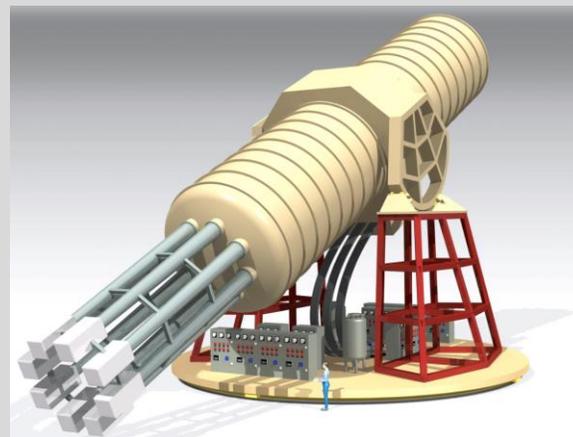


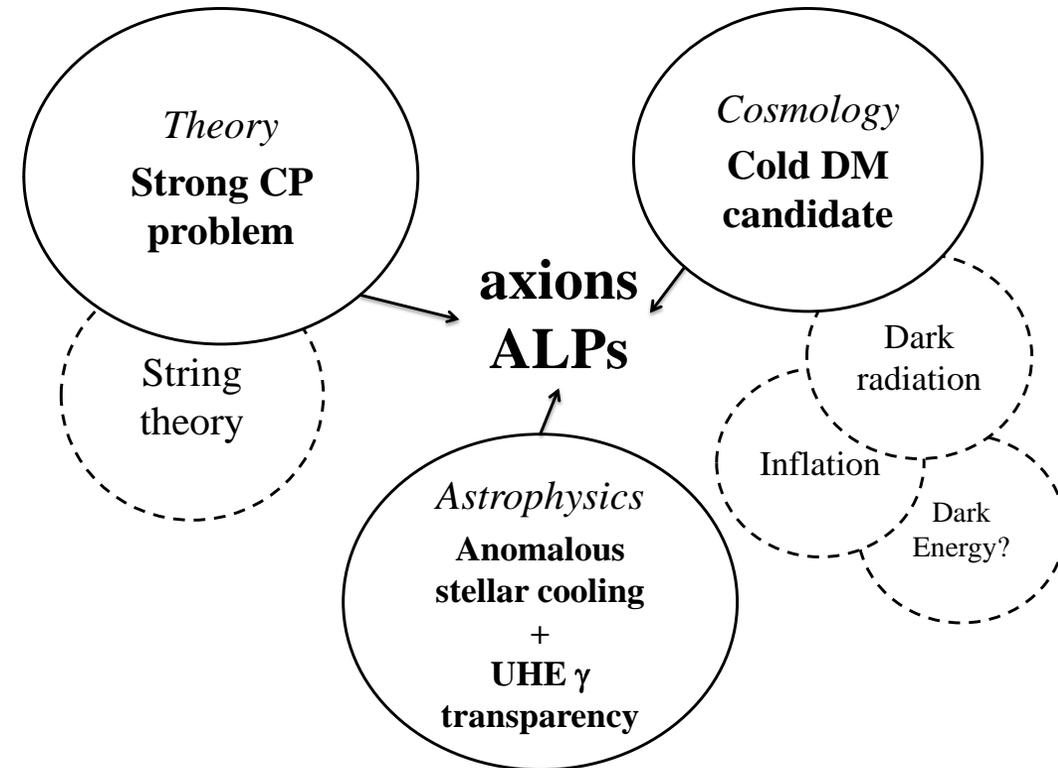
Experimental searches for axions

Igor G. Irastorza
Universidad de Zaragoza
Light Scalars Workshop, Benasque, 8 April 2019



Why axions?

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

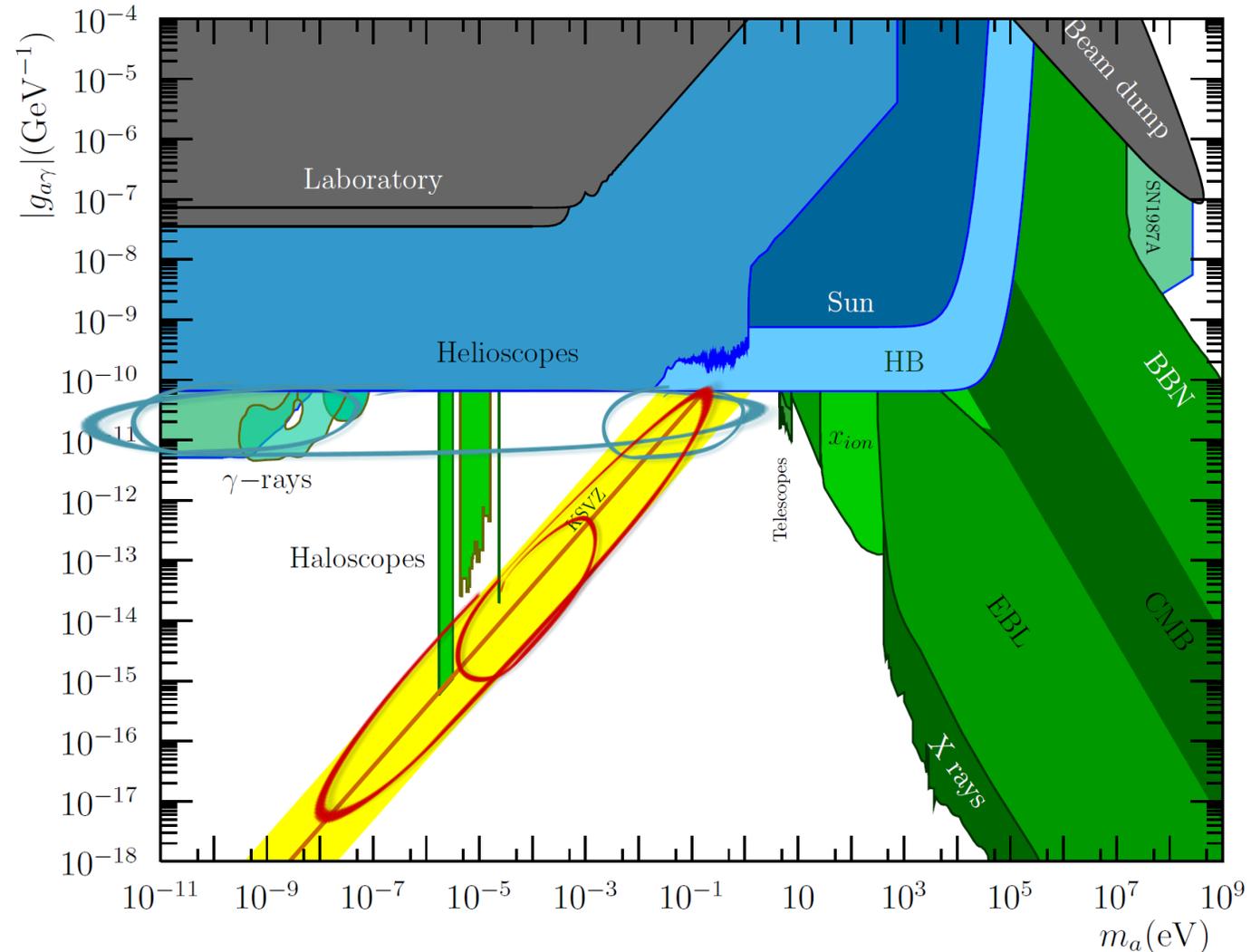


Recent experimental review:
I. G. Irastorza and J. Redondo,
Prog.Part.Nucl.Phys. 102 (2018) 89-159
[arXiv:1801.08127]

Axion/ALP searches motivation

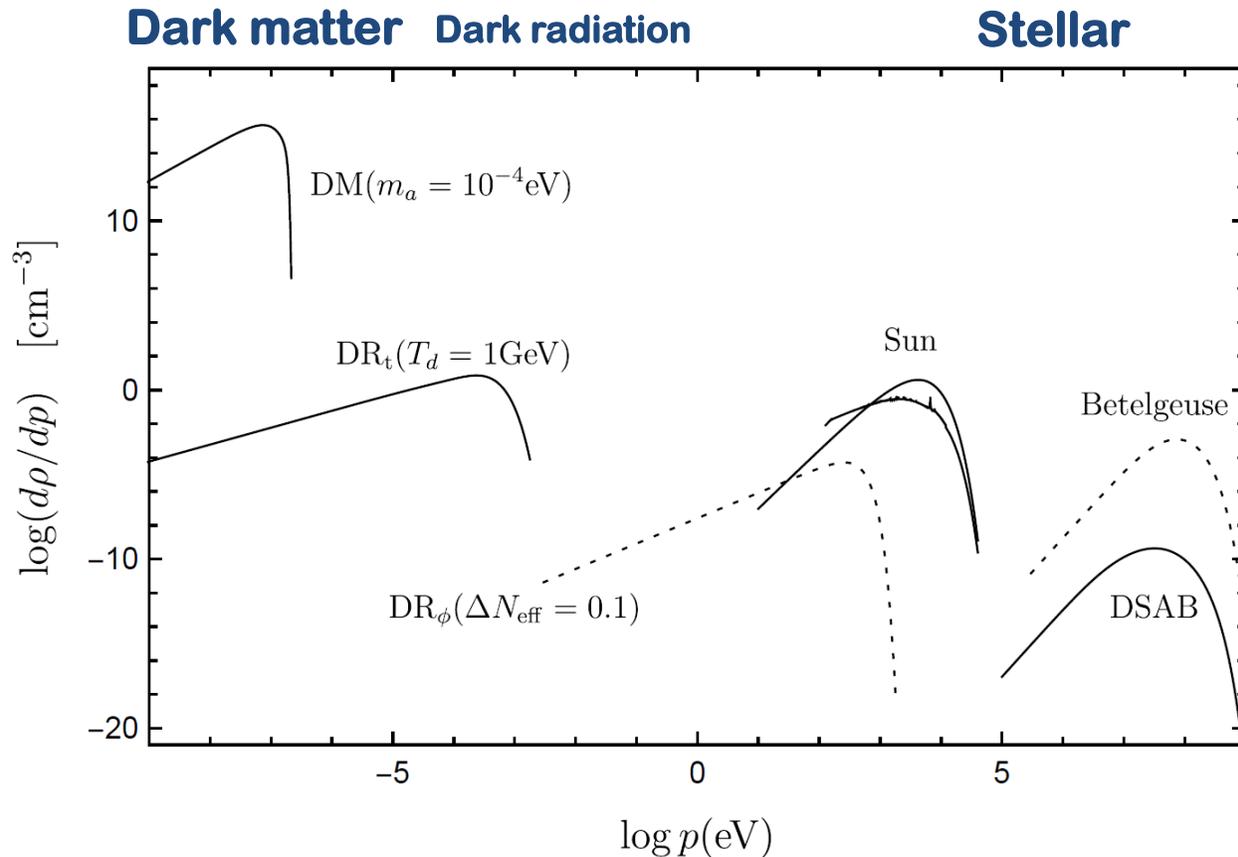
“Focuses of interest”
in the ALP parameter space

Theory
Astrophysics
Cosmology



Sources of axions

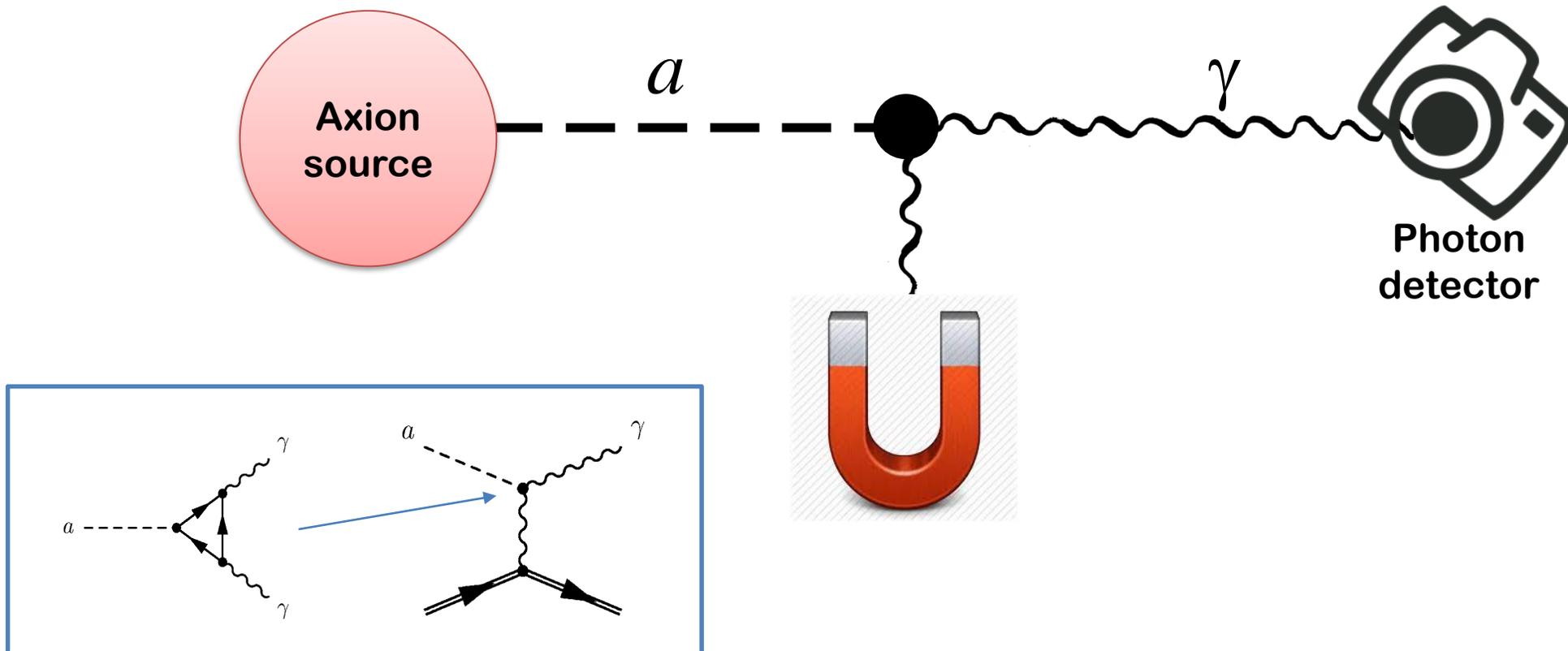
Natural sources



Laboratory sources

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

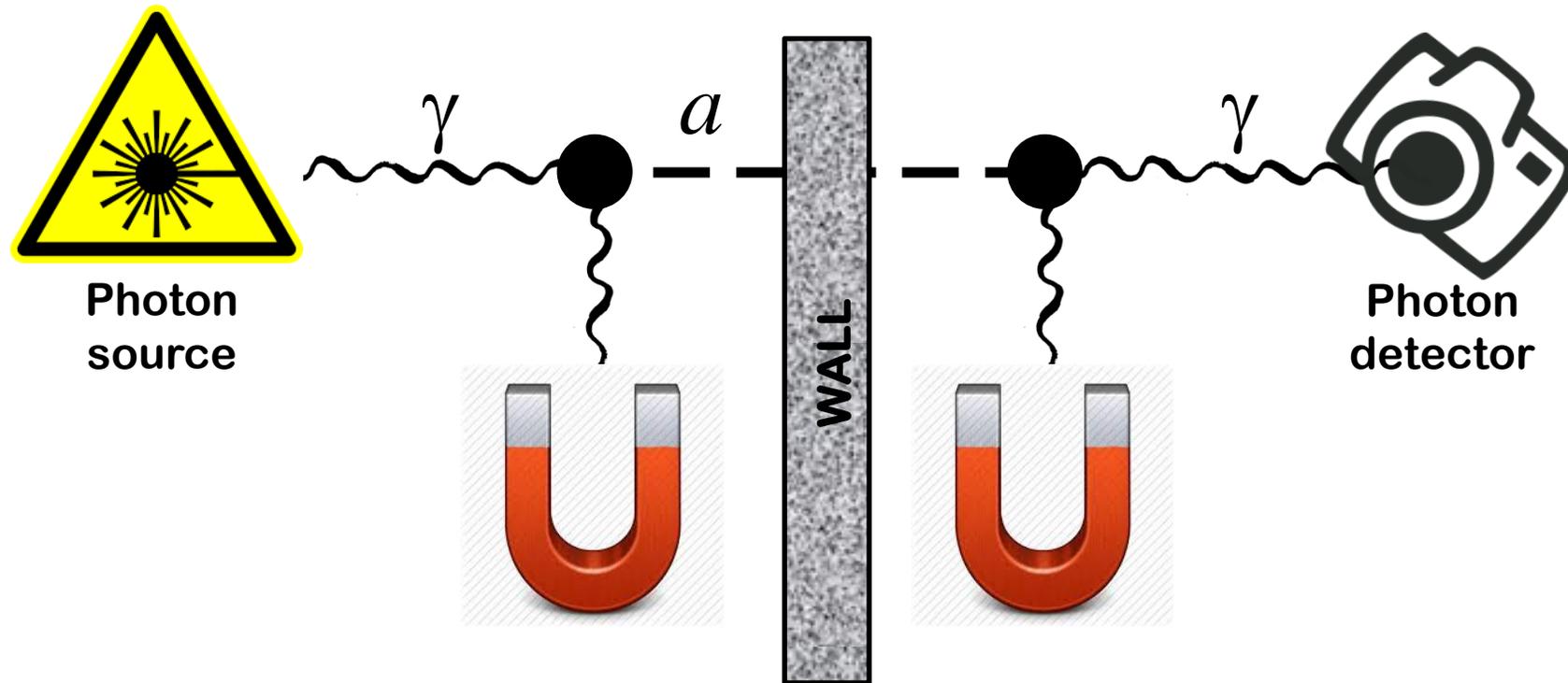
How to detect an axion?



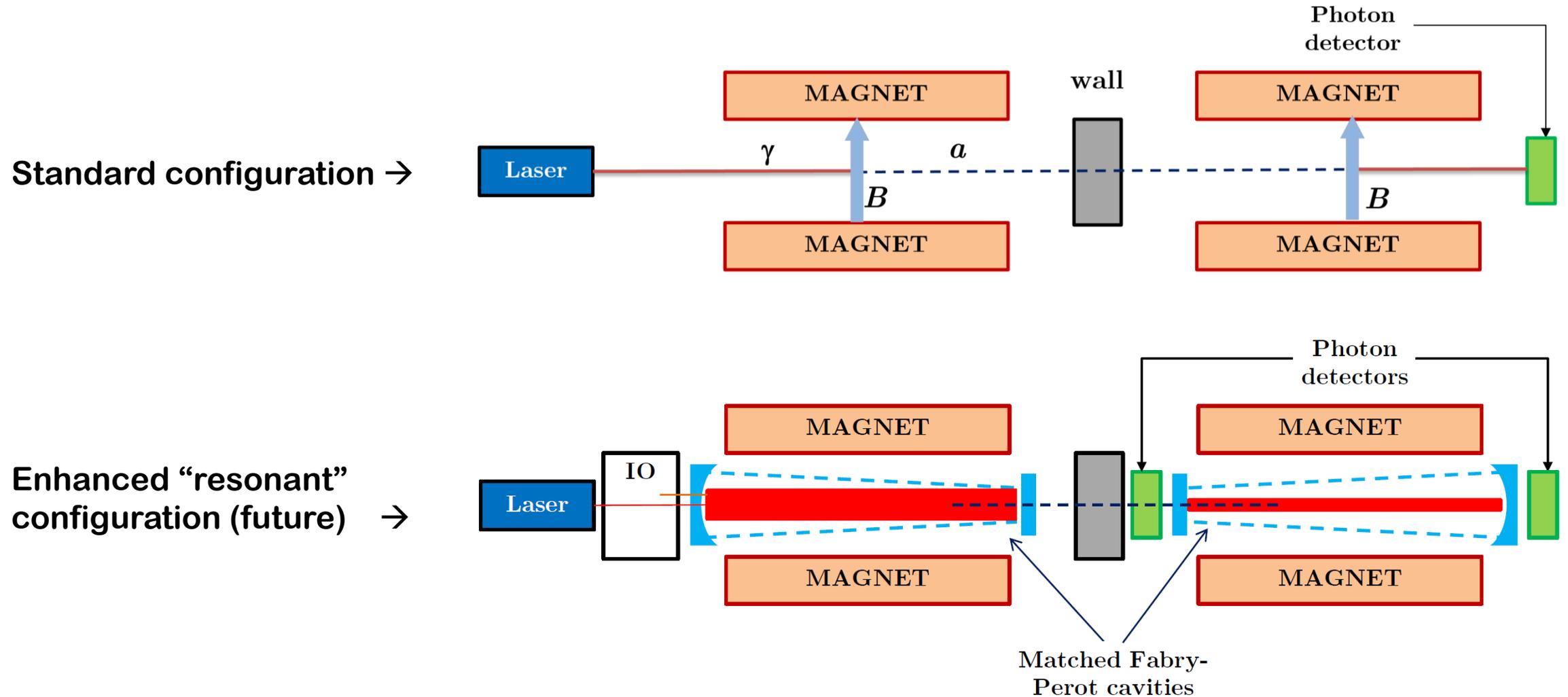
Detection of axions

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



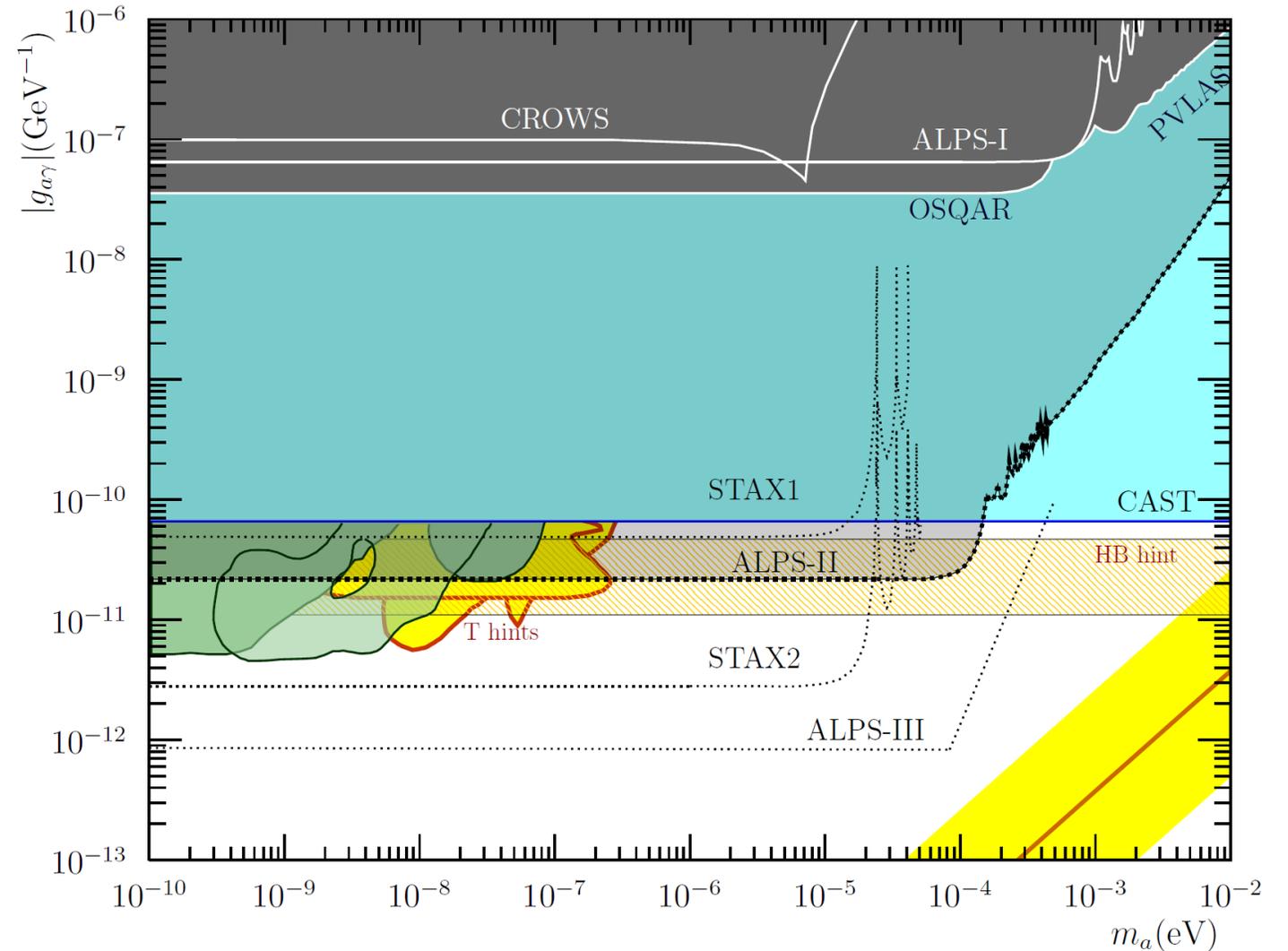
Light-shining-through-wall (LSW)



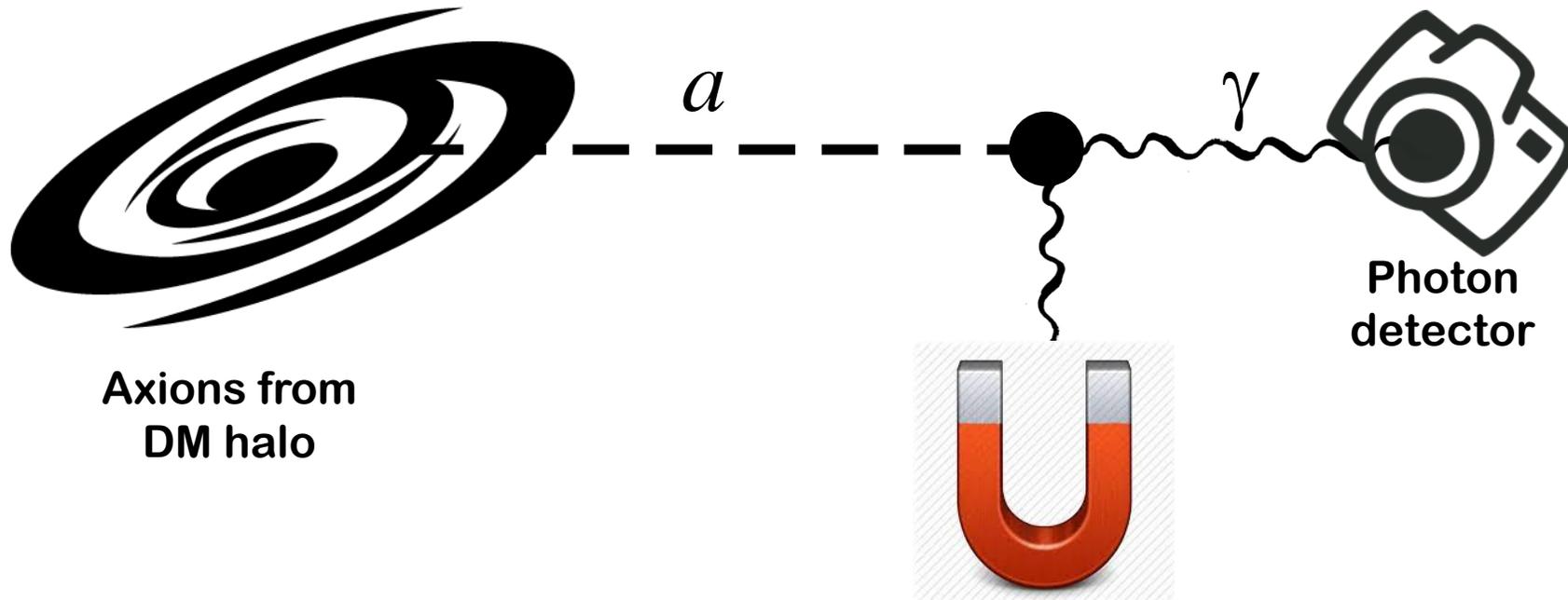
Laboratory experiments sensitivity

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, together with future possible projects, with some key experimental parameters. The last column represents the sensitivity achieved (or expected) in terms of an upper limit on $g_{a\gamma}$ for low m_a . For microwave LSW (CROWS and STAX) the quality factors Q are listed. * The limit is better for specific m_a values, see Figure 6



Dark matter axions



Detecting DM axions: “haloscopes”

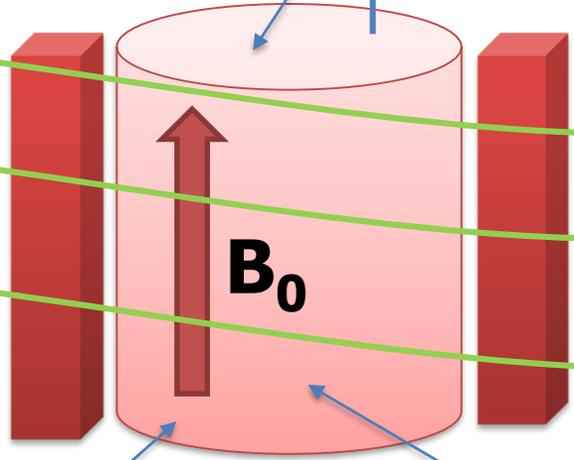
- Assumption: DM is mostly axions
- Resonant cavities (Sikivie, 1983)
 - Primakoff conversion inside a “tunable” resonant cavity
 - Energy of photon = $m_a c^2 + O(b^2)$

Primakoff conversion of DM axions into microwave photons inside cavity

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

Axion DM field
Non-relativistic
Frequency \leftarrow axion mass

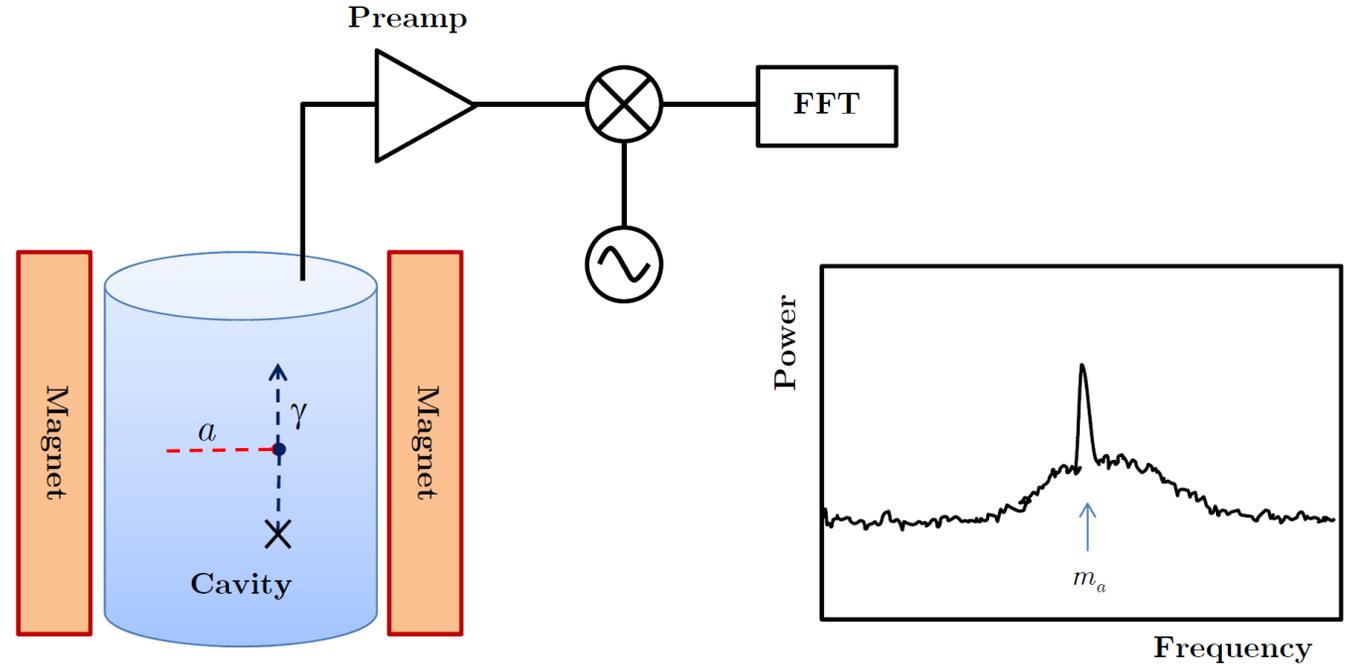
Cavity dimensions smaller than de Broglie wavelength of axions



If cavity tuned to the axion frequency, conversion is “boosted” by resonant factor (Q quality factor)

Detecting DM axions: “haloscopes”

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



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

(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

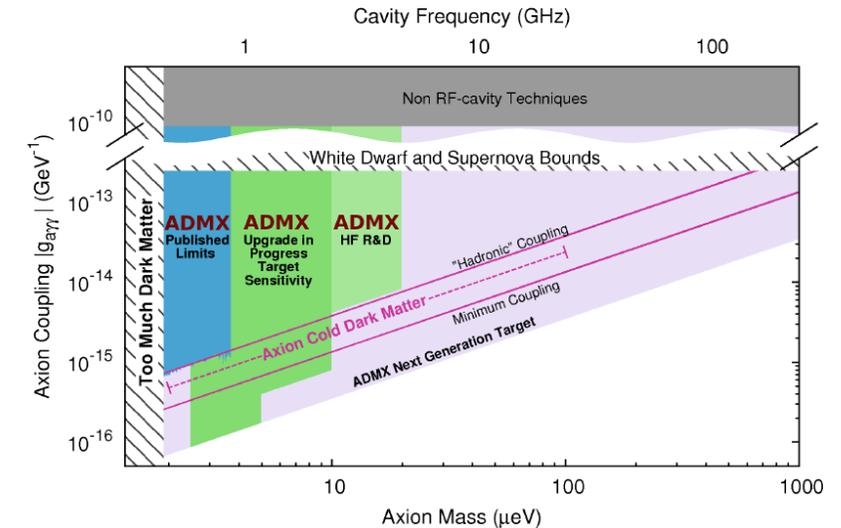
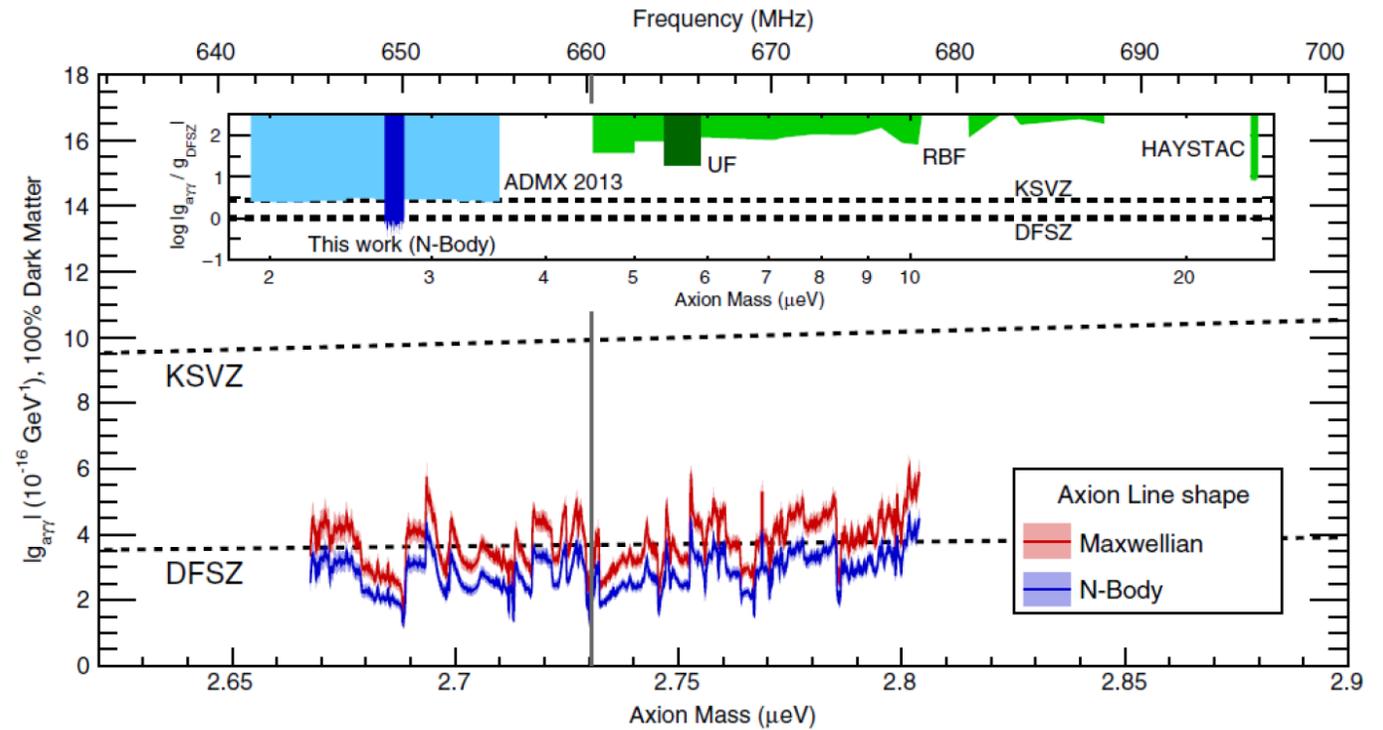


ADMX

- 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?



Higher- m_a haloscopes

- Problematic: higher $m_a \rightarrow$ lower $V \rightarrow$ lower sensitivity

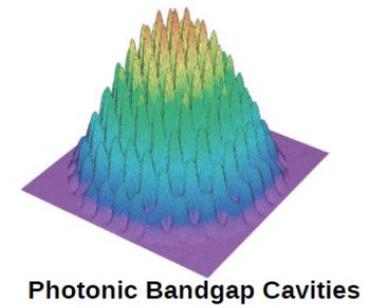
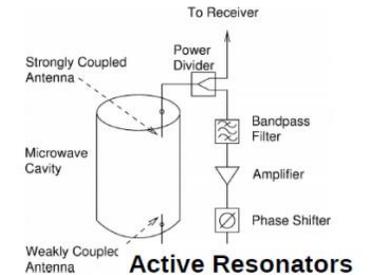
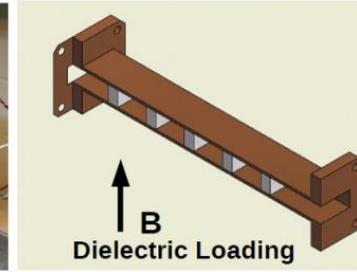
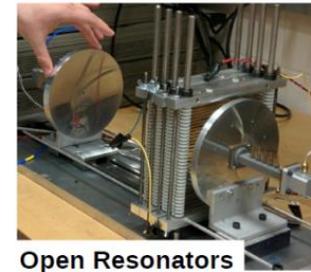
$$F \sim \rho_a^2 g_{a\gamma}^4 m_a^2 B_e^4 V^2 T_{\text{sys}}^{-2} |\mathcal{G}|^4 Q$$

- R&D to go to:

- Higher B magnets
- Larger instrumented volumes
- Lower noise sensors
- Higher Q cavities

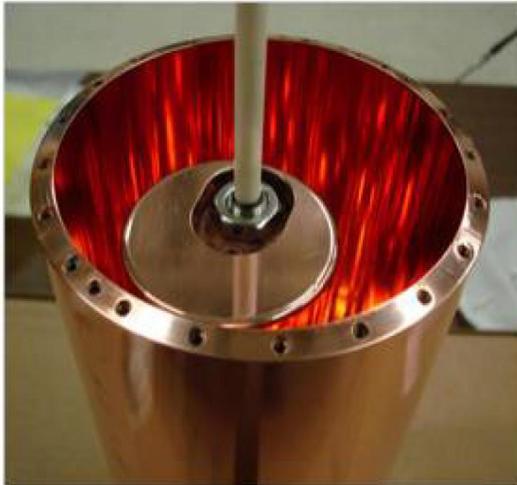
Active R&D inside ADMX

A subset of ideas being explored...



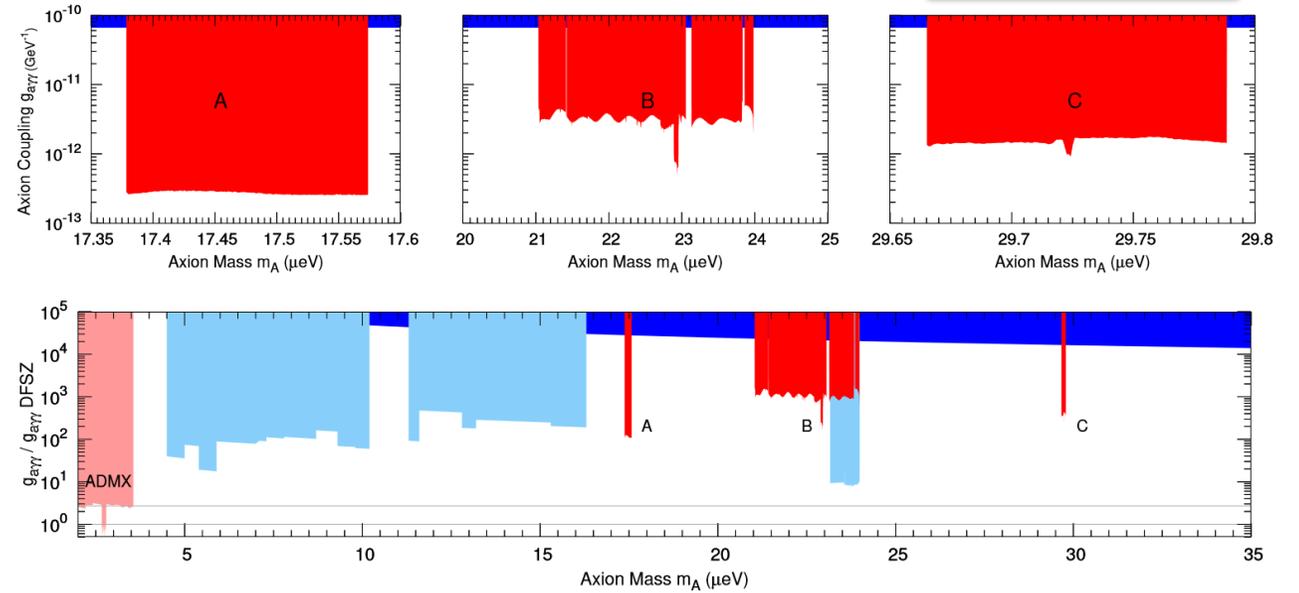
HAYSTAC

- 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

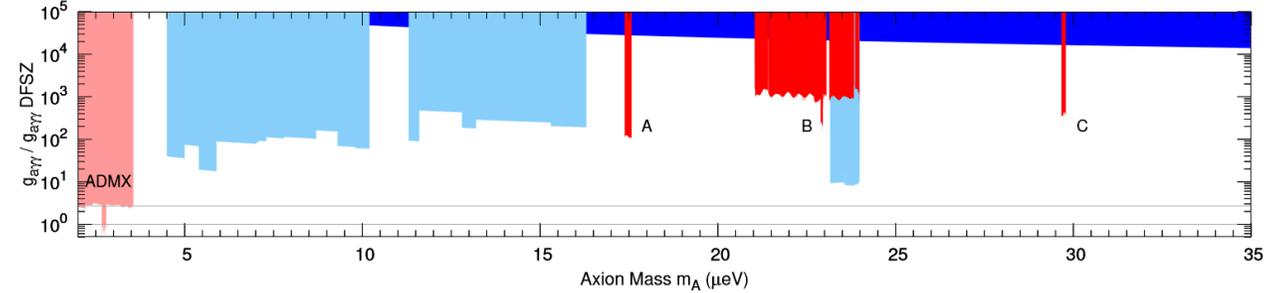
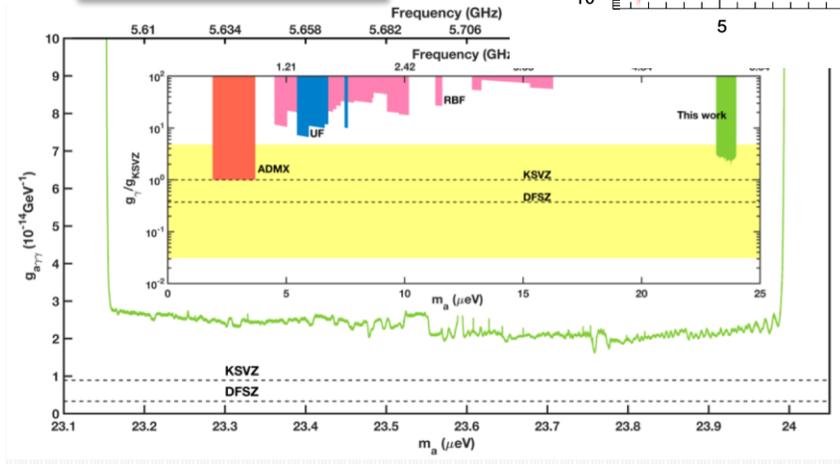


& ADMX-Sidecar

arXiv:1901.00920



arXiv:1803.03690

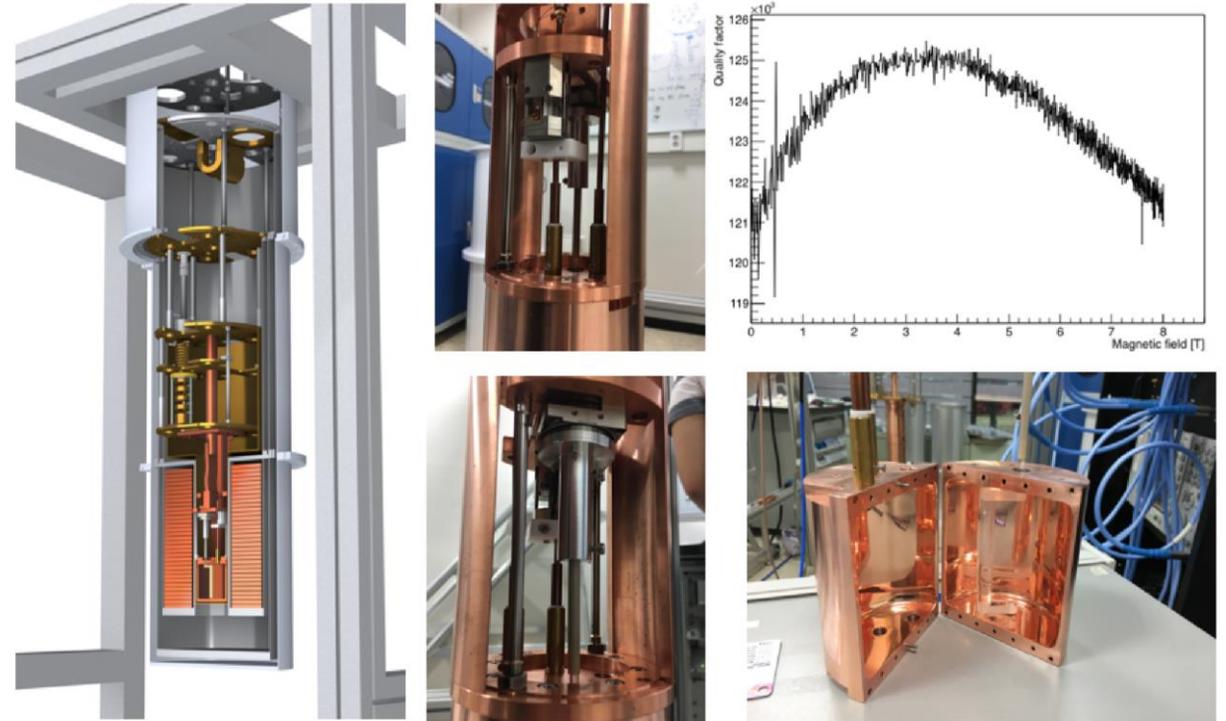
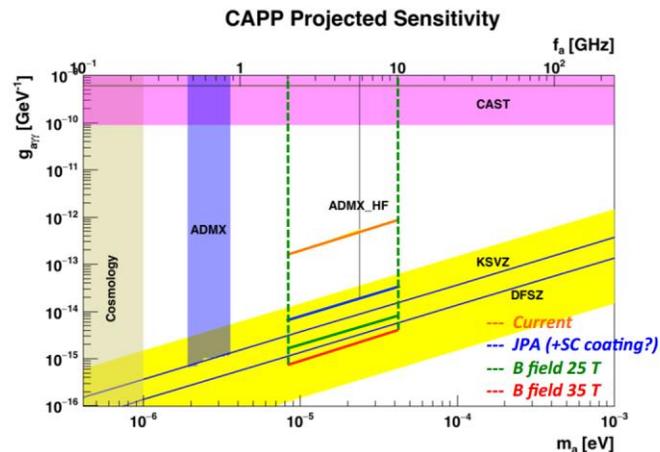


- Small cavity inside the ADMX system
- Uses 2 modes
- First results recently released, @ 17.4, 21-24, 29.7 μeV .

CULTASK @ CAPP

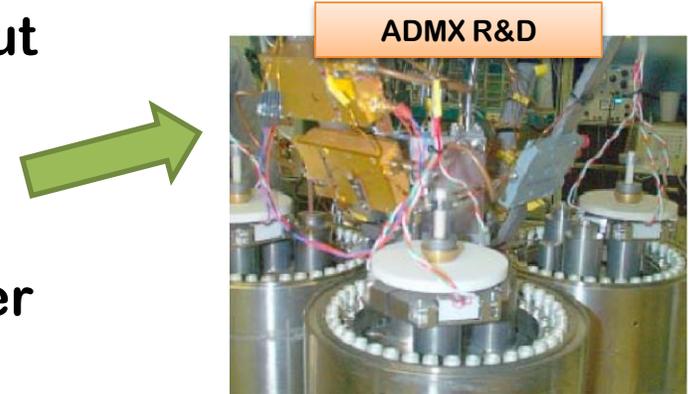
- CAPP: recently created “Center for Axion and Precision Physics” at **South Korea**
- Main goal to “build a large axion DM experiment in Korea”
- Many R&D lines ongoing:

- Ultrahigh field superconducting magnets
- Superconducting films to get high G cavities
- Low noise sensors (SQUIDs)
- New cavity designs & multi-cavity phase locking schemes

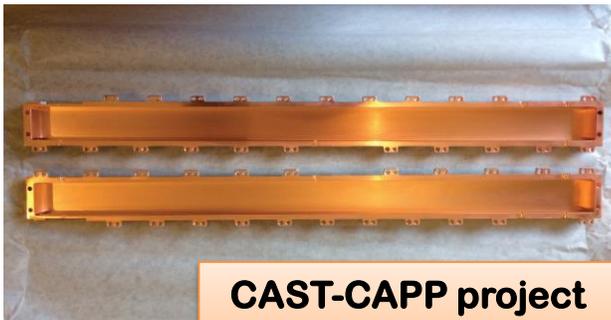


New cavity designs

- 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 .

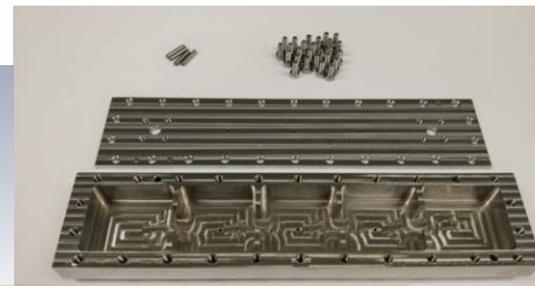
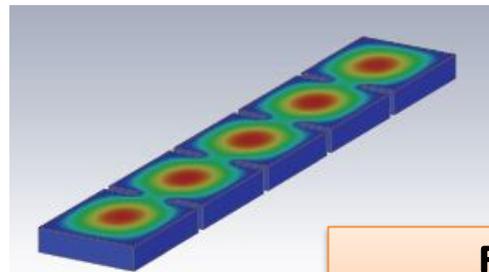


Long thin cavities: m_a is fixed by small dimensions, but V can be ~larger

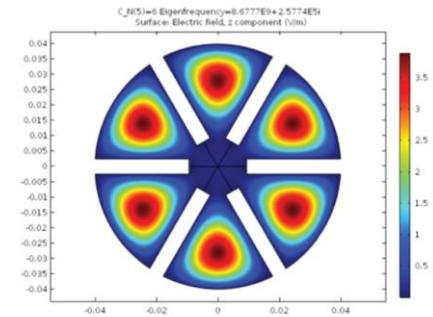


CAST-CAPP project
in the CAST magnet

Properly designed arrays of cavities with couplings



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



“Pizza cavity”
at CAPP

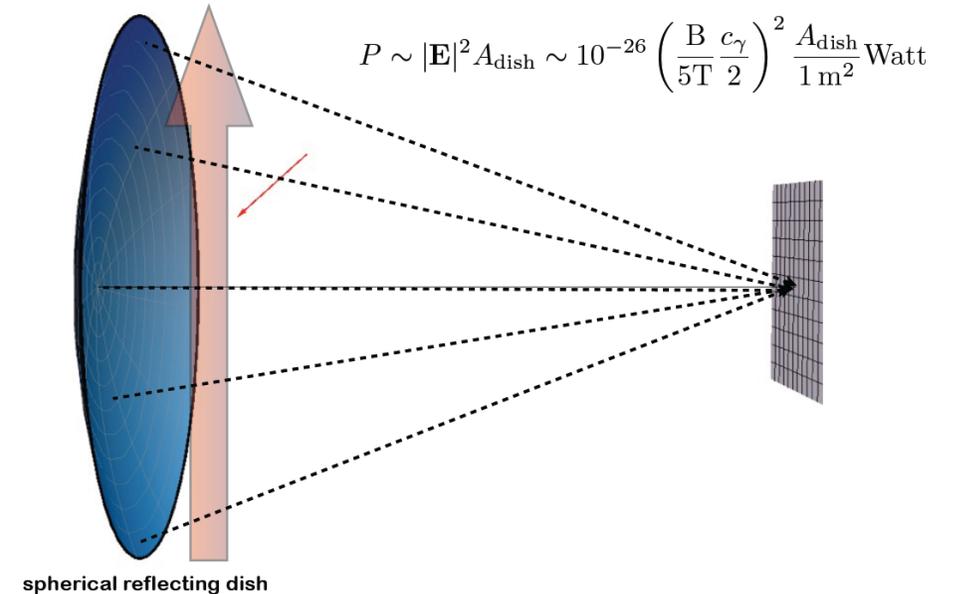
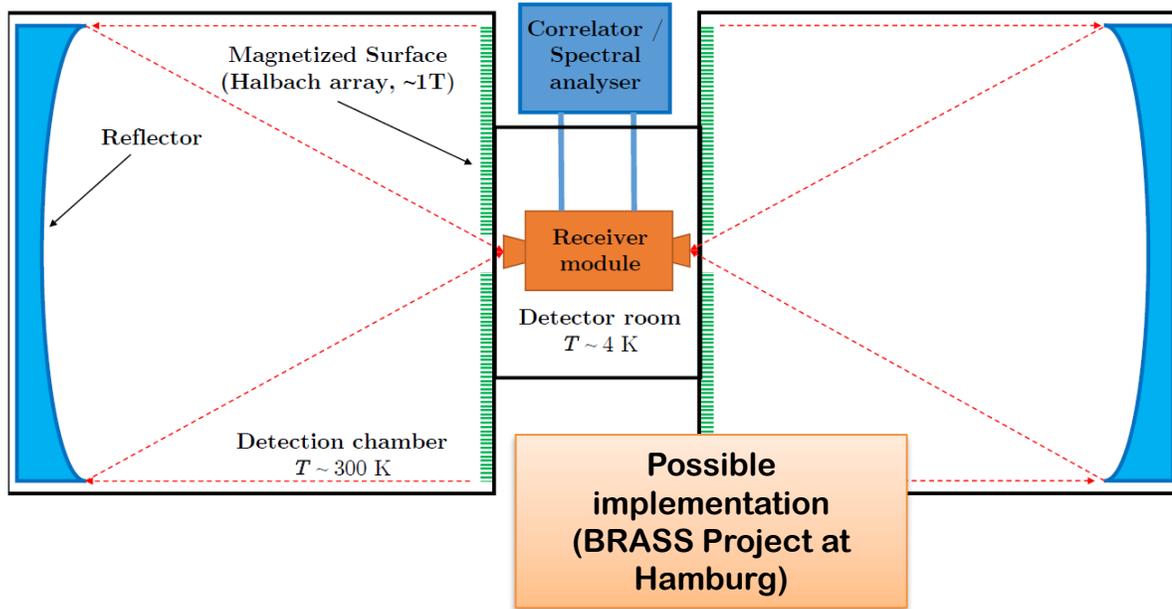
*Also
ORGAN
project in
Australia

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 ?

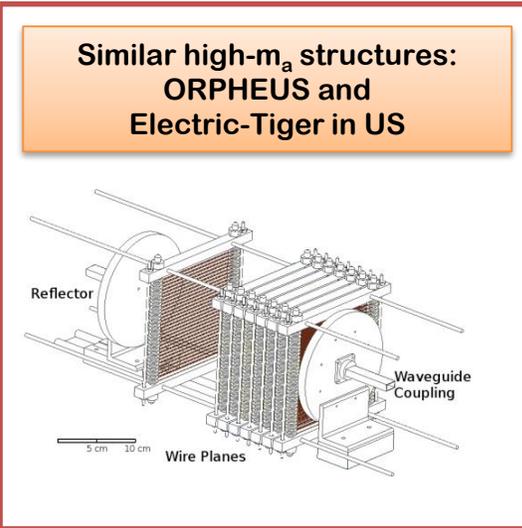
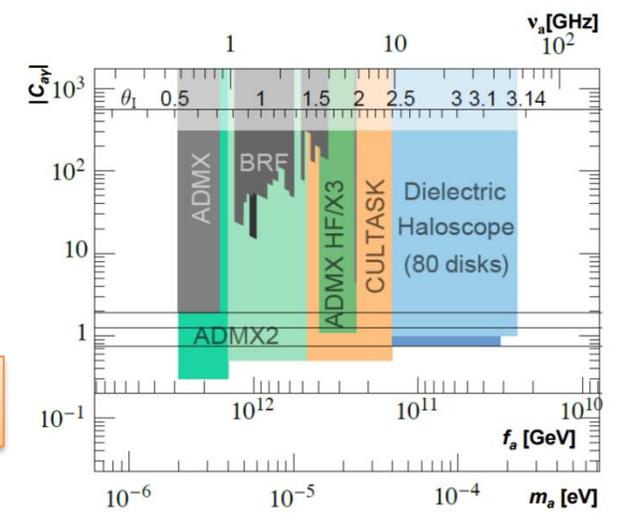
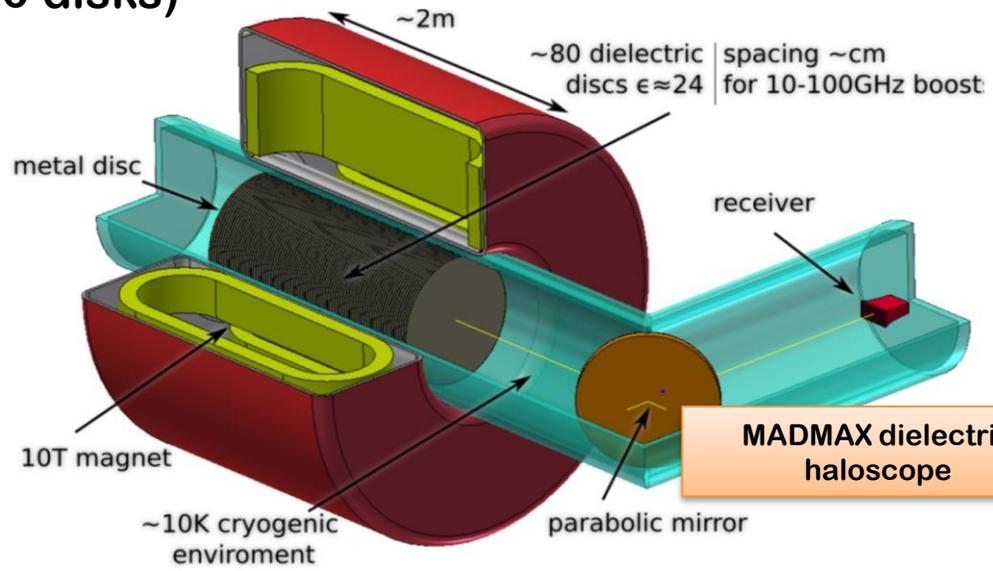
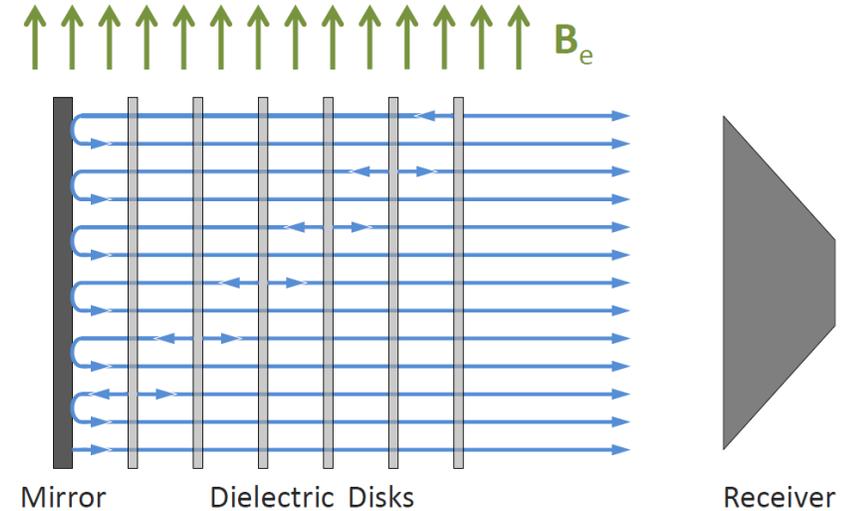
Resonance versus area

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



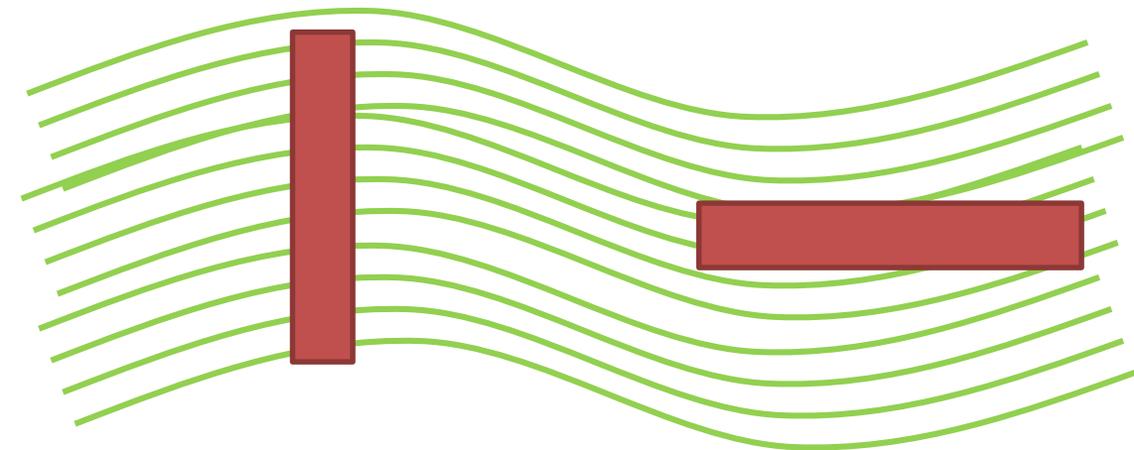
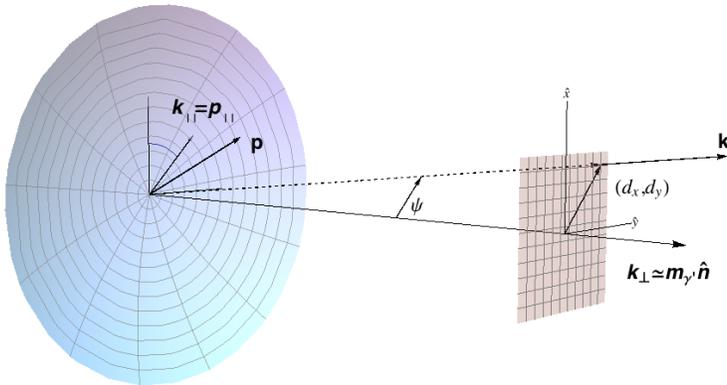
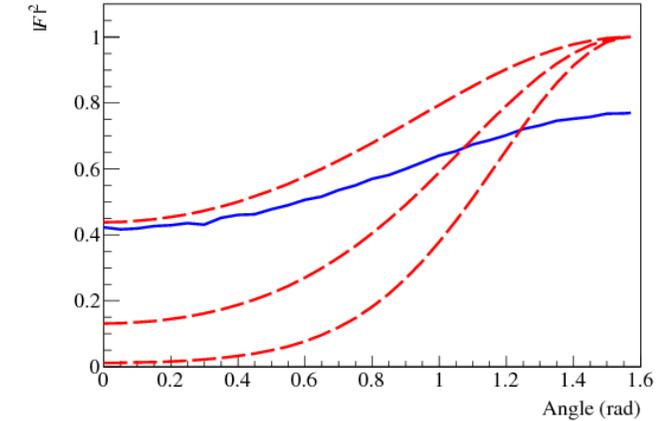
Dielectric haloscopes

- 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 $\sim m^3$ 10T experiment (80 disks)



Directional effects

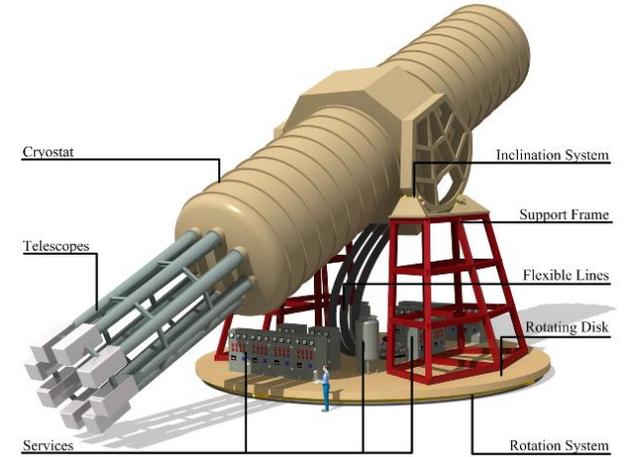
- DM directionality would be a powerful signature to confirm a putative signal
- Long aspect-ratio cavities should show a directional dependence if $L > \lambda_{\text{deBroglie}}$
- **Dish antennas**: small parallel component proportional to axion momentum
 - pixelised detector at the focal point could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



An “axion astronomy” era would follow a discovery

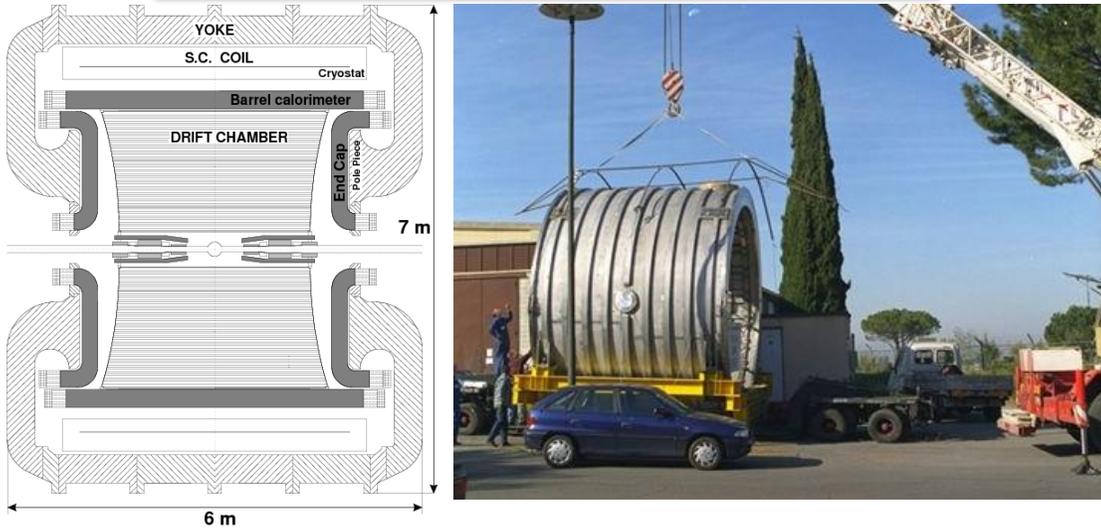
Lower m_a haloscopes

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

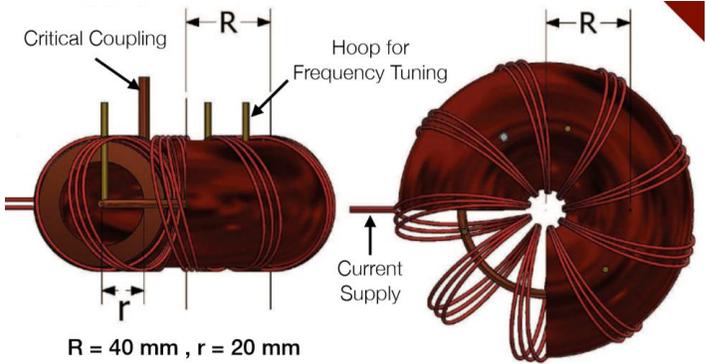
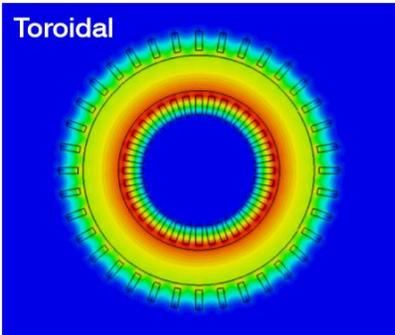


KLASH proposal: use of 50 m³, 0.6T, KLOE magnet at LNF

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

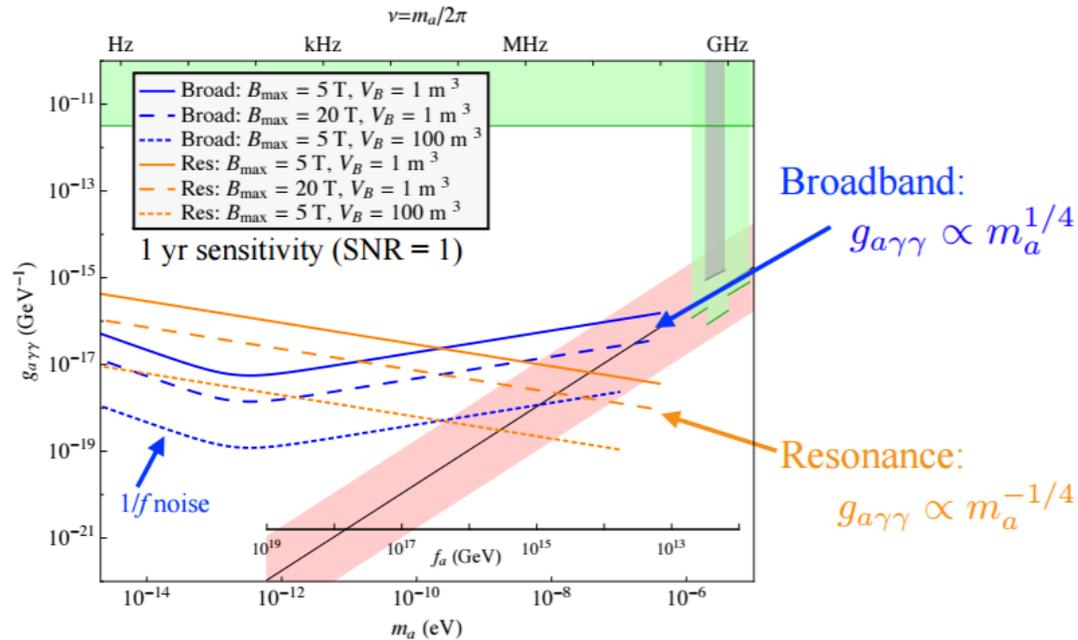
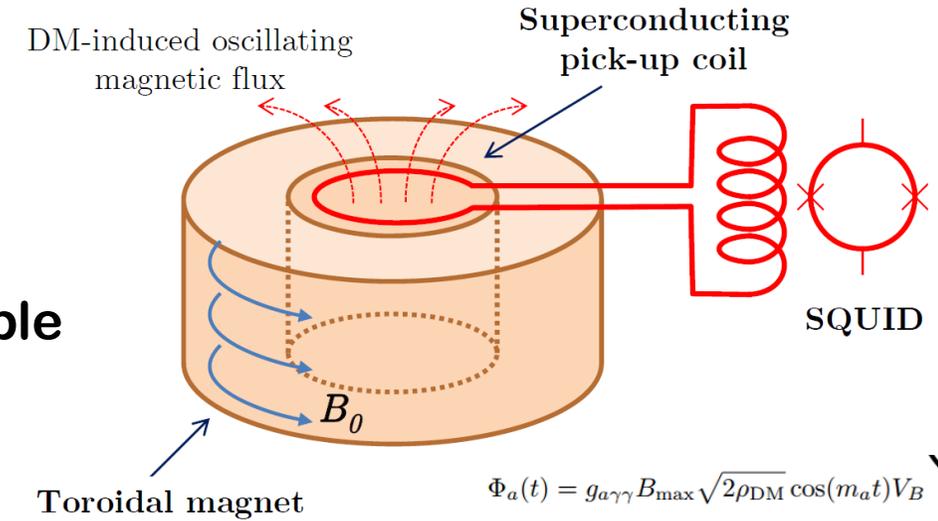


Use of large toroidal magnets: ACTION proposal at CAPP



Pick-up coil & resonant circuit

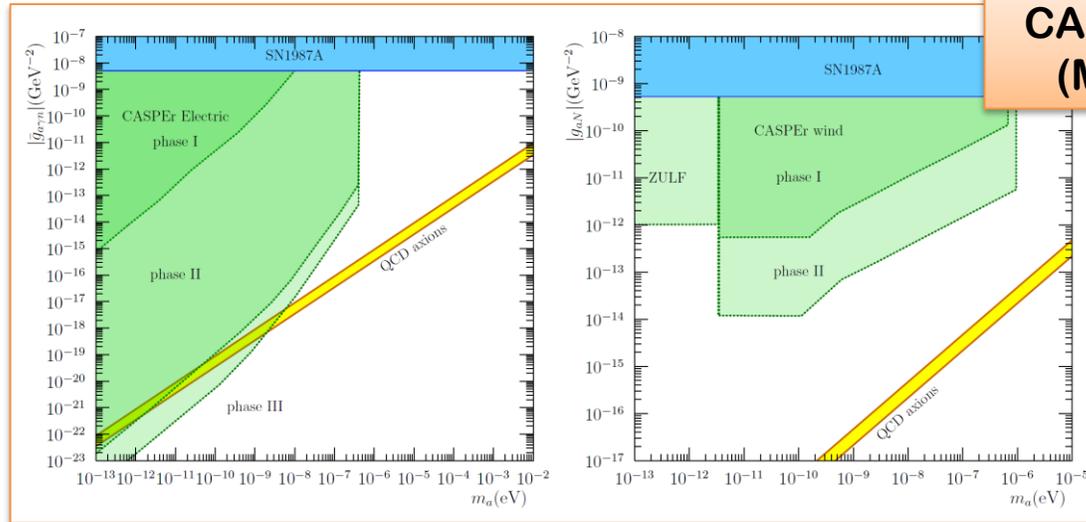
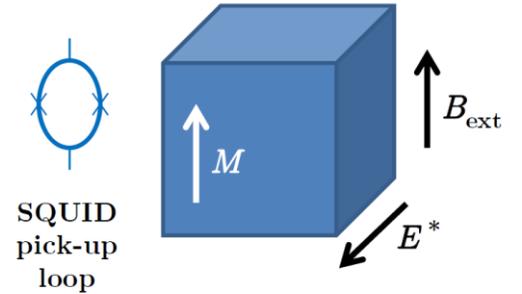
- DM-induced oscillating B in the center of a toroidal magnet
- Resonance is achieved externally with a circuit (no cavity)
- Both **wideband** search and **resonance** search possible



- Competitive at very low m_a
- ABRACADABRA at MIT
 - First data from 10 cm prototype just released: 1810.12257
- 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)

$$\frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

Coupling to gluon field
CASPEr Electric

$$\frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$

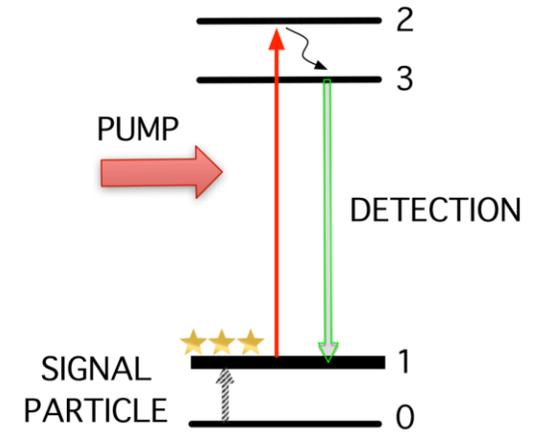
Coupling to fermions
CASPEr Wind

Phys. Rev. X 4, 021030 (2014)

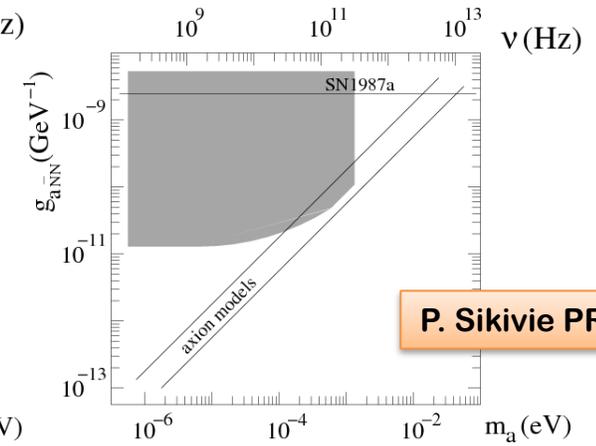
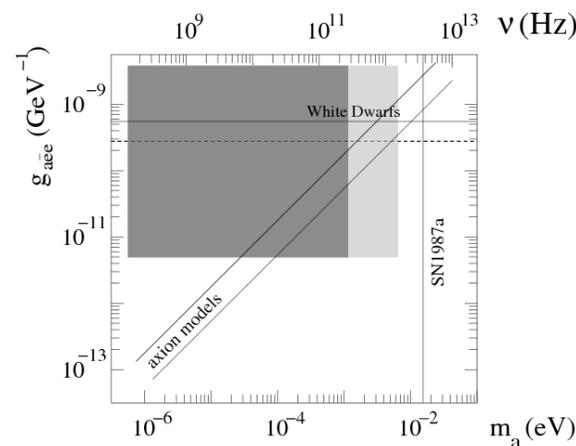
- Also QUAX experiment (Padova):
 - Electron spin precession
 - Sensitive to “axion DM wind” through axion-electron coupling

DM-induced atomic transitions

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

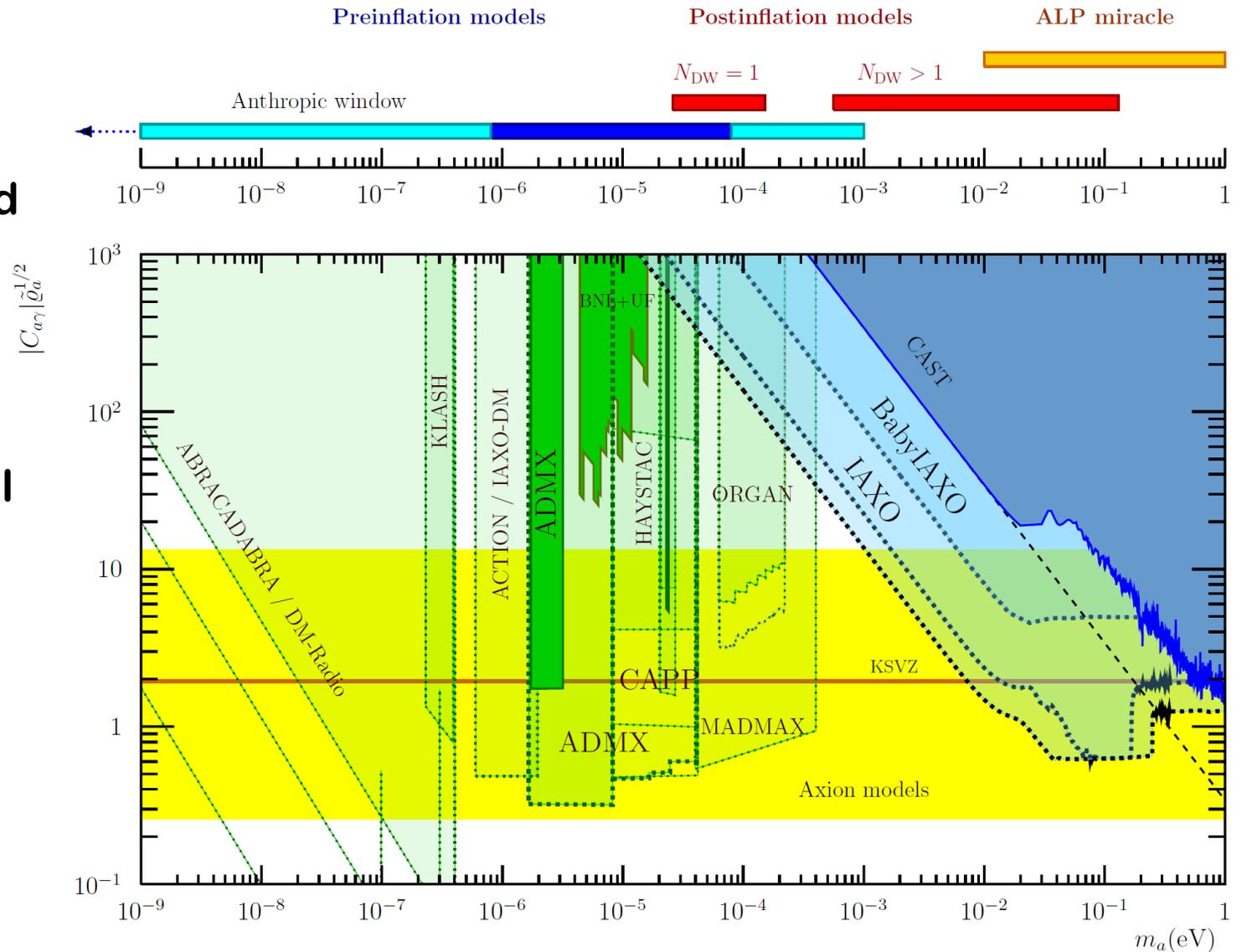


Relevant sensitivity for $m_a \sim 10^{-4}$ eV seems possible for kg-sized samples

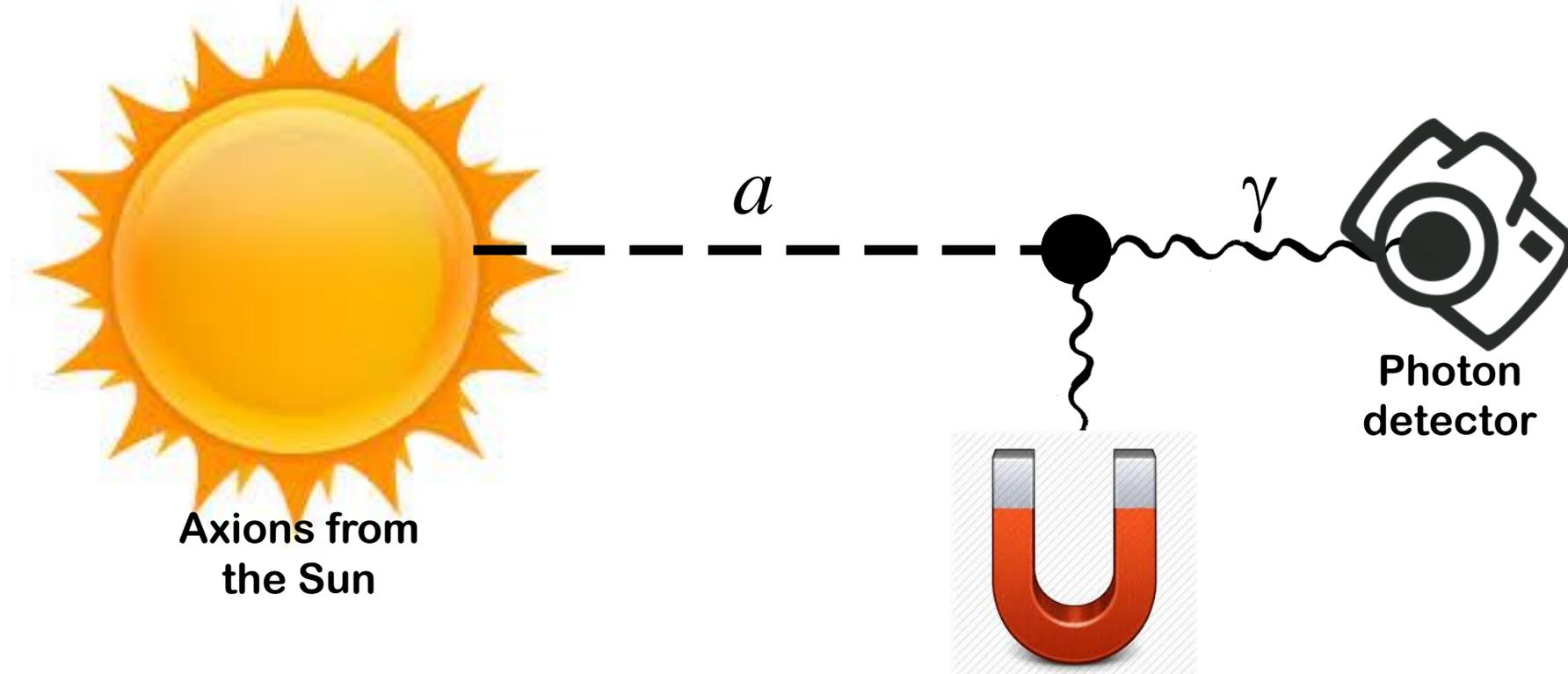


P. Sikivie PRL 113(14)

- 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 successful R&D phase
- **Caution:** Green areas rely on axion as DM hypothesis...

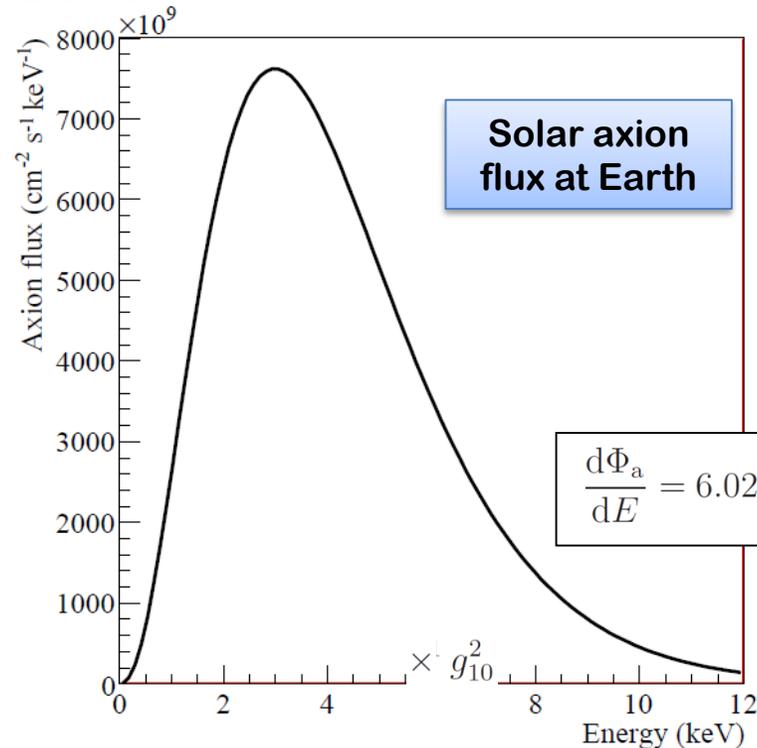
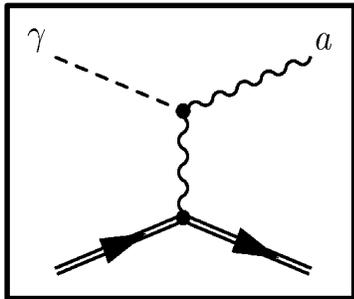


Solar axions



Solar axions

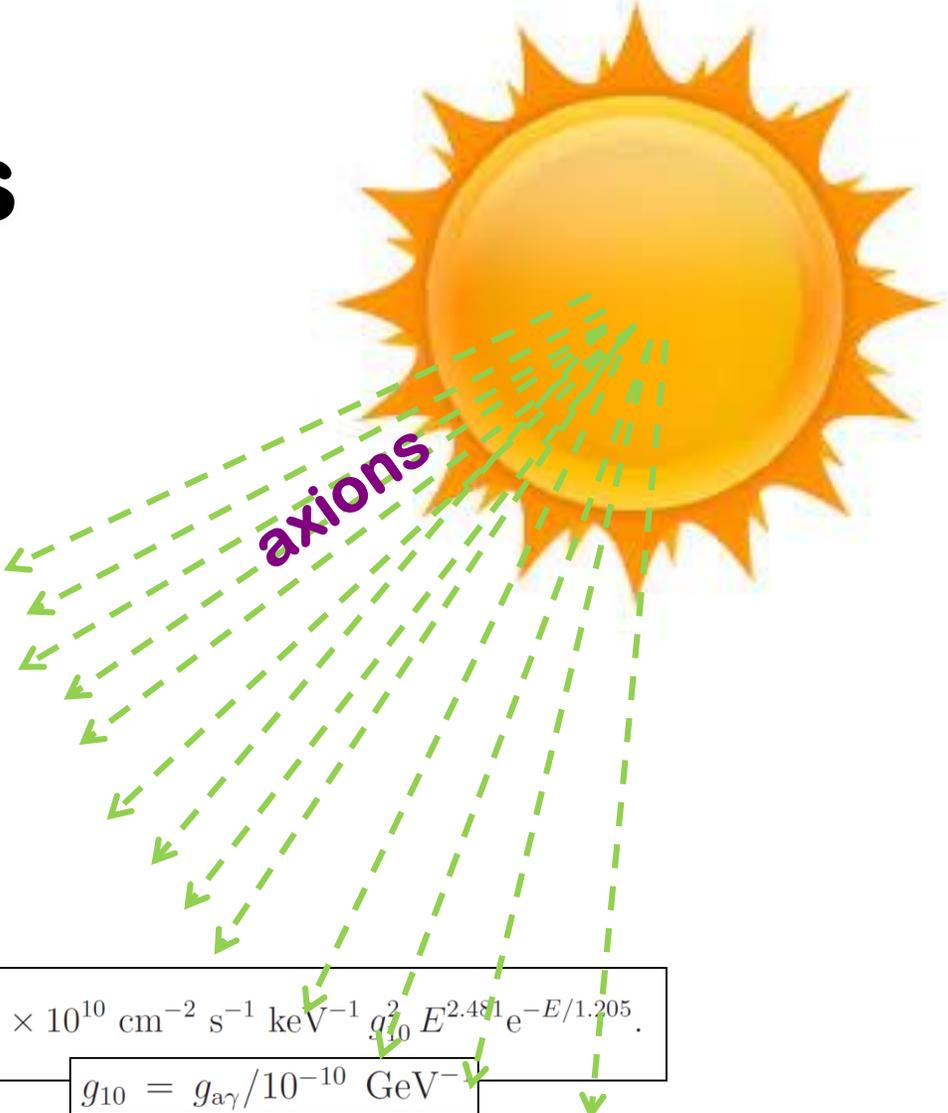
- Solar axions produced by photon-to-axion conversion of the solar plasma photons in the solar core



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

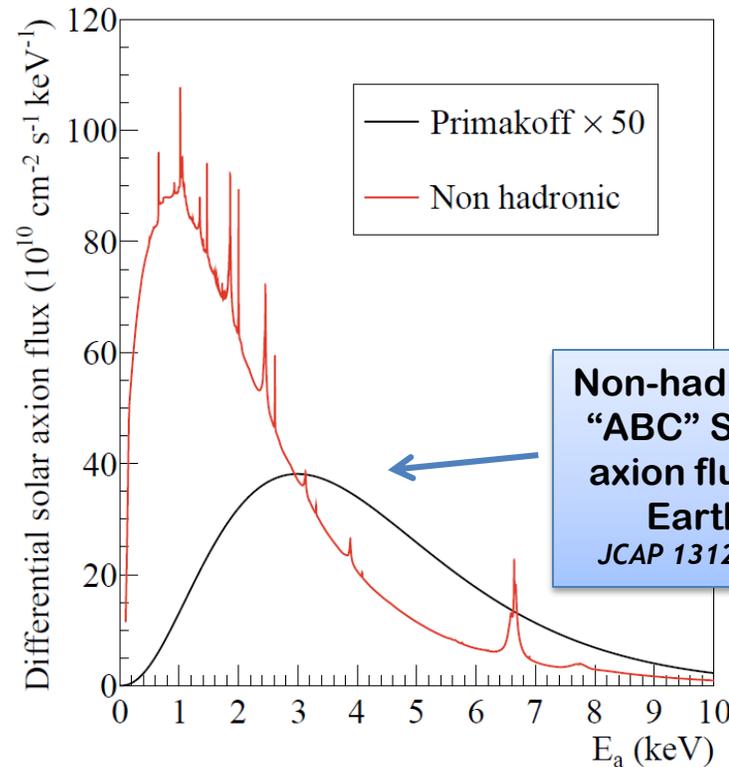
$$g_{10} = g_{a\gamma} / 10^{-10} \text{ GeV}^{-1}$$

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



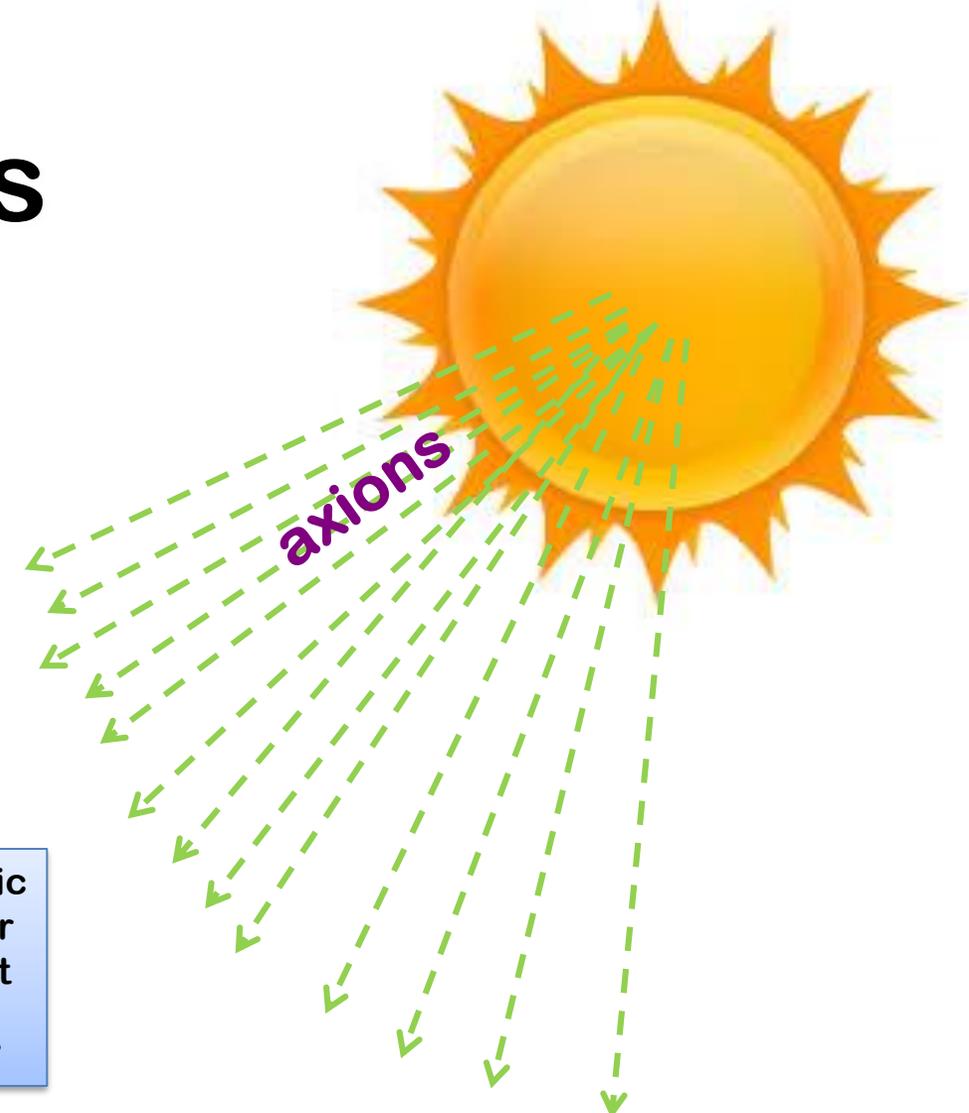
Solar Axions

- 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

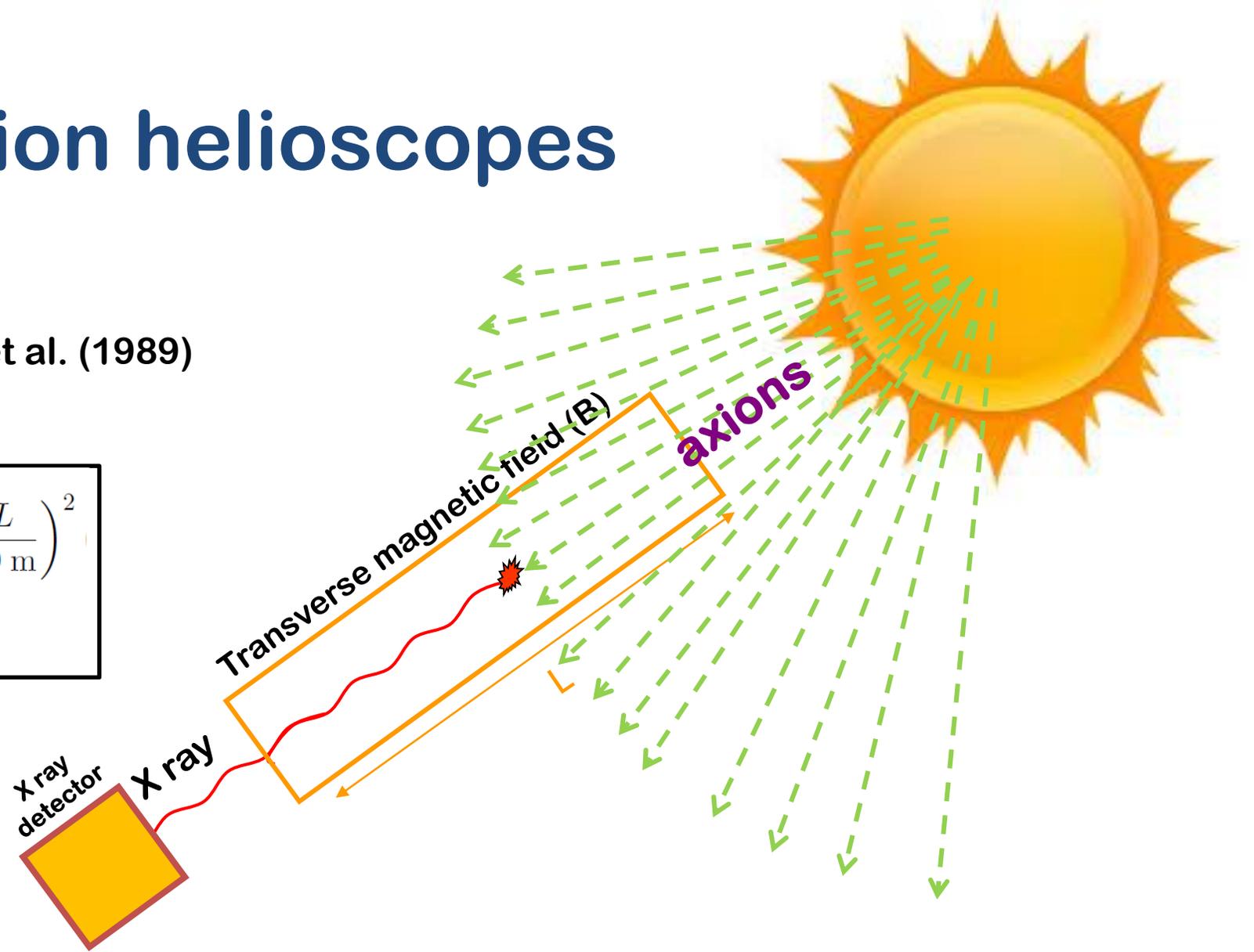
Axion helioscope concept

P. Sikivie, 1983

+ K. van Bibber, G. Raffelt, et al. (1989)

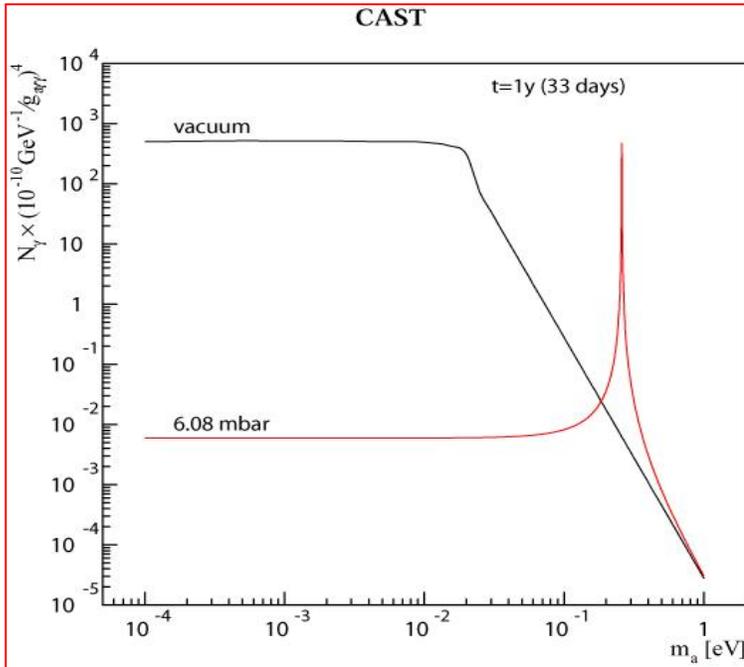
(use of buffer gas)

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

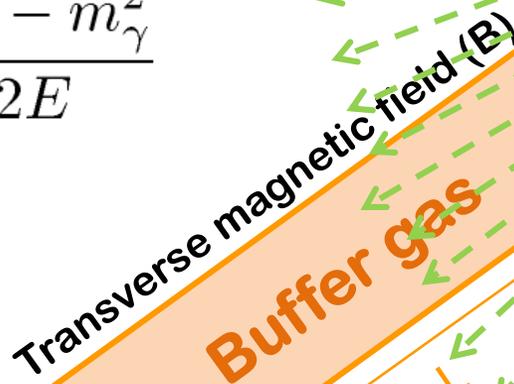
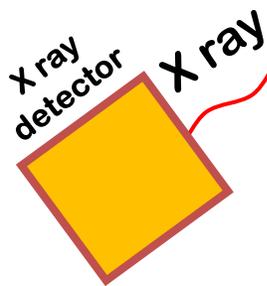


Buffer gas for higher masses

Coherence condition ($qL \ll 1$) is recovered for a narrow mass range around m_γ

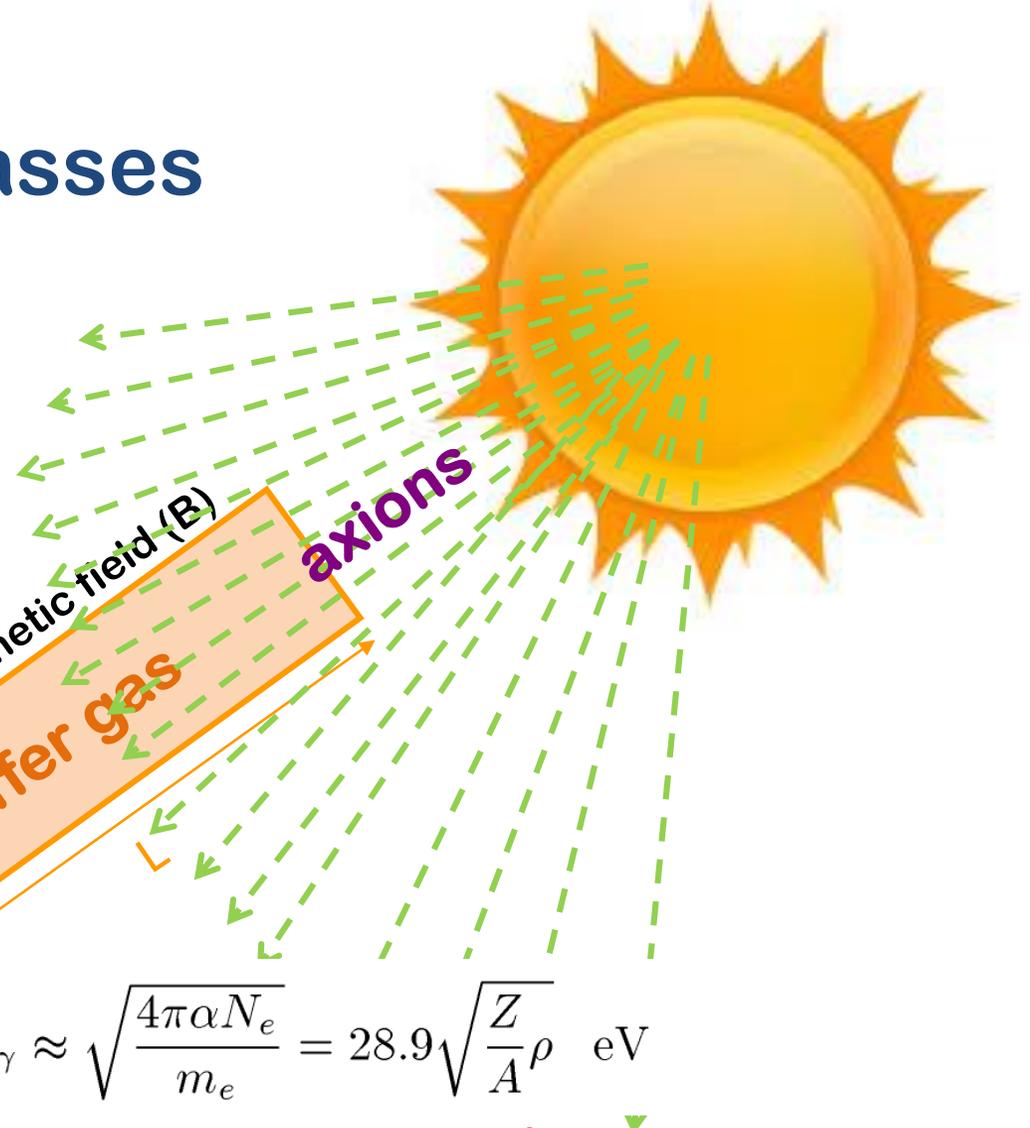


$$|q| = \frac{m_a^2 - m_\gamma^2}{2E}$$



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

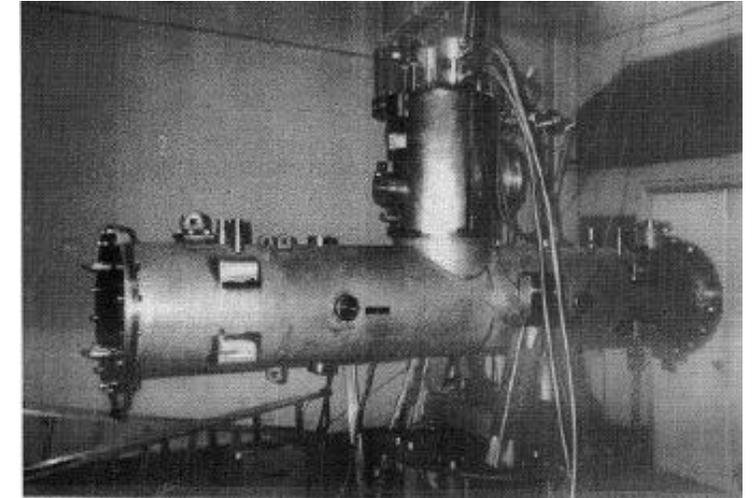
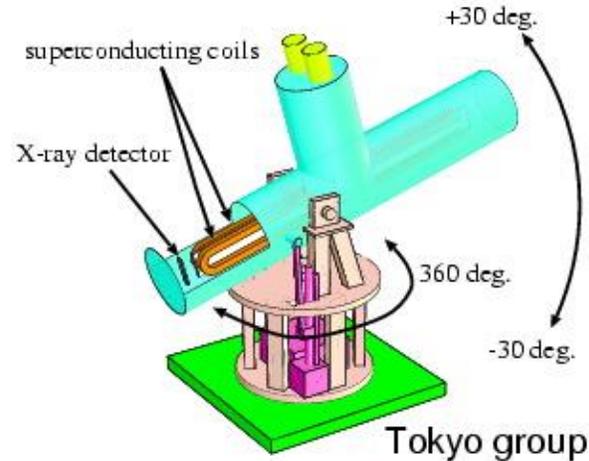
N_e : number of electrons/cm³
 r : gas density (g/cm³)



Axion Helioscopes

- Previous helioscopes:

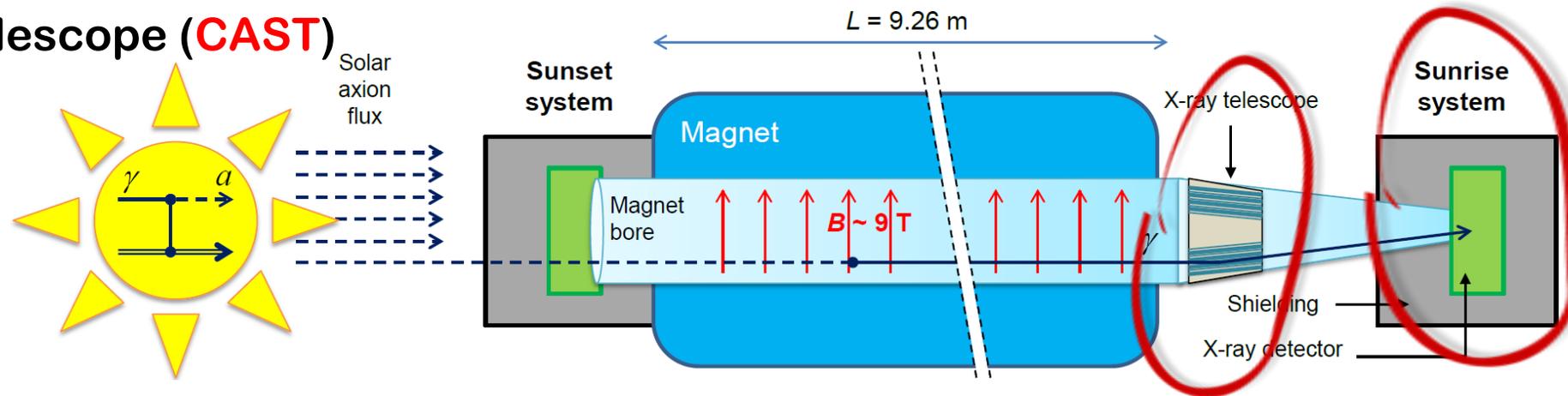
- First implementation at Brookhaven (just few hours of data) [Lazarus et al. PRL 69 (92)]
- TOKYO Helioscope (SUMICO): 2.3 m long 4 T magnet



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 $\pm 8^\circ V \pm 40^\circ H$ (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.

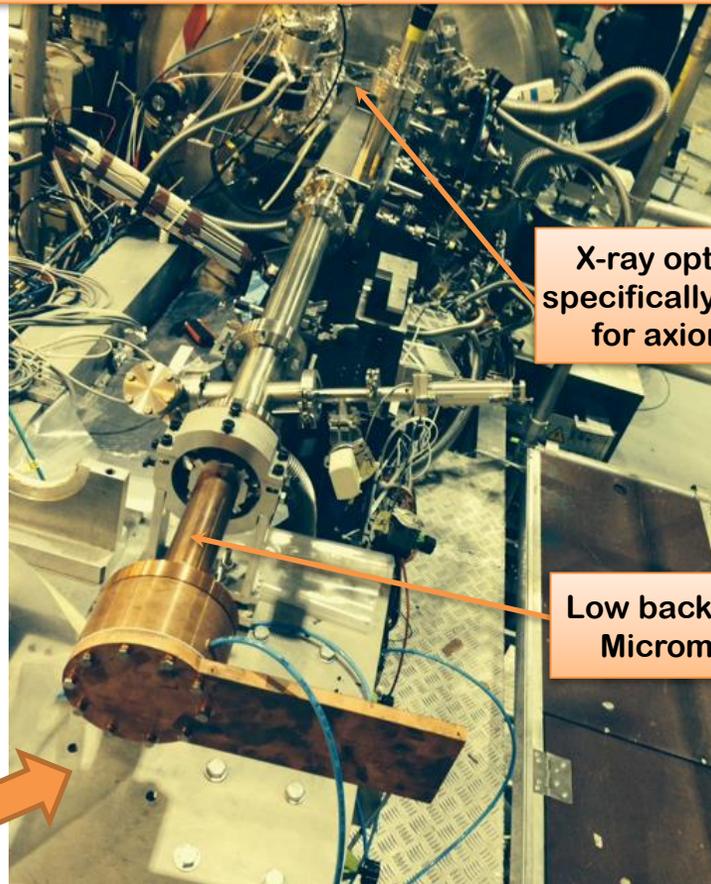


CAST hunting axions (movie credit: M. Rosu / CERN)

Latest CAST limit

2003 – 2004	CAST phase I <ul style="list-style-type: none"> • vacuum in the magnet bores
2006	CAST phase II - ⁴He Run <ul style="list-style-type: none"> • axion masses explored up to 0.39 eV (160 P-steps)
2007	³He Gas system implementation
2008 - 2011	CAST phase II - ³He Run <ul style="list-style-type: none"> • axion masses explored up to 1.17 eV • bridging the dark matter limit
2012	<ul style="list-style-type: none"> • Revisit 4He Run with improved detectors
2013-2015	<ul style="list-style-type: none"> • New vacuum phase with improved detectors → Result released in 2017

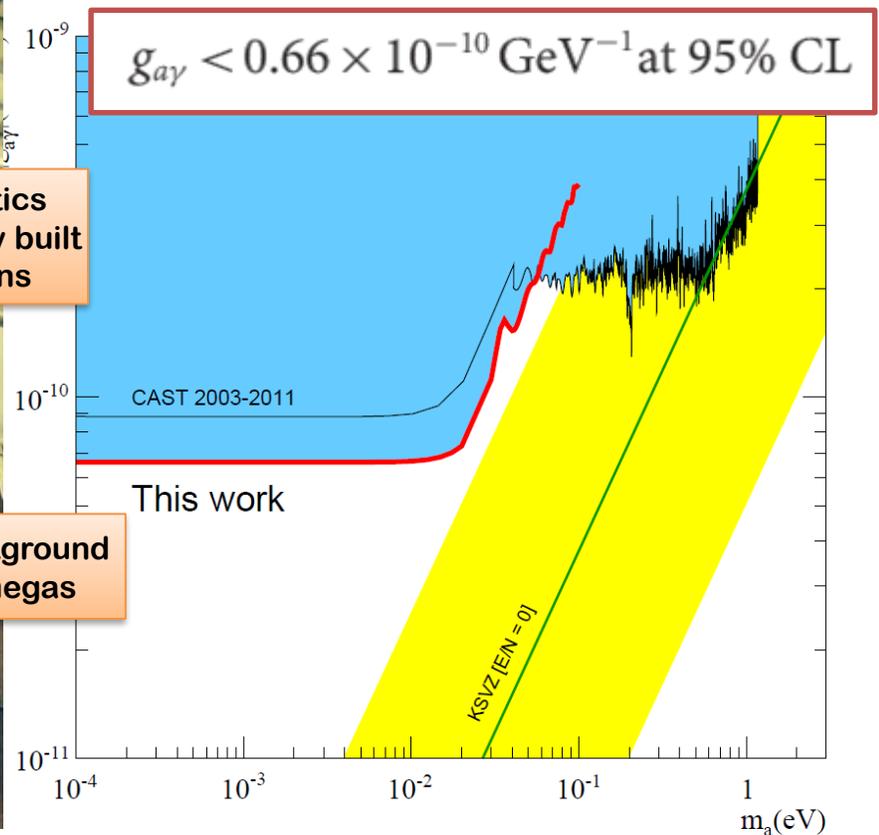
Enabled by the IAXO pathfinder system



New CAST limit on the axion-photon interaction

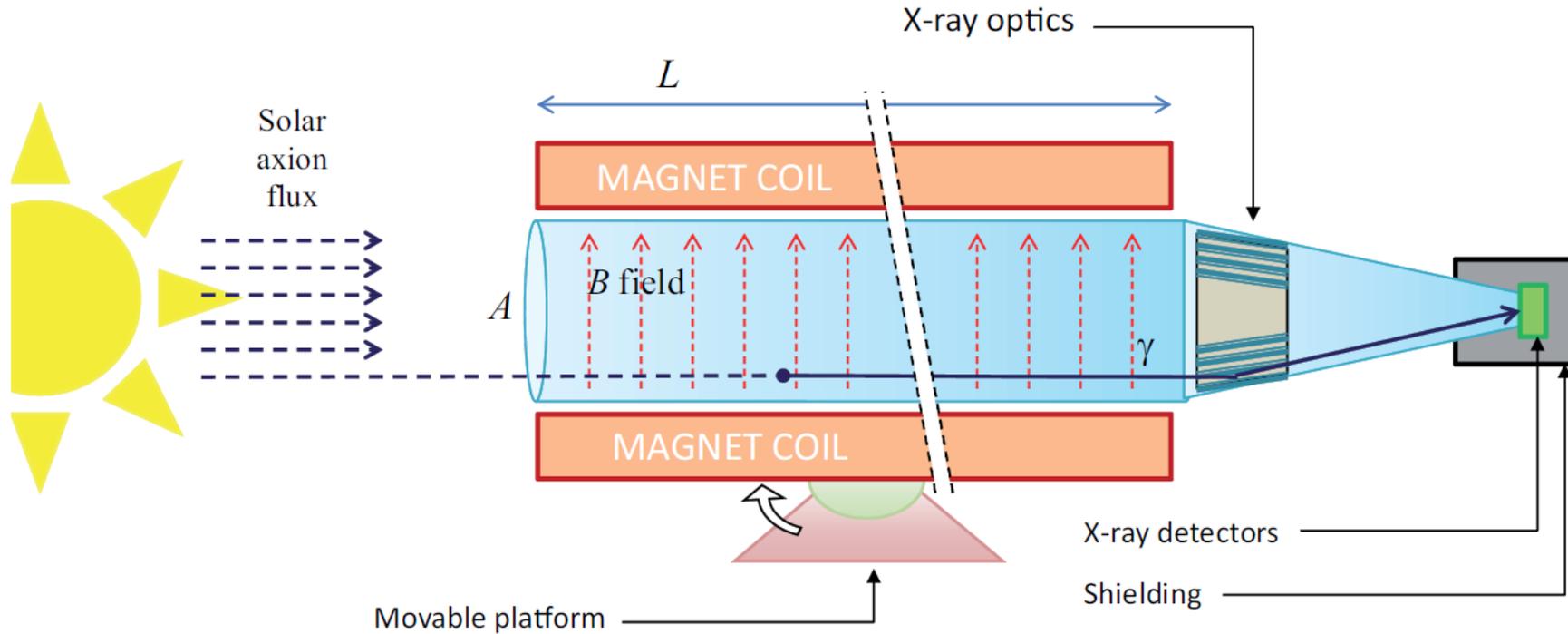
CAST Collaboration[†]

Hypothetical low-mass particles, such as axions, provide a compelling explanation for the dark matter in the universe. Such particles are predicted by the best motivated theories. To test this prediction, the CAST Collaboration



IAXO – Concept

IAXO
International Axion
Observatory



Enhanced axion helioscope:
JCAP 1106:013,2011

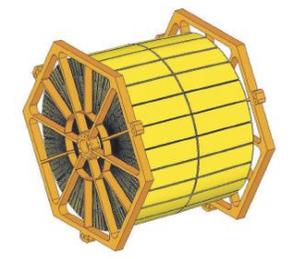
$$g_{a\gamma}^4 \propto \underbrace{b^{1/2} \epsilon^{-1}}_{\text{detectors}} \times \underbrace{a^{1/2} \epsilon_o^{-1}}_{\text{optics}} \times \underbrace{(BL)^{-2} A^{-1}}_{\text{magnet}} \times \underbrace{t^{-1/2}}_{\text{exposure}}$$

4+ orders of magnitude better SNR that CAST

IAXO technologies – Baseline

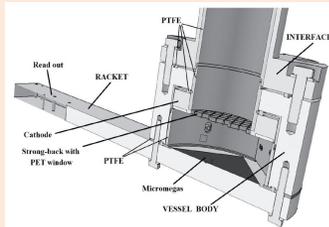
IAXO telescopes

- 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



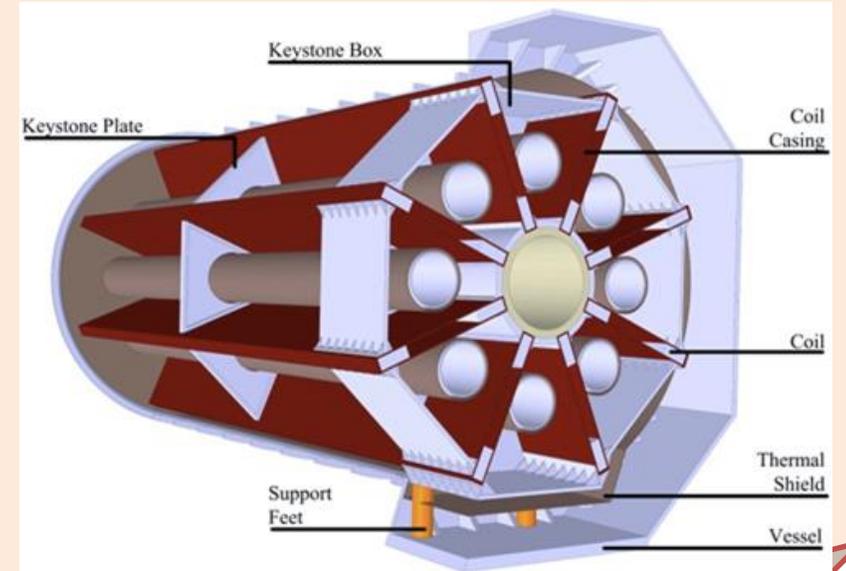
IAXO detectors

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



IAXO magnet

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



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

Rotation System

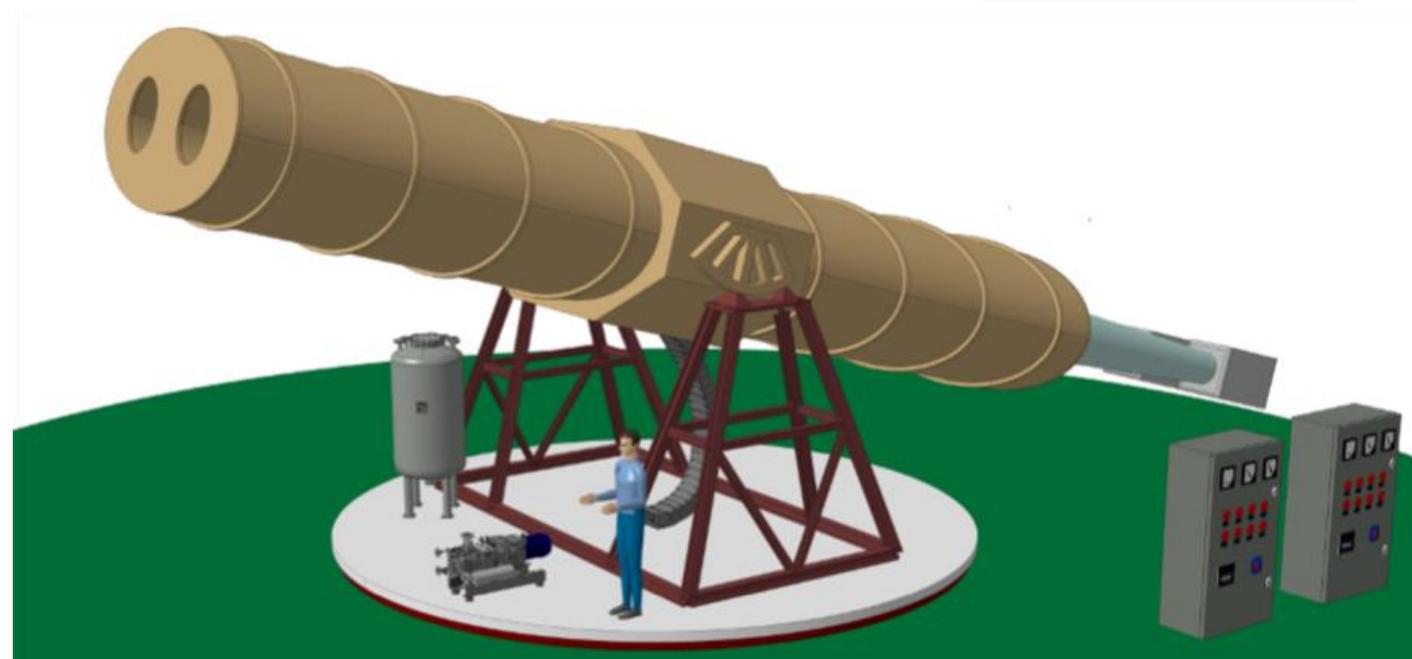
BabyIAXO

- Intermediate experimental stage before IAXO
- Two magnet bores of similar dimensions of final IAXO bores → detection line representative of final ones.
- Test & improve all systems. Risk mitigation for full IAXO

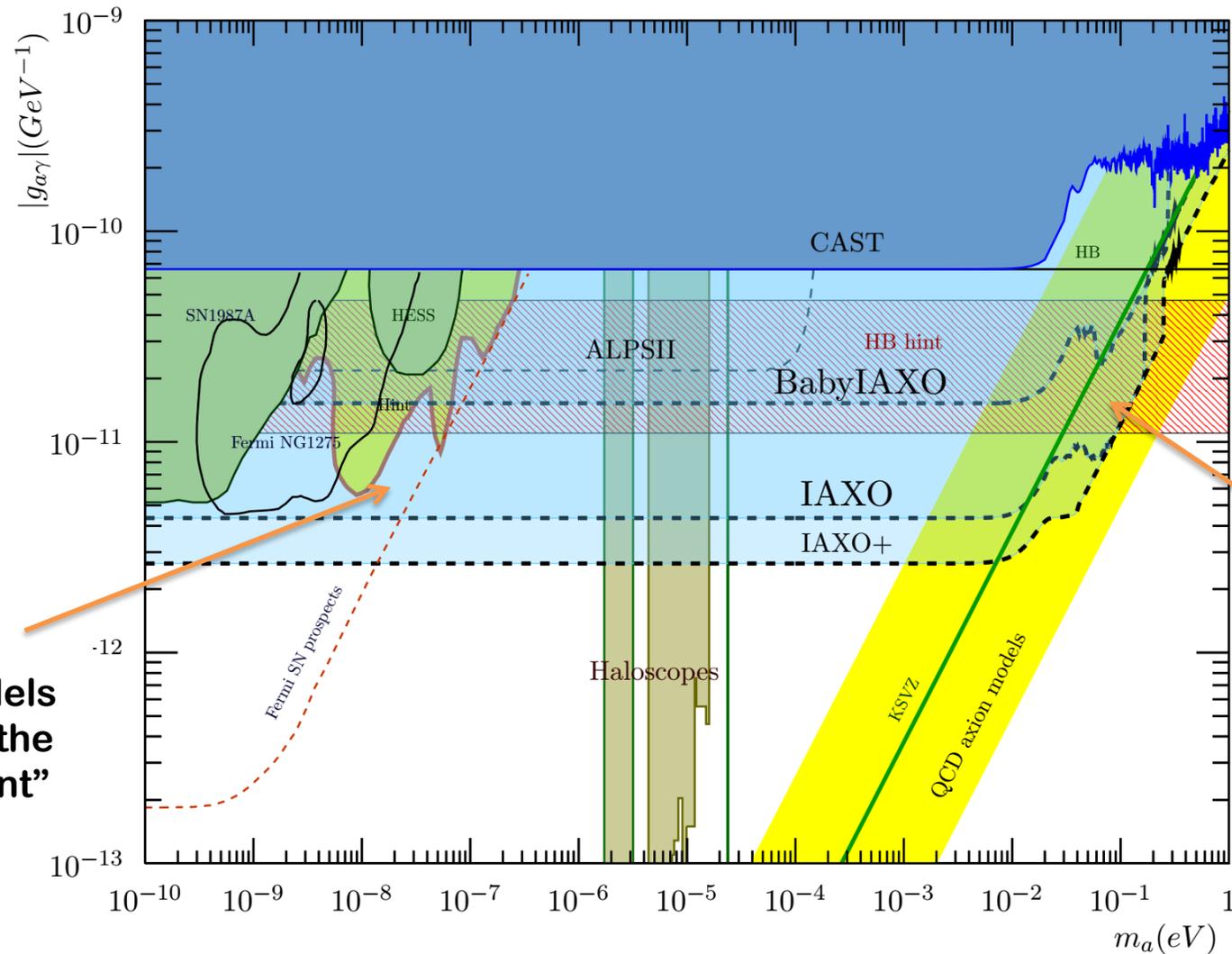
Magnetic length [m]	10
Field in bore [T]	~2
Aperture [m ²]	2x0.38

10x CAST B^2L^2A

- Will produce relevant physics
- Move earlier to “experiment mode”
- BabyIAXO CDR finished. Moving to Technical Design
- Under review to be sited at DESY



Helioscopes & astrophysics hints

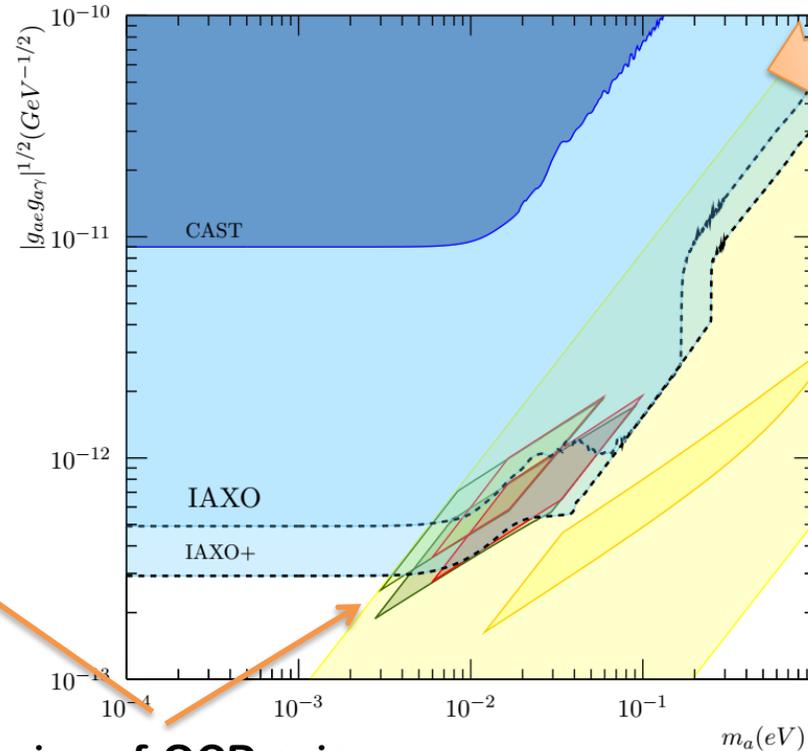
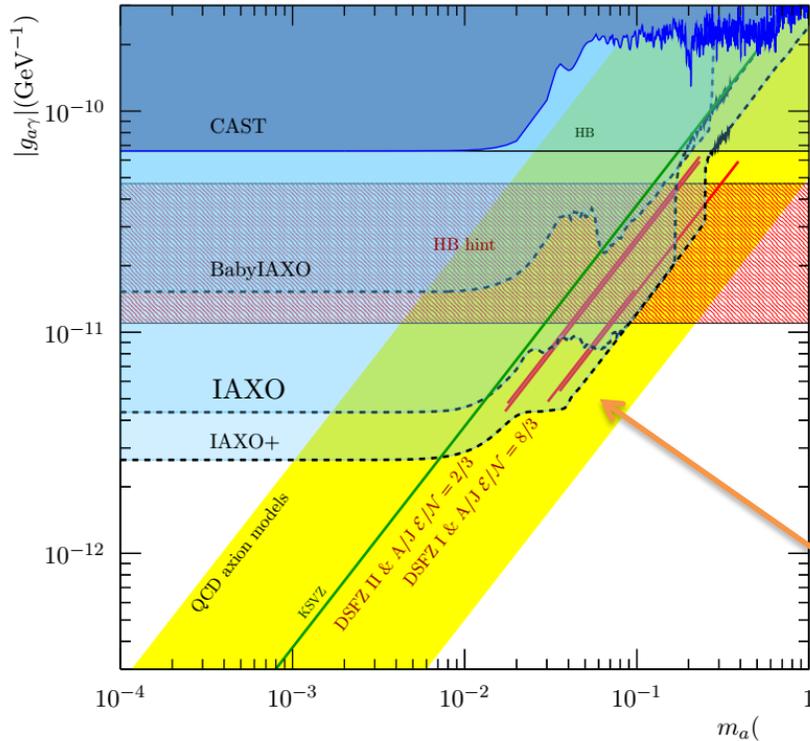


IAXO will fully explore ALP models invoked to solve the “transparency hint”

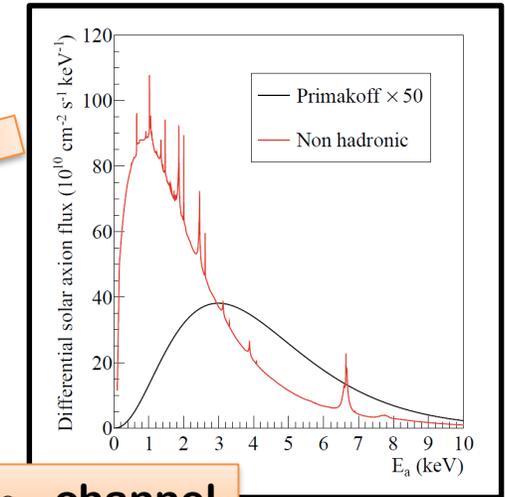
... as well as a large fraction of the axion & ALP models invoked in the “stellar cooling anomaly”
 But for this the g_{ae} is particularly interesting

IAXO & stellar cooling

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



Region of QCD axion models that solve the stellar anomaly



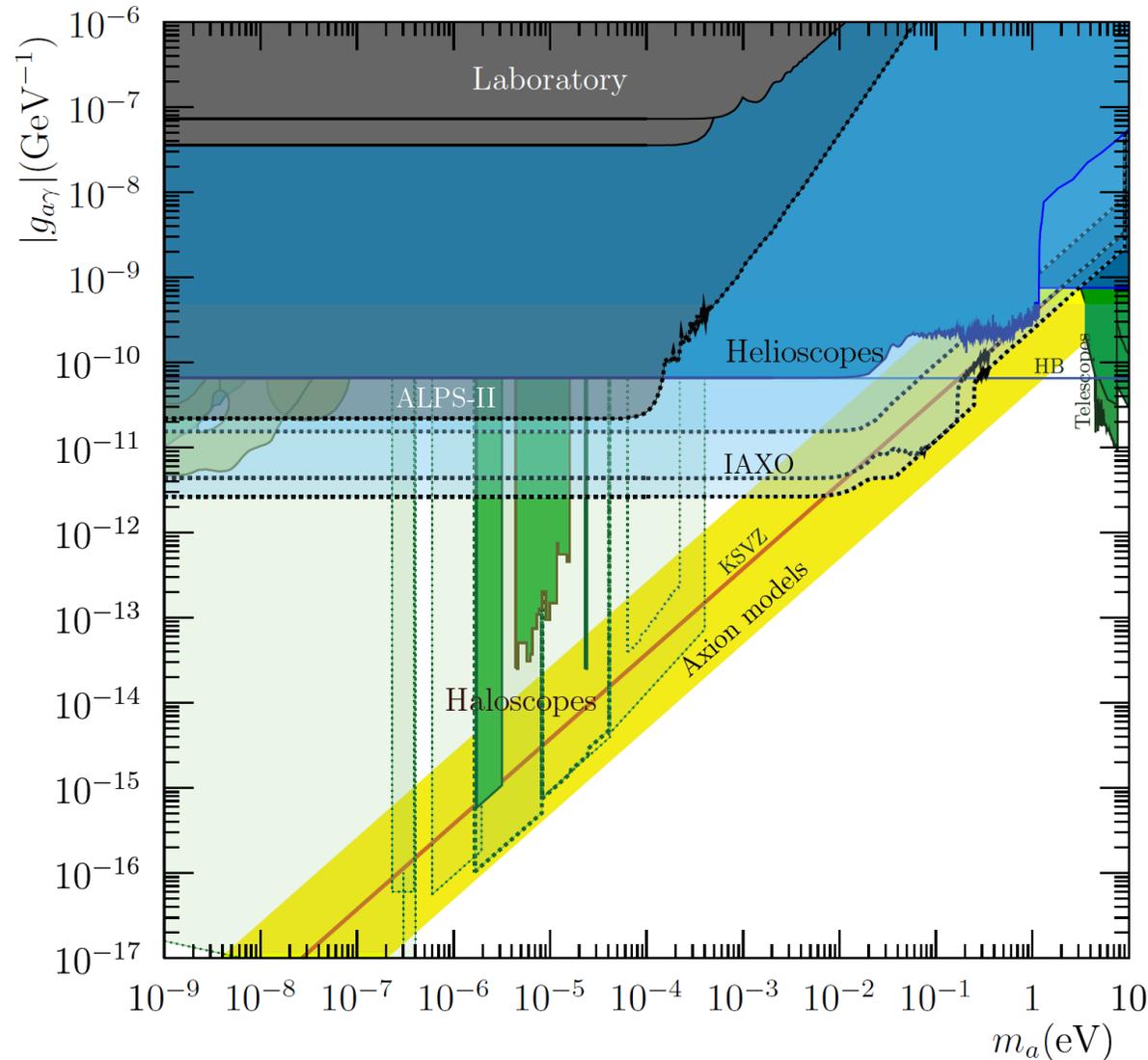
g_{ae} channel

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

M. Giannotti et al.
JCAP 1710 (2017) 010
[arXiv:1708.02111](https://arxiv.org/abs/1708.02111)

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

- Helioscopes (IAXO) will probe astrophysically 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

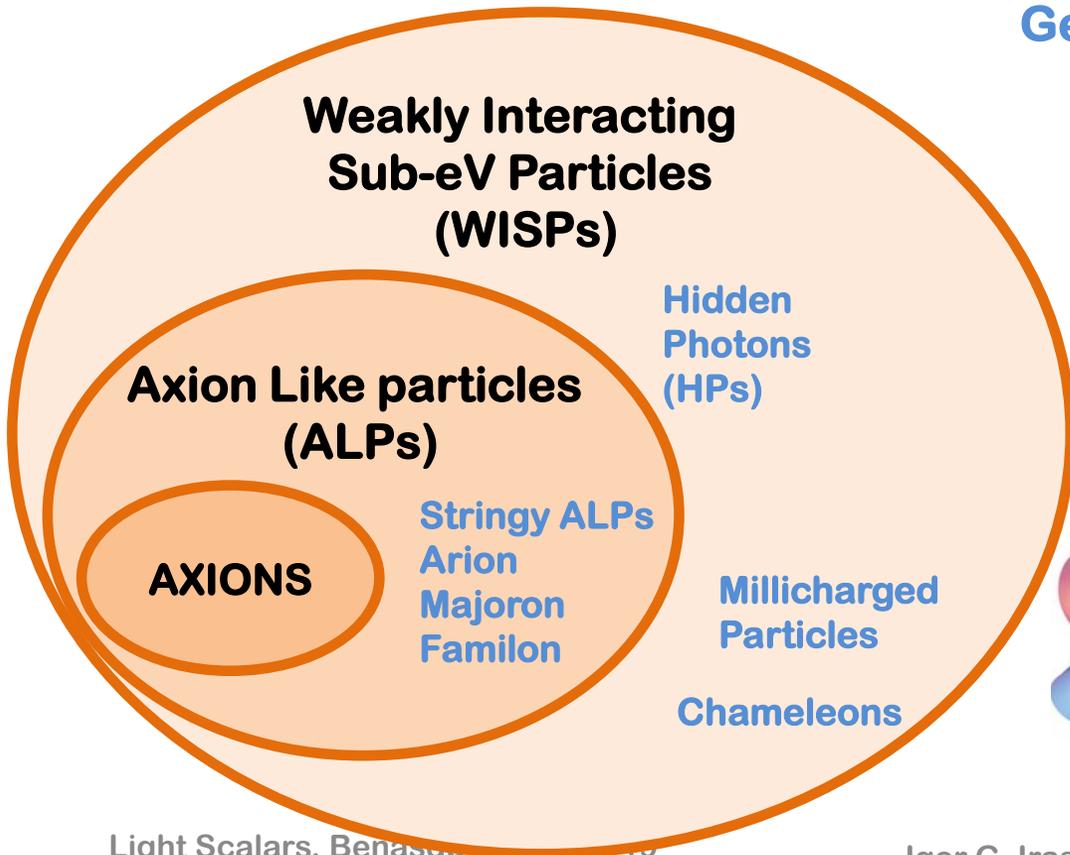
- Experimental search for axions → field of increasing interest
- Increasing experimental effort (still small!)
- Consolidation of classical detection lines: ADMX, CAST, ALPs,...
 - ADMX and CAST have firstly probed interesting (small) fraction of par space.
 - Helioscopes: IAXO next generation
 - Haloscopes: 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

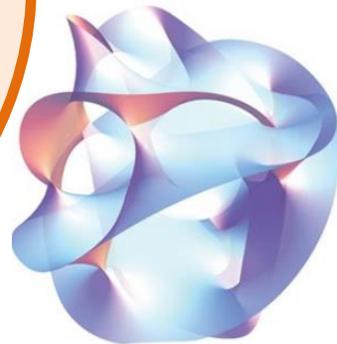
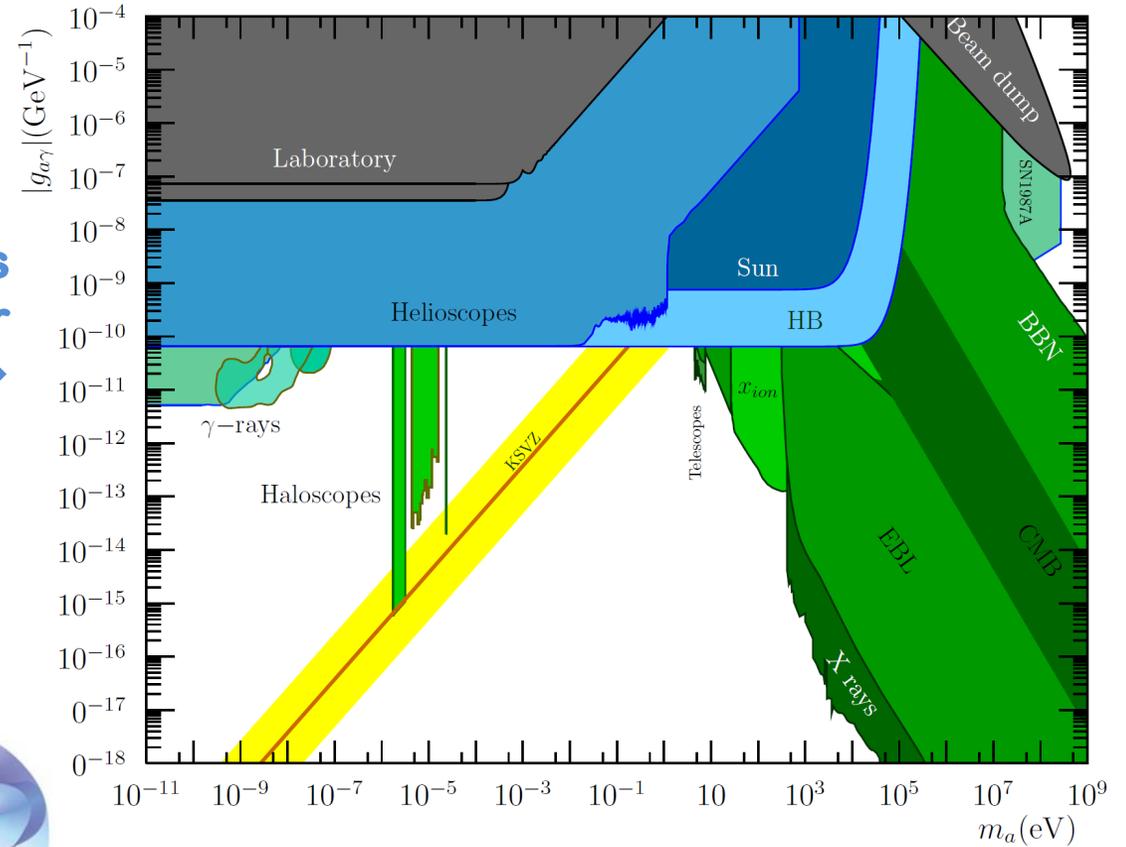
Backup slides

Beyond axions

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

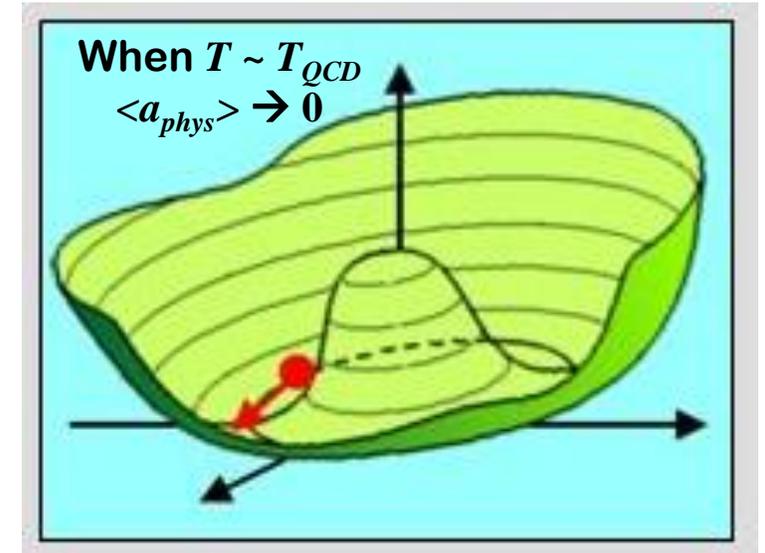
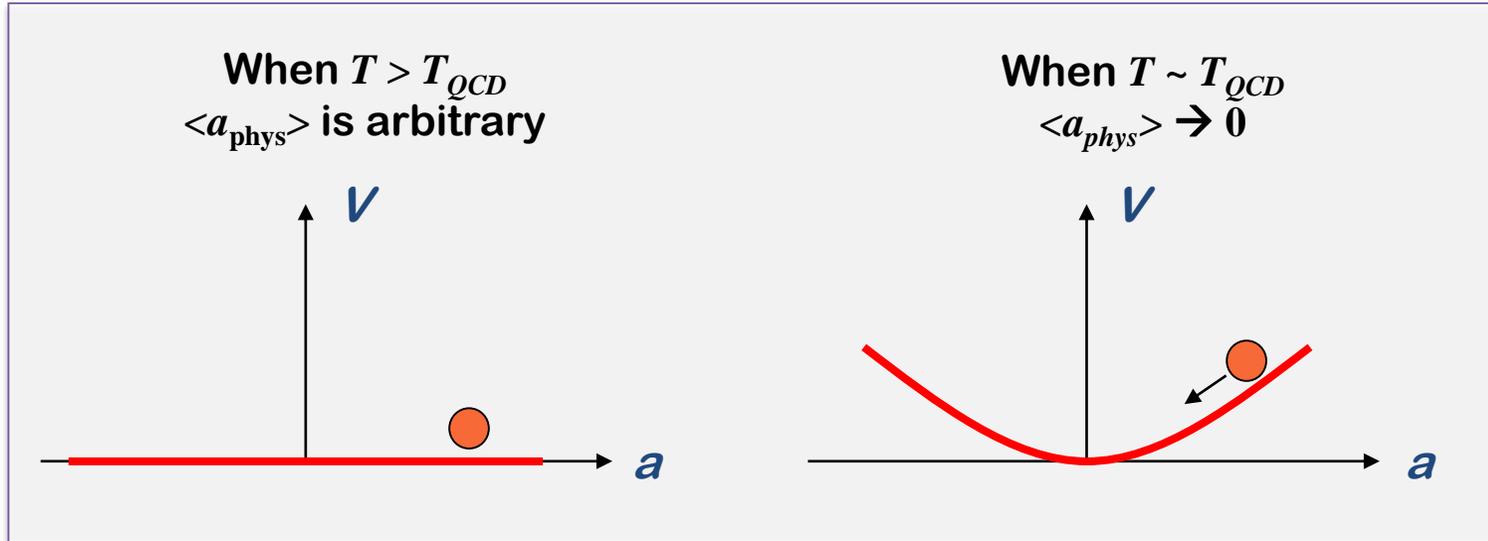


Generic ALPs parameter space →



String theory predicts a plenitude of ALPs

Cosmological axions: **axion realignment**



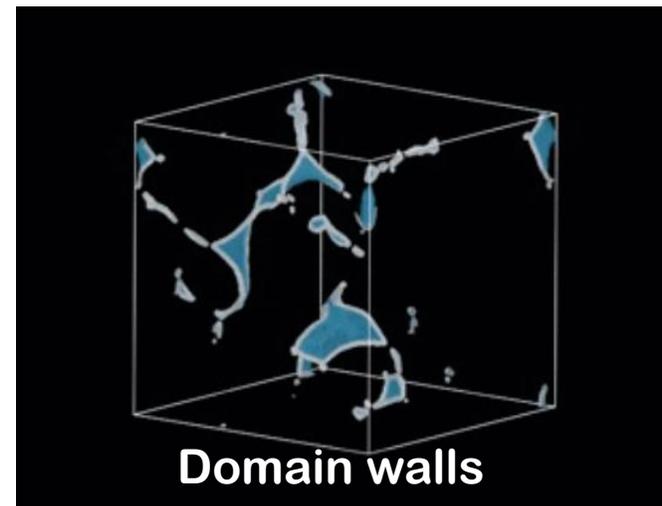
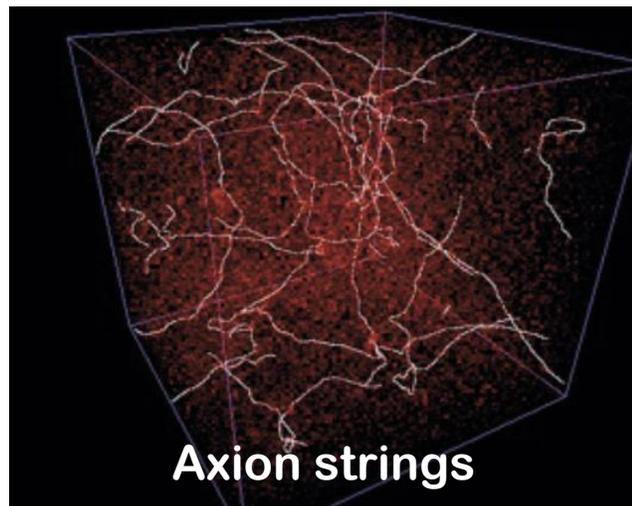
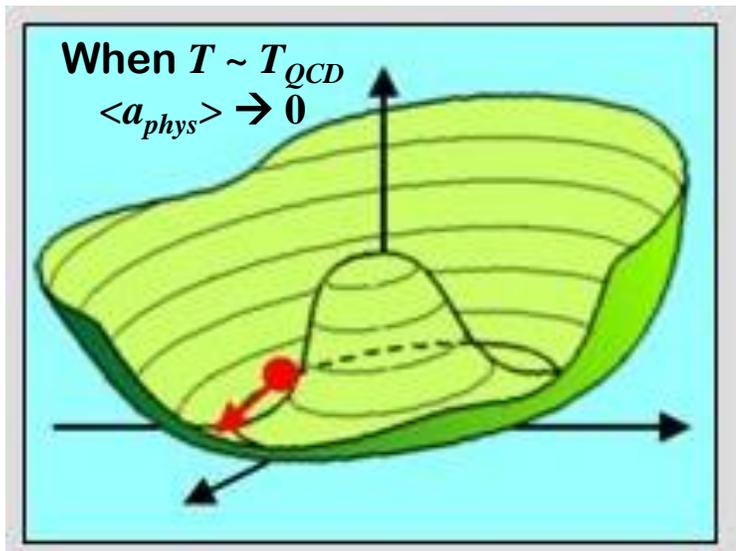
As the Universe cools down below T_{QCD} , space is filled with low energy axion field fluctuations \rightarrow act as cold dark matter

Their density depends on the **initial value of $\langle a_{phys} \rangle$** (“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**



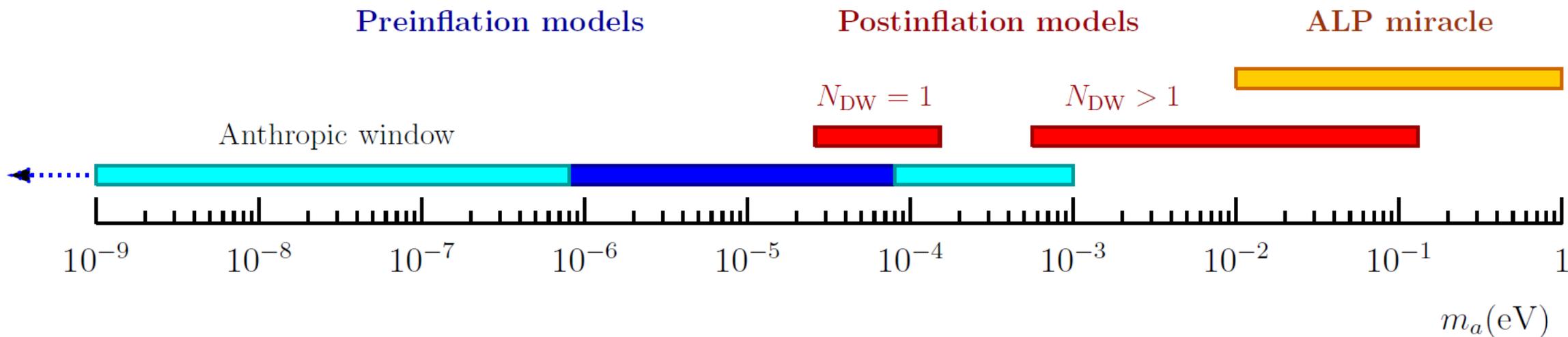
But inflation may “wipe out” topological defects... Did inflation happen before or after the creation of defects (PQ transition) ?

pre-inflation or post-inflation scenarios

Computation of axion DM density from defect decay is complicated (\rightarrow 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 $m_a \sim 1$ eV)

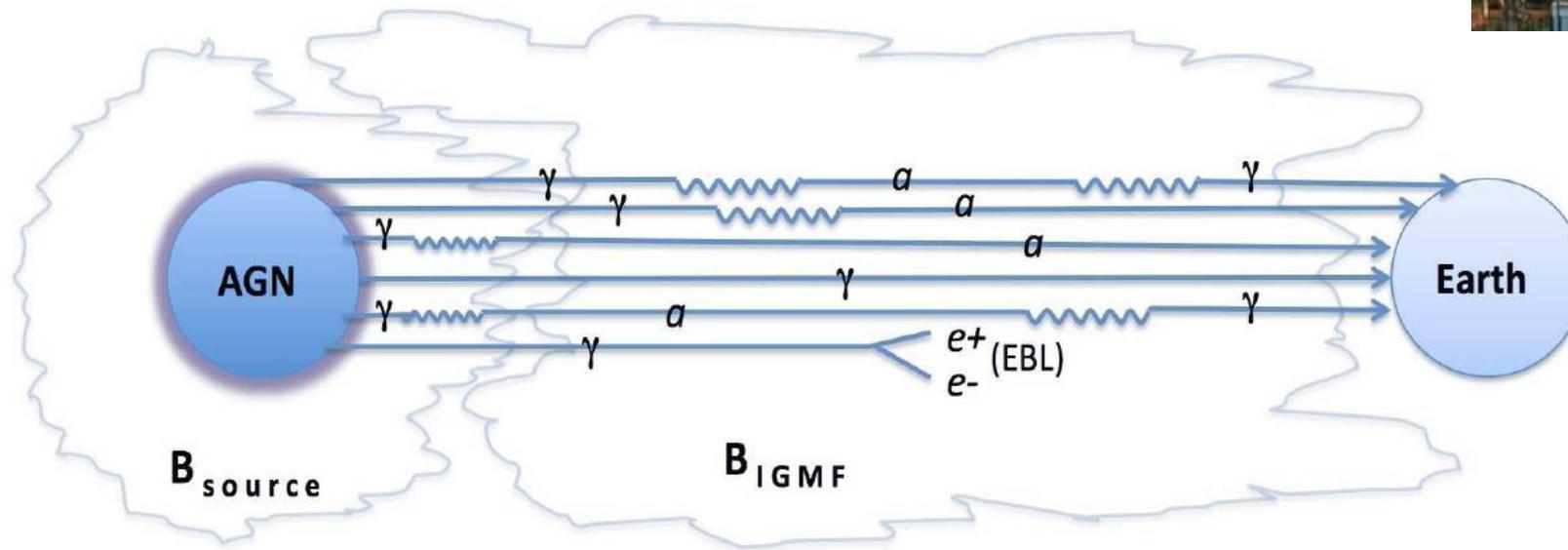


Astrophysical hints for axions

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

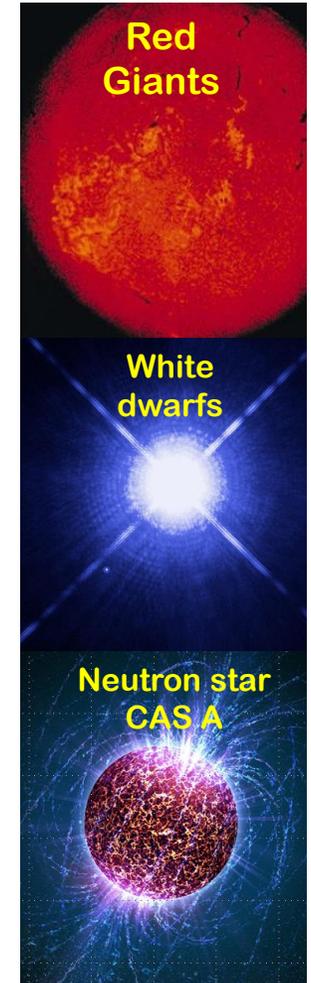
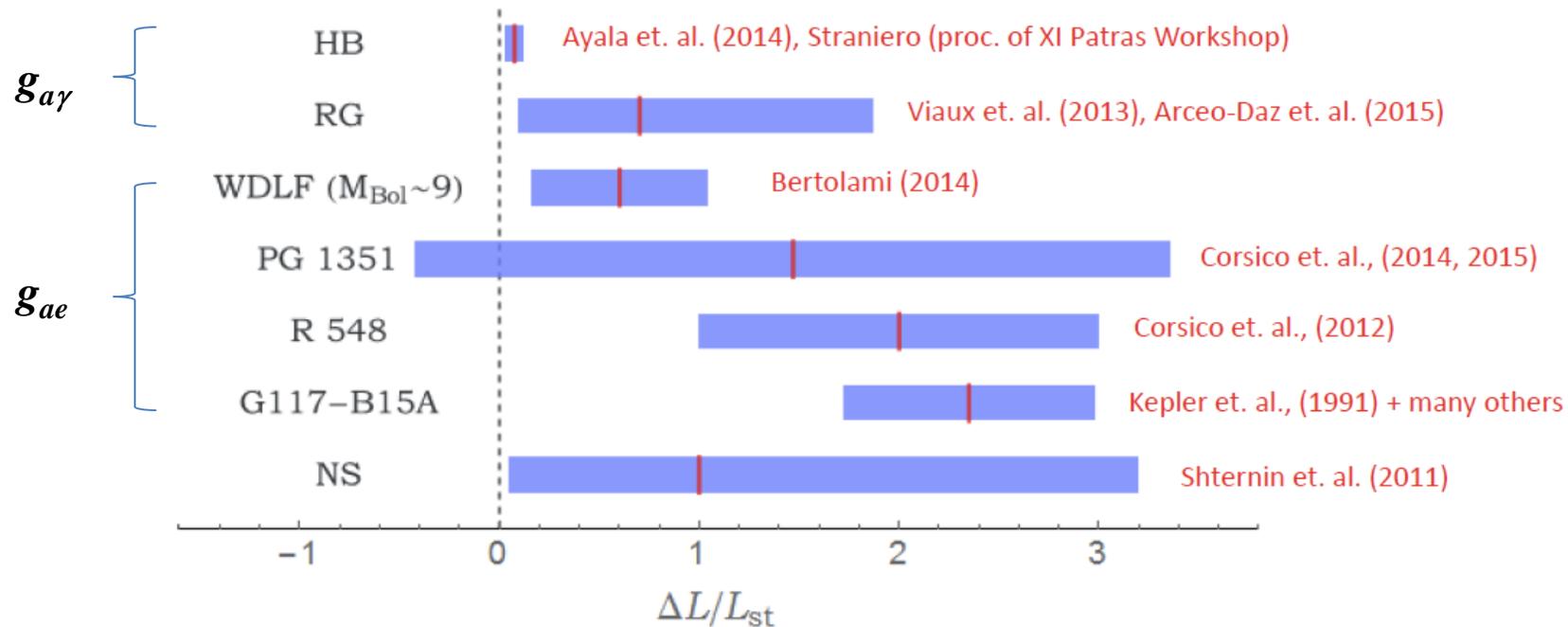


ALP: $g_{a\gamma} \sim 10^{-12} - 10^{-10} \text{ GeV}^{-1}$
 $m_a \lesssim 10^{-(10-7)} \text{ eV}$



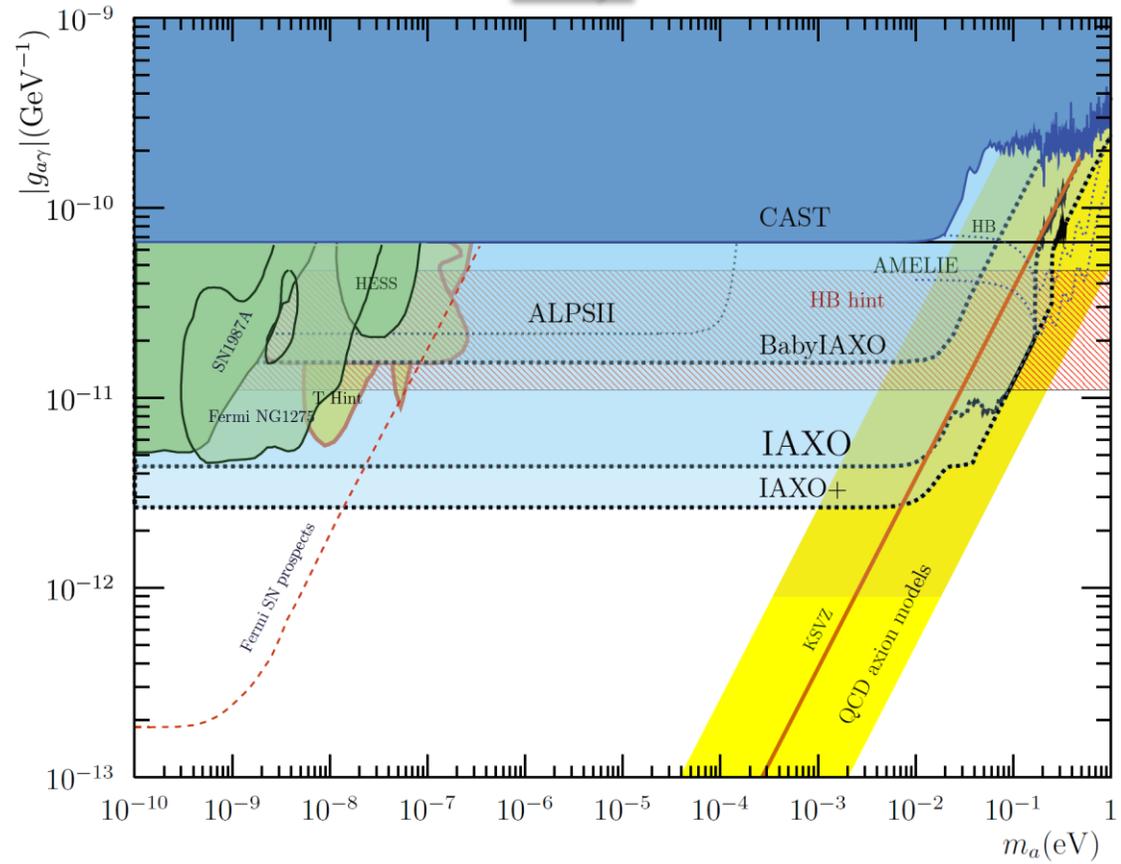
Astrophysical hints for axions

- Most stellar systems seem to cool down faster than expected.
- Presence of axions/ALPs offer a good joint explanation (M. Giannotti et al. JCAP 1710 (2017) 010, arXiv:1708.02111)

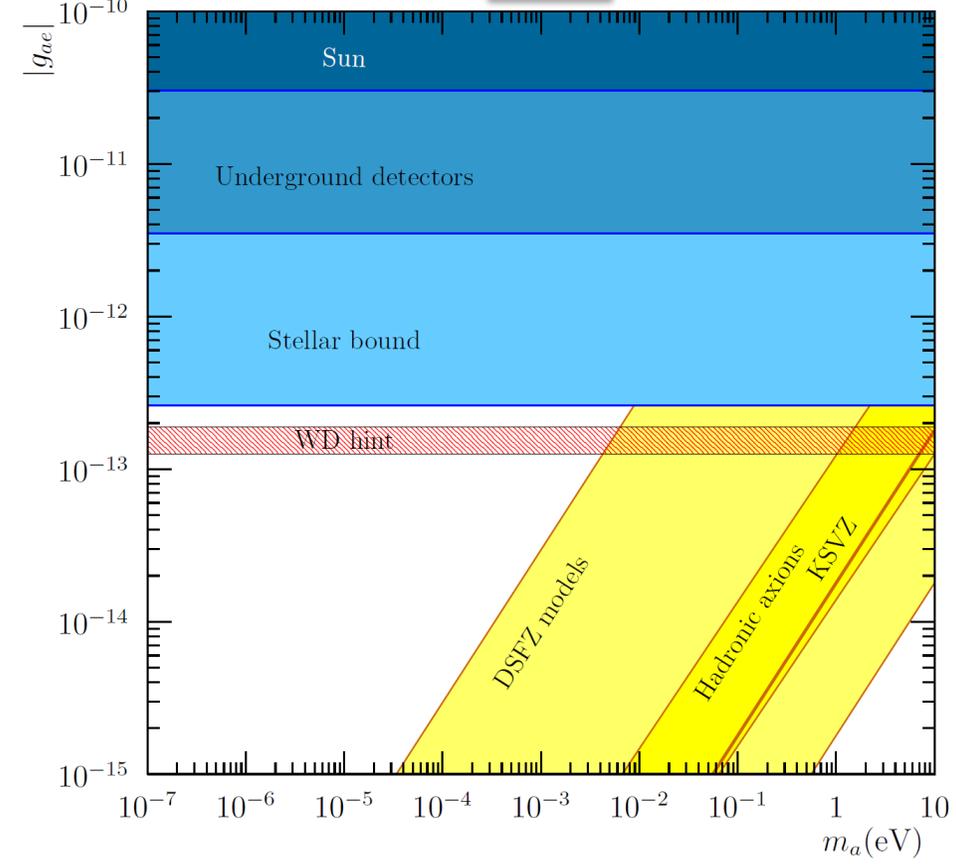


Astrophysical hints for axions

$g_{a\gamma}$



g_{ae}

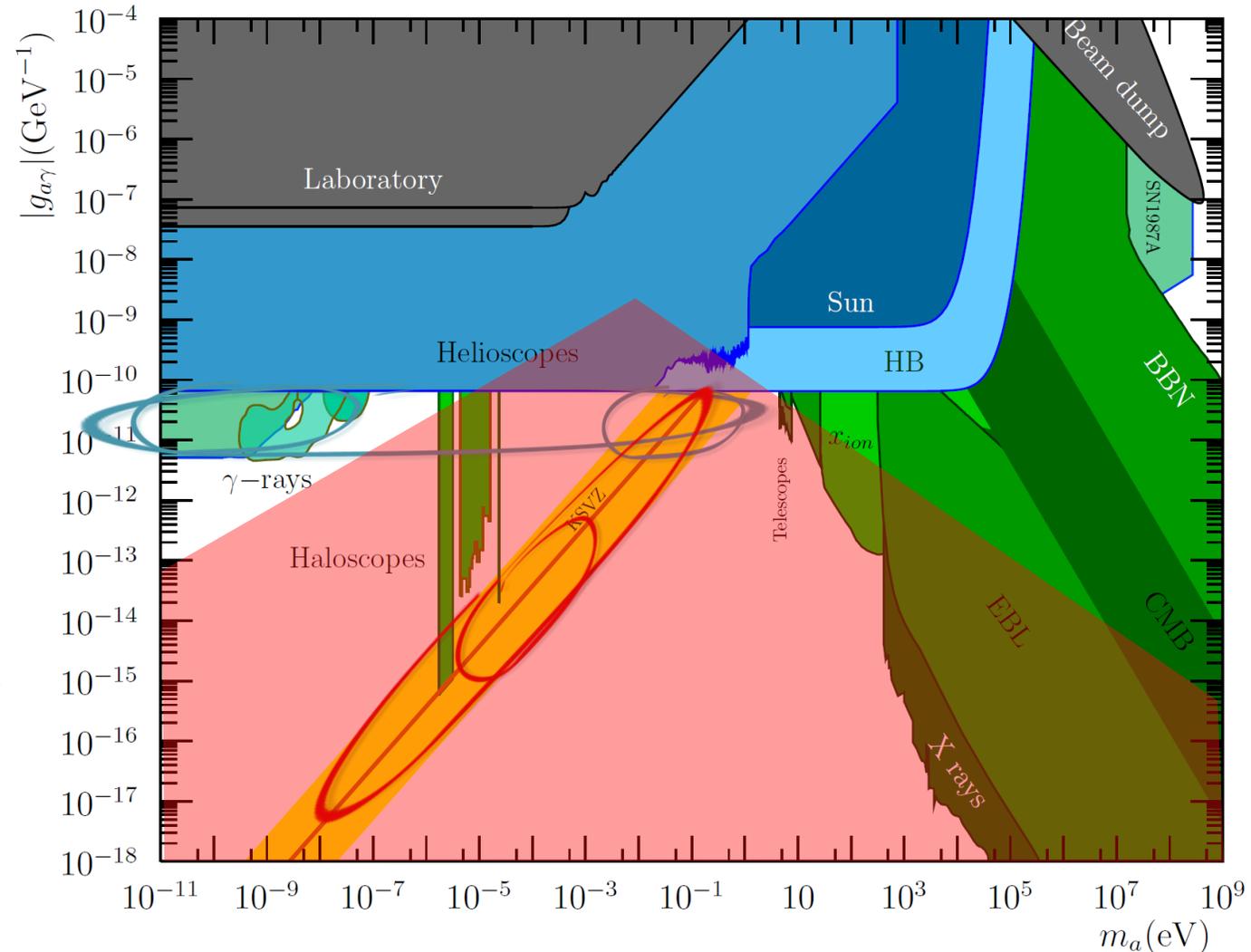


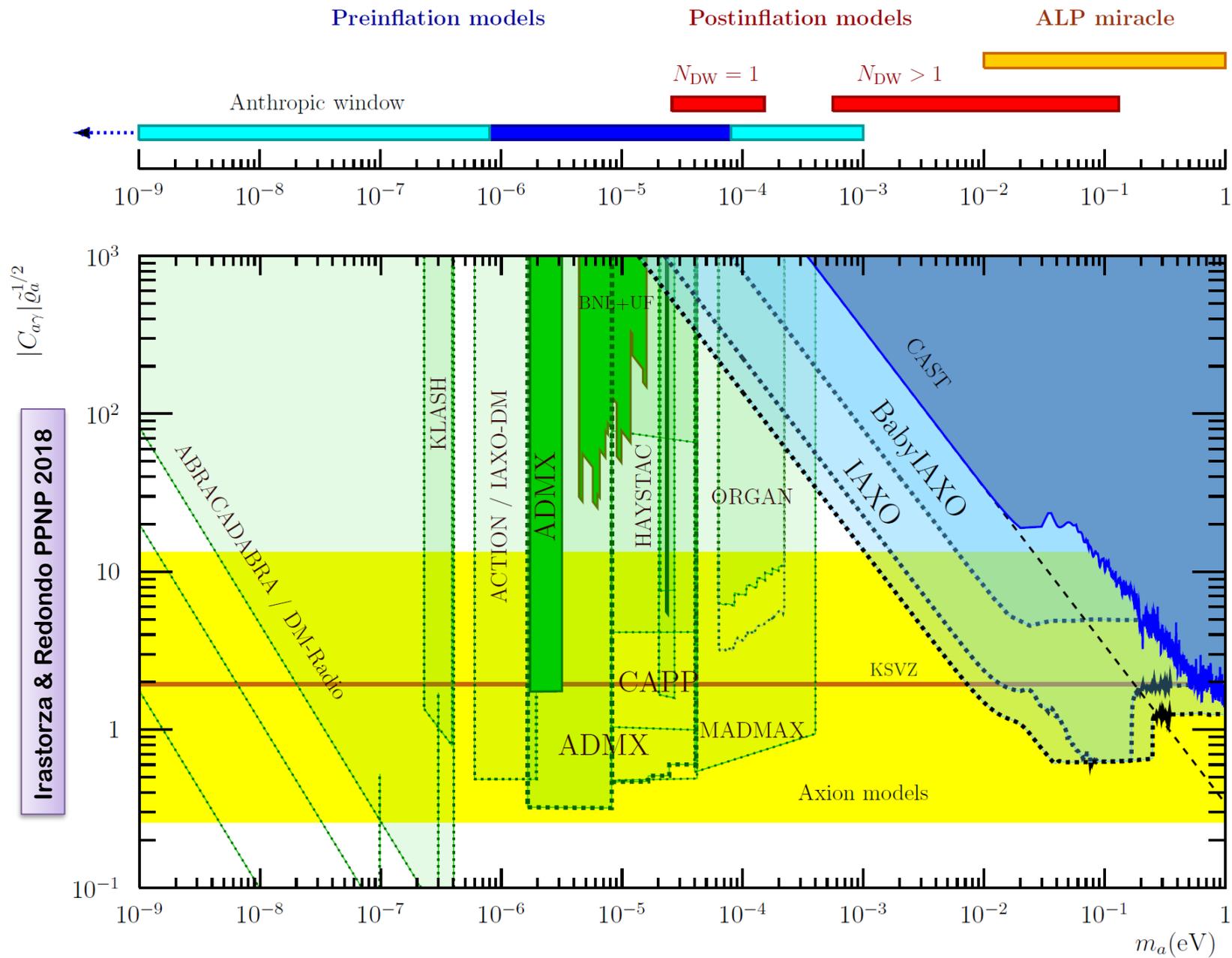
Axion/ALP searches motivation

“Focuses of interest”
in the ALP parameter space

Theory
Astrophysics
Cosmology

Generic
ALP DM
models





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-tuning 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

Glueon coupling

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

generic

Mass

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

generic

Photon coupling

$$g_{a\gamma\gamma} (\mathbf{E} \cdot \mathbf{B}) a$$

$$g_{a\gamma\gamma} = \frac{\alpha}{2\pi f_a} \left(\frac{E}{N} - 1.92 \right)$$

*generic but value
model dependent*

Fermion couplings

Electron coupling
Nucleon coupling

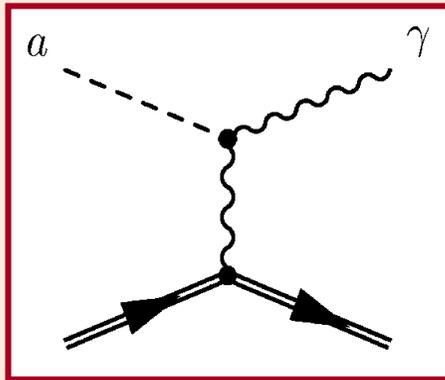
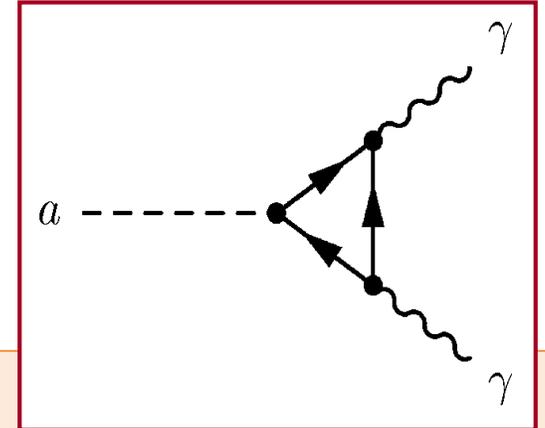
...

Model dependent

Axion phenomenology

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

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



- **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

**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

ALPS experiment

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

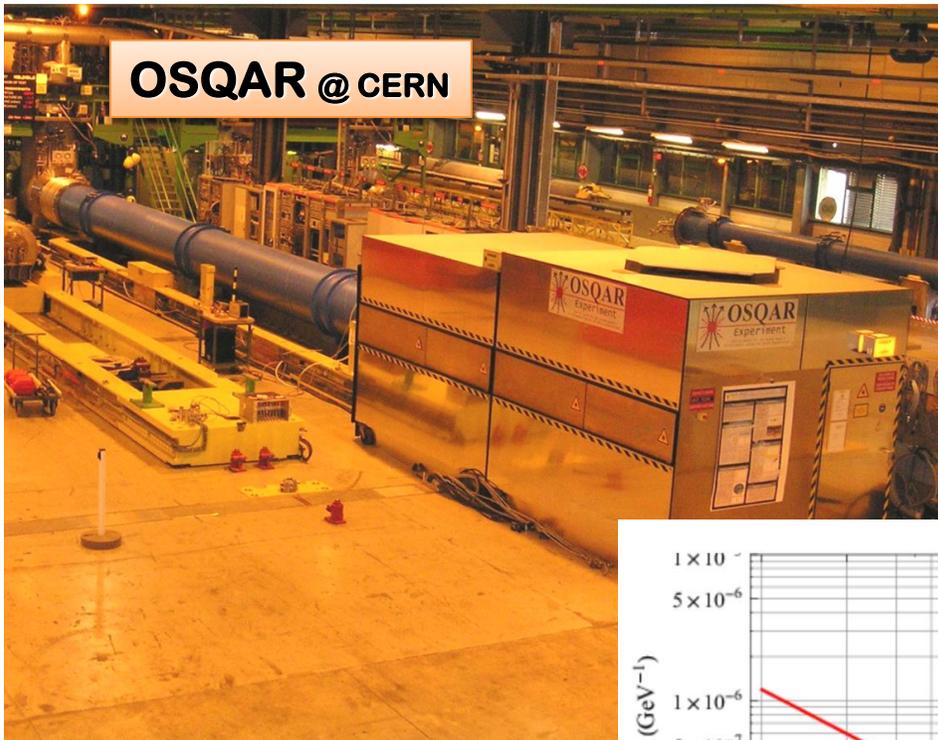


- ALP II under preparation
- (resonant, 10+10 magnets,...)

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

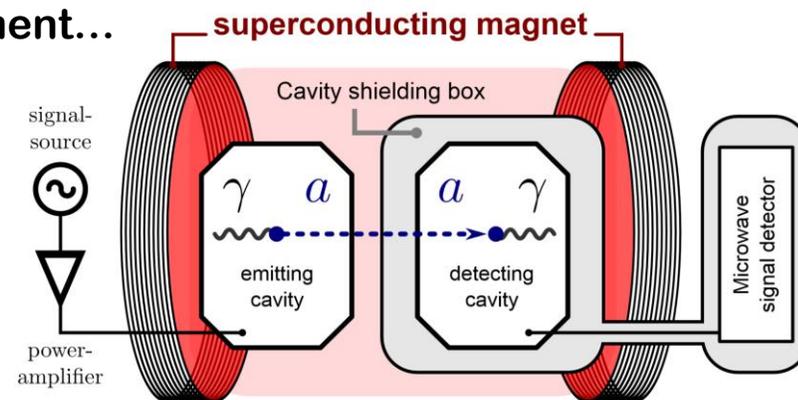
Other LSW experiments

OSQAR @ CERN



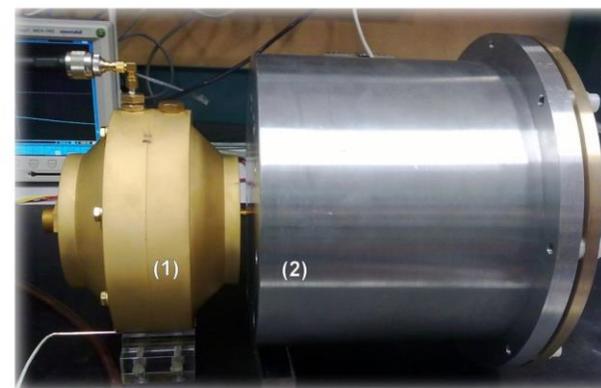
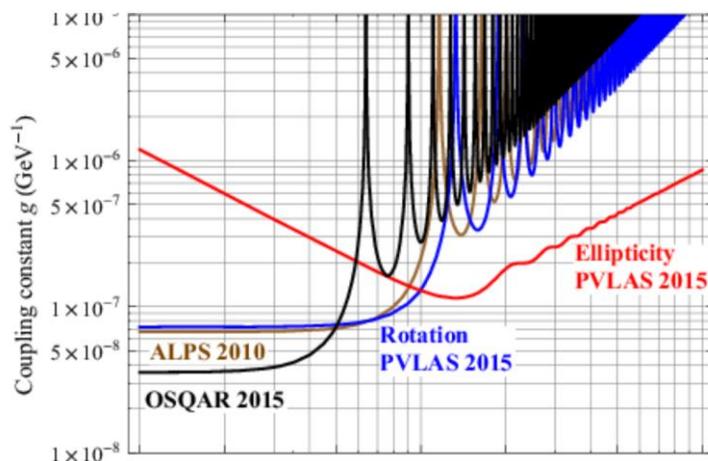
CROWS experiment @ CERN

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



Also:

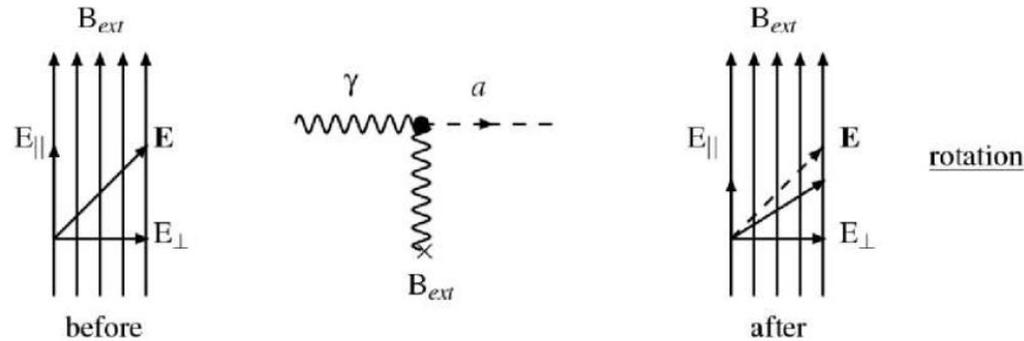
- GammeV & REAPR @ Fermilab, US
- BMV @ Toulouse
- ...



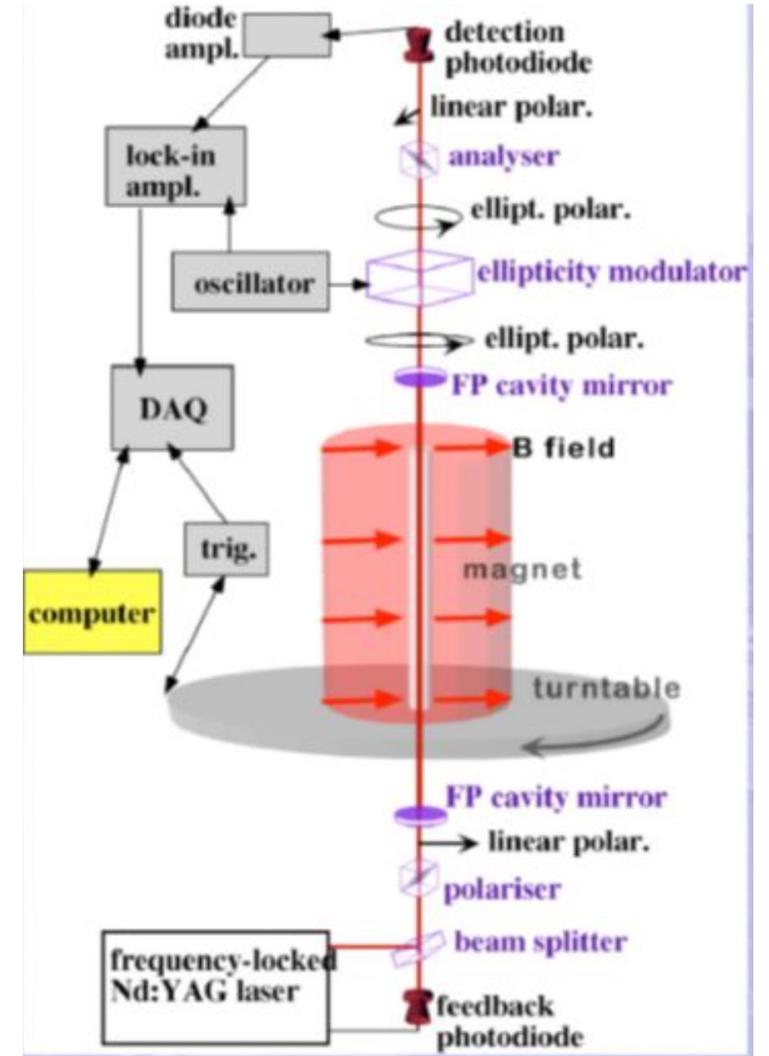
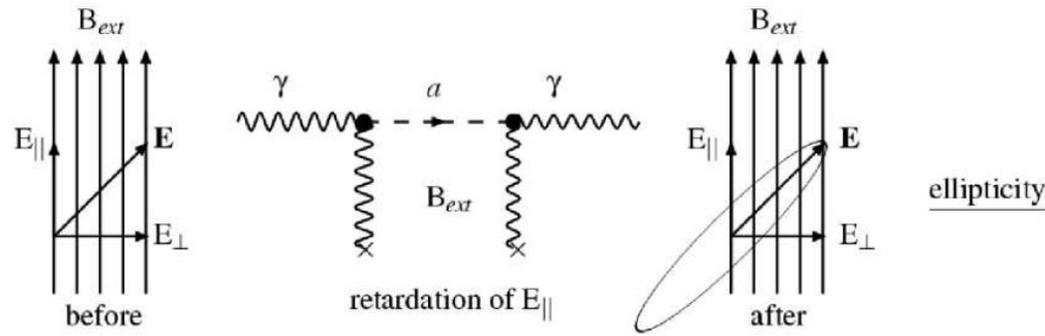
Polarization experiments

PVLAS experiment: study QED vacuum birefringence (standard effect), but also sensitivity to ALPs:

Dichroism:
Production of real particles



Ellipticity:
Production of massive virtual particles

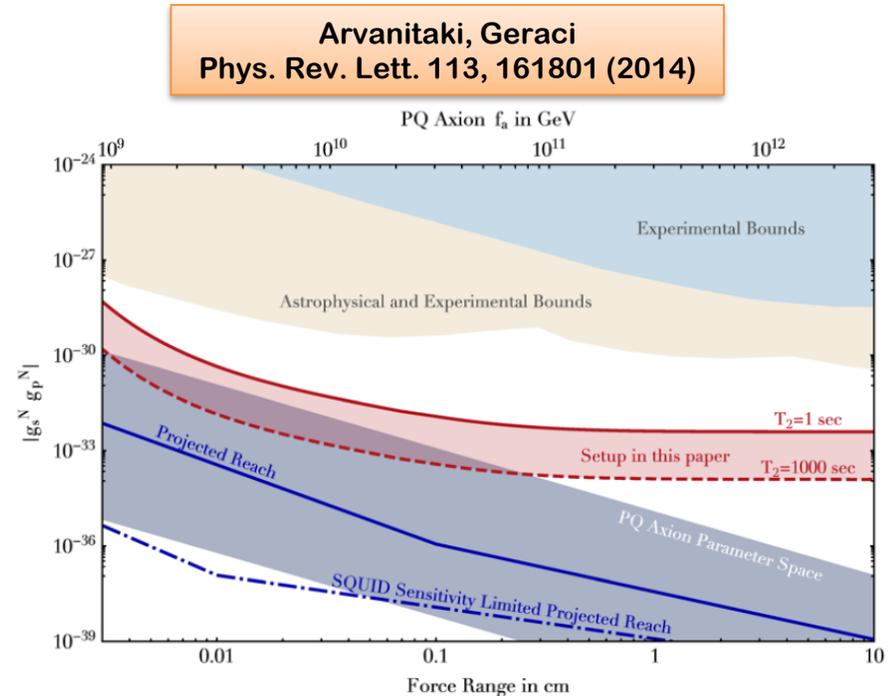
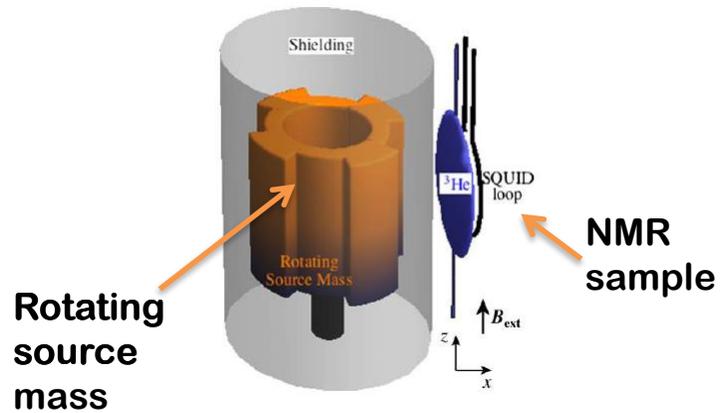


Axion-mediated macroscopic forces

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

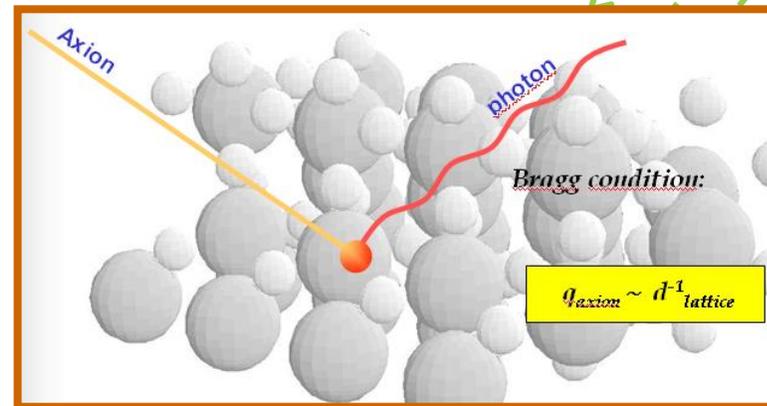
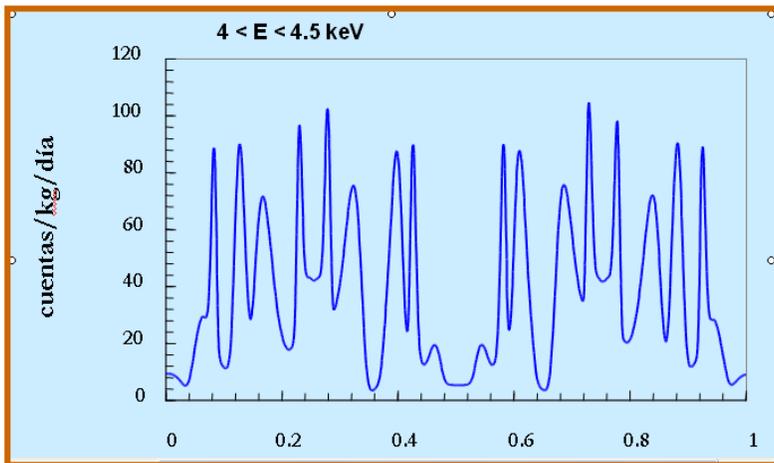
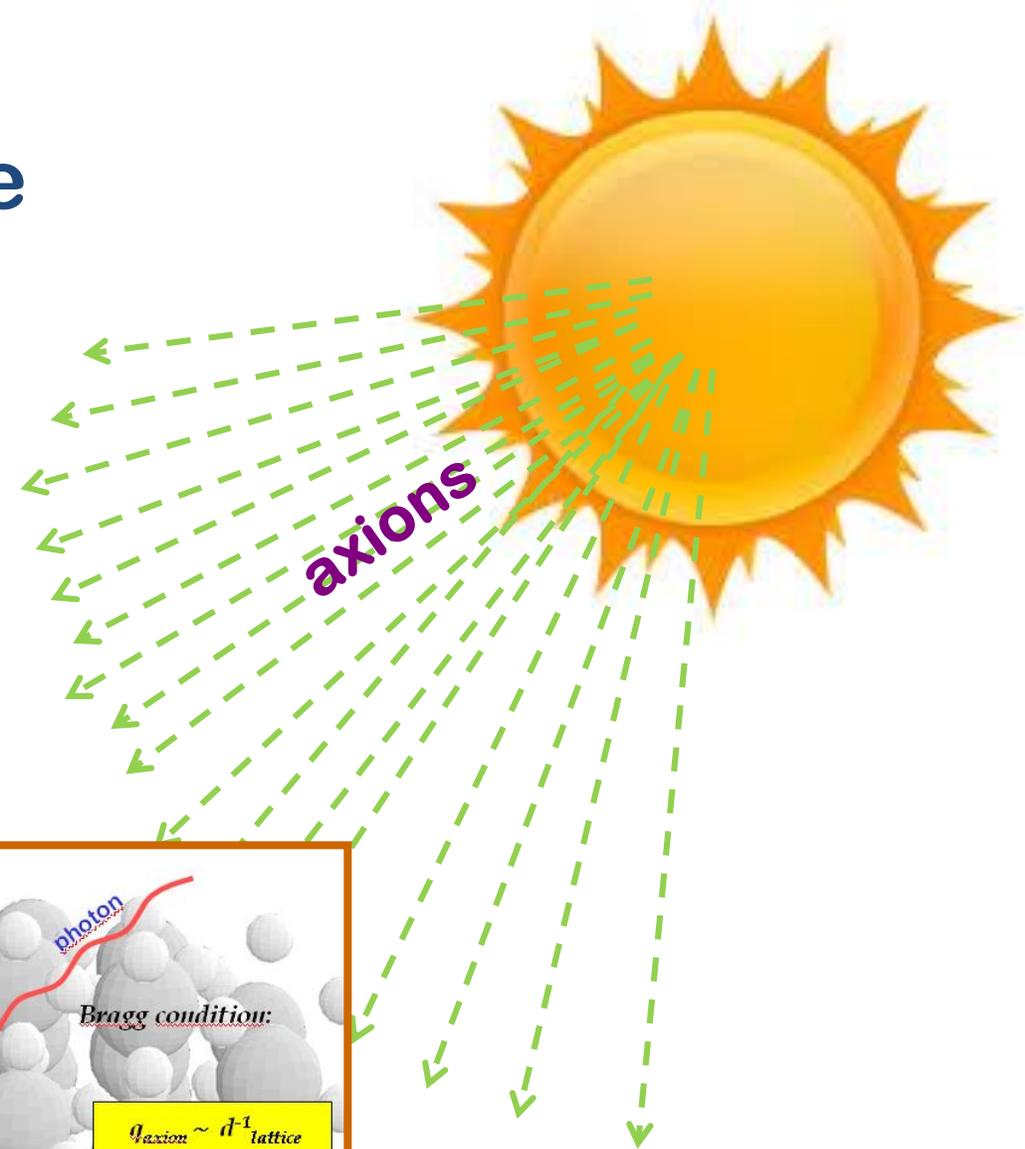
Recently proposed: ARIADNE experiment
Short-range force by NMR technique

Good prospects for sub-meV axion



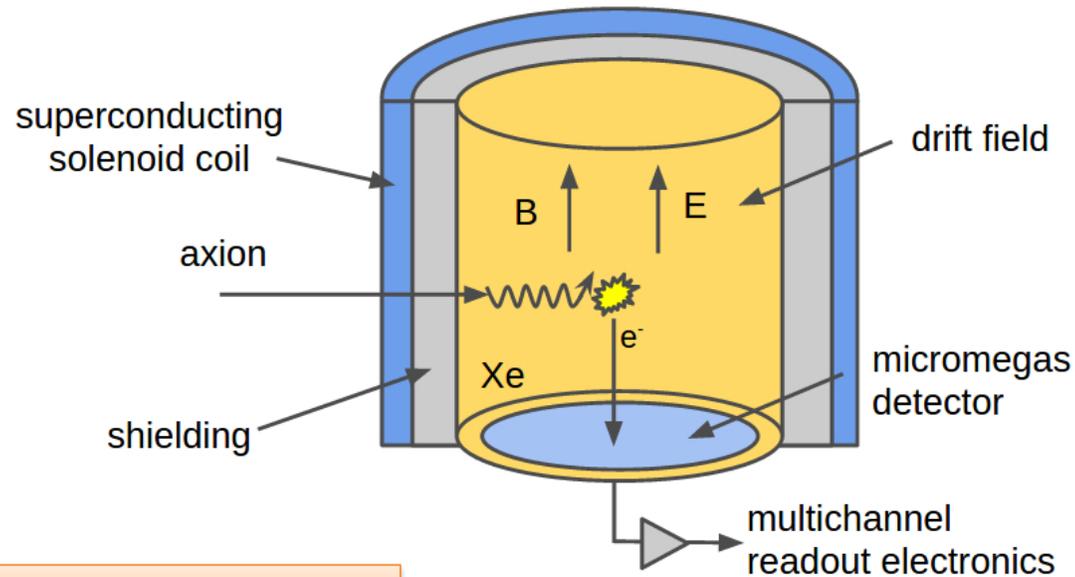
Other types of helioscope

- 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:

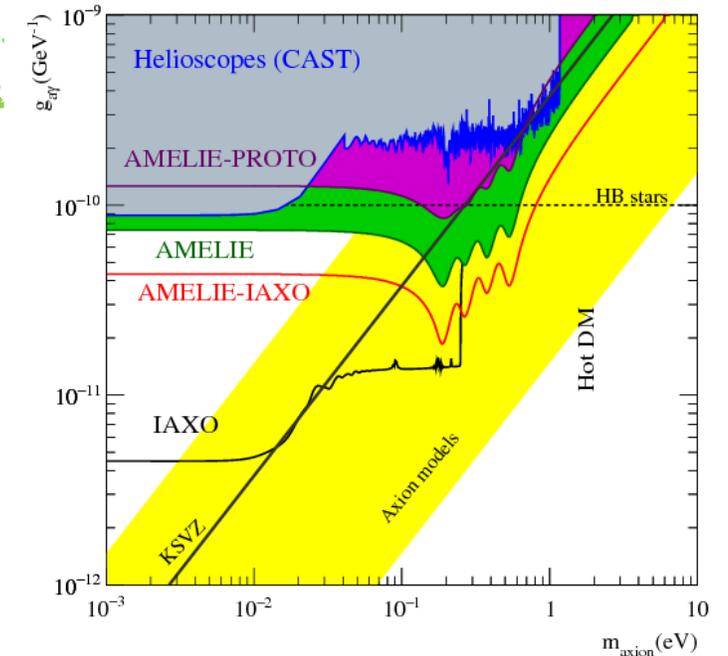


Other types of helioscope

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

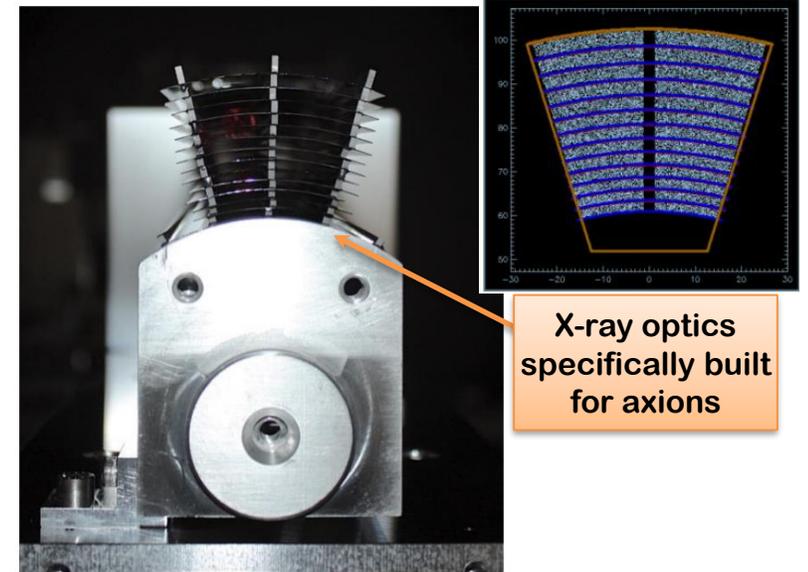
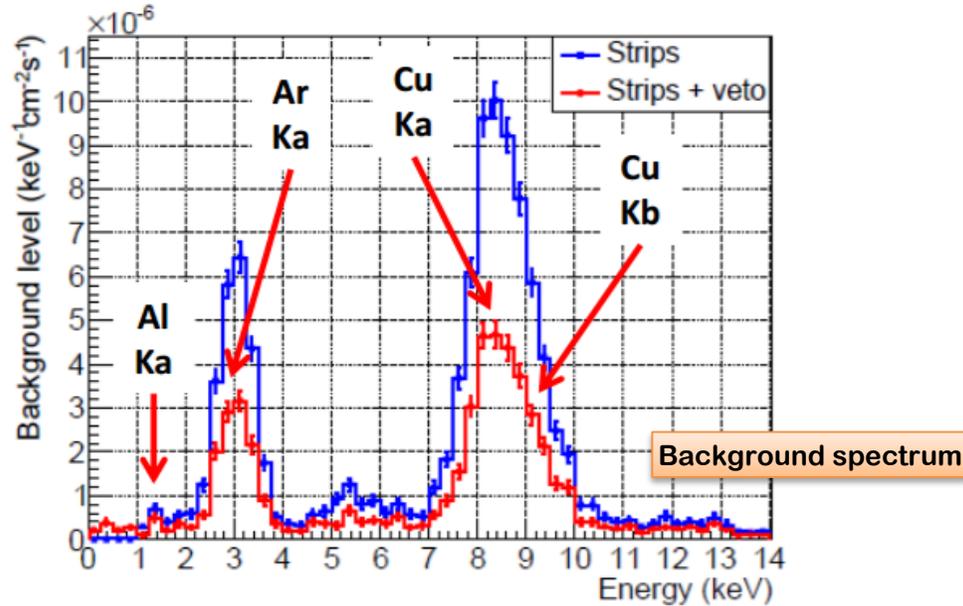


Galán et al, arXiv:1508.03006

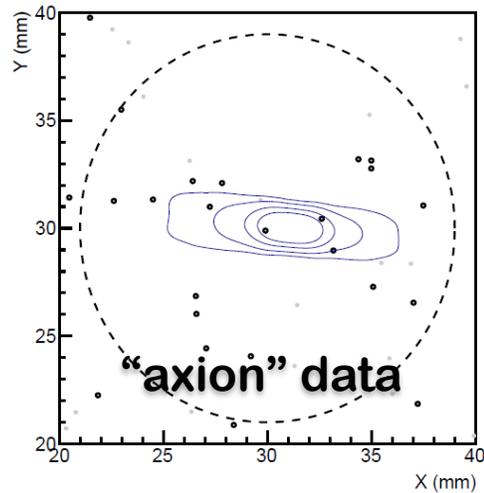
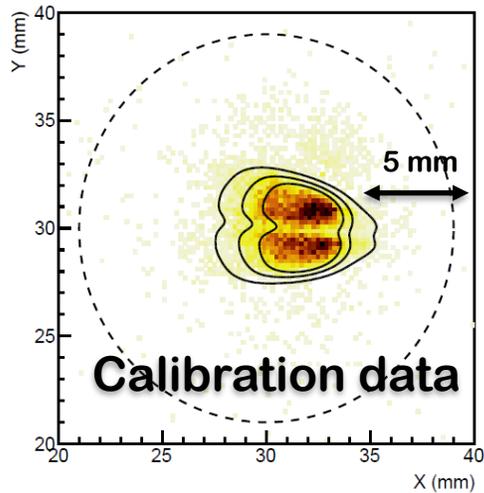


IAXO pathfinder system in CAST

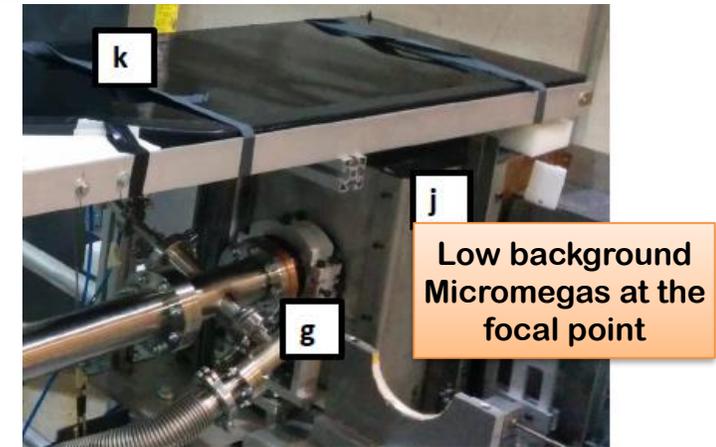
Test MM detector +
slumped-glass x-
ray optics together



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

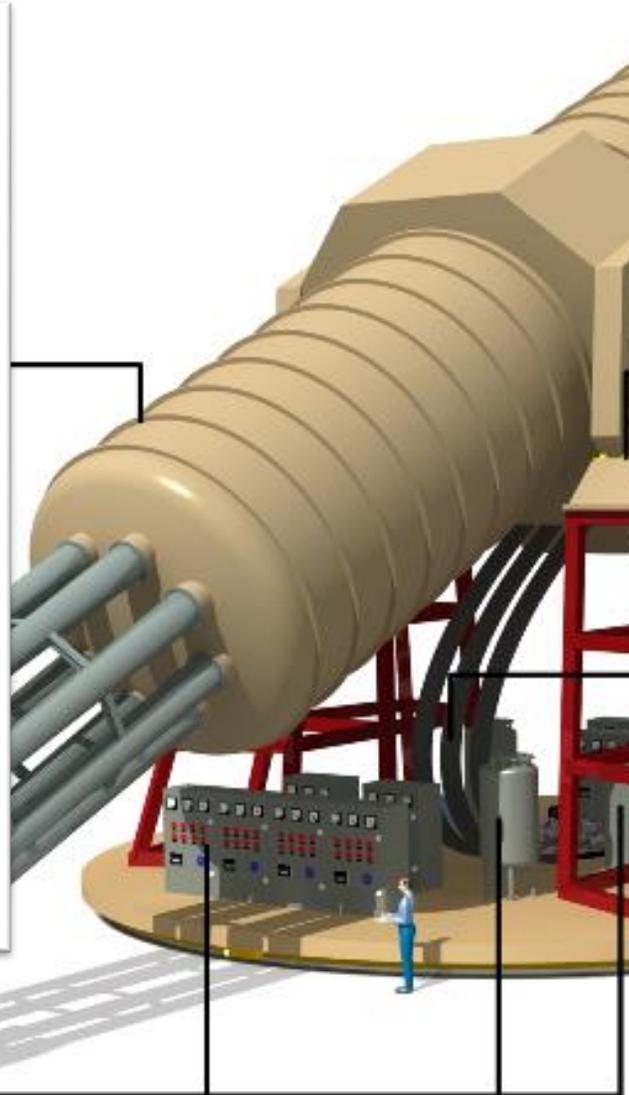


- Best SNR of any previous detector
- 290 tracking hour acquired (6.5 months operation)
- 3 counts observed in RoI (1 expected)



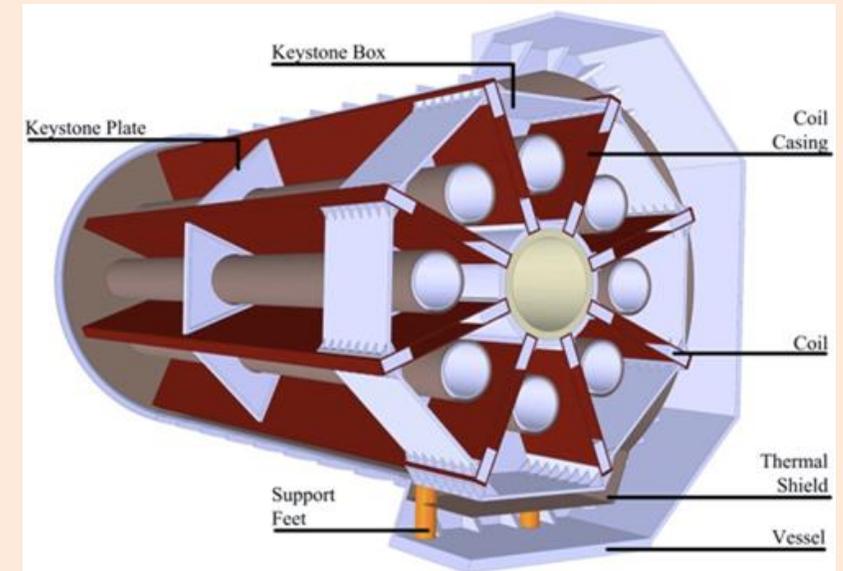
IAXO technologies – magnet

Property		Value
Cryostat dimensions:	Overall length (m)	25
	Outer diameter (m)	5.2
	Cryostat volume (m ³)	~ 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)	~ 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 × 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)	~150
	at 60-80 K (kW)	~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



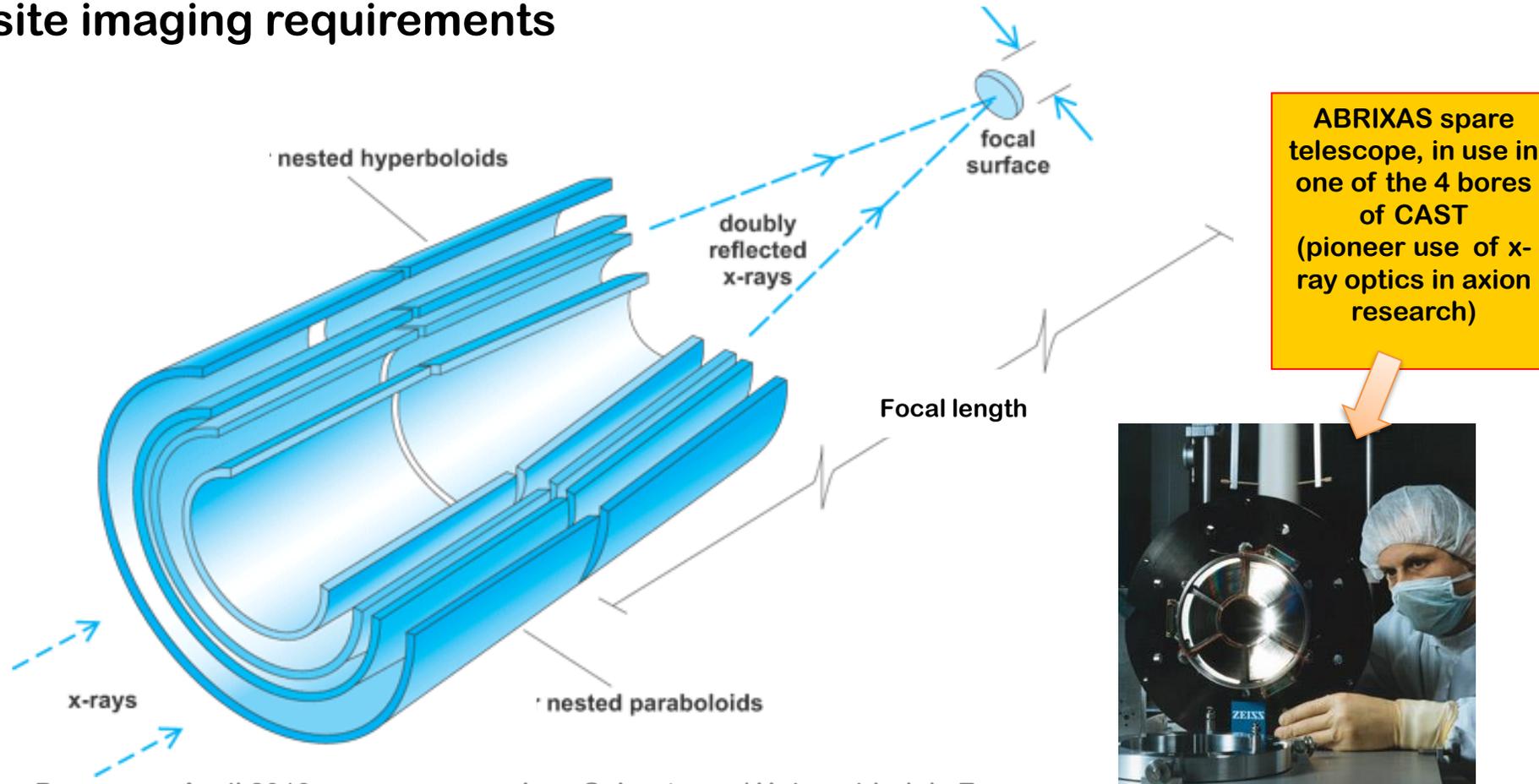
Baseline developed at:
 IAXO Letter of Intent: CERN-SPSC-2013-022
 IAXO Conceptual Design: JINST 9 (2014)
 T05002 (arXiv:1401.3233)

Services

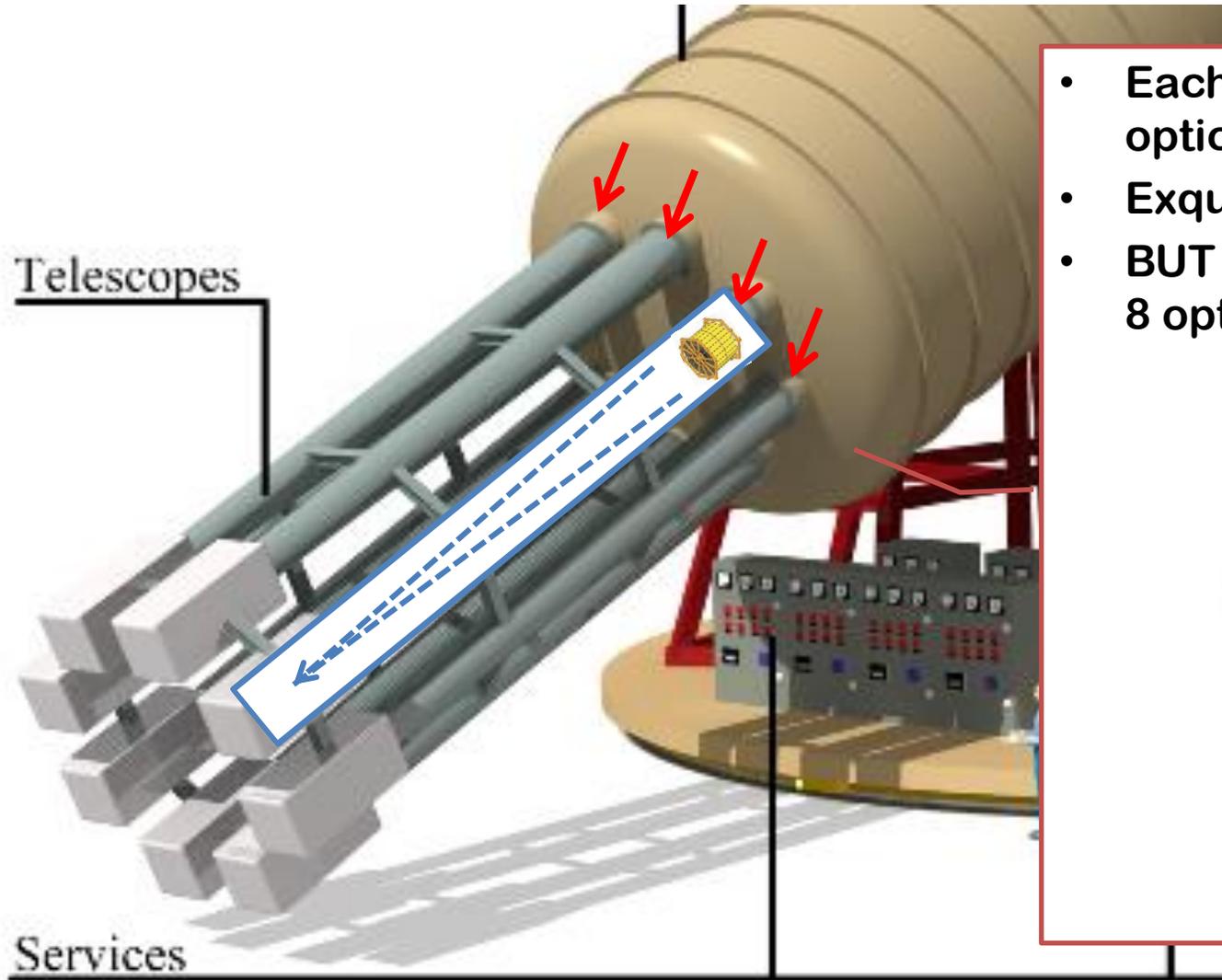
Rotation System

IAXO x-ray optics

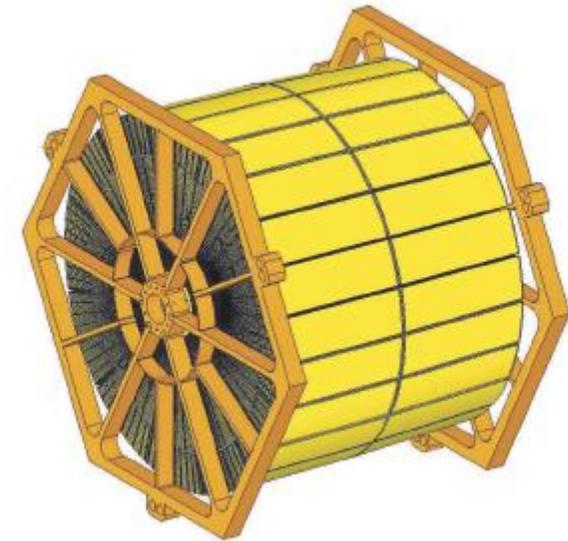
- X-rays are focused by means of grazing angle reflection (usually 2)
- Many techniques developed in the x-ray astronomy field. But usually costly due to exquisite imaging requirements



IAXO x-ray optics

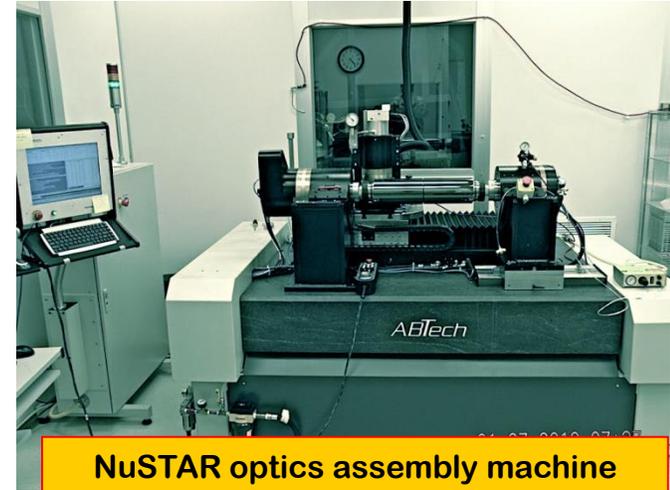


- Each bore equipped with an x-ray optics
- Exquisite imaging not required
- BUT need cost-effective way to build 8 optics of 600 mm diameter each.

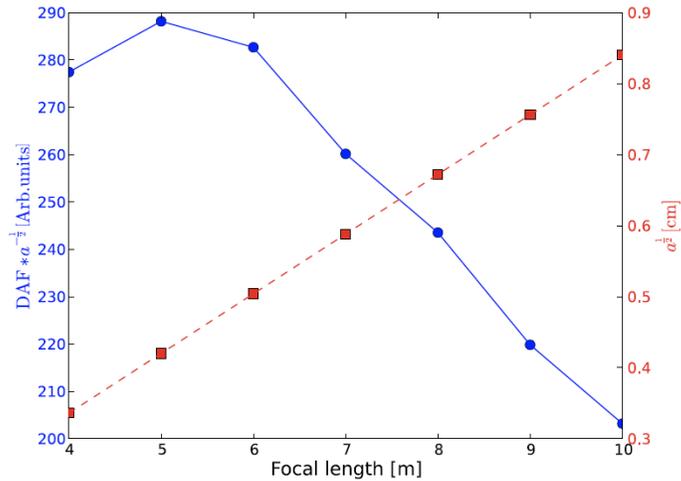


IAXO x-ray optics

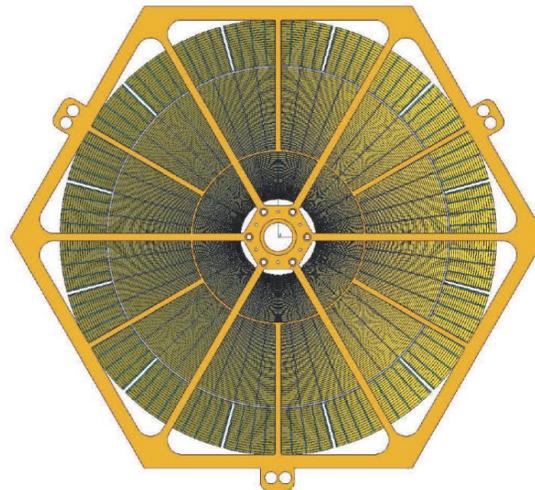
- Technique of choice for IAXO: optics made of slumped glass substrates coated to enhance reflectivity in the energy regions for axions.
- Same technique successfully used in NuSTAR mission, recently launched
- The specialized tooling to shape the substrates and assemble the optics is available
- Hardware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



IAXO x-ray optics



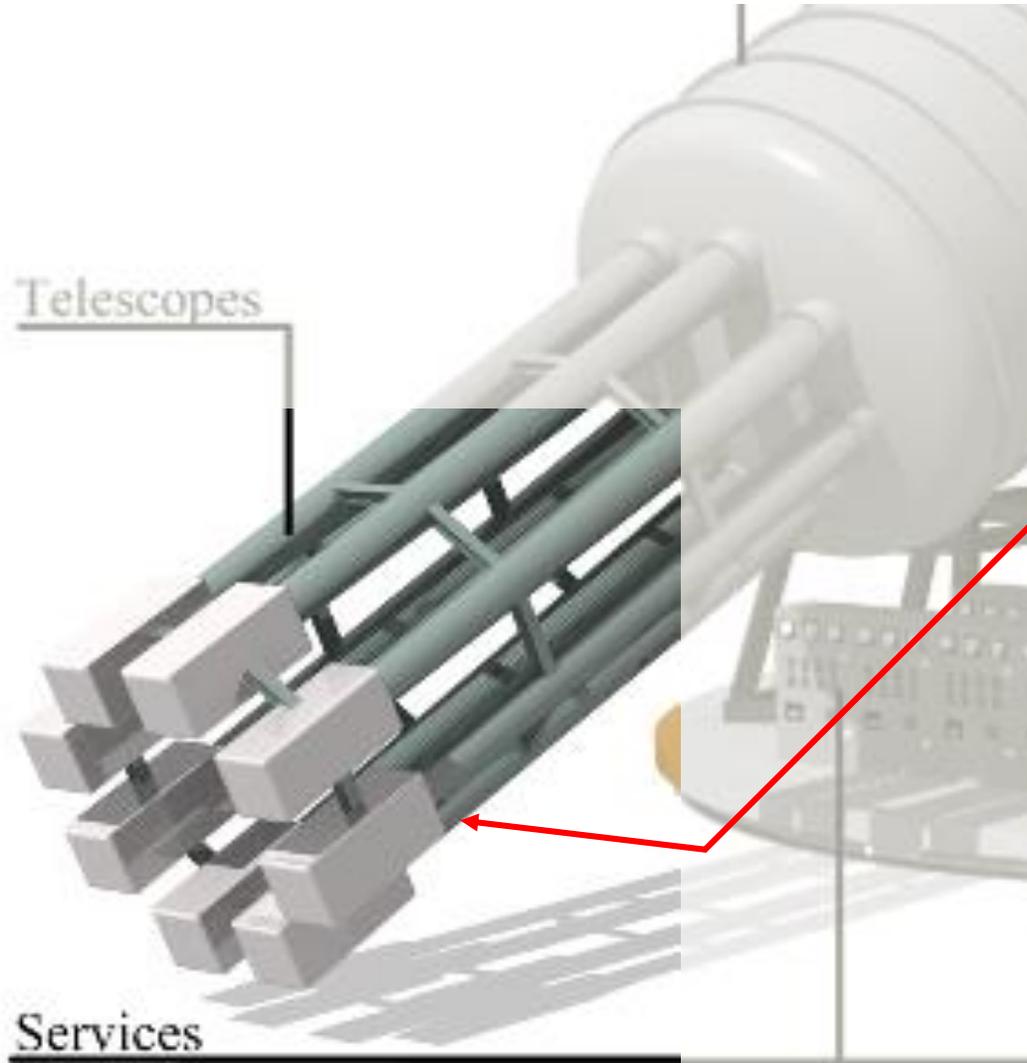
Optimal focal length ~5 m



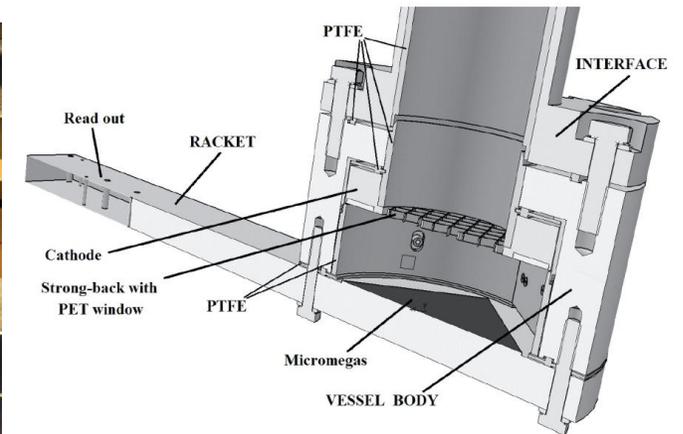
IAXO optics conceptual design
AC Jakobsen et al, Proc. SPIE
8861 (2013)

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 ₄ C 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 low background detectors

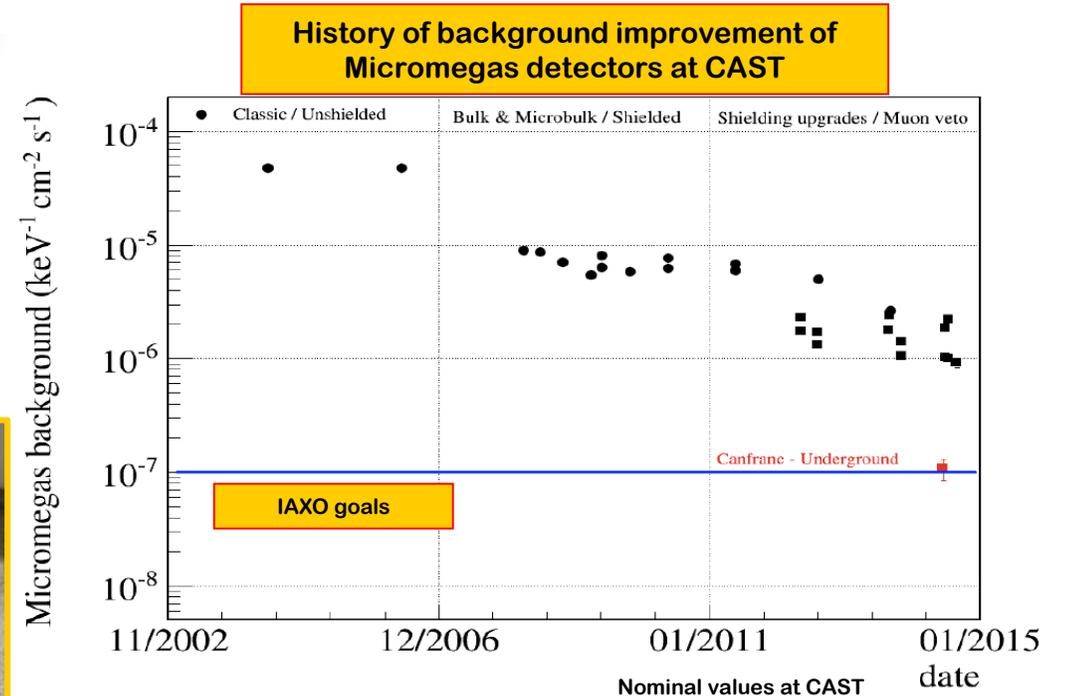


- 8 detector systems
- Baseline: small Micromegas-TPC chambers:
 - Shielding
 - Radiopure components
 - Offline discrimination



IAXO low background MM detectors

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

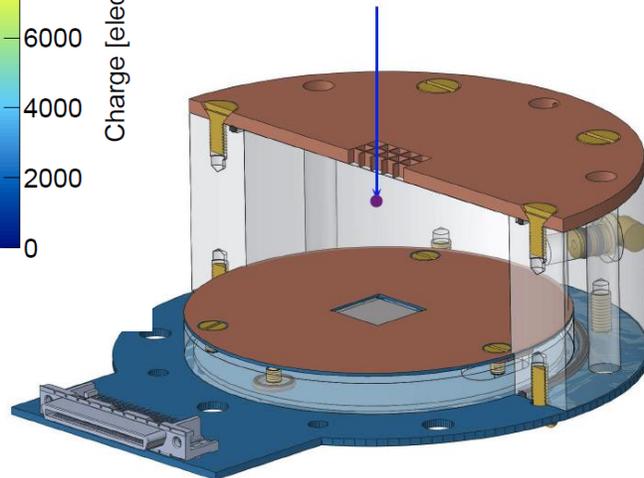
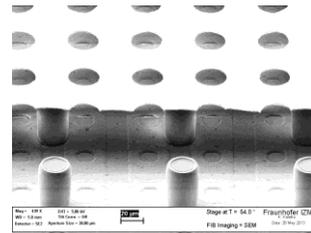
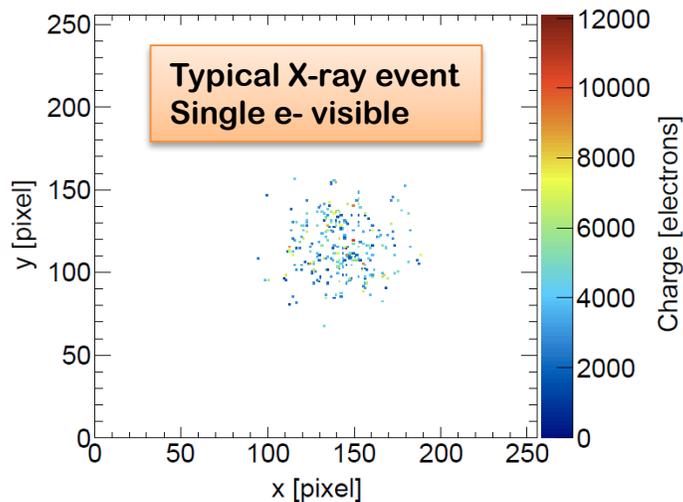


- Active program of development.
- IAXO-D0 test-platform to explore background sources and improve levels

Additional detector technologies for IAXO

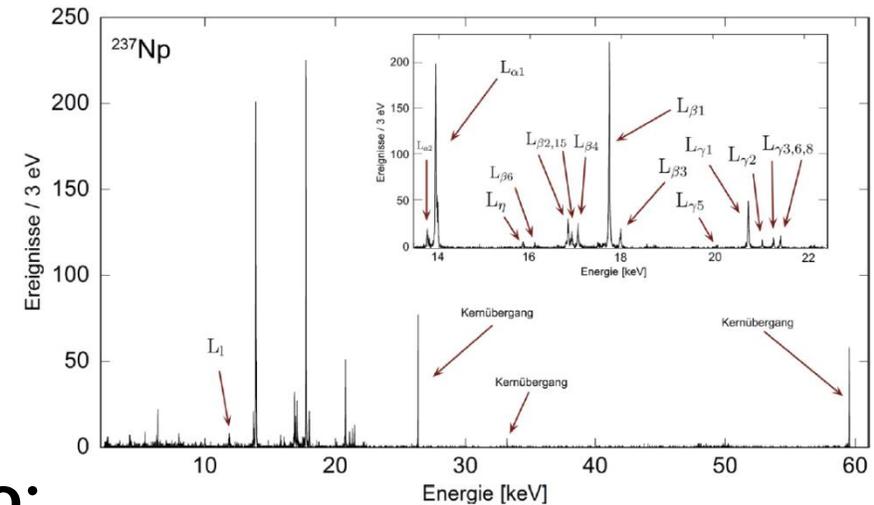
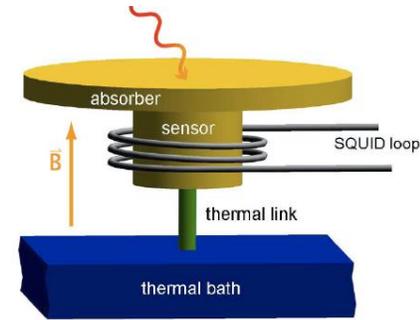
Ingrid detectors (U. Bonn):

- 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