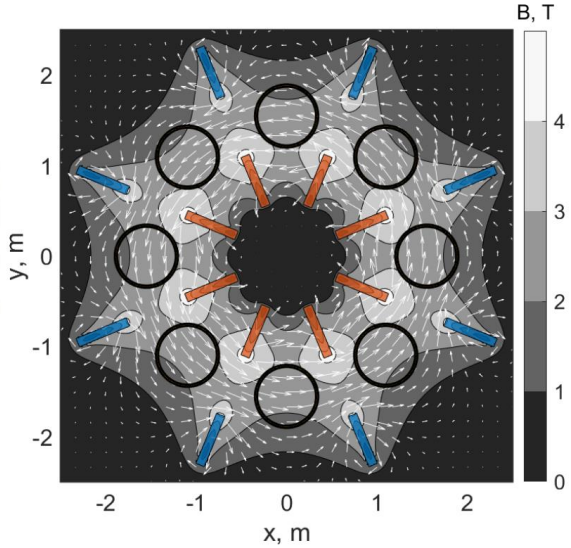
BabyIAXO magnet

- "Common coil" configuration chosen
  - Minimal risk: conservative design choices
  - Cost-effective: Best use of existing infrastructure (tooling) at CERN
  - Prototyping character: winding layout very close to that of IAXO toroidal design.





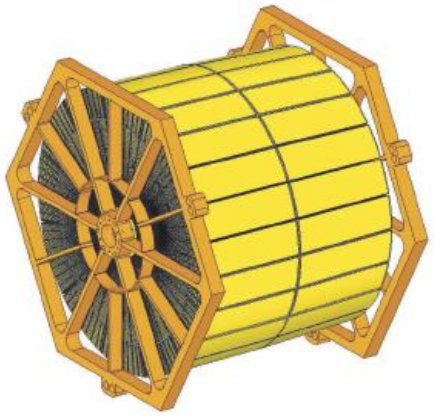


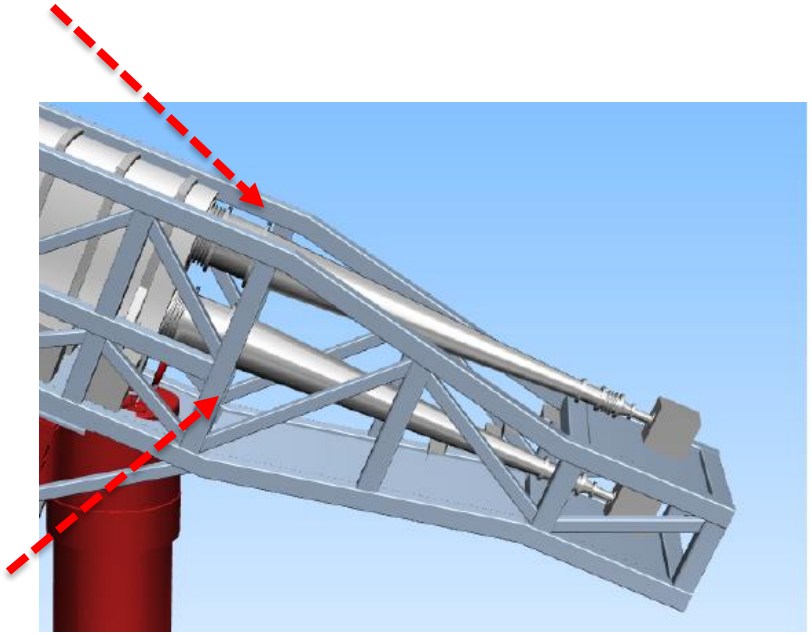


BabyIAXO optics

- 2 detection lines in BabyIAXO
- Optics:
  - IAXO Custom segmented-glass optics and flight spare XMM optics from ESA
  - Prototyping + physics considerations
  - Risk reduction for final IAXO segmented-glass optics
  - XMM optics specs very close to IAXO optics design
  - ESA preliminary support to the use of XMM optics in BabyIAXO

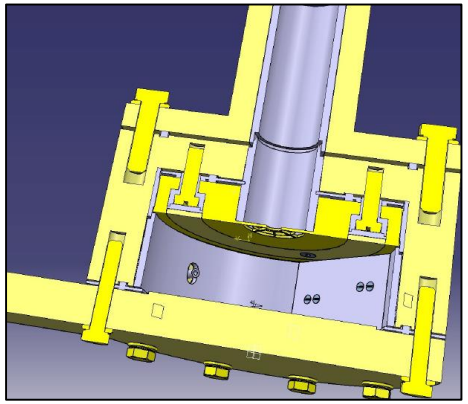
    (2 XMM optics exist)



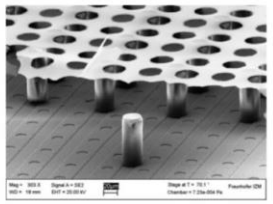


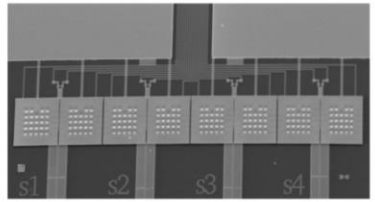
BabyIAXO detectors

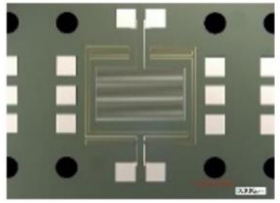
- **Detectors (baseline option):**
  - 2 "microbulk" Micromegas detectors
  - "Discovery detectors" (priority to low background)
  - Experience in CAST
  - Low background capability, radiopurity, shielding.



- **Beyond baseline:**
  - "high precision" detectors (post-discovery?)
  - Better threshold & resolution
  - 2 low-background Micromegas setups
  - R&D in several technologies: GridPix, MMCs, TES, NTD, SSD.

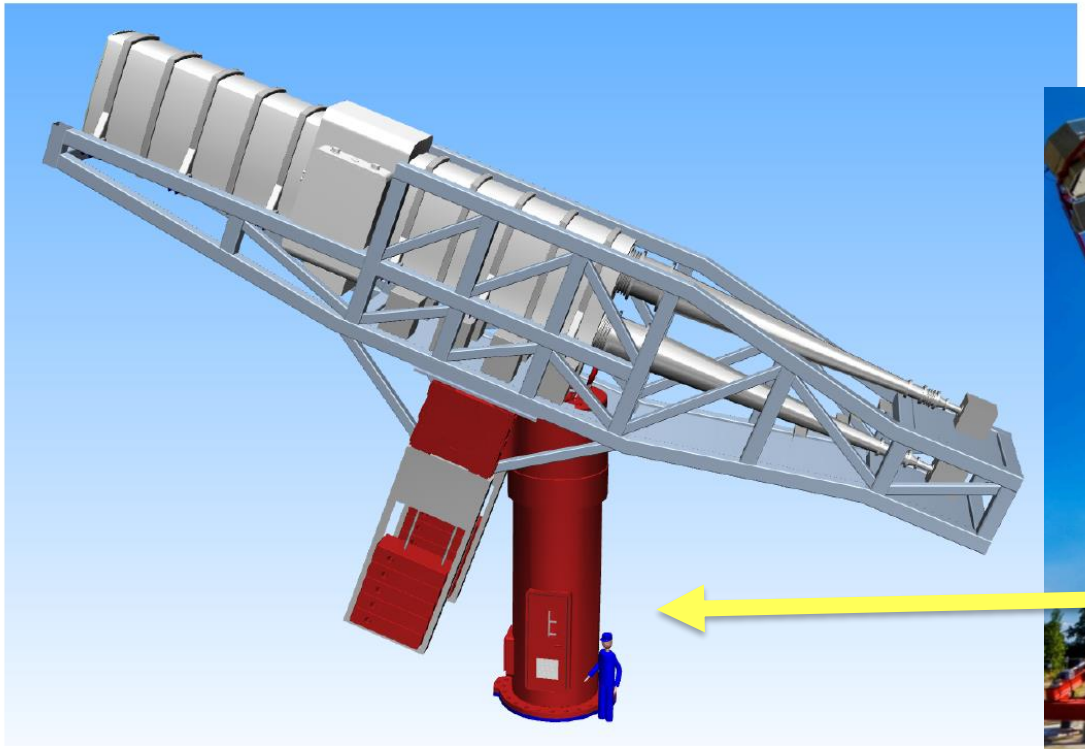




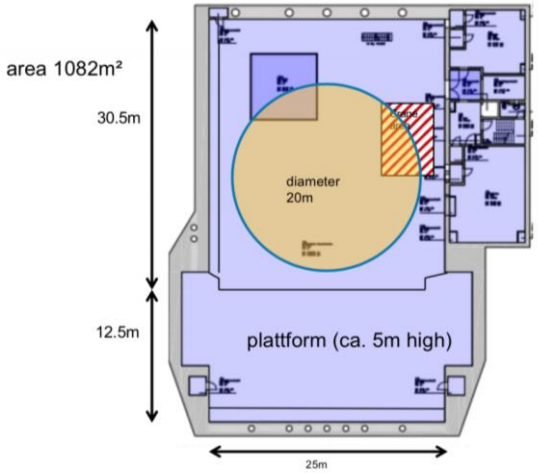


BabyIAXO platform & infrastructure

- **Existing CTA MST mount matches BabyIAXO specs remarkably well**



- **HERA South hall: perfect site for BabyIAXO**



BabyIAXO: beyond baseline

- **Baseline program is realistic and low-risk. No pending R&D.**

- **After that, the BabyIAXO infrastructure would be available for further activities "beyond-baseline"**
- **New detectors with improved performance to: 1) extended physics runs or 2) preparatory tests for IAXO (in the event of a discovery, high-precision detectors)**
- **Implementation of "haloscope" schemes inside the BabyIAXO magnet (RF cavities or other resonant structures)**
- **Assist the final IAXO program with ancillary actions.**
- **Definition of "beyond-baseline" BabyIAXO program will depend on future R&D results.**

IAXO collaboration

17 institutions from Germany, Spain, US, France, Russia, Italy, Croatia, S. Africa, CERN.
Know-how portfolio nicely emcompasses IAXO needs:

Institution	short name	(*)	Superconducting magnets	X-ray optics	Detector & electronics	Axion phenomenology	Low background techniques	General infrastructures & engineering
Barry U. (USA)	BARRY	10				x		
Irfu/CEA-Saclay (France)	IRFU	1	x		x	x	x	x
U. Cape Town (S. Africa)	UCT	16				x		
ICCUB Barcelona (Spain)	ICCUB	5			x			
LLNL (USA)	LLNL	7		x		x		
St. Petersburg NPI (Russia)	PNPI	6				x		
Heidelberg U. (Germany)	UHEI	9			x		x	
U. of Zaragoza (Spain)	UNIZAR	4			x	x	x	
MIT (USA)	MIT	14		x				
INR Moscow (Russia)	INR	11	x			x		
RBI Zagreb (Croatia)	RBI	12				x		
U. Bonn (Germany)	UBONN	8			x			
U. Siegen (Germany)	USIEGEN	17			x			
JGU Mainz (Germany)	JGUM	15			x			
INAF - Brera (Italy)	INAF	2		x				
DESY (Germany)	DESY	13				x	x	x
CERN (Switzerland)	CERN	3	x					x
(**) CEFCA (Spain)	CEFCA							x
(**) CNM-IMB Barcelona (Spain)	CNM				x			
(**) DTU (Denmark)	DTU			x				
(**) U. Columbia (US)	UC			x				
(**) MPI-Munich (Germany)	MPI				x			
(**) CSNSM-Orsay (France)	CSNSM				x			

- **Likely to grow in the future, more groups showing interest…**
- **Work Breakdown Structure being defined.**

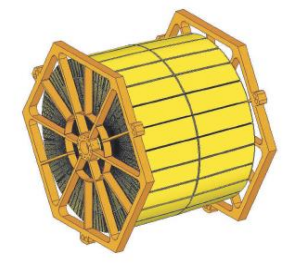
BabyIAXO (& IAXO) timeline

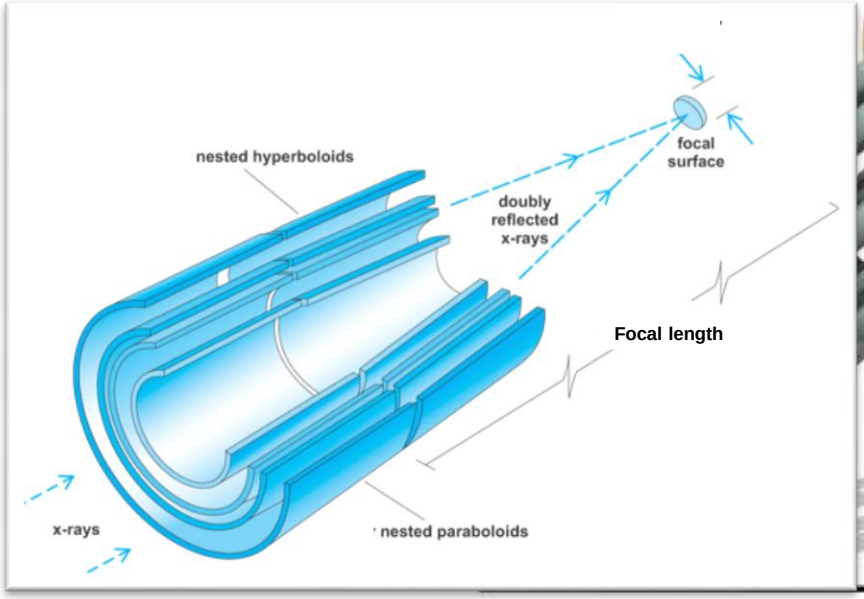
		2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029+
	Design											
	Construction											
	Commissioning											
Data taking	Vacuum phase											
	Upgrade to gas											
	Gas phase											
	Beyond-baseline											
IAXO	Design											
	Construction						Tentative					

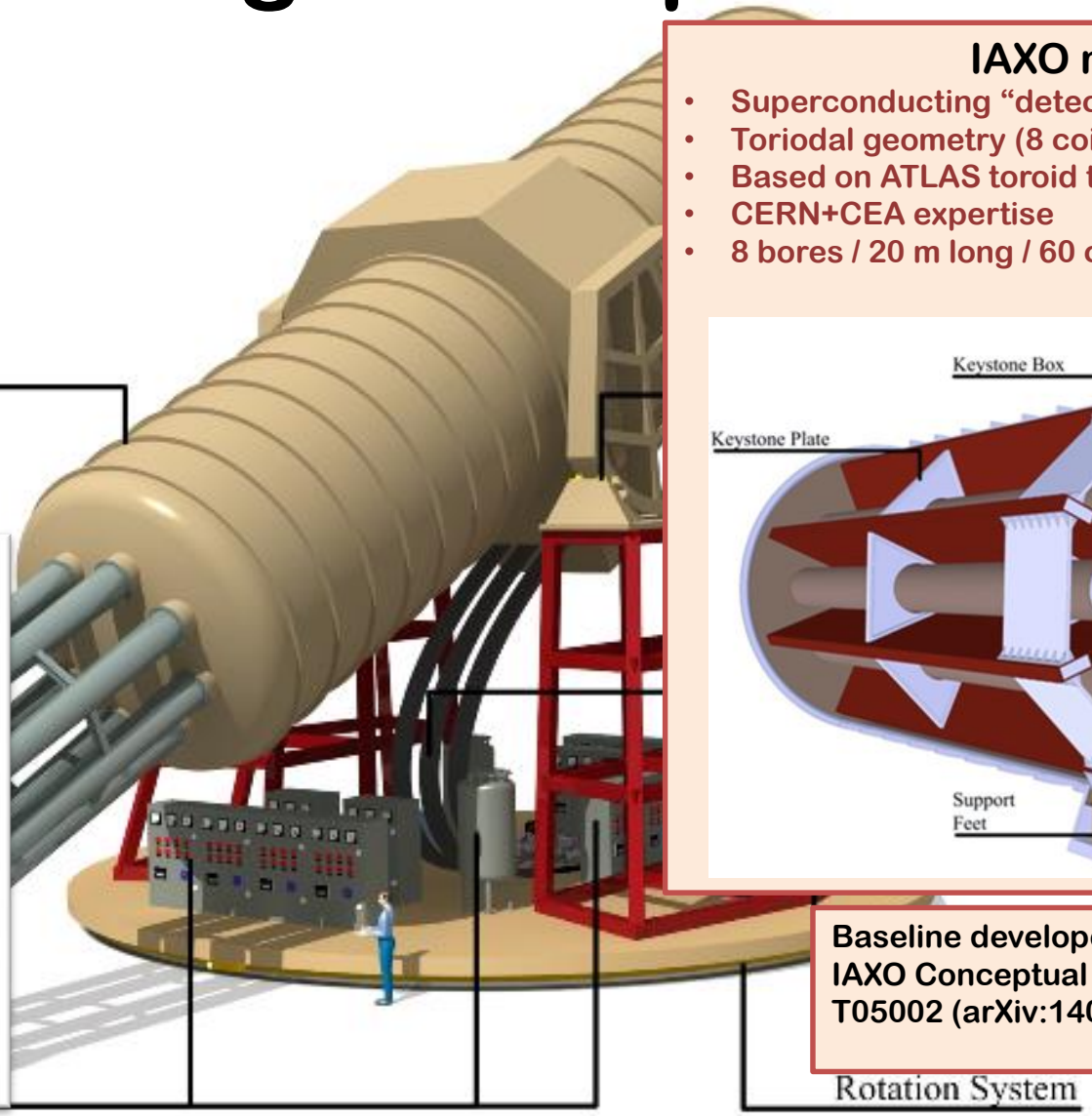
IAXO magnet & optics

IAXO telescopes

- Slumped glass technology with multilayers
- Cost-effective to cover large areas
- Similar to NuSTAR optics
- Focal length ~5 m
- 60-70% efficiency
- LLNL+UC+DTU + MIT + INAF

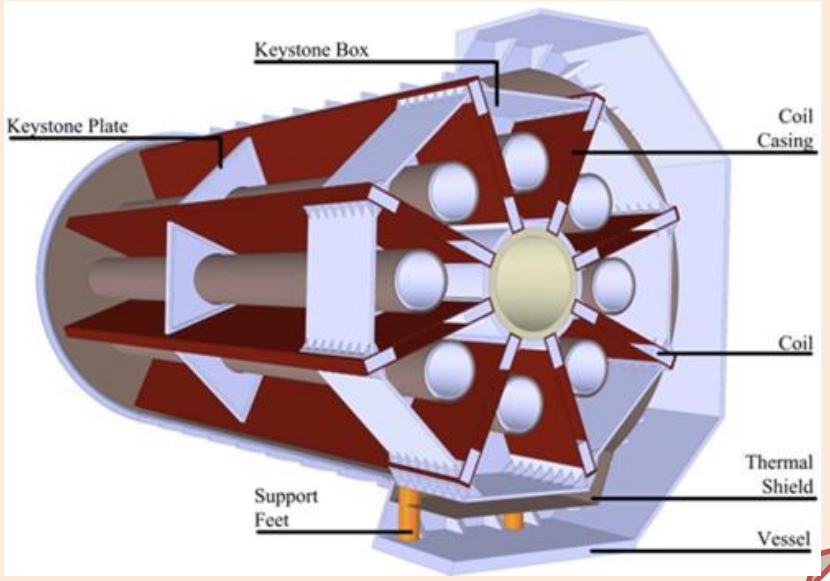






IAXO magnet

- Superconducting "detector" magnet.
- Toriodal geometry (8 coils)
- Based on ATLAS toroid technical solutions.
- CERN+CEA expertise
- 8 bores / 20 m long / 60 cm Ø per bore

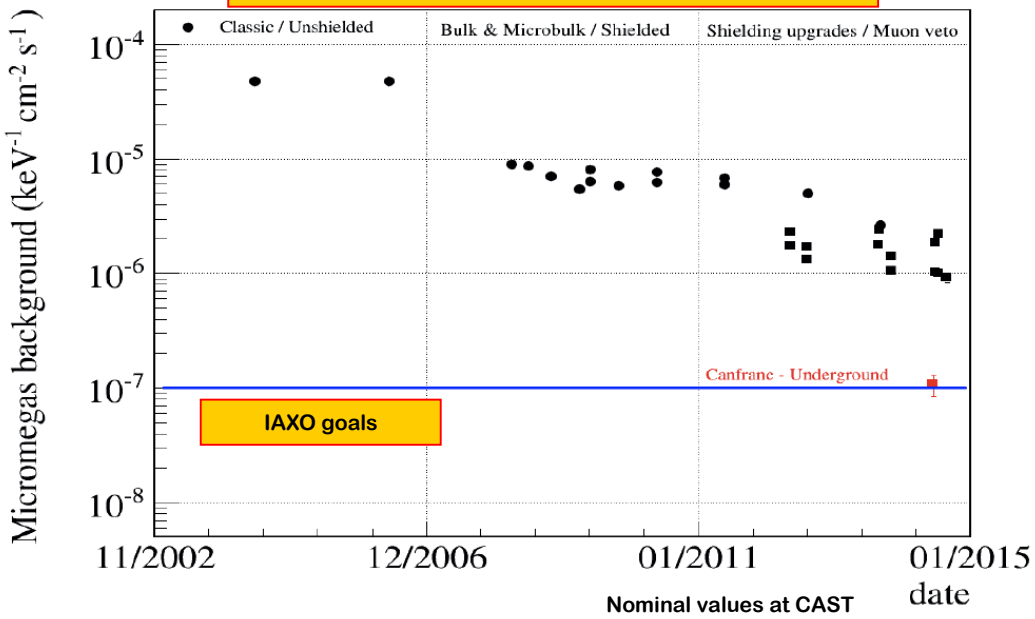


Baseline developed at:
IAXO Conceptual Design: JINST 9 (2014) T05002 (arXiv:1401.3233)

IAXO low background MM detectors

- Goal background level for IAXO:
  - $10^{-7} – 10^{-8}$ c keV^{-1} cm^{-2} s^{-1}
- Already demonstrated:
- ~8×10^{-7} c keV^{-1} cm^{-2} s^{-1}
  (in CAST 2014 result)
  - 10^{-7} c keV^{-1} cm^{-2} s^{-1}
    (underground at LSC)

History of background improvement of Micromegas detectors at CAST

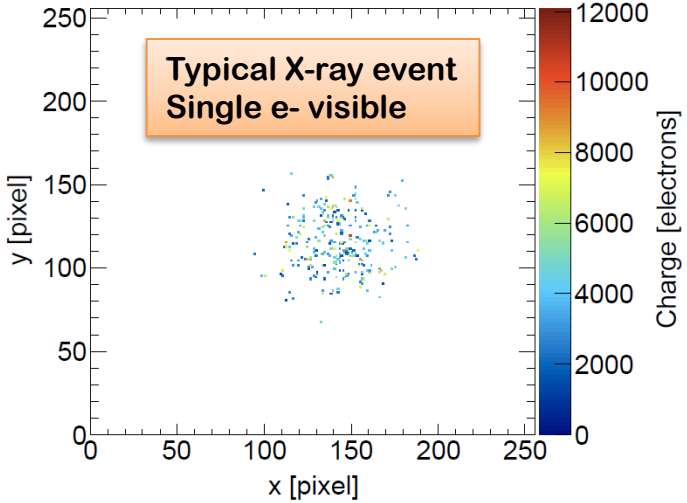


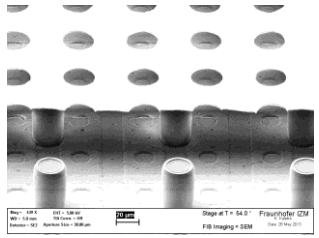
- Active program of development.
- IAXO-D0 test-platform to explore background sources and improve levels

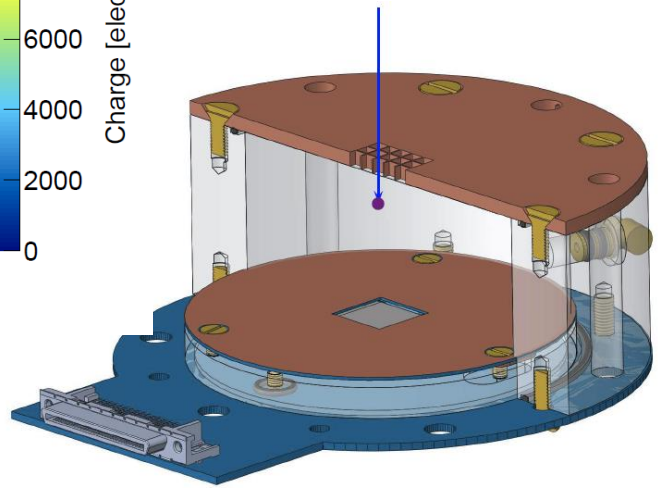
Additional detector technologies for IAXO

GridPix detectors (U. Bonn):

- Micromegas on top of a CMOS chip (Timepix)
- Very low threshold (tens of eV)
- Tested in CAST

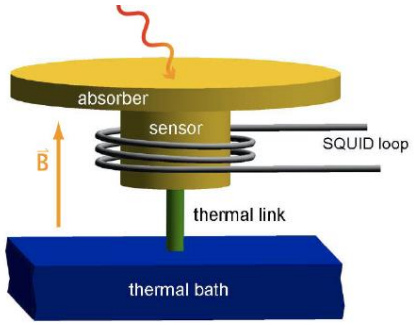


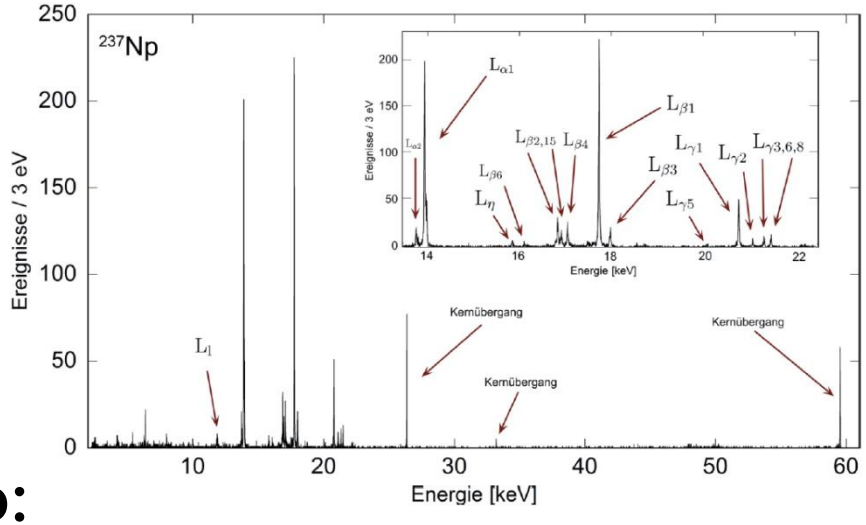




MMC detectors (U. Heidelberg):

- Extremely low threshold and energy resolution (~eV scale)
- Low background capabilities under study



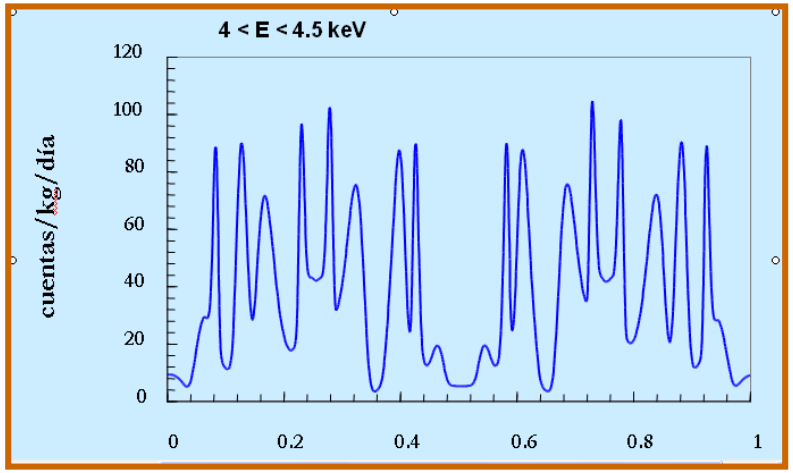


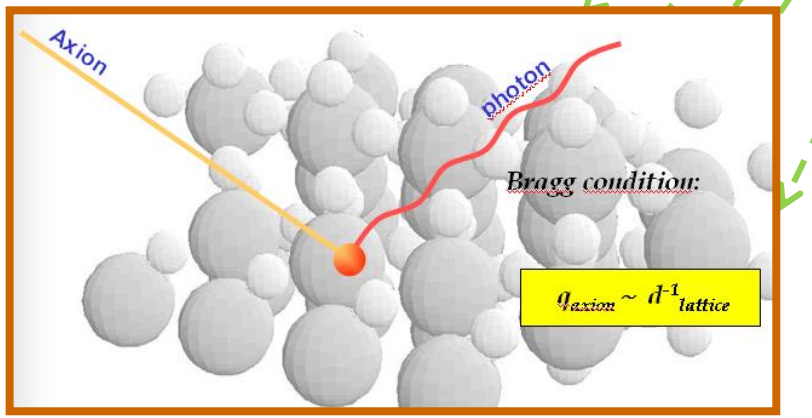
Also:

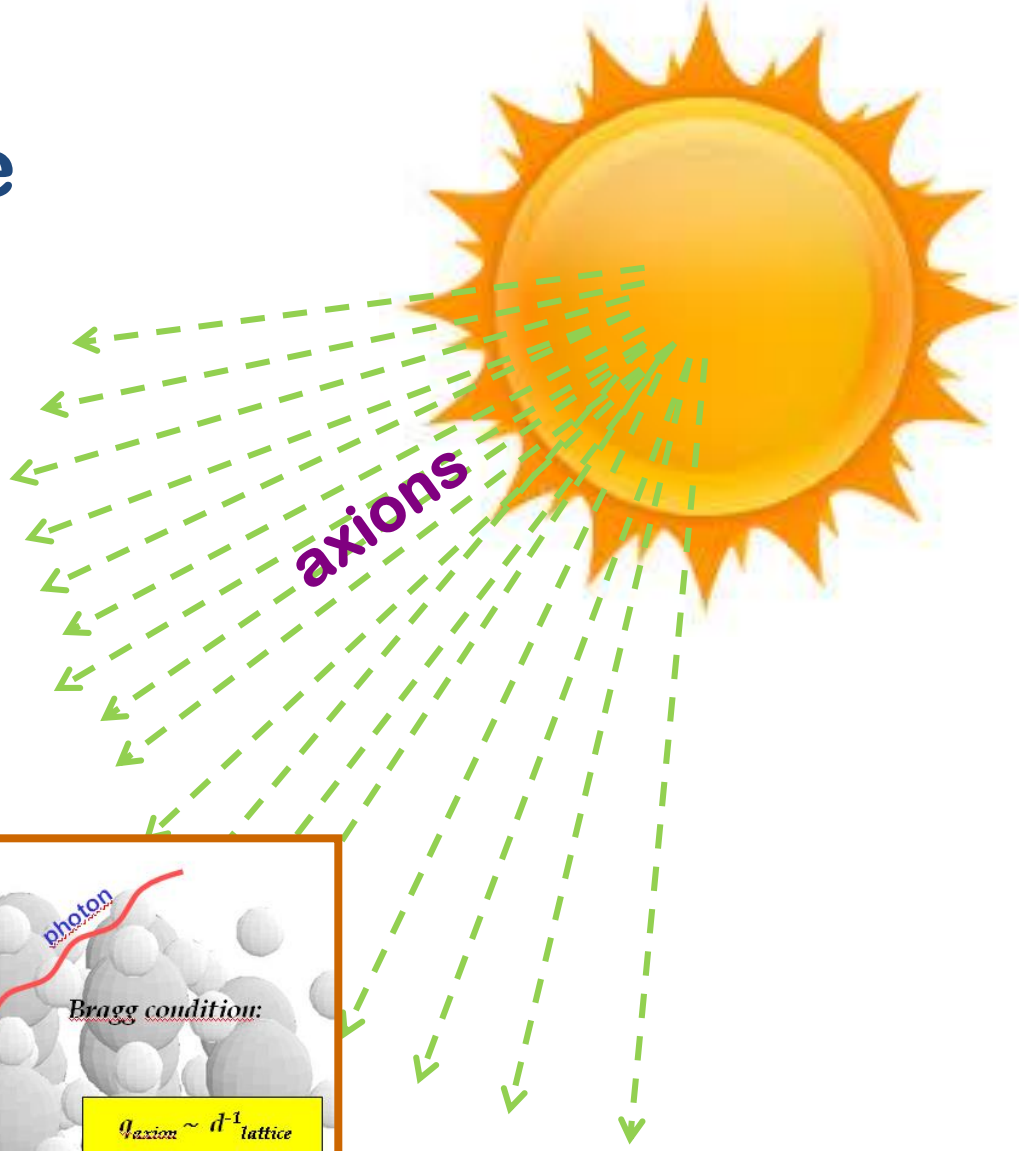
- Transition Edge Sensors (TES)
- Silicon Drift Detectors (SDD)

Other types of helioscope

- Instead of magnetic field, one can use the electromagnetic field of crystals…
- « Primakoff-Bragg » effect
- WIMP-like experiments provide limit to axions: SOLAX, COSME, DAMA, EDELWEISS, CDMS, etc…
- Characteristical temporal pattern:

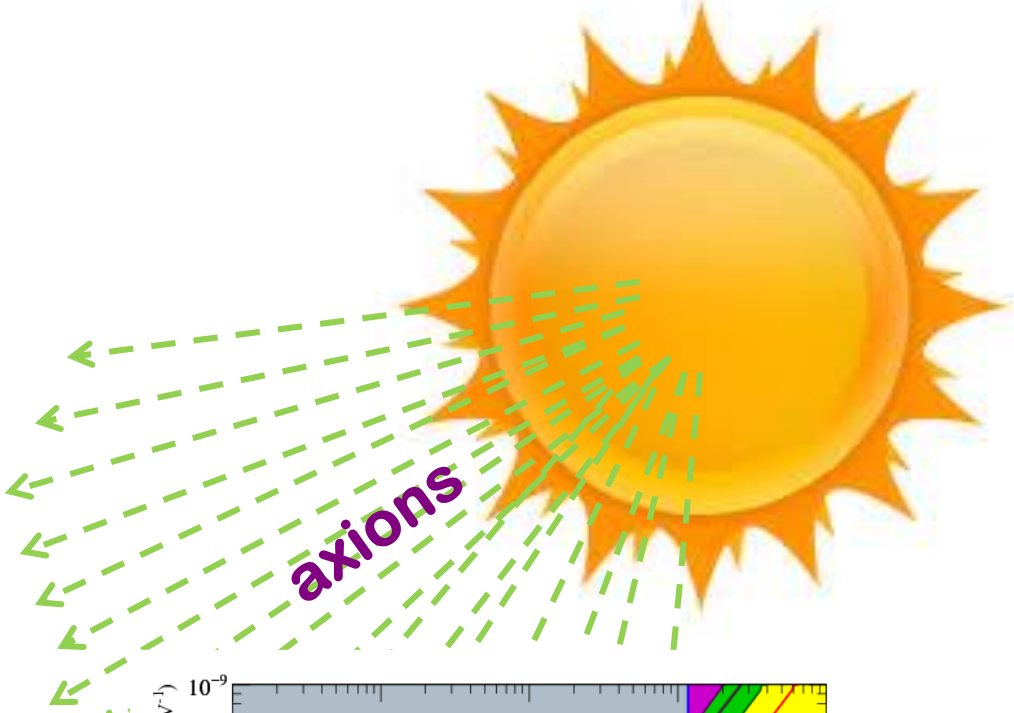


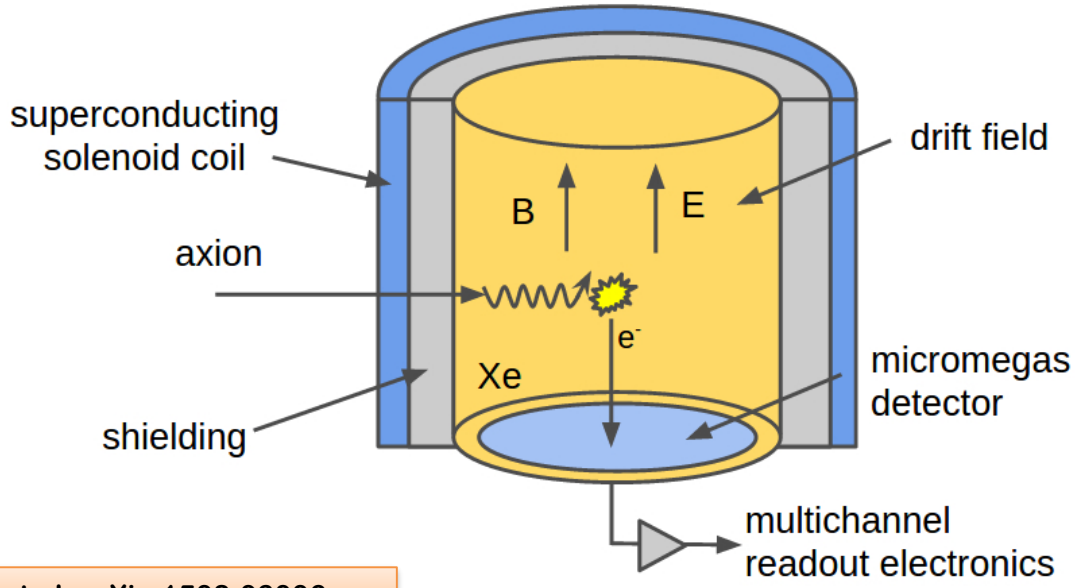




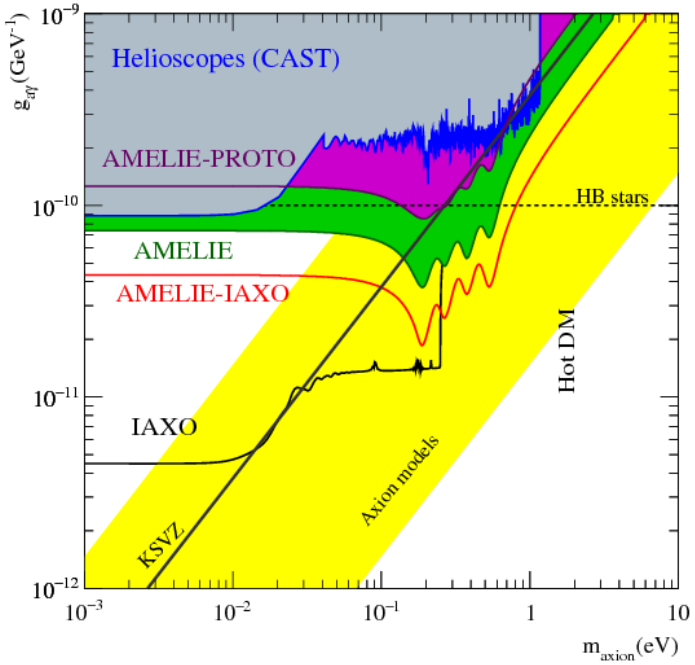
Other types of helioscope

- « TPC in a magnetic field »: conversion and absorption happening in the gas
- Competitive only for high axion mass ~0.1-10 eV
- No coherence, but large volume can compensate. Also no preferred direction, so no tracking needed





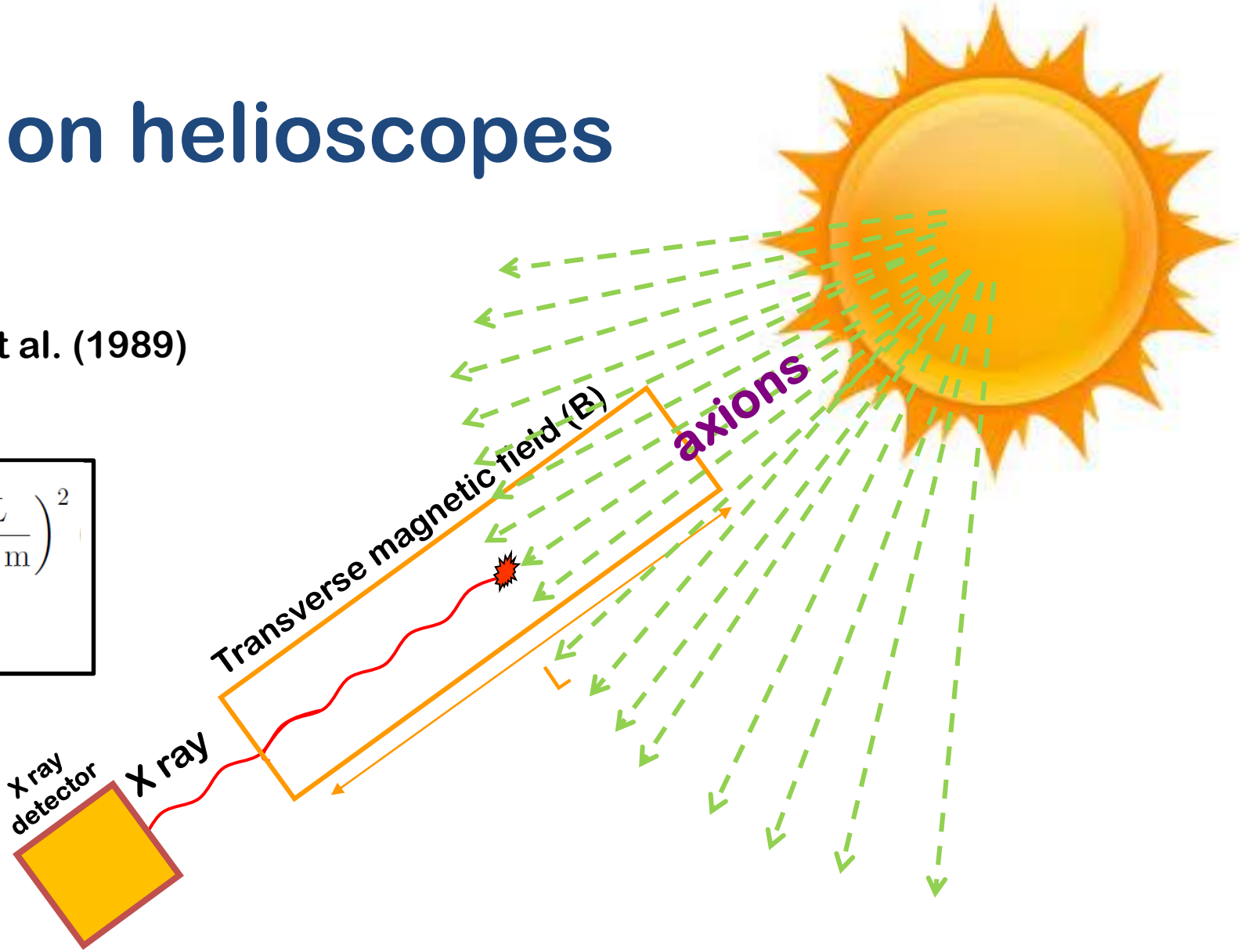
Galán et al, arXiv:1508.03006



Axion helioscopes

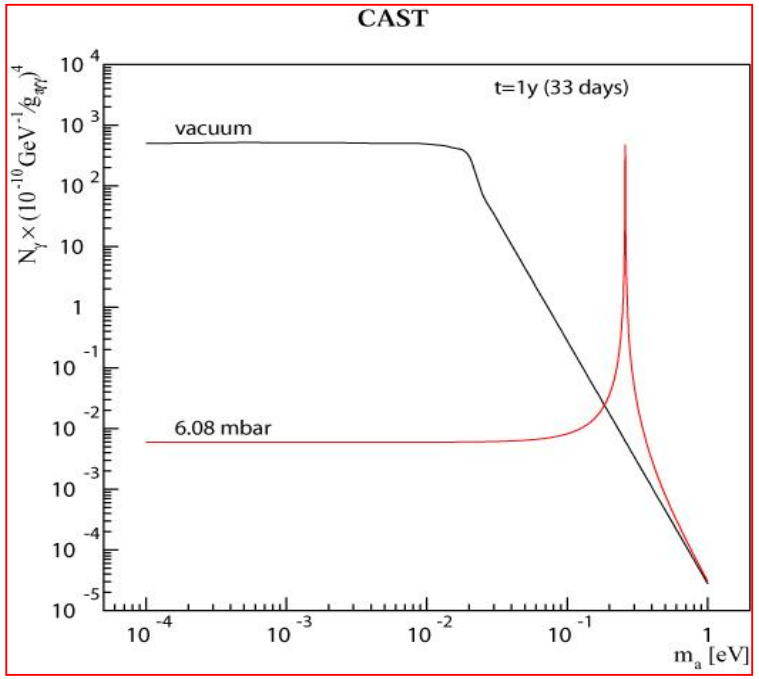
Axion helioscope concept
P. Sikivie, 1983
+ K. van Bibber, G. Raffelt, et al. (1989)
(use of buffer gas)

$$P_{a\gamma} = 2.6 \times 10^{-17} \left(\frac{B}{10\ \mathrm{T}}\right)^2 \left(\frac{L}{10\ \mathrm{m}}\right)^2 \left(g_{a\gamma} \times 10^{10}\ \mathrm{GeV}\right)^2 \mathcal{F}$$

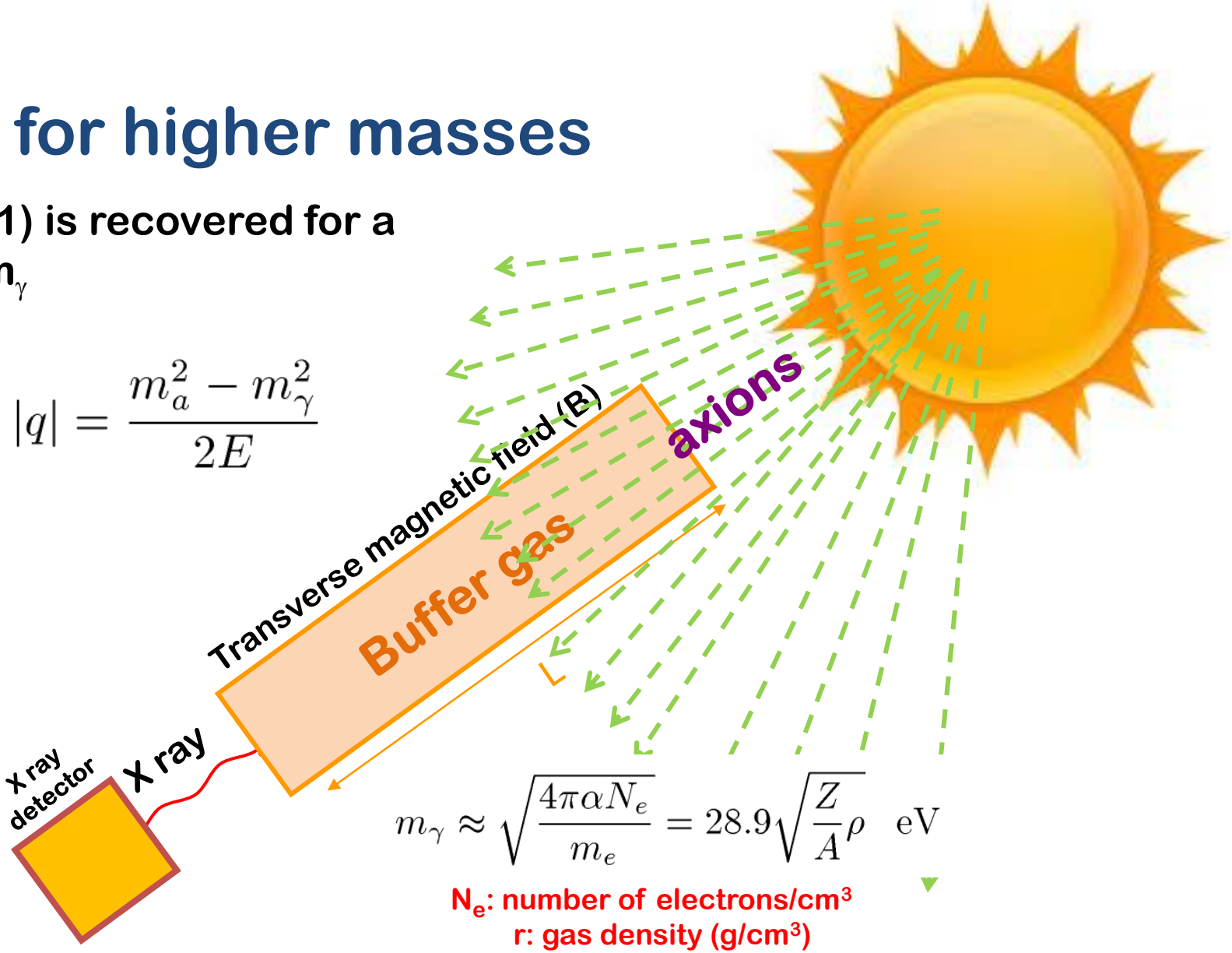


Buffer gas for higher masses

Coherence condition (qL << 1) is recovered for a narrow mass range around m_γ



$$|q| = \frac{m_a^2 - m_\gamma^2}{2E}$$



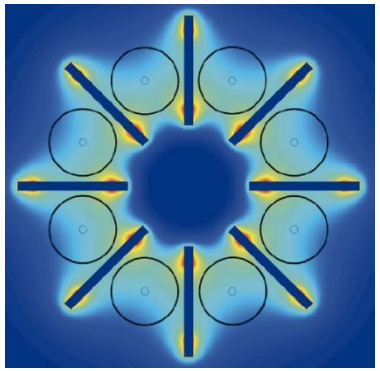
$$m_\gamma \approx \sqrt{\frac{4\pi\alpha N_e}{m_e}} = 28.9\sqrt{\frac{Z}{A}\rho} \quad \text{eV}$$

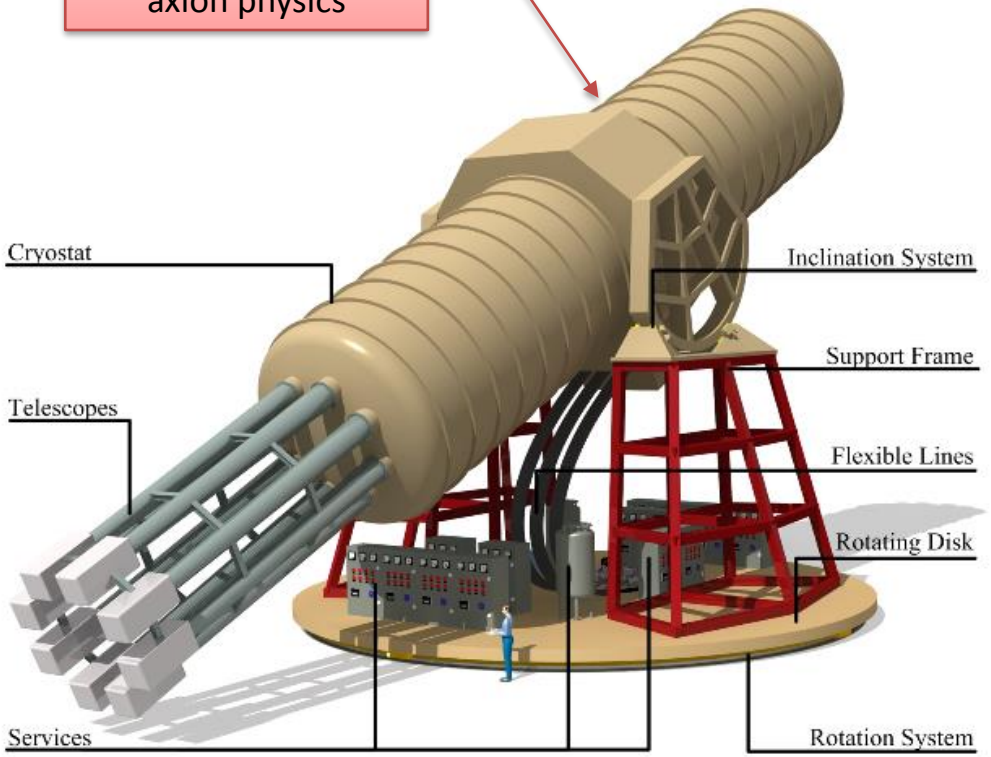
N_e: number of electrons/cm^3
r: gas density (g/cm^3)

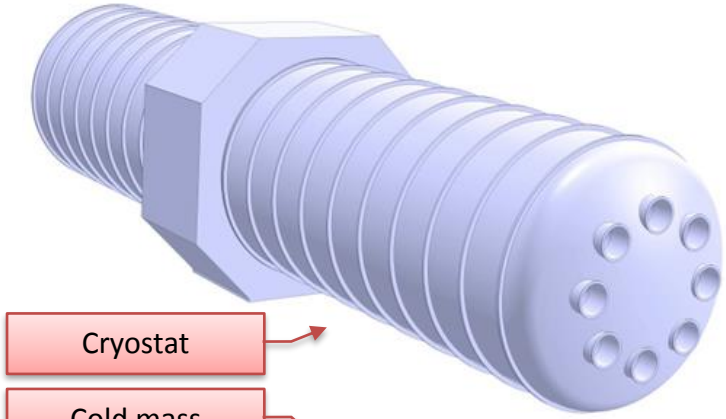
IAXO magnet

TOROIDAL CONFIGURATION specifically built for axion physics

Each conversion bore (between coils) 600 mm diameter

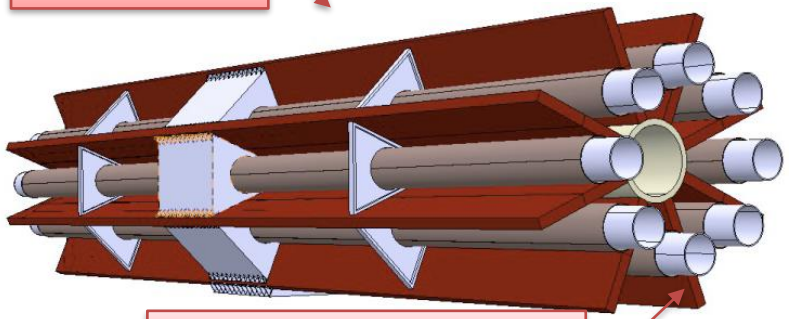






Cryostat

Cold mass

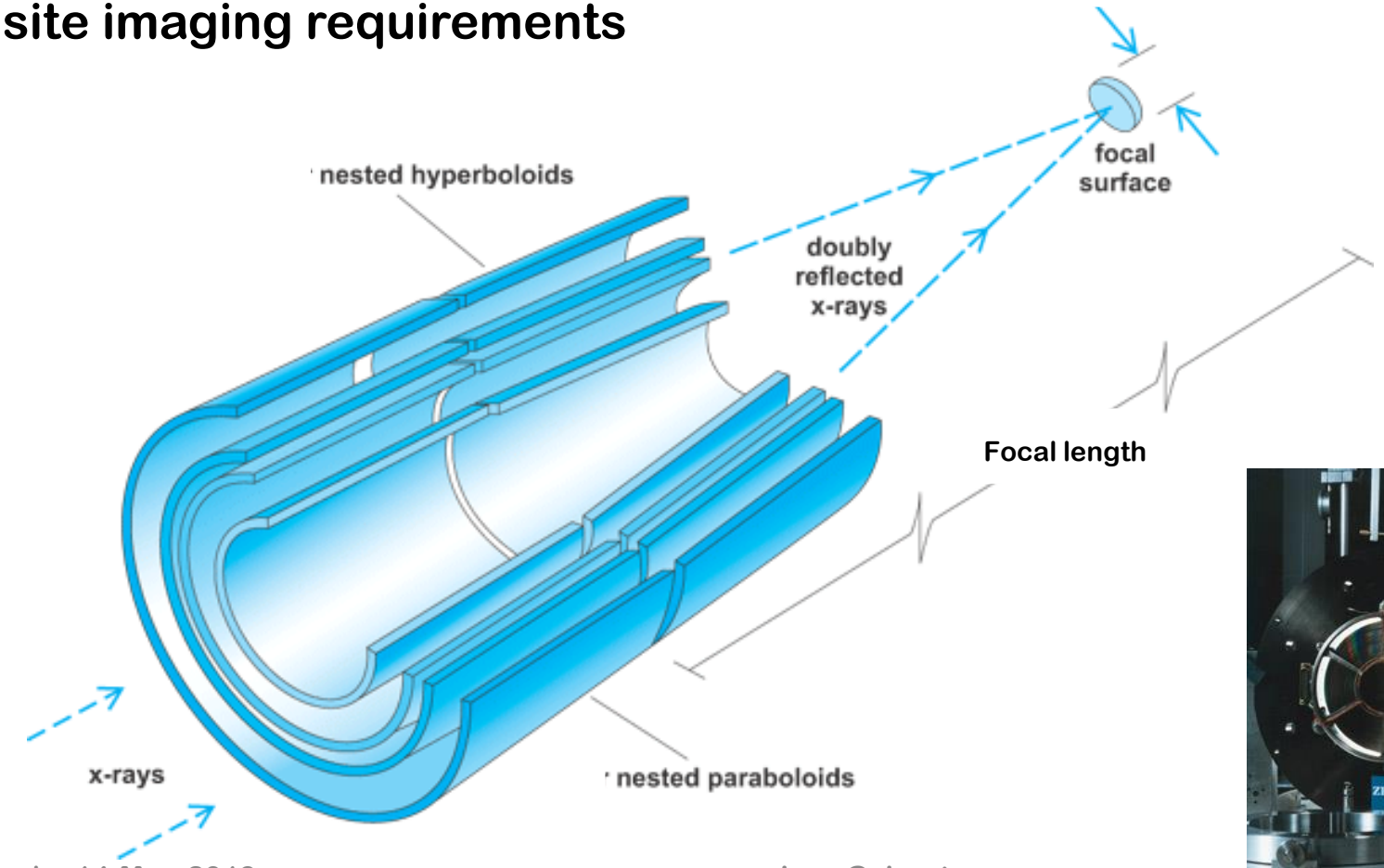


Bores go through cryostat

Magnetic length 20 m Total cryostat length 25 m

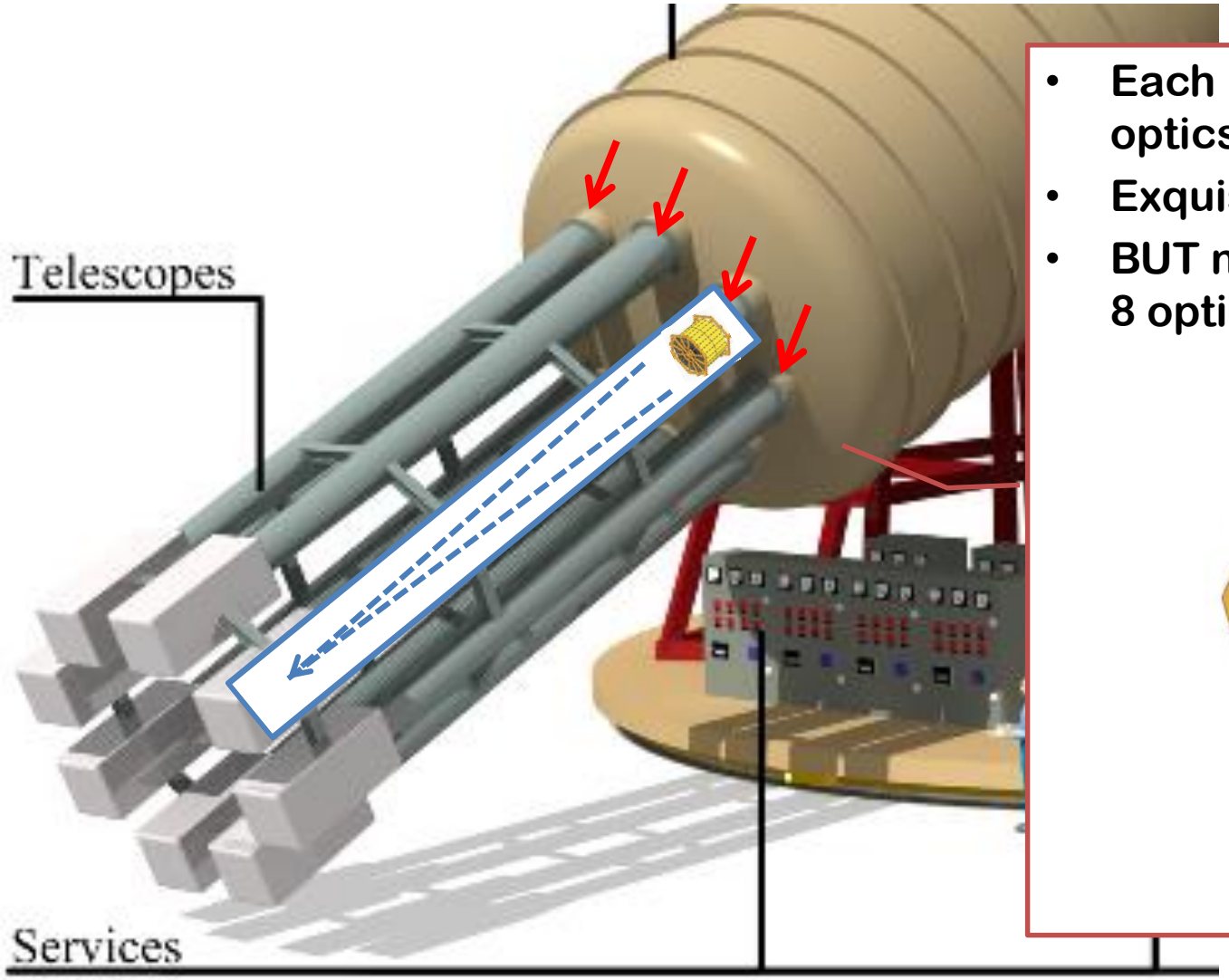
IAXO x-ray optics

- X-rays are focused by means of grazing angle reflection (usually 2)
- Many techniques developed in the x-ray astronomy field. But usually costly due to exquisite imaging requirements



ABRIXAS spare telescope, in use in one of the 4 bores of CAST (pioneer use of x-ray optics in axion research)

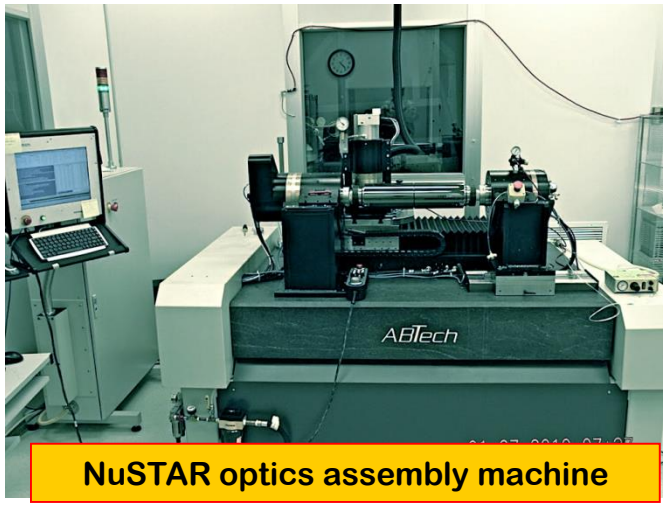
IAXO x-ray optics



- Each bore equipped with an x-ray optics
- Exquisite imaging not required
- BUT need cost-effective way to build 8 optics of 600 mm diameter each.

IAXO x-ray optics

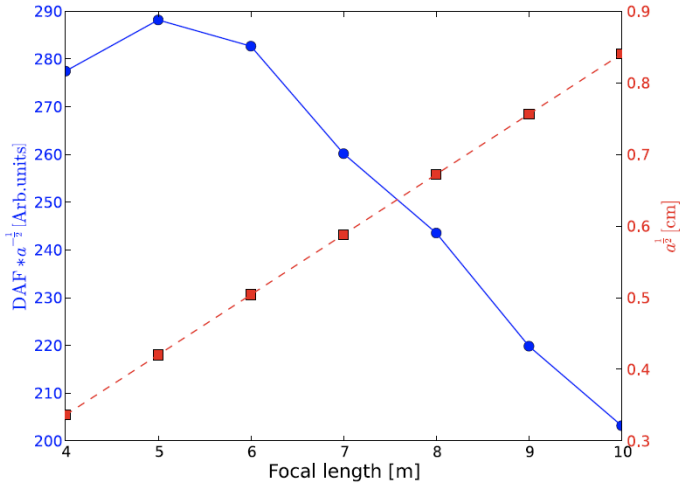
- Technique of choice for IAXO: optics made of slumped glass substrates coated to enhance reflectivity in the energy regions for axions.
- Same technique successfully used in NuSTAR mission, recently launched
- The specialized tooling to shape the substrates and assemble the optics is available
- Hardware can be easily configured to make optics with a variety of designs and sizes



NuSTAR optics assembly machine

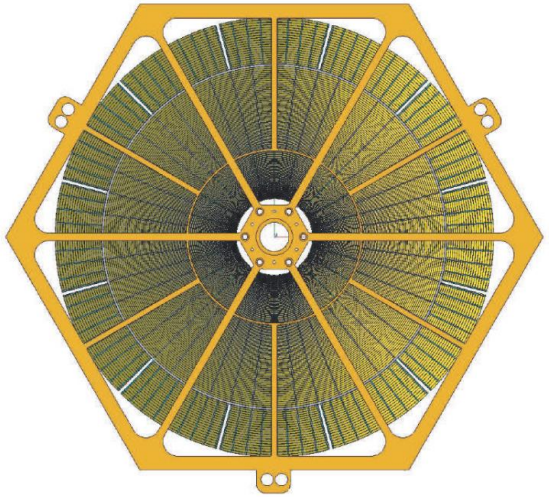
NuSTAR telescope ~400 mm Ø

IAXO x-ray optics



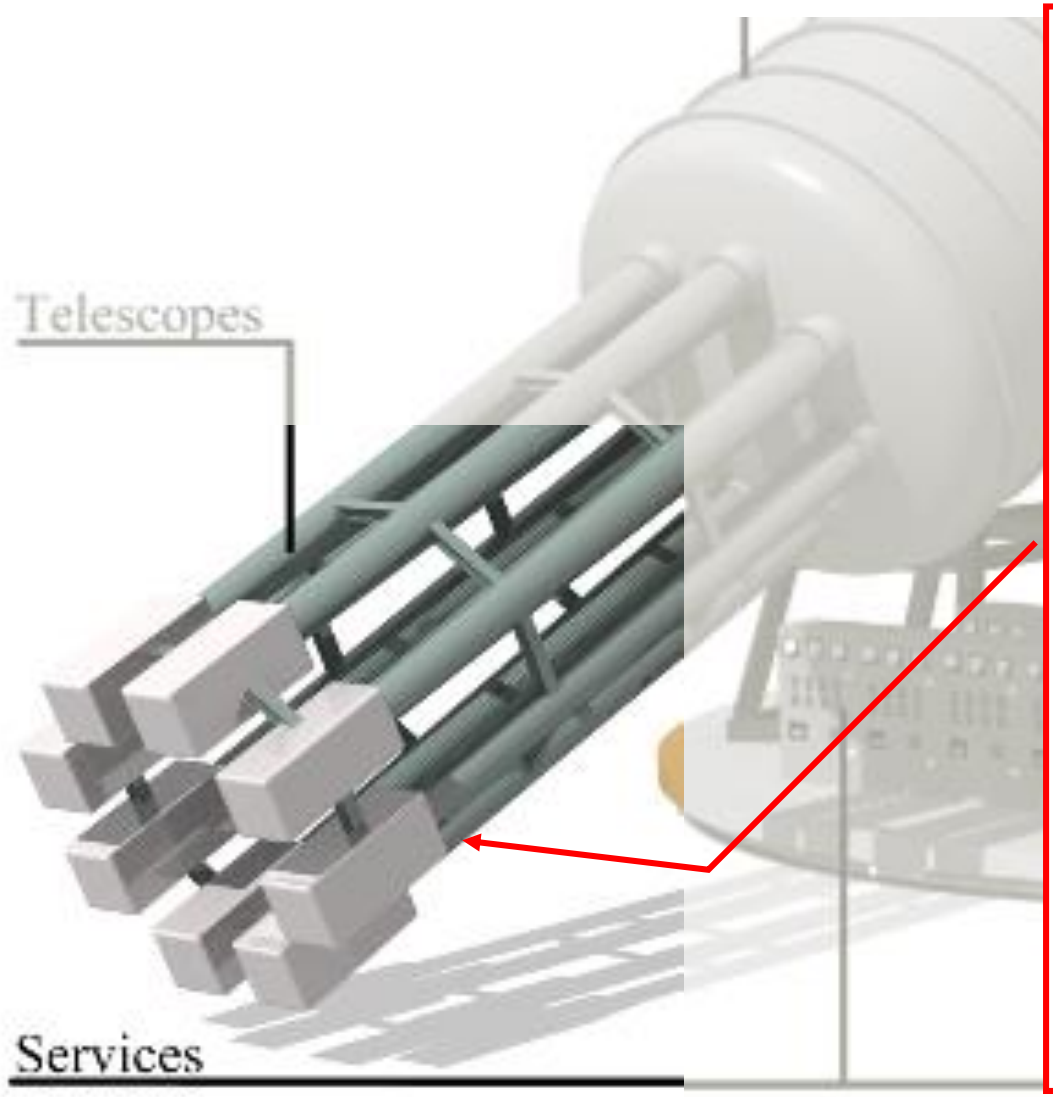
Optimal focal length ~5 m

Telescopes	8
N, Layers (or shells) per telescope	123
Segments per telescope	2172
Geometric area of glass per telescope	0.38 m^2
Focal length	5.0 m
Inner radius	50 mm
Outer Radius	300 mm
Minimum graze angle	2.63 mrad
Maximum graze angle	15.0 mrad
Coatings	W/B_4C multilayers
Pass band	1−10 keV
IAXO Nominal, 50% EEF (HPD)	0.29 mrad
IAXO Enhanced, 50% EEF (HPD)	0.23 mrad
IAXO Nominal, 80% EEF	0.58 mrad
IAXO Enhanced, 90% EEF	0.58 mrad
FOV	2.9 mrad

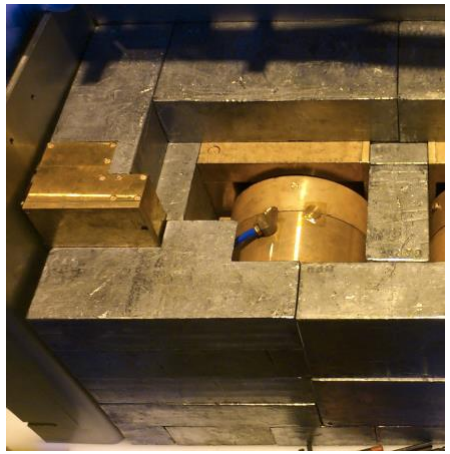


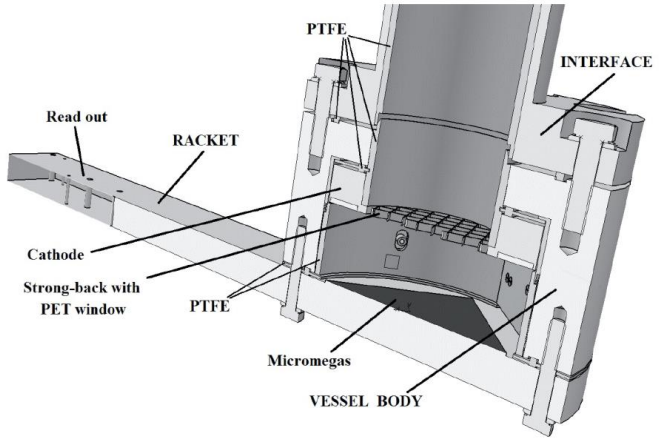
IAXO optics conceptual design
AC Jakobsen et al, Proc. SPIE 8861 (2013)

IAXO low background detectors



- 8 detector systems
- Baseline: small Micromegas-TPC chambers:
  - Shielding
  - Radiopure components
  - Offline discrimination



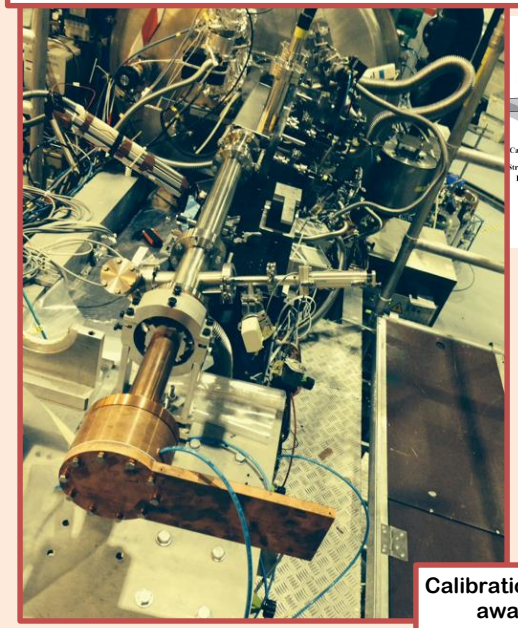


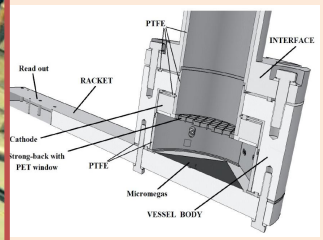
IAXO technologies – Baseline

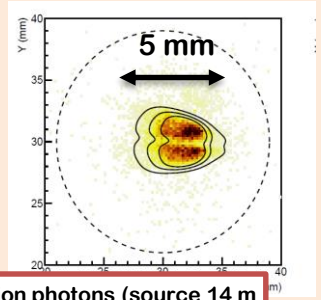
IAXO detectors

- Micromegas gaseous detectors
- Radiopure components + shielding
- Discrimination from event topology in gas
- Long trajectory in CAST
- Zaragoza + CEA + Bonn + others expertise

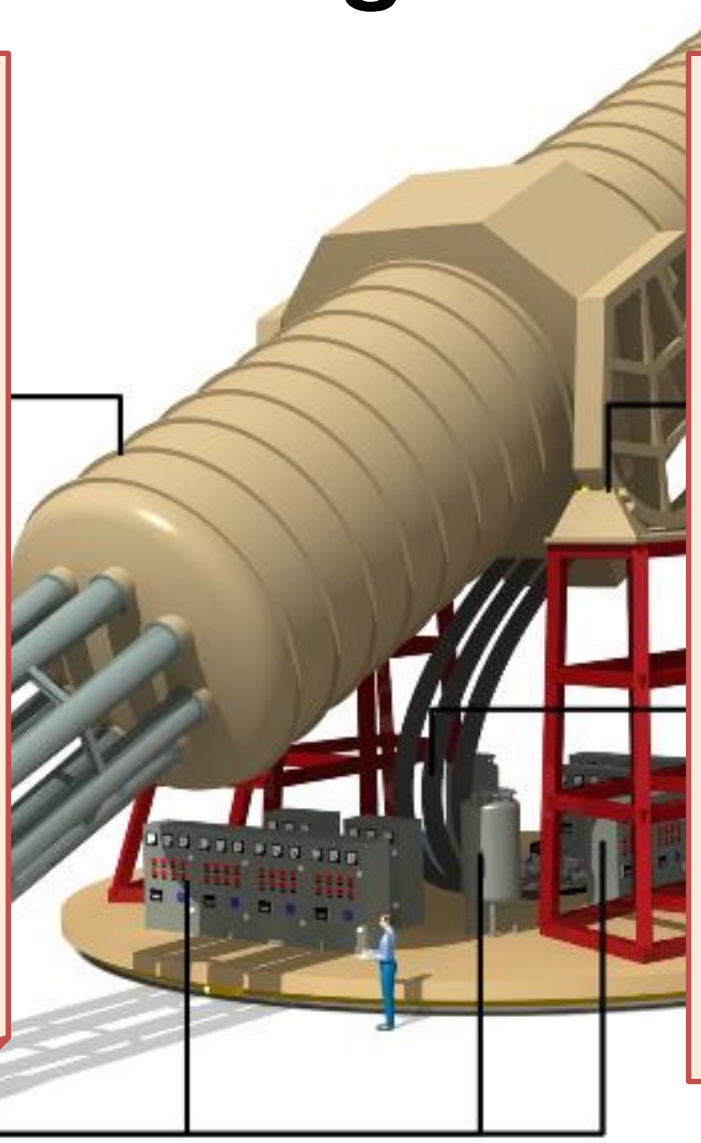
Optics+detector IAXO pathfinder system (in operation in CAST during 2014-5)







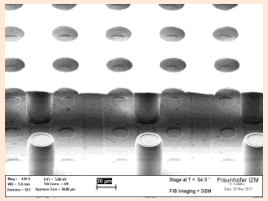
Calibration photons (source 14 m away) focused onto the Micromegas

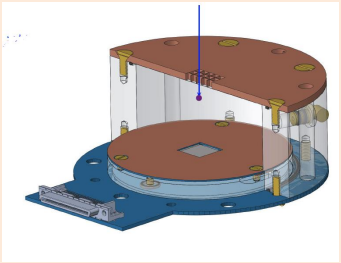


IAXO detectors

Ingrid detectors

- Better threshold
- U. Bonn

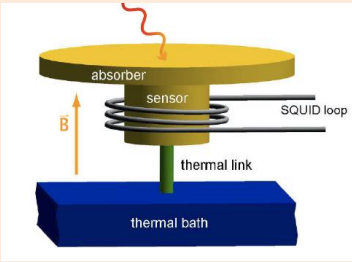




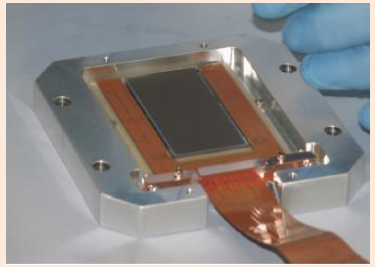
MMC (Magnetic Metallic Calorimeters)
TES (Transition Edge Sensors)

- Very good E resolution & threshold
- Heidelberg + CEA + CNSMS

Solar axion spectroscopy:
Axion-electron ABC spectrum
Axion mass determination



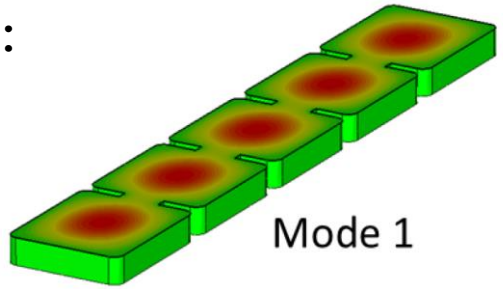
Low noise CCDs

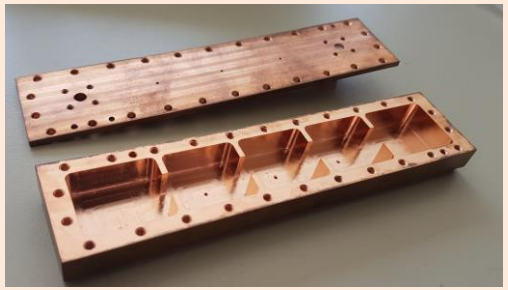


Additional physics cases

- Use of (Baby)IAXO large magnetic volume for axion DM setups.
- Various possible arrangements in IAXO. Leverage the huge magnetic volume available:
  1. Single large cavity tuned to low masses
  2. Thin long cavities tuned to mid-high masses. Possibility for directionality. Add several coherently? → e.g. RADES R&D
  3. Pick-up coils for vely low mass detection

RADES concept: array of small cavities interconnected with irises:

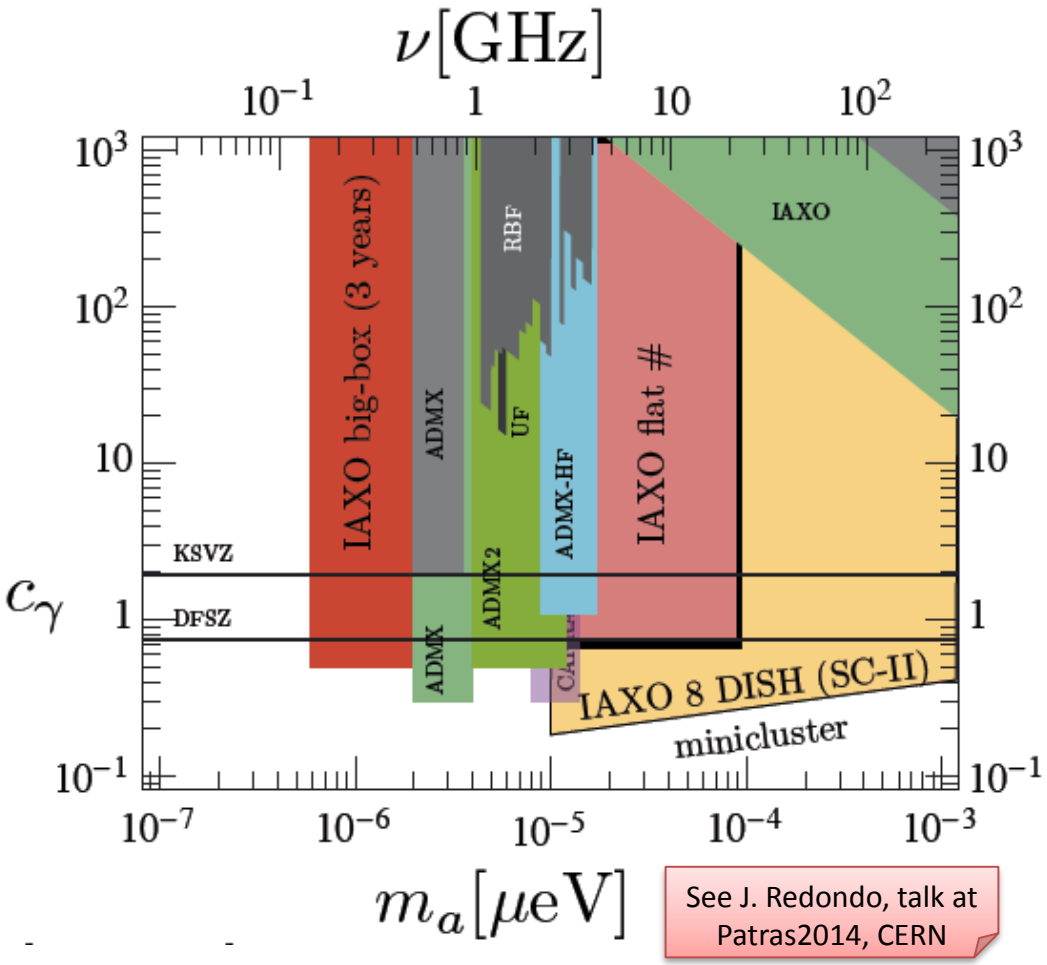




Installed successfully in CAST last year, and first engineering run took place Nov-Dec2017

Additional IAXO physics cases

direct detection or relic axions/ALPs



See J. Redondo, talk at Patras2014, CERN

- Promising as further pathways for IAXO beyond the helioscope baseline
- First indications that IAXO could improve or complement current limits at various axion/ALP mass ranges…
- **Caution**: preliminary studies still going on. Important know-how to be consolidated. Precise implementation in IAXO under study.

sensitivity prospects to be considered **tentative**

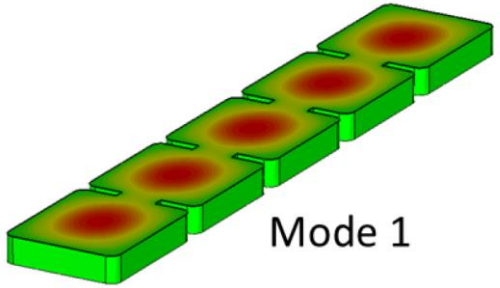
RADES

Haloscope FOM:

$$\mathcal{F} \sim g_{a\gamma}^4 m_a^2 B^4 V^2 T^{-2} C^2 Q$$

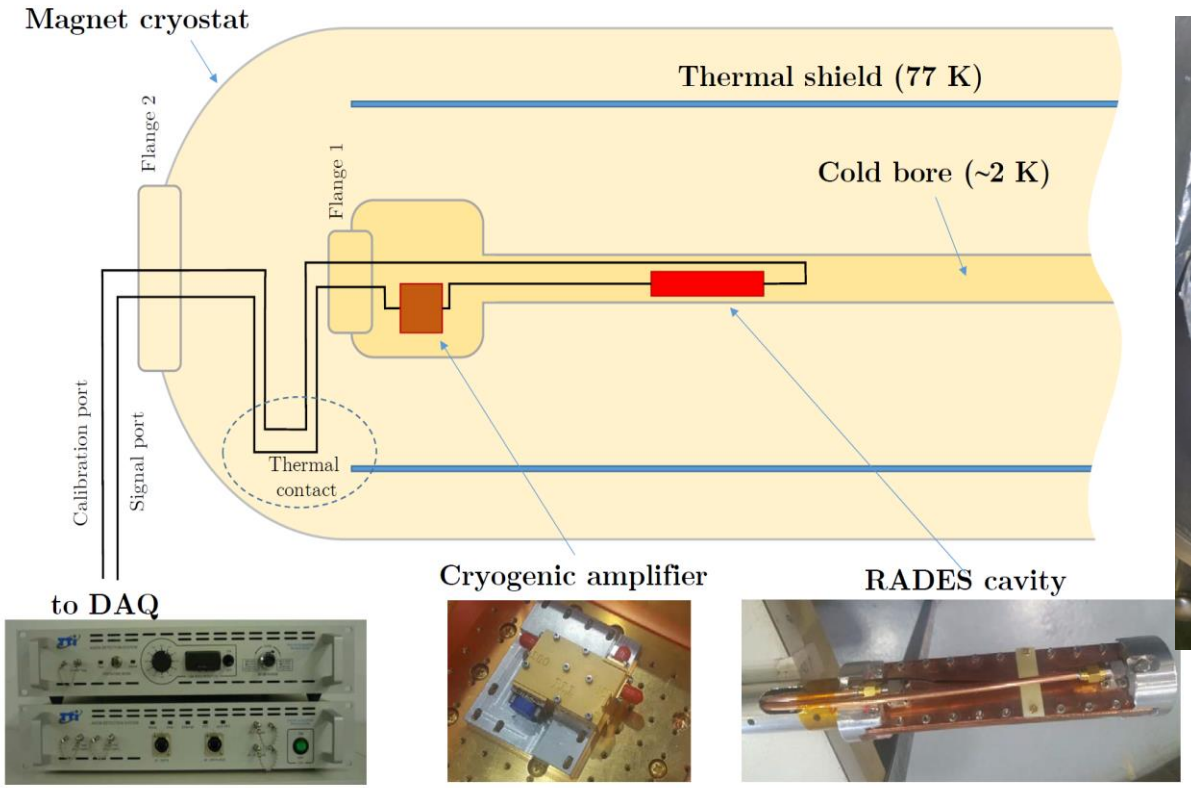
V is usually linked with m_a ($V \sim 1/m_a^3$) how to go to much higher V *and* higher m_a ?

- **RADES concept: array of small cavities interconnected with irises:**
  - **No need to phase match externally**
  - **Clear prescription to optimize coupling to axion:**
  - **Robust and flexible scaling up**
  - **Preference for long aspect-ratio: CAST (and IAXO) magnets**
  - **Problem: how to tune.**



- **First RADES cavity with 5 subcavities, non-tunable (f = 8.5 GHz; m_a = 34.75 μeV)**

RADES in CAST



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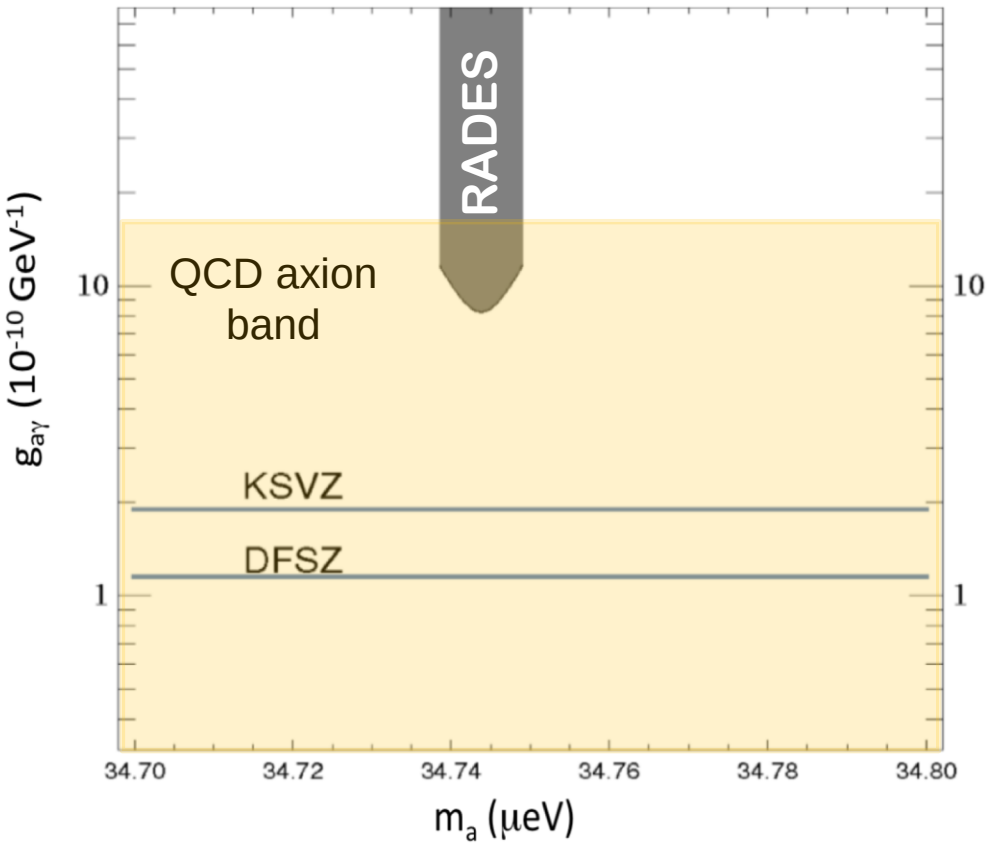
RADES in CAST



Sensitivity to (optimistically coupled) QCD axions with this very simple setup.

Only a factor of a few away from KSVZ.

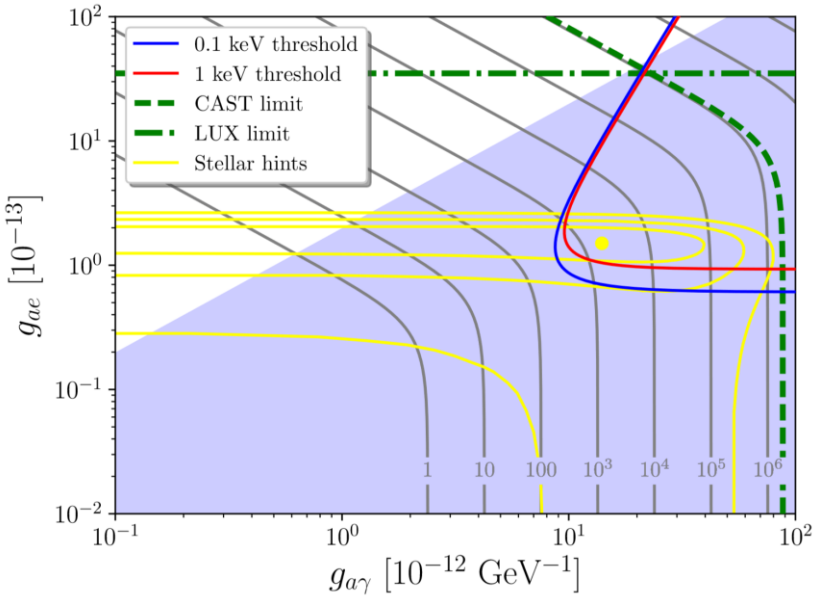
[But at a fixed m_a value]

Challenge for next runs:

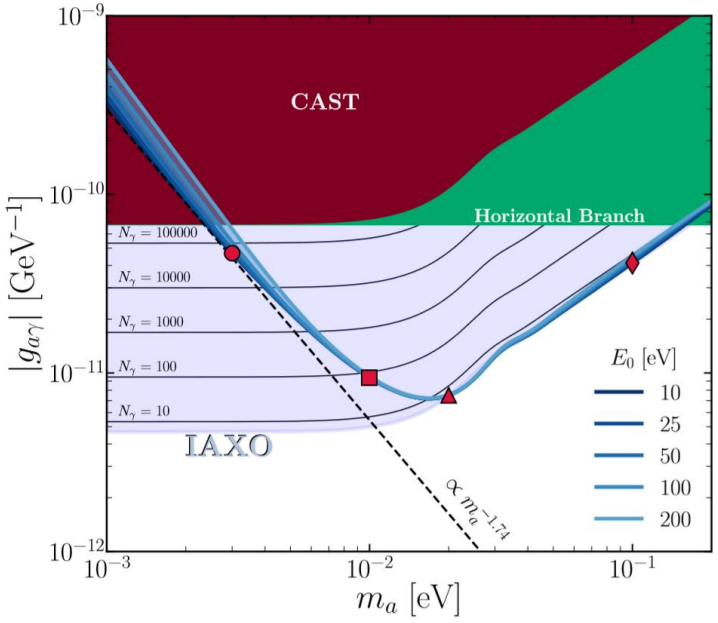
- **Larger cavities**
- **Tuning**

IAXO physics case grows…

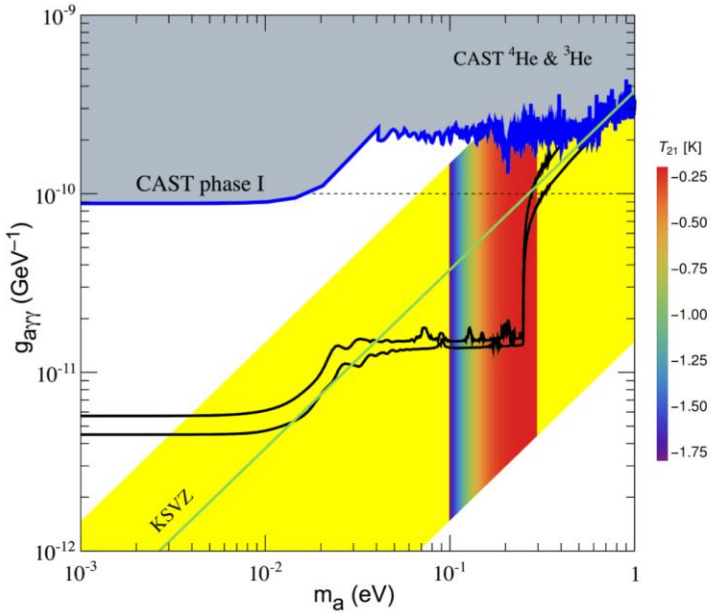
Distinguishing axion models with IAXO
Jaeckel et al. arXiv:1811.09278



"Weighing" the solar axion
Dafni et al. arXiv:1811.09278



Axion-DM explanation of EDGES 21 cm observation
Houston et al. arXiv:1812.03931



- **Summary of current status ar future prospects…**
- **A diverse experimental landscape has emerged with potential to cover a substanti fraction of parameter space**
- **Caution: many of these prospects still rely on a prior succesful R&D phase**
- **Caution: Green areas rely on axion as DM hypothesis…**