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

8th Patras Workshop on Axions, WIMPs and WISPs
Chicago, IL. 22nd of July 2012

J. Ruz, *on behalf of the CAST Collaboration*

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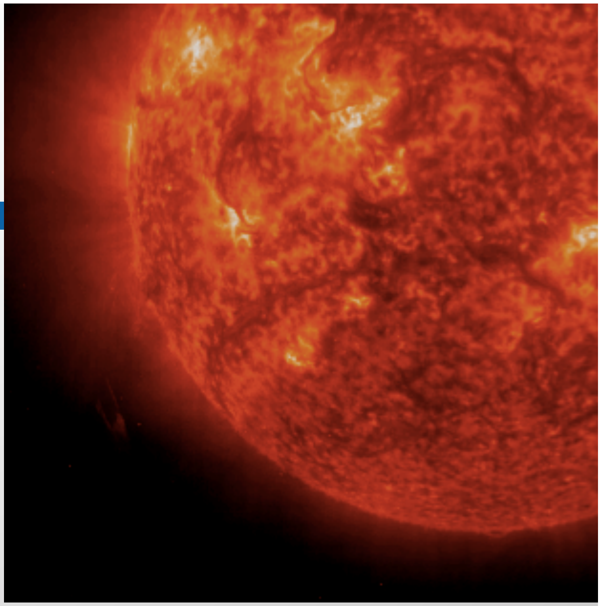
Outlook

- Axions in astrophysics
- Detection of solar axions
  - The helioscope concept
  - The coherence condition
- Axion models
- Hadronic axions at CAST
  - Axion flux
  - Results
- Non-hadronic axions at CAST
  - Axion flux
  - Expected photons
  - Analysis method
  - Extraction of a limit
  - Results
- Near term future at CAST

Axions in astrophysics

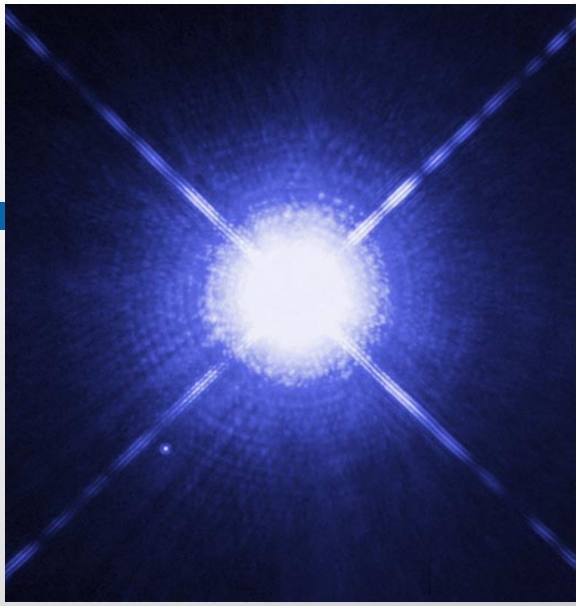


- **Axions can be produced in the core of stars, like the Sun, by Primakoff conversion of plasma photons.**
  - Axions drain energy from stars and may alter their lifetime.
    → Limits can be derived for axion properties
  - Solar Age: $g_{a\gamma} \leq 3 \times 10^{-9} \mathrm{GeV}^{-1}$
  - Helioseismology: $g_{a\gamma} \leq 1 \times 10^{-9} \mathrm{GeV}^{-1}$
  - Neutrino flux: $g_{a\gamma} \leq 7 \times 10^{-10} \mathrm{GeV}^{-1}$ [arXiV 0807.2926]
  - Horizontal branch stars: $g_{a\gamma} \leq 1 \times 10^{-10} \mathrm{GeV}^{-1}$
  - SN 1987A

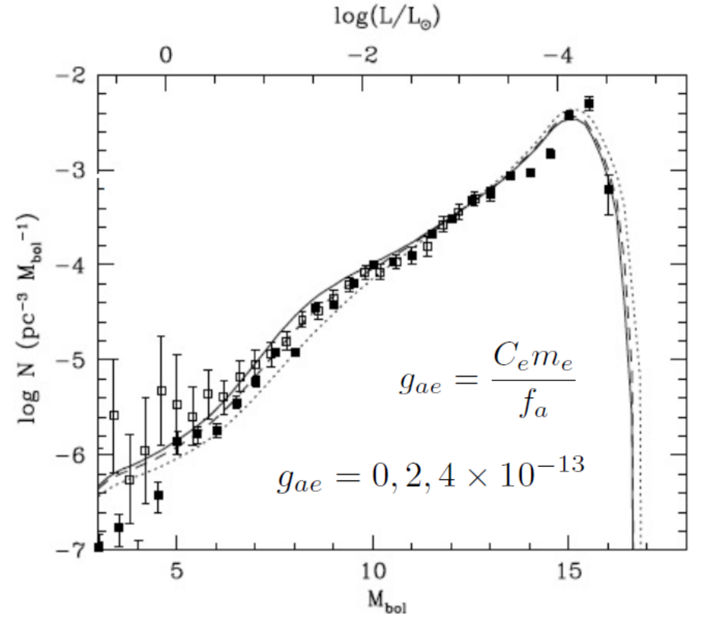
See Raffelt hep-ph/0611118 and references therein

- **Axion decay may produce γ-ray emission lines originating from certain places (e.g., galactic center).**
  - But axion decay constant is normally very long (>> Age of Universe)

Axions in astrophysics



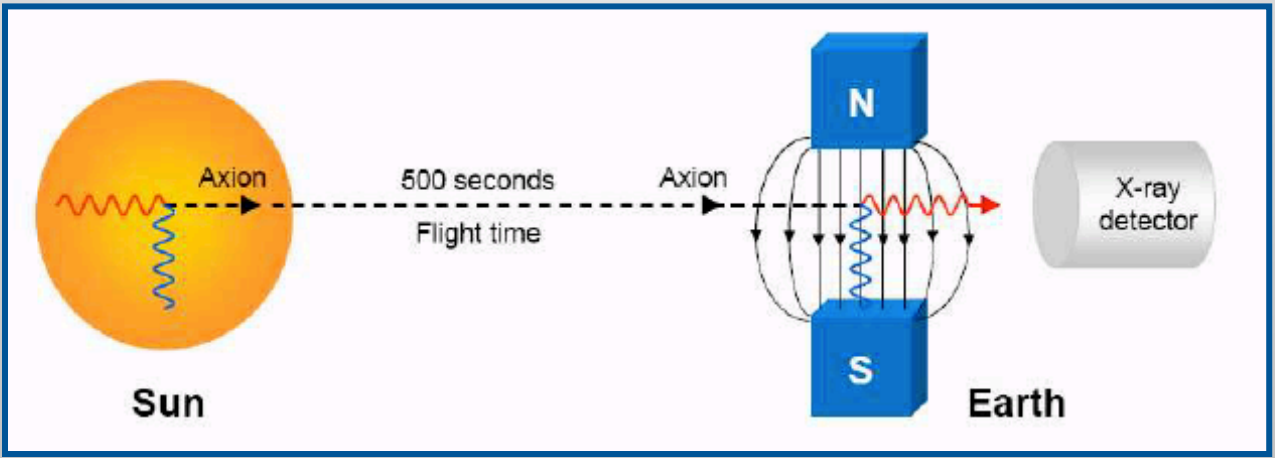
- **Axions may have a wider impact:**
  The cooling of white dwarfs
  - Luminosity function (WD’s per unit magnitude) altered by axion cooling
  - Claim of detection of new cooling mechanism (Isern 2008)
  - Axion-electron coupling of ~1x10^{-13} (→ axion masses of 2-5 meV or larger) **fits data**.



Detection of solar axions

- **The Helioscope concept**

Axions created in the solar core travel towards Earth where by means of an intensive electromagnetic field they can be converted to photons via Primakoff effect



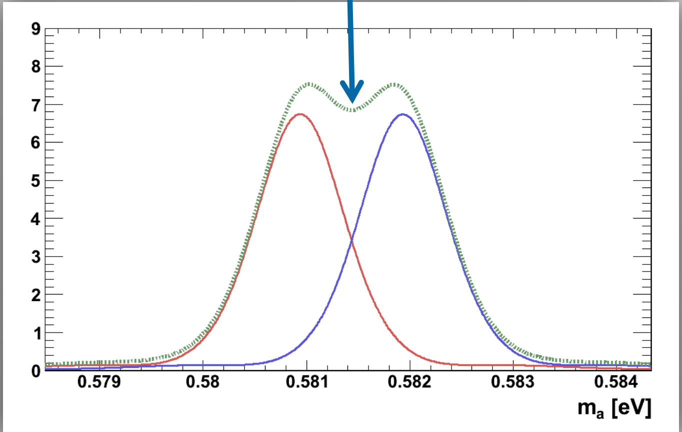
The interaction of an axion converting to a photon via Primakoff effect in the presence of magnetic fields is the proposed detection mechanism

Detection of solar axions

The coherence condition

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

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

$$\downarrow$$

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

Axion models

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

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

$$\uparrow$$

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

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

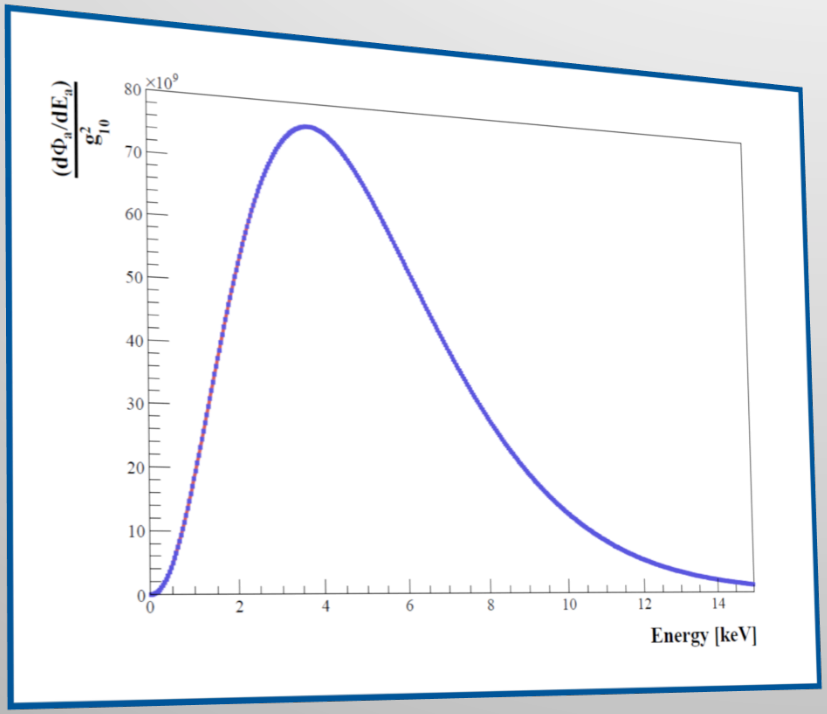
  ➢ Hadronic axion models

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

  ➢ Non-hadronic axion models

Hadronic axions at CAST

- Primakoff production of axions in the Sun



Differential axion flux at the Earth surface due to Primakoff production in the solar core

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

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

Hadronic axions from the Sun

- 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

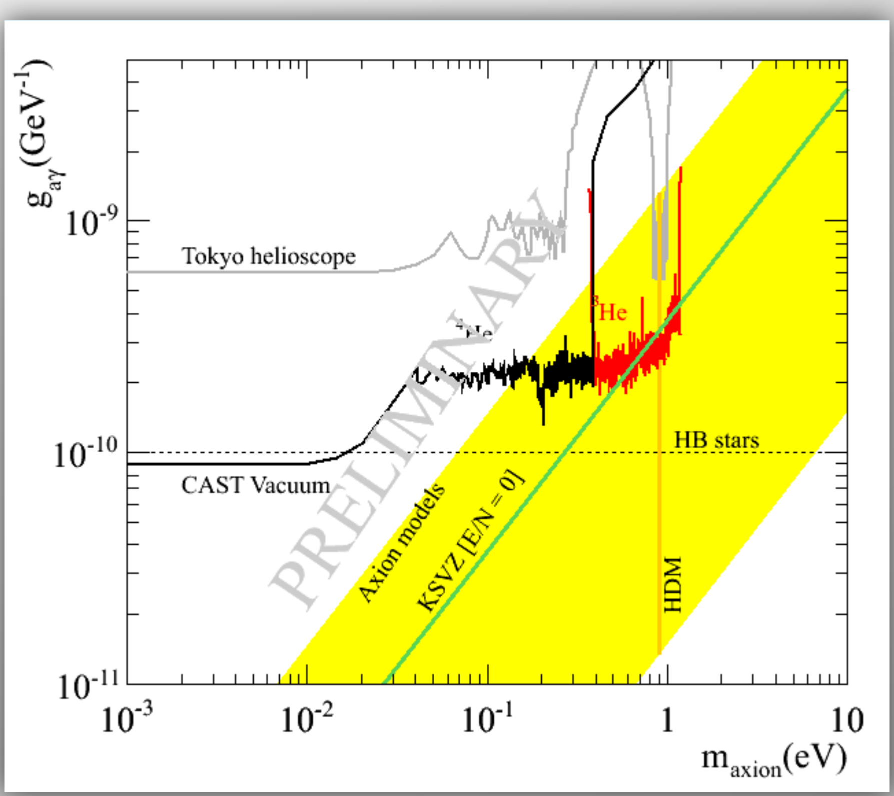
☐ First Results from ^{3}He Phase

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

Phys.Rev.Lett. 107:261302, 2011

☐ Preliminary analysis of rest ^{3}He Phase

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



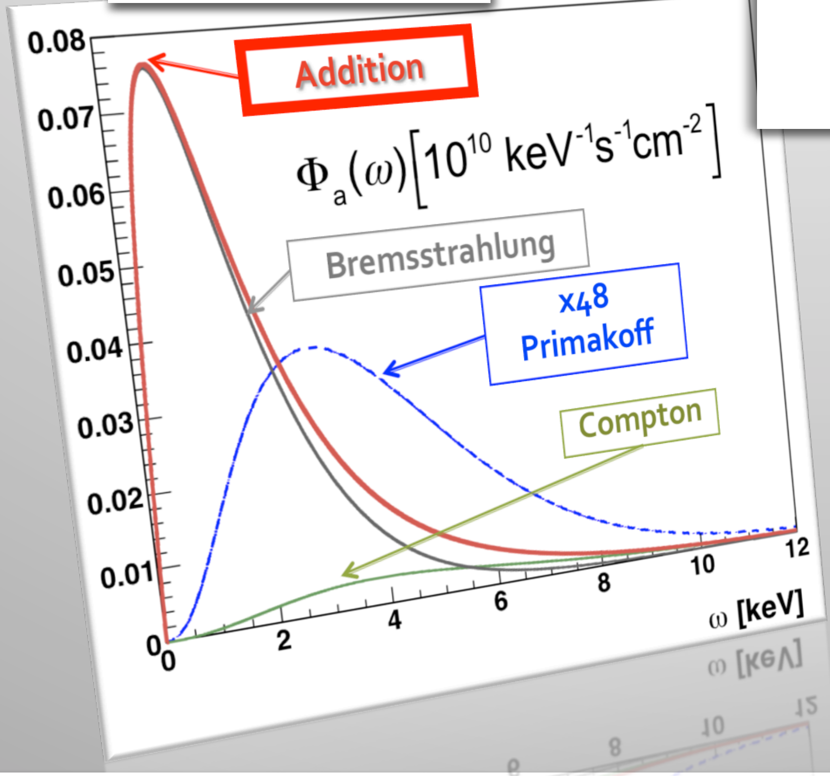
But we know that other processes might be at play …

Non-hadronic axions at CAST

- Primakoff and electron production of axions in the Sun

$$g_{a\gamma} = 1\times 10^{-12}\,\mathrm{GeV}^{-1}$$

$$g_{ae} = 1\times 10^{-13}$$



Special thanks to J. Redondo and G. Raffelt

Axion-recombination subdominant

Work in progress

- No significant signal observed
- White Dwarf compatible?

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

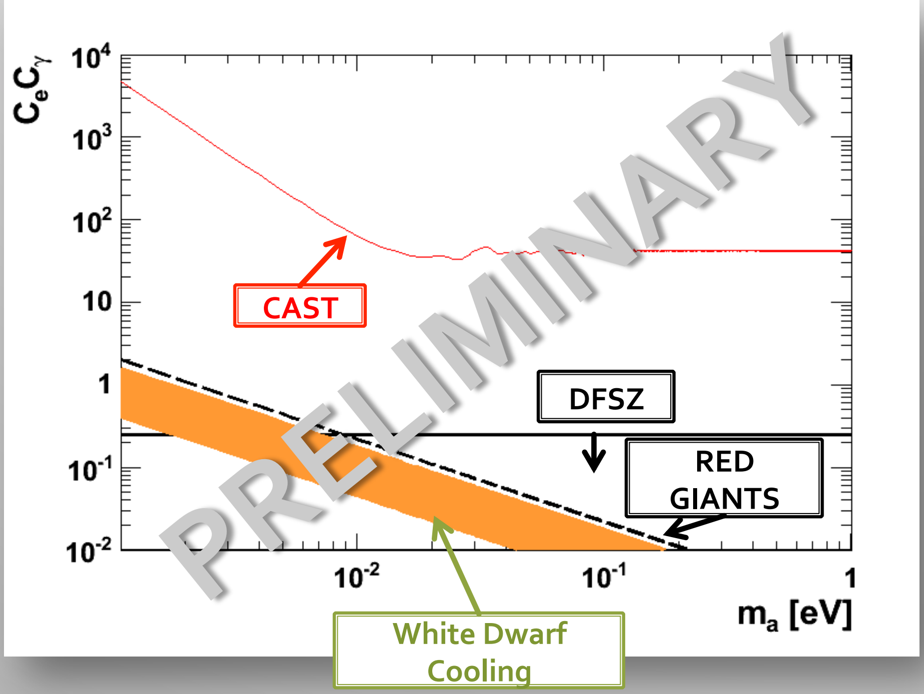
$$\mathcal{L}_{aee} = C_e \frac{\partial_\mu a}{2 f_a} \overline{\psi}_e \gamma_5 \gamma^\mu \psi_e \longleftarrow \boxed{g_{ae} = \frac{C_e m_e}{f_a}}$$

Non-hadronic axions at CAST

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

Axion-electron Yukawa coupling

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



$$C_e C_\gamma < \frac{1}{4}$$

⇩

DFSZ Models

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

Near term future at CAST

- **Current CAST science program** approved by CERN, runs through 2014
- **Schedule for the near future**
  - **Re-visit ^{4}He phase (2012) and vacuum phase (2013-14):**

    Better detectors → higher sensitivity

    New optics → increased discovery potential

    - Improve present limits
    - Study axion-electron coupling g_{ae}

      Direct access to DFSZ models
  - **Possible access to:**
    - Exotica
      - Paraphotons, chameleons, low energy axions
    - Relic axions

See Konstantin's talk

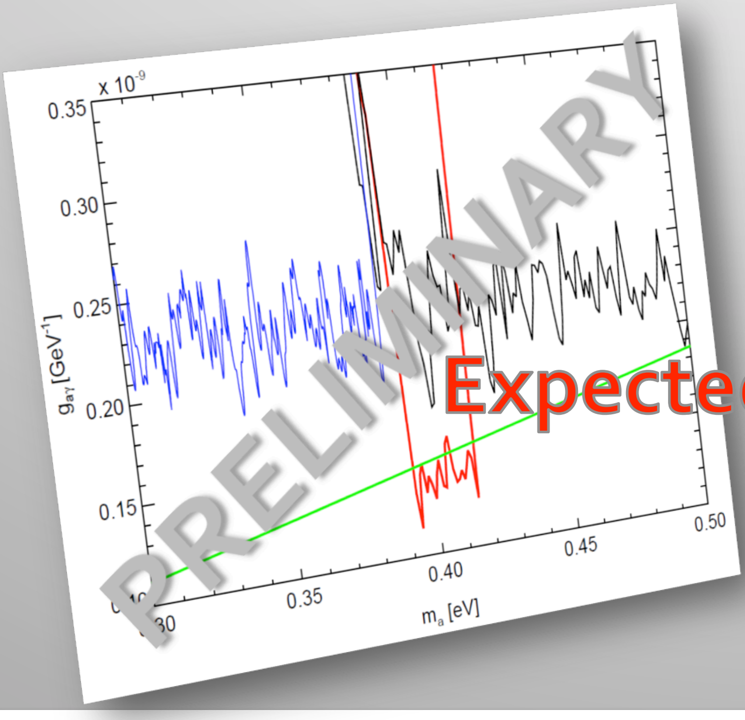
See Julia's talk

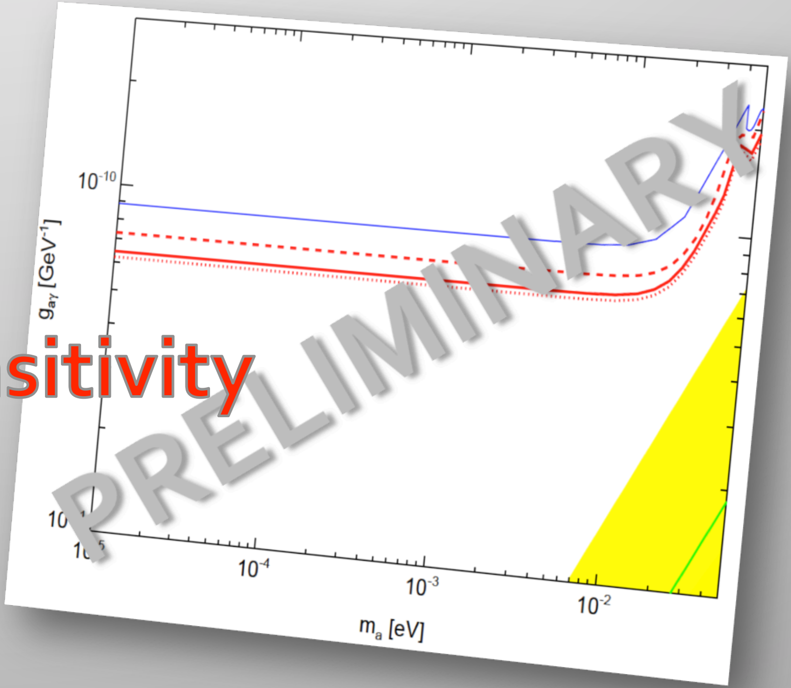
- Improvement for CAST →

Large parts of the QCD favored models could be explored in the coming decade with IAXO

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)





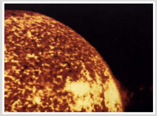
Expected sensitivity

Thank you!

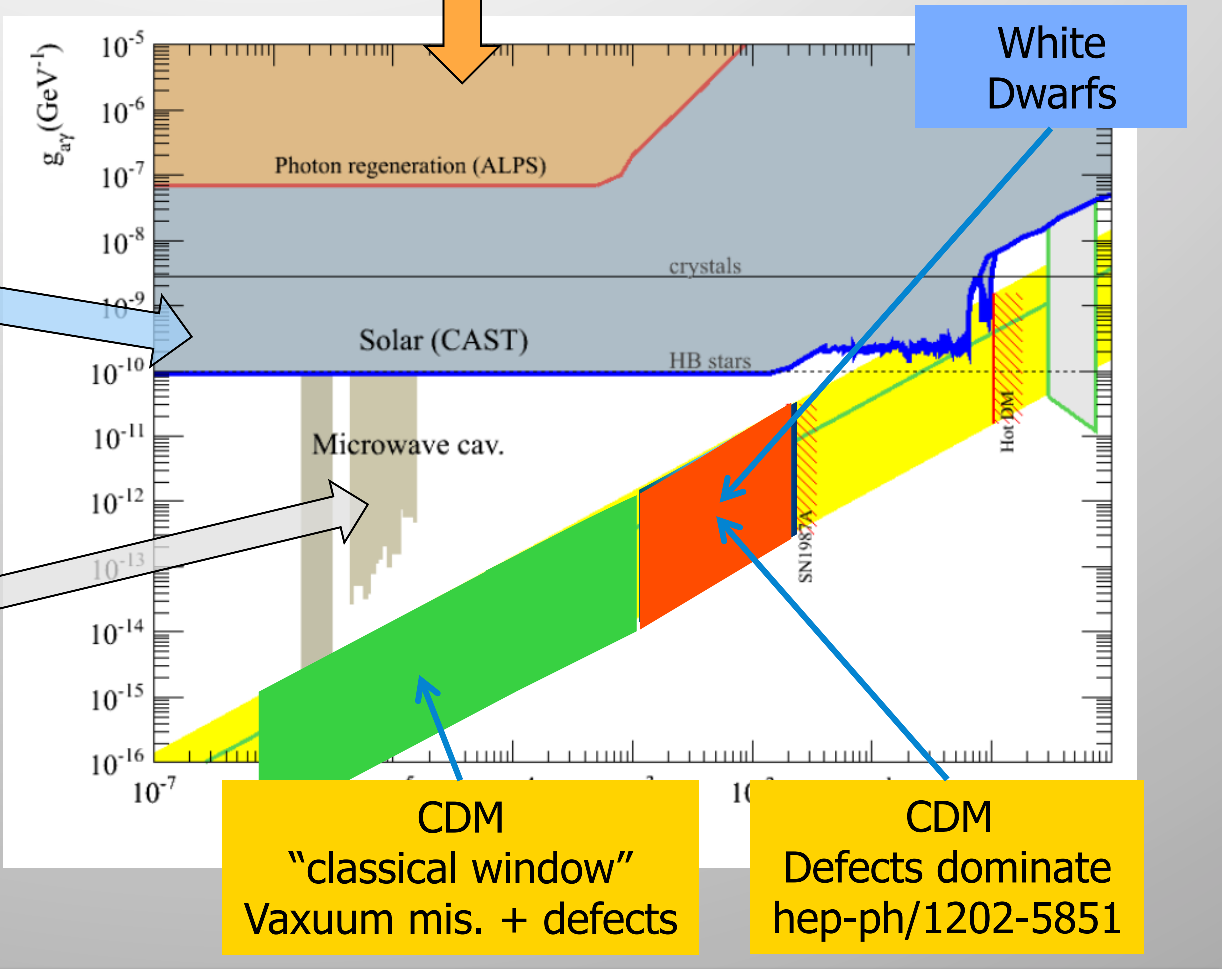
Backup slides

Axion parameter space

- 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)



White Dwarfs

CDM
"classical window"
Vaxuum mis. + defects

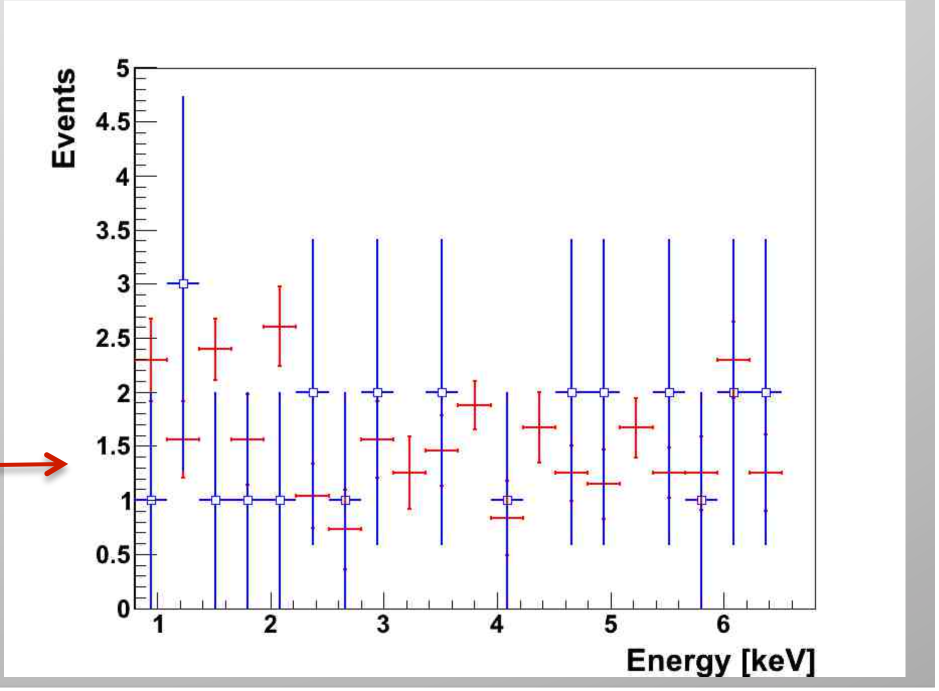
CDM
Defects dominate
hep-ph/1202-5851

Non-hadronic axions at CAST

- **The CCD Detector of CAST**
  - Energy range [0.8-6.8] keV with ΔE=0.3 keV
  - Vacuum data of First Phase 2004
    - Tracking exposure: 197 hours
    - Background exposure: 1890 hours
  - Efficiency included
  - 1 bore
  - Spot size: 9.4 mm^2

CCD data 2004

- **Blue: tracking counts**
- **Red: background expectation**



Detection at CAST

- **Axion flux:**

$$\left(\frac{d\phi_a}{dE_a}\right)_T = \left(\frac{d\phi_a}{dE_a}\right)_C + \left(\frac{d\phi_a}{dE_a}\right)_B + \left(\frac{d\phi_a}{dE_a}\right)_P = g_{ae}^2 \cdot C + g_{ae}^2 \cdot B + g_{a\gamma}^2 \cdot P$$

- **Expected photons:**

$$N_\gamma \propto g_{ae}^2 \cdot g_{a\gamma}^2 \times H(C+B) + \boxed{g_{a\gamma}^4 \times (H \cdot P)}$$

  - In the non-hadronic models the contribution from electron coupling is ~900 times stronger than the Primakoff in the Sun this term can be neglected. z

$$\Downarrow$$

$$N_\gamma \propto g_{ae}^2 \cdot g_{a\gamma}^2 \times H(C+B)$$

Analysis method

Binned likelihood

- Poissonian distribution:

$$L = \prod_{j}^{n} \left(\frac{e^{-\lambda_j} \lambda_j^{t_j}}{t_j!} \right) \left(\frac{t_j!}{e^{-t_j} t_j^{t_j}} \right) \rightarrow$$

$j = bin\ index$

$\lambda_j = mean\ j\_bin$

$t_j = tracking\ counts\ j\_bin$

$b_j = background\ counts\ j\_bin$

$$\boxed{\lambda_j \propto g_{ae}^2 \cdot g_{a\gamma}^2 \times H(C+B) + b_j}$$

$$-\tfrac{1}{2}\chi^2 = \log\left[\prod_{j}^{n} e^{-\lambda_j + t_j} \left(\frac{\lambda_j}{t_j} \right)^{t_j} \right] = \sum_{j}^{n} \left(t_j - \lambda_j \right) + \sum_{j}^{n} t_j \left(\log \lambda_j - \log t_j \right)$$

Analysis method

Unbinned likelihood

- Poissonian distribution:
  - Dividing the total exposure in small k-time intervals so that only one or zero counts can be observed in the detector

$$L = \prod_{k}^{t} L_k = \prod_{k}^{t} \left[L_k(t_i = 0) \times L_k(t_i = 1) \right] = \prod_{k}^{t} \prod_{j}^{n} e^{-\lambda_j + t_j} \left(\frac{\lambda_j}{t_j} \right)^{t_j} \longrightarrow$$

k = time interval
j = bin index
λ_j = mean j_bin
t_j = tracking counts j_bin
b_j = background counts j_bin

$$\boxed{\lambda_j \propto g_{ae}^2 \cdot g_{a\gamma}^2 \times H(C + B) + b_j}$$

$$-\tfrac{1}{2}\chi_T^2 = \sum_{k}^{t} \left[-\tfrac{1}{2}\chi_{ko}^2 - \tfrac{1}{2}\chi_{k1}^2 \right] = \sum_{k}^{t} \left[-\sum_{j}^{n} \lambda_j + \sum_{j}^{n} (1 - \lambda_j) + \sum_{j}^{n} t_j \log \lambda_j \right]$$

IAXO

Large parts of the QCD favored models could be explored in the coming decade with IAXO

See Julia's talk