Experimental search for Solar axions: the CAST experiment

Claudio Bonanno
`claudio.bonanno@pi.infn.it`

UNIVERSITÀ DI PISA

First year PhD seminar
22/10/2018

The strong CP problem

The axion (Peccei and Quinn, 1977; Weinberg, 1978, Wilczek, 1978) is by now one of the most robust and simple solution of the strong CP problem.

Quantum Chromo-Dynamics (QCD) admits CP-violating effects through a θ-term in the Lagrangian:

$$\mathcal{L}_\theta = -\theta \frac{\alpha_s}{8\pi} \tilde{G}_a^{\mu\nu} G^a_{\mu\nu}$$

If $\theta = 0$ then no CP breaking but, in principle, $\theta \in [0, 2\pi)$.

So far no experimental evidence of strong CP violation has been found $\implies$ θ_{exp} is compatible with 0.

The most stringent upper bound comes from the measure of the neutron electric dipole moment:

$$d_n^{theo} \sim \theta \left(10^{-16}\ e \cdot \mathrm{cm}\right), \qquad |d_n^{exp}| \lesssim 10^{-26}\ e \cdot \mathrm{cm}$$

$$\implies |\theta_{exp}| \lesssim 10^{-10}$$

The Peccei-Quinn axion

Peccei and Quinn's idea: θ is a field and it is dynamically set to zero by the Peccei-Quinn (PQ) symmetry $U(1)_{PQ}$. This new symmetry spontaneously breaks at a very high energy scale f_a.
The PQ symmetry dynamically protects QCD from CP-violating effects and its spontaneous breaking provides a new light boson: the axion.
Main characteristics of the PQ axion:

- electrically neutral and pseudo-scalar;
- very light: $m_a = 6 \text{ eV} \left(\frac{10^6 \text{ GeV}}{f_a}\right)$;
- coupled to photons: $g_{a\gamma\gamma} = g_\gamma \frac{\alpha_{EM}}{\pi} \frac{1}{f_a} \propto m_a$;
- Dark Matter candidate: $\Omega_a \equiv \frac{\rho_a}{\rho_c} = \left(\frac{6 \cdot 10^{-6} \text{ eV}}{m_a}\right)^{\frac{7}{6}}$.

Axion - photon coupling

The axion-photon coupling $g_{a\gamma\gamma}$ is a key parameter from an experimental point of view:

- all of the most sensitive search strategies are based on axion-photon conversion through an external magnetic field (we'll come back to this in the following),
- measuring $g_{a\gamma\gamma}$ provides information about m_a and the scale of new physics f_a since $g_{a\gamma\gamma} \propto m_a \propto f_a^{-1}$,
- axion-photon coupling gives hints about ultraviolet physics at energies $\gtrsim f_a$ because of the model-dependent factor g_γ.

$$g_{a\gamma\gamma} = g_\gamma \frac{\alpha_{EM}}{\pi} \frac{1}{f_a} \propto m_a$$

Fantastic Axions and Where to Find Them

The open mass window for the PQ axion is set by astrophysical and cosmological constraints:

- quenching of neutrino pulses emitted by the explosion of supernova SN1987A: $m_a \lesssim 10^{-2}$ eV
- observed density of Dark Matter: $m_a \gtrsim 10^{-6}$ eV

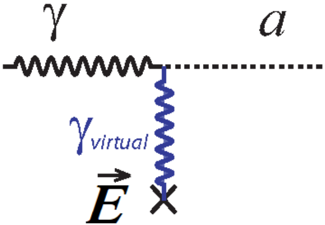
This translates in the following window for the scale f_a and for the coupling $g_{a\gamma\gamma}$:

- 10^9 GeV $\lesssim f_a \lesssim 10^{12}$ GeV
- 10^{-15} GeV^{-1} $\lesssim g_{a\gamma\gamma} \lesssim 10^{-11}$ GeV^{-1}

Axion helioscopes are interesting experiments since are capable to probe this window.

Solar production of axions

The Sun could produce axion through the Primakoff effect, i.e. converting core photons to axions in the background of the Coulomb field of the stellar plasma.



(K. Zioutas et al., 2009)

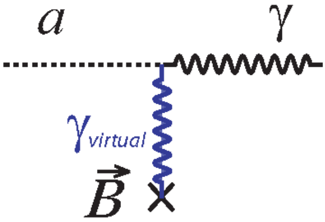
The axion luminosity of the Sun is:

$$\mathcal{L}_a/\mathcal{L}_\odot \simeq \left(\frac{g_{a\gamma\gamma}}{10^{-10}\ \text{GeV}^{\text{-1}}}\right)^2 2\cdot 10^{-3},$$

For $g_{a\gamma\gamma} = 10^{-11}$ GeV$^{\text{-1}}$ ($m_a \sim 10^{-2}$ eV), the small but non-negligible fraction $\mathcal{L}_a \simeq 2\cdot 10^{-5}\mathcal{L}_\odot$ is produced.

Axion Helioscopes

The main idea underlying axion helioscopes is to exploit the inverse Primakoff effect to convert solar axion back into photons through a transverse magnetic field B in a region of length L.



(K. Zioutas et al., 2009)

The conversion probability is:

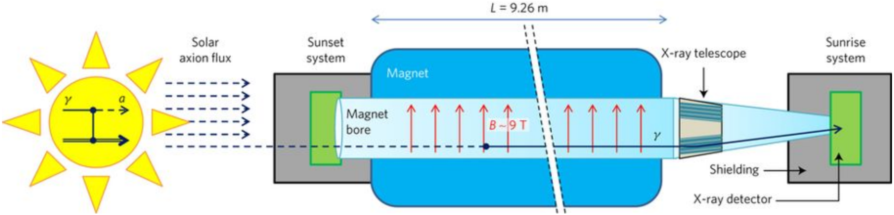
$$P_{a\to\gamma} \simeq 3\cdot 10^{-17}\left(\frac{B}{10\ \mathrm{T}}\right)^2\left(\frac{L}{10\ \mathrm{m}}\right)^2\left(\frac{g_{a\gamma\gamma}}{10^{-10}\ \mathrm{GeV}^{\text{-1}}}\right)^2.$$

CAST: experimental apparatus

The CERN Axion Solar Telescope (CAST) is a third generation axion helioscopes that took data between 2003 and 2015.

The experimental apparatus consists of:

- LHC dipole prototype magnet, made up of two straight bores;
- 4 detectors, placed at each end of the bores, in order to perform measure both at sunrise and at sunset;
- an x-ray focusing optics to collect reconverted axions into the spot area of one the sunrise detector;
- a movable platform to track the Sun for ~ 3 hours per day.



(CAST Collaboration, 2017)

CAST: technical details

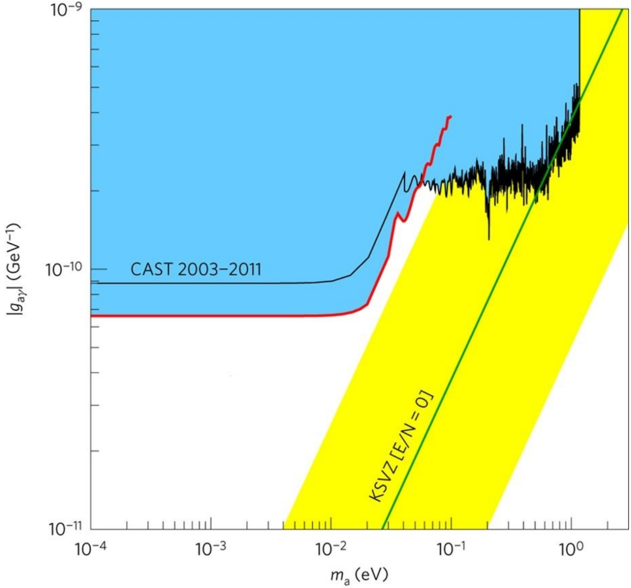
The superconductive magnet provides a magnetic field $B \simeq 9$ T over a region $L \simeq 9.26$ m. This gives a probability conversion $P_{a\to\gamma} \simeq 10^{-19}$ for $g_{a\gamma\gamma} = 10^{-11}$ GeV^{-1}.

We expect $E_a \sim T_{\mathrm{core}\odot} \sim O(1$ keV$)$, the expected photon flux from reconverted axions is $\phi_\gamma \simeq 1.8 \left(\frac{g_{a\gamma\gamma}}{10^{-10}\ \mathrm{GeV}^{-1}}\right)^4$ counts/day.

This implies $\phi_\gamma \simeq 1.8 \cdot 10^{-4}$ counts/day for $g_{a\gamma\gamma} = 10^{-11}$ GeV^{-1}, i.e. ~ 1 event every 16 years.

To observe such a tiny signal, low background detectors, with high efficiency in the keV range, were employed, but no signal above background was measured.

Latest CAST Results

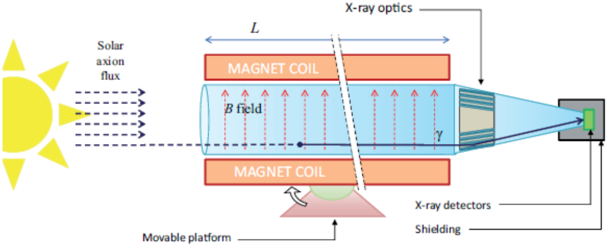


(CAST Collaboration; 2017)

Next generation helioscopes: IAXO

International AXion Observatory (IAXO) is expected to improve CAST results thanks to:

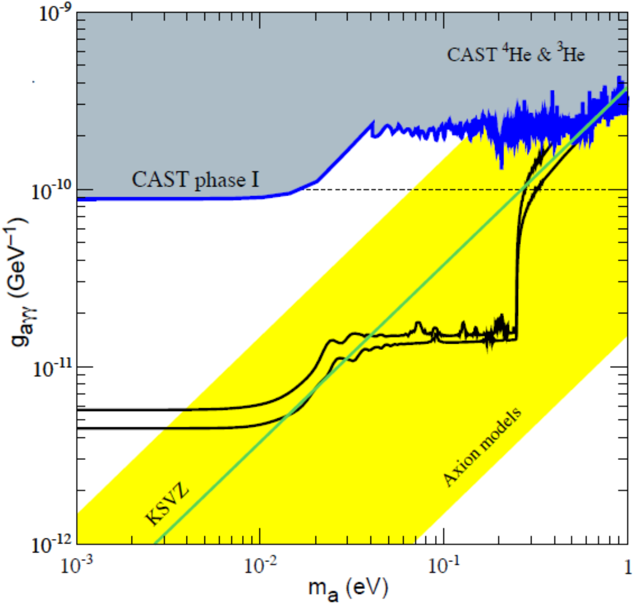
- entire cross sectional area of the magnet covered by x-ray focusing optics to improve signal-to-noise ratio by more than an order of magnitude,
- new magnet, made up of 8 one-meter-long coils, will provide $B = 5.4$ T and $L = 25$ m to increase $P_{a\to\gamma}$ by a factor ~ 3.



(P. W. Graham, I. G. Irastorza, S. K. Lamoreaux, A. Lindner, and K. A. van Bibber; 2016)

The IAXO collaboration formed in 2017 and soon a scaled-down prototype version of the experiment will be operative.

IAXO expected sensitivity



(P. W. Graham, I. G. Irastorza, S. K. Lamoreaux, A. Lindner, and K. A. van Bibber; 2016)

Summary and conclusions

Summarizing and concluding:

- axions are a well-motived extension of the Standard Model: solution to strong-CP problem + Dark Matter candidate;
- axion helioscopes experiments are capable of reaching the expected window for the PQ axion;
- CAST has been able to put the most stringent experimental bound on the axion-photon coupling but is still far from the open window for PQ axion;
- IAXO should be able, in the next future, to explore the open window for the PQ axion and probe part of the axion models band.

References

[1] G. Carosi, A. Friedland, M. Giannotti, M. J. Pivovaroff, J. Ruz, J. K. and Vogel, *Probing the axion-photon coupling: phenomenological and experimental perspectives. A snowmass white paper*, "Proceedings, 2013 Community Summer Study on the Future of U.S. Particle Physics: Snowmass on the Mississippi", 2013;

[2] G. G. di Cortona, E. Hardy, J. P. Vega, and G. Villadoro, *The QCD axion, precisely*, J. High Energ. Phys., **34**, 2016;

[3] P. W. Graham, I. G. Irastorza, S. K. Lamoreaux, A. Lindner, and K. A. van Bibber, *Experimental Searches for the Axion and Axion-Like Particles*, Ann. Rev. Nucl. Part. Sci., **65**, 2016.

Experimental bounds on axion-photon coupling