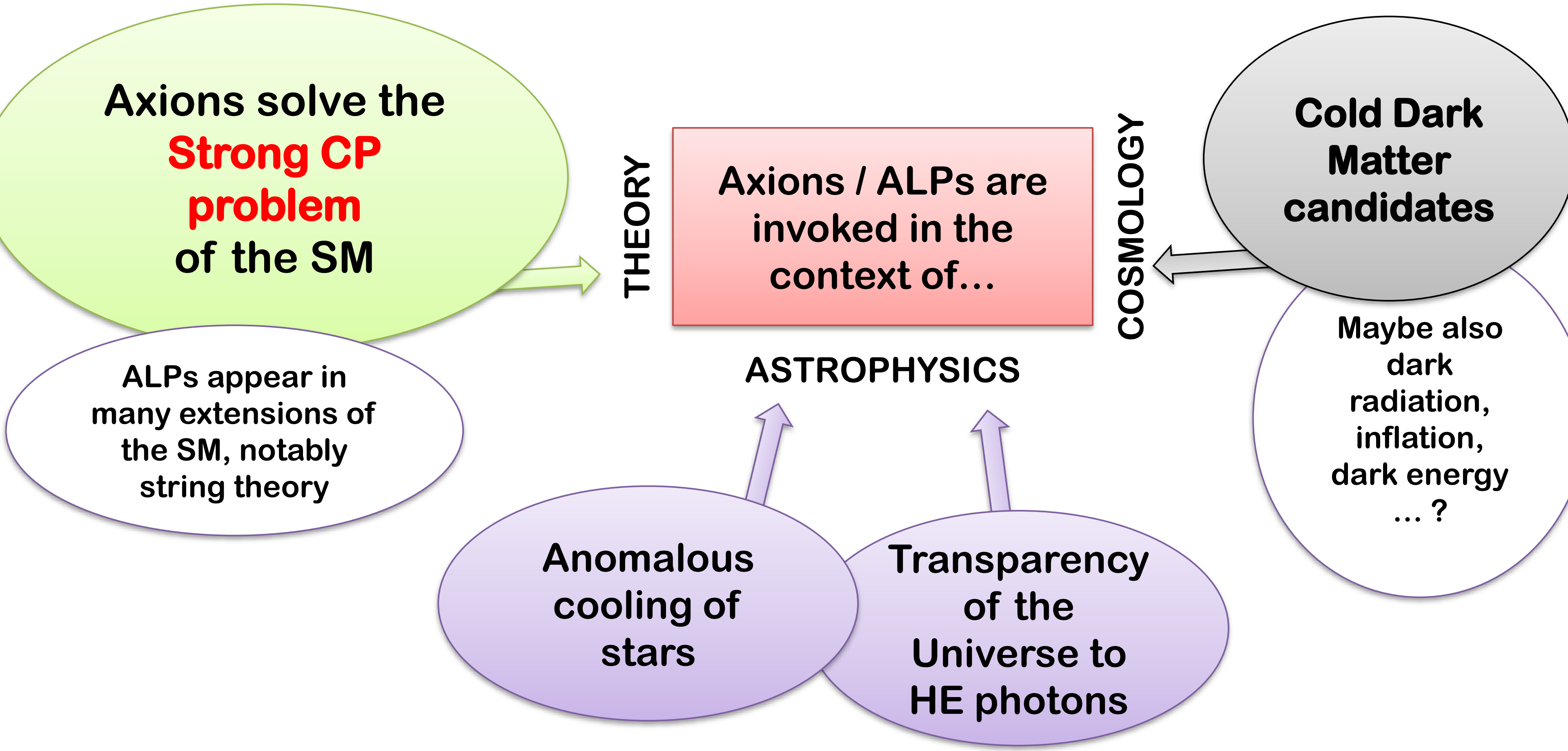
Search for axions with the International AXion Observatory (IAXO)

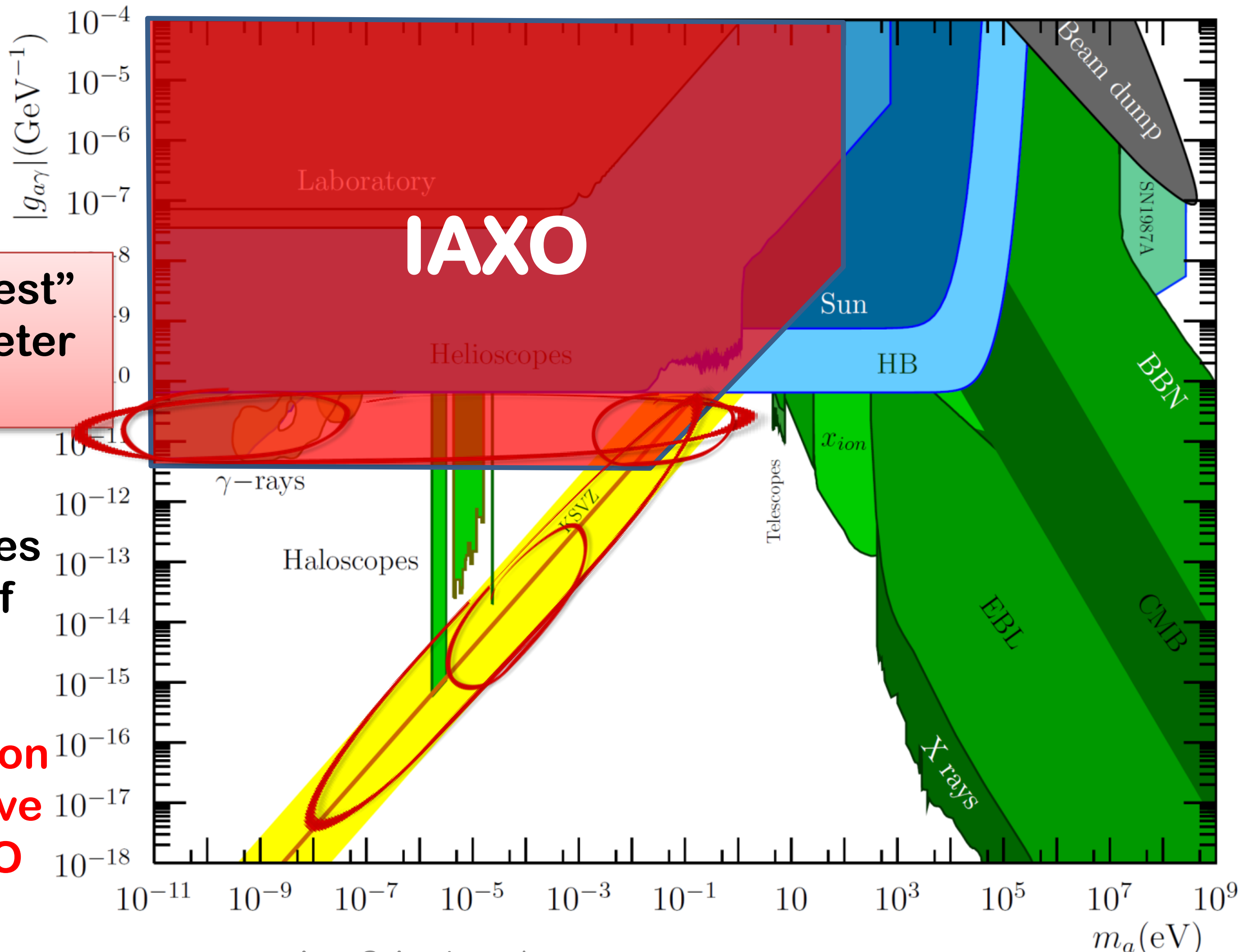
Igor G. Irastorza (U. Zaragoza)
on behalf of the IAXO collaboration

Dark Matter Review Meeting, LSC, February 7th 2018

Axion motivation in a nutshell



Axion/ALP searches motivation

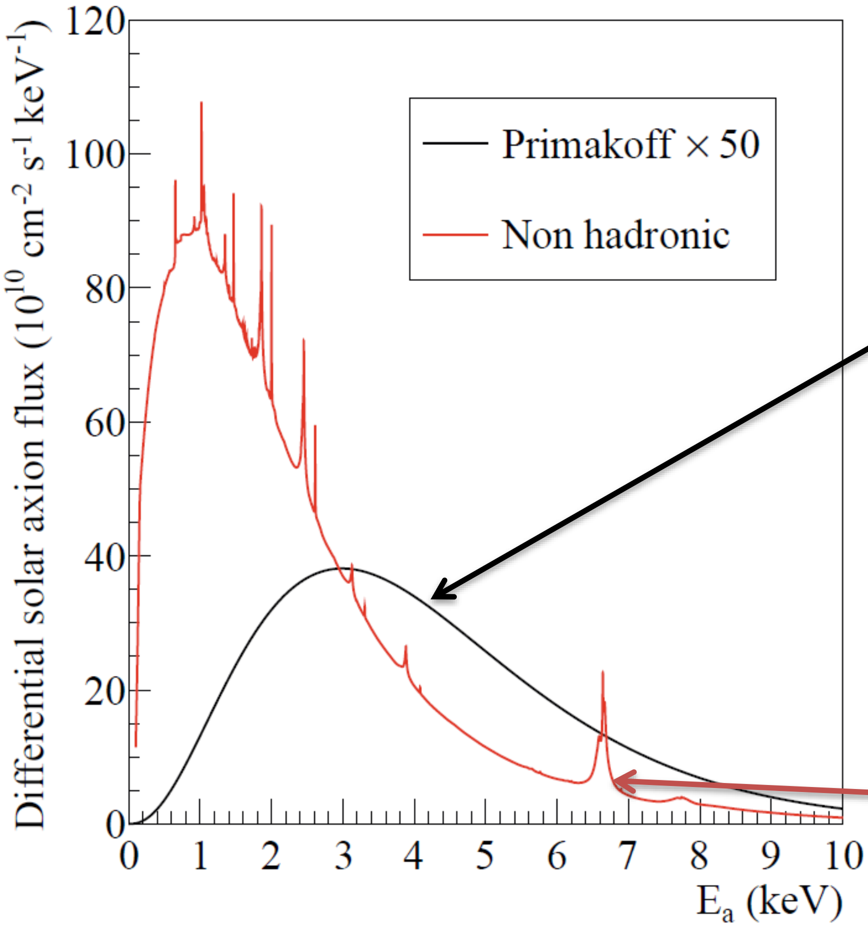


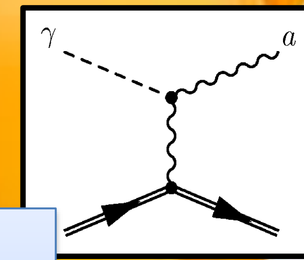
“Focuses of interest” in the ALP parameter space

IAXO addresses partially all of them

meV+ QCD axion region exclusive target of IAXO

Solar Axions





Standard Primakoff spectrum

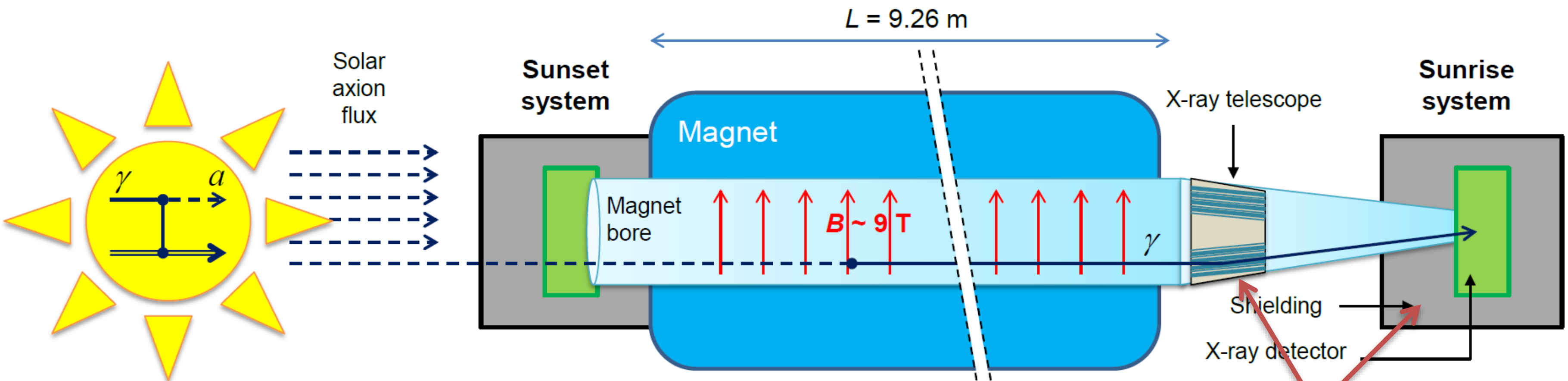
Robust prediction from axion models. Conversion of solar plasma fotons into axion (only axion-photon coupling involed)

van Bibber PRD 39 (89)
CAST JCAP 04(2007)010

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

Redondo, JCAP 1312 008

Axion helioscopes



X-ray Focussing & low-background Later innovations by CAST

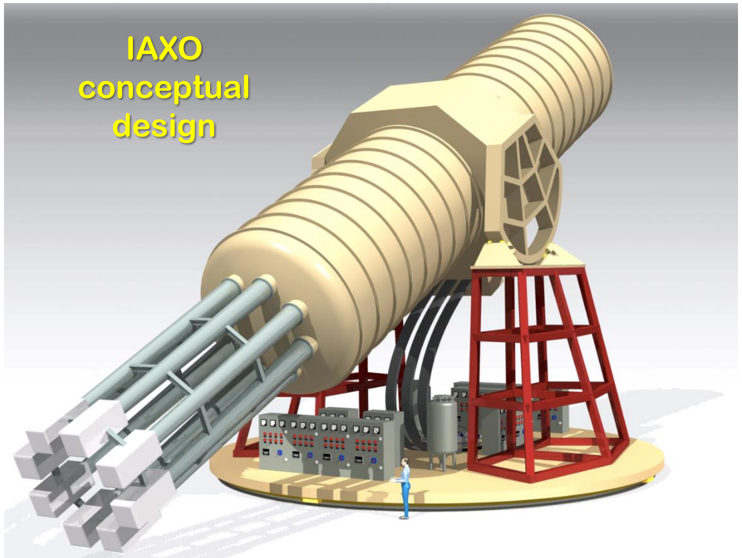
Axion helioscope concept
P. Sikivie, 1983
+ K. van Bibber, G. Raffelt, et al. (1989)
(use of buffer gas)

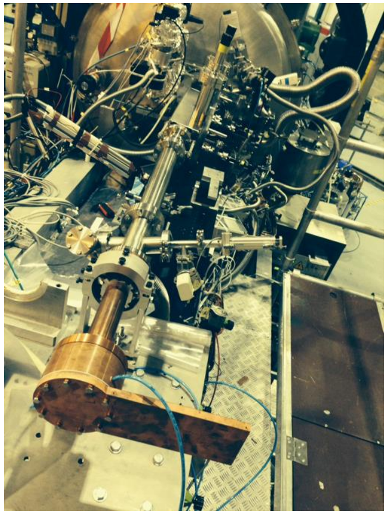
$$g_{a\gamma}^4 \propto \underbrace{b^{1/2}\epsilon^{-1}}_{\text{detectors}} \times \underbrace{a^{1/2}\epsilon_o^{-1}}_{\text{optics}} \times \underbrace{(BL)^{-2}A^{-1}}_{\text{magnet}} \times \underbrace{t^{-1/2}}_{\text{exposure}}$$

Pioneer implementations of helioscope concept:
Brookhaven (just few hours of data) [Lazarus et at. PRL 69 (92)]
TOKYO Helioscope (SUMICO): 2.3 m long 4 T magnet

IAXO experiment reminder

- Next generation "axion helioscope" after CAST
- Purpose-built large-scale magnet
  - >300 times larger B^2L^2A than CAST magnet
  - Toroid geometry
  - 8 conversion bores of 60 cm Ø, ~20 m long
- Detection systems (XRT+detectors)
  - Scaled-up versions based on experience in CAST
  - Low-background techniques for detectors
  - Optics based on slumped-glass technique used in NuStar
- ~50% Sun-tracking time
- Large magnetic volume available for additional "axion" physics (e.g. DM setups)





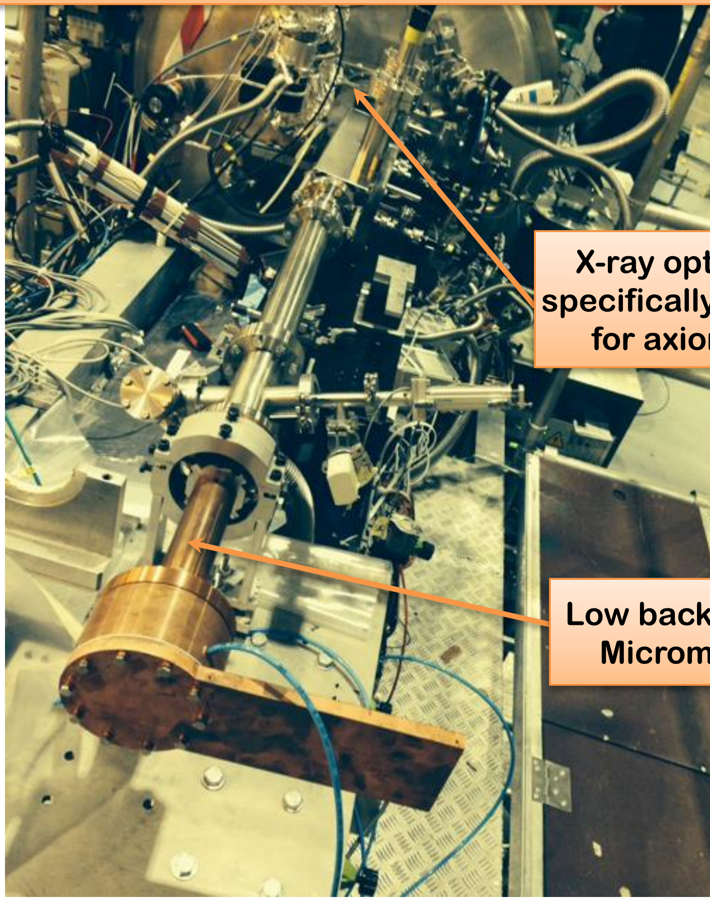
IAXO pathfinder system at CAST

In operation in 2014-15

Last CAST results published in Nature Physics last May
Nature Phys. 13 (2017) 584-590

Latest CAST limit

Enabled by the IAXO pathfinder system

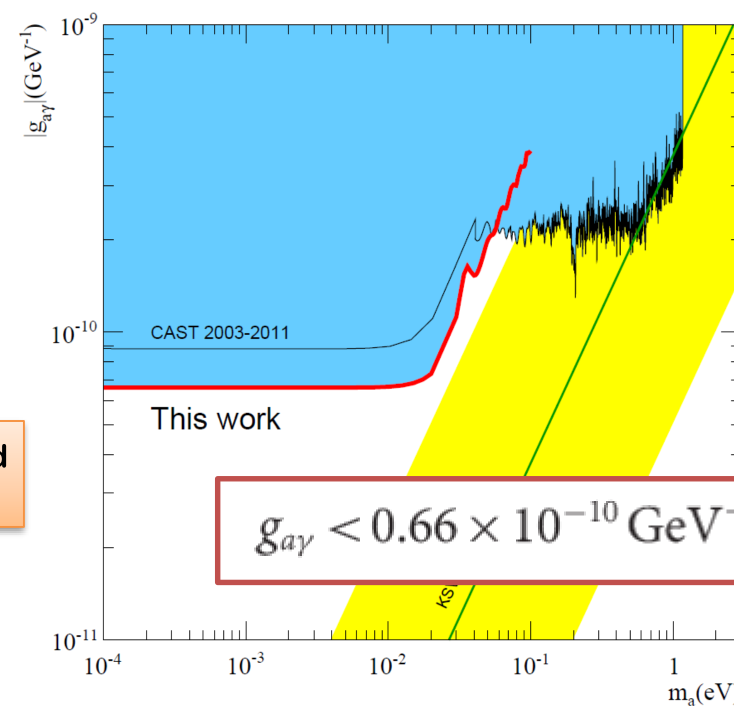


nature physics
ARTICLES
PUBLISHED ONLINE: 1 MAY 2017 | DOI: 10.1038/NPHYS4109
OPEN

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 Telescope (CAST) uses a 9 T refurbished Large Hadron Collider test magnet directed towards the Sun. In the strong magnetic
2013–2015 run, thanks
ibout a factor of three.
onfidence level) set by



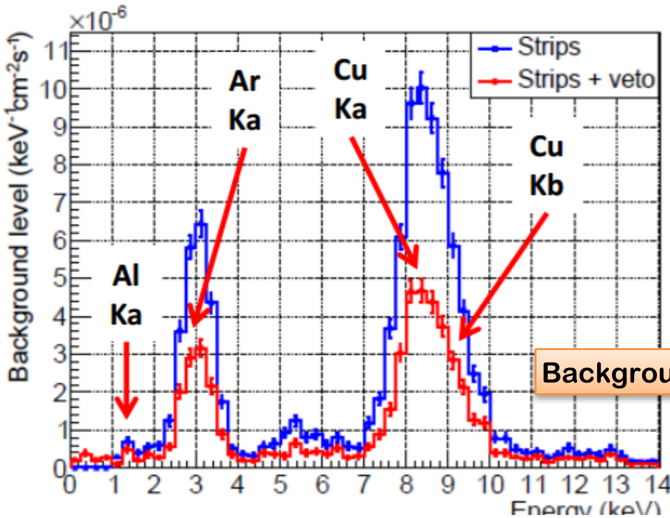
$$g_{a\gamma} < 0.66 \times 10^{-10}\,\mathrm{GeV}^{-1} \text{ at 95\% CL}$$

IAXO pathfinder system in CAST

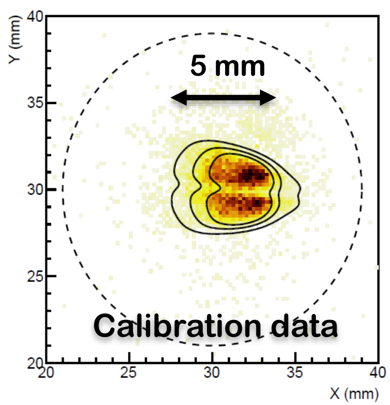
Detector: JCAP12 (2015)
Physics: Nature Physics (10.1038/nphys4109)

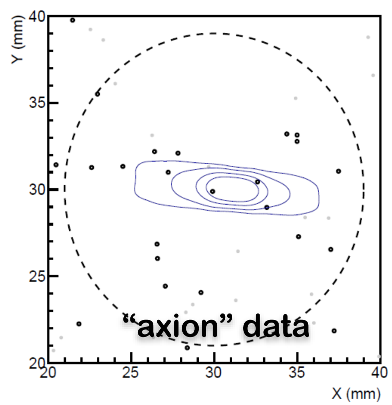
Test MM detector + slumped-glass x-ray optics together

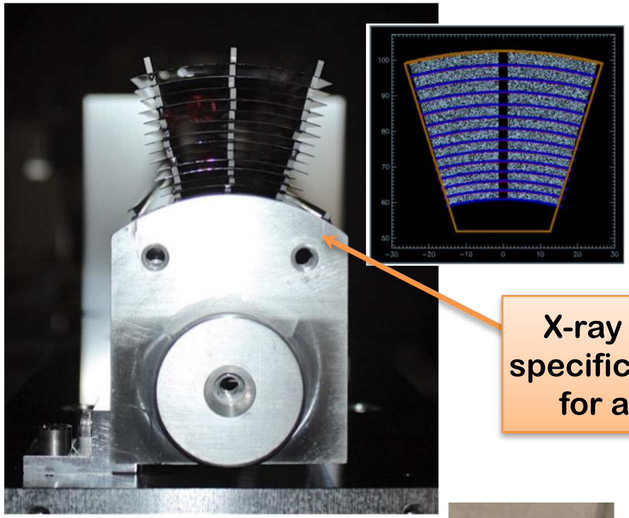
Best SNR than any other CAST detector ever!!



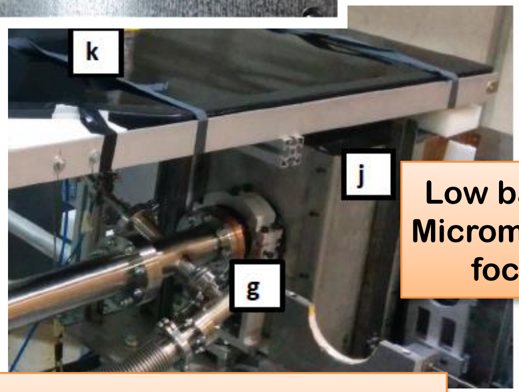
Background spectrum







X-ray optics specifically built for axions



Low background Micromegas at the focal point

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

IAXO-D0 at UNIZAR

- Based on IAXO pathfinder (improved):
  - Electroformed Cu chamber and pipes
  - Enlarged Pb shielding
  - 4π active shielding
  - AGET electronics (auto-trigger)
  - Operation with Xe
- New lab at UNIZAR
  - Comissioning of the system underway
- Software tools available
  - Background model underway

Goals: Bkg level: 10^{-7}-10^{-8} keV^{-1} cm^{-2} s^{-1}
Energy threshold: ~0.1 keV

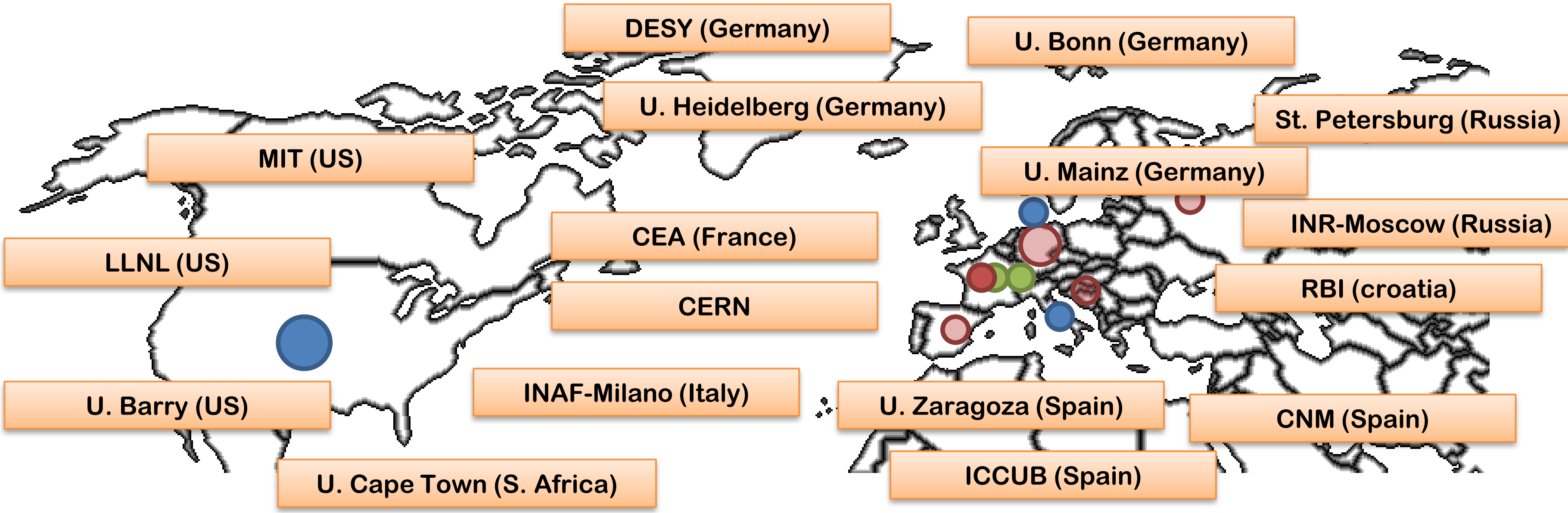
Test facility for other IAXO detector candidates

IAXO most recent milestones

- Collaboration formally established in the last collaboration meeting at DESY (last July):
  - 17 institutions to sign IAXO bylaws
  - Management structure defined. Positions being elected.
- Near term goal: BabyIAXO → Full experiment "scaled-down IAXO"
  - Test bench for magnet, optics and detectors. Risk reduction, but also opportunity to go beyond baseline FOM for IAXO (→ IAXO+)
  - Intermediate scale, but representative of full IAXO dimensions
  - **Relevant physics** outcome
- Experimental site for IAXO: Strong interest from DESY
  - BabyIAXO: DESY, INR
- Magnet under design with CERN support. (Applied Fellow started last month)
- IAXO progress is being followed by "Physics Beyond Colliders" process at CERN (to provide feedback for the European Strategy Part Phy)
- Construction of BabyIAXO could happen in 2-3 years. MoU under preparation, collaboration addressing funding bodies.

IAXO collaboration

17 institutions from Germany, Spain, US, France, Russia, Croatia, S. Africa, CERN.

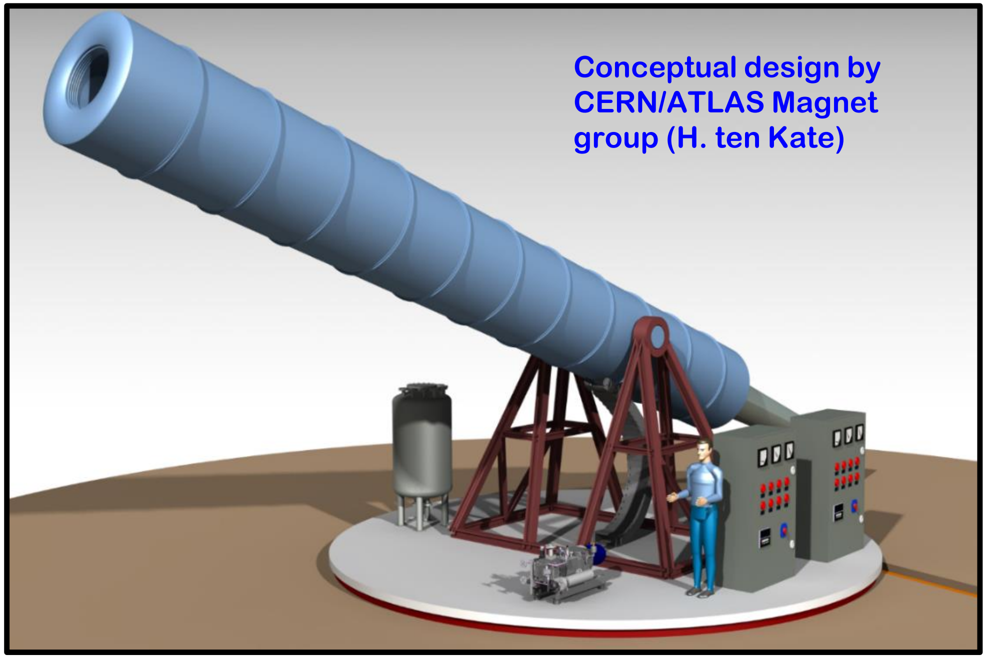


- Likely to grow in the future, more groups showing interest…
- New partners welcome…

BabyIAXO

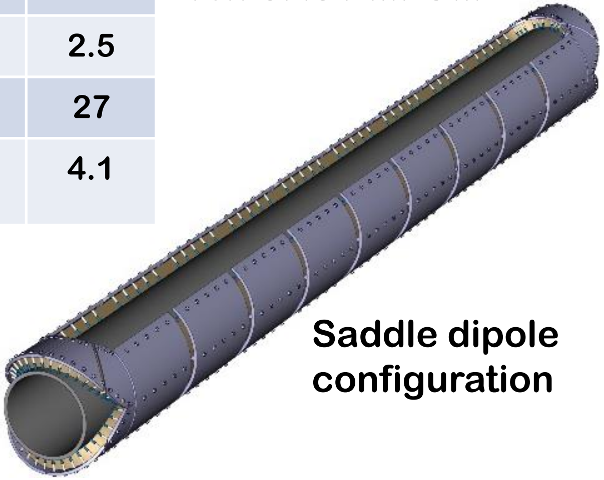
- Single bore magnet
- Bore dimensions similar to full IAXO bores → detection line representative of final ones.
- New magnet configuration (saddle dipole). Potential to go to higher B.
- Test & improve all systems. Risk mitigation for full IAXO
- Produce relevant physics
- More staged access to funds
- Move earlier to "experiment mode"

- BabyIAXO CDR finished. Moving to Technical Design



Free bore [m]	0.6
Magnetic length [m]	10
Field in bore [T]	2.5
Stored energy [MJ]	27
Peak field [T]	4.1

10x CAST MFOM



Saddle dipole configuration

IAXO physics potential ("white paper")

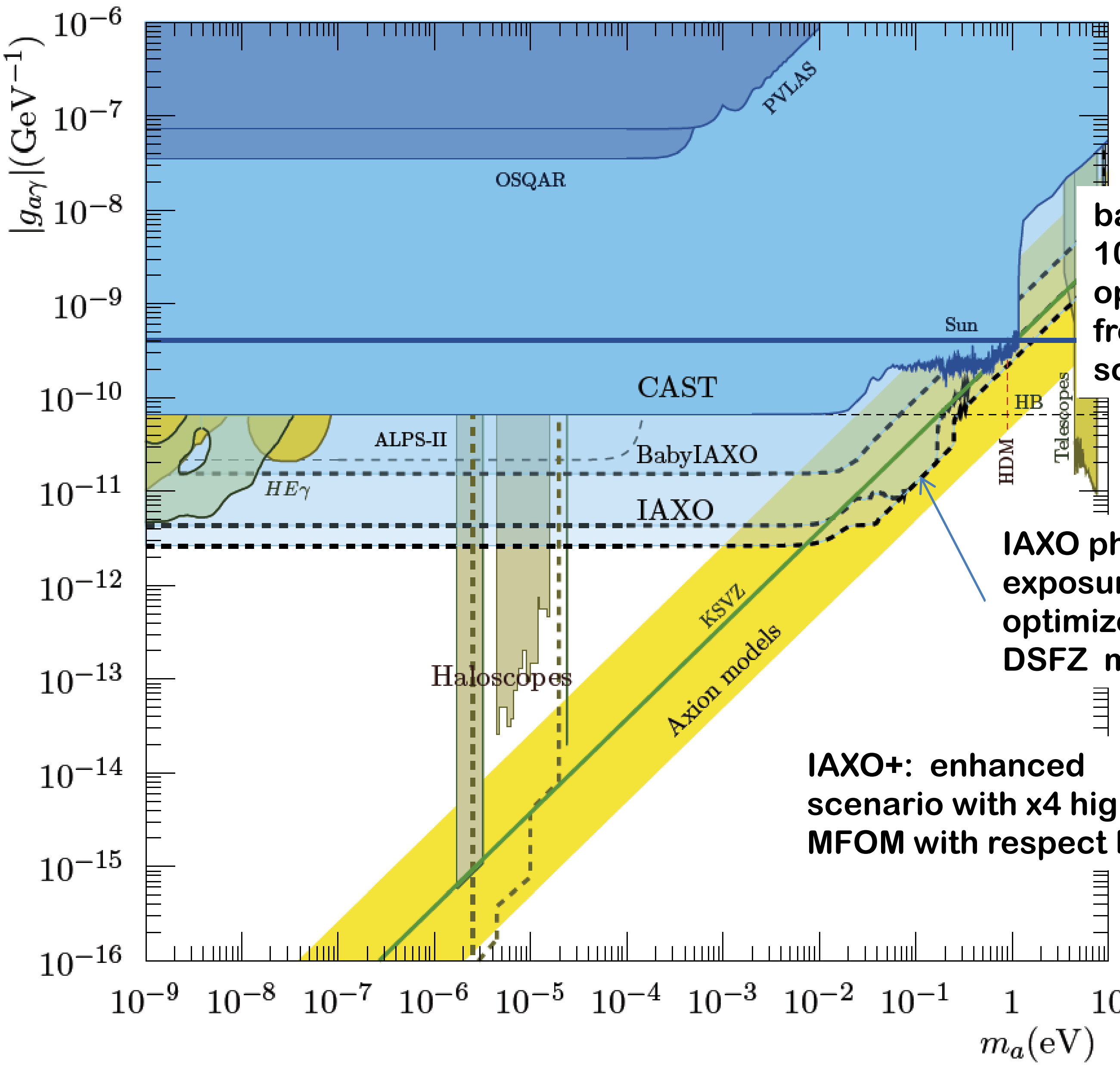
Physics potential of the International Axion Observatory (IAXO)

IAXO Collaboration

- Comprehensive review of IAXO physics case:
  - Theory
  - Cosmology
  - Astro hints
  - Updated IAXO sensitivity plots
- Very advanced draft…
- Many contributors from the theory/pheno community

Contents

Updated IAXO sensitivity regions

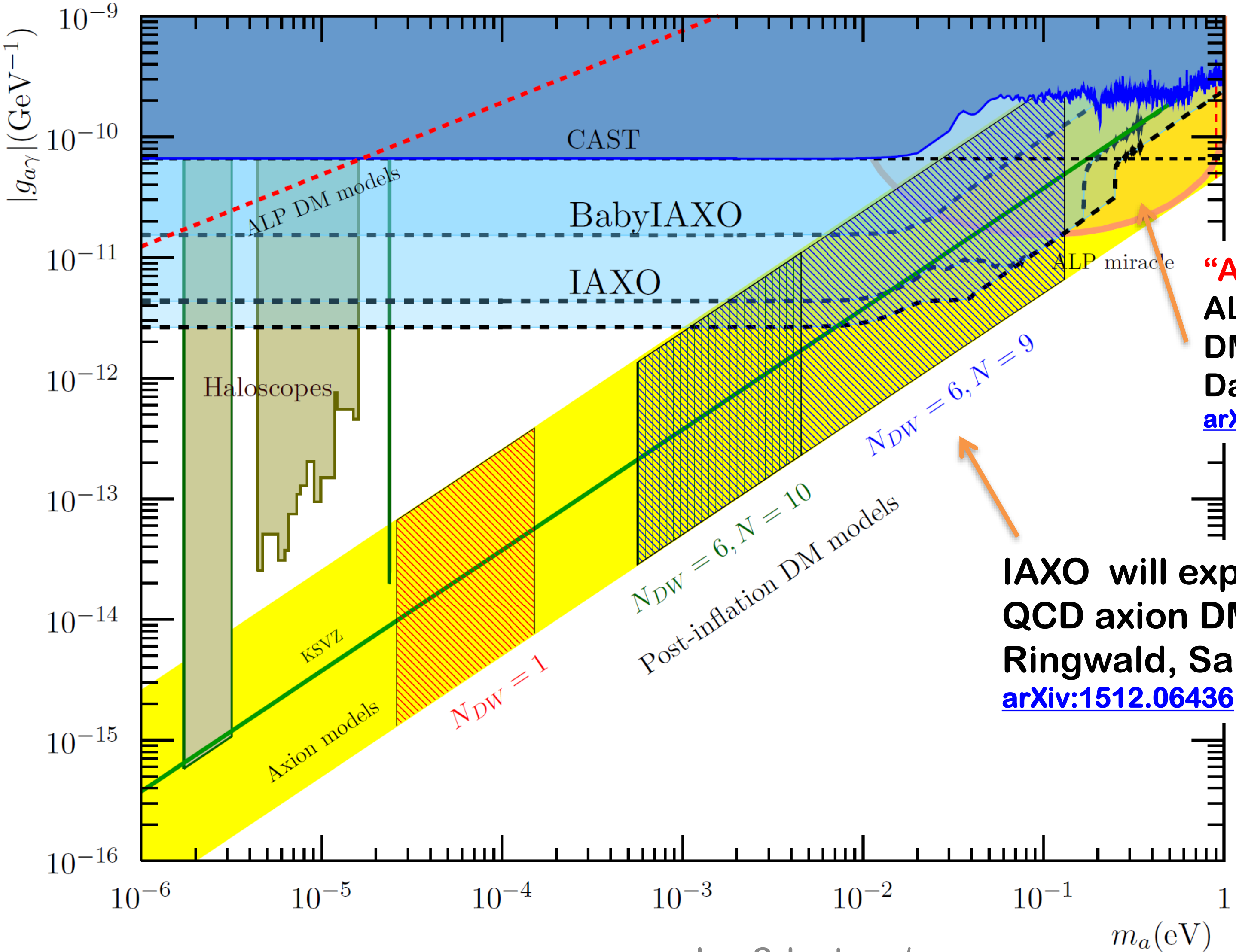


babyIAXO prospects: 10xFOM magnet + optics and detector from conservative scenario of LoI

IAXO phase II: exposure rearranged to optimize sensitivity to DSFZ models

IAXO+: enhanced scenario with x4 higher MFOM with respect LoI

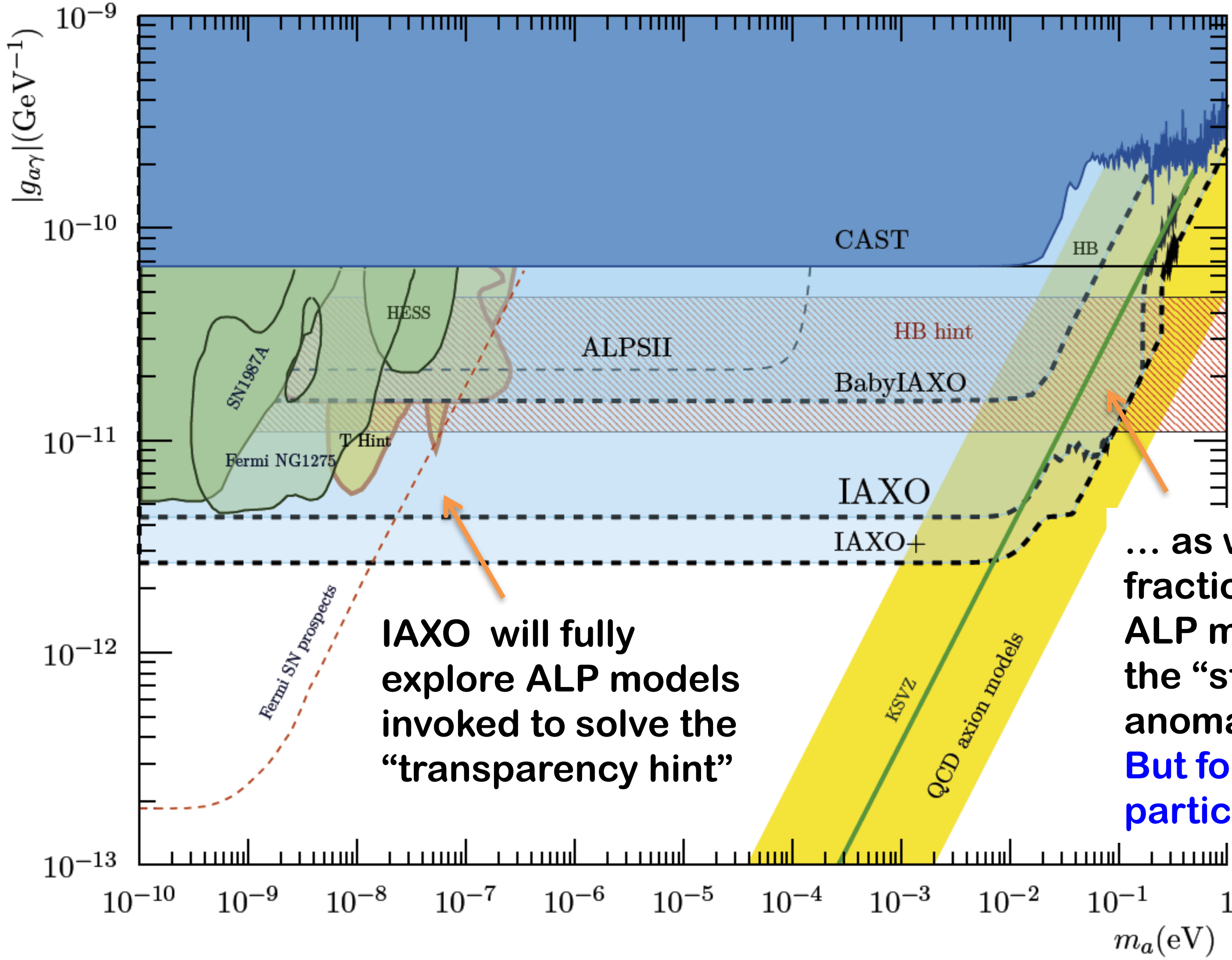
IAXO & meV axion cosmology



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

IAXO will explore viable QCD axion DM models
Ringwald, Saikawa 2016
arXiv:1512.06436

IAXO & astrophysics hints



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

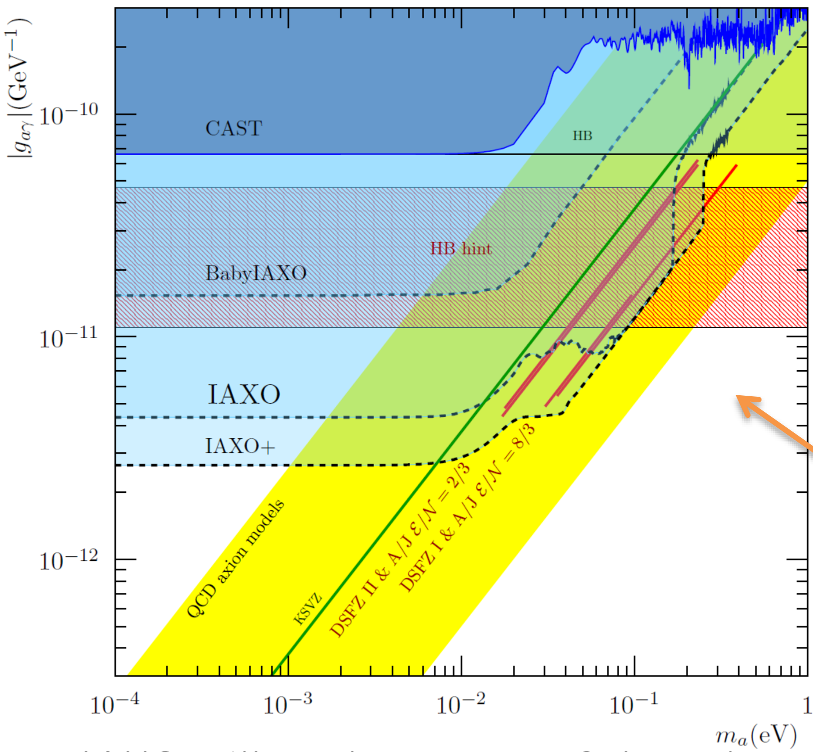
… as well as a large fraction of the axion & ALP models invoked in the "stellar cooling anomaly"

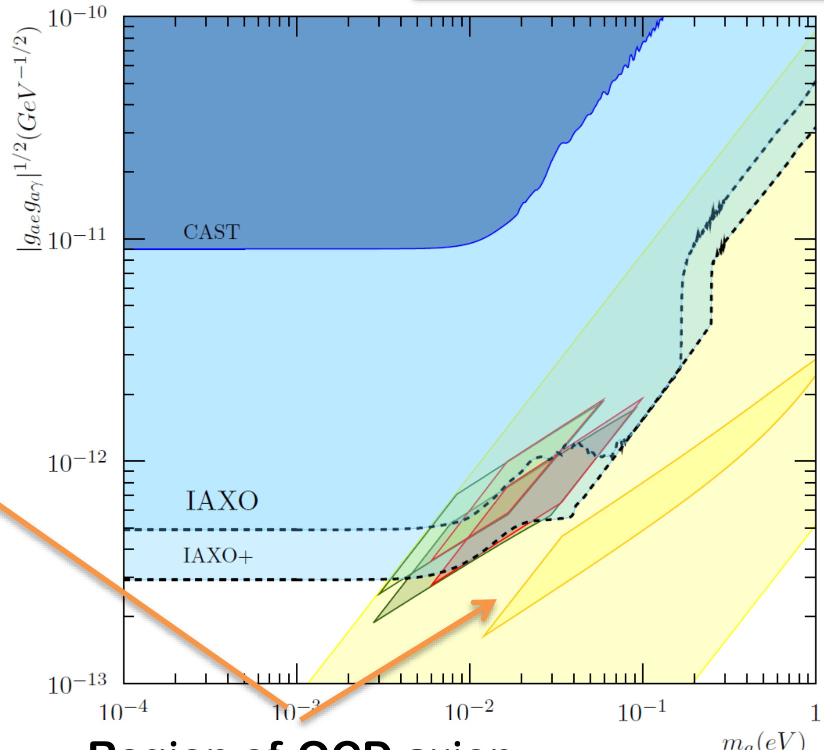
But for this the g_{ae} is particularly interesting

IAXO & stellar cooling

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

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





Region of QCD axion models that solve the stellar anomaly

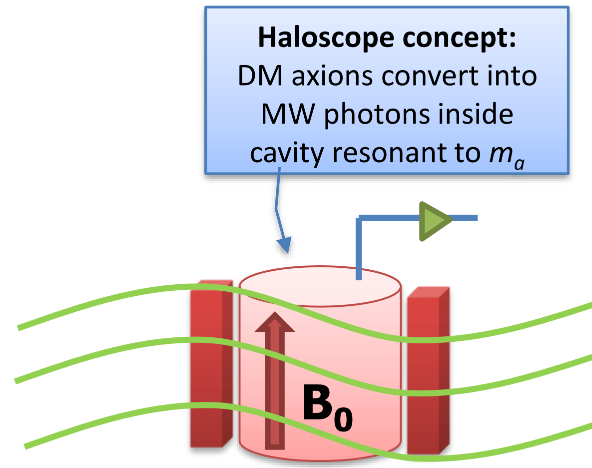
- IAXO will explore most of the relevant models (especially with IAXO+)
- Only experiment with such capability

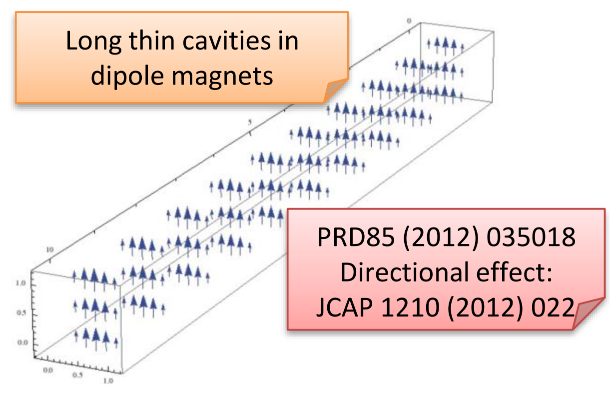
IAXO physics reach summary

- IAXO will improve the experimental "helioscope frontier" by more than 1 order of magnitude in sensitivity to $g_{a\gamma\gamma}$
  (= by more than 10000 in terms of signal to noise ratio)
- IAXO will probe a large fraction of QCD axion models in the meV to eV mass band.
- No other proposed technique can probe QCD axions in this region.
  ← Uniqueness of IAXO.
- IAXO will fully probe the ALP region invoked to solve the transparency anomaly
- IAXO will largely probe the axion region invoked to solve the stellar cooling anomaly
- IAXO will partially explore viable QCD axion DM models, and largely probe the "ALP miracle" models solving both DM and inflation.
- IAXO will probe a large unexplored ALP parameter space, also generically motivated dark radiation, string theory,...
- All this, independent of the axion-as-DM hypothesis.
- Large complementarity with other detection strategies

IAXO-DM

- **IAXO large magnetic volume offers an appealing environament for competitive 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? → RADES R&D**
  3. **Pick-up coils for vely low mass detection (toroidal geometry prefereed)**
- **RADES (Relic Axion Detector Exploratory Setup): testing mulicell cavity geometry inside the CAST Magnet**





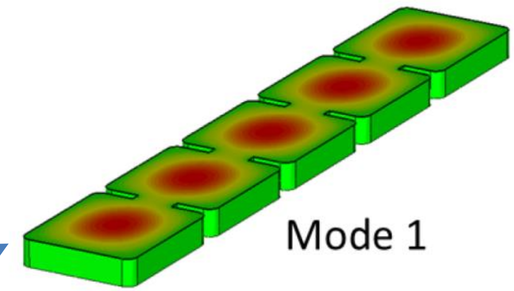
RADES

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

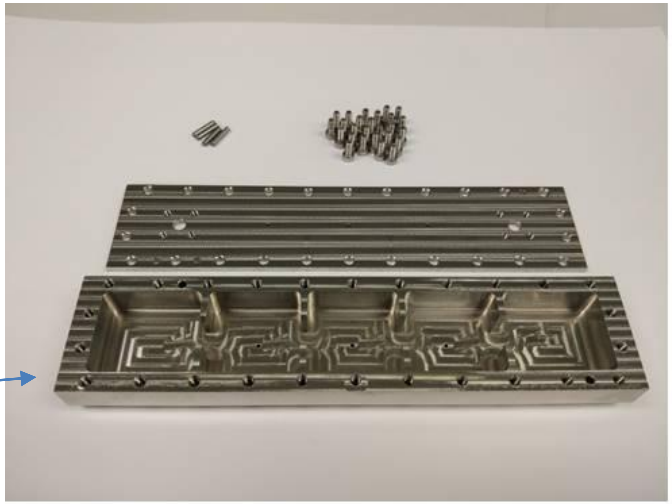
Haloscope FOM:

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

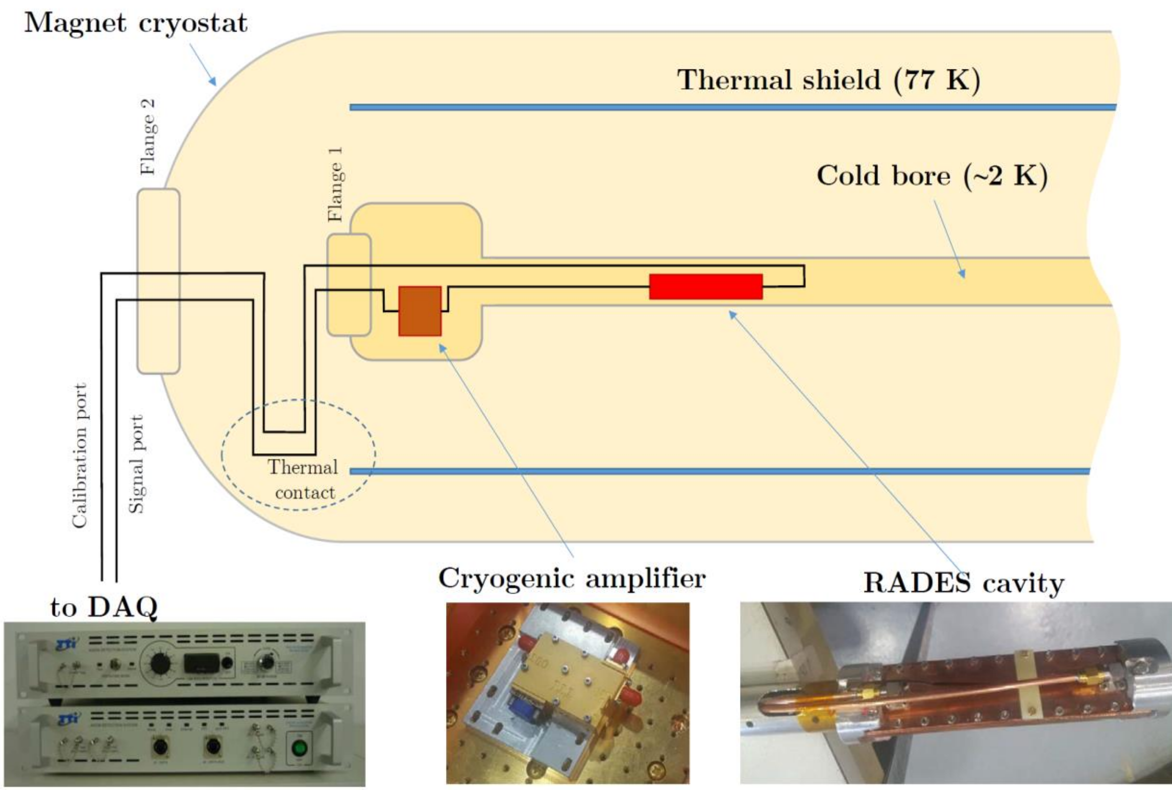
- **RADES concept: array of small cavities interconnected with irises:**
  - No need to phase match externally
  - Clear prescription to optimize coupling to axion:
  - Robust and flexible scaling up
  - Preference for long aspect-ratio: CAST (and IAXO) magnets
  - Problem: how to tune.



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

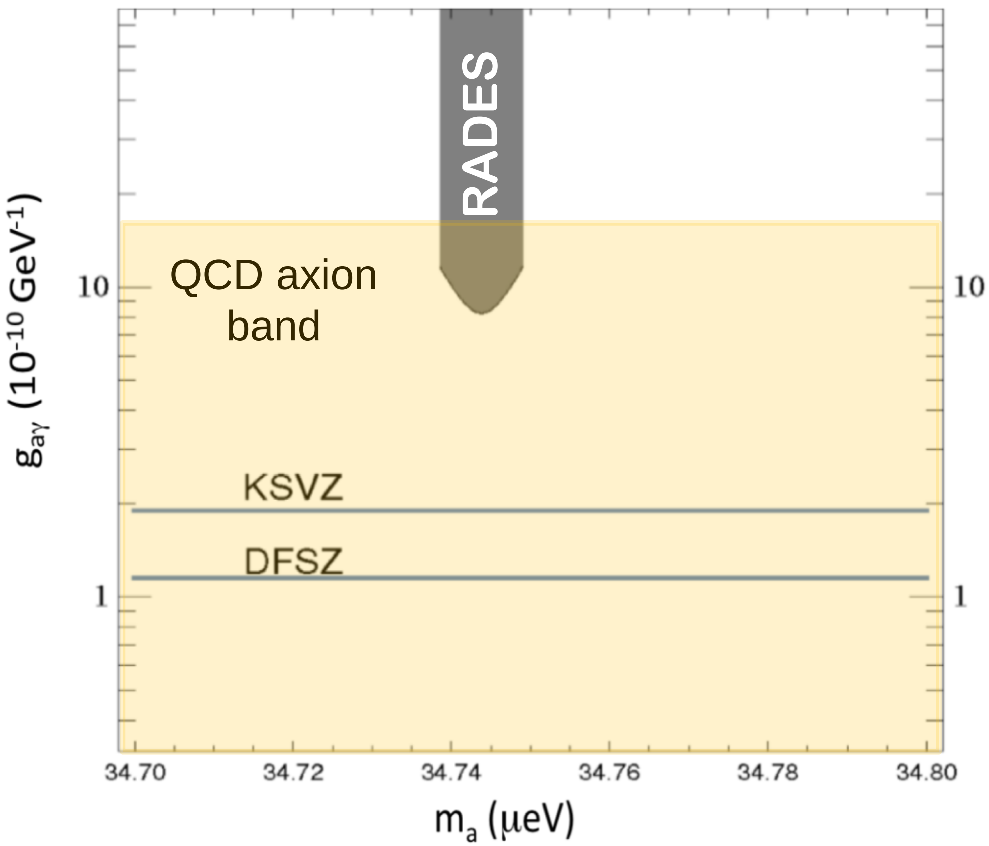


RADES in CAST



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

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 near-term milestones

1) **Finish definition of management structures of the collaboration (almost there)**
2) **Finish and release "physics potential" paper (next weeks).**
3) **Technical Design of BabyIAXO (2018 – CERN support)**
4) **Site definition (2018)**
   - **DESY: possible sites identified and "reserved"**
   - **INR: interest expressed, possible synergy with local resources**
5) **Build BabyIAXO (2-3 years). Collaboration addressing funding bodies**
   - **MoU under preparation to cover BabyIAXO phase, especially magnet construction.**
   - **Optics: aim is building full optics. Back-up plan with existing optics (first contacts with ESA Science Directorate already ongoing)**
6) **Full IAXO TDR with feedback from BabyIAXO phase**

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

IAXO in Spain

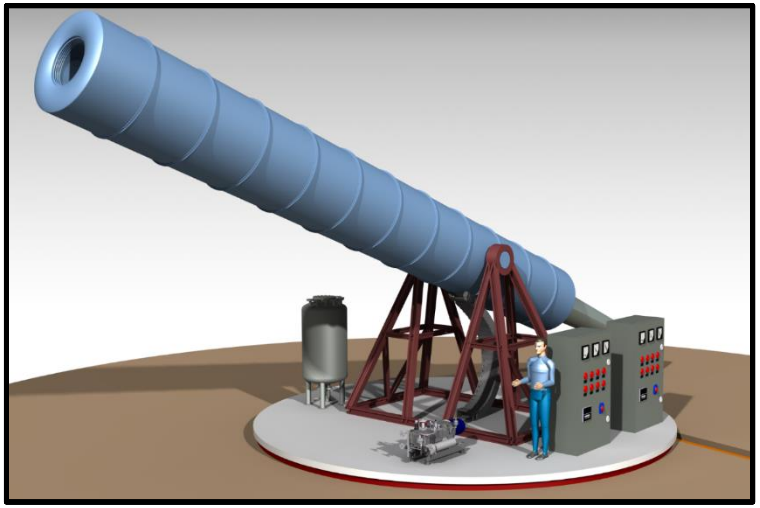
- Axion & IAXO in Spain meeting organized in 2016 to raise awareness in our community
- Coordinated project active (FPA2016-76978-C3):
  - UNIZAR: physics / coordination / low background detectors (IAXO-D0)
  - CNM: R&D new readouts
  - UPCT: R&D RF cavities (RADES)
- New groups showed interest…
  - ICCUB: formally joined the collaboration.

  physics + low background electronics +…

- More groups are very welcome!

Conclusions

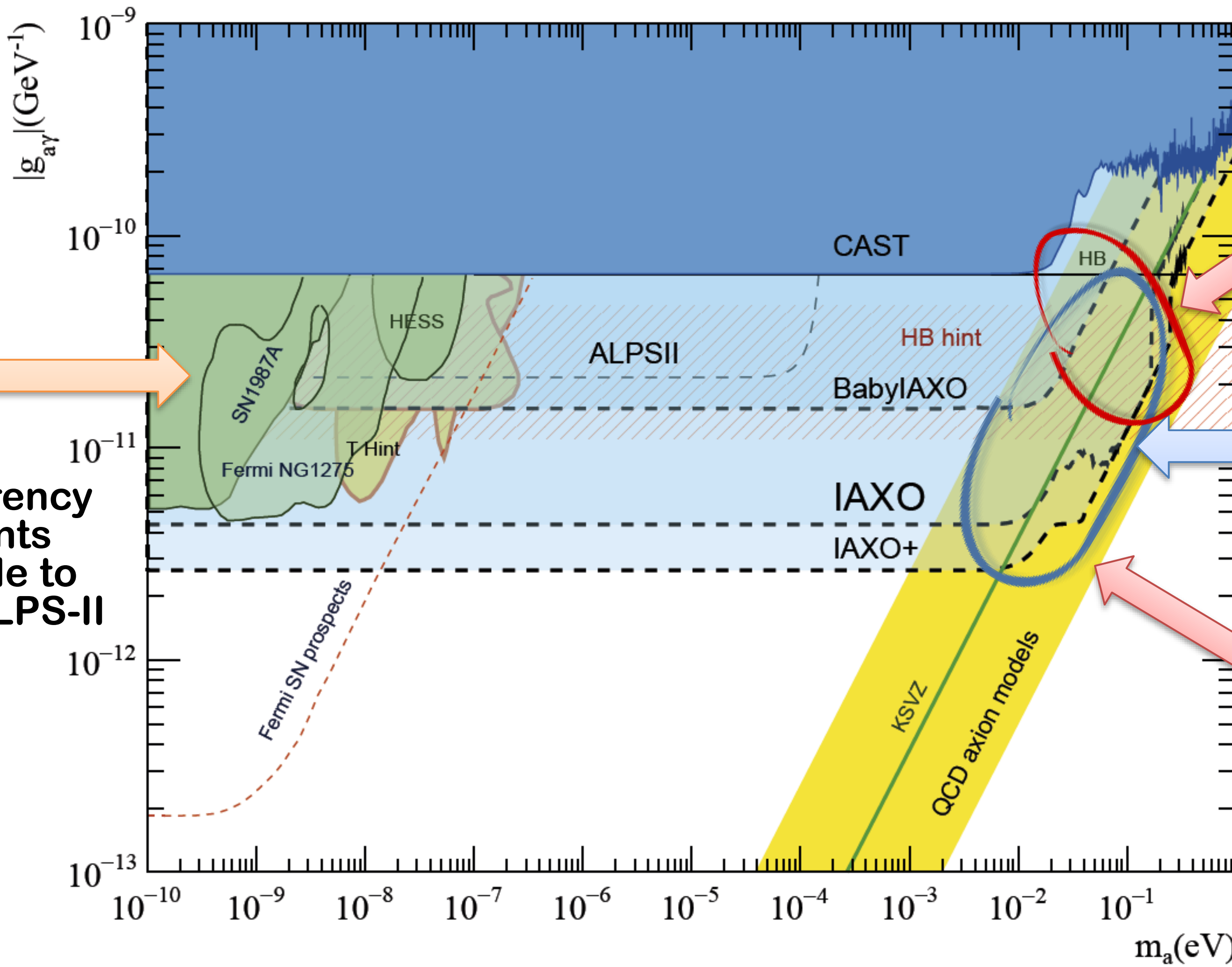
1) Important milestones regarding establishment of the collaboration
2) Near term planning better defined.
3) BabyIAXO → very appealing new experimental stage that can
    1) Enhance final FOM of experiment
    2) Catalyze near-term activities in the collaboration towards an intermediate experiment with relevant physics outcome
4) Physics case of IAXO getting sharpened by recent studies. Physics potential updated – new paper to be published soon



IAXO → singular project in the axion experimental landscape with high visibility of Spanish participation.
Great opportunity for our community. New partners are welcome!

Backup slides…

BabyIAXO & IAXO physics reach



"ALP miracle" DM + inflation

Transparency ALP hints accesible to IAXO & ALPS-II

Anomalous stellar cooling hints

QCD axions at meV scale – **they are DM candidates**

Detecting axions



Source	Experiments	Model & Cosmology dependency	Technology
Relic axions	ADMX, ADMX-HF, Casper, CAPP, …	High	New ideas emerging, Active R&D going on,…
Lab axions	ALPS, OSQAR, fifth force exps,…	Very low	
Solar axions	SUMICO, CAST, **IAXO**	Low	Ready for large scale experiment

- **Helioscopes → do not rely on the axion being the dominant DM component. Solar axion emission robust prediction**
- **Helioscopes → No R&D needed. Technology mature enough for a large scale experiment (IAXO)**
- **Large complementarity with other detection strategies**

IAXO status of project

- **2011: First studies concluded** (JCAP 1106:013,2011)
- **2013: Conceptual Design finished** (arXiv:1401.3233) **and LoI to CERN SPSC** [CERN-SPSC-2013-022]
- **2014: Positive recommendations from SPSC.**
- **2015-16: Transition phase towards TDR (technical design)**
  - Engaging funding agencies
  - Community meetings in many countries
  - Preparatory activities (IAXO pathfinder system at CAST)
  - Preparation of collaboration bylaws and MoU to carry out TDR work.
  - First discussions on experimental site options
  - First dicussion on long-term plan to built full experiment

- **2017: Formal constitution of collaboration** (expected for summer)
  - “Founding” IAXO collaboration meeting to happen in July 2017, DESY

IAXO in the axion landscape



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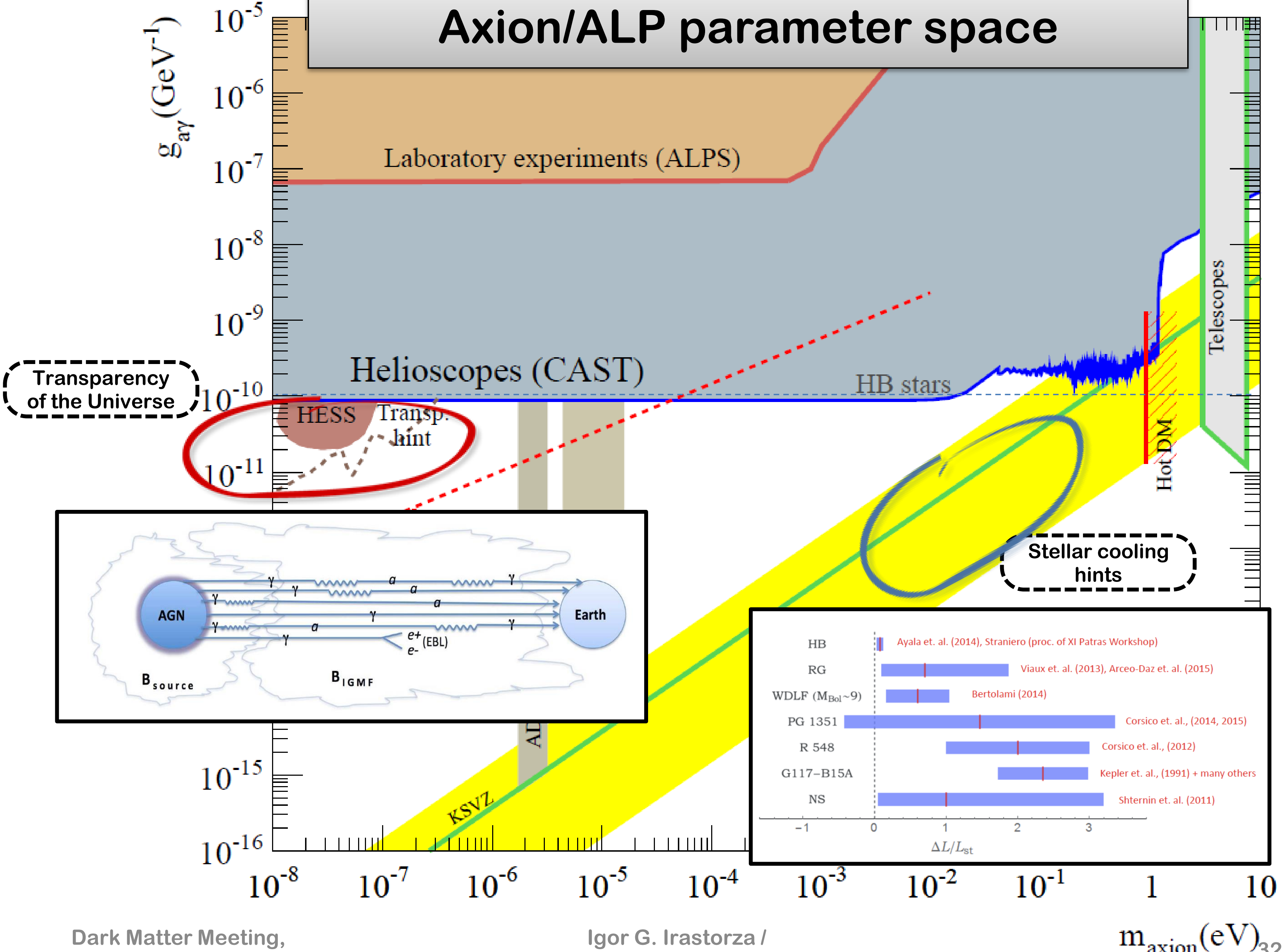
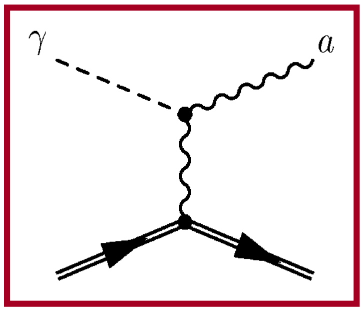
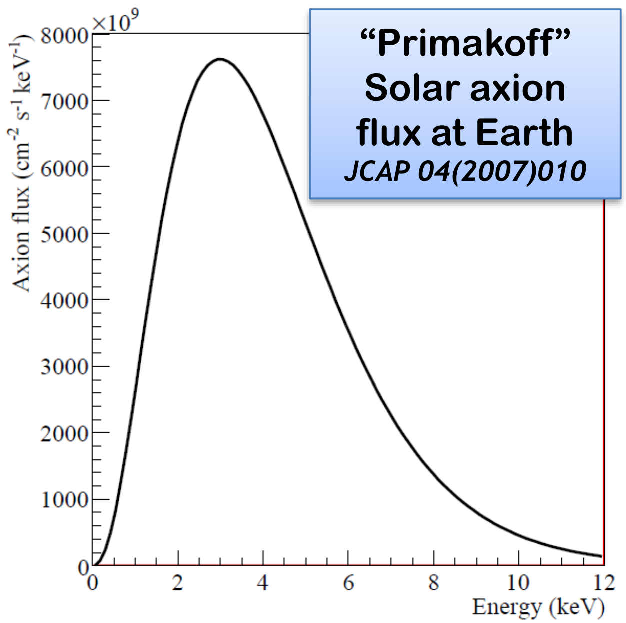
Axion/ALP parameter space



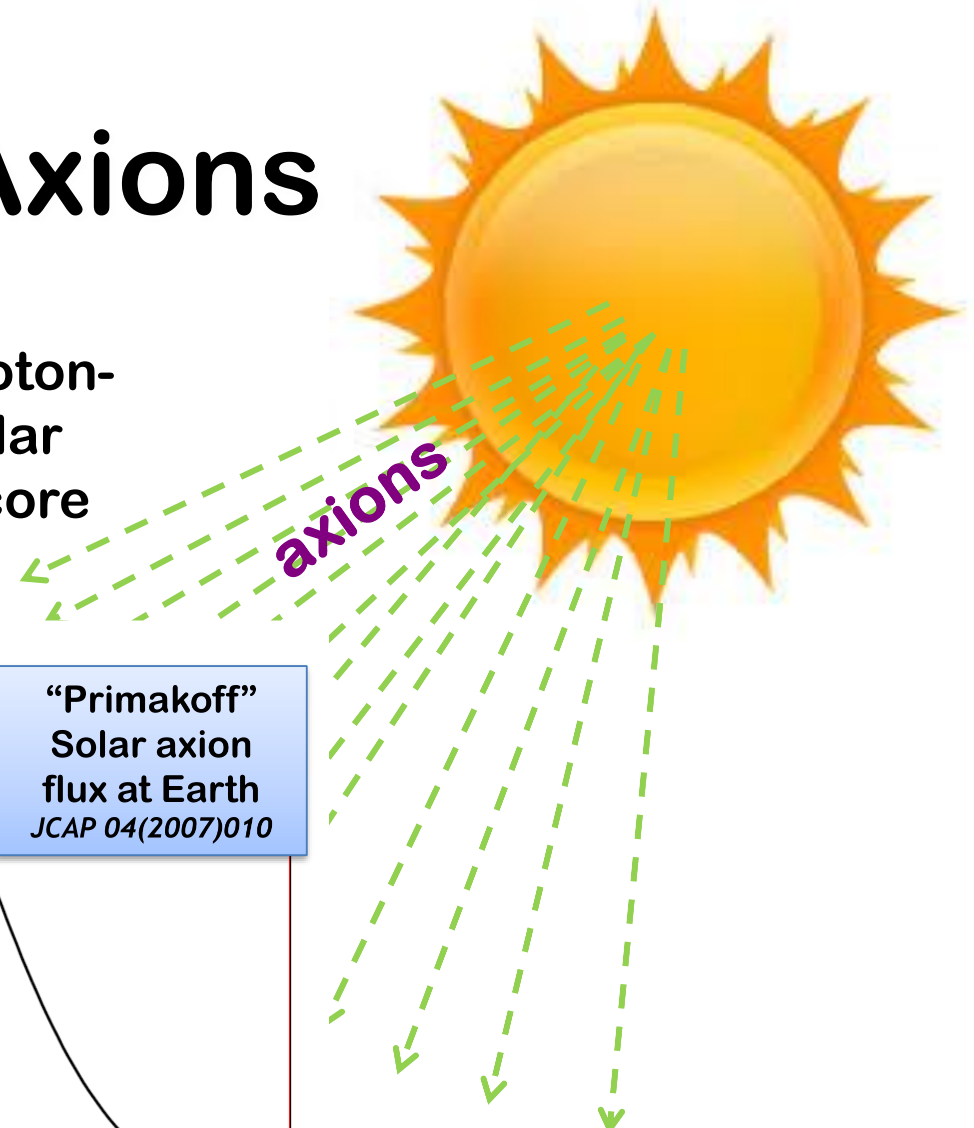
Solar Axions

- **Solar axions produced by photon-to-axion conversion of the solar plasma photons in the solar core**





"Primakoff" Solar axion flux at Earth
JCAP 04(2007)010



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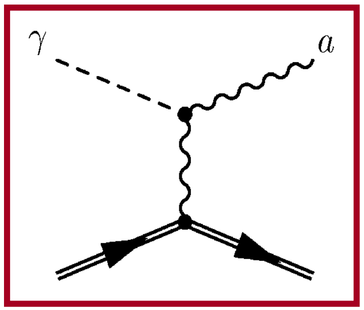
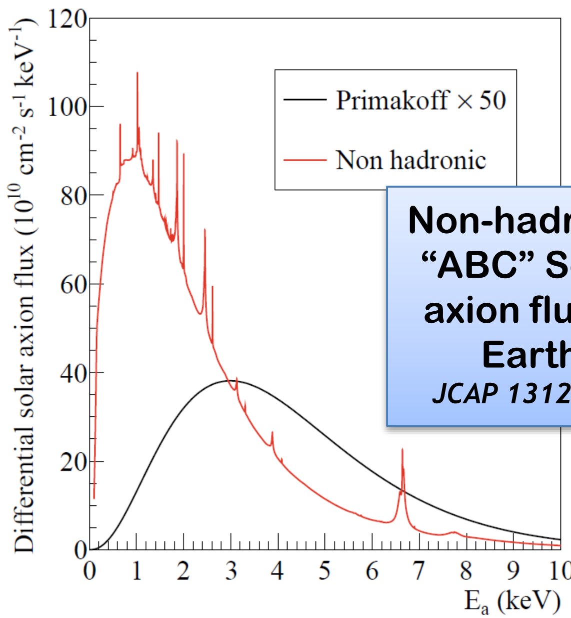
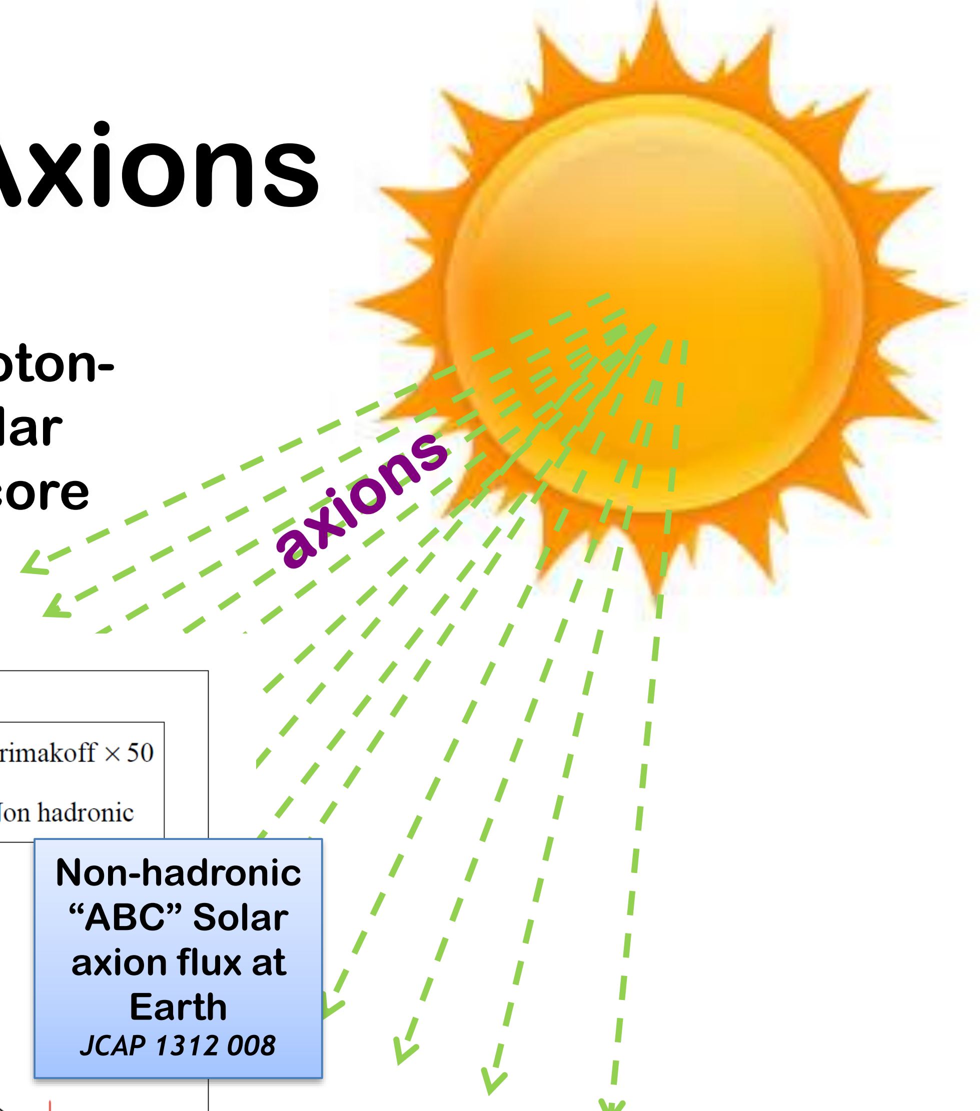






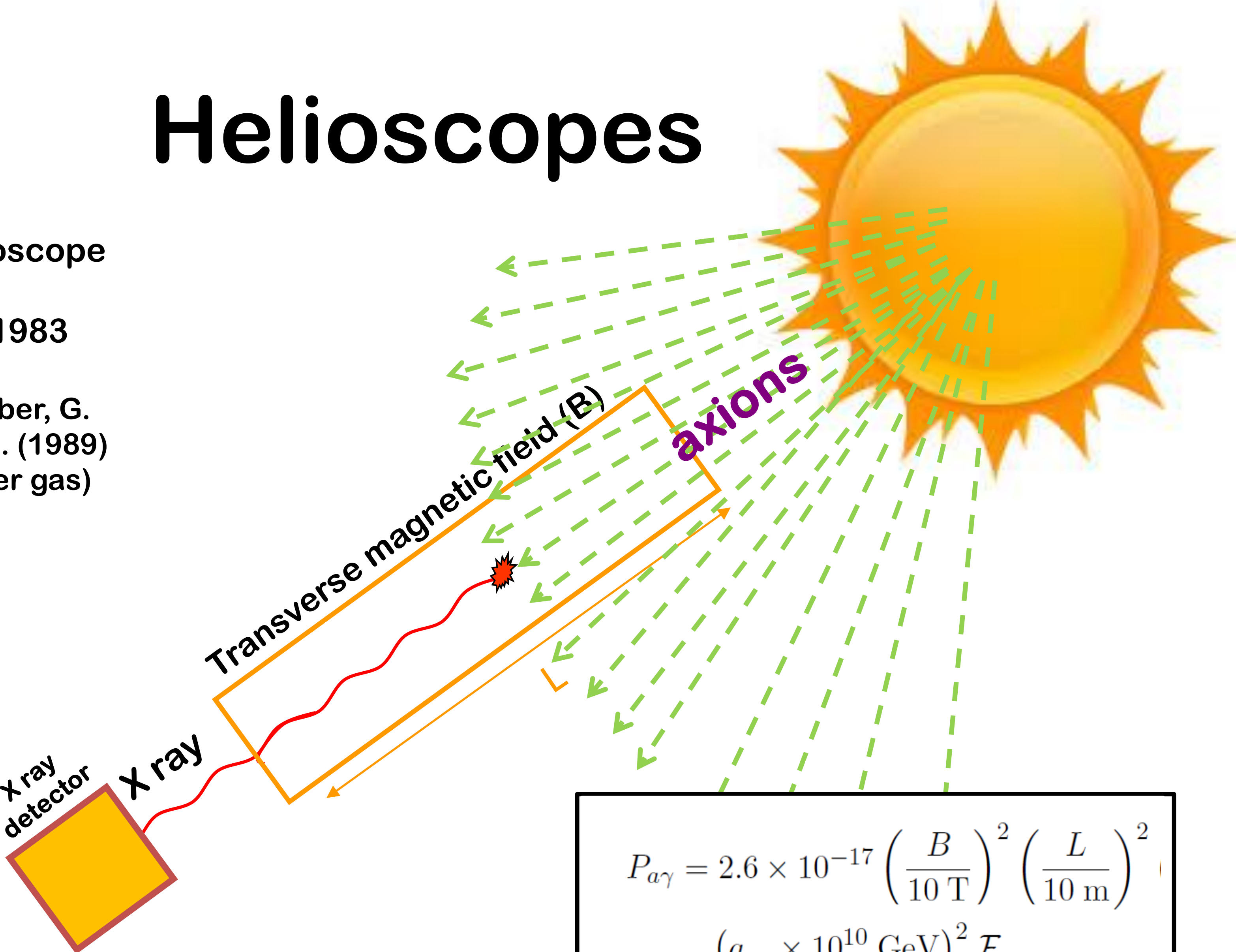
Non-hadronic “ABC” Solar axion flux at Earth
JCAP 1312 008

*** if the axion couples with the electron (g_{ae})**
(non hadronic axion)

Helioscopes

Axion helioscope concept
P. Sikivie, 1983

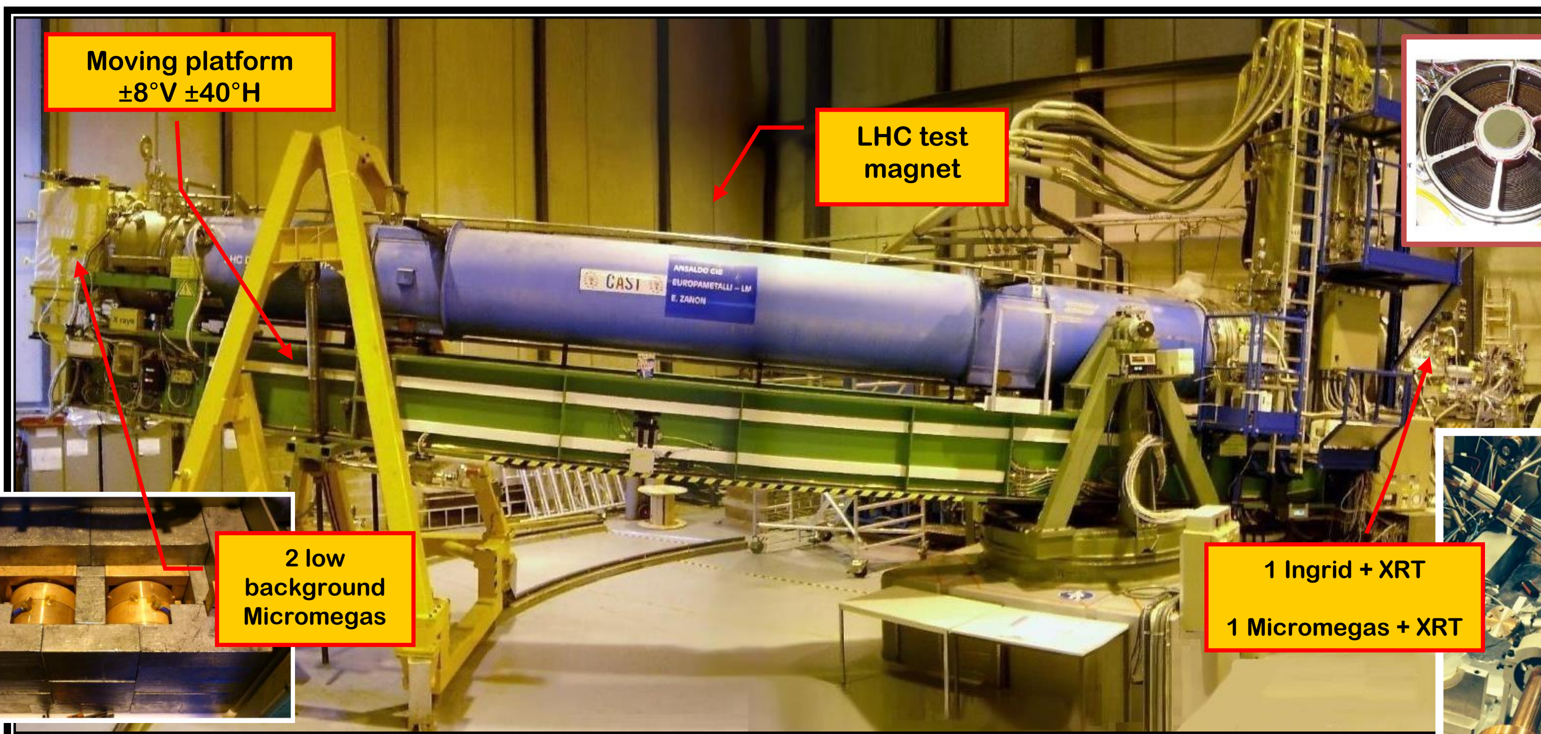
+ K. van Bibber, G. Raffelt, et al. (1989) (use of buffer gas)

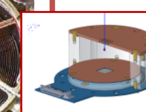


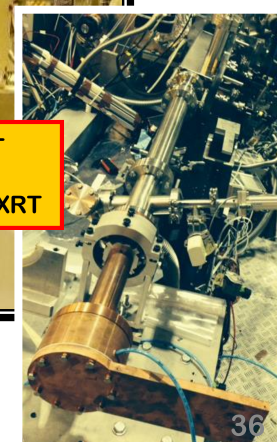
$$P_{a\gamma} = 2.6 \times 10^{-17} \left(\frac{B}{10\ \mathrm{T}}\right)^2 \left(\frac{L}{10\ \mathrm{m}}\right)^2 \left(g_{a\gamma} \times 10^{10}\ \mathrm{GeV}\right)^2 \mathcal{F}$$

CAST experiment @ CERN

- Decommissioned LHC test magnet (L=10m, B=9 T)
- Moving platform ±8°V ±40°H (to allow up to 50 days / year of alignment)
- 4 magnet bores to look for X rays
- 2 X ray telescopes to increase signal/noise ratio.

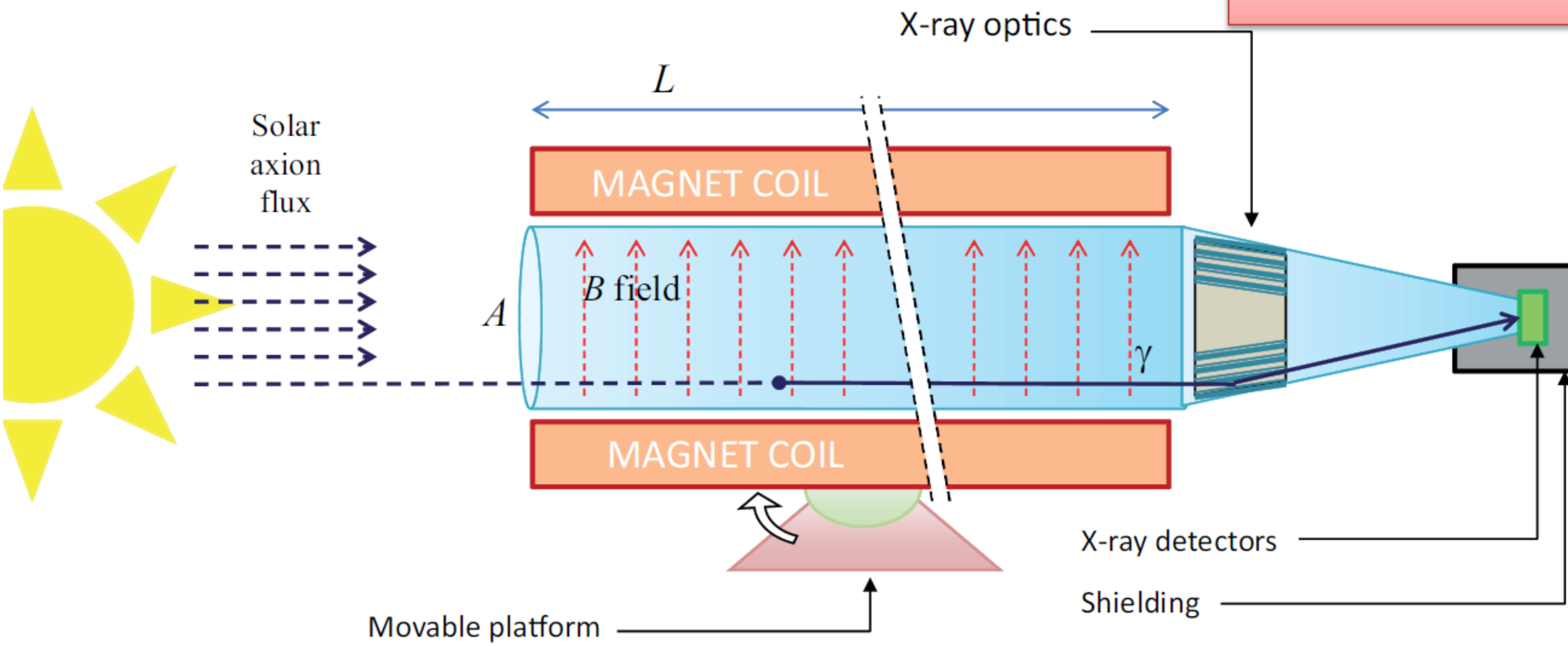






IAXO – Concept

Enhanced axion helioscope:
JCAP 1106:013,2011

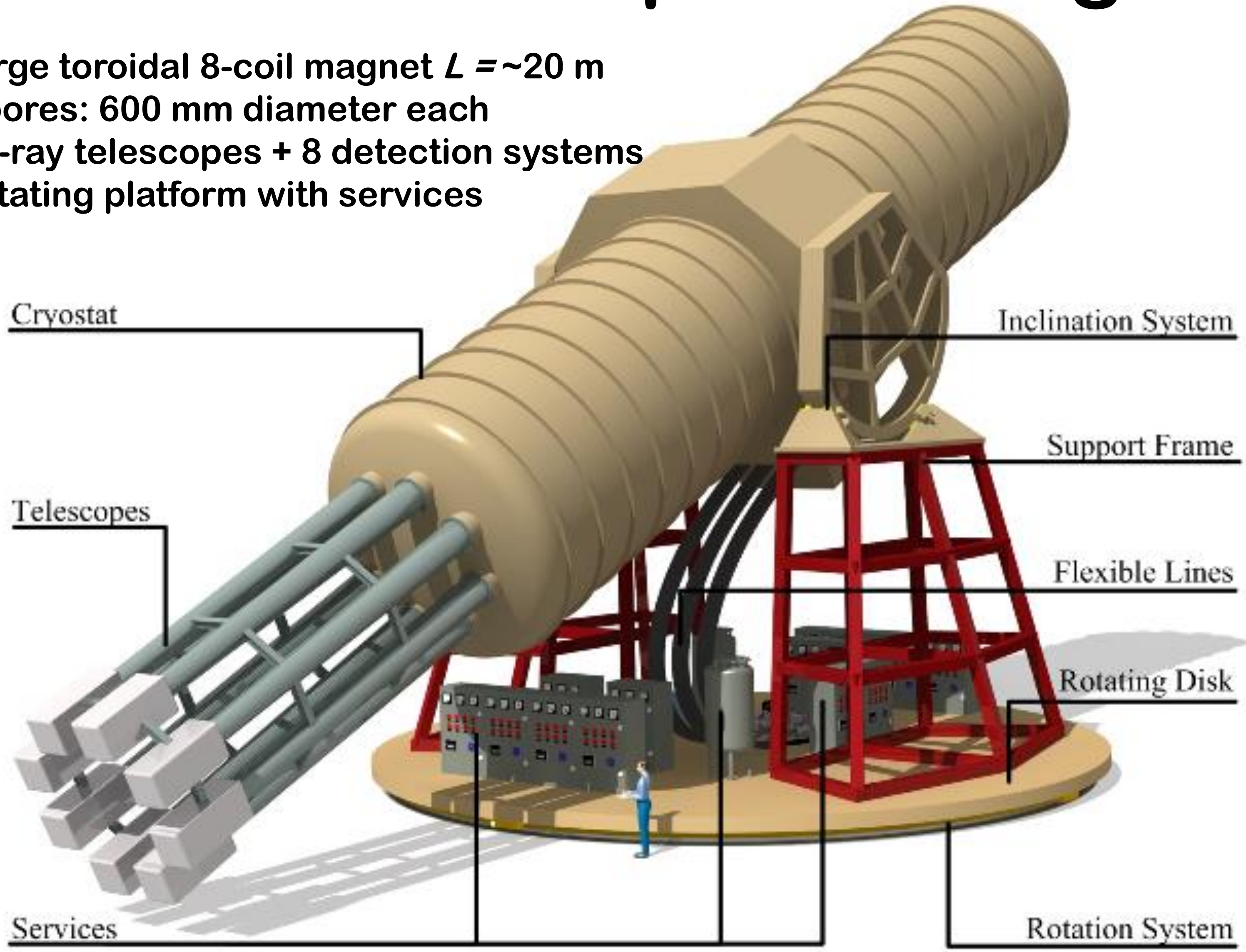


$$g_{a\gamma}^4 \propto \underbrace{b^{1/2}\epsilon^{-1}}_{\text{detectors}} \times \underbrace{a^{1/2}\epsilon_o^{-1}}_{\text{optics}} \times \underbrace{(BL)^{-2}A^{-1}}_{\text{magnet}} \times \underbrace{t^{-1/2}}_{\text{exposure}}$$

4+ orders of magnitude better SNR that CAST (JCAP 1106:013)

IAXO – Conceptual Design

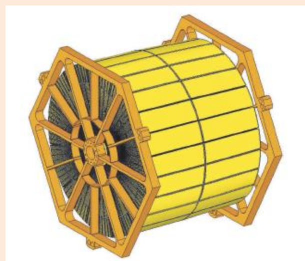
- Large toroidal 8-coil magnet $L = \sim 20$ m
- 8 bores: 600 mm diameter each
- 8 x-ray telescopes + 8 detection systems
- Rotating platform with services



IAXO technologies – Baseline

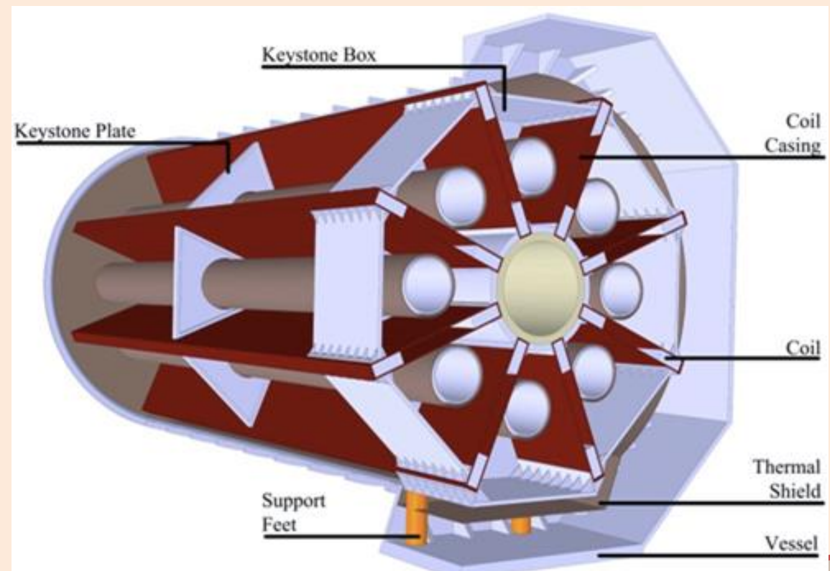
IAXO telescopes

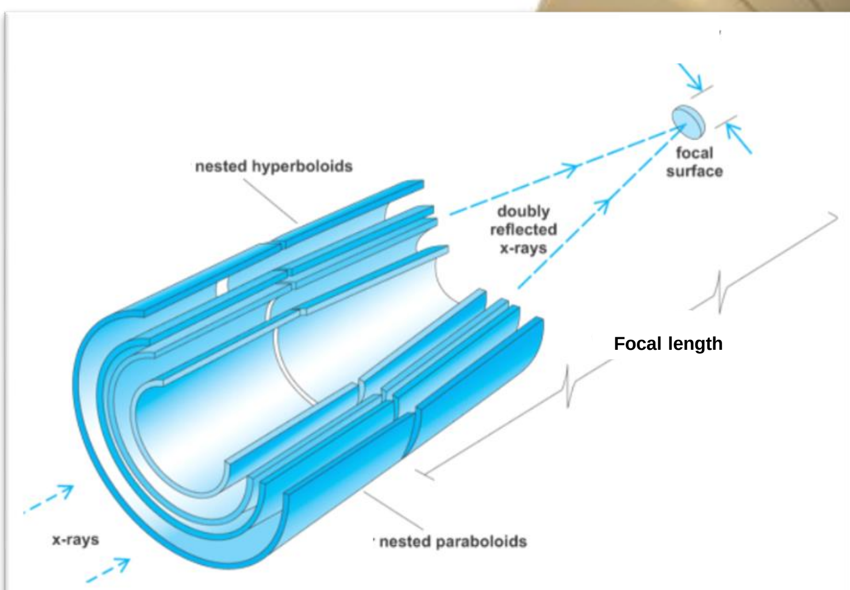
- Slumped glass technology with multilayers
- Cost-effective to cover large areas
- Based on NuSTAR developments
- Focal length ~5 m
- 60-70% efficiency
- LLNL+UC+DTU
  + MIT + INAF



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





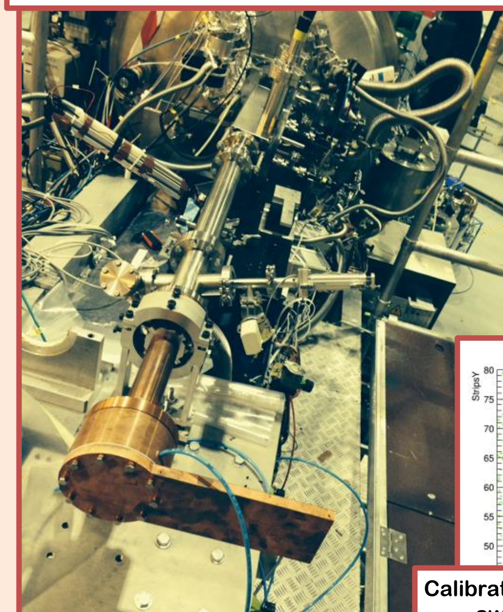
Baseline developed at:
IAXO Letter of Intent: CERN-SPSC-2013-022
IAXO Conceptual Design: JINST 9 (2014) T05002 (arXiv:1401.3233)

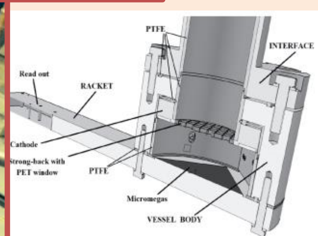
IAXO technologies – Baseline

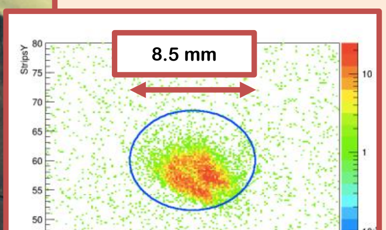
IAXO detectors

- 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)





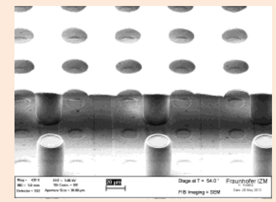


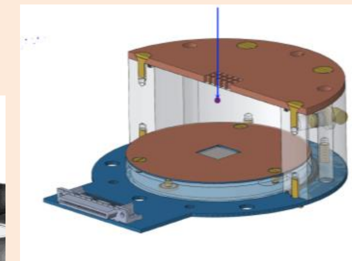
Calibration photons (source 14 m away) focused onto the Micromegas

IAXO detectors

Ingrid detectors

- Better threshold
- U. Bonn

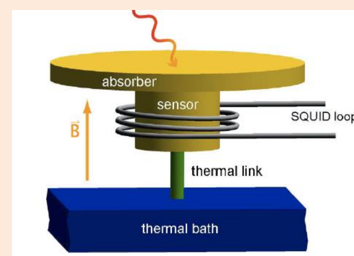




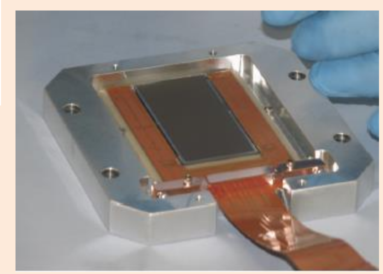
MMC (Magnetic Metallic Calorimeters)
TES (Transition Edge Sensors)

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

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



Low noise **CCDs**

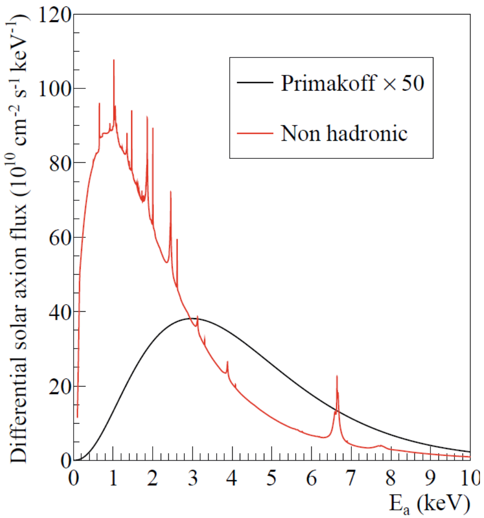


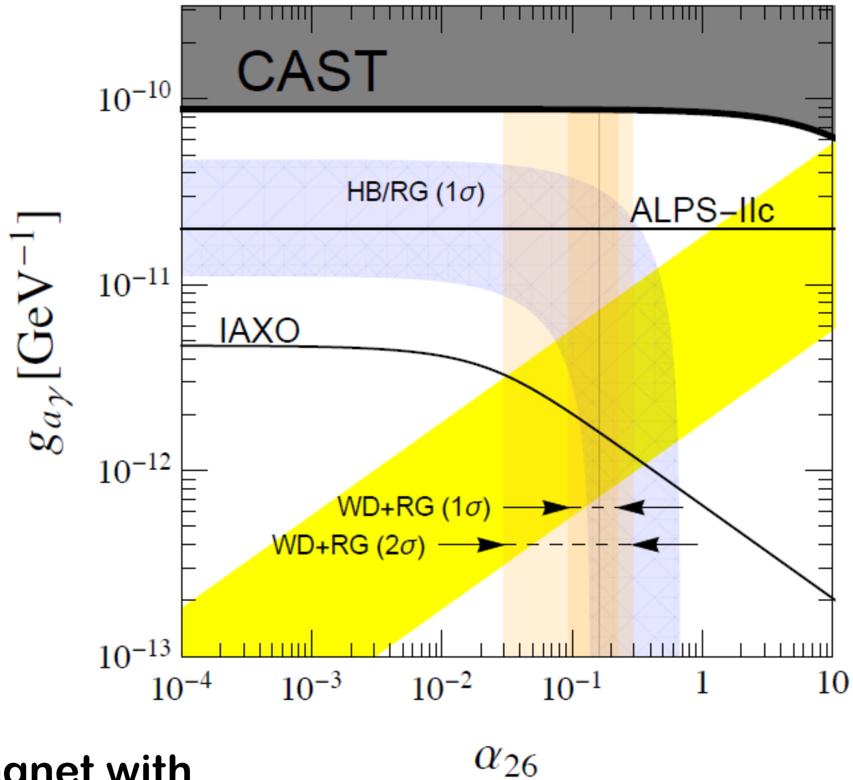
Services

Rotation System

Axion-electron coupling

ABC-produced solar axions





Sensitive to g_{ae} values down to ~10^{-13}

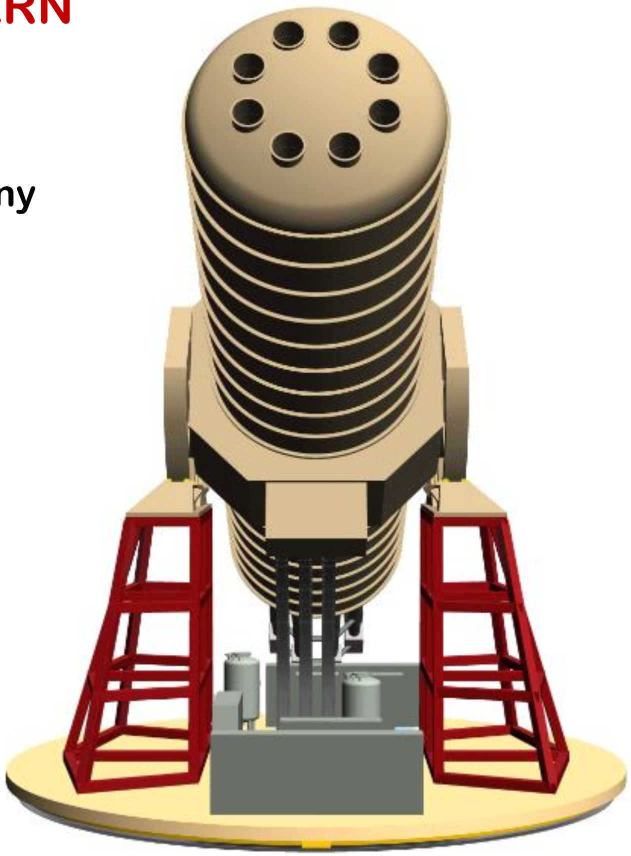
And more…

- Dark Matter Axions (→ use of IAXO magnet with cavities / RF antennas)
- ALPs from Dark Radiation
- ALPs from nearby Supernova (connection with SNEWS) → MeV photon detector at the other end
- …

Conclusions

- **IAXO:** best use of technologies (magnet, optics, detectors) and past trajectory of CAST at CERN
- **IAXO will probe deep into unexplored** axion+ALP parameter space:
  - **QCD axions** at the few meV scale → not at reach of any other technique
  - ALPs at the $g_{a\gamma\gamma}$ ~10^{-12} GeV^{-1} scale
  - ALPs at the g_{ae} ~10^{-13} scale
- IAXO as a generic "axion/ALP facility"

- First steps towards TDR after the positive recommendation from CERN SPSC.
- Large community now endorsing the project.
- Longer-term strategy towards construction under discussion. Site: CERN but also DESY or LNF
- Looking forward to Study Group process



Why to search for axions?

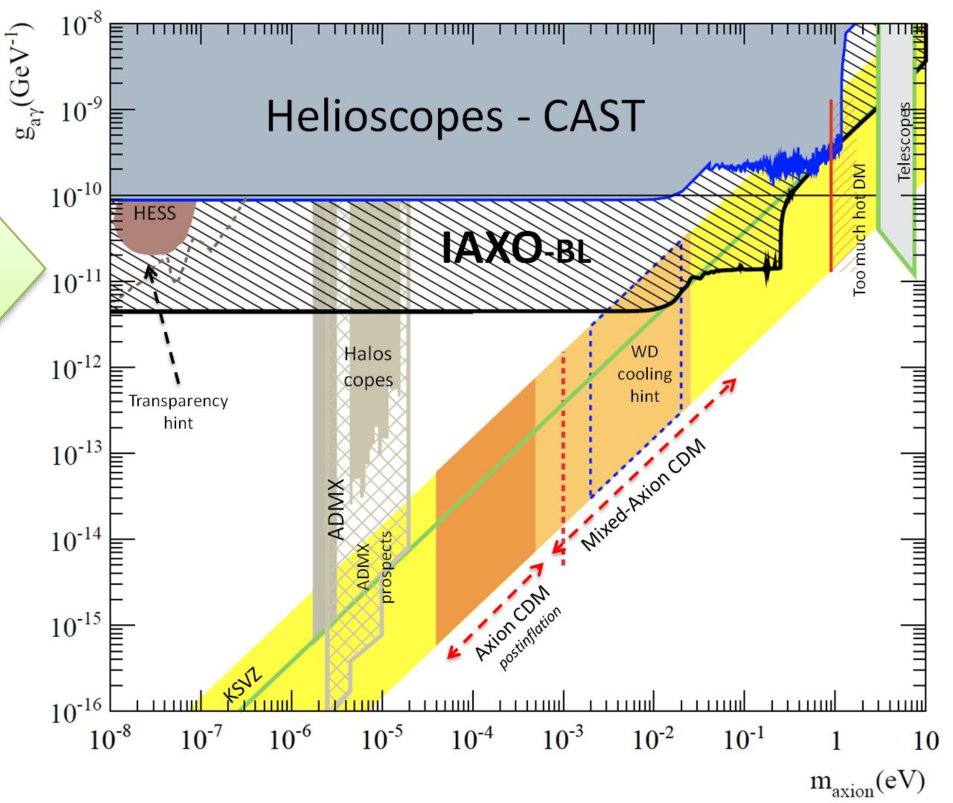
- Most compelling solution to the **Strong CP problem** of the SM

- 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
  - Anomalous cooling of different types of star

- Relevant axion/ALP parameter space at **reach of current and near-future experiments**
- Still too little experimental effort devoted to axions when compared to WIMPs

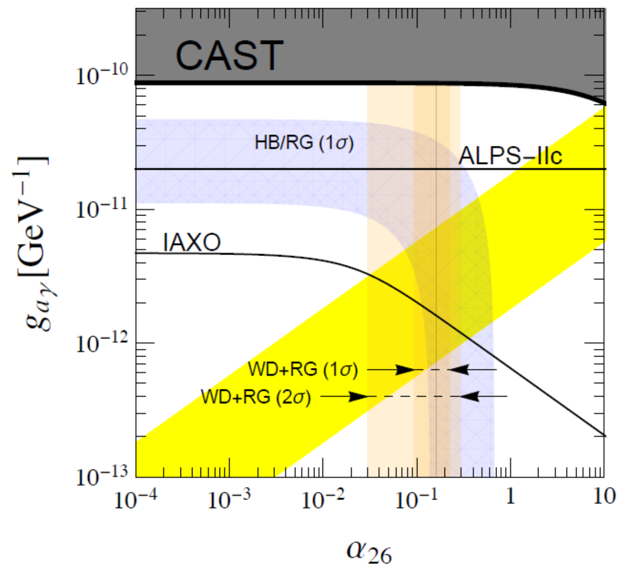
An ALP with $g_{a\gamma} \sim 10^{-11-12}$ GeV^{-1}

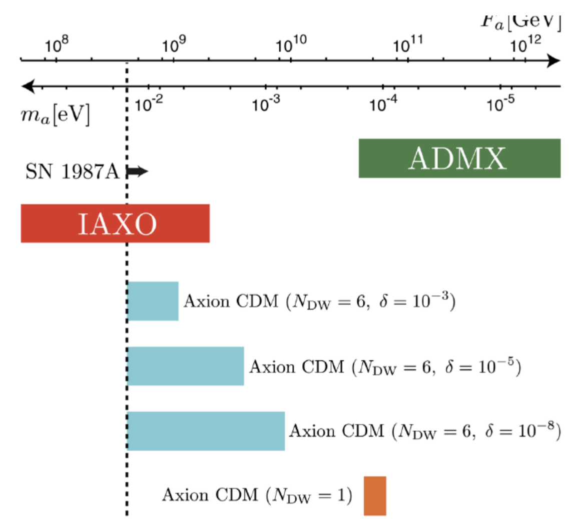
- **Well beyond current upper bounds on the $g_{a\gamma}$ coupling** (CAST & HB stars ~ 10^{-10} GeV^{-1})
- **String theory ALPs**
- **Invoked to explain the anomanlous transparency of the Universe to UHE gammas**
- **Could explain some anomalous stellar cooling observations**



The multi-meV axion

- **Is compatible with all current axion bounds.**
- **Is invoked in several anomalous stellar cooling scenarios**
  - Gianotti et al. JCAP1605 (2016) 057 [arXiv:1512.08108]
- **Can be the cold DM in some models**
  - with NDW>1 and bias term to break the discrete symmetry (Kawasaki et al. PRD91 (2015), Ringwald et al. arXiv:1512.06436)
  - or it can be a subdominant DM component
- **Very hard to detect (→ IAXO!)**
- **SN axion background**
  - Raffelt et al. PRD84 (11)





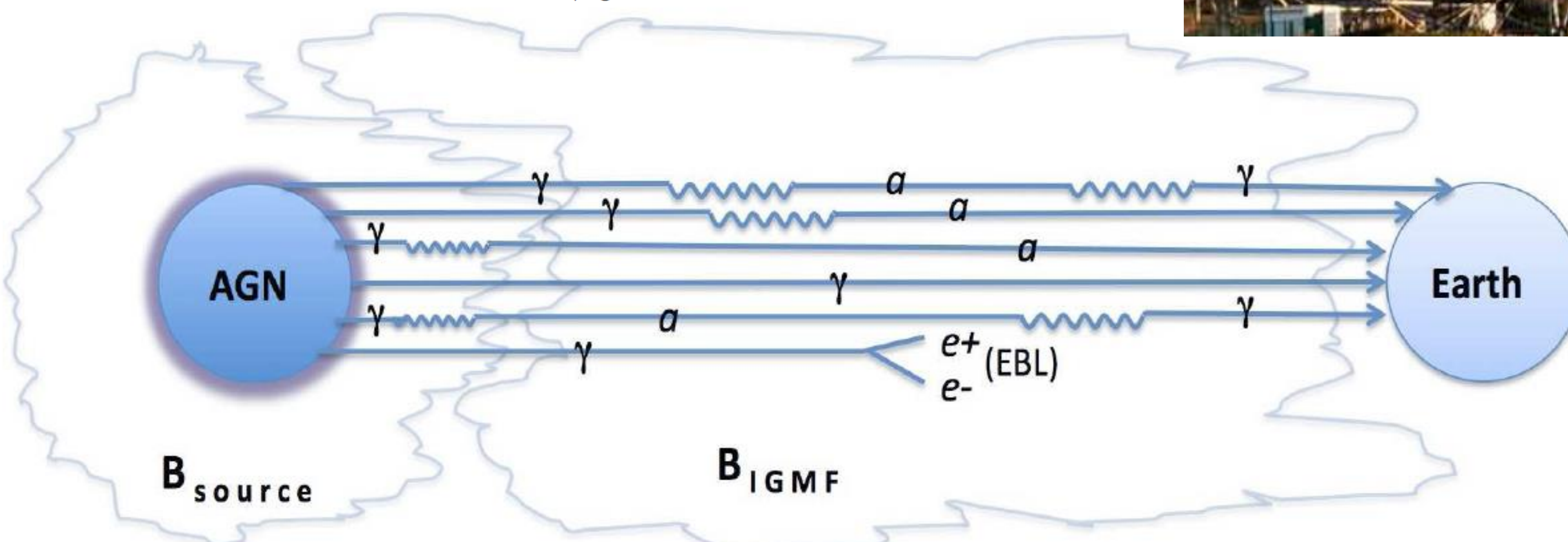
Astrophysical hints for axions

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

ALP:

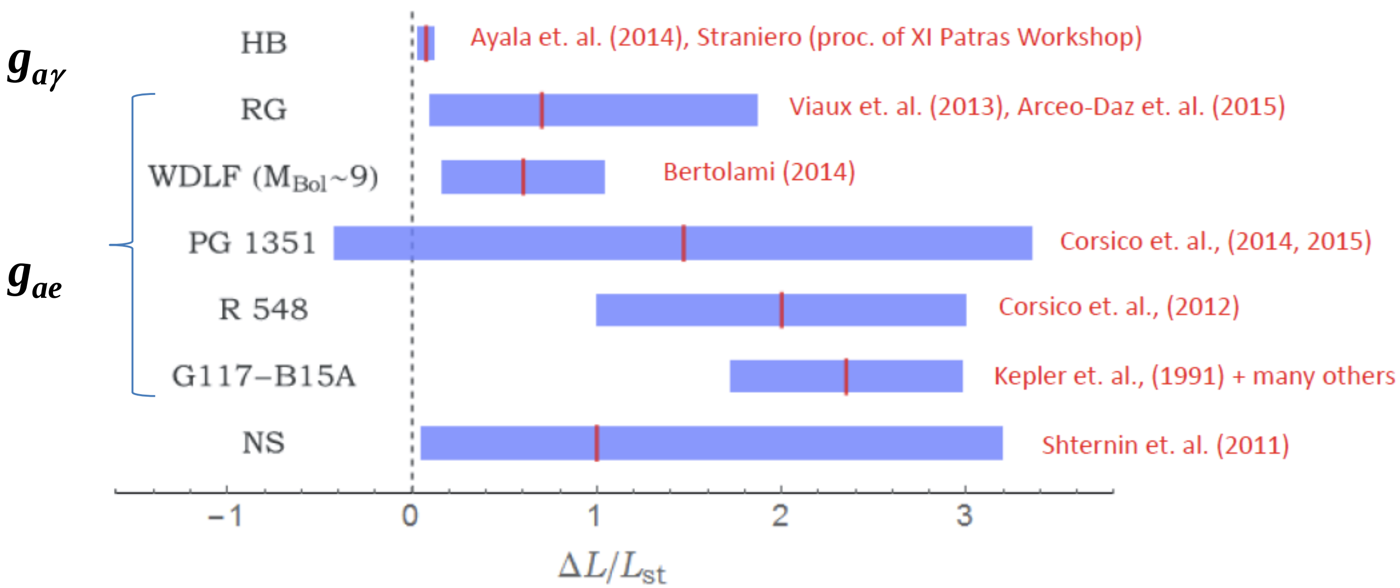
$$g_{a\gamma} \sim 10^{-12}\text{–}10^{-10}\ \mathrm{GeV}^{-1}$$

$$m_a \lesssim 10^{-(10-7)}\ \mathrm{eV}$$



Astrophysical hints for axions (II)

- **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**



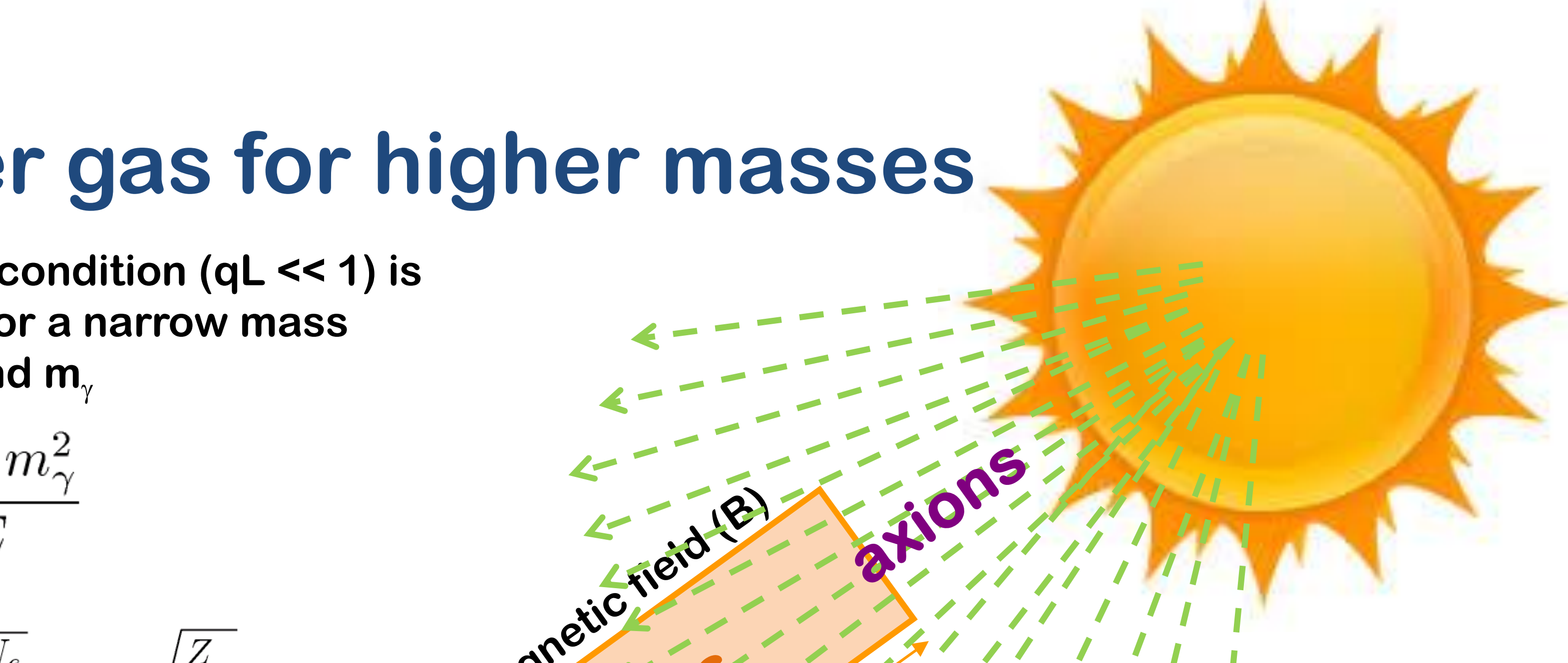
Buffer gas for higher masses

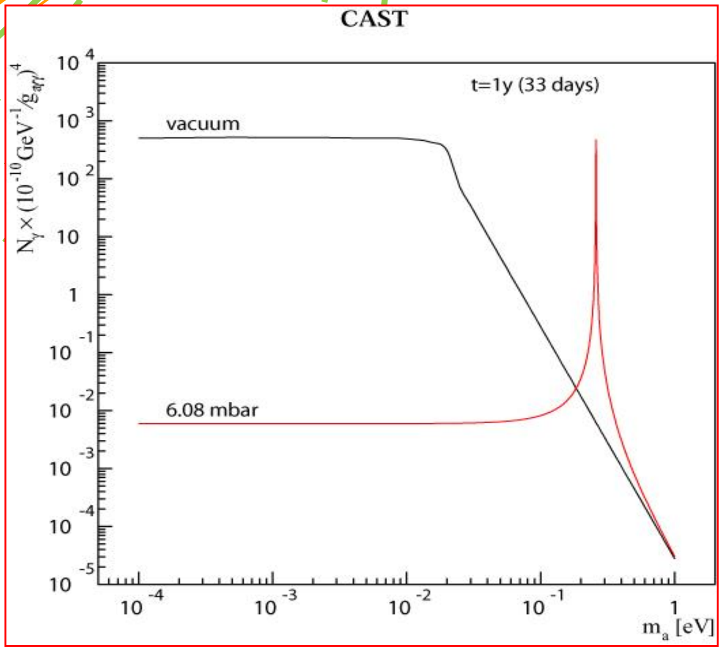
Coherence condition (qL << 1) is recovered for a narrow mass range around m_γ

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

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

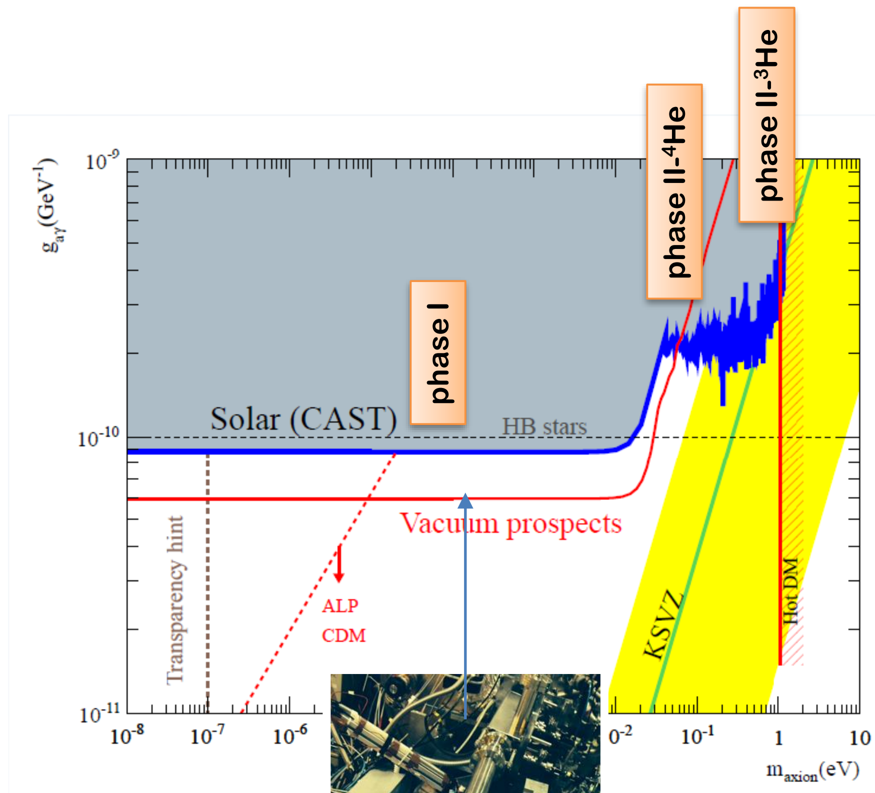
N_e: number of electrons/cm^3
r: gas density (g/cm^3)

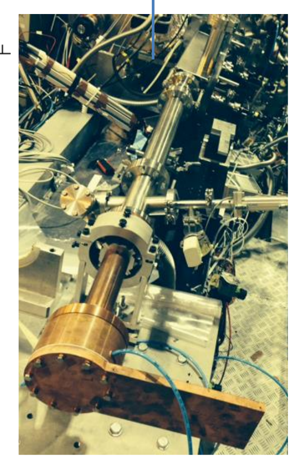




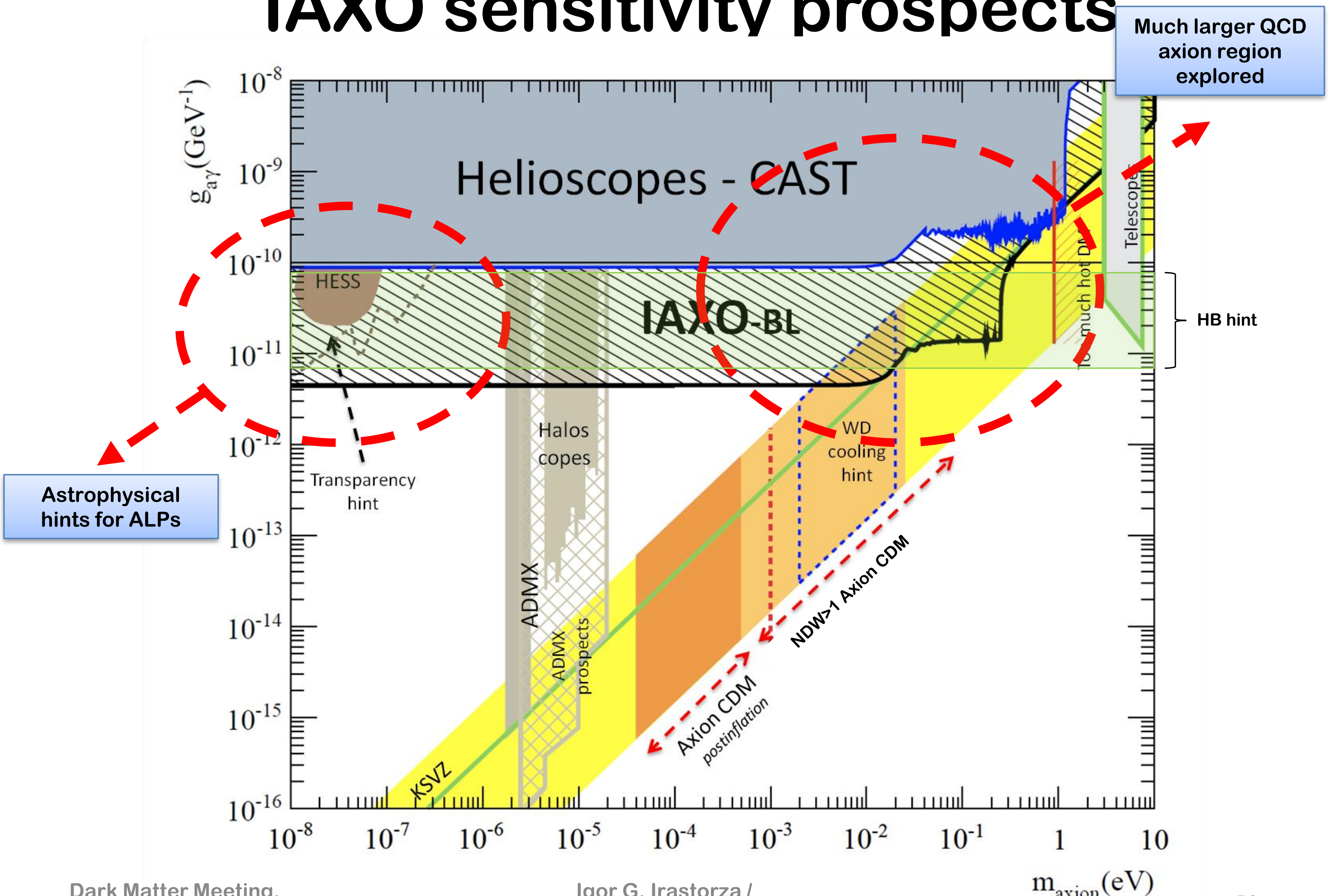
CAST results (solar axions)

2003 – 2004	CAST phase I • vacuum in the magnet bores
2006	CAST phase II - ^{4}He Run • axion masses explored up to 0.39 eV (160 P-steps)
2007	^{3}He Gas system implementation
2008 - 2011	CAST phase II - ^{3}He Run • axion masses explored up to 1.17 eV • bridging the dark matter limit
2012	•Revisit 4He Run with improved detecors
2013-2015	•Revisit vacuum phase with improved detectors **•Analisis ongoing.** **•New result soon available**





IAXO sensitivity prospects



CERN SPSC recommendations

SPSC Draft minutes [Jan 2014]

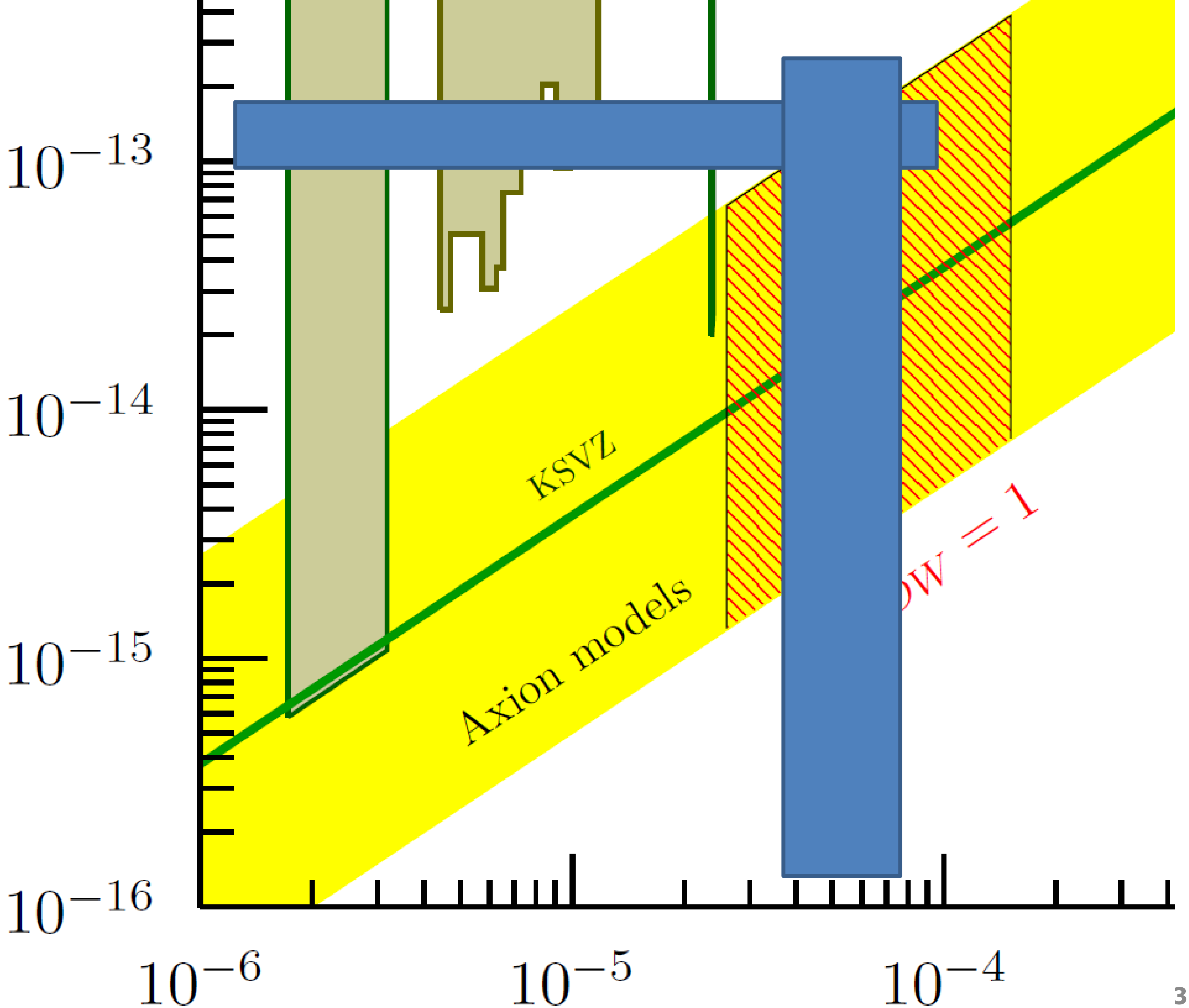
The Committee **recognises** the physics motivation of an International Axion Observatory as described in the Letter of Intent SPSC-I-242, and considers that the proposed setup makes appropriate use of state-of-the-art technologies i.e. magnets, x-ray optics and low-background detectors.
The Committee **encourages** the collaboration to take the next steps towards a **Technical Design Report**.
The Committee recommends that, in the process of preparing the TDR, the possibility to **extend the physics reach** with additional detectors compared to the baseline goal should be investigated. The collaboration should be further strengthened.
Considering the required funding, the SPSC **recommends** that the R&D for the TDR should be pursuit within an MOU involving all interested parties.

This was endorsed by the Research Board in March2014

Minutes of the 206th CERN Research Board held on March2014:
https://cds.cern.ch/record/1695812/files/M-207.pdf

Mid term plans (+4 years)
towards IAXO construction

- **Site:**
  - CERN is Plan A, but alternatives under consideration: it may affect funding strategies. Some preliminary interest from a number of institutions.
- **Magnet:**
  - Magnet construction → main resources challenge
  - Plan A: Form international consortium, coordinated by CERN (+CEA?) to collectively support the magnet construction, by means of inkind contributions to the effort.
  - Plan B: Large investment by host institution (IAXO being hosted outside CERN)
- **X-ray optics:**
  - Construction efforts distributed among groups pushing x-ray technologies for IAXO: US (LLNL, UC, MIT) + Europe (DTU, INAF-Milano)
- **Detectors:**
  - Efforts distributed among groups pushing each detector technology (actual decisions taken after TDR):
    - Micromegas: Zaragoza, CEA
    - Ingrid: Bonn
    - CCD: FNAL?, LPNHE?
    - MMCs/TES: Heidelberg, Orsay, CEA


10^{-13}
10^{-14}
10^{-15}
10^{-16}
KSVZ
Axion models
10^{-6}
10^{-5}
10^{-4}

IAXO costs

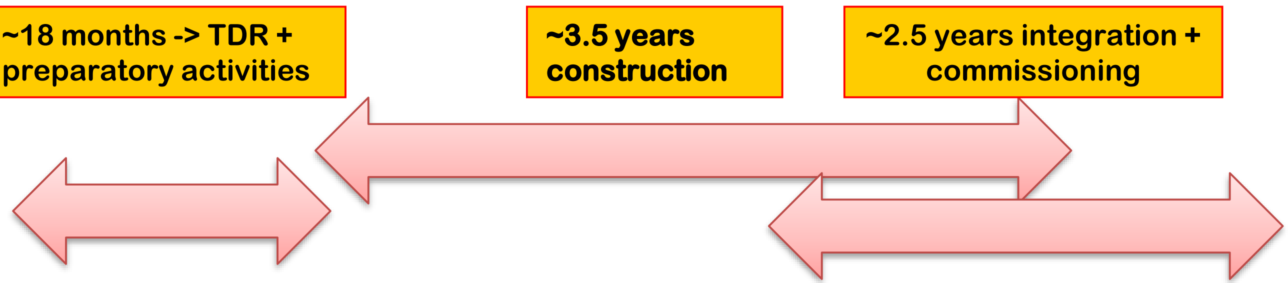
Item	Cost (MCHF)	Subtotals (MCHF)
Magnet		31.3
Eight coils based assembled toroid	28	
Magnet services	3.3	
Optics		16.0
Prototype Optic: Design, Fabrication, Calibration, Analysis	1.0	
IAXO telescopes (8 + 1 spare)	8.0	
Calibration	2.0	
Integration and alignment	5.0	
Detectors		5.8
Shielding & mechanics	2.1	
Readouts, DAQ electronics & computing	0.8	
Calibration systems	1.5	
Gas & vacuum	1.4	
Dome, base, services building and integration		3.7
Sum		**56.8**

Table 5: Estimated costs of the IAXO setup: magnet, optics and detectors. It does not include laboratory engineering, as well as maintenance & operation and physics exploitation of the experiment.

Comments/caveats:

- Costs are for construction, and do not include operations and science support
- Costs based on initial estimates that need to be confirmed at TDR
- Labor for engineering, maintenance & operations not included
- Estimates do not include contingencies

IAXO timeline



Years		1				2				3				4				5				6			
Months		3	6	9	12	15	18	21	24	27	30	33	36	39	42	45	48	51	54	57	60	63	66	69	72
Magnet																									
Design	T0	■	■																						
	T1-T8		■	■	■	■	■																		
Demo coil				■	■	■	■	■	■	■	■														
Production								■	■	■	■	■	■	■	■	■	■	■	■						
Integration														■	■	■	■	■	■	■	■				
Services														■	■	■	■	■	■	■	■				
Optics																									
Optic design study		■	■																						
Prototype construction				■	■																				
Calibration						■																			
Finalize design							■																		
Build assembly machines								■	■	■	■														
Procure mandrels & ovens								■	■	■	■														
Build coating facilities								■	■	■	■														
Slump glass												■	■	■	■	■	■	■	■	■	■				
Deposit coatings													■	■	■	■	■	■	■	■	■	■	■		
Assemble optics															■	■	■	■	■	■	■	■	■		
Calibrate optics																		■	■		■			■	
Installation																							■	■	■
Detectors																									
Prototype		■	■	■	■	■	■																		
Construction (incl. spares)								■	■	■	■	■	■	■	■	■	■	■	■						
Installation & commissioning																				■	■	■	■	■	■