

Particle dark matter: An overview

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Abstract. I discuss some compelling suggestions about particles which could be the dark matter in the Universe, with special attention to experimental searches for them.

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This is the write-up of a talk given at a conference where I was probably the only particle physicist. My task was to give an overview of one area of cosmology which has a symbiotic relation with particle physics — viz., the candidates for dark matter.

I could proceed in two ways. One is to give very brief outlines of all different suggestions (or all I know about) for dark matter candidate particles. The second is to focus on a few compelling ones, and give some details of them. After some thought, I chose the second path. I will divide this talk into three sections, by three different kinds of particles which are potential candidates for dark matter.

1. Light neutrinos

Neutrinos interact very feebly, only through weak interactions. Despite this fact, they were in thermal equilibrium in the very early Universe because the density of particles was much higher at that time, and so the mean free path (or the average reaction time) was small. At that stage, their number density differed from that of the photons only because one is a fermion and the other is a boson, and the relation was

$$n_\nu = \frac{3}{4}n_\gamma. \quad (1)$$

This age of thermal equilibrium ended once the density of the particles became small enough in an expanding Universe, and it happened when the temperature was about 1 MeV. After that, the neutrinos followed only the overall expansion. The photon number density also fell by the cube of the scale factor, so the ratio remained the same. The only exception to this statement occurred when the temperature dropped somewhat below the electron mass, and e^+e^- annihilations produced new photons. This event increased the photon number density by a factor of 11/4, so that in the present Universe

$$(n_\nu)_0 = \frac{3}{4} \frac{4}{11} (n_\gamma)_0 \approx 110 \text{ cm}^{-3}. \quad (2)$$

If the neutrinos are massive, the energy density is obtained by multiplying this by the mass. The total energy density of the Universe is parametrized by $10^4 h^2 \Omega \text{ eV/cm}^3$, where h is the Hubble parameter in units of $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Thus, the fraction of energy density contributed by light neutrinos would be

$$F_\nu = \frac{m_\nu n_\nu}{10^4 h^2 \Omega \text{ eV/cm}^3} = \left(\frac{m_\nu}{92 \text{ eV}} \right) \cdot \frac{1}{h^2 \Omega}. \quad (3)$$

Atmospheric neutrino data indicate neutrino masses of order 10^{-1} eV . Solar neutrino data indicate even smaller masses. Although these do not apply for all neutrino species, it surely is suggestive of the fact that $F_\nu \ll 1$.

Before discarding light neutrinos as dark matter candidates on this ground, I would like to emphasize that there is a very strong assumption implicit in this entire argument, viz. that the neutrinos have no chemical potential so that their number is the same as that of the antineutrinos. If chemical potential is nonzero, the number density of neutrinos depend on it as well as the temperature, and one cannot even start with the simple relation of eq. (1).

If the neutrinos have chemical potential, they can contribute a larger fraction to the energy density of the Universe. This issue has been analyzed recently [1]. We show the results in figure 1. The horizontal axis corresponds to neutrino mass. The vertical axis is $n_\nu - n_{\bar{\nu}}$ in units of the CMBR n_γ in the present Universe. The lines in this plot correspond to the values $h^2 \Omega F_\nu = 1/8, 1/4$ and $1/2$ respectively, starting from the inner line.

2. Axions

So far we talked about light neutrinos. They are known to exist. The other candidates to be discussed have not yet been detected in any experiment. Thus, I need some motivation for talking about them.

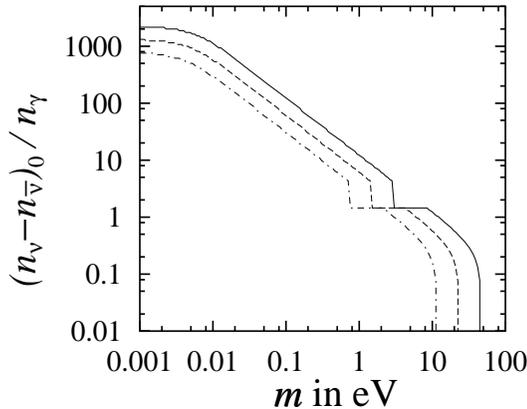


Figure 1. Neutrino mass and degeneracy allowed by cosmological energy density bounds. The curves are contours for $h^2 \Omega F_\nu = 1/8, 1/4$ and $1/2$ respectively. From ref. [1].

For the case at hand, the motivation comes from strong interactions. These interactions are believed to be described by the gauge theory called QCD. In a gauge theory, one decides on some symmetry of the Lagrangian and writes down all terms that are consistent with this symmetry. For strong interactions, this symmetry was found in the 1970s. If one cares to do only perturbative calculations with the Lagrangian obtained from this symmetry, there is no problem. If, however, one includes non-perturbative effects, one encounters one term which violates parity and time-reversal symmetries:

$$\mathcal{L}_{\text{QCD}} = \mathcal{L}_{\text{pert}} + \frac{\theta g^2}{32\pi^2} G_{\mu\nu} \tilde{G}_{\mu\nu}, \quad (4)$$

where $G_{\mu\nu}$ is the generalization of the electromagnetic field-strength tensor for the relevant symmetry. Here g is the gauge coupling constant, and θ is an arbitrary parameter.

The term involving this parameter is the generalization of a term $\vec{E} \cdot \vec{B}$, which violates parity and time-reversal symmetries. Among other things, this term will give rise to an electric dipole moment for the neutron. The experimental bounds are very strong on this, which restricts this parameter severely: $\theta < 10^{-10}$.

Very small parameters always present certain conceptual difficulties in quantum field theories. If they are not zero, one has to justify them by some symmetry. Peccei and Quinn discovered such a symmetry by introducing a Higgs field $\hat{a}(x)$ which has an interaction

$$- \frac{g^2}{32\pi^2} \frac{\hat{a}(x)}{f_{\text{PQ}}} G_{\mu\nu} \tilde{G}_{\mu\nu}, \quad (5)$$

where f_{PQ} has the dimensions of mass. The field, of course, has other interactions, including a potential of its own, which is minimum at $\hat{a} = \theta f_{\text{PQ}}$. In general, now, we can write $\hat{a}(x) = \theta f_{\text{PQ}} + a(x)$. This field $a(x)$ vanishes at the minimum and is qualified to be a quantum field. It is called the *axion field*.

Notice how it has solved our original problem. If we add the terms shown in eqs (4) and (5) and use the definition of the quantum field, we see that the parameter θ cancels out. Said another way, θ is forced to equal to zero by this procedure. We have an interaction of the axion obtained by replacing \hat{a} by a in eq. (5), but that does not violate parity and time reversal provided the axion is intrinsically negative under these symmetries.

We now examine how the axion can be important as the dark matter. The equation of motion of the axion field, neglecting its interactions, is

$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0, \quad (6)$$

assuming the field to be spatially homogeneous. This is similar to the Klein–Gordon equation, but there are two differences. One of them is the second term on the left side, which shows the effects of the expansion of the Universe. The other is hidden in the notation, and is the fact that the ‘mass’ m_a appearing in the equation is not a constant. It arises due to co-operative effects, and depends on the temperature.

At early times, when the temperature was very high, m_a was zero. This is because all non-perturbative effects involve a factor $\exp(-1/g^2)$, which is negligible since at high energies g is very small for QCD. In this stage, the solution of eq. (6) is given by $a = \text{constant}$. As the Universe cools down, g increases, and becomes large enough to make the non-perturbative effects important when the temperature drops down sufficiently, say

below a value T_{QCD} . To find the solution after this time, let us first forget about H and also the time-dependence of m_a . In that case, the solution would be

$$a = A \cos m_a t, \quad (7)$$

where A is a constant. If $H \ll m_a$ and also the time variation of m_a is small, we can still try a solution like this, where now both A and m_a should be regarded as functions of time. Substituting the solution in eq. (6), we now obtain

$$\frac{d}{dt}(m_a A^2) = -3H m_a A^2, \quad (8)$$

or

$$m_a A^2 R^3 = \text{constant}, \quad (9)$$

where R is the scale factor of the Universe, i.e., $H = \dot{R}/R$. The energy density in these oscillations, at the present time, would be given by

$$\rho_0 = \frac{1}{2} (m_a^2 A^2)_0. \quad (10)$$

The axion mass in the present Universe is determined by f_{PQ} . It depends mildly on the axion models, and is given by

$$(m_a)_0 f_{\text{PQ}} \simeq m_\pi f_\pi, \quad (11)$$

where the quantities on the right sides relate to properties of the pions, and are very well-known. However, we don't know the magnitude of the oscillations in the present Universe. Therefore, we use eq. (9) to write

$$\rho_0 = \frac{1}{2} (m_a)_0 (m_a A^2)_T \times (R^3/R_0^3), \quad (12)$$

where R is the value of the scale factor at any arbitrary temperature T . The oscillations started, as we said, around $T \simeq T_{\text{QCD}} \simeq 100$ MeV. At that time, $m_a \simeq H \simeq T^2/M_P$, and $A \simeq f_{\text{PQ}}$. Using these estimates and utilizing the fact that $R/R_0 = T_0/T$, we obtain

$$\rho_0 \simeq \frac{1}{2} \frac{m_\pi f_\pi}{f_{\text{PQ}}} \cdot \left(\frac{T_{\text{QCD}}^2 f_{\text{PQ}}^2}{M_P} \right) \cdot \left(\frac{T_0}{T_{\text{QCD}}} \right)^3, \quad (13)$$

which gives

$$\Omega_a \simeq 10^{-12} \frac{f_{\text{PQ}}}{1 \text{ GeV}}. \quad (14)$$

Thus, axions can be an important source of dark matter if f_{PQ} is close to 10^{12} GeV.

Let us now see what is experimentally known about these axions. In figure 2, we show the present status [2]. The horizontal axis is the axion mass. The vertical axis denotes its coupling with two photons, which allows the decay mode $a \rightarrow \gamma\gamma$. As I said earlier, there

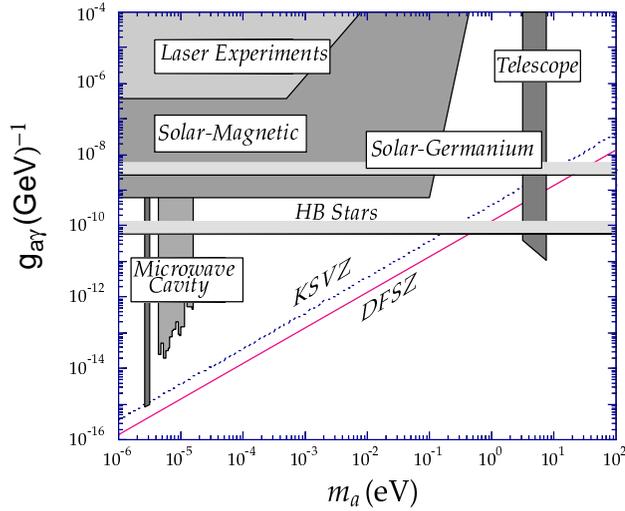


Figure 2. Summary of axion search results. The shaded regions are excluded. Taken from ref. [2]. Some of the legends have been slightly edited to conform with the notations used in this paper.

is slight model dependence in these quantities. The predictions of two compelling models are shown in the graph by the lines marked DFSZ and KSVZ.

If the axion mass is in the eV range, the decay photons could be detected through telescopes, and the failure to do so has been indicated in the figure. However, if f_{PQ} indeed equals 10^{12} GeV and we take eq. (11) as a strict equality, the axion mass comes out to be 10^{-5} eV. So, if the axions has to contribute significantly to the energy density of the Universe, we should find them around that value of mass. In this case, the two photon decay mode is so slow that the axion can be considered stable on cosmological time scales. However, because of the coupling, the axions may be resonantly converted into a microwave signal in a cavity where a strong magnetic field is present. These experiments are very promising. As we see, they are already probing very close to the interesting region.

3. WIMPs

We now come to the WIMPs, which is an acronym for “Weakly Interaction Massive Particles.” There are a variety of ways in which such particles may be motivated. The most recent and most compelling of them is supersymmetry. Supersymmetric models have new particles — bosonic partners of known fermions and fermionic partners of known bosons. There are phenomenologically strong reasons to suspect that these new particles, or “superpartners”, can be produced or annihilated only in pairs. If that is true, the lightest of these superpartners will be a stable particle. It will not decay spontaneously. These can be examples of WIMPs. There are other models also which predict WIMPs.

The number density of these WIMPs in the early Universe is governed by the Boltzmann equation. In the homogeneous and isotropic Universe, this takes the form

$$\frac{dn}{dt} = -3Hn - \sigma v(n^2 - n_{\text{eq}}^2), \tag{15}$$

where n_{eq} is the equilibrium number density for the temperature at any given time. The decrease of number density due to the expansion of the Universe is represented in the first term in this equation, and the same due to pair annihilations goes in the second term.

It is convenient to switch to dimensionless variables defined by

$$y = \frac{n}{s}, \quad x = m/T, \tag{16}$$

where m is the mass of the WIMP and s is the entropy of the background photons at a temperature T . The evolution equation now becomes

$$\frac{dy}{dx} = -\frac{y_{\text{eq}}}{x} \frac{\Gamma_{\text{ann}}}{H(x)} \left[\left(\frac{y}{y_{\text{eq}}} \right)^2 - 1 \right], \tag{17}$$

where $\Gamma_{\text{ann}} = n_{\text{eq}}\sigma v \sim m^3 x^{-3/2} e^{-x} \sigma v$, putting in the equilibrium number density for a non-relativistic particle. The important thing to notice here is that y hardly changes if $\Gamma_{\text{ann}} \ll H(x)$ at any given era characterized by a temperature determined by x . Using $H(x) \sim T^2/M_P = m^2/M_P x^2$, we find

$$\frac{\Gamma_{\text{ann}}}{H(x)} \sim m M_P x^{1/2} e^{-x} \sigma v. \tag{18}$$

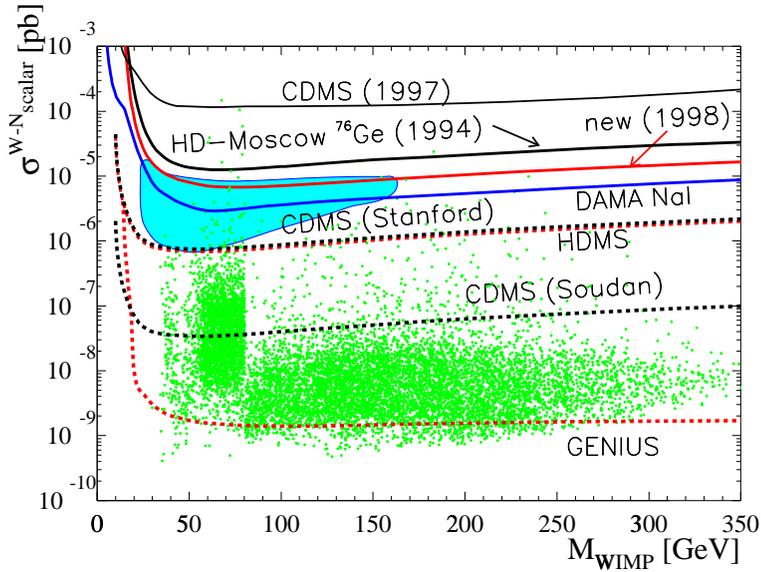


Figure 3. Summary of WIMP search results and future prospects. From ref. [3].

As $x \rightarrow \infty$, i.e., for large time, this ratio goes to zero. It means that after a while, the pair annihilation rate will be negligible, because the Universe has meanwhile become large enough so that the particles do not find each other. The remnant density of the WIMPs can be obtained by numerical integration of eq. (17), but a rough estimate can be obtained by the density at the era when $\Gamma_{\text{ann}} = H(x)$. The solution of x eq. (18) is now determined once the mass and the annihilation cross-section are known. After this era, the number density just scales inversely as the volume of the Universe.

Let me now turn to the experimental searches [4]. These are summarized in figure 3. As I just said, the parameters which determine the density of WIMPs in the present Universe are the mass and the annihilation cross-section. The two axes in this plot are precisely these two parameters. For the cross-section, only the cross-section with the nucleons is probed in the experiments. The solid lines are exclusions plots from already published data, and the dotted lines are projections for future experiments. The scatter plots are expected values of the parameters for various choices of the basic parameters in the supersymmetric model. It does seem that the experiments in the near future will be able to decide whether WIMPs really dominate the energy density of the Universe.

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