Astrophysical and Cosmological Axion Limits

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Solar Axions
Search for Solar Axions

- Primakoff production
- Axion flux
- Magnet S
- Axion-Photon-Oscillation

- Tokyo Axion Helioscope ("Sumico")
  (Results since 1998, up again 2008)
- CERN Axion Solar Telescope (CAST)
  (Data since 2003)

Alternative technique:
Bragg conversion in crystal
Experimental limits on solar axion flux from dark-matter experiments
(SOLAX, COSME, DAMA, CDMS ...)
Astrophysical bounds on the masses of axions and Higgs particles

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(Received 27 April 1978)

Lower bounds on the mass of a light scalar (Higgs) or pseudoscalar (axion) particle are found in three ways: (1) by requiring that their effect on primordial nucleosynthesis not yield a deuterium abundance outside present experimental limits, (2) by requiring that the photons from their decay thermalize and not distort the microwave background, and (3) by requiring that their emission from helium-burning stars (red giants) not disrupt stellar evolution. The best bound is from (3); it requires the axion or Higgs-particle mass to be greater than about 0.2 MeV.

The first process considered is the Primakoff process,\(^\text{(7)}\) \(\gamma + Z \rightarrow \phi + Z\), shown in Fig. 2. The cross section for this process near threshold is

\[
|\sigma| = 64\pi a Z^2 \frac{\omega \Gamma(\phi - 2\gamma)}{m^2_\phi} \frac{\left(\omega^2 - m^2_\phi\right)^{1/2}(\omega - m_\phi)}{(m^2_\phi - 2\omega m_\phi)^2},
\]

\(\text{(7)}\)

First discussion of Primakoff effect for WW axions \((m_\alpha \gg T)\)

For “invisible axions” \((m_\alpha \ll T)\) screening effects crucial

(G.R., PRD 33, 897:1986)
Solar Neutrino Limit on Solar Energy Losses

Self-consistent models of the present-day Sun provide a simple power-law connection between a new energy loss $L_a$ (e.g. axions) and the all-flavor solar neutrino flux from the B8 reaction as measured by SNO.

$$\Phi^a_{\text{B8}} = \Phi^0_{\text{B8}} \left(\frac{L_\odot + L_a}{L_\odot}\right)^{4.6}$$

Solar model prediction and SNO measurements imply roughly

$$L_a \lesssim 0.1 L_\odot$$

Gondolo & Raffelt, arXiv:0807.2926

Schlattl, Weiss & Raffelt, hep-ph/9807476
LHC Magnet Mounted as a Telescope to Follow the Sun

Cern Axion Solar Telescope
Helioscope Limits

CAST-II results (He-4 filling): JCAP 0902 (2009) 008
CAST-II results (He-3 filling, range 1): PRL 107 (2011) 261302

Solar neutrino limit
First experimental crossing of the KSVZ line
Next Generation Axion Helioscope (IAXO)

Axions from Normal Stars
Galactic Globular Cluster M55

M55

Georg Raffelt, MPI Physics, Munich

Vistas in Axion Physics, INT, Seattle, 23–26 April 2012
Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W. Harris, 2000)
Color-Magnitude Diagram for Globular Clusters

- Particle emission delays helium ignition,
- Tip of RGB brighter

Particle emission reduces helium burning lifetime, i.e. number of HB stars

Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000)
Parameter Space for Axion-Like Particles (ALPs)

\[ \mathcal{L}_{a\gamma\gamma} = -\frac{g_{a\gamma\gamma}}{4} F \tilde{F} a \]
\[ = g_{a\gamma\gamma} E \cdot B a \]
\[ \Gamma_{a\rightarrow\gamma\gamma} = \frac{g_{a\gamma}^2 m_a^3}{64\pi} \]

Axion Line

Invisible axion (DM)

ALP - Photon Coupling [GeV⁻¹]

ALP Mass [eV]
Parameter Space for Axion-Like Particles

- Laser Experiments
- CAST Solar Axions
- HB Stars
- Invisible axion (DM)
- Axion Line
- Invisible axion (DM)

ALP Mass [eV] vs. ALP-Photon Coupling [GeV⁻¹]

Georg Raffelt, MPI Physics, Munich
Vistas in Axion Physics, INT, Seattle, 23–26 April 2012
Shining TeV Gamma Rays through the Universe

VHE: $E \gtrsim 100$ GeV

Figure from a talk by Manuel Meyer (Univ. Hamburg)
Shining TeV Gamma Rays through the Universe

Figure from a talk by Manuel Meyer (Univ. Hamburg)
Parameter Space for Axion-Like Particles

- Laser Experiments
- CAST Solar Axions
- HB Stars

- Invisible axion (DM)
- TeV γ rays

How to make progress?

Axion Line

Invisible axion (DM)

ALP Mass [eV]

ALP–Photon–Coupling [GeV⁻¹]
SN 1987A Neutrino Signal
Supernova 1987A Energy-Loss Argument

Emission of very weakly interacting particles would “steal” energy from the neutrino burst and shorten it. (Early neutrino burst powered by accretion, not sensitive to volume energy loss.)

Late-time signal most sensitive observable
Axion Emission from a Nuclear Medium

Axion-nucleon interaction:

\[ \mathcal{L}_{\text{int}} = \frac{c_N}{2 f_a} \bar{\Psi}_N \gamma_\mu \gamma_5 \Psi_N \partial^\mu a = \frac{c_N}{2 f_a} J^A_\mu \partial^\mu a \]

Energy-loss rate (erg cm^{-3} s^{-1})

\[ Q = \int d\Gamma_a \int d\Gamma_{\text{Nucleons}} |M|^2 \omega \quad (\text{axion energy } \omega) \]

\[ = \left( \frac{c_N}{2 f_a} \right)^2 \frac{n_B}{4 \pi^2} \int_0^\infty d\omega \omega^4 S(-\omega) \]

Dynamical structure function, in nonrelativistic limit correlator of nucleon spin density operator

\[ S(\omega, k) = \frac{4}{3n_B} \int_{-\infty}^{+\infty} dt \, e^{i\omega t} \langle \sigma(t, k) \cdot \sigma(0, k) \rangle \]

Early calculations using one-pion exchange potential without many body effects or multiple-scattering effects over-estimated emission rate, see e.g.

Cooling Time Scale

Exponential cooling model: $T = T_0 e^{-t/4\tau}$, constant radius, $L = L_0 e^{-t/\tau}$

Fit parameters are $T_0$, $\tau$, radius, 3 offset times for KII, IMB & BST detectors

Loredo and Lamb, Bayesian analysis
astro-ph/0107260
Long-Term Cooling of EC SN (Garching 2009)

Neutrino opacities with strong NN correlations and nucleon recoil in neutrino-nucleon scattering.
Exponential cooling with \( \tau = 2.6 \) s
Barely allowed by SN 1987A

Neutrino opacities without these effects
(\( \sim \) Basel case?)
Much longer cooling times

L. Hüdepohl et al. (Garching Group), arXiv:0912.0260
Axion Bounds and Searches

- **Experiments**
  - Tele
  - CAST
  - ADMX (Seattle & Yale)

- **Too much hot dark matter**
- **Too much cold dark matter (misalignment with Θ_i = 1)**

- **Globular clusters (a-γ-coupling)**
- **SN 1987A Too many events**
- **Too much energy loss**

- **Globular clusters (helium ignition) (a-e coupling)**

**Parameters**

- \( f_a \) [GeV]
- \( m_a \) [keV, eV, meV, μeV, neV]

**Experiments** and **Axion Bounds**

- Direct searches
- Globular clusters
- SN 1987A
- Too much cold dark matter (misalignment with Θ_i = 1)

**Energy Levels**

- 10^3, 10^6, 10^9, 10^{12}, 10^{15} [GeV]
- 10^3, 10^6, 10^9, 10^{12}, 10^{15} [GeV]

**Couplings**

- a-γ-coupling
- a-e coupling
Axion Bounds and Searches

Experiments

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

Telescope

CAST

Direct searches

ADMX (Seattle & Yale)

White dwarf cooling?

Too much cold dark matter (misalignment with Θ_i = 1)
Do White Dwarfs Need Axion Cooling?

White dwarf luminosity function (number of WDs per brightness interval)

No axions

With axion cooling ($g_{ae} = 2.2 \times 10^{-13}$ near globular cluster lir)

Isern et al., arXiv:1204.3565
Diffuse Supernova Axion Background (DSAB)

- Neutrinos from all core-collapse SNe comparable to photons from all stars
- Diffuse Supernova Neutrino Background (DSNB) similar energy density as extra-galactic background light (EBL), approx 10% of CMB energy density
- DSNB probably next astro neutrinos to be measured

- Axions with $m_a \sim 10$ meV near SN 1987A energy-loss limit
- Provide DSAB with compatible energy density as DSNB and EBL
- No obvious detection channel

Raffelt, Redondo & Viaux
work in progress (2011)
New macroscopic forces?

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(Received 17 January 1984)

The forces mediated by spin-0 bosons are described, along with the existing experimental limits. The mass and couplings of the invisible axion are derived, followed by suggestions for experiments to detect axions via the macroscopic forces they mediate. In particular, novel tests of the T-violating axion monopole-dipole forces are proposed.

Tests of Newton’s law & equivalence principle:
Scalar axion coupling \((g_s^N)^2\)

Torsion balance using polarized electron spins
Axion couplings \(g_s^N g_p^e\)
T-violating force

Spin-spin forces hard to measure
Axion couplings \((g_s^e)^2\)
Long-Range Force Experiments

Long-range force limits from tests of Newton’s law and equivalence principle (Mostly from Eöt-Wash Group, Seattle)

Limits from long-range $g_s^N$ limits times astrophysical $g_p^e$ limits, compared with direct $g_s^N g_p^e$ constraints
Limits on CP Violation from Long-Range Forces

Assume axion scalar CP-violating force with nucleons

\[ g_s^N = \Theta_{\text{eff}} \frac{f_\pi}{f_a} \sim \Theta_{\text{eff}} \frac{m_a}{m_\pi} \]

Eötvös-Wash constraint provides best limit around \( m_a \sim 1 \text{ meV} \)
Cosmological Constraints

Sun
Globular Cluster
Supernova 1987A
Dark Matter
Lee-Weinberg Curve for Neutrinos and Axions

**Axions**

\[ \log(\Omega_a) \]

- Non-Thermal Relics
- Thermal Relics

- \( \Omega_M \)
- 10 \( \mu \text{eV} \)
- 10 \text{eV}

**Neutrinos & WIMPs**

\[ \log(\Omega_\nu) \]

- Thermal Relics

- \( \Omega_M \)
- 10 \text{eV}
- 10 \text{GeV}
Axion Hot Dark Matter from Thermalization after $\Lambda_{\text{QCD}}$

$$L_{\alpha \pi} = \frac{C_{\alpha \pi}}{f_{\alpha} f_{\pi}} \left( \pi^0 \pi^+ \partial_\mu \pi^- + \pi^0 \pi^- \partial_\mu \pi^+ - 2 \pi^+ \pi^- \partial_\mu \pi^0 \right) \partial_\mu \alpha$$

Chang & Choi, PLB 316 (1993) 51

Hannestad, Mirizzi & Raffelt, hep-ph/0504059
Credible regions for neutrino plus axion hot dark matter (WMAP-7, SDSS, HST) Hannestad, Mirizzi, Raffelt & Wong [arXiv:1004.0695]

Marginalizing over neutrino hot dark matter component

\[ m_a < 0.7 \text{ eV (95\% CL)} \]

Assuming no axions

\[ \sum m_\nu < 0.4 \text{ eV (95\% CL)} \]

Figure 1. 2D marginal 68\% and 95\% contours in the \( \sum m_\nu - m_a \) plane. The blue lines correspond to our results using CMB+HPS, and the red lines using CMB+HPS+HST.
BBN limits on sub-MeV mass axions

- Axions essentially in thermal equilibrium throughout BBN
- $e^+e^-$ annihilation partly heats axions \(\rightarrow\) missing photons
- Reduced photon/baryon fraction during BBN
- Reduced deuterium abundance, using WMAP baryon fraction

Cadamuro, Hannestad, Raffelt & Redondo, arXiv:1011.3694 (JCAP)
Axion Bounds and Searches

- **Too much hot dark matter**
- **Globular clusters (a-γ-coupling)**
- **SN 1987A**
  - Too many events
  - Too much energy loss
- **Globular clusters (helium ignition)**
  - (a-e coupling)
- **White dwarf cooling?**
- **Too much cold dark matter**
  - (misalignment with Θ_i = 1)
- **Direct searches**
  - ADMX (Seattle & Yale)
- **Tele scope**
  - CAST
- **Experiments**

### Energy Levels

- **[GeV]** $f_a$
- $10^3$ keV
- $10^6$ eV
- $10^9$ meV
- $10^{12}$ μeV
- $10^{15}$ neV

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**Creation of Cosmological Axions**

**T \sim f_\alpha (very early universe)**
- U_{PQ}(1) spontaneously broken
- Higgs field settles in “Mexican hat”
- Axion field sits fixed at $\alpha_i = \Theta_i f_\alpha$

**T \sim 1 \text{ GeV} (H \sim 10^{-9} \text{ eV})**
- Axion mass turns on quickly by thermal instanton gas
- Field starts oscillating when $m_\alpha \geq 3H$
- Classical field oscillations (axions at rest)

*Axions are born as nonrelativistic, classical field oscillations*  
*Very small mass, yet cold dark matter*
Cosmic Axion Density

Modern values for QCD parameters and temperature-dependent axion mass imply (Bae, Huh & Kim, arXiv:0806.0497)

\[ \Omega_a h^2 = 0.195 \Theta_i^2 \left( \frac{f_a}{10^{12}\text{GeV}} \right)^{1.184} = 0.105 \Theta_i^2 \left( \frac{10\text{\,\mu eV}}{m_a} \right)^{1.184} \]

If axions provide the cold dark matter: \( \Omega_a h^2 = 0.11 \)

\[ \Theta_i = 0.75 \left( \frac{10^{12}\text{GeV}}{f_a} \right)^{0.592} = 1.0 \left( \frac{m_a}{10\text{\,\mu eV}} \right)^{0.592} \]

- \( \Theta_i \sim 1 \) implies \( f_a \sim 10^{12} \text{ GeV} \) and \( m_a \sim 10 \text{ \,\mu eV} \) ("classic window")
- \( f_a \sim 10^{16} \text{ GeV} \) (GUT scale) or larger (string inspired) requires \( \Theta_i \lesssim 0.003 \) ("anthropic window")
THE NOT-SO-HARMLESS AXION

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A COSMOLOGICAL BOUND ON THE INVISIBLE AXION

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COSMOLOGY OF THE INVISIBLE AXION

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Received 10 September 1982

We identify a new cosmological problem for models which solve the strong CP puzzle with an invisible axion, unrelated to the domain wall problem. Because the axion is very weakly coupled, the energy density stored in the oscillations of the classical axion field does not dissipate rapidly; it exceeds the critical density needed to close the universe unless \( f_a < 10^{12} \text{ GeV} \), where \( f_a \) is the axion decay constant. If this bound is saturated, axions may comprise the dark matter of the universe.
Creation of Adiabatic vs. Isocurvature Perturbations

**Inflaton field**

De Sitter expansion imprints
scale invariant fluctuations

Slow roll

Reheating

Inflaton decay → matter & radiation
Both fluctuate the same:
Adiabatic fluctuations

**Axion field**

De Sitter expansion imprints
scale invariant fluctuations

Inflaton decay → radiation
Axion field oscillates late → matter
Matter fluctuates relative to radiation:
Entropy fluctuations
Adiabatic vs. Isocurvature Temperature Fluctuations

Adapted from Fox, Pierce & Thomas, hep-th/0409059
Isocurvature Forecast

Hubble scale during inflation

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

\[ \log(H_I/\text{GeV}) \]

\[ \Theta_i = \pi/1000 \]

\[ \pi/100 \]

\[ \pi/10 \]

\[ \pi/2 \]

Isocurvature fluctuations

\[ \alpha > \alpha_{\text{obs}} \]

Current data

Planck

CVL

Tensors

\[ r > r_{\text{obs}} \]

\[ f_a < H_I \]

Hamann, Hannestad, Raffelt & Wong, arXiv:0904.0647
# Cold Axion Populations

## Case 1
**Inflation after PQ symmetry breaking**

- Homogeneous mode oscillates after
  \[ T \lesssim \Lambda_{\text{QCD}} \]
- Dependence on initial misalignment angle
  \[ \Omega_a \propto \Theta_i^2 \]
- Dark matter density a cosmic random number ("environmental parameter")

  - Isocurvature fluctuations from large quantum fluctuations of massless axion field created during inflation
  - Strong CMB bounds on isocurvature fluctuations
  - Scale of inflation required to be small

## Case 2
**Reheating restores PQ symmetry**

- Cosmic strings of broken $U_{\text{PQ}}(1)$ form by Kibble mechanism
- Radiate long-wavelength axions
- $\Omega_a$ independent of initial conditions
- $N = 1$ or else domain wall problem

Inhomogeneities of axion field large, self-couplings lead to formation of mini-clusters

- **Typical properties**
  - Mass $\sim 10^{-12} \, M_{\text{sun}}$
  - Radius $\sim 10^{10} \, \text{cm}$
  - Mass fraction up to several 10%
Axion Production by Domain Wall and String Decay

Recent numerical studies of collapse of string-domain wall system

$$\Omega_a h^2 = (16 \pm 6) \left( \frac{f_a}{10^{12} \text{GeV}} \right)^{1.19} \times \left( \frac{g_{*1}}{70} \right)^{-0.41} \left( \frac{\Lambda}{400 \text{ MeV}} \right)$$

Implies a CDM axion mass of

$$m_a \sim 1 \text{ meV}$$


Remains to be confirmed, interpretation of numerical studies not entirely straightforward
Axion Bounds and Searches

- Direct searches
- Too much CDM (misalignment)
- Telescope Experiments
- Globular clusters (a-γ-coupling)
- SN 1987A: Too many events
- Too much energy loss
- Globular clusters (helium ignition) (a-e coupling)
- Too much hot dark matter
- Too much cold dark matter (misalignment with Θ_i = 1)
- White dwarf cooling?
- String/DW decay
- ADMX (Seattle & Yale)
- Anthropic Range

10^3 10^6 10^9 10^{12} 10^{15} [GeV] f_a

m_a

keV eV meV μeV neV

10^{-3} 10^{-6} 10^{-9} 10^{-12} 10^{-15} [GeV]
Excluding CDM Axions With Radiation Density?

Cosmic radiation density derived from data of WMAP-7+ACT+HST (Hamann, arXiv:1110.4271), PLANCK will settle (Paper expected Jan 2013)

CDM axions reaching thermal equilibrium with photons after BBN? Sucks up photons, increases effective neutrino density. (Erken, Sikivie, Tam & Yang arXiv:1104.4507, PRL 2012)

CDM axions excluded?

My opinion: Doubts about axion-photon thermalization.

$N_{\text{eff}} = 3.046$  $N_{\text{eff}} = 6.77$
Pie Chart of Dark Universe

- Dark Energy: 73% (Cosmological Constant)
- Ordinary Matter: 4% (of this only about 10% luminous)
- Dark Matter: 23%
- Neutrinos: 0.1–2%