

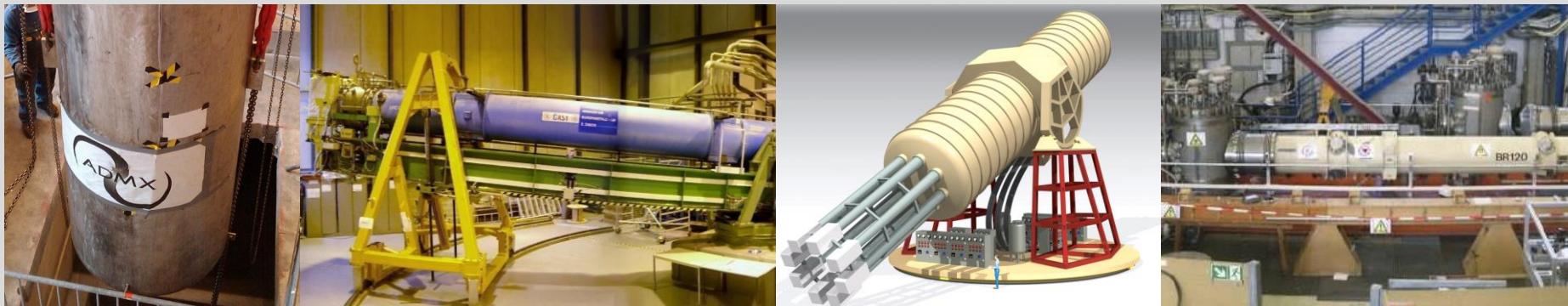
Experimental Axion Review

Igor G. Irastorza

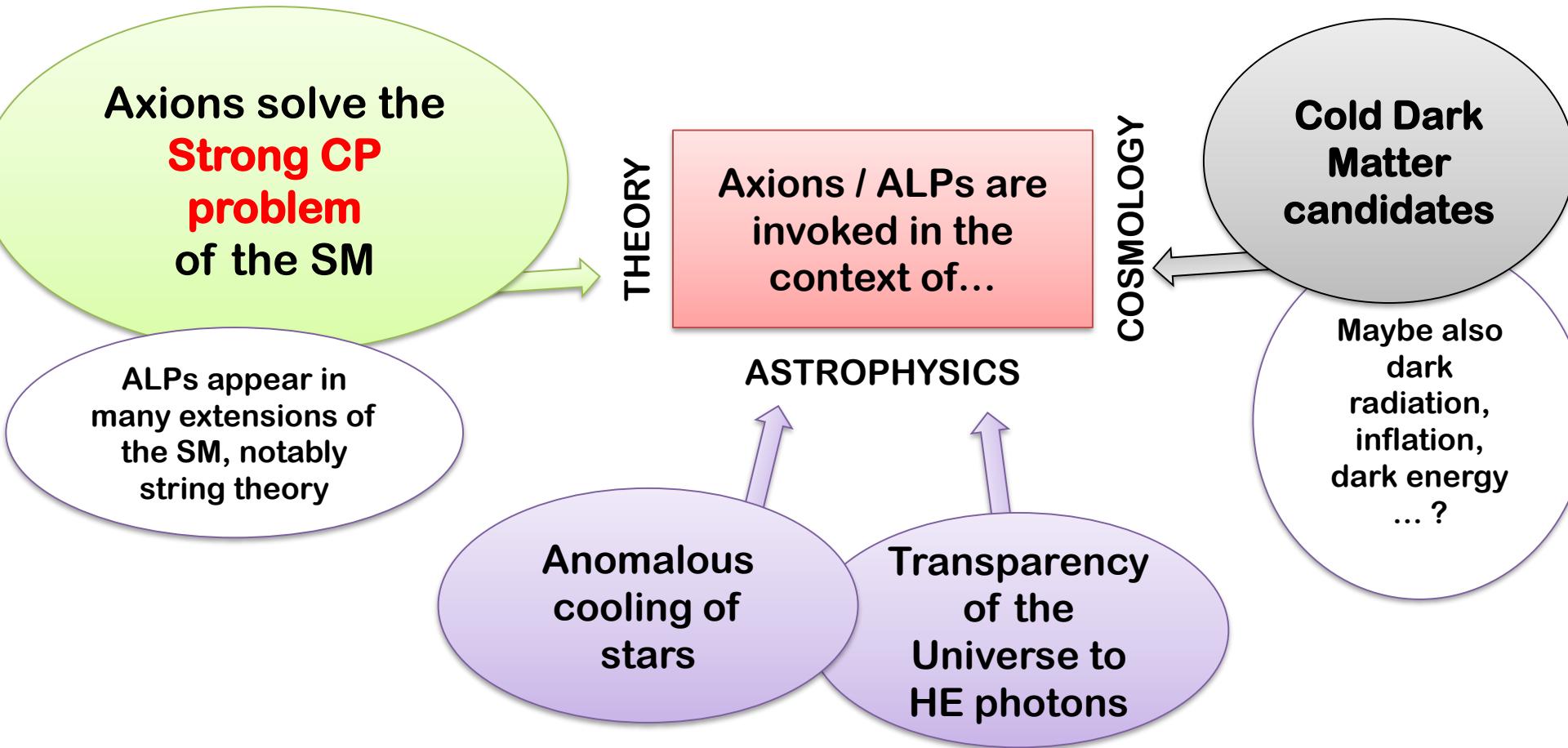
Universidad de Zaragoza

EPS Conference of High Energy Physics, Venice, Italy

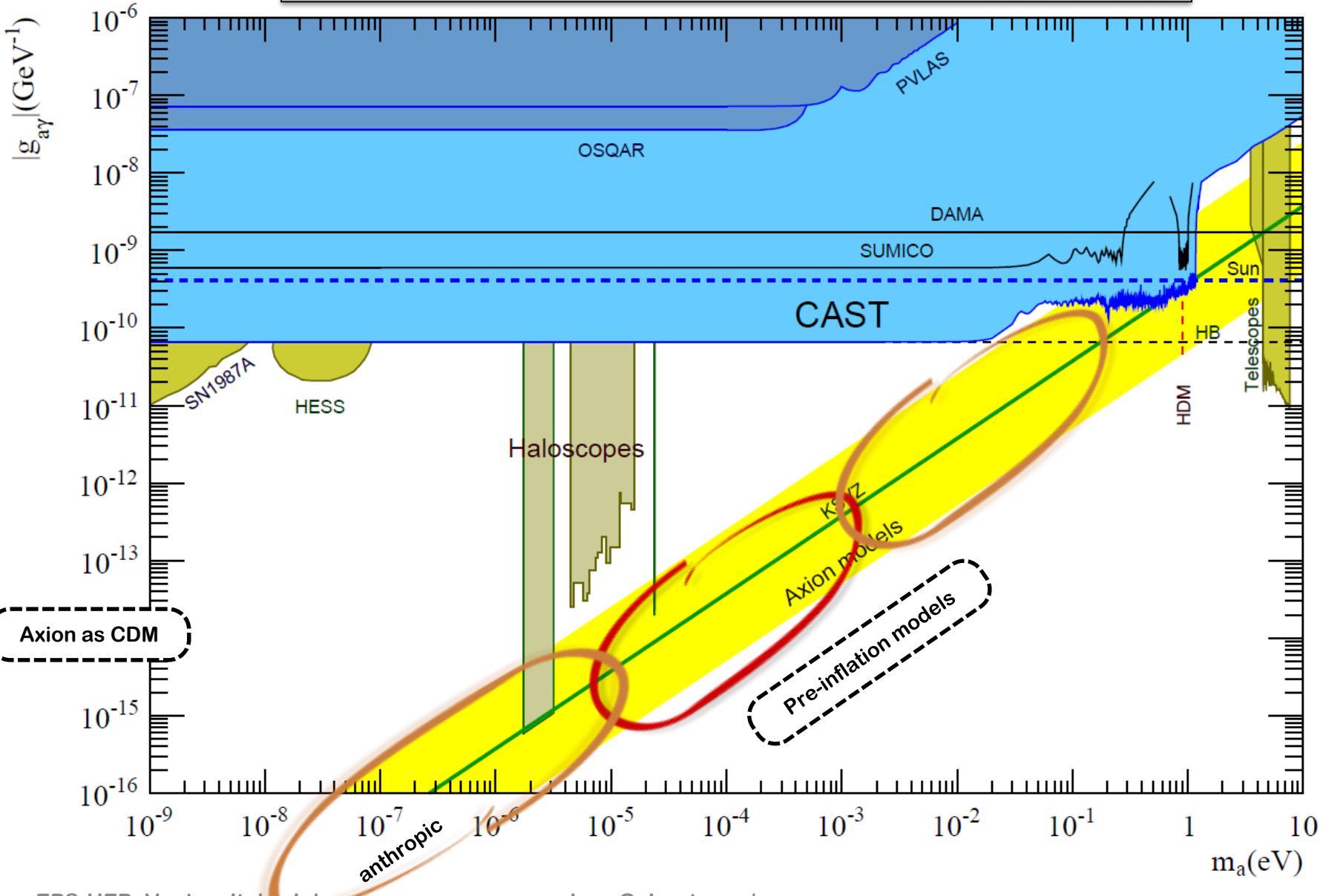
7 July 2017



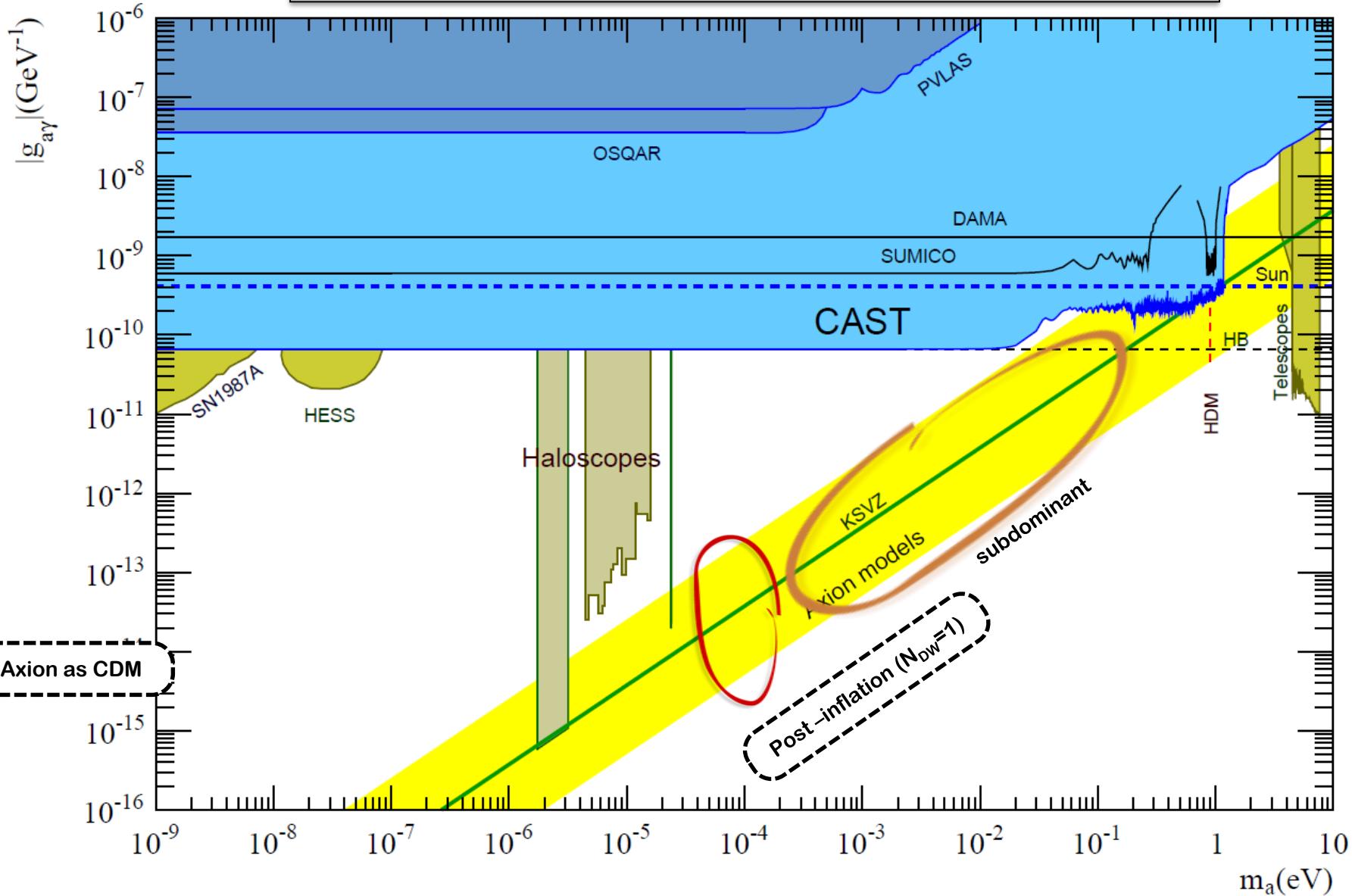
Why axions?



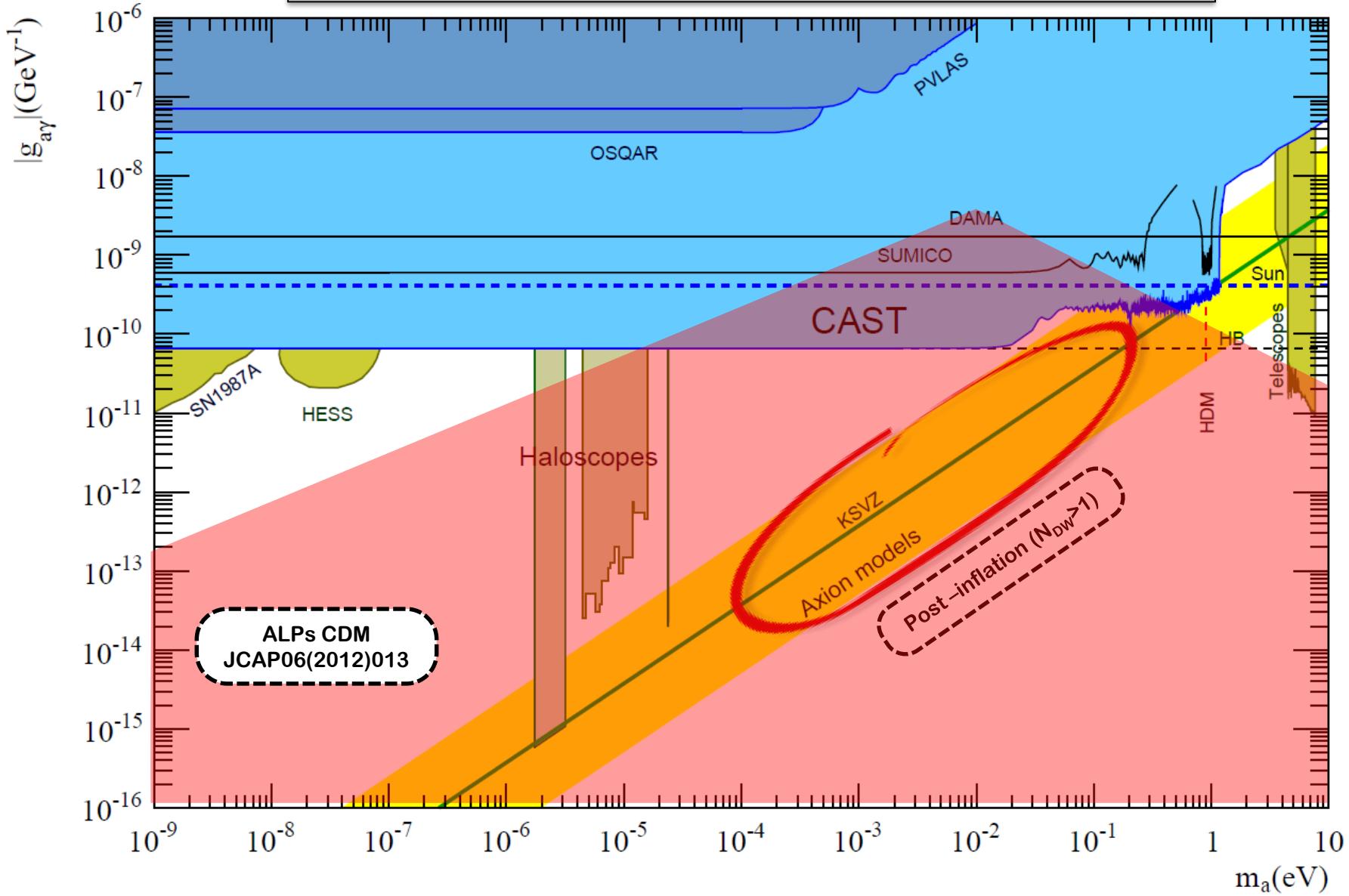
Axion/ALP parameter space



Axion/ALP parameter space



Axion/ALP parameter space

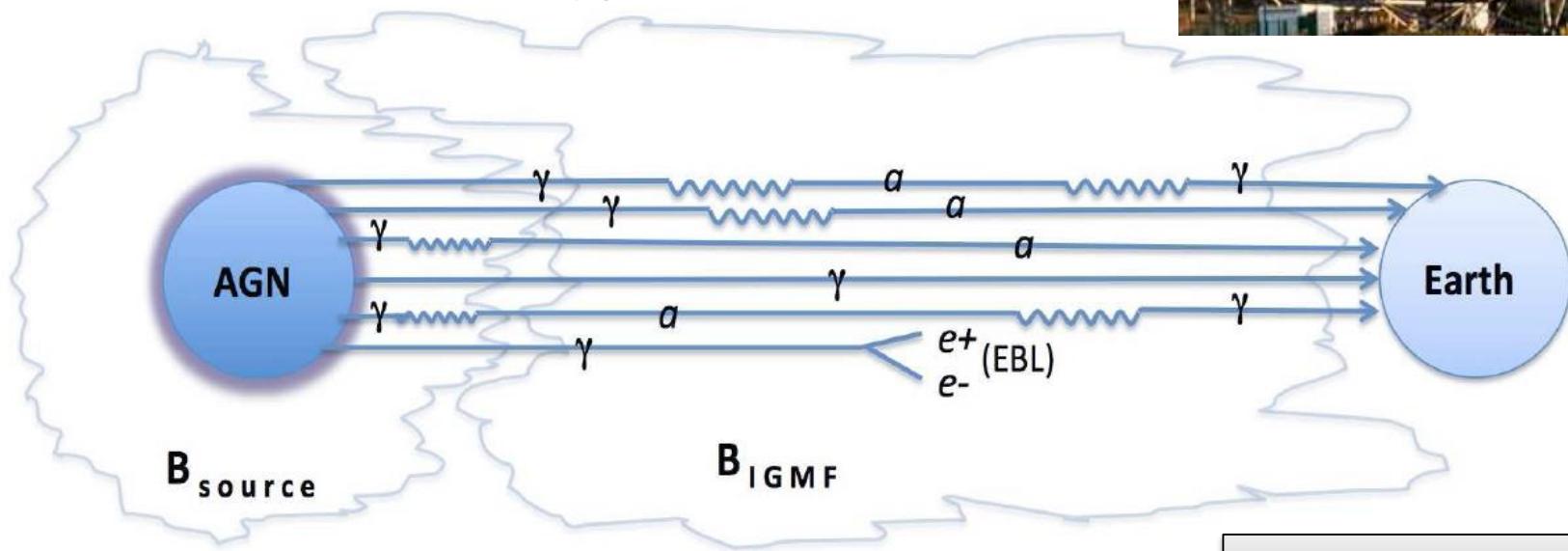


Astrophysical hints for axions

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

ALP:

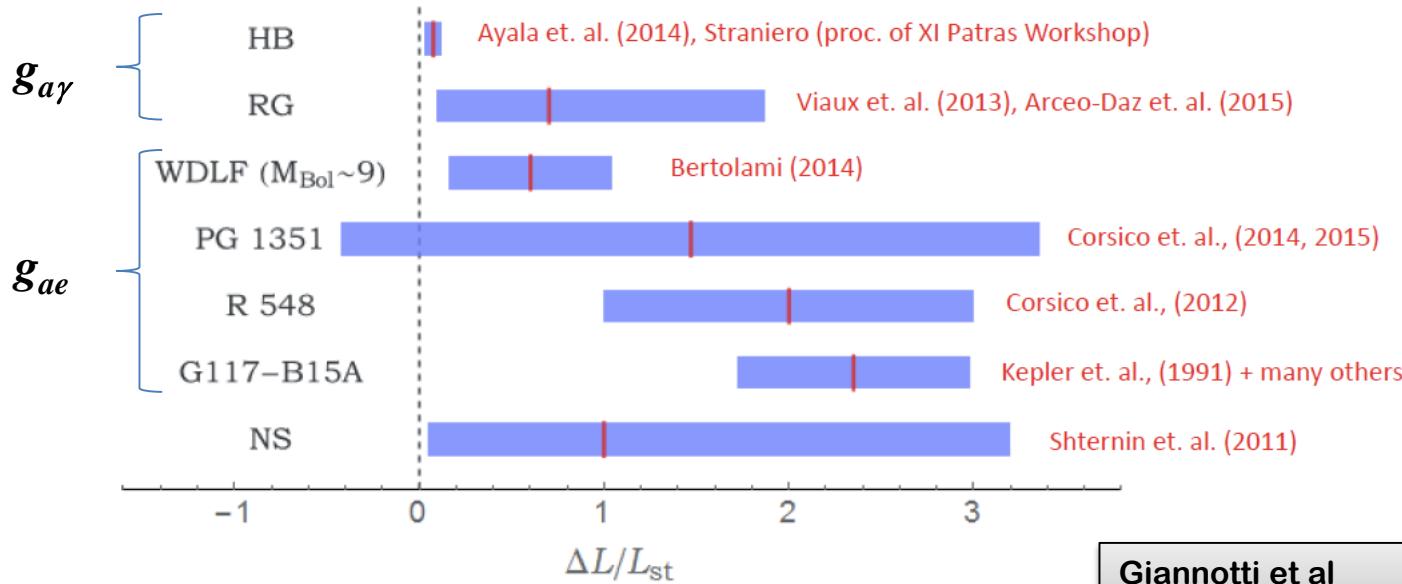
$$g_{a\gamma} \sim 10^{-12}-10^{-10} \text{ GeV}^{-1}$$
$$m_a \lesssim 10^{-(10-7)} \text{ eV}$$



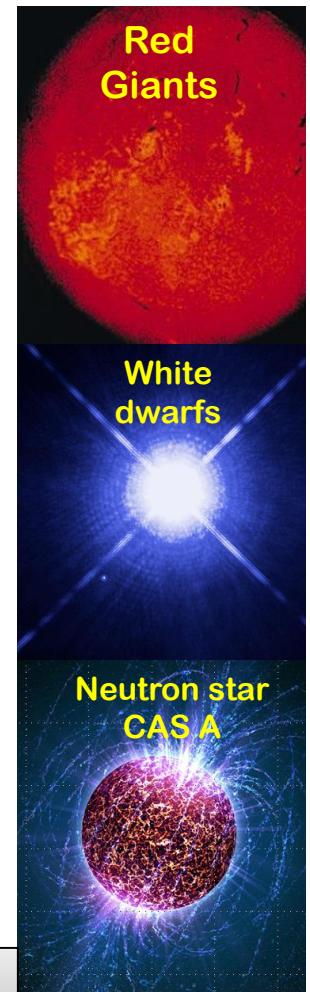
Many authors, e.g.
[Meyer, Horns, Troitsky,
Roncadelli...]

Astrophysical hints for axions (II)

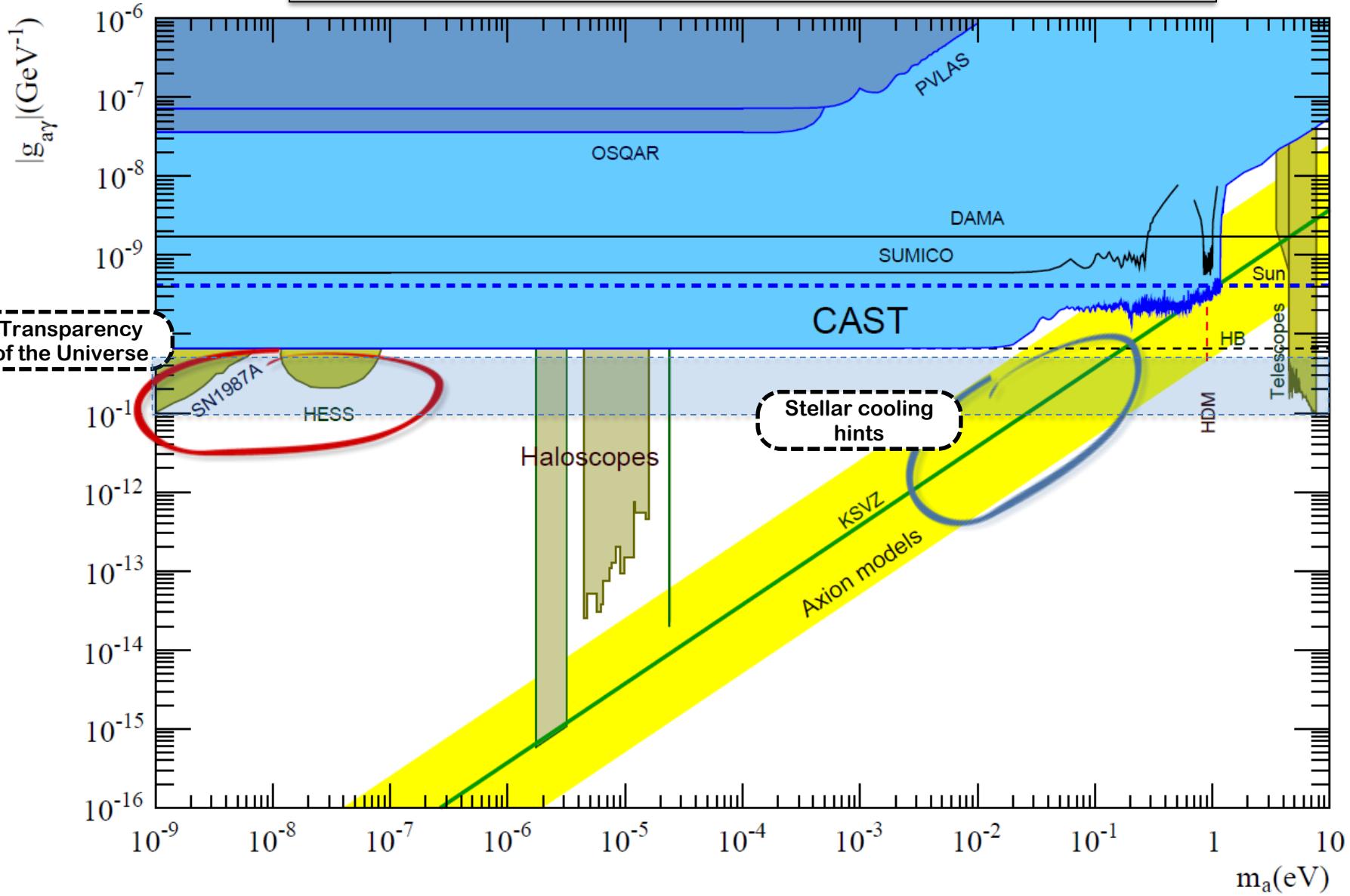
- Most stellar systems seem to cool down faster than expected.
- Presence of axions/ALPs offer a good joint explanation
- Parameters at reach of IAXO!



Giannotti et al
arXiv:1512.08108

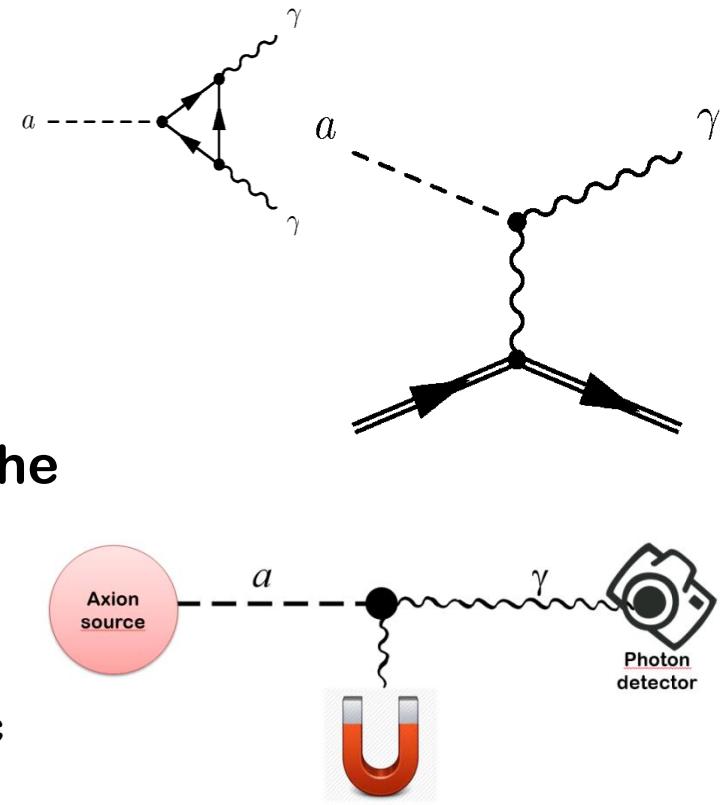


Axion/ALP parameter space



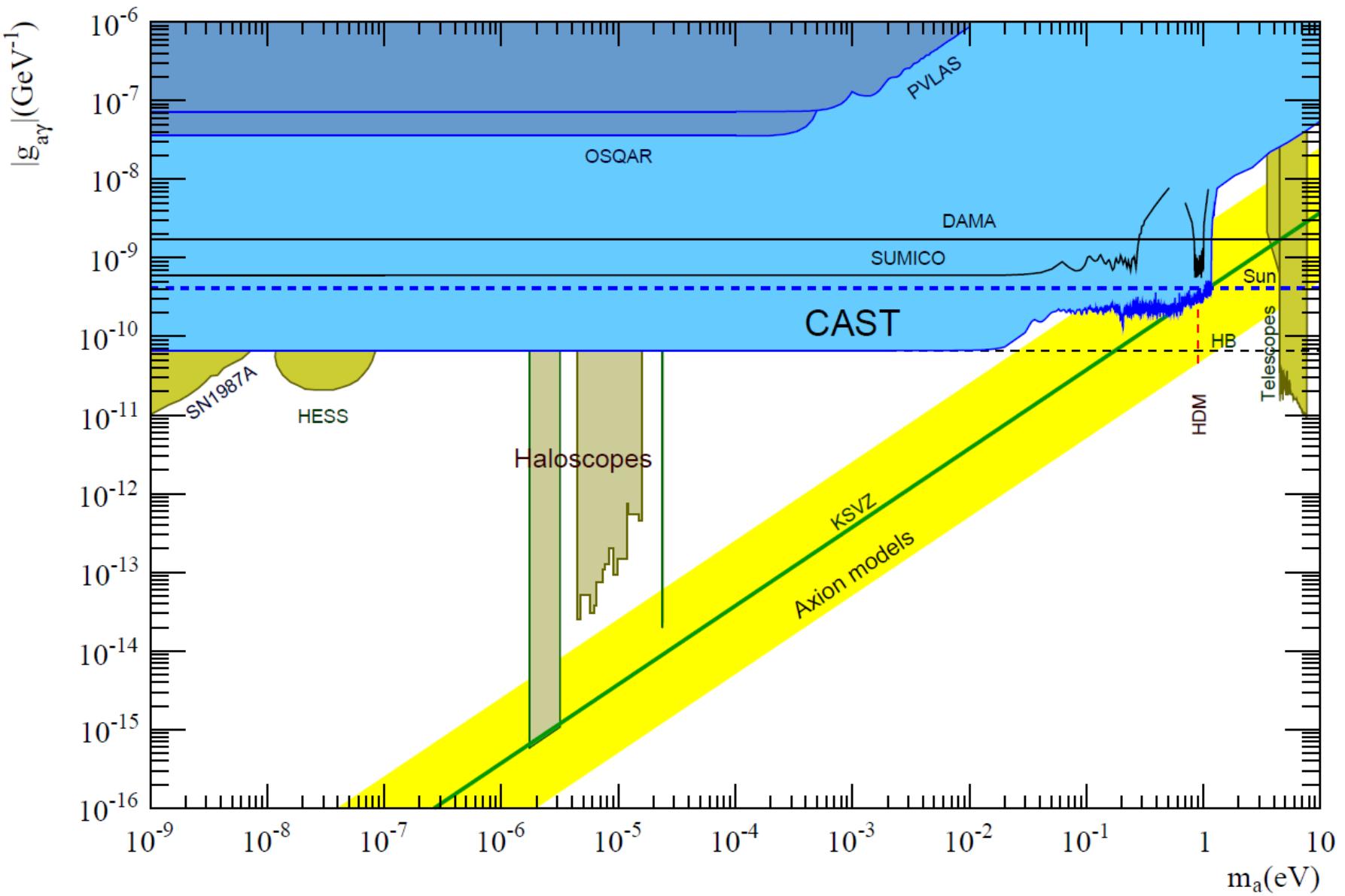
Detection of axions

- Axion – photon coupling *generically* present in every axion model.
 - **Axion-photon conversion** in the presence of an electromagnetic field (**Primakoff effect**)
 - Most detection techniques based on the axion-to-photon conversion inside **magnets**
- Other couplings possible, but less generic (model dependent)
→ axion-electron coupling
→ axion-nucleon coupling



Detection of axions

Source	Experiments	Model & Cosmology dependency	Technology
Relic axions	 ADMX, HAYSTAC, CASPER, CULTASK, and many others ...	High	New ideas emerging, Active R&D going on,...
Lab axions	 ALPS, OSQAR, CROWS, ARIADNE,...	Very low	
Solar axions	 SUMICO, CAST, IAXO	Low	Ready for large scale experiment



Detecting DM axions: “haloscopes”

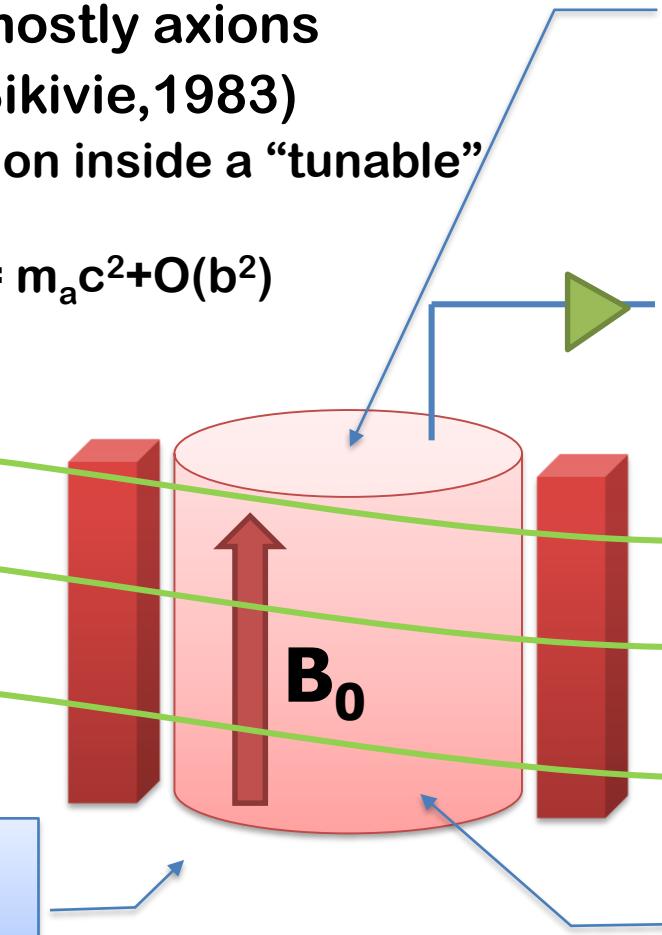
- Assumption: DM is mostly axions
- Resonant cavities (Sikivie, 1983)
 - Primakoff conversion inside a “tunable” resonant cavity
 - Energy of photon = $m_a c^2 + O(b^2)$

Primakoff conversion of
DM axions into
microwave photons
inside cavity

$$P_0 = g_{a\gamma}^2 V B^2 C \frac{\rho_a}{m_a} Q$$

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)

ADMX

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



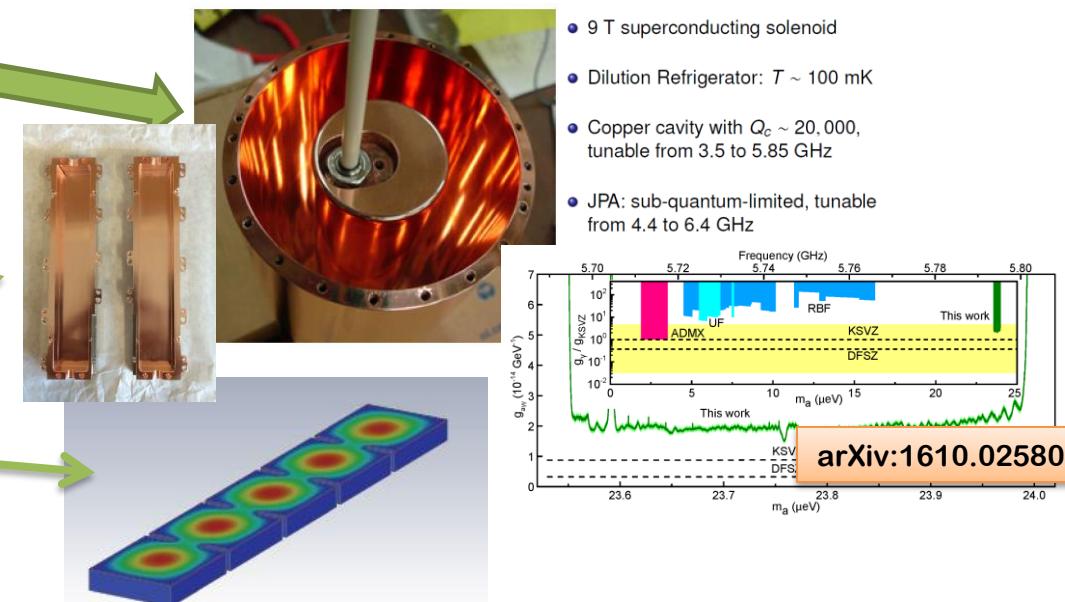
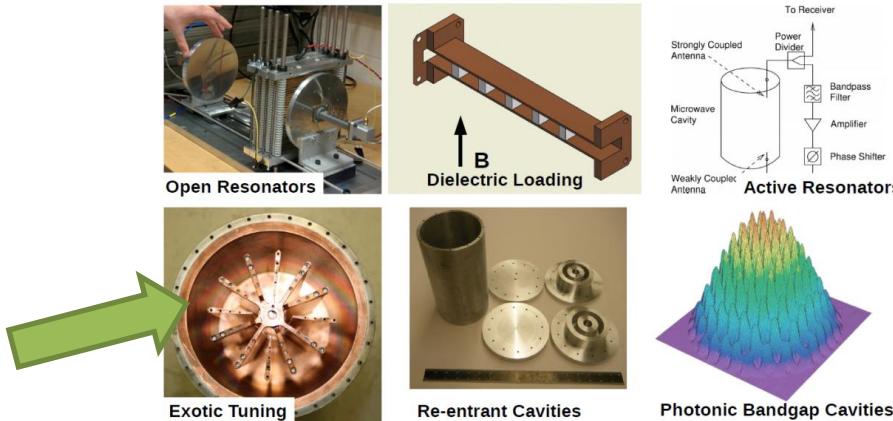
High frequency haloscopes

A subset of ideas being explored...

- Problematic: higher $m_a \rightarrow$ lower $V \rightarrow$ lower sensitivity
- Active R&D inside ADMX,

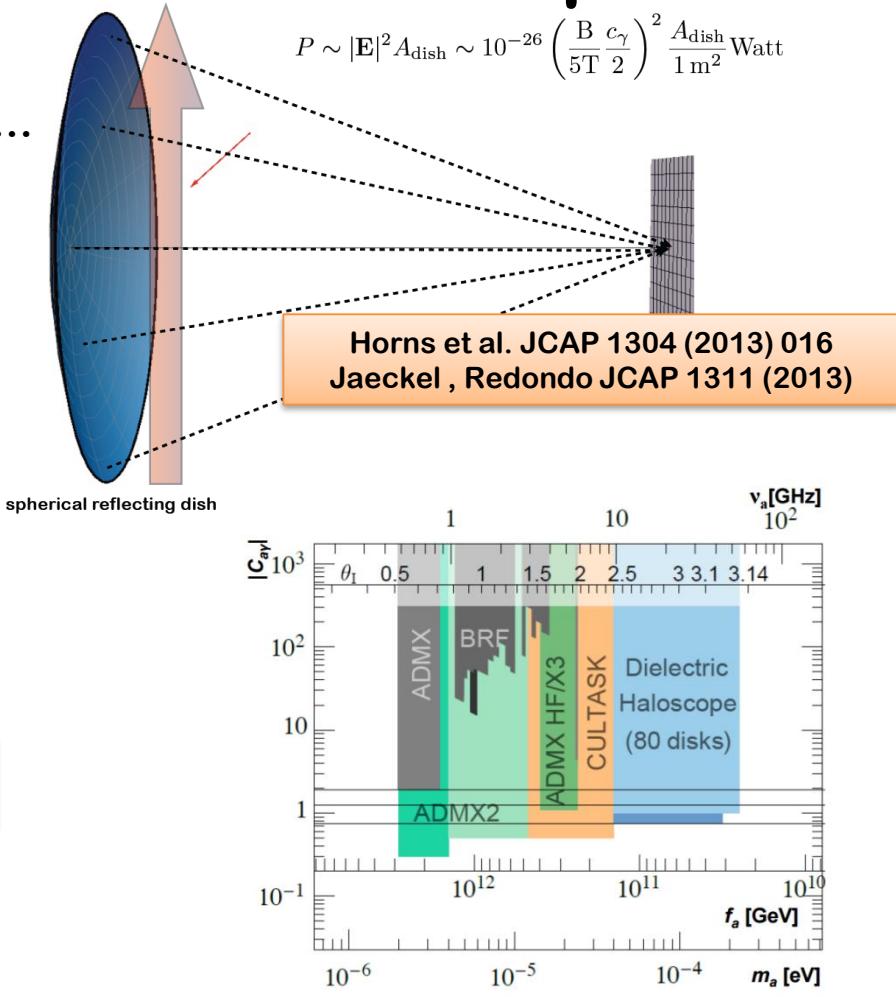
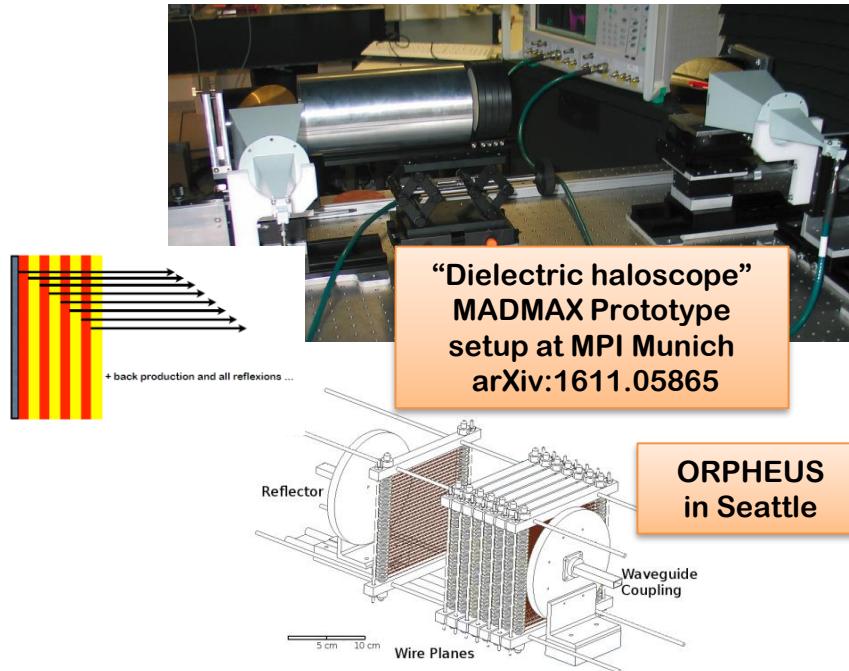
and many new projects:

- HAYSTAK (before ADMX-HF)
- CULTASK @ Korea
 - CAPP new institute in Korea
very important effort
+ lots of R&D
- CAST-CAPP
- RADES @ CAST
- ORGAN in Australia



Beyond haloscopes... Dish antennas & dielectric haloscopes

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



- Also: DM-induced atomic transitions (AXIOMA)

EPS-HEP, Venice, Italy,
July 2017

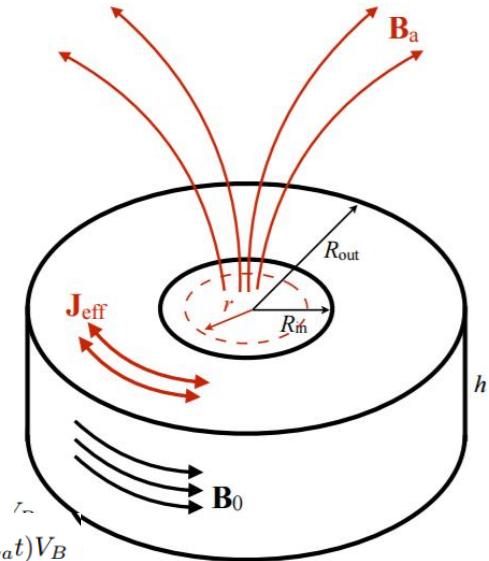
Igor G. Irastorza /
Universidad de Zaragoza

arXiv:1611.05865

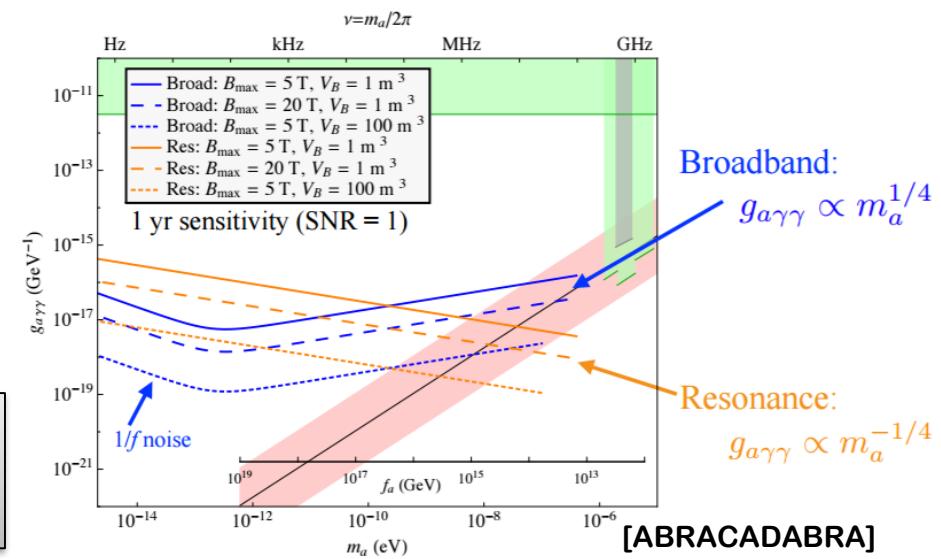
Beyond haloscopes...

Pick-up resonant LC circuit

- DM-induced oscillating B in the center of a toroidal magnet
- Both wideband search and resonance search possible
- Competitive at very low m_a
- Several teams starting R&D
 - DM-radio (SLAC)
 - ABRACADABRA (MIT)



$$\Phi_a(t) = g_{a\gamma\gamma} B_{\max} \sqrt{2\rho_{\text{DM}}} \cos(m_a t) V_B$$



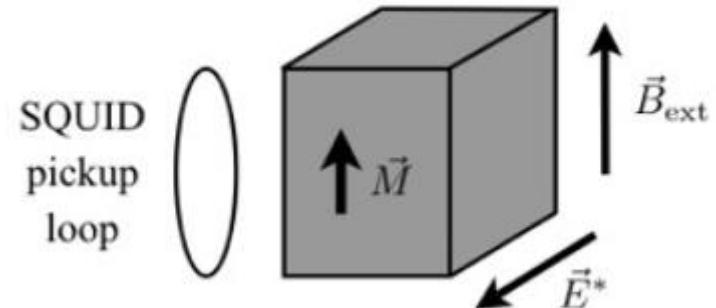
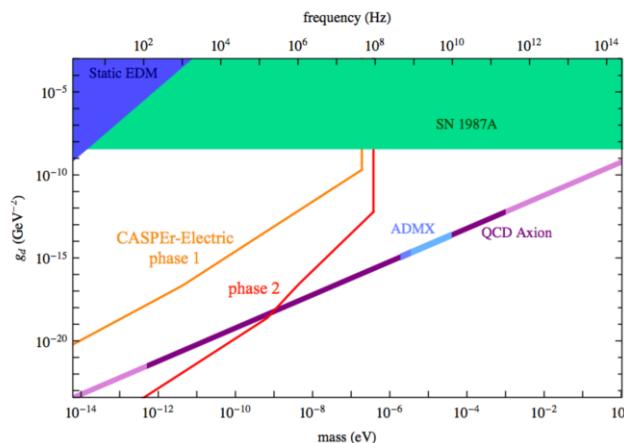
Sikivie et al arXiv:1310.8545

DM-Radio (SLAC) arXiv:1610.09344

ABRACADABRA (MIT) arXiv:1602.01086

Beyond haloscopes... DM-induced spin precession

- CASPEr experiment
(Mainz-Berkeley)
- Can test gluon & fermion couplings
- Competitive at very low m_a



$$\frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu} \quad \xleftarrow{\hspace{1cm}} \quad \text{Coupling to gluon field} \\ \text{CASPER Electric}$$

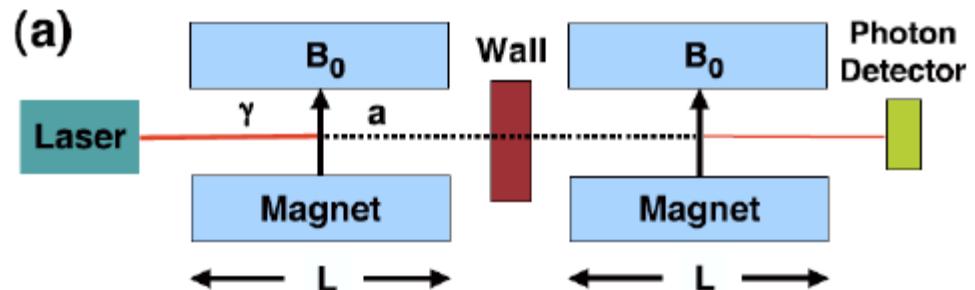
$$\frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f \quad \xleftarrow{\hspace{1cm}} \quad \text{Coupling to fermions} \\ \text{CASPER Wind}$$

Phys. Rev. X 4, 021030 (2014)

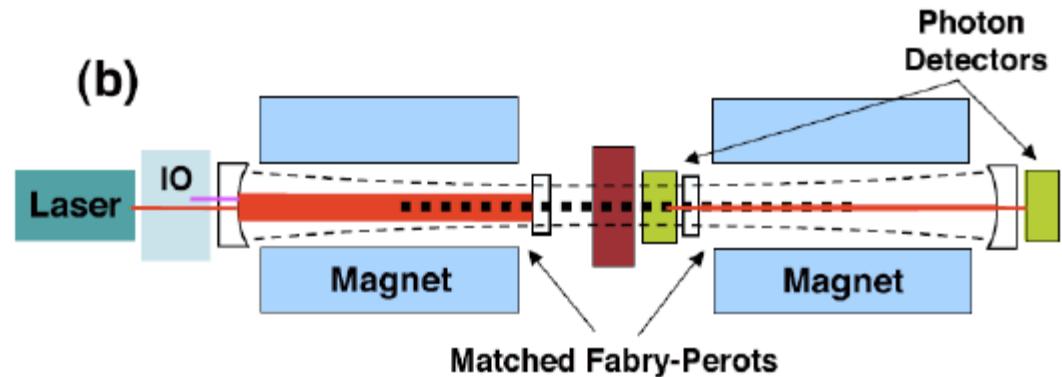
- Also QUAX experiment (Padova):
 - Sensitive to “axion DM wind” through axion-electron coupling

Light shining through wall

Standard configuration →



Enhanced “resonant” configuration (future) →



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

Also axion-induced effects like ellipticity/dichroism can be searched for.

ALPS @ DESY-Hamburg

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



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

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

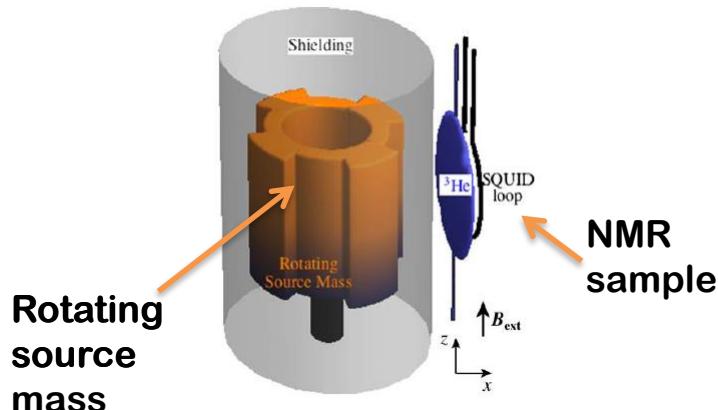
Axion-mediated macroscopic forces

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

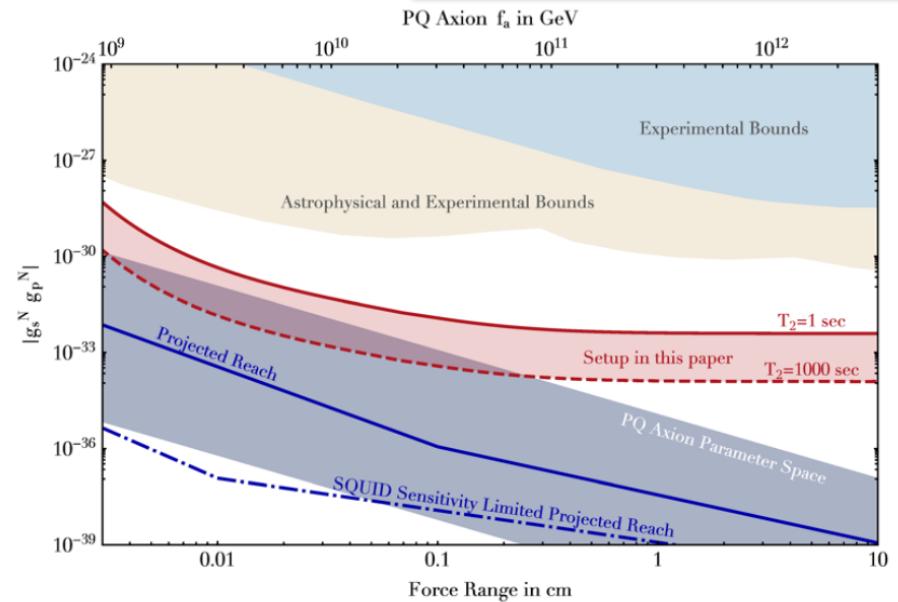
Recently proposed: ARIADNE experiment

Short-range force by NMR technique → direct probe of gluon term

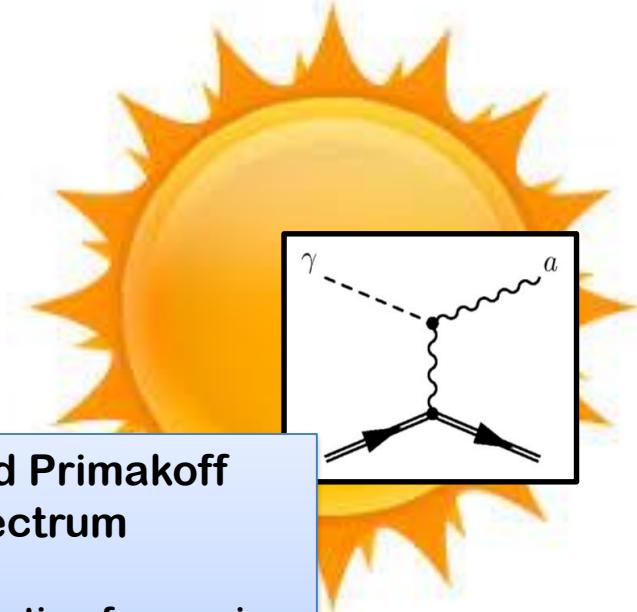
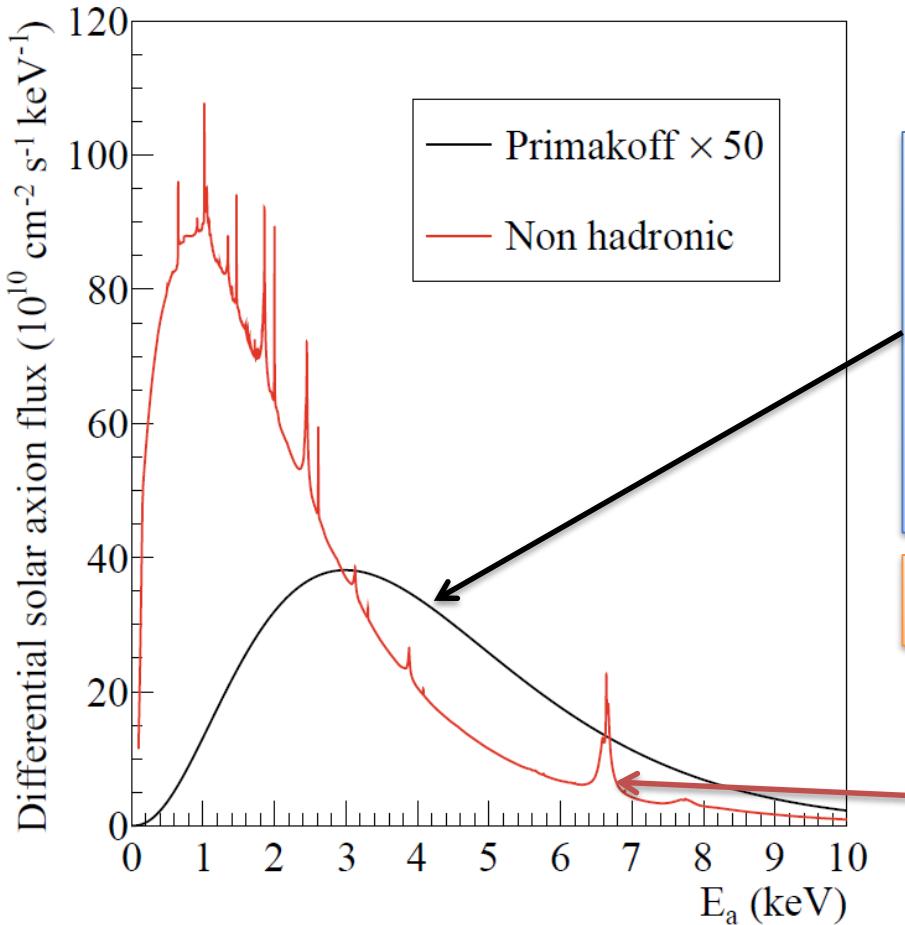
Good prospects for sub-meV axion



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



Solar Axions



Standard Primakoff spectrum

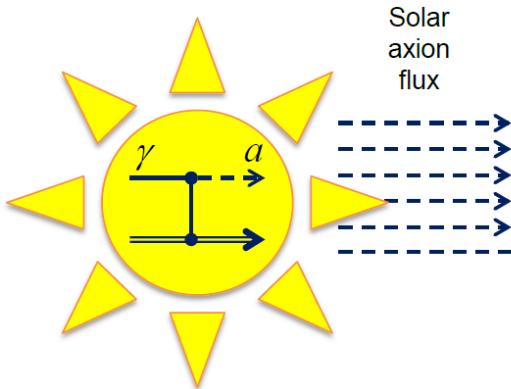
Robust prediction from axion models. Conversion of solar plasma photons into axion (only axion-photon coupling involved)

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

Non-hadronic “ABC” Solar axion flux at Earth (only if axion couples to electron)

Redondo, JCAP 1312 008

Axion helioscopes



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

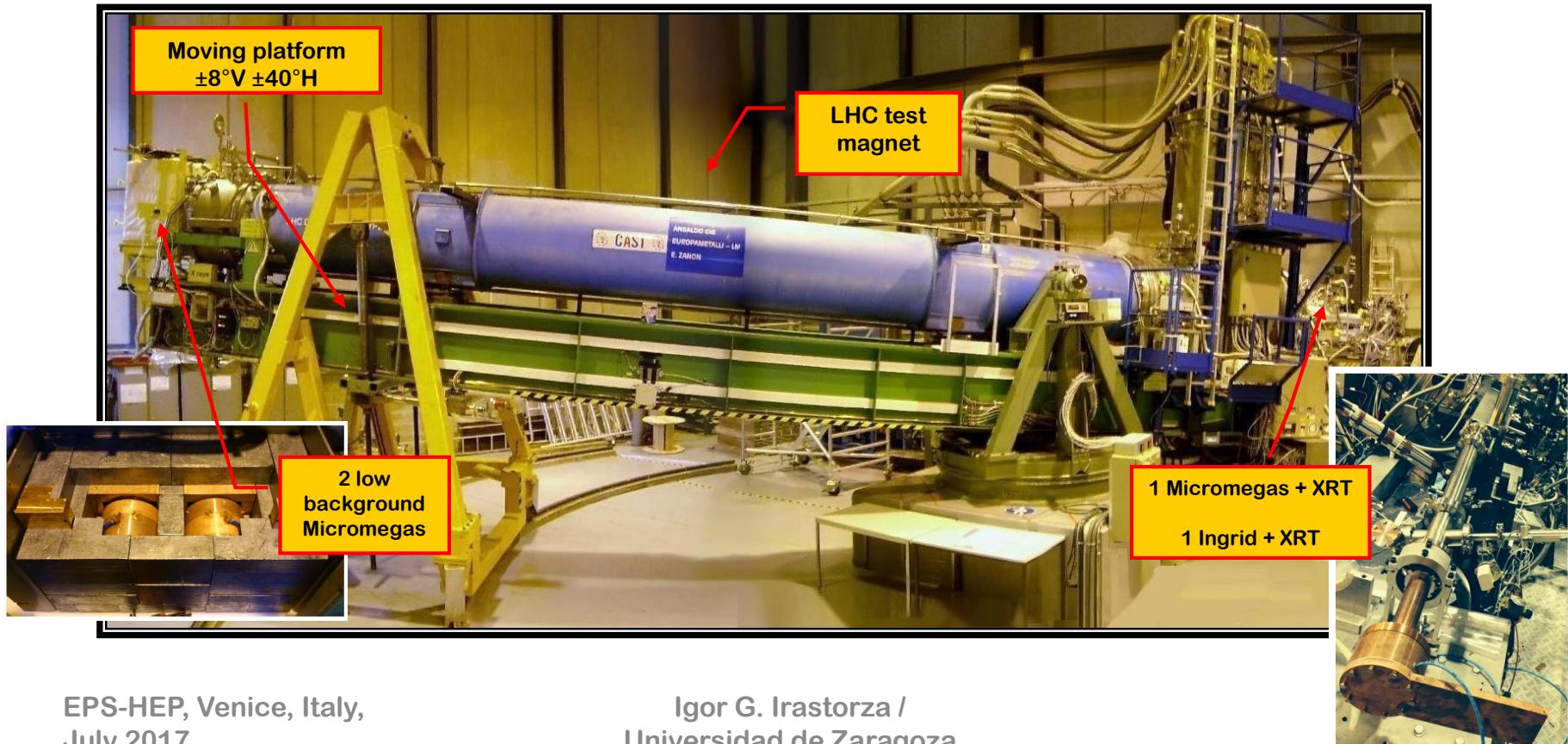
X-ray Focussing &
low-background
Later innovations by
CAST

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

Pioneer implementations of helioscope concept:
Brookhaven (just few hours of data) [Lazarus et al. PRL 69 (92)]
TOKYO Helioscope (SUMICO): 2.3 m long 4 T magnet

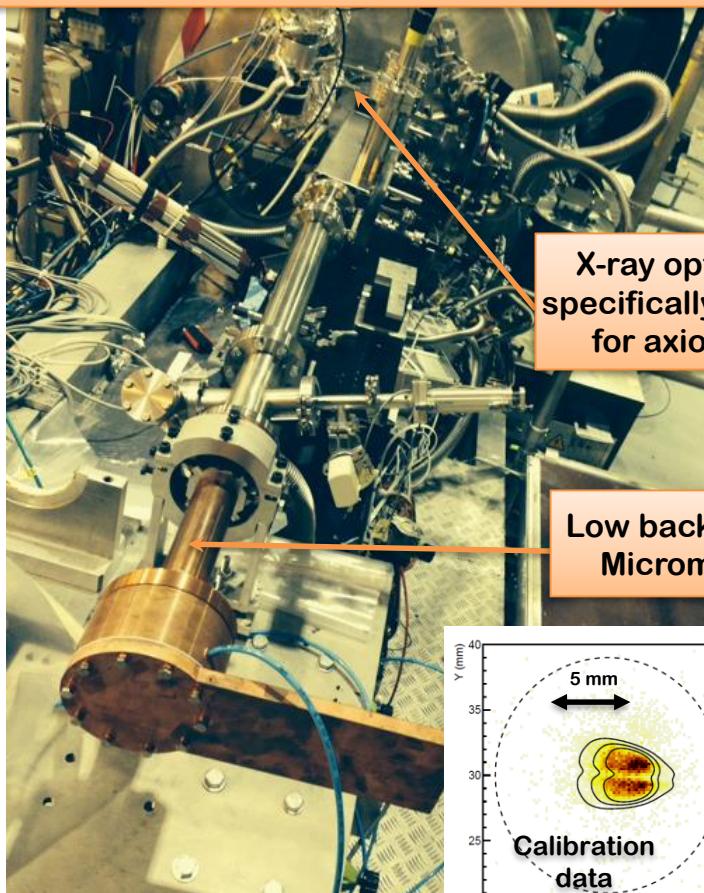
CAST experiment @ CERN

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



Last CAST limit

Enabled by the
IAXO pathfinder system



nature
physics

ARTICLES

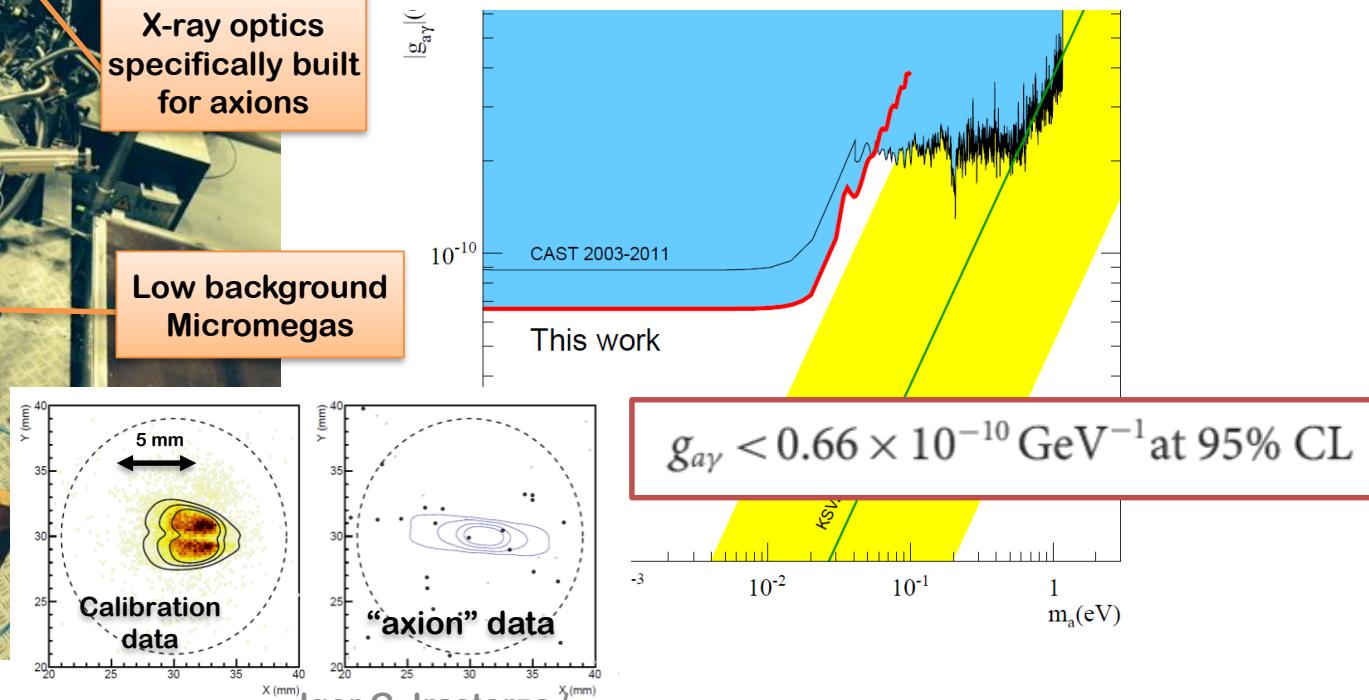
PUBLISHED ONLINE: 1 MAY 2017 | DOI: 10.1038/NPHYS4109

OPEN

New CAST limit on the axion-photon interaction

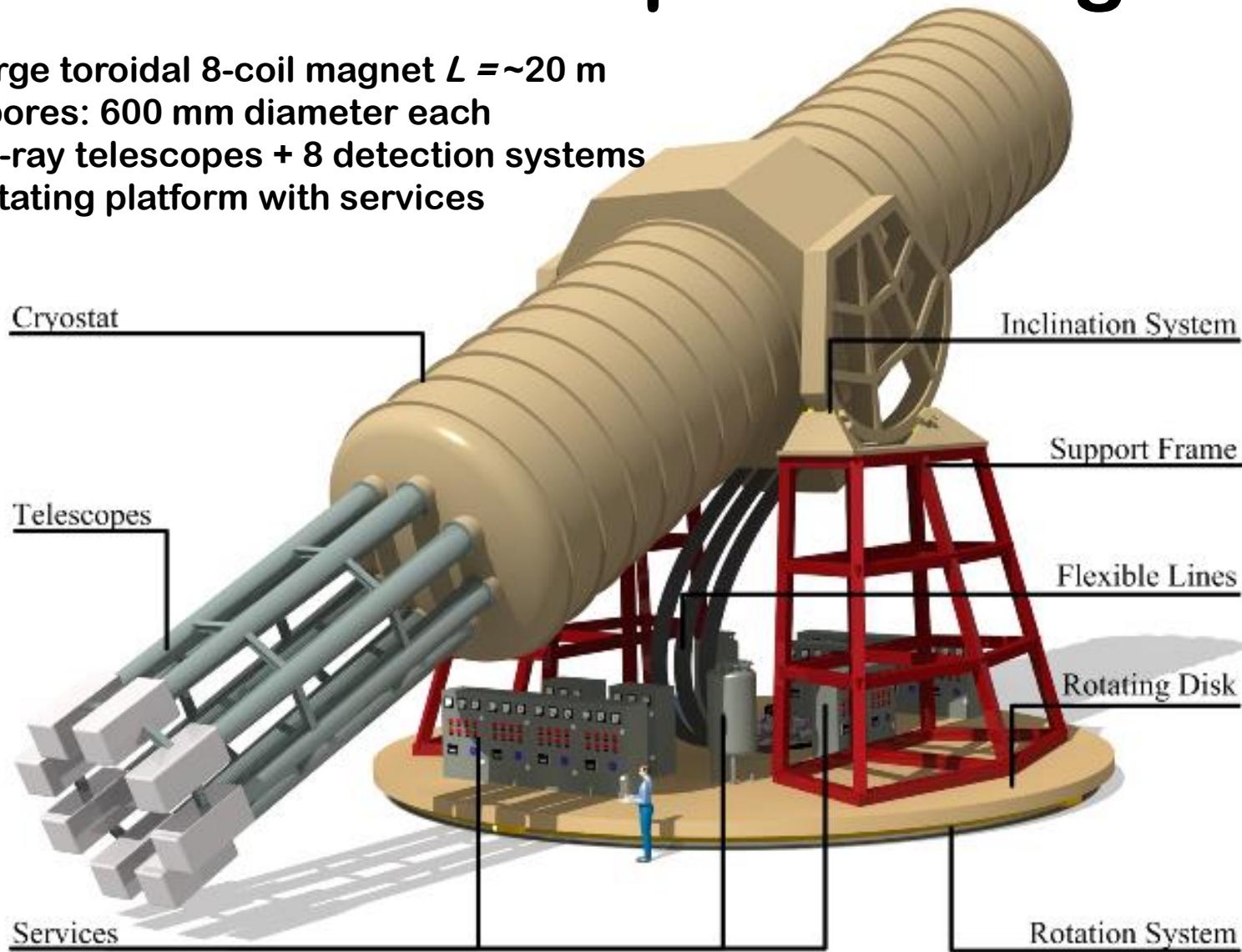
CAST Collaboration[†]

Hypothetical low-mass particles, such as axions, provide a compelling explanation for the dark matter in the universe. Such particles are expected to emerge abundantly from the hot interior of stars. To test this prediction, the CERN Axion Solar Telescope (CAST) uses a 9 T refurbished Large Hadron Collider test magnet directed towards the Sun. In the strong magnetic field, solar axions can be converted to X-ray photons which can be recorded by X-ray detectors. In the 2013–2015 run, thanks to low-background detectors and a new X-ray telescope, the signal-to-noise ratio was increased by about a factor of three. Here, we report the best limit on the axion-photon coupling strength ($0.66 \times 10^{-10} \text{ GeV}^{-1}$ at 95% confidence level) set by CAST, which now reaches similar levels to the most restrictive astrophysical bounds.



IAXO – Conceptual Design

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

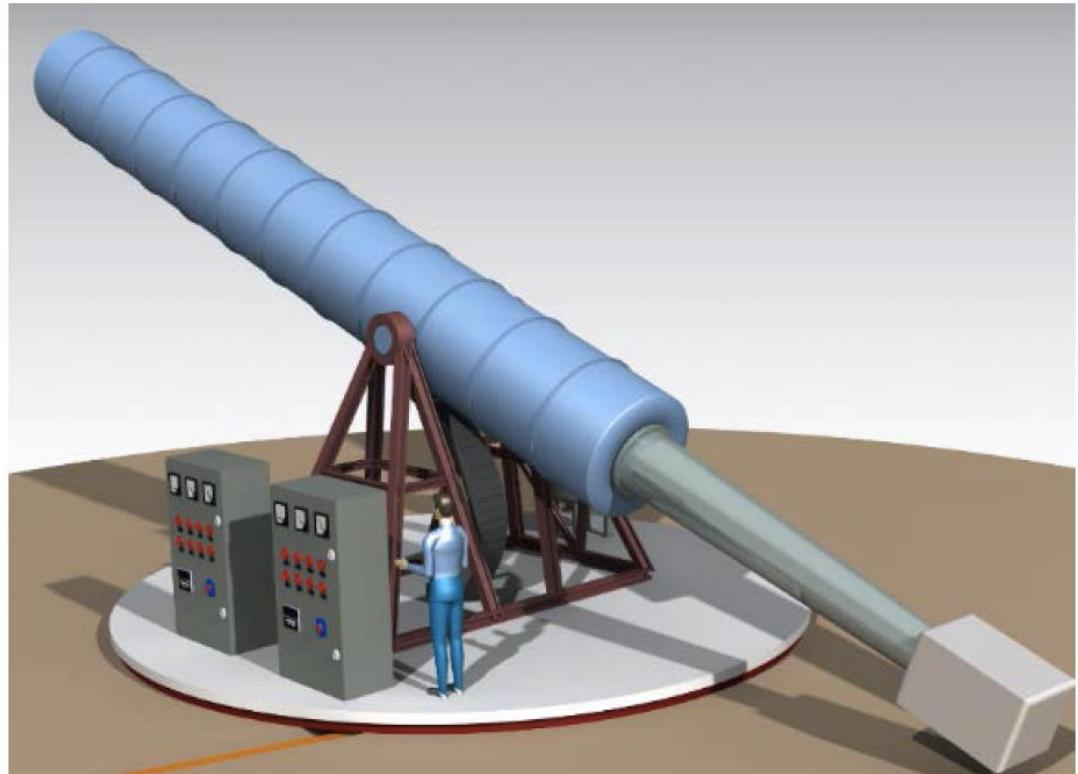


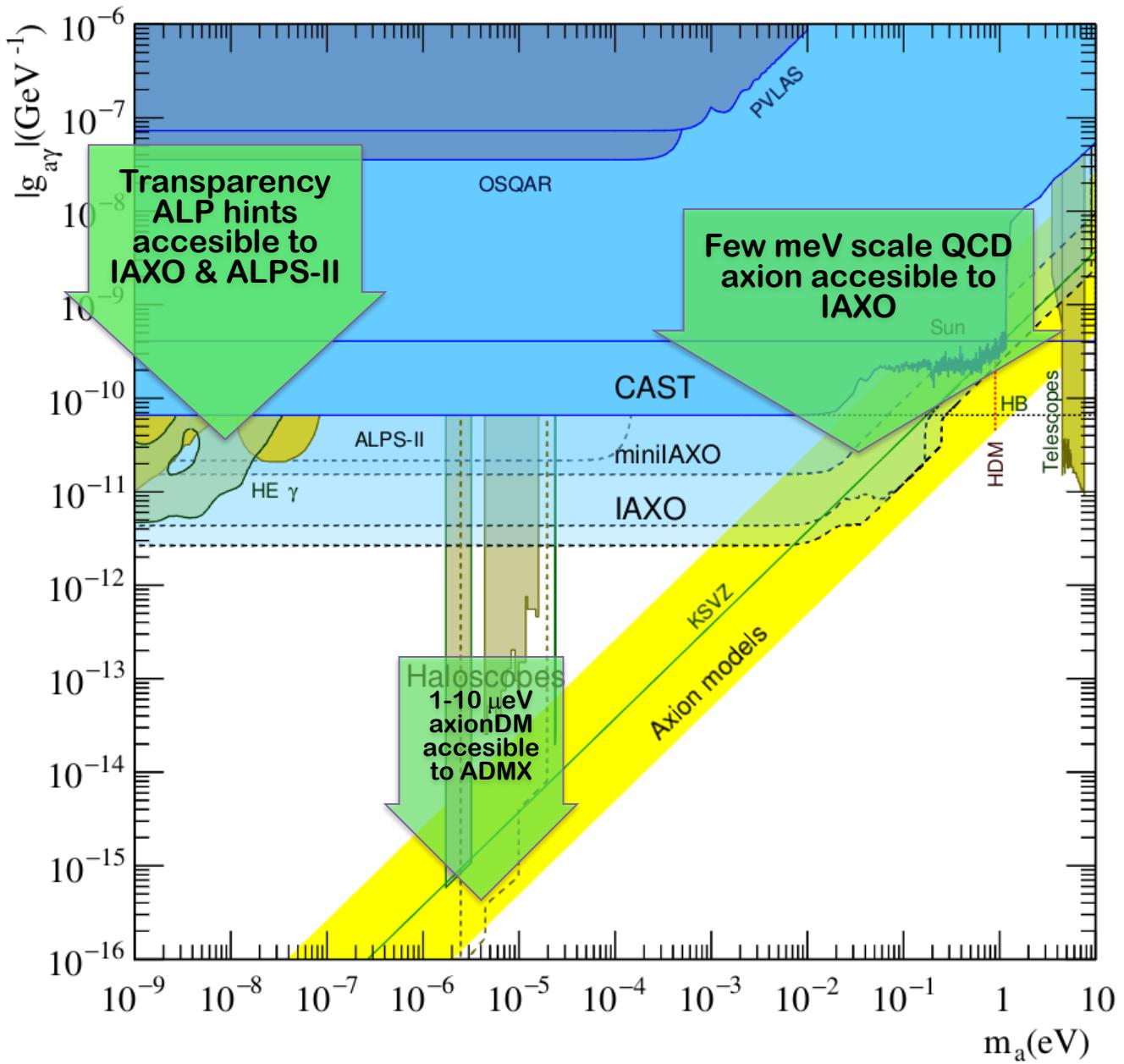
BabyIAXO – first step towards IAXO

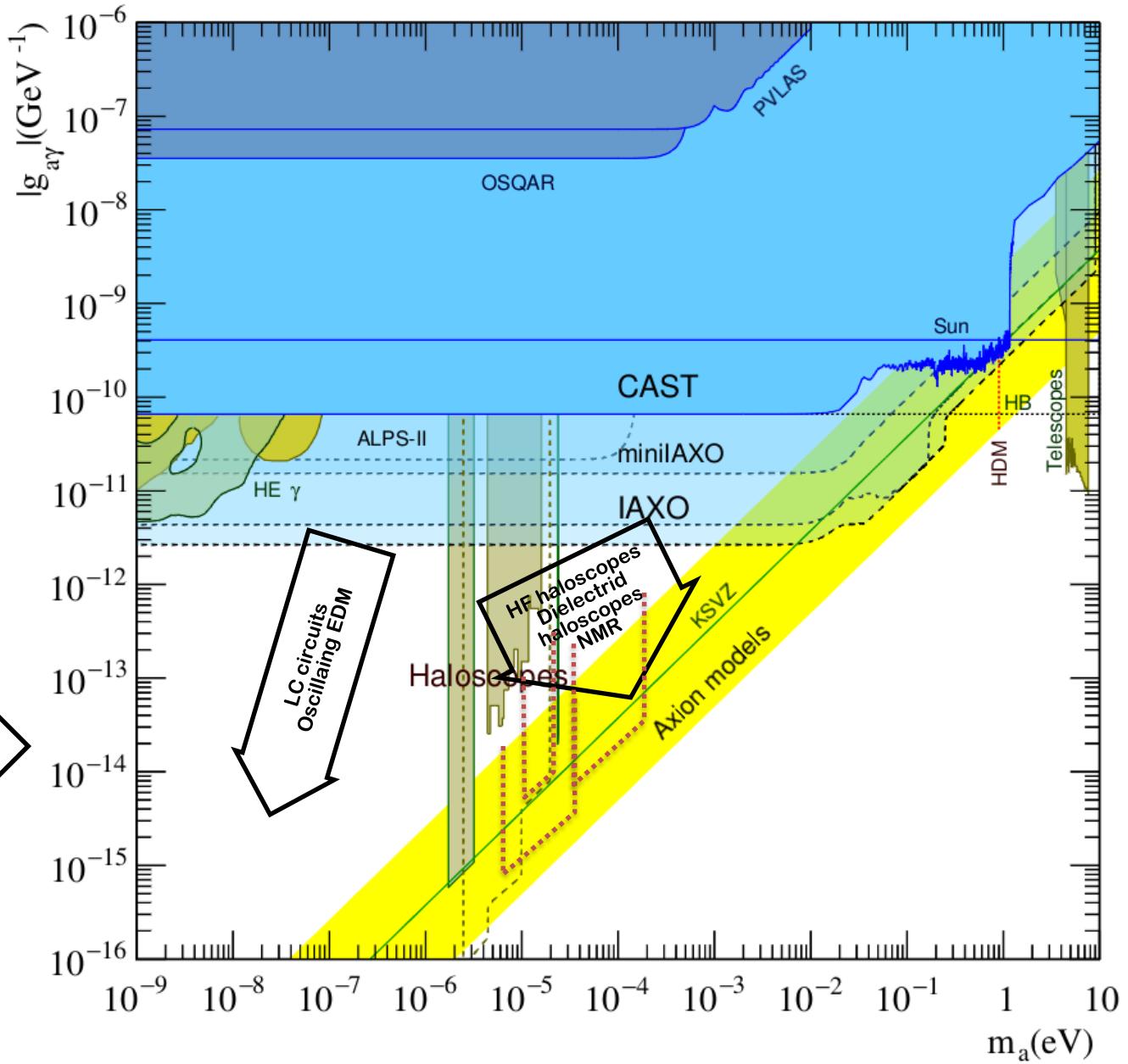
- Prototype of magnet design for full IAXO
- Test optics & detectors
- Provide relevant intermediate physics outcome
- Better access to funding & engage community into experimental activity

IAXO collaboration formally established with 17 participant institutions in recent meeting 3-4 July 2017

DESY strong candidate to host the experiment

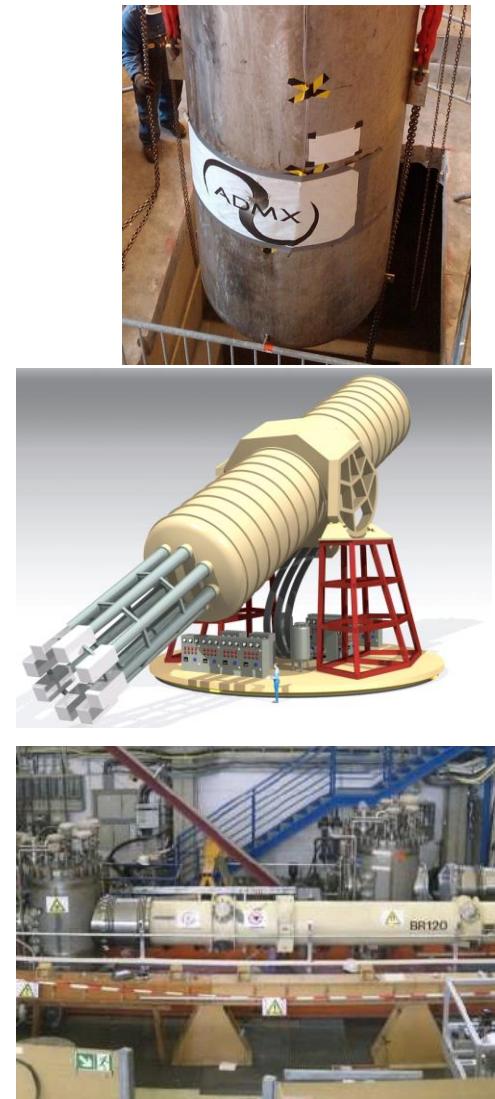






Conclusions

- Increasing interest for axions:
 - Beyond axions: ALPs
 - Increasing experimental effort (still small!)
 - Consolidation of classical detection lines: ADMX, CAST, ALPs,...
 - ADMX and CAST have firstly probed interesting (small) fraction of par space.
 - Helioscopes: next generation IAXO.
 - Haloscopes:
 - ADMX, CAPP → R&D to go higher m_a
 - New ideas to tackle new regions:
 - Dielectric haloscope, NMR,...
 - Large fraction of parameter space at reach of near-future experiments
 - **chances of discovery!**
- Good timing for axions... stay tuned



Backup slides...

Axions: theory motivation

- Peccei-Quinn solution to the **strong CP problem** or **why QCD seems not to violate CP**, while one would expect to do so
- New U(1) symmetry introduced in the SM: Peccei Quinn symmetry of scale f_a
- The AXION appears as the **Nambu-Goldstone boson** of the spontaneous breaking of the PQ symmetry

This QCD term is **CP violating**.

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

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



θ absorbed in
the definition of a

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

$\theta = a/f_a$ relaxes to zero...

CP conservation is preserved “dinamically”

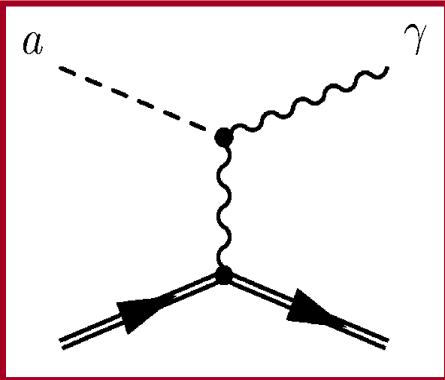
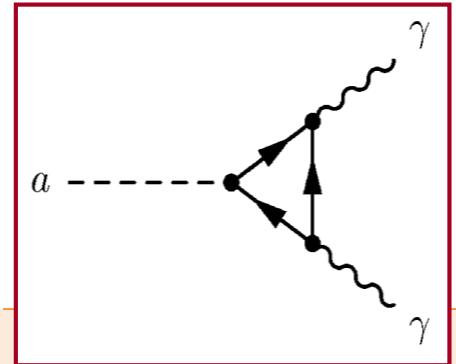
$a \rightarrow$ New field: the axion. Very light:

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

Axion phenomenology

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

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



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

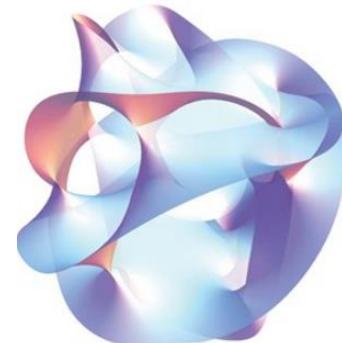
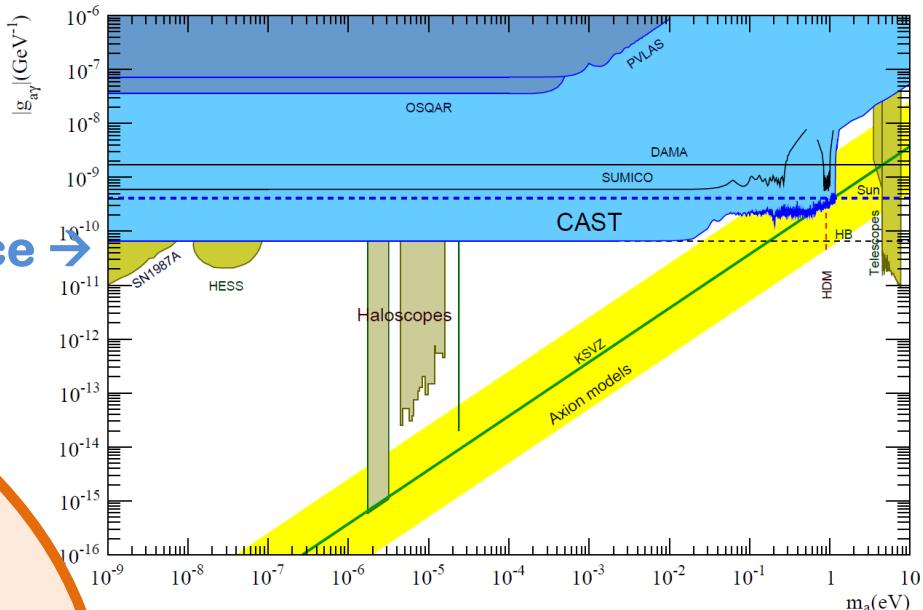
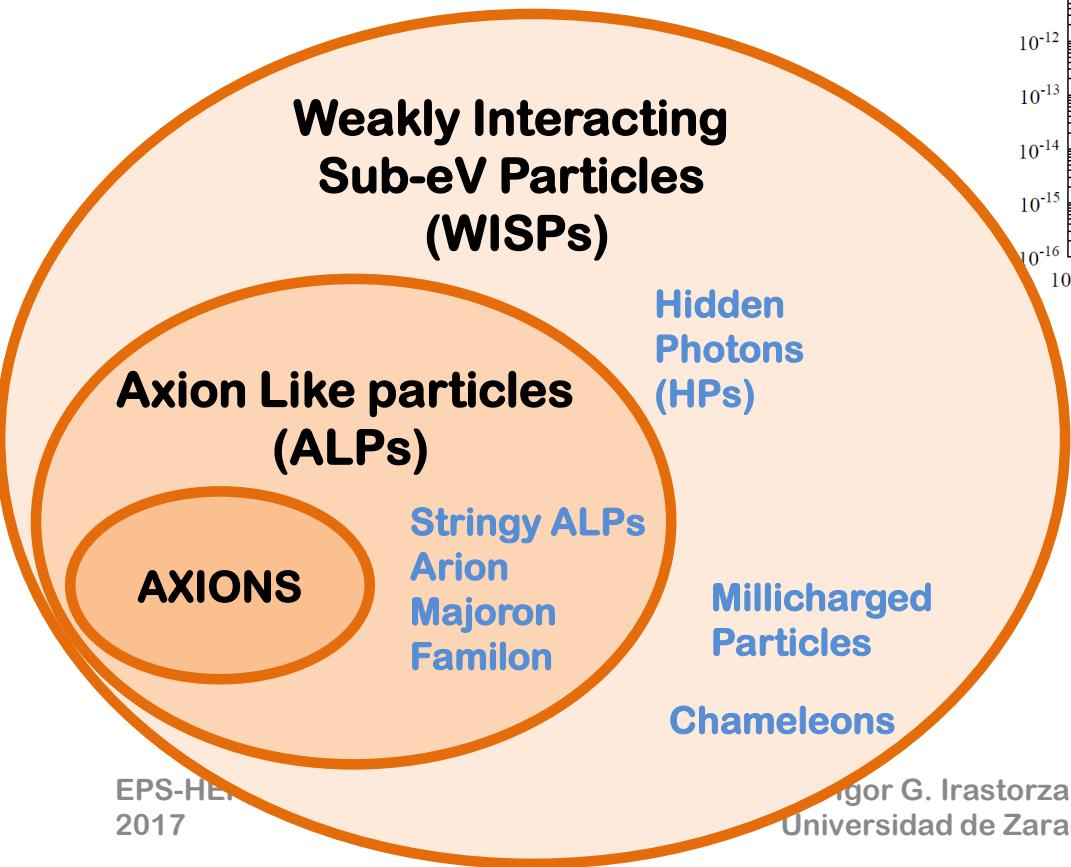
This is probably the most relevant of axion properties.

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

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

Axions: theory motivation

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

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

This term is **CP violating**.

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

2 contributions of
very different origin...

From non-observation of
neutron electric dipole
moment:

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

- Why so small?
- High fine-tunning required for this to work in the SM

Axions: theory motivation

- Peccei-Quinn solution to the **strong CP problem** or **why QCD seems not to violate CP**, while one would expect to do so
- New U(1) symmetry introduced in the SM: Peccei Quinn symmetry of scale f_a
- The AXION appears as the **Nambu-Goldstone boson** of the spontaneous breaking of the PQ symmetry

“Axion lagrangian”

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

θ absorbed in
the definition of a



$\theta = a/f_a$ relaxes to zero...

CP conservation is preserved “dinamically”

The axion

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

(Weinberg, Wilcek)

- **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)

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

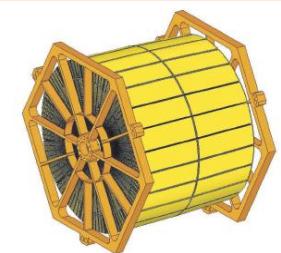


$$m_a \simeq 0.6 \text{ eV} \frac{10^7 \text{ GeV}}{f_a}$$

IAXO technologies – Baseline

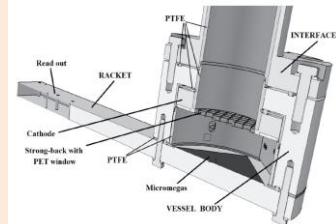
IAXO telescopes

- 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



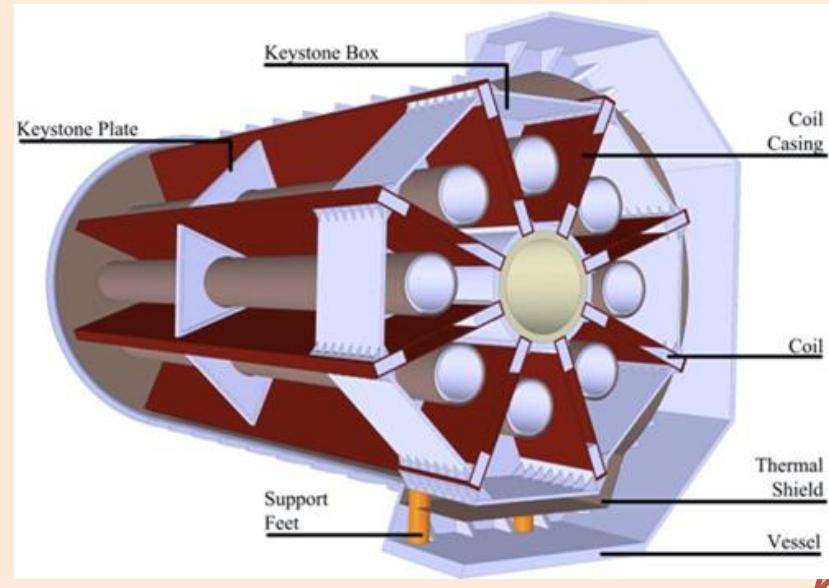
IAXO detectors

- 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.
- Toroidal 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)

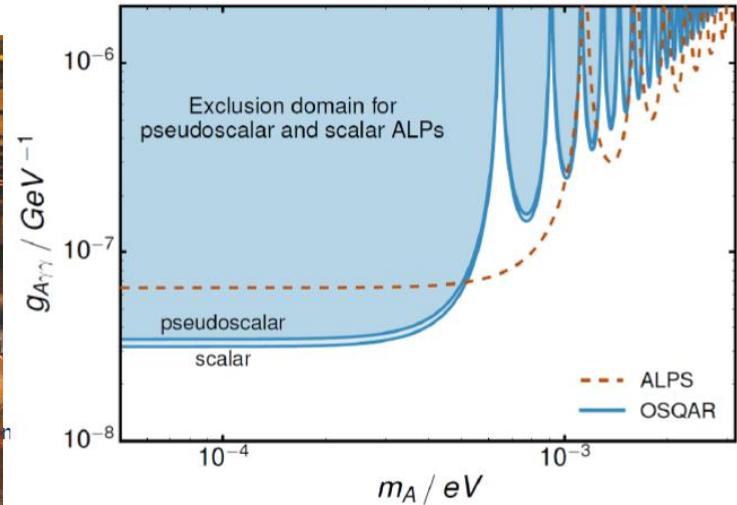
SERVICES

EPS-HEP, Venice, Italy,
July 2017

Igor G. Irastorza /
Universidad de Zaragoza

Rotation System

OSQAR @ CERN

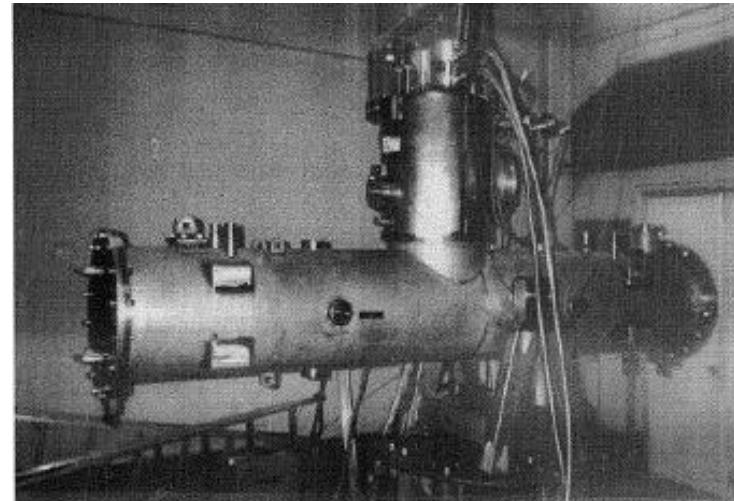
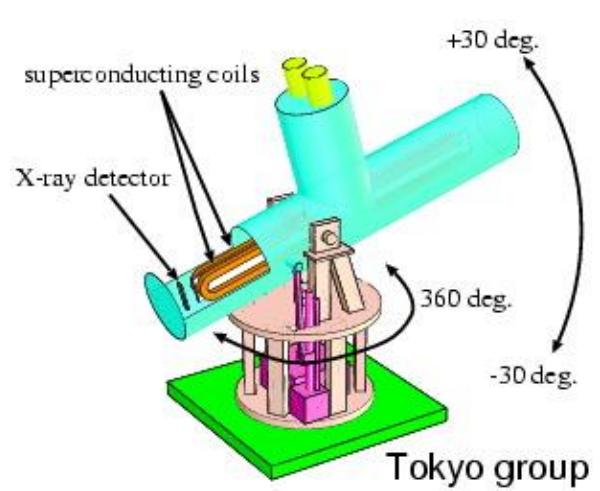


Also:

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

Axion Helioscopes

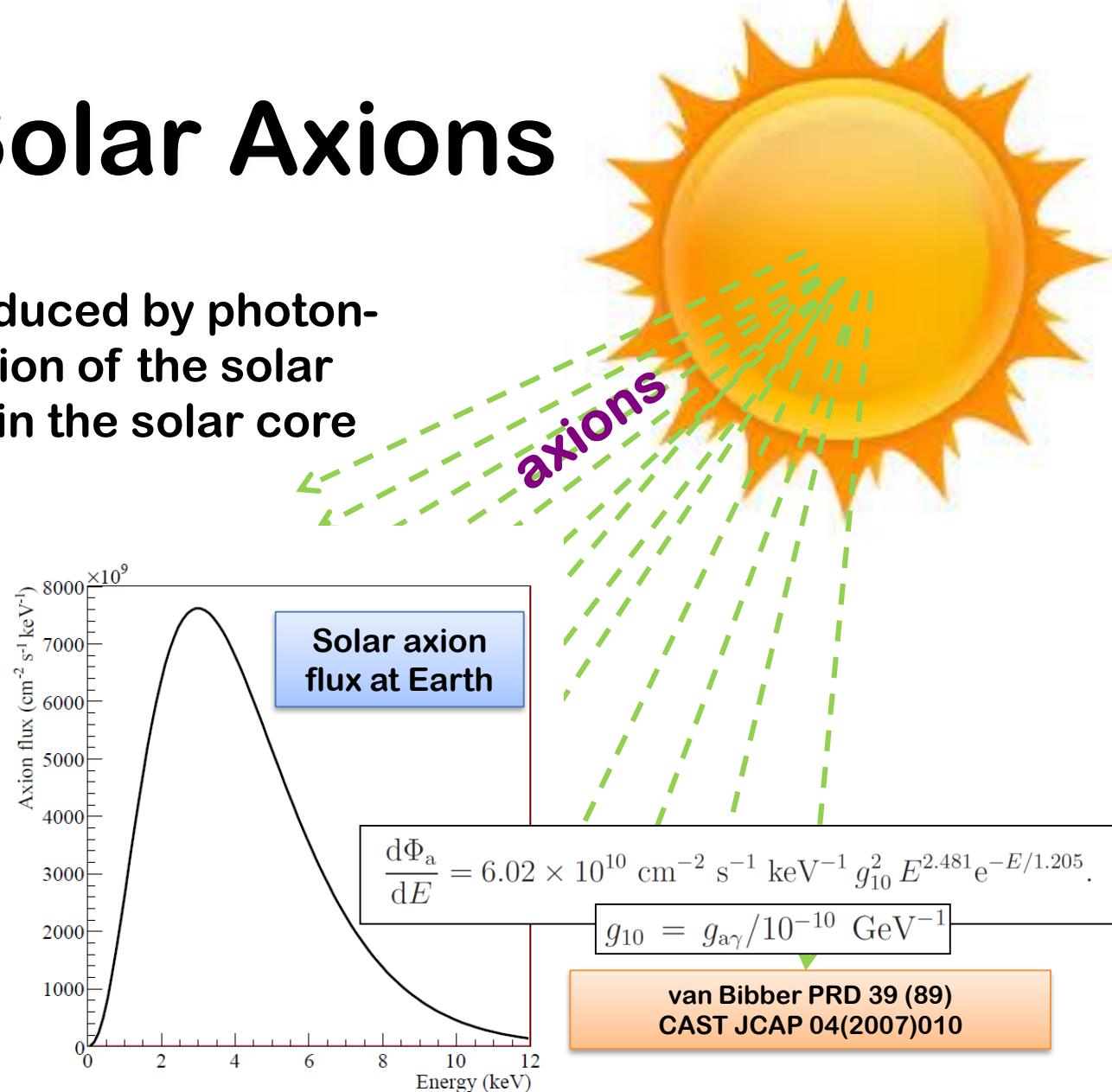
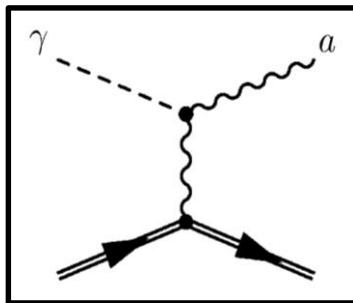
- Previous helioscopes:
 - First implementation at Brookhaven (just few hours of data) [Lazarus et al. PRL 69 (92)]
 - TOKYO Helioscope (SUMICO): 2.3 m long 4 T magnet



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

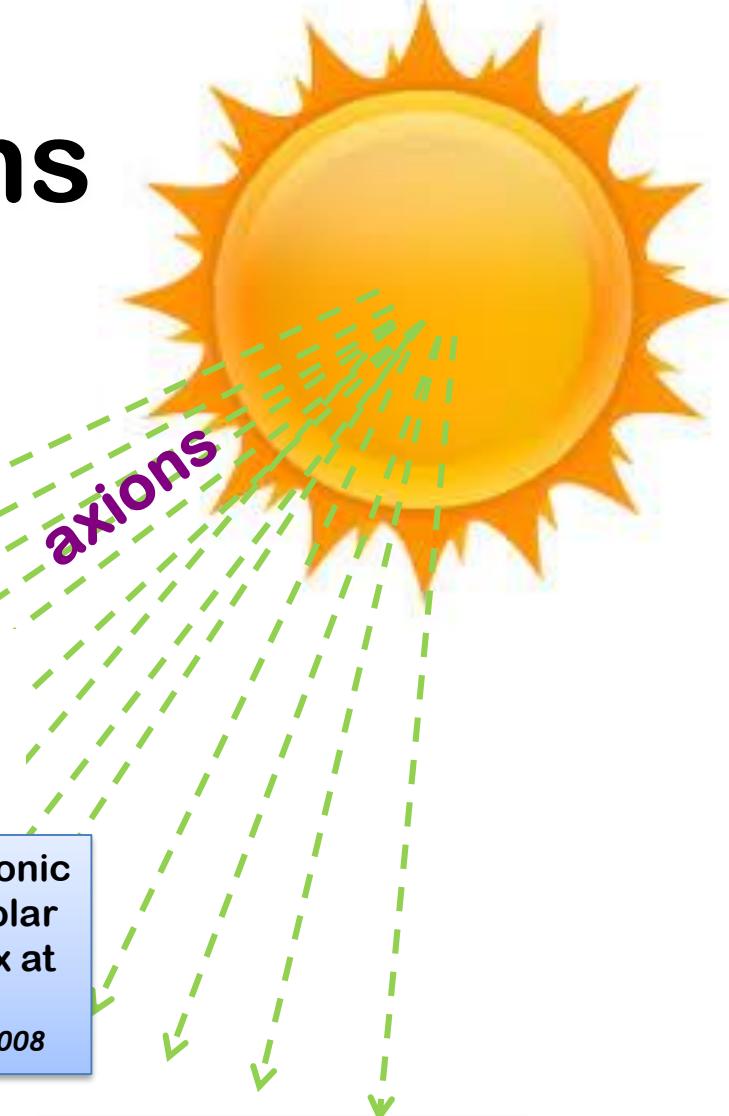
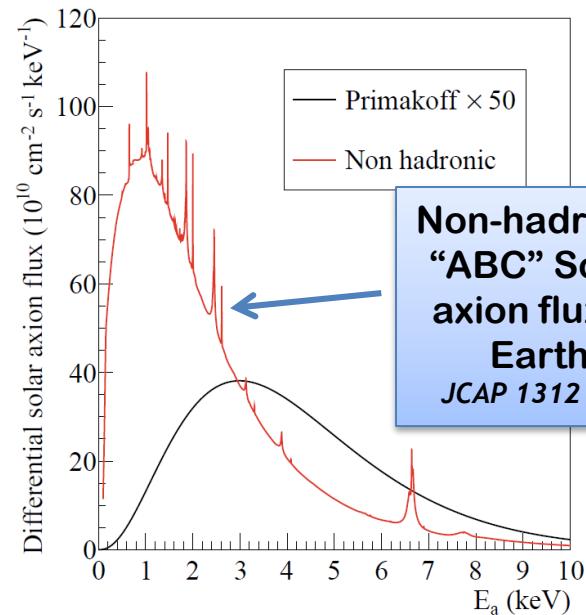
Solar Axions

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



Solar Axions

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



* 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)

