Shadow dark matter, sterile neutrinos and neutrino events at IceCube

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Abstract

The excess of high energy neutrinos observed by the IceCube collaboration might originate from baryon number violating decays of heavy shadow baryons from dark mirror sector which produce shadow neutrinos. These sterile neutrino species then oscillate into ordinary neutrinos transferring to them specific features of their spectrum. In particular, this scenario can explain the end of the spectrum above 2 PeV or so and the presence of the energy gap between 400 TeV and 1 PeV.

Recently the IceCube Collaboration published the data on high-energy neutrinos collected between 2010 and 2013, containing 35 candidate events in the energy range from 30 TeV to 2 PeV, which show an evident excess over the expected background of the events with \( E > 60 - 100 \) TeV or so \([1]\). On the other hand, no events were observed in the gap between 400 TeV and 1 PeV while three most energetic shower events emerged at the end of the spectrum with energies between 1-2 PeV where the atmospheric background is practically vanishing. The spectrum is apparently cut off at energies larger than about 2 PeV. The gap in the energy spectrum is difficult to explain in known models of high-energy neutrinos of astrophysical origin.

Here we present a model \([2]\) that may explain such a spectrum. It is based on the idea that dark matter of the universe emerges from a parallel gauge sector, with particles and interactions sharing many similarities with ordinary particle sector. Such a shadow sector would contain particles like quarks which form composite baryons, as well as leptons and neutrinos which are all sterile for ordinary gauge interactions. Particularly interesting example is represented by so-called mirror world \([3]\), which has the particle and interaction content exactly identical to that of ordinary sector, with the same gauge and Yukawa coupling constants.

Taking into consideration also attractive possibilities for physics beyond the Standard Model related to supersymmetric (SUSY) grand unified theory (GUT), one can consider that at higher energies our physics is presented by SUSY GUT, e.g. \( SU(5) \) or \( SU(6) \) which breaks down to the Standard Model \( SU(3) \times SU(2) \times U(1) \) at the scale \( M_G \approx 2 \times 10^{16} \) GeV. Supersymmetry breaking at \( M_{SB} \approx 1 \) TeV triggers the electroweak symmetry breaking and the Higgs field gets the vacuum expectation value (VEV) \( v = 174 \) GeV. In this view, we assume that at higher energies also mirror sectors is presented by the identical SUSY GUTs, \( SU(5)' \) or \( SU(6)' \), which breaks down to its standard subgroup \( SU(3)' \times SU(2)' \times U(1)' \) at the same scale \( M_G' \approx 2 \times 10^{16} \) GeV. However, following refs. \([4, 5]\), we assume that the symmetry between two sectors is broken later so that the electroweak symmetry breaking scale \( v' \) in mirror sector is much larger than ordinary electroweak scale. Namely, if \( v' \approx 10^{11} \) GeV, the lightest shadow baryons have masses order few PeV, and they decay due to baryon violating GUT gauge bosons, with decay time comparable to the age of the Universe, producing energetic shadow neutrinos which then oscillate into active neutrinos (with oscillation probabilities \( \sim 10^{-9} \) or so) transferring their spectrum to the latter. \( ^{1}\) It is worth to note that the decaying dark matter model, with a fraction of dark matter of about 10 per cent decaying before of present epoch could reconcile the Planck collaboration results

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\(^{1}\) For other type of decaying dark matter model see e.g. Ref. \([6]\).
on the CMB measurements with low redshift astrophysical measurements [9].

In other words, we consider a supersymmetric grand unification theory $SU(5) \times SU(5)'$ or $SU(6) \times SU(6)'$. As discussed in ref. [2], our proposal can be more nicely realized in SUSY $SU(6)$ theory [7] which gives natural solution to the so called hierarchy and doublet-triplet splitting problems via the Goldstone boson mechanism, relating the electroweak symmetry breaking scale to the supersymmetry breaking scale $M_{SB}$, and in addition naturally explains the fermion mass spectrum. In both sectors the GUT symmetries are broken at the scale $M_G \approx 2 \times 10^{16}$ GeV. Below this scale our sector is represented by the minimal SUSY Standard Model (MSSM) $SU(3) \times SU(2) \times U(1)$ with chiral superfields of quarks $q_i = (u, d, l)$ and leptons $l_i = (\nu, e)$, $e_i^\dagger$ ($i = 1, 2, 3$ is family index) and two Higgs superfields $h$ and $\tilde{h}$, described by the Yukawa superpotential $W = Y_{ij}q_i^\dagger e^\dagger_j h + Y_{ij}d_i^\dagger d^\dagger_j \tilde{h} + Y_{ij}l_i^\dagger l^\dagger_j h$. Supersymmetry is then broken at the scale $M_{SB} \sim 1$ TeV inducing also the electroweak symmetry breaking.

As for parallel mirror sector, below the scale $M_G \approx 2 \times 10^{16}$ GeV we have supersymmetric $SU(3)' \times SU(2)' \times U(1)'$ theory with the similar particle content, quarks $q_i' = (u', d', l')$, $e_i', e_i'^\dagger$, leptons $l_i' = (\nu', e')$, $e_i'^\dagger$, and two Higgs superfields $h'$ and $\tilde{h}'$. At the scale $M_G$ mirror gauge coupling constants $g_i^{3,1,1}$ are equal to the ordinary gauge constants $g_i^{3,2,1}$, and coupling constants in the Yukawa superpotential $W' = Y_{ij}'q_i'^\dagger e^\dagger_j' h' + Y_{ij}'d_i'^\dagger d^\dagger_j' \tilde{h}' + Y_{ij}'l_i'^\dagger l^\dagger_j' h'$ have exactly the same pattern as in $W$. We assume, however, that in mirror sector supersymmetry and electroweak symmetry are both broken at the scale of about $10^{11}$ GeV.

Hence, below GUT scale, the gauge coupling constants $g_i^{3,2,1}$ and $g_i^{3,2,1}$ evolve down in energies in both sectors in the same way up to scales of about $10^{11}$ GeV where the supersymmetry is spontaneously broken in mirror sector (see Fig. 1). However, below this scale ordinary sector still remains supersymmetric and constants evolve down by the renormalization group (RG) equations as in the MSSM, down to scale $M_{SB} \sim 1$ TeV where supersymmetry is effectively broken. After that the Higgses $h$ and $\tilde{h}$ are not protected anymore by the supersymmetry and they get VEVs $v_1 = v \cos \beta$, $v_2 = v \sin \beta$, $v = 174$ GeV, which induce the electroweak symmetry breaking and generate the fermion masses. The masses of lightest fermions, $m_e \approx 0.5$ MeV, $m_d \approx 3$ MeV and $m_\nu \approx 5$ MeV respectively for electron, up-quark and down quark, are related to smallness of the Yukawa constants of the first generation. At the QCD scale $\alpha \approx 200$ MeV gauge interactions of $SU(3)$ become strong and confine the quarks into baryons, with lightest ones being proton and neutron with masses of about 1 GeV and spin 1/2.

Let us consider now parallel mirror sector where supersymmetry is broken at the scale $M_{SB} \sim 10^{11}$ GeV, supposedly due to non-zero $F$ or $D$ terms of some auxiliary fields. Hence shadow scalars, including squarks and sleptons as well as the gauginos and the Higgs doublets $h'$ and $\tilde{h}'$ all acquire soft masses order $M_{SB}$. Respectively shadow Higgses can get VEVs $v'_1 = v' \cos \beta'$ and $v'_2 = v' \sin \beta'$, which break mirror electroweak symmetry at the scale $v' \leq M_{SB}'$. Therefore, the masses of shadow fermions are rescaled, modulo renormalization factors order 1, by a factor $\xi = v'/v$ with respect to ordinary fermion masses. Namely, taking $v' / v = 10^9$ and assuming $\tan \beta' = \tan \beta$, by the RG running of gauge and Yukawa constants from the GUT scale down in energies, one obtains for the masses of lightest mirror fermions $M_E \approx 4$ PeV, $M_D \approx 1.1$ PeV and $M_\nu \approx 1.9$ PeV, where capital letters $E$, $D$, $U$ denote respectively the shadow electron $e'$, down quark $d'$ and up quark $u'$. (Notice, that in mirror sector up-quark becomes heavier that in down-quark due to the difference in the RG running of the Yukawa constants [2].) One the other hand, the RG evolution of the $SU(3)'$ gauge constant $g'_5$ shows that the shadow QCD scale becomes $\Lambda' \sim 100$ TeV (c.f. $\Lambda \approx 200$ MeV in ordinary QCD), as it is shown on Fig. 1. Therefore, $M_U, M_D \gg \Lambda'$ and the shadow QCD looks like a rescaled version of our QCD but without light quarks, containing only the heavy quarks like $c$ and $b$. In fact, $M_U$ and $M_D$ are larger than $\Lambda'$ by about the same factor as the ordinary beauty and charm quark masses, $m_b$ and $m_c$, are larger with respect to ordinary QCD scale $\Lambda$.

\[ \text{Figure 1: RG running of gauge couplings below the GUT scale in ordinary and shadow sectors, } \alpha_i = g_i^2 / 4\pi \text{ and } \alpha'_i = g_i'^2 / 4\pi. \]

\[ \text{Interestingly, if supersymmetry breaking is transferred to our sector via gravity or other Planck scale mediators, this would nicely explain ordinary soft masses order } M_{SB} = M_{SB}' / M_{\text{Planck}} \sim 1 \text{ TeV.} \]
As far as in shadow sector up quark $U$ is heavier than down quark $D$, the lightest shadow baryon should be shadow $\Delta^-$ baryon of spin 3/2, consisting of three down quarks $D$ and having mass $M_{\Delta} \approx 3M_D = 3.3$ PeV. All states, containing up quark $U$, will be unstable against weak decays, $U \to D\bar{E}\nu'$. As for mesons, the lightest pseudoscalar is shadow neutral pion $\pi^0$ consisting of $D\bar{D}$, with mass $M_0 \approx 2M_D = 2.2$ PeV, while the lightest vector meson $\rho^0(D\bar{D})$ is slightly heavier than $\pi^0$. (Another neutral pion consisting of $U\bar{U}$ becomes much heavier, with mass of about 3.8 PeV.) Charged Pion $\pi^\pm$ as well as $\rho^\pm$-meson consisting of $D\bar{D}$ will have mass $M \approx M_U + M_D = 3$ PeV, with $\rho^\pm$ a bit heavier than $\pi^-$. All pseudoscalar and vector mesons have excited states with mass gap order $\Delta'$ between the levels, just like $c\bar{c}$ or $b\bar{b}$ states in our QCD.

Now we come to the role of baryon violation and proton decay which is fundamental prediction of the GUTs. The heavy gauge bosons of $SU(5)$ with baryon violating couplings between quarks and leptons induce the decay of the lightest ordinary baryons (proton, or neutron bound in nuclei), with lifetime $\tau_p \sim M_0^4(\alpha_G^2/m_p^2)^{-1} \sim 10^{31}$ Gyr or so, where $\alpha_G$ is gauge coupling constant at the GUT scale $M_G \sim 2 \times 10^{16}$ GeV [8]. In the shadow sector, the similar couplings of GUT gauge bosons should destabilize the shadow $\Delta$ baryon. However, taking into account that the latter is much heavier than the ordinary proton, $M_\Delta/m_p \sim 10^{6}$, its lifetime must be about 30 orders of magnitude smaller than the proton lifetime. Hence we get $\tau_\Delta \sim M_0^4(\alpha_G^2/m_\Delta^2)^{-1} \sim 100$ Gyr or so, comparable to the age of the Universe $t_U = 14$ Gyr.

The principal decay mode of $\Delta$ baryon is in vector mesons, $\Delta^- \to \rho^-_u + \nu'_{\mu}$, where generically $\nu'_{\mu}$ is a superposition of shadow neutrino flavor eigenstates $\nu'_{\mu \nu}$. Each decay produces monoenergetic neutrinos $\nu'_{\mu \nu}$ with energies $E_\nu = \frac{1}{3}M_\Delta(1 - M_0^2/M_\Delta^2)$, where $M_0$ is the mass of $\rho^0_\mu$-meson and $M_\Delta/2$ are the masses of its excitations. In Fig. 2(a) the spectrum of neutrinos produced by decay of galactic dark matter is shown by sharp peaks (solid blue) for $M_0$, $M_1$, $M_2$ respectively being 3.0, 3.1 and 3.2 PeV. Due to close degeneracy between the masses of $\Delta$-baryon and $\rho^0_\mu$ mesons, the neutrino energies are $E_\nu \ll 1$ PeV while the most of initial energy $= M_\Delta$ is taken away by vector mesons $\rho^0_\mu$.

However, vector mesons readily decay into mirror pion and photon, $\rho^0_\mu \to \pi^- + \nu'$, and subsequent decay of the pion produces the neutrino once again (solid red curves in Fig. 2(a)). Shadow $\pi^-$ has two decay modes, two body $\pi^- \to e^-\nu'$ and three body $\pi^- \to \pi^0 e^-\bar{\nu}'_e$, where $\pi^0_j$, $j = 0, 1, \ldots$ are the basic shadow pion and its excited states. Interestingly, the 2-body and 3-body branching ratios are comparable. This fact is intimately related to the value $\lambda' \sim 100$ TeV [2]. Two body decay produces neutrinos with a narrow energy spectrum concentrated around $M_\Delta/2 \approx 1.6$ PeV, while the three body decay, due to smaller phase space, produces less energetic neutrinos with a wide spectrum extending up to the value $E_{\text{max}} = M_\Delta - M_0 - M_\pi \approx M_U - M_D - M_\pi \approx 0.4$ PeV.

Fig. 2(a) shows the final spectrum of shadow neutrinos $\nu'_e$ and $\nu'_{\mu}$, including the neutrinos produced by the decay of dark matter in the galactic halo, and extragalactic neutrinos produced by the decay of cosmological dark matter at large redshifts. For definiteness, in Fig. 2(a) we assume that dark matter entirely consists of shadow baryons $\Delta$, i.e. the fraction $f_{\Delta} = 1$, and take the decay time $\tau_\Delta$ as 10 times the Universe
age, $\tau_\Delta = 10 t_L$. The fraction of extragalactic neutrinos strongly depends on the decay time $\tau_\Delta$, it increases with $\tau_\Delta$ decreasing. In correspondence, the energy gap becomes less pronounced and at $\tau_\Delta < 0.1 t_L$ or so it practically disappears since cosmological contribution from high redshifts become dominant. In this case dark matter cannot be entirely from mirror sector, the later can constitute only a smaller fraction and other type of stable dark matter should be also invoked\textsuperscript{3}.

The shadow neutrinos may have mixing with ordinary ones \textsuperscript{4}. We assume that operators mixing $\nu_{\alpha\mu\tau}$ and $\nu'_{\alpha\mu\tau}$ states respect a conservation of a combined lepton number $\mathcal{L} = L - L'$ \textsuperscript{10}, and that all operators for neutrino masses are suppressed by the Planck scale $M_{Pl}$ \textsuperscript{5}. Hence, for neutrino masses and mixing we consider the following operators (family indices are suppressed):

\[
\frac{A\chi}{M_{Pl}} \ll hh + \frac{A\bar{\chi}}{M_{Pl}} \ell' h' h' + \frac{D}{M_{Pl}} \ell' h h'.
\]

where $\chi$ and $\bar{\chi}$ are gauge singlet chiral superfields with lepton numbers $\mathcal{L} = -2$ and 2 respectively, with VEVs $\langle \chi \rangle = \langle \bar{\chi} \rangle = \mu$ breaking the lepton number. Alternatively, $\chi$ and $\bar{\chi}$ can be promoted as flavon sextet and anto-sextet fields of the flavor symmetry $SU(3)_F$ \textsuperscript{11} between three families assuming that it is a common gauge symmetry between two sectors \textsuperscript{12}. This would give an certain guideline for obtaining predictive patterns for active and sterile neutrino masses and mixing.

Here the first two terms give the Majorana masses respectively to ordinary neutrinos $\nu_{\alpha\mu\tau}$ and their shadow (sterile) partners $\nu'_{\alpha\mu\tau}$, while third term induces the mixing (Dirac) terms between active and shadow neutrinos. Then total 6x6 mass matrix of $\nu$ and $\nu'$ states reads \textsuperscript{13}:

\[
M_\nu = \begin{pmatrix}
m_\nu & m_{\nu'} \\
m_{\nu'} & m_{\nu''}
\end{pmatrix} = \frac{\nu^2}{M} \begin{pmatrix}
A \Lambda & D \zeta \\
D^T \zeta & A \Lambda \zeta^2
\end{pmatrix}
\]

where $\zeta = \nu'/\nu$ and $\Lambda = \mu/M_{Pl}$. Therefore, taking e.g. $\lambda \sim 10^{-5}$ and constants $A, D \sim 10^{-2}$, we see that shadow neutrinos acquire masses $\sim 10$ keV and active sterile mixing angles are $\sim 10^{-4}$.

Fig. 2(b) shows how the spectrum of shadow neutrinos shown on Fig. 2(a) and transferred to ordinary neutrinos via active-sterile mixings will be seen by the IceCube. Here the effective areas for the neutrino detection by IceCube \textsuperscript{11} and characteristic error bars in estimation of neutrino energies (of about 13\%) are taken into account. The obtained spectrum of events indeed look very much like the spectrum observed by the IceCube \textsuperscript{11}.

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