Direct Measurement of Upward-going Ultrahigh Energy Dark Matter at the Pierre Auger Observatory

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Abstract

In the present paper, it is assumed that there exist two dark matter particles: superheavy dark matter particles (SHDM), whose mass $\sim$ inflaton mass, and light fermion dark matter (DM) particles which are the ultrahigh energy (UHE) products of its decay. The Earth will be taken as a detector to directly search for the UHE DM particles. These upward-going particles, which pass through the Earth and air and interact with nuclei, can be detected by the fluorescence detectors (FD) of the Pierre Auger observatory (Auger), via fluorescent photons due to the development of an EAS. The event rates of UHE DM particles measured at the FD of Auger are evaluated in the incoming energy range between 1 EeV and 1 ZeV when the different lifetimes of decay of SHDM. And the UHE DM fluxes are estimated at the FD of Auger when the different lifetimes of decay of SHDM. Finally, according to the Auger data from 2008 to 2019, the upper limit for UHE DM fluxes is estimated at 90% C.L. at the FD of Auger.

Keywords: Superheavy dark matter, Ultrahigh energy dark matter particle, Neutrino

1 Introduction

The nature and origin of dark matter (DM) is one of the important topics in particle physics, cosmology and astrophysics. And sufficient evidences for the existence of DM and its dominance in matter in our universe are provided by cosmological and astrophysical observations [1][2]. It is indicated by the Planck observations with measurements of the cosmic microwave background that 26.6% of the overall energy density of the universe is nonbaryonic DM [3]. A restriction on dark matter, which indicate that the DM particle is nonrelativistic or "cold", arises from large-scale N-body simulations [4][5]. DM is distributed in a halo surrounding a galaxy. This DM halo with a local density of 0.3 GeV/cm$^3$ is assumed and its relative speed to the Sun is 230 km/s [6]. At present, one searches for thermal DM particles via direct and indirect measurements [7][14]. Because of the very small cross sections of the interactions between them and nuclei (maybe O(10$^{-47}$ cm$^2$)) [9][11], so far no one has found these DM particles yet.
The Superheavy Dark Matter (SHDM) $\phi$, based on the possibility of particle production due to time varying gravitational fields, is an alternative DM scenario \[17\]-\[27\]. There are three requirements in this scenario: (a) SHDM in the early Universe never reaches Local Thermal Equilibrium (LTE); (b) SHDM has a mass with the same order of magnitude as the inflaton mass, that is $m_\phi \sim m_{inflaton}$; (c) the lifetime of SHDM exceeds the age of the Universe $t_0$ ($\sim 10^{17}$ s), that is $\tau_\phi > t_0$ [15]. Since direct measurement of SHDM is impossible, the best way to search for SHDM is through the indirect detection of its decay or annihilation products. The annihilation of SHDM is unobservable since its cross section is bounded by unitarity ($\sigma_{ann} \propto \frac{1}{m_\phi^2}$). So the measurement of the products of decay of SHDM is an unique way to test the existence of SHDM. One has considered the decay of SHDM as a source of very high energy (VHE) or ultrahigh energy (UHE) cosmic rays in the past [15, 16, 28–36]. This is the so-called "top-down" models, where a flux of Standard Model (SM) particles (protons, gamma rays, neutrinos and so on) is produced by the decay of SHDM into the partons. However, it is different from this decay mode referred to above that the products of the decay of SHDM are only a UHE class of light fermion dark matter [37–40], not SM particles, in my work.

Then it is a reasonable assumption that there exist at least two DM species in the Universe. One is a non-thermal and non-relativistic dark sector generated by the early universe with its bulk comprised of a superheavy relic, SHDM $\phi$, in the Universe. The other is the stable DM particles $\chi$ which is UHE products of the decay of SHDM ($\phi \rightarrow \chi\bar{\chi}$). It is assumed that SHDM comprises of the bulk of present-day DM. Since the decay of long-living SHDM, meanwhile, the present-day DM may also contain a small component which is UHE DM particles. Although the fraction of these relativistic DM particles is small in the Universe, their large interaction cross sections (including between themselves and between them and SM particles) make it possible to measure them. Due to the reasons mentioned above, one has to shift more attention to direct and indirect detection of UHE DM particles. In the present paper, a $Z'$ portal dark matter model [41, 42] is taken for UHE DM particles $\chi$ to interact with nuclei. And, for the $\chi\chi Z'$ and $qqZ'$ interactions, their vertexes are both assumed to be vector-like. These UHE DM particles may be found by their interaction with nuclei. Thus it is indicated that there exist SHDM particles in the Universe.

Extreme energy cosmic rays (EECRs) is a puzzling and important topic in astroparticle physics, especially, their energy spectrum and components. There is the GZK-cutoff in the energy spectrum of EECRs at about $5 \times 10^{19}$ eV since extreme energy cosmic protons interact with photons for the Cosmic microwave background. The Pierre Auger Observatory (Auger) is a detector array for the measurement of EECRs, covering an area of 3000 km$^2$, for the measurement of EECRs and located outside the town of Malargue, in the Province of Mendoza, Argentina. EECRs are detected in a hybrid mode at Auger, that is it consists of about 1600 surface detectors (SD) to measure secondary particles at ground level and four fluorescence detectors (FD), each consisting of 6 optical telescopes, to measure the development of extensive air showers (EAS) in the atmosphere [43]. In the present work, the Earth will be taken as a detector to directly measure the UHE DM particles $\chi$ induced by the decay of SHDM $\phi$ ($\phi \rightarrow \chi\bar{\chi}$). These upward-going particles $\chi$, which pass through the Earth and air and interact with nuclei, can be detected by the FD at Auger, via fluorescent photons due to the
development of an EAS. In this detection, the main contamination is from the diffuse neutrinos in the Universe.

In what follows, the UHE DM and background (from astrophysical neutrinos) event rates and UHE DM fluxes will be estimated at the FD of Auger when the different $\tau_\phi$. And according to the Auger data, the UHE DM flux limit will be estimated at 90% C.L. at the FD of Auger in the present paper.

2 Estimation of UHE DM flux

The following considers a scenario where the dark matter sector is composed of two particle species in the Universe. One is a superheavy particle species $\phi$, the other is much lighter particle species $\chi$ ($m_\chi \ll m_\phi$), due to the decay of $\phi$, with a very large lifetime. And $\phi$ comprises the bulk of present-day dark matter. The lifetime for the decay of SHDM to SM particles is strongly constrained ($\tau \geq O(10^{26} - 10^{29})$s) by diffuse gamma and neutrino observations \[16, 44–46\]. In the present work, it is considered an assumption that SHDM could only decay to UHE DM particles, not SM particles. So $\tau_\phi$ is taken to be between $10^{17}$ s (the age of the Universe) and $10^{26}$ s in the present paper.

The UHE DM flux is composed of galactic and extragalactic components. So the total flux $\psi_\chi = \psi^G_\chi + \psi^{EG}_\chi$, where $\psi^G_\chi$ and $\psi^{EG}_\chi$ are the UHE DM galactic and extragalactic fluxes, respectively. Then the UHE DM flux from the Galaxy is obtained via the following equation \[36\]:

$$\psi_\chi = \int_{E_{\text{min}}}^{E_{\text{max}}} F^G \frac{dN_\chi}{dE_\chi} dE$$  

with

$$F^G = 1.7 \times 10^{-8} \times \frac{10^{26}s}{\tau_\phi} \times \frac{1TeV}{m_\phi} cm^{-2}s^{-1}sr^{-1}.$$ (2)

where $\frac{dN_\chi}{dE_\chi} = 2\delta(E_\chi - \frac{m_\phi}{2})$, and $E_\chi$ and $N_\chi$ are the energy and number of UHE DM particles, respectively.

The UHE DM flux from the extra galaxy is obtained via the following equation \[16, 37\]:

$$\psi^{EG}_\chi = F^{EG} \int_{E_{\text{min}}}^{E_{\text{max}}} dE \int_0^\infty dz \frac{1}{\sqrt{\Omega_\Lambda + \Omega_m (1+z)^3}} \frac{dN_\chi}{dE_\chi} [(1+z)E_\chi]$$  

with

$$F^{EG} = 1.4 \times 10^{-8} \times \frac{10^{26}s}{\tau_\phi} \times \frac{1TeV}{m_\phi} cm^{-2}s^{-1}sr^{-1}.$$ (4)

where $z$ represents the red-shift of the source, $\Omega_\Lambda = 0.685$ and $\Omega_m = 0.315$ from the PLANCK experiment \[3\].
In the present paper, a $Z'$ portal dark matter model \cite{41,42} is taken for UHE DM particles to interact with nuclei via a neutral current interaction mediated by a heavy gauge boson $Z'$. This new gauge boson is considered as a simple and well-motivated extension of SM (see Fig. 1(a) in Ref. \cite{37}). Since the interaction vertexes ($\chi\chi Z'$ and $qq Z'$) are assumed to be vector-like in the present work, the effective interaction Lagrangian can be written as follows:

$$L = \bar{\chi} g_{\chi\chi Z'} \gamma^\mu \chi Z'_\mu + \sum_{q_i} \bar{q}_i g_{qq Z'} \gamma^\mu q_i Z'_\mu$$  \hspace{1cm} (5)

where $q_i$'s are denoting the SM quarks, and $g_{\chi\chi Z'}$ and $g_{qq Z'}$ are denoting the $Z'$-$\chi$ and $Z'$-$q_i$ couplings, respectively. This Deep inelastic scattering (DIS) cross-section is computed in the lab-frame and its parameters are taken to be the same as the ones in Ref. \cite{37}, that is, the coupling constant $G (G = g_{\chi\chi Z'} g_{qq Z'})$ is chosen to be 0.05 and the $Z'$ and $\chi$ masses are taken to be 5 TeV, 10 GeV, respectively. Theoretical models that encompass the UHE DM spectrum have been discussed in the literature in terms of $Z$ or $Z'$ portal sectors with $Z'$ vector boson typically acquiring mass through the breaking of an additional U(1) gauge group at the high energies (see Ref. \cite{41,42}). The DIS cross section for UHE DM interaction with nuclei is obtained by the following function (see Fig. 1(b) in Ref. \cite{37}):

$$\sigma_{\chi N} = 6.13 \times 10^{-43} \text{cm}^2 \left(\frac{E_\chi}{1 \text{GeV}}\right)^{0.518}$$ \hspace{1cm} (6)

where $E_\chi$ is the energy of UHE DM particles.

The DIS cross-section for UHE neutrino interaction with nuclei is computed in the lab-frame and given by simple power-law forms \cite{47} for neutrino energies above 1 EeV:

$$\sigma_{\nu N}(CC) = 4.74 \times 10^{-35} \text{cm}^2 \left(\frac{E_\nu}{1 \text{GeV}}\right)^{0.251}$$ \hspace{1cm} (7)

$$\sigma_{\nu N}(NC) = 1.80 \times 10^{-35} \text{cm}^2 \left(\frac{E_\nu}{1 \text{GeV}}\right)^{0.256}$$ \hspace{1cm} (8)

where $E_\nu$ is the neutrino energy. Then the above equations show that $\sigma_{\chi N}$ is smaller by 10-11 orders of magnitude, compared to $\sigma_{\nu,\bar{\nu} N}$, near the GZK-cutoff scale.

The UHE DM and neutrino interaction lengths can be obtained by

$$L_{\nu,\chi} = \frac{1}{N_A \rho \sigma_{\nu,\chi N}}$$  \hspace{1cm} (9)

where $N_A$ is the Avogadro constant, and $\rho$ is the density of matter, which UHE DM particles and neutrinos interact with.
4 Evaluation of the numbers of UHE DM and neutrinos measured by FD of Auger

UHE DM particles 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 DM interaction with atmospheric nuclei. The secondary particles generated by these UHE hadrons will develop into an EAS. And the most dominant particles in an EAS are electrons moving through 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 FD of Auger (see Fig. 1). Since these signatures are similar to DIS of UHE neutrinos, the FD of Auger is unable to discriminate between their signatures. Only the geometrical analysis is used to discriminate between UHE DM particles and neutrinos. In the present paper, it is made an assumption that there exists air under an altitude of H = 100 km.

The number of UHE DM particles, \( N_{\text{det}} \), detected by the FD of Auger can be obtained by the following function:

\[
N_{\text{det}} = R \times T \times \int_{E_{\text{min}}}^{E_{\text{max}}} \int_0^{\theta_{\text{max}}} \int_{S_{\text{eff}}} \eta \Phi_\chi P(E, D_e, D) \frac{2\pi R_e^2 \sin(\theta)}{D_e^2} dS d\theta dE \tag{10}
\]

where \( R_e \) is the radius of the Earth and taken to be 6370 km, \( \theta \) is the polar angle for the Earth (see Figure 1), \( \theta_{\text{max}} \) is the maximum of \( \theta \) and taken to be \( \frac{2\pi}{3} \) for rejecting neutrino events from the spherical crown near the FD of Auger. Here the calculation of the solid angle is simplified by the method of the observational area contraction as a point. \( R \) is the duty cycle for Auger and taken to be 15% [48]. \( T \) is the lifetime of taking data for Auger and taken to be 20 years in the present work. \( dS = dx \times dy \) is the horizontal surface element. \( S_{\text{eff}} \) is the effective observational area for the FD of Auger and about 3000 km\(^2\). \( E \) is the energy of an incoming particle and varies from \( E_{\text{min}} \) to \( E_{\text{max}} \). Here \( \Phi_\chi = \frac{d\psi_\chi}{dE_\chi} \). The detection efficiency for an EAS \( \eta \) is assumed to be 100% at the FD of Auger in the present paper (the trigger efficiency for the FD of Auger is equal to 100% above 1 EeV [49]).

\[
P(E, D_e, D) = \exp \left( \frac{D}{L_{\text{air}}} \right) \exp \left( \frac{-D_e}{L_{\text{earth}}} \right) \left[ 1 - \exp \left( \frac{-D}{L_{\text{air}}} \right) \right] \tag{11}
\]

where \( D = \frac{H}{\cos(\frac{\theta}{2})} \) is the effective length in the detecting zone for the FD of Auger in the air, \( D_e = \frac{R_e(1 + \cos\theta)}{\theta} \) is the distances through the Earth, and \( L_{\text{earth,air}} \) are the UHE DM interaction lengths with the Earth and air, respectively.

The diffuse astrophysical neutrinos is roughly estimated with a diffuse neutrino flux of \( \Phi_\nu = 0.9^{+0.32}_{-0.27} \times (E_\nu/100\text{TeV}) \times 10^{-18}\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1} \) [50], where \( \Phi_\nu \) represents the per-flavor flux, by the above method.
5 Results and conclusion

The numbers of UHE DM particles and neutrinos detected by the FD of Auger are evaluated at different incoming energies (1 EeV < E < 1 ZeV), respectively. Since the FD of Auger can only measure the deposited energy for an EAS, $E_{sh}$, in the atmosphere, it is important to determine the inelasticity parameter $y$. $y = 1 - \frac{E_{X',\text{lepton}}}{E_{in}}$ (where $E_{in}$ is the incoming DM particle or neutrino energy and $E_{X',\text{lepton}}$ is the outgoing DM particles or lepton energy). For UHE DM particles, $E_{sh} = y E_{in}$. Since an EAS due to the neutrino interaction with nuclei via a neutral current is much smaller than that via a charged current, the charged current be only considered in the neutrino interaction with nuclei. Then $E_{sh} = (1 - y) E_{in}$ for neutrinos. The mean values of $y$ for UHE DM particles and neutrinos are computed by Ref. [37] and [51], respectively, and their results are used to the calculation of $E_{sh}$ in the present paper.

Fig. 2 shows the event rates for DM particles and astrophysical neutrinos measured by the FD of Auger at different $E_{sh}$'s. The numbers of the detected UHE DM particles can reach about $7.2 \times 10^6$ and $2.8 \times 10^5$ at the energies with 1 EeV and 100 EeV in twenty years when $\tau_\phi = 10^{18}$ s, respectively, as shown in Fig. 2 (see the blue dash line). The numbers of the detected UHE DM particles can reach about $7.2 \times 10^3$ and 280 at the energies with 1 EeV and 100 EeV in twenty years when $\tau_\phi = 10^{21}$ s, respectively, as shown in Fig. 2 (see the green dot line). The numbers of the detected UHE DM particles can reach about 7 and 1 at the energies with 1 EeV and 10 EeV in twenty years when $\tau_\phi = 10^{24}$ s, respectively, as shown in Fig. 2 (see the red dash dot line). The event rates for astrophysical neutrinos is smaller by 14 orders of magnitude at 1 EeV, compared to UHE DM when $\tau_\phi = 10^{24}$ s, as shown in Fig. 2 (see the black solid line). So the neutrino background can be neglected in the UHE DM detection at all. According to the results described above, it is possible that UHE DM particles are directly detected at the FD of Auger when $\tau_\phi \lesssim 10^{24}$ s.

Fig. 3 shows UHE DM fluxes estimated when $\tau_\phi = 10^{18}$ s (blue dash line), $10^{21}$ s (green dot line) and $10^{24}$ s (red dash dot line) and the upper limit for UHE DM flux at 90\% C.L. (black solid line) at the FD of Auger. According to the Auger data from 2008 to 2019 [52–54], no upward-going events are measured at the FD of Auger in this period of time. Meanwhile, the expected neutrino events is neglected at all. So the upper limit for the number of UHE DM particles $N_{up}$ is equal to 2.44 at 90\% C.L. with the Feldman-Cousins approach [55]. This limit excludes UHE DM flux below near 100 EeV when $\tau_\phi = 10^{18}$ s. Thus we know UHE DM particles can be measured at the FD of Auger when $10^{18} < \tau_\phi \lesssim 10^{24}$ s in the future.

JEM-EUSO is a fluorescence detector and of the larger observational area ($2 \times 10^5$ km$^2$ in the Nadir mode and $7 \times 10^5$ km$^2$ in the tilted mode. Its duty cycle $\sim 10\%$) [56]. For measuring UHE DM particles, JEM-EUSO has an advantage over the FD of Auger. So searching for UHE DM particles will depend on the beginning of taking data at JEM-EUSO or the long running time for Auger. This might prove whether there exist SHDM particles in the Universe.

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Fig. 1: UHE DM particles pass through the Earth and air and can be measured by the FD of Auger, via fluorescent photons due to the development of an EAS. $\theta$ is the polar angle for the Earth.

Fig. 2: The UHE DM and astrophysical neutrino event rates are evaluated at the FD of Auger. The blue dash line is denoting the UHE DM event rate when $\tau_\phi = 10^{18}$ s. The green dot line is denoting the UHE DM event rate when $\tau_\phi = 10^{21}$ s. The red dash dot line is denoting the UHE DM event rate when $\tau_\phi = 10^{24}$ s. The black solid line is denoting the astrophysical neutrino event rate.
Fig. 3: The UHE DM and fluxes and their upper limit at 90% C.L. are estimated at the FD of Auger. The blue dash line is denoting the UHE DM flux when $\tau_\phi = 10^{18}$ s. The green dot line is denoting the UHE DM flux when $\tau_\phi = 10^{21}$ s. The red dash dot line is denoting the UHE DM flux when $\tau_\phi = 10^{24}$ s. The black solid line is denoting their upper at 90% C.L. at the FD of Auger.