Direct Detection of Ultrahigh-energy WIMPs with a Satellite Detector Like JEM-EUSO

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Abstract

The possibility of directly detecting ultrahigh-energy (UHE) weakly interacting massive particles (WIMPs) are considered by the WIMPs’ interaction with the nuclei in the air. Because neutrinos dominate the events from the spherical crown near the Extreme Universe Space Observatory on board the Japanese Experiment Module (JEM-EUSO), all the events from this region are ignored in my work. Then the numbers of UHE WIMPs and neutrinos detected by JEM-EUSO are evaluated at different energies (1 PeV < E < 100 EeV) in 10 years, respectively. If the energy thresholds are taken to be 20 EeV; neutrino events can be almost rejected in the detection of UHE WIMPs. According to my evaluation, O(10–100) UHE WIMP events can be detected by JEM-EUSO at energies above 70 EeV in 10 years.

Key words: dark matter – neutrinos

1. Introduction

It is indicated by the Planck data with measurements of the cosmic microwave background that 26.6% of the overall energy density of the universe is nonbaryonic dark matter (Ade et al. 2016). Weakly interacting massive particles (WIMPs), predicted by extensions of the Standard Model (SM) of particle physics, are a class of candidates for dark matter (Bertone et al. 2005). They are distributed in a halo surrounding a galaxy. A WIMP halo of a galaxy with a local density of 0.3 GeV cm$^{-3}$ is assumed, and its relative speed to the Sun is 230 km s$^{-1}$ (Lewin & Smith 1996). At present, one mainly searches for thermal WIMPs via direct and indirect detections (Kang et al. 2013; Aguilar et al. 2014; Agnese et al. 2015; Akerib et al. 2017; Albert et al. 2017; Ambrosi et al. 2017; Aprile et al. 2017; Cui et al. 2017). Because of the very small cross sections of the interactions between these WIMPs and nuclei (maybe O($10^{-47}$ cm$^{-2}$)) (Aprile et al. 2017; Cui et al. 2017), but so far one has not found dark matter yet.

It is a reasonable assumption that there exist various dark matter particles in the universe. Then it is possible that this sector may be composed of nonthermal (and nonrelativistic) components. And these particles may also contain a small component that is relativistic and highly energetic. Although the fraction of these relativistic dark matter particles is small in the universe, their large interaction cross sections (including between themselves and between them and the SM particles) make it possible to find them. Because of the reasons mentioned above, one has to shift more attention to direct and indirect detection of ultrahigh-energy (UHE) WIMPs. In fact, Bhattacharya et al. 2015 discussed the possibility that the PeV events are UHE dark matter particles at IceCube. And the possibility that UHE WIMPs are indirectly probed by IceCube via detecting UHE neutrino signatures from the Earth’s core has been discussed in my other work (Xu 2018).

The relativistic WIMPs are mainly generated by two mechanisms in the universe. One is through the collision of UHE cosmic ray particles and thermal WIMPs. This collision will result in some UHE WIMP flux. The other is that UHE WIMPs originated in the early universe. There is a nonthermal dark sector generated by the early universe, with its bulk composed of a very massive relic $\phi$ in the universe. This superheavy dark matter (Khlopov & Chechetkin 1987; Chung et al. 1998, 1999; Covi et al. 2010; Feldstein et al. 2013) decays to another much lighter WIMPs $\chi$, and its lifetime is greater than the age of the universe. This leads to a small but significant flux of UHE WIMPs (Li & Tao 2000; Esmaïli et al. 2012; Bhattacharya et al. 2015; Bai et al. 2016; Bhubal Dev et al. 2016).

The present work is only focused on direct detection of UHE WIMPs $\chi$ induced by the decay of superheavy dark matter $\phi$ ($\phi \rightarrow \chi \bar{\chi}$). These UHE WIMPs $\chi$, which pass through the Earth and air and interact with nuclei, can be detected by a satellite detector like the Extreme Universe Space Observatory on board the Japanese Experiment Module (JEM-EUSO; Adams et al. 2012), via fluorescent and Cerenkov photons due to the development of extensive air showers. In this detection, the main contamination is from the diffuse neutrinos in the Galaxy.

In what follows, the UHE WIMP and background event rates from diffuse neutrinos will be estimated at JEM-EUSO. And the possibility of direct detection of UHE WIMPs induced by the decay of superheavy dark matter will be discussed.

2. UHE WIMPs Flux in the Galaxy

The following considers a scenario where the dark matter sector is composed of at least two particle species in the universe (Bhattacharya et al. 2015). One is a co-moving nonrelativistic scalar species $\phi$, with mass $m_\phi \geq 1$ PeV; the other is a much lighter particle species $\chi$ ($m_\chi \ll m_\phi$), due to the decay of $\phi$, with a very large lifetime. And $\chi$ comprises the bulk of present-day dark matter. The lifetime for the decay of heavy dark matter to SM particles is strongly constrained ($\tau \geq O(10^{26}\text{--}10^{29})$ s) by diffuse gamma and neutrino observations (Esmaïli et al. 2012; Murase & Beacom 2012; Rott et al. 2015; Kachelriess et al. 2018). The present work considers an assumption that superheavy dark matter could not decay to SM particles. And $\tau_\phi$ is taken to be $10^{22}$ s. Because the WIMP flux only depends on the two-body decay of superheavy dark matter and the dark matter distribution in the galactic halo, it is the same as the neutrino flux due to the decay of superheavy dark
matter in Esmaili et al. (2012), Bai et al. (2016):
\[ \psi_\chi = \frac{1}{4\pi m_\chi \tau_\phi} \int \frac{dN_\chi}{dE_\chi} \rho_{\text{halo}} d\Sigma dE, \]
where \( \rho_{\text{halo}} \) is the density profile of dark matter particles in the Galaxy and \( s \) is a line of sight. \( \frac{dN_\chi}{dE_\chi} = \delta (E_\chi - \frac{m_\chi}{2}) \) and \( E_\chi \) and \( N_\chi \) are the energy and number of UHE WIMP, respectively. Then the UHE WIMPs flux from the Galaxy is obtained via the following equation (Bai et al. 2016):
\[ \psi_\chi = \int_{E_{\text{min}}}^{E_{\text{max}}} F \frac{dN_\chi}{dE_\chi} dE \]
with
\[ F = 1.7 \times 10^{-12} \text{ cm}^{-2} \text{s}^{-1} \text{ sr}^{-1} \times \frac{10^{28} \, s}{\tau_\phi} \times 1 \text{ PeV} \times \frac{1}{m_\phi}. \]

3. UHE WIMP Interaction with Nuclei

In the present paper, a \( Z^\prime \) portal dark matter model (Alves et al. 2014; Hooper 2015) is taken for WIMPs to interact with nuclei within the JEM-EUSO detecting zone (see Figure 1). In this model, a new \( Z^\prime \) gauge boson is considered as a simple and well-motivated extension of SM (see Figure 1(a) in Bhattacharya et al. 2015). And the parameters in the model are taken to be the same as the ones in Bhattacharya et al. (2015); that is, the interaction vertices \( (\chi xZ^\prime \text{ and } ggZ) \) are assumed to be vector-like, the coupling constant \( G = g_{\chi Z^\prime} g_{ggZ} \) is chosen to be 0.05, and the \( Z^\prime \) and \( \chi \) masses are taken to be 5 TeV and 10 GeV, respectively. Theoretical models that encompass the WIMP spectrum have been discussed in the literature in terms of \( Z \) or \( Z^\prime \) portal sectors, with the \( Z^\prime \) vector boson typically acquiring mass through the breaking of an additional U(1) gauge group at the high energies (see Alves et al. 2014; Hooper 2015). The UHE WIMP interaction cross section with the nucleus is obtained by the following function (see Figure 1(b) in Bhattacharya et al. 2015):
\[ \sigma_{\chi N} = 6.13 \times 10^{-43} \text{ cm}^2 \left( \frac{E_\chi}{1 \text{ GeV}} \right)^{0.518}, \]
where \( E_\chi \) is the UHE WIMP energy.

For neutrino energies above 1 PeV, the interaction cross sections with nuclei are given by simple power-law forms (Block et al. 2010):
\[ \sigma_{\nu N}(CC) = 4.74 \times 10^{-35} \text{ cm}^2 \left( \frac{E_\nu}{1 \text{ GeV}} \right)^{0.251}, \]
\[ \sigma_{\nu N}(NC) = 1.80 \times 10^{-33} \text{ cm}^2 \left( \frac{E_\nu}{1 \text{ GeV}} \right)^{0.256}, \]
where \( E_\nu \) is the neutrino energy. Then the above equations show that \( \sigma_{\nu N} \) is smaller by 10–11 orders of magnitude, compared with \( \sigma_{\chi N} \), at energies between 20 and 100 EeV.

The WIMP and neutrino interaction length can be obtained by
\[ L_{\nu, \chi} = \frac{1}{N_A \rho \sigma_{\nu, \chi}}, \]
where \( N_A \) is the Avogadro constant, and \( \rho \) is the density of matter, which WIMPs and neutrinos interact with.

4. Evaluation of the Numbers of UHE WIMPs and Neutrinos Detected by JEM-EUSO

UHE WIMPs reach the Earth and pass through the Earth and air; meanwhile, these particles interact with matter of the Earth and air. Hadrons are produced by UHE WIMP interaction with atmospheric nuclei. The secondary particles generated by these UHE hadrons will develop into a cascade. And the most dominant particles in a cascade are electrons moving through the atmosphere. Ultraviolet fluorescence photons are emitted by electron interaction with nitrogen. The emitted photons are isotropic, and their intensity is proportional to the energy deposited in the atmosphere. A small part of them will be detected by the JEM-EUSO detector (see Figure 1). Because these signatures are similar to deep inelastic scattering of UHE neutrinos via neutral current, JEM-EUSO is unable to discriminate between their signatures. Only the geometrical analysis is used to discriminate between UHE WIMPs and neutrinos in the present paper.

JEM-EUSO is a space science observatory to explore the extreme-energy cosmic rays and upward-going neutrinos in the universe (Takahashi & JEM-EUSO Collaboration 2009). It will be installed into the International Space Station (ISS) after 2020. The ISS maintains an orbit with an altitude of \( \sim 400 \text{ km} \) and circles the Earth in roughly 90 minutes. The JEM-EUSO telescope has a wide field of view (FOV: \( \pm 30^\circ \)) and observes extreme-energy particles in two modes (nadir and tilted modes) via fluorescent and Cerenkov photons due to the development of extensive air showers. JEM-EUSO is tilted by an angle of \( 30^\circ \) in the tilted mode. JEM-EUSO has a observational area of about \( 2 \times 10^5 \text{ km}^2 \) and \( 7 \times 10^5 \text{ km}^2 \) in nadir and tilted modes, respectively. The duty cycle for JEM-EUSO, \( R \), is taken to be 10%.

The number of UHE WIMPs, \( N_{\text{det}} \), detected by JEM-EUSO can be obtained by the following function:
\[ N_{\text{det}} = R \times T \times (A)_{\text{eff}} \times \Phi_\chi, \]
where \( T \) is the lifetime of the JEM-EUSO experiment, \( \Phi_\chi = \frac{d\phi_\chi}{dE_\chi} \), and \( (A)_{\text{eff}} \) is the observational area \( \times \) the effective solid angle \( \times P(E, D_e, D) \). Here
P(E, D_e, D) = \exp \left( -\frac{D_e}{\text{exp} \ 1} \right) \left[ 1 - \exp \left( -\frac{D}{\text{exp} \ 1} \right) \right]

is the probability that UHE WIMPs interact with air after traveling a distance between \(D_e\) and \(D_e + D\), where \(D\) is the effective length in the JEM-EUSO detecting zone in the air, \(D_e\) are the distances through the Earth, and \(L_{\text{earth,air}}\) are the UHE WIMP interaction lengths with the Earth and air, respectively.

In what follows, \((A\Omega)_{\text{eff}}\) is roughly considered, and then the numbers of UHE WIMPs detected by JEM-EUSO are evaluated. Here it is assumed that the observational area of JEM-EUSO is regarded as a point in the calculation of the effective solid angle \(\Omega\). Under this approximation,

\[
(A\Omega)_{\text{eff}} = P(E, D_e, D)A \int_0^{\theta_{\text{max}}} \frac{2\pi R_e^2 \sin \theta}{D_e^2} \, d\theta,
\]

where \(A\) is the observational area, \(R_e\) is the radius of the Earth, \(\theta\) is the polar angle for the Earth (see Figure 1), \(\theta_{\text{max}}\) is the maximum of \(\theta\), \(D_e = \frac{R_e(1 + \cos \theta)}{\cos \frac{\theta}{2}}\), \(D = \frac{H}{c\gamma^{30/3} \sin \frac{\theta}{2} + \cos \frac{\theta}{2}}\) and

\[
D = R_e \left( \cos \frac{\theta}{2} + \sin \frac{\theta}{2} \sqrt{\tan \left( \frac{2\pi}{3} - \frac{\theta}{2} \right) \sin \frac{\theta}{2} + \cos \frac{\theta}{2} \right) \right)
\]

are the nadir and tilted modes, respectively. Here \(H\) is the altitude of ISS.

The background due to diffuse neutrinos is roughly estimated with a diffuse neutrino flux of \(\Phi_{\nu} = 0.9^{+0.30}_{-0.27} \times (E_{\nu}/\text{100 TeV}) \times 10^{-18} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}\) (Aartsen et al. 2016), where \(\Phi_{\nu}\) represents the per-flavor flux, by the above method.

5. Results

The number of UHE WIMPs and neutrinos detected by JEM-EUSO are evaluated at different energy at different \(\theta\), respectively. We can obtain neutrino contamination percentages in the upward-going events detected by JEM-EUSO by

\[
\text{Neutrino\%} = \frac{N_{\nu}}{N_{\text{WIMP}} + N_{\nu}}.
\]

where \(N_{\text{WIMP}}\) and \(N_{\nu}\) are the numbers of UHE WIMPs and neutrinos detected by JEM-EUSO at different energy at different \(\theta\), respectively. Figure 2 shows Neutrino percentage at different energy at different \(\theta\) when \(\tau_\phi = 10^{25}\) s. From this figure, we know that neutrinos dominate the detected upward-going events in the spherical crown near the observational area of JEM-EUSO at energies below \(\sim 100\) PeV. So the events from this zone should be ignored for rejecting neutrino background. Besides, this figure shows that the neutrino contamination is less than \(10^{-10}\) in the signal region of \(0 < \theta < 150^\circ\) and \(20 \text{ EeV} < E < 100 \text{ EeV}\). So we almost confirm that the events are UHE WIMPs from this region.

5.1. Nadir Mode

The number of UHE WIMPs and neutrinos detected by JEM-EUSO are evaluated at different energy (1 PeV < \(E < 100\) EeV) at the different \(\theta_{\text{max}}\) (150°, 120°, and 90°) in 10 years in the nadir mode when \(\tau_\phi = 10^{25}\) s, respectively (see Figures 3–5). Figure 3 shows that the number of UHE WIMPs and neutrinos at \(\theta_{\text{max}} = 150^\circ\). Because JEM-EUSO can only measure the deposited energy \(E_{\text{dep}}\) in the air, it
is important to determine the inelasticity parameter \( y = \frac{E_{\text{dep}}}{E_{\text{in}}} \) (where \( E_{\text{in}} \) is the incoming particle energy). According to the calculation in Bhattacharya et al. (2015), \( y \) for WIMP is about 0.29 at 70–100 EeV. The UV fluorescence intensity maximum is \( \sim 7500 \) photons m\(^{-2}\) sr\(^{-1}\) ns\(^{-1}\) by a 100 EeV extensive air shower (EAS), and the night glow for the moonless condition is about 500 photons m\(^{-2}\) sr\(^{-1}\) ns\(^{-1}\) (Bertaima et al. 2015). The UV fluorescence intensity is proportional to the electron energy loss. The electron energy losses are calculated via the CORSIKA program (version 7.69, with GHEISHA+SIBYLL as the low- and high-energy hadronic interaction model and with NKG+EGS4 as the electromagnetic interaction) (Heck et al. 1998). A thinning level \( \epsilon_{\text{th}} \) and the maximum weight limitations for electromagnetic and hadronic interactions are taken to be \( 10^{-4} \), \( \epsilon_{\text{th}} \cdot \xi(E_{\text{GeV}}) \), and \( 10^{-2} \cdot \epsilon_{\text{th}} \cdot \xi(E_{\text{GeV}}) \), respectively. The energy cuts for \( \gamma \), electrons, muons, and hadrons are 100 keV, 100 keV, 10 MeV, and 50 MeV in this work, respectively. One thousand showers each of 70 and 100 EeV WIMPs and 100 EeV Protons, inclined with a zenith angle = 60°, are used to estimate the electron energy losses for \( X_{\text{max}} \) (\( X_{\text{max}} \) is the depth of shower maximum). Boosted products of WIMP interaction with air are nucleons, fragments of nuclei, or nuclei. According to the estimation with the CORSIKA program, the stronger intensity is produced by a shower initiated by nuclei. Nitrogen is the most abundant element in the atmosphere (about 78%). So here the 70 and 100 EeV WIMP events are simulated with the showers initiated by 20 and 29 EeV nitrogen nuclei, respectively. According to the calculation, the intensity maximums are \( \sim 2170 \) and \( \sim 2910 \) photons m\(^{-2}\) sr\(^{-1}\) ns\(^{-1}\) for the EAS initiated by 70 EeV and 100 EeV WIMPs, respectively. If the energy threshold for JEM-EUSO is taken into account (about 20 EeV; Fenu 2017), the energy threshold for WIMPs is taken to be 70 EeV at JEM-EUSO in the present paper. The number of detected UHE WIMPs can reach about 28 and 7 at the energies with 70 and 100 EeV in 10 years, respectively. Figure 4 shows that the number of UHE WIMPs and neutrinos at \( \theta_{\text{max}} = 120^\circ \). The number of detected UHE WIMPS can reach about 15 and 12 at the energies with 70 and 100 EeV in 10 years, respectively. Figure 5 shows that the number of UHE WIMPs and neutrinos at \( \theta_{\text{max}} = 90^\circ \), respectively. The number of detected UHE WIMPs can reach about 8 and 7 at the energies with 70 and 100 EeV in 10 years, respectively.

### 5.2. Tilted Mode

The number of UHE WIMPs and neutrinos detected by JEM-EUSO are evaluated at different energy (1 PeV < \( E < 100 \) EeV) at the different \( \theta_{\text{max}} \) (150°, 120°, and 90°) in 10 years in the tilted mode when \( \tau_{\phi} = 10^{25} \) s, respectively (see Figures 6–8). Figure 6 shows that the number of UHE WIMPs and neutrinos at \( \theta_{\text{max}} = 150^\circ \). If the energy threshold for WIMPs is taken into account at JEM-EUSO about 70 EeV), the number of detected UHE WIMPs can reach about 86 and 72 at the energies with 70 and 100 EeV in 10 years, respectively. Figure 7 shows that the number of UHE WIMPs and neutrinos at \( \theta_{\text{max}} = 120^\circ \). The number of detected UHE WIMPs can reach about 86 and 72 at the energies with 70 and 100 EeV in 10 years, respectively. Figure 8 shows that the number of UHE WIMPs and neutrinos at \( \theta_{\text{max}} = 90^\circ \), respectively. The number of detected UHE WIMPs can reach...
about 41 and 35 at the energies with 70 and 100 EeV in 10 years, respectively.

6. Discussion and Conclusion

According to the results described above, it is possible that UHE WIMPs are directly detected with a satellite detector like JEM-EUSO. The calculation of the solid angle is simplified by the method of the observational area contraction as a point. This produces some deviations for the event rates of UHE WIMPs and neutrinos, but they cannot have an effect on the conclusion that it is possible that O(10–100) UHE WIMP events are detected by JEM-EUSO in 10 years, especially when \( \theta_{\max} \) is a less value, such as \( \theta_{\max} \leq 120^\circ \).

Constrained by the lifetime of ISS, JEM-EUSO has the operation time of five years. So the WIMP event rates have only a half of the above evaluated ones. Because \( \Phi_\chi \) is proportional to \( \frac{1}{\tau} \), the above results actually depend on the lifetime of superheavy dark matter. For example, the WIMP event rate for JEM-EUSO is \( \sim 430 \) and \( \sim 360 \) events/five years at 70 and 100 EeV in the case of \( \theta_{\max} = 120^\circ \) in the tilted mode when \( \tau_\phi = 10^{24} \) s. respectively. The WIMP event rate for JEM-EUSO is \( \sim 43 \) and \( \sim 36 \) events/five years at 70 and 100 EeV in the case of \( \theta_{\max} = 120^\circ \) in the tilted mode when \( \tau_\phi = 10^{25} \) s, respectively. And the WIMP event rate for JEM-EUSO is \( \sim 4 \) and \( \sim 3 \) events/five years at 70 and 100 EeV in the case of \( \theta_{\max} = 120^\circ \) in the tilted mode when \( \tau_\phi = 10^{26} \) s, respectively.

Thus it can be seen, it is possible that UHE WIMPs are detected at JEM-EUSO under the assumption that the superheavy dark matter \( \phi \) is unable to decay to SM particles. If the signatures from the signal region (see Figure 2) are measured by JEM-EUSO, there must be new physical particles, which could be UHE WIMPs, in the universe. It is also possible that UHE WIMPs are directly probed by the detectors based on the ground, such as the Pierre Auger observatory, when the lifetime of superheavy dark matter is less than \( 10^{26} \) s. Besides, UHE SM particles due to the annihilation between UHE and thermal WIMPs could be measured. For example, UHE neutrinos from the solar center due to the annihilation between UHE and thermal WIMPs could be measured by a neutrino telescope like IceCube.

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