Experimental searches for axions

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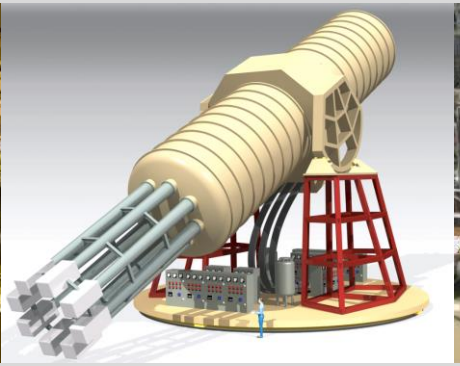
Universidad de Zaragoza

TeV Particle Astrophysics (TeVPA2016), CERN,
12 September 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 $\theta < 10^{-11}$ while O(1) would be expected

θ absorbed in the definition of a

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

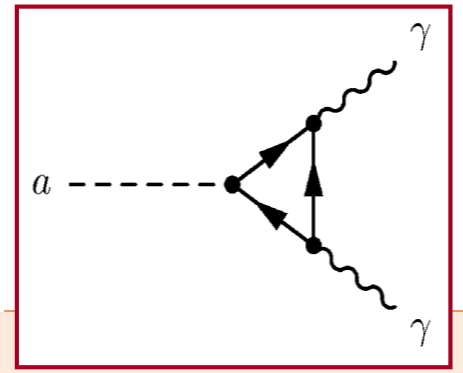
$\theta = a/f_a$ relaxes to zero…
CP conservation is preserved "dinamically"

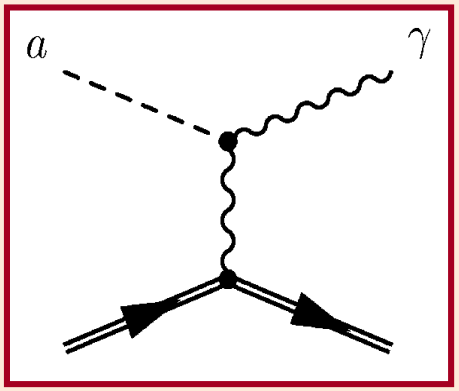
a → New field: the axion. Very light: $m_a \simeq 0.6 \text{ eV} \frac{10^7 \text{GeV}}{f_a}$

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**)

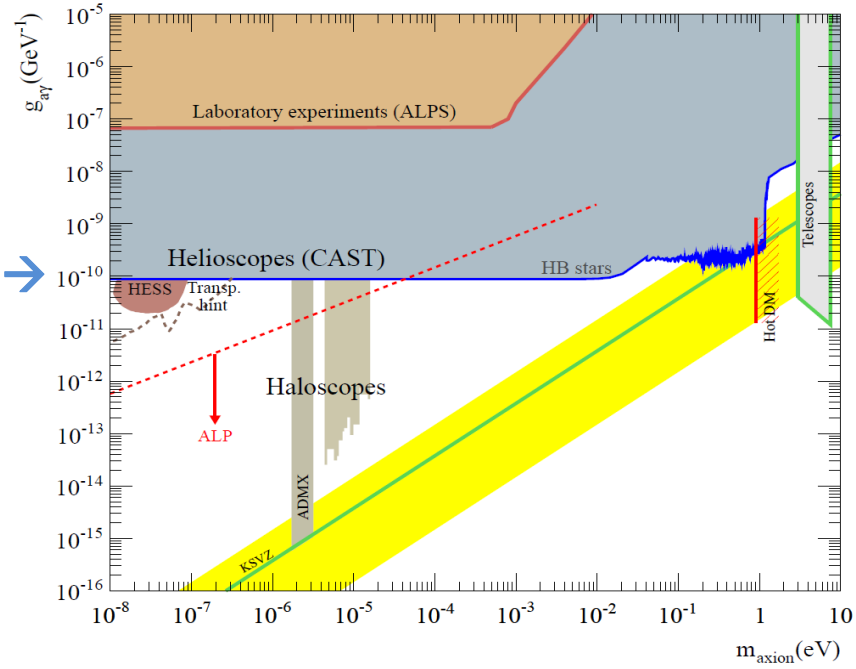
This is probably the most relevant of axion properties.

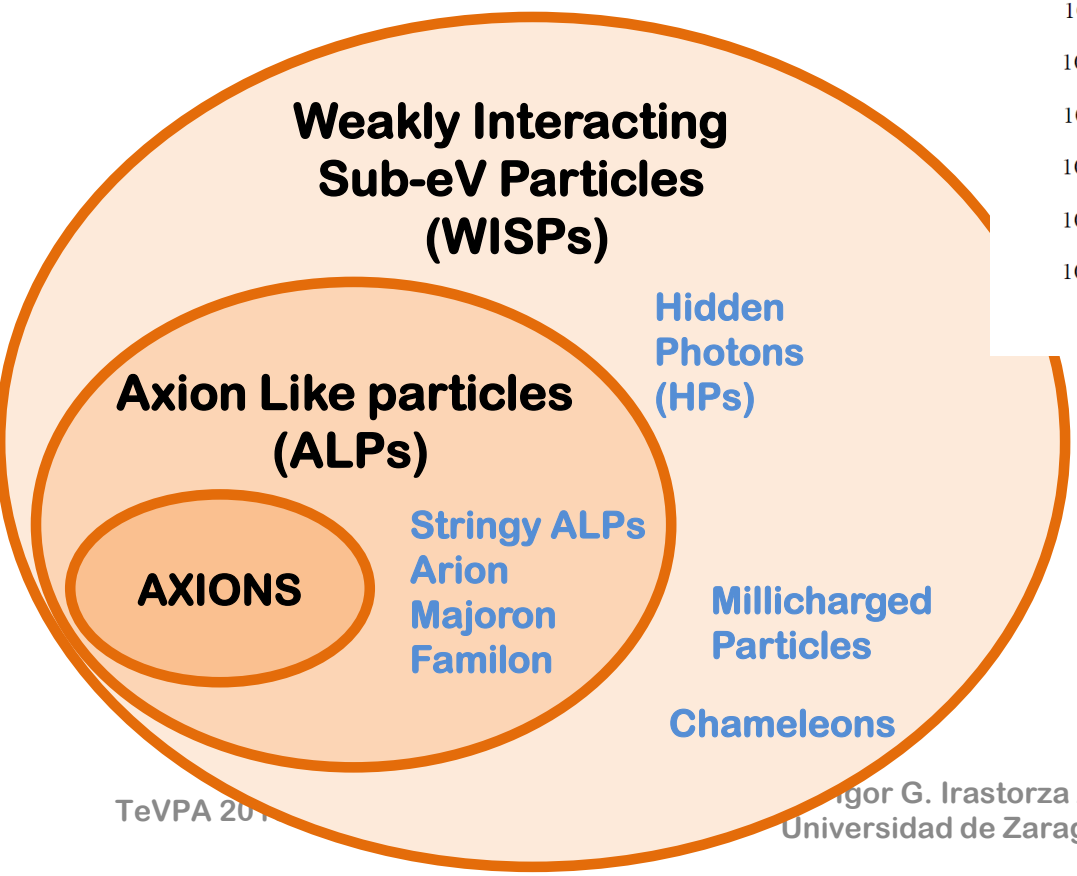
Most axion detection strategies are based on the axion-photon coupling

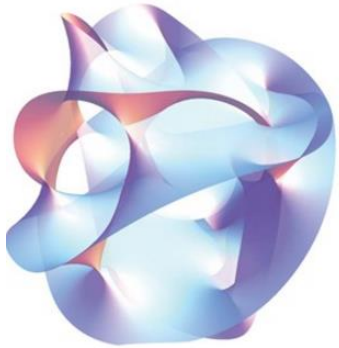
Beyond axions

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

Generic ALPs parameter space →

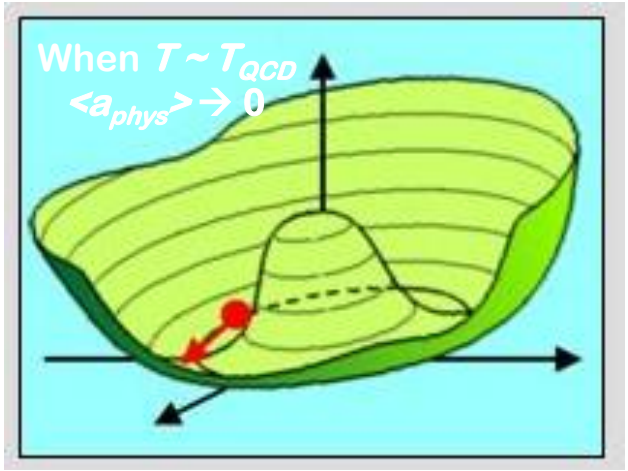






String theory predicts a plenitude of ALPs

Non thermal cosmological axions

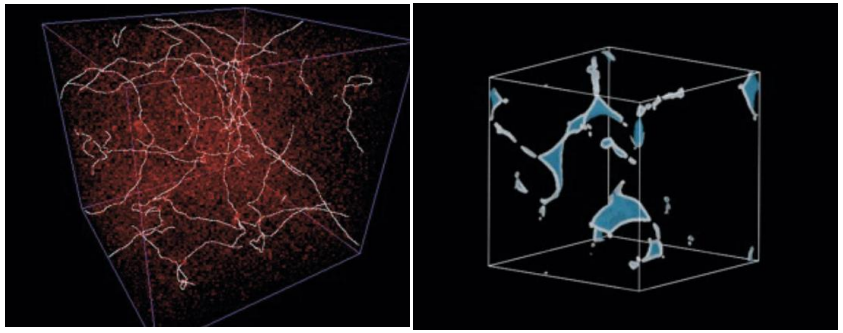


Axion realignment

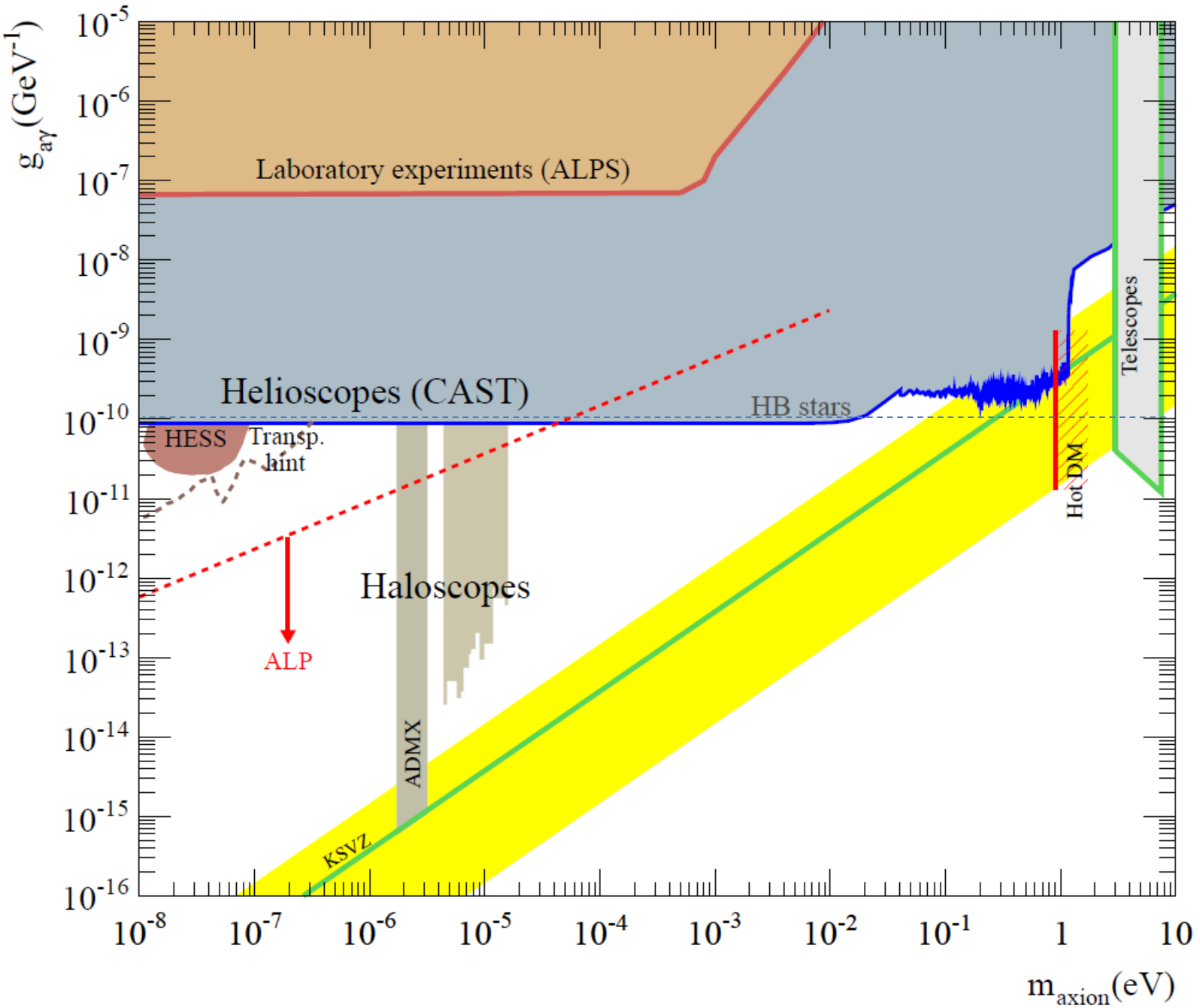
As the Universe cools down below T_{QCD}, space is filled with low energy axion field fluctuations.

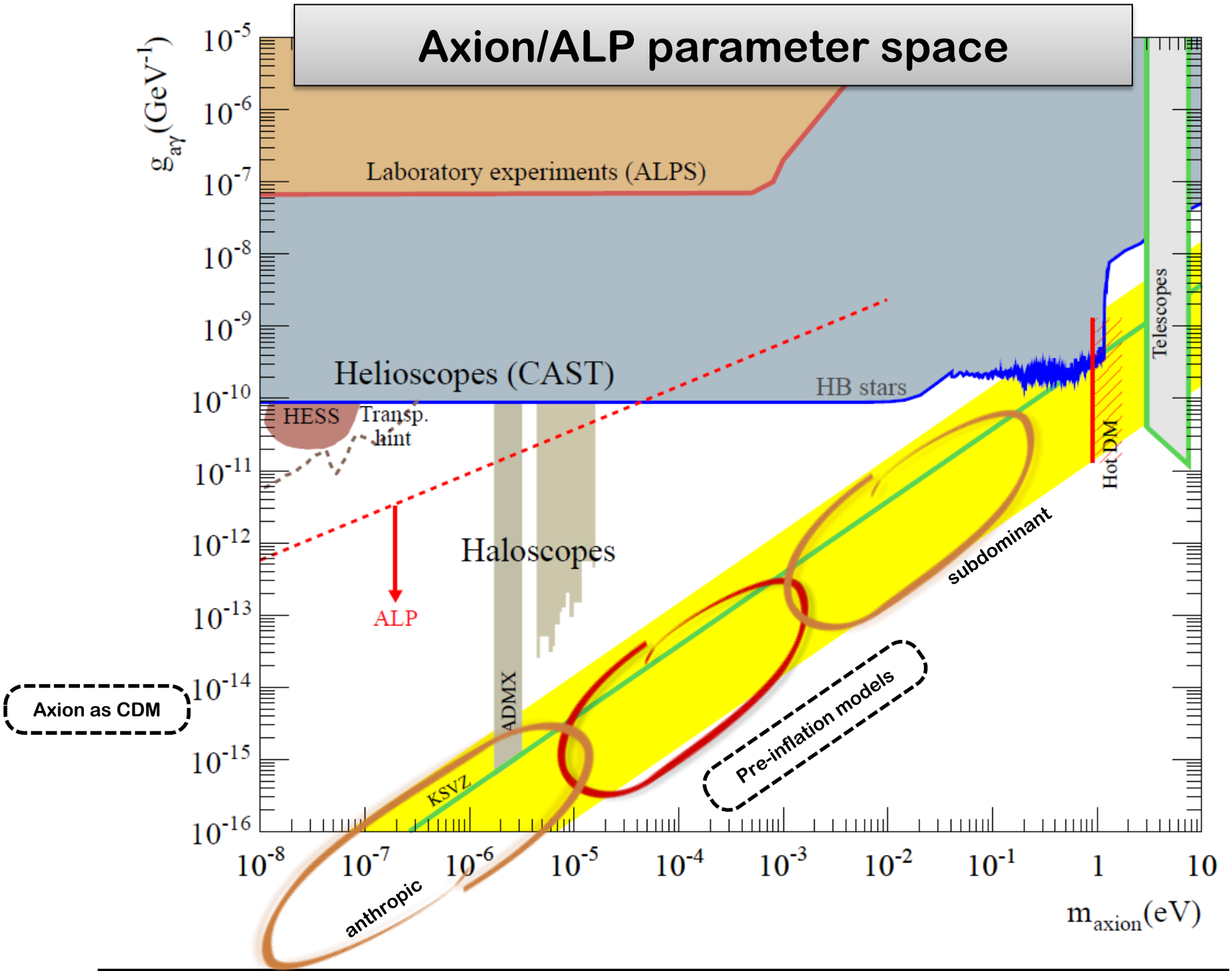
Their density depends on the initial value of $\langle a_{phys} \rangle$ ("misalignment angle")

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
Telescopes
HESS
Transp.
Haloscopes
ALP
ADMX
KSVZ
Hot DM
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
$g_{a\gamma}$ (GeV^{-1})
10^{-5}
10^{-6}
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Laboratory experiments (ALPS)
Helioscopes (CAST)
HB stars
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Transp. dint
Haloscopes
ALP
ADMX
Hot DM
Telescopes
subdominant
Pre-inflation models
KSVZ
anthropic
Axion as CDM
10^{-8}
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10^{-6}
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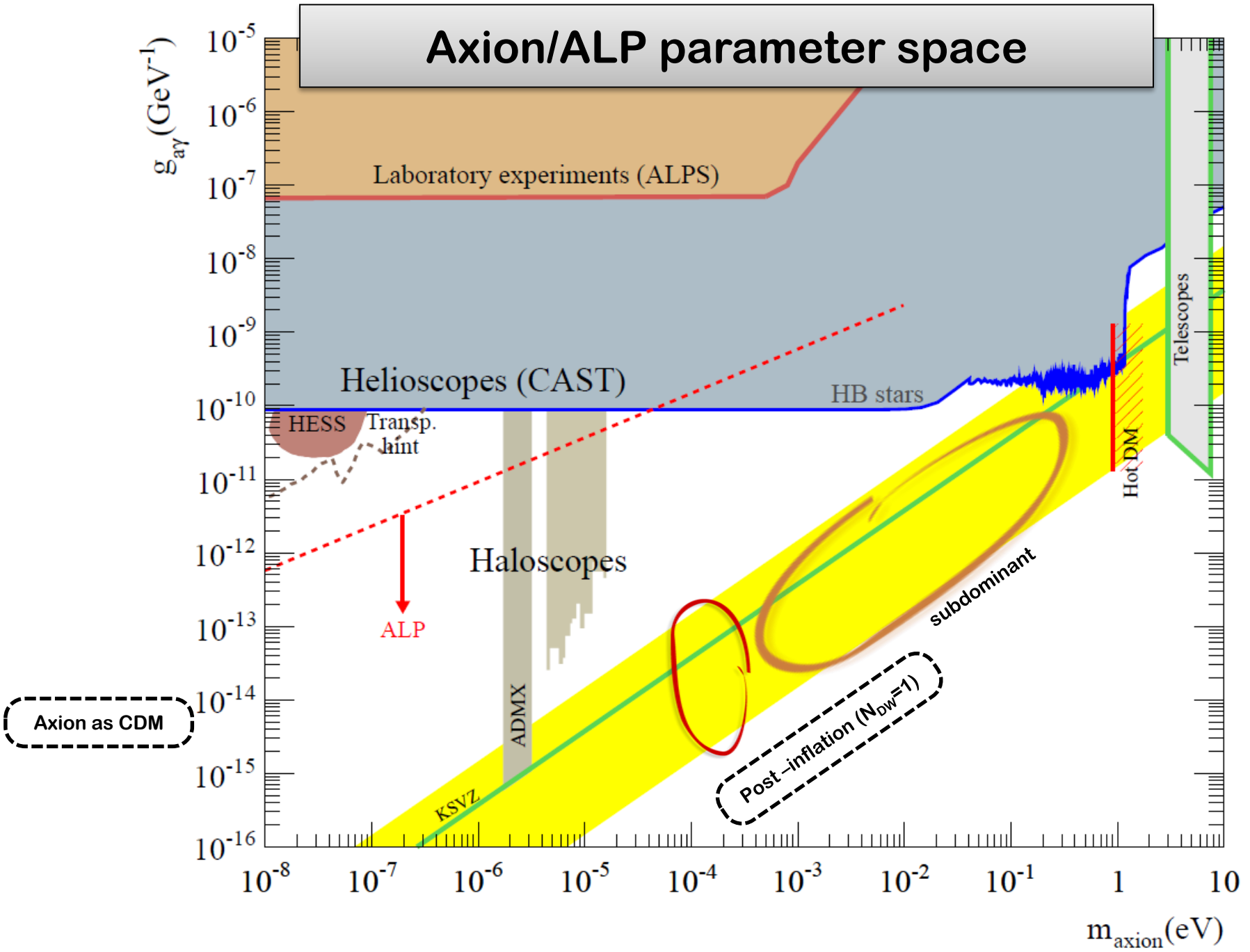
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
m_{axion}(eV)


Axion/ALP parameter space
$g_{a\gamma}$(GeV^{-1})
10^{-5}
10^{-6}
10^{-7}
10^{-8}
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10^{-10}
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Laboratory experiments (ALPS)
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HB stars
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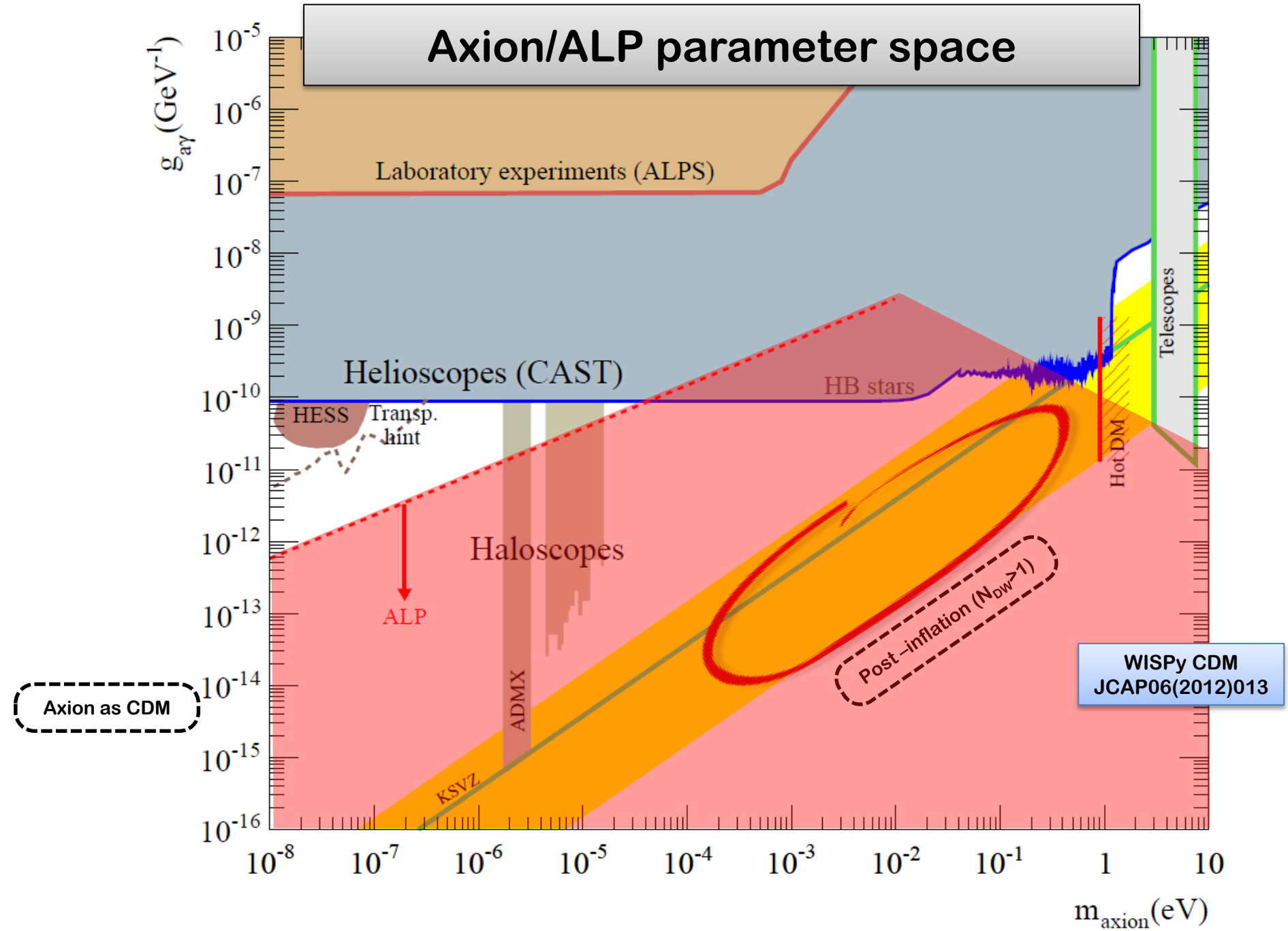
Hot DM
Haloscopes
ALP
ADMX
KSVZ
subdominant
Post-inflation (N_{DW}=1)
Axion as CDM
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
m_{axion}(eV)


Axion/ALP parameter space
Laboratory experiments (ALPS)
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HB stars
HESS
Transp. hint
Telescopes
Hot DM
Haloscopes
ALP
ADMX
KSVZ
Post-inflation (N_{DW}>1)
Axion as CDM
WISPy CDM
JCAP06(2012)013
$g_{a\gamma}$ (GeV^{-1})
m_{axion} (eV)
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
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10^{-11}
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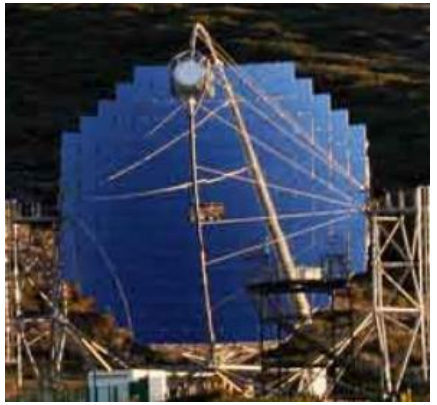
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10

Astrophysical hints for axions

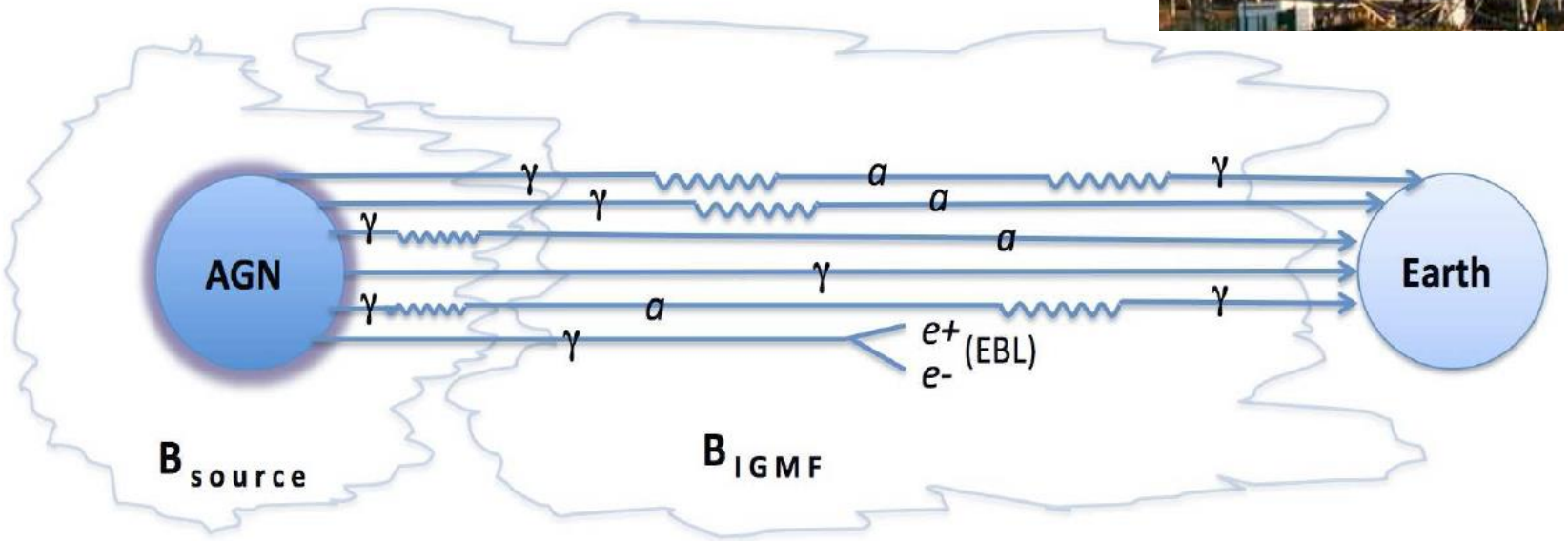
- **Gama ray telescopes like MAGIC or HESS observe HE photons from very distant sources…**



ALP:

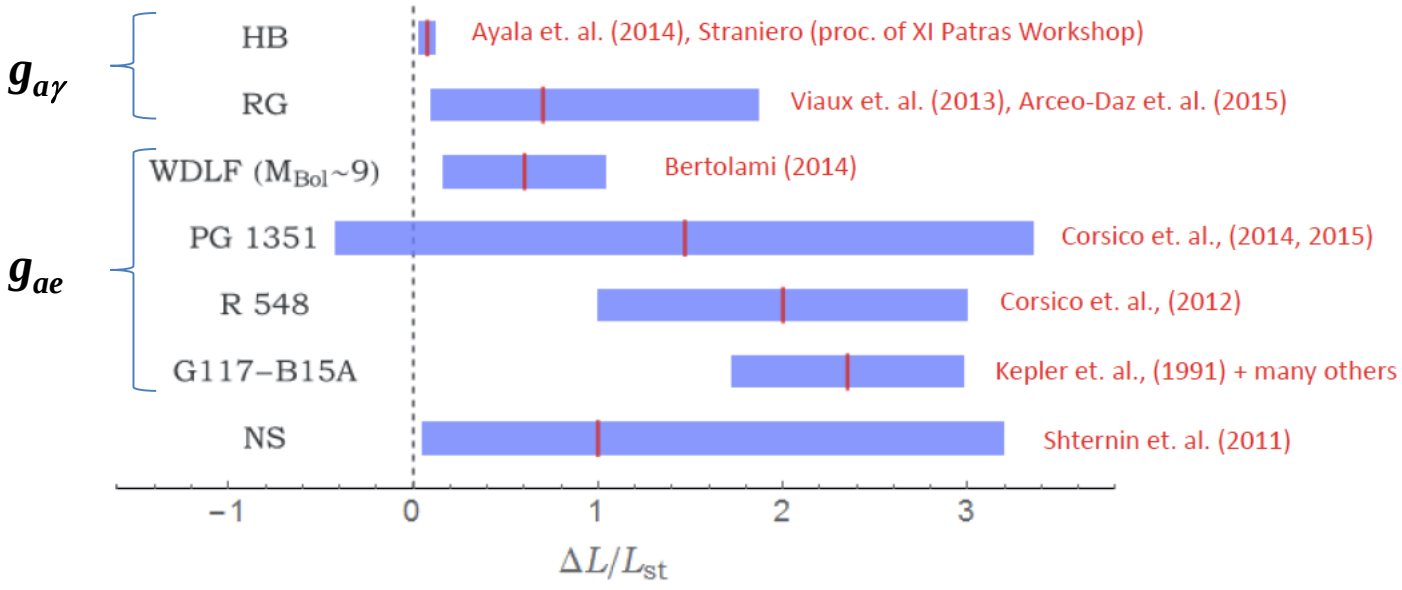
$$g_{a\gamma} \sim 10^{-12}\text{–}10^{-10}\ \mathrm{GeV}^{-1}$$

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

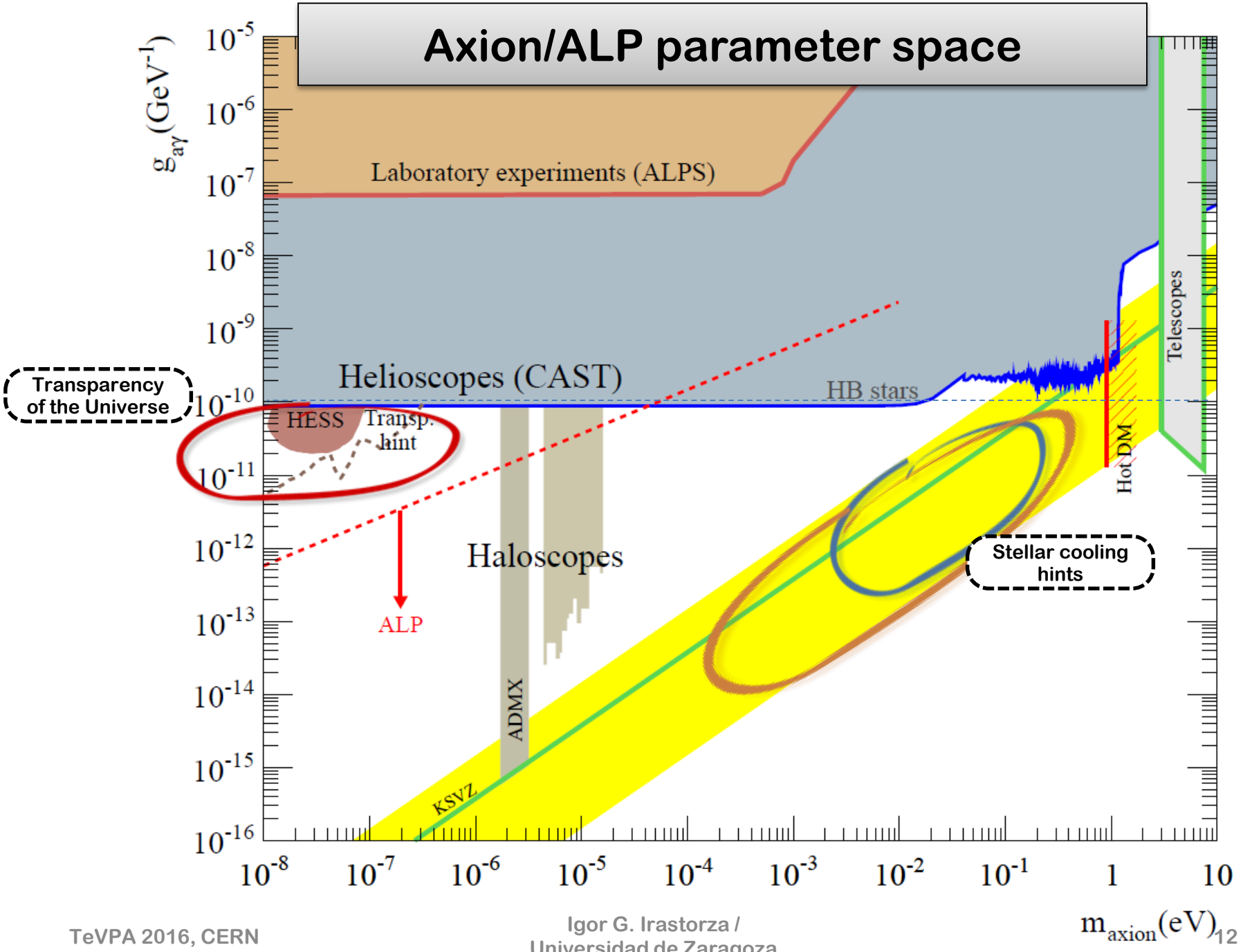


Astrophysical hints for axions (II)

- **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**



Axion/ALP parameter space



Axion motivation in a nutshell

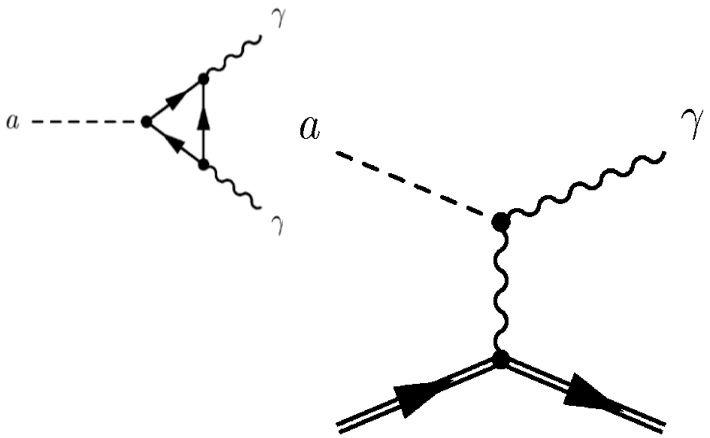
- Most compelling solution to the **Strong CP problem** of the SM

- 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 ?

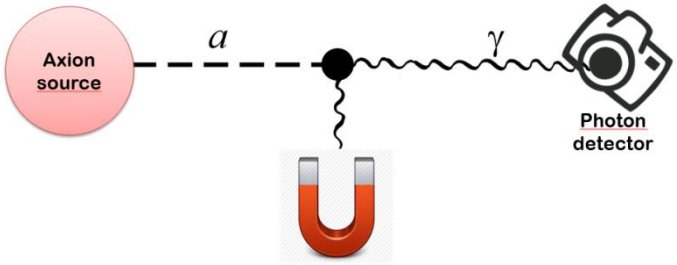
- Relevant axion/ALP parameter space at **reach of current and near-future experiments**
- Still too little experimental efforts devoted to axions when compared e.g. to WIMPs…

Detection of axions

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



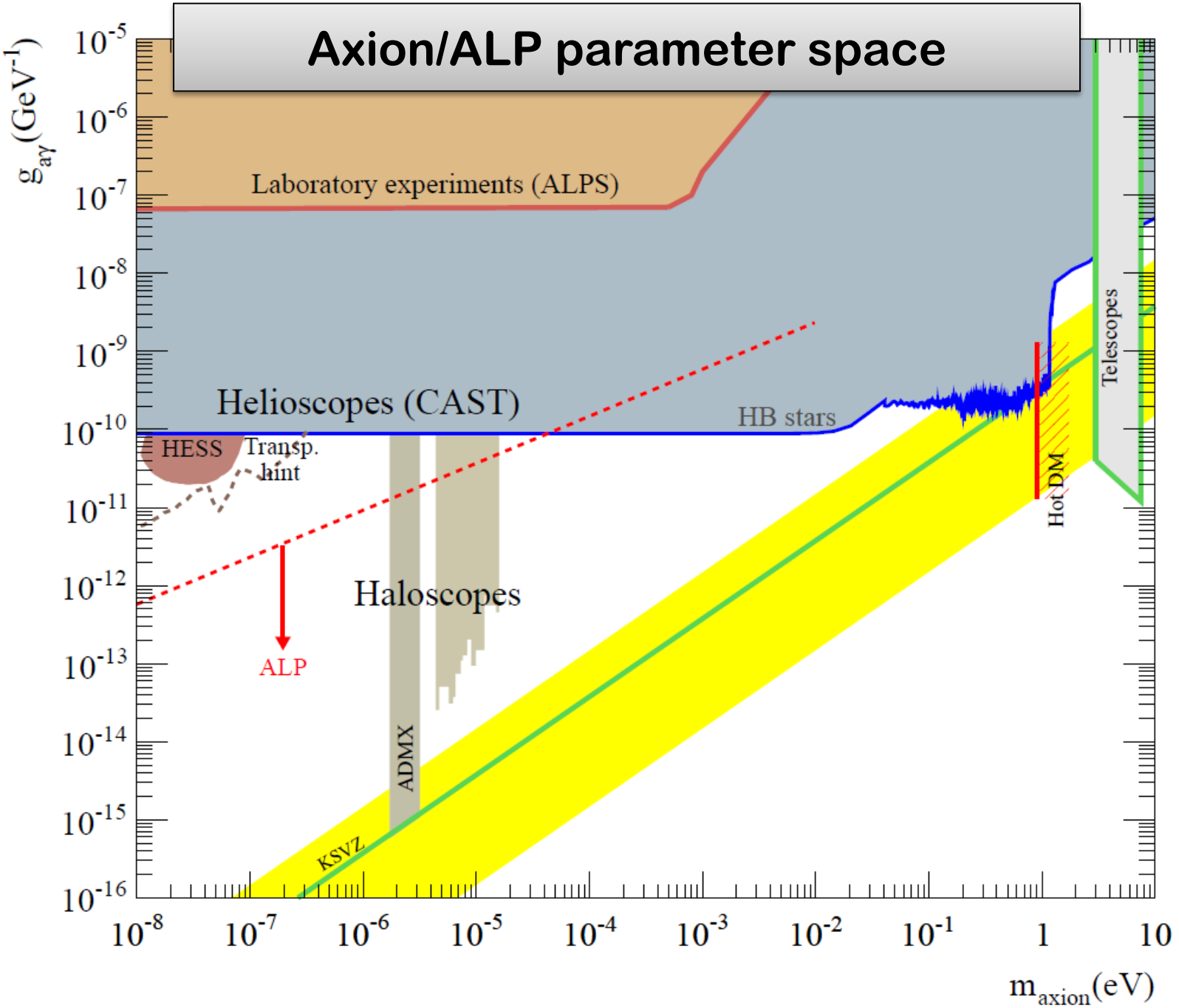
- **Axion-photon conversion** in the presence of an electromagnetic field (**Primakoff effect**)
- Most detection techniques based on the axion-to-photon conversion inside **magnets**



→ 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, 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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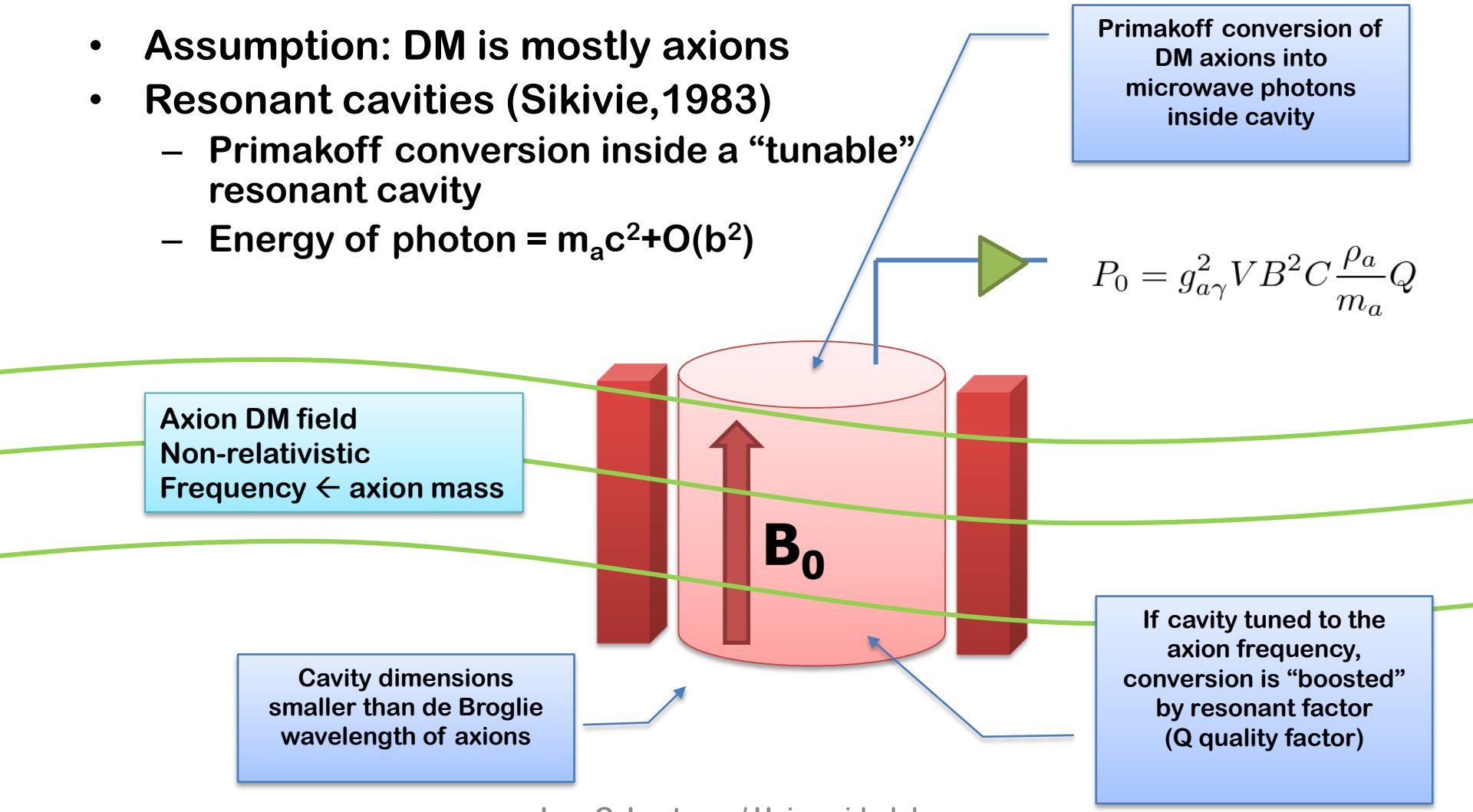
ALP
ADMX
KSVZ
Hot DM
Telescopes
m_{axion}(eV)

Detecting DM axions: "haloscopes"

- Assumption: DM is mostly axions
- Resonant cavities (Sikivie,1983)
  - Primakoff conversion inside a "tunable" resonant cavity
  - Energy of photon = $m_a c^2 + O(b^2)$



ADMX

- Leading haloscope experiment
- Many years of R&D
- high Q cavity (1 m x 60 cm Ø)
- 8 T superconducting solenoid
- Low noise receivers based on SQUIDs + dilution refrigeration at 100 mK.
- Sensitivity to **few μeV** proven
- Good support through Gen 2 DM US program
- Current program will surely cover 1-10 μeV with high sensitivity (i.e. reaching ever pessimistic coupling). What about higher masses?

Haloscopes at higher axion masses

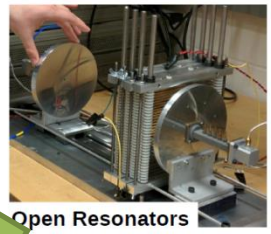
- **Problemetic: higher m_a → lower V → lower sensitivity**

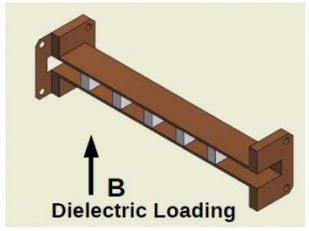
- **Active R&D inside ADMX**
- **X3 (before ADMX-HF)**
- **CAPP in Korea → very important effort**
  - **CULTASK & others…**
- **CAST as haloscope: CAST-CAPP, RADES.**

Also…

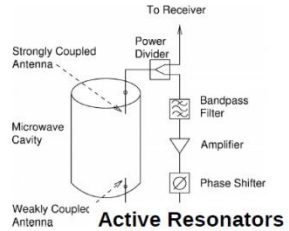
- **Dish antennas**
- **CASPEr**

A subset of ideas being explored...


Open Resonators



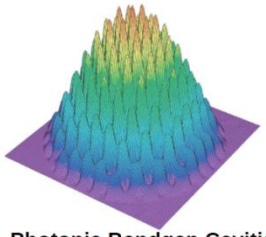
Dielectric Loading



Active Resonators

Exotic Tuning

Re-entrant Cavities


Photonic Bandgap Cavities

ADMX-HF

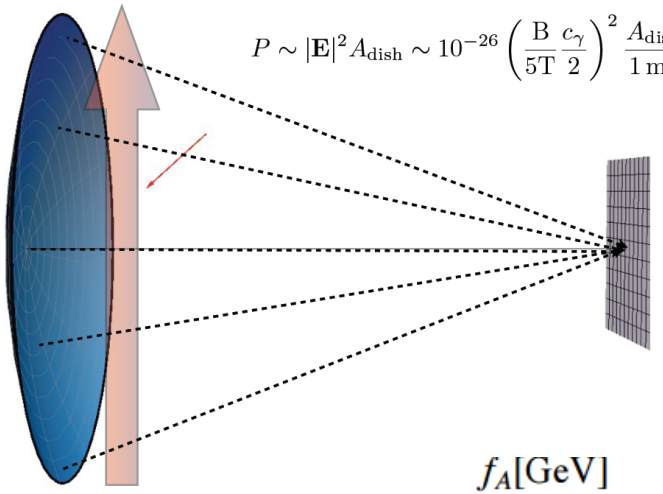
- 9 T superconducting solenoid
- Dilution Refrigerator: $T \sim 100$ mK
- Copper cavity with $Q_c \sim 20,000$, tunable from 3.5 to 5.85 GHz
- JPA: sub-quantum-limited, tunable from 4.4 to 6.4 GHz

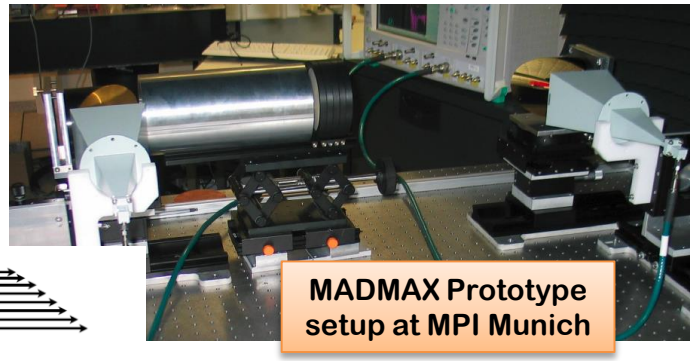
Beyond haloscopes…

Horns et al. JCAP 1304 (2013) 016
Jaeckel , Redondo JCAP 1311 (2013)

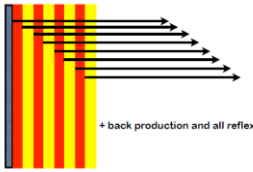
- **Dish antennas:**
  No resonance, but large area possible…
- **Realistic sensitivity limited, but boost possible with dielectric multilayer**
- **Directionality possible**

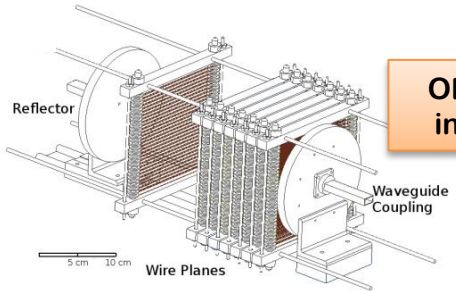
$$P \sim |\mathbf{E}|^2 A_{\rm dish} \sim 10^{-26} \left(\frac{\rm B}{5\rm T}\frac{c_\gamma}{2}\right)^2 \frac{A_{\rm dish}}{1\,\rm m^2}\,\rm Watt$$





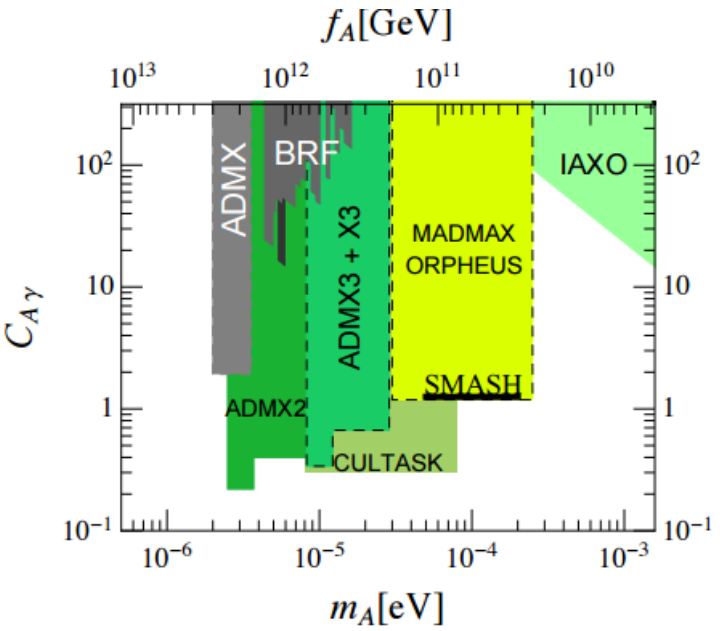
MADMAX Prototype setup at MPI Munich





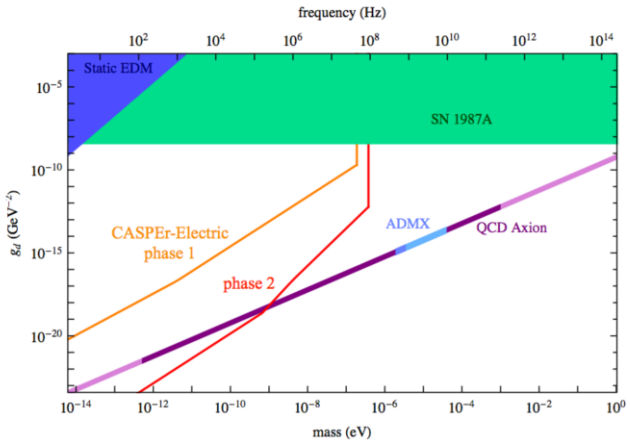
ORPHEUS in Seattle

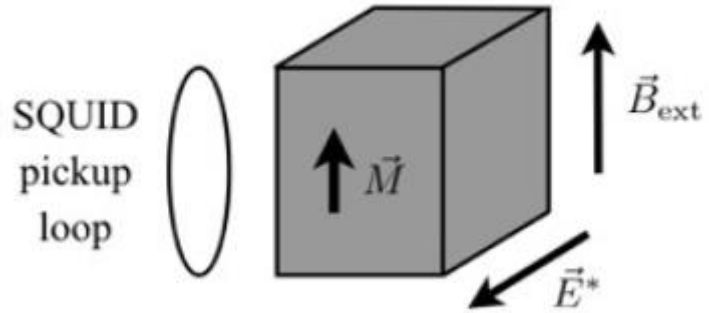
Plot from Ballesteros et al 1608.05414



Beyond haloscopes…

- **DM-induced spin precession?: CASPEr experiment (Mainz-Berkeley)**
- **Competitive at very low m_a**





$\frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$ ← Coupling to gluon field **CASPEr Electric**

$\frac{\partial_\mu a}{f_a}\bar{\Psi}_f\gamma^\mu\gamma_5\Psi_f$ ← Coupling to fermions **CASPEr Wind**

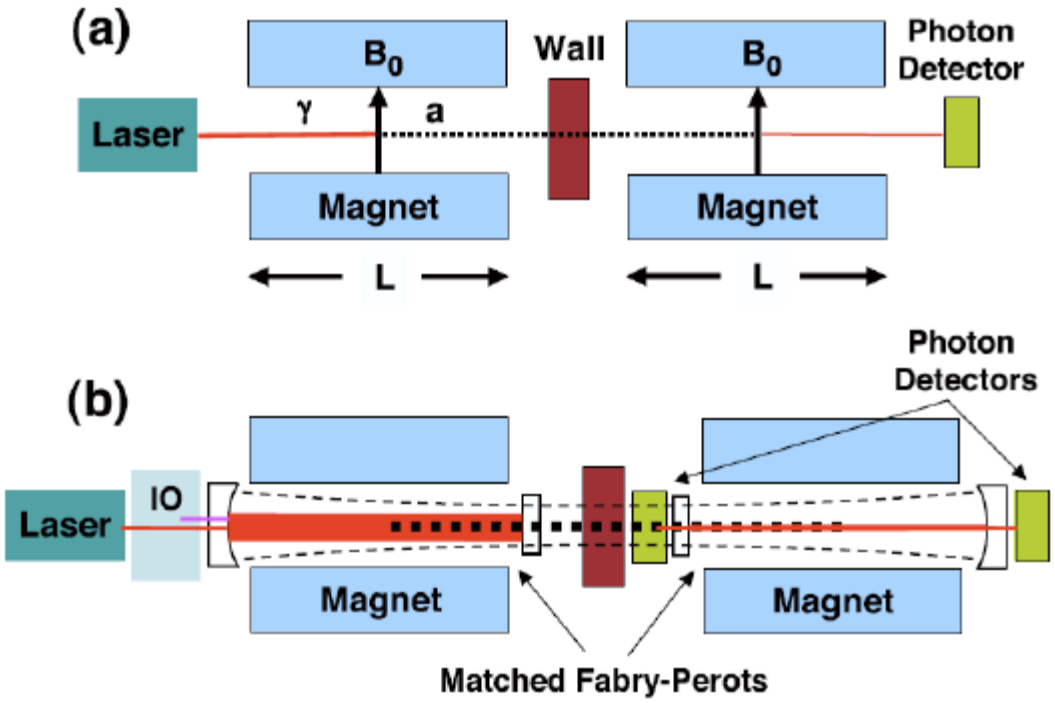
Phys. Rev. X 4, 021030 (2014)

- **Also QUAX experiment (Padova):**
  - **Sensitive to "axion DM wind" through axion-electron coupling**

Light shining through wall

Standard configuration →

Enhanced “resonant” configuration (future) →



2007: http://link.aps.org/doi/10.1103/PhysRevLett.98.172002

ALPS @ DESY-Hamburg

Any Light Particle Search @ DESY: ALPS I concluded in 2010

- **ALP II under preparation**
- **(resonant, 10+10 magnets,…)**
- **Also: OSQAR@CERN, CROWS@CERN, PVLAS @ Ferrara, GammeV & REAPR @ Fermilab, US, BMV @ Toulouse**

parameter	scaling	ALPS I	ALPS IIc	sens. gain
BL (total)	$g_{a\gamma} \propto (BL)^{-1}$	22 Tm	468 Tm	21
PC built up ($P_{\text{laser,eff.}}$)	$g_{a\gamma} \propto \beta_{\text{PC}}^{-1/4}$	1 (kW)	150 (kW)	3.5
rel. photon flux $\dot{n}_{\text{prod}}$	$g_{a\gamma} \propto \dot{n}_{\text{prod}}^{-1/4}$	1 (532 nm)	2 (1064 nm)	1.2
RC built up β_{RC}	$g_{a\gamma} \propto \beta_{\text{RC}}^{-1/4}$	1	40,000	14
detector eff. DE	$g_{a\gamma} \propto DE^{-1/4}$	0.9	0.75	0.96
detector noise DC	$g_{a\gamma} \propto DC^{1/8}$	$1.8{\cdot}10^{-3}$ s^{-1}	10^{-6} s^{-1}	2.6
combined				3082

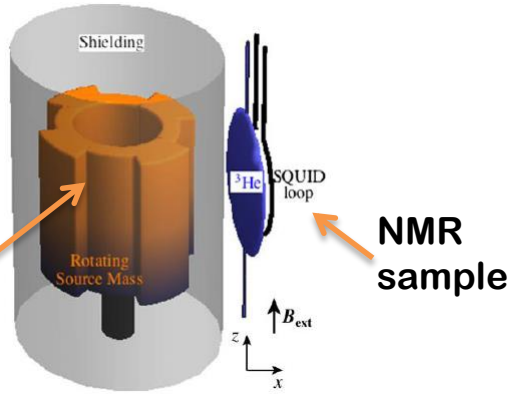
Axion-mediated macroscopic forces

Axions could be detected as short-range deviation of gravity…
(but traditionally though without enough sensitivity to QCD axions)

Recently proposed: ARIADNE experiment
Short-range force by NMR technique

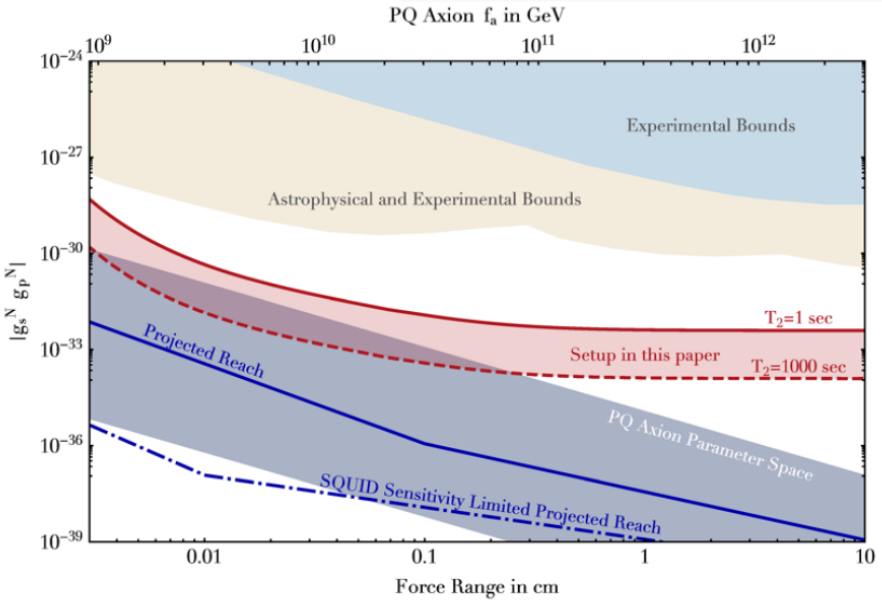
Good prospects for sub-meV axion

Arvanitaki, Geraci
Phys. Rev. Lett. 113, 161801 (2014)



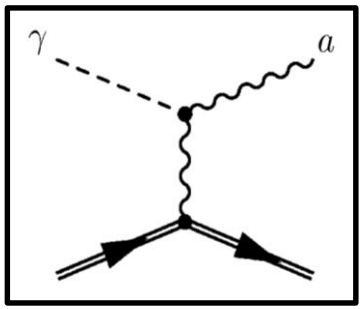
Rotating source mass

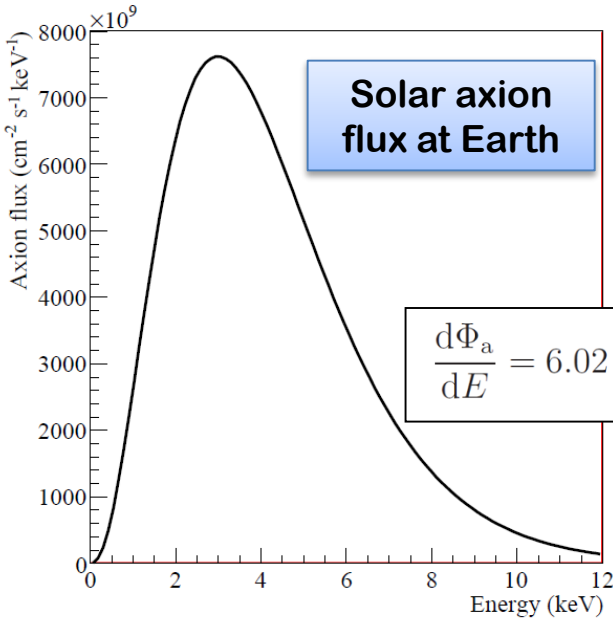
NMR sample



Solar Axions

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





Solar axion flux at Earth

axions

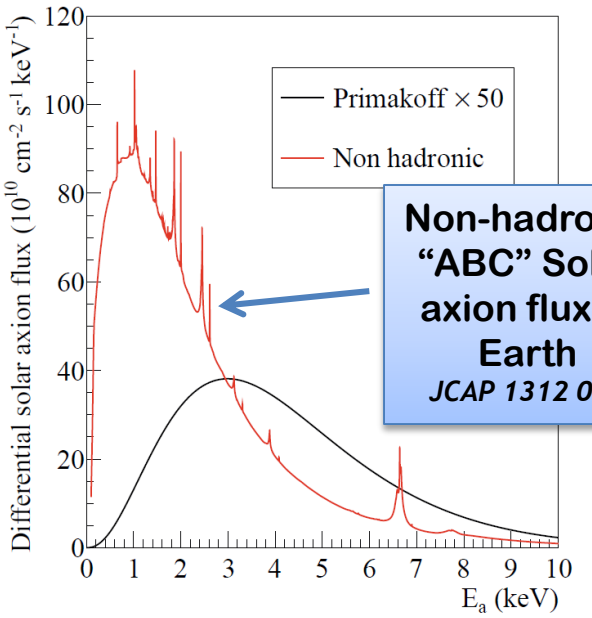
$$\frac{d\Phi_a}{dE} = 6.02 \times 10^{10}\ \mathrm{cm^{-2}\ s^{-1}\ keV^{-1}}\ g_{10}^2\, E^{2.481} e^{-E/1.205}.$$

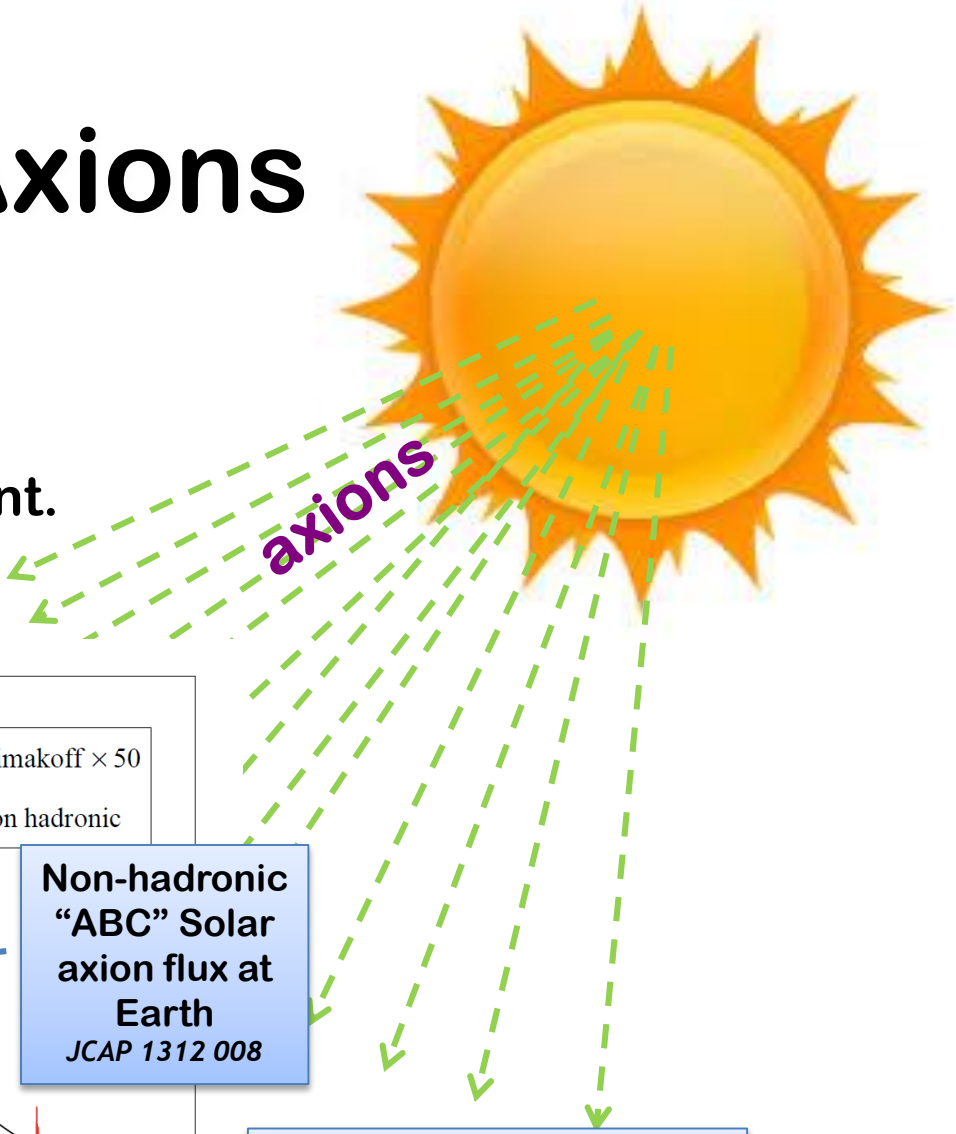
$$g_{10} = g_{a\gamma}/10^{-10}\ \mathrm{GeV^{-1}}$$

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.**



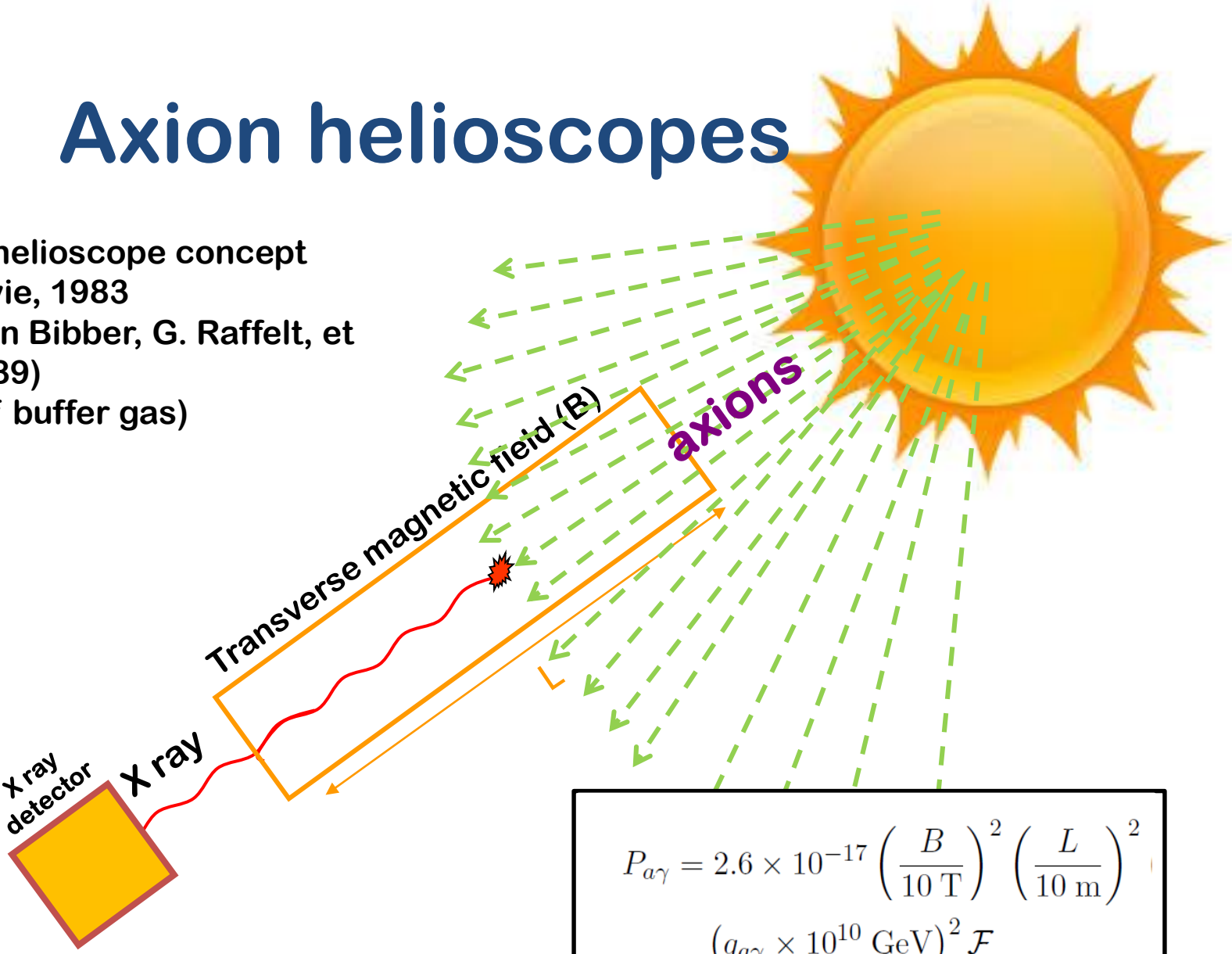


Non-hadronic "ABC" Solar axion flux at Earth
JCAP 1312 008

*** 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)



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

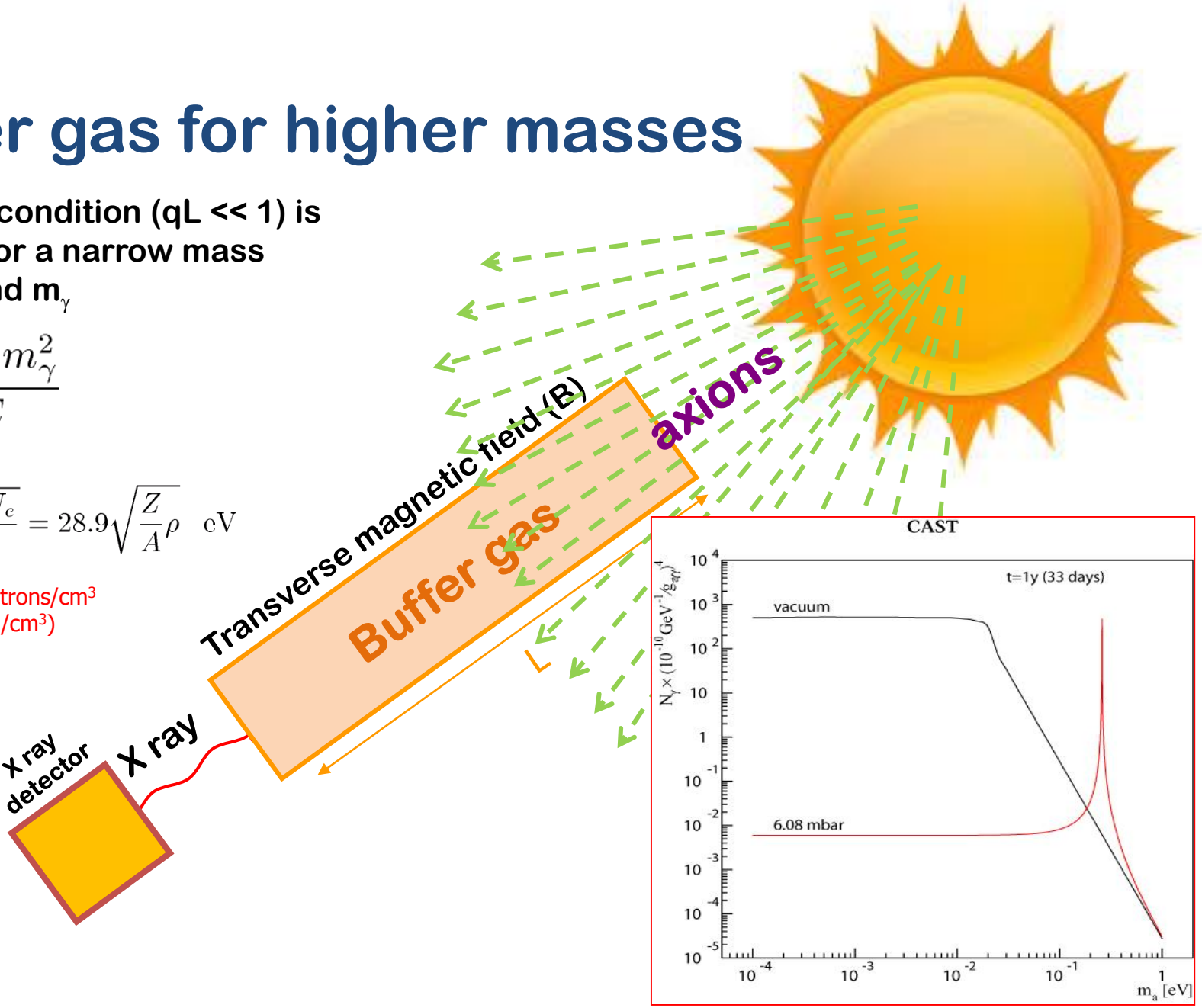
Buffer gas for higher masses

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

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

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

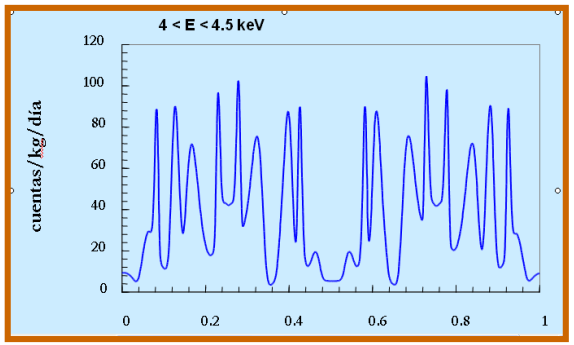
N_e: number of electrons/cm^3
ρ: gas density (g/cm^3)

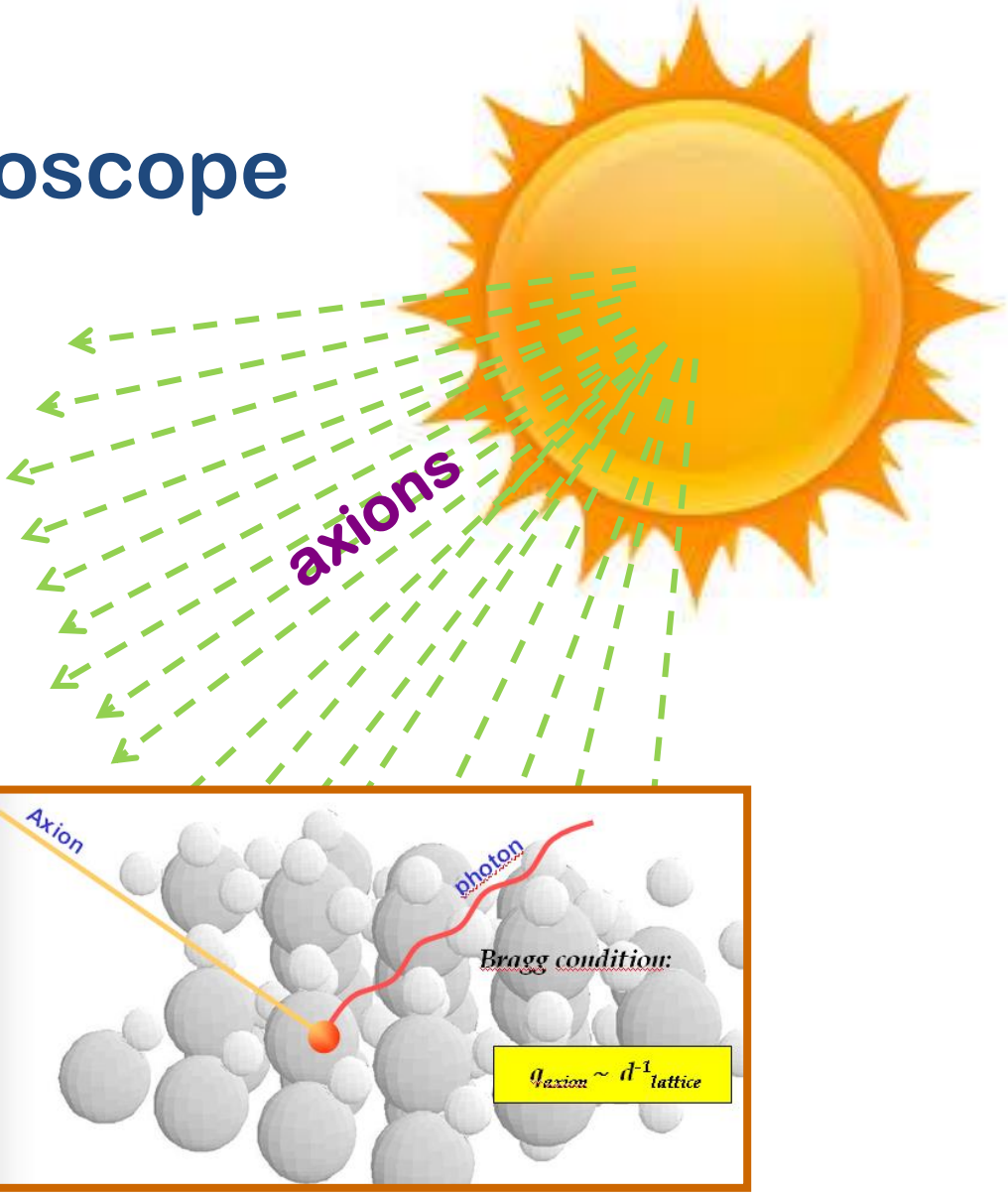


Other types of helioscope

- 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:

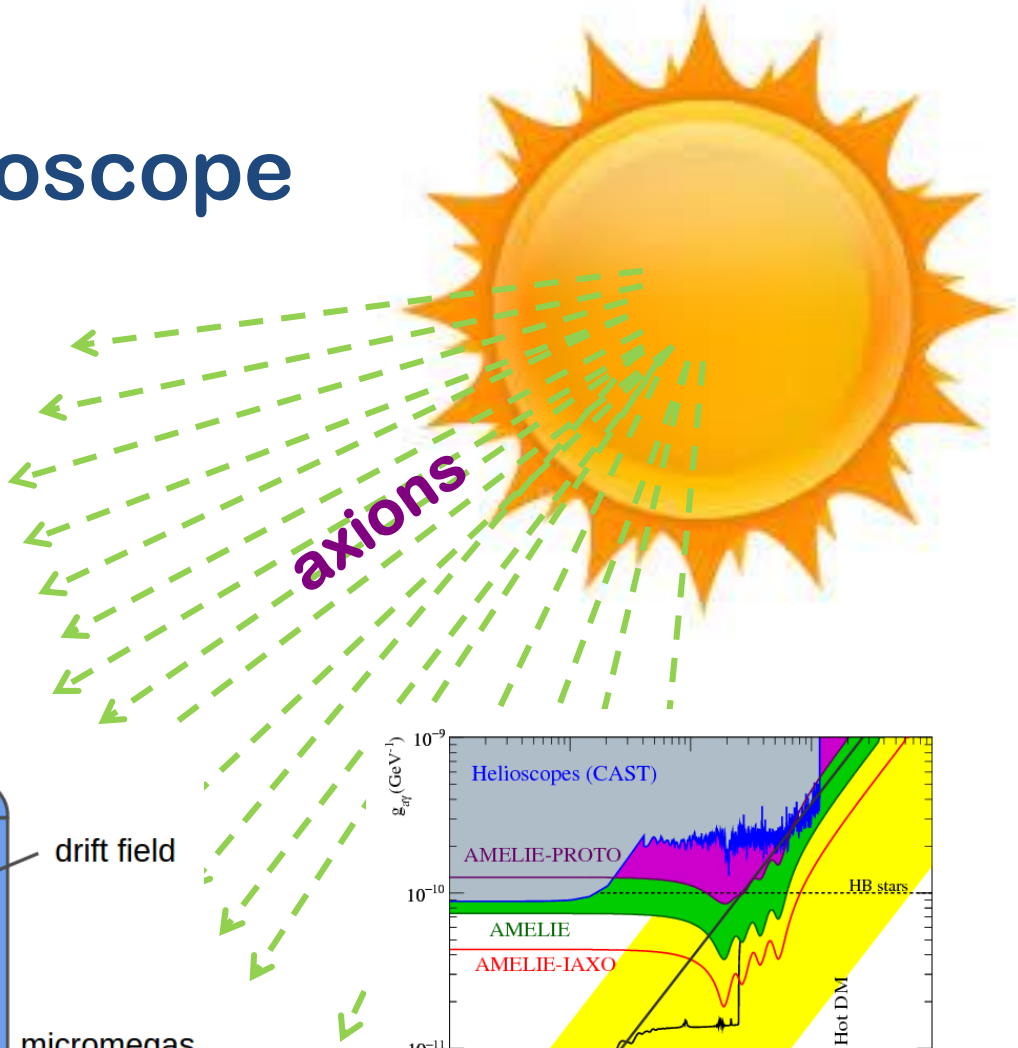
«

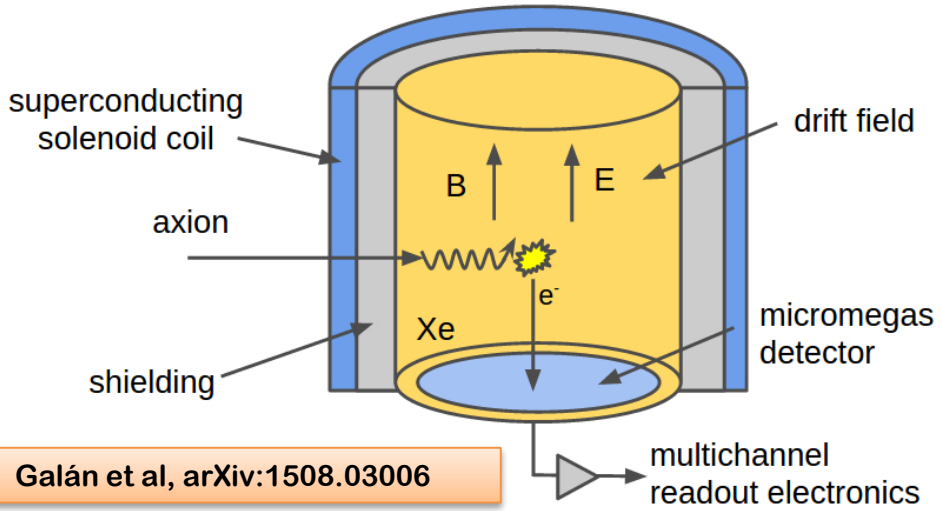




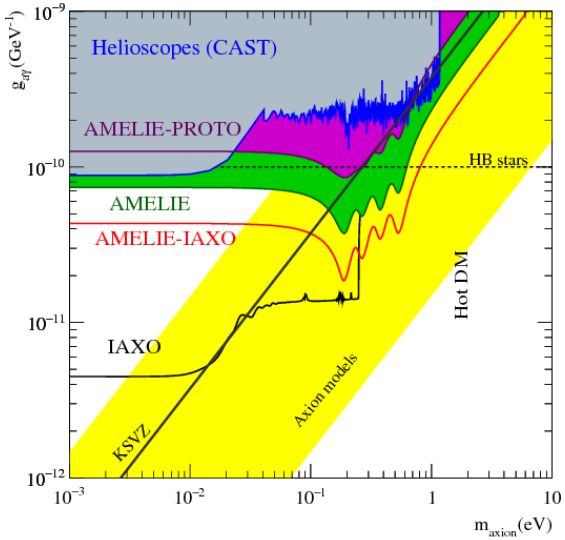
Other types of helioscope

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



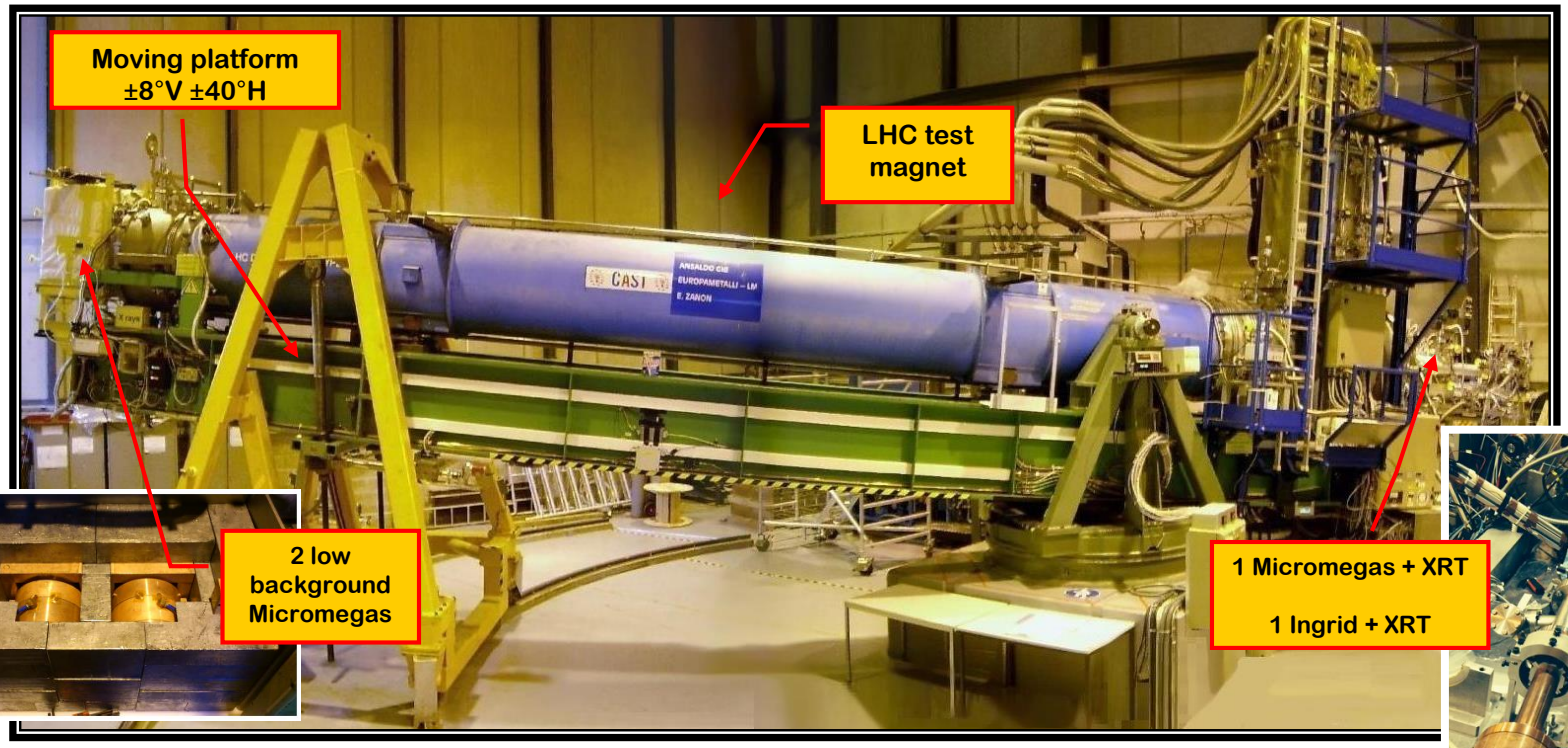


Galán et al, arXiv:1508.03006



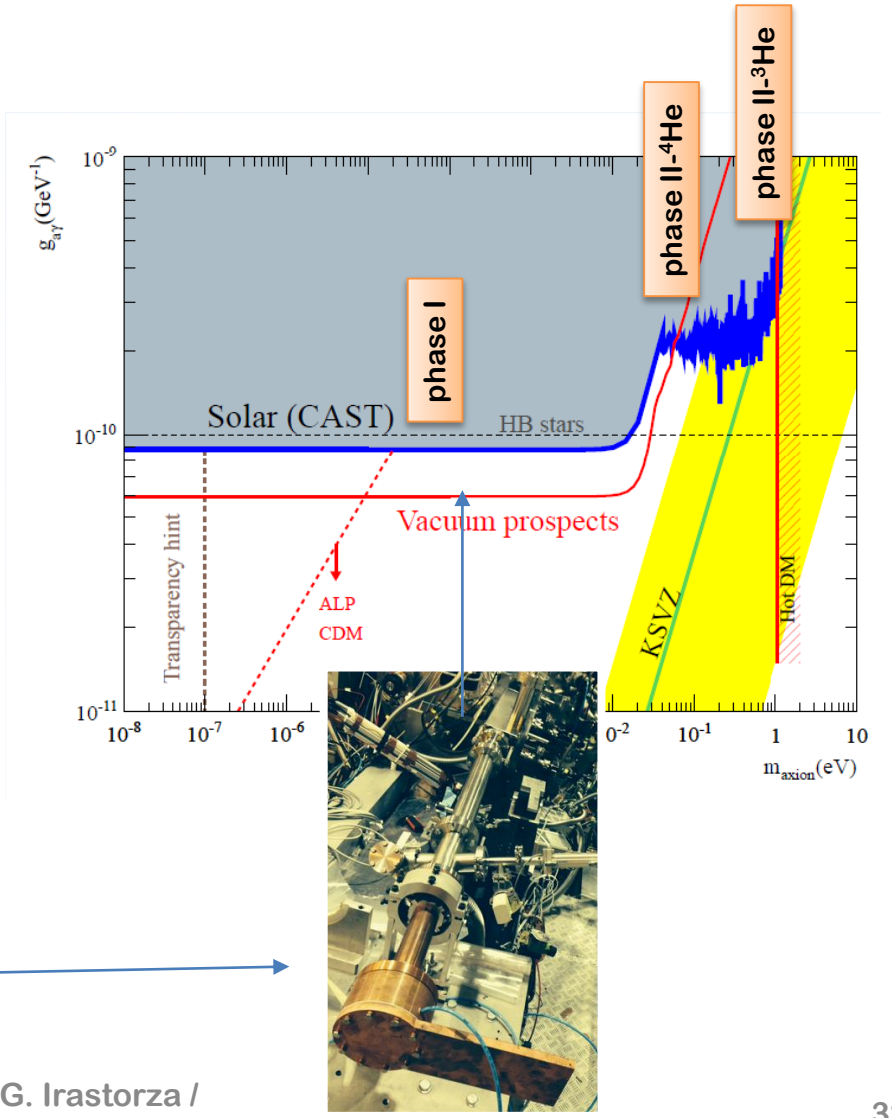
CAST experiment @ CERN

- 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.



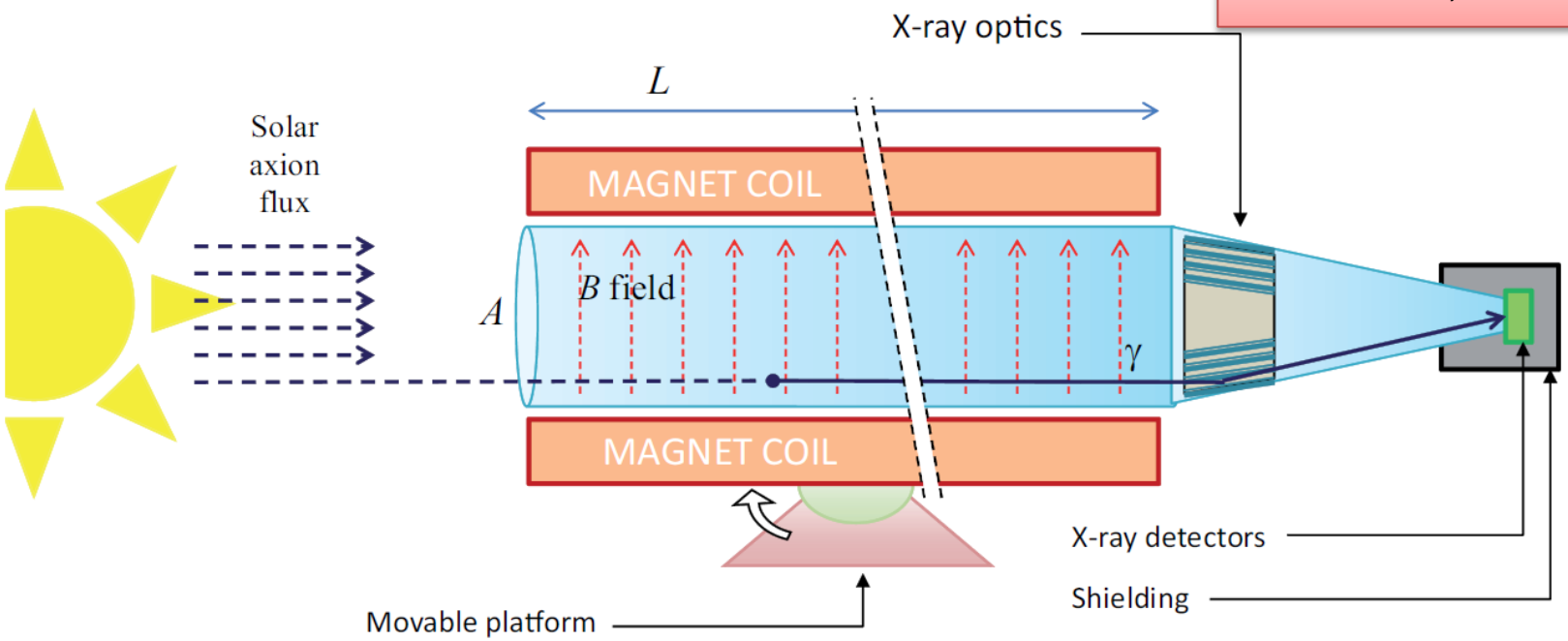
CAST results

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 •**Analisis ongoing.** •**New result soon available**



IAXO – Concept

Enhanced axion helioscope:
JCAP 1106:013,2011

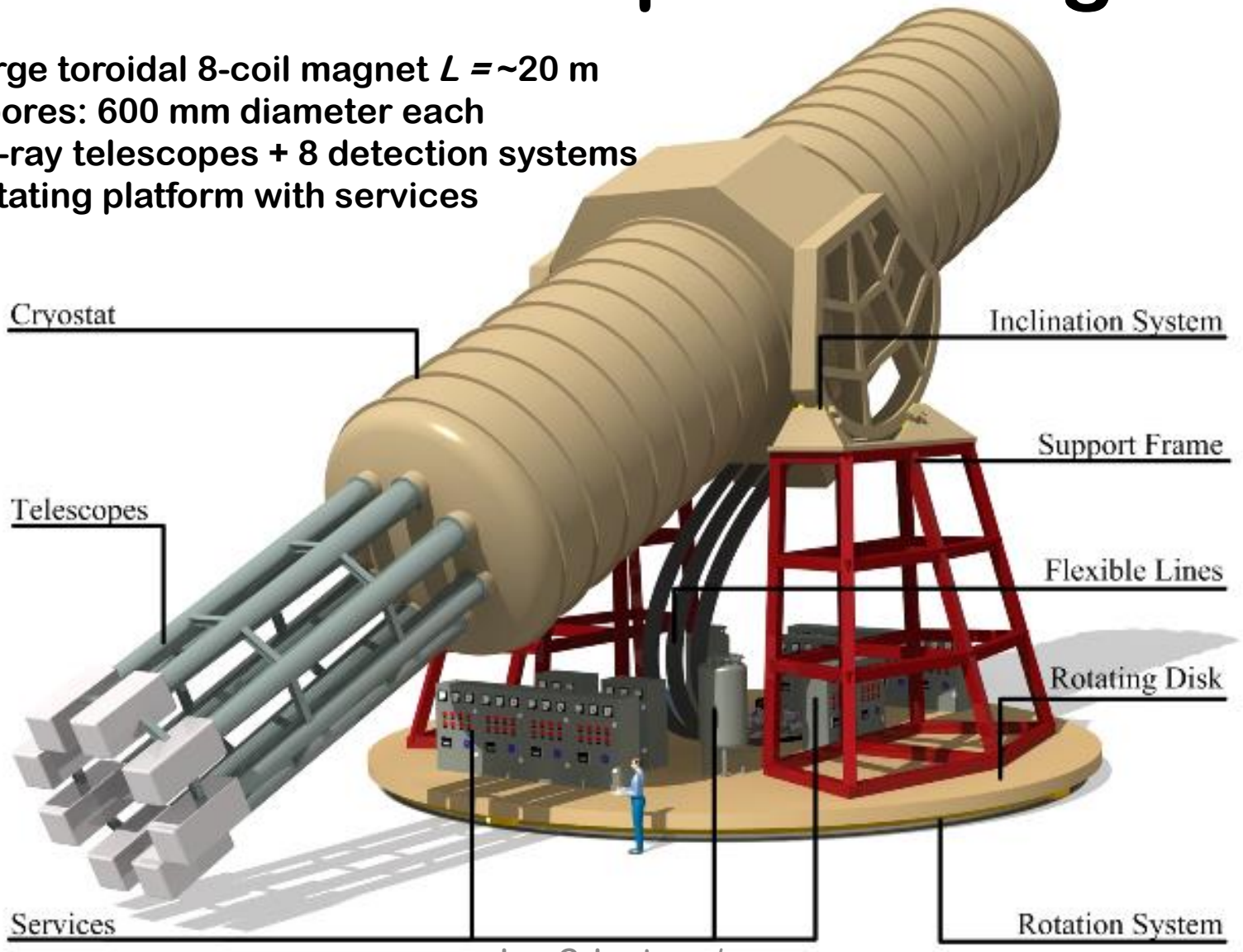


$$g_{a\gamma}^4 \propto \underbrace{b^{1/2}\epsilon^{-1}}_{\text{detectors}} \times \underbrace{a^{1/2}\epsilon_o^{-1}}_{\text{optics}} \times \underbrace{(BL)^{-2}A^{-1}}_{\text{magnet}} \times \underbrace{t^{-1/2}}_{\text{exposure}}$$

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

IAXO – Conceptual Design

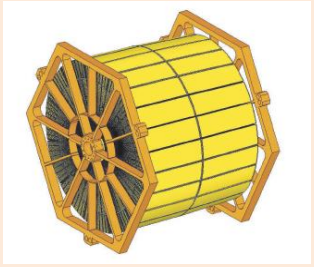
- **Large toroidal 8-coil magnet L = ~20 m**
- **8 bores: 600 mm diameter each**
- **8 x-ray telescopes + 8 detection systems**
- **Rotating platform with services**



IAXO technologies – Baseline

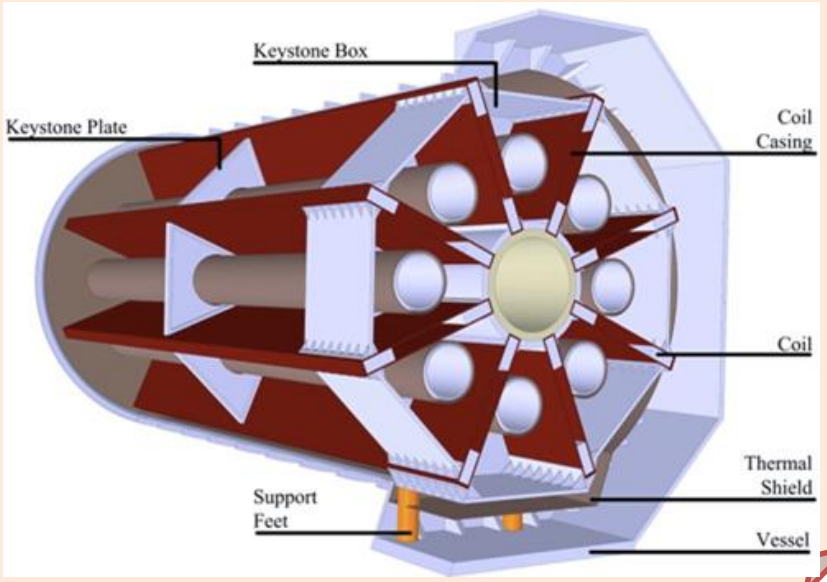
IAXO telescopes

- 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



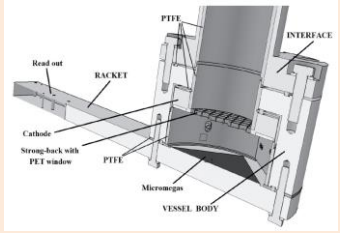
IAXO magnet

- 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



IAXO detectors

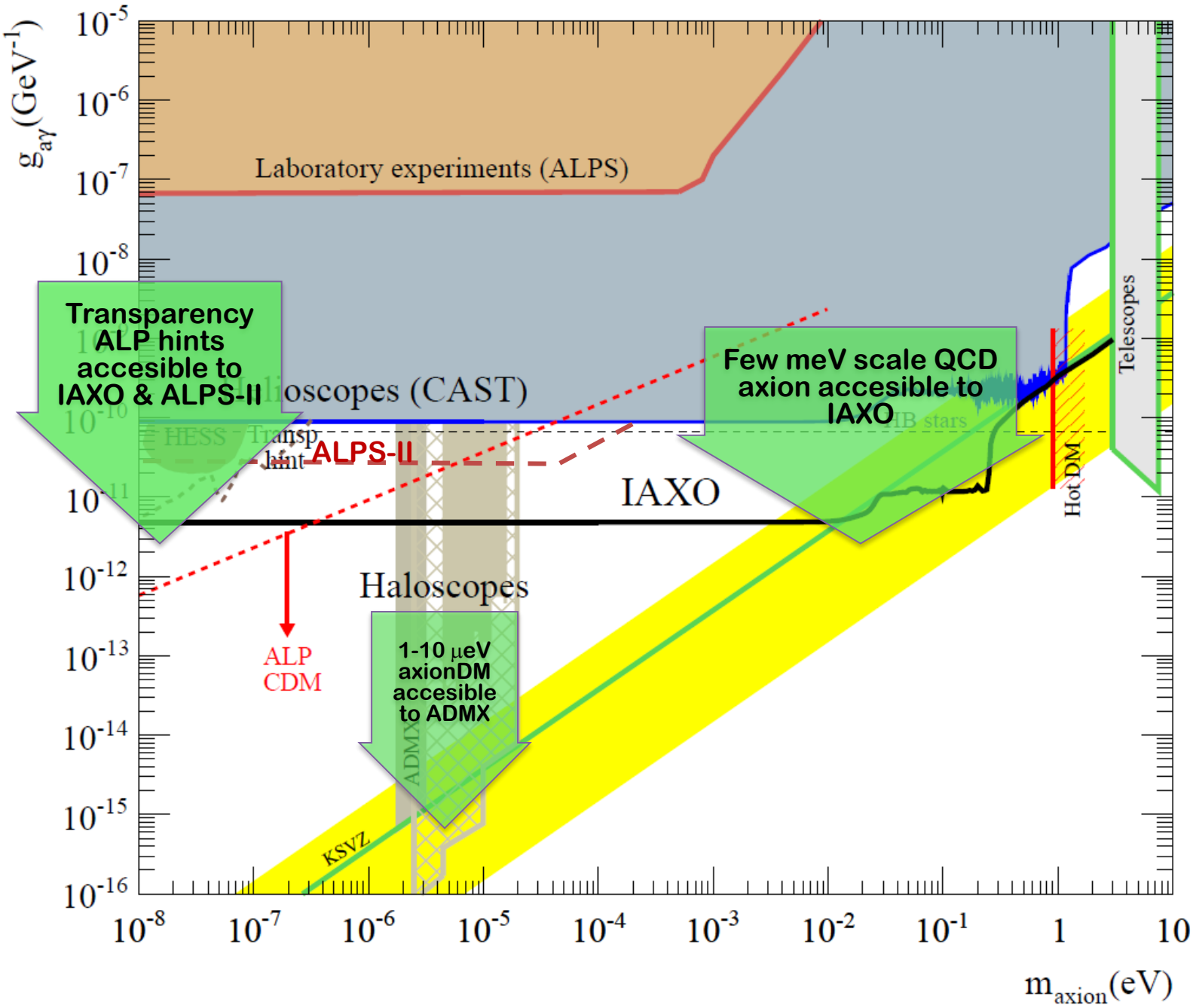
- Micromegas gaseous detectors
- Radiopure components + shielding
- Discrimination from event topology in gas
- Long trajectory in CAST
- Zaragoza + CEA (+ others) expertise
- Also considered: Ingrid, MMCs, CCDs

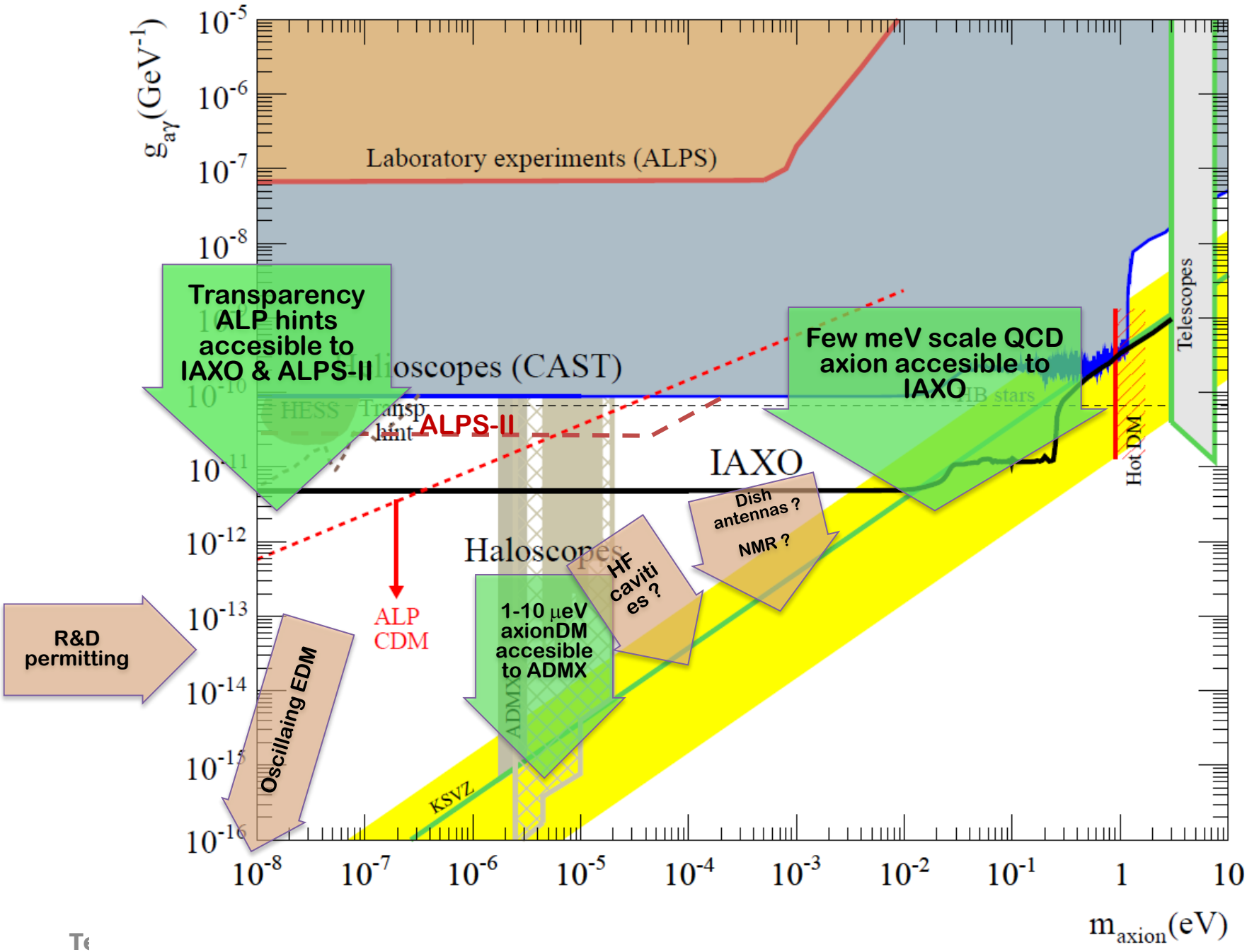


Baseline developed at:
IAXO Letter of Intent: CERN-SPSC-2013-022
IAXO Conceptual Design: JINST 9 (2014) T05002 (arXiv:1401.3233)

Services

Rotation System


$g_{a\gamma}$(GeV^{-1})
Laboratory experiments (ALPS)
Transparency
ALP hints
accesible to
IAXO & ALPS-II
oscopes (CAST)
HESS
Transp
hint
ALPS-II
IAXO
Few meV scale QCD
axion accesible to
IAXO
HB stars
Telescopes
Hot DM
Haloscopes
ALP
CDM
1-10 μeV
axionDM
accesible
to ADMX
ADMX
KSVZ
m_{axion}(eV)


$g_{a\gamma}$(GeV^{-1})
Laboratory experiments (ALPS)
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IAXO
HB stars
Telescopes
Hot DM
Haloscopes
Dish
antennas ?
NMR ?
HF
caviti
es ?
1-10 μeV
axionDM
accesible
to ADMX
ADMX
ALP
CDM
R&D
permitting
Oscillaing EDM
KSVZ
m_{axion}(eV)

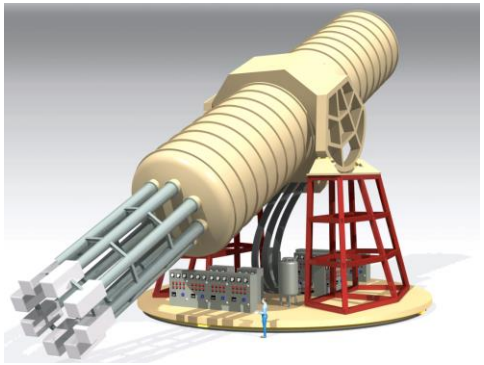
Conclusions

- 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: IAXO next generation
- Haloscopes: ADMX, CAPP → R&D to go higher m_a
- New ideas to tackle new regions: Dish antenna, dielectric layers, NMR,…

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

Good timing for axions… stay tuned



Backup slides…

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:

$$|\theta| < 0.7 \times 10^{-11}$$

•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 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

"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 "dinamically"

The axion

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

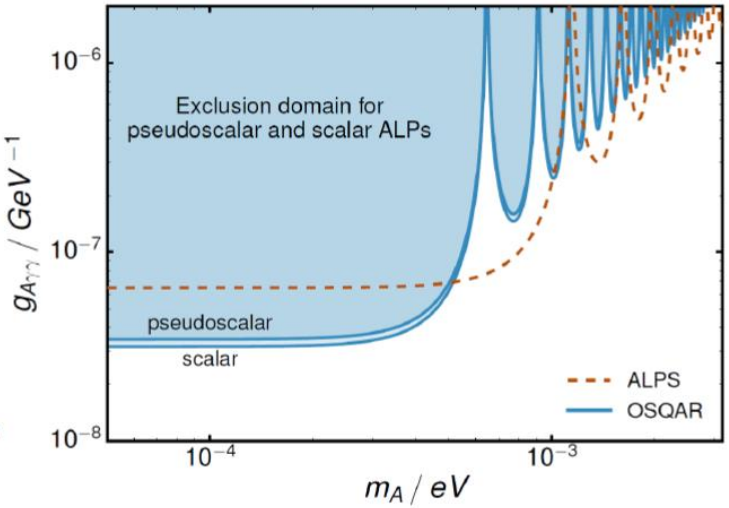
  (Weinberg, Wilcek)

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

- **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)

$$m_a \simeq 0.6 \text{ eV} \frac{10^7 \text{GeV}}{f_a}$$

OSQAR @ CERN

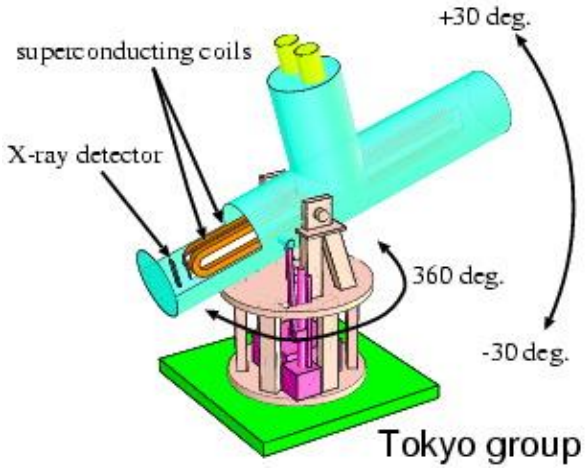


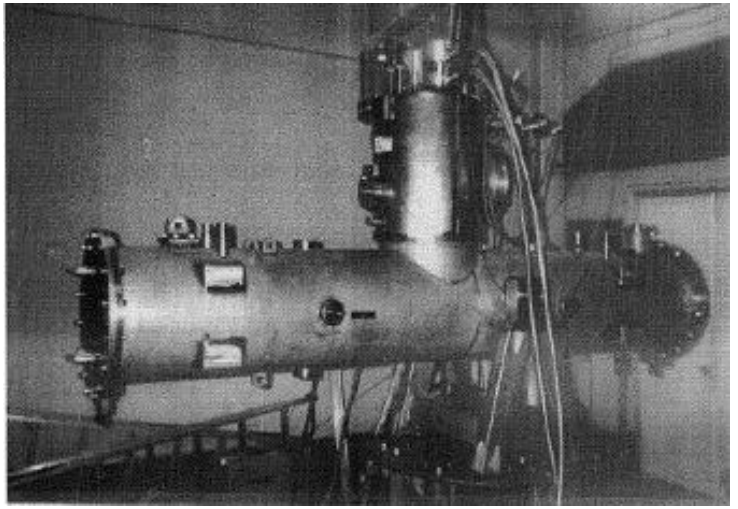
Also:

- **GammeV & REAPR @ Fermilab, US**
- **BMV @ Toulouse**
- **PVLAS @ Ferrara**
- **CROWS @ CERN**
- **…**

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**



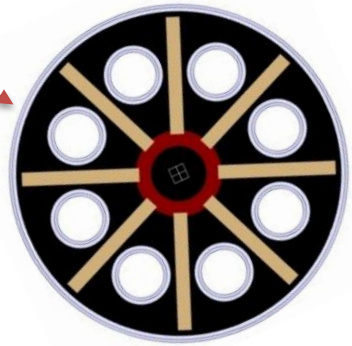


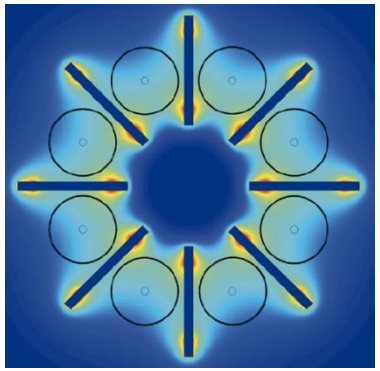
- **Presently running:**
  - **CERN Axion Solar Telescope (CAST)**

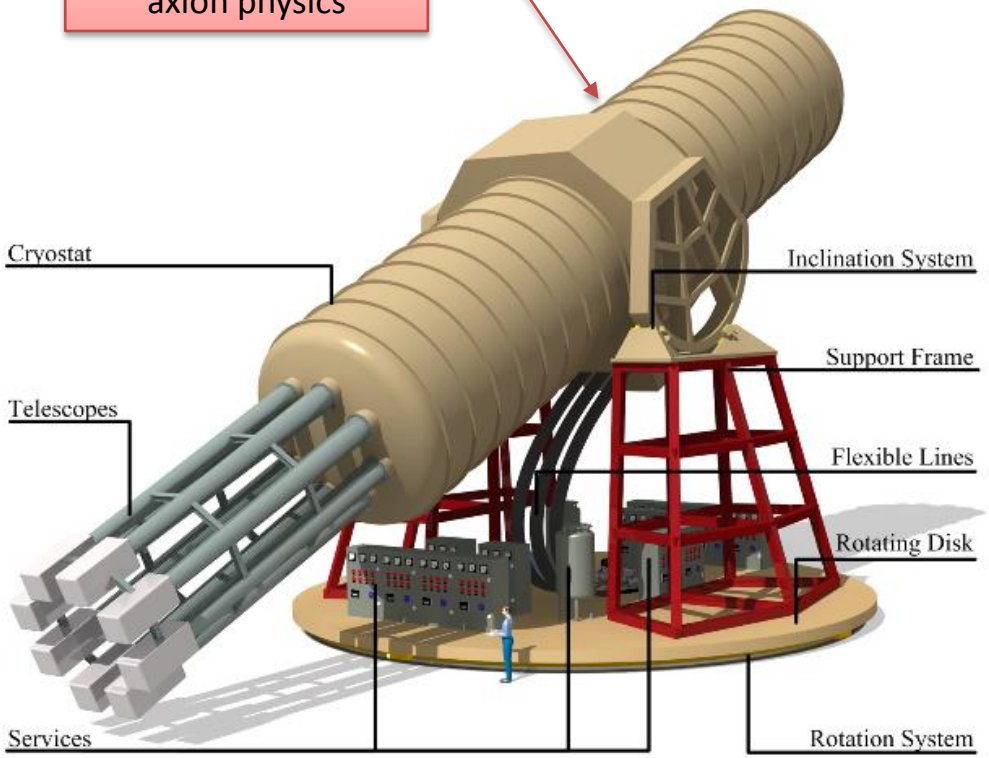
IAXO magnet

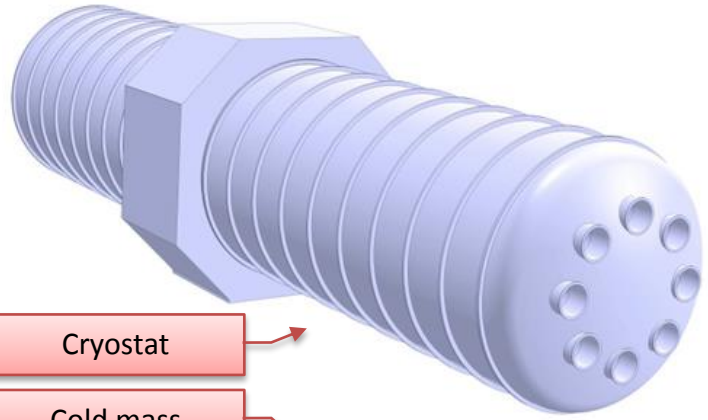
TOROIDAL CONFIGURATION specifically built for axion physics

Each conversion bore (between coils) 600 mm diameter



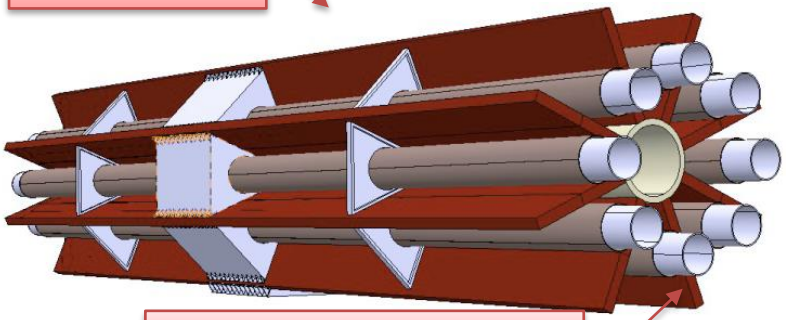






Cryostat

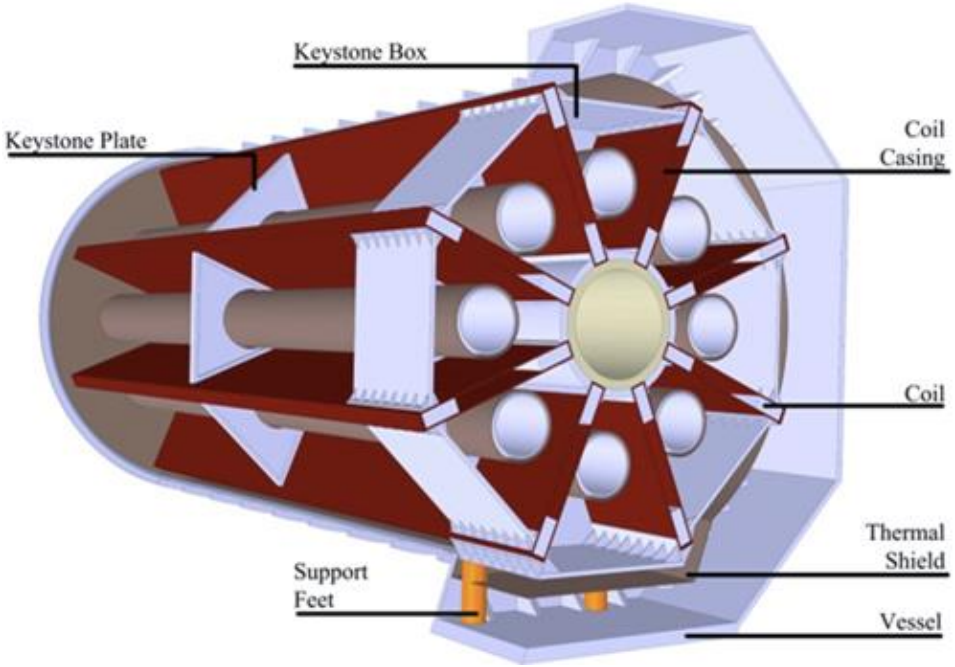
Cold mass



Bores go through cryostat

Magnetic length 20 m Total cryostat length 25 m

IAXO magnet



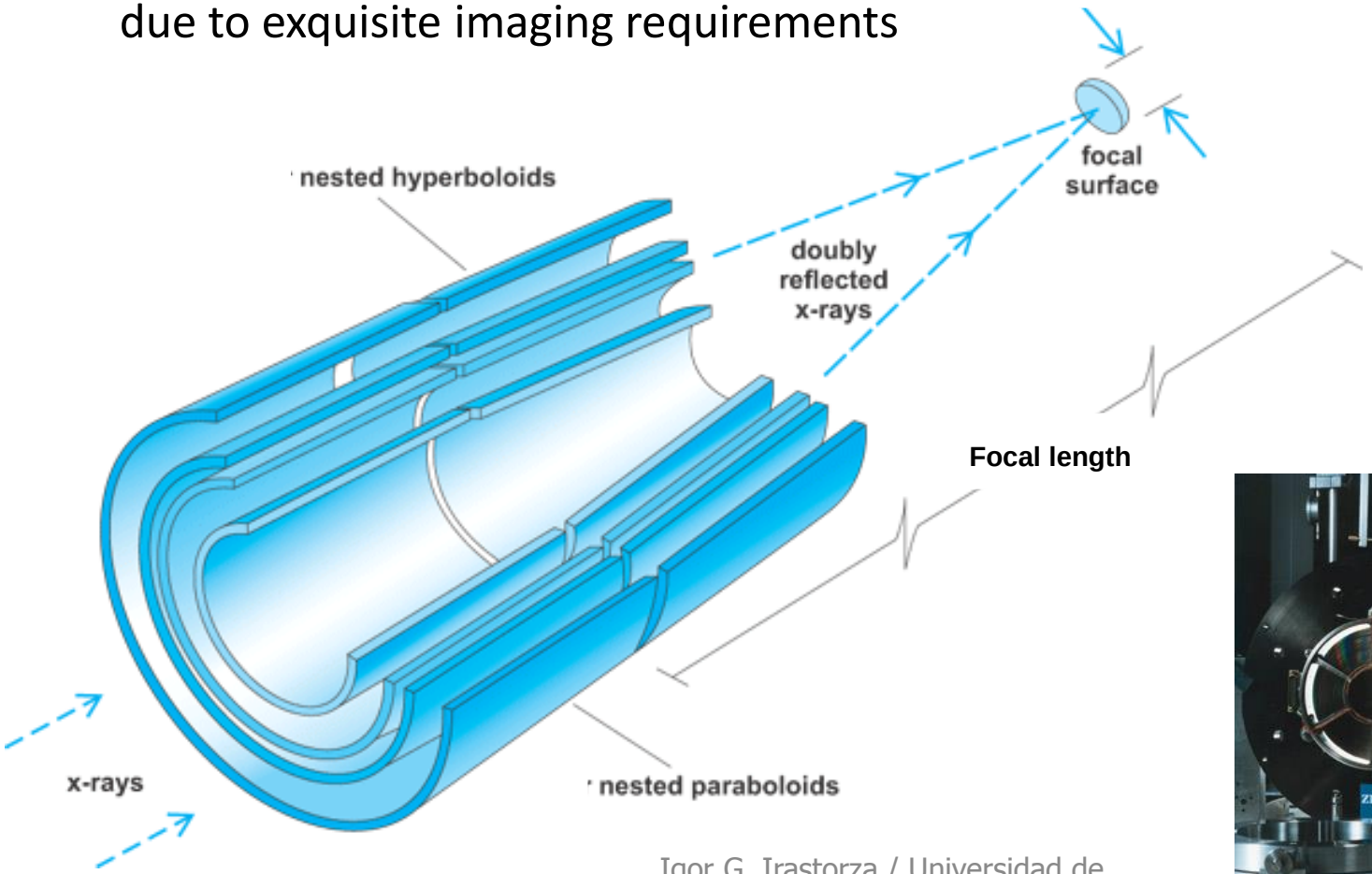
Property		*Value*
Cryostat dimensions:	Overall length (m)	25
	Outer diameter (m)	5.2
	Cryostat volume (m^3)	$\sim$ 530
Toroid size:	Inner radius, R_{in} (m)	1.0
	Outer radius, R_{out} (m)	2.0
	Inner axial length (m)	21.0
	Outer axial length (m)	21.8
Mass:	Conductor (tons)	65
	Cold Mass (tons)	130
	Cryostat (tons)	35
	Total assembly (tons)	$\sim$ 250
Coils:	Number of racetrack coils	8
	Winding pack width (mm)	384
	Winding pack height (mm)	144
	Turns/coil	180
	Nominal current, I_{op} (kA)	12.0
	Stored energy, E (MJ)	500
	Inductance (H)	6.9
	Peak magnetic field, B_p (T)	5.4
	Average field in the bores (T)	2.5
Conductor:	Overall size (mm^2)	35 $\times$ 8
	Number of strands	40
	Strand diameter (mm)	1.3
	Critical current @ 5 T, I_c (kA)	58
	Operating temperature, T_{op} (K)	4.5
	Operational margin	40%
	Temperature margin @ 5.4 T (K)	1.9
Heat Load:	at 4.5 K (W)	$\sim$150
	at 60-80 K (kW)	$\sim$1.6

IAXO magnet concept presented in:

- IEEE Trans. Appl. Supercond. 23 (ASC 2012)
- Adv. Cryo. Eng. (CEC/ICMC 2013)
- IEEE Trans. Appl. Supercond. (MT 23)

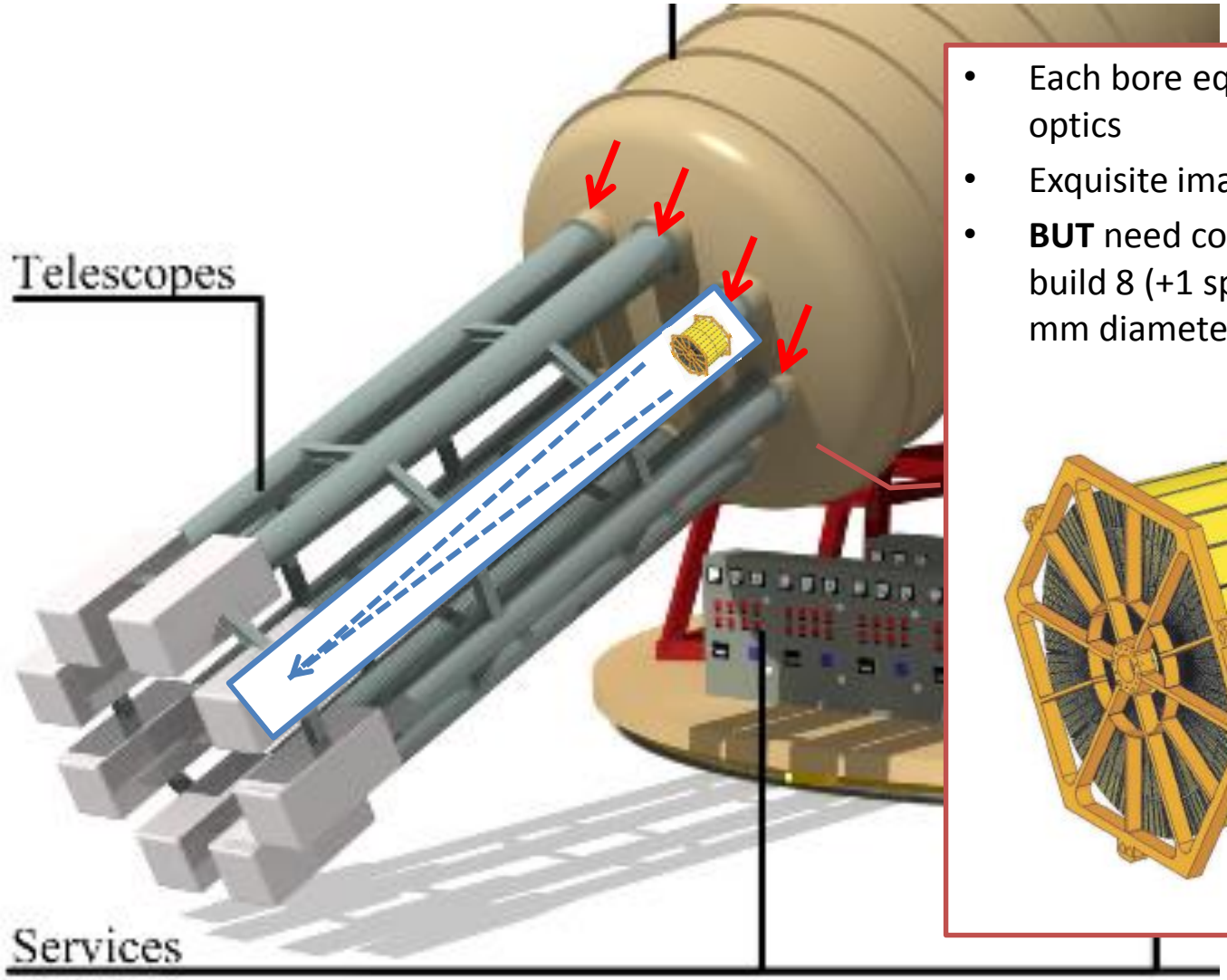
IAXO x-ray optics

- 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

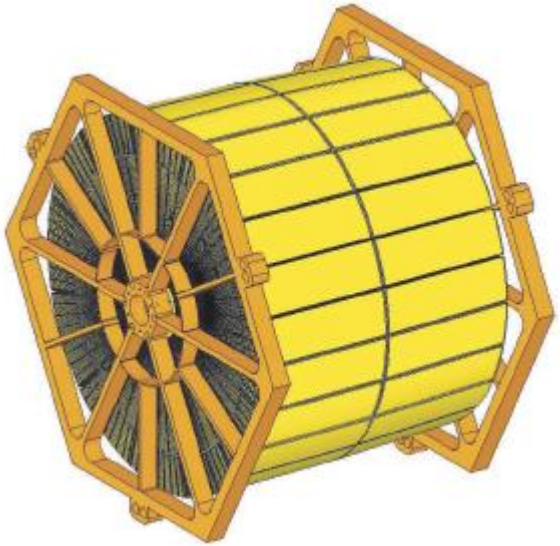


ABRIXAS spare telescope, in use in one of the 4 bores of CAST (pioneer use of x-ray optics in axion research)

IAXO x-ray optics

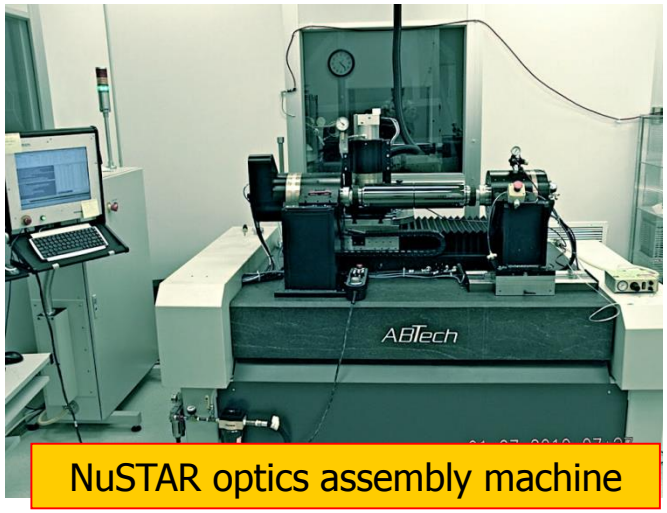


- Each bore equipped with an x-ray optics
- Exquisite imaging not required
- **BUT** need cost-effective way to build 8 (+1 spare) optics of 600 mm diameter each



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



NuSTAR optics assembly machine

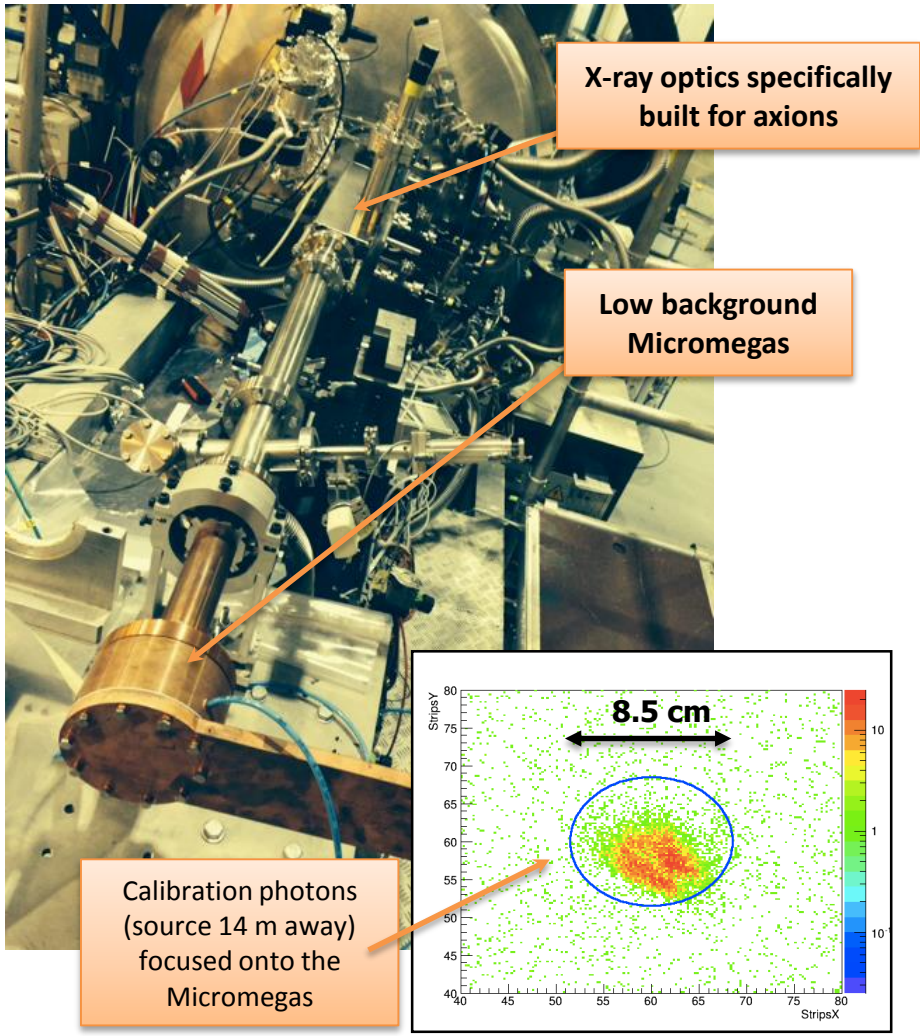
- The specialized tooling to shape the substrates and assemble the optics is now available
- Hardware can be easily configured to make optics with a variety of designs and sizes
- Key institutions in NuSTAR optics: LLNL, U. Columbia, DTU Denmark. All in IAXO !

NuSTAR telescope
~400 cm Ø

IAXO low background detectors

Optics+detector pathfinder system in CAST

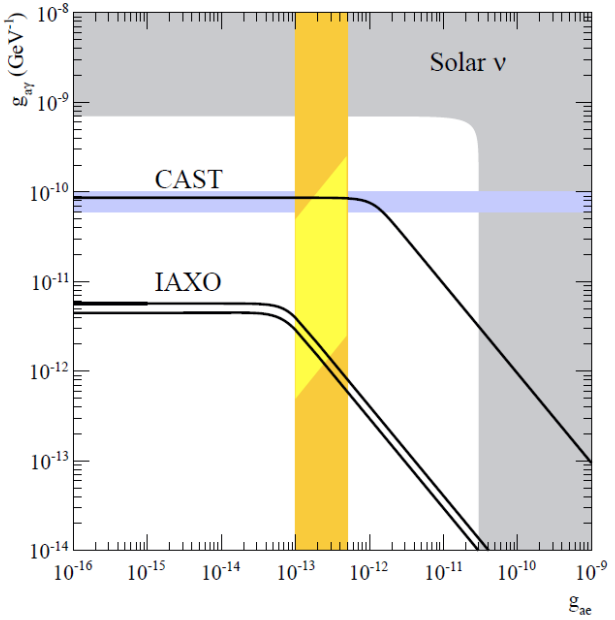
- **IAXO optics+detector joint system**
  - Newly designed MM detector (following IAXO CDR)
  - New x-ray optics fabricated following technique proposed for IAXO (but much smaller, adapted to CAST bore)
  - First time low background + focusing in the same system
  - Very important operative experience for IAXO
- Installed & commissioned successfully in CAST last september. Now taking data



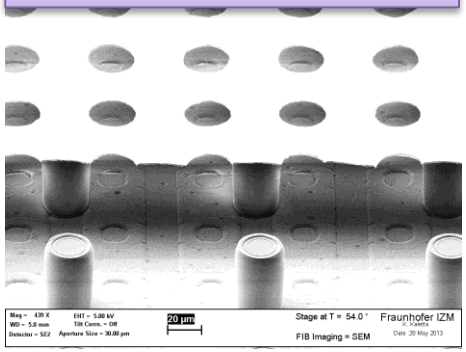
Additional IAXO physics cases

- Detection of “ABC”-produced solar axions (with relevant g_{ae} values)
- More specific WISPs models at the **low energy frontier** of particle physics:
  - Paraphotons / hidden photons
  - Chamaleons
  - Non-standard scenarios of axion production

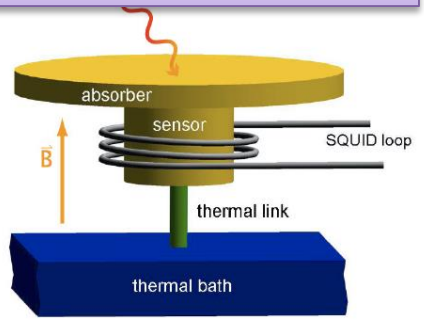
– Possible addition technologies to push E thresholds down:



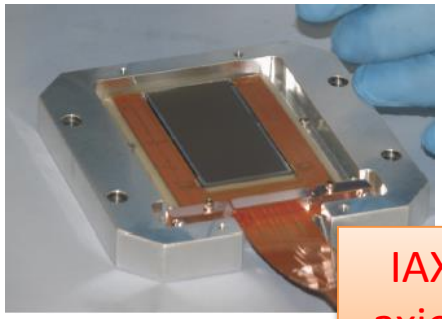
GridPix/Ingrid detectors



Magnetic Metallic Calorimeter (MMC)



Low-noise CCDs



IAXO as “generic axion/ALP facility”

AXION Cosmology

- **Axions are produced** in the early Universe by a number of processes:
  - Axion realignment
  - Decay of axion strings
  - Decay of axion walls

  → NON-RELATIVISTIC (COLD) AXIONS

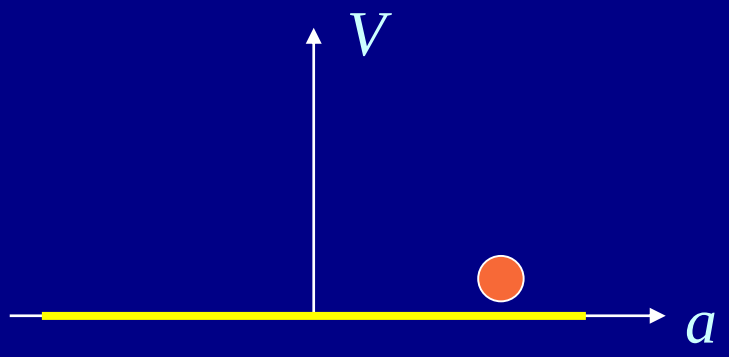
  - Thermal production

  → RELATIVISTIC (HOT) AXIONS

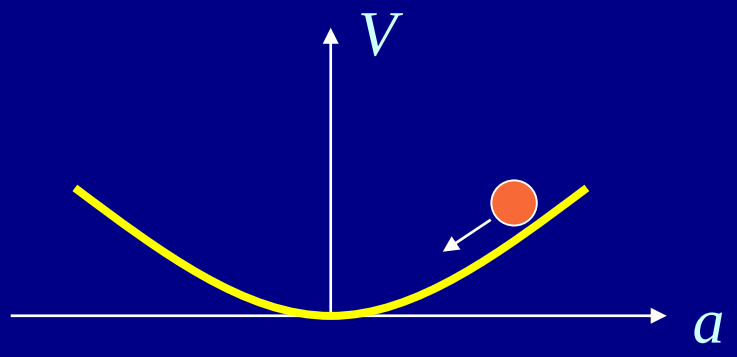
AXION Cosmology

- **Axion realignment**:

When $T > T_{QCD}$
$<a_{phys}>$ is arbitrary



When $T \sim T_{QCD}$
$<a_{phys}> \rightarrow 0$



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")

Axion Cosmology

- The **CDM axion relic density** is uncertain as it depends on several factors:
- Inflation before PQ transition CASE 1
  - "initial misaligment angle" $<a_{phys}>_0$ varies spatially → Averaged.
  - Contributions from axion strings and domain walls must be computed→ difficult (see Sikivie astro-ph/0610440)
- Late-inflation scenario (inflation after PQ transition) CASE 2
  - The "initial misaligment angle" $<a_{phys}>_0$ unique for all visible universe.
  - Strings and walls wiped out by inflation. Not contributing. And in any case difficult to compute their contribution.
- Very approximately:

$$\Omega_a \sim 0.15 \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{7/6} \left(\frac{0.7}{h}\right)^2 \alpha_1^2$$

CASE 2

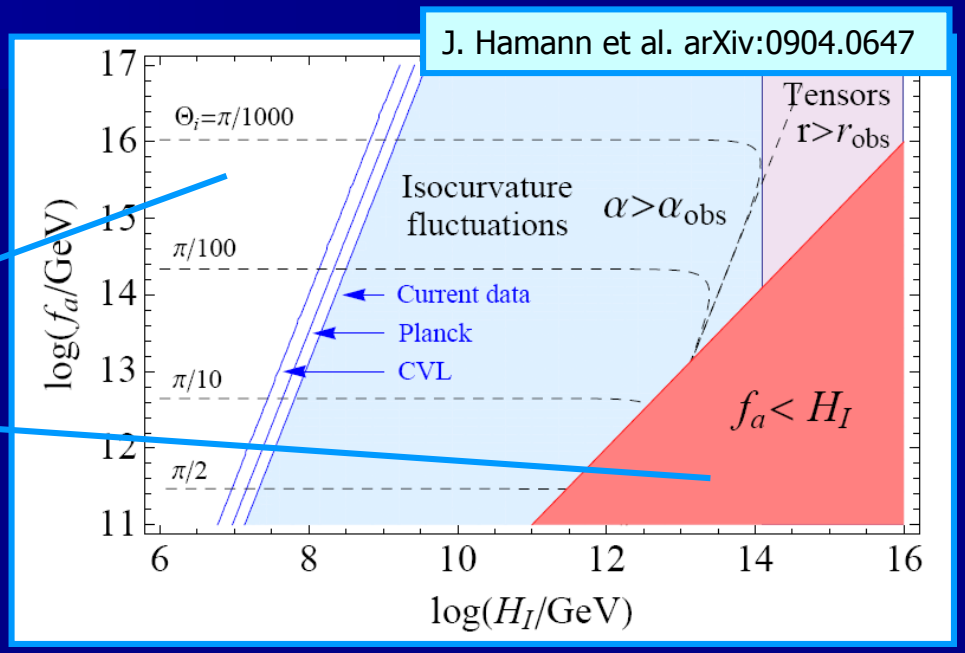
$$\sim 0.7 \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{7/6} \left(\frac{0.7}{h}\right)^2$$

CASE 1

Sikivie astro-ph/0610440

Axion Cosmology

- Which value for f_a (and therefore mass) gives the right amount of axion density?
  - Late-inflation: Wide range of mass possible if initial misalignment "tuned"
  - Late-inflation: Mass determined but calculation uncertain.



- In general…
  - Range of axion masses of **10^{-6} – 10^{-3} eV** are of interest for the axion to be the (main component of the) CDM.

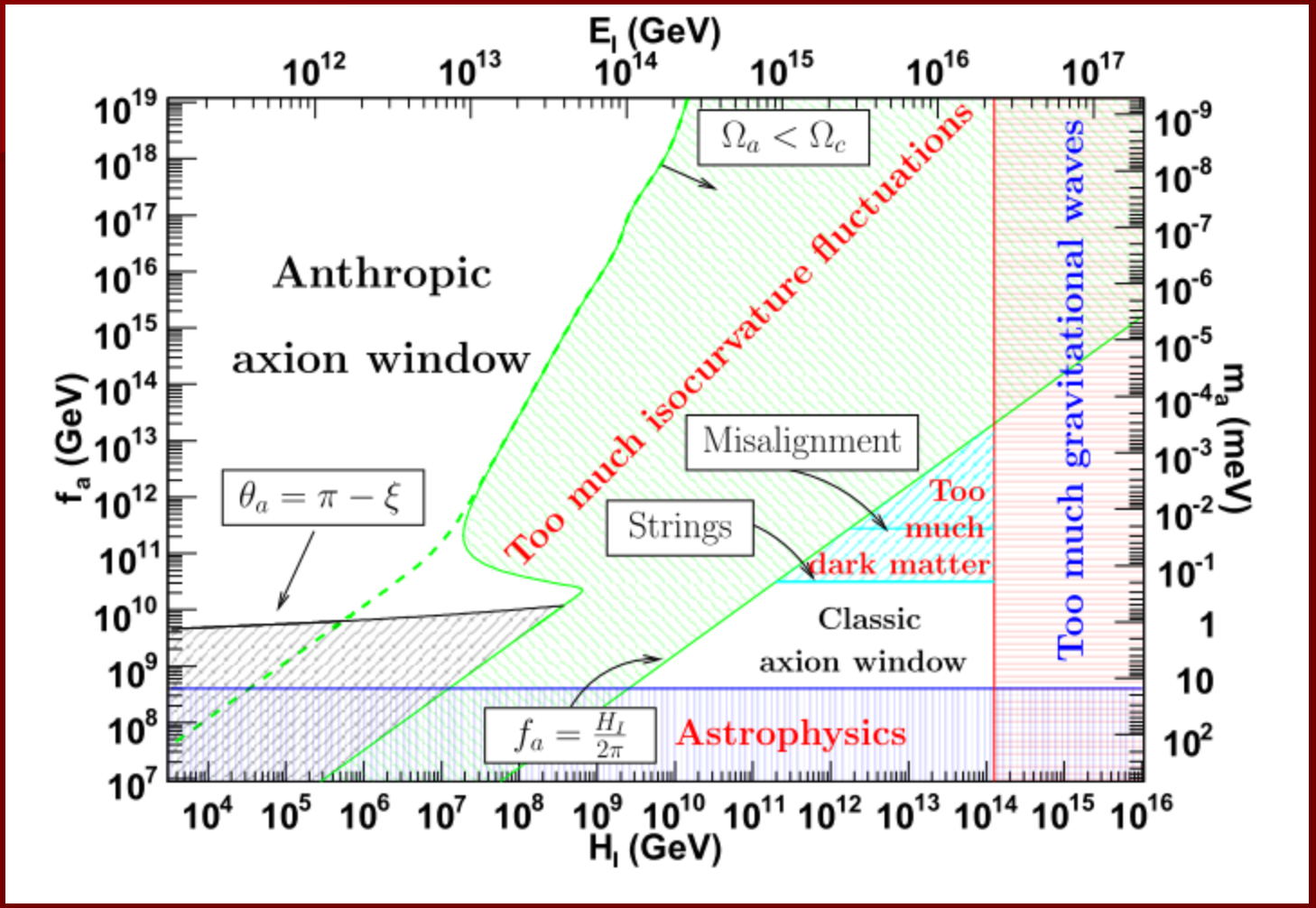
$$\Omega_a \sim 0.5 \left(\frac{10^{-5}\ \mathrm{eV}}{m_a} \right)^{7/6}$$

Axion Cosmology

- **Relativistic axions (HDM)** are created by thermal production:
  - At high T, axions are in creation-annihilation equilibrium with the rest of particles (thermal population of axions, satisfying Boltzmann equation).
  - When the Universe cools down below T_D, the axion freeze-out temperature, the thermal population decouples and its density red-shifts till today.

$$T_{\rm D} \sim 5 \times 10^{11}\,{\rm GeV} \left(\frac{f_a}{10^{12}\,{\rm GeV}} \right)^2$$

- In order to have substantial relativistic axion density, the axion mass must be close to 1 eV. (ma >1.02 eV gives densities too much in excess to be compatible with latest CMB data) Hannestad et al, JCAP 0804 (2008) 019 [0803.1585 (astro-ph)]

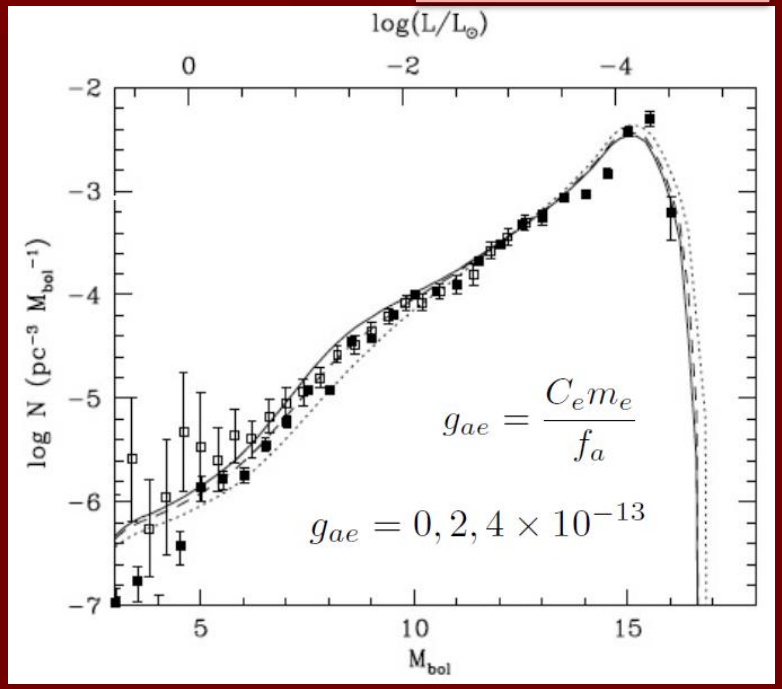


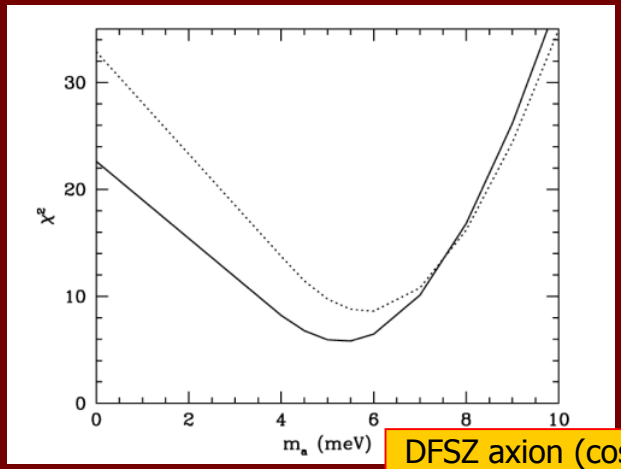
- From Wantz 2010

The cooling of white dwarfts

- Luminosity function (WD's per unit magnitude) altered by axion cooling
- Claim of detection of new cooling mechanism (Isern 2008)
- Axion-electron coupling of ~1x10^{-13} (→ axion masses of 2-5 meV or larger) **fits data**.

(Isern et al. 2008,2010)

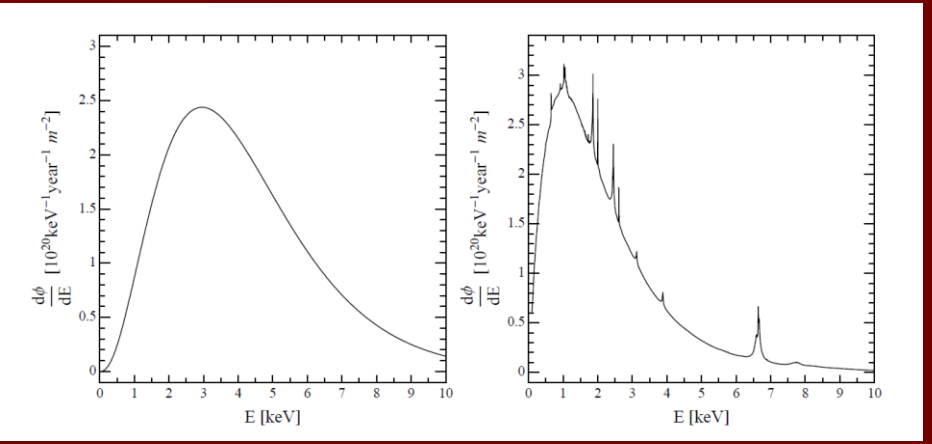




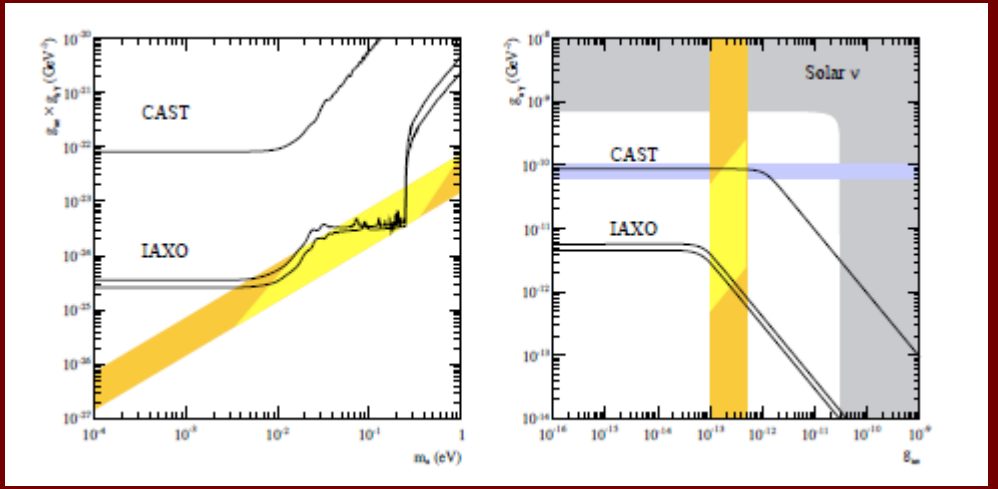
DFSZ axion (cosβ=1)

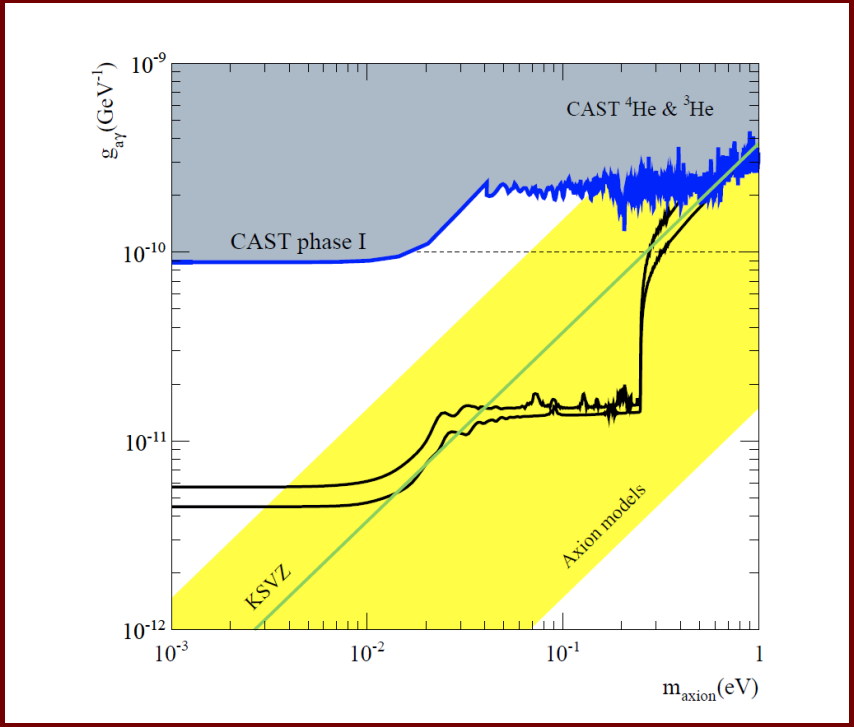
The cooling of white dwarfs

- meV masses seem out of reach of even for an improved axion helioscope… BUT
- Axion-electron coupling provides extra axion emission from the Sun…
- Extra emission concentrated at lower energies (~1 keV)



- **Such axion could produce a detectable signal in IAXO**



IAXO sensitivity prospects

- Factor ~20 better in $g_{a\gamma}$ (~$10^{4\text{-}5}$ in signal strength!!)