Solar axion searches: status and prospects

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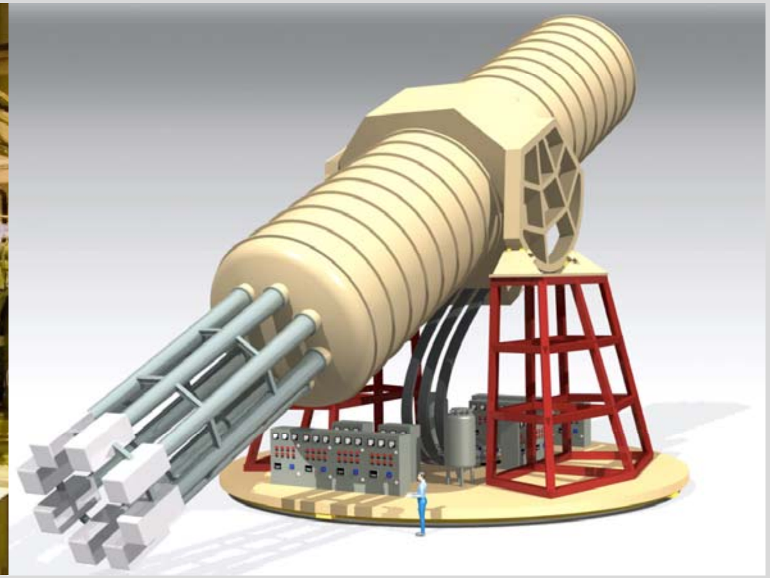
Universidad de Zaragoza

8th Symposium on Large TPCs for low energy rare event searches

6 December 2016



Axions: theory motivation

- Peccei-Quinn solution to the **strong CP problem** or **why QCD seems not to violate CP,** while one would expect to do so
- 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

This QCD term is **CP violating**.

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

Experimentally θ < 10^{-11} while O(1) would be expected

θ absorbed in the definition of a

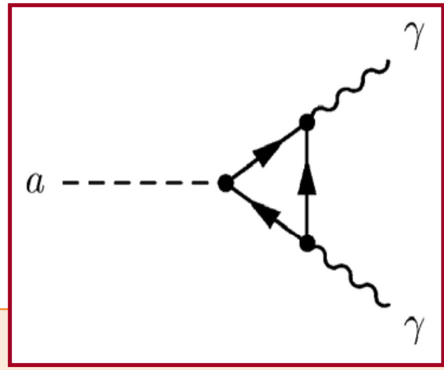
$$\frac{\alpha_s}{8\pi f_a} aG\tilde{G}$$

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

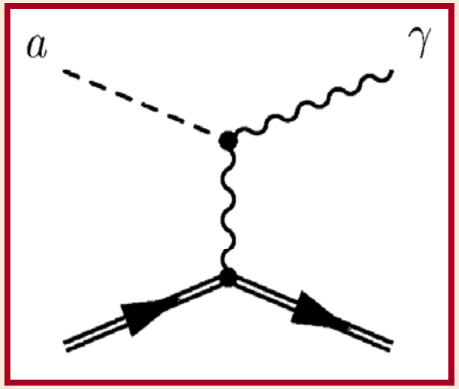
a → New field: the axion. Very light: $m_a \simeq 0.6 \text{ eV} \frac{10^7 \text{GeV}}{f_a}$

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**)

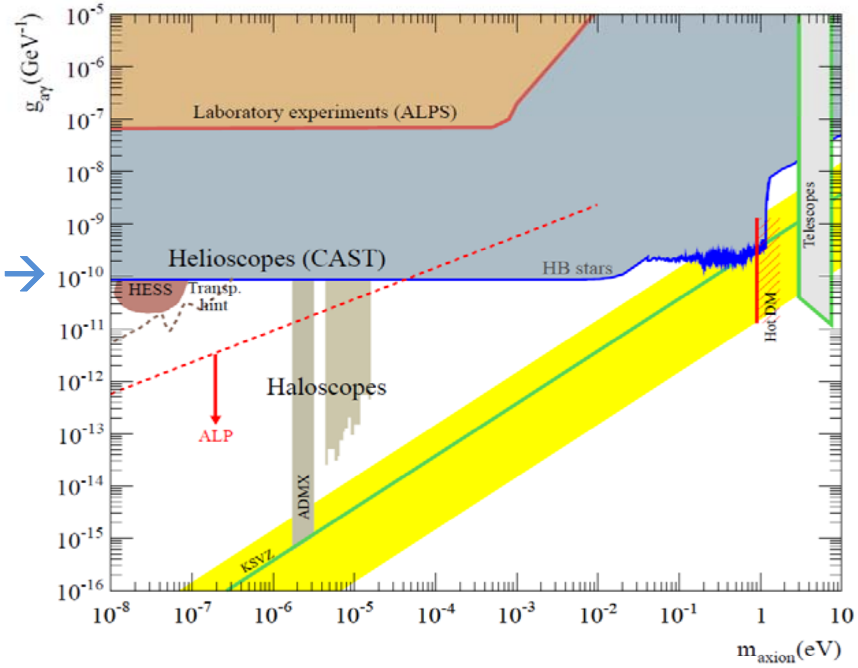
This is probably the most relevant of axion properties.

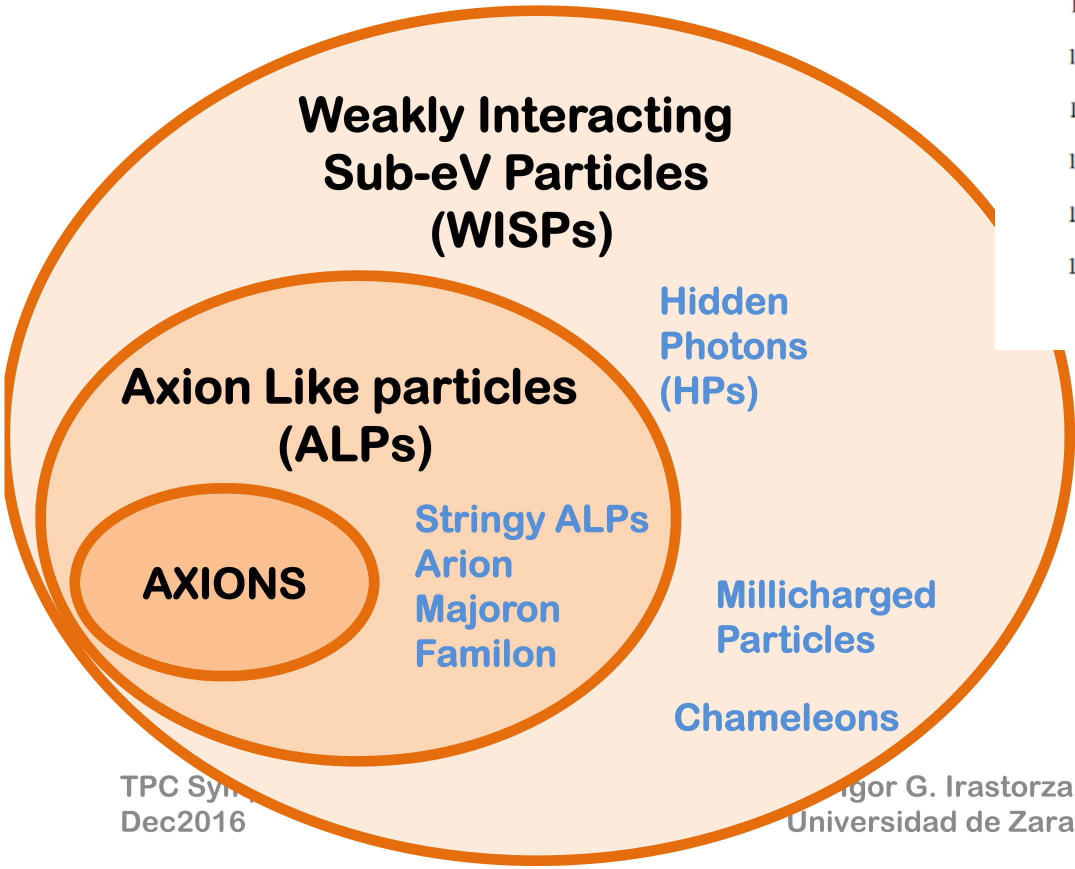
Most axion detection strategies are based on the axion-photon coupling

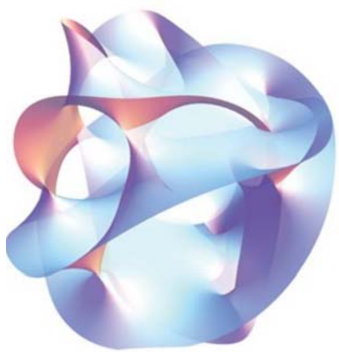
Beyond axions

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

Generic ALPs parameter space →

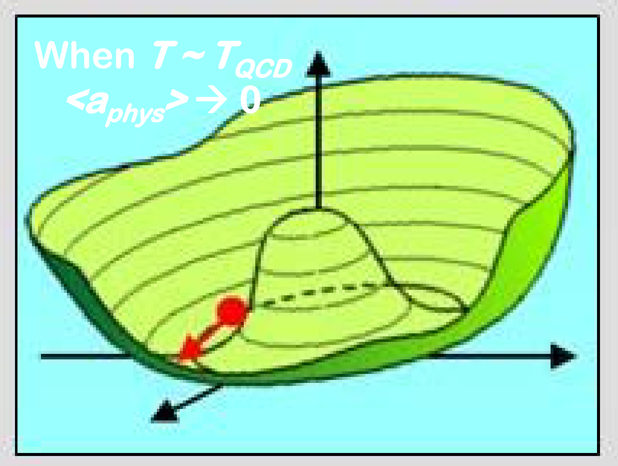






String theory predicts a plenitude of ALPs

Non thermal cosmological axions

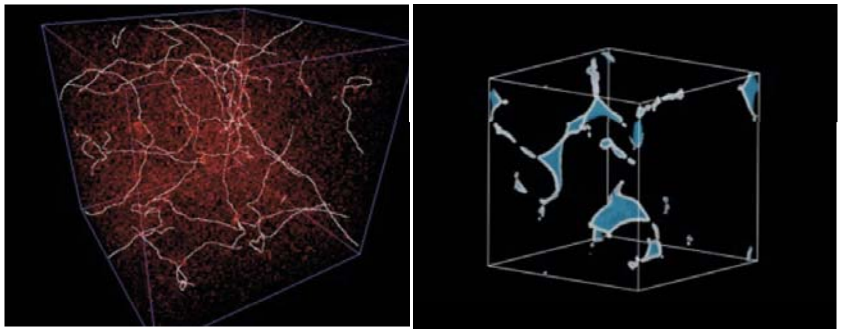


Axion realignment

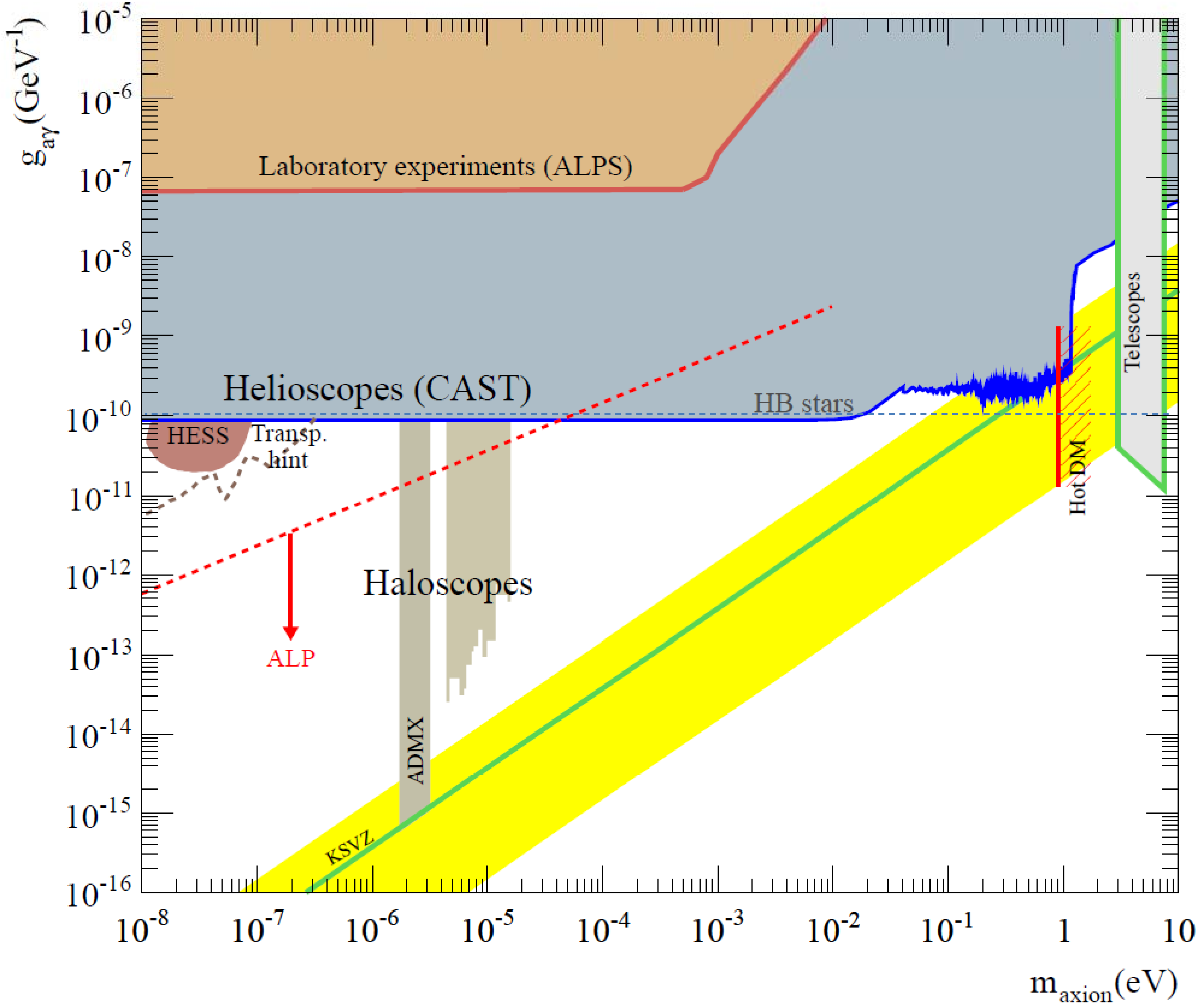
As the Universe cools down below T_{QCD}, space is filled with low energy axion field fluctuations.

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

But also… topological defects

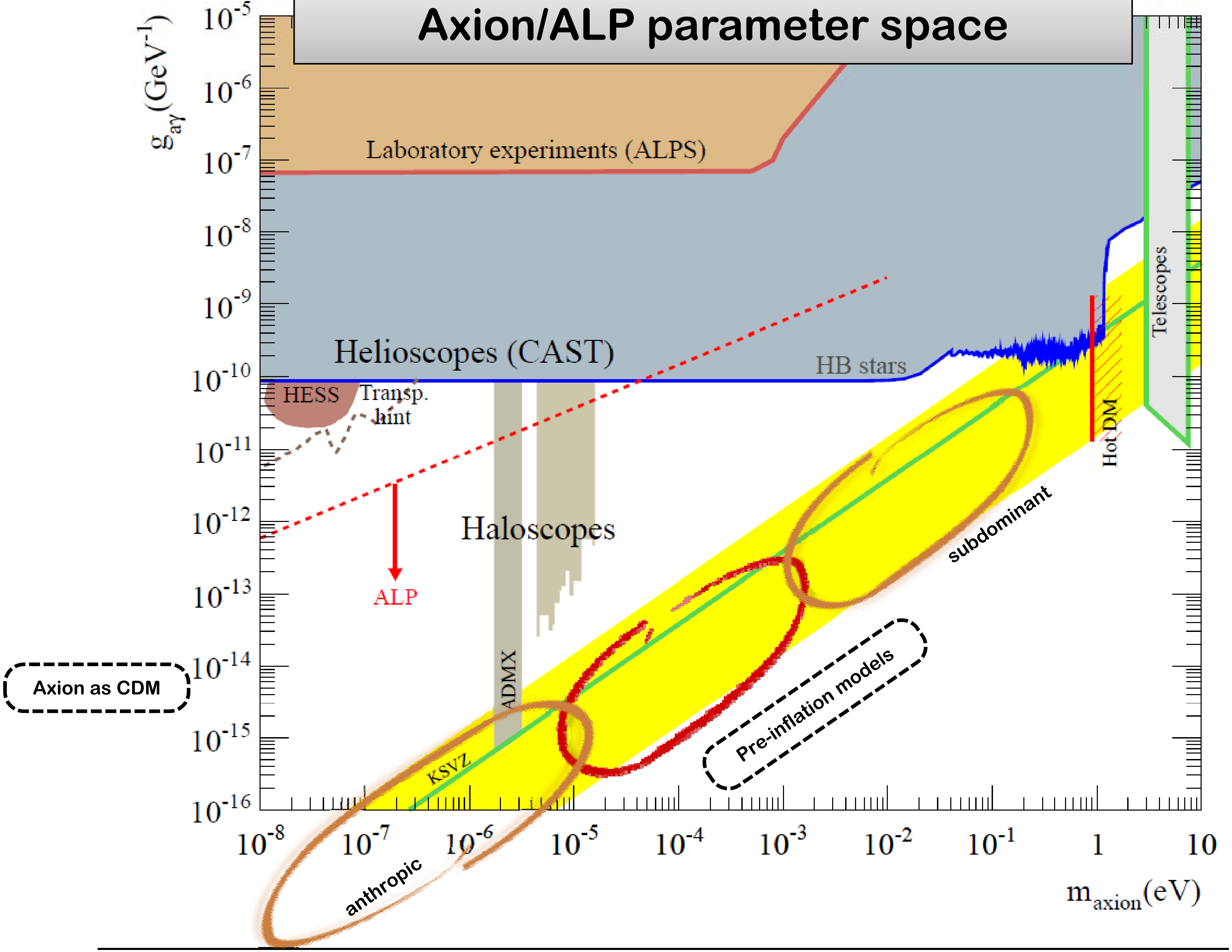


But inflation may "wipe out" topological defects… Did inflation happen before or after the creation of defects (PQ transition) ? *pre-inflation or post-inflation scenarios*

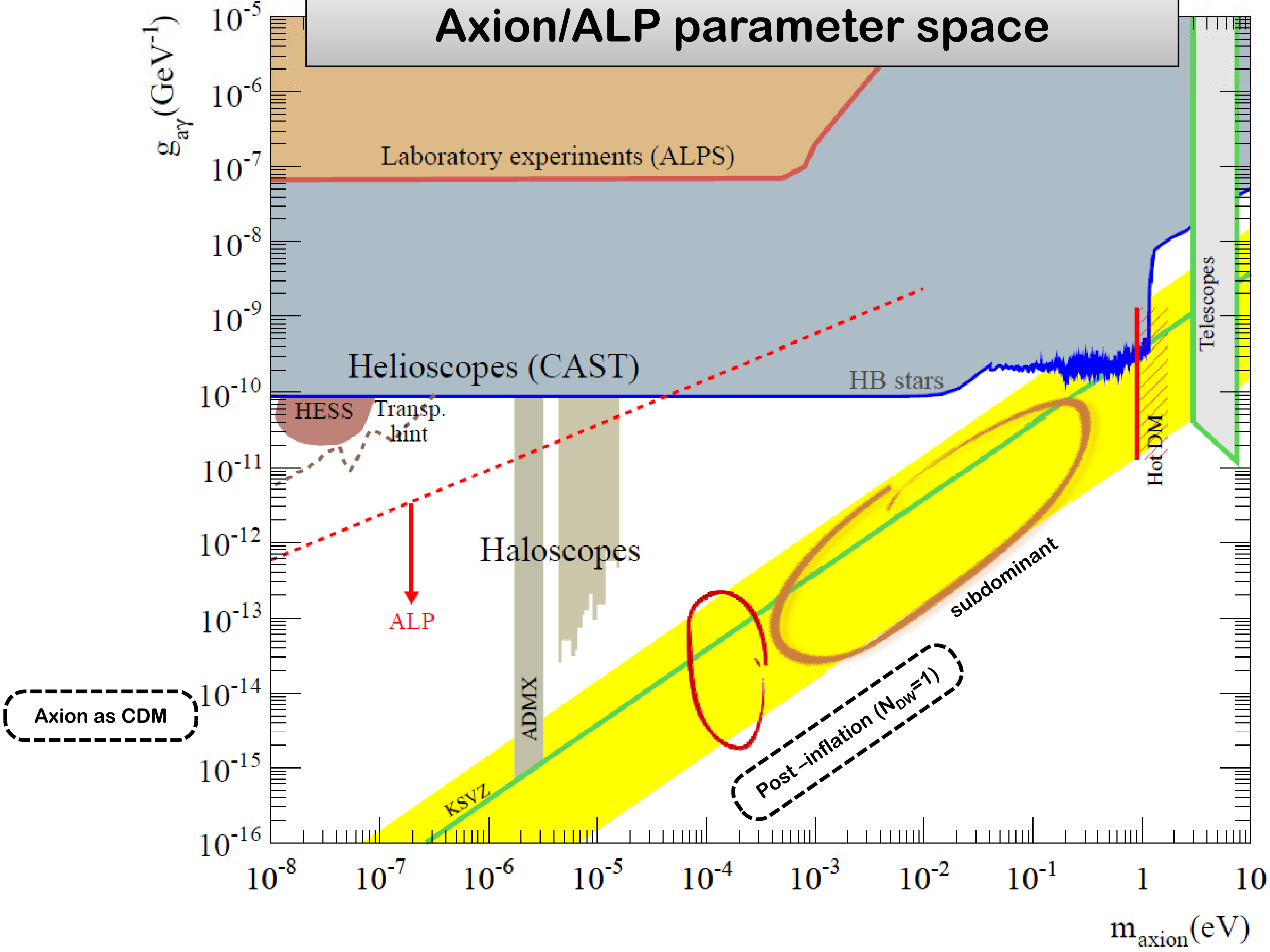


$g_{a\gamma}$ (GeV^{-1})
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
Laboratory experiments (ALPS)
Helioscopes (CAST)
HB stars
HESS
Transp. hint
ALP
Haloscopes
ADMX
KSVZ
Hot DM
Telescopes
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
m_{axion} (eV)

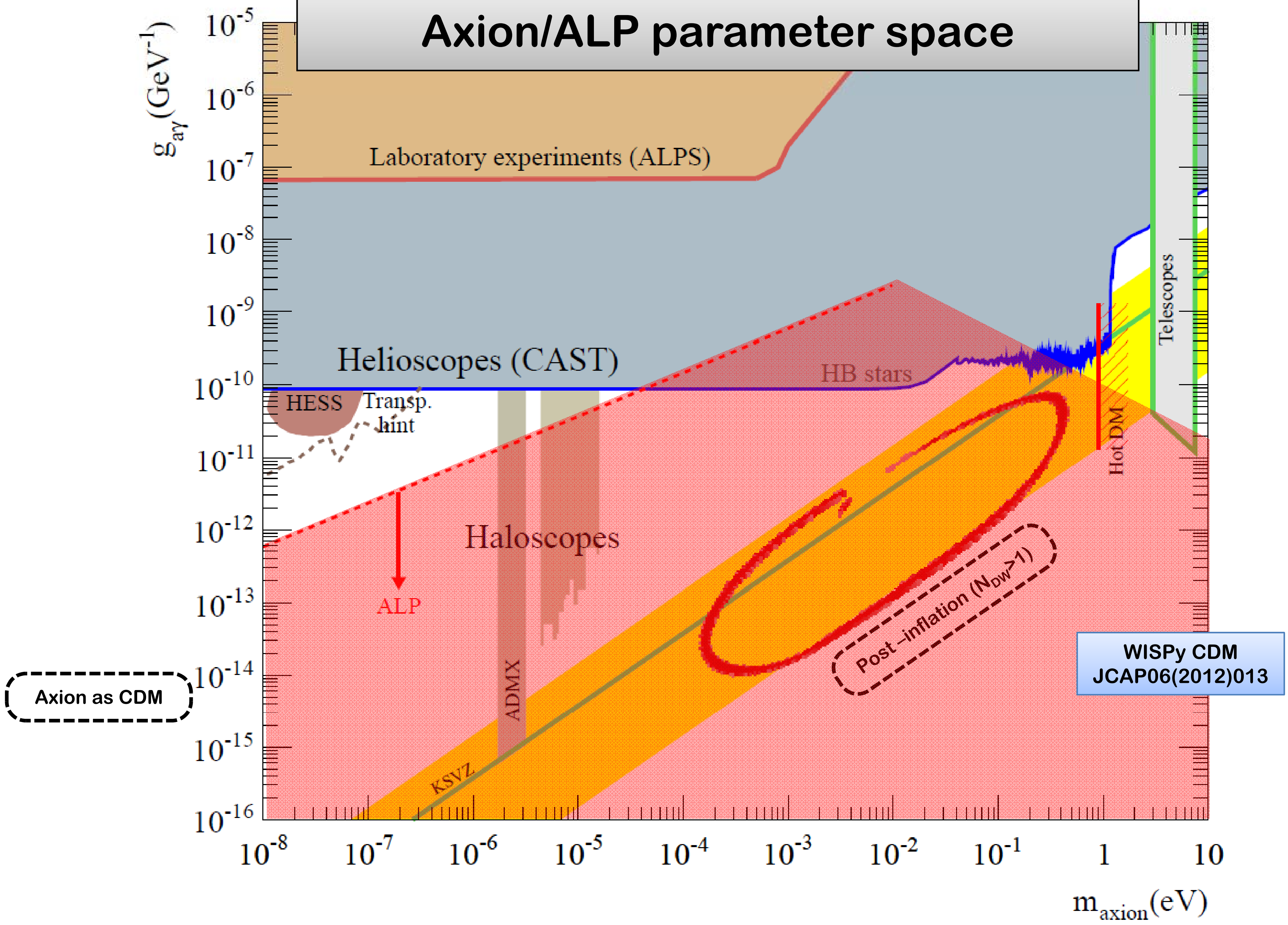
Axion/ALP parameter space



Axion/ALP parameter space



Axion/ALP parameter space



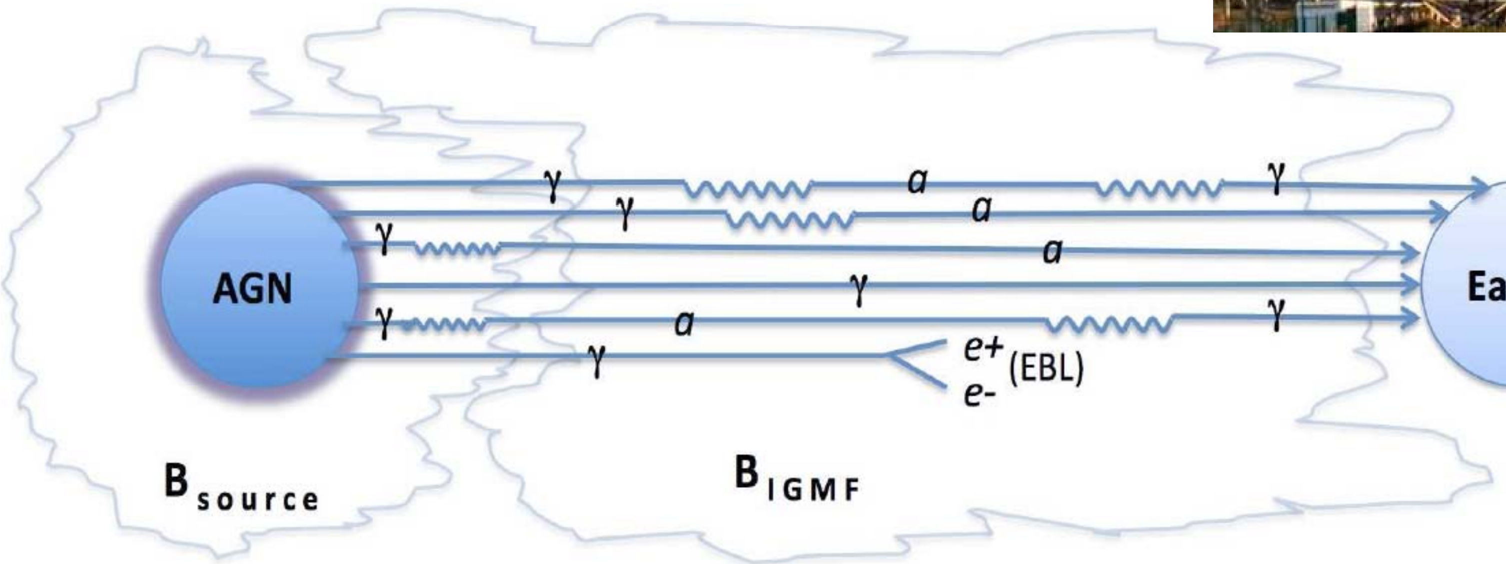
Astrophysical hints for axions

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

ALP:

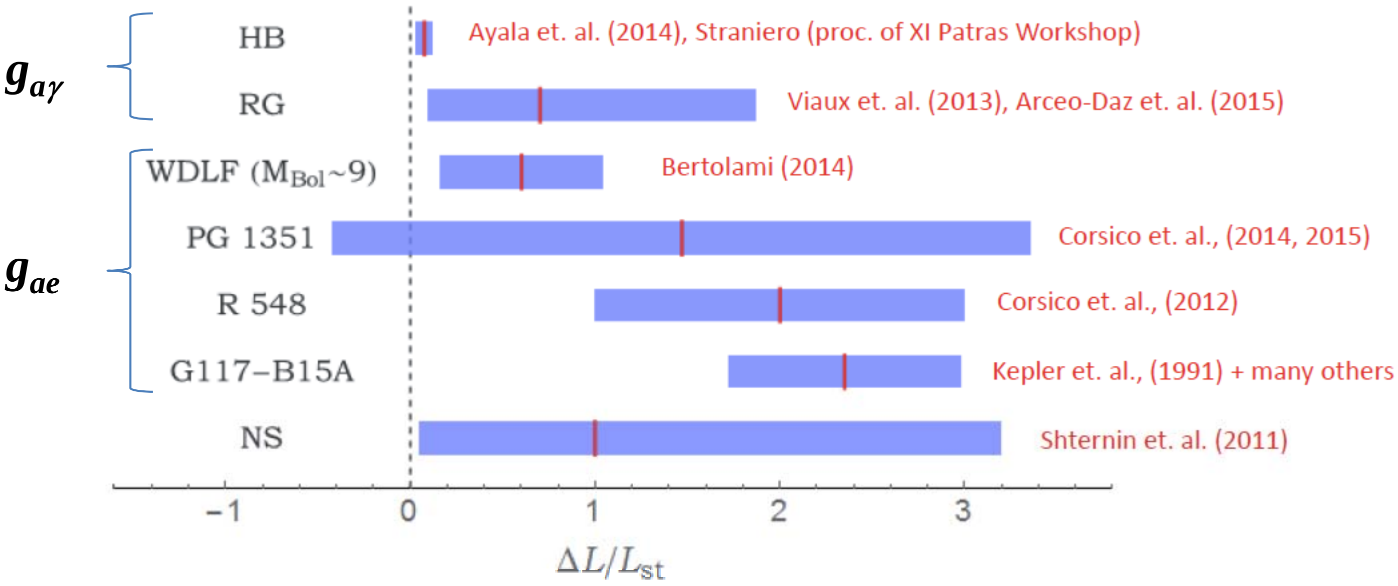
$$g_{a\gamma} \sim 10^{-12}\text{–}10^{-10}\ \text{GeV}^{-1}$$

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

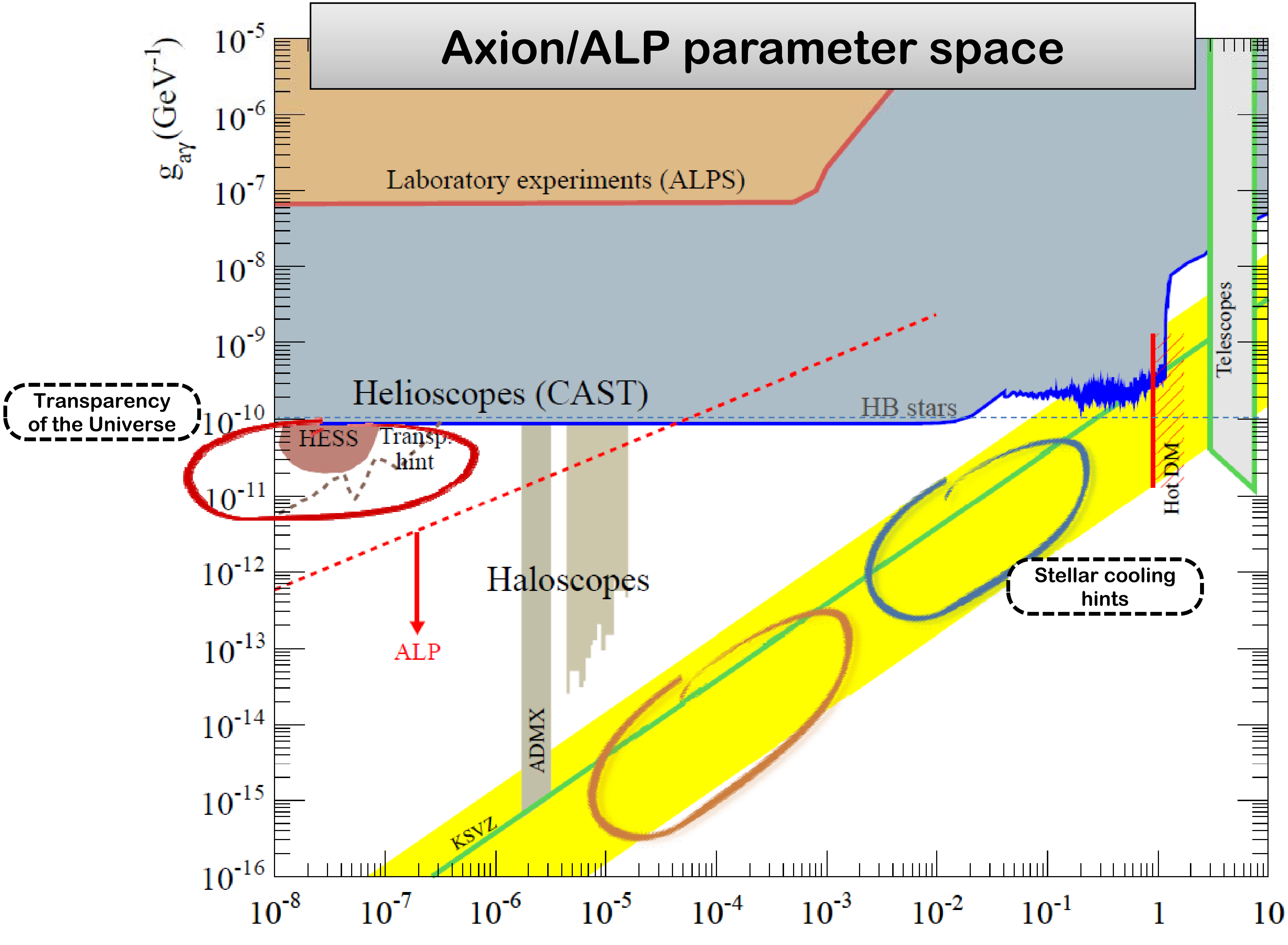


Astrophysical hints for axions (II)

- 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



Axion/ALP parameter space



Axion motivation in a nutshell

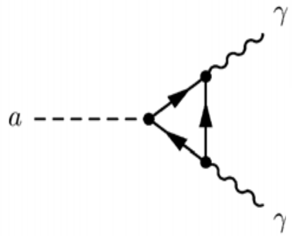
- **Most compelling solution to the Strong CP problem of the SM**

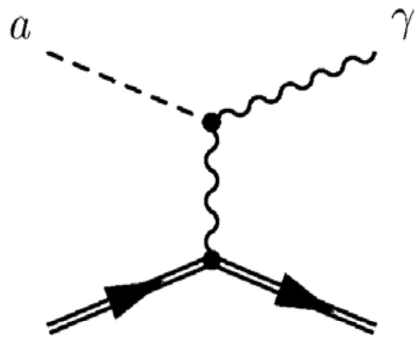
- **Axion-like particles (ALPs) predicted by many extensions of the SM (e.g. string theory)**
- **Axions, like WIMPs, may solve the DM problem *for free*. (i.e. not *ad hoc* solution to DM)**
- **Astrophysical hints for axion/ALPs?**
  - **Transparency of the Universe to UHE gammas**
  - **Stellar anomalous 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**
- **Still too little experimental efforts devoted to axions when compared e.g. to WIMPs…**

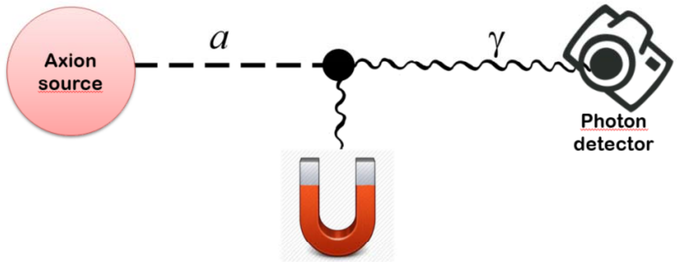
Detection of axions

- Axion – photon coupling *generically* present in every axion model.





- **Axion-photon conversion** in the presence of an electromagnetic field (**Primakoff effect**)
- Most detection techniques based on the axion-to-photon conversion inside **magnets**



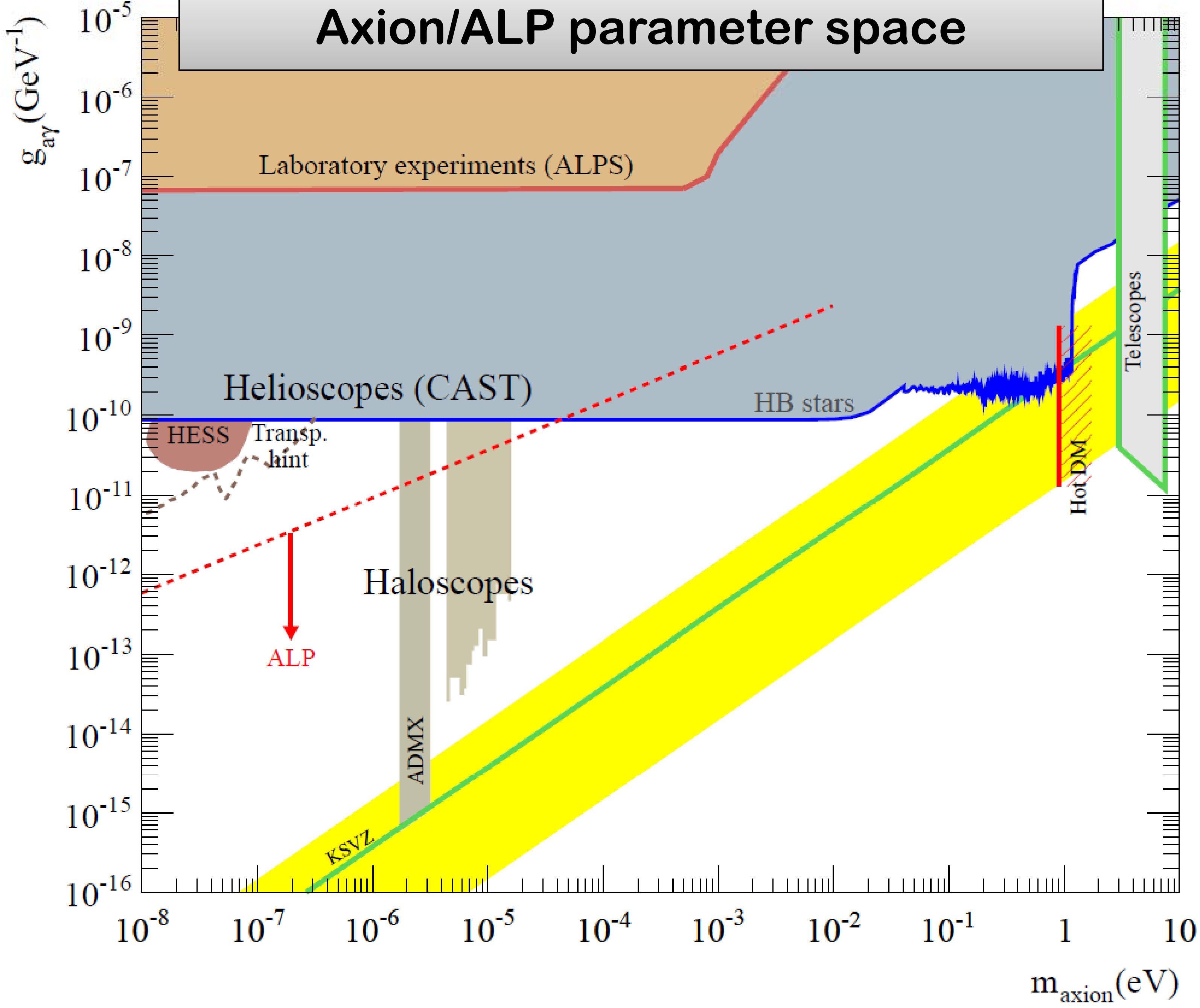
→ Other couplings possible, but less generic (model dependent)

  → axion-electron coupling
  → axion-nucleon coupling

Detection of axions

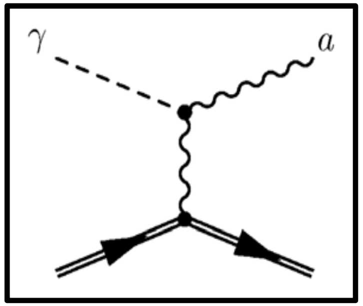
Source	Experiments	Model & Cosmology dependency	Technology
Relic axions 	ADMX, X3, CASPEr, CULTASK, CAST-CAPP, MADMAX, RADES, QUAX, …	High	New ideas emerging, Active R&D going on,…
Lab axions 	ALPS, OSQAR, CROWS, fifth force exps,…	Very low	
Solar axions 	SUMICO, CAST, IAXO	Low	Ready for large scale experiment

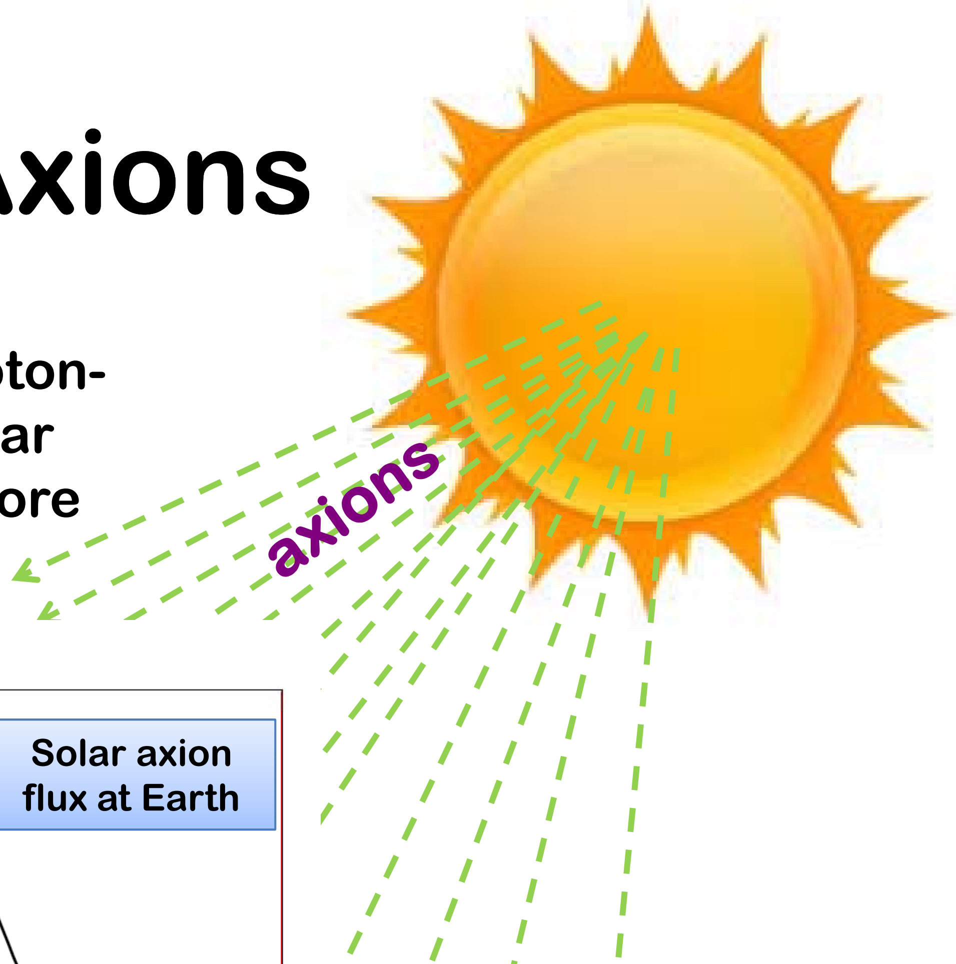
Axion/ALP parameter space

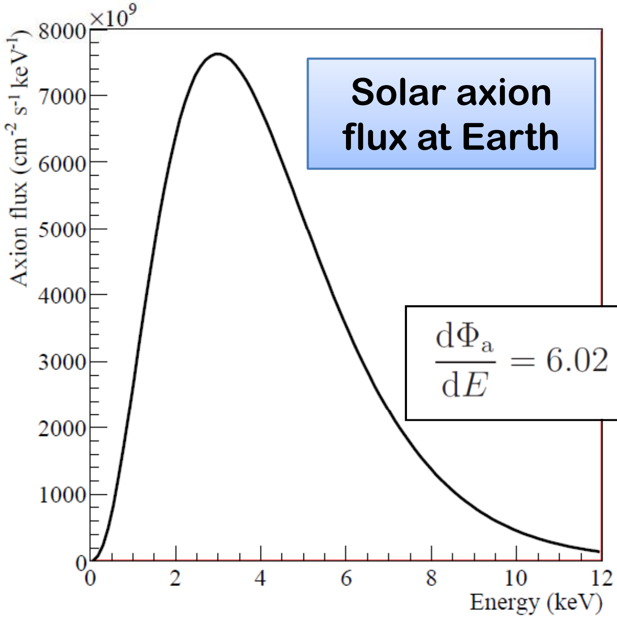


Solar Axions

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







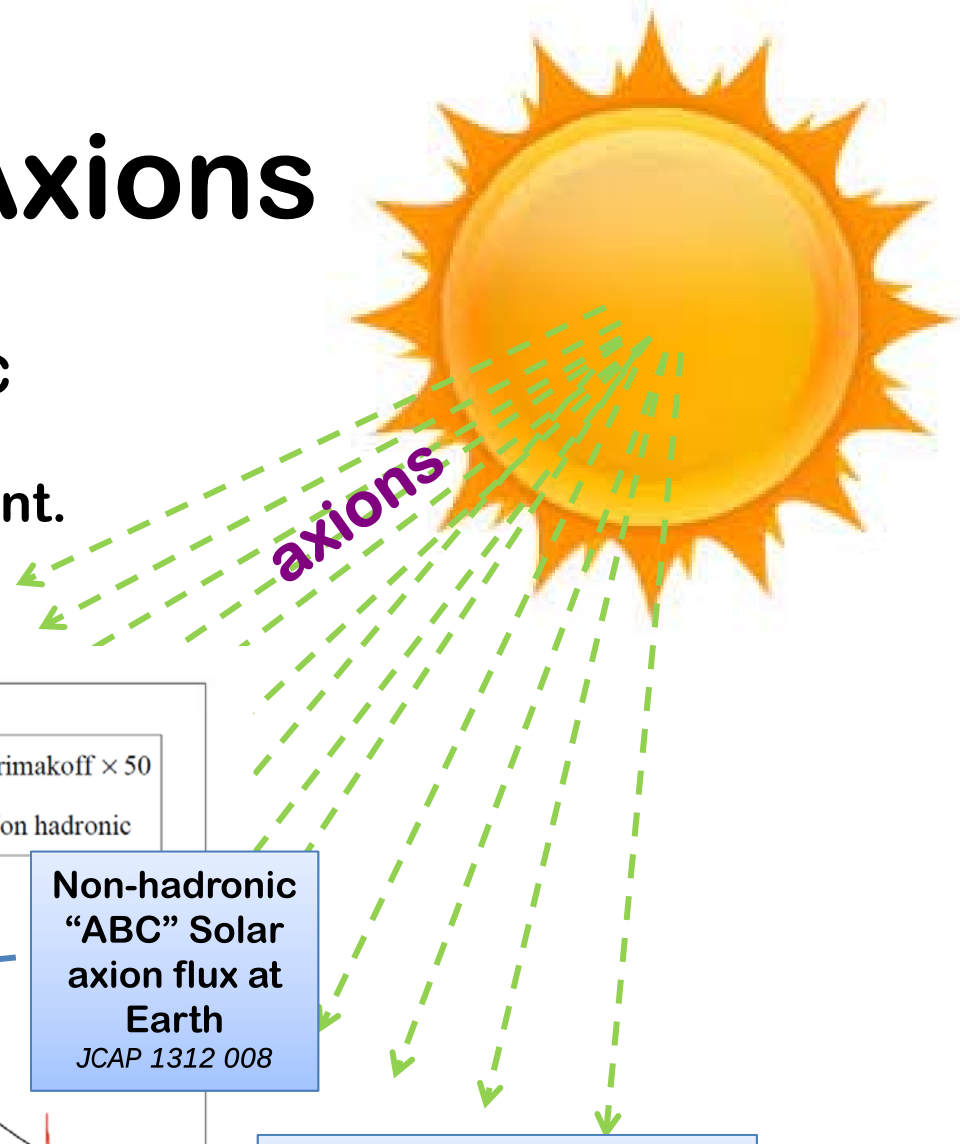
$$\frac{d\Phi_a}{dE} = 6.02 \times 10^{10}\ \mathrm{cm^{-2}\ s^{-1}\ keV^{-1}}\ g_{10}^2\ E^{2.481} e^{-E/1.205}.$$

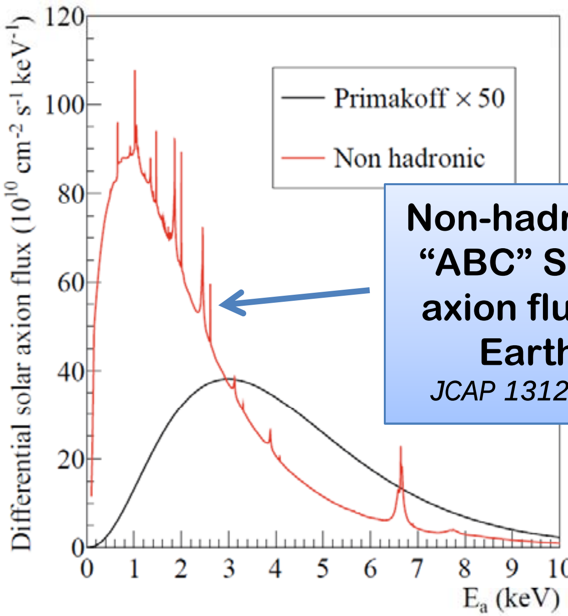
$$g_{10} = g_{a\gamma}/10^{-10}\ \mathrm{GeV^{-1}}$$

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

Solar Axions

- In addition to Primakoff, "ABC axions" may be x100 more intense… but model-dependent.



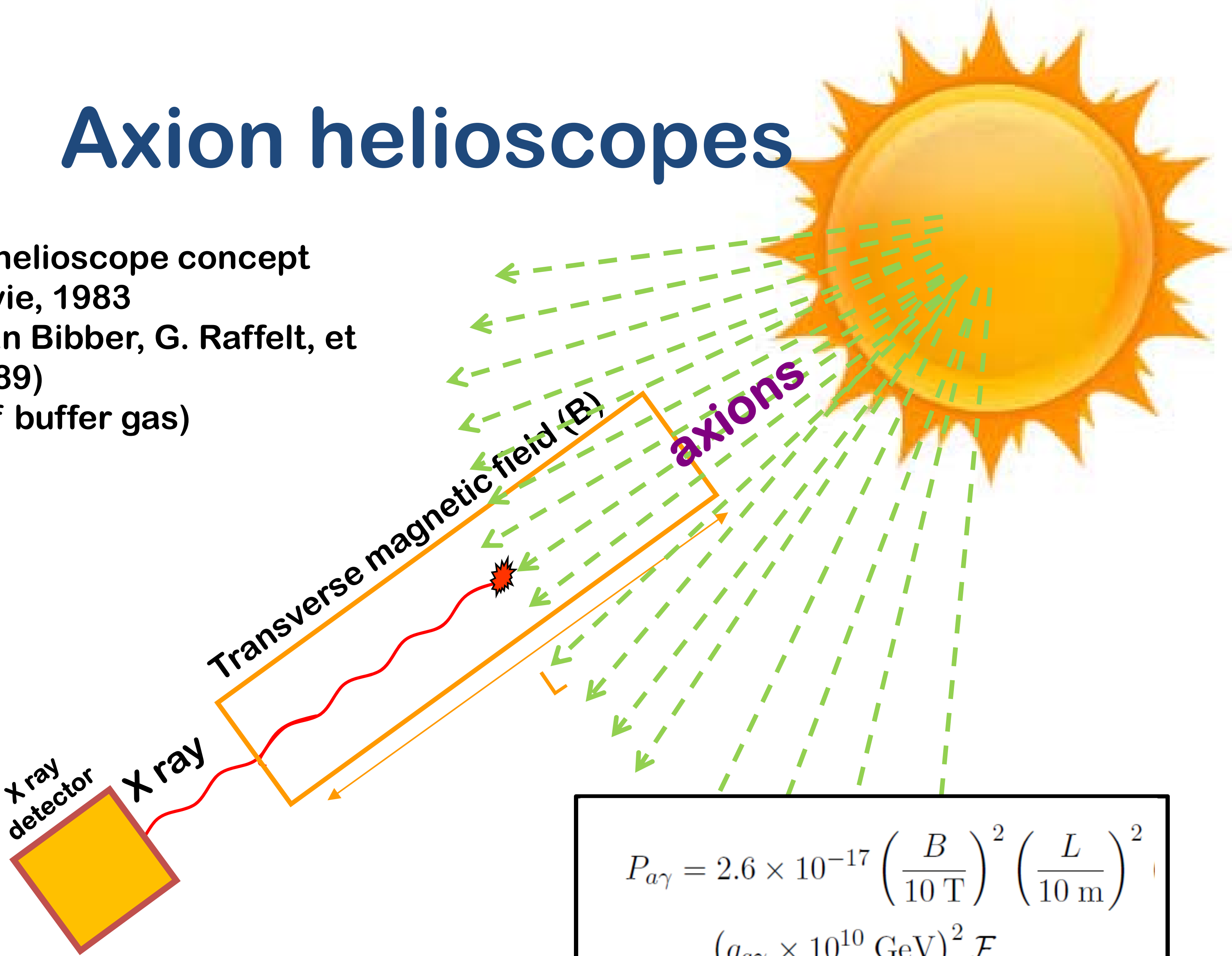


Non-hadronic "ABC" Solar axion flux at Earth
JCAP 1312 008

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

Axion helioscopes

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



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

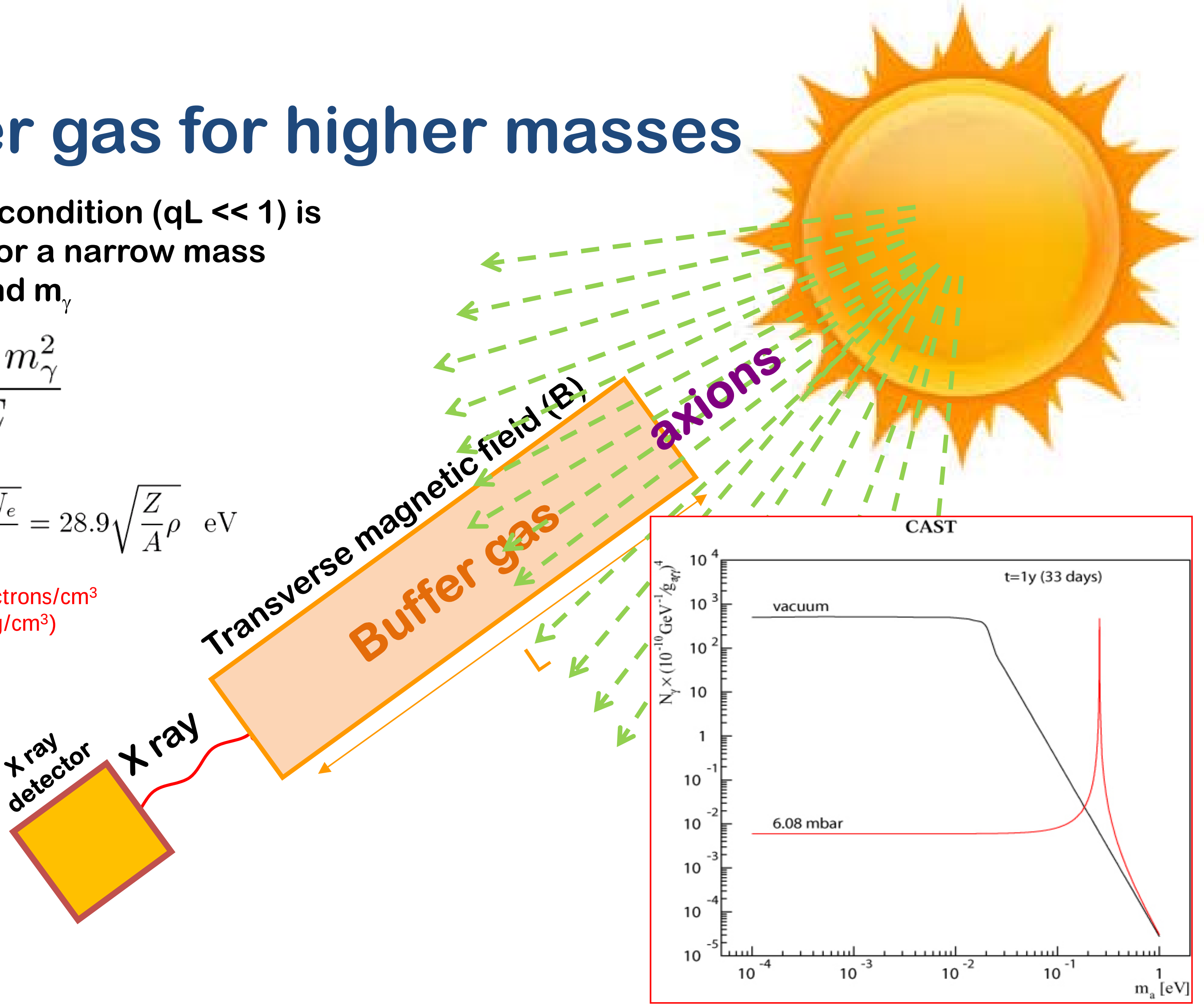
Buffer gas for higher masses

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

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

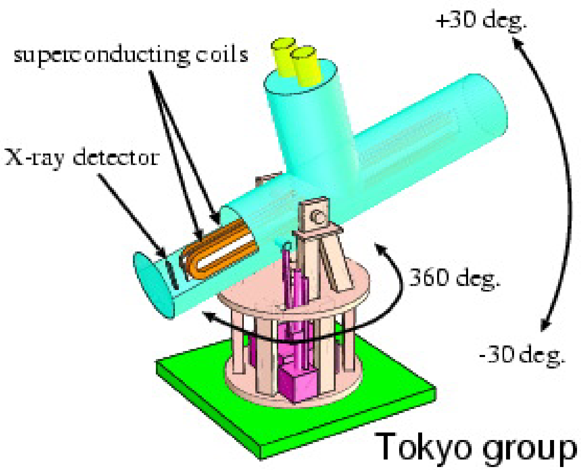
$$m_\gamma \approx \sqrt{\frac{4\pi\alpha N_e}{m_e}} = 28.9\sqrt{\frac{Z}{A}\rho} \quad \text{eV}$$

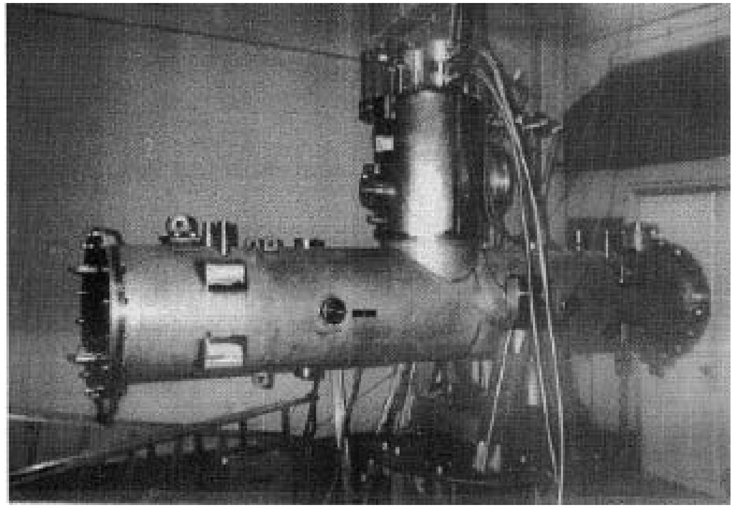
N_e: number of electrons/cm^3
ρ: gas density (g/cm^3)



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**



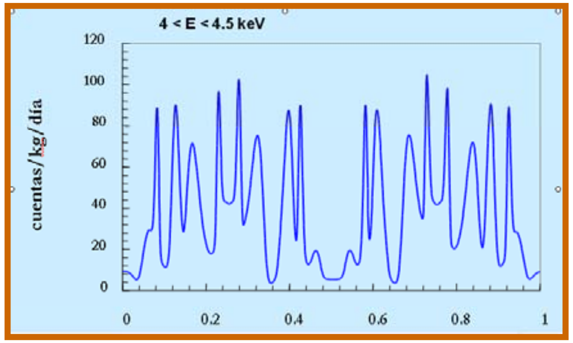


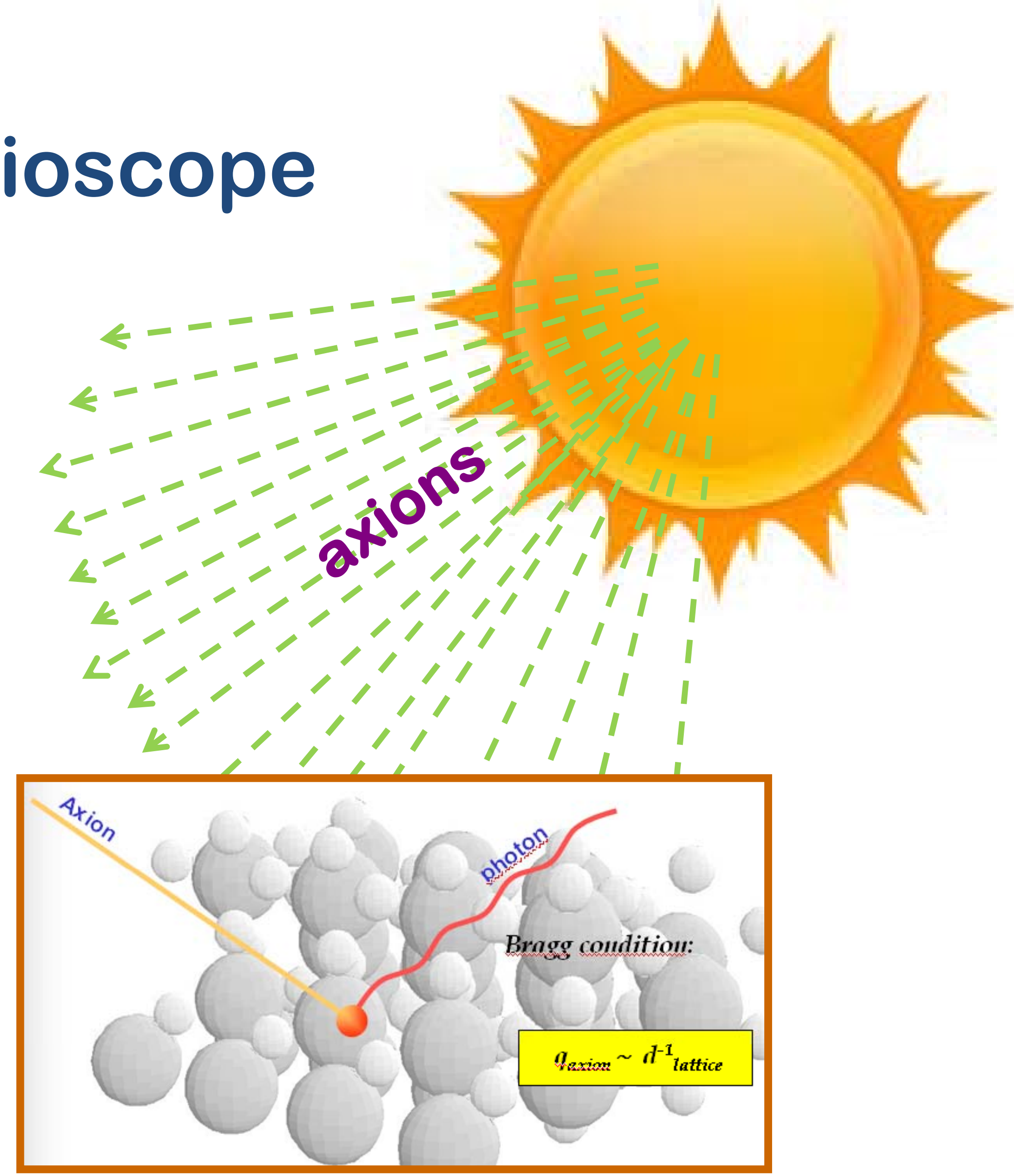
- **Presently running:**
  - **CERN Axion Solar Telescope (CAST)**

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:

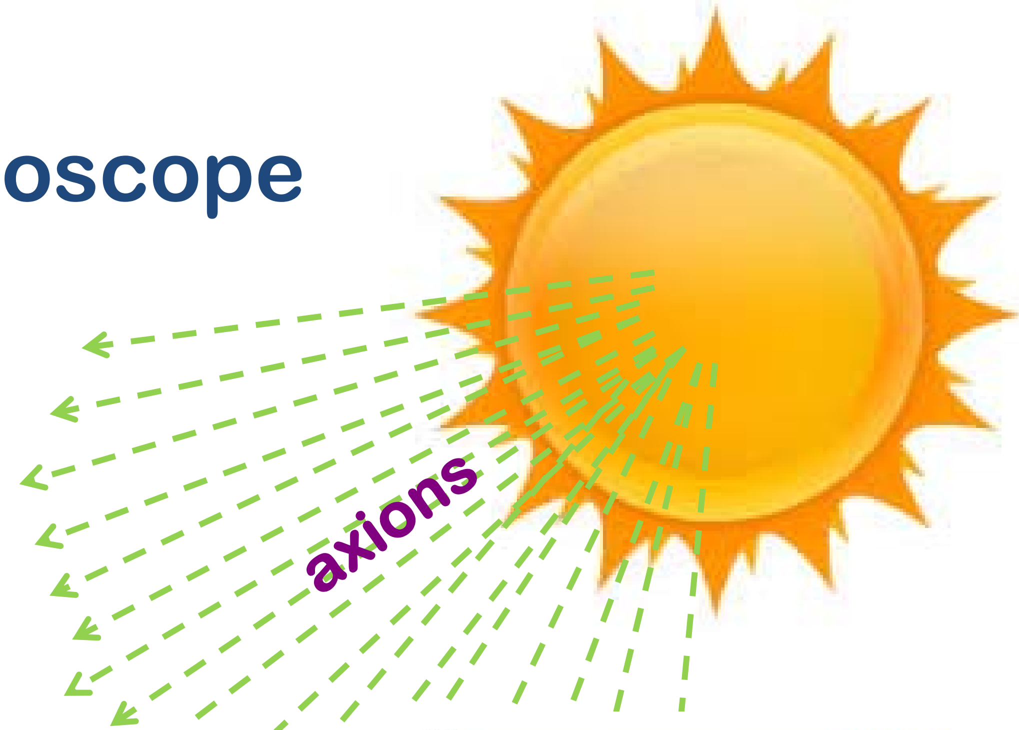
«

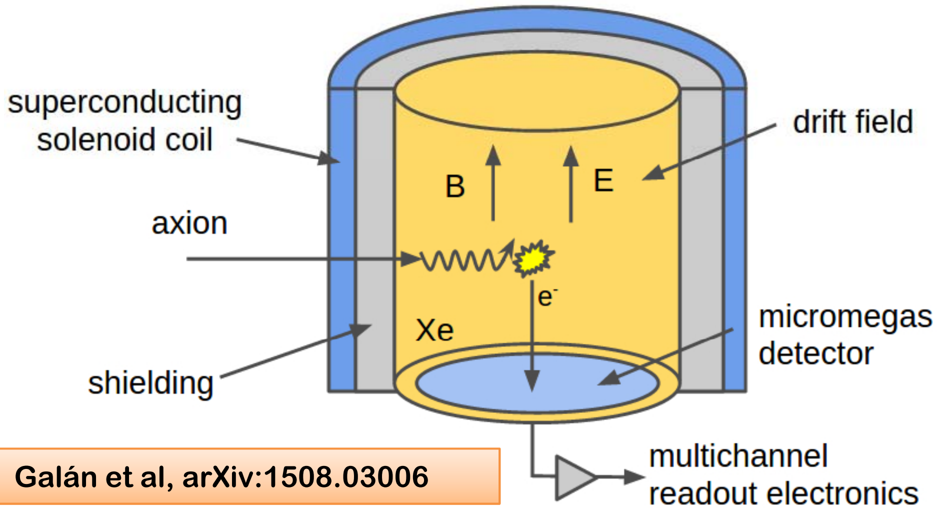




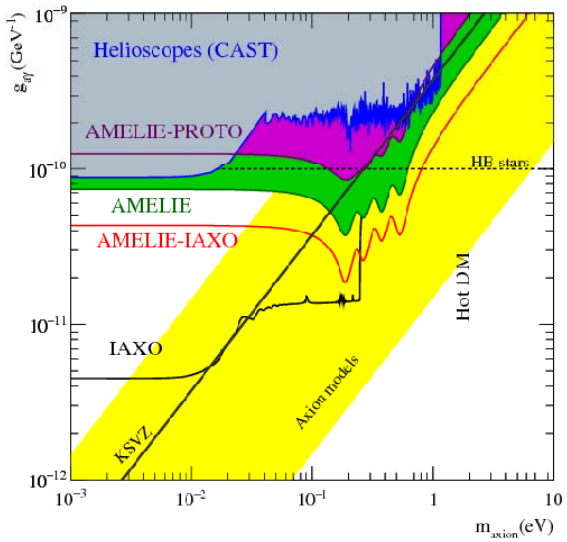
Other types of helioscope

- « TPC in a magnetic field »: conversion and absorption happening in the gas
- Competitive only for high axion mass
- Old idea recently studied



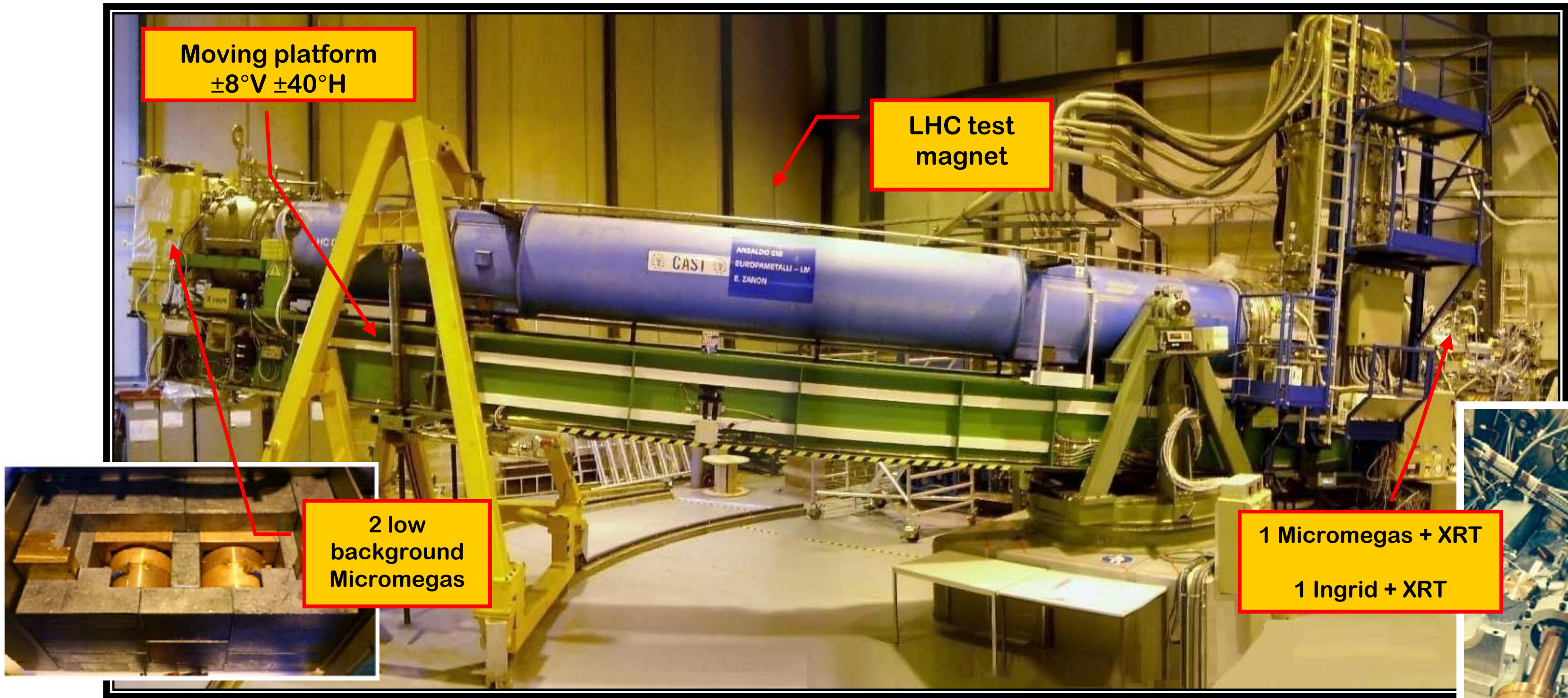


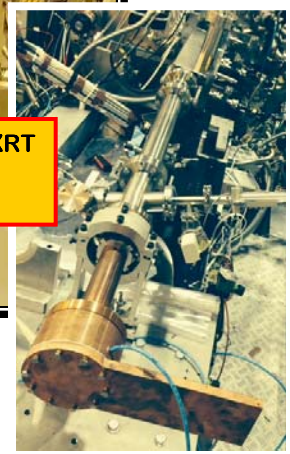
Galán et al, arXiv:1508.03006



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
- 3 X rays detector prototypes being used.
- X ray Focusing System to increase signal/noise ratio.



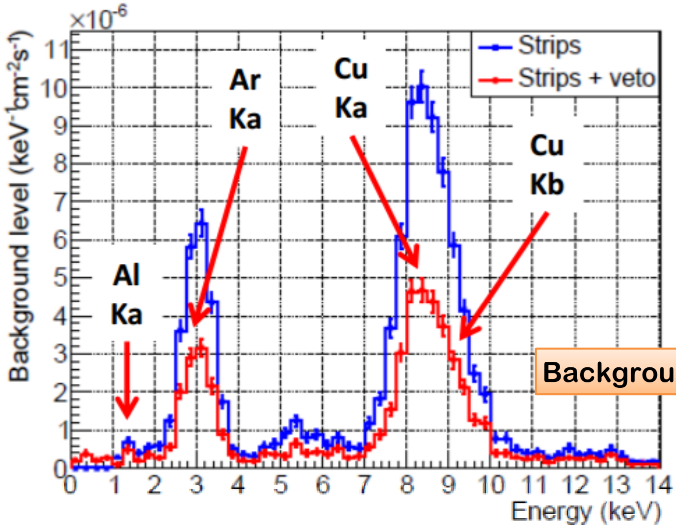


IAXO pathfinder system in CAST

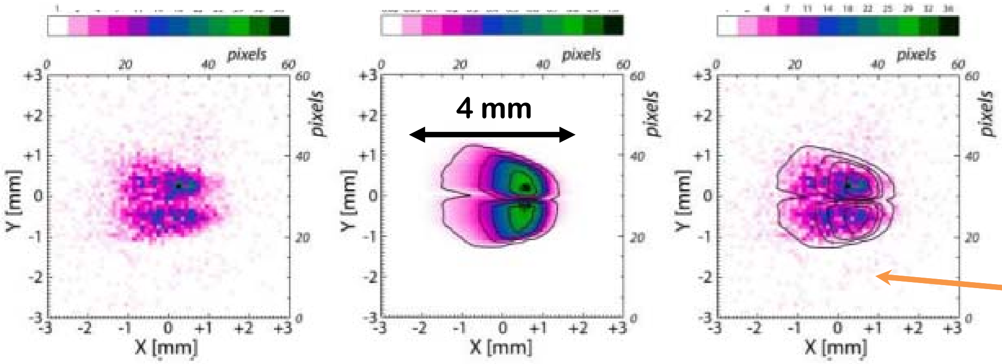
See JCAP12 (2015) 008

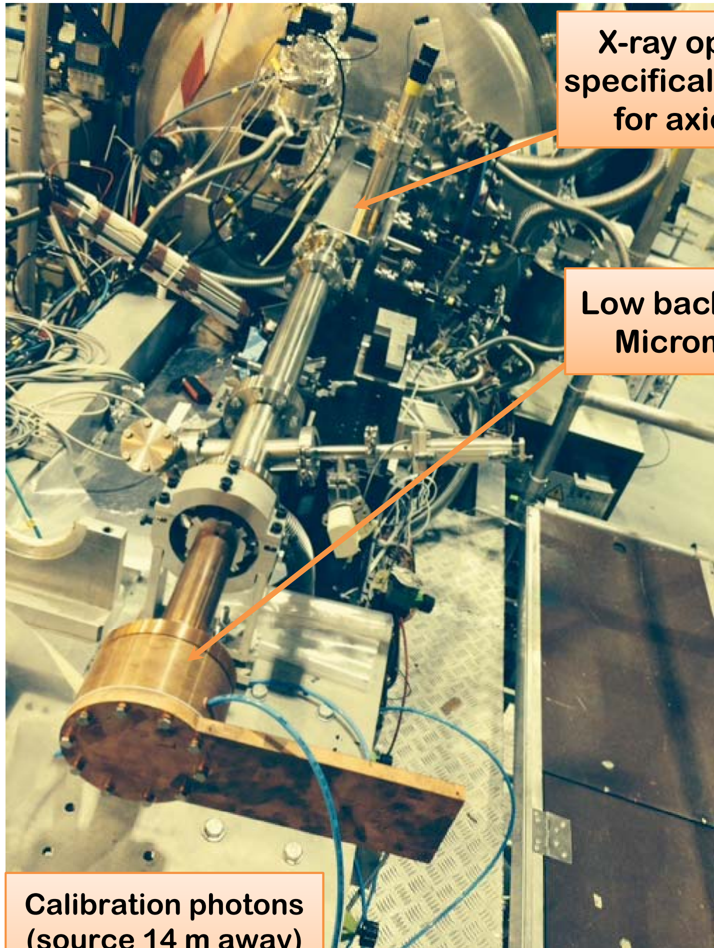
Test MM detector + slumped-glass x-ray optics together

Best SNR than any other CAST detector ever!!



Background spectrum





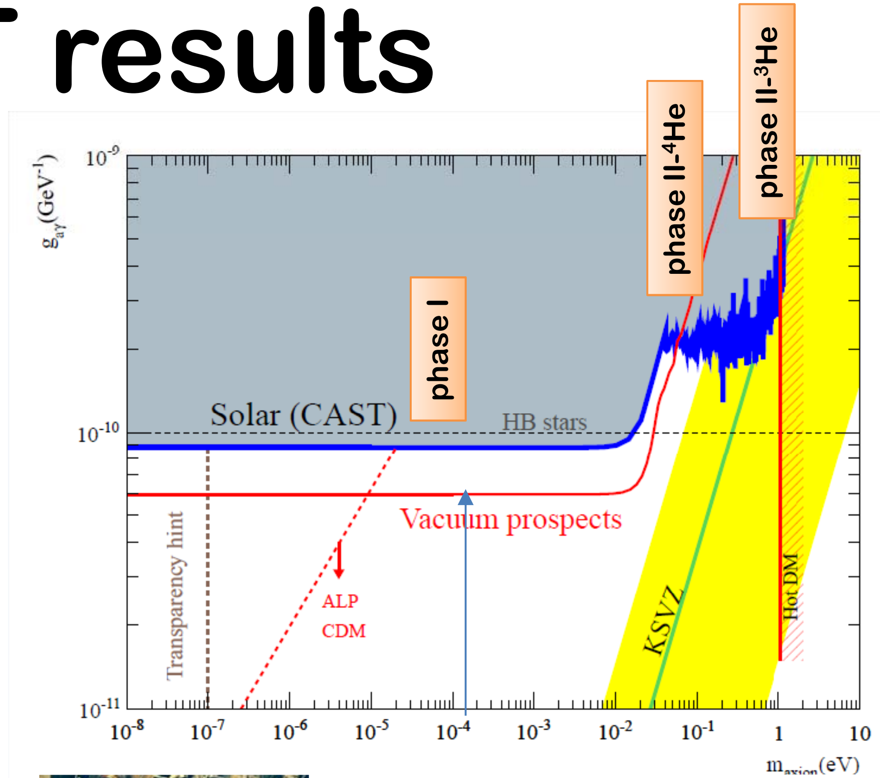
X-ray optics specifically built for axions

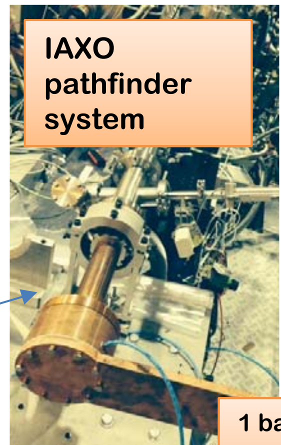
Low background Micromegas

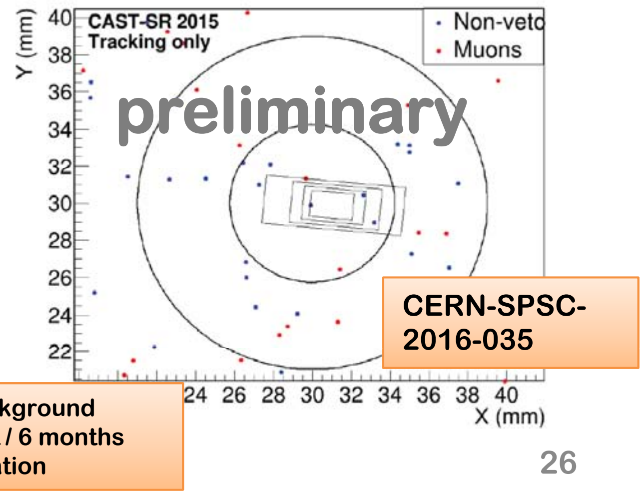
Calibration photons (source 14 m away) focused onto the Micromegas

CAST results

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 •New result to be released very soon

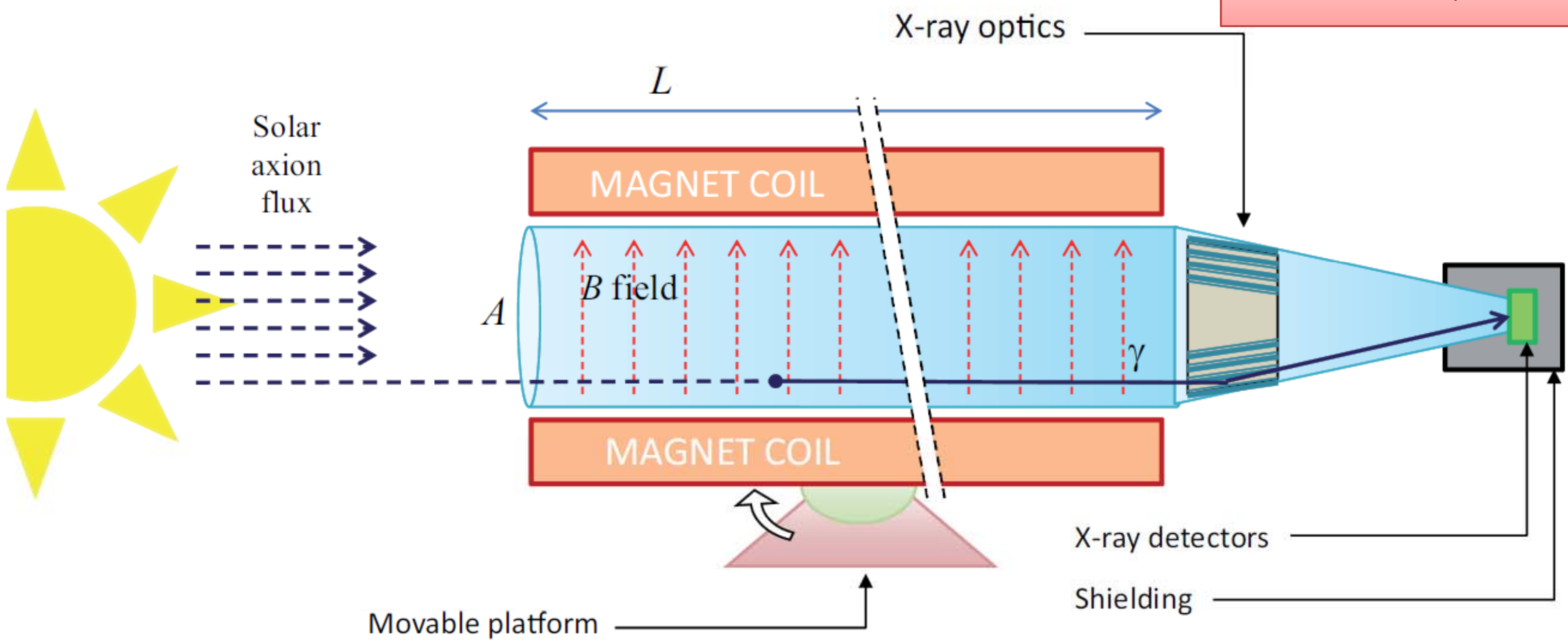






IAXO – Concept

Enhanced axion helioscope:
JCAP 1106:013,2011

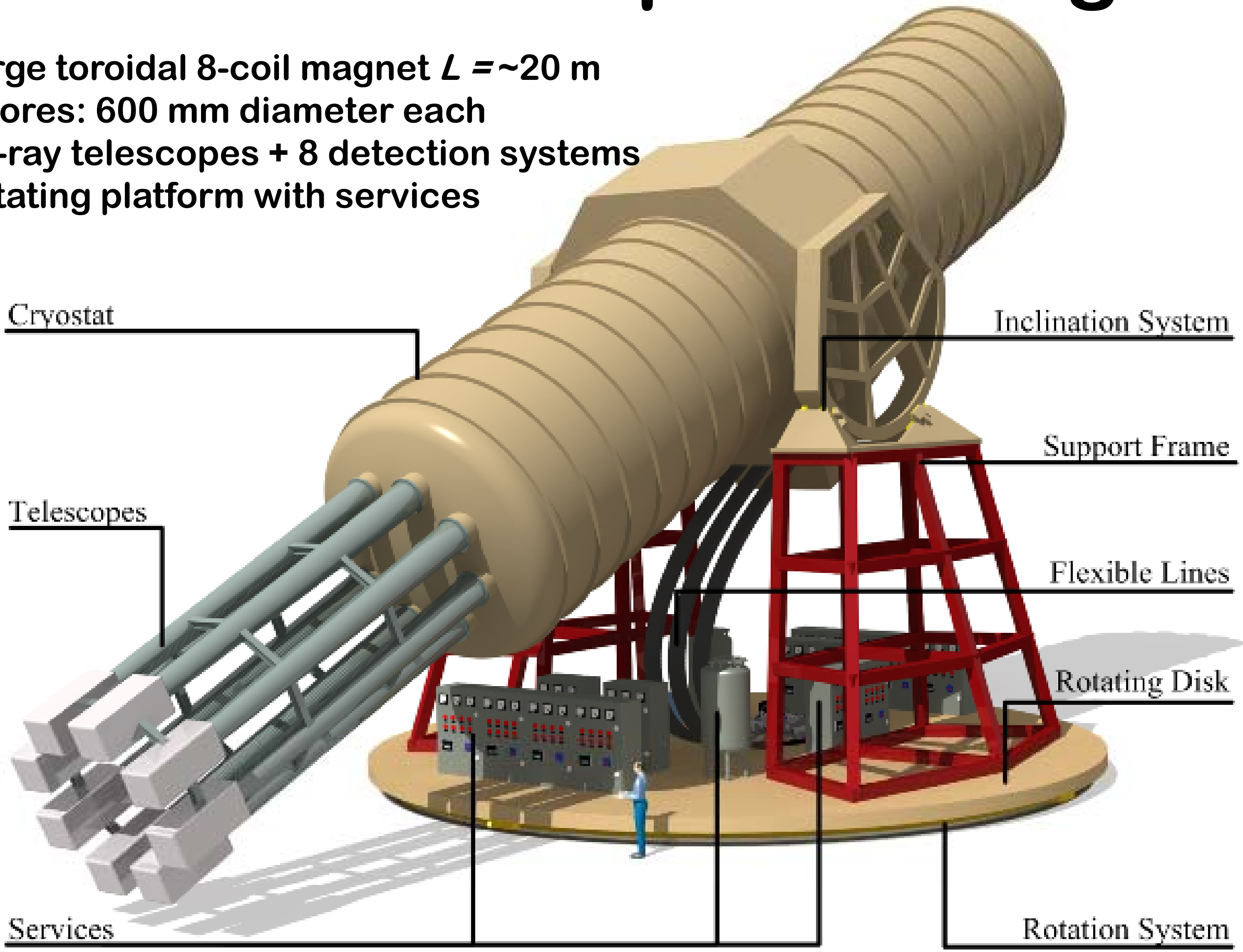


$$g_{a\gamma}^{4} \propto \underbrace{b^{1/2}\epsilon^{-1}}_{\text{detectors}} \times \underbrace{a^{1/2}\epsilon_{o}^{-1}}_{\text{optics}} \times \underbrace{(BL)^{-2}A^{-1}}_{\text{magnet}} \times \underbrace{t^{-1/2}}_{\text{exposure}}$$

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

IAXO – Conceptual Design

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

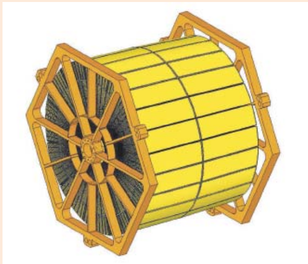


IAXO technologies – Baseline

Services
Rotation System

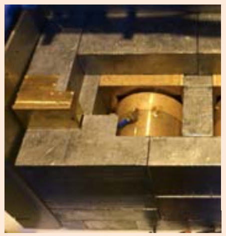
IAXO telescopes

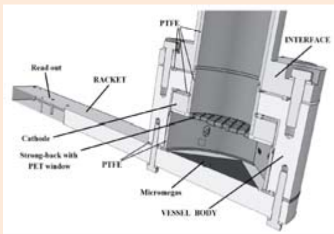
- Slumped glass technology with multilayers
- Cost-effective to cover large areas
- Based on NuSTAR developments
- Focal length ~5 m
- 60-70% efficiency
- LLNL+UC+DTU+MIT expertise



IAXO detectors

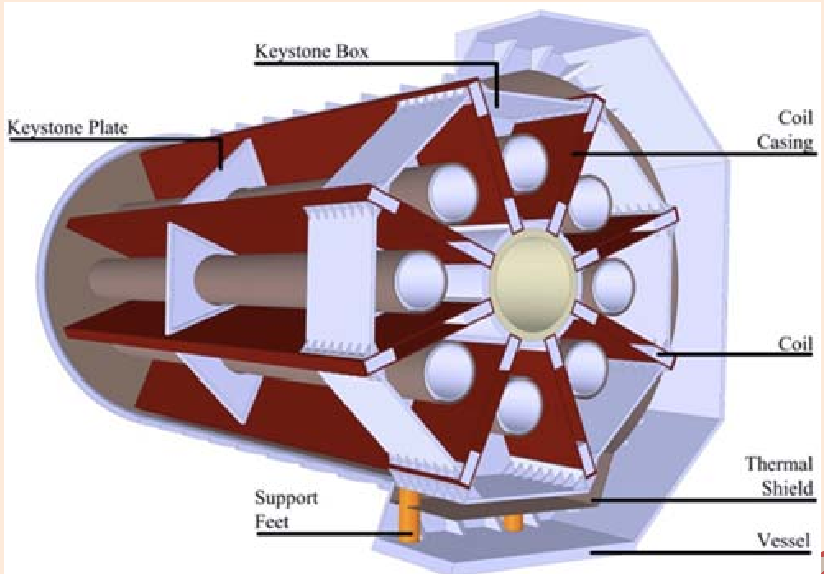
- Micromegas gaseous detectors
- Radiopure components + shielding
- Discrimination from event topology in gas
- Long trajectory in CAST
- Zaragoza + CEA (+ others) expertise
- Also considered: Ingrid, MMCs, CCDs



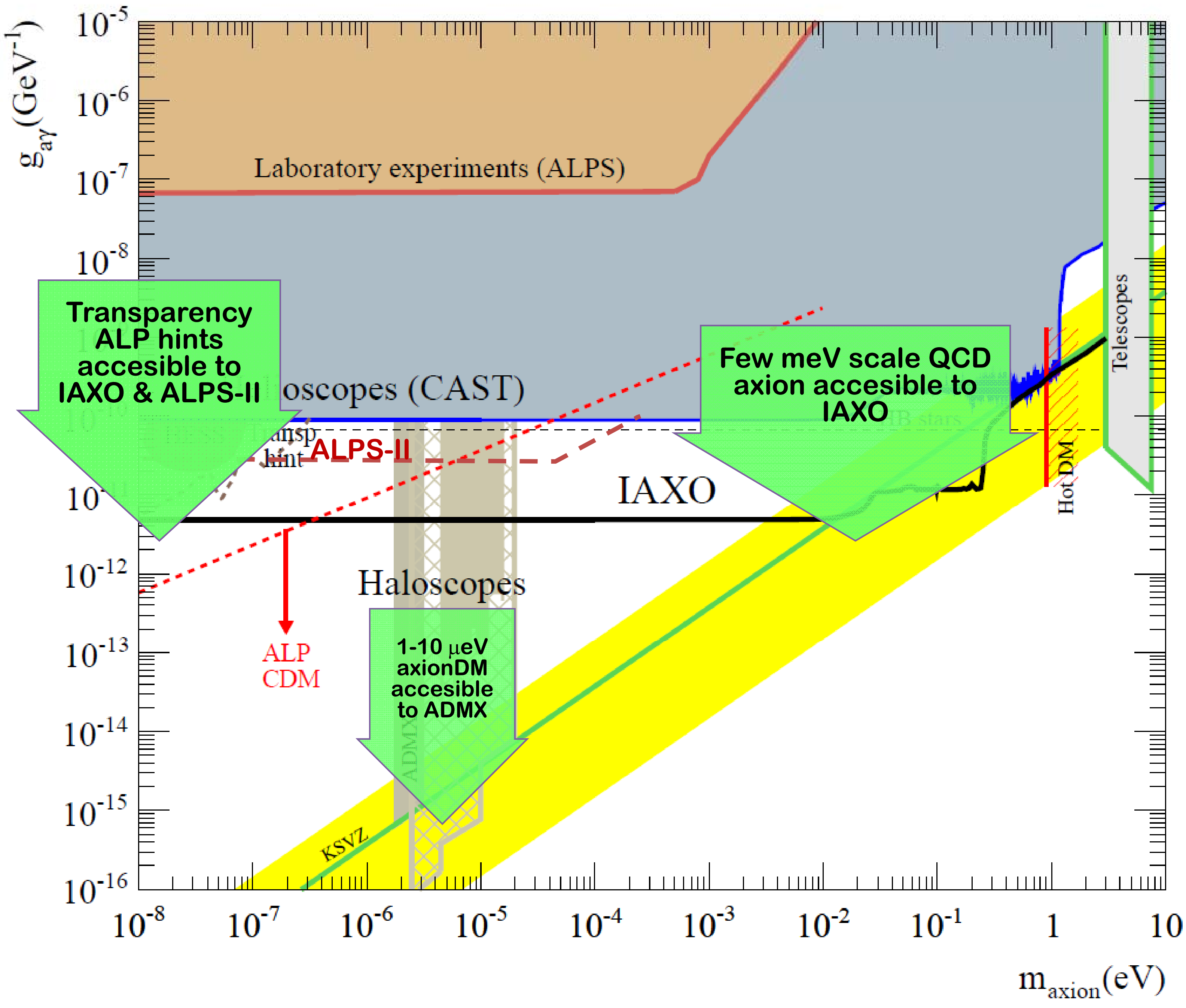


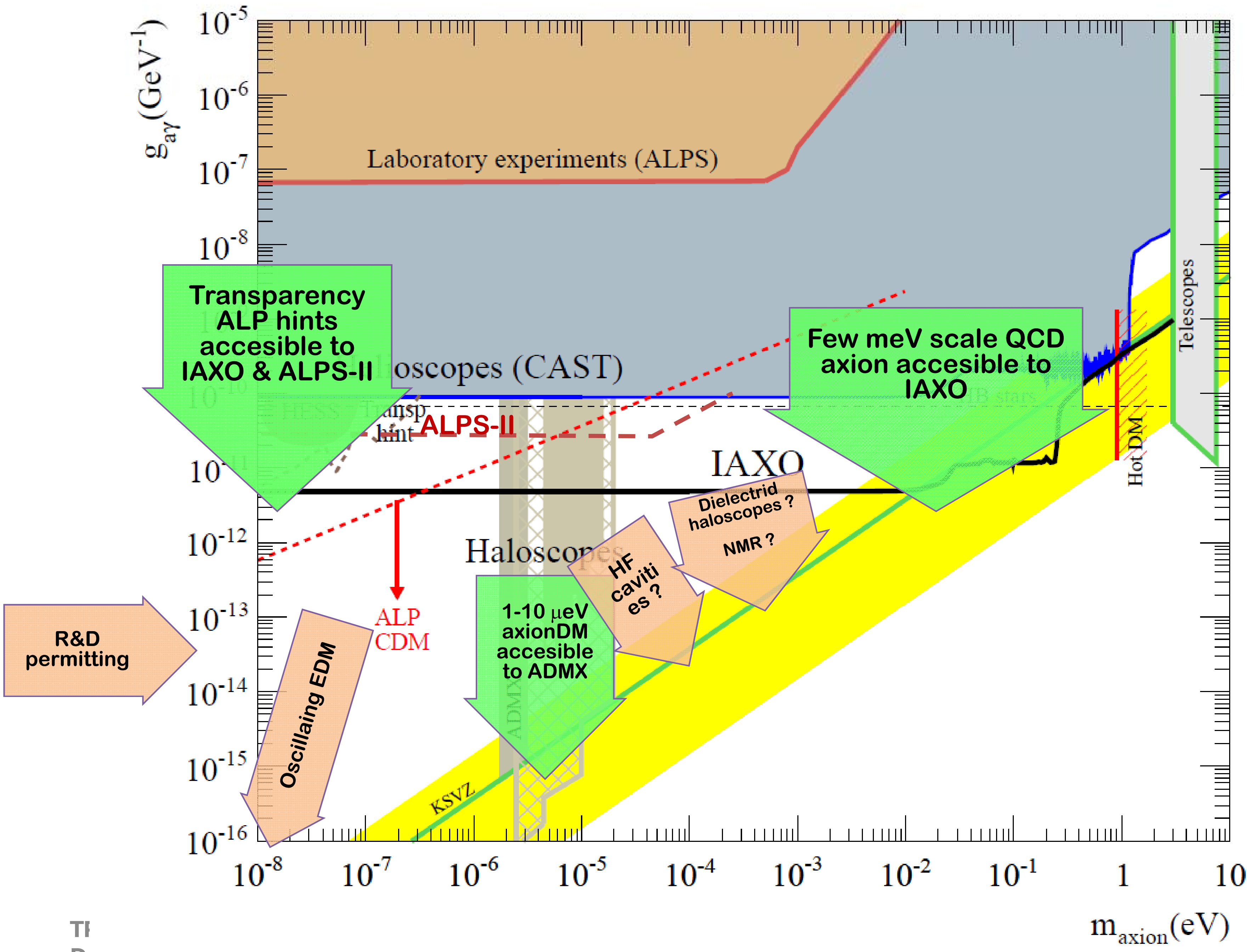
IAXO magnet

- 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)


$g_{a\gamma}$ (GeV^{-1})
m_{axion} (eV)
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
Laboratory experiments (ALPS)
oscopes (CAST)
Transparency ALP hints accesible to IAXO & ALPS-II
Few meV scale QCD axion accesible to IAXO
ALPS-II
IAXO
Haloscopes
ALP CDM
1-10 μeV axionDM accesible to ADMX
KSVZ
Telescopes
Hot DM



Laboratory experiments (ALPS)
Transparency ALP hints accesible to IAXO & ALPS-II
Helioscopes (CAST)
HESS
Transp hint
ALPS-II
IAXO
Few meV scale QCD axion accesible to IAXO
HB stars
Telescopes
Hot DM
Dielectrid haloscopes ?
NMR ?
HF cavities ?
Haloscopes
ALP CDM
1-10 μeV axionDM accesible to ADMX
ADMX
R&D permitting
Oscillaing EDM
KSVZ
$g_{a\gamma}$ (GeV^{-1})
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
m_{axion} (eV)

TI
D

Conclusions

- **Increasing interest for axions:**
  - **Beyond axions: ALPs / WISPs**
- **Increasing experimental effort (still small!)**
- **Consolidation of classical detection lines: ADMX, CAST, ALPs,…**
  - **ADMX and CAST have firstly probed interesting (small) fraction of par space.**

- **Helioscopes: next generation IAXO.**
- **Haloscopes:**

  ADMX, CAPP,… → R&D to go higher m_a
- **New ideas to tackle new regions:**

  Dielectric haloscope, NMR,…

- **Large fraction of parameter space at reach of near-future experiments**
  - **chances of discovery!**

Good timing for axions… stay tuned