Dark Matter Axions

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Outline

• Axion motivation and properties

• Production in the early universe and Bose-Einstein condensation

• Axion search methods
The Strong CP Problem

\[ \mathcal{L}_{\text{QCD}} = \ldots + \bar{\theta} \frac{g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^a_{\mu\nu} \]

where

\[ \bar{\theta} = \theta - \text{arg} \left( m_u m_d \ldots m_t \right) = \theta - \text{arg} \text{det} \left( Y^u Y^d \right) \]

The absence of P and CP violation in the strong interactions requires

\[ \bar{\theta} \leq 10^{-10} \]

from upper limit on the neutron electric dipole moment
If a $U_{PQ}(1)$ symmetry is assumed,

$$\mathcal{L} = \ldots + \frac{\alpha}{f_\alpha} \frac{g^2}{32\pi^2} G_\mu^a \tilde{G}^{a\mu\nu} + \frac{1}{2} \partial_\mu a \partial^\mu a$$

$$\tilde{\theta} = \frac{\alpha}{f_\alpha}$$ relaxes to zero,

and a light neutral pseudoscalar particle is predicted: the axion.

Weinberg, Wilczek 1978
$m_a \simeq \frac{6 \text{ eV}}{\frac{10^6 \text{ GeV}}{f_a}}$ 

\[ \mathcal{L}_{a\bar{f}f} = ig_f \frac{a}{f_a} \bar{f} \gamma_5 f \]

\[ \mathcal{L}_{a\gamma\gamma} = g_\gamma \frac{a}{f_a} \vec{E} \cdot \vec{B} \]

$g_\gamma = 0.97$ in KSVZ model
$0.36$ in DFSZ model
The remaining axion window

\[ m_a (\text{eV}) \quad 1 \quad 10^{-5} \quad 10^{-10} \]

\[ f_a (\text{GeV}) \quad 10^5 \quad 10^{10} \quad 10^{15} \]

laboratory searches

stellar evolution

cosmology
Axion production by vacuum realignment

\[ n_a(t_1) \approx \frac{1}{2} m_a(t_1) a(t_1)^2 \approx \frac{1}{2t_1} f_a^2 \alpha(t_1)^2 \]

\[ \rho_a(t_0) \approx m_a n_a(t_1) \left( \frac{R_1}{R_0} \right)^3 \propto m_a^{-\frac{7}{6}} \]

Axions are cold dark matter

Density
\[ \Omega_a \sim \left( \frac{10^{-5} \text{ eV}}{m_a} \right)^{\frac{7}{6}} \alpha(t_1)^2 \]

Velocity dispersion
\[ \delta v_a(t_0) \sim 3 \cdot 10^{-17} c \left( \frac{10^{-5} \text{ eV}}{m_a} \right)^{\frac{5}{6}} \]

Phase space density
\[ \mathcal{N} = \frac{(2\pi)^3 n(t)}{\frac{4\pi}{3} (m_a \delta v)^3} \sim 10^{61} \left( \frac{f_a}{10^{12} \text{ GeV}} \right)^{\frac{8}{3}} \]
Bose-Einstein Condensation

if identical bosonic particles are highly condensed in phase space and their total number is conserved and they thermalize

then most of them go to the lowest energy available state
why do they do that?

by yielding their energy to the non-condensed particles, the total entropy is increased.
the axions thermalize and form a BEC after a time $\mathcal{T}$

For $t < \mathcal{T}$:
- the axion fluid obeys classical field equations, behaves like CDM

For $t > \mathcal{T}$:
- the axion fluid does not obey classical field equations, does not behave like CDM
the axion BEC rethermalizes

\[ t < \tau \]

the axion fluid obeys classical field equations, behaves like CDM

\[ t > \tau \]

the axion fluid does not obey classical field equations, does not behave like CDM
τ = ?
Quantum axion field dynamics

\[ H = \sum_j \omega_j a_j^\dagger a_j + \sum_{ijkl} \frac{1}{4} \Lambda_{ij}^{kl} a_k^\dagger a_l^\dagger a_i a_j \]

From \( \frac{1}{4!} \lambda \phi^4 \) self-interactions

\[ \Lambda_{\phi} \frac{\bar{p}_3, \bar{p}_4}{\bar{p}_1, \bar{p}_2} = -\frac{\lambda}{4m^2 V} \delta_{\bar{p}_1 + \bar{p}_2, \bar{p}_3 + \bar{p}_4} \]

From gravitational self-interactions

\[ \Lambda_{g} \frac{\bar{p}_3, \bar{p}_4}{\bar{p}_1, \bar{p}_2} = -\frac{4\pi G m^2}{V} \delta_{\bar{p}_1 + \bar{p}_2, \bar{p}_3 + \bar{p}_4} \left( \frac{1}{|\bar{p}_1 - \bar{p}_3|^2} + \frac{1}{|\bar{p}_1 - \bar{p}_4|^2} \right) \]

O. Erken et al., PRD 85 (2012) 063520
Thermalization occurs due to gravitational interactions

\[ \Gamma_g \sim 4\pi Gnm^2 l^2 \quad \text{with} \quad l = (m \delta v)^{-1} \]

\[ \sim 5 \cdot 10^{-7} H(t_1) \left( \frac{f}{10^{12} \text{ GeV}} \right)^{\frac{2}{3}} \]

\[ \Gamma_g(t)/H(t) \propto t \ a(t)^{-1} \propto a(t) \]
Gravitational interactions thermalize the axions and cause them to form a BEC when the photon temperature

\[ T_\gamma \sim 500 \text{ eV} \left( \frac{f}{10^{12} \text{ GeV}} \right)^{\frac{1}{2}} \]

After that

\[ \delta v \sim \frac{1}{m t} \]

\[ \Gamma_g(t) / H(t) \propto t^3 a(t)^{-3} \]
Tidal torque theory

Stromberg 1934; Hoyle 1947; Peebles 1969, 1971

neighboring protogalaxy
Tidal torque theory with ordinary CDM

the velocity field remains irrotational

$\nabla \times \vec{v} = 0$
in their lowest energy available state, the axions fall in with net overall rotation
Galactic halos have inner caustics as well as outer caustics.

If the initial velocity field is dominated by net overall rotation, the inner caustic is a ‘tricusp ring’.

If the initial velocity field is irrotational, the inner caustic has a ‘tent-like’ structure.

(Arvind Natarajan and PS, 2005).
simulation by Arvind Natarajan

in case of net overall rotation
The caustic ring cross-section

an elliptic umbilic catastrophe

\[ D_{4} \]
in case of irrotational flow
The caustic rings are predicted to be in the galactic plane with radii

\[ (n = 1, 2, 3...) \]

\[ a_n = \frac{40 \text{kpc}}{n} \left( \frac{V_{\text{rot}}}{220 \text{km/s}} \right) \left( \frac{j_{\text{max}}}{0.18} \right) \]
Axion Search Techniques

the cavity haloscope
the axion helioscope
shining light through walls
axion to magnon conversion
NMR methods
axion mediated long-range forces
LC circuit
atomic transitions
Axion dark matter is detectable

\[ \mathcal{L}_{a\gamma\gamma} = g_\gamma \frac{a}{f_a} \vec{E} \cdot \vec{B} \]

PS '83
\[ h\nu = m_a c^2 \left(1 + \frac{1}{2} \beta^2\right) \]

\[ \beta = \frac{\nu}{c} \approx 10^{-3} \]

\[ Q_a \approx 10^6 \]
\[ a \rightarrow \gamma \]

conversion power on resonance

\[
P = \left( \frac{\alpha g_\gamma}{\pi f_a} \right)^2 V B_0^2 \rho_a C m_a^{-1} Q_L
\]

\[= 2 \cdot 10^{-22} \text{ Watt} \left( \frac{V}{500 \text{ liter}} \right) \left( \frac{B_0}{7 \text{ Tesla}} \right)^2 \left( \frac{C}{0.4} \right) \]

\[
\left( \frac{g_\gamma}{0.36} \right)^2 \left( \frac{\rho_a}{5 \cdot 10^{-25} \text{ gr/cm}^3} \right) \left( \frac{m_a c^2}{h \text{ GHz}} \right) \left( \frac{Q_L}{10^5} \right)
\]

search rate for \( s/n = 4 \)

\[
\frac{df}{dt} = \frac{1.2 \text{ GHz}}{} \left( \frac{P}{2 \cdot 10^{-22} \text{ Watt}} \right)^2 \left( \frac{3 K}{T_n} \right)^2
\]
Axion Dark Matter eXperiment

<table>
<thead>
<tr>
<th>Magnet with Insert (side view)</th>
<th>Magnet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stepping motors</td>
<td></td>
</tr>
<tr>
<td>Liquid helium</td>
<td></td>
</tr>
<tr>
<td>Amplifier, refrigerator Tuner</td>
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<tr>
<td>Tuning rods</td>
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<tr>
<td>Superconducting magnet</td>
<td></td>
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<tr>
<td>8T, 6 tons</td>
<td></td>
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<tr>
<td>Pumped LHe → T ~ 1.5 k</td>
<td></td>
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<tr>
<td>8 T, 1 m × 60 cm ⊘</td>
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ADMX hardware

high Q cavity  experimental insert
ADMX in its second generation

*Supported by DOE Grants DE-FG02-97ER41029, DE-FG02-96ER40956, DE-AC52-07NA27344, DE-AC03-76SF00098, NSF Grant PHY-1067242, and the Livermore LDRD program
Upgrade with SQUID Amplifiers

The basic SQUID amplifier is a flux-to-voltage transducer

SQUID noise arises from Nyquist noise in shunt resistance scales linearly with T

However, SQUIDs of conventional design are poor amplifiers above 100 MHz (parasitic couplings).

Flux-bias to here
Quantum-limited SQUID-based amplification

- SQUIDs have been measured with $T_N \sim 50 \text{ mK}$
- Compared to $\sim 2 \text{ K}$ for HFET amplifiers
- Near quantum–limited noise
- Provides a large increase in ADMX sensitivity

J. Clarke et al.
Will scan the lower-mass decade at or below DFSZ sensitivity
ADMX-HF at Yale

- Multi-post system that consists of 3 rotors connected on common axis and 3 stators.
- 4” ID cavity: Six 0.5” diameter rods
- Freq. span 4.7- 6.0 GHz
FIG. 3. Our exclusion limit at 90% confidence. The light green shaded region is a 1σ error band. The large notch around 5.704 GHz is the result of cutting spectra around a previously unidentified intruder mode. The narrow notches correspond to frequencies where synthetic axion signals were injected in one of the scans. The inset shows our results (green) together with previous cavity limits from ADMX (magenta, [7]) and early experiments at Brookhaven (RBF, blue, [18]) and the University of Florida (UF, cyan, [19]). The axion model band [13] is shown in yellow.
Axion to photon conversion in a magnetic field

\[ p(a \leftrightarrow \gamma) = \left( \frac{\alpha g_\gamma}{\pi f_a} \right)^2 B_0^2 \left( \frac{\sin \frac{q_z L}{2}}{q_z} \right)^2 \]

with \[ q_z = \frac{m_a^2 - \omega_{pl}^2}{2E_a} \]

Theory
- P. S. '83
- L. Maiani, R. Petronzio and E. Zavattini '86
- K. van Bibber et al. '87
- G. Raffelt and L. Stodolsky, '88
- K. van Bibber et al. '89

Experiment
- D. Lazarus et al. '92
- R. Cameron et al. '93
- S. Moriyama et al. '98, Y. Inoue et al. '02
- K. Zioutas et al. 04
- E. Zavattini et al. 05
Tokyo Axion Helioscope

- refrigerators
- superconducting magnet
- PIN photodiodes
- vacuum vessel
- turntable
- gas container
- solar axions

$E \sim 3$ keV
Cern Axion Solar Telescope
IAXO — Conceptual Design

- Large toroidal 8-coil magnet $L \approx 20$ m
- 8 bores: 600 mm diameter each
- 8 x-ray optics + 8 detection systems
- Rotating platform with services

Cryostat

Telescopes

Services

Inclination System

Support Frame

Flexible Lines

Rotating Disk

Rotation System

Axion DM Meeting, Canfranc, Mar 2014

Igor G. Irastorza / Universidad de Zaragoza
Shining light through walls

\[ \text{rate} \propto \frac{1}{f_a^4} \]

K. van Bibber et al. ‘87
A. Ringwald ‘03
R. Rabdan, A. Ringwald and C. Sigurdson ‘05
P. Pugnat et al. '05
C. Robilliard et al. '07
A. Afanasev et al. '08
A. Chou et al. '08
K. Ehret et al. '10
Limits from "light through wall" axion searches
Resonantly Enhanced Axion-Photon Regeneration

F. Hoogeveen (1996); P.S., D. Tanner and K. van Bibber (2007)
ALPS II at DESY

Expected sensitivity: $2 \cdot 10^{-11} \text{ GeV}^{-1}$
Axion to magnon conversion

R. Barbieri, M. Cerdonio, G. Fiorentini and S. Vitale

\[ \mathcal{H}_{a\bar{e}e} = \frac{g_e}{2f_a} \vec{\sigma}_e \cdot \vec{\nabla} a \]
QUAX Proposal


\[
\text{Rate} = 1.2 \times 10^{-3} \left( \frac{m_a}{200 \, \mu\text{eV}} \right)^2 \left( \frac{V}{100 \, \text{cm}^3} \right) \left( \frac{n_S}{2 \cdot 10^{28} / \text{m}^3} \right) \left( \frac{\tau}{2 \, \mu\text{s}} \right)
\]

48 GHz

\[ T = 116 \, \text{mK} \]
NMR techniques

P. Graham, S. Rajendran; D. Budker, M. Ledbetter, A. Sushkov

use nuclear spins coupled to axion DM

\[ g_{aNN} (\partial_\mu a) \bar{N} \gamma^\mu \gamma_5 N \implies H_N \supset g_{aNN} \tilde{\nabla} a \cdot \tilde{S}_N \]
the axion field induces an oscillating nuclear electric dipole moment

\[ d_e \sim 10^{-16} \, \text{e cm} \, \frac{a(x)}{f_a} \]
FIG. 2: Estimated constraints in the ALP parameter space in the EDM coupling $g_d$ (where the nucleon EDM is $d_n = g_d a$ and $a$ is the local value of the ALP field) vs. the ALP mass $\ell$. The green region is excluded by the constraints on excess cooling of supernova 1987A $\ell$. The blue region is excluded by existing, static nuclear EDM searches $\ell$. The QCD axion is in the purple region, whose width shows the theoretical uncertainty $\ell$. The solid red and orange regions show sensitivity estimates for our phase 1 and 2 proposals, set by magnetometer noise. The red dashed line shows the limit from magnetization noise of the sample for phase 2. The ADMX region shows what region of the QCD axion has been covered (darker blue) $\ell$ or will be covered (lighter blue) $\ell$. Phase 1 is a modification of current solid state static EDM techniques that is optimized to search for a time varying signal and can immediately begin probing the allowed region of ALP dark matter. To calculate limits from previous (static) EDM searches as well as our sensitivity curves, we assume the ALP is all of the dark matter.
Axion dark matter detection using an LC circuit

PS, D. Tanner and N. Sullivan, 2013

\[ \nabla \times \vec{B}_a = \vec{j}_a \equiv g_{a\gamma\gamma} \vec{B}_0(\vec{x}) \partial_t a(\vec{x}, t) \]

circuit should be cooled to milli-Kelvin temperatures
a) using ADMX magnet   b) CMS magnet
Axion dark matter detection using atomic transitions

\[ \mathcal{L}_{a\bar{f}f} = -\frac{g_f}{2f_a} \partial_\mu a(x) \bar{f}(x) \gamma^\mu \gamma_5 f(x) \]

\( f \) is electron, or nucleon

\[ H_{a\bar{f}f} = +\frac{g_f}{2f_a} \vec{\sigma}_f \cdot \vec{\nabla} a \]

- tune using the Zeeman effect
- use laser techniques to count axion induced transitions
- must cool to milli-Kelvin temperatures
Wire array detector

- pass currents through superconducting wires
- produce \[ \vec{B} = \hat{x}B_0 \cos(qz) \]
- enhance the quality factor by placing the array in a confocal resonator
- tune to \[ q = m_a \]

PS, D. Tanner and Y. Wang, 1992
G. Rybka, A. Wagner et al. 2004
Dielectric Haloscope

A. Caldwell et al., arXiv 1611.05865 (Madmax)

FIG. 1. A dielectric haloscope consisting of a mirror and several dielectric disks placed in an external magnetic field $B_e$ and a receiver in the field-free region. A parabolic mirror (not shown) could be used to concentrate the emitted power into the receiver. Internal reflections are not shown.
wire arrays

axion-magnon conv.

atomic transitions

\[ g_{\text{array}} \left( \text{GeV}^{-1} \right) \]

\[ m_a \text{ (eV)} \]

-12
-10
-8
-6
-4
-2
0
10
100
1000
10000
100000
1000000
10000000
100000000
1000000000

\[ 10^{-24} \]

\[ 10^{-22} \]

\[ 10^{-20} \]

\[ 10^{-18} \]

\[ 10^{-16} \]

\[ 10^{-14} \]

\[ 10^{-12} \]

\[ 10^{-10} \]

\[ 10^{-8} \]

\[ 10^{-6} \]

\[ 10^{-4} \]

\[ 10^{-2} \]

\[ 10^{0} \]
Conclusions

• Axion dark matter is well motivated

• Axion dark matter can be detected over most of the plausible mass range
FIG. 2: Reach in the coupling vs interaction range plane for the monopole-dipole axion mediated interactions. The band bounded by the red (dark) solid line and dashed line denotes the limit set by transverse magnetization noise of the sample for the specific setup described in the text, for $T_2$ ranging from 1 s to 1000 s. The blue (darker) solid line is a future projection obtained by scaling the setup using parameters chosen in Table 1. The blue (darker) dot-dashed line is the projected limit set by the SQUID sensitivity. We limit the integration time in all setups to $10^6$ sec. The shaded band is the parameter space for the PQ axion with $C_f = 1$. Additional uncertainties [14] and model dependence [15] can produce variations of this axion parameter space. Experimental as well as combined experimental and astrophysical bounds are also presented [9][11].