Search for solar axions with the CAST experiment

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for the
CAST Collaboration

CAST: CERN Axion Solar Telescope

The CAST Collaboration

CEA Saclay -- CERN -- Dogus University -- Lawrence Livermore National Laboratory -- Max-Planck-Institut für Solar System Research/Katlenburg-Lindau -- Max-Planck-Institut für extraterrestrische Physik -- Max-Planck-Institut für Physik -- National Center for Scientific Research Demokritos -- NTUA Athens -- Rudjer Boskovic Institute-- Institute for Nuclear Research (Moscow)-- TU Darmstadt -- University of British Columbia -- University of Chicago -- Universität Frankfurt -- Universität Freiburg -- University of Florida -- University of Patras -- University of Thessaloniki -- Universita di Trieste -- Universidad de Zaragoza

Outline:

- Axions
- The CAST experiment
  - Physics
  - Magnet, detectors
  - Results and prospects

CAST
**Axions**

The strong CP problem:

\[ \mathcal{L}_{\text{strong CP}} = \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}_{a\mu\nu} \]

\[ \bar{\theta} = \theta + \text{Arg det } M \]

(QCD vacuum + EW quark mixing)

- direct contribution to the electric dipole moment of the neutron \( d_n \)
- strong experimental bound on \( d_n \) requires \( \bar{\theta} \leq 10^{-9} \)

**Peccei-Quinn solution:**

- new global chiral U(1)\(_{PQ}\) symmetry spontaneously broken at scale \( f_a \)
- associated pseudo Nambu-Goldstone boson: **axion**!

\[ \mathcal{L}_a = \frac{1}{2} \partial_\mu a \partial^\mu a - \frac{\alpha_s}{8\pi f_a} a G_a^{\mu\nu} \tilde{G}_{a\mu\nu} \]

\[ \Rightarrow \bar{\theta} \text{ absorbed in the definition of } a \]

**Axion mass:**

\[ m_a = 6 \text{ eV} \frac{10^6 \text{ GeV}}{f_a} \]
Axions

Axion properties:

- very low mass and coupling constant \((f_a >> f_{\text{weak}}, g \sim 1/f_a, m_a \sim 1/f_a)\)
- practically stable
- neutral pseudoscalar
- candidate for dark matter

Axion-photon coupling:

- axion-photon coupling via triangle loop
- axion-pion mixing

\[
g_{a\gamma} = \frac{\alpha}{2\pi f_a} \left[ \frac{E}{N} - \frac{2(4 + z + w)}{3(1 + z + w)} \right] = \frac{\alpha}{2\pi f_a} \left[ \frac{E}{N} - 1.92 \pm 0.08 \right]
\]
**CAST: Physics**

**Principle of the Axion helioscope**

*CAST: Physics*

**Principle of the Axion helioscope**


**Sun:** a thermal photon converts into an axion via Primakoff process in the solar plasma

**Earth:** an axion converts into a photon in a strong transverse magnetic field

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- expected number of photons

\[ N_\gamma = \int \frac{d\Phi_a}{dE_a} P_{a \rightarrow \gamma} S t dE_a \]

- differential axion flux at the Earth:

\[ \langle E_a \rangle = 4.2 \text{ keV} \]
CAST: Physics

- conversion probability in gas
  (in vacuum: $\Gamma = 0$, $m_\gamma = 0$):

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

$L$ = magnet length, $\Gamma$ = absorption coeff.

$$q = \left| \frac{m_\gamma^2 - m_a^2}{2E_a} \right| \quad \text{axion-photon momentum transfer}$$

$$m_\gamma (\text{eV}) \approx \sqrt{0.02 \frac{P(\text{mbar})}{T(\text{K})}} \quad \text{effective photon mass} \quad (T=1.8 \text{ K})$$

- coherence condition:

$$qL < \pi \quad \Rightarrow \quad \sqrt{m_\gamma^2 - \frac{2\pi E_a}{L}} < m_a < \sqrt{m_\gamma^2 + \frac{2\pi E_a}{L}}$$
CAST: Physics

CAST operation:

Phase I

- Vacuum in the magnet bores: $m_a < 2.3 \times 10^{-2}$ eV (during 2003 and 2004)

Phase II

- $^4$He gas pressure increased from 0 - 14 mbar: $m_a < 0.39$ eV (during 2005 and 2006)
- $^3$He gas pressure increased from 14 - 120 mbar: $m_a < 1.16$ eV (2008 – 2010)

CAST phase I final results:
JCAP (2007) 0704, 010
CAST: Physics

- Novel technique (developed by CAST) for observing axion solar signature: Off-resonance spectra

- **S = 0**
- **S = FWHM/2**
- **S = FWHM**
- **S = 3×FWHM**

S = Shift from the resonance
CAST: Setup

Exposure time:
2×1.5h per day

- LHC test magnet (B=9 T, L=9.26 m)
- Rotating platform (hor. ±40°, ver. ±8°)
- X-ray detectors
- X-ray Focusing Device
**CAST: Tracking precision**

**GRID measurements**

- Horizontal and vertical encoders determine the magnet orientation
- Correlation between encoder value-magnet orientation has been established for a number of points (GRID)
- Periodical measurements show that CAST points to the Sun within the required precision

**Solar filming**

- Twice per year (March and September) we can film the Sun through the window
- A camera is placed on top of the magnet and is aligned with the bore axis

Tracking precision $\approx 0.01^\circ$
CAST: Detectors before 2007

X-ray telescope + CCD (sunrise side)

0.18 counts/h (1-7 keV)

- 200×64 pixels (1×3 cm²)
- Pixel size: 150×150 µm²

- from 43 mm Ø (LHC magnet aperture) to ~3 mm Ø
- signal-to-noise improvement (up to 200!)
CAST: Detectors before 2007

unshielded Micromegas (sunrise side)

25 counts/h (2-10 keV)

- Drift
- Gas: 95% Ar + 5% isobutane
- Micromesh
- Strips
- Conversion Space: 20 mm
- Amplification Space: 50 μm
- Geometry: 30 cm × 15 cm × 10 cm
- Gas: Ar 95%, CH₄ 5%

shielded TPC (sunset side)

85 counts/h (2-12 keV)

- Covering both magnet bores
- Geometry: 30 cm × 15 cm × 10 cm
- Gas: Ar 95%, CH₄ 5%
**CAST: Detectors after 2007**

- **Sunrise side**: CCD+Telescope & shielded MM (bulk)
- **Sunset side**: 2 shielded MM (bulk and Microbulk)

### H3 phase

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<th>CCD</th>
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<td>0.18</td>
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<tr>
<td>Counts/h (1-7 keV)</td>
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**Sunrise side**

- CCD+Telescope & shielded MM (bulk)

**Sunset side**

- 2 shielded MM (bulk and Microbulk)

**Diagram Details**

- Inox mesh 30 µm vacrel 128 µm
- Readout pads

**Microbulk**

- Micromesh 5µm copper
- Kapton 50 µm
- Readout pads
**CAST: Gas system for the $^3$He phase**

$^3$He gas system
- Accuracy in measuring the quantity of gas introduced in the cold bore (100 ppm)
- Flexible operation modes (stepping and ramping)
- Hermetic system to avoid loss of $^3$He
- Absence of thermo-acoustic oscillations
- Protection of cold thin X-ray windows during a quench

**X-ray windows**
- High X-ray transmission (polypropylene 15 µm)
- Robust (strongback mesh)
- Minimum He leakage
- Mechanical endurance to sudden rise of pressure
CAST: Phase II ($\text{He}^4$) results

Example: pressure $P = 8.909$ mbar

$^4\text{He phase}$

![Graphs showing energy distributions for TPC and Micromegas detectors.]

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CAST: Phase II (He⁴) results

one single tracking

integrated trackings

background

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CAST: Phase II (He⁴) results

- no signal over background observed
- preliminary limit: $g_{\gamma} < 2.2 \times 10^{-10} \text{ GeV}^{-1}$ for $m_a < 0.39 \text{ eV}$
Conclusions

- CAST phase I: the most stringent limit on the axion-photon coupling constant $g_{a\gamma}$ (exceeding astrophysical constraints) for $m_a < 0.02$ eV

- $^4$He phase II: CAST entered in the theoretically favoured region of axion models

- $^3$He phase II: with upgraded detectors and sophisticated gas system, CAST aims to explore the range of axion masses up to 1.16 eV until the end of 2010

... and more ... axions from M1 nuclear transitions, Kaluza-Klein and low energy axions ...