Recent constraints on axion-photon and axion-electron coupling with the CAST experiment

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J. Ruz *on behalf of the CAST Collaboration*

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Outlook

- Axions
  - Motivation and models
  - Axions in cosmology and astrophysics
  - Classic axion searches
- Solar axions
  - Detection of solar axions
  - The coherence condition
  - CAST results
  - Near term future with CAST
  - IAXO: the next generation
- Conclusions

Axions: motivation, models, phenomenology and cosmology

Axion motivation

- **Peccei-Quinn solution** to the strong CP problem
  - New U(1) symmetry introduced:
    - –Peccei Quinn symmetry of scale f_a
    - –The AXION appears as the Nambu-Goldstone boson of the spontaneous PQ symmetry breaking

"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"

Axion models

- **Axion decay constant**
  - The axion mass and the scale of the interaction are closely related

$$m_a = \frac{m_u + m_d}{\sqrt{m_u m_d}} \frac{m_\pi f_\pi}{f_a} = 6\,\mathrm{meV}\,\frac{10^9\ \mathrm{GeV}}{f_a}$$

$$\boxed{z = 0.56} \longleftarrow z = \frac{m_u}{m_d} \subseteq [0.35, 0.6]$$

  - The nature of axion implies they must interact with hadrons and photons

    ➢ Hadronic axion models

  - GUT motivated axion models suggest that axions can also significantly interact with leptons

    ➢ Non-hadronic axion models

Axion cosmology

- **Axions could be produced** in the early Universe by a number of processes:

  - Axion realignment
  - Decay of axion strings
  - Decay of axion walls

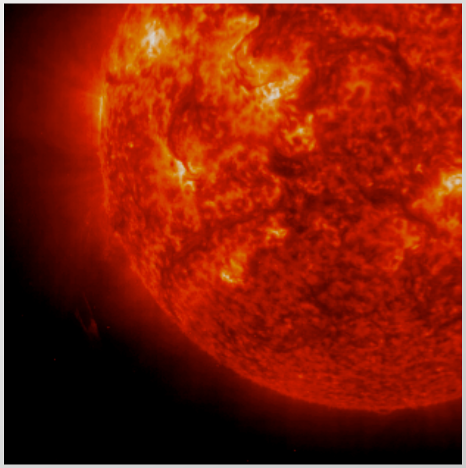
  → NON-RELATIVISTIC (COLD) AXIONS Cold Dark Matter (CDM) candidate

  - Thermal production

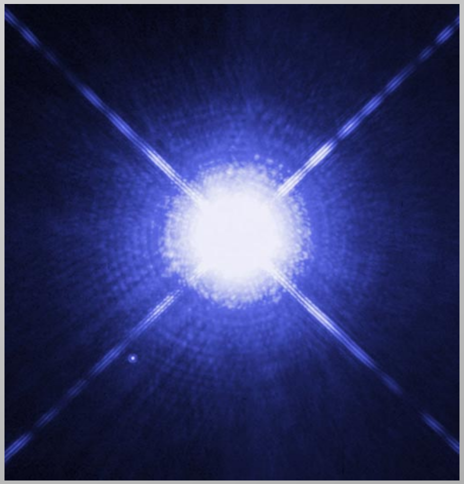
  → RELATIVISTIC (HOT) AXIONS Hot Dark Matter (HDM) candidate

Hannestad et al, JCAP 08 (2010) 001 (arXiv:1004.0695)

Axions in astrophysics



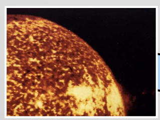
- **Axions can be produced in the core of stars,** like the Sun, by Primakoff conversion of plasma photons.
- **Axion decay** may produce γ-ray emission lines originating from certain places (e.g., galactic center).



- **Axions may have a wider impact:** The cooling of white dwarfs

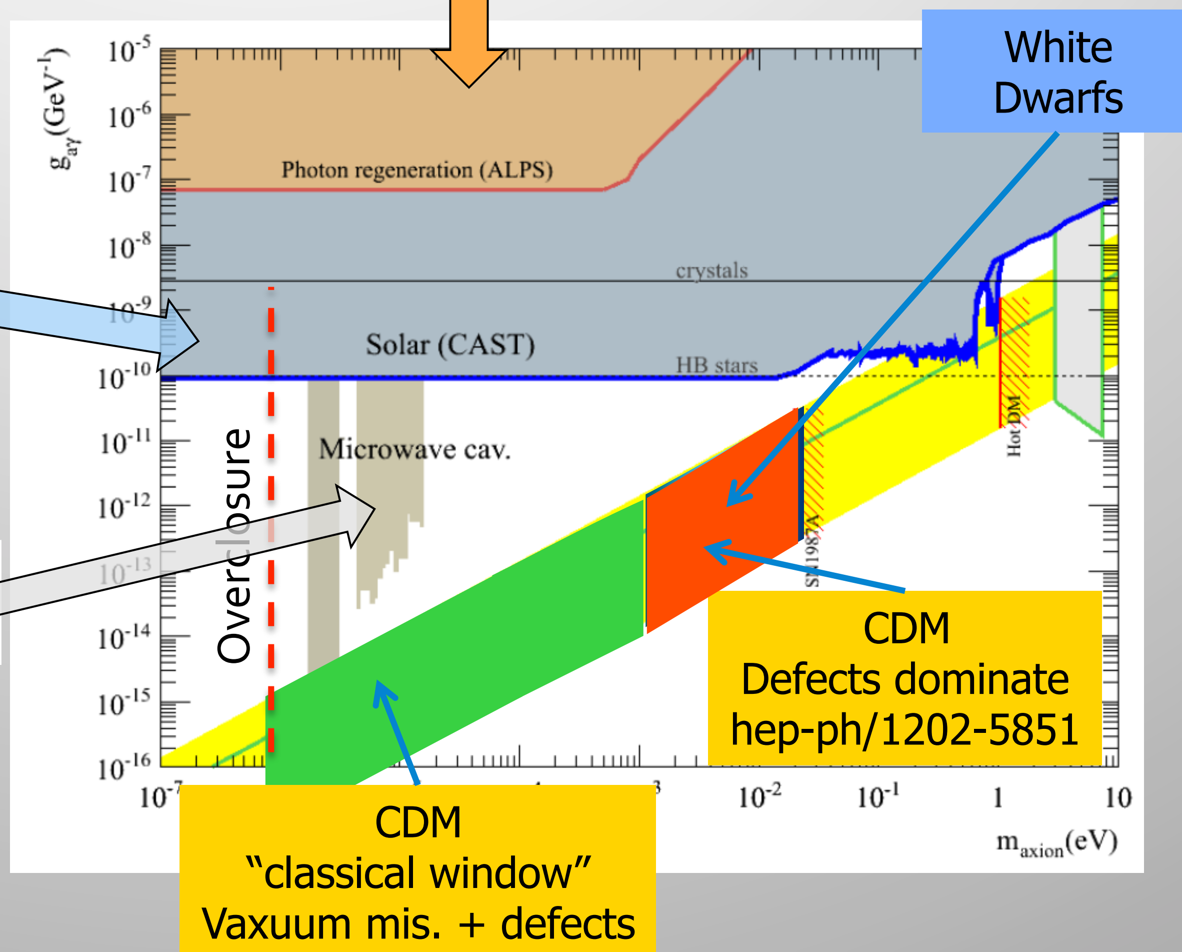
Classic axion searches

- Laboratory axions
  - → Shining-Light-through-Walls (OSQAR, LIPSS, ALPS)
  - → Polarization (PVLAS)
- Solar axions



  - → Crystals (SOLAX,COSME)
  - → Helioscopes (Tokyo, **CAST**)
- Halo axions (relics of Big Bang)

  - → Haloscopes (ADMX,Carrack)
  - → Telescopes (Haystack)

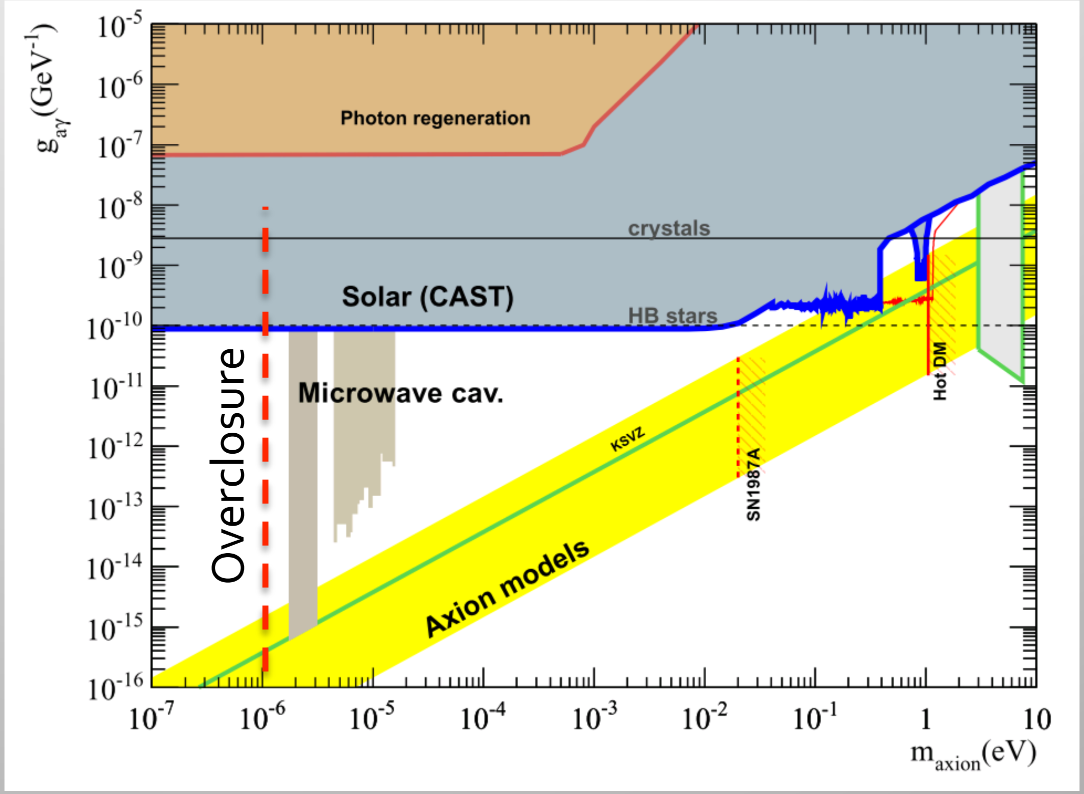


Axion-like particles (ALP)

- Any pseudoscalar (or scalar) particle, neutral, light, and coupled to the photon, is considered an ALP, whatever the theory behind it.

(or WISPs = Weakly Interacting Scalar Particle)

- In this wider context, $g_{a\gamma}$ and m_a are two independent "phenomenological" parameters.
- The QCD-inspired axions (or "proper" axion) lies in a limited region of this space, shown as the yellow band



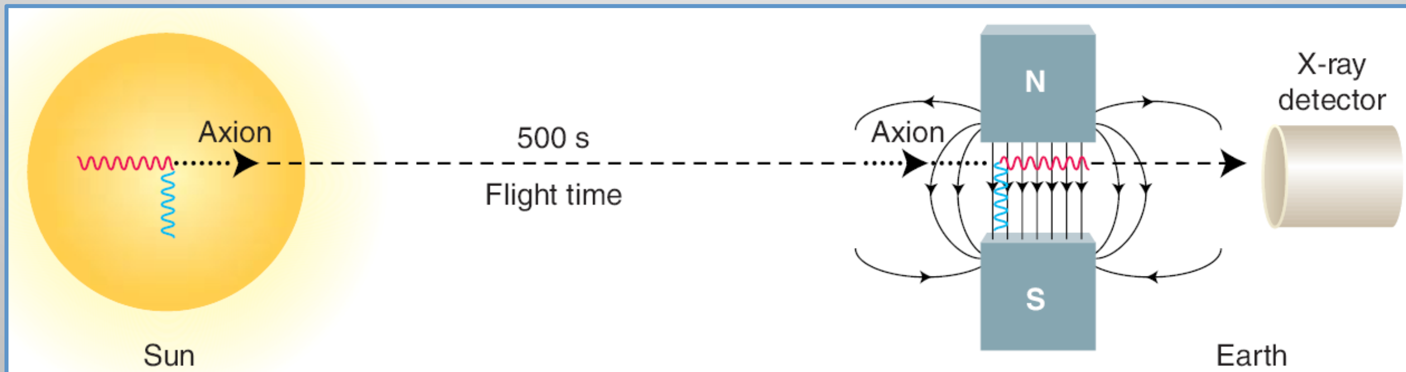
Solar axions: the helioscope concept

Production and detection of axions

- First axion helioscope proposed by P. Sikivie

Sikivie *PRL* 51:1415 (1983)

  - Blackbody photons (keV) in solar core can be converted into axions in the presence of strong electromagetic fields in the plasma
  - Reconversion of axions into x-ray photons is possible in strong laboratory magnetic fields



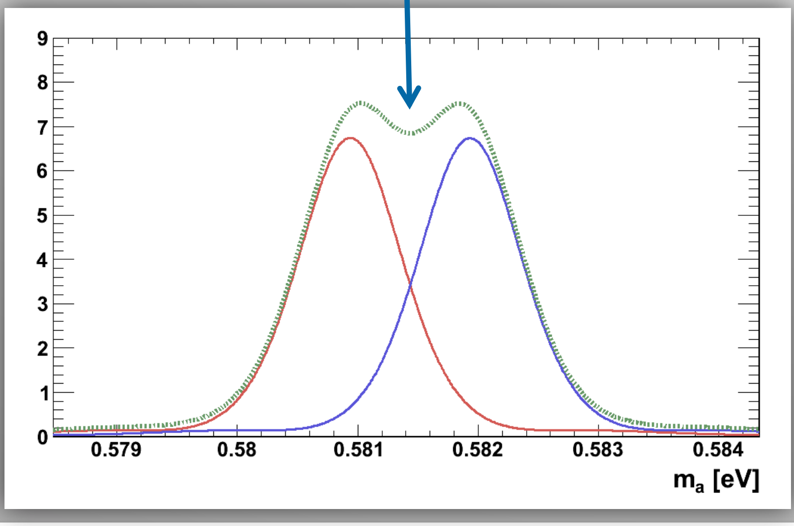
- Idea refined by K. van Bibber et al. by using buffer gas to restore coherence over long magnetic field

Van Bibber et al. *PhysRevD* 39:2089 (1989)

Detection of solar axions

The axion mass band for which a Primakoff based experiment is sensitive can be extracted from the coherence condition

The converted photons may acquire an effective mass in the presence of gas extending the axion mass sensitivity range of an experiment that has a fixed magnet length



Conversion Probability

$$P_{a\gamma} = g_{10}^2 \times \left(\frac{B_\perp}{2}\right)^2 \frac{1}{q^2 + \Gamma^2/4}\left[1 + e^{-\Gamma L} - 2e^{-\Gamma L/2}\cos qL\right]$$

Coherence Condition

$$\left(m_a^2/keV^2\right) << \left(m_\gamma^2/keV^2\right) + 2\left(\frac{E_a/keV}{L \cdot keV}\right)$$

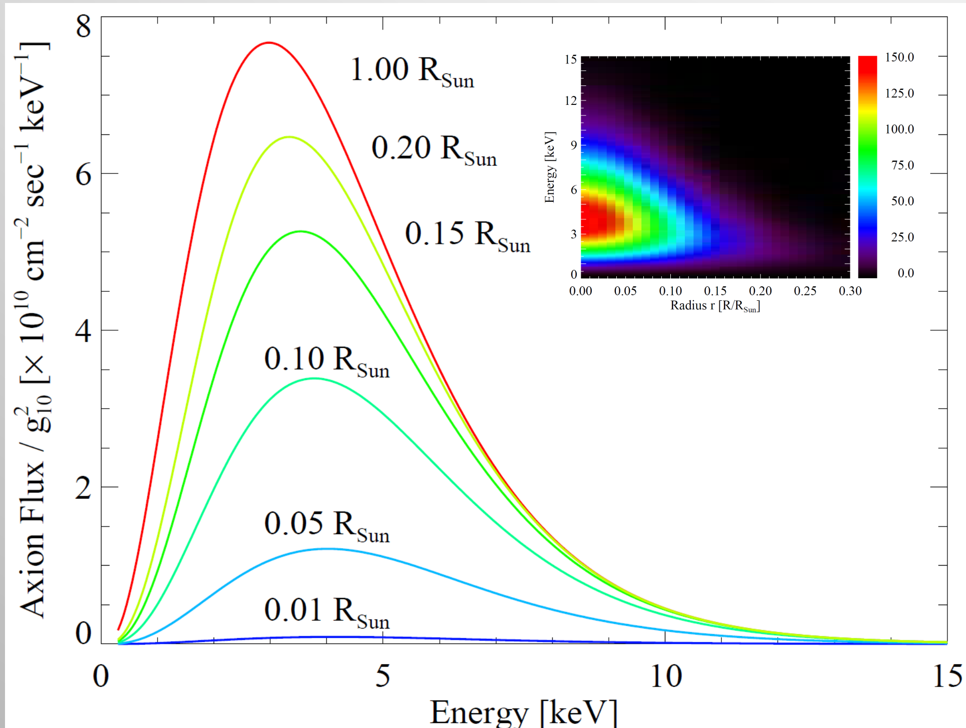
Axion-to-photon conversion in the presence of a nearly homogeneous magnetic field **B** is only effective when the polarization plane is parallel to the incident particle

CAST experiment @ CERN

- Decommissioned LHC test magnet (L=10 m, B=9 T)
- Moving platform ±8°V, ±40°H (allows 3 hours/day of solar tracking)
- 4 magnet bores to look for x-rays from axion conversion
- X-ray focusing system to increase signal/background ratio

Hadronic axions from the Sun

- **Primakoff production of axions in the Sun**



Expected axion flux from the Sun as function of energy.
→Solar Physics + Primakoff effect: only one unknown parameter g_{10}

Serpico&Raffelt,
based on SSM BP2004 of Bahcall et al.

$$\mathcal{L}_{a\gamma\gamma} = -\frac{C_\gamma \alpha}{8\pi f_a} F_{\mu\nu}\tilde{F}^{\mu\nu} a = -\frac{g_{a\gamma}}{4} F_{\mu\nu}\tilde{F}^{\mu\nu} a$$

- No significant signal observed
- Typical upper limit
- Touching KSVZ benchmark

Hadronic axions with CAST

- To date, interpretation of solar axion experimental results has looked at photon-axion coupling: hadronic models

❑Vacuum Phase

$$m_a \leq 0.02\ eV$$

Phys.Rev.Lett.94:121301, 2005

JCAP 04 (2007) 010

❑^{4}He Phase

$$0.02\ eV \leq m_a \leq 0.39\ eV$$

JCAP 02 (2009) 008

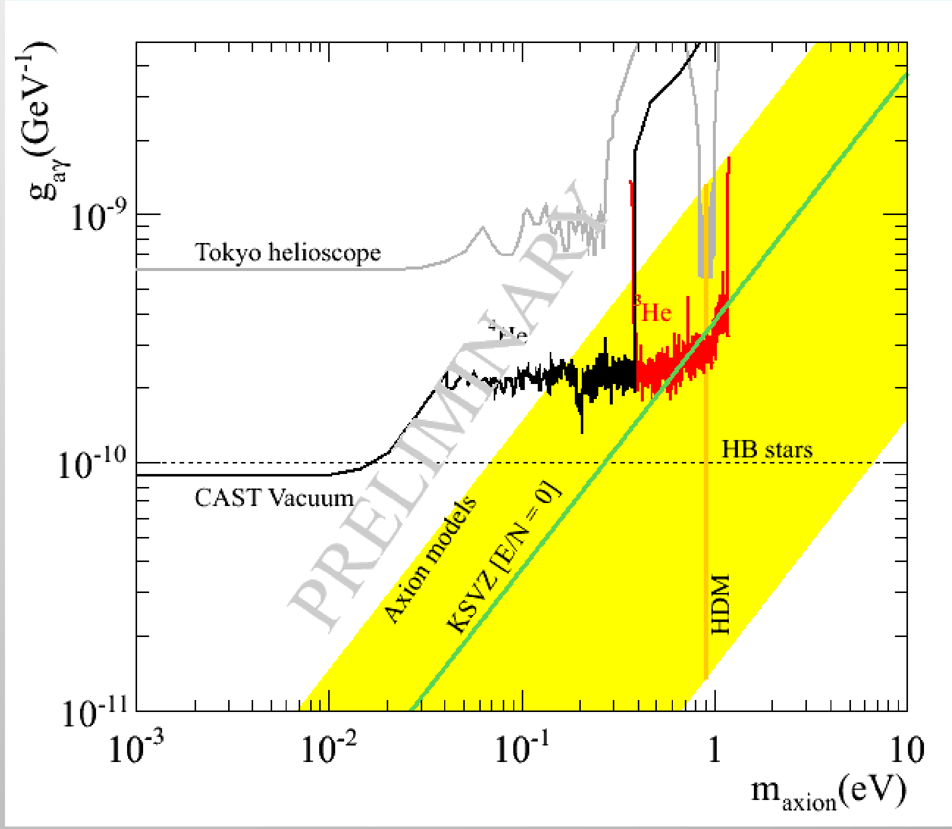
❑First Results from ^{3}He Phase

$$0.39\ eV \leq m_a \leq 0.65\ eV$$

Phys.Rev.Lett. 107:261302, 2011

❑Preliminary analysis of rest ^{3}He Phase

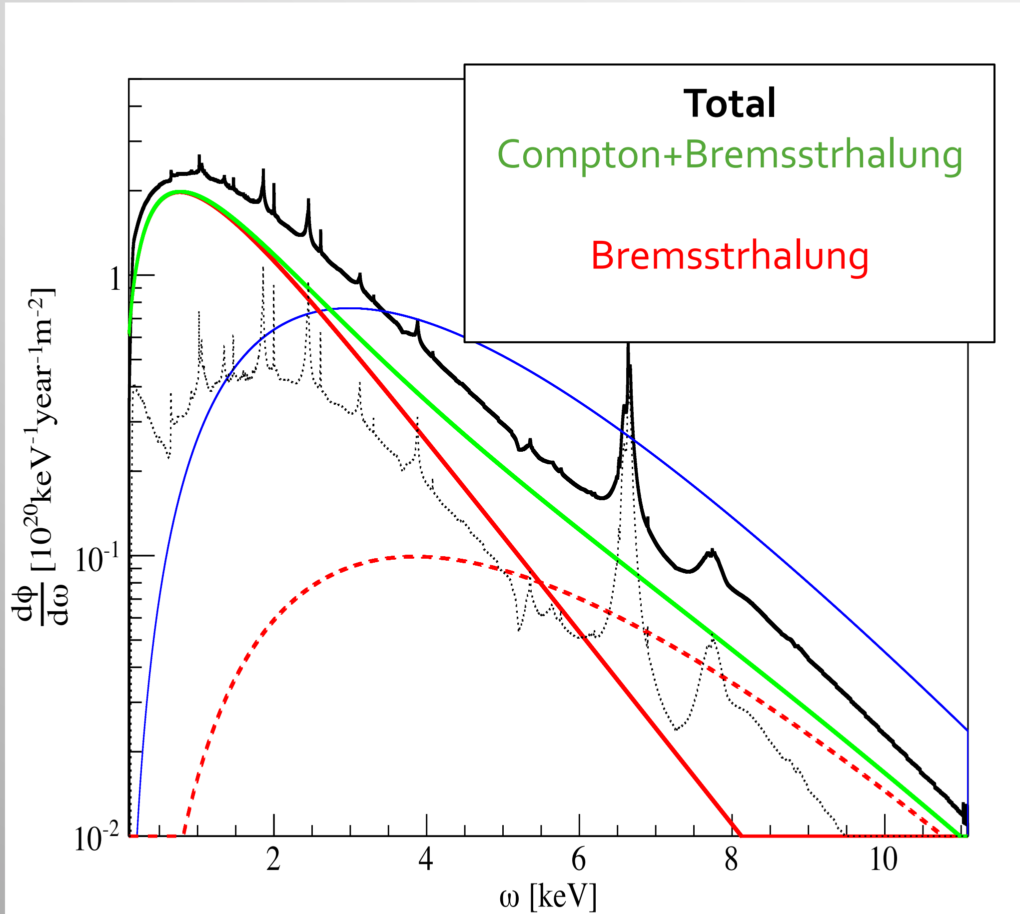
$$0.65\ eV \leq m_a \leq 1.18\ eV$$



But we know that other processes might be at play …

Non-hadronic axions at CAST

- Primakoff and electron production of axions in the Sun



$$g_{a\gamma} = 1\times10^{-12}\mathrm{GeV}^{-1}$$

$$g_{ae} = 1\times10^{-13}$$

- No significant signal observed
- White Dwarf compatible?

$$\mathcal{L}_{a\gamma\gamma} = -\frac{C_\gamma \alpha}{8\pi f_a} F_{\mu\nu}\tilde{F}^{\mu\nu} a = -\frac{g_{a\gamma}}{4} F_{\mu\nu}\tilde{F}^{\mu\nu} a$$

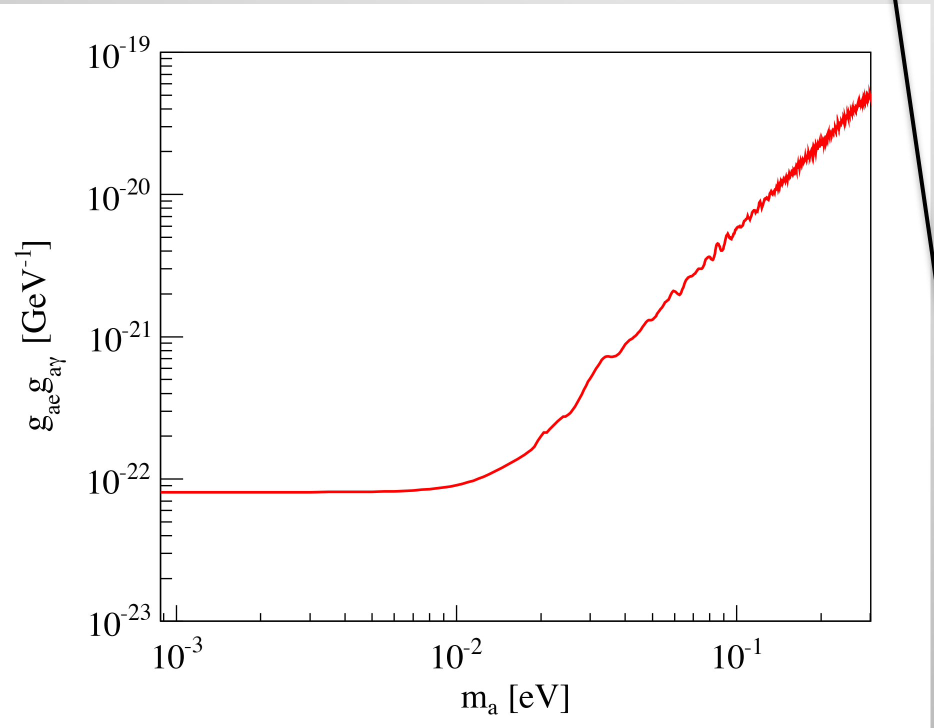
$$\mathcal{L}_{aee} = C_e \frac{\partial_\mu a}{2 f_a} \bar{\psi}_e \gamma_5 \gamma^\mu \psi_e \longleftarrow \boxed{g_{ae} = \frac{C_e m_e}{f_a}}$$

Non-hadronic axions at CAST

- **Extraction of a limit,** a generic limit can be expressed as

Axion-electron Yukawa coupling

$$C_e C_\gamma = g_{ae} g_{a\gamma} \frac{2\pi}{\alpha} \frac{1}{m_e} \left[\frac{6\,\mathrm{meV} \cdot 10^9\,\mathrm{GeV}}{m_a} \right]^2$$



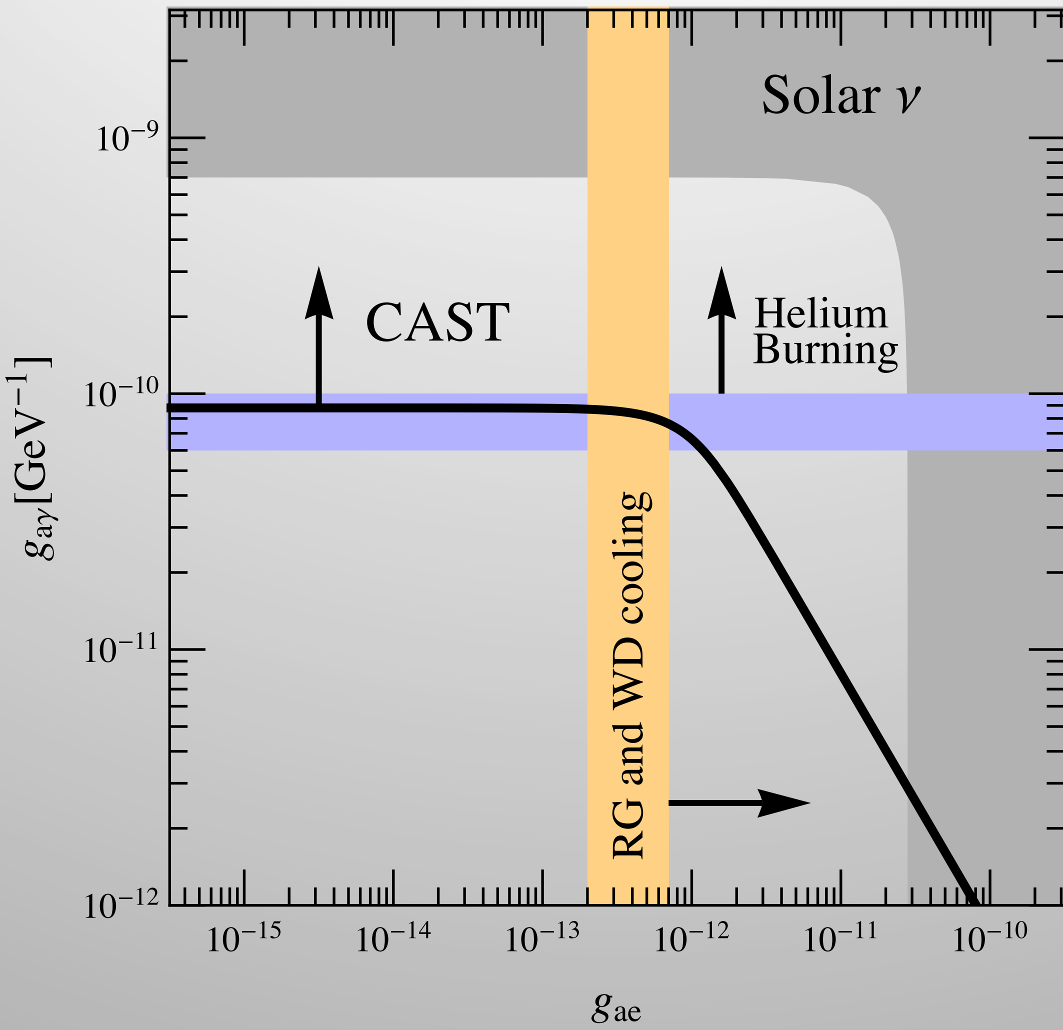
$$g_{ae} \times g_{a\gamma} \leq 8.1 \times 10^{-23}\, GeV^{-1}$$

Model dependent parameter

$$C_\gamma = \frac{E}{N} - \frac{2(4m_d + m_u)}{3(m_u + m_d)} \approx \frac{E}{N} - 1.92$$

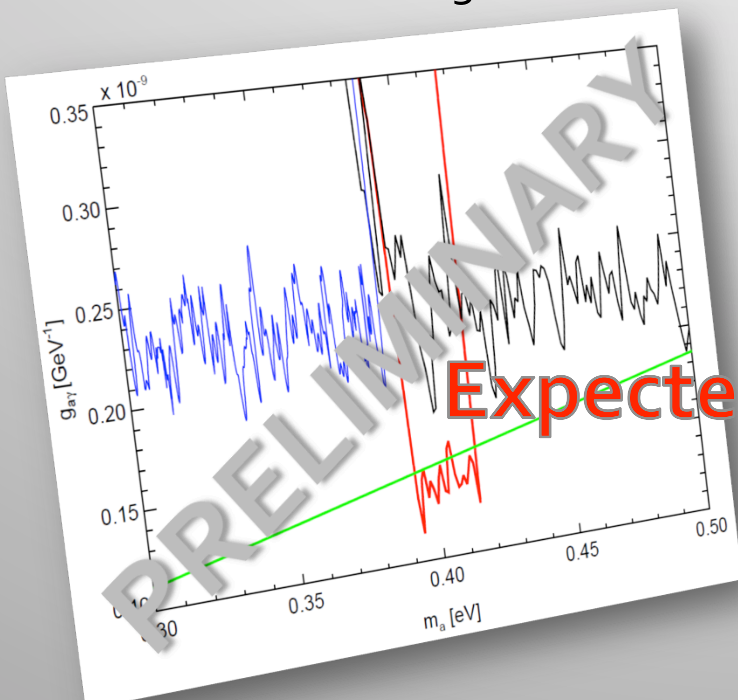
Electromagnetic and color anomalies ratio

Axions with CAST

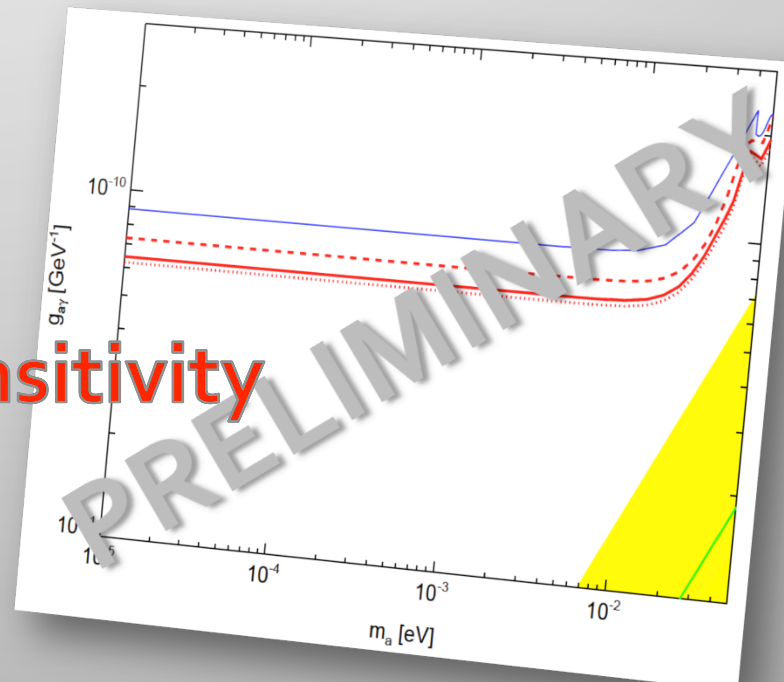


Near term future at CAST

- **Re-visit 4He phase (ongoing)**
- **Re-visit vacuum phase (2013-14)**
  - ❑ Better detectors, new optics →higher sensitivity and increased discovery potential (red line)
  - ❑ Probing standard KSVZ model (green line)

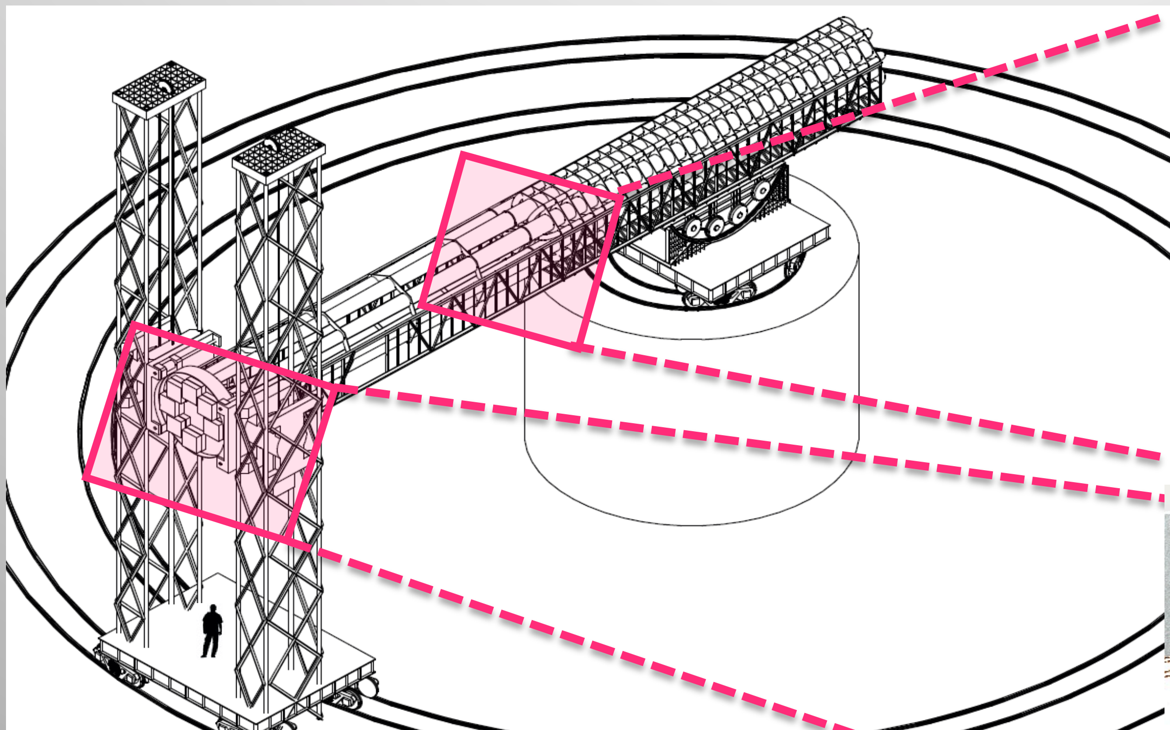


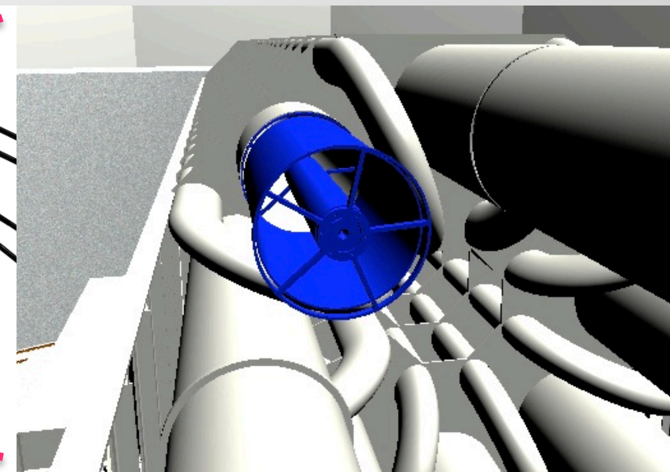
Expected sensitivity



IAXO: the next generation

- **Challenge:** move a 25-meter long structure (15 m for the magnet, another 10 m for the x-ray telescopes) that weighs 200 tons
- **Solution:** borrow from other heavy-industry and ground-based astronomy



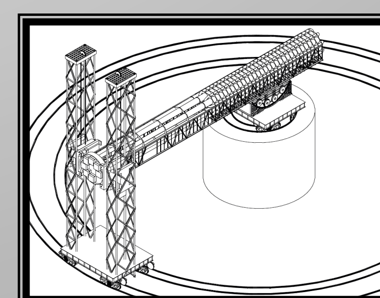


Stay tune for J. Vogel presentation

Conclusions

- **CAST** is established as a reference result in experimental axion physics:
  - CAST PRL2004 most cited experimental paper in axion physics
  - The use of 4He and 3He gases in the conversion region at CAST has successfully managed to establish the most restringing limits on the coupling to photons for axion masses up to 1.18 eV
  - Competitive limits on axion-electron coupling have been set for the vacuum case of CAST
  - Near term future runs will further improve the present limits of CAST

- **IAXO**: 4^{th} generation helioscope. Stay tune for Dr. Vogel's talk



Thank you!