Journey at the axion meV mass frontier

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Abstract. The cooling speed of white dwarfs suggests a possible new energy-loss channel, consistent with axions if their Yukawa coupling to electrons is 10^{-13} corresponding to a mass of a few meV. In this case axions provide less than 0.1% of the cosmic cold dark matter, whereas core-collapse supernovae release a large fraction of their energy in the form of axions. These axions would be extremely challenging to detect, but may be accessible to the next generation axion helioscope.

1. The strong CP problem and axions

The theory of quantum chromodynamics has an infinite number of possible vacuum states, which generally violate the discrete symmetries of parity (P) and time reversal (T). They are specified by the theta angle, θ, which appears in the Lagrangian multiplying the topological charge operator involving the gluonic field strength $G^a_{\mu\nu}$

$$\mathcal{L}_a \ni \theta \frac{\alpha_s}{8\pi} \epsilon^{\alpha\beta\mu\nu} G^a_{\alpha\beta} G^a_{\mu\nu}, \tag{1}$$

which violates P and T. If θ is nonzero this term generates electric dipole moments (EDMs) for hadrons, most importantly for neutrons, of typical nucleonic size, $d_n \sim \theta \times$e fm. The current attempts to measure the neutron EDM have failed, setting a breathtaking upper limit on the value of theta, $\theta \lesssim 10^{-10}$. Why nature chose such a tiny value? This is the *strong CP problem.*

The QCD vacuum energy density depends on the temperature. At high temperatures, it does not depend on theta and therefore whatever set the initial conditions of the big bang could not have had any preference for any vacuum. At temperatures below the QCD scale, Λ, instantons contribute to the energy density as $E(\theta) \sim \Lambda^4 \sin^2\theta$ and the P, T conserving vacuum ($\theta = 0$) is favored, which with hindsight suggests a solution.

The solution proposed by R. Peccei and H. Quinn and shipshaped by S. Weinberg and F. Wilczek is to replace theta —a mere phase— by a field, the axion (a) as $\theta \to a/f_a$. This introduces a new energy scale f_a, the axion decay constant. Since the axion is dynamical, it can roll down the instantonic potential and set its v.e.v. to zero even if initially it was different [1, 2]. This solves the strong CP problem and has a very interesting consequence: the energy stored in the small oscillations of the axion field around this minimum behave as a cold dark matter fluid!

The defining property of an axion model is the coupling (1) with $\theta \to a/f_a$. This appears by construction in supergravity, string theory, or if the axion is the Nambu-Goldstone boson of an color-anomalous axial global symmetry (Peccei-Quinn symmetry). This coupling mixes the axion with the η' and, through it, with the rest of neutral strangeless pseudoscalar mesons proving the axion with:

- mass (actually one can think of the axion as Weinberg's $\mathrm{U}(1)_A$ meson)

$$m_a \sim m_\pi f_\pi / f_a \sim 6 \text{ meV } (10^9\,\text{GeV}/f_a) \tag{2}$$

- model-independent couplings to hadrons (or quarks), h, and a two photon coupling

$$\mathcal{L}_a \ni \sum_h C_h \frac{\partial_\mu a}{2 f_a} \bar{h} \gamma^\mu \gamma^5 h + C_{a\gamma} \frac{a}{4 f_a} \frac{\alpha}{2\pi} F_{\mu\nu} \widetilde{F}^{\mu\nu} \tag{3}$$

where $C's$ are $\mathcal{O}(1)$ numbers. This minimal axion model is called hadronic (or KSVZ after its proposers). In a broad class of models (such as in grand unified theories or in the original axion proposal) the Peccei-Quinn symmetry involves also leptons and consequently the axion gets couplings to them as well (with structure equivalent to the coupling with hadrons), see [2]. Very often the following notation for the couplings is used: $g_{ah} = C_h m_h / f_a$ and $g_{a\gamma} = \alpha C_{a\gamma} / 2\pi f_a$.

2. The search for axions

The phenomenology of the axion is determined by the unknown value of f_a, which can strongly suppress the axion interactions. There are three frontlines in the quest of finding the axion, laboratory experiments, cosmology and stellar evolution. Purely laboratory searches in which axions would be produced in the lab (rare decays, beam dump and nuclear reactor experiments) exclude axion masses roughly above the keV, where axion couplings are not too tiny. The most relevant experimental searches nowadays search for much weakly interacting axions which are not produced efficiently in laboratories. These are the so-called axion haloscopes [3], which aim at detecting axion dark matter in the galactic halo, and helioscopes [3] which aim at detecting axions emitted by the Sun. We will discuss the later further on, since they are the most relevant for axion masses at the meV frontier.

A variety of cosmological arguments excludes the range 1 eV to 300 keV, because the thermal population of axions created during the big bang modifies the cosmic microwave background or the output of big bang nucleosynthesis [4]. Thermal axions, if cosmologically stable, are *hot* dark matter and, if unstable, produce some late entropy injection. The previously mentioned coherent axion oscillations around their v.e.v. give *cold* dark matter, which would overclose the universe for $f_a > 10^{11}$ GeV [6] allowing a (model-dependent) lower limit of $\sim \mu$eV for the axion mass. The ADMX experiment [7] is currently looking for dark matter axions in this ballpark and a number of new experiments have been recently proposed or are currently underway to broaden the sensitivity in mass [9].

Axions in the remaining window are very light and extremely weakly interacting and as such, are prone to affect stellar evolution [8]. Weakly interacting particles are scarcely produced in stellar interiors but have great chances of leaving the star unimpeded. This drains energy very efficiently from stellar cores accelerating nuclear power consumption and the cooling of stars. By comparing observations with numerical simulations of stellar evolution one can obtain strong bounds on any exotic energy loss channel, such as those provided by axions. The constraints are usually not very precise, roughly requiring exotic stellar energy losses (per unit time) to be smaller than the standard luminosity emitted by the star (photon surface luminosity or the luminosity in neutrinos emitted from the cores).

The most relevant cases studied so far are: globular cluster (GC) stars (red giants and horizontal-branch stars), white dwarfs, supernova 1987A, neutron stars and the Sun. Altogether they are able to exclude axions with masses $\gtrsim 10$ meV, which corresponds to huge values of $f_a \lesssim 10^9$GeV [8].

As by today, the only hope to discover meV-mass axions is detecting the solar axion emission by means of an helioscope [3]. Axions entering into a homogeneous macroscopic magnetic field can coherently convert into photons of the same energy by means of their two-photon coupling. Helioscopes utilize long and strong magnetic fields, tracking the Sun during long periods to detect the corresponding photons from axion conversion, whose typical energies are in the X-ray range which corresponds to the temperature of the solar core.

The CERN solar axion telescope (CAST) is the most powerful of such helioscopes ever built [10]. Its primary goal was to test hadronic axions in the sub eV range which are only disfavored by the SN1987A and neutron star cooling arguments —the most unreliable of the axion bounds due to the lack of data and the uncertain calculation of the axion emission from a nuclear medium. A next generation axion helioscope covering all the way to the 10 meV frontier has recently proven to be feasible [11]. The main improvement with respect to CAST shall come from the use of a dedicated magnet with an aperture of several m^2 (CAST uses a decommissioned LHC magnet with 30 cm^2!). However, the most ambitious goals can only be achieved if a considerable effort is devoted to increase also the length of the magnet, the X-ray focusing capabilities and the detector background rejection. An international collaboration is starting to be formed to further develop designing criteria for such a machine, recently baptized as the International AXion Observatory (IAXO) [12].

3. The meV frontier

Besides the possibility of detecting solar axions, the meV frontier of axion physics encompasses a number of very interesting phenomenological consequences [13].

In the early 1990s it became possible to test the cooling speed of pulsating white dwarves (WD), ZZ Ceti stars, by their measured period decrease. The star G117-B15A was cooling too fast, an effect that could be attributed to axion losses if the axion-electron coupling was $g_{ae} \sim 2 \times 10^{-13}$ [14]. In past years, observations and theory have improved and the G117-B15A cooling speed still favors a new energy-loss channel [15]. The number of WDs per unit luminosity as a function of luminosity (luminosity function, LF) is also a tracer of WD cooling [16]. A recent reexamination of the WDLF including new catalogues and theoretical improvements confirms the previous axion bounds but also points out that a certain amount of exotic cooling can help fitting the data, even if this preference is not very significant [17]. The authors suggest that axion bremsstrahlung in electron collisions with nuclei (C,O) can successfully fit the needs. In this case, axions would play a role at intermediate temperatures between the initial neutrino-cooling phase and the final surface-cooling phase. The required Yukawa coupling is $g_{ae} \sim (0.6 \div 1.7) \times 10^{-13}$.

Axion cooling of supernovae (SN) has been widely discussed in the context of SN1987A. The 10 s observed duration of the neutrino burst supports the current picture of core collapse and cooling by quasi-thermal neutrino emission from the neutrino sphere. Axion cooling from the core can be much more effective, thus shortening the neutrino pulse and reducing its intensity. The SN1987A neutrino burst duration precludes a dominant role for axions but the bound on f_a is quite uncertain due to the model-dependent axion-nucleon couplings, the uncertain emission rate from a dense nuclear medium, and the sparse data. The WD and SN1987A constraints are accidentally very similar, meaning that axions with WD inspired parameters will have some effect in similar supernovae. Given the uncertainties this does not preclude the WD interpretation, but a SN would lose a significant fraction of its energy in the form of axions.

Axions saturating the SN1987A limit are emitted as copiously as neutrinos from SN cores [13]. In this situation one not only expects a strong axion burst from each SN, but also a large cosmic diffuse background flux from all past SNe, the diffuse SN axion background (DSAB) in analogy to the diffuse SN neutrino background (DSNB). All past SNe in the universe provide a local electron antineutrino flux of order 10 cm^{-2} s^{-1} detectable in a future Gd-enriched version of SuperK or a future large scintillator detector with a rate of a few events per year. The present-day average core-collapse rate is $R_{cc} \sim 10^{-4}/\mathrm{Mpc}^3\mathrm{yr}$, which grows as 10^z until redshift $z = 1$ then flattening or slightly decreasing. Assuming that every SN releases 3×10^{53} erg in the form of neutrinos of all flavors and integrating over R_{cc}, leads to a present-day DSNB of 26 meV cm^3, almost identical with the extragalactic background light (EBL). For meV-mass axions, therefore, the energy density of the DSAB can be comparable to the DSNB and the EBL, and indeed would be *the most important axion population in the universe.*

Detecting these axions is extremely challenging (they would interact much more weakly than neutrinos of comparable energy!). The DSNB will be detectable in Super-Kamiokande and in next generation large-scale detectors, but the DSAB produces a much smaller signal. Photons from axion conversion in astrophysical magnetic fields may provide a detectable signal if exceeding the diffuse gamma-ray background in the 30 MeV region ($\sim 10^6/\mathrm{cm}^2\mathrm{s\,sr}$ MeV), which requires an axion-photon conversion probability $P_{a\to\gamma} \sim 10^{-4}$. After a distance l in a transverse magnetic field of strength B, we have

$$P_{a\to\gamma} = (g_{a\gamma}B/q)^2 \sin^2(ql/2)\,, \tag{4}$$

where q is the momentum transfer. For $m_a = 7$ meV, the oscillation length $\pi/q \simeq 2\pi E/m_a^2$ is 1500 km for an axion energy $E = 30$ MeV. For these parameters, $P_{a\to\gamma} \sim 10^{-21}$ $(\mathrm{B/Gauss})^2$ is too small any realistic astrophysical magnetic field to play a role.

Axion-like particles (ALPs) [18], in contrast, might have much smaller mass for the same coupling $g_{a\gamma}$ so that large conversions and astrophysical signatures are conceivable. In particular, they might be responsible for the WD cooling anomaly, but of course they do not solve the strong CP problem.

The next galactic SN will provide a high-statistics signal of 10 MeV range neutrinos. What about the comparable energy release in 100 MeV axions? The largest conceivable SN signal is in a future megaton detector and if the red supergiant Betelgeuse at a distance of 200 pc collapses. Unfortunately, even this scenario provides at most a few events $a + p \to N + \pi$ at the highest energies. Intriguingly, in this case IAXO could also conceivably observe a very few events if can be pointed to the core collapse in time. This will be possible through the detection of the pre-collapse phase through the detection of Si neutrinos. This scenario requires a much more careful study, since the background due to neutrino events will be large, albeit predominantly at lower energies. Nevertheless, these measurements can be very important in the case of a positive signal from the IAXO search for solar axions.

4. Conclusions

Axions remain one of the most appealing solutions of the strong CP problem. The intriguing hints from white dwarf cooling, corresponding to $f_a \sim 10^9$GeV and masses of few meV have very interesting consequences. Axions would be a subdominant part of dark matter but all past supernovae would have produced an extremely elusive diffuse axion background of 30 MeV axions, which constitutes in this case the most relevant axion population of the universe. At present there are no clear ideas how to detect it. However, axions with these parameters might be discoverable in the next generation axion helioscope, IAXO. Such an instrument could also play a role in detecting the axion burst from the next galactic supernova.

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