Search for axion-like particles in astrophysical observations

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Outline

1 Axions
   - Motivations
   - Axion-photon interaction

2 Astrophysical searches
   - Shining light through the Sun
   - Gamma-ray astronomy and axions

3 Summary
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**Motivations for axions**

- Strong CP problem and dark matter

**QCD Lagrangian:**

\[
\mathcal{L} = -\frac{1}{4} \text{Tr} G_{\mu\nu} G^{\mu\nu} - \frac{n_f g^2 \theta}{32\pi^2} \text{Tr} G_{\mu\nu} \tilde{G}^{\mu\nu} + \bar{\psi} \left( i \gamma^\mu D_\mu - M_q e^{i\theta' \gamma^5} \right) \psi
\]

contains CP violating term:

\[
\mathcal{L}_{CP} = -\frac{g^2}{32\pi^2} \Theta \text{Tr} G_{\mu\nu} \tilde{G}^{\mu\nu}
\]

**Neutron electric dipole moment**

\[d_n \approx \Theta \ 10^{-16} \text{e} \cdot \text{cm} < 10^{-25} \text{e} \cdot \text{cm}\]

**Problem: why so small?**

\[\Theta < 10^{-9}\]
Strong CP problem: dynamical solution

Postulate new global U(1) symmetry - Peccei-Quinn symmetry
Re-interpret $\Theta$ as a scalar field $a$ - axion - Nambu-Goldstone boson

$$\mathcal{L}_{CP} = -\frac{g^2}{32\pi^2} \Theta \text{Tr} G_{\mu\nu} \tilde{G}^{\mu\nu} \implies \mathcal{L}_{CP} = -\frac{g^2}{32\pi^2} \frac{a(x)}{f_a} \text{Tr} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

CP-symmetry dynamically restored

Axion mass

$$m_a \approx \frac{f_\pi m_\pi}{f_a} \approx \frac{6.0 \text{ eV}}{f_a/10^6 \text{ GeV}}$$
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Axion-photon conversion/oscillations

Axion-photon interaction

Raffelt and Stodolsky, 1988

\[ i \partial_z \Psi = - (\omega + \Delta) \Psi, \quad \Psi = \begin{pmatrix} A_\parallel \\ A_\perp \\ a \end{pmatrix}, \quad \Delta \equiv \begin{pmatrix} \Delta_p & 0 & \Delta_{a\gamma} \\ 0 & \Delta_p & \Delta_{a\gamma} \\ \Delta_{a\gamma} & \Delta_{a\gamma} & \Delta_m \end{pmatrix} \]

\[ \Delta_p = \frac{\omega_p^2}{2\omega}, \quad \Delta_m = \frac{m_a^2}{2\omega}, \quad \Delta_{a\gamma} = \frac{B}{2M}, \quad M = g_{a\gamma}^{-1} \]

Photon-axion conversion probability

\[ P_{\gamma \rightarrow a} = \frac{4B^2 \omega^2}{M^2 (\omega_p^2 - m_a^2)^2 + 4B^2 \omega^2} \sin^2 \left( \pi \frac{z}{l_{osc}} \right), \]

\[ l_{osc} = \frac{4\pi \omega M}{\sqrt{M^2 (\omega_p^2 - m_a^2)^2 + 4B^2 \omega^2}}, \quad B = \text{const}, \quad \omega_p = \text{const} \]
“Shining light through the wall”

- X-rays from the Sun with axion signatures: Zioutas et al, arXiv:0903.1807, Hannah et al, astro-ph/0702217; Davoudsia, Huber 2006, ...
- Detection of laser photons “through the wall”: ALPS, arXiv:0905.4159; GammeV, arXiv:0908.1529 [hep-ex], ...
- Appearance of photons from nowhere (dark matter or cosmic axions search): ADMX, astro-ph/0603108; Fairbairn et al arXiv:0706.0108; ...
Axions
Astrophysical searches
Summary

Motivations
Axion-photon interaction

CAST - CERN axion solar telescope

"Axion helioscope" technique
Strong magnet $B = 9$ Tesla, $L = 9.26$ m (LHC test magnet)
x-ray detector at the end of pipe
Observes the Sun 1.5 hour at both sunrise and sunset
Expected axion flux: $(g_{a\gamma}/(10^{-10}\text{GeV}^{-1}))^2 \times 3.75 \times 10^{11} \text{ cm}^{-2} \text{ s}^{-1}$
Average solar axion energy 4.2 keV
Variable-pressure gas filling

Primeakoff effect

Sikivie, 1983
CAST and other limits

Zioutas, Tsagri, Papaevangelou, Dafni, arXiv:0903.1807
Cooling limits and dark matter

Globular cluster stars

Cooling of red giants by $\gamma + A \rightarrow A + a$:
$g_{a\gamma} < 10^{-10} \text{ GeV}^{-1}$

Axions as a hot dark matter

Thermal axions can form hot dark matter, but the axion decay into photons leads to limit:
$m_a < 1 \text{ eV}$

Axions as a cold dark matter

- Axions can be a dominant cold dark matter component with mass $m_a > 10 \mu\text{eV}$
- Can be probed by ADMX (microwave resonator in magnetic field) $1 \mu\text{eV} < m_a < 100 \mu\text{eV}$
Axion Bounds

Experiments
- Too much hot dark matter
  - Globular clusters (a-γ-coupling)
  - Too many events
  - Too much energy loss
  - SN 1987A (a-N-coupling)

Direct searches
- CAST
- ADMX
- CARRACK

[GeV] \( f_a \)

\( \begin{array}{c}\text{meV} \\
\text{keV} \\
\text{eV} \\
10^3 \\
10^6 \\
10^9 \\
10^{12} \\
10^{15} \\
\end{array} \)

Experiments search for axion-like particles in astrophysical observations
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Astronomy

Astronomers Studying an Eclipse by Antoine Caron (1571)
Solar occultation of 3C 279 γ-ray source?

- 271 sources in 3EG catalogue
- 101 identified
- 1 occulted by the Sun
- 3C 279 (brightest QSO)
- ecliptic latitude 0.2°
- once per year, October 8
- occultation period ≈ 8.5 hours
Shining light through the Sun by axions

**Fairbairn, T.R., Troitsky, astro-ph/0610844**

### Conditions
- **Axion mass:** \( m_a \sim 10^{-3} \text{eV} \)
- **Inverse coupling:** \( M = 10^5 - 10^6 \text{GeV} \)
- **Photon energy:** around GeV

### Probablity of photon emerging

![Graph showing probability of photon emerging with different photon energies and maximum depths.](image)

- **Axes:**
  - Y-axis: Probability of photon emerging
  - X-axis: Maximum depth (cm)

- **Graphs:**
  - Blue line: 1x10^5 GeV
  - Red dashed line: 3x10^5 GeV
  - Green dashed line: 1x10^6 GeV
  - Black dotted line: Photon

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Search for axion-like particles in astrophysical observations
Solar halo and disk emission


- Upper figure: Model angular profile of the solar emission above 100 MeV.
- Lower figure: Inverse-Compton emission modelled for a region of 10° from the Sun for 300-500 MeV. Intensity is given in cm$^{-2}$ s$^{-1}$ sr$^{-1}$.
- Sum of disk and extended components of solar emission ($10^{-7}$ cm$^{-2}$ s$^{-1}$).

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>solar disk flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;100</td>
<td>0.54±0.32</td>
</tr>
<tr>
<td></td>
<td>4.44 ± 2.03</td>
</tr>
</tbody>
</table>


$F_{3C279}^{occult} \approx (6.2^{+3.7}_{-2.7}) \cdot 10^{-7}$ cm$^{-2}$ s$^{-1}$

$F_{3C279} \approx (8.6 \pm 0.5) \cdot 10^{-7}$ cm$^{-2}$ s$^{-1}$
Launched in June 2008
- $E = 30$ MeV to 300 GeV
- Sensitivity about 50 times that of EGRET at 100 MeV

Fermi goals:
- particle acceleration in AGNs, pulsars, and SNRs
- resolve the $\gamma$-ray sky
- $\gamma$-ray bursts
- probe dark matter and early Universe
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γ-ray astronomy

- Predicted in 40s
- Detected in 60s
- γ-rays absorbed by atmosphere
- Ballons
- Satellites (recent INTEGRAL, EGRET, Fermi, ...)
- Atmospheric imaging Cherenkov telescopes (H.E.S.S., MAGIC, VERITAS, ...)
- Sources: AGN, pulsars, SNR, secondary cosmic rays
Universe is not transparent for photons of energies above 1 TeV because of extragalactic background light (EBL)

Sanchez-Conde et al arXiv:0905.3270

Fairbairn, TR, Troitsky, arXiv:0901.4085
3C 279 observation by MAGIC

Distant Quasar
3C 279

5.3 Billion Light Years Away

Extragalactic Background Light
Product of the History of all Stars and Galaxies

How Transparent is the Universe for Very-High Energy Gamma-Rays?

Very-High Energy Gamma Radiation

MAGIC Ground-Based Gamma-Ray Telescope for E>80 GeV Gamma Rays

The Universe is More Transparent than Previously Believed.

Background image credits: NASA E/PO, Sonoma State University, Aurore Simonnet; HST, NASA, STScI.
Axion-photon mixing in astrophysical objects

Photon-axion conversion probability

\[ P_{\gamma \rightarrow a} = \frac{4B^2 \omega^2}{M^2 \left( \omega_p^2 - m_a^2 \right)^2 + 4B^2 \omega^2} \sin^2 \left( \pi \frac{Z}{l_{\text{osc}}} \right), \]

\[ l_{\text{osc}} = \frac{4\pi \omega M}{\sqrt{M^2 \left( \omega_p^2 - m_a^2 \right)^2 + 4B^2 \omega^2}}, \quad B = \text{const}, \quad \omega_p = \text{const} \]
Correlation of UHECR events with BL Lacs

- Charged particles are deflected in IGMF and in GMF.
- Neutral particles are absorbed at $> 10^{18}$ eV, $> 100$ Mpc.
- Cannot be $\nu$ (shower development).
- Probability of correlation is higher in the low panel (exposure + magnetic field) than upper (exposure).
- Correlation by chance is about 2.4%.
- Axions parameters: mass $10^{-7}$ eV, coupling $10^{-10}$ GeV$^{-1}$.
Other effects of axionlike particles in astrophysical observations

- Detection of TeV photons from blazars
  Simet, Hooper, Serpico, arXiv:0712.2825

- White dwarf luminosity function
  Isern, Garcia-Berro, Torres, Catalan, arXiv:0806.2807

- Large-scale correlation in polarization of quazars
  Payez, Cudell, Hutsemekers, arXiv:0805.3946

- Polarization of extragalactic radio sources
  Payez, Cudell, Hutsemekers, arXiv:0805.3946

- Solar X-rays
  Zioutas et al, arXiv:0903.1807

- ...
Axion-like particles (ALP) can be searched in astrophysical observations. In case of discovery they could provide significant contribution to dark matter, depending on their masses;

Continuous effort in exploring of axion-like particle parameters is taken in laboratory experiments using helioscopes (CAST, Tokyo), cavity experiments (ADMX and others) and laser experiments (ALPS and others);

Many interesting effects with axion-like particles could be searched using atmospheric imaging Cherenkov telescopes (H.E.S.S., MAGIC and future CTA) and space-based telescopes (Fermi).