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Right-handed neutrinos as superheavy dark matter

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Abstract: We propose that right-handed neutrinos are very long-lived dark matter. The long lifetime is realized by the separation of the wavefunction of right-handed neutrinos and that of other fermions in an extra dimension. Such long-lived and superheavy dark matter can naturally explain observed ultra high energy cosmic rays above the GZK cutoff (5×10^{19}eV) and huge amounts of cold dark matter simultaneously. Furthermore, the exponentially suppressed Yukawa couplings of right-handed neutrinos leads to the high predictablilty on the mass parameter of the neutrinoless double beta decay, as all the models which predict very small neutrino mass of one generation.

Keywords: Dark Matter, High Energy Cosmic Rays, Neutrino Physics.

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Contents

1. Introduction

One of the long-standing mysteries in modern cosmology is the nature of dark matter. The energy density of dark matter should be about 30 % of that of the universe, but baryons and observed astrophysical objects can constitute only a few percent of the energy. Therefore physics beyond standard model is needed to explain huge amounts of dark matter. They may be supersymmetric particles, topological defects or composite objects.

Another mystery of cosmology is the existence of ultra high energy cosmic rays (UHECR). Cosmic rays above the GZK cutoff [1] (5×10^{19}eV) cannot be explained by usual acceleration mechanisms.

These mysteries can be explained simultaneously by introducing long-lived superheavy dark matter X [2]–[5]. Its lifetime is longer than the age of the universe, and its mass is larger than the energy scale of the GZK cutoff. Such particles would overclose the universe if once they were in a thermal equilibrium [6]. But they can be generated gravitationally during the reheating epoch just after the end of inflation [2, 7].

In this paper, we identify X as one kind of right-handed neutrino ν_R. For simplicity of discussion, we assume that this X is electron right-handed neutrino $(\nu_R)_e$, but any generation of right-handed neutrino can play a role of superheavy dark matter.

The typical mass scale of the right-handed neutrinos is very large, $M_{\nu_R} \sim 10^{14}$GeV, in order to explain the very small mass scale of left-handed neutrinos by seesaw mechanism [8]. Thus right-handed neutrinos can be candidates of superheavy dark matter.[1]

We have to explain why the lifetime of such heavy objects is very long. We can realize the very long lifetime by introducing an extra dimension. If the compactification scale of the extra dimension is extremely small, no laboratory and astrophysical constraints apply, so we can use an extra dimension.

[1] in reference [9], It is argued that right-handed can be the candidate of dark matter, but not superheavy.

We assume that the wavefunction of right-handed electron neutrinos localize far away from the localization place of other fermions. The interaction between them is exponentially suppressed because of this separation, and thus we can achieve the extremely long lifetime.

Furthermore, because of this suppression, the mass of the lightest left-handed neutrino becomes extremely small. This leads to the high predictability on the mass scale relevant to the neutrinoless double beta decay [10], as all models that predict very small neutrino mass of one generation. If the large angle MSW solution [11] of solar neutrino deficit is correct, as recent experiments suggest [12], GENIUS [13] may be able to detect the signal of the neutrinoless double beta decay.

2. The model

We realize the exponentially small Yukawa couplings of right-handed electron neutrinos by the separation of the wavefunction of the right-handed electron neutrinos and that of other fermions in the extra dimension. Again note that, the Yukawa couplings of electron right-handed neutrino do not have to be exponentially suppressed. It can be muon right-handed neutrino, or tau right-handed neutrino. But for simplicity, we assume that it is electron right-handed neutrino.

We assume that our world has one extra dimension. Let us denote the coordinate of the extra dimension by y. Then by using a five-dimensional domain wall scalar field, we can localize four-dimensional chiral fermions at different four-dimensional slices in the fifth dimension [14]. Its wavefunction $\phi(y)$ is given by

$$\phi(y) = \frac{\sqrt{\mu}}{(\pi/2)^{1/4}} e^{-\mu^2(y-y_0)^2}\,, \tag{2.1}$$

where μ is the mass parameter of the domain wall scalar field, and y_0 is the localization position of chiral fermions. We assume that the right-handed electron neutrinos are localized at $y = r$, higgs doublets are not localized anywhere, and all other fermions are localized at $y = 0$. It is shown in figure 1.

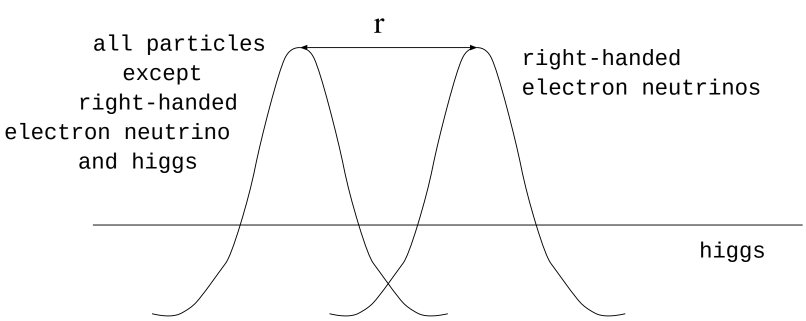

Figure 1: The five-dimensional wave function. The overlap between right-handed electron neutrinos and other fermions is exponentially suppressed.

Thus the overlap between the wavefunction of right-handed electron neutrinos and that of other lepton doublets is exponentially suppressed and Yukawa coupling terms become

$$\begin{aligned}\mathcal{L}_{4\mathrm{d}} &= \sum_\alpha y_{\alpha e}(\bar{l}_L)_\alpha H(\nu_R)_e \int dy \phi_{l_L}(y)\phi_{\nu_R}(y) \\ &= \sum_\alpha e^{-\mu^2 r^2/2} y_{\alpha e}(\bar{l}_L)_\alpha H(\nu_R)_e\,. \end{aligned} \tag{2.2}$$

Thus Yukawa couplings are exponentially suppressed. Let us denote all exponentially suppressed quantities by ϵ. Then the lagrangian of neutrino sector becomes

$$\mathcal{L} = \epsilon_{\alpha e}(\bar{l}_L)_\alpha H(\nu_R)_e + \sum_{\alpha,\beta\neq e} y_{\alpha\beta}(\bar{l}_L)_\alpha H(\nu_R)_\beta + \sum_{\alpha\beta}(M_{\nu_R})_{\alpha\beta}(\nu_R)^c_\alpha(\nu_R)_\beta\,, \tag{2.3}$$

where

$$(M_{\nu_R})_{\alpha\beta} \sim M \begin{pmatrix} a & \epsilon & \epsilon \\ \epsilon & b & c \\ \epsilon & c & d \end{pmatrix}. \tag{2.4}$$

Since right-handed mu and tau neutrinos are localized far away from right-handed electron neutrinos, as other usual fermions, some parts of Majorana mass matrix of right-handed neutrinos are also exponentially suppressed. By using seesaw mechanism [8], we can naturally realize the very small left-handed mu and tau neutrino masses if we take $M \sim 10^{14}\mathrm{GeV}$ and $b, c, d \sim \mathrm{O}(1)$. Since Yukawa couplings of a right-handed electron neutrino are extremely small, a do not need to be O(1), but we take $a \sim \mathrm{O}(1)$ here.

Therefore the mass of the lightest neutrino m_1 is extremely small because of the exponentially small Yukawa coupling:

$$\begin{aligned} m_1 &\sim \frac{e^{-\mu^2 r^2} y^2 v^2}{M} \\ &\sim e^{-\mu^2 r^2} 10^{-1}\mathrm{eV}\,. \end{aligned} \tag{2.5}$$

Here v is the VEV of higgs bosons. The masses of other neutrinos are determined by the experiments of atmospheric [15] and solar [12] neutrino oscillations: $m_2 \sim \sqrt{\delta m^2_{\mathrm{sol}}}$ and $m_3 \sim \sqrt{\delta m^2_{\mathrm{atm}}}$.

3. Ultra high energy cosmic ray

It was pointed out that the flux of cosmic rays should be suddenly dumped at the GZK cutoff (5×10^{19}eV) [1] because of the interaction between cosmic rays and cosmic microwave background radiation photons. Though the absence of the GZK cutoff is now experimentally established [16, 17, 18, 19]. So we should propose a scenario to explain the observed UHECR.

"Top-Down" scenarios assume some superheavy objects with very long lifetime. It may be topological defects [20, 21, 22], composite objects [23, 24, 25], or superheavy dark

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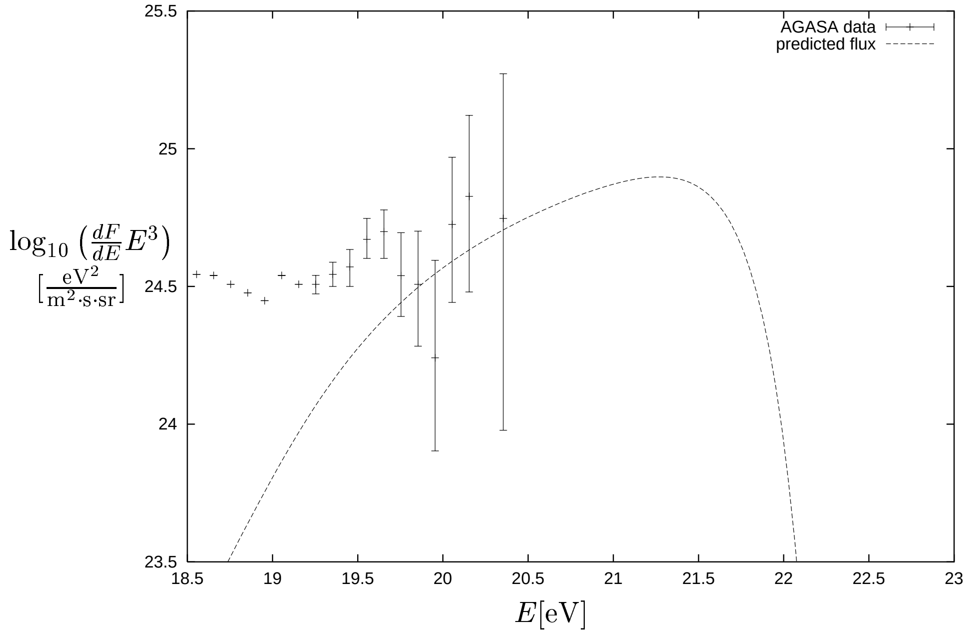

Figure 2: The observed UHECR events and the prediction of our model.

matter [26, 27, 3, 4, 5]. (for a detailed review, see [28].) In order to explain UHECR by superheavy dark matter X, it must satisfy the following conditions [3, 28].

$$\begin{aligned} m_X &\gtrsim 10^{12}\mathrm{GeV}\,, \\ 10^{10}\mathrm{yr} \lesssim \tau_X &\lesssim 10^{22}\mathrm{yr}\,, \\ 10^{-12} \lesssim \Omega_X h^2 &\lesssim 1\,. \end{aligned} \tag{3.1}$$

In our scenario, right-handed electron neutrinos are the superheavy dark matter. Its mass $M_{\nu_R} \sim 10^{14}$GeV naturally leads to the energy above the GZK cutoff. The long lifetime is realized by the exponentially suppressed Yukawa couplings.

In order to explain UHECR and the missing energy of the universe simultaneously, we took $m_{\nu_R} = 2 \times 10^{14}$GeV, $\tau_{\nu_R} = 10^{20}$yr and $n_{\nu_R} = 4.5 \times 10^{-15}\mathrm{m}^{-3}$. This long lifetime can be realized by a moderate fine-tuning: $\mu r \sim 12$. We can explain the energy of the CDM: $\Omega_{\nu_R} = 0.2$. This compactification scale $r \sim \frac{12}{\mu}$ can be extremely small if the mass scale μ is extremely large, so no laboratory and astrophysical constraints for extra dimensions apply in this case.

And under these conditions,the predicted UHECR flux becomes consistent with observations as shown in figure 2.

We calculated this flux by the MLLA approximation [29] and used SUSY QCD. Though it was pointed out that this is not reliable for large x and its normalization is uncertain [23], it can be used as a benchmark.

Since these UHECR mainly come from our galaxy halo because dark matter is concentrated on it, there should be some anisotropy in the observed UHECR events [30]. Future observatories may be able to see it.

Right-handed electron neutrinos decay into higgs bosons and left-handed lepton doublets. There exists a constraint for heavy particles X which can decay into left-handed neutrinos [31, 32, 33]:

$$\frac{\tau_X}{t_0} BR(X \to \nu \text{ anything})^{-1} \geq 2.4 \times 10^5 \left(\frac{\Omega_X}{0.2}\right) \left(\frac{h}{0.65}\right)^2 \left(\frac{10^{14}\text{GeV}}{m_X}\right)^{3/4} . \tag{3.2}$$

Our model satisfies this condition.

4. Neutrinoless double beta decay

If observed, the neutrinoless double beta decay($0\nu\beta\beta$) may become the strongest evidence for the lepton flavor violation. The $0\nu\beta\beta$ decay rate is determined by the mass parameter

$$|m_{\nu_e\nu_e}| \equiv |\sum_i U_{ei}^2 m_i| \,, \tag{4.1}$$

where U_{ei} is the MNS matrix [34]. In our model, the mass of the lightest neutrino is extremely small, so its contribution can be neglected. As all models that predict very small neutrino mass of one generation, this fact leads into the high predictability of neutrinoless double beta decay.

The mass parameter is described by U_{e3} and the parameters of atmospheric and solar neutrino oscillations [35]: $\delta m^2_{\text{atm}} \sim m^2_{\nu_3}$, $\delta m^2_{\text{sol}} \sim m^2_{\nu_2}$, and $\tan^2\theta_{\text{sol}} \equiv |\frac{U_{e2}}{U_{e1}}|^2$. It becomes

$$\begin{aligned} |m_{\nu_e\nu_e}| &= |U_{e2}^2 m_2 + U_{e3}^2 m_3| \\ &= |(1-|U_{e3}|^2)\sin^2\theta_{\text{sol}}\sqrt{\delta m^2_{\text{sol}}} + |U_{e3}|^2 e^{i\alpha}\sqrt{\delta m^2_{\text{atm}}}| \,, \end{aligned} \tag{4.2}$$

where α denotes the relative phase between the two terms.

We calculate the value of $|m_{\nu_e\nu_e}|$ for the large angle MSW solution, the small angle MSW solution, and the LOW solutions. We take $\delta m^2_{\text{atm}} \sim 3,2 \times 10^{-3}\text{eV}^2$. We also required $|U_{e3}| \leq 0.15$ from the CHOOZ experiment [36].

The result is shown in figure 3, 4 and 5. In the case of the large angle MSW solution, $|m_{\nu_e\nu_e}|$ is mainly sensitive to the parameter of the solar neutrino oscillation, $\sin^2\theta_{\text{sol}}\sqrt{\delta m^2_{\text{sol}}}$. It is very encouraging to see that GENIUS [13] may be able to detect the signal of the neutrinoless double beta decay in most of the paramater region if the large angle MSW solution, which seems to be the most favored one [37], is correct.

5. Summary

In this paper we propose that the right-handed neutrinos can be candidates of superheavy dark matter, which is needed to explain huge amounts of cold dark matter and UHECR simultaneously. The long lifetime of the right-handed neutrinos is realized by the separation between the wavefunction of the right-handed neutrinos and that of other fermions in the extra dimension. Our model also have high predictability on the mass parameter of the neutrinoless double beta decay.

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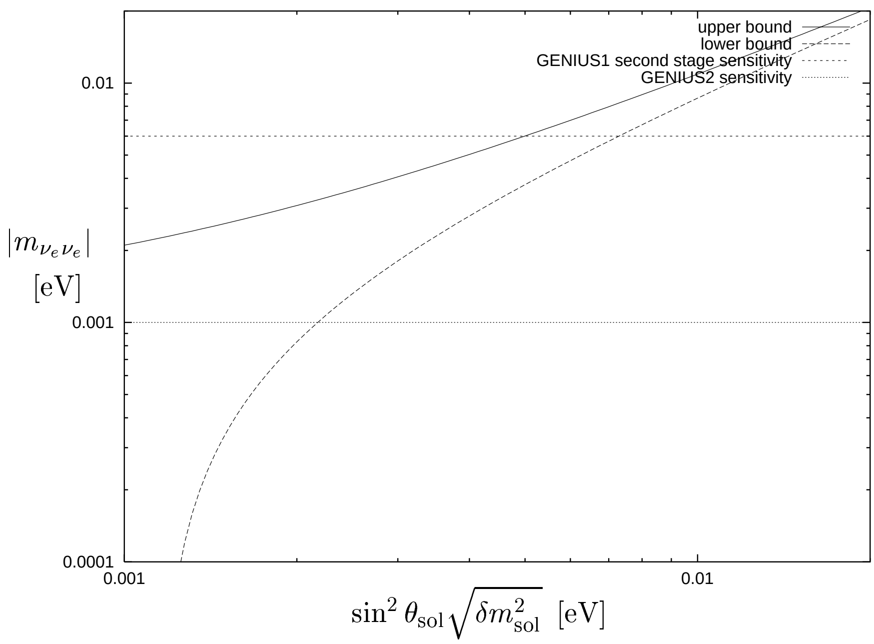

Figure 3: The predicted value of $|m_{\nu_e\nu_e}|$ for the large angle MSW solution.

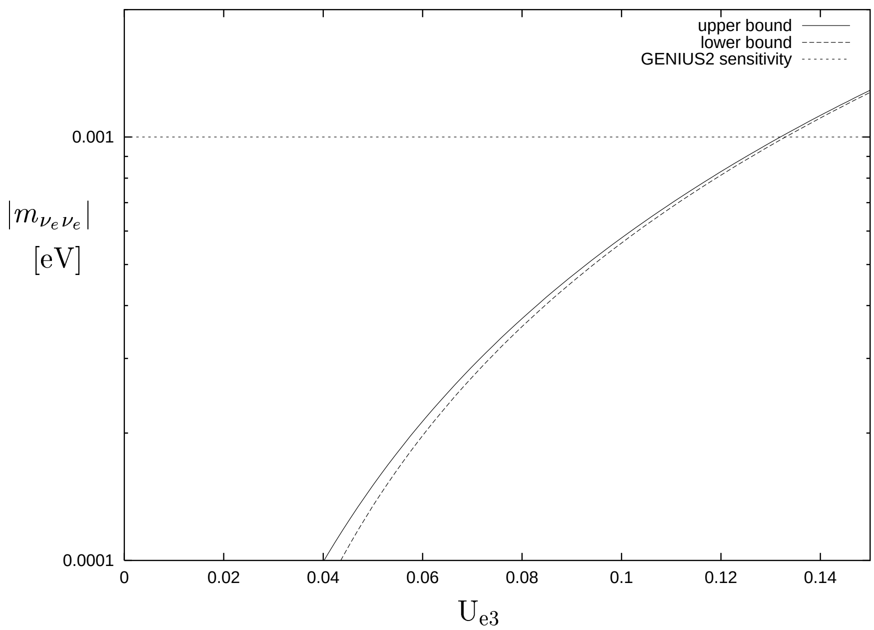

Figure 4: The predicted value of $|m_{\nu_e\nu_e}|$ for the small angle MSW solution.

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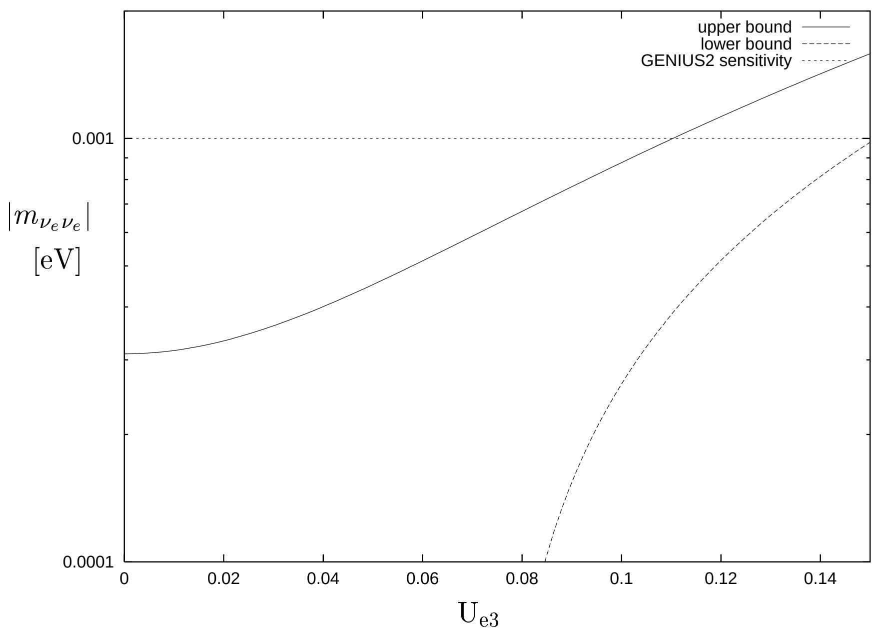

Figure 5: The predicted value of $|m_{\nu_e\nu_e}|$ for the LOW solution.

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