Axions

Ciaran O'Hare

- **Strong CP problem**
- **Peccei-Quinn mechanism**
- **Axion-like particles (ALPs)**
- **Axion cosmology**
- **Experimental searches for axions and ALPs**

Strong CP problem

Most general QCD lagrangian:

Gluon fields — **Quarks** — **CP-violating term**

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + \sum_q \bar{q}(i\gamma_\mu D^\mu - \mathcal{M}_q) q + \frac{\theta g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

Gives an electric dipole moment (EDM) to the neutron

Which is constrained to very small value

Hence QCD seems to have no CP violation

$$|d_n| = \frac{e\, m_u m_d}{(m_u + m_d) m_n^2} \bar{\theta} \quad < 2.9 \times 10^{-26}\, e\,\mathrm{cm} \quad \Longrightarrow \quad \bar{\theta} < 10^{-10}$$

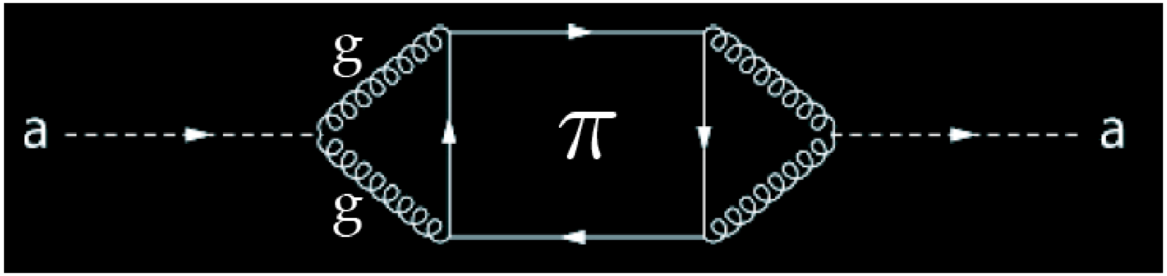
Why is the CP-violating phase so unnaturally small?

Peccei-Quinn mechanism

- Solution to strong-CP problem = promote phase to dynamical field

$$\mathcal{L}_{\text{QCD+axion}} = \ldots + \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{g^2}{32\pi^2}\frac{a(x)}{f_a}G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

- Field driven to zero under spontaneous breaking of a new global U(1) symmetry (Peccei-Quinn symmetry)
- Comes with a Goldstone boson: a new particle called **the axion**
- **Small mass** given by QCD instanton effects – pion mixing



$$m_a \sim 6\,\text{eV}\left(\frac{10^6\,\text{GeV}}{f_a}\right)$$

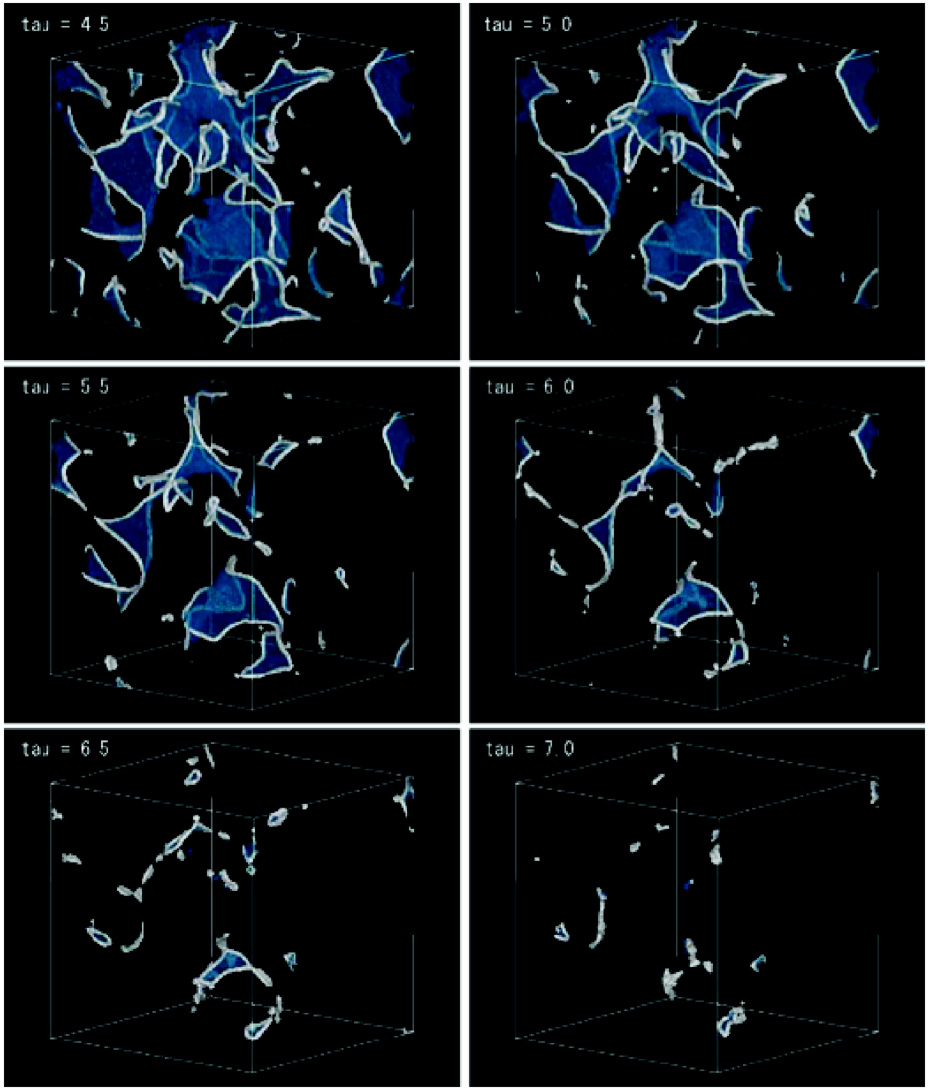
Axion-like particles

- Generalisation of axions to any light pseudoscalar associated with a spontaneously broken U(1) **–** but **do not** solve the strong CP problem
- Also called WISPs: Weakly Interacting sub-eV particles
- Candidates include hidden sector photons and axions predicted by string theory

Axion cosmology

- Axions produced in early Universe by various mechanisms e.g.,
  - Vacuum realignment (oscillations around minimum of potential)
  - Decay of topological defects (axion strings and domain walls)

- Quantity and production mechanism depends on whether PQ phase transition happens before or after inflation



Hiramatsu et al 2012

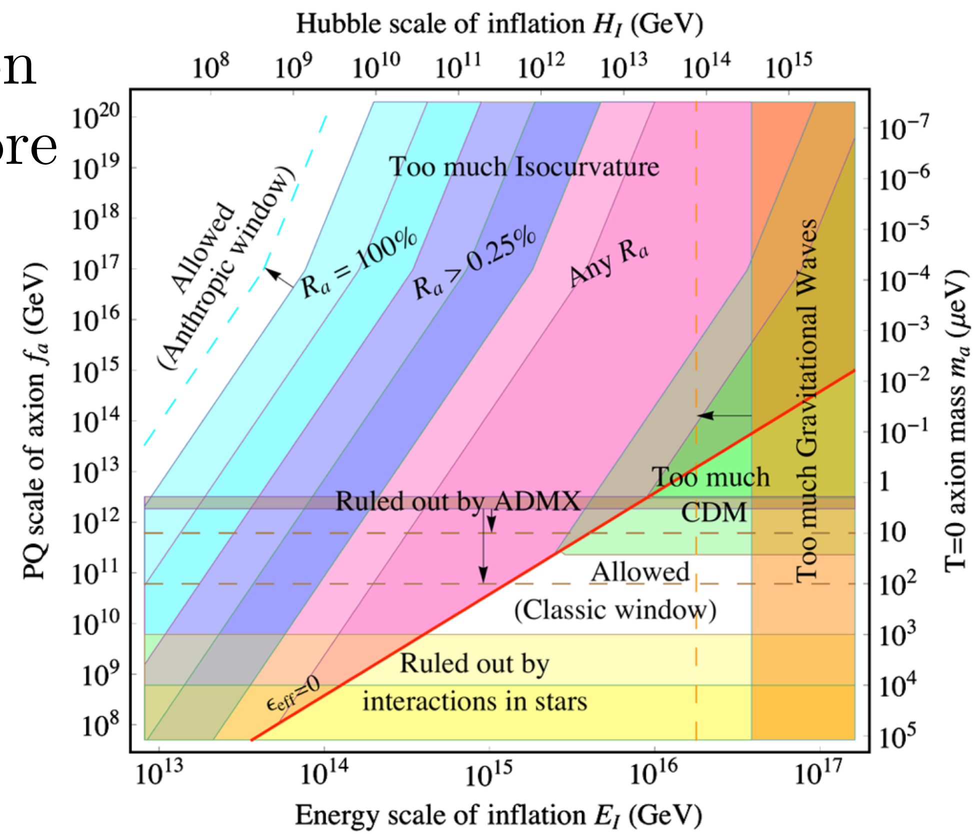
Axions as dark matter

- Density of axions today dependent on whether phase transition occurs before or after inflation

$$\Omega_a h^2 \sim 0.236 \, \langle \theta_i^2 f(\theta_i) \rangle \left(\frac{m_a}{6.2\,\mu\mathrm{eV}} \right)^{-7/6}$$

- Axions can be dominant DM for

$m_a < 10^{-3}$ eV
(but highly model dependent!)



Hertzburg *et al.* 2008

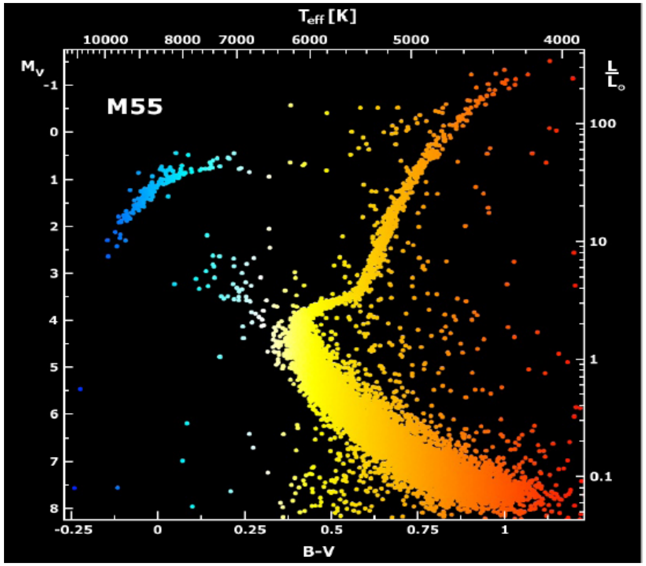
- Scale as dark matter should: $\rho \propto (1+z)^3$
- Are cold at CMB decoupling timescales: $v_a/c < 10^3$

But do they form large scale stucture?

Constraints from astrophysics

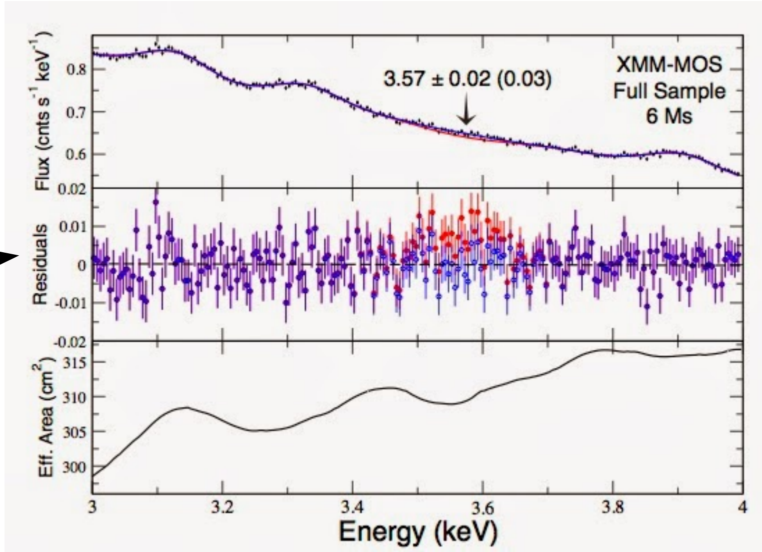
Constraints from astrophysical scenarios where there might be significant axion-photon or axion-electron interactions

- Solar neutrinos [Gondolo & Raffelt, 2008]
- Red giant horizontal branch [Harris, 2000]
- Supernova 1987A [Raffelt et al. 2012]
- Extragalactic background light (EBL) [Overduin et al 1993]



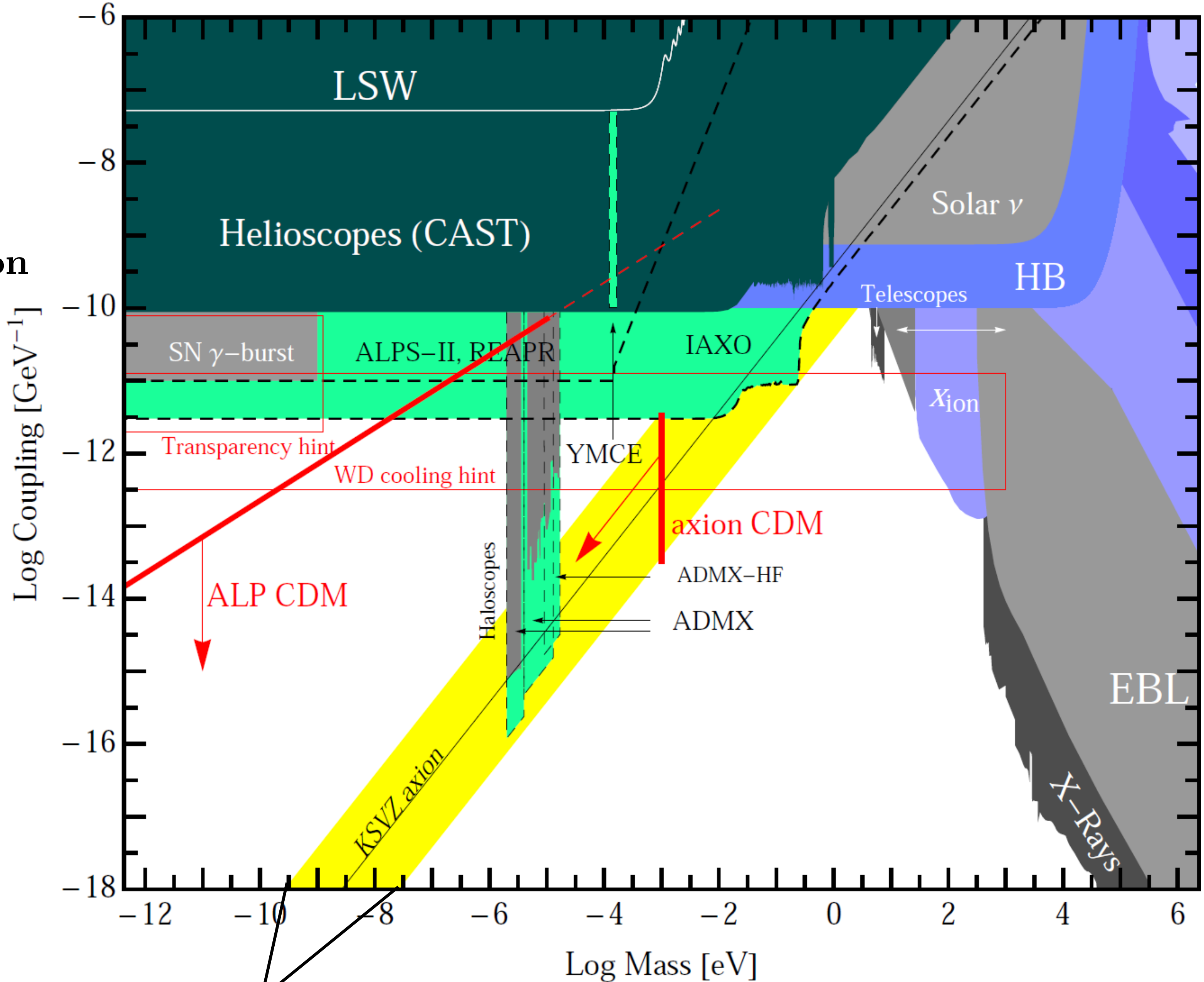
+ potential hints?

- White dwarf cooling [Isern 2012]
- 3.5 keV line [Conlon 2014]
- Neutron star cooling [Leinson et al 2014]



Constraints on axions/ALPs

Axion-photon coupling



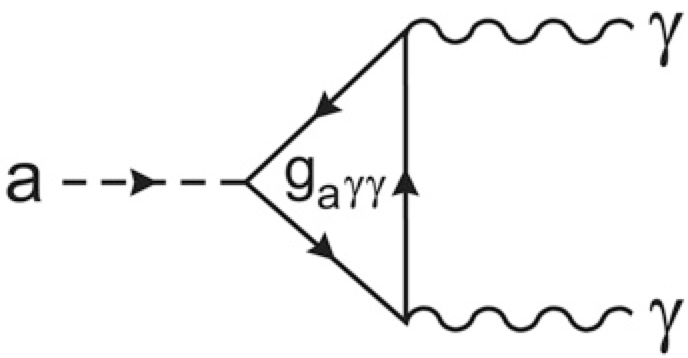
"Natural" QCD axion range

Primakoff effect

- Axions convert into photons in magnetic fields

$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4}\, g_{a\gamma}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} = g_{a\gamma}\, a\, \vec{E}\cdot\vec{B}$$

Axion photon coupling

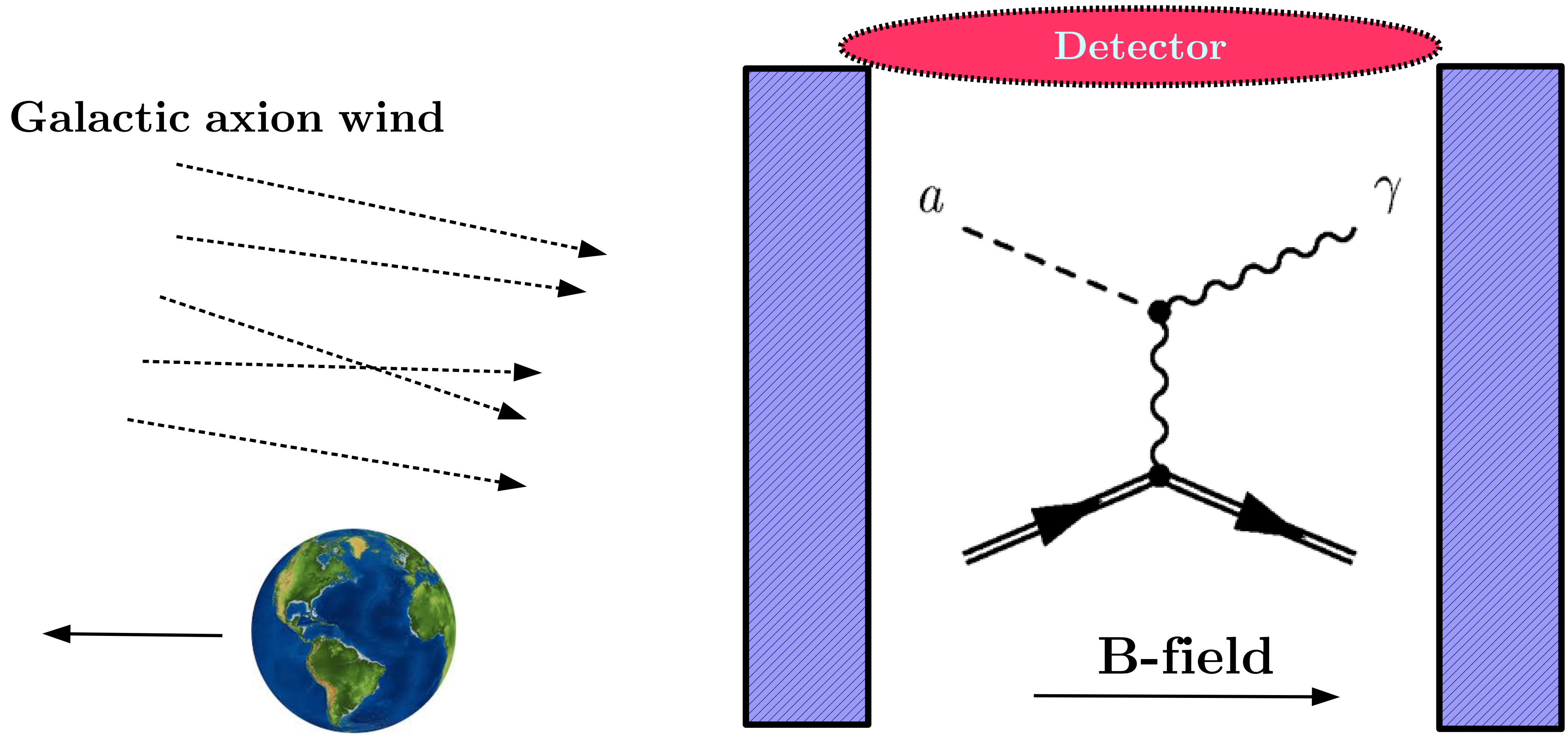


Search for evidence of this interaction:

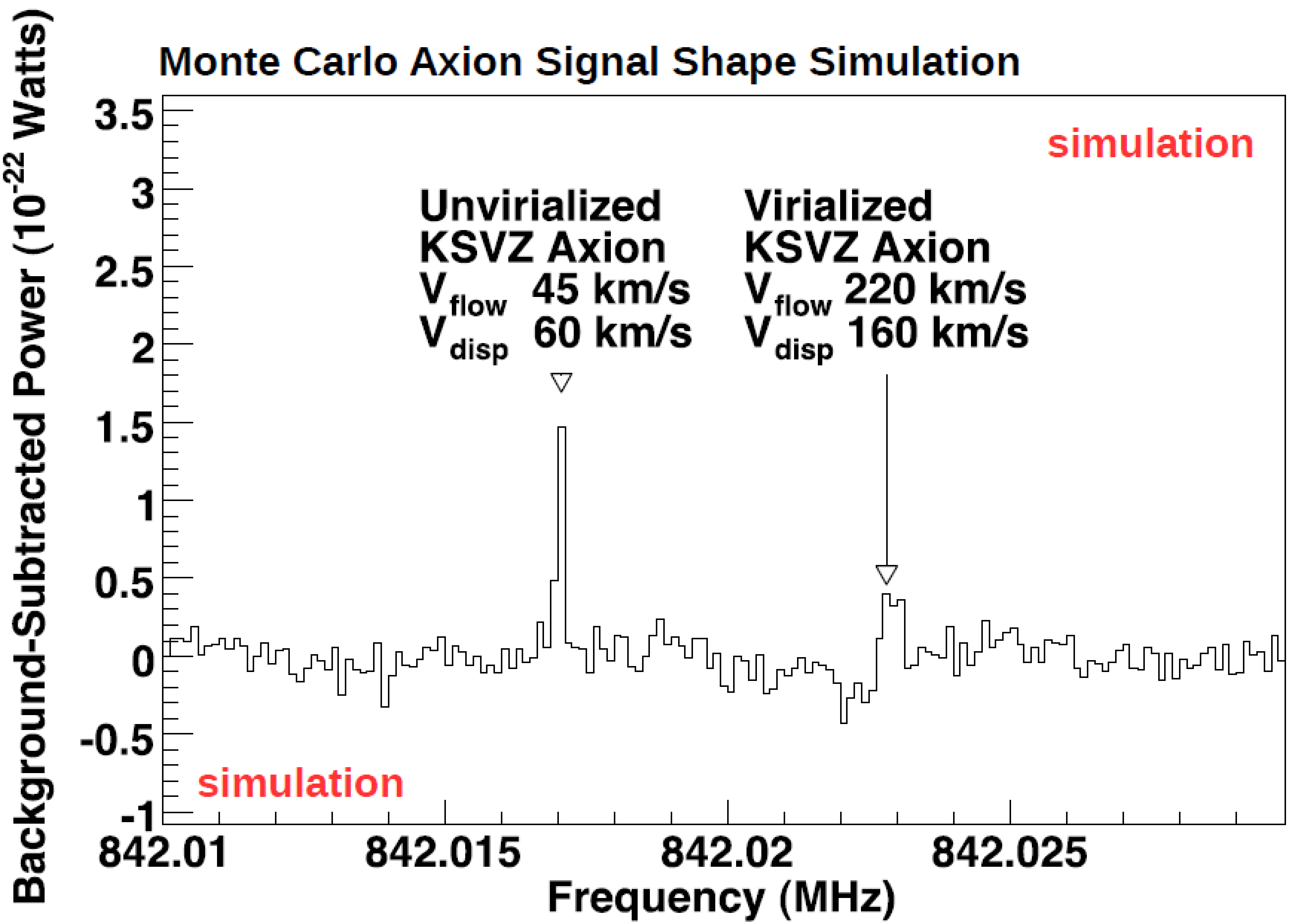
- Galactic axions converting into photons (*haloscope*)
- Solar axions converting into photons (*helioscope*)
- Light converting into axions (*light shining through a wall experiment*)

Haloscopes

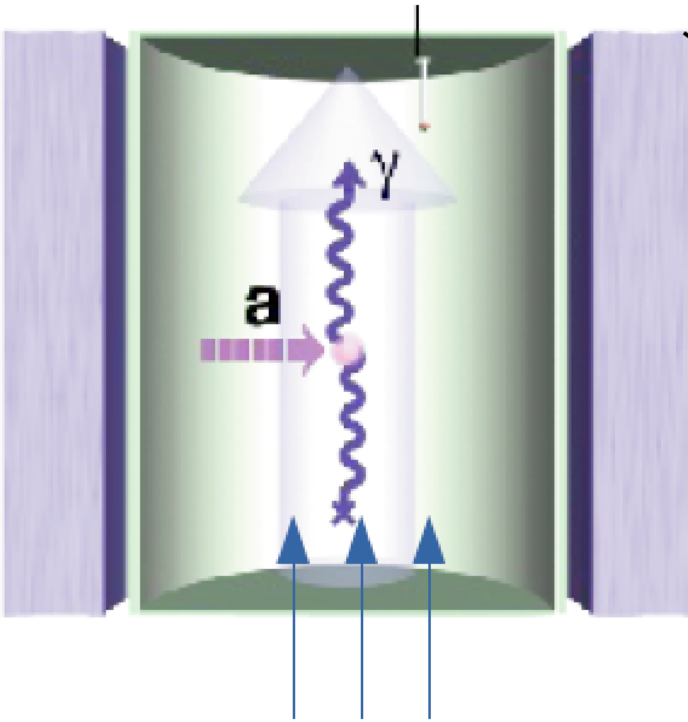
- Search for **Galactic** axions and ALPs
- EM Cavity with strong magnetic field
- Amplified signal when resonance frequency of cavity = axion mass

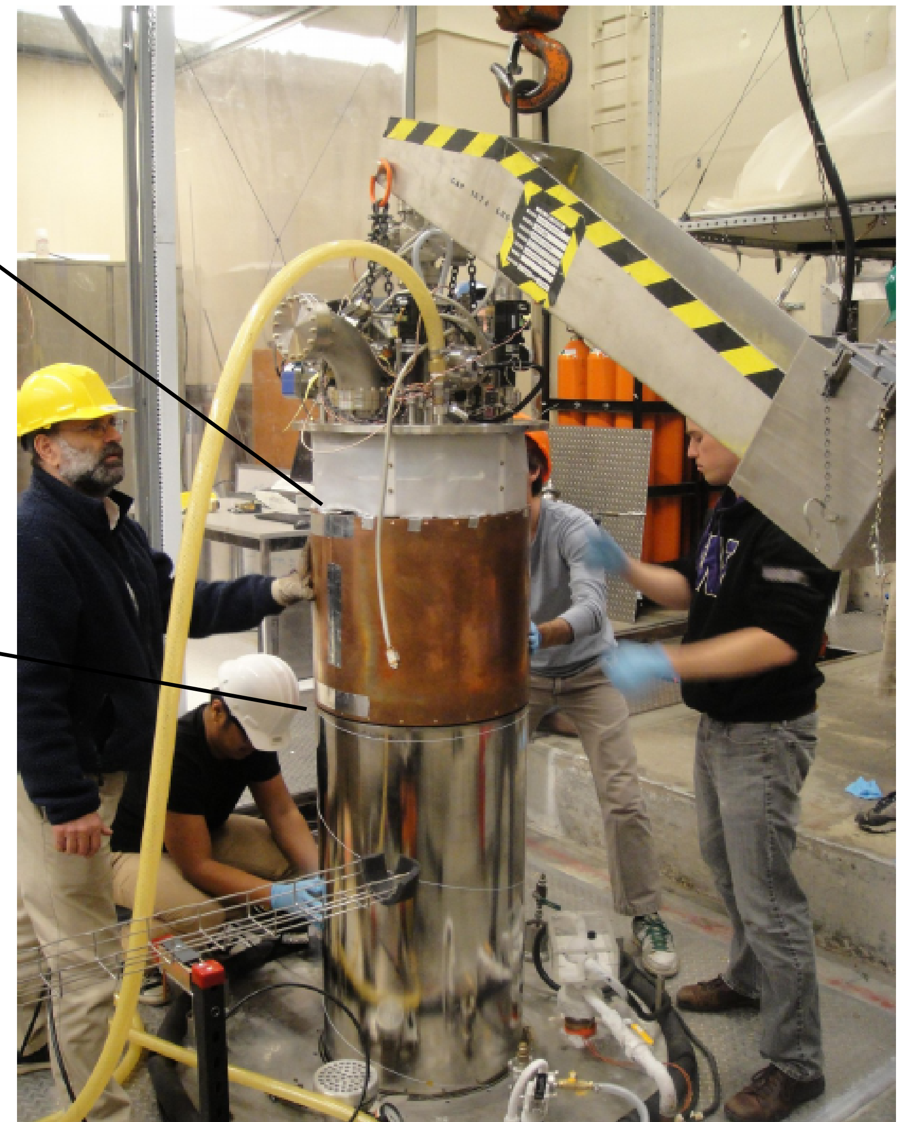


Haloscope signal



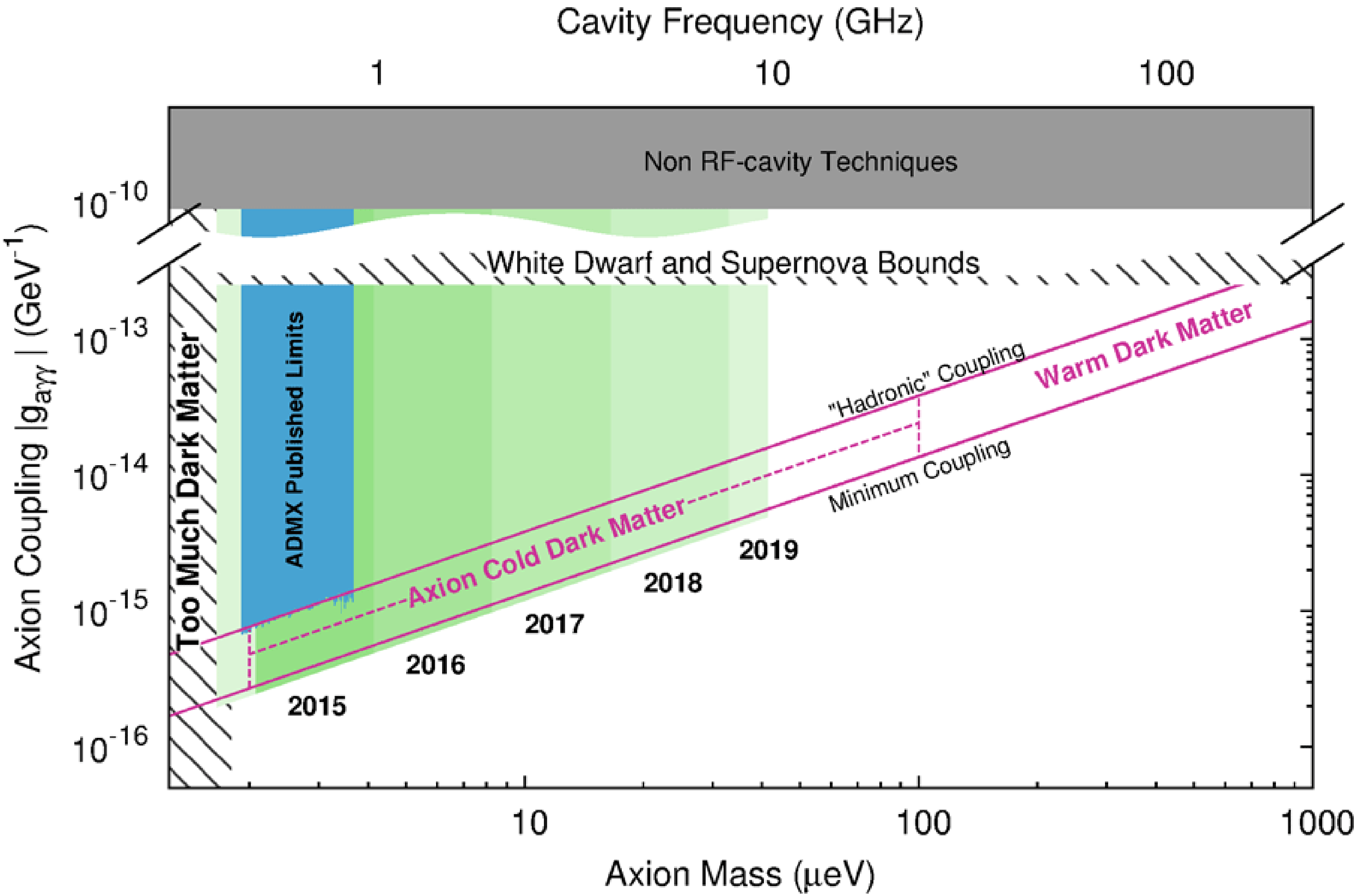
Axion Dark Matter eXperiment (ADMX)





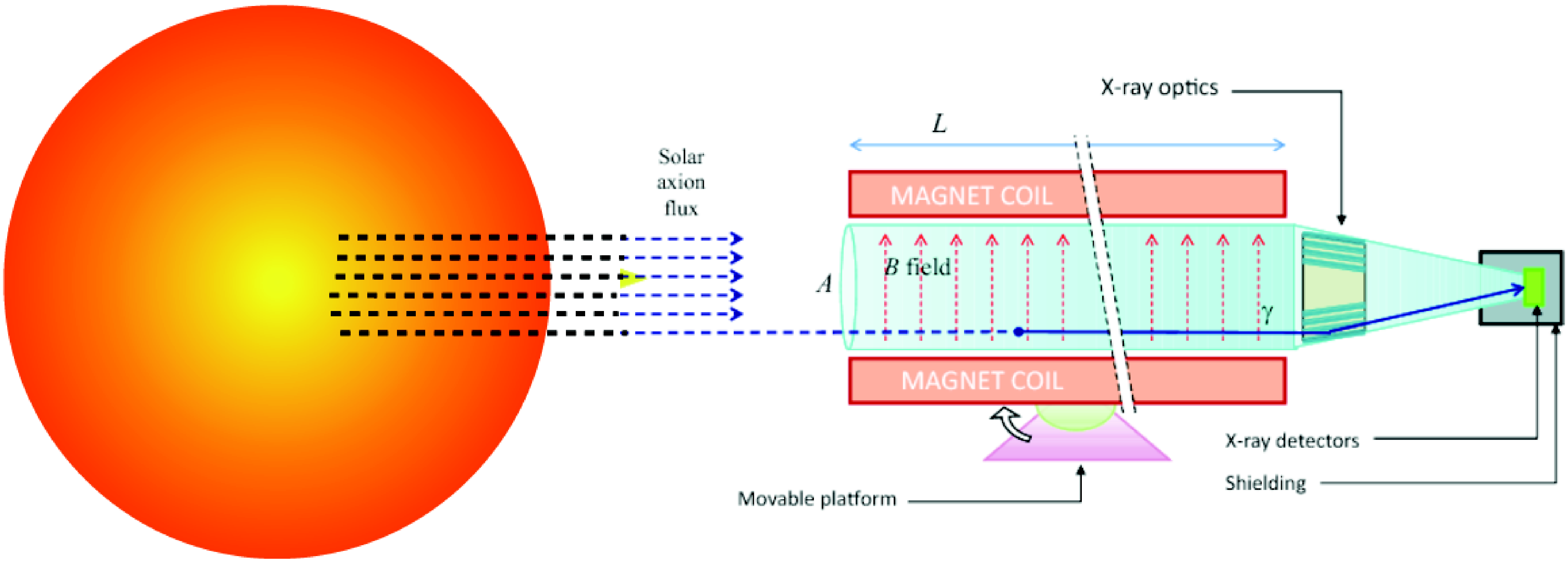
- B = 8T
- L = 1m
- Cavity frequency adjusted with tuning rods

ADMX Sensitivity map



Helioscopes

- **Solar** axions - Point cavity at the sun



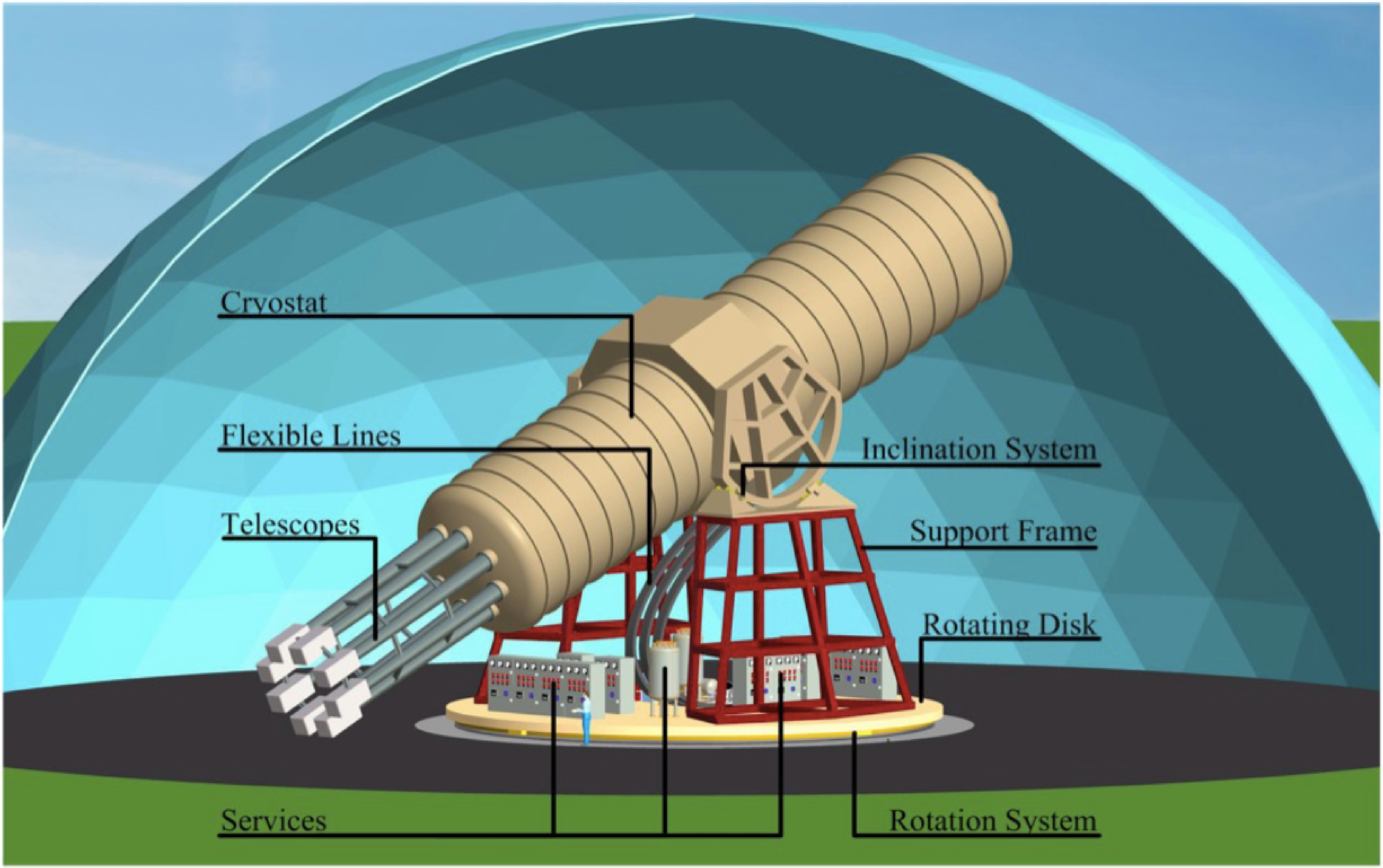
$$P(a \leftrightarrow \gamma) = \left(\frac{2g_{a\gamma}B_T\omega}{m_a^2}\right)^2 \sin^2\left(\frac{m_a^2 L}{4\omega}\right)$$

- Large magnetic field
- Match frequency to axion mass

CERN Axion Solar Telescope (CAST)

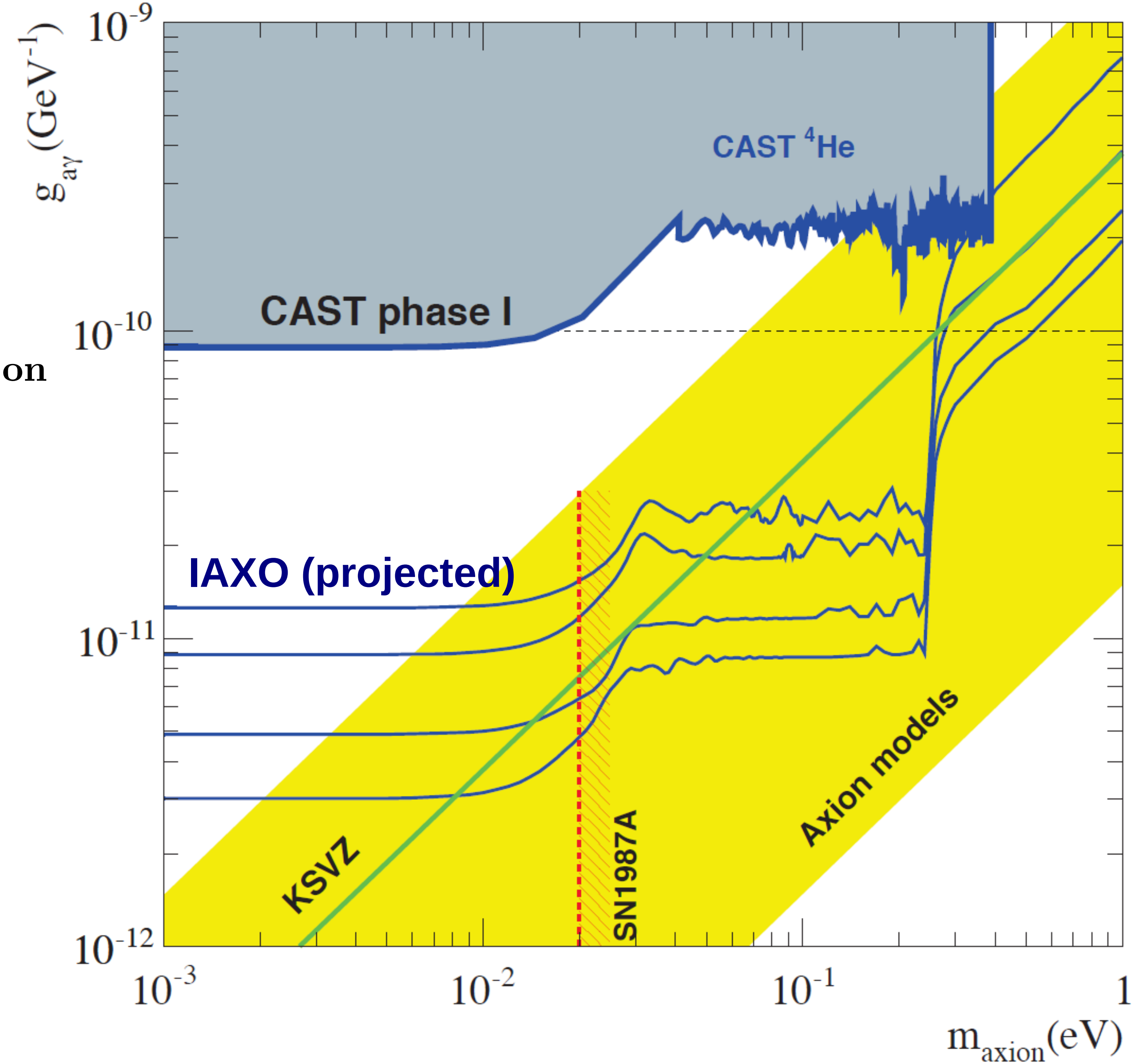
- B = 9T
- L = 8.3m
- 1-2 hour Solar tracking per day

International AXion Observatory (IAXO, planned)

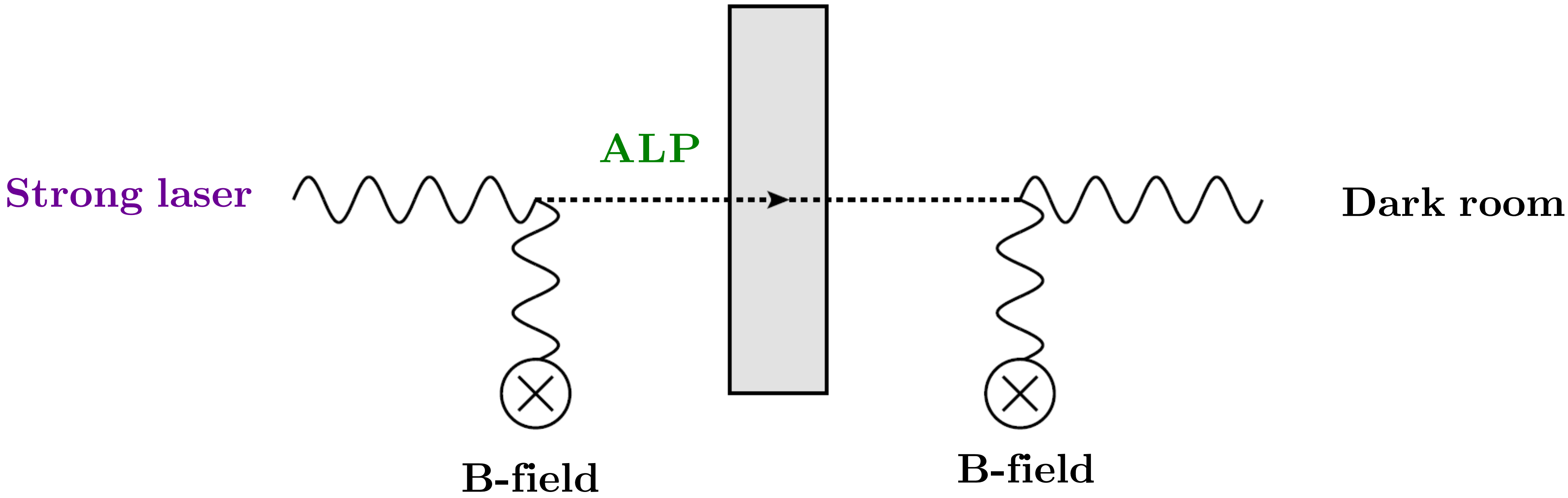


CAST/IAXO Sensitivity map

Axion-photon coupling



Light-shining-through-a-wall Experiment



Conversion probability

$$P(\gamma \to \phi) = 4\frac{g^2 B_{\rm ext}^2 \omega^2}{m_\phi^4} \sin^2\left(\frac{m_\phi^2 L}{4\omega}\right)$$

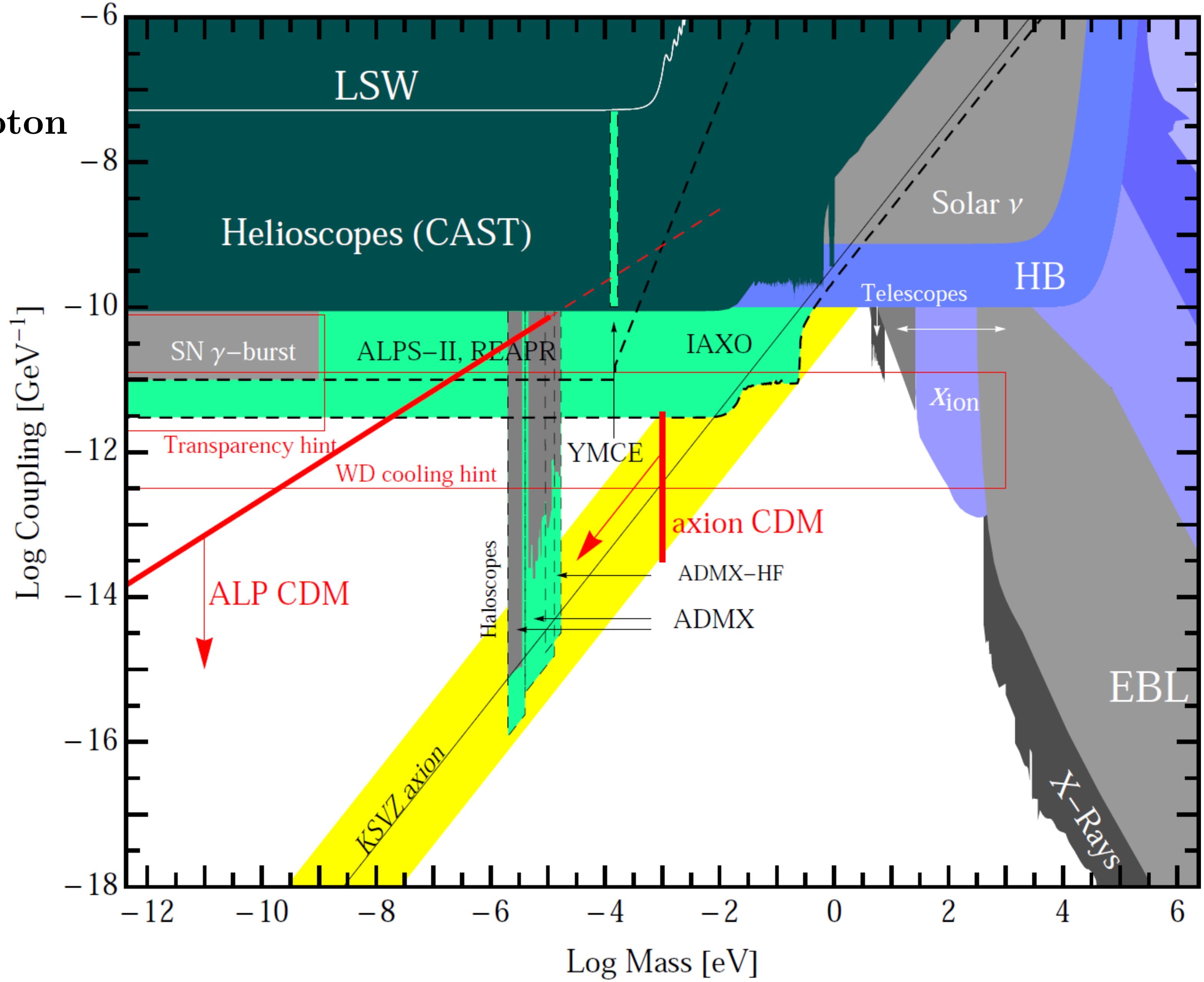
Any Light Particle Search (ALPS)

- $B = 5.3T$
- 16 m total length
- Currently Being upgraded to ALPS II

LASER **Superconducting magnet** **Detector**

Constraints on axions/ALPs

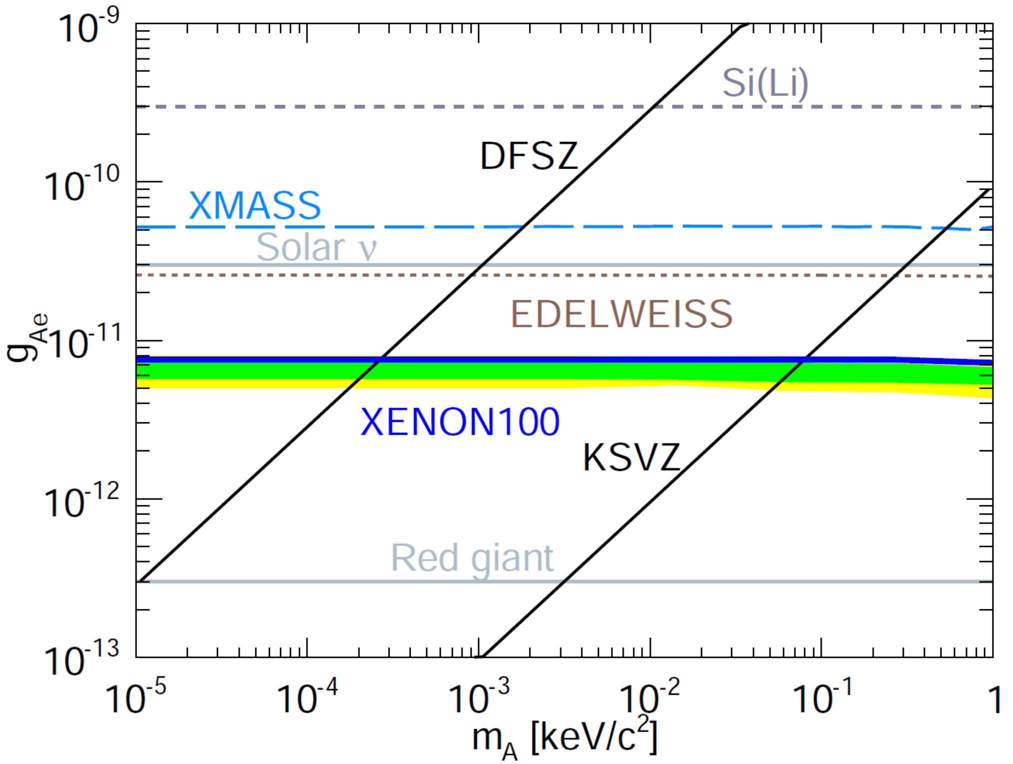
Axion-photon coupling



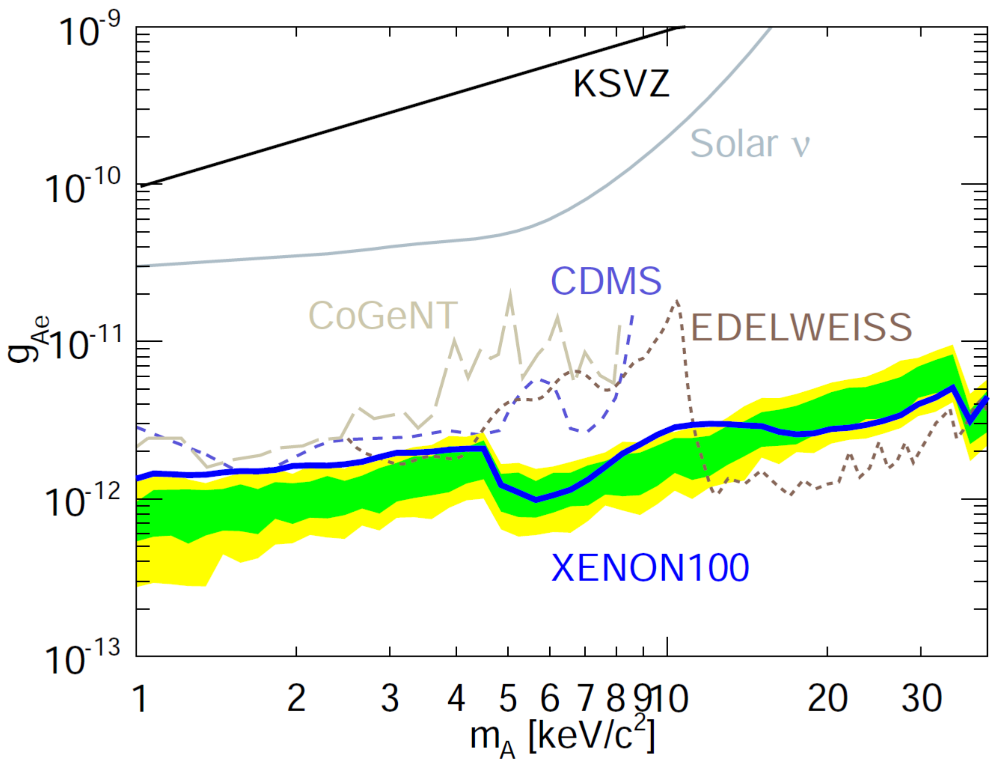
Detection with WIMP detectors

- Detect axions via axio-electric effect with electrons (analogous to photoelectric effect)
- Limits on axion-electron coupling:

Solar axions



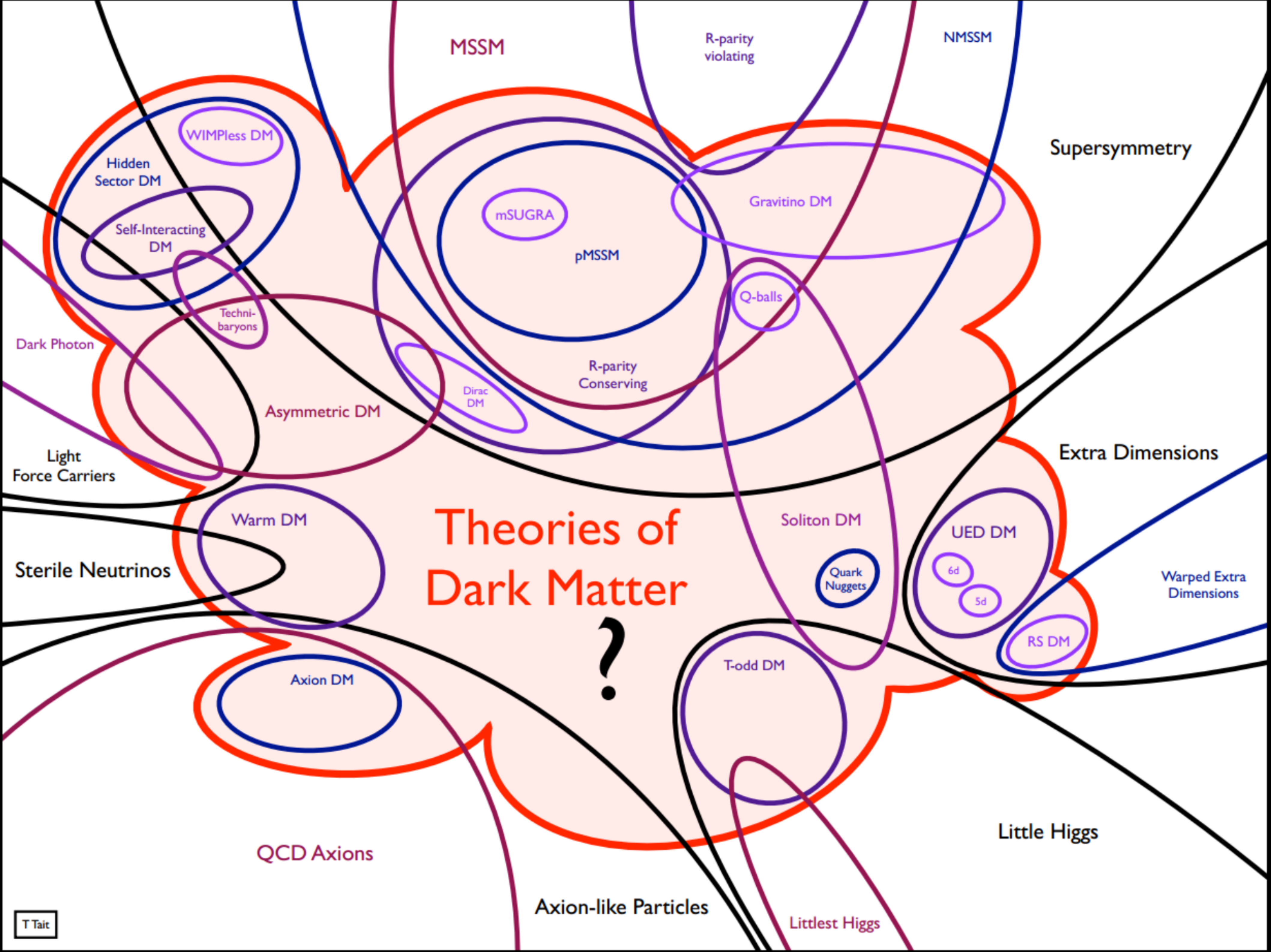
Galactic ALPs



Xenon100 collaboration, 2014

Summary

- New pseudoscalar particle to solve strong CP problem
- Axion and their generalisation ALPs are dark matter candidates
- Constraints (and hints) from astrophysics and cosmology already exist
- Laboratory search is ongoing
- With the exception of haloscopes, axions/ALPs can be detected even if they are not dark matter
- Be on the lookout for results from, CAST, ADMX, IAXO, ALPSII, ARIADNE, CASPEr...



MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
mSUGRA
pMSSM
Gravitino DM
Q-balls
Techni-baryons
Dark Photon
R-parity Conserving
Dirac DM
Asymmetric DM
Light Force Carriers
Extra Dimensions
Warm DM
Theories of Dark Matter
?
Soliton DM
UED DM
Sterile Neutrinos
Quark Nuggets
6d
5d
Warped Extra Dimensions
RS DM
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait