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Axions—motivation, limits and searches

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Abstract
The axion solution of the strong CP problem provides a number of possible windows to physics beyond the standard model, notably in the form of searches for solar axions and for galactic axion dark matter, but in a broader context also inspires searches for axion-like particles in pure laboratory experiments. We briefly review the motivation for axions, astrophysical limits, their possible cosmological role, and current searches for axions and axion-like particles.

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(Some figures in this article are in colour only in the electronic version)

1. Introduction

Quantum chromodynamics is a CP-violating theory, implying that the neutron should have a large electric dipole moment, far in excess of experimental limits [1]. One elegant solution of this ‘strong CP problem’ was proposed by Peccei and Quinn (PQ) who postulated a new global U(1) symmetry that is spontaneously broken at some large energy scale, allowing for the dynamical restoration of the CP symmetry [2, 3]. Weinberg [4] and Wilczek [5] realized that an inevitable consequence of this mechanism is a new pseudoscalar boson, the axion, which is the Nambu-Goldstone boson of the PQ symmetry. The axion solution would open a new low-energy window to high-energy physics. String theory provides another motivation in that axion-like fields typically appear so that plausibly one of them could play the role of the QCD axion [6].

The PQ symmetry is explicitly broken at low energies by instanton effects so that the axion acquires a small mass

$$m_a = \frac{z^{1/2}}{1+z}\frac{f_\pi m_\pi}{f_a} = \frac{6.0\ \mathrm{eV}}{f_a/10^6\ \mathrm{GeV}}, \tag{1}$$

where f_a is the axion decay constant or PQ scale that governs all axion properties, $f_\pi = 93$ MeV is the pion decay constant, and $z = m_u/m_d$ is the mass ratio of up and down quarks.

We will follow the previous axion literature and assume the canonical value $z = 0.56$ [7, 8], although it could vary in the range 0.3–0.6 [9].

Axions were not found in early searches, ruling out 'standard axions' where f_a would have been related to the electroweak scale $f_{\rm EW}$. 'Invisible' axion models with $f_a \gg f_{\rm EW}$ were quickly constructed [10–14] and quickly recognized to be far from inconsequential because they can provide the dark matter of the universe [15–18] and can be searched in realistic experiments [19–22].

The properties of axions are closely related to those of neutral pions. One generic property is a two-photon interaction that plays a key role for most searches,

$$\mathcal{L}_{a\gamma} = \tfrac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = -g_{a\gamma} \mathbf{E} \cdot \mathbf{B} a. \tag{2}$$

Here, F is the electromagnetic field-strength tensor, $\tilde{F}$ its dual, and $\mathbf{E}$ and $\mathbf{B}$ are the electric and magnetic fields, respectively. The coupling constant is

$$g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - \frac{2}{3}\frac{4+z}{1+z}\right) = \frac{\alpha}{2\pi}\left(\frac{E}{N} - \frac{2}{3}\frac{4+z}{1+z}\right)\frac{1+z}{\sqrt{z}}\frac{m_a}{m_\pi f_\pi}, \tag{3}$$

where, E and N, respectively, are the electromagnetic and colour anomaly of the axial current associated with the axion field. In grand unified models, e.g. the DFSZ model [12, 13], axions couple to ordinary quarks and leptons, implying $E/N = 8/3$, whereas in the KSVZ model [10, 11] $E/N = 0$. While these cases are often used as generic examples, in general E/N is not known so that for fixed f_a a broad range of $g_{a\gamma}$ values is possible [23]. Still, barring fine-tuned cancellations, $g_{a\gamma}$ scales from the corresponding pion interaction by virtue of equation (3). Taking the model-dependent factors to be of order unity defines the 'axion line' in the m_a-$g_{a\gamma}$ plane.

Axions transform into photons and vice versa in external B fields [19], a phenomenon similar to neutrino oscillations [24]. This effect can have intriguing applications, although the relevant range of $g_{a\gamma}$ and m_a typically is far away from the axion line because for a given $g_{a\gamma}$ the implied m_a usually suppresses conversion effecs by energy–momentum conservation. Therefore, beginning with 'arions' [25, 26], the axion relation between $g_{a\gamma}$ and m_a was often taken to be relaxed, postulating nearly massless axion-like particles for which 'ALPs' has recently become standard coinage. While CAST [27] (solar axions) and ADMX [21] (galactic dark matter) are the only experiments that probe ALPs on the axion line, we will briefly review other searches, notably the puzzling signal in the PVLAS experiment [28].

Section 2 is devoted to searches for axions and axion-like particles based on their two-photon interaction and the relevant astrophysical limits. In section 3 other astrophysical limits are summarized. Section 4 is devoted to the possible cosmological role of axions before turning to a summary in section 5.

2. Axion–photon interaction: searches, limits, applications

2.1. Searches for solar axions

Particles with a two-photon vertex, including neutral pions and gravitons besides the hypothetical axions, can transform into photons in external electric or magnetic fields, an effect first discussed by Primakoff in the early days of pion physics [29]. Therefore, stars produce these particles from thermal photons in the fluctuating electromagnetic fields of the stellar plasma [30]. Calculating the solar axion flux is straightforward except for the proper inclusion of screening effects [31, 32]. The transition rate for a photon of energy E into an axion of the same energy (recoil effects are neglected) is [33]

$$\Gamma_{\gamma\to a} = \frac{g_{a\gamma}^2 T \kappa_s^2}{32\pi}\left[\left(1+\frac{\kappa_s^2}{4E^2}\right)\ln\left(1+\frac{4E^2}{\kappa_s^2}\right)-1\right], \tag{4}$$

where T is the temperature (natural units with $\hbar = c = k_B = 1$ are used). The screening scale in the Debye–Hückel approximation is

$$\kappa_s^2 = \frac{4\pi\alpha}{T}\left(n_e + \sum_{\text{nuclei}} Z_j^2 n_j\right), \tag{5}$$

where n_e is the electron density and n_j that of the jth ion of charge Z_j. Near the solar centre $\kappa_s \approx 9$ keV and $(\kappa_s/T)^2 \approx 12$ is nearly constant throughout the Sun. The axion flux at Earth, based on a standard solar model, is well approximated by

$$\frac{d\Phi_a}{dE} = g_{10}^2\, 6.0\times 10^{10}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{keV}^{-1} E^{2.481}\, \text{e}^{-E/1.205}, \tag{6}$$

where E is in keV and $g_{10} = g_{a\gamma}/(10^{-10}\ \text{GeV}^{-1})$. The integrated flux parameters are

$$\Phi_a = g_{10}^2\, 3.75\times 10^{11}\ \text{cm}^{-2}\ \text{s}^{-1} \qquad L_a = g_{10}^2\, 1.85\times 10^{-3} L_\odot. \tag{7}$$

The maximum of the distribution is at 3.0 keV, the average energy is 4.2 keV.

This flux can be searched with the inverse process where an axion converts into a photon in a macroscopic B field, the 'axion helioscope' technique [19]. One would look at the Sun through a 'magnetic telescope' and place an x-ray detector at the far end. The conversion can be coherent over a large propagation distance and is then pictured as a particle oscillation effect [24]. The conversion probability is

$$P_{a\to\gamma} = \left(\frac{g_{a\gamma} B}{q}\right)^2 \sin^2\left(\frac{qL}{2}\right), \tag{8}$$

where L is the path length and q the axion–photon momentum difference; in vacuum it is $q = m_a^2/2E$. For $qL \lesssim 1$ the oscillation length exceeds L. For $qL \ll 1$ we have $P_{a\to\gamma} = (g_{a\gamma} BL/2)^2$, implying an x-ray flux of

$$\Phi_\gamma = 0.51\ \text{cm}^{-2}\text{day}^{-1} g_{10}^4 \left(\frac{L}{9.26\ \text{m}}\right)^2 \left(\frac{B}{9.0\ \text{T}}\right)^2. \tag{9}$$

For $qL \gtrsim 1$ this rate is reduced by the momentum mismatch. A low-Z gas would provide a refractive photon mass m_γ so that $q = \left|m_\gamma^2 - m_a^2\right|/2E$. For $m_a \approx m_\gamma$ the maximum rate can thus be restored [34].

Early helioscope searches were performed in Brookhaven [35] and Tokyo [36, 37]. Solar axions could also transform in electric crystal fields, but the limits obtained by SOLAX [38], COSME [39] and DAMA [40] are less restrictive and require an axion luminosity exceeding the helioseismological constraint $g_{10} \lesssim 10^{-9}\ \text{GeV}^{-1}$ [41].

The first helioscope that can actually reach the 'axion line' is the CERN axion solar telescope (CAST), using a refurbished LHC test magnet with $B = 9.0$ T and two pipes of length $L = 9.26$ m. The magnet is mounted with $\pm 8^\circ$ vertical movement, allowing for observation of the Sun for 1.5 h at both sunrise and sunset. CAST operated for about 6 months in 2003. The non-observation of a signal above background in all three detectors leads to the exclusion range shown in figure 1. In the mass range $m_a \lesssim 0.02$ eV the new limit is [27]

$$g_{a\gamma} < 1.16\times 10^{-10}\ \text{GeV}^{-1} \qquad (95\%\ \text{CL}). \tag{10}$$

The data taken in 2004 do not show any apparent signal above background, leading to limits comparable to the sensitivity prospected in figure 1.

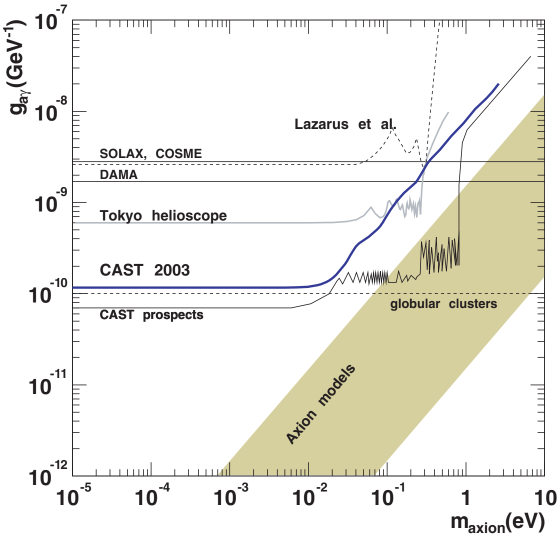

Figure 1. Exclusion limit (95% CL) from CAST 2003 compared with other constraints discussed in the text [27]. The shaded band represents typical theoretical models ('axion line'). Also shown is the future sensitivity foreseen in the CAST proposal.

In the ongoing phase II, a variable-pressure helium filling provides an effective photon mass. The vapour pressure of He^4 at 1.8 K, the magnet's operating temperature, allows one to reach m_a up to 0.26 eV. In the next phase, He^3 will be used because its higher vapour pressure allows one to reach 0.8 eV. Yet higher masses require an isolating gas cell in the bore where He^3 at 5.4 K would allow one to reach m_a of 1.4 eV.

For $m_a \lesssim 10^{-4}$, a competitive method to search for solar axions could be to look with an x-ray satellite at the Sun when it is shadowed by the Earth and search for x-rays from the axion–photon conversion in the Earth's magnetic field [42]. A related idea is to look for high-energy γ-rays, e.g. with the GLAST satellite, that 'pass through the Sun' by magnetic conversion and back conversion [43].

2.2. *Do axions escape from the Sun?*

CAST can detect axions only if they actually escape from the Sun. Their mean-free path (mfp) against the Primakoff process is the inverse of equation (4). As an example we consider 4 keV axions and note that at the solar centre $T \approx 1.3$ keV and $\kappa_s \approx 9$ keV. The axion mfp is then $\lambda_a \approx g_{10}^{-2} 6 \times 10^{24}$ cm $\approx g_{10}^{-2} 8 \times 10^{13} R_\odot$, or about 10^{-3} of the radius of the visible universe. Therefore, $g_{a\gamma}$ would have to be more than 10^7 larger than the CAST limit for axions to be re-absorbed in the Sun. Even in this extreme case they are not harmless because they would carry the bulk of the energy flux that otherwise is carried by photons. The mfp of low-mass particles that are trapped in the Sun should be shorter than that of photons (about 10 cm near the solar centre) to avoid a dramatic modification of the solar structure [44]. This requirement is so extreme that for anything similar to axions the possibility of re-absorption is not a serious possibility.

2.3. *Globular cluster stars*

The most restrictive astrophysical limit on $g_{a\gamma}$ arises from globular cluster stars. A globular cluster is a gravitationally bound system of stars that formed at the same time and thus differ

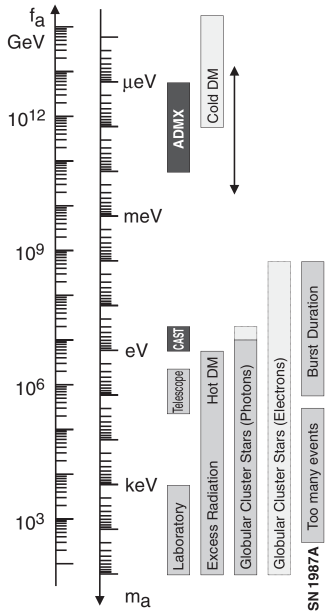

Figure 2. Axion limits and foreseen search ranges as discussed in the text. A light-gray 'exclusion bar' means that it strongly depends on cosmological or axion-model assumptions. The black bars indicate ongoing or near-future axion searches.

primarily in their mass. A globular cluster provides a homogeneous population of stars, allowing for detailed tests of stellar-evolution theory. The stars surviving since formation have masses somewhat below $1M_\odot$. In a colour-magnitude diagram, where one plots essentially the surface brightness versus the surface temperature, stars appear in characteristic loci, allowing one to identify their state of evolution.

The stars on the horizontal branch (HB) have reached helium burning where their core (about $0.5M_\odot$) generates energy by fusing helium to carbon and oxygen with a core-averaged energy release of about 80 erg g^{-1} s^{-1}. On the other hand, the average Primakoff energy loss is approximately $g_{10}^2 30$ erg g^{-1} s^{-1}. The main effect would be an acceleration of the consumption of helium and thus a reduction of the HB lifetime by a factor $80\big/\big(80 + 30g_{10}^2\big)$, i.e., by about 30% for $g_{10} = 1$. Number counts in 15 globular clusters [45] reveal typically 100 HB stars in the used fields of view. This is compared with the number of red giants (evolutionary phase before helium ignition, but after core-exhaustion of hydrogen) and shows that the HB lifetime in any one cluster is established within about 20–40%. Note that the Primakoff losses are much smaller for red giants so that their lifetime is not reduced by Primakoff emission.

Compounding the results of all 15 clusters, the helium-burning lifetime agrees with expectations to within about 10% [46, 47]. Of course, with modern data these results likely could be improved. Either way, a reasonably conservative limit is (figures 1 and 2)

$$g_{a\gamma} < 10^{-10}\ \mathrm{GeV}^{-1}. \tag{11}$$

It is comparable to the CAST limit equation (10), but applies for higher masses because the relevant temperature is about 10 keV so that significant threshold effects only begin at about $m_a \gtrsim 30$ keV. For QCD axions the coupling increases with mass so that the limit reaches to even larger masses.

In the helium-burning core, convection and semi-convection dredges helium fuel to the burning site near the core's centre so that 25–30% of all helium is burnt during the HB phase. Therefore, while the standard theoretical predictions depend on a phenomenological treatment of convection, there is limited room for additional energy supply, even if the treatment of convection were grossly incorrect.

2.4. ALP–photon conversion in astrophysical magnetic fields

Large-scale magnetic fields are ubiquitous in astrophysics so that photon–axion conversions could be of interest. In practice, the energy–momentum mismatch typically prevents this effect from being important anywhere near the 'axion line.' On the other hand, 'axion-like particles' (ALPs) with smaller masses may well exist and could then have intriguing consequences. Examples are the polarization of radio galaxies [48] and quasars [49, 50], the diffuse x-ray background [51], or ultra-high-energy cosmic rays if they have a photon component [52, 53].

One interesting cosmological consequence is the dimming of distant sources by photon–ALP conversion in intergalactic B fields [54–62], for a review see [63]. The apparent dimming of distant SNe Ia is usually attributed to accelerated cosmic expansion. All things considered, the required dimming cannot be caused by photon–ALP conversion, but this effect may still figure for a detailed interpretation of the cosmic equation of state implied by current and future SN Ia data.

Preventing excessive suppression of photon–ALP conversion in this context requires $m_a \lesssim 10^{-16}$–10^{-15} eV, i.e., the ALP mass should be smaller than the photon plasma frequency in the intergalactic medium. For such small masses, the absence of γ-rays from SN 1987A implies $g_{a\gamma} \lesssim 1 \times 10^{-11}$ GeV^{-1}, valid for $m_a \lesssim 10^{-9}$ eV [64, 65]. The ALPs would have been emitted in SN 1987A by the Primakoff effect and converted in the galactic magnetic field. A similar argument applied to the nearby red giant Betelgeuse yields a slightly less restrictive limit [66], but of course depends on fewer assumptions. ALP–photon conversion in stellar magnetic fields is also possible, notably in the magnetic fields of Sun spots [67] or the strong magnetic fields of pulsars [68, 69], although at present no new limit or positive signature is available from these considerations.

2.5. Dichroism and birefringence in laboratory magnetic fields

Magnetic fields induce vacuum birefringence in that electromagnetic radiation with polarization parallel ($\parallel$) or perpendicular ($\perp$) to B has a different refractive index induced by a one-loop QED correction to Maxwell's equations [70, 71]. This vacuum Cotton–Mouton effect has never been measured, but can be searched in the laboratory by propagating a linearly polarized laser beam in a strong B field and measure a small ellipticity that develops [72].

ALPs, axions, neutral pions, and other particles with a two-photon vertex also contribute to this effect in that the photon mixes with them in a transverse B field [24, 73]. If sufficiently light, these particles also cause vacuum dichroism, i.e., the $\parallel$ and $\perp$ polarization states are absorbed differently due to photon–ALP conversion. The observable effect is a rotation of the plane of polarization. A huge effect of this sort has been reported by the PVLAS collaboration [28], where the amplitude of the observed dichroism is roughly 10^4 times larger than the expected QED ellipticity amplitude. An instrumental origin has not been identified, but further tests and modifications of the experiment will be performed.

In PVLAS, the superconducting magnet is rotated to modulate the signal because a static dichroism or birefringence is overwhelmed by residual instrumental effects. It has been proposed that the B field rotation mixes sidebands to the primary laser frequency with a separation corresponding to the rotation frequency [74]. While such effects would in principle occur, the quantitative treatment in this paper vastly overestimates the effect; not even the use of electromagnetic units is correct. The slow magnet rotation does not cause a 10^4-fold enhancement of the QED effect.

Still, the exciting possibility that an ALP has been detected is damped by the extreme requirements on its properties [28, 75]

$$g_{a\gamma} = 2\text{–}5 \times 10^{-6}\ \text{GeV}^{-1} \qquad \text{and} \qquad m_a = 1\text{–}1.5\ \text{meV}. \tag{12}$$

With this coupling strength, the Sun's ALP luminosity would exceed its photon emission by more than a factor of 10^6 and thus could live only for 1000 years. A number of models have been proposed to circumvent this problem in that the ALP properties and interactions could strongly depend on the environment in the Sun or on energy [76–81]. It has become clear that to square the particle interpretation of PVLAS with the astrophysical limits is a tall order. Therefore, barring the identification of an instrumental effect that causes the PVLAS signature, the best hope is to test this hypothesis directly, notably in a new generation of 'shining light through walls' experiments [82–89].

3. Other astrophysical limits

3.1. Axion–electron interaction

Besides their generic interaction with photons, axions also interact with fermions Ψ by a derivative interaction of the form

$$\mathcal{L} = \frac{C}{2f_a}\bar{\Psi}\gamma_5\gamma_\mu\Psi\partial^\mu a \qquad \text{or} \qquad \mathcal{L} = -\mathrm{i}\frac{Cm}{f_a}\bar{\Psi}\gamma_5\Psi a, \tag{13}$$

where C is a model-dependent numerical factor and m the fermion mass. The pseudoscalar form is equivalent when only a single axion is attached to the fermion line in a given Feynman graph. Subtleties for axion–nucleon interactions in a nuclear medium arise because of the axion–pion mixing [90]. The pseudoscalar form suggests to quantify the interaction in terms of a dimensionless Yukawa coupling $g = Cm/f_a$ and associated 'fine structure constant' $\alpha_a = g^2/4\pi$.

In stellar plasmas, axions can be emitted by the Compton process $\gamma + \mathrm{e} \to \mathrm{e} + a$, bremsstrahlung $\mathrm{e} + Ze \to Ze + \mathrm{e} + a$, bound-free and free-bound transitions, or pair annihilation $\mathrm{e}^+ + \mathrm{e}^- \to \gamma + a$. For the Sun, $L_a = \alpha_a 6.0 \times 10^{21} L_\odot$ with 25% due to the Compton process [31]. Helioseismology conservatively implies that a new energy-loss channel cannot exceed 20% of $L_\odot$ [41], implying $\alpha_a < 3 \times 10^{-23}$. Avoiding excessive white-dwarf cooling [91] or a delay of helium ignition in globular-cluster stars [46, 47] implies $\alpha_a \gtrsim 1 \times 10^{-26}$. In the DFSZ model we have $C_e = \cos^2\beta/3$, assuming three families of fermions. For $\cos^2\beta = 1$ the exclusion range is shown in figure 2. Near the limit, axion emission can affect the cooling speed and thus the period decrease of ZZ Ceti stars (pulsating white dwarfs), although a previously measured anomalous period decrease of the star G117-B15A has disappeared in the light of more recent analyses [92].

3.2. Axion–nucleon interaction

The axion–electron interaction provides extremely restrictive limits, but in hadronic axion models this coupling does not exist at tree level. Axions are a QCD phenomenon, so their interactions with pions, nucleons and photons are far more generic than those with electrons. Unfortunately, the astrophysical arguments leading to the electron coupling cannot be trivially recycled because axions couple to the nucleon spin and thus at low energies do not interact with α particles. Therefore, processes of the sort $\gamma + \alpha \to \alpha + a$ do not occur, although they provide limits on the scalar or vector coupling of new bosons [93, 94].

However, the Sun largely consists of hydrogen so that axions are produced by the Compton-like process $\gamma + p \to p + a$. The cross section is $\sigma = (4\pi/3)\alpha\alpha_a E^2/m^4$ with m being the fermion mass, i.e., the energy loss rate caused by protons relative to electrons is suppressed by a factor $(m_e/m_p)^4 = 0.9 \times 10^{-13}$. Taking the proton density in the Sun to be $1/2$ that of electrons, using $L_a = \alpha_a 1.5 \times 10^{21} L_\odot$ for the solar axion luminosity from the electron Compton process, and observing that helioseismology allows at most a 20% exotic energy loss, we find $\alpha_a \lesssim 3 \times 10^{-9}$ for the axion–proton interaction.

Much more restrictive limits arise from the observed neutrino burst of supernova (SN) 1987A [95–104]. The burst lasted for about 10 s, in agreement with the usual picture of neutrino trapping and slow diffusive energy loss of the collapsed SN core. Excessive axion losses would have shortened the burst duration. On the other hand, if axions interact so strongly that their mfp is similar to that of neutrinos, they will not much affect the neutrino signal. The results from different numerical simulations and treatments agree reasonably well [46, 47] and lead to the 'consolidated' exclusion range shown in figure 2.

Early papers found more restrictive limits, but they overestimated the emission rate. The main process is nucleon–nucleon bremsstrahlung. Axions couple to the nucleon spin so that only spin-nonconserving interactions contribute, i.e., the nuclear tensor force. If it is modelled by one-pion exchange, the interaction rate is so large that axions emitted from different collisions would destructively interfere, leading to a suppression of the Landau–Pomeranchuk–Migdal type [102]. Later it was noted that one-pion exchange may be a poor model for the relevant conditions and the bremsstrahlung rate was calculated on the basis of measured nuclear phase shifts, leading to a much smaller emission rate [104]. However, this result applies only in the low-energy limit. Either way, the 'naive' bremsstrahlung rate used in early studies is reduced. Since the SN 1987A limits suffer from these and other nuclear-physics uncertainties, but also from the sparse experimental data, it is not easily possible to quantify an objective error estimate.

If axions interact so strongly that they are trapped more efficiently than neutrinos, still a significant flux will be emitted. It interacts with oxygen in the water Cherenkov detectors that have recorded the SN 1987A signal and could have mimicked some of the signal [105]. This argument excludes another range of axion parameters (figure 2).

4. Axions in cosmology

4.1. Thermal axions and hot dark matter

Axions are produced in the hot thermal plasma of the early universe and, since they have a mass, contribute to the cosmic dark matter. Before the QCD confinement transition at $T = \Lambda_{\rm QCD}$, the relevant processes involve quarks and gluons, e.g., the gluonic Primakoff effect caused by the axions's generic two-gluon vertex [106, 107]. After confinement, the most generic interaction process involves pions, $\pi + \pi \leftrightarrow \pi + a$ [108]. Note that thermal pions begin disappearing only at $T \lesssim 30$ MeV, long after the QCD epoch. Axions decouple after the QCD epoch if $f_a \lesssim 3 \times 10^7$ GeV, i.e., for $m_a \gtrsim 0.2$ eV.

Thermal axions provide a cosmic hot dark matter component fully analogous to neutrinos. Therefore, the usual neutrino mass limits from cosmic large-scale structure data can be adapted to the axion case [109, 110]. Relying only on the pion process for thermalization, for hadronic axions $m_a < 1.05$ eV (95% CL), although this limit probably could be somewhat improved with a more recent set of cosmological data. For comparison, we note that this limit corresponds to $\sum m_\nu < 0.65$ eV (95% CL).

Axions or axion-like particles with a two-photon vertex decay into two photons with a rate

$$\Gamma_{a\to\gamma\gamma} = \frac{g_{a\gamma}^2 m_a^3}{64\pi} = \frac{\alpha^2}{256\pi^3}\left[\left(\frac{E}{N} - \frac{2}{3}\frac{4+z}{1+z}\right)\frac{1+z}{\sqrt{z}}\right]^2 \frac{m_a^5}{m_\pi^2 f_\pi^2}$$
$$= 1.1\times 10^{-24}\ \mathrm{s}^{-1}\left(\frac{m_a}{\mathrm{eV}}\right)^5, \tag{14}$$

where the first expression is general, the second applies to axions, and the numerical one assumes $z = 0.56$ and the hadronic case $E/N = 0$. Comparing with the age of the universe of 4.3×10^{17} s reveals that axions decay on a cosmic time scale for $m_a \gtrsim 20$ eV. The decay photons would cause a variety of observable consequences [111], depending on the axion mass, so that cosmology alone entirely rules out axions with $m_a > 1$ eV (figure 2). The low-mass end is covered by the hot dark matter argument, seamlessly connecting to high masses to avoid excess radiation from axion decays [111].

Hot dark matter axions would be partially trapped in galaxies and galaxy clusters. Searching for a decay line [112, 113] provides direct limits on a range of axion masses marked 'telescope' in figure 2.

4.2. Non-thermal axions and cold dark matter

The main cosmological interest in axions derives, of course, from their possible role as the dominant cold dark matter component. Almost immediately after 'invisible' axion models had been constructed it was recognized that they can be abundantly produced by the 'misalignment mechanism' [15–17]. After the spontaneous breaking of the PQ symmetry at some high-energy scale, the axion field relaxes to a location somewhere in the Mexican hat potential. Near the QCD epoch, instanton effects explicitly break the PQ symmetry, the very effect that causes the dynamical PQ symmetry restoration. This 'tilting of the Mexican hat' causes the axion field to roll toward the CP-conserving minimum, but this motion does not stop there. Rather, coherent oscillations of the axion field are excited that ultimately represent a condensate of cold dark matter. The cosmic matter density in this homogeneous field mode is [114]

$$\Omega_a h^2 \approx 0.7\left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{7/6}\left(\frac{\Theta_\mathrm{i}}{\pi}\right)^2, \tag{15}$$

where $-\pi \leqslant \Theta_\mathrm{i} \leqslant \pi$ is the initial 'misalignment angle' relative to the CP-conserving position. If the PQ symmetry breaking takes place after inflation, Θ_i will take on different values in different patches of the universe. The approximate average contribution is [114, 115]

$$\Omega_a h^2 \approx 0.3\left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{7/6}. \tag{16}$$

Comparing with the cosmic cold dark matter density of $\Omega_\mathrm{CDM} h^2 \approx 0.13$ this implies that axions with $m_a \approx 10\ \mu$eV would provide the dark matter (figure 2).

However, this number sets only a crude scale of the expected mass for axion dark matter. Apart from the overall particle-physics uncertainties entering this result, the cosmological sequence of events crucially matters. Assuming axions make up the cold dark matter of the universe, significantly smaller masses are possible if inflation took place after the PQ transition and the initial value Θ_i was relatively small. Conversely, if the PQ transition takes place after inflation, there are additional sources for nonthermal axion production, notably the formation and decay of cosmic strings and domain walls associated with the breaking of the PQ symmetry

[18, 114]. Therefore, the mass of cosmic dark matter axions could be significantly larger than the 10 μeV scale. For a recent review of axion cosmology we refer to [114].

If axions are the dark matter of our galaxy, they are accessible to direct searches by the axion 'haloscope' technique. A microwave resonator is placed in a strong magnetic field and thus can be driven by the galactic axion field due to the two-photon coupling [19, 20]. After a series of pilot experiments, the ADMX experiment in Livermore has reached the axion line in a narrow range of masses [21]. The project will be upgraded in several stages so that it should be able to cover the range 1 μeV $\leqslant m_a \leqslant$ 100 μeV within the upcoming decade. Therefore, axion dark matter can be detected in a realistic range of parameters [116].

In the exciting event that dark matter axions are found, intriguing opportunities for observational axion cosmology open up. The fine energy resolution that is possible with a microwave resonator allows one to study the detailed axion velocity distribution that may reveal narrow peaks from the phase-space folding that occurred during galaxy formation [22, 114].

5. Summary

Axions remain a well-motivated solution of the strong CP problem. Ongoing and near-future searches for solar axions by CAST and for galactic cold dark matter axions by ADMX cover realistic parameters and thus have a chance to detect these elusive particles. If CAST were to detect solar axions, they would contribute a small hot dark matter component of the universe so that these two experimental directions are complementary. There remains a range of axion parameters, roughly corresponding to 0.1 meV $\lesssim m_a \lesssim$ 10 meV, where axions are not excluded, yet no detection strategy has been proposed. Perhaps we will not have to worry about this gap if axions show up in one of the accessible search ranges.

Unfortunately, the PVLAS signature likely has nothing to do with the strong CP problem or dark matter. The particle interpretation is in severe conflict with astrophysical arguments so that plausible theoretical models are hard to construct. However, the effect is so large that it can be tested relatively easily at several forthcoming 'shining light through walls' experiments. Even if no new particle is confirmed, a strong push is made towards measuring the QED-implied birefringence of a magnetized vacuum. Such a measurement would be an astounding achievement in itself.

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References

[1] Baker C A *et al* 2006 An improved experimental limit on the electric dipole moment of the neutron *Phys. Rev. Lett.* **97** 131801 (*Preprint* hep-ex/0602020)
[2] Peccei R D and Quinn H R 1977 CP Conservation in the presence of pseudoparticles *Phys. Rev. Lett.* **38** 1440
[3] Peccei R D and Quinn H R 1977 Constraints imposed by CP conservation in the presence of pseudoparticles *Phys. Rev.* D **16** 1791
[4] Weinberg S 1978 A new light boson? *Phys. Rev. Lett.* **40** 223
[5] Wilczek F 1978 Problem of strong P and T invariance in the presence of instantons *Phys. Rev. Lett.* **40** 279
[6] Svrcek P and Witten E 2006 Axions in string theory *J. High Energy Phys.* JHEP06(2006)051 (*Preprint* hep-th/0605206)

[7] Gasser J and Leutwyler H 1982 Quark masses *Phys. Rep.* **87** 77
[8] Leutwyler H 1996 The ratios of the light quark masses *Phys. Lett.* B **378** 313 (*Preprint* hep-ph/9602366)
[9] Yao W M *et al* (Particle Data Group) 2006 Review of particle physics *J. Phys. G: Nucl. Part. Phys.* **33** 1
[10] Kim J E 1979 Weak interaction singlet and strong CP invariance *Phys. Rev. Lett.* **43** 103
[11] Shifman M A, Vainshtein A I and Zakharov V I 1980 Can confinement ensure natural CP invariance of strong interactions? *Nucl. Phys.* B **166** 493
[12] Zhitnitsky A R 1980 On possible suppression of the axion hadron interactions *Sov. J. Nucl. Phys.* **31** 260
Zhitnitsky A R 1980 On possible suppression of the axion hadron interactions *Yad. Fiz.* **31** 497
[13] Dine M, Fischler W and Srednicki M 1981 A simple solution to the strong CP problem with a harmless axion *Phys. Lett.* B **104** 199
[14] Kim J E 1987 Light pseudoscalars, particle physics and cosmology *Phys. Rep.* **150** 1
[15] Preskill J, Wise M B and Wilczek F 1983 Cosmology of the invisible axion *Phys. Lett.* B **120** 127
[16] Abbott L F and Sikivie P 1983 A cosmological bound on the invisible axion *Phys. Lett.* B **120** 133
[17] Dine M and Fischler W 1983 The not-so-harmless axion *Phys. Lett.* B **120** 137
[18] Davis R L 1986 Cosmic axions from cosmic strings *Phys. Lett.* B **180** 225
[19] Sikivie P 1983 Experimental tests of the invisible axion *Phys. Rev. Lett.* **51** 1415
Sikivie P 1984 Experimental tests of the invisible axion *Phys. Rev. Lett.* **52** 695 (erratum)
[20] Bradley R *et al* 2003 Microwave cavity searches for dark-matter axions *Rev. Mod. Phys.* **75** 777
[21] Asztalos S J *et al* 2004 An improved RF cavity search for halo axions *Phys. Rev.* D **69** 011101 (*Preprint* astro-ph/0310042)
[22] Duffy L D *et al* 2006 A high resolution search for dark-matter axions *Phys. Rev.* D **74** 012006 (*Preprint* astro-ph/0603108)
[23] Cheng S L, Geng C Q and Ni W T 1995 Axion-photon couplings in invisible axion models *Phys. Rev.* D **52** 3132 (*Preprint* hep-ph/9506295)
[24] Raffelt G and Stodolsky L 1988 Mixing of the photon with low mass particles *Phys. Rev.* D **37** 1237
[25] Anselm A A and Uraltsev N G 1982 A second massless axion? *Phys. Lett.* B **114** 39
[26] Anselm A A and Uraltsev N G 1982 Long range 'arion' field in the radiofrequency band *Phys. Lett.* B **116** 161
[27] Zioutas K *et al* (CAST Collaboration) 2005 First results from the CERN axion solar telescope (CAST) *Phys. Rev. Lett.* **94** 121301 (*Preprint* hep-ex/0411033)
[28] Zavattini E *et al* (PVLAS Collaboration) 2006 Experimental observation of optical rotation generated in vacuum by a magnetic field *Phys. Rev. Lett.* **96** 110406 (*Preprint* hep-ex/0507107)
[29] Primakoff H 1951 Photo-production of neutral mesons in nuclear electric fields and the mean life of the neutral meson *Phys. Rev.* **81** 899
[30] Dicus D A, Kolb E W, Teplitz V L and Wagoner R V 1978 Astrophysical bounds on the masses of axions and Higgs particles *Phys. Rev.* D **18** 1829
[31] Raffelt G G 1986 Astrophysical axion bounds diminished by screening effects *Phys. Rev.* D **33** 897
[32] Altherr T, Petitgirard E and del Río Gaztelurrutia T 1994 Axion emission from red giants and white dwarfs *Astropart. Phys.* **2** 175 (*Preprint* hep-ph/9310304)
[33] Raffelt G G 1988 Plasmon decay into low mass bosons in stars *Phys. Rev.* D **37** 1356
[34] van Bibber K, McIntyre P M, Morris D E and Raffelt G G 1989 A practical laboratory detector for solar axions *Phys. Rev.* D **39** 2089
[35] Lazarus D M, Smith G C, Cameron R, Melissinos A C, Ruoso G, Semertzidis Y K and Nezrick F A 1992 A search for solar axions *Phys. Rev. Lett.* **69** 2333
[36] Moriyama S, Minowa M, Namba T, Inoue Y, Takasu Y and Yamamoto A 1998 Direct search for solar axions by using strong magnetic field and x-ray detectors *Phys. Lett.* B **434** 147 (*Preprint* hep-ex/9805026)
[37] Inoue Y, Namba T, Moriyama S, Minowa M, Takasu Y, Horiuchi T and Yamamoto A 2002 Search for sub-electronvolt solar axions using coherent conversion of axions into photons in magnetic field and gas helium *Phys. Lett.* B **536** 18 (*Preprint* astro-ph/0204388)
[38] Avignone F T *et al* (SOLAX Collaboration) 1998 Experimental search for solar axions via coherent Primakoff conversion in a germanium spectrometer *Phys. Rev. Lett.* **81** 5068 (*Preprint* astro-ph/9708008)
[39] Morales A *et al* (COSME Collaboration) 2002 Particle dark matter and solar axion searches with a small germanium detector at the Canfranc underground laboratory *Astropart. Phys.* **16** 325 (*Preprint* hep-ex/0101037)
[40] Bernabei R *et al* 2001 Search for solar axions by Primakoff effect in NaI crystals *Phys. Lett.* B **515** 6
[41] Schlattl H, Weiss A and Raffelt G 1999 Helioseismological constraint on solar axion emission *Astropart. Phys.* **10** 353 (*Preprint* hep-ph/9807476)
[42] Davoudiasl H and Huber P 2006 Detecting solar axions using earth's magnetic field *Phys. Rev. Lett.* **97** 141302 (*Preprint* hep-ph/0509293)

[43] Fairbairn M, Rashba T and Troitsky S 2006 Shining light through the Sun *Preprint* astro-ph/0610844
[44] Raffelt G G and Starkman G D 1989 Stellar energy transfer by keV mass scalars *Phys. Rev.* D **40** 942
[45] Buzzoni A, Fusi Pecci F, Buonanno R and Corsi C E 1983 Helium abundance in globular clusters: the R-method *Astron. Astrophys.* **128** 94
[46] Raffelt G G 1996 *Stars as Laboratories for Fundamental Physics* (Chicago, IL: University of Chicago Press)
[47] Raffelt G G 1999 Particle physics from stars *Ann. Rev. Nucl. Part. Sci.* **49** 163 (*Preprint* hep-ph/9903472)
[48] Harari D and Sikivie P 1992 Effects of a Nambu-Goldstone boson on the polarization of radio galaxies and the cosmic microwave background *Phys. Lett.* B **289** 67
[49] Hutsemekers D, Cabanac R, Lamy H and Sluse D 2005 Mapping extreme-scale alignments of quasar polarization vectors *Astron. Astrophys.* **441** 915 (*Preprint* astro-ph/0507274)
[50] Gnedin Y N, Piotrovich M Y and Natsvlishvili T M 2006 PVLAS experiment: some astrophysical consequences *Preprint* astro-ph/0607294
[51] Krasnikov S V 1996 New astrophysical constraints on the light pseudoscalar photon coupling *Phys. Rev. Lett.* **76** 2633
[52] Gorbunov D S, Raffelt G G and Semikoz D V 2001 Axion-like particles as ultrahigh-energy cosmic rays? *Phys. Rev.* D **64** 096005 (*Preprint* hep-ph/0103175)
[53] Csáki C, Kaloper N, Peloso M and Terning J 2003 Super-GZK photons from photon axion mixing *J. Cosmol. Astropart. Phys.* JCAP05(2003)005 (*Preprint* hep-ph/0302030)
[54] Csáki C, Kaloper N and Terning J (CKT I) 2002 Dimming supernovae without cosmic acceleration *Phys. Rev. Lett.* **88** 161302 (*Preprint* hep-ph/0111311)
[55] Csáki C, Kaloper N and Terning J (CKT II) 2002 Effects of the intergalactic plasma on supernova dimming via photon axion oscillations *Phys. Lett.* B **535** 33 (*Preprint* hep-ph/0112212)
[56] Deffayet C, Harari D, Uzan J P and Zaldarriaga M 2002 Dimming of supernovae by photon-pseudoscalar conversion and the intergalactic plasma *Phys. Rev.* D **66** 043517 (*Preprint* hep-ph/0112118)
[57] Grossman Y, Roy S and Zupan J 2002 Effects of initial axion production and photon axion oscillation on type Ia supernova dimming *Phys. Lett.* B **543** 23 (*Preprint* hep-ph/0204216)
[58] Bassett B A and Kunz M 2004 Cosmic acceleration versus axion photon mixing *Astrophys. J.* **607** 661 (*Preprint* astro-ph/0311495)
[59] Ostman L and Mörtsell E 2005 Limiting the dimming of distant type Ia supernovae *J. Cosmol. Astropart. Phys.* JCAP02(2005)005 (*Preprint* astro-ph/0410501)
[60] Csáki C, Kaloper N and Terning J 2005 Exorcising $w < -1$ *Ann. Phys.* **317** 410 (*Preprint* astro-ph/0409596)
[61] Mirizzi A, Raffelt G G and Serpico P D 2005 Photon axion conversion as a mechanism for supernova dimming: limits from CMB spectral distortion *Phys. Rev.* D **72** 023501 (*Preprint* astro-ph/0506078)
[62] Song Y S and Hu W 2006 Constraints on supernovae dimming from photon-pseudo scalar coupling *Phys. Rev.* D **73** 023003 (*Preprint* astro-ph/0508002)
[63] Mirizzi A, Raffelt G G and Serpico P D 2006 Photon axion conversion in intergalactic magnetic fields and cosmological consequences *Preprint* astro-ph/0607415
[64] Brockway J W, Carlson E D and Raffelt G G 1996 SN 1987A gamma-ray limits on the conversion of pseudoscalars *Phys. Lett.* B **383** 439 (*Preprint* astro-ph/ 9605197)
[65] Grifols J A, Massó E and Toldrǎ R 1996 Gamma rays from SN 1987A due to pseudoscalar conversion *Phys. Rev. Lett.* **77** 2372 (*Preprint* astro-ph/9606028)
[66] Carlson E D 1995 Pseudoscalar conversion and x-rays from stars *Phys. Lett.* B **344** 245
[67] Carlson E D and Tseng L S 1996 Pseudoscalar conversion and x-rays from the sun *Phys. Lett.* B **365** 193 (*Preprint* hep-ph/9507345)
[68] Dupays A, Rizzo C, Roncadelli M and Bignami G F 2005 Looking for light pseudoscalar bosons in the binary pulsar system J0737-3039 *Phys. Rev. Lett.* **95** 211302 (*Preprint* astro-ph/0510324)
[69] Lai D and Heyl J 2006 Probing axions with radiation from magnetic stars *Preprint* astro-ph/0609775
[70] Heisenberg W and Euler H 1936 Consequences of Dirac's theory of positrons *Z. Phys.* **98** 714 (*Preprint* physics/0605038)
[71] Adler S L 1971 Photon splitting and photon dispersion in a strong magnetic field *Ann. Phys., NY* **67** 599
[72] Iacopini E and Zavattini E 1979 Experimental method to detect the vacuum birefringence induced by a magnetic field *Phys. Lett.* B **85** 151
[73] Maiani L, Petronzio R and Zavattini E 1986 Effects of nearly massless, spin zero particles on light propagation in a magnetic field *Phys. Lett.* B **175** 359
[74] Mendonça J T, Dias de Deus J and Castelo Ferreira P 2006 Higher harmonics in non-linear vacuum from QED effects without low mass intermediate particles *Phys. Rev. Lett.* **97** 100403 (*Preprint* hep-ph/0606099)
[75] Cameron R *et al* 1993 Search for nearly massless, weakly coupled particles by optical techniques *Phys. Rev.* D **47** 3707

[76] Massó E and Redondo J 2005 Evading astrophysical constraints on axion-like particles *J. Cosmol. Astropart. Phys.* JCAP09(2005)015 (*Preprint* hep-ph/0504202)

[77] Massó E and Redondo J 2006 Compatibility of CAST search with axion-like interpretation of PVLAS results *Phys. Rev. Lett.* **97** 151802 (*Preprint* hep-ph/0606163)

[78] Antoniadis I, Boyarsky A and Ruchayskiy O 2006 Axion alternatives *Preprint* hep-ph/0606306

[79] Mohapatra R N and Nasri S 2006 Reconciling the CAST and PVLAS results *Preprint* hep-ph/0610068

[80] Jäckel J, Massó E, Redondo J, Ringwald A and Takahashi F 2006 The need for purely laboratory-based axion-like particle searches *Preprint* hep-ph/0610203

[81] Redondo J 2006 A model solving the PVLAS-CAST puzzle *Preprint* hep-ph/0610213

[82] Rabadan R, Ringwald A and Sigurdson K 2006 Photon regeneration from pseudoscalars at X-ray laser facilities *Phys. Rev. Lett.* **96** 110407 (*Preprint* hep-ph/0511103)

[83] Kötz U, Ringwald A and Tschentscher T 2006 Production and detection of axion-like particles at the VUV-FEL: letter of intent *Preprint* hep-ex/0606058

[84] Lindner A 2006 Search for axion-like particles at DESY: the ALPS project Talk given at *Axions at the Institute for Advanced Study (20–22 October 2006, IAS, Princeton, NJ)* (http://www.sns.ias.edu/∼axions)

[85] Cantatore G Probing the quantum vacuum with polarized light: results and outlook from the PVLAS experiment Talk given at *Axions at the Institute for Advanced Study (20–22 Oct. 2006, IAS, Princeton, NJ)* (http://www.sns.ias.edu/∼axions)

[86] Afanasev A V, Baker O K and McFarlane K W 2006 Production and detection of very light spin-zero bosons at optical frequencies *Preprint* hep-ph/0605250

[87] Afanasev A 2006 LIPSS project: a search for photon regeneration at optical frequencies Talk given at *Axions at the Institute for Advanced Study (20–22 October 2006, IAS, Princeton, NJ)* (http://www.sns.ias.edu/∼axions)

[88] Battesti R 2006 The BMV project Talk given at *Axions at the Institute for Advanced Study (20–22 October 2006, IAS, Princeton, NJ)* (http://www.sns.ias.edu/∼axions)

[89] Pugnat P 2006 Laser-based experiments in high magnetic field for QED test and axion search at CERN Talk given at *Axions at the Institute for Advanced Study (20–22 October 2006, IAS, Princeton, NJ)* http://www.sns.ias.edu/∼axions

[90] Carena M and Peccei R D 1989 The effective Lagrangian for axion emission from SN 1987A *Phys. Rev.* D **40** 652

[91] Raffelt G G 1986 Axion constraints from white dwarf cooling times *Phys. Lett.* B **166** 402

[92] Isern J and García-Berro E 2003 White dwarf stars as particle physics laboratories *Nucl. Phys. Proc. Suppl.* **114** 107

[93] Grifols J A and Massó E 1986 Constraints on finite range baryonic and leptonic forces from stellar evolution *Phys. Lett.* B **173** 237

[94] Grifols J A, Massó E and Peris S 1989 Energy loss from the Sun and red giants: bsounds on short range baryonic and leptonic forces *Mod. Phys. Lett.* A **4** 311

[95] Ellis J R and Olive K A 1987 Constraints on light particles from Supernova 1987A *Phys. Lett.* B **193** 525

[96] Raffelt G and Seckel D 1988 Bounds on exotic particle interactions from SN 1987A *Phys. Rev. Lett.* **60** 1793

[97] Turner M S 1988 Axions from SN 1987A *Phys. Rev. Lett.* **60** 1797

[98] Mayle R, Wilson J R, Ellis J R, Olive K A, Schramm D N and Steigman G 1988 Constraints on axions from SN 1987A *Phys. Lett.* B **203** 188

[99] Mayle R, Wilson J R, Ellis J R, Olive K A, Schramm D N and Steigman G 1989 Updated constraints on axions from SN 1987A *Phys. Lett.* B **219** 515

[100] Burrows A, Turner M S and Brinkmann R P 1989 Axions and SN 1987A *Phys. Rev.* D **39** 1020

[101] Burrows A, Ressell M T and Turner M S 1990 Axions and SN 1987A: axion trapping *Phys. Rev.* D **42** 3297

[102] Janka H T, Keil W, Raffelt G and Seckel D 1996 Nucleon spin fluctuations and the supernova emission of neutrinos and axions *Phys. Rev. Lett.* **76** 2621 (*Preprint* astro-ph/9507023)

[103] Keil W, Janka H T, Schramm D N, Sigl G, Turner M S and Ellis J R 1997 A fresh look at axions and SN 1987A *Phys. Rev.* D **56** 2419 (*Preprint* astro-ph/9612222)

[104] Hanhart C, Phillips D R and Reddy S 2001 Neutrino and axion emissivities of neutron stars from nucleon nucleon scattering data *Phys. Lett.* B **499** 9 (*Preprint* astro-ph/0003445)

[105] Engel J, Seckel D and Hayes A C 1990 Emission and detectability of hadronic axions from SN 1987A *Phys. Rev. Lett.* **65** 960

[106] Turner M S 1987 Thermal production of not so invisible axions in the early universe *Phys. Rev. Lett.* **59** 2489
Turner M S 1988 Thermal production of not so invisible axions in the early universe *Phys. Rev. Lett.* **60** 1101

[107] Massó E, Rota F and Zsembinszki G 2002 On axion thermalization in the early universe *Phys. Rev.* D **66** 023004 (*Preprint* hep-ph/0203221)

[108] Chang S and Choi K 1993 Hadronic axion window and the big bang nucleosynthesis *Phys. Lett.* B **316** 51 (*Preprint* hep-ph/9306216)

[109] Hannestad S and Raffelt G 2004 Cosmological mass limits on neutrinos, axions, and other light particles *J. Cosmol. Astropart. Phys.* JCAP04(2004)008 (*Preprint* hep-ph/0312154)

[110] Hannestad S, Mirizzi A and Raffelt G 2004 New cosmological mass limit on thermal relic axions *J. Cosmol. Astropart. Phys.* JCAP07(2004)002 (*Preprint* hep-ph/0504059)

[111] Masso E and Toldra R 1997 New constraints on a light spinless particle coupled to photons *Phys. Rev.* D **55** 7967 (*Preprint* hep-ph/9702275)

[112] Bershady M A, Ressell M T and Turner M S 1991 Telescope search for multi-eV axions *Phys. Rev. Lett.* **66** 1398

[113] Ressell M T 1991 Limits to the radiative decay of the axion *Phys. Rev.* D **44** 3001

[114] Sikivie P 2006 Axion cosmology *Preprint* astro-ph/0610440

[115] Turner M S 1986 Cosmic and local mass density of invisible axions *Phys. Rev.* D **33** 889

[116] van Bibber K Microwave cavity searches for dark-matter axions Talk given at *Axions at the Institute for Advanced Study (20–22 Oct. 2006, IAS, Princeton, NJ)* http://www.sns.ias.edu/∼axions