Axion Dark Matter: Motivation and Search Techniques

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Motivation

Axions solve the strong CP problem

Axions are present in many models of beyond-the-Standard Model physics

Axions are a form of cold dark matter

Axion BEC explains the existence and properties of caustic rings in galactic halos
- Axion Search Techniques

  - the cavity haloscope
  - the axion helioscope
  - shining light through walls
  - NMR methods
  - axion mediated long-range forces
  - LC circuit
  - atomic transitions
The Strong CP Problem

\[ L_{QCD} = \ldots + \bar{\theta} \frac{g^2}{32\pi^2} G^a_{\mu\nu} \Phi^{a\mu\nu} \]

where

\[ \bar{\theta} = \theta - \arg (m_u m_d \ldots m_t) \]

\[ = \theta - \arg \det (Y^u Y^d) \]

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,

$$L = \ldots + \frac{a}{f_a} \frac{g^2}{32 \pi^2} G^a_{\mu \nu} \varepsilon^{\mu \nu} + \frac{1}{2} \partial_\mu a \partial^\mu a + \ldots$$

$$\bar{\theta} = \frac{a}{f_a} \text{ relaxes to zero,}$$

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

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

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

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

$g_\gamma = 0.97 \ \text{in KSVZ model}$

$0.36 \ \text{in DFSZ model}$
The remaining axion window

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

\[ f_a (\text{GeV}) \]

Laboratory searches

Stellar evolution

Cosmology
Axion production by vacuum realignment

\[ T \geq 1 \text{GeV} \]

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

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

Cold axion properties

- **number density**
  \[ n(t) : \frac{4 \cdot 10^{47}}{\text{cm}^3} \left( \frac{f_a}{10^{12} \text{ GeV}} \right)^{\frac{5}{3}} \left( \frac{a(t_1)}{a(t)} \right)^3 \]

- **velocity dispersion**
  \[ \delta v(t) : \frac{1}{m_a t_1} \frac{a(t_1)}{a(t)} \quad \text{if decoupled} \]

- **phase space density**
  \[ \mathcal{N} : n(t) \frac{(2\pi)^3}{4\pi \left( m_a \delta v \right)^3} : 10^{61} \left( \frac{f_a}{10^{12} \text{ GeV}} \right)^{\frac{8}{3}} \]
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 $\mathcal{T}$

$t < \mathcal{T}$

the axion fluid obeys classical field equations, behaves like CDM

$t > \mathcal{T}$

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

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

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

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

From gravitational self-interactions

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

O. Erken et al., PRD 85 (2012) 063520
After $t_1$, axions thermalize in the “condensed” regime

$$\Gamma \gg \delta E$$

$$\frac{d}{dt} N_l = i \sum_{ijk} \frac{1}{2} (\Lambda_{ij}^{kl} a_i^\dagger a_j^\dagger a_k a_l - h.c.)$$

implies

$$\Gamma \sim \frac{1}{4} n \lambda m^{-2} \quad \text{for} \quad \lambda \phi^4$$

and

$$\Gamma \sim 4\pi G n m^2 \ell^2 \quad \text{for self-gravity}$$

($\ell \equiv 1/\delta p$)
Thermalization occurs due to gravitational interactions

PS + Q. Yang, PRL 103 (2009) 111301

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

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

\[ \Gamma_g(t)/H(t) \propto t \alpha(t)^{-1} \propto \alpha(t) \]
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

\[ \delta V : \frac{1}{m t} \]

\[ \Gamma_g(t) / H(t) \propto t^3 a(t)^{-3} \]
Axion BEC thermalization has also been discussed by

• Saikawa and Yamaguchi, Phys. Rev. D87 (2015) 085010

• S. Davidson and Elmer, JCAP 1312 (2013) 034

• J. Berges and J. Jaeckel, Phys. Rev. D91 (2015) 025020

Guth et al. write: "... we conclude that while a Bose-Einstein condensate is formed, the claim of long-range correlation is unjustified."

the axion BEC is inhomogeneous because it is gravitationally unstable. However it does have the long range correlations that are characteristic of BEC. The BEC correlation length is not to be identified with the scale of homogeneity.
Tidal torque theory

neighboring protogalaxy

Stromberg 1934; Hoyle 1947; Peebles 1969, 1971
Tidal torque theory with ordinary CDM

neighboring protogalaxy

\[ \nabla \times v = 0 \]

the velocity field remains irrotational
in their lowest energy available state, the axions fall in with net overall rotation
simulation by Arvind Natarajan

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

an elliptic umbilic catastrophe

$D_4$
On the basis of the self-similar infall model (Filmore and Goldreich, Bertschinger) with angular momentum (Tkachev, Wang + PS), the caustic rings were predicted to be in the galactic plane with radii \((n = 1, 2, 3...\)

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

\(j_{\text{max}} \approx 0.18\) was expected for the Milky Way halo from the effect of angular momentum on the inner rotation curve.
Axion Search Techniques

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

\[ \mathcal{L}_{a\gamma\gamma} = g_\gamma \frac{a}{f_a} \vec{E} \cdot \vec{B} \]
\[ h\nu = m_a c^2 \left( 1 + \frac{1}{2}\beta^2 \right) \]

\[ \beta = \frac{v}{c} : 10^{-3} \]

\[ Q_a : 10^6 \]

\[ \frac{dP}{d\nu} \]

\[ Q_a^{-1} \nu \]

\[ m_a c^2 / h \]

\[ Q_L^{-1} \nu \]
Axion Dark Matter eXperiment

see talks here by G. Carosi and B. Brubaker

Magnet with Insert (side view)

- Stepping motors
- Liquid helium
- Amplifier, refrigerator
- Tuner
- Tuning rods
- Superconducting magnet
- 8T, 6 tons
- Pumped LHe → T ~ 1.5 k

Magnet

- 8 T, 1 m × 60 cm Ø
Gen 2 ADMX sensitivity

Will scan the lower-mass decade at or below DFSZ sensitivity
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
IAXO – Conceptual Design

- Large toroidal 8-coil magnet $L = \sim 20$ m
- 8 bores: 600 mm diameter each
- 8 x-ray optics + 8 detection systems
- Rotating platform with services
Shining light through walls

rate \propto \frac{1}{f_a^4}

K. van Bibber et al. '87
A. Ringwald '03
R. Rabadan,
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

(a) Laser → \( \gamma \) → \( a \) → Wall → \( B_0 \) → Magnet → \( B_0 \) → Magnet → Photon Detector

(b) Laser → IO → Magnet → Matched Fabry-Perots → Magnet

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

Expected sensitivity: \(2 \cdot 10^{-11} \text{ GeV}^{-1}\)
PVLAS Laser experiments
Solar search HB Stars
Resonantly enhanced photon regeneration
Microwave cavity dark matter searches
Axion models
Macroscopic forces mediated by axions

\[ L_{af} = g_f \frac{m_f}{f_a} a f (i\gamma_5 + \theta_f) f \]

forces coupled to the \( f \) spin density
forces coupled to the \( f \) number density

background of magnetic forces

Theory:
J. Moody and F. Wilczek '84

Experiment:
A. Youdin et al. '96
W.-T. Ni et al. '96

\( \theta_f : 10^{-17} \)
NMR with long range axion field

A. Arvanitaki and A. Geraci, 2014

\[ H_{\text{int}} = \frac{g_f m_f \theta_f}{f_a} a(x) \]

the rotating mass on the left produces an oscillating axion field

\[ H_{\text{int}} = \frac{g_f m_f}{f_a} \vec{\nabla} a(x) \cdot \vec{\sigma} \]

the oscillating axion field is an effective magnetic field in an NMR experiment

\[ \omega = \gamma_N B_0 \]
the axion field induces an oscillating nuclear electric dipole

\[ d_e \sim 10^{-16} \text{ e cm} \frac{a(x)}{f_a} \]
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 $[17]$. The green region is excluded by the constraints on excess cooling of supernova 1987A $[17]$. The blue region is excluded by existing, static nuclear EDM searches $[17]$. The QCD axion is in the purple region, whose width shows the theoretical uncertainty $[17]$. 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) $[34]$ or will be covered (lighter blue) $[59, 60]$. 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

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

circuit should be cooled to milli-Kelvin temperatures
Axion dark matter detection using atomic transitions

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

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

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

\( \bar{f} \) is electron, or nucleon
Conclusions

• Axion dark matter is well motivated

• Axion dark matter can be detected over most of the plausible mass range