Experimental searches for axions

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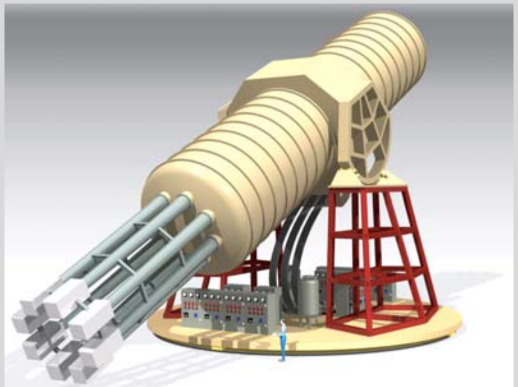



Outline

- Motivation for the axion (short)
  - Theory
  - Astrophysics
  - Cosmology
- Axion detection
- Types of experiments
  - Axions in the lab
  - Dark Matter axions
  - Solar axions
- Status of searches and future prospects

- Recent experimental review:
  - "New experimental approaches in the search for axion-like particles"
    I. G. Irastorza and J. Redondo arXiv:1801.08127

Axions: theory motivation

- **Axion: introduced to solve the strong CP problem**
- **In QCD, nothing prevents from introducing a term like:**

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

This term is CP violating.

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

2 contributions of very different origin…

From non-observation of neutron electric dipole moment:

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

•Why so small?

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

Axions: theory motivation

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

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

"Axion lagrangian"

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

θ absorbed in the definition of a

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

The axion

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

(Weinberg, Wilcek)

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

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

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

Axion phenomenology

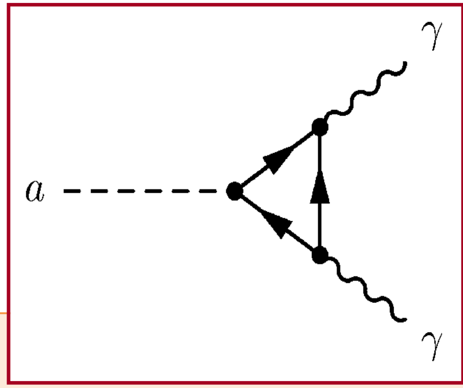
- **Some phenomenology depends on the "axion model", e.g.**
  - **KSVZ axions are "hadronic axions" (no coupling with leptons at tree level)**
  - **DFSZ axions couple to electrons**

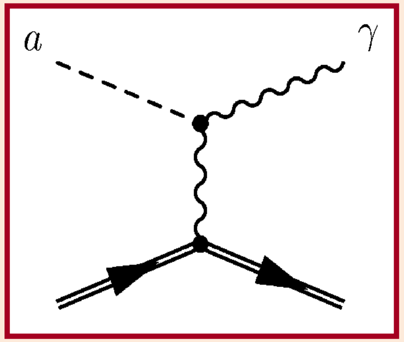
Gluon coupling	Mass	Photon coupling	Fermion couplings
$\frac{\alpha_s}{8\pi f_a} aG\tilde{G}$	$m_A = 5.70(7)\mu\text{eV} \times \left(\frac{10^{12}\text{GeV}}{f_A}\right)$	$g_{a\gamma\gamma}(\mathbf{E}\cdot\mathbf{B})a$ $g_{a\gamma\gamma} = \frac{\alpha_s}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$	Electron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

Axion phenomenology

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

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





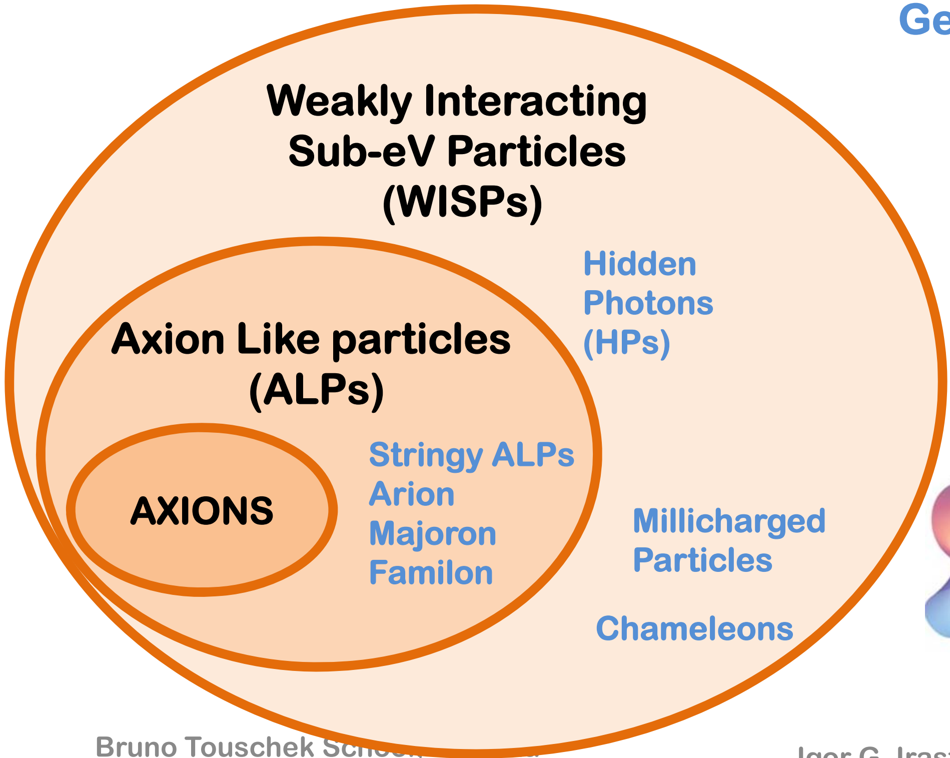
- **Axion-photon conversion** in the presence of an electromagnetic field (**Primakoff effect**)

This is probably the most relevant of axion properties.

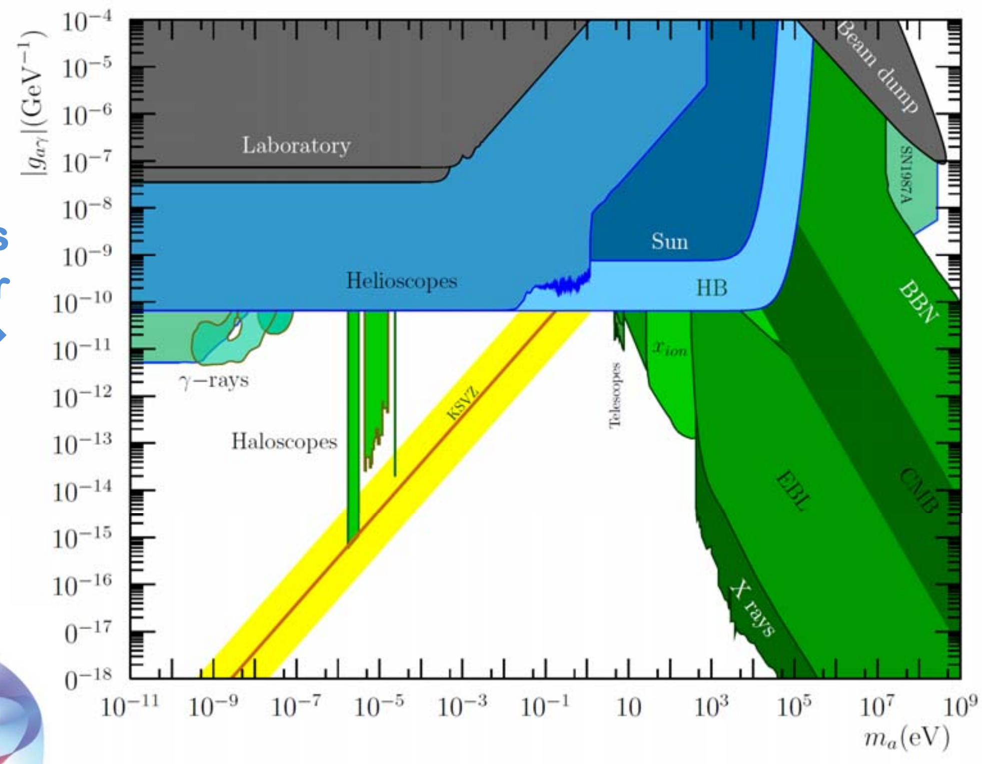
Most axion detection strategies are based on the axion-photon coupling

Beyond axions

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



Generic ALPs parameter space →

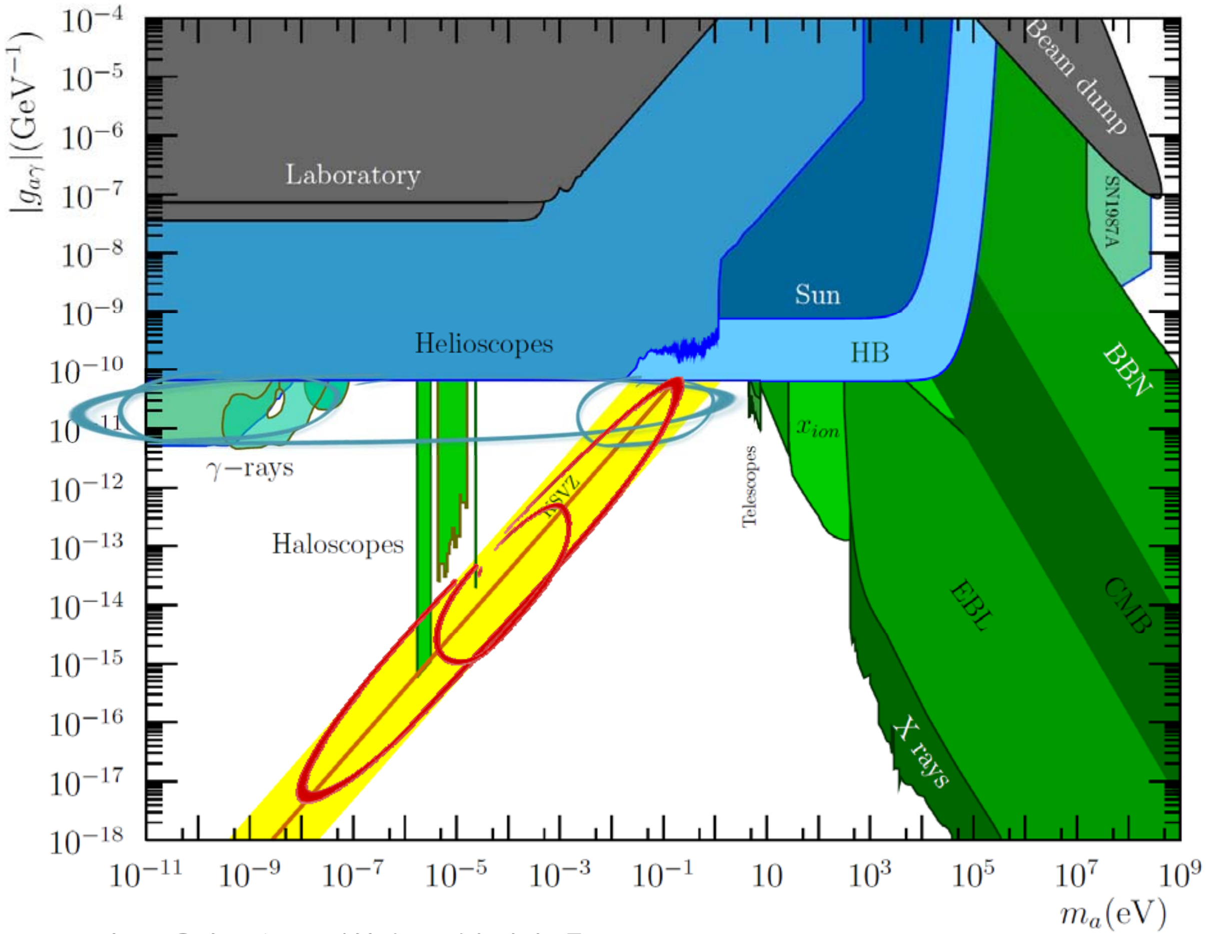


String theory predicts a plenitude of ALPs

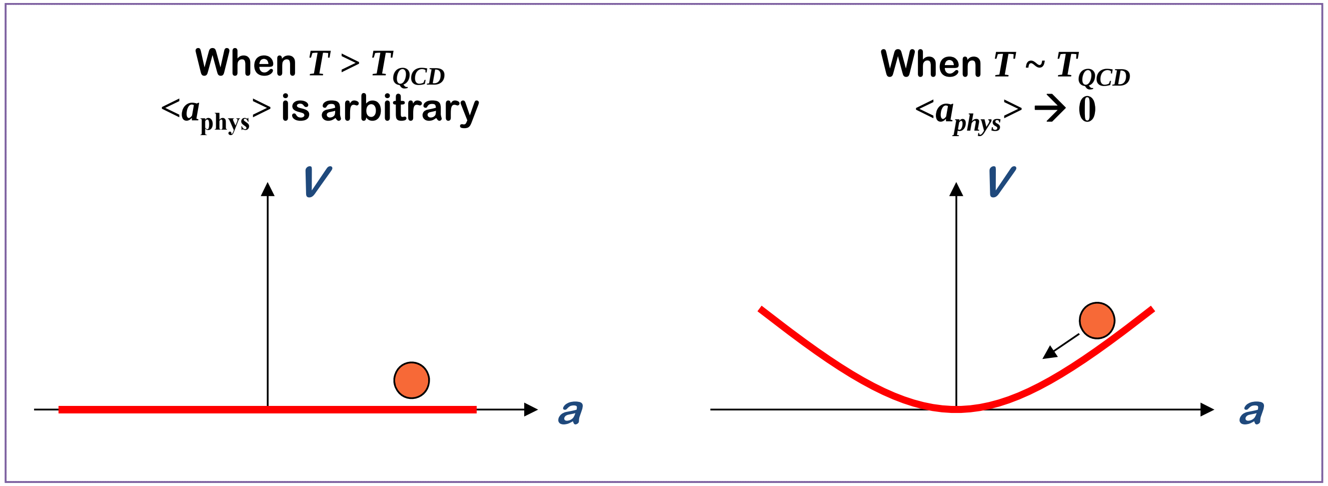
Axion/ALP searches motivation

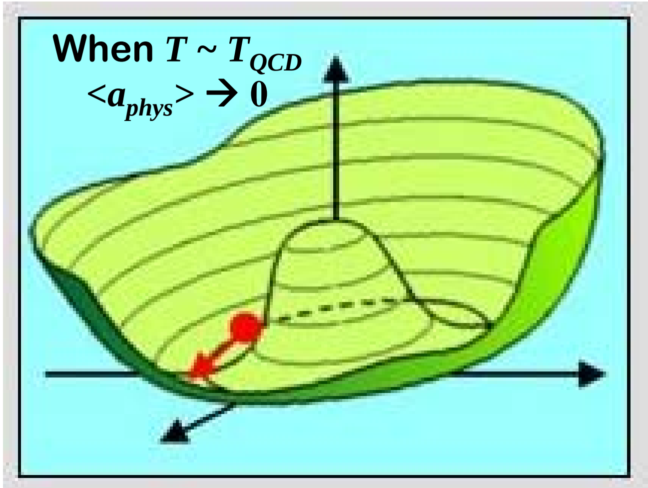
"Focuses of interest" in the ALP parameter space

Theory
Astrophysics
Cosmology



Cosmological axions: axion realignment



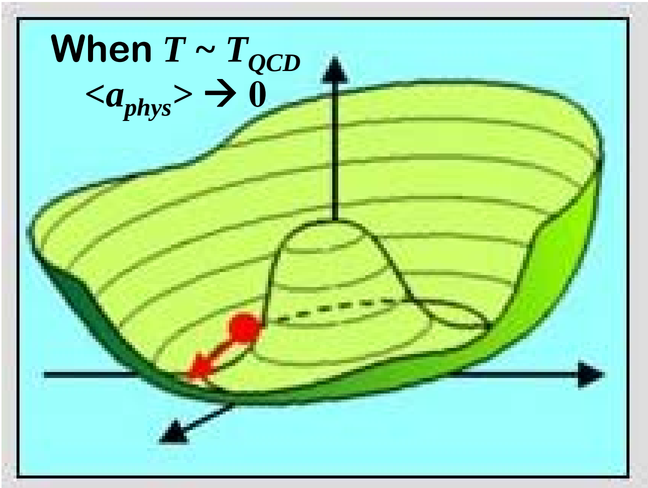


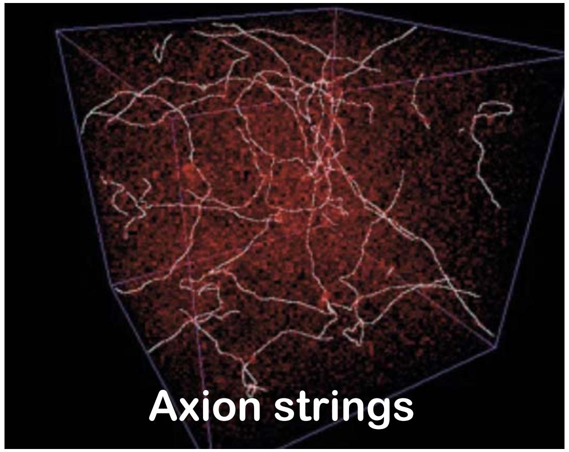
As the Universe cools down below T_{QCD}, space is filled with low energy axion field fluctuations → act as cold dark matter

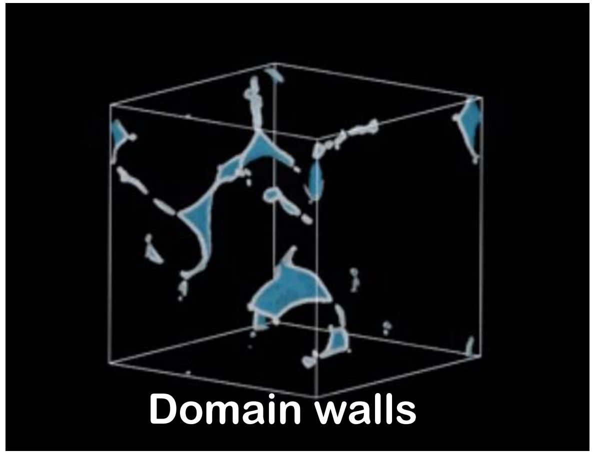
Their density depends on the initial value of $<a_{phys}>$ ("misalignment angle") which:

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

Cosmological axions: topological defects







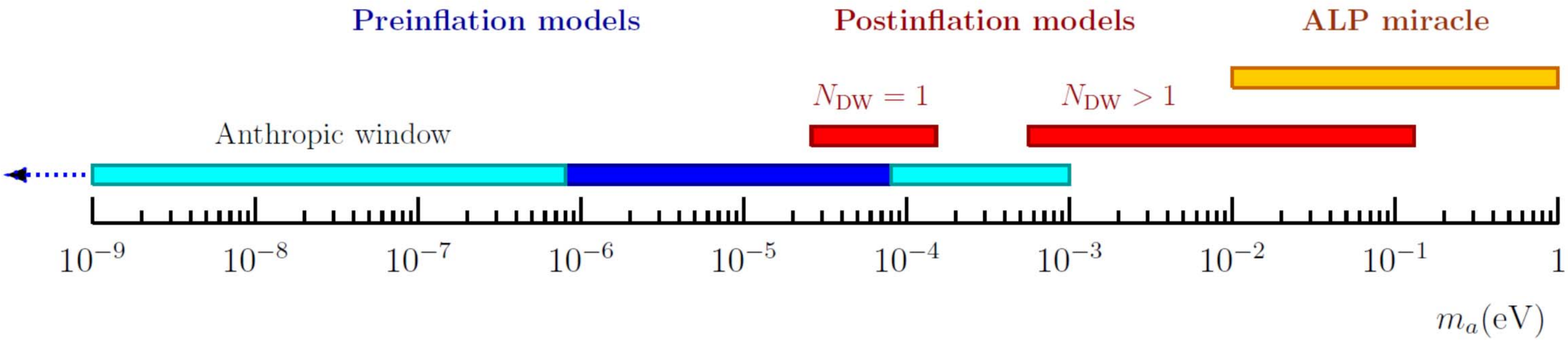
- But inflation may "wipe out" topological defects… Did inflation happen before or after the creation of defects (PQ transition) ?

  pre-inflation or post-inflation scenarios

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

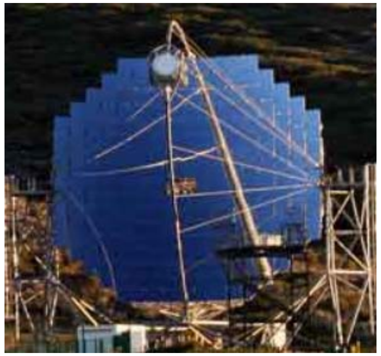
Axion DM density vs axion mass

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



Astrophysical hints for axions

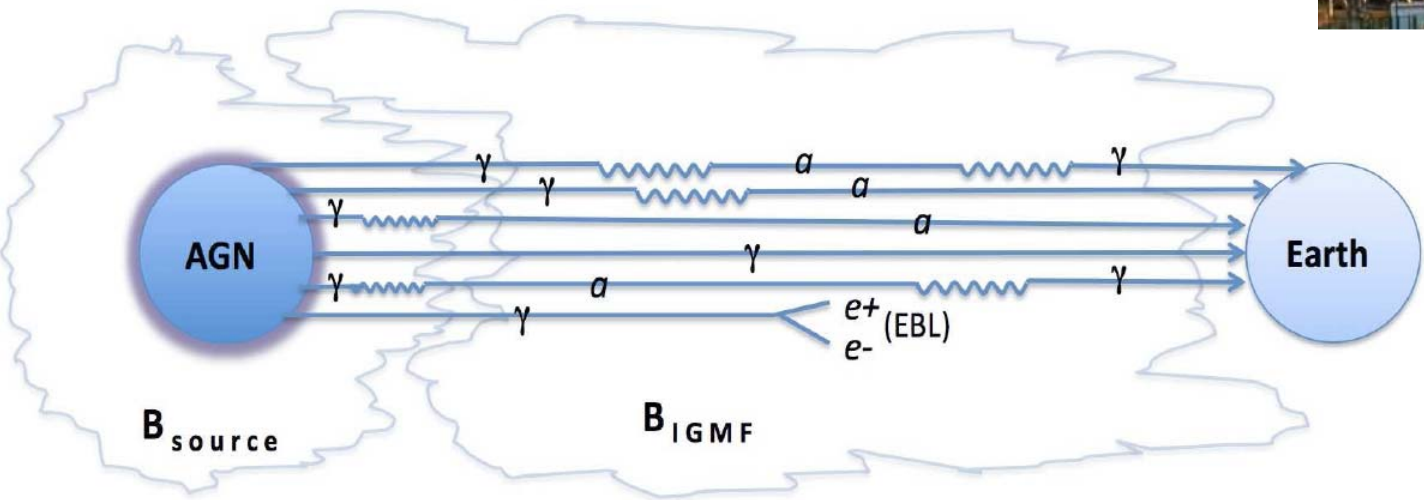
- **Gama ray telescopes like MAGIC or HESS observe HE photons from very distant sources…**



ALP:

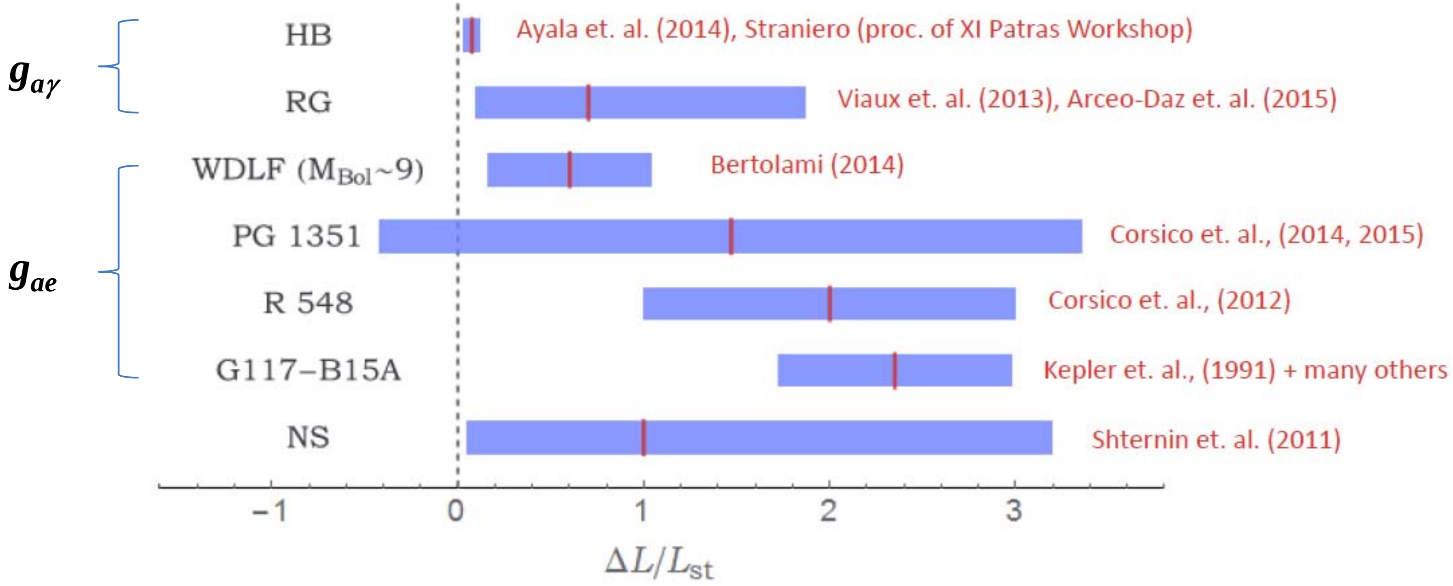
$$g_{a\gamma} \sim 10^{-12}\text{–}10^{-10}\ \mathrm{GeV}^{-1}$$

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



Astrophysical hints for axions

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



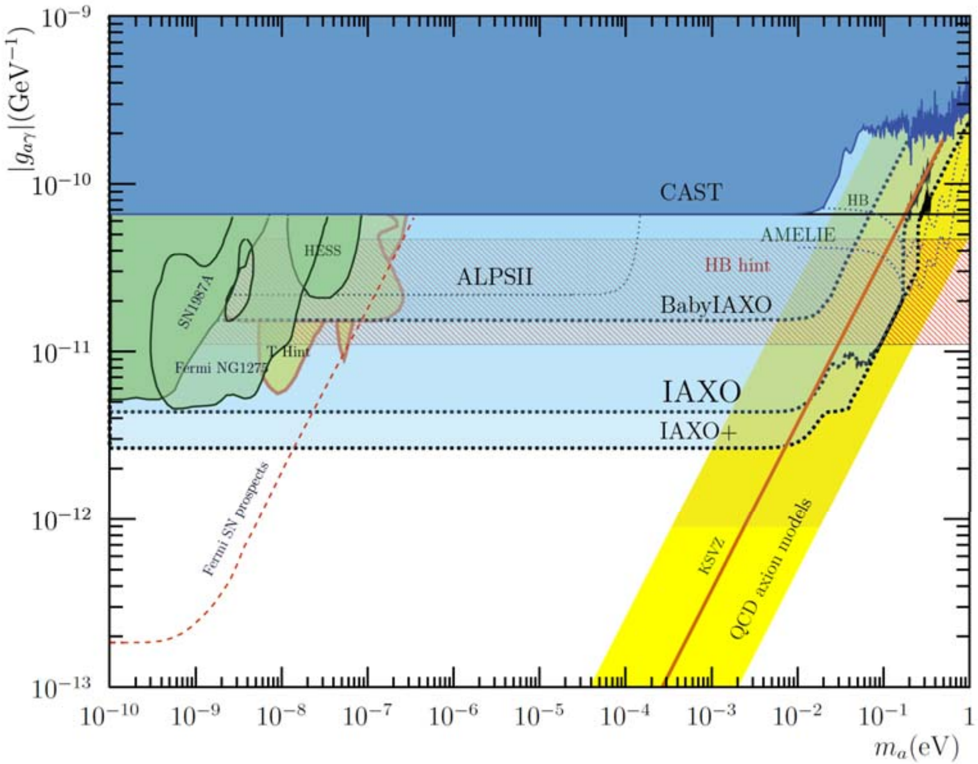
Astrophysical bounds

Coupling	Bound	Observable	Best fit?
$g_{a\gamma}, \bar{g}_{a\gamma}$	$< 0.65 \times 10^{-10}$ GeV^{-1} (95% C.L.)	HB/RG stars in 39 GCs [310]	0.29×10^{-10} GeV^{-1}
g_{ae}	$< 2.6 \times 10^{-13}$ (95% C.L.)	WD cooling + RGB tip M5 + HB/RG in GCs [73]	$\sim 1.5 \times 10^{-13}$
g_{ap}	$< 0.9 \times 10^{-9}$	SN1987A ν-pulse duration [25]	0
g_{an}	$< 0.8 \times 10^{-9}$	Neutron star cooling [327]	0
g_{an}	$< 0.5 \times 10^{-9}$	CAS A NS cooling [73, 331]	$\sim 0.4 \times 10^{-9}$
$\bar{g}_{ae}$	$< 0.7 \times 10^{-15}$	Luminosity of the RGB tip [160]	-
$\bar{g}_{aN}$	$< 1.1 \times 10^{-12}$	Luminosity of the RGB tip [160]	-
$\bar{g}_{a\gamma N}$	$< 3 \times 10^{-9}$ GeV^{-2}	SN1987A ν-pulse duration [333]	0

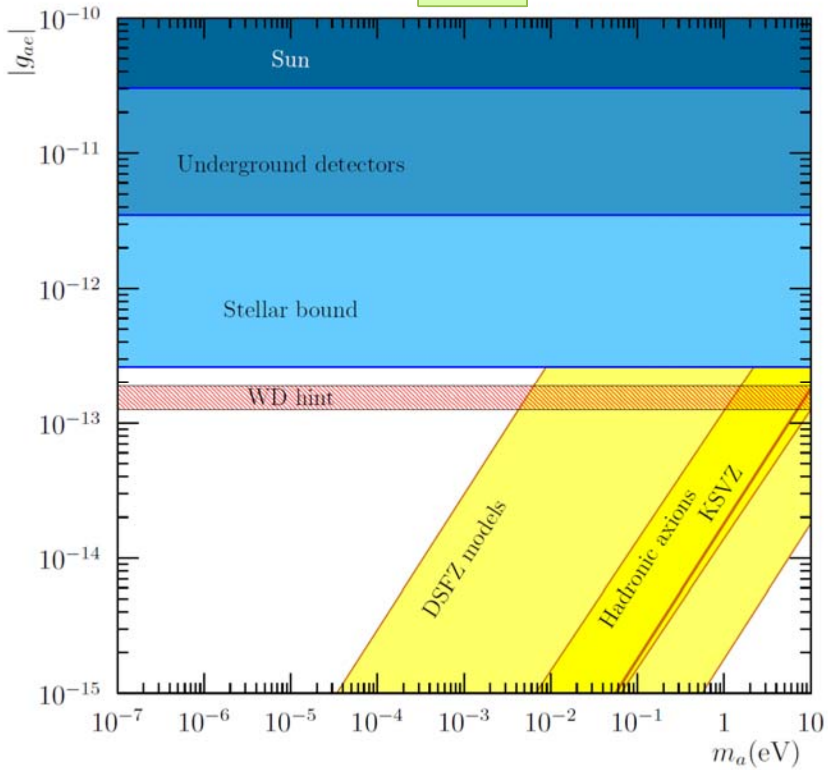
Table 2: Summary of Axtrophysical bounds and hints on an ALP coupled to photons, electrons, protons and neutrons.HB,RG bounds are valid for masses $m_a \lesssim 10$ keV, WD cooling ones vary but $m_a \lesssim 1$ keV should be ok, SN and NS require $m_a \lesssim 1$ MeV.

Astrophysical hints for axions

$g_{a\gamma}$



g_{ae}

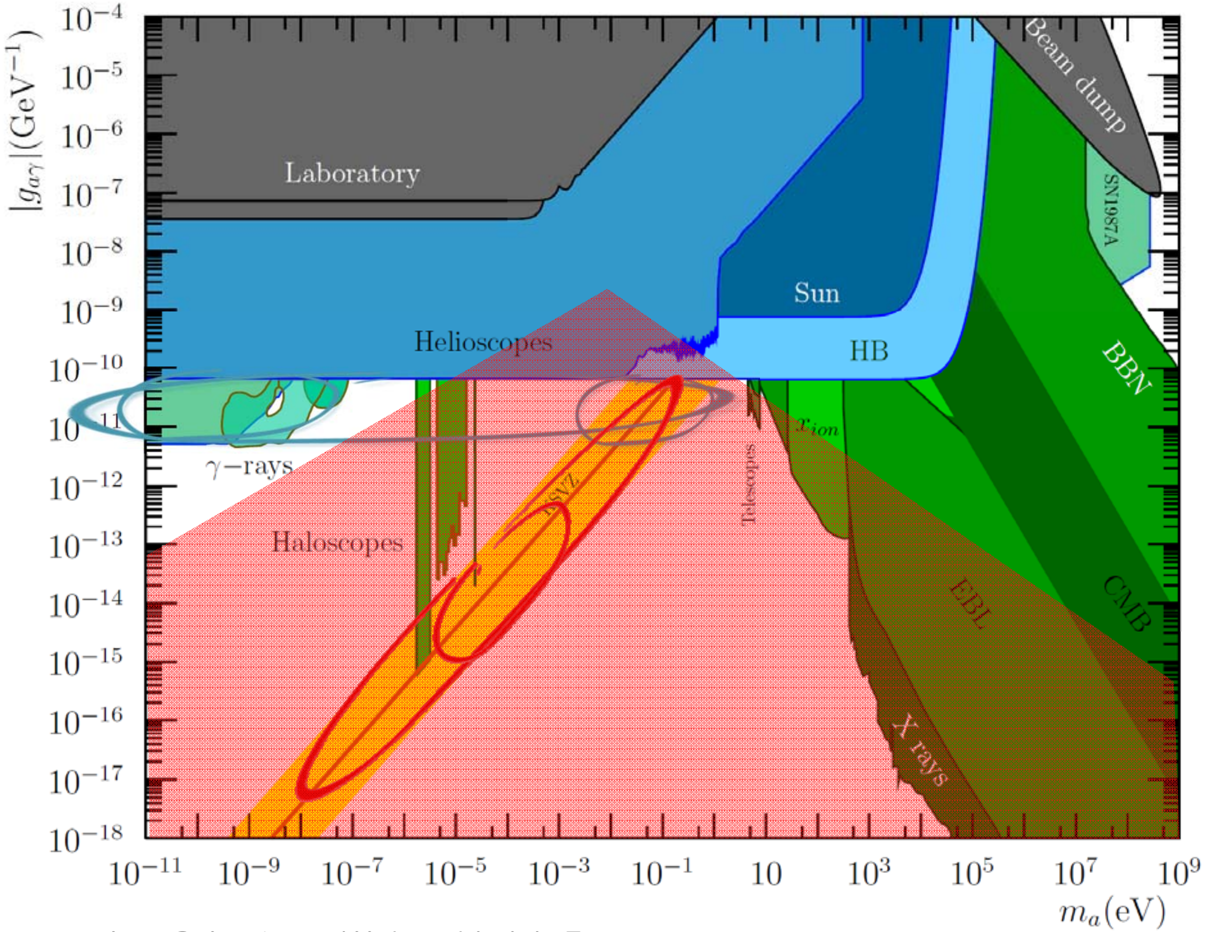


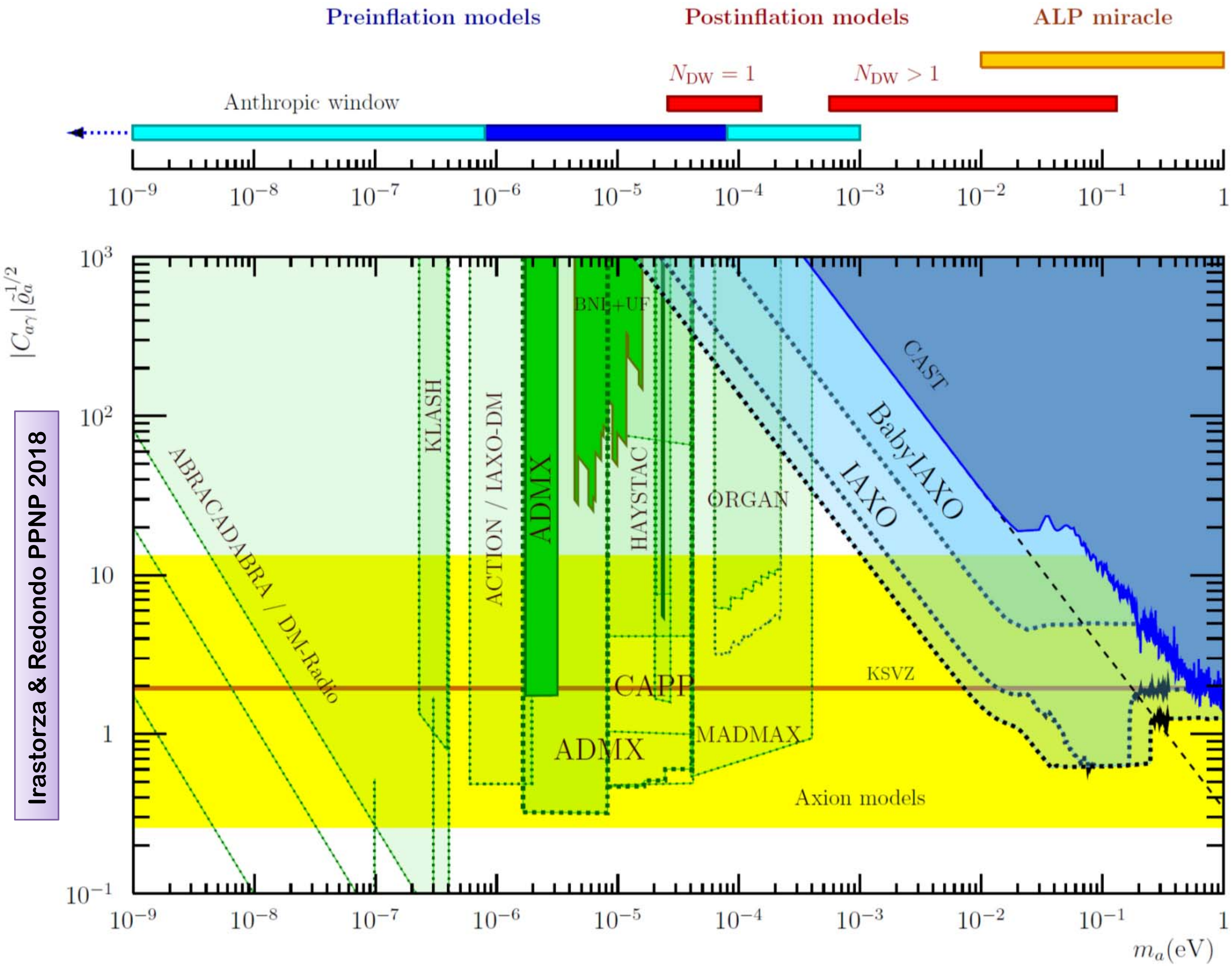
Axion/ALP searches motivation

“Focuses of interest” in the ALP parameter space

Theory
Astrophysics
Cosmology

Generic ALP DM models

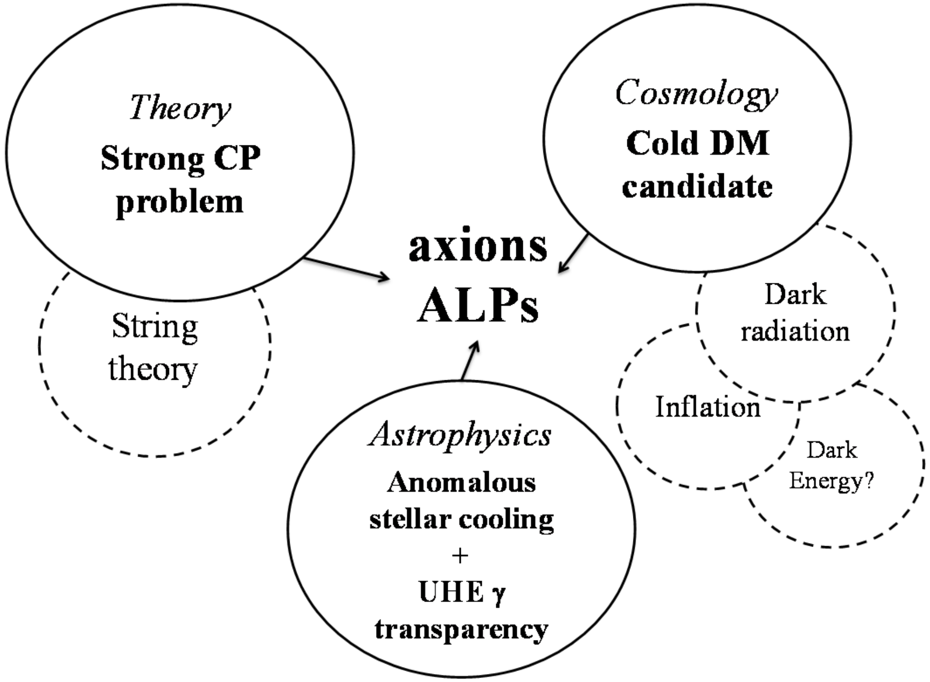




Preinflation models
Postinflation models
ALP miracle
$N_{DW} = 1$
$N_{DW} > 1$
Anthropic window
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1
$|C_{a\gamma}|\tilde{\varrho}_a^{-1/2}$
10^3 10^2 10 1 10^{-1}
Irastorza & Redondo PPNP 2018
BNL+UF
CAST
BabyIAXO
IAXO
KLASH
ACTION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

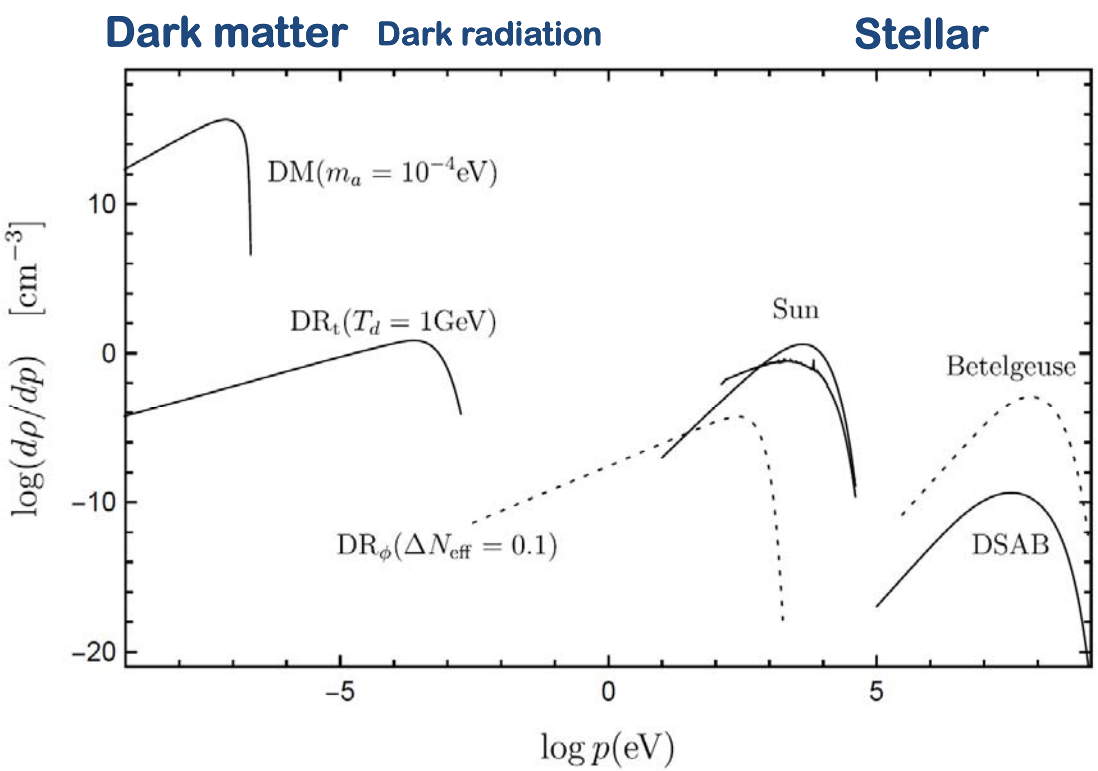
Axion motivation in a nutshell

- 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…



Sources of axions

Natural sources



Laboratory sources

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

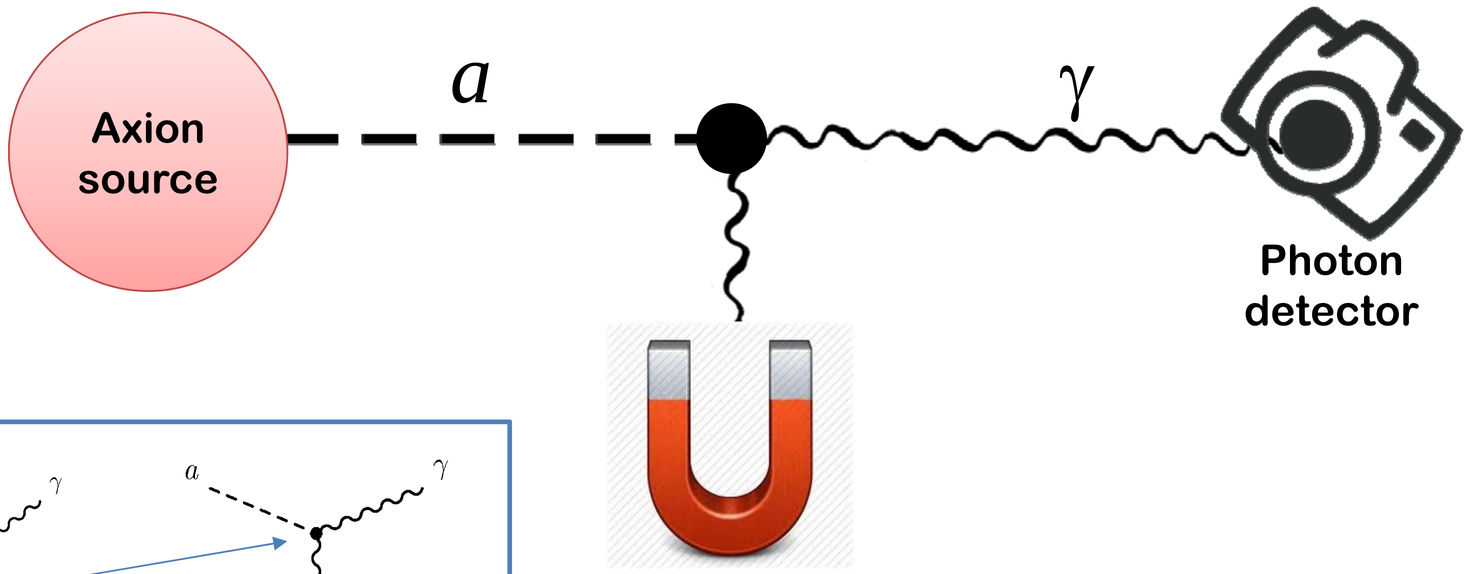
Most detection strategies rely on the axion-photon conversion

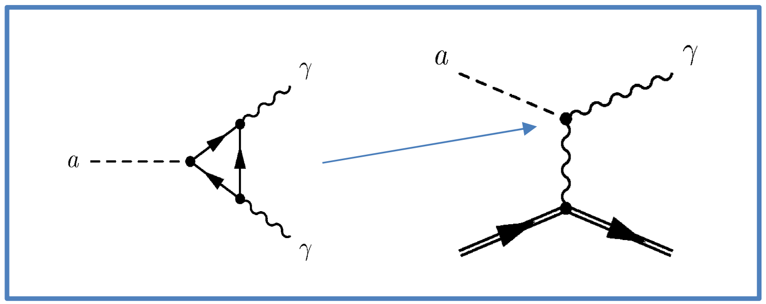
Axion detection strategies

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

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

How to detect an axion?

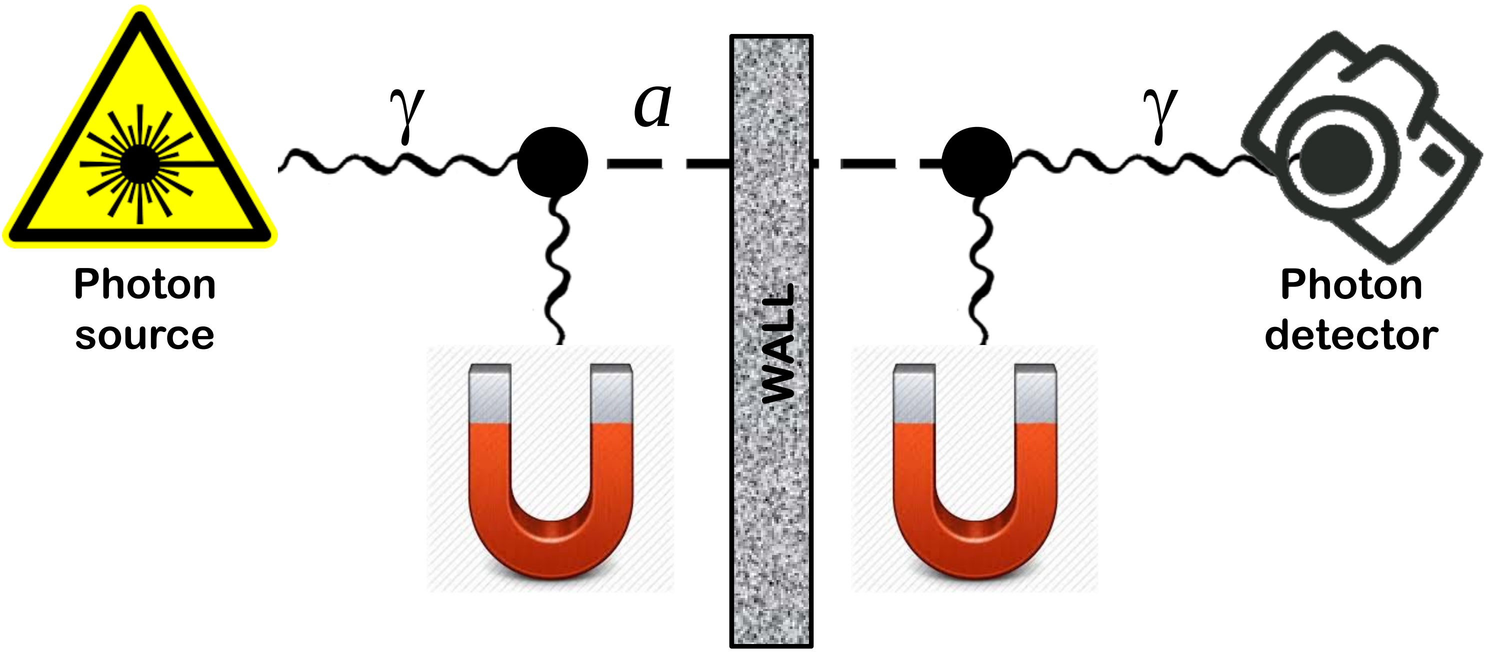




Detection of axions

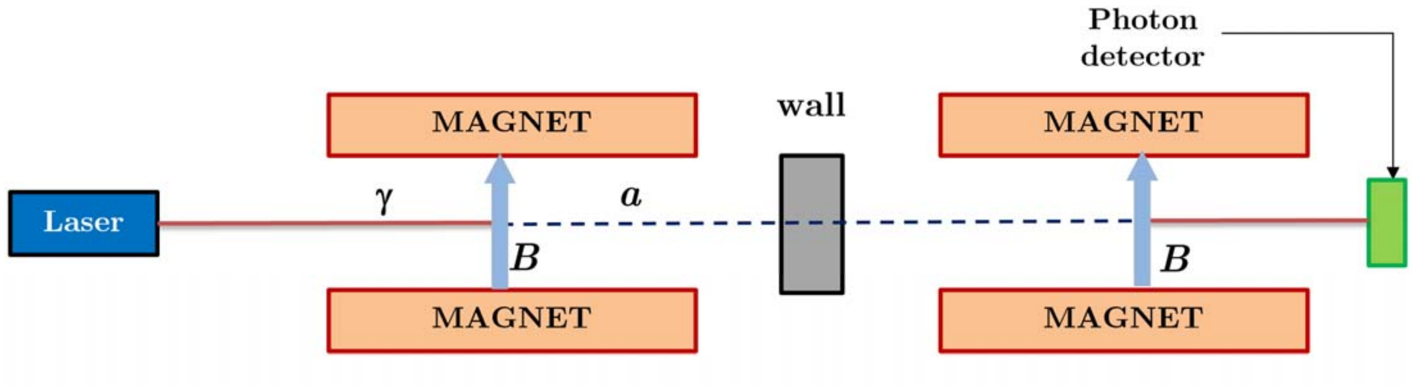
Source		Experiments	Model & Cosmology dependency	Technology
Relic axions		ADMX, HAYSTAC, CASPEr, CULTASK, CAST-CAPP, MADMAX, ORGAN, RADES, QUAX, …	High	New ideas emerging, Active R&D going on,…
Lab axions		ALPS, OSQAR, CROWS, ARIADNE,…	Very low	
Solar axions		SUMICO, CAST, (Baby)IAXO	Low	Ready for large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

Laboratory axions

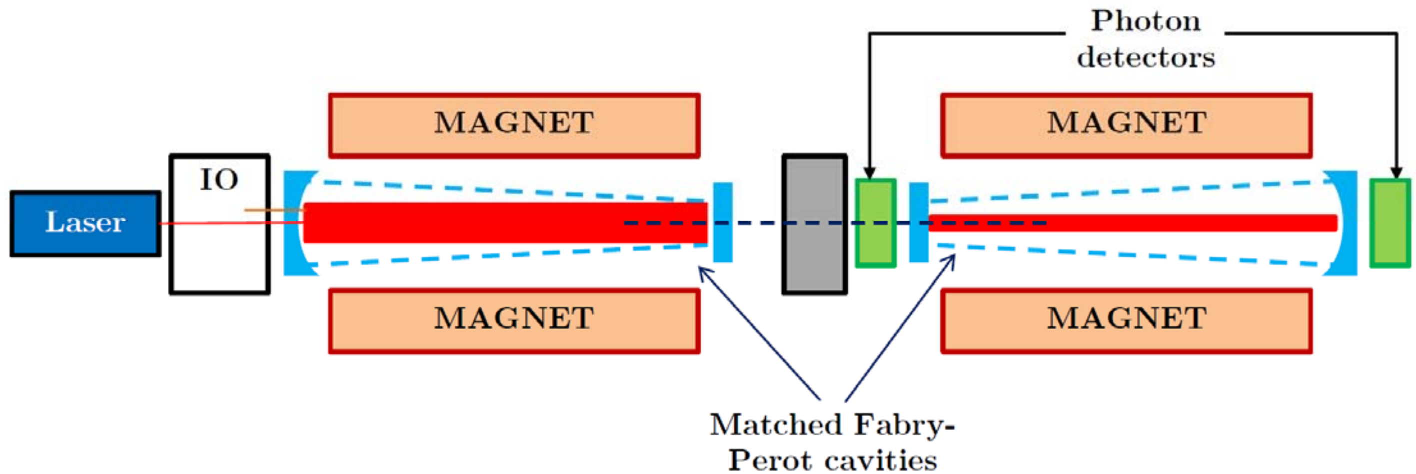


Light-shining-through-wall (LSW)

Standard configuration →



Enhanced "resonant" configuration (future) →



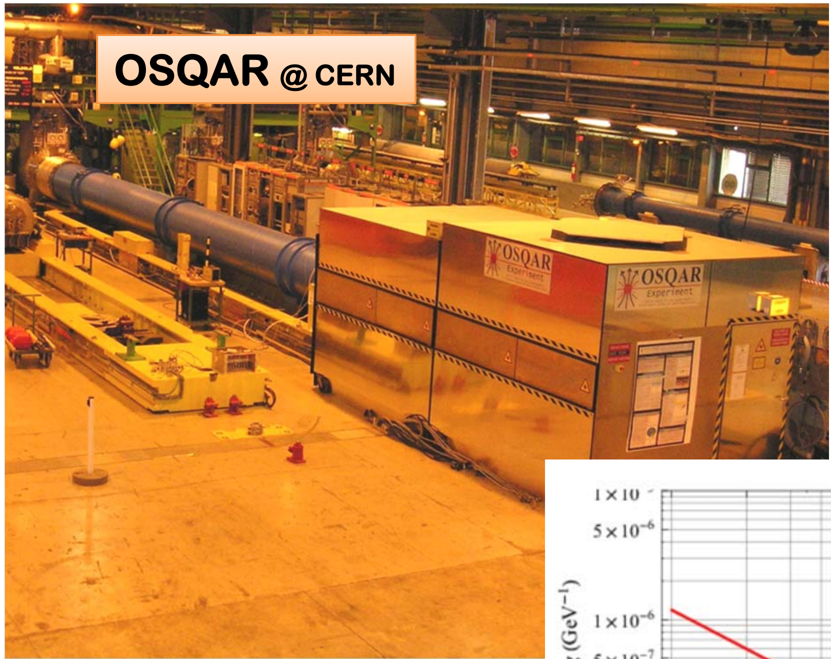
ALPS experiment

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

- **ALP II under preparation**
- **(resonant, 10+10 magnets,…)**

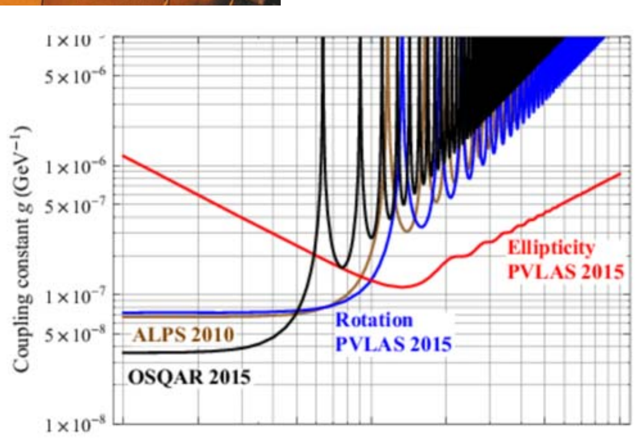
parameter	scaling	ALPS I	ALPS IIc	sens. gain
BL (total)	$g_{a\gamma} \propto (BL)^{-1}$	22 Tm	468 Tm	21
PC built up ($P_{laser,eff.}$)	$g_{a\gamma} \propto \beta_{PC}^{-1/4}$	1 (kW)	150 (kW)	3.5
rel. photon flux $\dot{n}_{prod}$	$g_{a\gamma} \propto \dot{n}_{prod}^{-1/4}$	1 (532 nm)	2 (1064 nm)	1.2
RC built up β_{RC}	$g_{a\gamma} \propto \beta_{RC}^{-1/4}$	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

Other LSW experiments



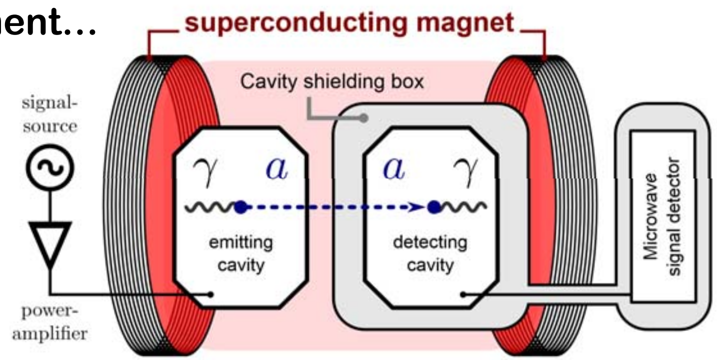
Also:

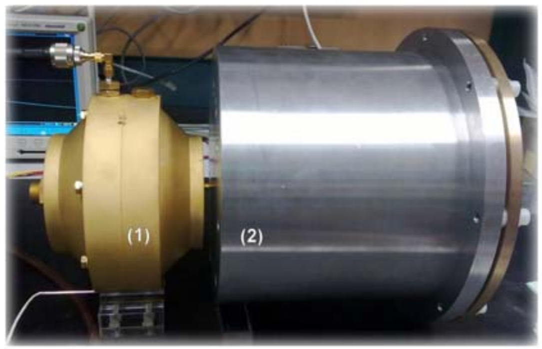
- GammeV & REAPR @ Fermilab, US
- BMV @ Toulouse
- …



CROWS experiment @ CERN

- Using microwave photons
- Resonant implementation easier
- Lose L enhancement…



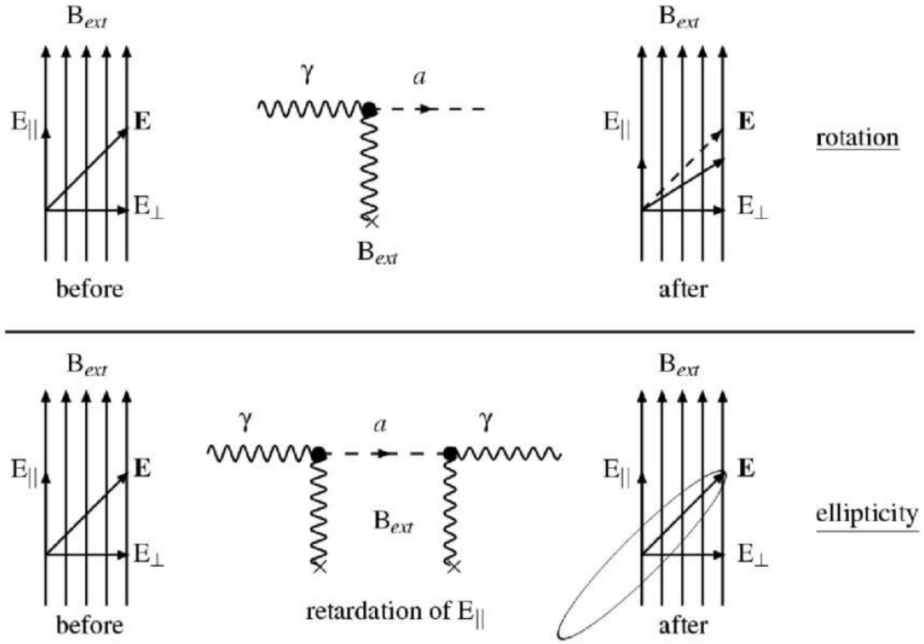


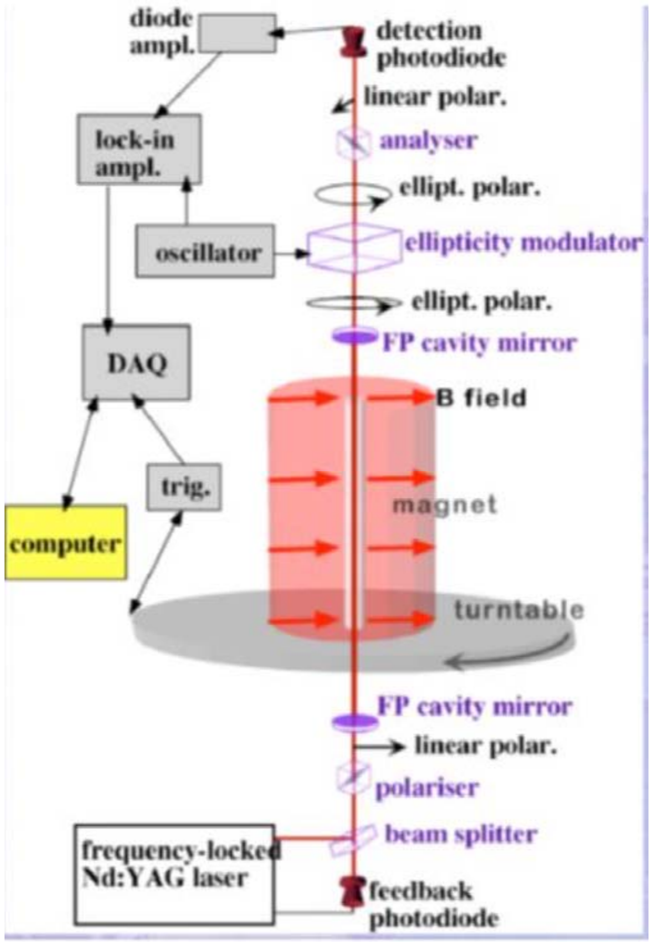
Polarization experiments

PVLAS experiment: study QED vacuum birrefringence (standard effect), but also sensitivty to ALPs:

Dichroism: Production of real particles

Ellipticity: Production of massive virtual particles

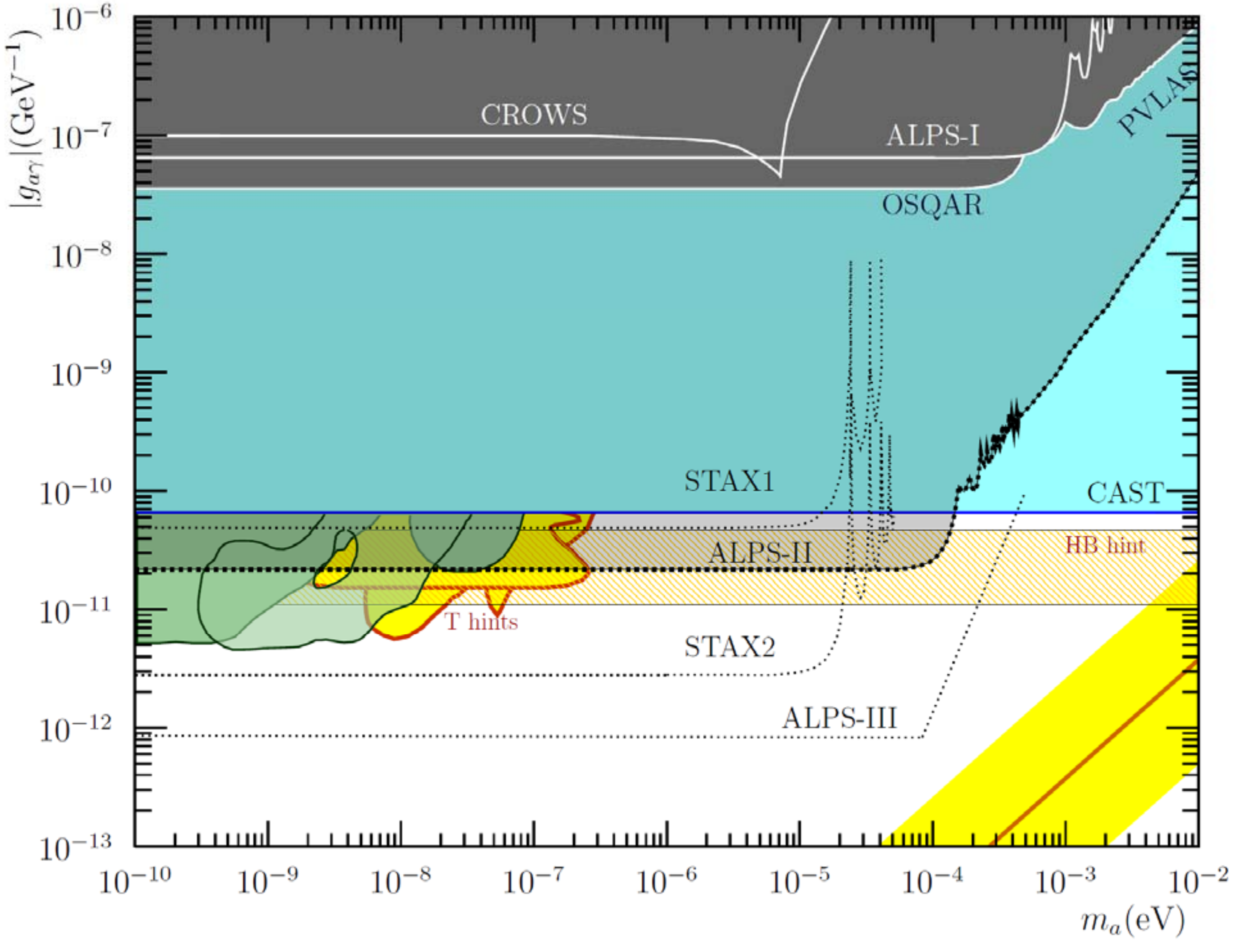




Laboratory experiments sensitivity

Experiment	status	B (T)	L (m)	Input power (W)	β_P	β_R	$g_{a\gamma}$[GeV^{-1}]
ALPS-I [433]	completed	5	4.3	4	300	1	5×10^{-8}
CROWS [435]	completed	3	0.15	50	10^4	10^4	9.9×10^{-8}(*)
OSQAR [434]	ongoing	9	14.3	18.5	-	-	3.5×10^{-8}
ALPS-II [436]	in preparation	5	100	30	5000	40000	2×10^{-11}
ALPS-III [437]	concept	13	426	200	12500	10^5	10^{-12}
STAX1 [438]	concept	15	0.5	10^5	10^4	-	5×10^{-11}
STAX2 [438]	concept	15	0.5	10^6	10^4	10^4	3×10^{-12}

Table 4: List of the most competitive recent LSW results, as well as the prospects for ALPS-II, togethe with future possible projects, with some key experimental parameters. The last column represents th sensitivity achieved (or expected) in terms of an upper limit on $g_{a\gamma}$ for low m_a. For microwave LSV (CROWS and STAX) the quality factors Q are listed. * The limit is better for specific m_a values, se Figure 6



Axion-mediated macroscopic forces

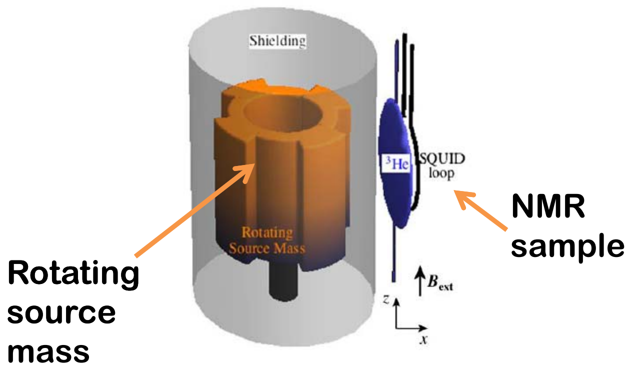
Axions could be detected as short-range deviation of gravity…

(but traditionally though without enough sensitivity to QCD axions)

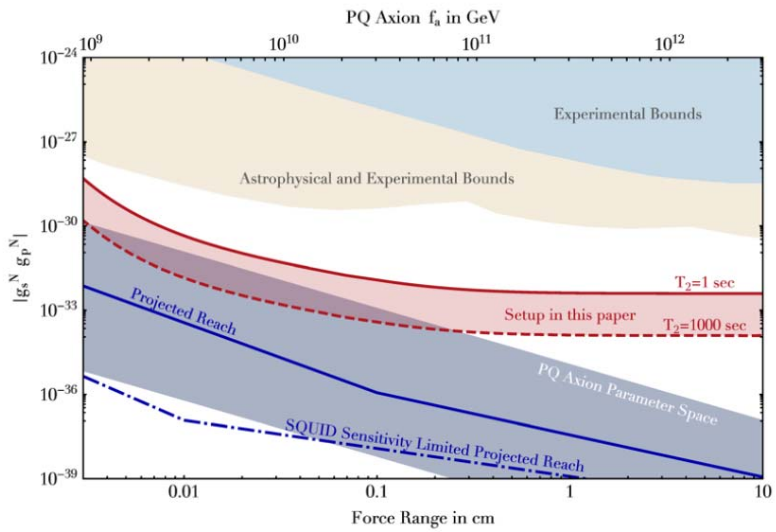
Recently proposed: ARIADNE experiment

Short-range force by NMR technique

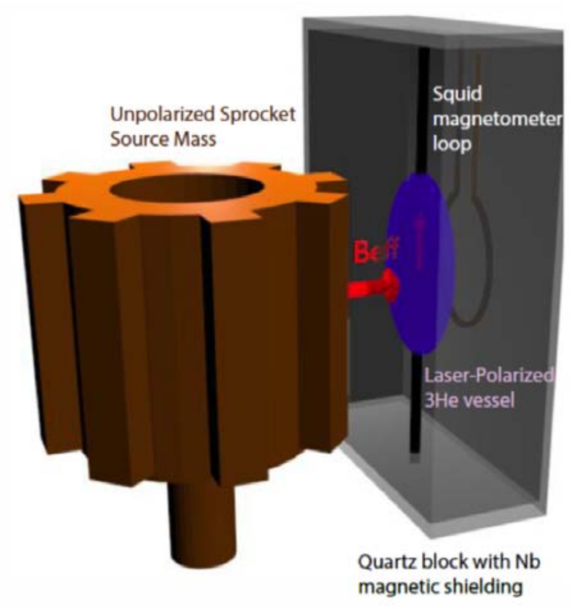
Good prospects for sub-meV axion



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



Axion-mediated macroscopic forces



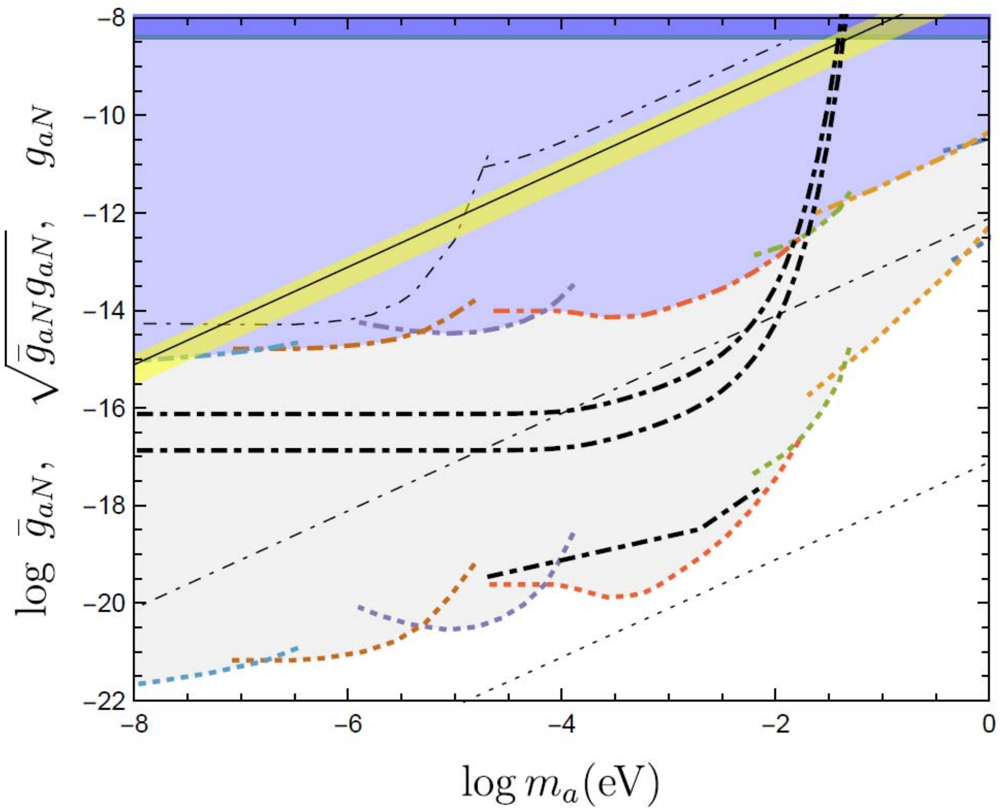
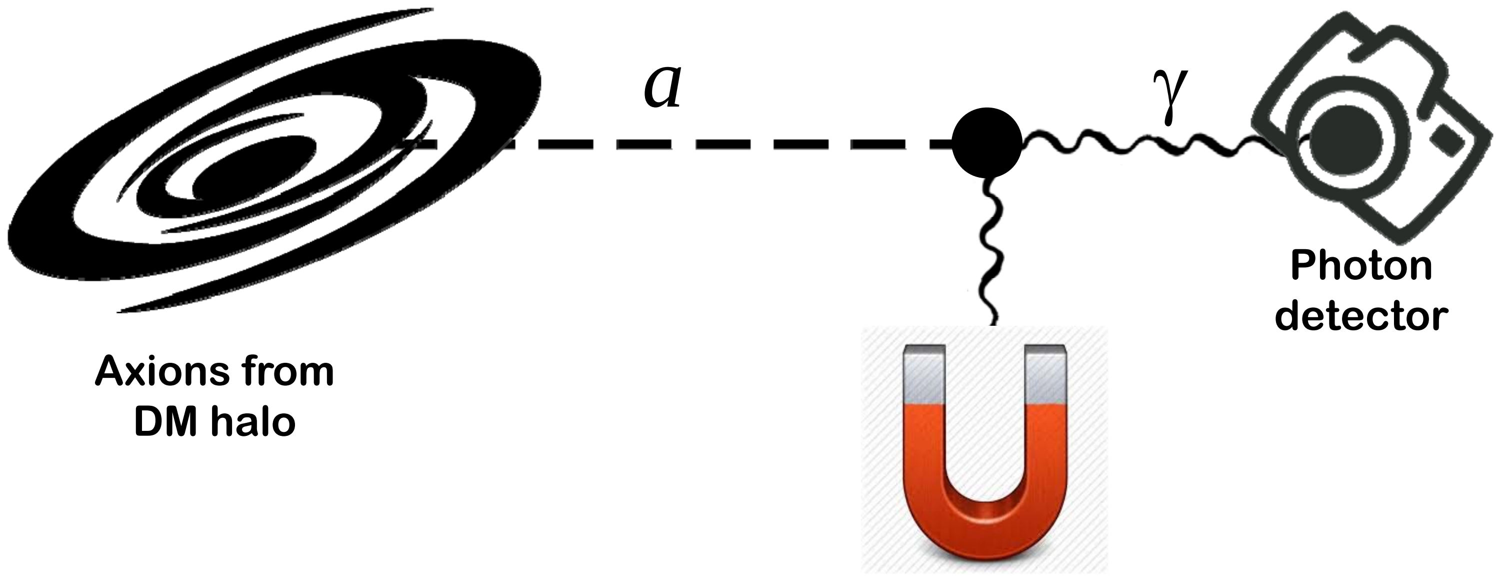


Figure 7: Left: Limits on ALP nucleon couplings: CP violating $\bar{g}_{aN}$ from laboratory 5th-force searches (dotted), CP conserving g_{aN} from the SN1987A cooling argument (solid) and their product $\bar{g}_{aN}g_{aN}$ (dot-dashed) from pure lab experiments (thin) and the direct product on the astro+lab constraints from [462]. The yellow band represents the range for the DFSZ QCD axion, g_{Ap}^{DFSZ}, and the line for KSVZ , g_{Ap}^{KSVZ}, while dotdashed and dotted lines are approximate *upper bounds* for the CP-violating axion couplings using $\theta_0 = 10^{-10}$. The ARIADNE prospects for $\bar{g}_{aN}g_{an}$ are shown as black dot-dashed curves. Right: Sketch of the ARIADNE experiment. Credit: ARIADNE collaboration, used with permission.

Dark matter axions

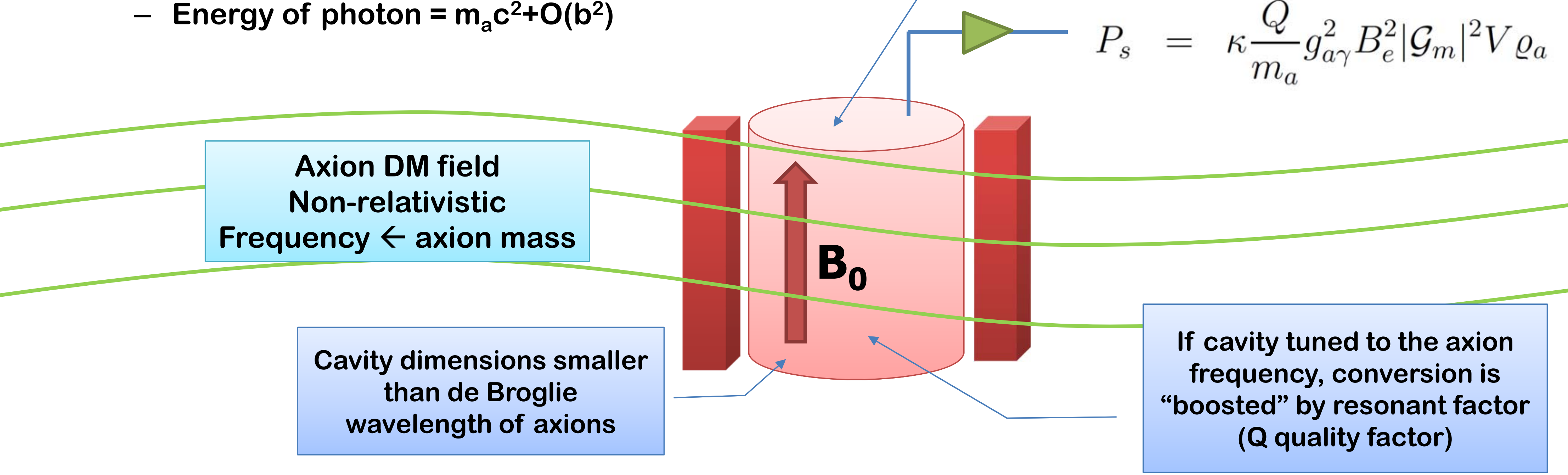


Detecting DM axions: “haloscopes”

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

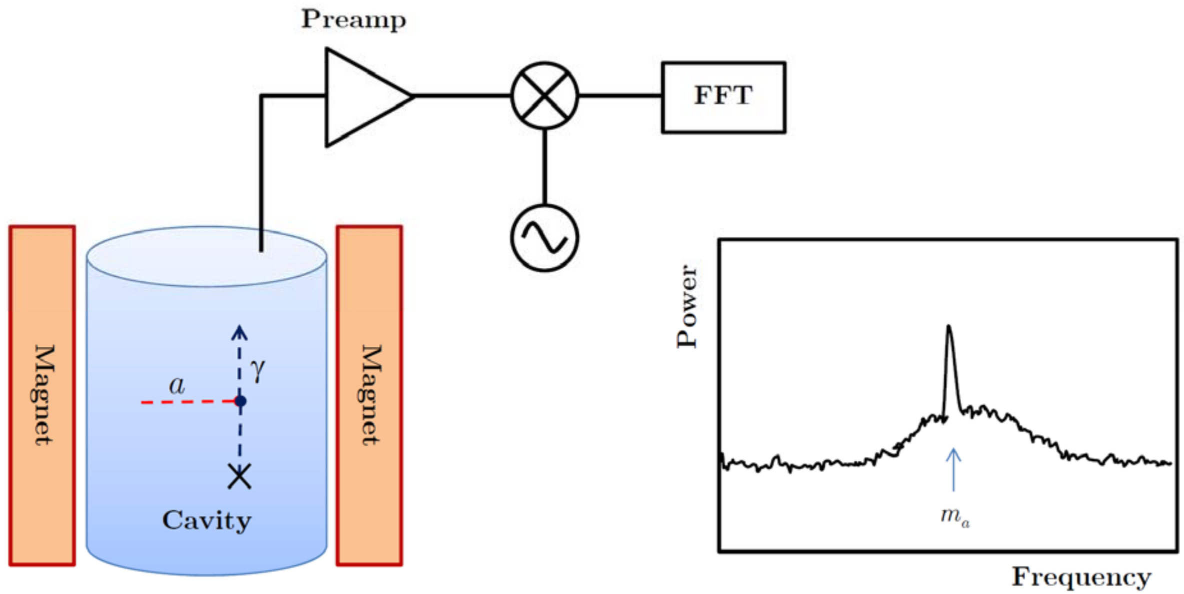
Primakoff conversion of DM axions into microwave photons inside cavity

$$P_s = \kappa \frac{Q}{m_a} g_{a\gamma}^2 B_e^2 |\mathcal{G}_m|^2 V \varrho_a$$



Detecting DM axions: “haloscopes”

Data taking proceeds by scanning small ($1/Q$) mass steps and taking limited data a each step



- **Figure of merit:** $$F \sim \varrho_a^2 g_{a\gamma}^4 m_a^2 B_e^4 V^2 T_{\rm sys}^{-2} |\mathcal{G}|^4 Q$$

(proportional to “time needed to scan a given mass range”)

ADMX

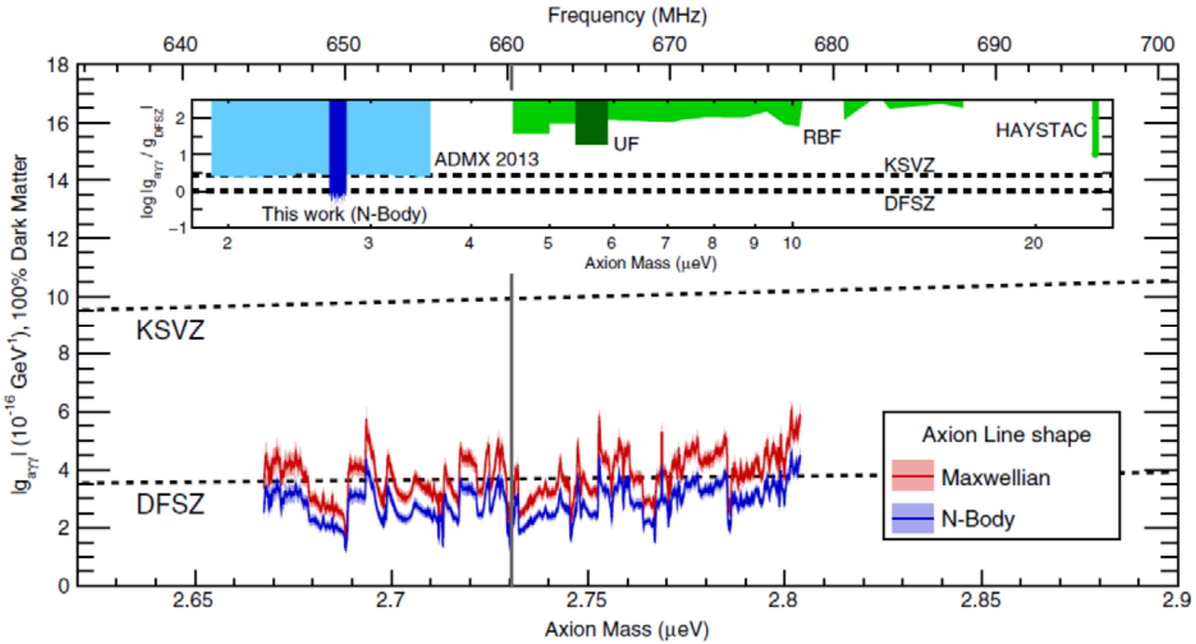
- **Leading haloscope experiment**
- **Many years of R&D**
- **high Q cavity (1 m x 60 cm Ø)**
- **Sited at U. of Washington**
- **8 T superconducting solenoid**
- **Low noise receivers based on SQUIDs + dilution refrigeration at 100 mK.**
- **Tuning achieved by set of movable rods**

- **Sensitivity to few μeV proven**
- **Good support through Gen 2 DM US program**

ADMX

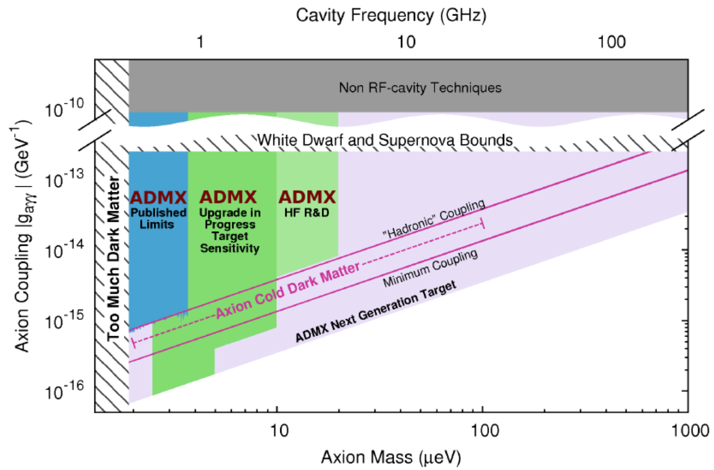
- First results >10 years ago.
- Last result recently published. First data down to DFSZ coupling…

PRL 120 (2018) 15301



- Current program will surely cover 1-10 μeV with high sensitivity (i.e. reaching even pessimistic coupling).

- What about higher masses?



Higer-m_a haloscopes

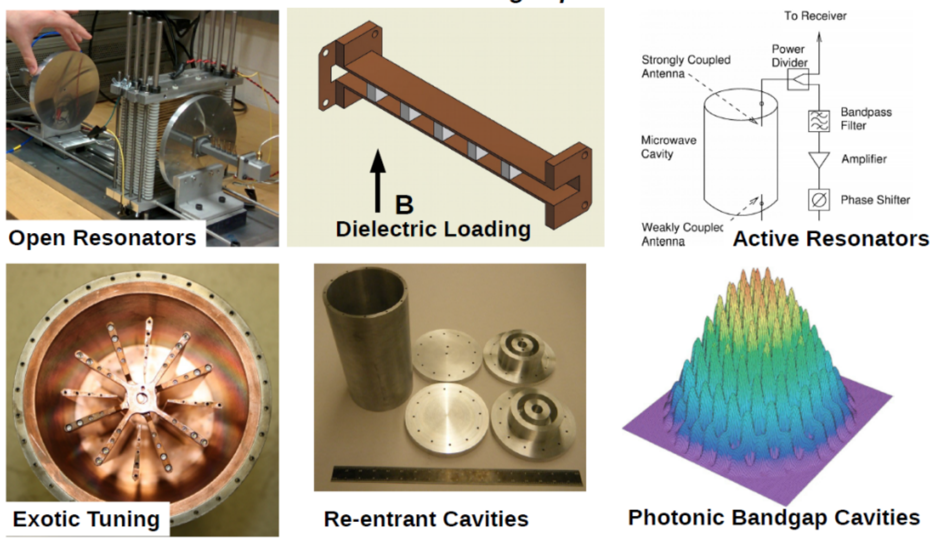
- **Problematic:** higher m_a → lower V → lower sensitivity

$$F \sim \varrho_a^2 g_{a\gamma}^4 m_a^2 B_e^4 V^2 T_{\rm sys}^{-2} |\mathcal{G}|^4 Q$$

- **R&D to go to:**
  - Higher B magnets
  - Larger instrumented volumen
  - Lower noise sensors
  - Higher Q cavities

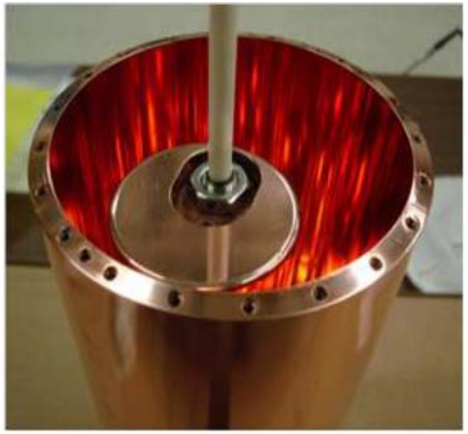
Active R&D inside ADMX

A subset of ideas being explored…

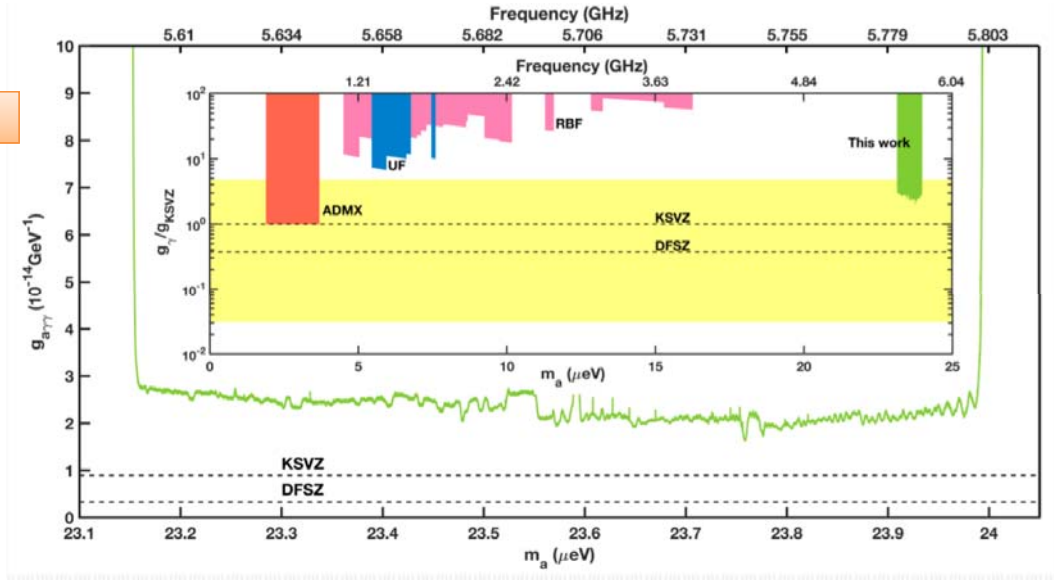


HAYSTAC

- Started as ADMX test bed for new ideas.
- Sited at Yale University
- Looks like scaled-down ADMX but better noise and higher B
- First results recently released. Close to KSVZ model in the 23-24 μeV range

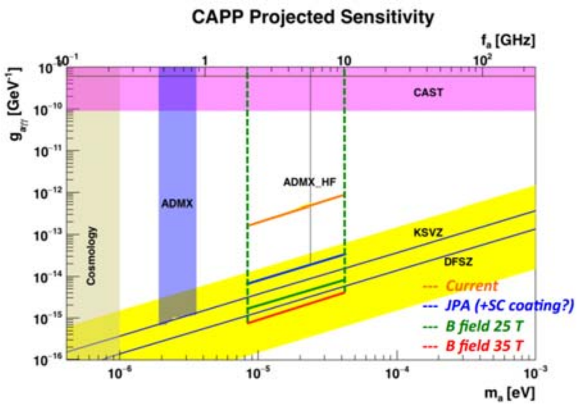


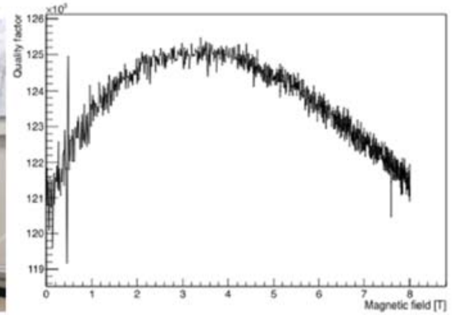
arXiv:1803.03690

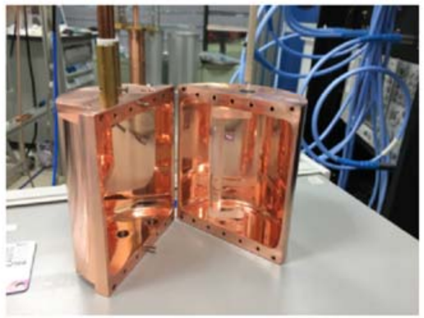


CULTASK @ CAPP

- **CAPP: recently created "Center for Axion and Precision Physics" at South Korea**
- **Main goal to "build a large axion DM experiment in Korea"**
- **Many R&D lines ongoing:**
  - **Ultrahigh field superconducting magnets**
  - **Superconducting films to get high G cavities**
  - **Low noise sensors (SQUIDs)**
  - **New cavity designs & multi-cavity phase locking schemes**







New cavity designs

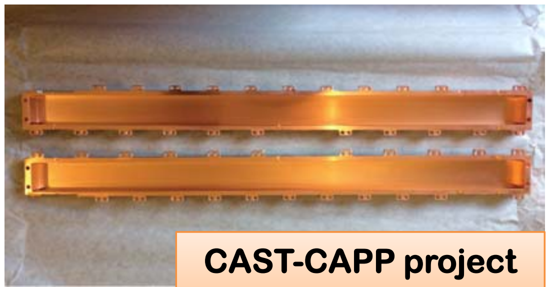
- **Combining the power of many smaller cavities is possible but challenging -> “phase matching”**
  - Probably only possible for “a few” cavities

- **New cavity designs to “decouple” V from m_a, and go for larger effective V *and* larger m_a.**

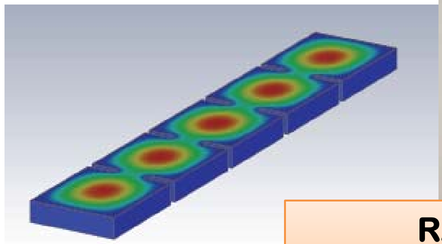
ADMX R&D

Long thin cavities: ma is fixed by small dimensions, but V can be ~larger

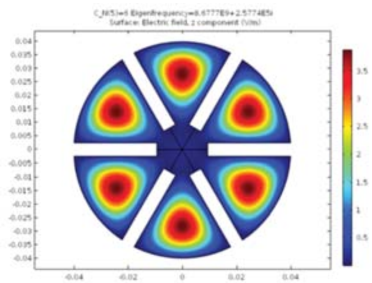
Properly designed arrays of cavities with couplings



CAST-CAPP project in the CAST magnet



RADES project
Filter-like cavities
in the CAST magnet at CERN



“Pizza cavity” at CAPP

*Also ORGAN project in Autralia

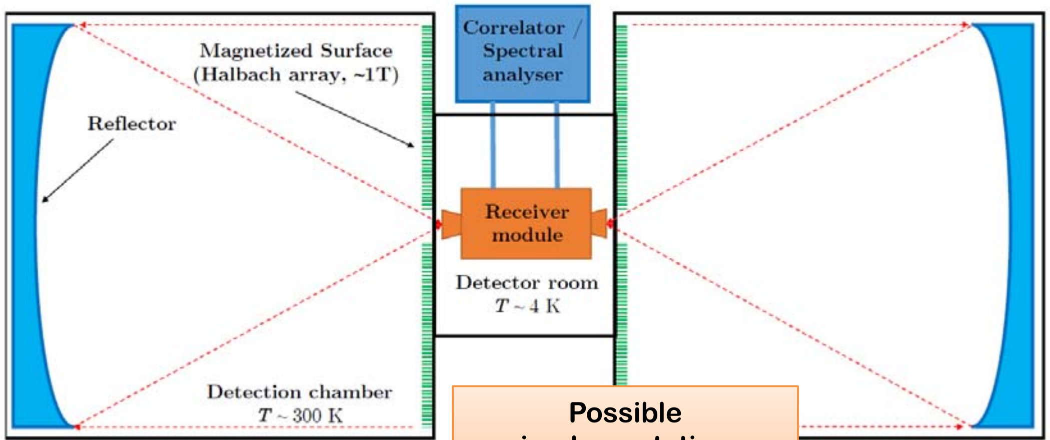
Magnetized dish antenna

- **DM field + B field + boundary condition in the dish**
  → photon emission normal to surface

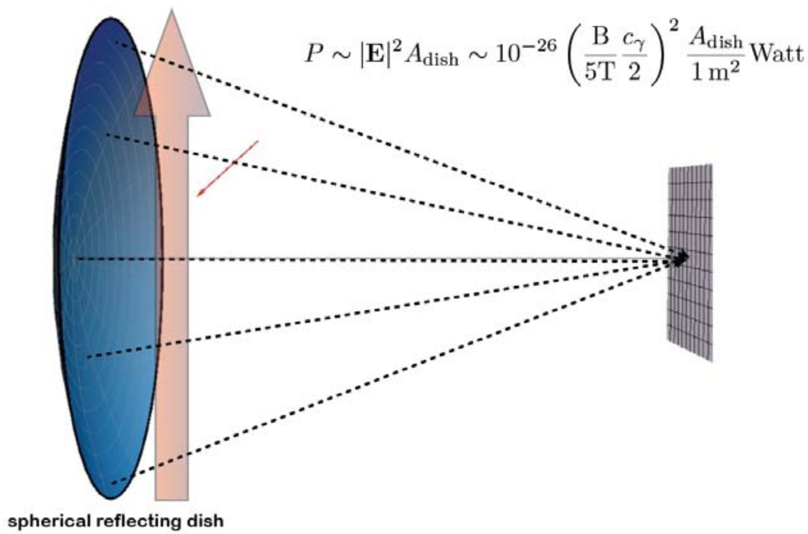
- **No resonance (loss a factor Q) BUT may be compensated with very large areas ?**

Resonance versus area

$$\frac{P_{\rm dish}}{P_{\rm haloscope}} \propto \frac{m_a^2 \mathcal{A}}{Q},$$

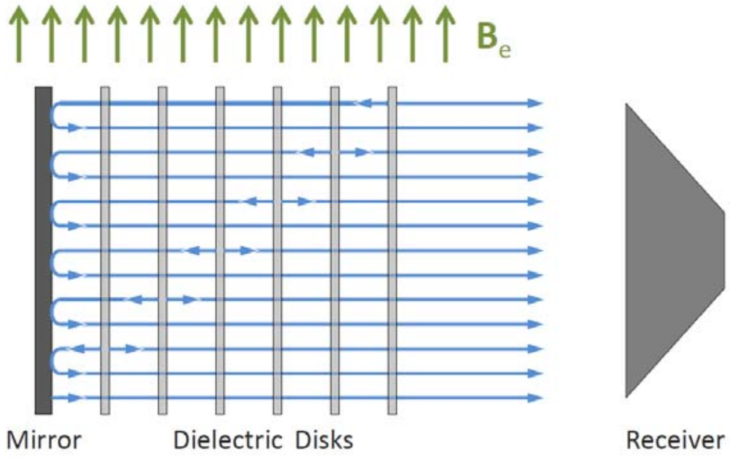


Possible implementation (BRASS Project at Hamburg)

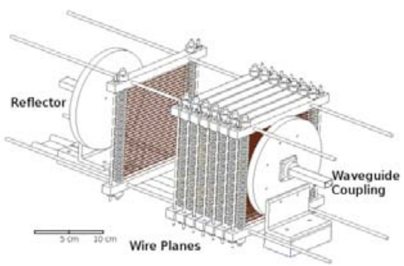


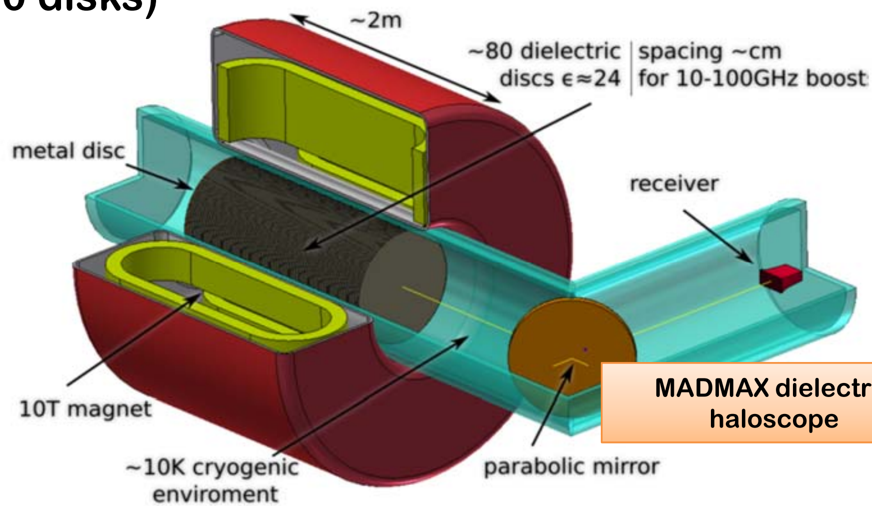
Dielectric haloscopes

- Effect of dish antenna “boosted” by the addition of many dielectric disks
- Some “mild” resonance
  - Concept between a haloscope and a dish antenna
  - It needs tuning! (challenging)
- Relevant sensitivity in the 10^{-4} eV ballpark for a ~m^3 10T experiment (80 disks)

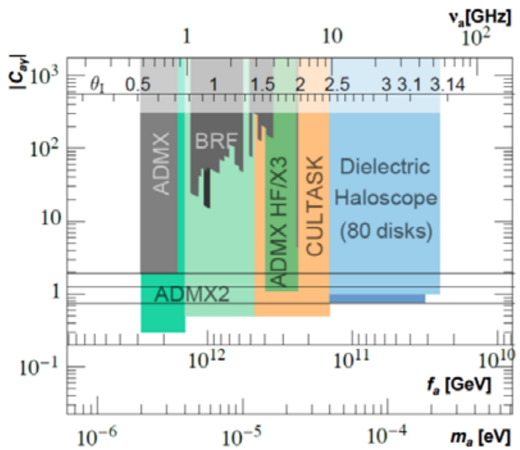


Similar high-m_a structures: ORPHEUS and Electric-Tiger in US





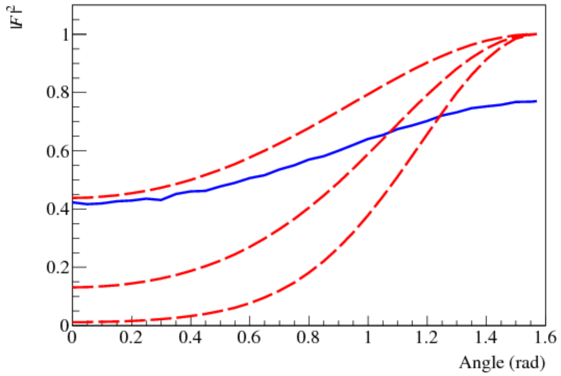
MADMAX dielectric haloscope

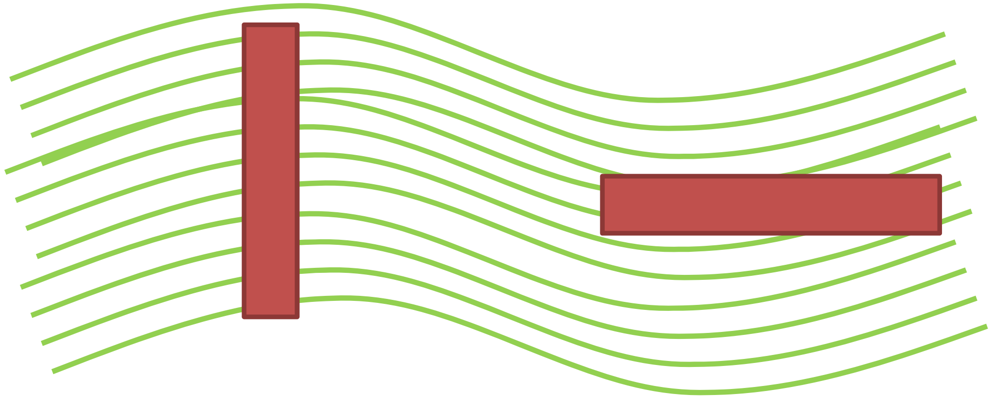


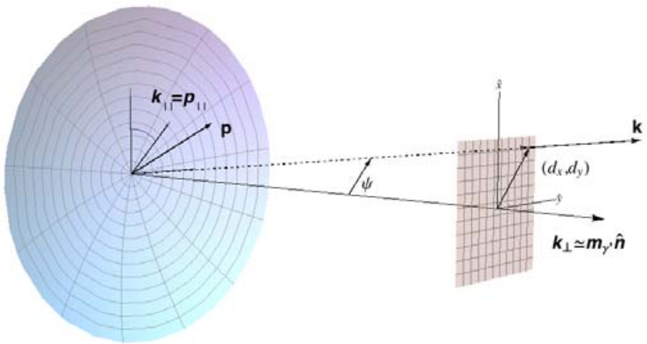
arXiv:1611.05865

Directional effects

- DM directionality would be a powerful signature to confirm a putative signal
- Long aspect-ratio cavities should show a directional dependence if L > ldeBroglie
- Dish antennas: small parallel component proportional to axion momentum
  - pixelised detector at the focal point could image velocity distribution



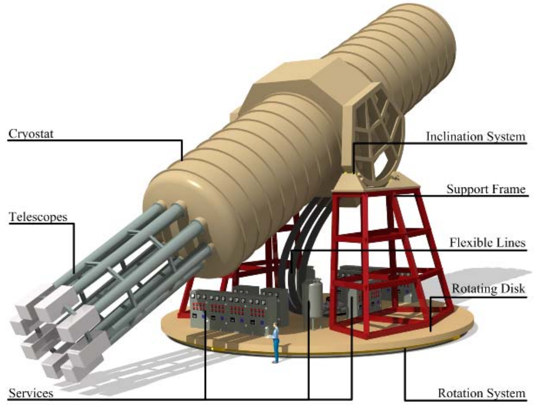




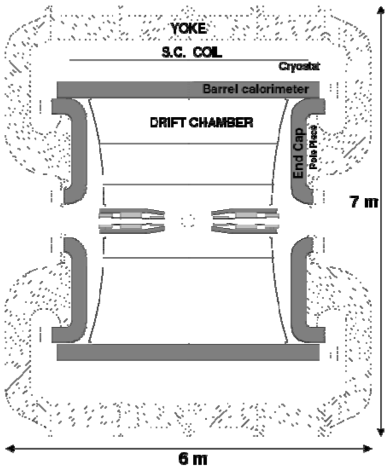
An “axion astronomy” era would follow a discovery

Lower m_a haloscopes

- **Large V haloscopes are technologically simpler, but expensive → huge magnet needed.**
- **Use of existing magnets could be an effective strategy**

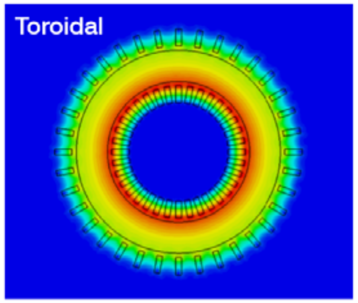


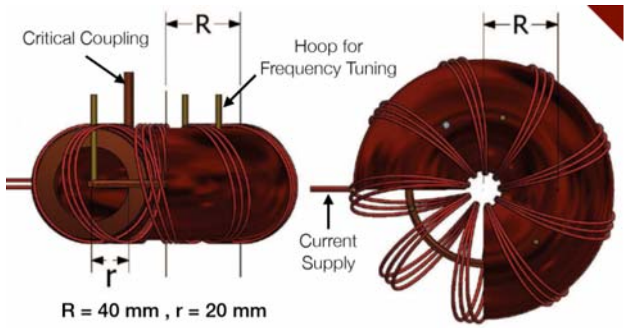
KLASH proposal: use of 50 m³, 0.6T, KLOE magnet at LNF



Future IAXO helioscope (see later) will offer $B^2V > \sim 100\ T^2m^3$

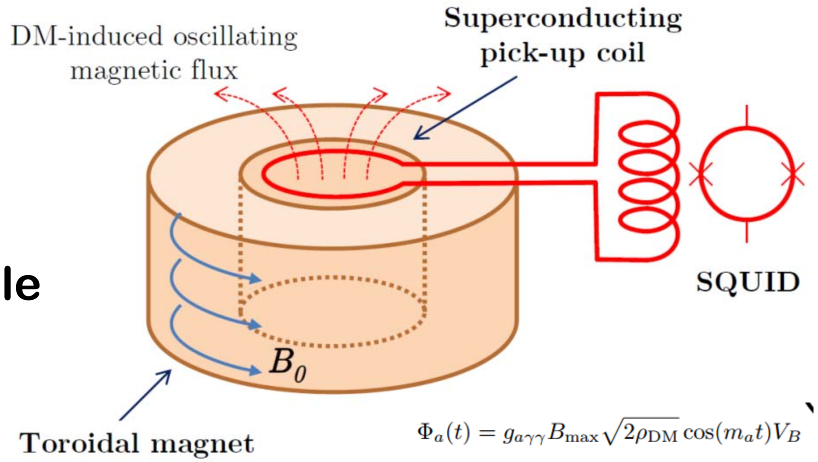
Use of large toroidal magnets: ACTION proposal at CAPP

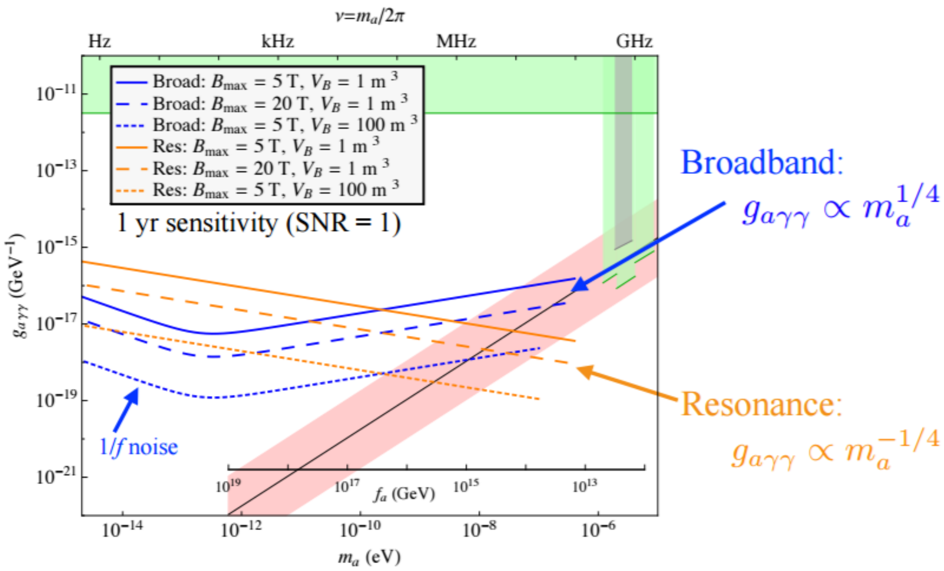




Pick-up coil & resonant circuit

- DM-induced oscillating B in the center of a toroidal magnet
- Resonance is achieved externally with a circuit (no cavity)
- Both wideband search and resonance search possible

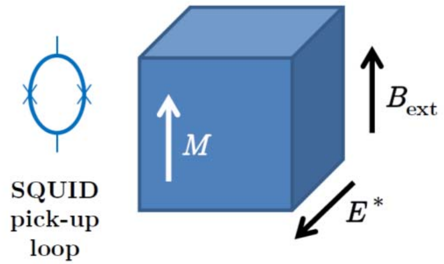




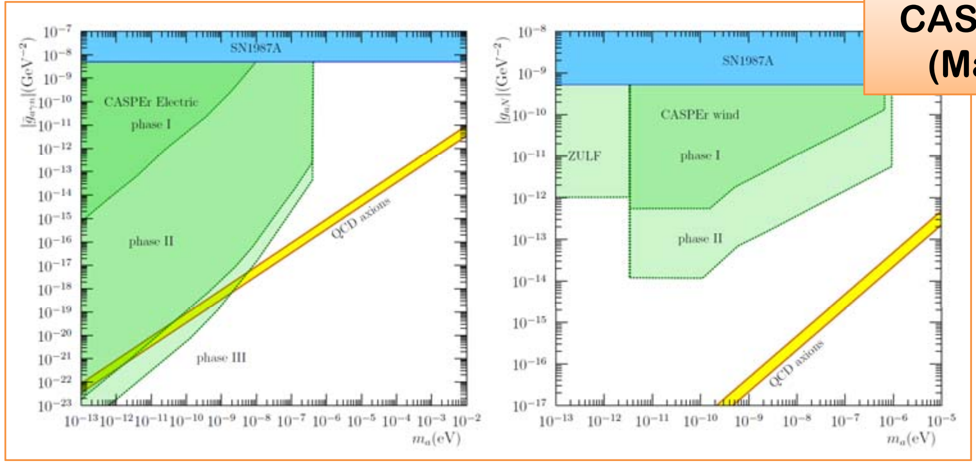
- Competitive at very low m_a
- ABRACADABRA at MIT
  - 10 cm prototype under preparation
- Also DM Radio at Stanford

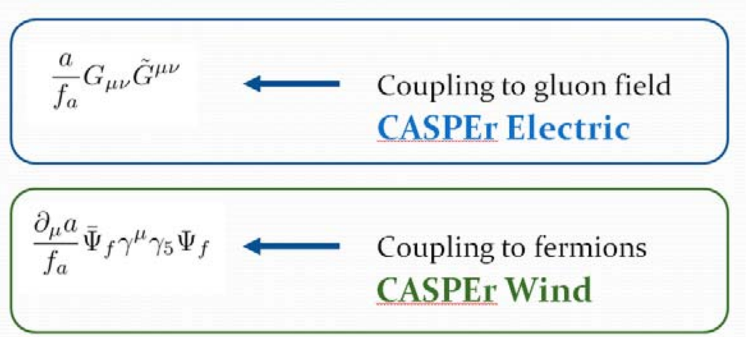
Spin precession experiments

- DM-induced spin precession → it can be detected with very sensitive NMR techniques
- Directly sensitive to the gluon term (also to fermionic couplings)
- Maybe important at very low m_a



CASPEr experiment (Mainz-Berkeley)



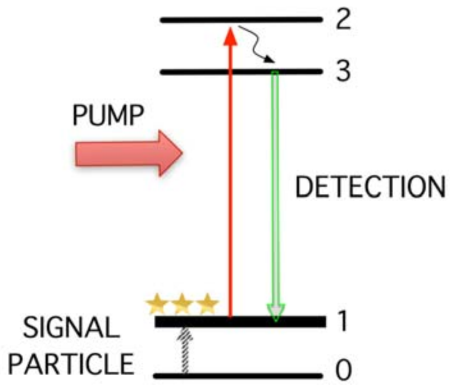


Phys. Rev. X 4, 021030 (2014)

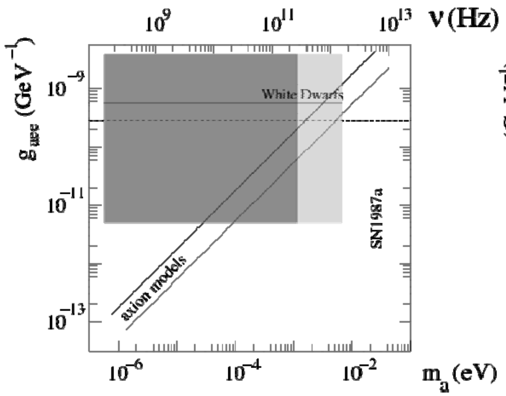
- Also QUAX experiment (Padova):
  - Electron spin precession
  - Sensitive to "axion DM wind" through axion-electron coupling

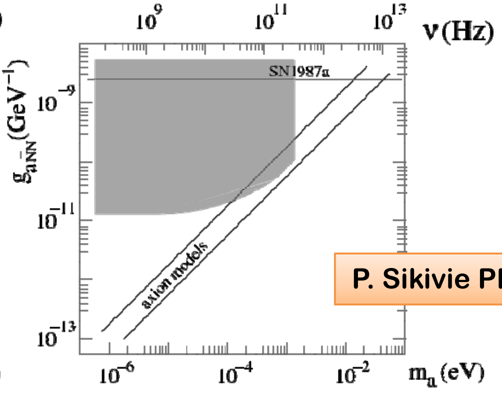
DM-induced atomic transitions

- DM can induce atomic excitations equal to m_a.
- Sensitive to axion-electron and axion-nucleon coupling
- Zeeman effect → create atomic transitions tunable to m_a
- Detection of excitation via pump laser
- AXIOMA → recent project aiming at an implementaiton



Relevant sensitivity for $m_a \sim 10^{-4}$ eV seems possible for kg-sized samples



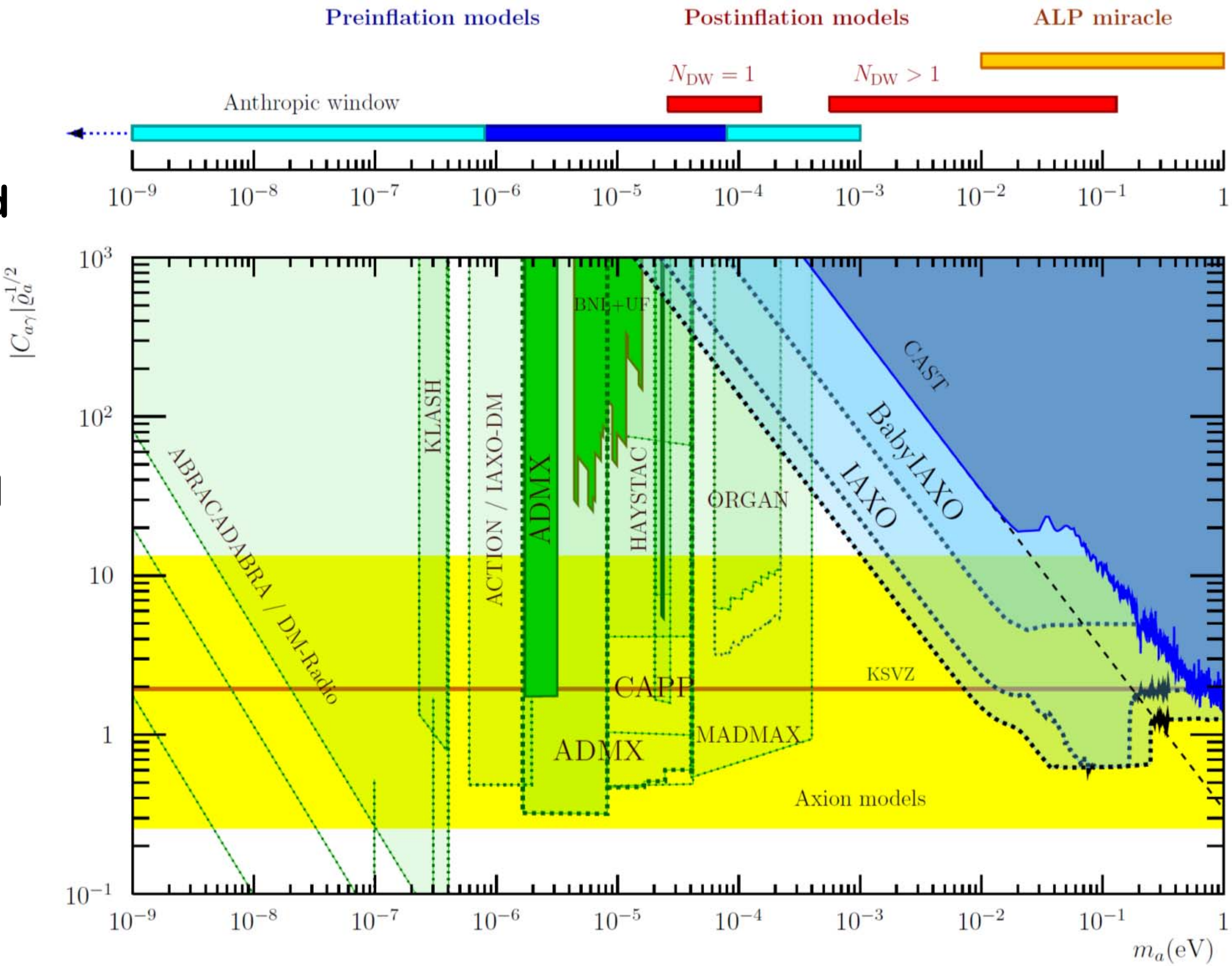


P. Sikivie PRL 113(14)

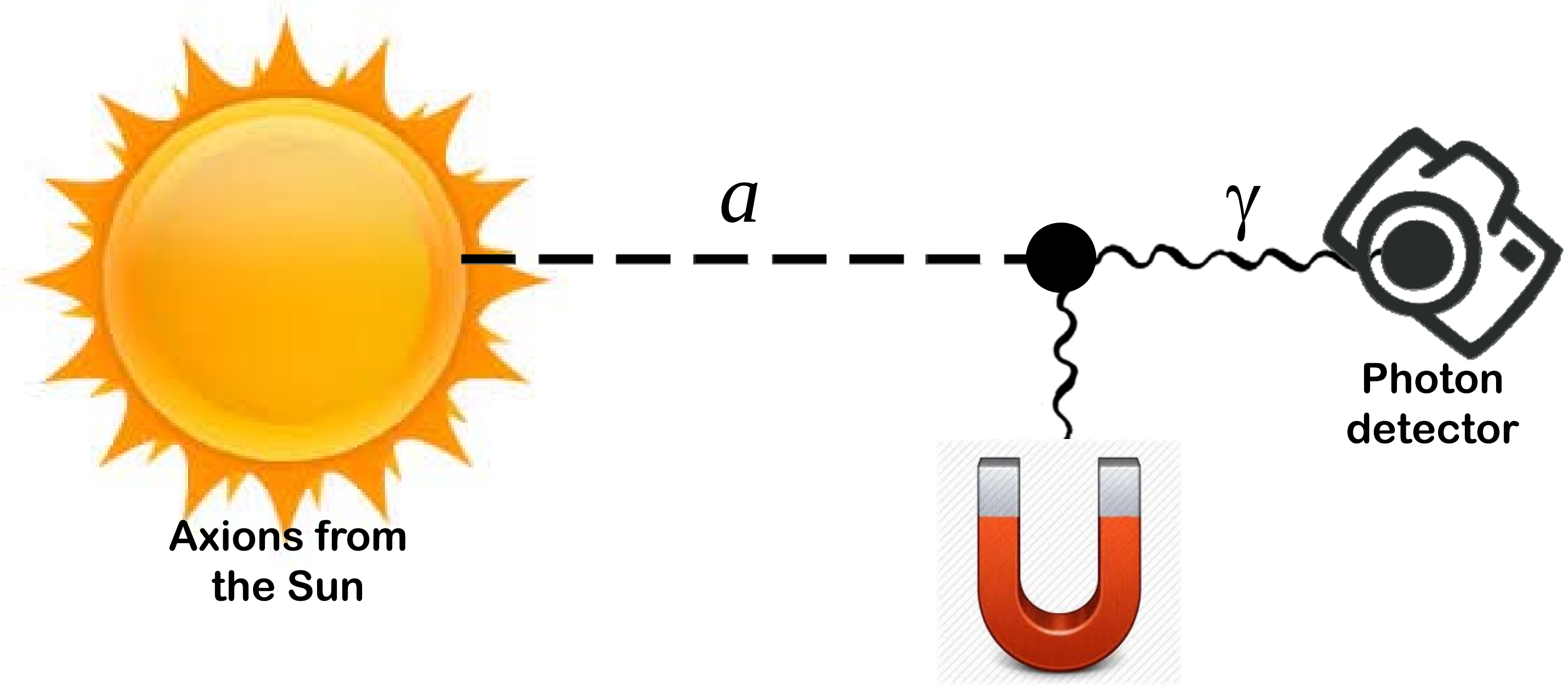
- **Summary of current status and future prospects…**

- **A diverse experimental landscape has emerged with potential to cover a substantial fraction of parameter space**

- **Caution: many of these prospects still rely on a prior succesful R&D phase**
- **Caution: Green areas rely on axion as DM hypothesis…**

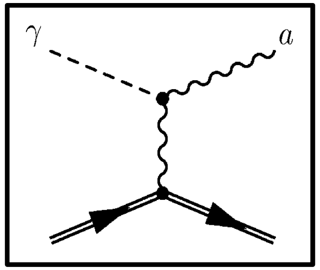


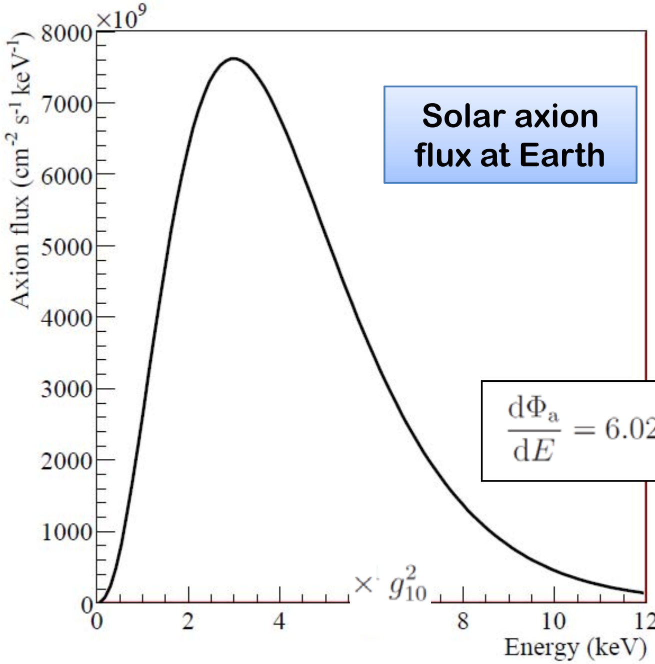
Solar axions

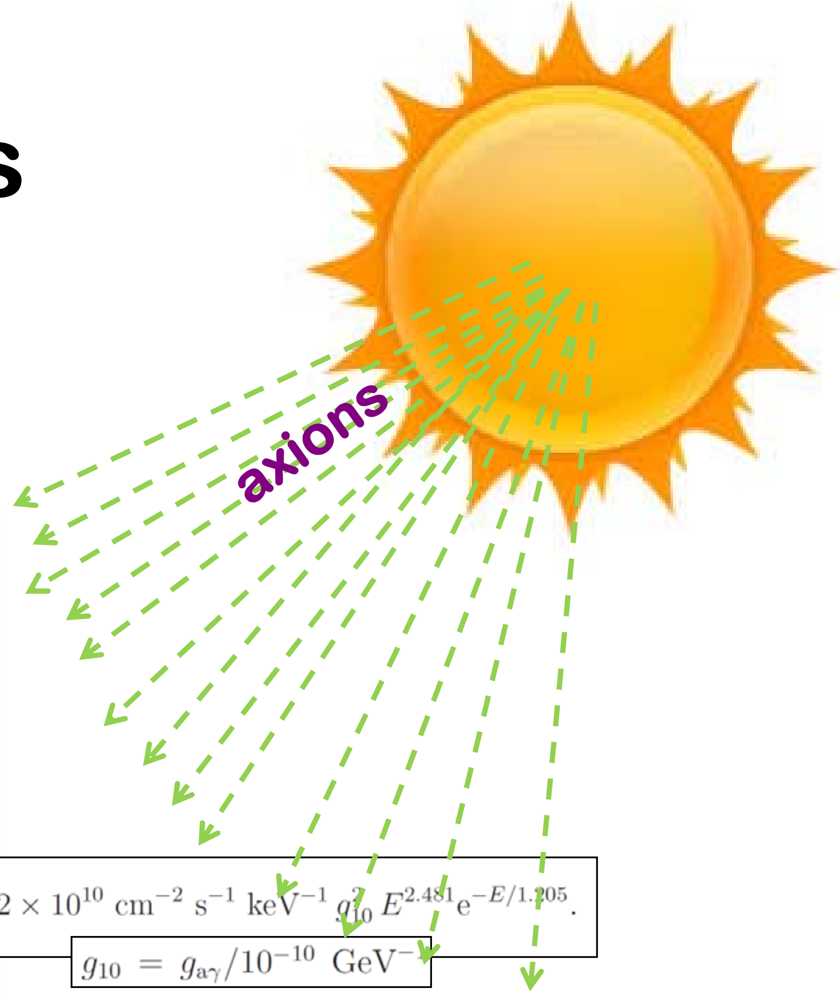


Solar axions

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







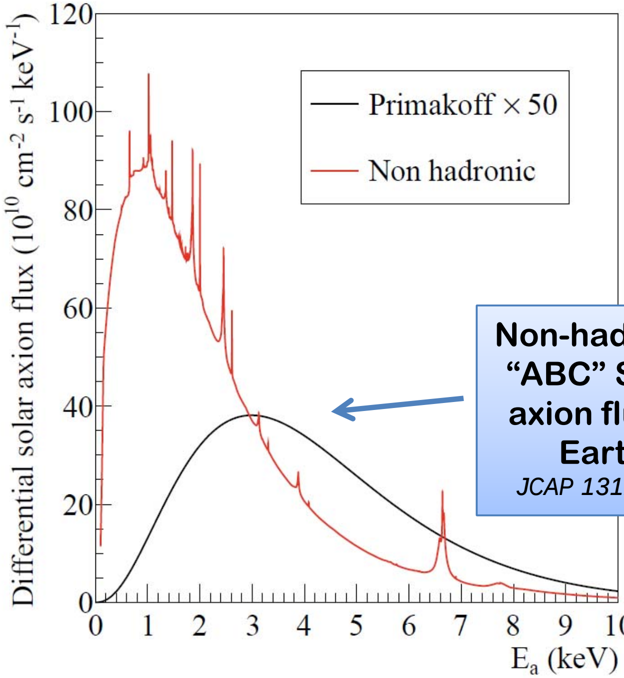
$$\frac{d\Phi_a}{dE} = 6.02 \times 10^{10}\ \mathrm{cm^{-2}\ s^{-1}\ keV^{-1}}\ g_{10}^2\ E^{2.481} e^{-E/1.205}.$$

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

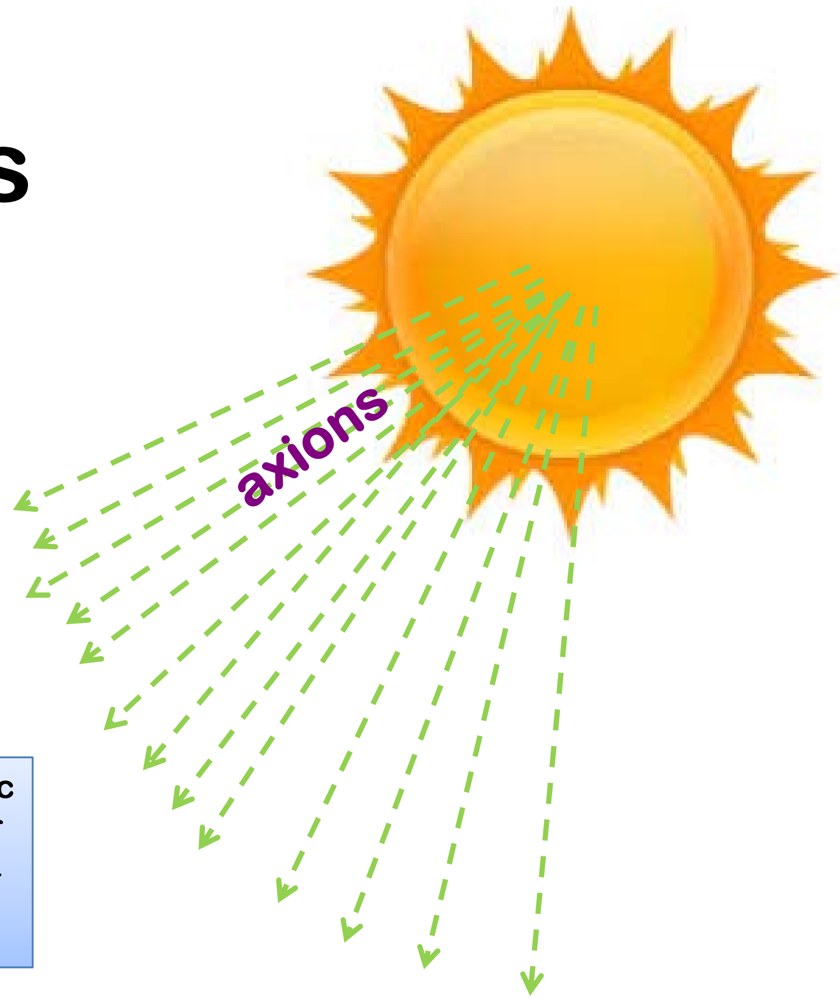
van Bibber PRD 39 (89)
CAST JCAP 04(2007)010

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

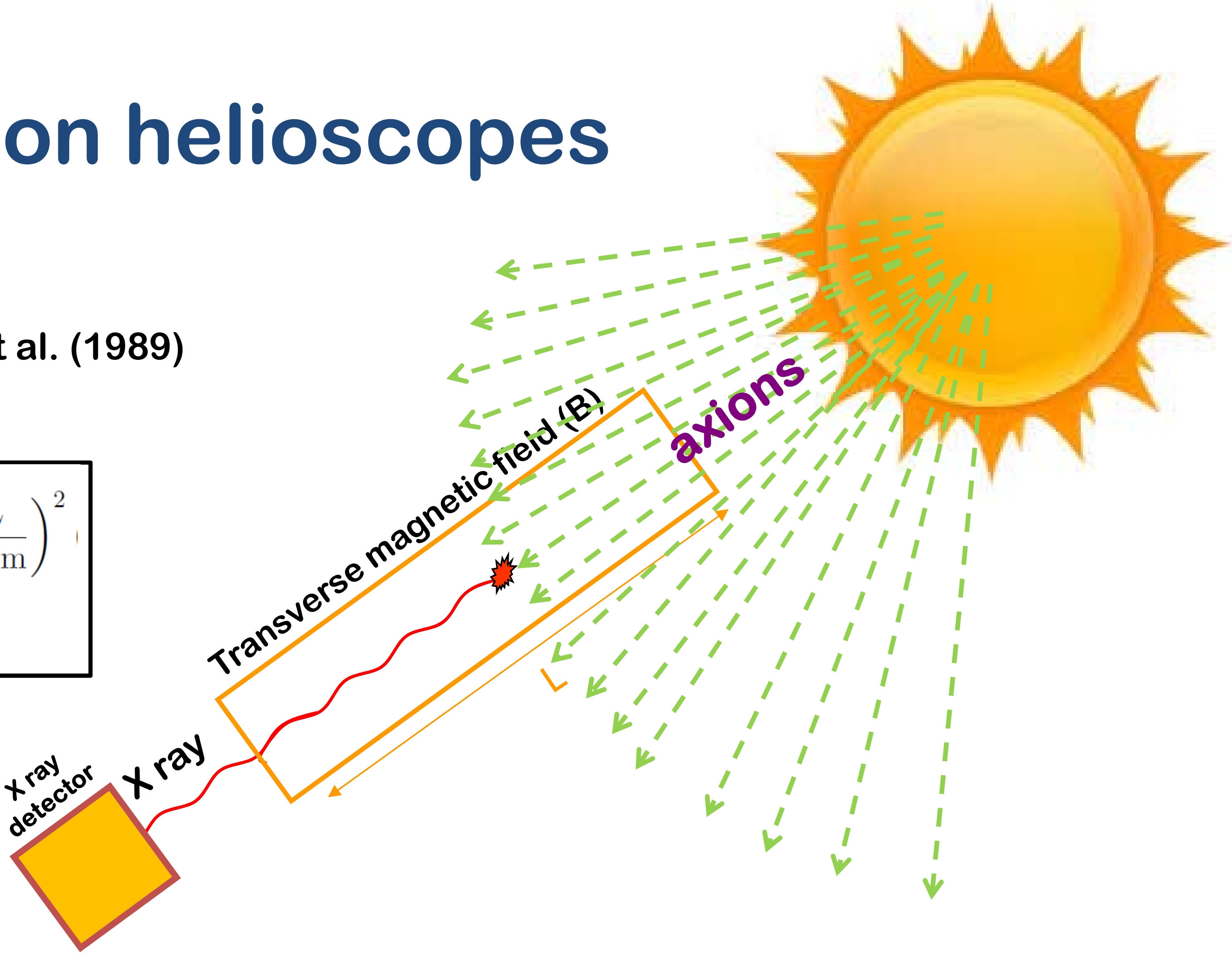


* if the axion couples with the electron (g_{ae})
(non hadronic axion)

Axion helioscopes

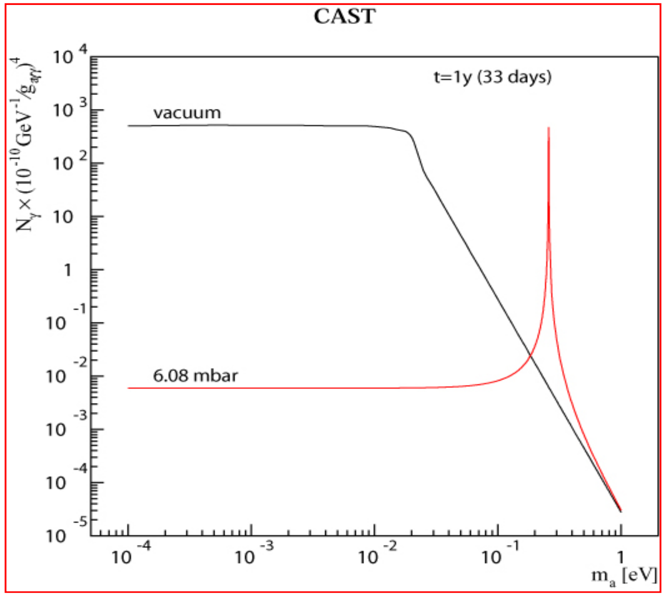
Axion helioscope concept
P. Sikivie, 1983
+ K. van Bibber, G. Raffelt, et al. (1989)
(use of buffer gas)

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

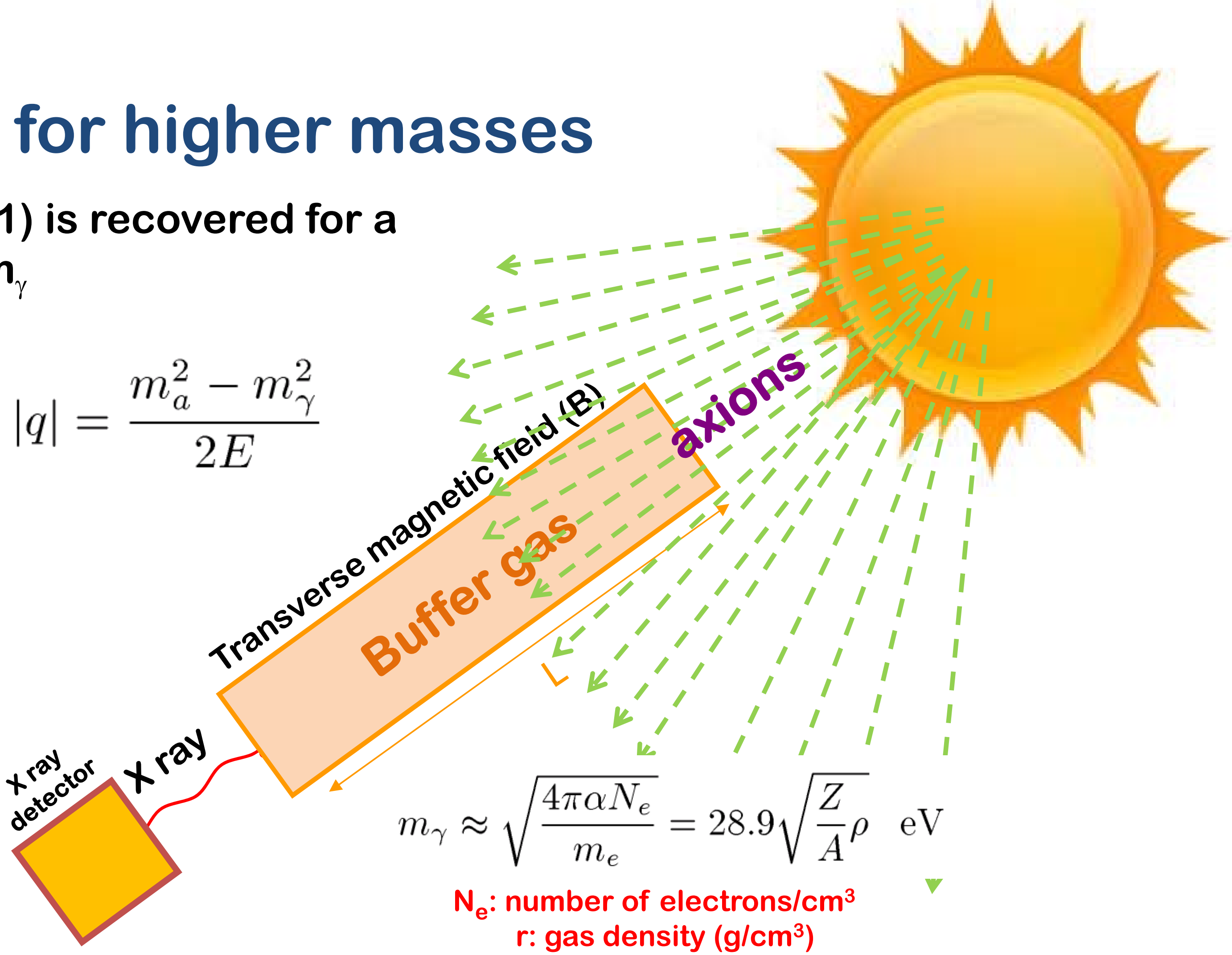


Buffer gas for higher masses

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



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

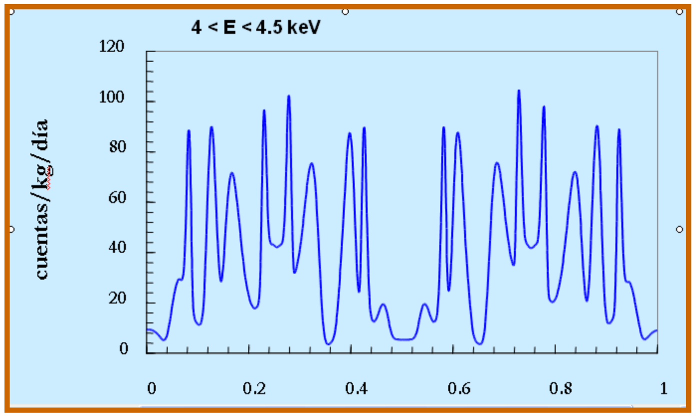


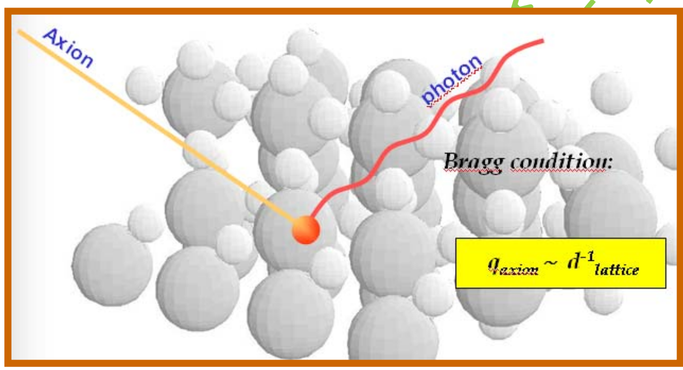
$$m_\gamma \approx \sqrt{\frac{4\pi\alpha N_e}{m_e}} = 28.9\sqrt{\frac{Z}{A}\rho} \quad \mathrm{eV}$$

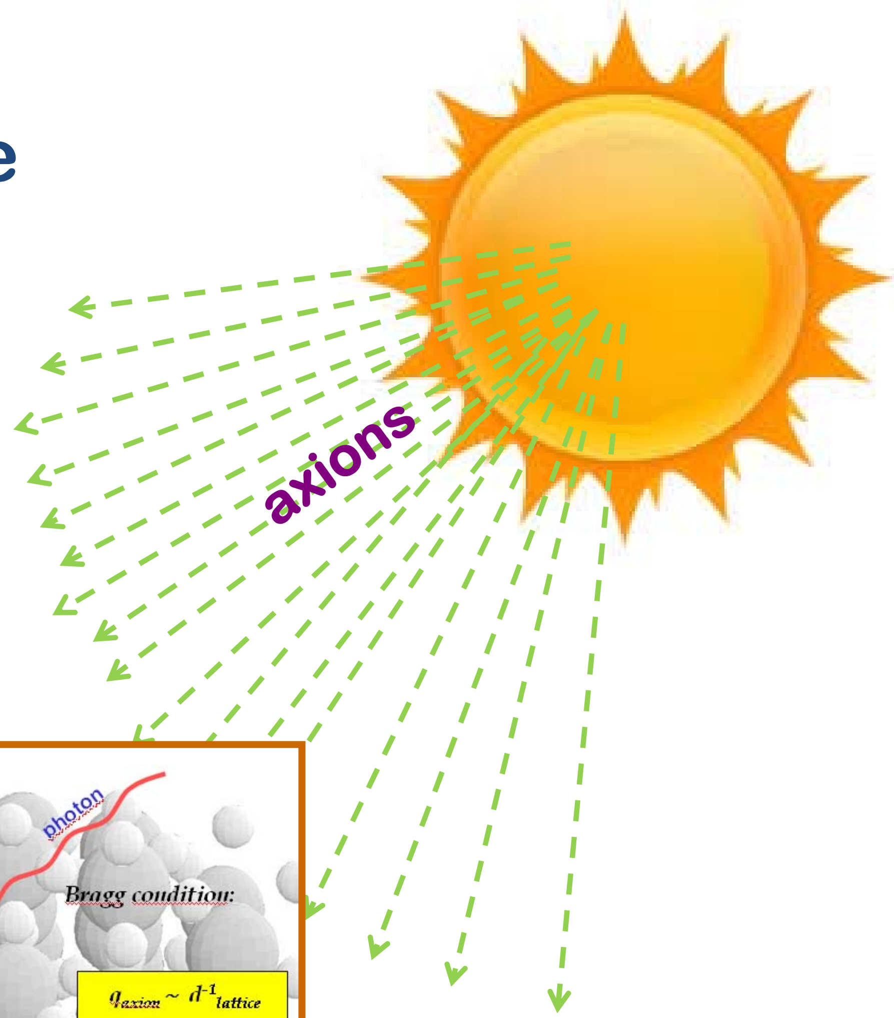
N_e: number of electrons/cm^3
r: gas density (g/cm^3)

Other types of helioscope

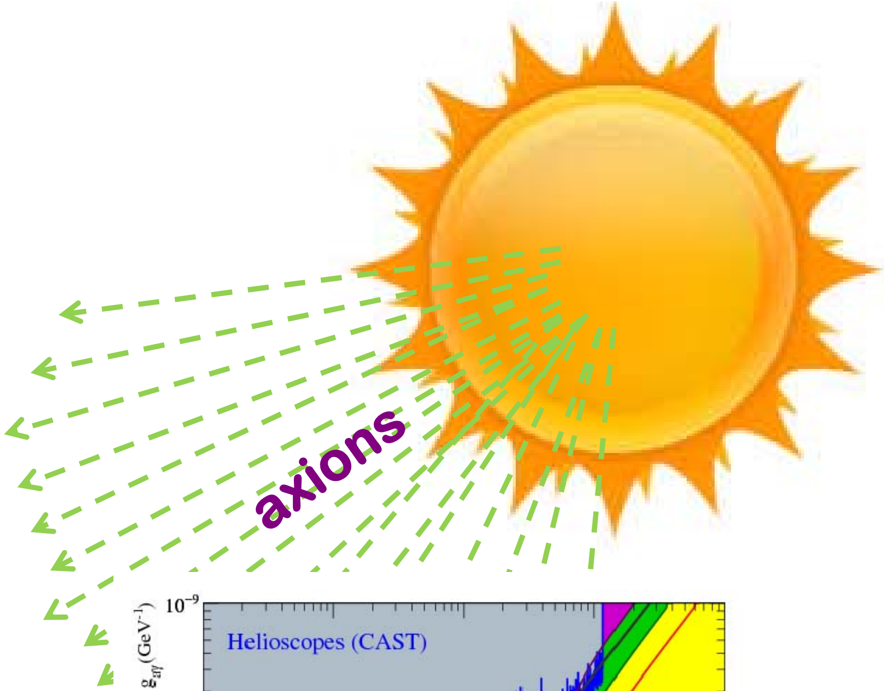
- **Instead of magnetic field, one can use the electromagnetic field of crystals…**
- **« Primakoff-Bragg » effect**
- **WIMP-like experiments provide limit to axions: SOLAX, COSME, DAMA, EDELWEISS, CDMS, etc…**
- **Characteristical temporal pattern:**



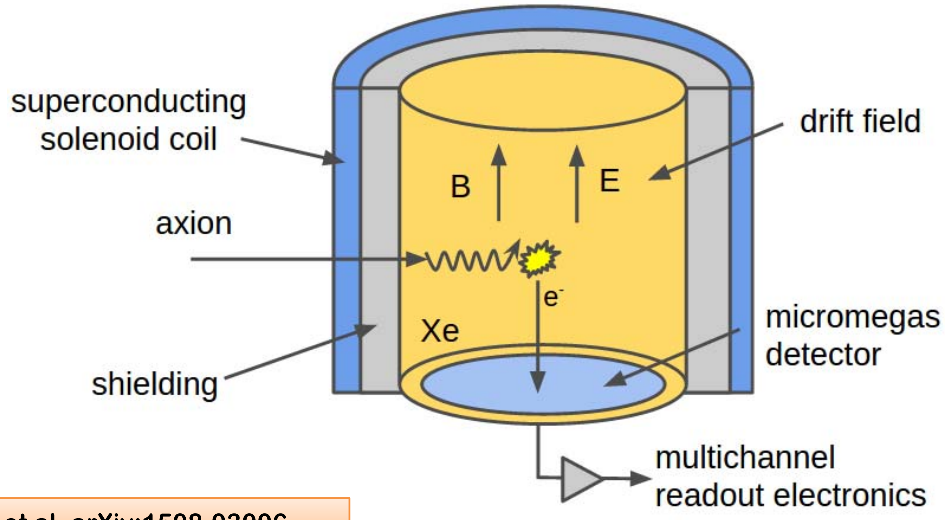


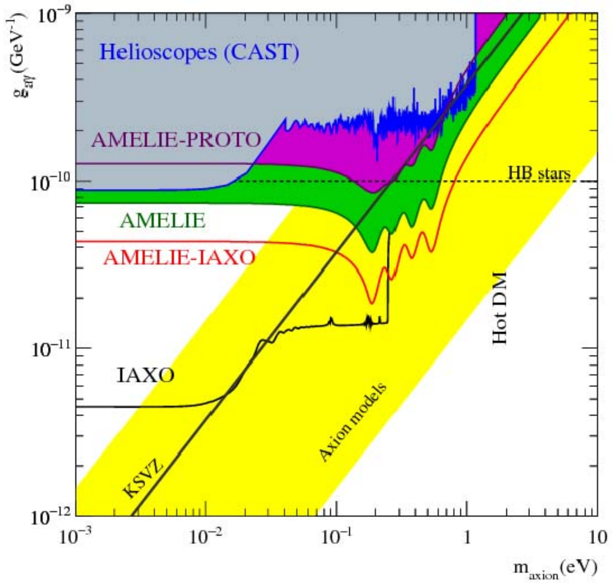


Other types of helioscope



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

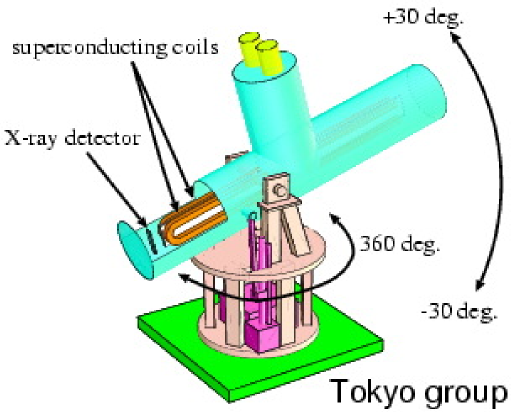


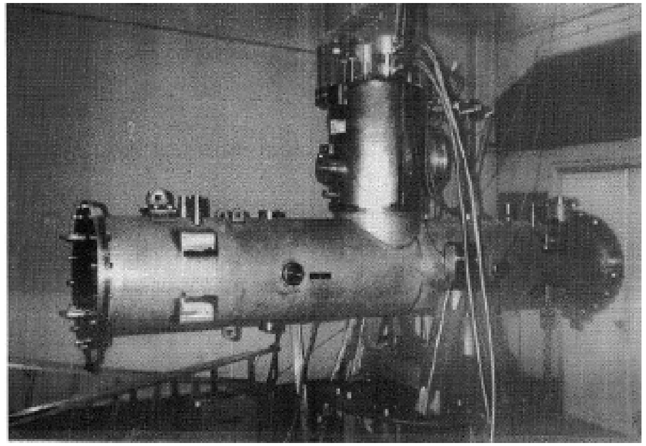


Galán et al, arXiv:1508.03006

Axion Helioscopes

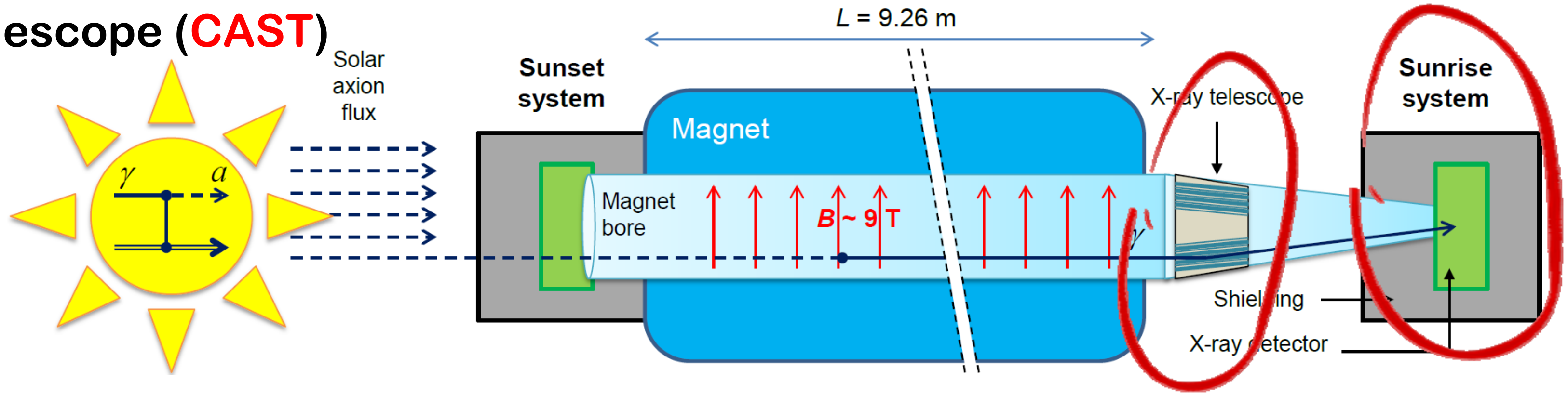
- **Previous helioscopes:**
  - First implementation at Brookhaven (just few hours of data) [Lazarus et at. PRL 69 (92)]
  - TOKYO Helioscope (SUMICO): 2.3 m long 4 T magnet





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

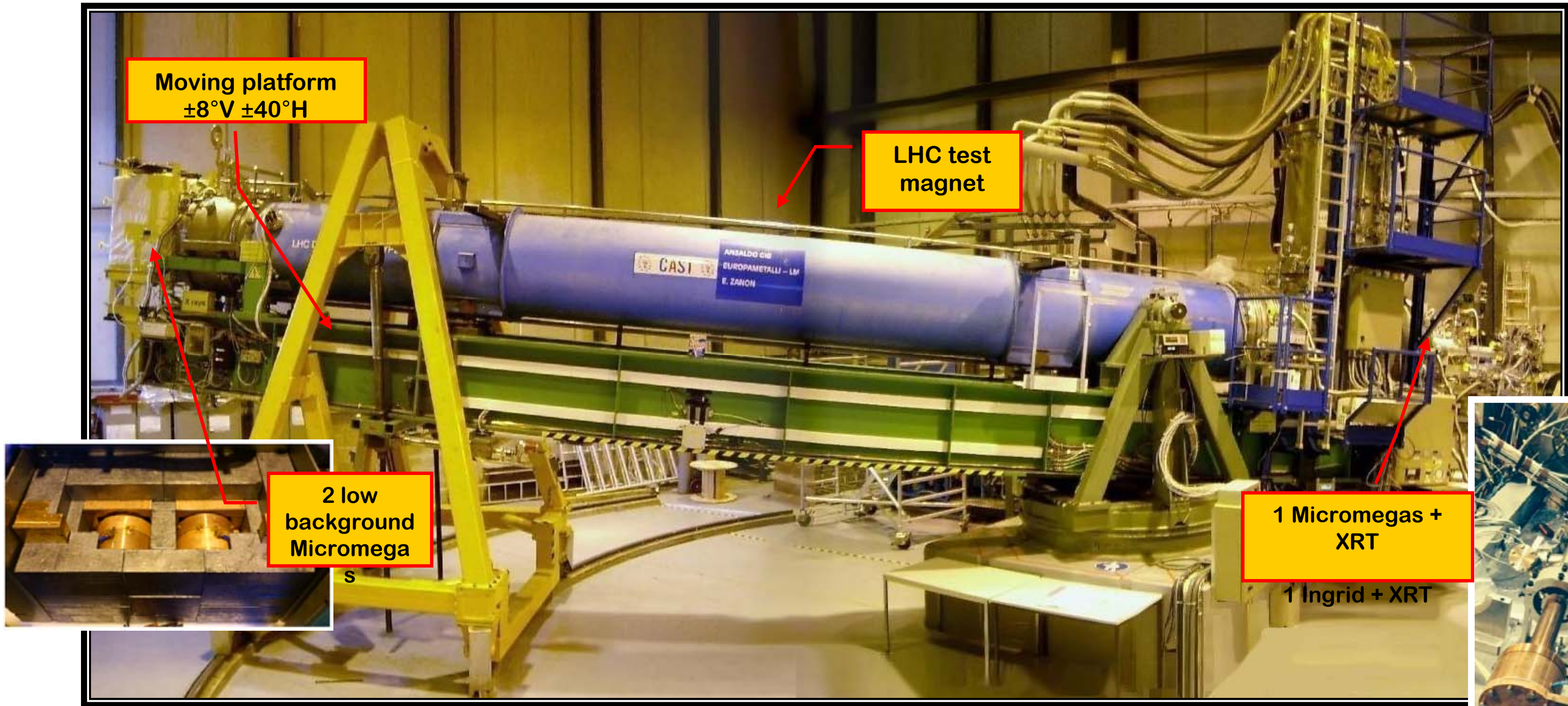
First helioscope using low background techniques & x-ray focusing

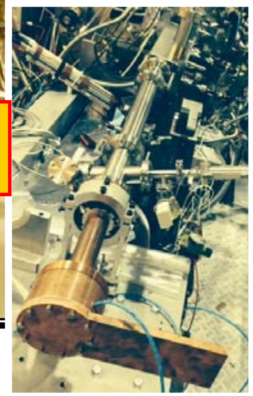


CAST experiment @ CERN

- 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 used.
- X ray Focusing System to increase signal/noise ratio.



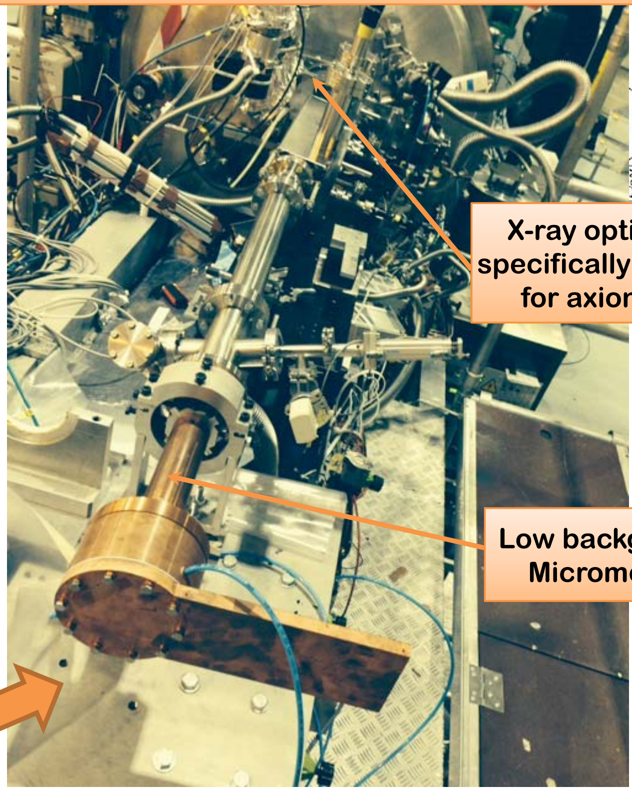


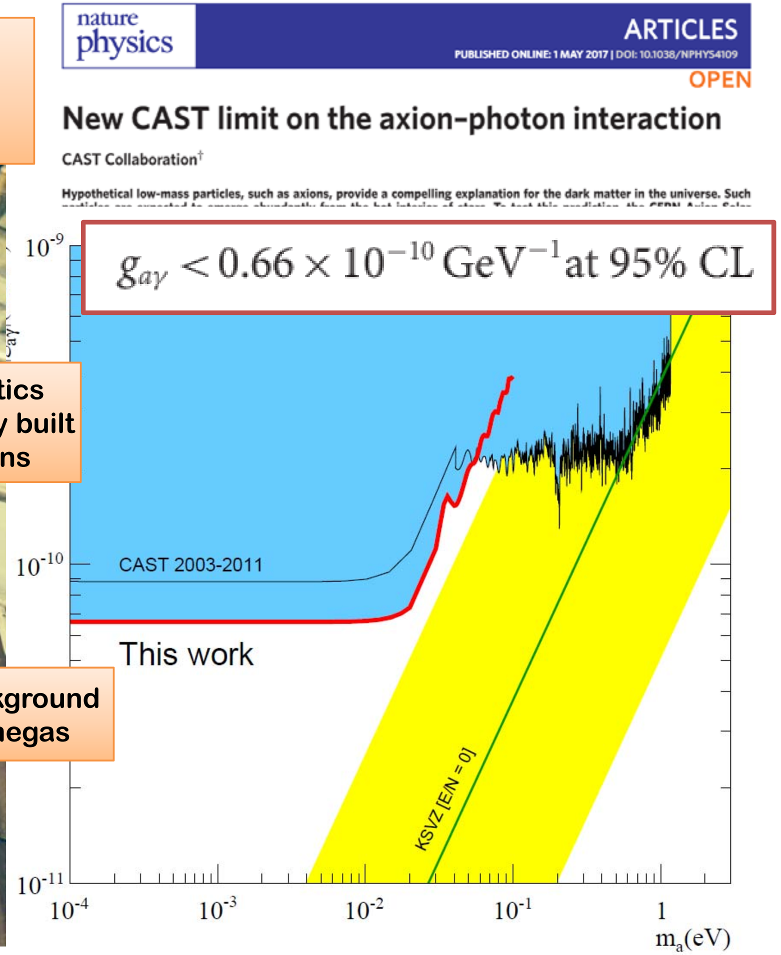
CAST hunting axions (movie credit: M. Rosu / CERN)

Latest CAST limit

2003 – 2004	**CAST phase I** • vacuum in the magnet bores
2006	**CAST phase II - ^4He Run** • axion masses explored up to 0.39 eV (160 P-steps)
2007	^3He Gas system implementation
2008 - 2011	**CAST phase II - ^3He Run** • axion masses explored up to 1.17 eV • bridging the dark matter limit
2012	•Revisit 4He Run with improved detecors
2013-2015	**•New vaccum phase with improved detectors** → Result released in 2017

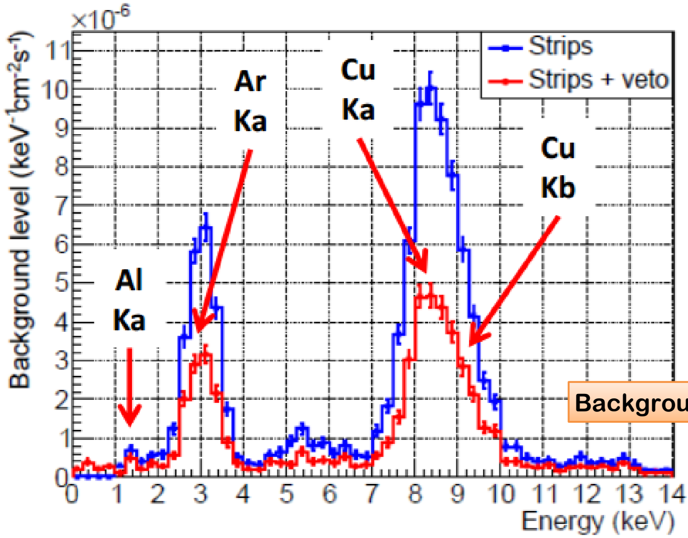
Enabled by the IAXO pathfinder system



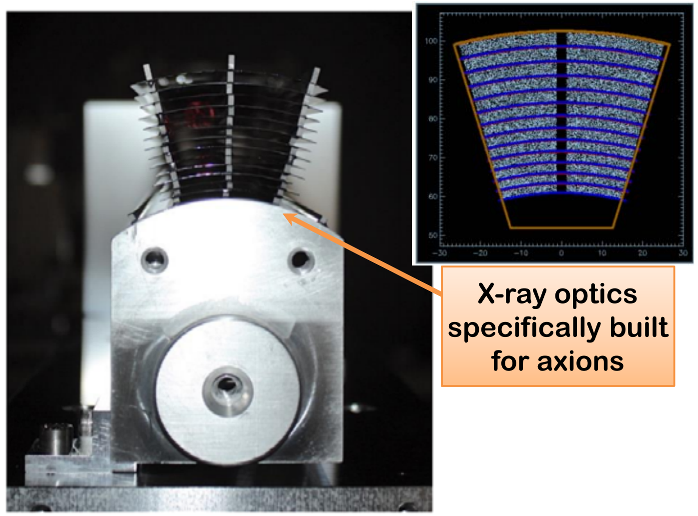


IAXO pathfinder system in CAST

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

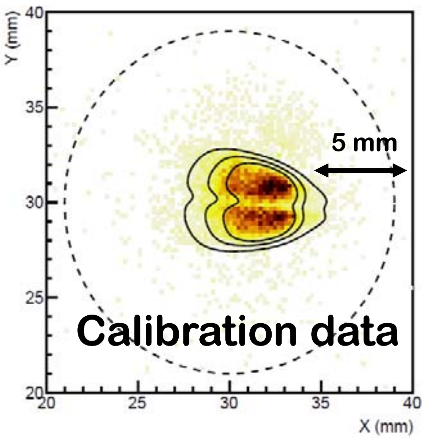


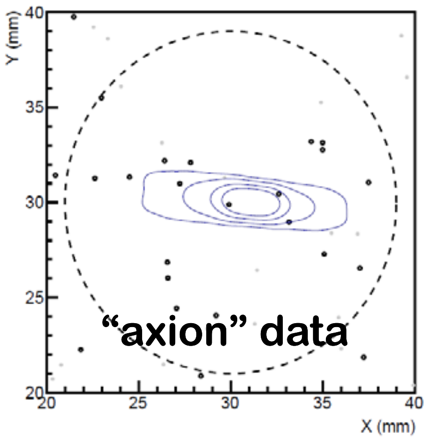
Background spectrum



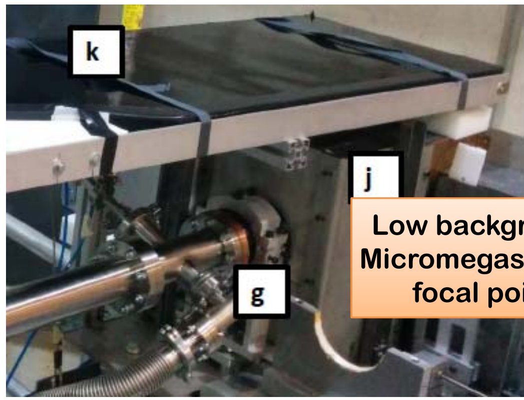
X-ray optics specifically built for axions

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





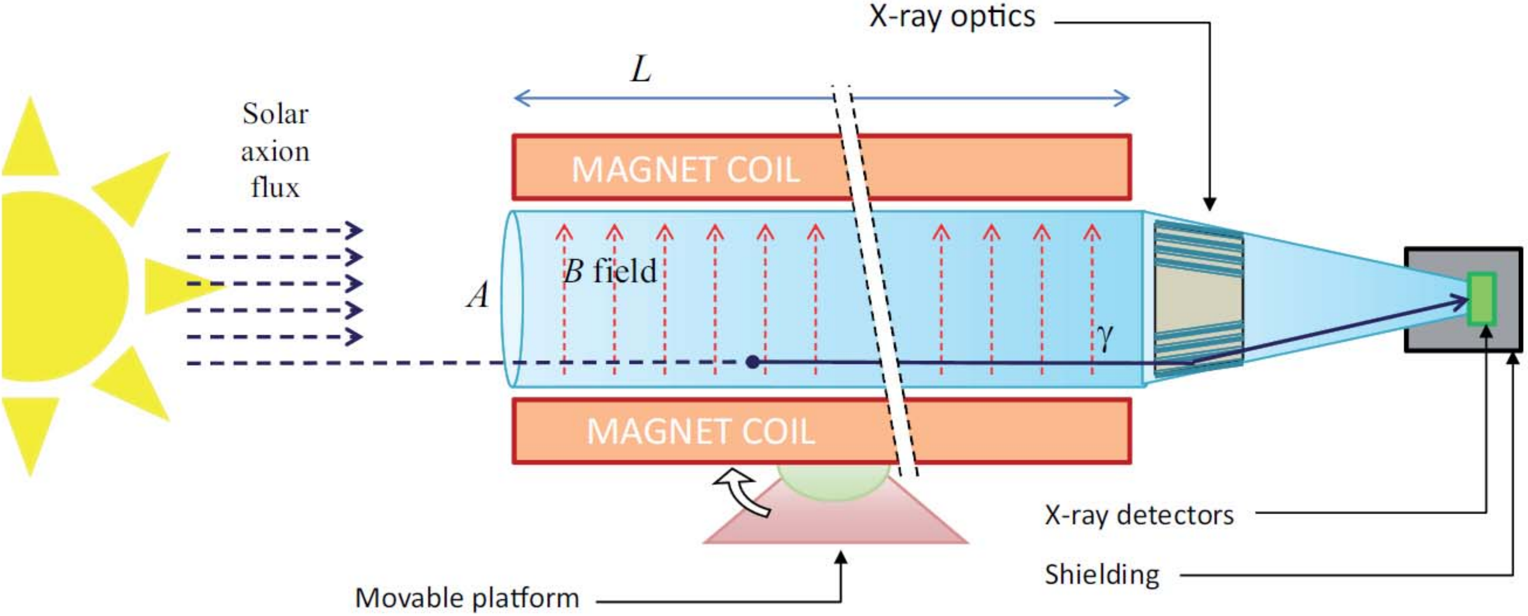
- Best SNR of any previous detector
- 290 tracking hour acquired (6.5 months operation)
- 3 counts observed in RoI (1 expected)



Low background Micromegas at the focal point

IAXO – Concept

IAXO
International Axion Observatory



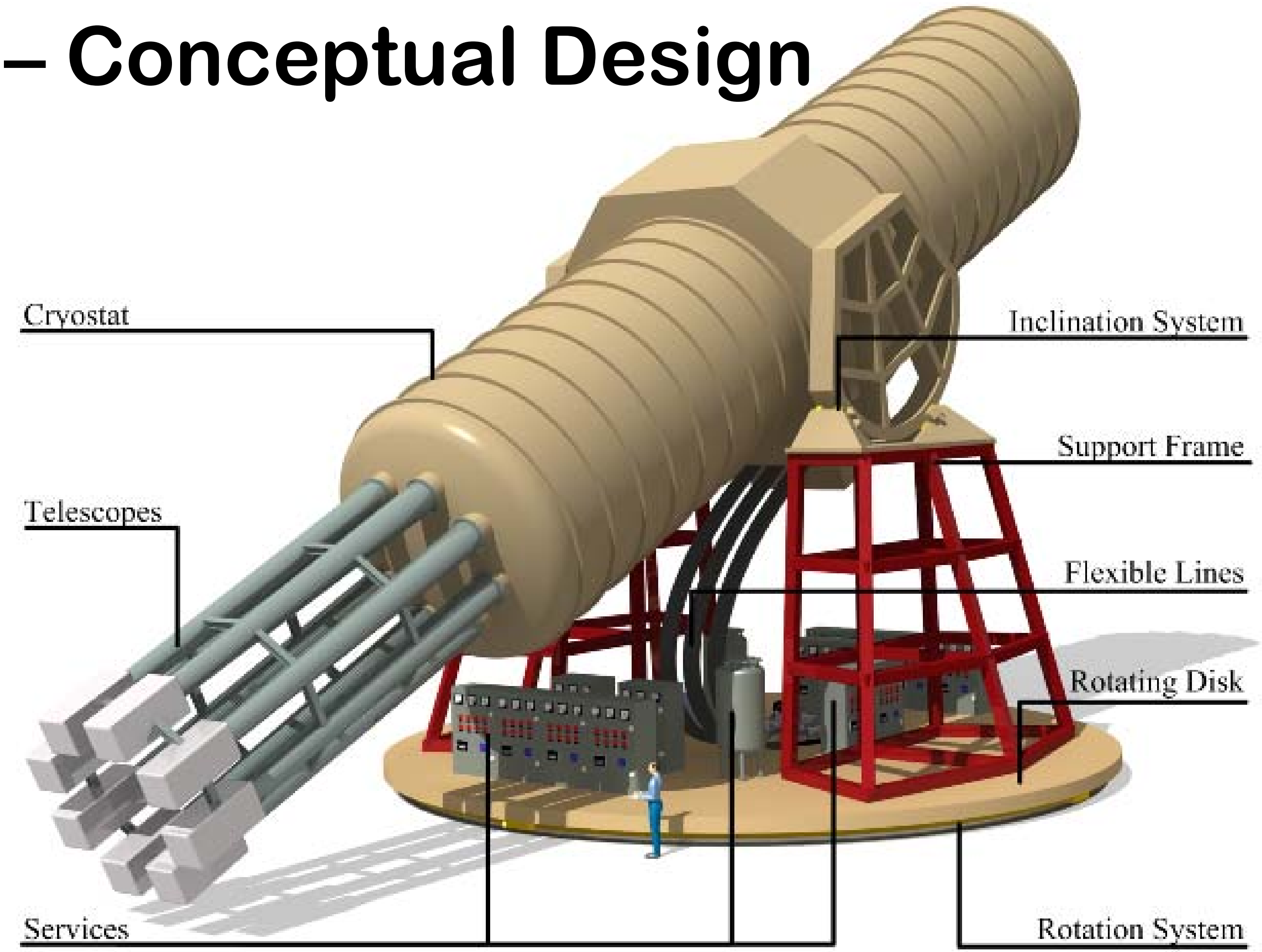
Enhanced axion helioscope:
JCAP 1106:013,2011

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

4+ orders of magnitude better SNR that CAST

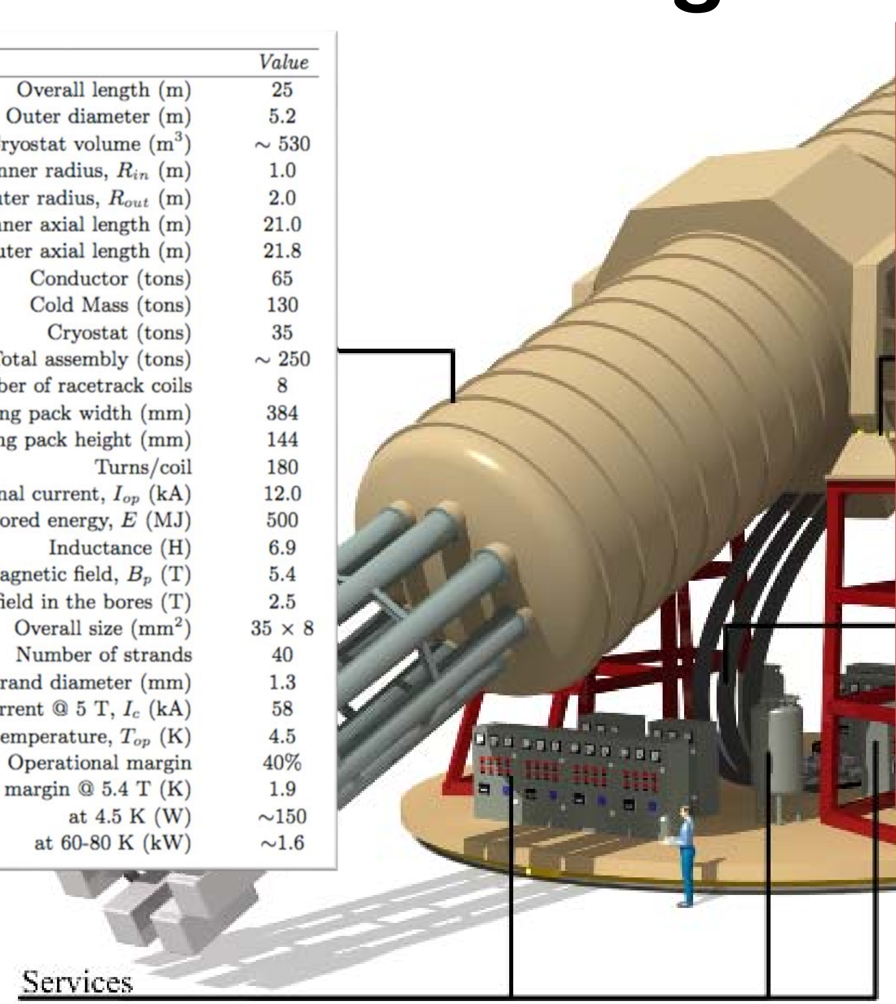
IAXO – Conceptual Design

- 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



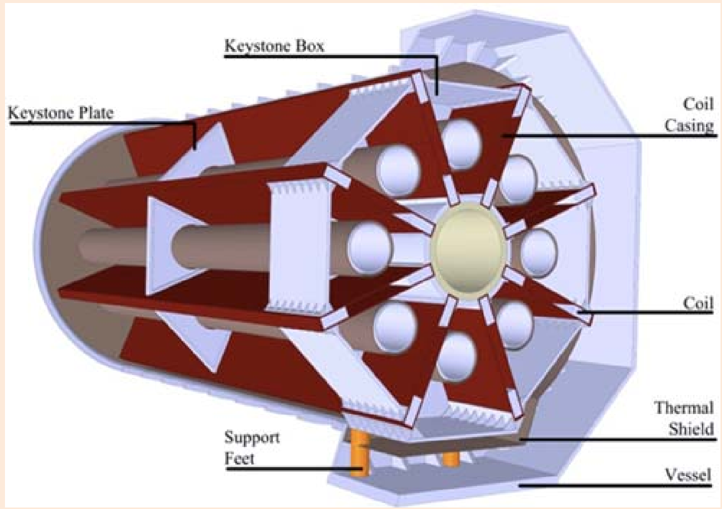
IAXO technologies – magnet

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

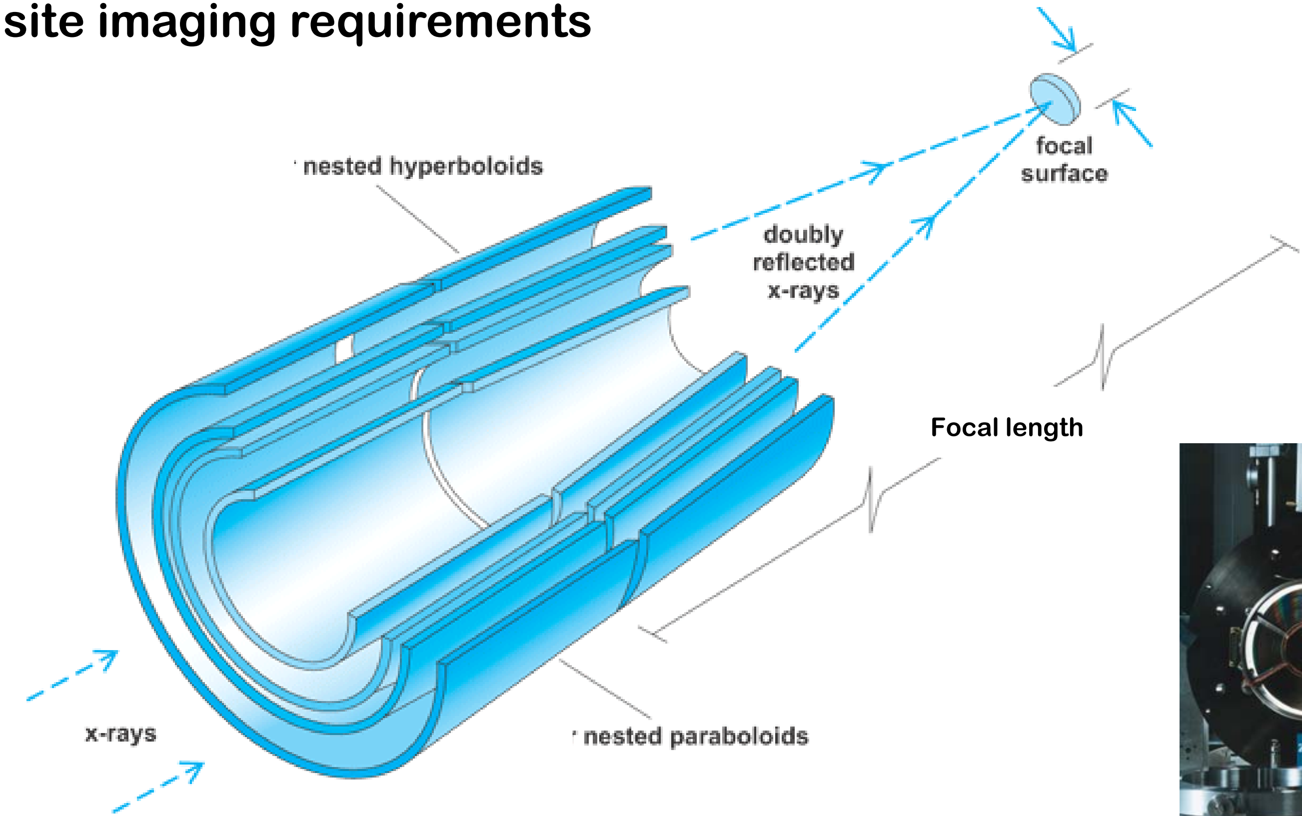
- Superconducting “detector” magnet.
- Toriodal geometry (8 coils)
- Based on ATLAS toroid technical solutions.
- CERN+CEA expertise
- 8 bores / 20 m long / 60 cm Ø per bore



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

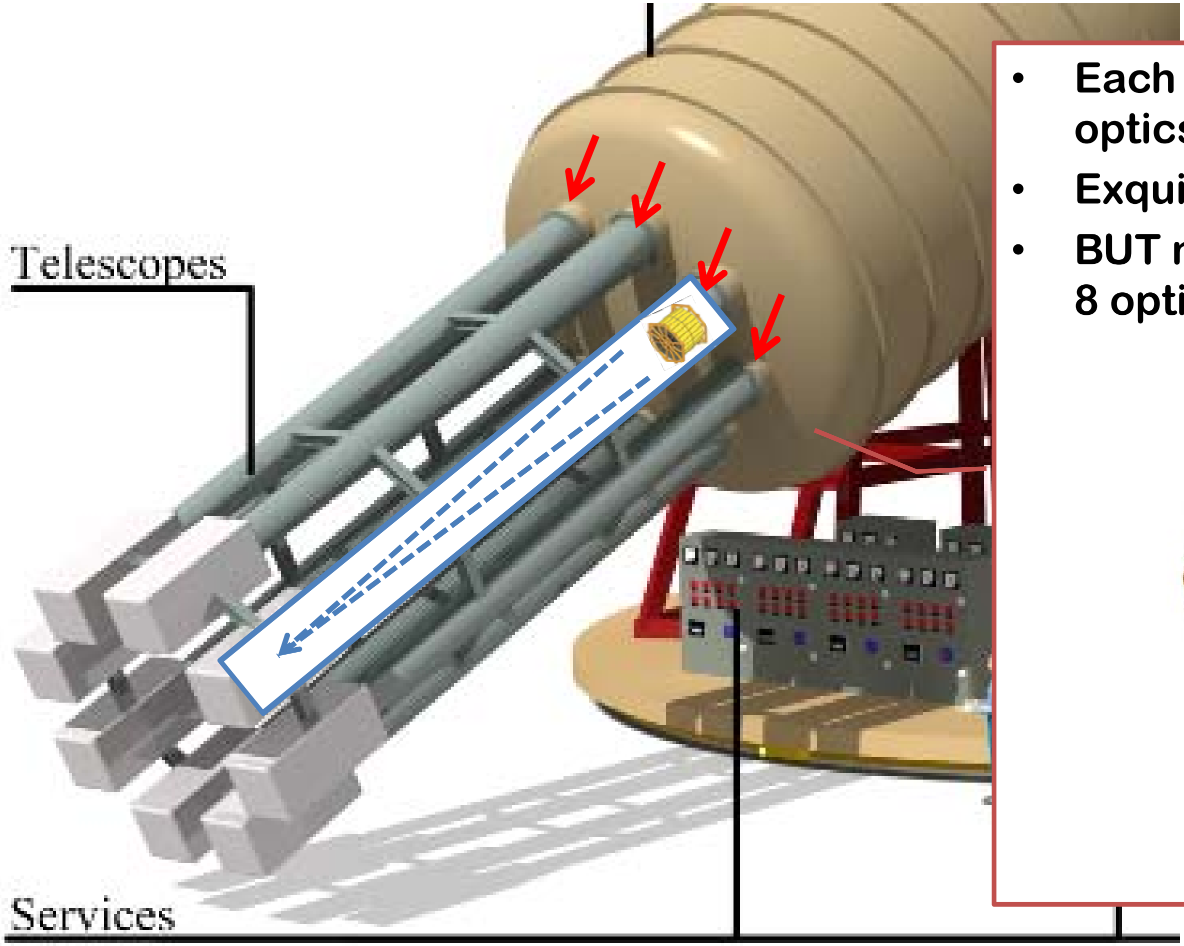
IAXO x-ray optics

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

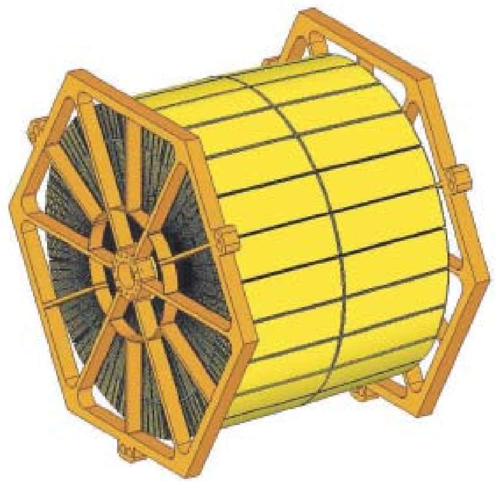


ABRIXAS spare telescope, in use in one of the 4 bores of CAST (pioneer use of x-ray optics in axion research)

IAXO x-ray optics

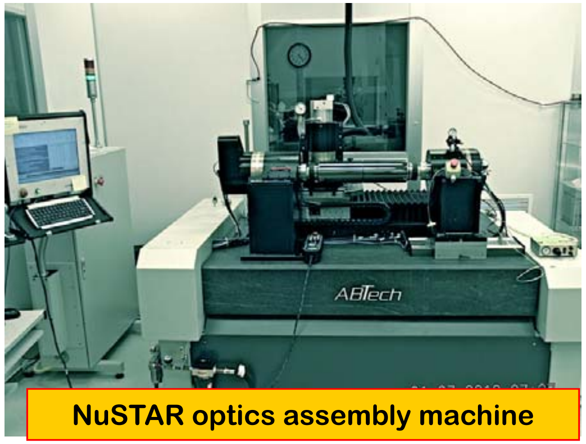


- Each bore equipped with an x-ray optics
- Exquisite imaging not required
- BUT need cost-effective way to build 8 optics of 600 mm diameter each.

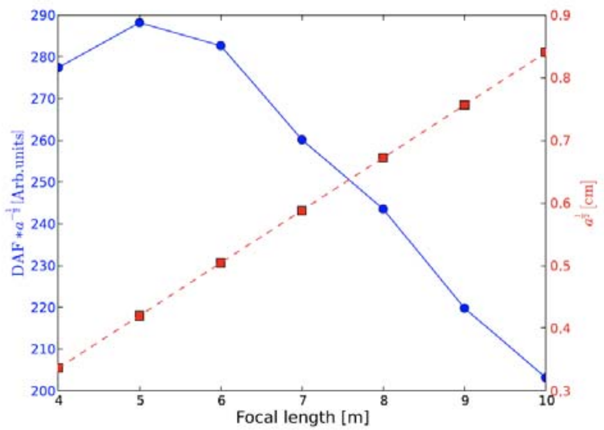


IAXO x-ray optics

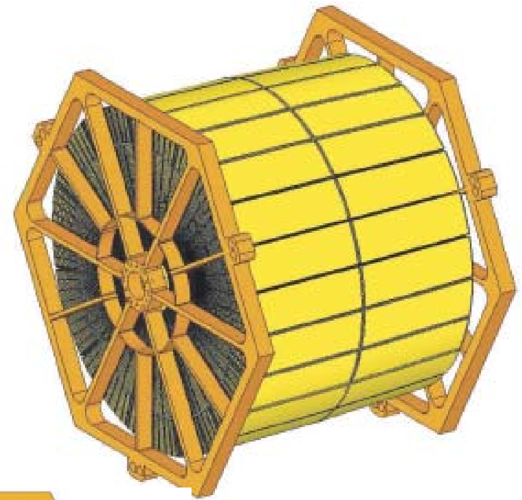
- Technique of choice for IAXO: optics made of slumped glass substrates coated to enhance reflectivity in the energy regions for axions.
- Same technique successfully used in NuSTAR mission, recently launched
- The specialized tooling to shape the substrates and assemble the optics is available
- Hardware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

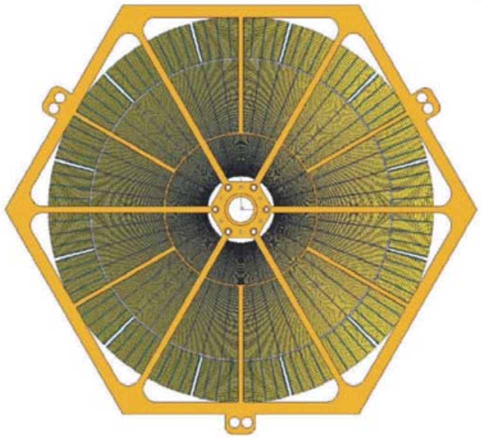


IAXO x-ray optics



Optimal focal length ~5 m

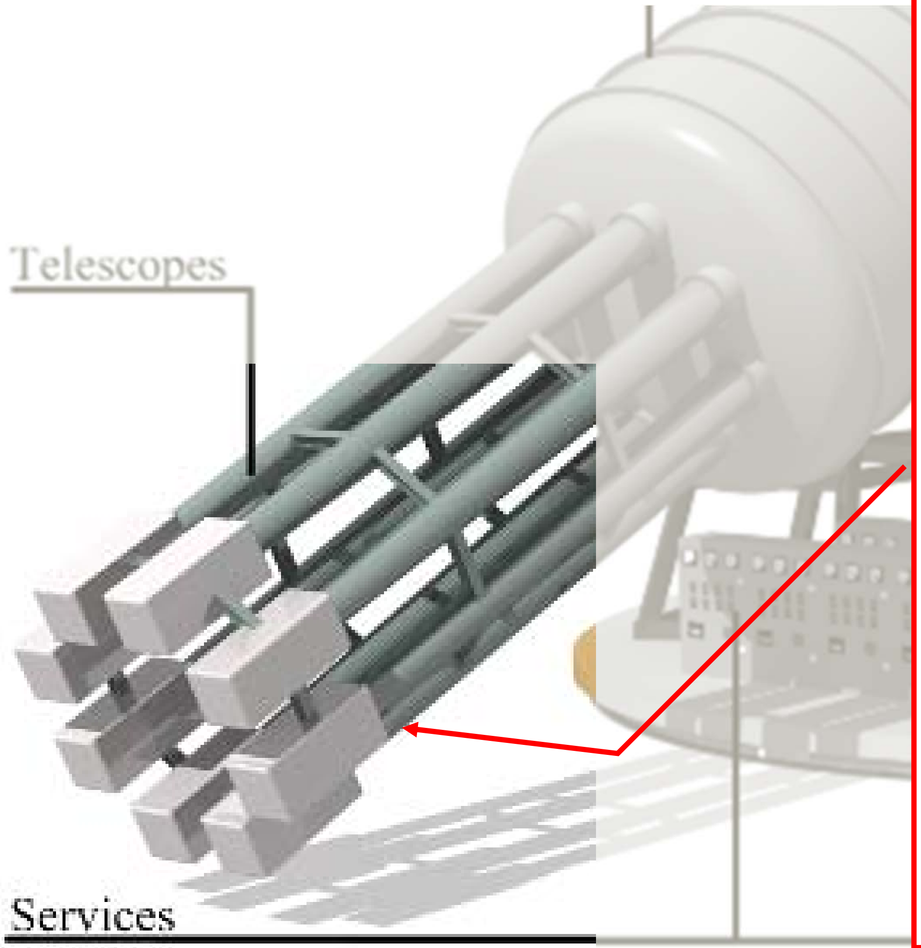




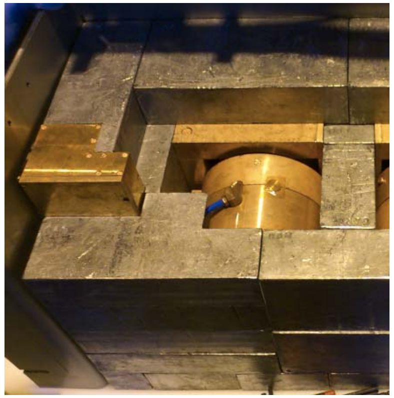
Telescopes	8
N, Layers (or shells) per telescope	123
Segments per telescope	2172
Geometric area of glass per telescope	0.38 m^2
Focal length	5.0 m
Inner radius	50 mm
Outer Radius	300 mm
Minimum graze angle	2.63 mrad
Maximum graze angle	15.0 mrad
Coatings	W/B_4C multilayers
Pass band	1–10 keV
IAXO Nominal,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

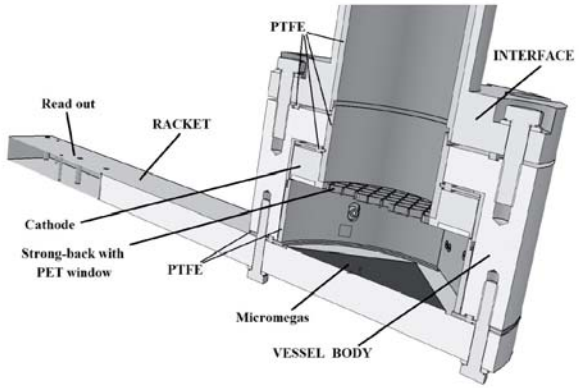
IAXO optics conceptual design
AC Jakobsen et al, Proc. SPIE 8861 (2013)

IAXO low background detectors



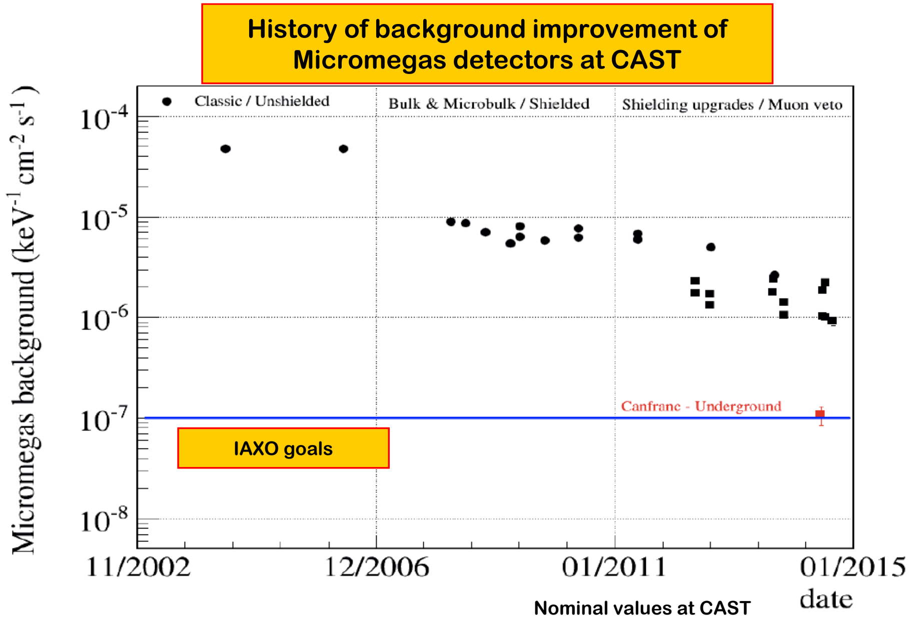
- 8 detector systems
- Baseline: small Micromegas-TPC chambers:
  - Shielding
  - Radiopure components
  - Offline discrimination





IAXO low background MM detectors

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

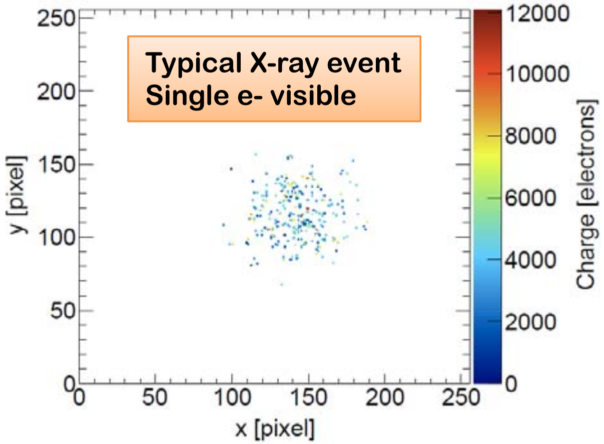


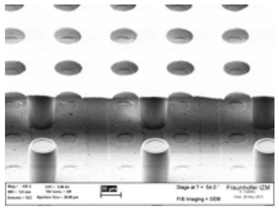
- Active program of development.
- IAXO-D0 test-platform to explore background sources and improve levels

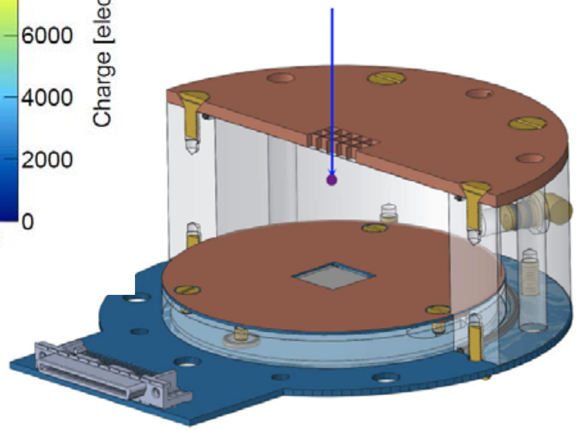
Additional detector technologies for IAXO

Ingrid detectors (U. Bonn):

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

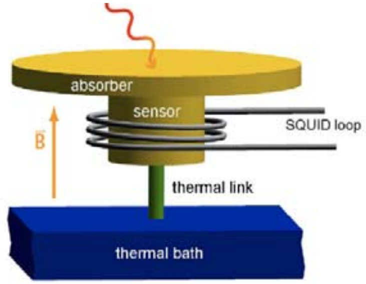


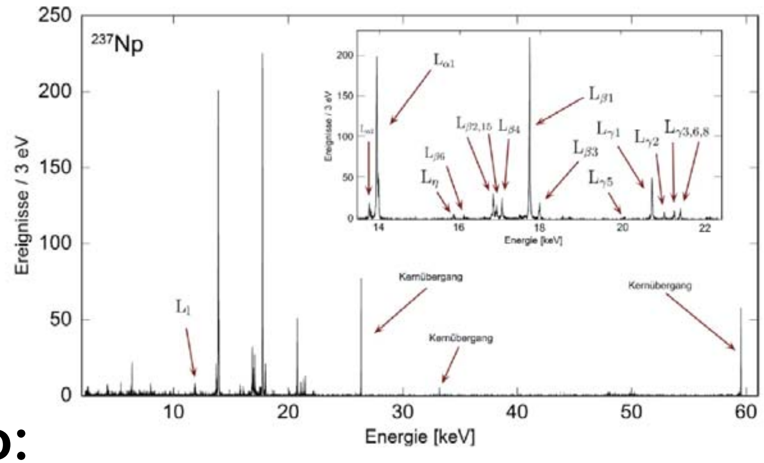




MMC detectors (U. Heidelberg):

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





Also:

- Transition Edge Sensors (TES)
- Si- detetors

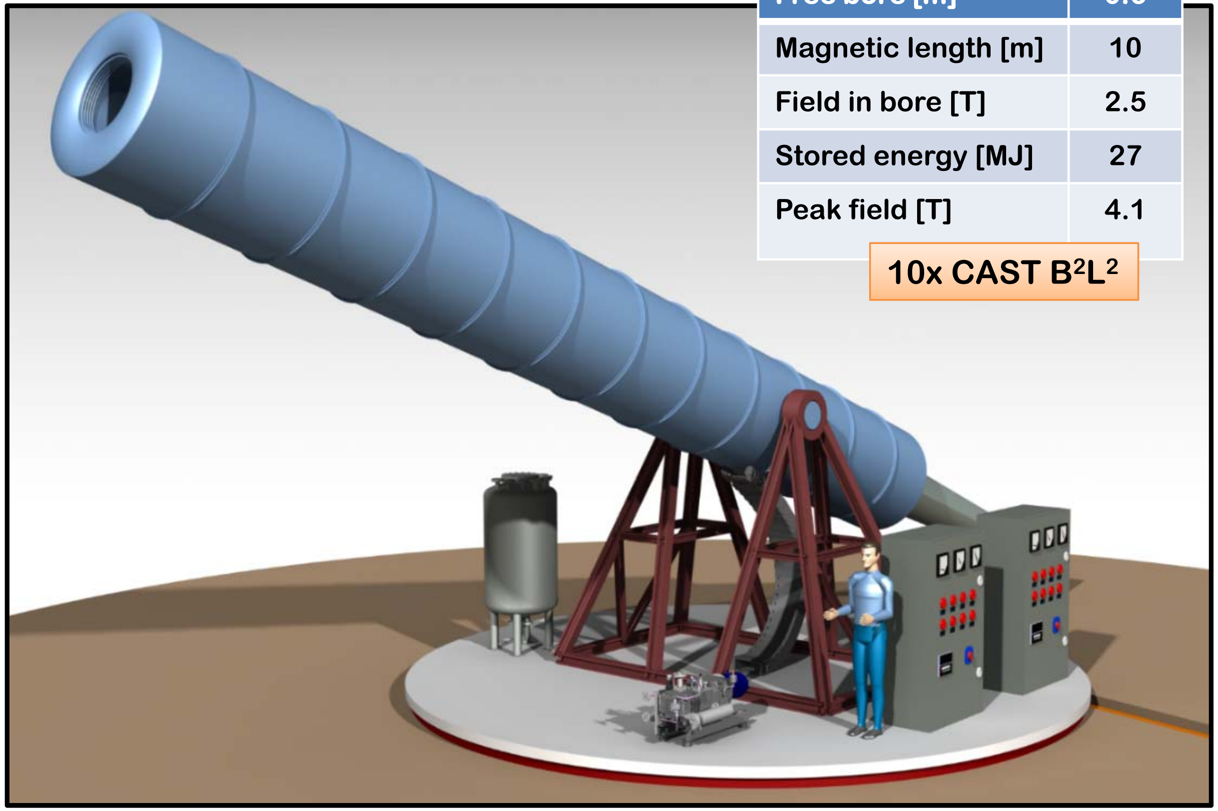
BabyIAXO

- Intermediate experimental stage before IAXO

- One single bore of similar dimensions of final IAXO bores → detection line representative of final ones.
- Test & improve all systems. Risk mitigation for full IAXO

- Will produce relevant physics
- Move earlier to "experiment mode"
- BabyIAXO CDR finished. Moving to Technical Design

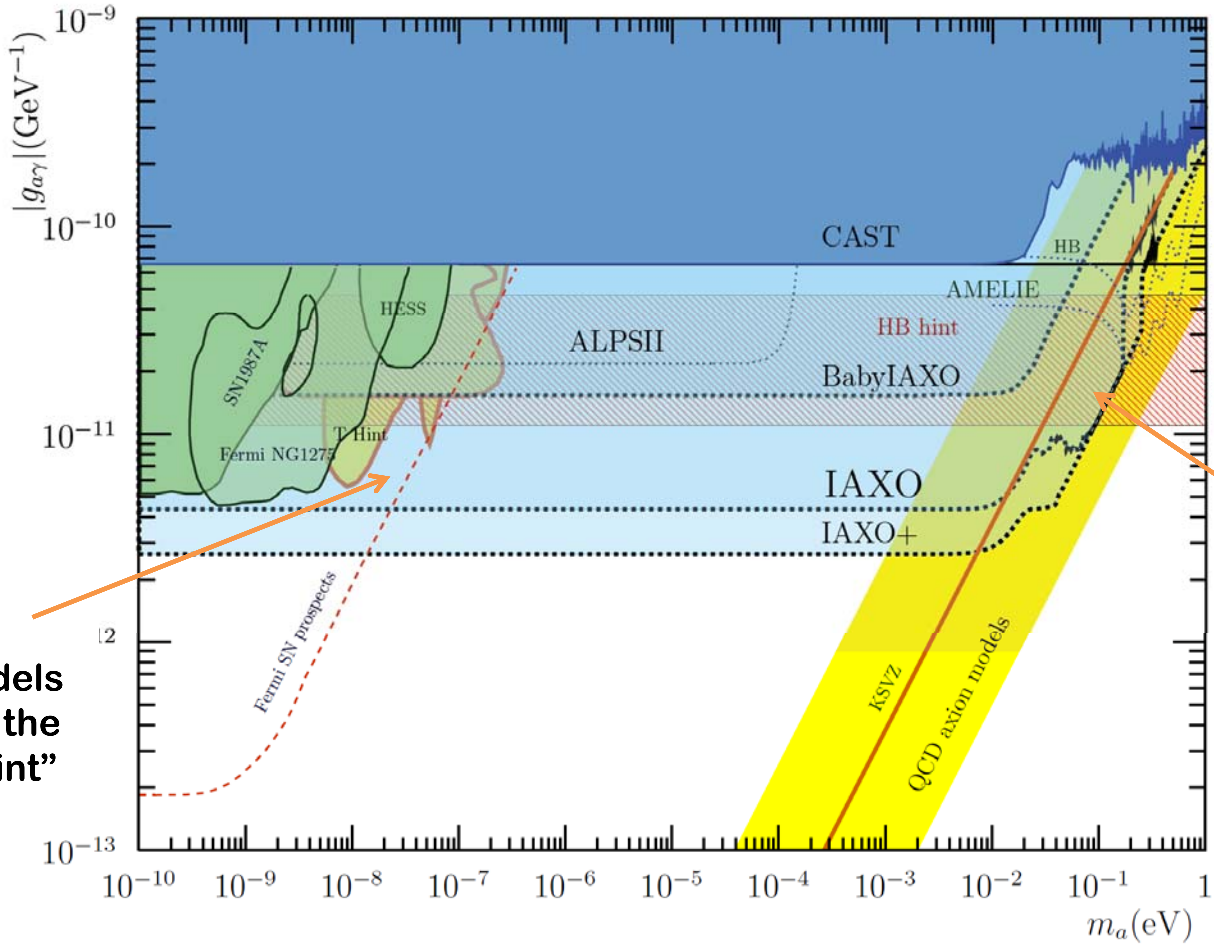
- TASTE: Another proposal of similar size proposed leveraging resources in Russia



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 B^2L^2

Helioscopes & astrophysics hints



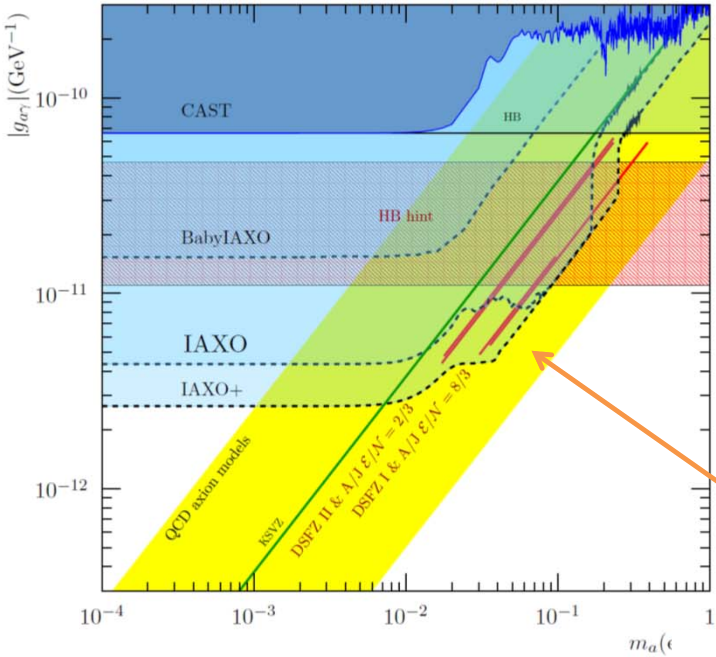
IAXO will fully explore ALP models invoked to solve the "transparency hint"

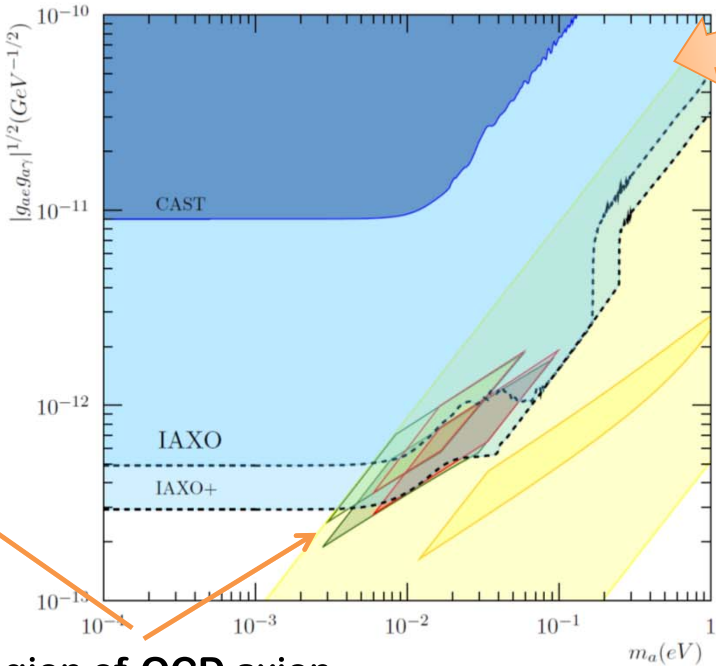
… as well as a large fraction of the axion & ALP models invoked in the "stellar cooling anomaly"

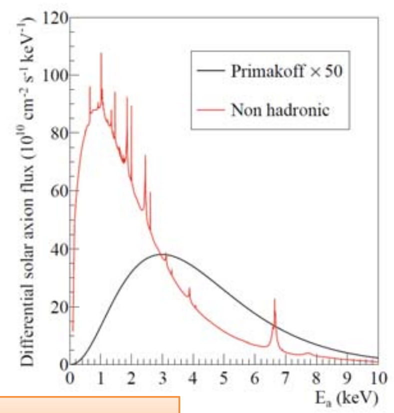
But for this the g_{ae} is particularly interesting

IAXO & stellar cooling

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







g_{ae} **channel**

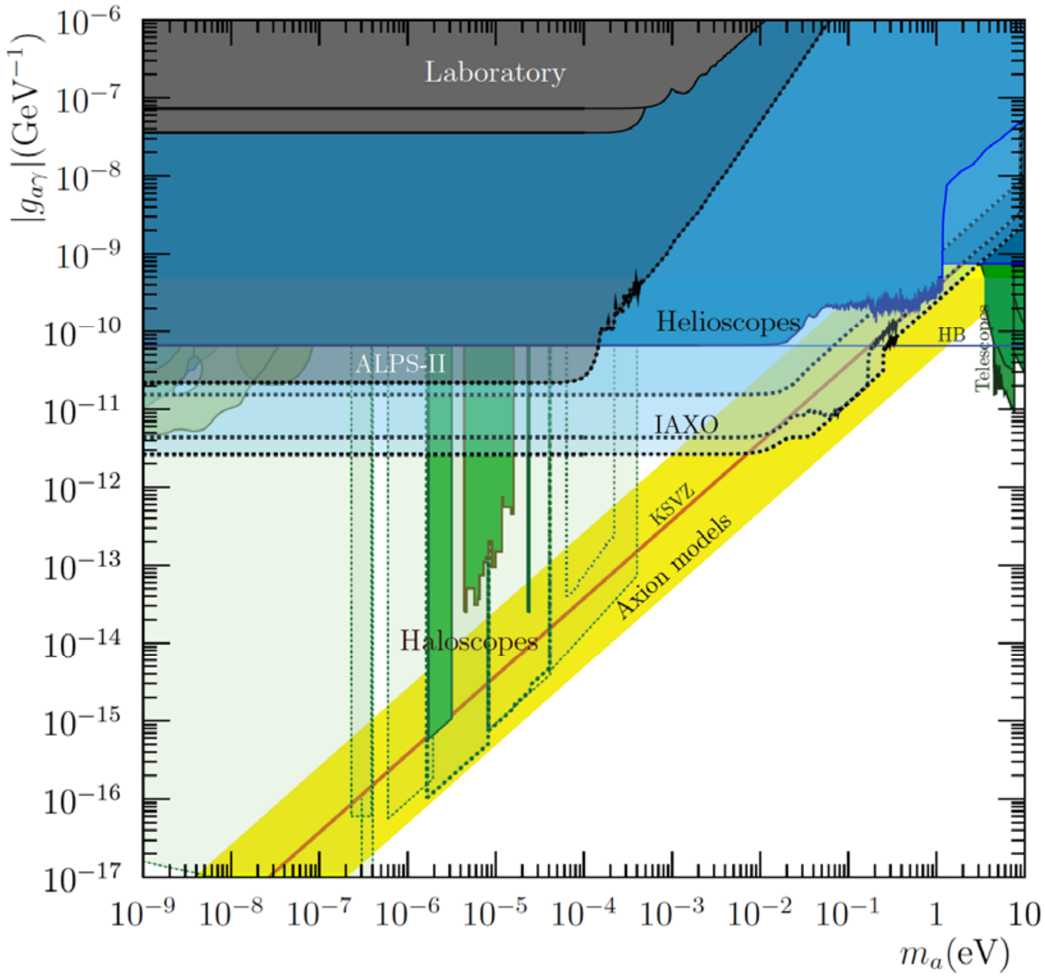
M. Giannotti et al.
JCAP 1710 (2017) 010
arXiv:1708.02111

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**

Overall picture (for $g_{a\gamma}$)

- **Helioscopes (IAXO) will probe astrophisically motivated ALP models**
  - **Haloscopes will soon probe 1-10 μeV QCD axions**
    - **Promising new haloscopes R&D to substantially expand explorable mass range**



- **Helioscopes (IAXO) will probe meV – eV QCD axion models**
- **… and most of the region hinted by stellar cooling**
- **In overall, a large fraction of the ALP parameter space may be explored in the future**

Conclusions

- **Experimental search for axions → field of increasing interest**
- **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**
  - Dielectric haloscopes, oscillating-B and EDMs, NMR…
- **Large fraction of parameter space at reach of near-future experiments**
  - chances of discovery!

Good timing for axions… stay tuned