Axions as dark matter candidates

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Topics in Particle Physics, Astrophysics and Cosmology | MEFT | IST

Overview

INTRODUCTION

What is the strong CP problem?

- The Quantum Chromodynamics (QCD) lagrangian admits a Charge-Parity (CP) violating term:

$$\mathcal{L}_{\Theta} = -\underset{\swarrow}{\overline{\Theta}}\frac{\alpha_s}{8\pi}\overbrace{G^{a}_{\mu\nu}}^{\substack{\text{color field}\\ \text{strength tensor}}}\underbrace{\tilde{G}^{a\mu\nu}}_{=\varepsilon^{\mu\nu\rho\sigma}G^{a}_{\rho\sigma}/2}$$

Θ parameter after
diagonalizing the quark masses
$\overline{\Theta} \in [-\pi, \pi]$

- Which should produce observable effects, such as the neutron electric dipole moment.
- If it exists, it is very small, $|d_n| < 2.9 \times 10^{-26}\text{e cm}$

$$\Rightarrow |\overline{\Theta}| < 9.1 \times 10^{-11}$$

- The fact that $\overline{\Theta}$ is so small is the strong CP problem.

Solutions to the strong CP problem

- The Peccei-Quinn (PQ) theory considers the $\overline{\Theta}$ parameter a dynamical variable, whose minimum is at $\overline{\Theta} = 0$.
- The PQ mechanism introduces a U(1) symmetry, which breaks spontaneously $\Rightarrow$ Nambu-Goldstone Boson: The Axion
- Non-perturbative effects cause the axion to acquire mass.
- The lagrangian term is modified to:

axion field

$$\mathcal{L} = \left(\frac{\phi_A}{f_A} - \overline{\Theta} \right) \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

axion decay constant

- In the chiral limit, $m_A f_A \approx m_\pi f_\pi$:

$$m_A = 5.691(51) \left(\frac{10^9 \mathrm{GeV}}{f_A} \right) \mathrm{meV}$$

Axion models

- Peccei-Quinn-Weinberg-Wilczek (PQWW): Introduces an additional complex scalar field, tied to the EW Higgs sector. It fixes $f_A = 250\text{GeV}$, and therefore it has been excluded by experiment.
- Kim-Shifman-Vainshtein-Zakharov (KSVZ): The additional scalar field is an electroweak singlet, which couples to heavy quarks and the axions are induced by the interactions of the heavy quarks with the other fields.
- Dine–Fischler–Srednicki–Zhitnitsky (DFSZ): Introduces an additional Higgs field as well as the electroweak singlet, which acquires a vacuum expectation value at the PQ symmetry breaking scale.

Axion couplings

- All axion couplings are proportional to f_A^{-1}.
- The axion-photon coupling is considered in most experiments.

$$\mathcal{L} = -\frac{g_{A\gamma\gamma}}{4}\overbrace{F_{\mu\nu}}^{\substack{\text{electromagnetic}\\ \text{strength-field tensor}}}\underbrace{\tilde{F}^{\mu\nu}}_{=\varepsilon^{\mu\nu\rho\sigma}F_{\rho\sigma}/2}\phi_A = -\overset{\substack{\text{coupling}\\ \text{constant}}}{\boxed{g_{A\gamma\gamma}}}\mathbf{E}\cdot\mathbf{B}\phi_A$$

$$g_{A\gamma\gamma} = \frac{\alpha_s}{2\pi f_A}\left(\frac{E}{\underset{\substack{\downarrow\\ \text{color}\\ \text{anomaly}}}{N}} - 1.92(4)\right) = \left(0.203(3)\frac{\overset{\substack{\text{electromagnetic}\\ \text{anomaly}\\ \nearrow}}{E}}{N} - 0.39(1)\right)\frac{m_A}{\mathrm{GeV}^2}$$

- **KSVZ:** $\frac{E}{N} = 0 \Rightarrow g_{A\gamma\gamma} = -0.39(1)\frac{m_A}{\mathrm{GeV}^2}$;
  $\Gamma_{A\gamma\gamma} = 1.1\times 10^{-24}\mathrm{s}^{-1}\left(\frac{m_A}{eV}\right)^5$
- **DFSZ:** $\frac{E}{N} = \frac{8}{3} \Rightarrow g_{A\gamma\gamma} = 0.151(3)\frac{m_A}{\mathrm{GeV}^2}$;
  $\Gamma_{A\gamma\gamma} = 1.72\times 10^{-25}\mathrm{s}^{-1}\left(\frac{m_A}{eV}\right)^5$

The two-photon decay width is:

$$\Gamma_{A\gamma\gamma} = \frac{g_{A\gamma\gamma}^2 m_A^3}{64\pi}$$

Cosmological production of axions

- The PQ symmetry breaks if $T < T_{PQ} \approx f_A$.

Symmetry breaking after inflation:

- $T_R > T_{PQ}$
- Symmetry is broken when $T < T_{PQ}$.
- The initial Θ_1 will acquire random values between $-\pi$ and π, for each Hubble patch.

$T_R = \frac{H_I}{2\pi} < 1.4 \times 10^{13}\mathrm{GeV}$

Symmetry breaking during inflation:

- $T_R < T_{PQ}$
- During inflation, cold massless axions are produced.
- The axion's mass becomes relevant when $T < \underset{\substack{\downarrow \\ \text{critical temperature} \\ m_A t_1 \approx 1}}{T_1} \approx 1\mathrm{GeV}$.

- Vacuum realignment is the main mechanism responsible for axion production.
- Other phenomena such as string decay and domain wall may contribute as well.

Vacuum Realignment

- When symmetry is broken, there's an initial misalignment angle.
- As the Universe cools down, the axion field will begin to oscillate according to:

$$\ddot{\phi}_A + 3H\dot{\phi}_A + m_A^2\phi_A = 0$$

- Until it relaxes to its minimum.
- Because the mass is negligible at first, the initial condition $\dot{\phi}_A = 0$ is satisfied, and the critical time is:

$$t_1 \approx 2 \times 10^{-7} s \left(\frac{f_A}{10^{12}\mathrm{GeV}}\right)^{1/3}$$

- As a consequence, the cosmic mass density created is:

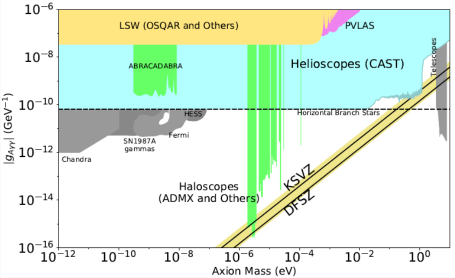
$$\underbrace{\Omega_A^{VR} h^2}_{\text{Hubble constant}} \approx 0.12 \left(\frac{6\mu\mathrm{eV}}{m_A}\right)^{1.165} \underbrace{F\Theta_1^2}_{F(\Theta_1, f_A)}$$

- In the $T_R > T_{PQ}$ case, the multiple Θ_1 values give an average of:

$$\Omega_A^{VR} h^2 \approx 0.12 \left(\frac{30\mu\mathrm{eV}}{m_A}\right)^{1.165}$$

Axions produced in stars

- Axions can be produced in stellar cores, where they act as energy sinks. ⇒ Studying these systems establishes constraints on the axion.
- The accelerated consumption of He in Horizontal Branch stars gives $|g_{A\gamma\gamma}| < 6.6 \times 10^{-11}\text{GeV}^{-1}$.
- In intermediate mass stars, the blue loop can disappear due to axion energy losses. The existence of Cepheids puts the constraint $g_{A\gamma\gamma} \leq 8 \times 10^{-11}\text{GeV}^{-1}$.
- The supernova SN1987 limits $f_A > 5 \times 10^{8}\text{GeV}$, based on nucleon-nucleon axion coupling.

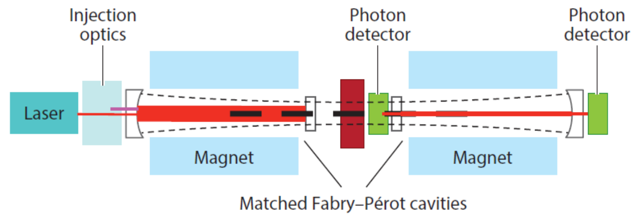


- The Sun also provides $g_{A\gamma\gamma} < 4.1 \times 10^{-10}\text{GeV}^{-1}$ based on the neutrino flux measured at SNO and helioseismology. In addition, measurements at CAST give a more restrictive bound of $g_{A\gamma\gamma} < 6.6 \times 10^{-11}\text{GeV}^{-1}$.

EXPERIMENTS

Types of experiments

- Helioscopes: Search for solar axions. (CAST, IAXO)
- Haloscopes: Search for dark matter halo axions (AMDX,)
- Laboratory experiments:
  - Light shinning through walls (ALPS I, ALPS II, OSQAR)
  - Polarization of light (PVLAS)

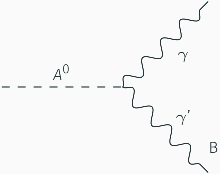


The CAST experiment

- The CERN Axion Solar Telescope (CAST) is a helioscope produced to detect solar axions.
- CAST operated between 2003 and 2015 with the goal of detecting axions emitted from the Sun. The cycle of operation analyzed started in 2013 and ended in 2015.

- The probability that an axion is converted back into photons is:

$$P_{A\to\gamma} = \left(g_{A\gamma\gamma} B \frac{\sin(m_A^2 L/2E)}{m_A^2/2E} \right)^2$$



- Thus, by maximizing B and L, this probability is enhanced.

Apparatus and data acquisition

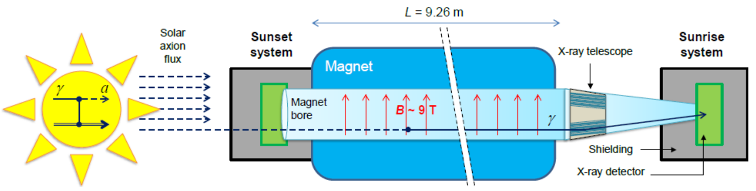
CAST is composed by:

- LHC magnet of $L = 9.26$m and $B \approx 9$T, on a movable platform.
- Two detection systems at sunrise (SR) and sunset (SS):
  - SS: two gas-based low background detectors $\Rightarrow$ SS1 + SS2.
  - SR: Micromegas detector. (only 2014 and 2015)
- An X-ray detector on the SR side.

CAST is able to follow the Sun 90minutes after sunrise and before sunset.

During the remaining time, it collects background data and performs calibrations (with an X-ray source, 12m away).

Twice a year, the pointing accuracy is monitored.

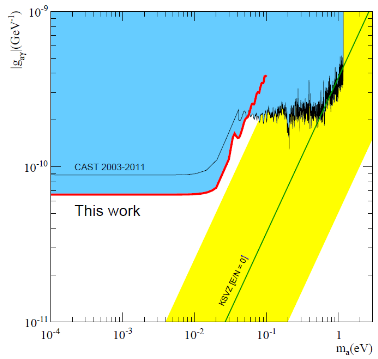


The data collected includes 1132.6h of solar axion sensitive conditions.

The energy range of interest was set to $[2, 7]$keV.

Data analysis and results

- The analysis consisted in maximizing an unbinned likelihood function $\log\mathcal{L}$:



$$\log\mathcal{L} \propto \underset{\substack{\downarrow \\ \text{Expected number of counts} \\ \text{integrated over t and E}}}{-R_T} + \sum_i^n \log(\overbrace{B(E_i, d_i)}^{\text{Background level}} + \underbrace{S(E_i, d_i, \mathbf{x}_i)}_{\substack{\text{Expected rate for} \\ \text{axion conversion}}})$$

$$S(E, d, \mathbf{x}) = \underbrace{\frac{d\Phi_A}{dE}}_{\substack{\text{Solar} \\ \text{axion flux}}} P_{A\to\gamma} \underbrace{\varepsilon(E, d, \mathbf{x})}_{\substack{\text{Detector} \\ \text{response}}}$$

$$\frac{d\Phi_A}{dE} = 6.02\times 10^{10} g_{10}^2 \frac{E^{2.481}}{e^{E/1.205}} [\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{keV}^{-1}]$$

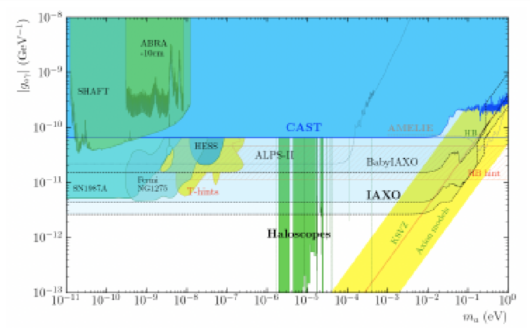
- Which was consistent with the absence of signal in the range tested. ⇒ An upper bound for $g_{A\gamma\gamma}$ was achieved.

$$g_{A\gamma\gamma} < 6.6\times 10^{-11}\mathrm{GeV}^{-1} \text{ for } m_A \lesssim 0.02\mathrm{eV}.$$

- Only statistical fluctuations were considered. Systematic errors were found negligible.

Future of CAST

- CAST cannot be improved much further. ⇒ A new helioscope will follow: The International Axion Observatory (IAXO).



- IAXO will have a new magnet, designed to improve $P_{A\to\gamma}$.
- It will also benefit from the Micromegas detector and X-ray detector.
- The signal to noise ratio will be 5 times better than CAST.
- The project will start with babyIAXO, which will test IAXO's subsystems.

- CAST is no longer operational, but its magnet si being used for dark energy search, with CAST/CAPP nad RADES.

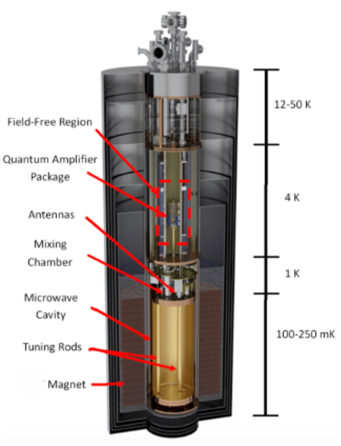
The ADMX experiment

- The Axion Dark Matter eXperiment (ADMX) uses a resonant microwave cavity, where dark matter axions are immersed in a static B field and convert into photons.
- The power deposited is:

$$P = (1.9 \times 10^{-22} W) \left(\frac{V}{136\mathrm{L}}\right) \left(\frac{B}{6.8\mathrm{T}}\right)^2 \underbrace{\left(\frac{c_{nlm}}{0.4}\right)}_{\text{form factor}} \left(\frac{g_\gamma}{0.97}\right)^2 \underbrace{\left(\frac{\rho_A}{0.45\mathrm{GeV}/\mathrm{cm}^3}\right)}_{\text{local dark matter density}} \underbrace{\left(\frac{f_A}{650\mathrm{MHz}}\right)}_{\text{photon frequency}} \underbrace{\left(\frac{G}{50000}\right)}_{\text{quality factor}}$$

- The majority of the improvements has focused on lowering the intrinsic noise of the first stage cryogenic amplifiers.
- Two runs of the detector were analyzed:
  - Run 1A (2017): B=6.8T; mass range $m_A \in [2.66, 2.81]\mu$eV; implemented a Microstrip Superconducting Quantum Interference Device (SQUID) Amplifier (MSA).
  - Run 1B (2018): B=7.6T; mass range $m_A \in [2.81, 3.31]\mu$eV; implemented a Josephson Parametric Amplifier(JPA).

Detector composition



- The resonant frequency of the cavity is adjusted by moving the tuning rods.
- The axions signal in the cavity is transmitted to the amplifiers through a variable depth antenna.
- The noise temperature of the system is determined by the physical and amplifier noise temperatures of the cryogenic electronics.
  - Run 1A: The cryogenic electronic package was at 320mK;
  - Run 1B: The temperature was 230mK.
- The field sensitive quantum amplifiers, switches and circulators are shielded from the intense magnetic field, being subjected to a field below 0.1mT.
- The final cooling stage of the detector consists of a dilution refrigerator, which circulates ^{3}He from ^{3}He-rich phase to a dilute phase in the mixing chamber.

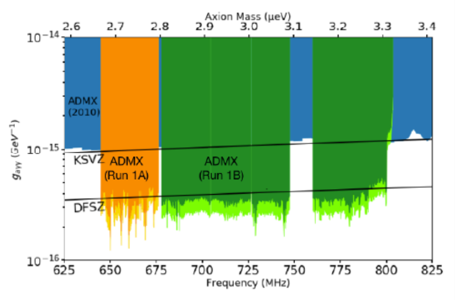
Data Acquisition

- The data was acquired through Experimental Physics and Industrial Control System (EPICS).
- In addition the the signal data, readings from temperature, pressure, magnetic field and current were also recorded.
- Run 1A used Cernox temperature sensors and Run 1B used Ruthenium Oxide sensors.
- Since background noise was significant compared to possible axion signals, it was necessary to distinguish the two signals. Both runs made multiple measurements of the noise from multiple components.

Data analysis and results

The data was analyzed in sets of $t = 100\text{s}$.

1. The background was filtered out.
    - Run 1A: Used a Savistky-Golay filter
    - Run 1B: Used a six-order Padé.
2. The data was scaled to the noise temperature and weighted by the difference to the cavity's resonant frequency.
3. All the individual scans were combined.
4. Axion-like signals were searched for by applying a convolution of a boosted Maxwell-Boltzmann shape predicted from the standard halo model and a signal shape predicted by N-body simulations.
5. Possible axion signals were identified and re-scanned.



- In these runs, the ADMX was able to reach DFSZ sensitivity, however, it will continue to search for axions, in higher frequency ranges (higher masses). $\Rightarrow$ Multiple cavities tuned in frequency.

Summary and Conclusions

Summary and conclusion

- The axion not only provides a solution to the strong CP problem, but it also constitutes a cold dark matter candidate:
    - Stable ($f_A \gg 1$);
    - It couples very weakly to the SM ($g \ll 1$);
    - Is it cold ($\beta \ll 1$);
    - It interacts through gavity.
- Even though it has not been confirmed yet, experiments are on the hunt for it with sensitivities compatible with theoretical models.
- ADMX and IAXO (still in the planning phase) constitute two of the most promising experiments.

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