Probing the eV-Mass Range for Solar Axions with the CAST Experiment (CERN Axion Solar Telescope)

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EPS HEP 2009, Krakow, July 16-22, 2009

- Theoretical Motivation for Axions
- Detection of Solar Axions
- The CAST Experiment
- Latest Results of Phase I and II

CAST

The strong CP-problem

CP-violation necessary in the standard model:
Explanation of matter-antimatter-asymmetry

CP-violation in weak interactions
CP-conservation in electromagnetic + strong interactions

QCD predicts violation in strong interactions

$$L_\theta = \bar{\theta}\,\frac{g^2}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a \quad \text{mit} \quad \tilde{G}^{\mu\nu}_a = -\frac{1}{2}\varepsilon^{\mu\nu\alpha\beta}\, G^a_{\alpha\beta}$$

HOWEVER:

So far no experiment has observed this CP-violation in QCD!

The Peccei-Quinn-Solution

A possible solution to the strong CP-problem:

Elimination of CP-violating term in QCD Lagrangian by introduction of new additional global U(1) symmetry

$$L_a = C\frac{a}{f_a}\frac{g^2}{32\pi^2}G^a_{\mu\nu}\tilde{G}_a^{\mu\nu}$$

New pseudo-scalar field → **AXION**

First proposed by Peccei & Quinn (1977)

Particle interpretation by Weinberg, Wilczek (1978)

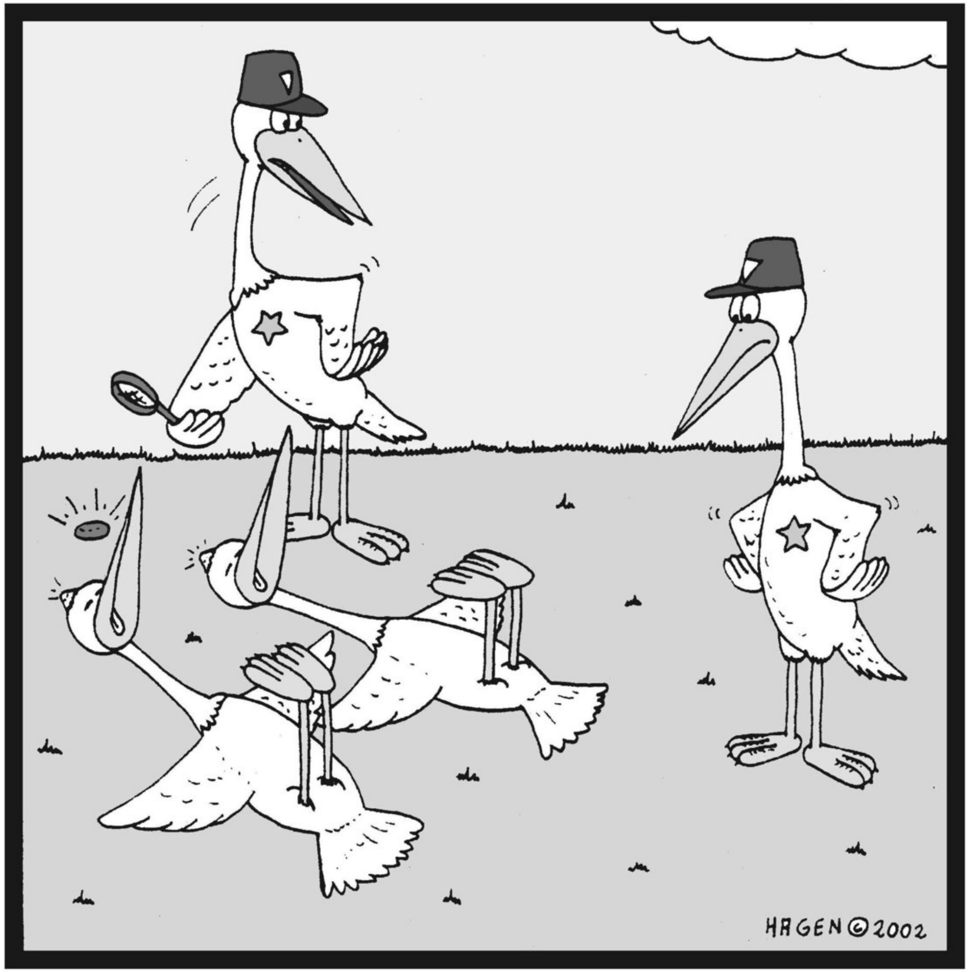
Theoretical Motivation for Axions

The Axion: Properties

- Neutral pseudo-scalar Goldstone-Boson
- Only feable interaction with ordinary matter
- Mass (from axion-π^0-mixing): $$m_a \approx 0.6\,\text{eV}\,\frac{10^7\,\text{GeV}}{f_a}$$
  $$f_a > 10^7\,\text{GeV}$$ (Astrophysical criterion)
- Coupling to photons: $$L_{a\gamma} \approx g_{a\gamma}\left(\vec{E}\cdot\vec{B}\right) a$$ with $$g_{a\gamma} \approx \frac{\alpha}{2\pi f_a} < 10^{-10}\,\text{GeV}^{-1}$$
- Mean lifetime: $\tau_a \approx 10^{17}$ yr for $m_a = 1\,\text{eV}$ i.e. $\tau_a > t_{\text{Universe}}$

Theoretical Motivation for Axions

The Axion: Killing two birds with one stone



Unbelievable! It looks like they've both been killed by the same stone...

Axions as

Solution to the strong CP-problem

Candidate for dark matter

Production of Axions in the Sun

Primakoff-Effekt: $\gamma + \gamma^* \rightarrow a$

Photons of blackbody radiation (X-ray photons) → Strong electric fields in solar core → Axions

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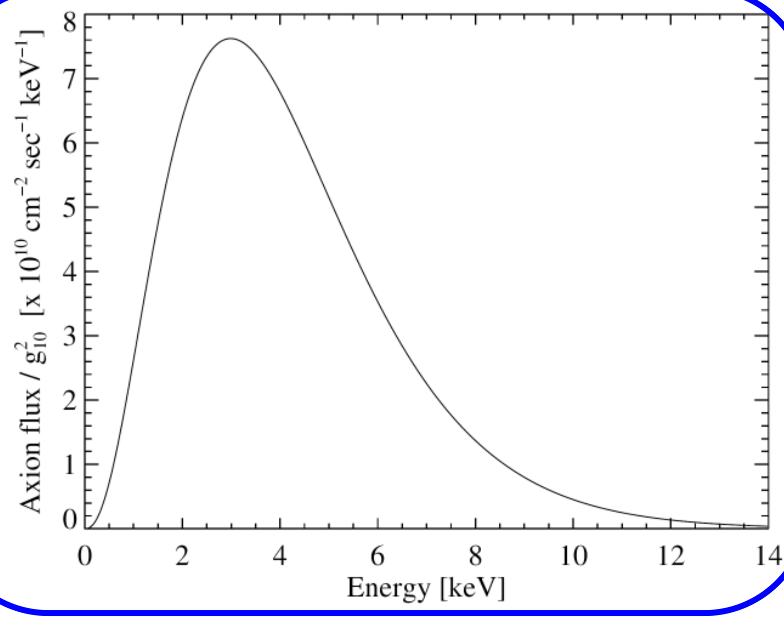
Solarer Axion flux at Earth

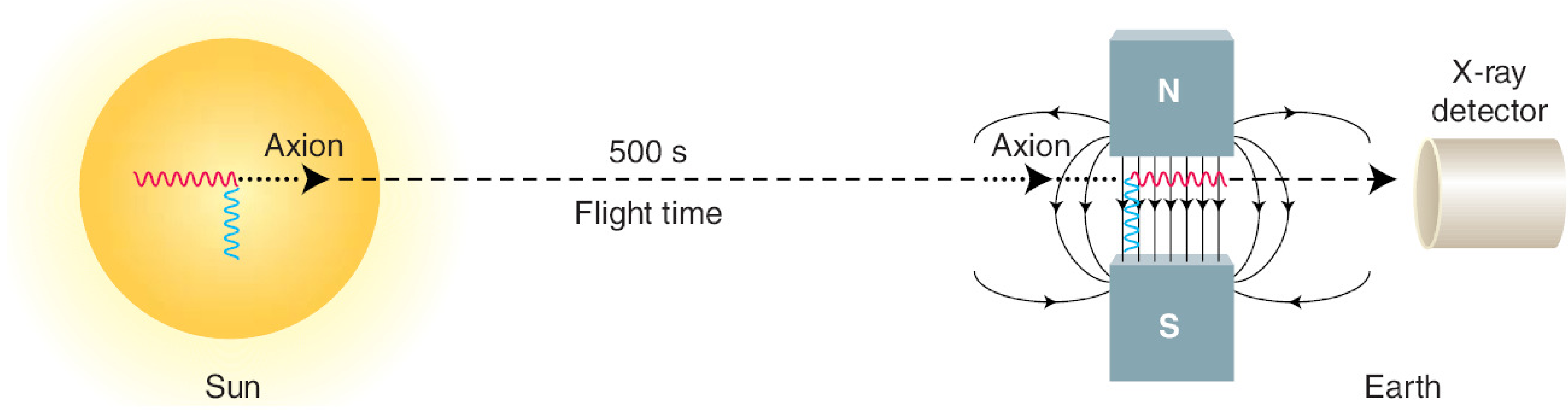
- Mean Energy of axions: $\langle E_a \rangle$ = 4.2 keV
- Flux of axions: $$\frac{d\Phi_a(E_a)}{dE_a} \propto g_{a\gamma}^2$$

(Serpico & Raffelt, based on standard solar model BP2004 of Bahcall et al.)



Detection of Solar Axions

Conversion Probability



$$\gamma + \gamma^* \rightarrow a$$

$$a + \gamma^* \rightarrow \gamma$$

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

With momentum transfer $q = \left|\frac{m_\gamma^2 - m_a^2}{2E_a}\right|$, effective photon mass $m_\gamma[eV] \approx \sqrt{0.02\frac{P[mbar]}{T[K]}}$

in ^{4}He and absorption Γ

Detection of Solar Axions

$$P_{a\to\gamma} = \left(\frac{BL}{2}\right)^2 \left(\frac{g_{a\gamma}}{10^{-10}GeV^{-1}}\right)^2 \frac{\sin^2\left(qL/2\right)}{\left(qL/2\right)^2}$$

(für Absorption $\Gamma = 0$)

$$P_{a\to\gamma} = \left(\frac{BL}{2}\right)^2 \left(\frac{g_{a\gamma}}{10^{-10} GeV^{-1}}\right)^2 \frac{\sin^2\left(qL/2\right)}{\left(qL/2\right)^2}$$

(für Absorption Γ = 0)

Coherence condition: qL/2 < π

CAST Phase I:
Vacuum in magnet
($m_\gamma = 0$, qL/2 < π)

Effective mass of photon $m_\gamma=0$

$$q = \left|\frac{m_\gamma^2 - m_a^2}{2E_a}\right| = \frac{m_a^2}{2E_a}$$

Range of axion masses: $m_a \leq 0.02$ eV

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$$P_{a\to\gamma} = \left(\frac{BL}{2}\right)^2 \left(\frac{g_{a\gamma}}{10^{-10}GeV^{-1}}\right)^2 \frac{\sin^2\left(qL/2\right)}{\left(qL/2\right)^2}$$ **(für Absorption Γ = 0)**

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Range of axion masses: $m_a \leq 0.02$ eV

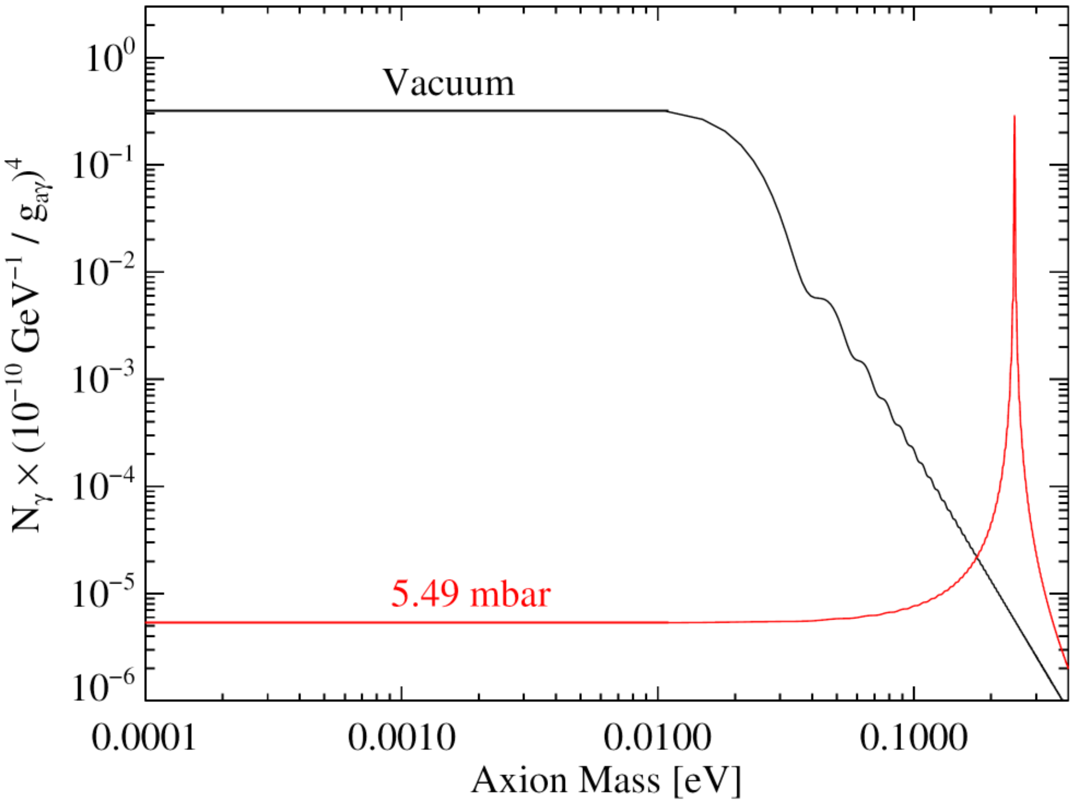
CAST Phase II:
^{4}He / ^{3}He in magnet
($m_\gamma \neq 0$, qL/2 < π)

Effective mass of photon $m_\gamma > 0$

$$m_\gamma[eV] \approx \sqrt{0.02\frac{P[mbar]}{T[K]}}$$

Extended range of axion masses

Expected Number of Photons from Axion Conversion



$$N_\gamma = \int \frac{d\Phi(E_a)}{dE_a} P_{a\to\gamma}(E_a)\, A\, \Delta t\, \varepsilon(E_a)\, dE_a \propto g_{a\gamma}^4$$

A: detector area, Δt: exposure time, $\varepsilon(E_a)$: efficiency

The CAST Experiment

The CAST Experiment

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MPE Garching
H. Bräuninger, R. Hartmann, P. Friedrich, M. Kuster, A. Nordt

MPI München
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National Technical University of Athens, Athen
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M.Pivovaroff, R. Soufli, K. van Bibber

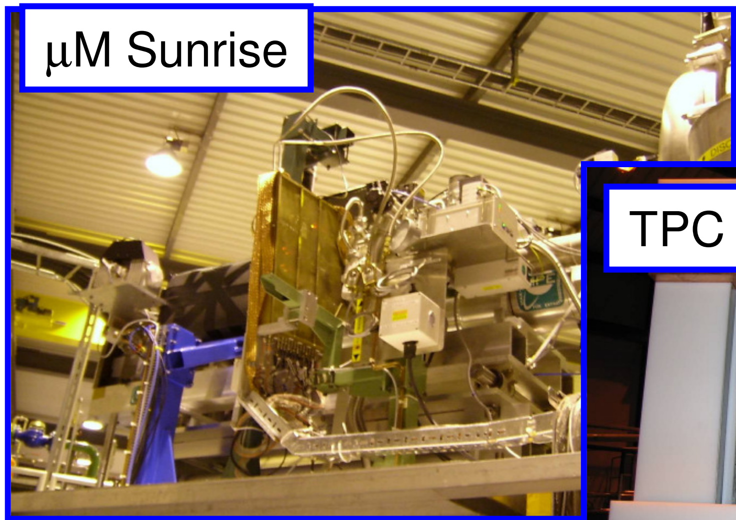
University of Chicago, Enrico Fermi Institute and KICP
J. Collar, D. Miller

Experimental Setup

- Prototype of an LHC dipole magnet (B=9.0 Tesla, L=9.3 m, T=1.8 K)
- Range of movement: 80° horizontally and ± 8° vertically
- Solar tracking possible during sunrise and sunset (2 x 1.5 h per day)
- Three X-ray detectors and one X-ray mirror optics:
  Micromegas (MM), Telescope and Charge Coupled Device (CCD),TPC/Micromegas

The CAST Experiment

CAST Detectors



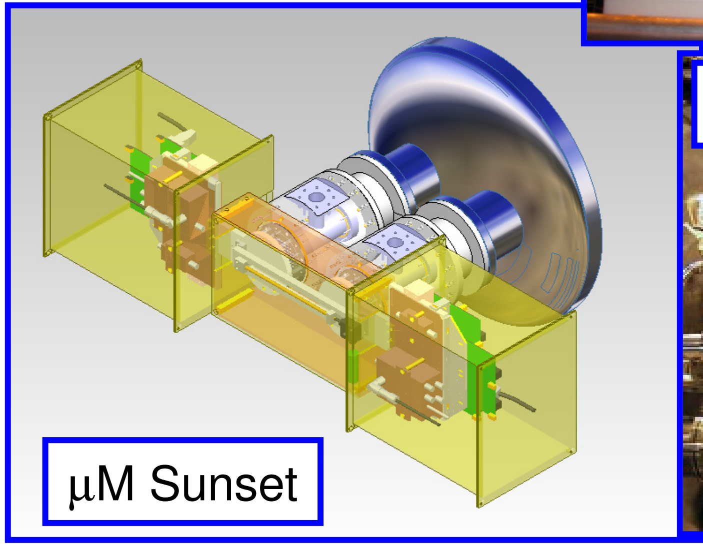
- **Phase I**

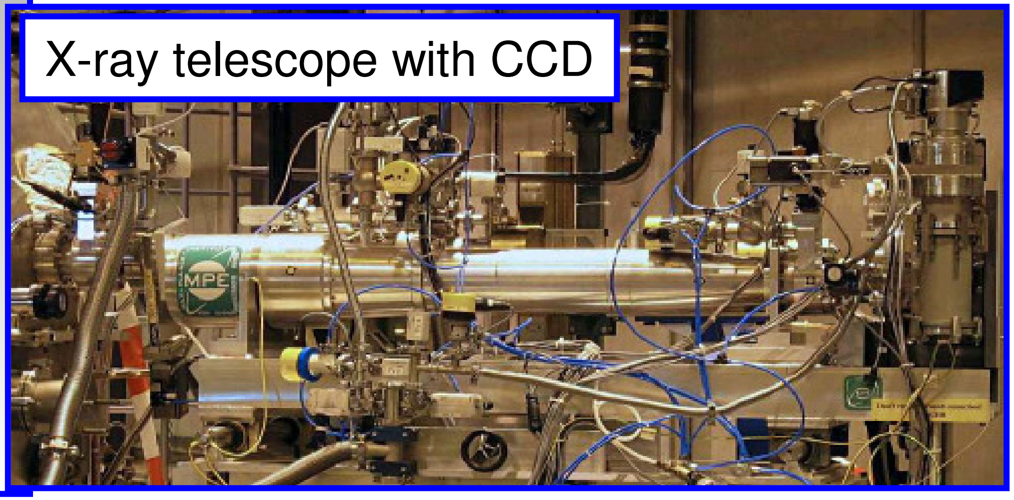
  2003-2004 Vacuum (m_a<0.20 eV)

- **Phase II**

  2005-2006 ^{4}He (m_a<0.39 eV)

  2007- … ^{3}He (m_a<1.16 eV)





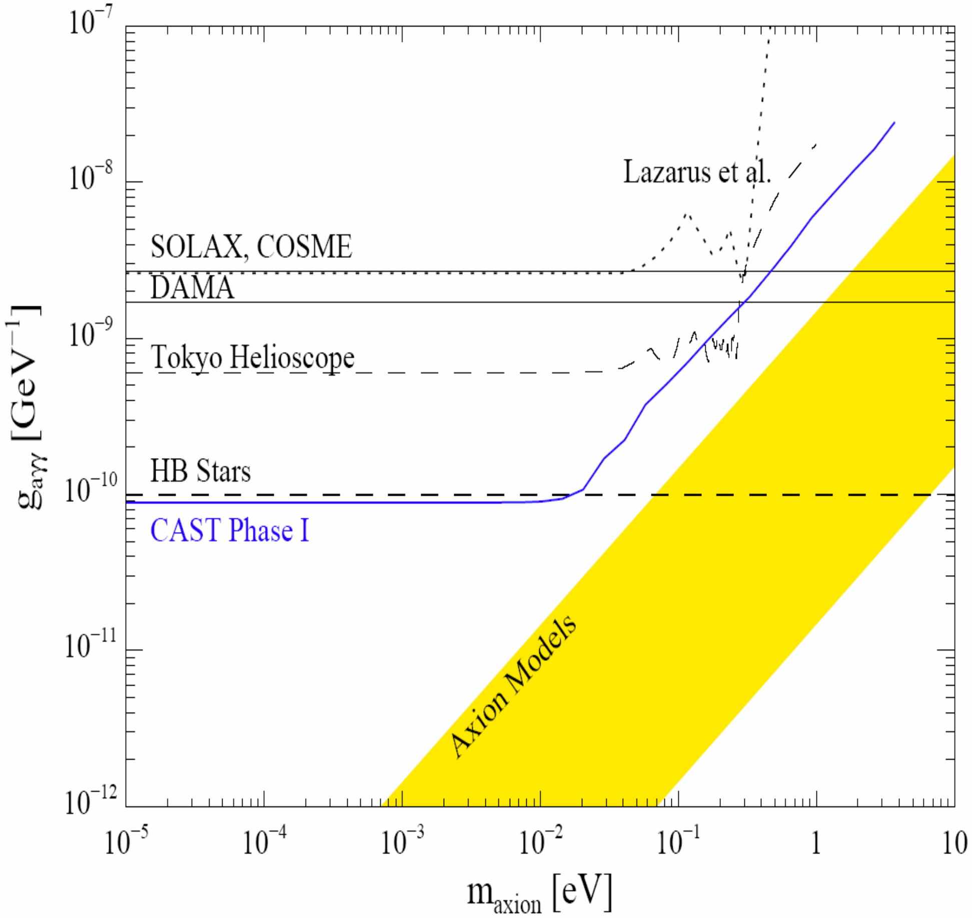
CAST Result Phase I

- No significant signal over background
- CAST Phase I yielded most restrictive experimental upper limit in wide axion mass range
- CAST is more sensitive than best astrophysical limit for axion masses $m_a < 0{,}02$ eV
- Improvement of the upper limit compared to previous experiments by a factor of 7
- Phase I results in JCAP

  (JCAP, 4, 10, 2007)

  and technical Papers of detectors

  (New J. Phys. 9 (2007) 169 [CCD/Telescope],
  New J. Phys. 9 (2007) 170 [MM],
  New J. Phys. 9 (2007) 171 [TPC])

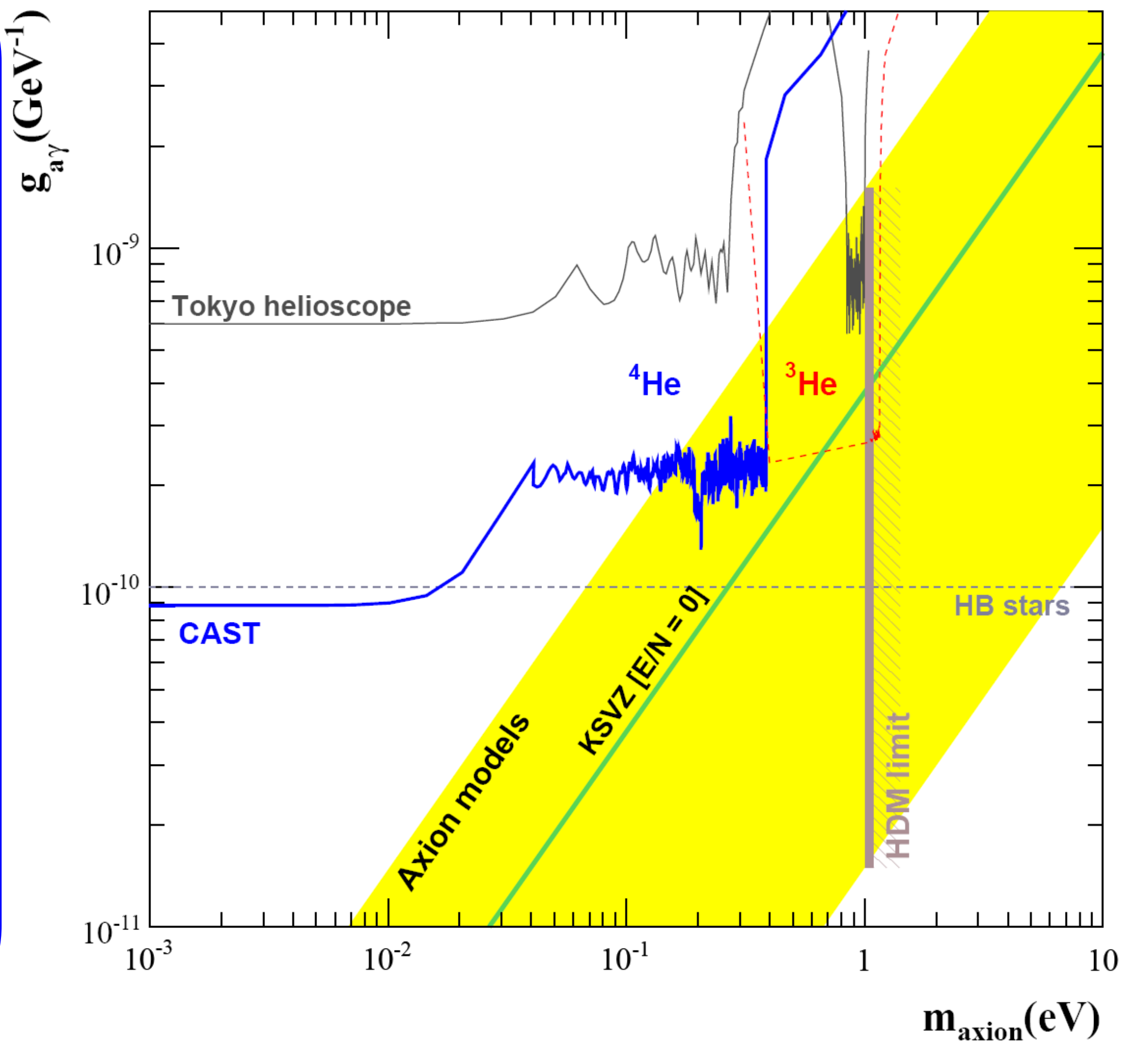


Upper Limit $g_{a\gamma\gamma}$ for $m_a < 0{,}02$ eV

$g_{a\gamma}$ (95%) = $0{,}88 \times 10^{-10}$ GeV^{-1}

CAST Result Phase I and II with ^4He

- 160 measured p-settings with ^4He in the magnet ($p=13.4$ mbar, $m_a=0.39$ eV)
- No significant signal observed
- CAST enters in theoretically favored model regions
- Typical upper limit:
  $g_{a\gamma}$ (95%) = $2{,}2 \times 10^{-10}$ GeV^{-1}
  for $m_a < 0.39$ eV
- ^4He analysis completed
  JCAP 02 (2009) 008
- ^3He measurements ongoing!
  (Over 250 new ^3He steps done!)



Latest Results of Phase I and II

CAST Phase I

No significant axion signal observed

Best experimental upper limit in large axion mass range up to 0.02 eV

$$g_{a\gamma}\,(95\%) = 0.88 \times 10^{-10}\ \mathrm{GeV}^{-1}$$

Comparable to best astrophysical limit

CAST Phase II

Upgraded detectors and sophisticated gas system for the use of helium

CAST enters theoretically favored axion parameter space

^{4}He run completed with typical upper limit for $0.02 < m_a < 0.39$ eV of

$$g_{a\gamma}\,(95\%) = 2.2 \times 10^{-10}\ \mathrm{GeV}^{-1}$$

Data taking with ^{3}He since 2007 (approved till 2010): $m_a < 1.2$ eV [0.66 eV]

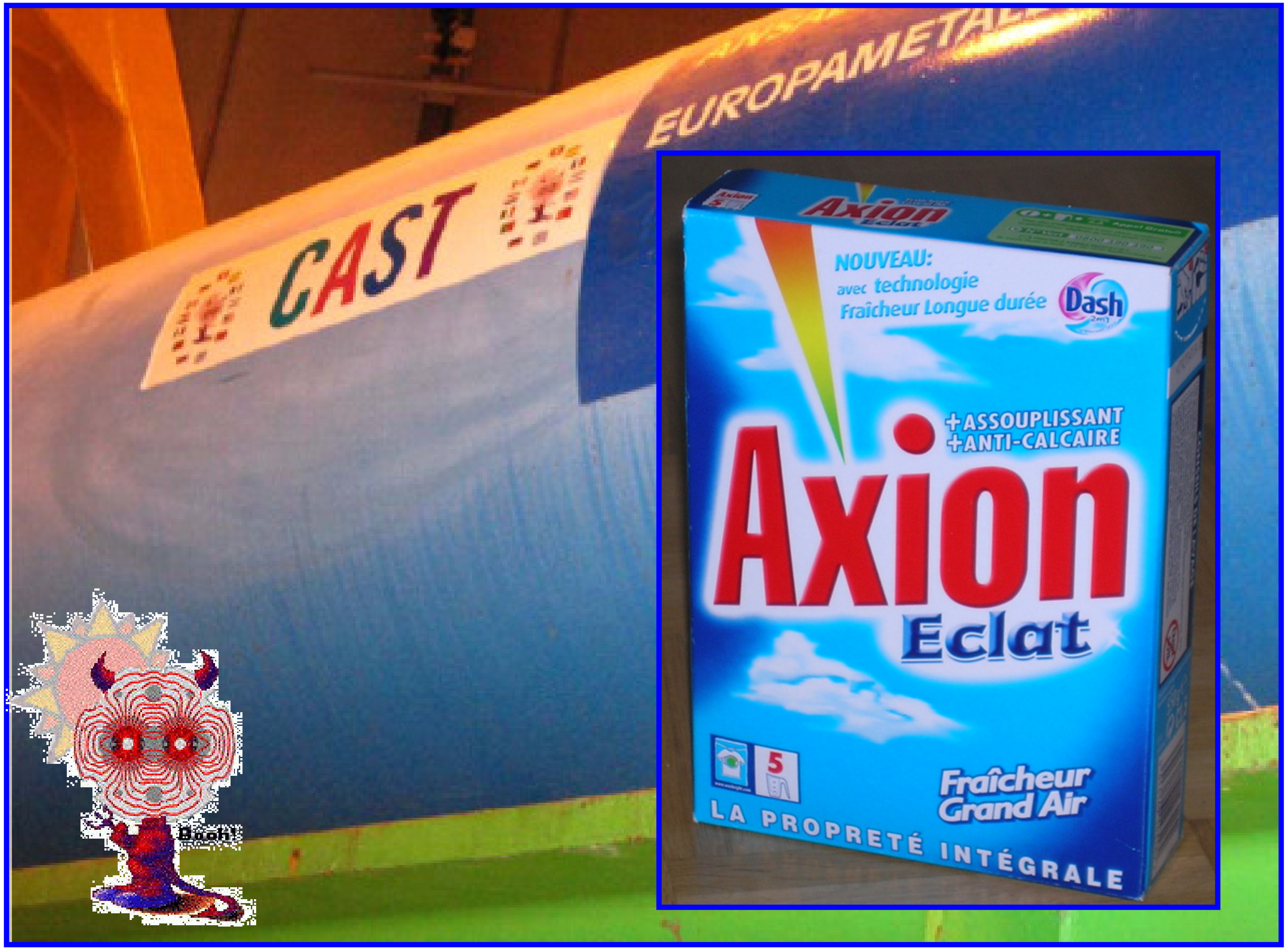
More interesting Physics done/to be done at CAST

Low energy solar axions (LES axions)

Kaluza-Klein axions

Galactic tracking for non-solar axions

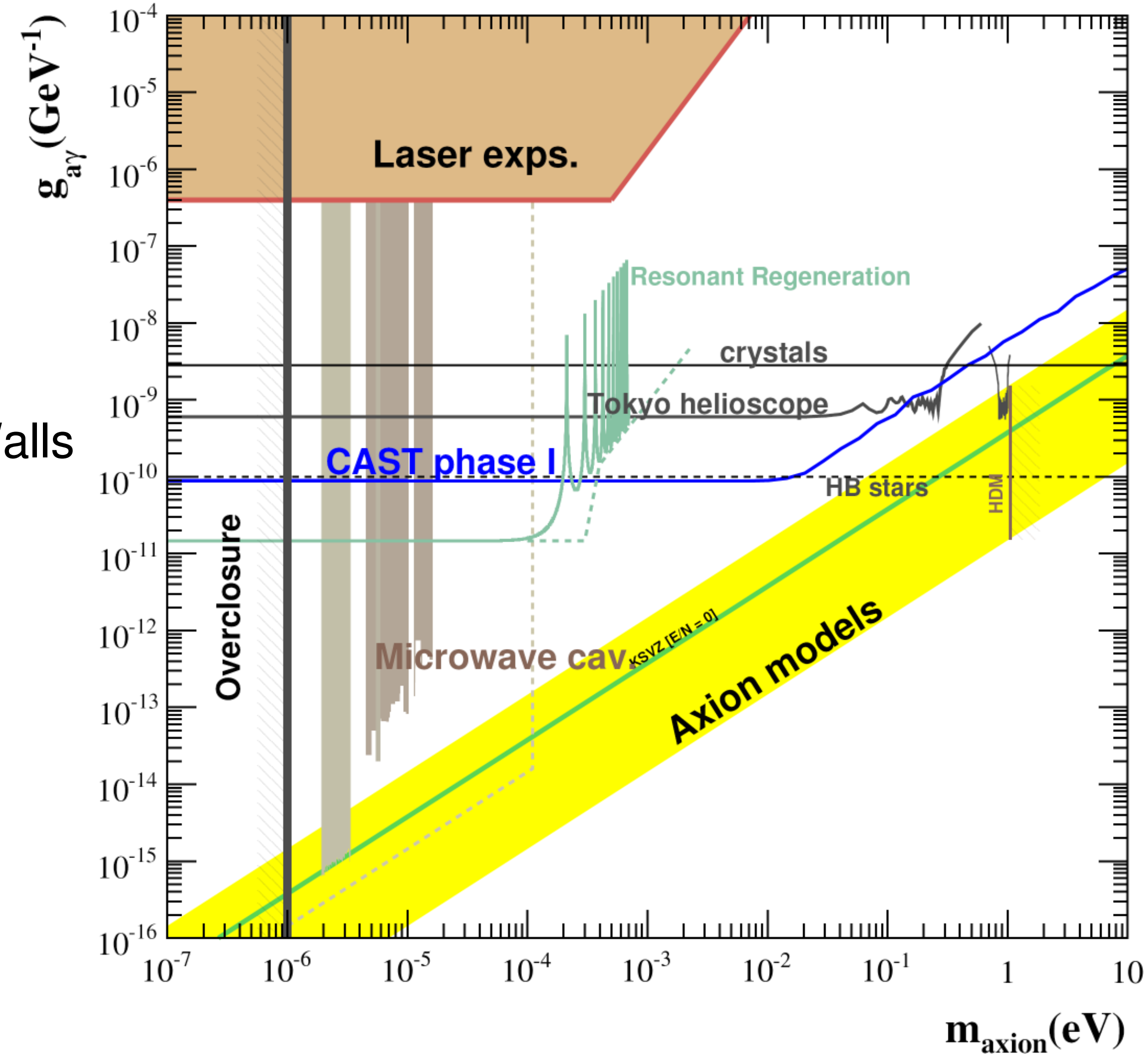
Axions ?!? Not yet... but we will see...



Backup

The Axion: Experimental searches

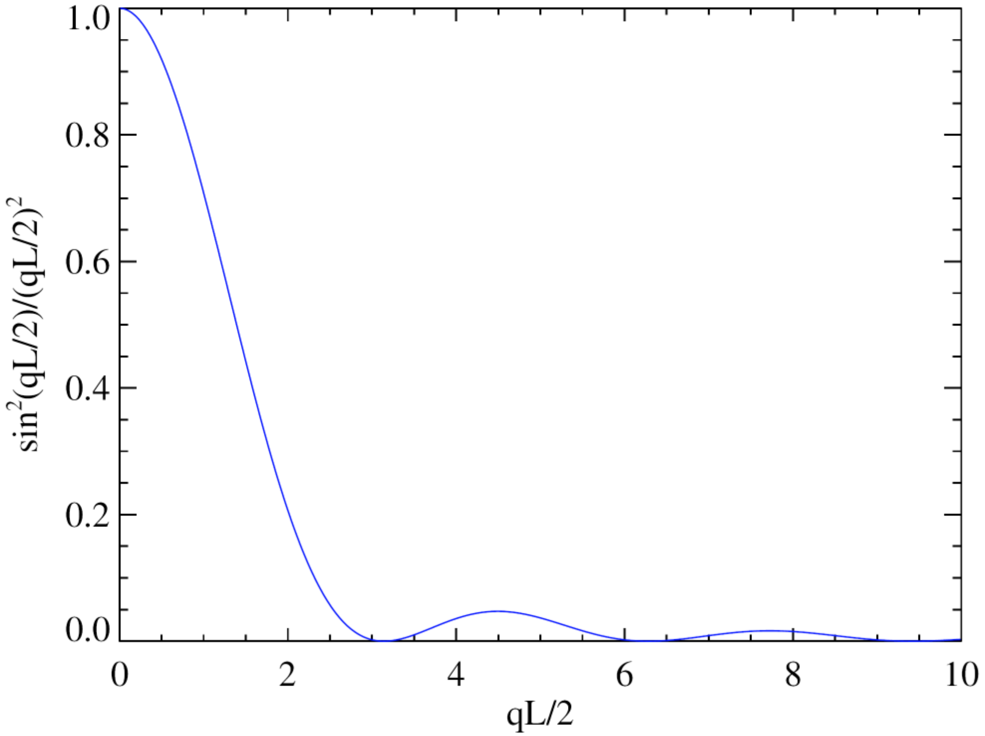
- Galactic axions
  - Haloscopes (ADMX, Carrack)
  - Telescopes (Haystack)
- Laboratory axions
  - Shining-Light-through-Walls (OSQAR, LIPSS, ALPS)
  - Polarization (PVLAS)
- Solar axions
  - Crystals (SOLAX,COSME)
  - Helioscopes (Tokyo, **CAST**)



Conversion probability and coherence condition

$$P_{a\to\gamma} = \left(\frac{BLg_{a\gamma}}{2}\right)^2 \frac{\sin^2\left(\frac{qL}{2}\right)}{\left(\frac{qL}{2}\right)^2}$$

(if absorption $\Gamma = 0$)

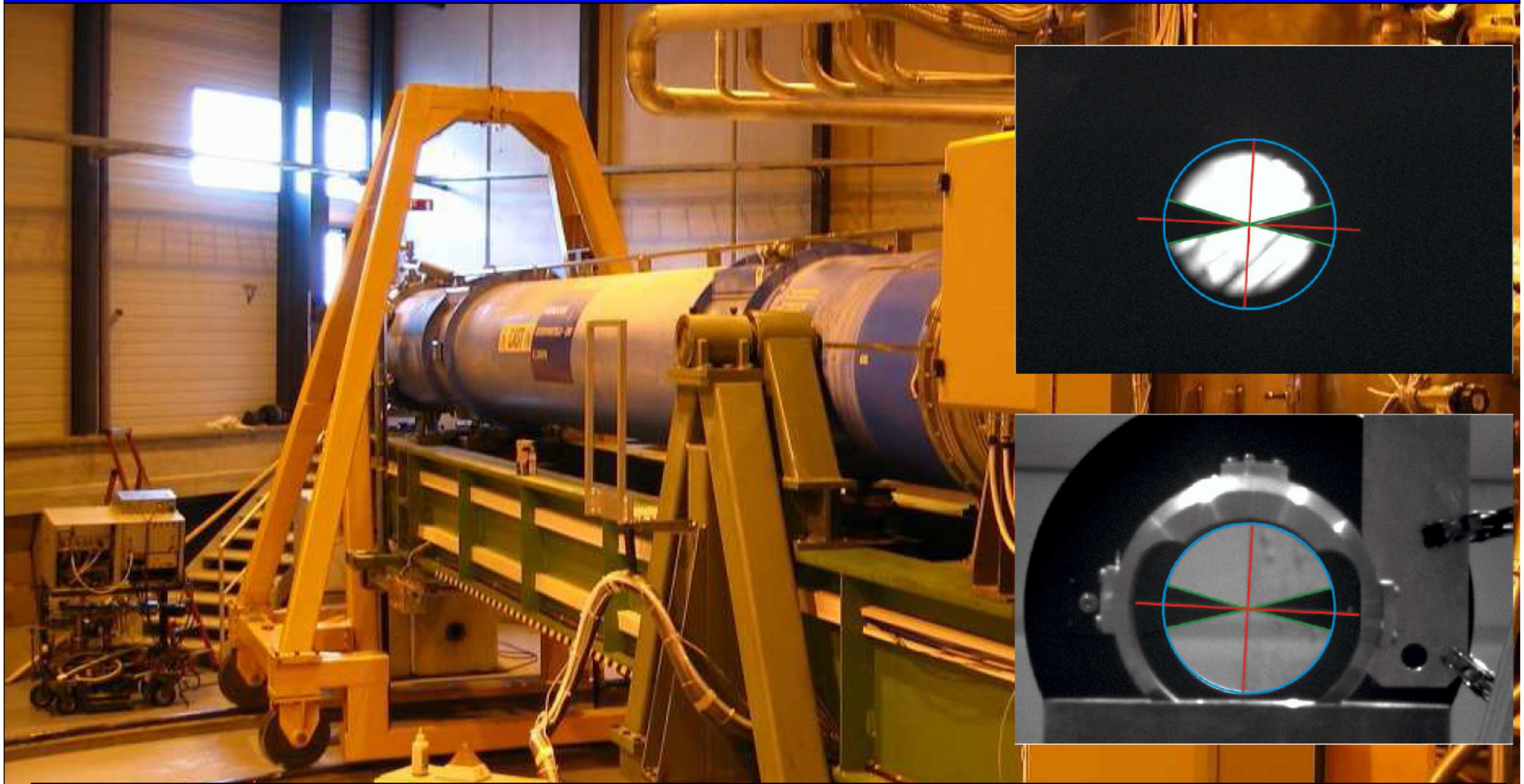


➡ **Coherence condition:**

$qL/2 < \pi$

The CAST Experiment

Solar Filming



In March and September, Sun is directly observable through window:

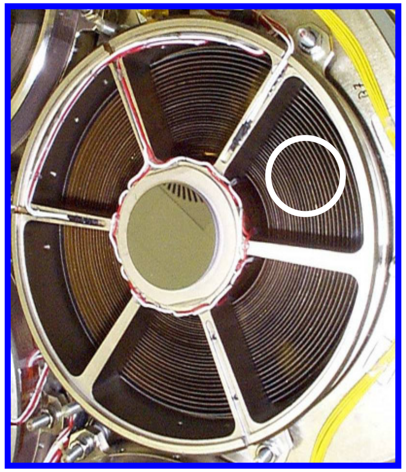
CAST is able to follow the Sun with required accuracy (0.02°)!

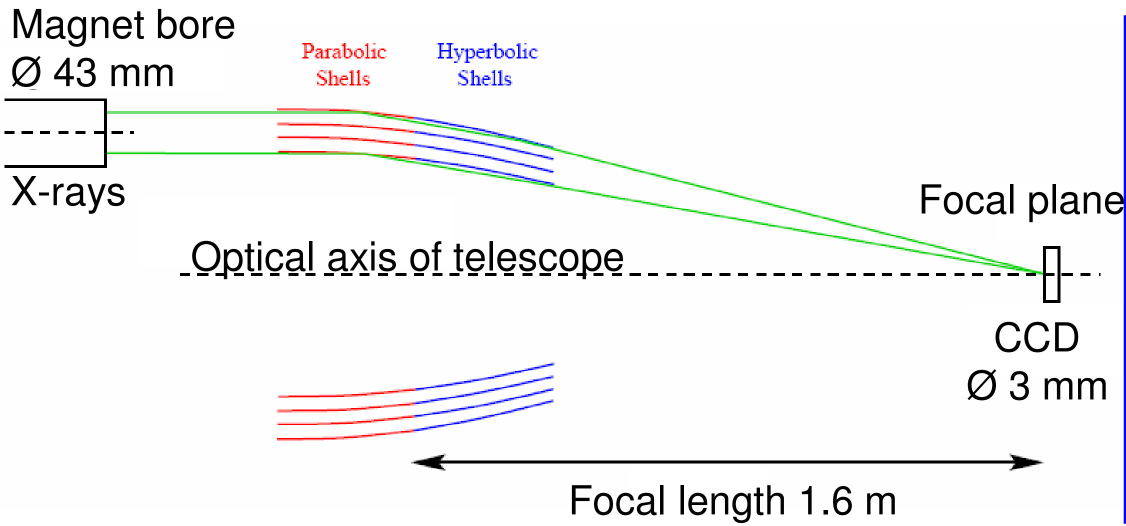
X-ray mirror optics and CCD detector

Experimental Setup

- Wolter-I-type telescope (Prototype of ABRIXAS mission)
- 27 nested, gold-coated mirror shells
- Only one sector of telescope illuminated at CAST

- pn-CCD (Prototype of XMM-Newton mission)
- Very good spatial and energy resolution
- Simultaneous measurement of signal and background possible





➡ **Improvement of signal-to-background ratio by a factor of ~150!**

Backup: Theoretical Motivation for Axions

The strong CP-problem

- New term in Lagrangian violates both P and CP:

$$G^a_{\mu\nu}\tilde{G}_a^{\mu\nu} \propto \vec{\mathbf{E}}\cdot\vec{\mathbf{B}}$$

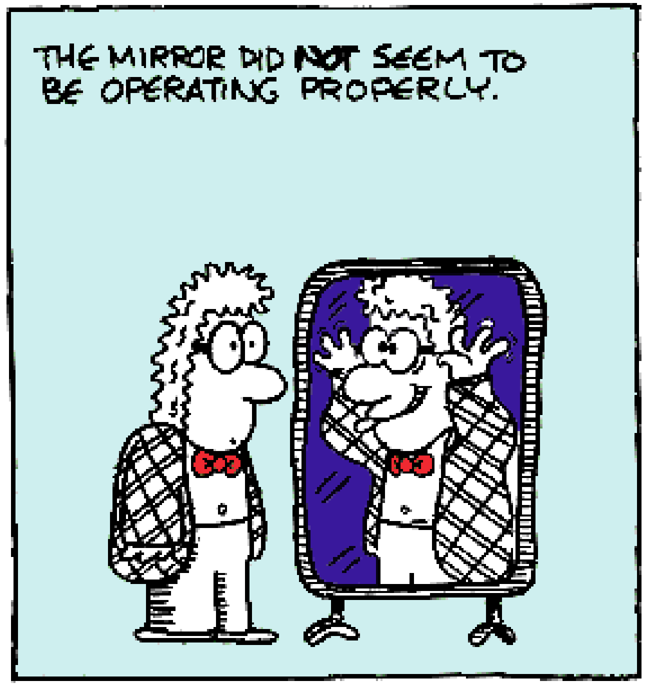
- Compare to

$$G^a_{\mu\nu}G_a^{\mu\nu} \propto \vec{\mathbf{B}}^2 - \vec{\mathbf{E}}^2$$

Since:

$$P(\vec{\mathbf{E}}) = -\vec{\mathbf{E}},\ P(\vec{\mathbf{B}}) = +\vec{\mathbf{B}}$$

$$C(\vec{\mathbf{E}}) = -\vec{\mathbf{E}},\ C(\vec{\mathbf{B}}) = -\vec{\mathbf{B}}$$



- **Strong CP-Problem:**

No violation of CP in strong interactions observed so far!

Could be observed via:

Electric dipole moment (EDM) of the neutron (Dependency on θ)