Axion Searches

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Universidad de Zaragoza
IMFP 2018, Salamanca

Outline

- Short introduction
- Types of searches and the main representatives
- Main results
- Conclusions

- A comprehensive, recent review:
  - “New experimental approaches in the search for axion-like particles” , I. G. Irastorza, J. Redondo, arXiv: 1801.08127

Strong-CP problem

- CP considered a global symmetry until experiment showed otherwise (K^0 decay)
- Violation seen only in weak interactions: predicted third generation quarks (Kobayashi-Maskawa)
- What about the strong interactions?

No reason why not:

$$\mathcal{L}_{\mathrm{CP}_{\mathrm{QCD}}} = -\underbrace{\left(\Theta - \arg\det M_q\right)}_{-\pi \leq \bar{\Theta} \leq +\pi} \frac{\alpha_s}{8\pi} G\tilde{G}$$

However, the experimental bounds give $|\bar{\theta}| < 10^{-10}$

No reason why it should be vanishing!! → Strong-CP problem

Elegant solution from Peccei-Quinn: $\boldsymbol{\theta} \rightarrow \boldsymbol{\theta}(\mathbf{x}, \mathbf{t})$

if θ dynamical, it can relax to 0

Axions

- Achieved introducing a U(1) symmetry, which is spontaneously broken
- Associated (psedo)Nambu-Goldostone boson: axion

The axions are the quanta of the $\boldsymbol{\theta(x,t)}$ field

$$\boldsymbol{\theta(x,t)} \rightarrow \frac{\boldsymbol{\alpha(x,t)}}{\boldsymbol{f_\alpha}}$$

Axion field

PQ scale

Phenomenological Properties

Gluon coupling

$$\mathcal{L}_{aG} = \frac{\alpha_s}{8\pi} \frac{a}{f_a} G\tilde{G}$$

generic

mass

$$m_a \approx \frac{6\ \mu\text{eV}}{f_a/10^{12}\ \text{GeV}}$$

generic

photon coupling

$$\mathcal{L}_{a\gamma} = g_{a\gamma}\ \mathbf{E}\cdot\mathbf{B}\ a$$

model dependent

and more…

Electron coupling
Nucleon coupling
Mesons coupling
…

Axions +

- Axion phenomenology driven by f_α, shared by many other Weakly Interacting Slim (Sub-eV) Particles (WISPs)

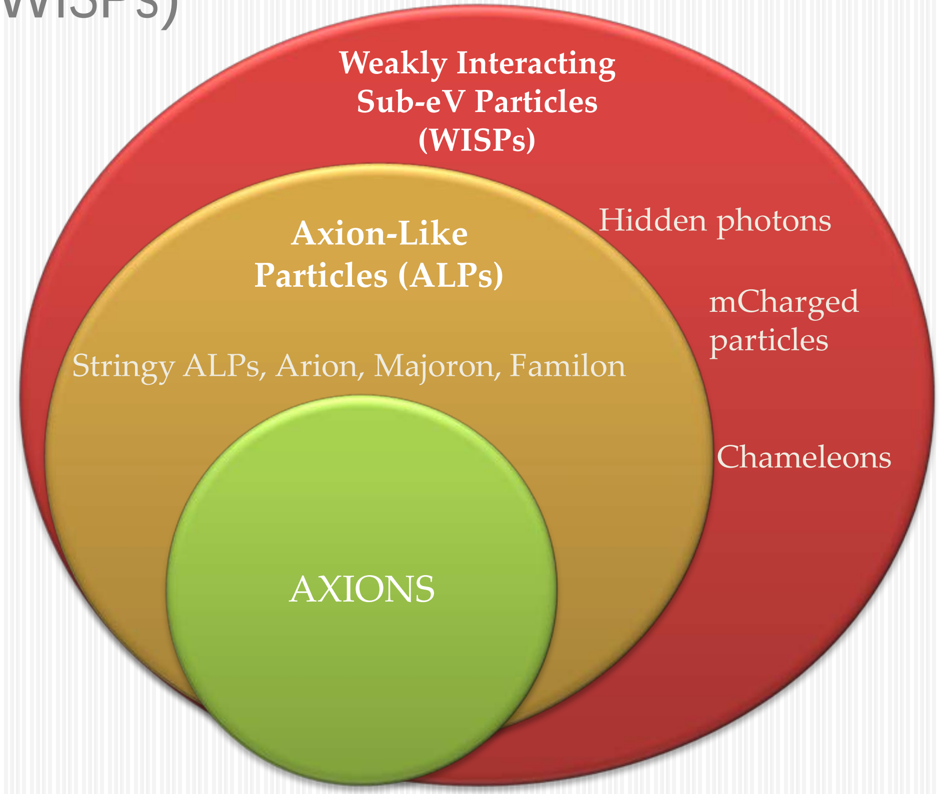
- QCD axions :

  $g_{\alpha i} \propto m_\alpha$

- Axion-like particles:

  $g_{ALP-\gamma}, m_{ALP}$ not correlated

- Generic coupling to two photons

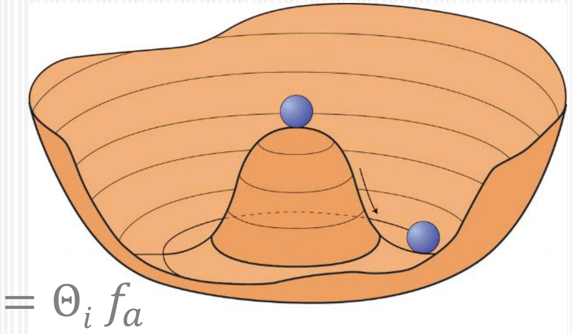


(string axions, hidden photons, chameleons, majorons...)

Axions and Cosmology

- A very strong DM candidate

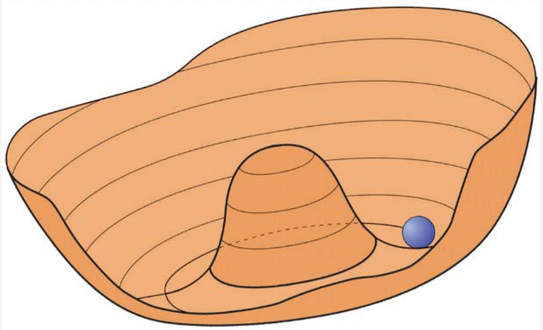
$U_{PQ}(1)$ spont. broken



$a_i = \Theta_i f_a$

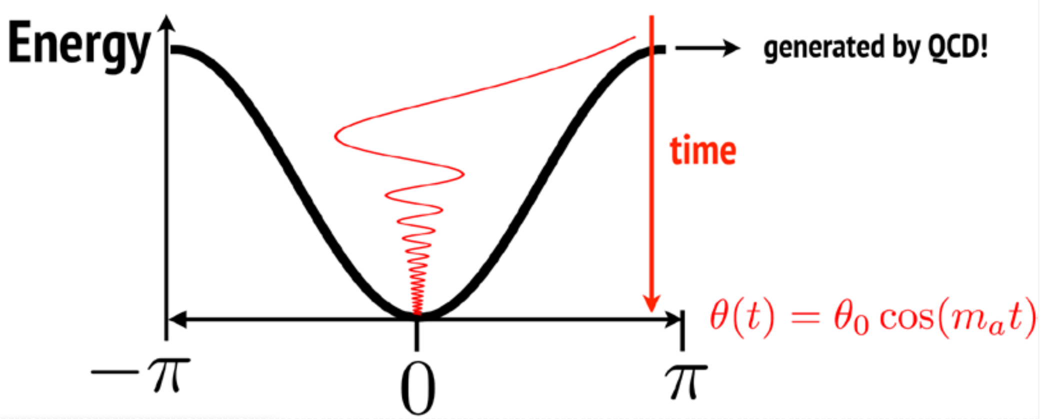
G. Raffelt

Axion mass turns on



G. Raffelt

Oscillations (axions at rest)



J. Redondo

- o Non-relativistic, small m_a but CDM

Initial conditions very important

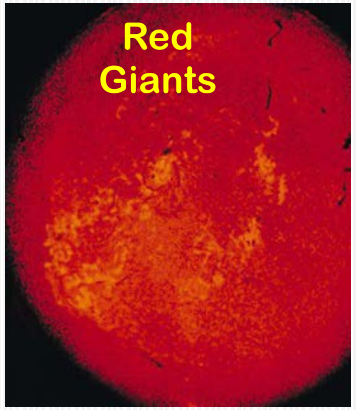
- o Pre-inflation scenarios
- o Post-Inflation scenarios

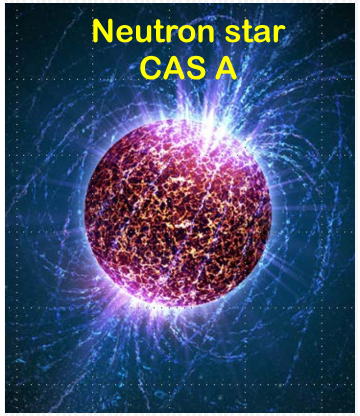
Each favours a different range of masses

Axions and Astrophysics

- Stars may be factories of axions
- Axion emission processes in Stars would be new cooling channels
- Energy-loss and lifetime arguments put constraints
- Several systems seem to cool down faster than expected
    - o Axion interpretation fits
    - o IAXO could check this

Giannotti et al.
JCAP05(2016)057
[arXiv:1512.08108]



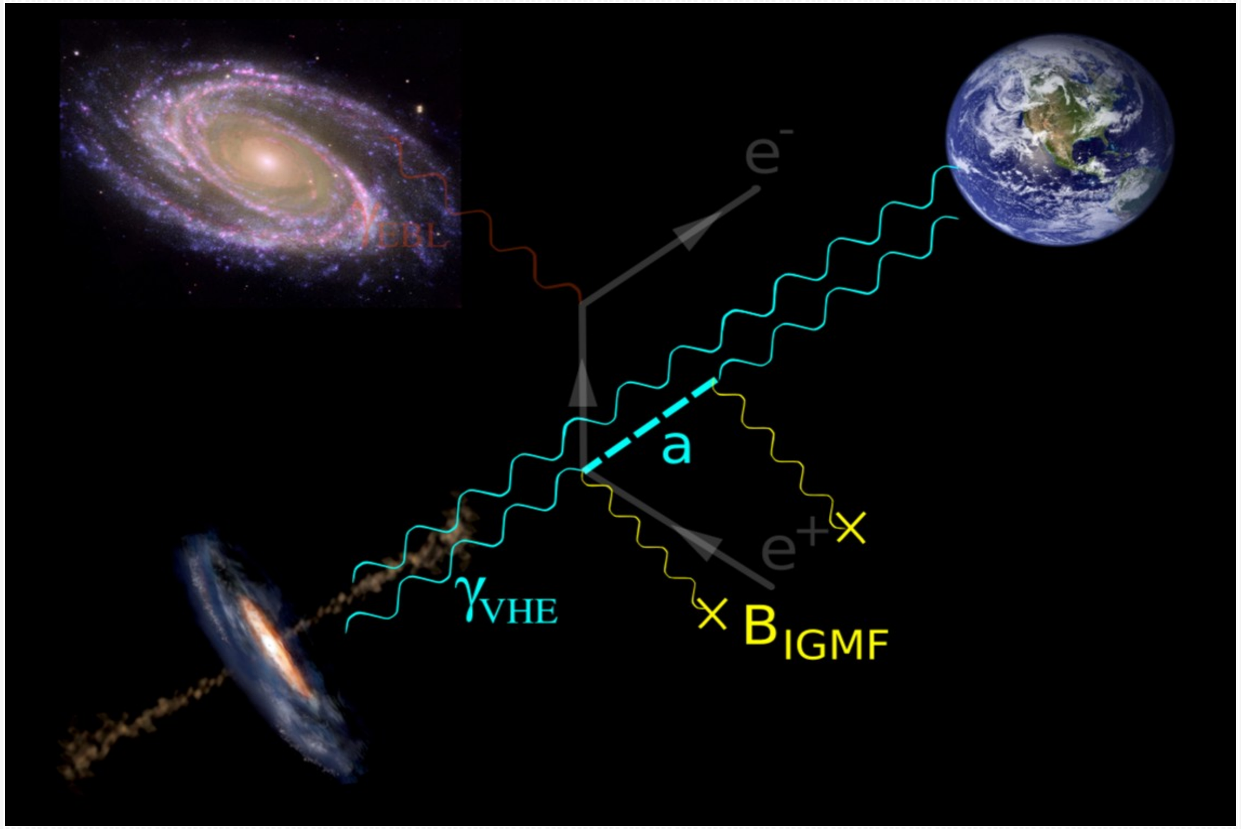


Axions and Astrophysics (II)

Ultra High energy photons detected at the big Gamma-ray telescopes (MAGIC, HESS)

How can they have travelled these big distances?

An ALP in action…?



Credit: Manuel Mayer

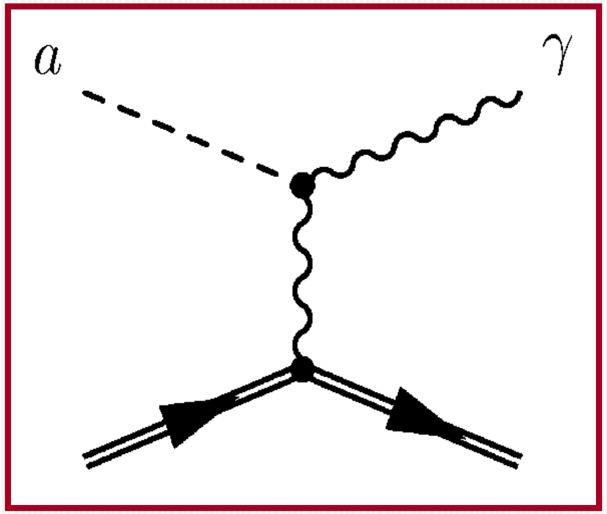
Axion detection

- Most of the searches are based on the axion-photon coupling
  - Present in practically every model

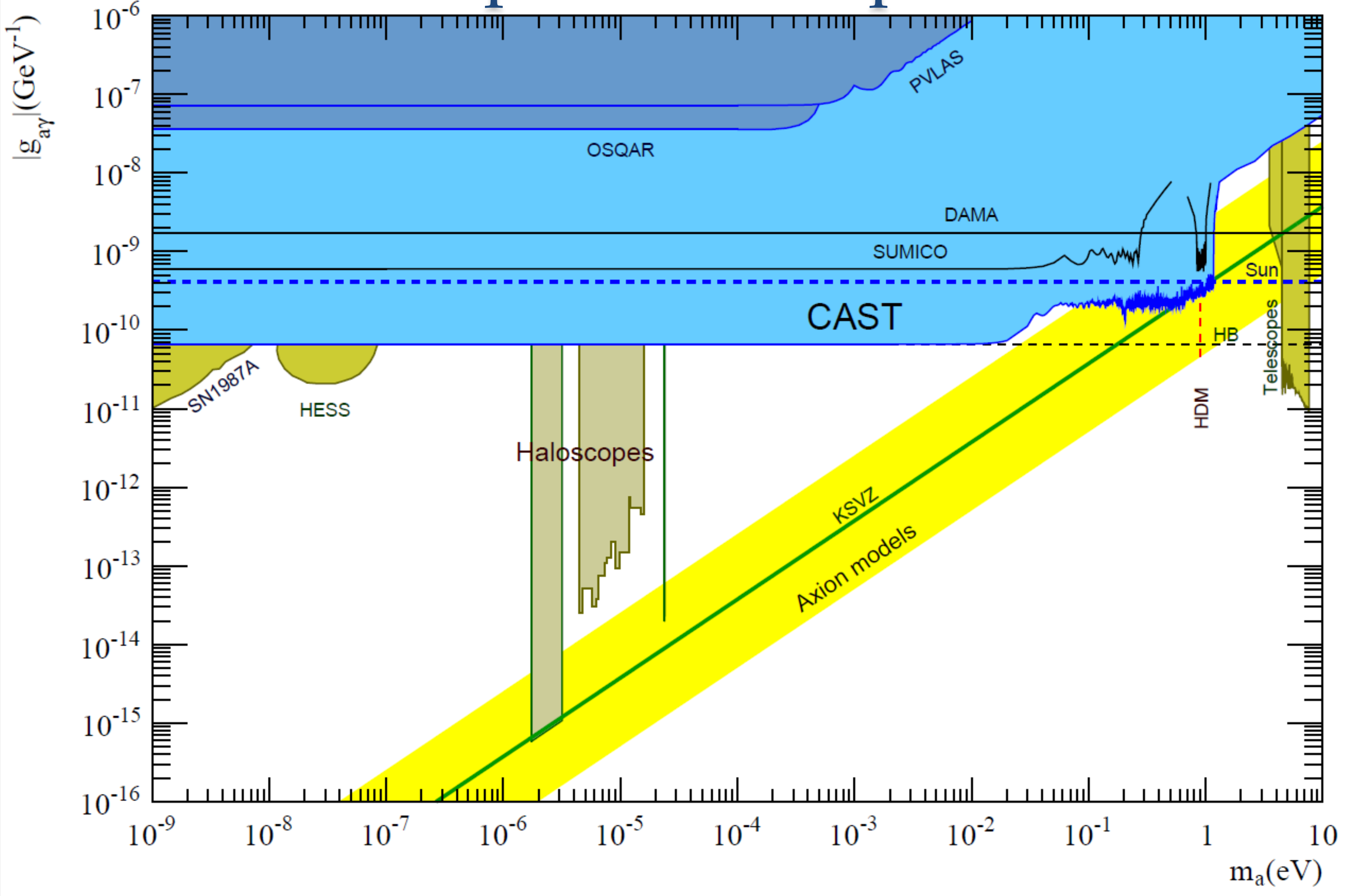
$$\mathcal{L}_{a\gamma} = g_{a\gamma}\, \mathbf{E} \cdot \mathbf{B}\, a$$

- And the axion-to-photon conversion in the presence of a strong electromagnetic field.

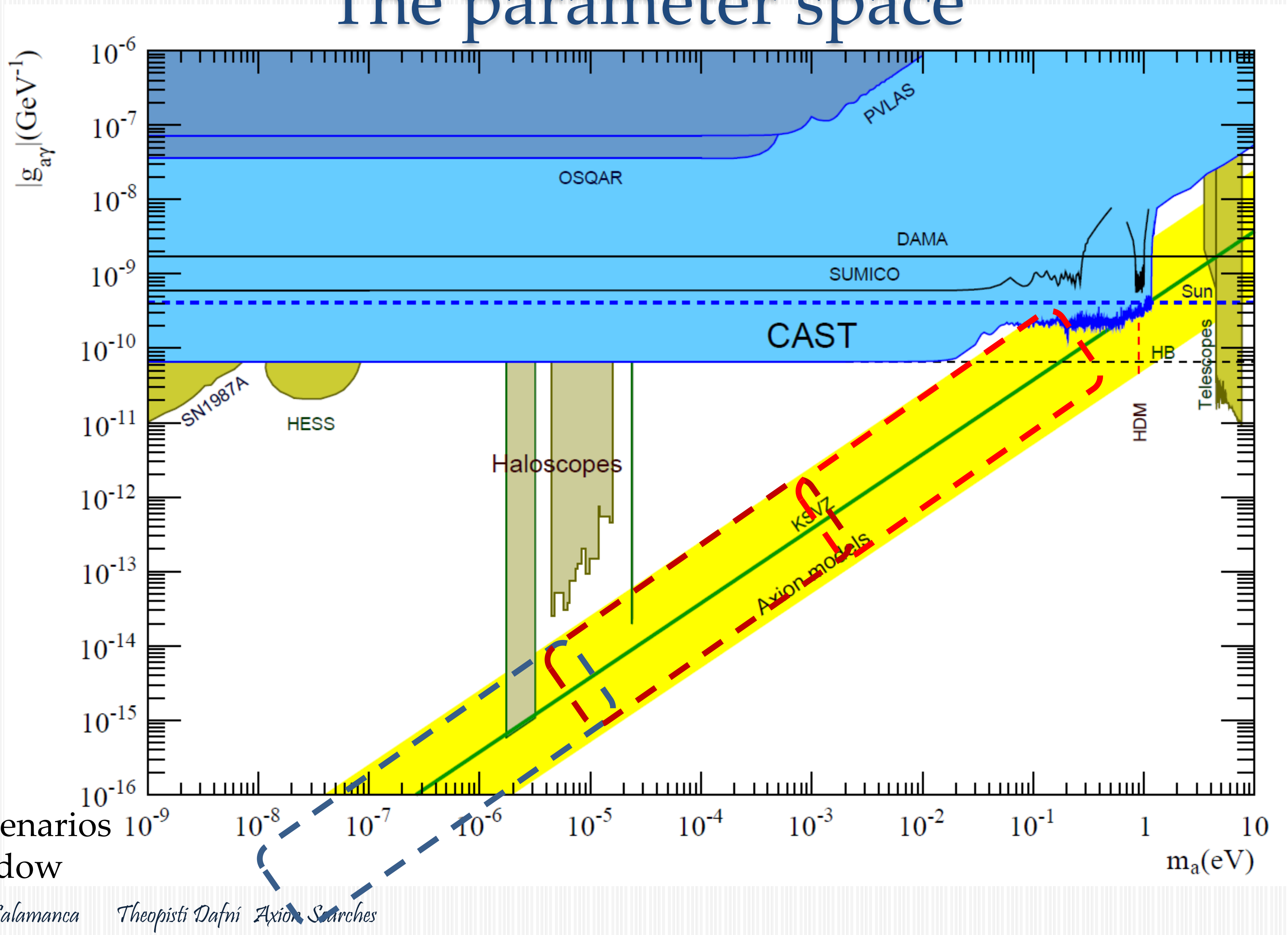
Primakoff effect



The parameter space



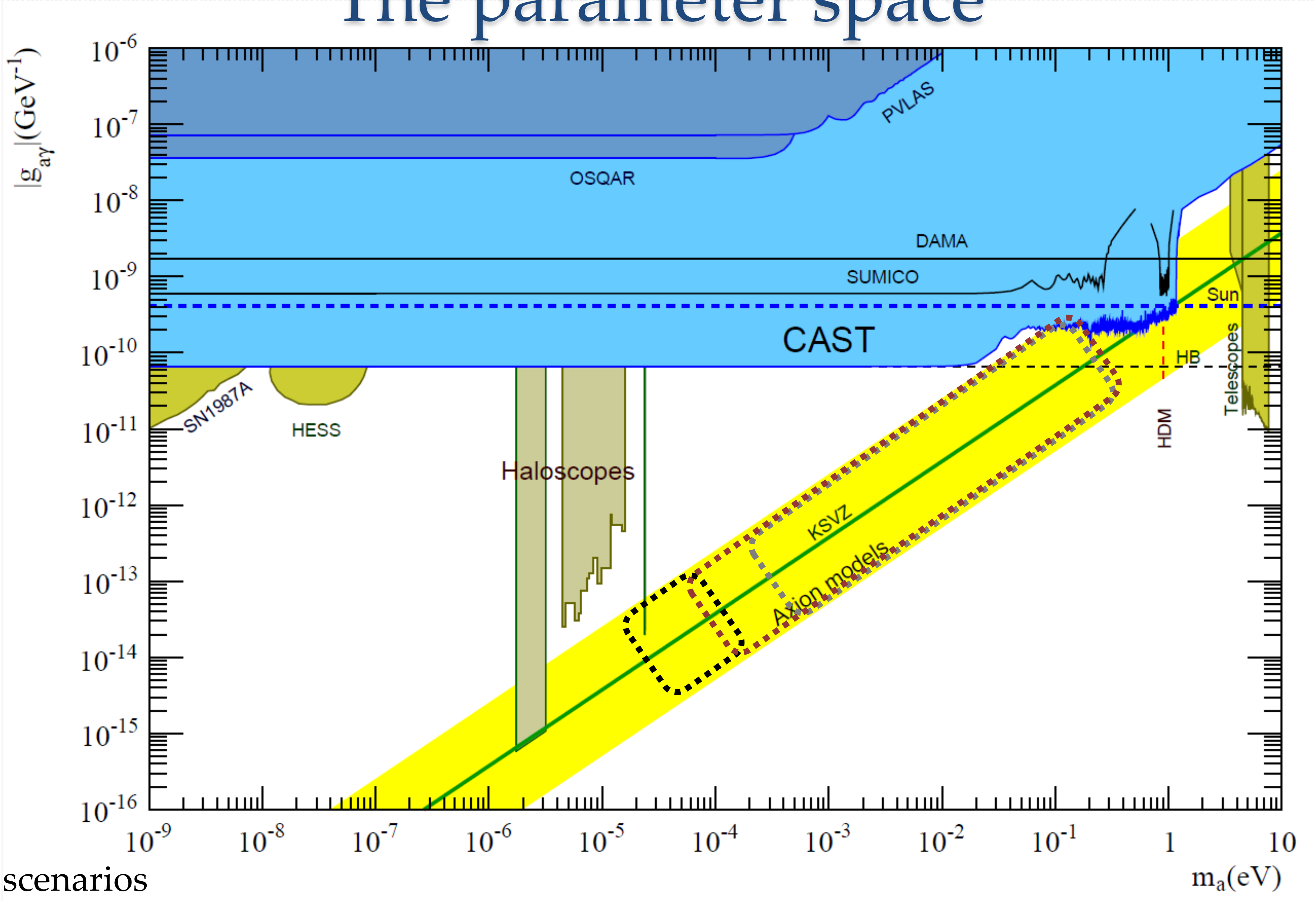
The parameter space



CDM axion

pre-inflation scenarios
Anthropic window

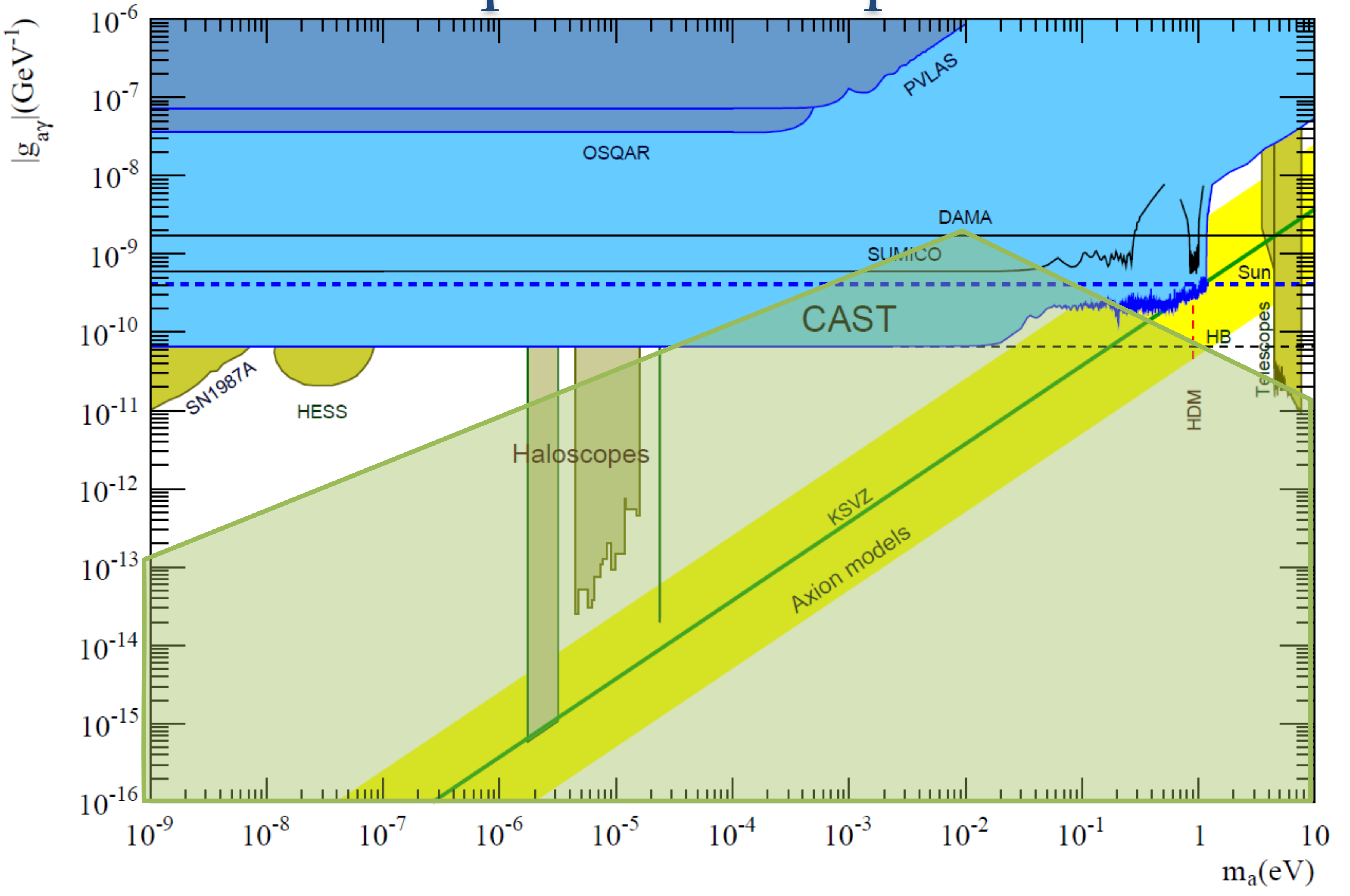
The parameter space



CDM axion

post-inflation scenarios

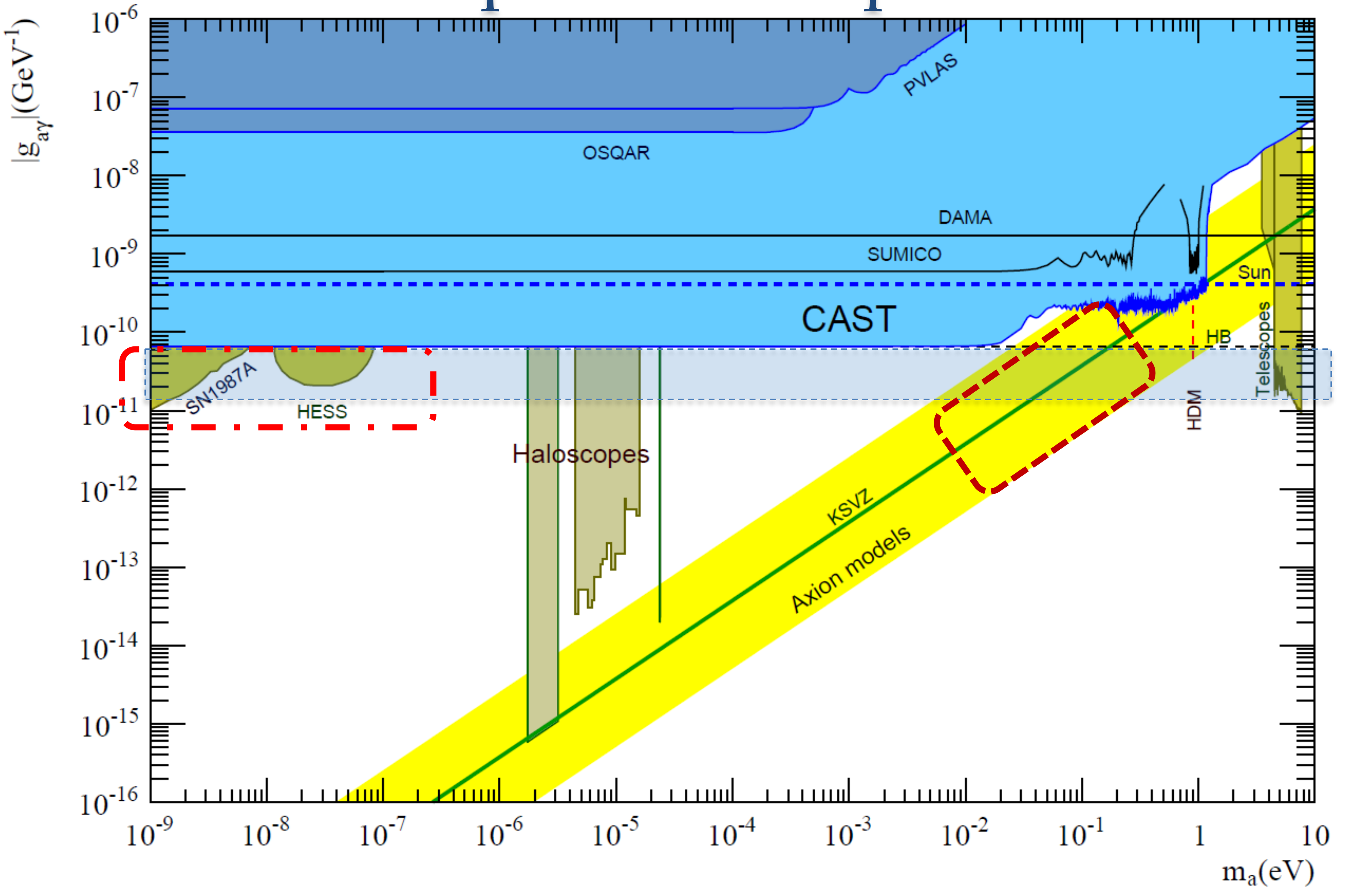
The parameter space



CDM ALPS

The parameter space

UHE photons

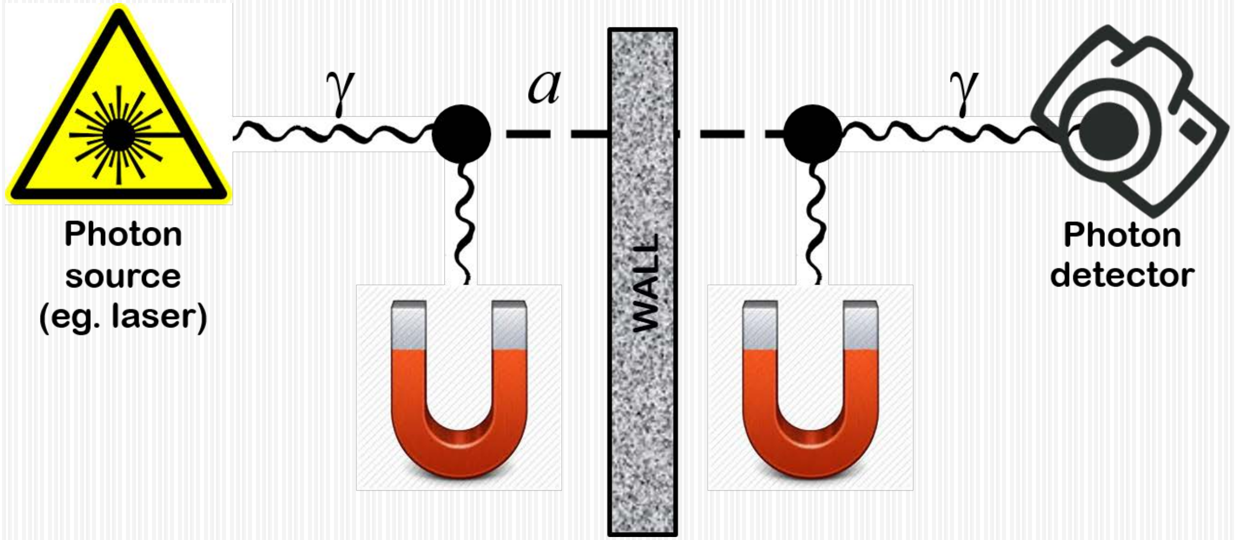


Star Cooling

Axion Searches

- Most of the searches are based on the axion-to-photon conversion
    - o Present in practically every model

Source	Experiments	Model & Cosmology dependency	Technology
Lab axions	ALPS, OSQAR, CROWS, 5th force exps,…	Very low	New ideas, Active R&D,…
Relic axions	ADMX, HAYSTAC, CASPEr, CULTASK, CAST-CAPP, MADMAX, RADES, QUAX, …	High	
Solar axions	SUMICO, CAST, IAXO	Low	Ready for large scale experiment

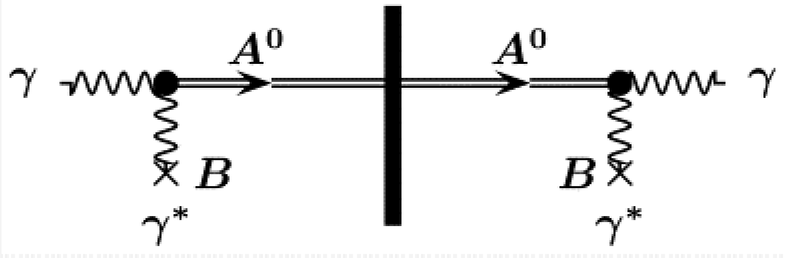


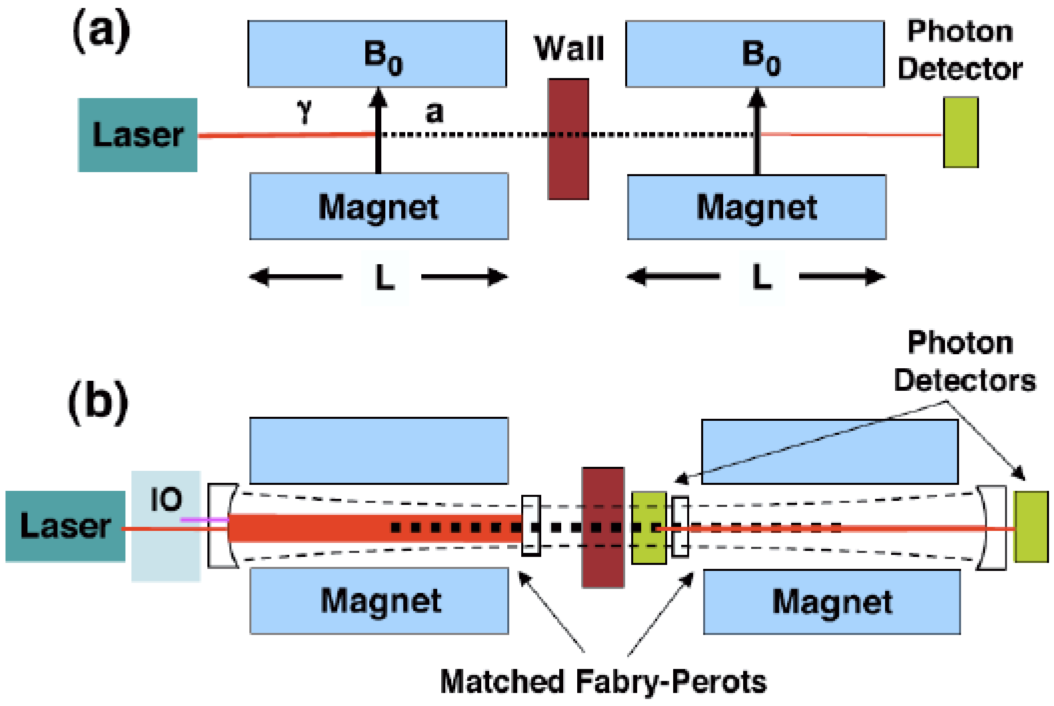
Laboratory Experiments

Creating and detecting Axion-Like Particles

Laboratory experiments

- "Light- Shining-through-a-wall" (LSW)
- Axion-like Particles factory:
  - o less uncertainty
  - o less sensitivity
- Configurations:
  - o Standard
  - o Enhanced (resonant)



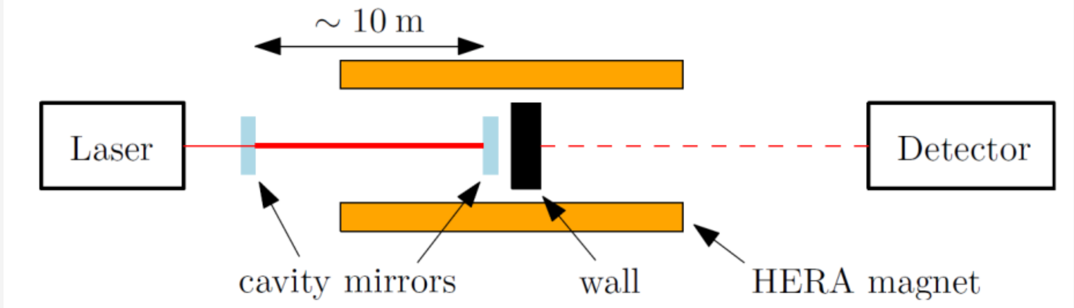


2007: http://link.aps.org/doi/10.1103/PhysRevLett.98.172002

ALPs @ DESY: Any-Light-Particle Search

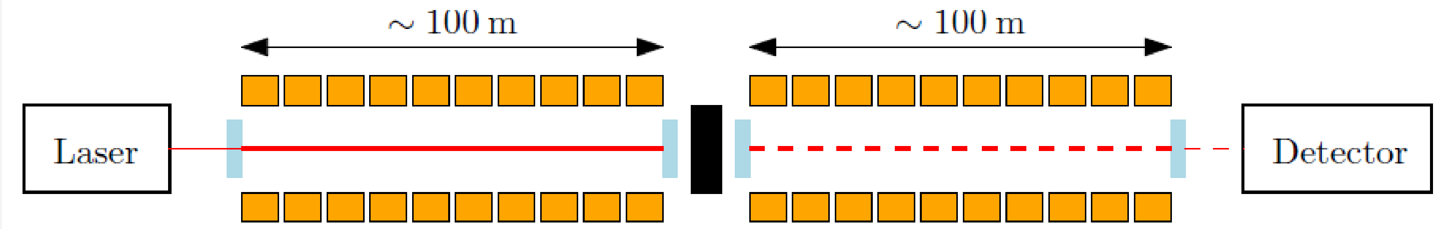
- ALPS-I: 2007-2010
  - o First successful operation of a large-sc optical resonator

ALPS-I



- ALPs-II Improvements in
  - o P_{laser}, n_{γ}, P_{RC}, $B \cdot L$, det. noise
  - o **x3000** gain in $g_{\alpha\gamma}$ wrt ALPS-I

ALPS-II

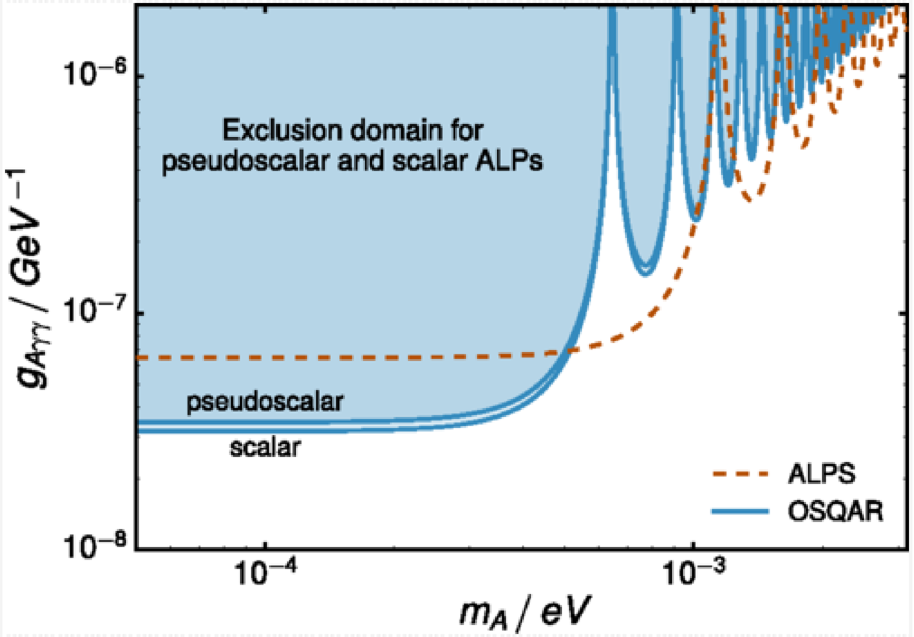


Ehret et al. PLB 689 (2010) 149
Baehre et al. JINST 8 (2013) T09001

OSQAR@ CERN

- At CERN, using LHC magnets (14m, 9T)
- Latest results (2015)

OSQAR. PRD 92 (2015) 092002

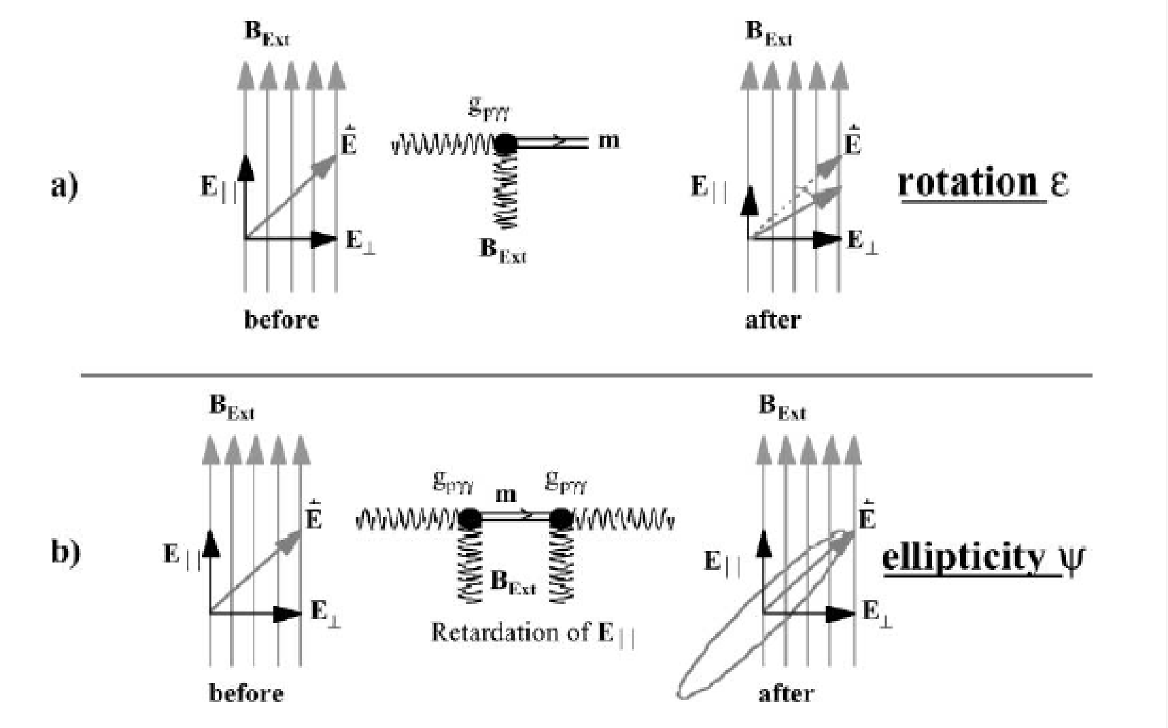


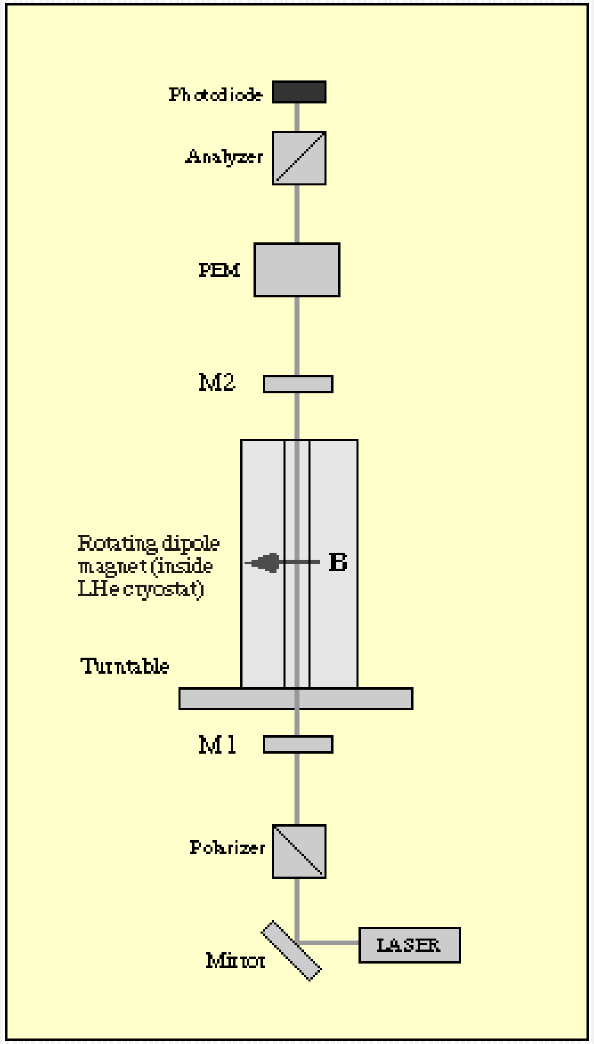
Polarisation experiments

- PVLAS: Studying QED birefringence

Dichroism: Production of real massive particle

Ellipticity: Production of virtual massive particle

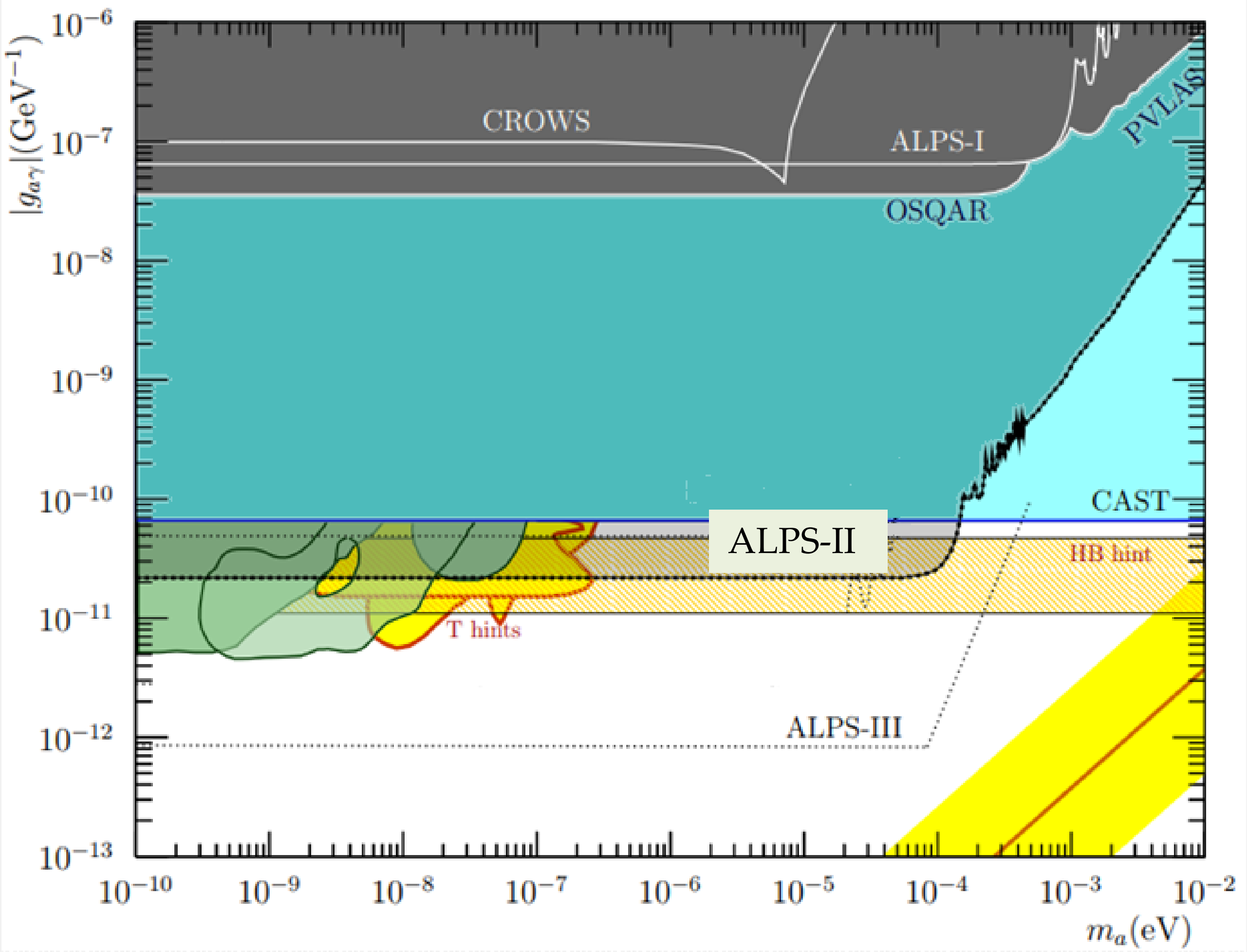




PVLAS PRL 96 (2006) 110406
Della Valle et al. EPJ C76 (2016)

Laboratory Experiments

- There is a long list of similar experiments
  - o BMV (Toulouse)
  - o GammeV (Fermilab)
  - o REAPR (Fermilab)
  - o CROWS (CERN): microwaves
- And some to come:
  - o ALPS-III
  - o STAX

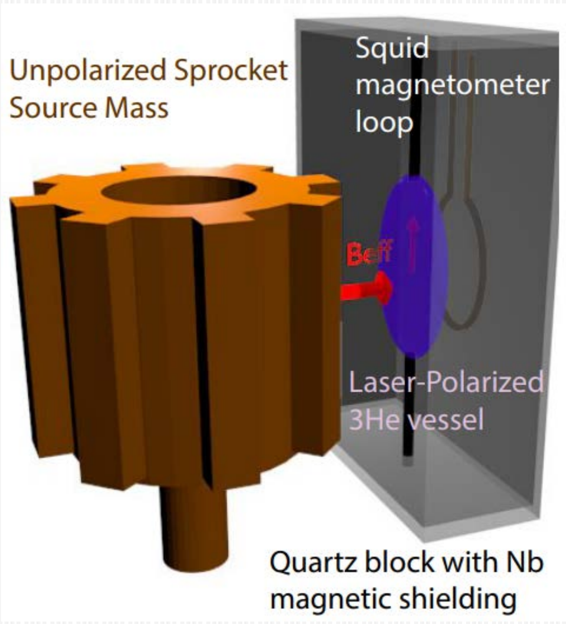


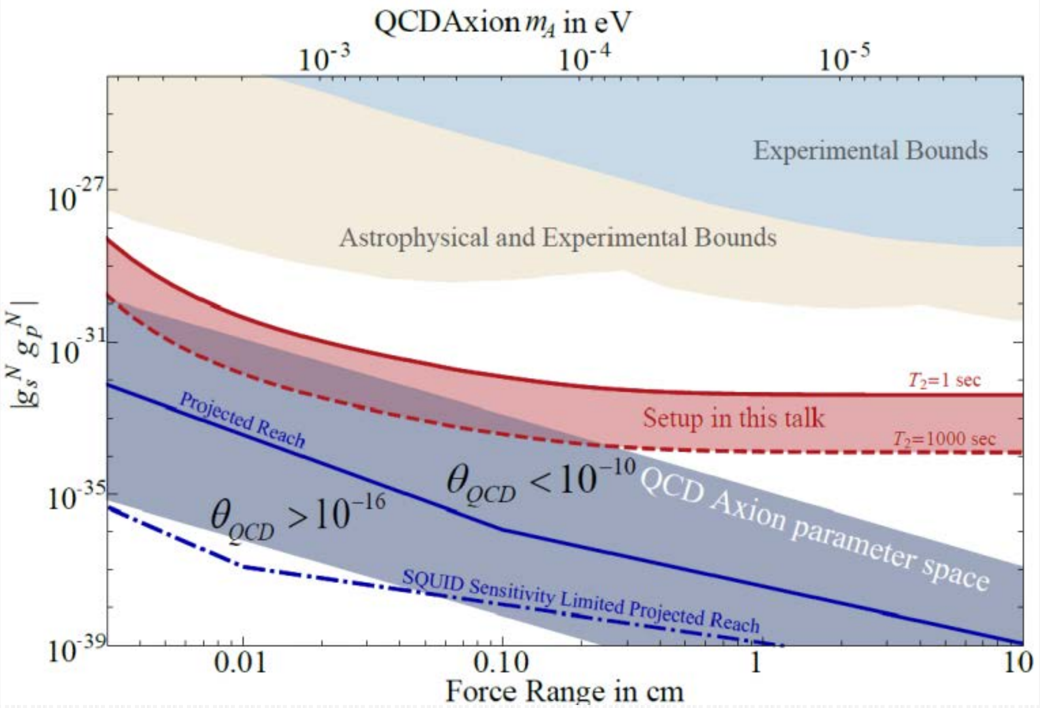
Axion-mediated macroscopic forces

- Axions and ALPs can mediate short-range forces between baryons
  - o Characteristics constraint by precision measurements of Newton’s law, although not with competitive sensitivity
- The ARIADNE experiment:

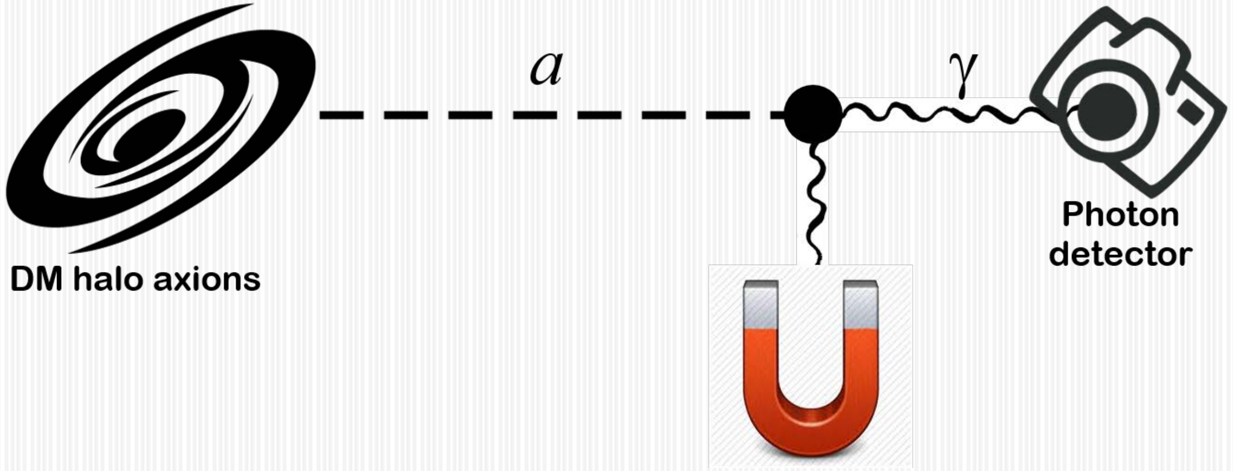
measure the force with NMR techniques

Arvanitaki, Geraci PRL 113 (2014) 161801
Geraci et al. arXiv:1710.05413





DM axion Searches



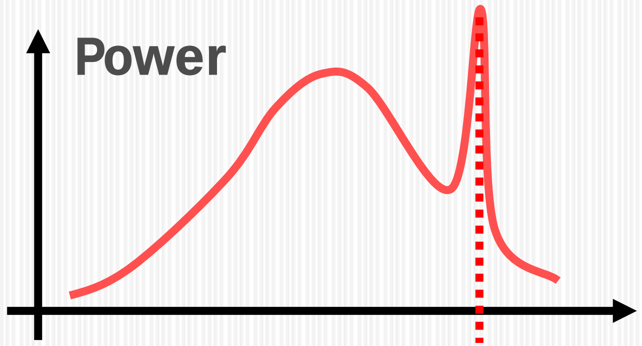
Axions are all around us

Relic axions

- Assuming that DM is axions (mainly)
- Haloscopes: Primakoff conversion inside a cavity to microwave photons
- f will match mass+ kinetic energy above

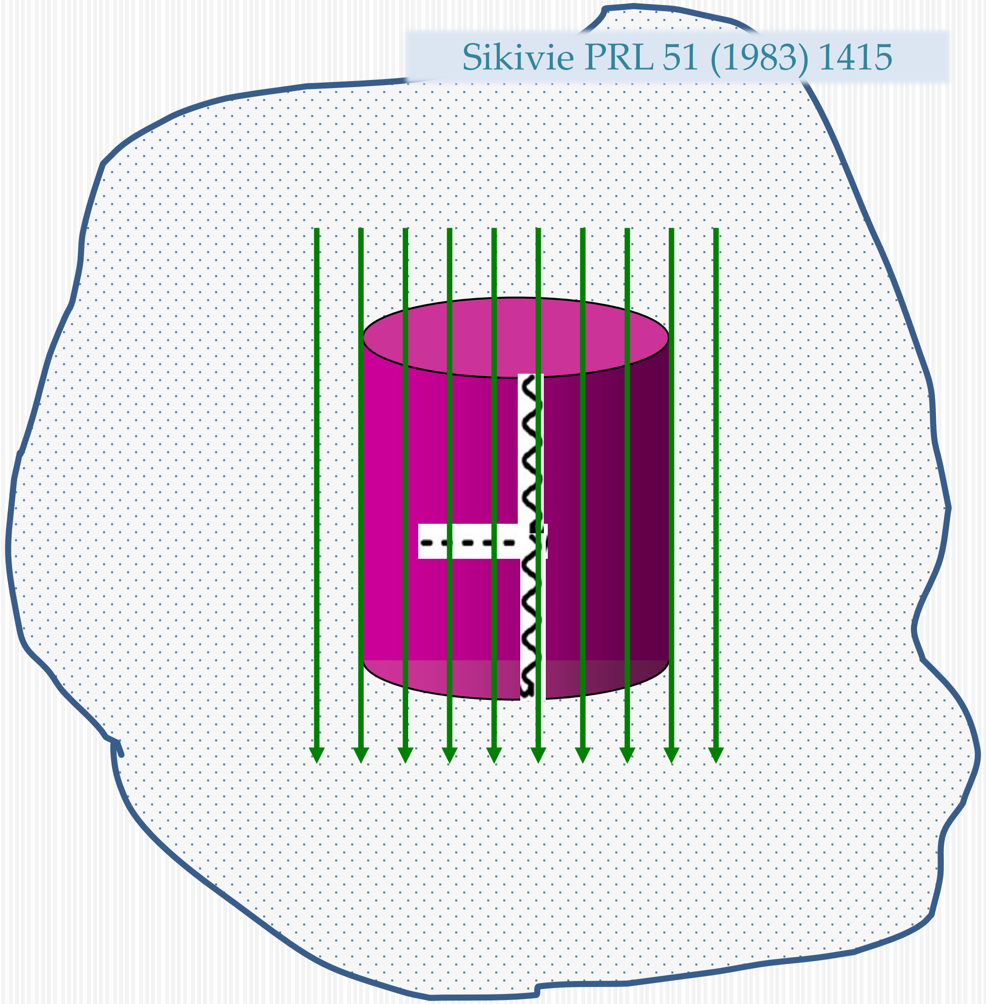
Thermal & detector noise

- A “tuned” cavity has increased sensitivity
- A “tunable” cavity in a range of m_a



$$P \propto g_{a\gamma}^2 V B^2 Q$$

Sikivie PRL 51 (1983) 1415



Relic axions: ADMX

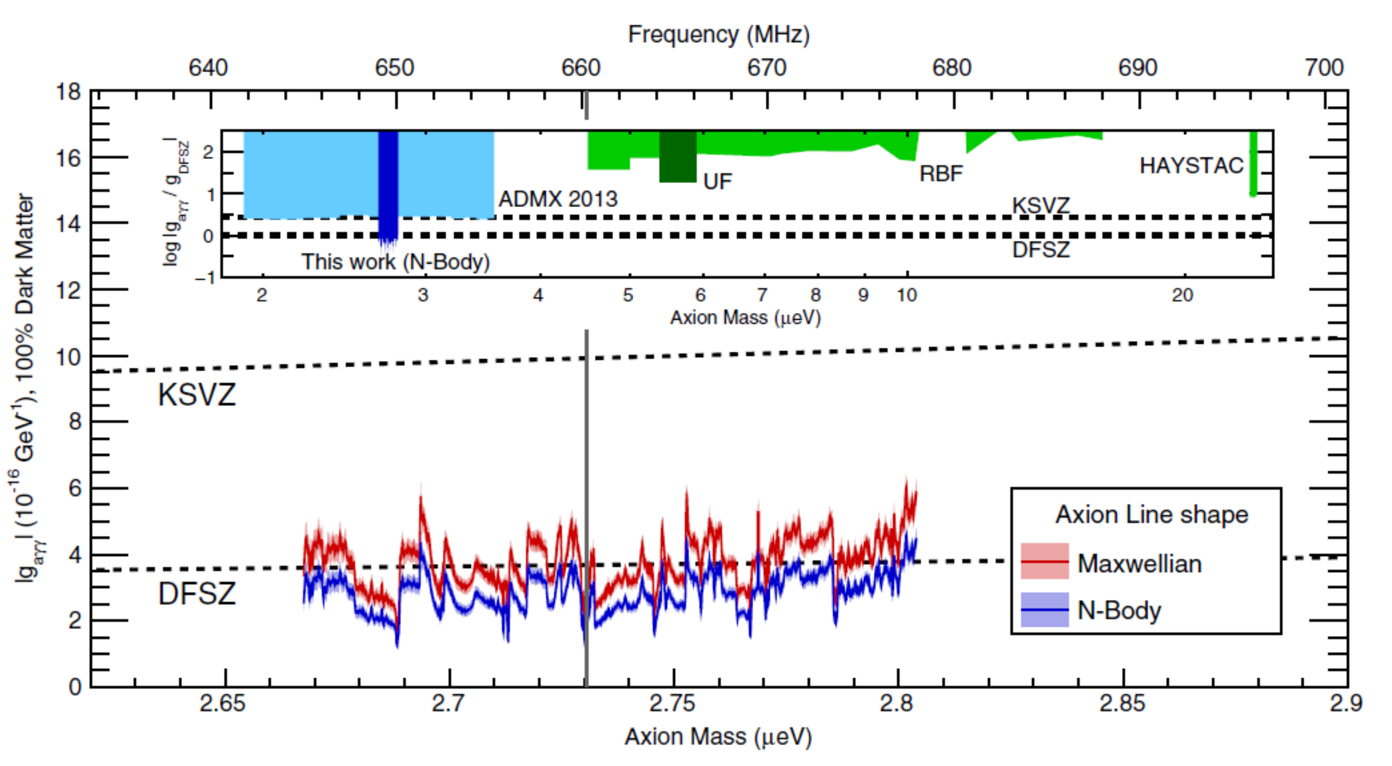
- Decades of R&D
- high Q cavity (1 m x 60 cm Ø)
- 8 T superconducting solenoid
- SQUID-based receivers
- dilution refrigeration at 100 mK.
- The most sensitive result in μeV range

- Good support through Gen 2 DM US program

Relic axions: ADMX (II)

- Latest result this week!
- Unprecedented sensitivity, most stringent value
- Crossing the DFSZ line

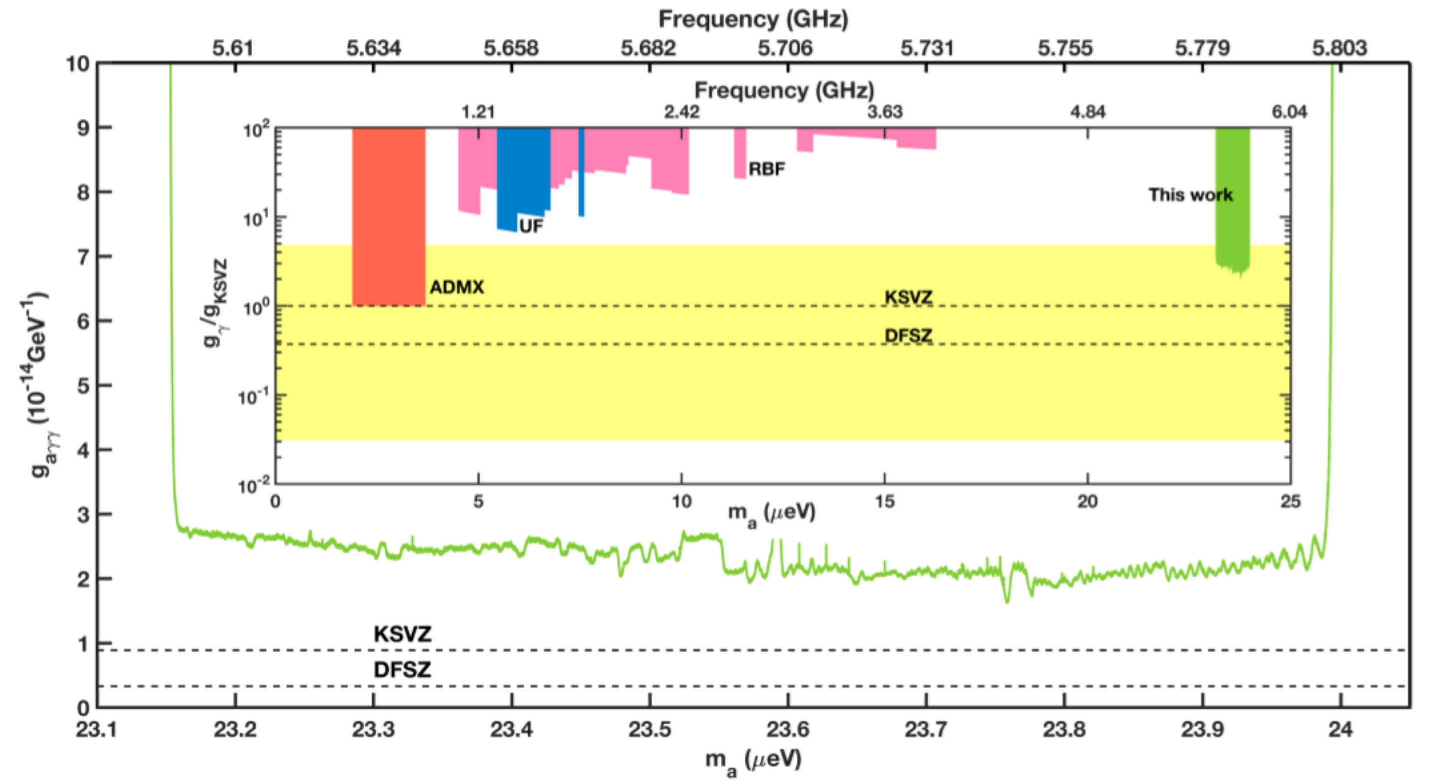
ADMX PRL 120 (2018) 151301



Relic axions: higher m_a

- Higher mass implies lower V and therefore lower signal
- Active R&D with several ideas being explored (eg. exotic tuning)
  - Started within ADMX
- HAYSTAC
  - Smaller ADMX-like cavity
  - Stronger B
  - Sensitivity for $m_a > 20\mu eV$

  - First phase concluded
  - Results already within the QCD band



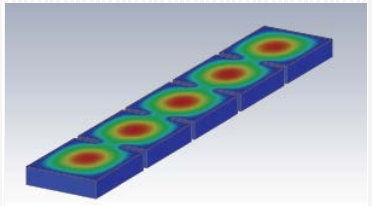
Zhong et al arXiv 1803.03690v1

Relic axions: higher m_a (II)

- Center for Axion and Precision Physics (Korea): determined to find it!
  - o CULTASK PoS CORFU2015 (2016) 047
    - Sensitivity beyond DKFZ for masses 4-40μeV
    - R&D on big aperture magnets: 18T, 25T up to 40(?)
  - o CAST-CAPP 10.3204/DESY-PROC-2015-02/miceli_lino
    - inserting long cavities in the CAST magnet

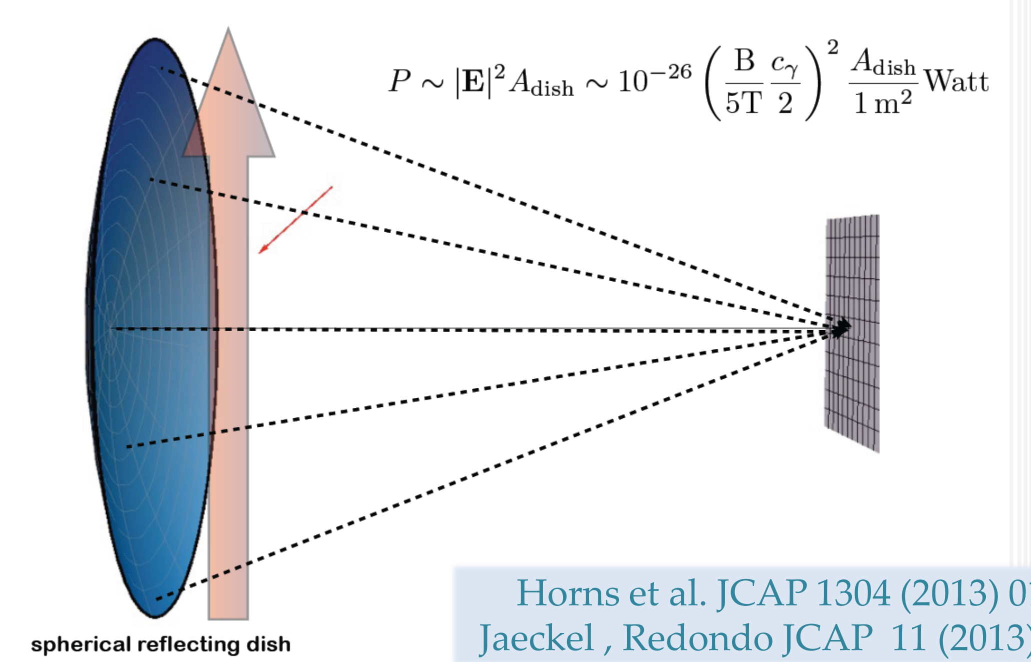
- REDES@CAST: arXiv: 1803. 01243
  - o filter-like cavities in the CAST magnet
  - o Cartagena, Valencia, Yebes, CERN, Zaragoza
  - o 10-100μeV

- ORGAN Phys. Dark Univ. 18 (2017) 67
  - o Thin, long cavities, different dimensions for the ~60-210μeV range
  - o Already some results



Relic axions: other haloscopes

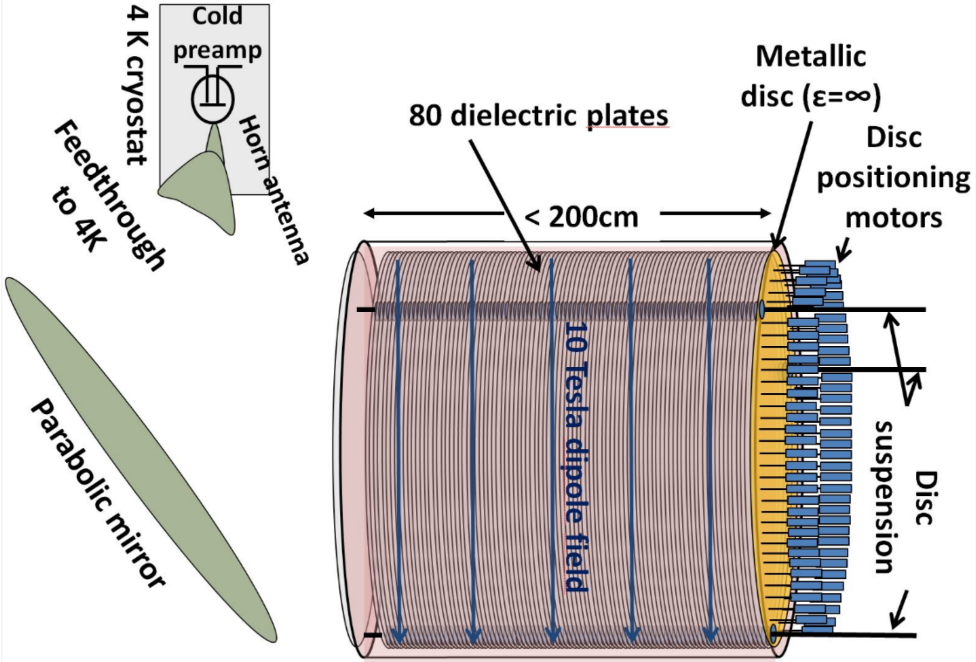
- Dish Antennas
- Compensates lack of resonance with huge V
- Broadband search possible
- Directionality info possible



Horns et al. JCAP 1304 (2013) 016
Jaeckel , Redondo JCAP 11 (2013) 016

- MADMAX
- A dielectric multilayer haloscope
- significant boost factor can be achieved
- 40-400μeV, 80 discs

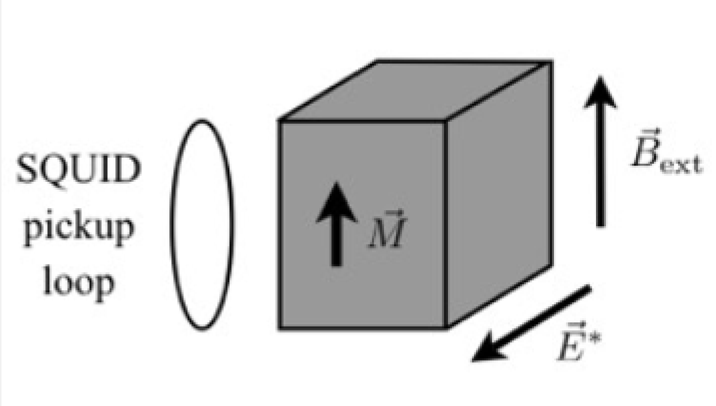
MADMAX PRL 118 (2017) 091801

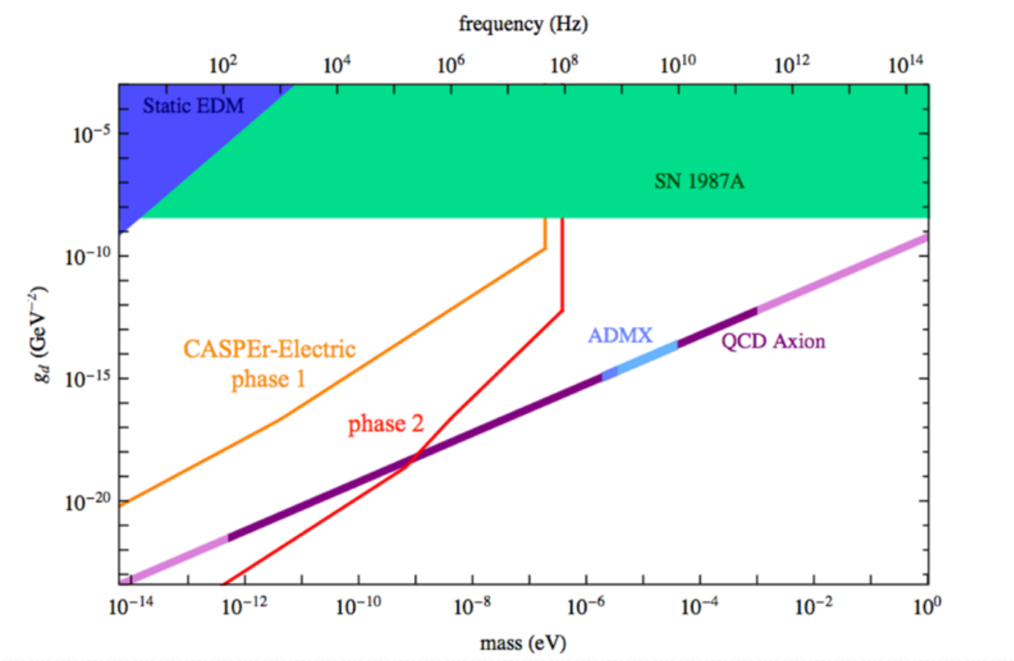


Relic axions: lower m_a

- What if the axion DM induces spin precession ?
- CASPEr
  - o Electric, exploring the coupling to gluons
  - o Wind, exploring the coupling to fermions

Phys. Rev. X 4 (2014) 021030



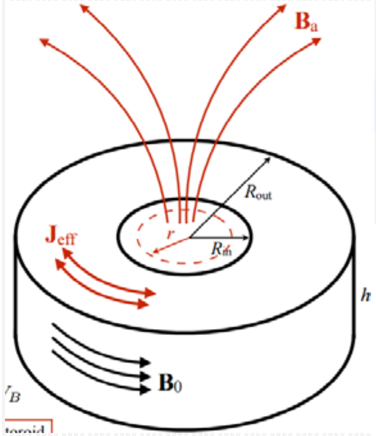


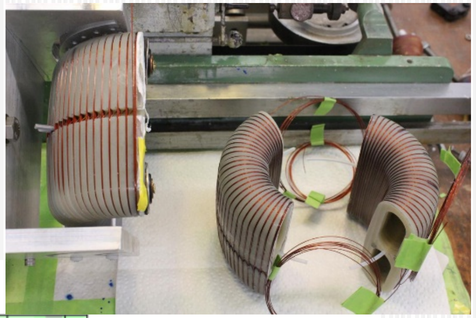
- QUAX (Padova)
  - o Axion DM- wind coupling to electrons

NIMA 842 (2016) 109

Relic axions: lower m_a (II)

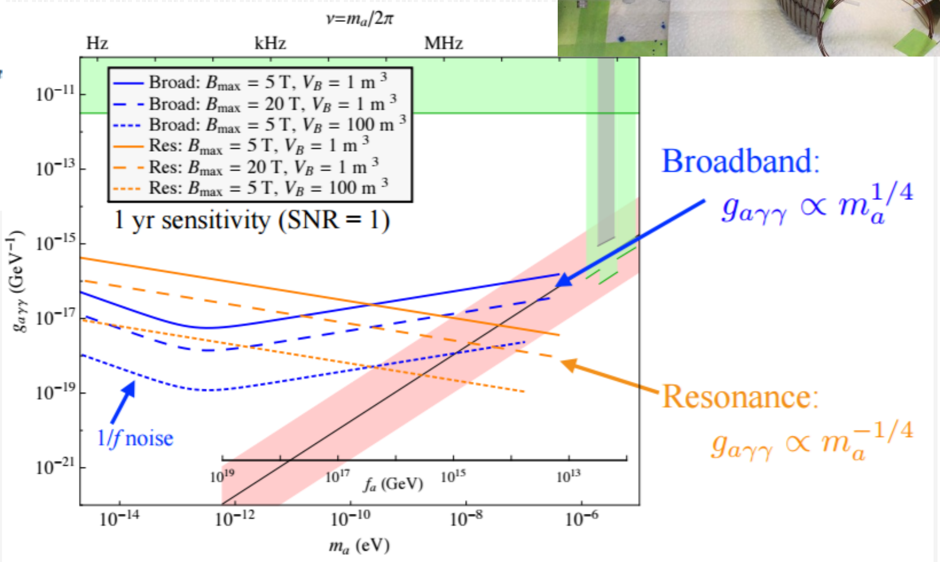
- What if the axion DM induces an oscillating B at the center of a toroidal magnet?





PRL 117 (2016) 141801

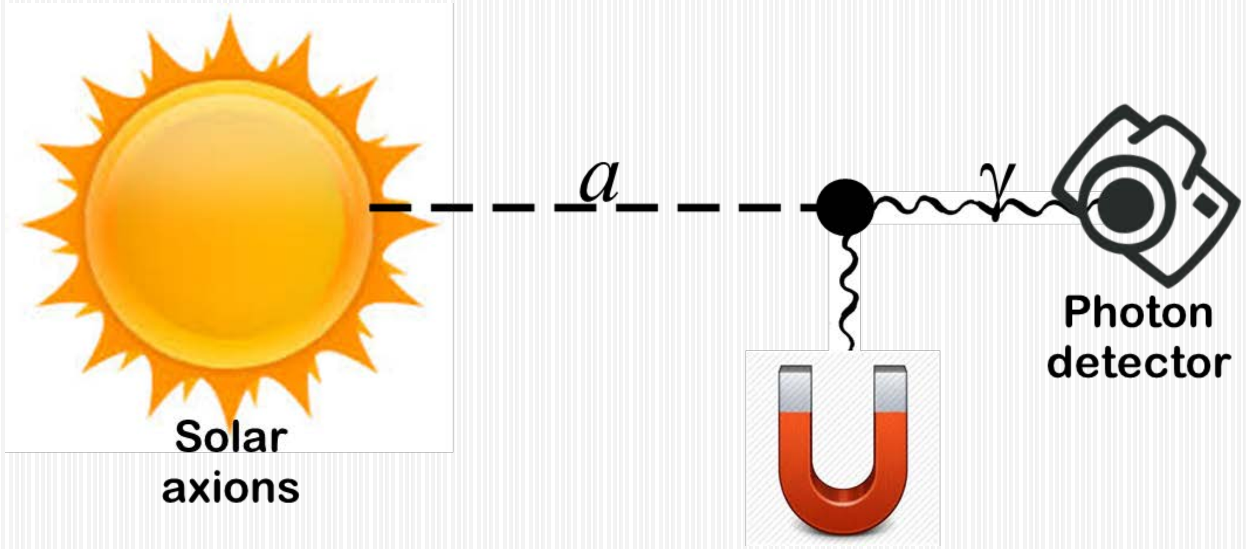
- ABRACADABRA (MIT)
  - o Wideband and resonance
  - o 10cm prototype



- DM Radio (Stanford)
  - o Hidden photons
  - o axions

arXiv:1610.09344

Solar Axion Searches



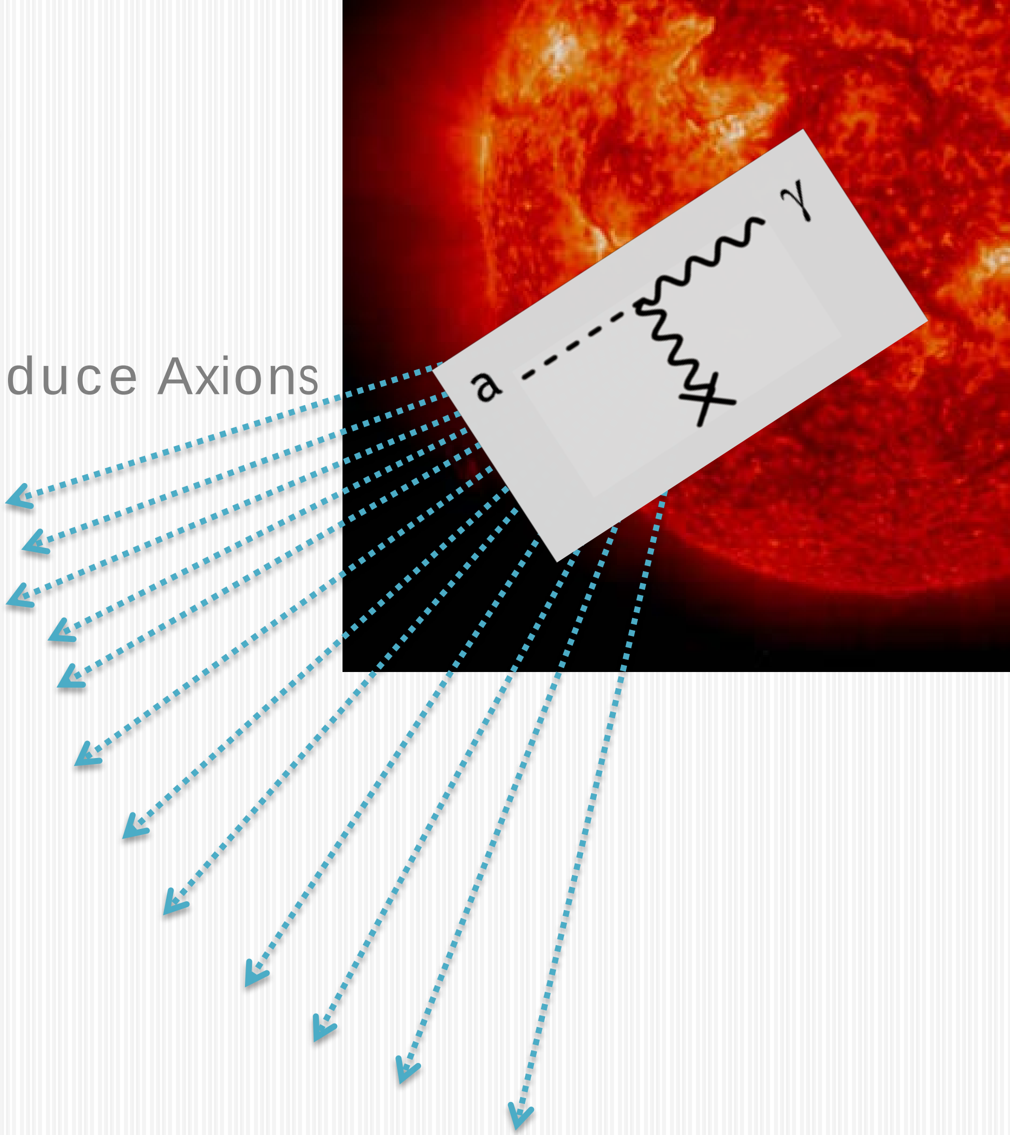
Axions and ALPs

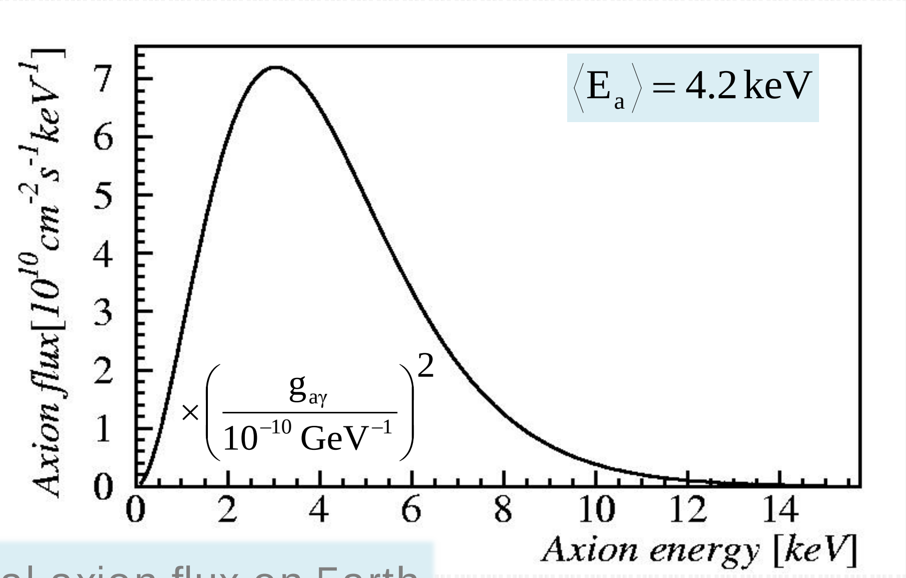
streaming out of the Sun

Solar Axions

- Production: Primakoff effect
  - o Thermal photons interacting with solar nuclei produce Axions

$$\mathcal{L}_{a\gamma} = g_{a\gamma}\, \mathbf{E} \cdot \mathbf{B}\, a$$



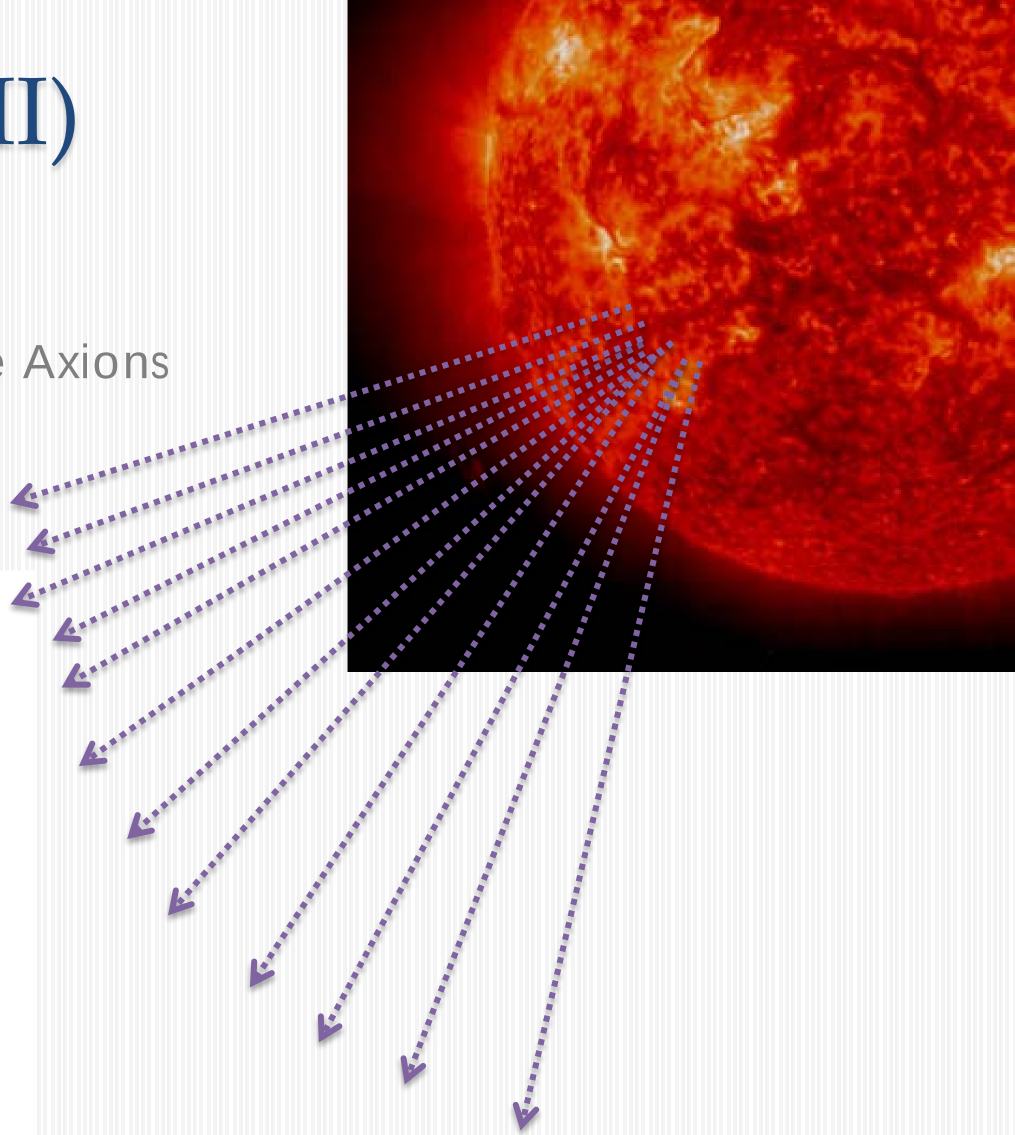


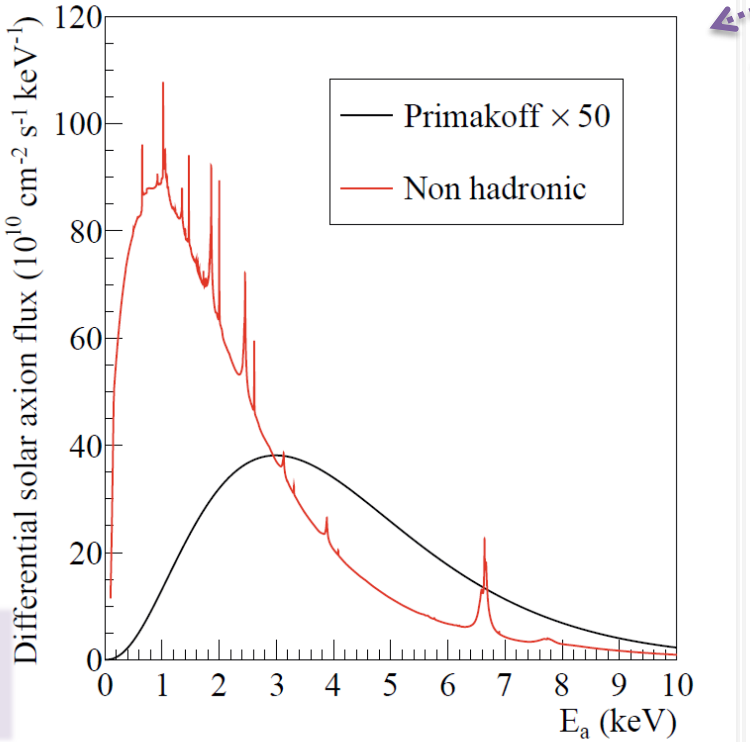
Differential axion flux on Earth

van Bibber PRD 39 (1989) 2089
CAST JCAP 04(2007)010

Solar Axions (II)

- Production: Primakoff effect $\mathcal{L}_{a\gamma} = g_{a\gamma}\, \mathbf{E} \cdot \mathbf{B}\, a$
  - Thermal photons interacting with solar nuclei produce Axions
- Other production: BCA processes
  - non-hadronic axions, coupling to e allowed g_{ae}
  - x100 coupling
  - Model dependent





Non-hadronic "BCA" Solar axion flux on Earth

Redondo JCAP 1312 008 (2013)

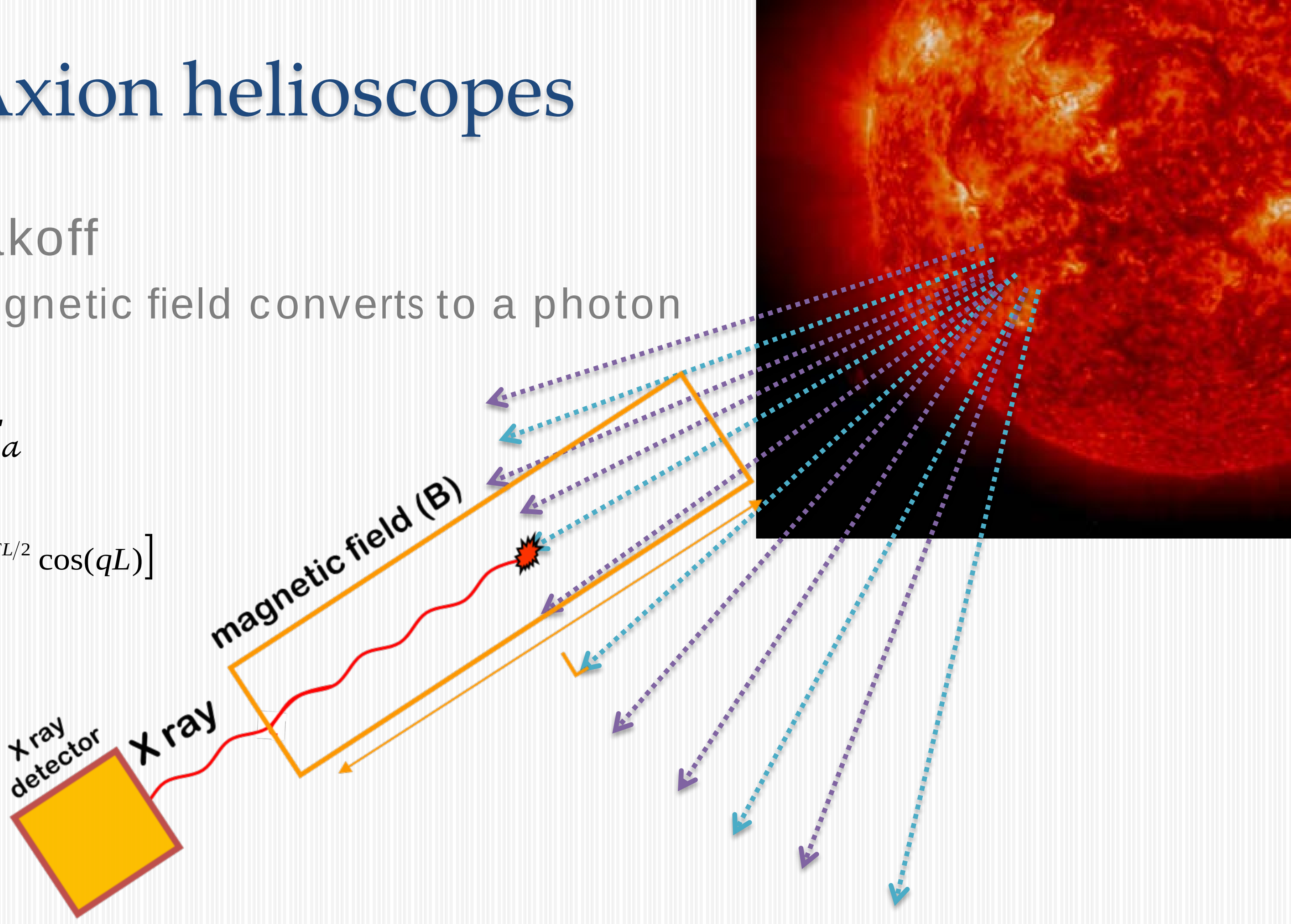
Axion helioscopes

- Detection: Inverse Primakoff
  - axion in a very strong magnetic field converts to a photon

$$N_\gamma = \int \frac{d\Phi_a}{dE_a} \cdot P_{a\to\gamma} \cdot S \cdot t \cdot dE_a$$

$$P_{a\to\gamma} = \left(\frac{Bg_{a\gamma}}{2}\right)^2 \frac{1}{q^2 + \Gamma^2/4}\left[1 + e^{-\Gamma L/2} - 2e^{-\Gamma L/2}\cos(qL)\right]$$

  - $\Gamma = 0$ for vacuum

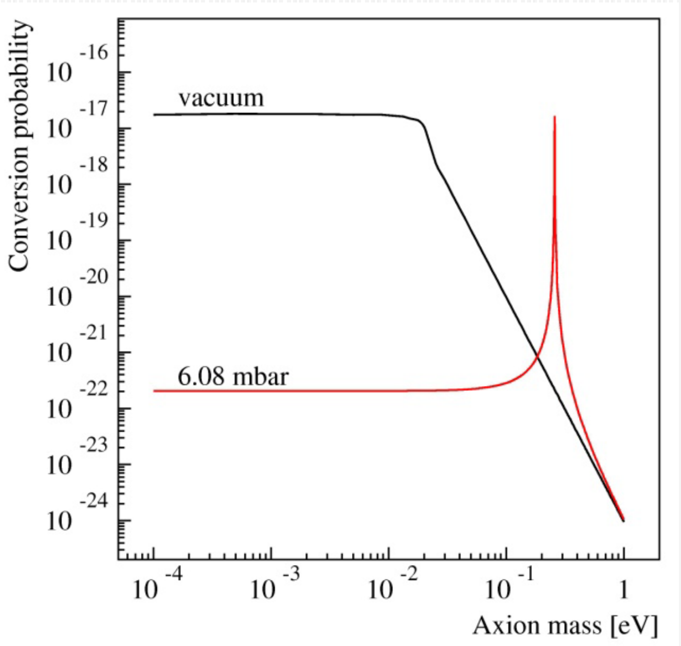


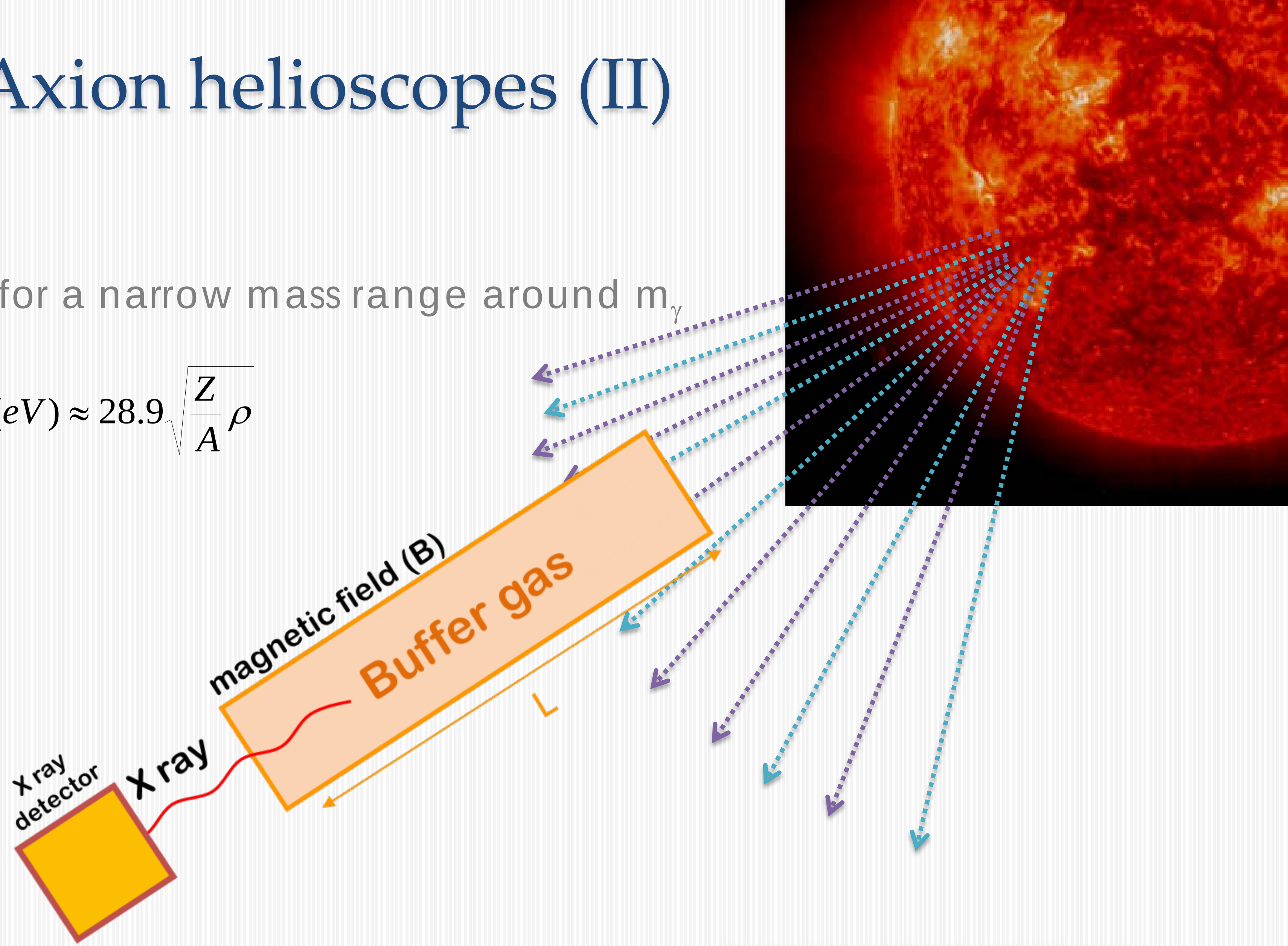
Sikivie PRL 51 (1983) 1415
van Bibber PRD 39 (1989) 2089

Axion helioscopes (II)

- Buffer gas:
  - o $\Gamma \neq 0$ for buffer gas
  - o Sensitivity recovered for a narrow mass range around m_γ

$$q = \frac{|m_\alpha - m_\gamma|}{2E_\alpha} \qquad m_\gamma(eV) \approx 28.9\sqrt{\frac{Z}{A}\rho}$$

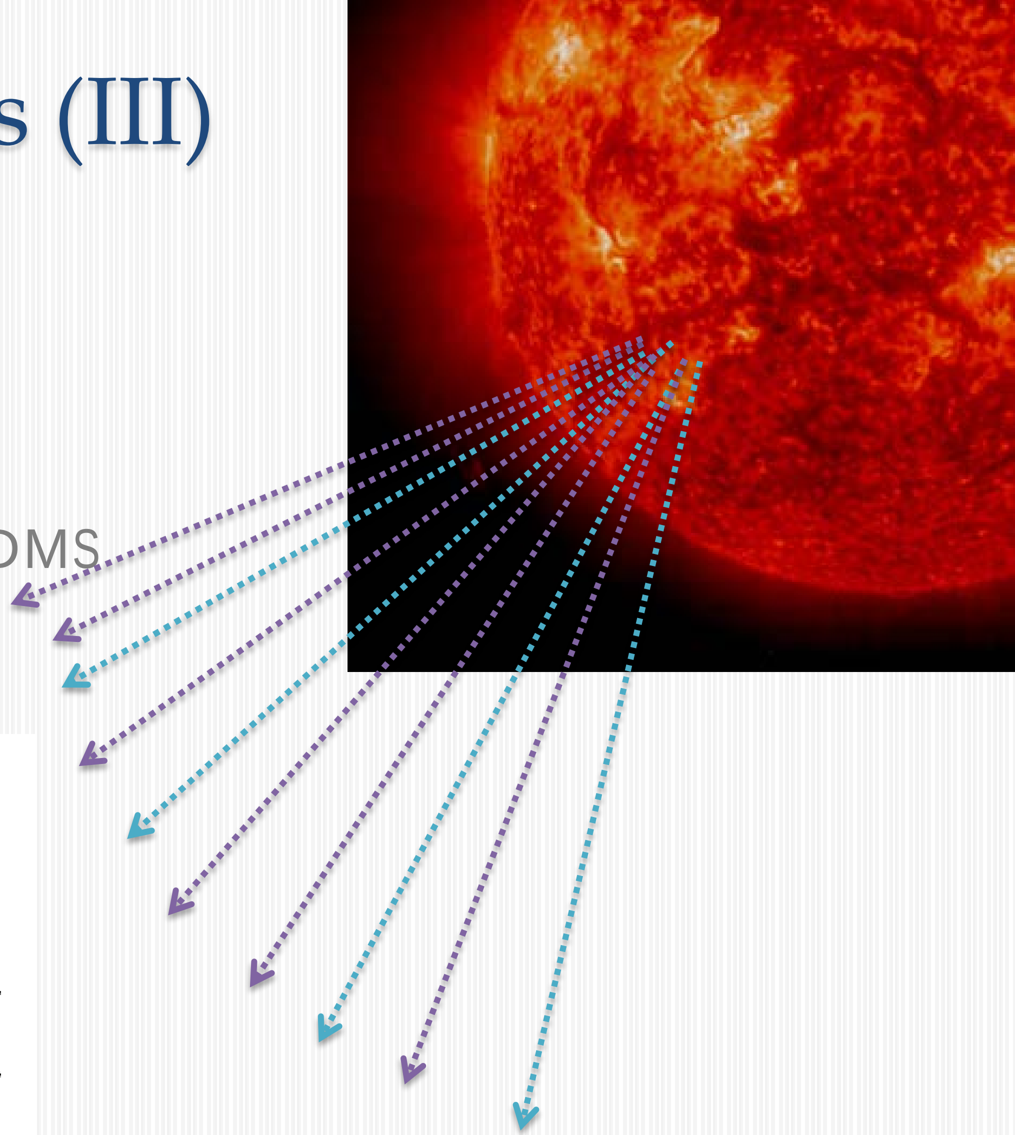


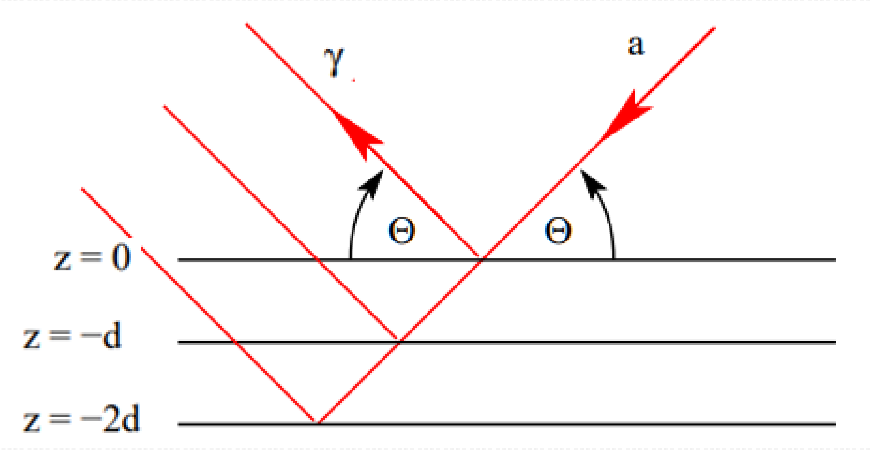


van Bibber PRD 39 (1989) 2089

Axion helioscopes (III)

- Instead of inverse Primakoff, Primakoff-Bragg
  - The axion reconverts into a photon in the electromagnetic field of a crystal
  - WIMP, ββ experiments can give limits
    - SOLAX, COSME, Edelweiss, DAMA/Libra, CDMS
  - Signal should have a temporal pattern

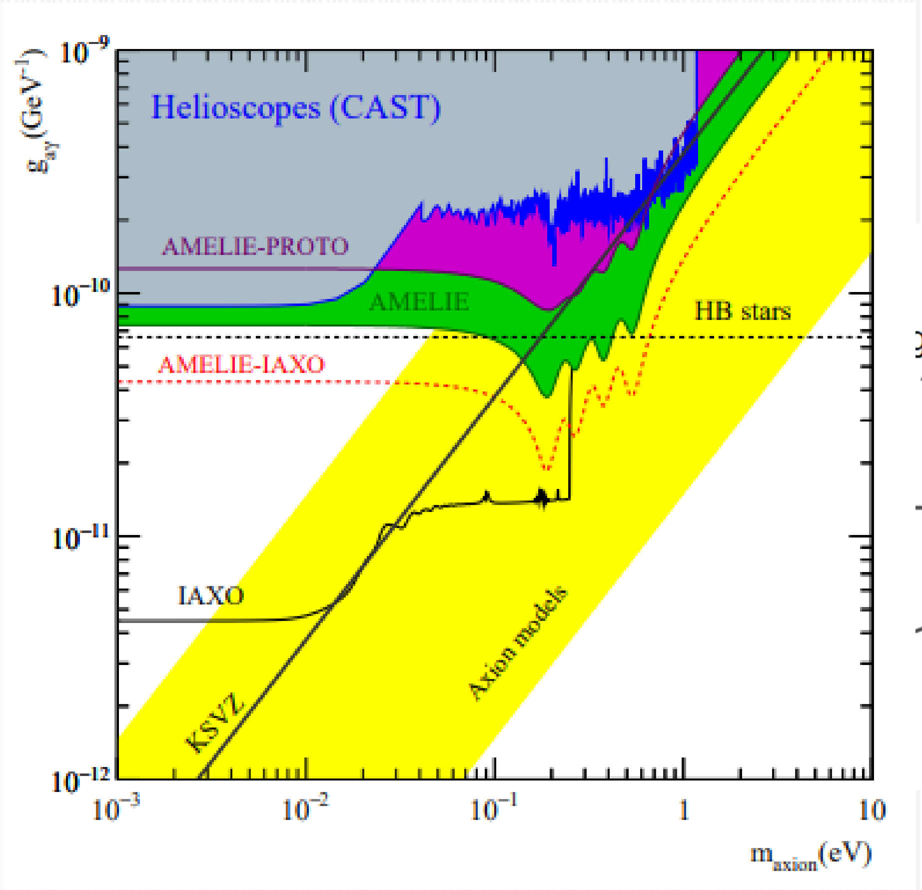


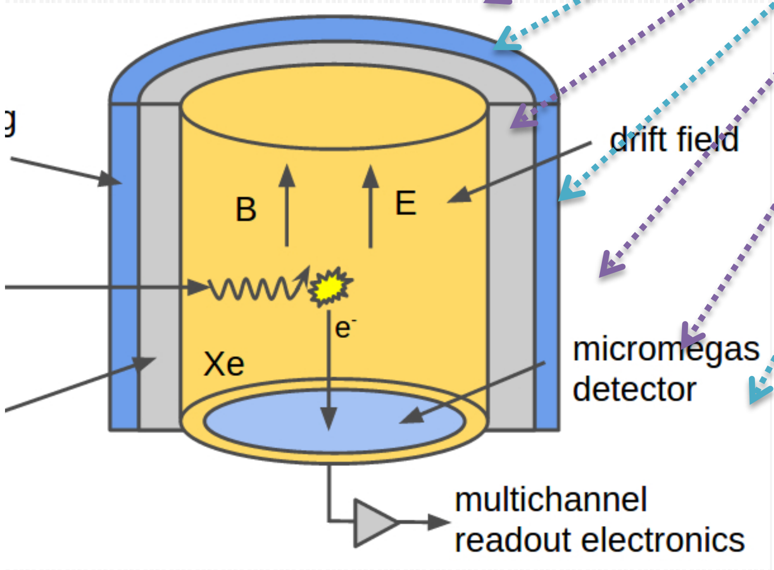


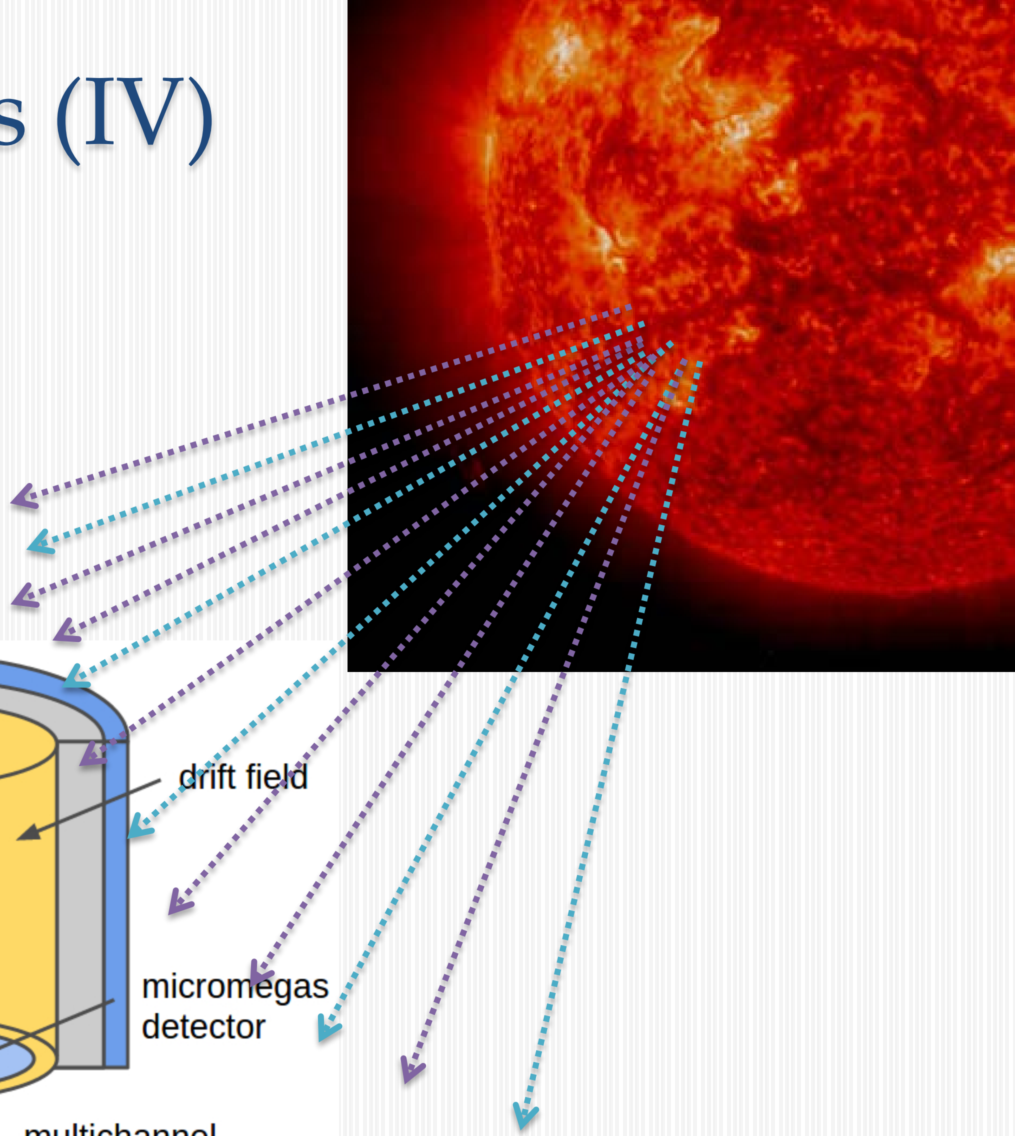
Paschos, Zioutas PLB 323 (1994)

Axion helioscopes (IV)

- The buffer gas is the detector
  - o High-Z for absorption, makes it sensitive to higher m_a







Galan et al. JCAP12 (2015) 012
van Bibber PRD 39 (1989) 2089

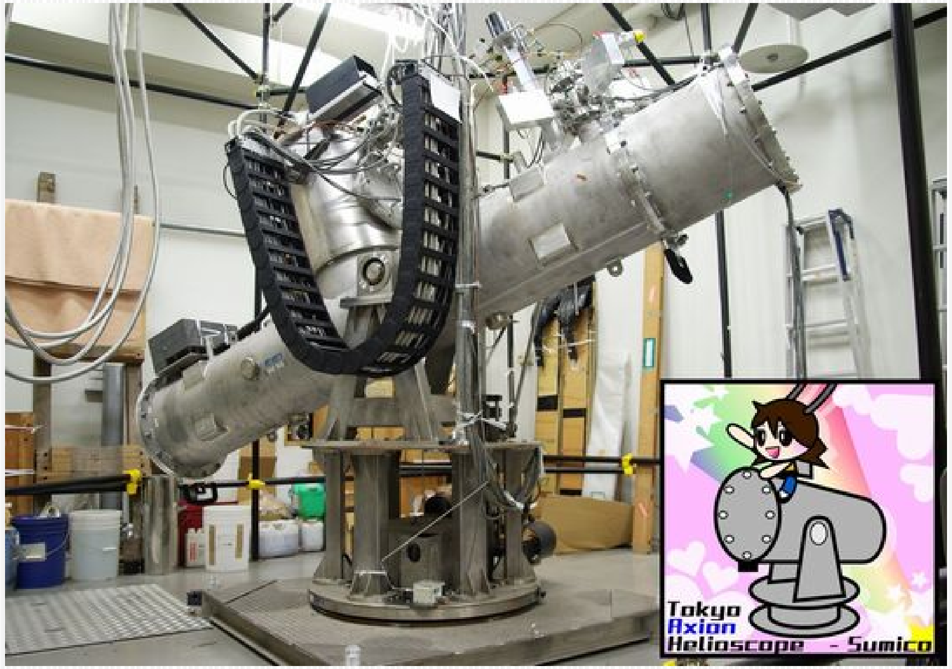
Axion Helioscopes

- 1st generation: Brookhaven
  - o Magnet without moving, few hours of data

Lazarus et al. PRL 69 (1992) 2333

- 2nd generation: SUMICO (Tokyo Helioscope)
  - o 2.3m long, 4T magnet
  - o Movable platform, ± 30°

Inoue et al. PLB 536 (2002) 18
Inoue et al. PLB 668 (2008) 93

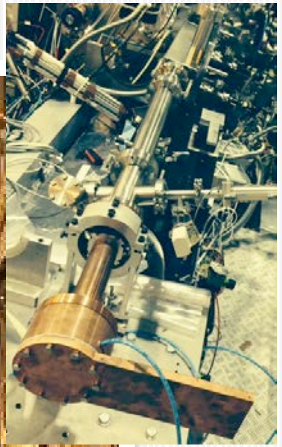


- 3rd generation: CAST
- Technology mature enough for the next generation helioscope

CERN Axion Solar Telescope

Decommissioned prototype LHC dipole magnet.

Spare ABRIXAS telescope



- ✯ XRT + mM
- ✯ XRT + Ingrid

- ✯ Two low-bkg mM(sunset)

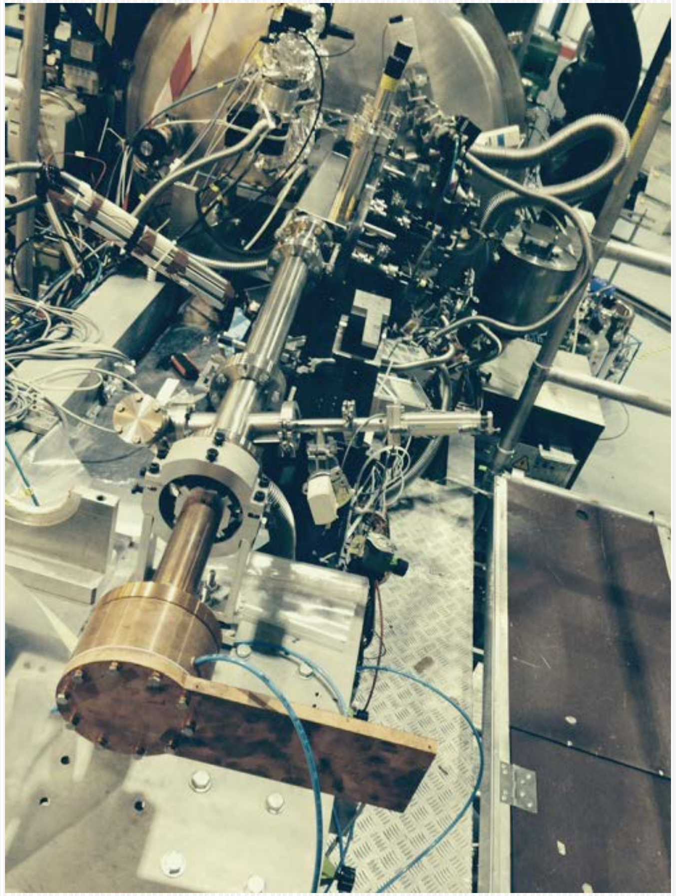
- ✯ Magnetic Field **B = 9T**
- ✯ Length (field) **L = 9.26m**
- ✯ Rotating platform

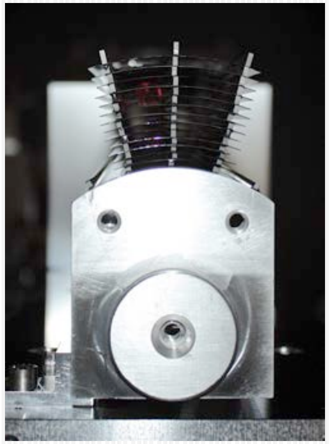
(Vertical: ±8°, Horizontal: ±40°)

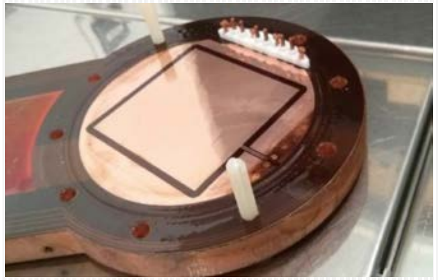
- ✯ 2x90 min solar tracking per day

Latest CAST result with the IAXO pathfinder

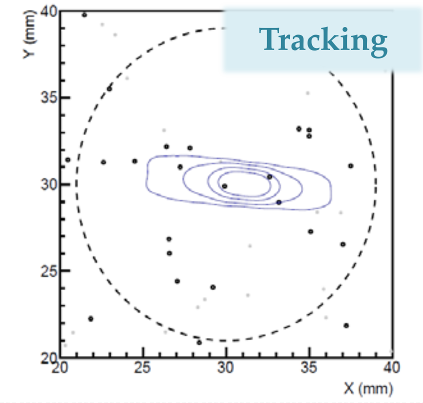
- The most stringent limit on $g_{a\gamma}$ for $m_a < 0.02eV$ (helioscopes)
- X-ray optics specifically built for axions, low-bkg mM at the focal point

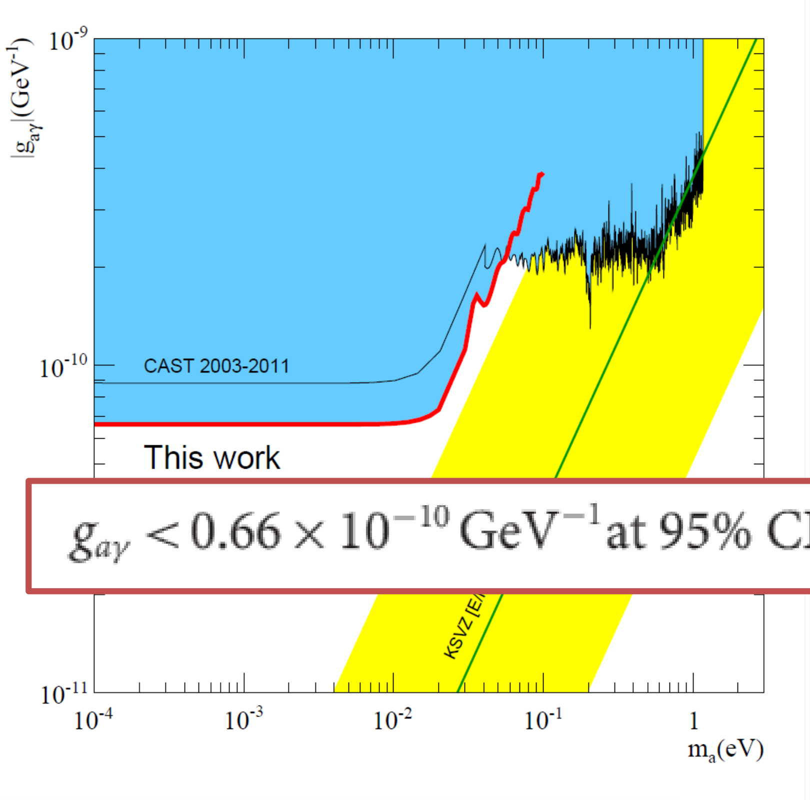






Calibration ⟷



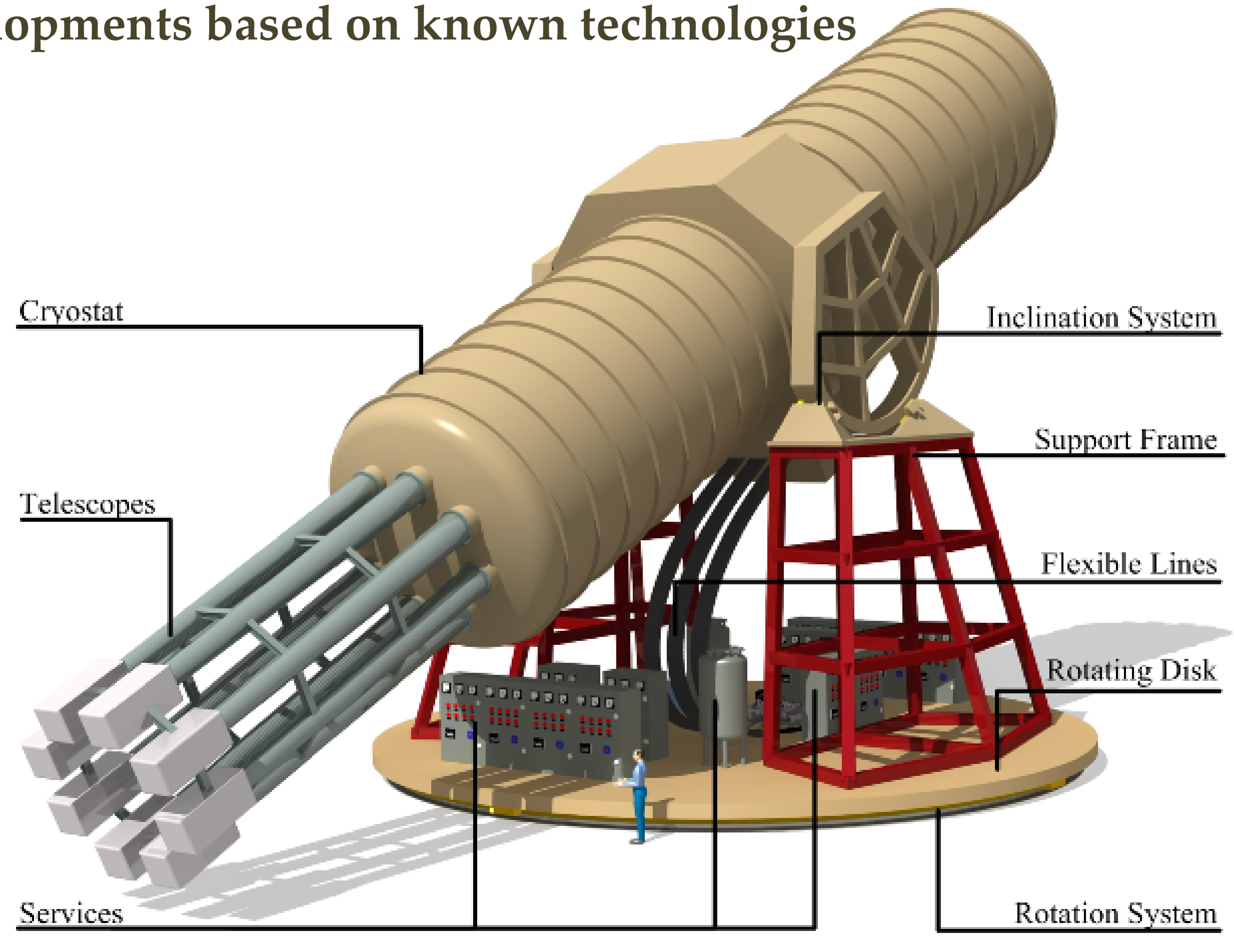


$$g_{a\gamma} < 0.66 \times 10^{-10}\,\mathrm{GeV}^{-1} \text{at 95\% CL}$$

CAST Nature Physics 13 (2017) 584-590

International AXion Observatory

All developments based on known technologies



CERN-SPSC-2013-022
Armengaud et al JINST 9 (2014) T05002

magnet, optics

$$g^4_{a\gamma} \sim B^2 L^2 A \quad \varepsilon_d b^{-1/2} \quad \varepsilon_o \alpha^{-1/2} \quad \varepsilon_t^{-1/2} t^{-1/2}$$

detectors, time

4+ orders of magnitude better SNR that CAST

An all-purpose axion observatory:

- non-hadronic axions
- WISPs
- non-standard axions
- relic axions

Magnet structure length: ~25m
Magnet structure diameter: ~5m
Total mass ~ 250ton

8 bores with 60cm diameter
8 focusing devices
8 low-background x-ray detectors

Rotating platform following the Sun for 12h a day

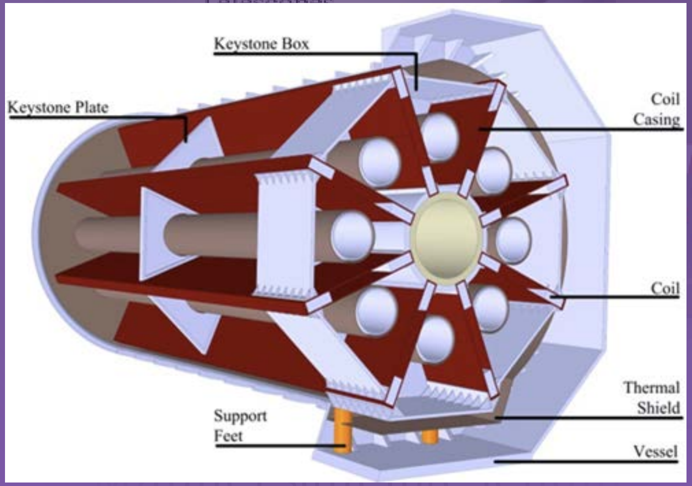
International AXion Observatory

All developments based on known technologies

CERN-SPSC-2013-022
Armengaud et al JINST 9 (2014) T05002

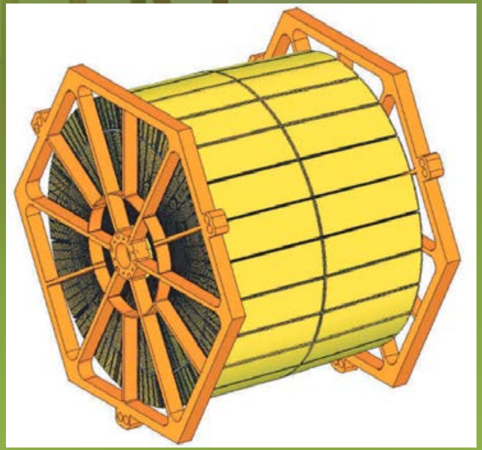
IAXO magnet

- Superconducting "detector" magnet.
- Toriodal geometry (8 coils) (ATLAS)
- CERN+CEA expertise
- 8 bores / 20 m long / 60 cm Ø per bore



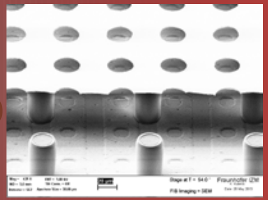
IAXO telescopes

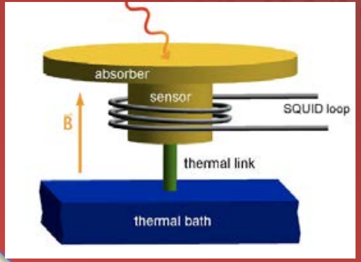
- Slumped glass, multilayers tech., cost-effective for large areas
- Based on NuSTAR developments
- LLNL+UC+DTU+MIT expertise
- Focal length ~5 m, 60-70% efficiency

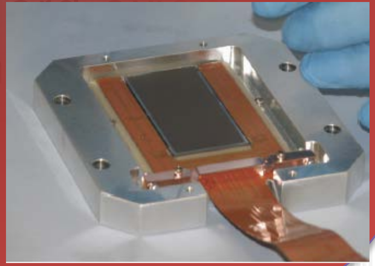


IAXO detectors

- Micromegas gaseous detectors
- Zaragoza + CEA (+ others) expertise
- Also considered: Ingrid, MMCs, CCDs







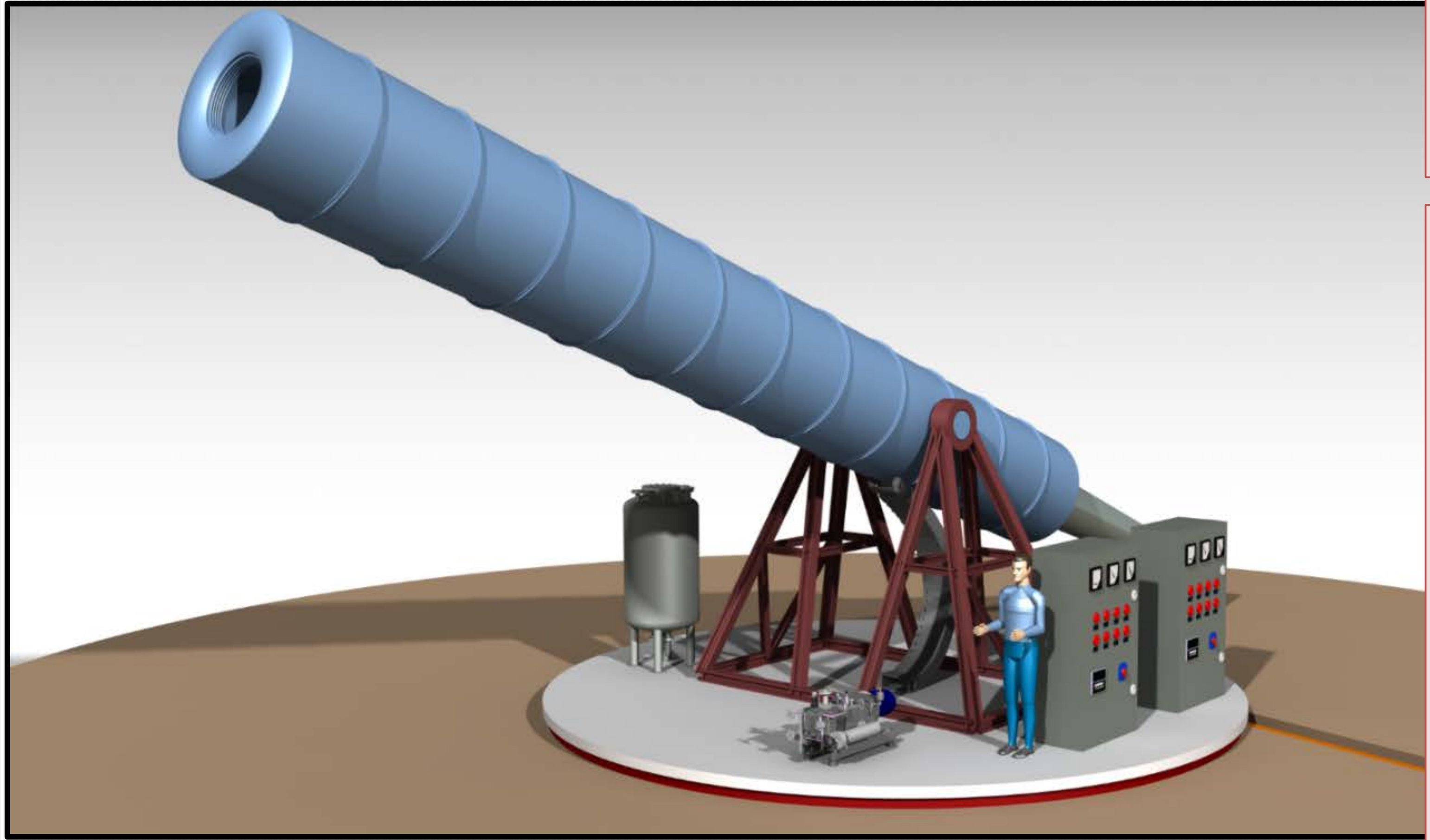
~5m

Total mass ~ 250ton

8 low-background x-ray detectors

for 12h a day

Baby IAXO



Full experimental stage

- ✓ Test alternative magnet design: higher FOM, simpler (less conductor), representative of full IAXO: full scale optics, full scale detectors
- ✓ Mobilize collaboration into full experimental status (build experiment, data taking, analysis,…)
- ✓ Produce relevant physics results.
- ✓ Staged access to funding

IAXO Collaboration officially formed in July 2017. DESY is a strong candidate to host the experiment.

Baby IAXO

Full experimental stage

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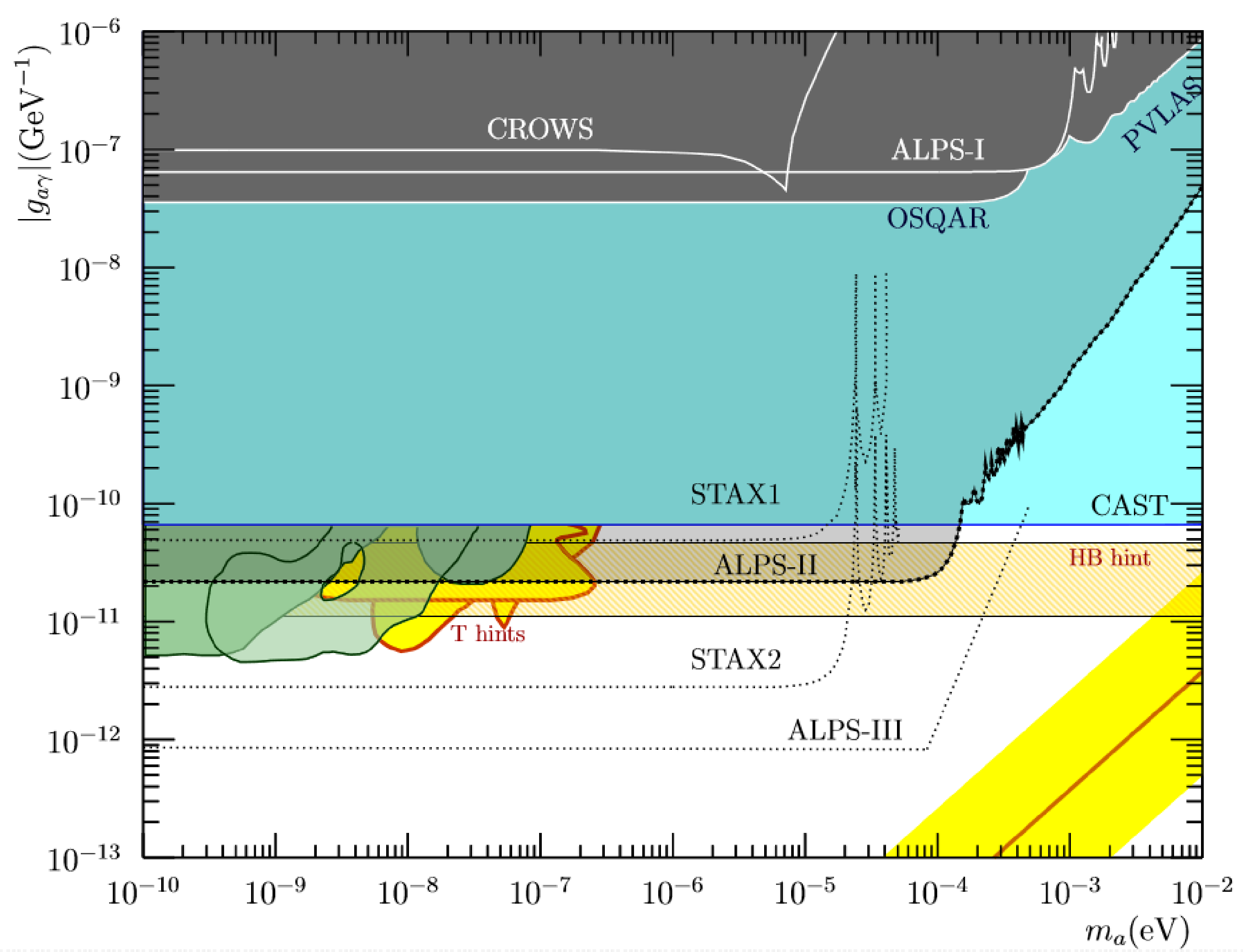
IA… …tion officially formed in July 2017. DESY is a strong candidate to host the experiment.

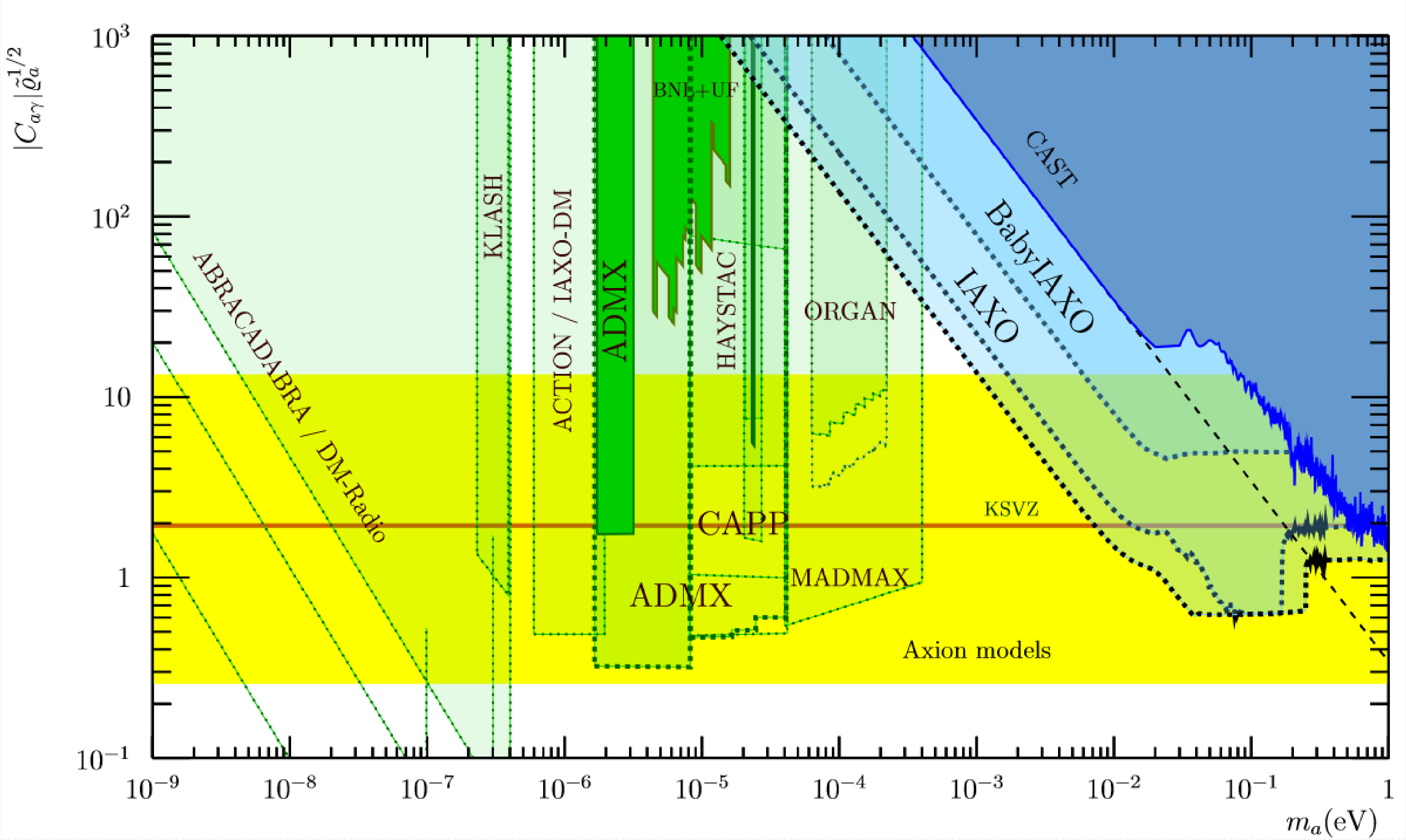
Let's sum up

- Axions are QUITE interesting
- A whole “zoo” of experimental efforts (properly triggered but also followed upon and further motivated by theory) are being undertaken

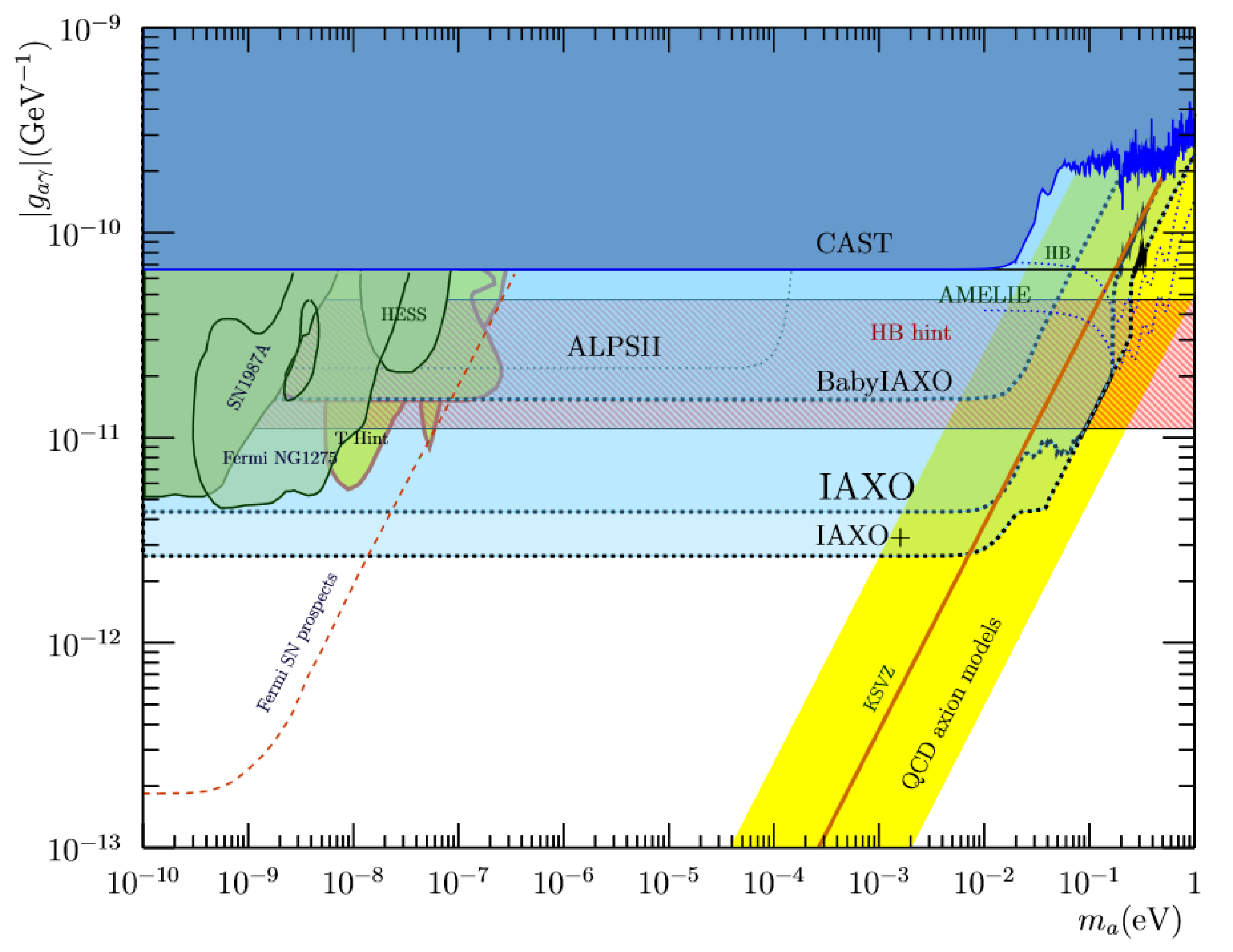
“Lab” axions current and future



Relic axions current and future



Solar axions current and future



Conclusions

- Axions (ALPs) are a hot topic
- Mature techniques have taken or will soon take the next step: ADMX, IAXO, ALPS-II
- Many new or not-so-new ideas are being tested or are to be tested soon.
  - o Higher mass cavities, dielectric haloscopes, NMR-based techniques, EDM measurements, oscillating fields…
- R&D permitting, a vast ground will be covered in the next decade or so
- Discovery must be near…
- Techniques are complementary and could check a possible signal…