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The meV mass frontier in axion physics

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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. We estimate the diffuse supernova axion background (DSAB) from all past supernovae, consisting of 30~MeV-range axions with a radiation density comparable to the extra-galactic background light. The DSAB would be extremely challenging to detect, but axions with white-dwarf inspired parameters may be accessible in a next or next-to-next generation axion helioscope.

The strong CP problem

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 so-called theta angle, which appears in the Lagrangian as

$$\mathcal{L}_\theta = \theta \frac{\alpha_s}{4\pi} \mathrm{Tr}\{G_{\mu\nu}\widetilde{G}^{\mu\nu}\}$$

This term strongly violates P and T and would generate electric dipole moments (EDMs) for hadrons, most importantly for neutrons, of typical nucleonic size

$$d_n \sim \theta \times \mathrm{e\,fm} \qquad .$$

The current attenpts to measure the neutron EDM have failed, setting a breathtaking upper limit on the value of theta, which in principle ranges $\{-\pi, \pi\}$

$$\theta \lesssim 10^{-10} \qquad \text{(!!!)}.$$

why nature chosed such a small value???? this is known as the ***strong CP problem***.

The QCD vacuum energy density actually 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 of the vacua. At low temperatures (below the QCD scale, L) QCD instantons contribute to the energy density

$$E(\theta) \sim L^4 \sin^2\theta$$

and the P and T conserving vacuum, $\theta = 0$ is favored. Note that transitions from one vacuum to another are forbiddden,

$$\langle \theta_1 | \theta_2 \rangle = 0$$

but with hindsight, this observations suggest a solution.

Axions

The solution proposed by R. Peccei and H. Quinn and shipshaped by S. Weinberg and F. Wilczek is to replace theta -which is just a mere phase- by a field, the axion, a

$$\theta \to \frac{a}{f_a}$$

which forces us to introduce a new energy f_a, known as the axion decay constant. Since the axion is dynamical, it can roll down the potential created after the QCD phase transition in the big bang and set its v.e.v. to zero even if initially was different.

This idea ***solves the strong CP problem*** and has a very interesting consequence: the oscillations of the axion field around his minimum after the set in of the QCD instantonic potential behave as a ***cold dark matter*** fluid! However, in this poster we shall not comment on this possibility further.

Axion properties- The defining property of an axion model is to couple to the pseudoscalar gluon density

$$\mathcal{L}_a \ni \frac{a}{f_a}\frac{\alpha_s}{4\pi} \mathrm{Tr}\{G_{\mu\nu}\widetilde{G}^{\mu\nu}\}$$

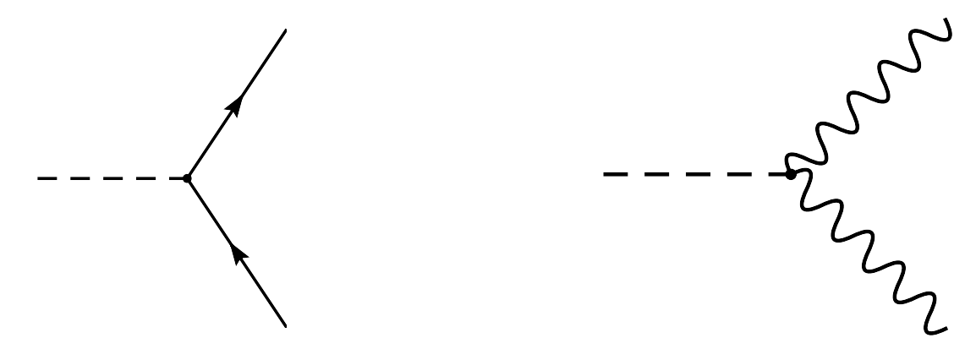
which appears by construction in string theory, or if the axion is the Nambu-Goldstone boson of an axial global symmetry which is color anomalous (normally called Peccei-Quinn symmetry).

At the low energies the axion mixes with the only other known example of NGB of a color anomalous symmetry (the $U(1)_A$ of light quarks) the would-be eta prime meson. Through this mixing, the axion overlaps with all the neutral strangeless pseudoscalar mesons and gets

- mass (one can think as the Weinberg´s $U(1)_A$ meson!)

$$m_a \sim \frac{m_\pi f_\pi}{f_a} \sim 6\ \mathrm{meV}\ \frac{10^9\ \mathrm{GeV}}{f_a},$$

- model-independent couplings to hadrons and a two photon anomalous coupling (C´s of O(1))



$$\frac{C_f}{2f_a}\bar{\Psi}_f\gamma^\mu\gamma_5\Psi_f\,\partial_\mu a \qquad \frac{C_{a\gamma}}{4f_a}\frac{\alpha}{2\pi}F_{\mu\nu}\tilde{F}^{\mu\nu}\,a$$

This minimal axion model receives the name KSVZ or is simply referred as hadronic model.

In a broad clase of models (such as in grand unified theories or in the origial axion proposal) the Peccei-Quinn symmetry involves also leptons and the axion consequently gets couplings to leptons, in particular to electrons. The structure is equivalent to the coupling with hadrons.

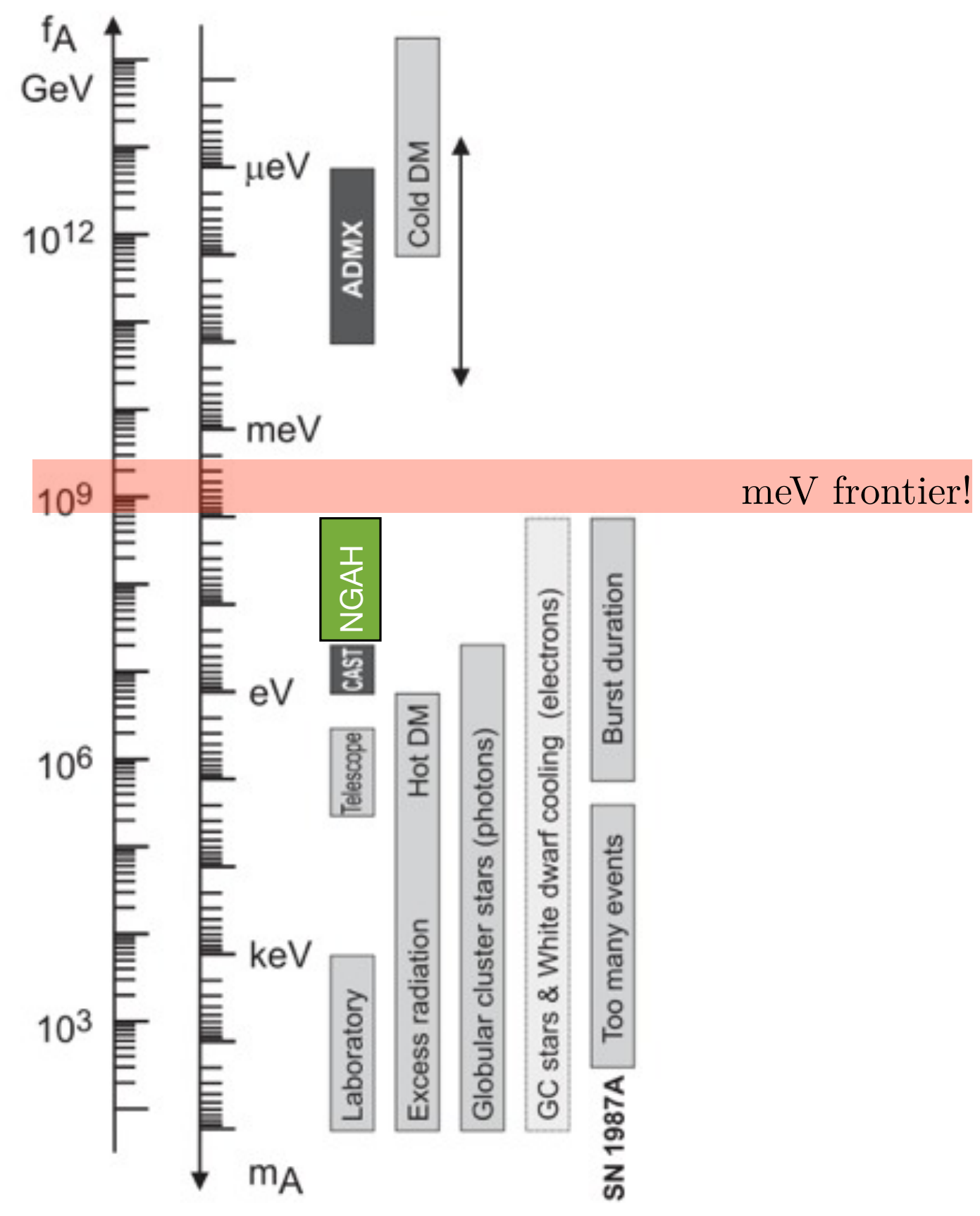
Sometimes the following notation for the coupligns is used:

$$g_{af} = \frac{C_f m_f}{f_a}\ ;\ g_{a\gamma} = \frac{C_{a\gamma}}{f_a}\frac{\alpha}{2\pi}$$

The search for axions

The axion phenomenology is essentially determined by the value of its decay constant, which can suppress very much the axion interactions with standard matter and radiation and partially seclude the axion.

There are three broad frontlines in the quest of finding the axion, laboratory searches, cosmology and stellar evolution. A schematic summary of the status of axion searches is as follows



Laboratory searches (beam dump and nuclear reactor experiments) excluded axion masses above the keV. A variety of cosmological arguments excludes the range 1 eV to 300 keV, because the thermal population of axions that would be created during the big bang would modify the cosmic microwave background CMB or the output of big bang nucleosynthesis BBN (thermal axions, if cosmologically stable are ***hot dark matter*** and if unstable they produce some late entropy injection). The ***cold dark matter*** window reffers to the previously mentioned axion oscillations around their v.e.v. and interestingly grows with f_a allowing an upper limit, which however is somehow model dependent.

The most stringent constraints come from stellar evolution. If axions are weakly interacting only a few of them will be produced in stellar interiors but these will have full chances of leaving the star unimpedded. This can drain energy very efficiently from stellar cores accelerating the cooling of stars. By comparring detailed numerical simulations of stellar evolution with observations we can constrain any exotic energy loss channel, such as provided by axions.

The constraints are usually not very precise, and correspond roughly with requiring that any exotic stellar energy loss (per unit time) should be smaller than the standard luminosity emitted by the star, i.e. the photon surface luminosity and the inner neutrino luminosity

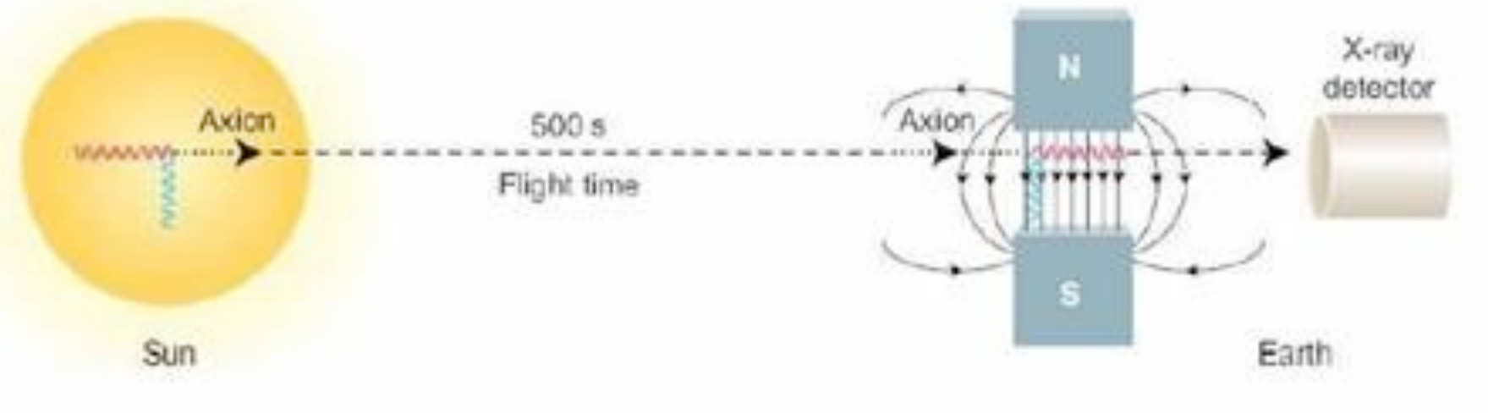
$$\left.\frac{dE}{dt}\right|_{\rm exotic} \lesssim \left.\frac{dE}{dt}\right|_{{\rm standard}=\gamma+\bar{\nu}+\nu}$$

The most relevant cases are: Globular cluster ***(GC)*** stars (Red Giants and Horizontal Branch stars), ***White dwarfs***, ***Supernova1987A***, Neutron stars and the Sun. Altogether they are able to exclude axions with masses > 10 meV, which corresponds to huge values of $f_a < 10^9$ GeV.

Axions models in the edge of the exclusion are therefore extremely light and very weakly interacting.

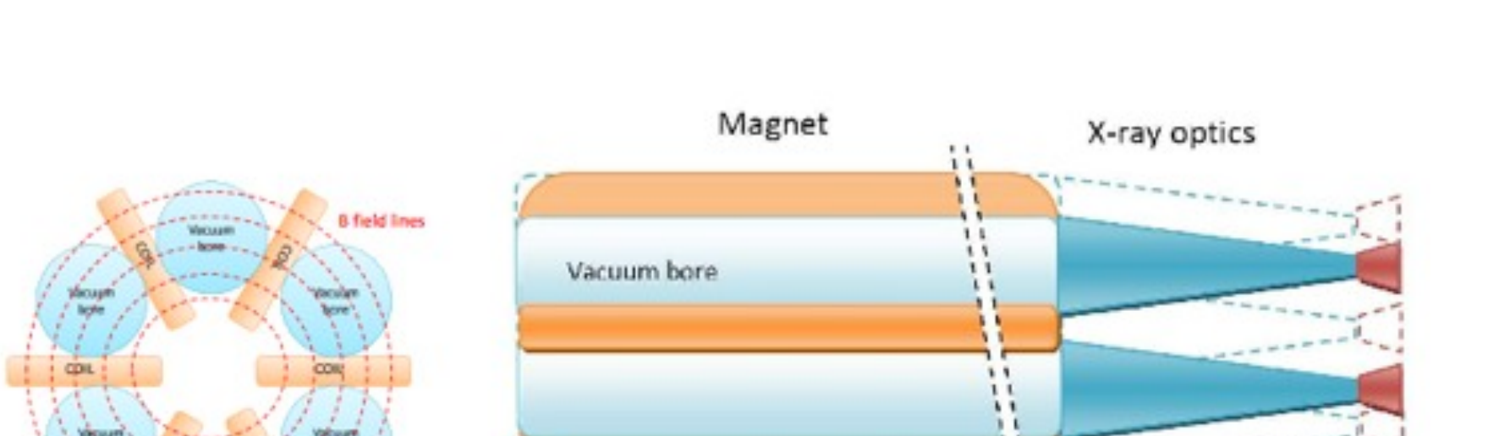
Axions from the Sun- The only idea so far to search for axions in the 10 meV range in a laboratory experiment is through a major revision of the concept of an helioscope experiment.

The idea of an helioscope is to exploit the two photon coupling to detect the putative flux of solar axions on earth. Axions entering into a homogeneous macroscopic magnetic field can coherently convert into photons of the same energy (a phenomenon that can be describe as oscillations), which is the typical solar interior temperature O(keV), corresponding to X-rays.



The CERN solar axion telescope CAST is the most powerful of such helioscopes ever built. It´s primary goal was to test hadronic axions in the sub eV range which are only disfavored by the SN1987A and neutron star cooling arguments which are the most uncertain of the axion bounds due to the lack of data and the extremely complicated calculation of the axion emission from a nuclear medium.

A next generation axion helioscope (***NGAH***) covering all the way to the 10 meV frontier has recently proven to be feasible. 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 decomissioned LHC magnet with 30 cm^2!).



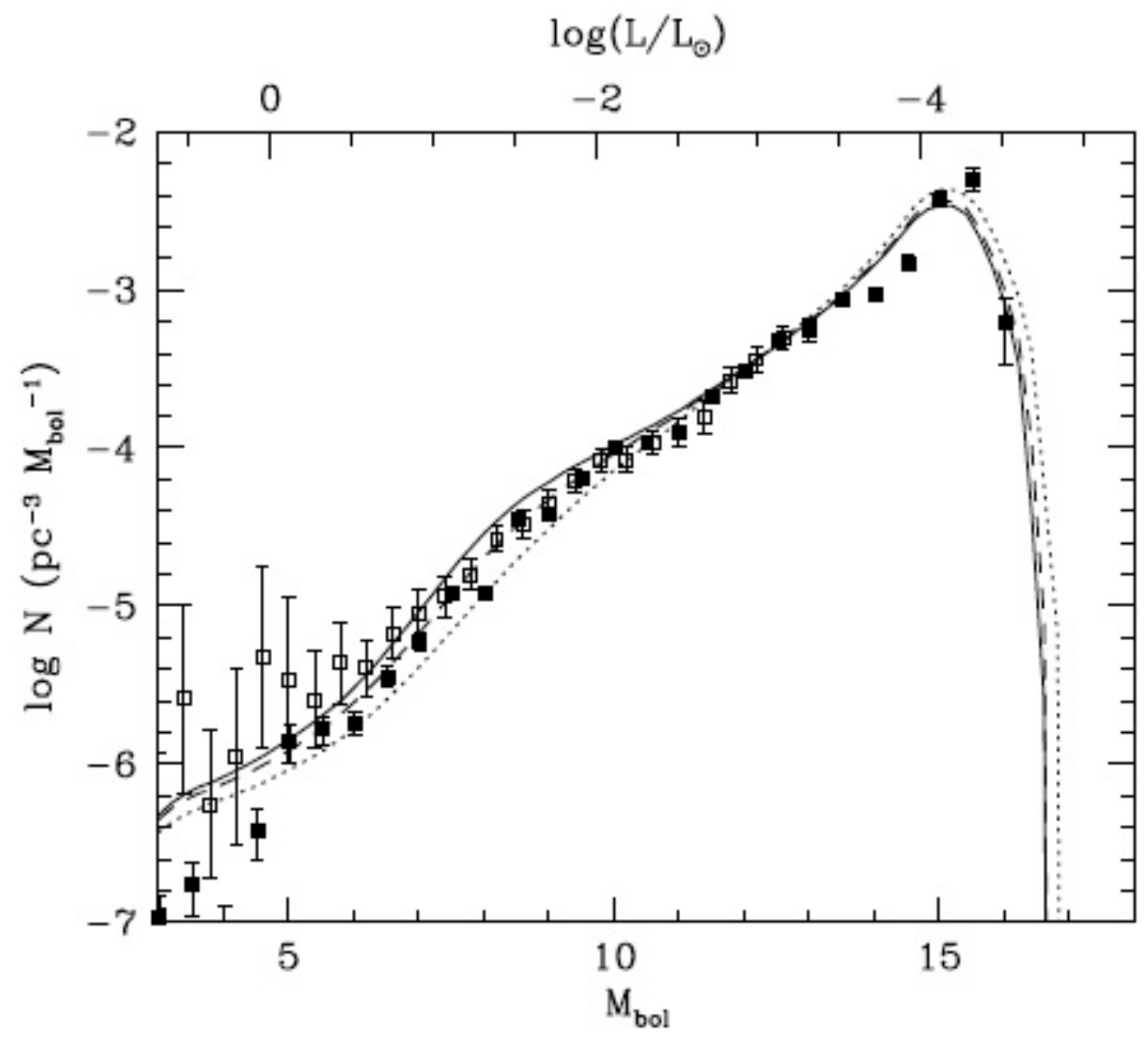
The meV frontier

Apart from the direct search of solar axions, the meV frontier of axion physics encompasses a number of very interesting phenomenological consequences.

White dwarves: hinting for the axion?

The number of white dwarves per unit luminosity, as a function of their luminosity (called luminosity function LF) is a standard tracer of the cooling speed of white dwarves. Axions contribute to the WD cooling more efficiently at intermediate temperatures (between the phases of neutrino cooling from the interior -initial hot phase- and the surface photon cooling -final cold phase-)

A recent reexamination of the WDLF including new catalogues and improvements in WD cooling theory confiirms the previous conservative bounds but also points out that a certain amount of exotic cooling can help fitting the data, even if this preference is not a very significant one.



The authors have only interpreted this luminosity as being caused by axion bremstrahlung in electron collisions with the most abundant nuclei in WD´s, C and O. The corresponding Yukawa coupling would then be

$$g_{ae} = 0.6 - 1.7 \times 10^{-13}$$

which of course lies slightly below the WD exclusion bound.

In the early 1990s it became possible to test the cooling speed of pulsating WDs, the class of ZZ Ceti stars, by their measured period decrease dP/Pdt. In particular, the star G117-B15A was cooling too fast, an effect that could be attributed to axion losses if g_{ae} was around 2×10^{-13} [11]. Over the past twenty years, observations and theory have improved and the G117-B15A cooling speed still favors a new energy-loss channel [12].

While complete confidence in this intriguing interpretation is certainly premature (perhaps even in the need for a novel WD cooling itself), the required axion parameters are very specific, motivating us to explore other consequences based on the WD benchmark.

WD vs. SN1987a arguments

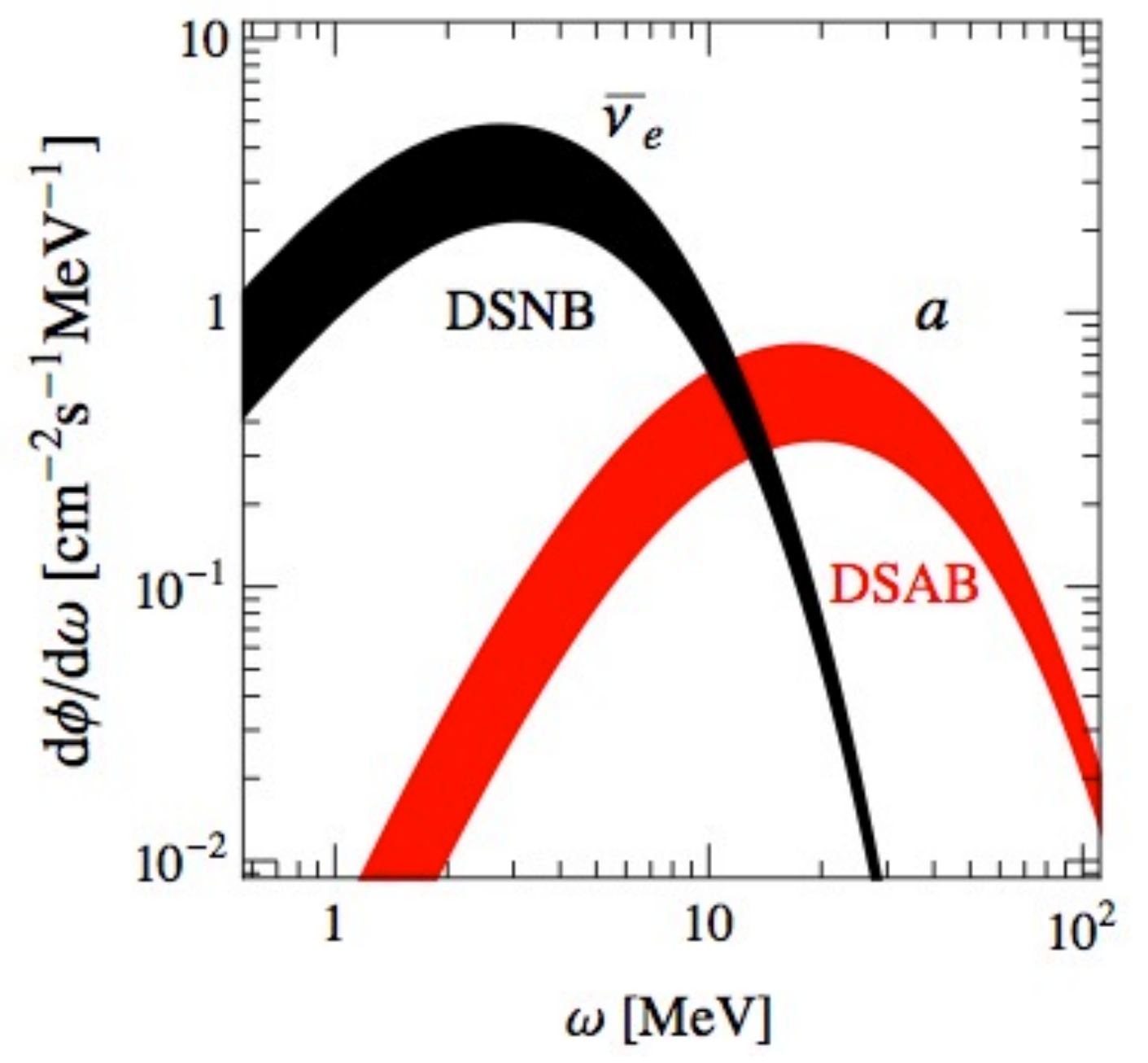
The WD and SN1987a constraints are accidentally very similar. This means that axions with WD inspired parameters will have some kind of effect in similar supernovas. If the bounds would be under perfect control, then could say that the impact on SNs should be only slight, since so it is the impact on WDs. However, the SN1987a argument is very far from being under perfect control and the impact on SNs from the WD inspired axions can be quite significant.

Axion cooling of SNe has been widely discussed in the context of SN 1987A. The 10 s duration of the neutrino burst supports the current picture of core collapse and cooling by quasi-thermal neutrino emission from the neutrino sphere. New particles that are more weakly interacting than neutrinos, such as the axions discussed here, can be produced in the inner SN core and leave it freely in contrast to neutrinos, which can escape only by diffusion because of the extreme density. The cooling can be done much more effective thus sortening the neutrino pulse and reducing its intensity. The SN 1987A neutrino burst duration precludes a dominant role for axions. Quantitatively, this argument depends on the model-dependent axion-nucleon couplings, the uncertain emission rate from a dense nuclear medium, and on sparse data. Giving the uncertainties this does not preclude the WD interpretation, but a SN would might lose a significant fraction of its energy in the form of axions.

The Diffuse SN axion background

Axions saturating the SN 1987A limit are emitted as copiously as neutrinos from SN cores. 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} that will become detectable in a 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 Rcc = 1.25×10^{-4} Mpc^{-3} yr^{-1} and increases with redshift proportional to 10^z until z = 1 and then flattens or slightly decreases . Assuming that every SN releases 3×10^{53} erg in the form of neutrinos of all flavors and integrating over Rcc, properly redshifting the energy, leads to a present-day DSNB of 26 meV cm^{-3}, almost identical with the 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***.



Our estimation of the DSAB is shown in the above plot assuming 1/2 of the energy of the core-collapse is emitted in axions. For comparison we show the standard electron antineutrino DSNB.

Detecting the DSAB?

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.

One may think that conversion in large-scale astrophysical magnetic fields may provide a detectable signal. It should exceed the diffuse gamma-ray background in the 30 MeV region as measured by EGRET (10^{-6} cm^{-2} s^{-1} sr^{-1} MeV^{-1}). The conversion probability would have to be of order 10^{-4}.

In a transverse B field and after travelling a distance l, the axion-photon oscillation probability is

$$P = \left(\frac{g_{a\gamma}B}{q}\right)^2 \sin^2\frac{ql}{2}$$

where q is the momentum transfer. For $m_a = 7$ meV we can neglect the photon plasma mass in interstellar space. The oscillation length π/q is 1500 km for E = 30 MeV. For these parameters, the maximum $P = 6 \times 10^{-22}$ (B/Gauss)^2, too small for any realistic astrophysical B-field configuration.

Axion-like particles (ALPs), in contrast, might have much smaller mass for the same coupling strenghts so that large conversions and astrophysical signatures are conceivable!

Of course, they don´t solve the strong CP problem ...

Next galactic SN

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. This scenario provides about 3×10^8 $\bar{\nu}_e$ inverse beta events but at most a few axion-induced events ($a+p \to N+\pi$) at the high energy tail.

Intriguingly, in this case the next generation helioscope 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 NGAH searching for solar axions.

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 has very interesting consequences. All past Supernove would have produced an extremely elusive diffuse axion background of 30 MeV axions, which constitutes the most relevant axion population of the universe. At present there are no ideas how to detect it. However, axions with these parameters might be discoverable in a next generation axion helioscope. Such an instrument could also play a role in detecting the axion burst from the next galactic SN.

Further Reading

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