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Decaying superheavy dark matter and subgalactic structure of the Universe

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Abstract

The collisionless cold dark matter (CCDM) model predicts overly dense cores in dark matter halos and overly abundant subhalos. We show that the idea that CDM are decaying superheavy particles which produce ultra-high energy cosmic rays with energies beyond the Greisen–Zatsepin–Kuzmin cutoff may simultaneously solve the problem of subgalactic structure formation in CCDM model. In particular, the Kuzmin–Rubakov's decaying superheavy CDM model may give an explanation to the smallness of the cosmological constant and a new thought to the CDM experimental search.

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1. Introduction

Recent cosmological observations such as dynamical mass, Type Ia supernovae, gravitational lensing, and cosmic microwave background anisotropies, concordantly predict a spatially flat universe containing a mixture of 5% baryons, 25% cold dark matter (CDM), and 70% vacuum-like dark energy [1,2], termed as the standard ΛCDM model. The identities and the nature of dark matter and dark energy are among some of the biggest puzzles in contemporary physics.

Although the nature of CDM is yet unknown, it is successfully treated in many aspects as weakly interacting particles. However, there exist serious discrepancies between observations and numerical simulations of CDM halos in collisionless cold dark matter (CCDM) models [3–5], which predict too much power on small scales, manifested as cuspy CDM cores in dwarf galaxies [6], galaxies like the Milky Way [7], and central regions of galaxy clusters [8] as well as a large excess of CDM subhalos or dwarf galaxies within the Local Group [5].

To alleviate the discrepancies, among many other attempts, models of non-standard interacting CDM have been proposed. They include self-interactions [9], annihilations [10], and decaying cold dark matter (DCDM) [11,12]. Although these models involve different interactions, almost all interactions result in an adiabatic expansion of the cuspy halo that lowers the core density and reduces the number of subhalos.

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However, both self-interacting and annihilating CDM models require embarrassing large interaction cross-sections that have made the models less appealing. Although DCDM models are viable, possible underlying particle physics has been ignored.

Another big puzzle in astrophysics is the origin of the ultra-high energy cosmic rays (UHECR). One may expect that UHECR should originate from some unknown astrophysical sources at extragalactic scales. Greisen, Zatsepin, and Kuzmin (GZK) [13] observed that due to inverse Compton scatterings of the relic photons the UHECR energy spectrum produced at cosmological distances should steepen abruptly at energy $\sim 10^{10}$ GeV. However, a number of cosmic ray events with energies beyond the GZK cutoff have been observed by Fly's Eye [14] and AGASA [15]. A simple solution to this impasse is to invoke new physics in which UHECR can be produced in a cosmologically local part of the Universe. Ideas such as long-lived metastable superheavy particles that are decaying at the present epoch [16–20], annihilations of stable supermassive particles in halos [21], and collapses of cosmic topological defects [22] have been proposed. In most of the models the superheavy objects can simultaneously be viable candidates for DM.

In this Letter, we try to address these issues at the same time within a single theoretical framework. We pursue the DCDM scenario, suggesting that the CDM is decaying weakly interacting superheavy particles with mass of the grand unification scale. In our scenario, not only the decay would produce much less concentrated cores in CDM halos, but also the decay products contain highly energetic quarks and leptons which lead to the production of ultra-high energy cosmic rays (UHECR) with energies beyond the Greisen–Zatsepin–Kuzmin cutoff. Moreover, the longevity of the superheavy particles may shed new light on the origin of the observed small value of the cosmological constant.

The Letter is organized as follows. In Section 2 we illustrate our idea by using the Kuzmin–Rubakov model. After briefly reviewing this model, we show in Section 3 how this model can be naturally fitted into the scenario of DCDM. We show how this model solves the cuspy halo problem, and find out the parameter space which allow us to solve the origin of UHECR as well. In Section 4 we discuss some phenomenological implications and suggest that some on-going experiments could test this scenario.

2. Kuzmin–Rubakov model

Here we will concentrate on a specific scenario proposed by Kuzmin and Rubakov (KR) [19] and show how the KR scenario for producing UHECR is related to the subgalactic structure of the Universe.

KR [19] considered an extended standard model with a new $SU(2)_X$ gauge interaction and two left-handed $SU(2)_X$ fermionic doublets $\mathbf{X}$ and $\mathbf{Y}$ and four right-handed singlets. Here at least two doublets are introduced because the $SU(2)_X$ anomaly prevents the number of $SU(2)_X$ doublets from being odd. All new particles are singlets of the standard model, while some conventional quarks and leptons may carry non-trivial $SU(2)_X$ quantum numbers. The $SU(2)_X$ gauge symmetry is assumed to be broken at certain high energy scale, giving large masses $m_{X,Y}$ to all $\mathbf{X}$ and $\mathbf{Y}$ particles. Furthermore, $\mathbf{X}$ and $\mathbf{Y}$ are assumed to carry different global symmetries, so there is no mixing between them. As such, both the lightest of $\mathbf{X}$ and the lightest of $\mathbf{Y}$, which we call X and Y respectively, are perturbatively stable. However, $SU(2)_X$ instantons induce effective interactions violating global symmetries of X and Y. Assume $m_X > m_Y$, then the instanton effects lead to the decay

$$X \to Y + \text{quarks} + \text{leptons} \tag{1}$$

with a long lifetime roughly estimated as $\tau_X \sim m_X^{-1} \times e^{4\pi/\alpha_X}$, where α_X is the $SU(2)_X$ gauge coupling constant. With the choices $m_X \gtrsim 10^{13}$ GeV and $\alpha_X \lesssim 0.1$, $\tau_X \gtrsim 10$ Gyr and X particles are decaying at the present epoch. There have been many discussions on the production of X particles in the early Universe. X particles may be produced thermally during reheating after inflation with the produced energy density comparable to the critical energy density of the Universe [19] (see also Refs. [18,25]). Also, it was realized in the same or different context that superheavy particles can be efficiently generated from vacuum quantum fluctuations during inflation [26] or couplings to the inflaton field during preheating [27].

The particles X and Y are good dark matter candidates. According to KR, there are two possible outcomes after X particles have decayed. If Y particles

are perturbatively stable, they are also stable against instanton-induced interactions in virtue of energy conservation and instanton selection rules. In addition, if $m_X \gtrsim m_Y$, an approximately equal amount of Y particles is produced in the early Universe. Therefore, the decay products would contain stable supermassive Y particles that constitute a dominant fraction of the CDM with a small admixture of X particles as well as highly energetic quark jets and leptons that subsequently produce UHECR. Alternatively, the Higgs sector and its interactions with fermions may be organized in such a way that Y particles are in fact perturbatively unstable. As such, Y particles would instantly decay into relativistic particles and leave metastable X particles being the CDM.

Intriguingly, it has been recently pointed out that if the longevity of the superheavy particles in the KR model is due to instanton-induced decays, the observed small but finite cosmological constant can be explained by instantons or vacuum tunnelling effects in a theory with degenerate vacua [23]. In such a theory, the vacuum energy density of the true ground state is smaller than that in one of the degenerate vacua where we live now by an exponentially small amount if quantum tunnelling between the degenerate vacua is allowed [24].

3. Resolution of the cuspy halo problem and UHECR

We now turn to the cuspy halo problem and show how this problem can be solved within the context of the KR model. Numerical simulations of CCDM halos show cuspy halo density profiles well fit with the generalized Navarro–Frenk–White (NFW) form [3–5],

$$\rho(r) = \rho_c \left(\frac{r}{r_c}\right)^{-\alpha} \left(1 + \frac{r}{r_c}\right)^{\alpha-3}, \tag{2}$$

with the slope parameter $\alpha \simeq 1$–1.5 and the concentration parameter $c \equiv r_{200}/r_c \simeq 20$, where r_c is the core radius, ρ_c is the mean density of the Universe at the time the halo collapsed, and r_{200} is the radius within which the mean density ρ_{200} is 200 times the present mean density of the Universe. However, observations indicate flat core density profiles with $\alpha \lesssim 0.5$ and smaller concentrations with $c \simeq 6$–8 [6–8]. Below we will simply study the effect of DCDM to the original NFW profile with $\alpha = 1$ [3] in Eq. (2). Defining $x = r/r_{200}$, it gives the halo mass profile $M(x) = M_{200}F(x)$ that is the mass within x and the associated rotational velocity $V(x) = V_{200}[F(x)/x]^{1/2}$, where $M_{200} = M(x=1)$, $V_{200} = V(x=1)$, and

$$F(x) = \frac{\ln(1+cx) - cx/(1+cx)}{\ln(1+c) - c/(1+c)}. \tag{3}$$

Suppose a CDM halo gas composed of X particles is formed at some high redshift with the NFW profile and a velocity dispersion

$$v_X = \sqrt{GM_{200,X}/2r_{200,X}},$$

where $M_{200,X}$ is the mass of X particles within the radius $r_{200,X}$. The observed velocity dispersion typically ranges from 10 to 1000 km/s for dwarf halo to cluster halo. In X's rest frame, the decay (1) produces a Y with a recoiling velocity $\gamma_{\rm rc} v_{\rm rc} = \delta(1-\delta/2)/(1-\delta)$, where $\gamma_{\rm rc} = 1/\sqrt{1-v_{\rm rc}^2}$ and $\delta = (m_X - m_Y)/m_X$, and highly relativistic quarks and leptons of energy $E_{q,l} = \gamma_{\rm rc} v_{\rm rc} m_X(1-\delta)$. The value of δ depends on the detail dynamics of the high energy model. Here we will treat it as an input parameter. There are two possibilities. When $1 \gtrsim \delta > v_X$, we find that Y would be relativistic and/or beyond the escape velocity of the halo. This together with the case of an unstable Y correspond to the scenario discussed in Ref. [11], to which readers may refer for details. In the following, we will discuss the case for $\delta < v_X$, i.e., nearly degenerate masses, in which stable Y particles would be bound to the halo with an averaged velocity about $\sqrt{v_X^2 + v_{\rm rc}^2}$ ($v_{\rm rc} \simeq \delta$) just after the decay of X particles. In particular, $\delta \simeq (1$–$2) \times 10^{-4}$ corresponds to the case considered in Ref. [12].

Let us assume that most X particles have decayed and that the halo of Y particles with the NFW profile has been formed by now. Using the virial theorem it can be shown that the core radius has expanded to

$$r_{c,Y} = r_{c,X}/y,$$
$$y \equiv \frac{1-2\delta}{1-\delta} - \frac{\delta^2}{v_X^2}\frac{(1-\delta/2)^2}{(1-\delta)^3}. \tag{4}$$

We will follow the method in Ref. [11] to work out the consequences of this core expansion. The difference is that here the mass inside $r_{200,X}/y$ is only slightly changed to $(1-\delta)M_{200,X}$. As such, the final density

within $r_{200,X}/y$ is $y^3(1-\delta)\rho_{200}$. To obtain $r_{200,Y}$, we solve for $r = yr_{200,Y}$ in Eq. (2) ($\alpha = 1$) within which the initial density is $y^{-3}(1-\delta)^{-1}\rho_{200}$. The resulting equation is $x^3F^{-1}(x) = y^3(1-\delta)$ and we find that $r_{200,Y} \simeq y^{0.2}r_{200,X}$ for $y \lesssim 1$ and $\delta \ll 1$. Hence, we obtain $c_Y \simeq y^{1.2}c_X$. To circumvent the over-concentration problem, y should be about 0.4, implying that $\delta \sim 0.77v_X$. Using $c_X = 20$, $y = 0.4$, and Eq. (3), we obtain the mass profiles and rotation curves of the original X halo and the presently formed Y halo shown in Fig. 1. We find that $M_{200,Y} \simeq 0.58M_{200,X}$ and $M_Y(r = 0.1r_{200,Y}) \simeq 0.27M_X(r = 0.1r_{200,X})$, and that $V_{200,Y} \simeq 0.83V_{200,X}$, $V_{\max,Y} \simeq 0.64V_{\max,X}$, and $r_{\max,Y} \simeq 2.5r_{\max,X}$, where $V_{\max}$ is the maximum rotational velocity at radius $r_{\max}$. In Fig. 1, we have also reproduced the mass profile and the rotation curve for the case [11] in which X decays into relativistic particles. This requires solving for $x = r/r_{200,X}$ in the equation $x^3F^{-1}(x) = y^4$, where the mass inside $r_{200,X}/y$ is $yM_{200,X}$ and $y = 0.5$ is the fraction of X particles that still remain by now. In this case, the softening of the central concentration is the same as in the Y halo, but the reduction in the halo mass profile and the flattening of the rotation curve are even more pronounced. Thus we have shown that one can put KR model which was originally proposed to explain the origin of UHECR into the DCDM model.

Now let us examine the production of UHECR in the scenario proposed here and the applicability of the virial theorem for obtaining the Y halo profile in Eq. (4). It was found that the level of the UHECR and the UHE neutrino fluxes produced from X decays is proportional to a single parameter $r_X = \xi_X t_0/\tau_X$ for a fixed m_X, where ξ_X is the present fraction of X particles in CDM and $t_0 = 13.7$ Gyr is the age of the Universe [18] and there $r_X = 5 \times 10^{-11}/\delta$ was used to fit the observed UHECR flux spectrum. Note that a factor of δ is added because the energy of the decay relativistic quarks and leptons is $E_{q,l} \sim \delta m_X$, where $\delta \sim 1$ for the case in Ref. [18] and here $\delta \sim 0.77v_X \sim 10^{-3}$ (where v_X is about 300 km/s) and $m_X = 10^{16}$ GeV, and also that the parameter r_X will be larger if the energy dissipation of the decay particles is taken into account [28]. Assume that the X halo is originally formed at 0.1–1 Gyr and that $\tau_X = 0.7$ Gyr. Then the dynamical effect of X decays on the halo is at work from about 0.7 Gyr to the present time. Since X and Y are non-relativistic and $\tau_X \ll t_0$,

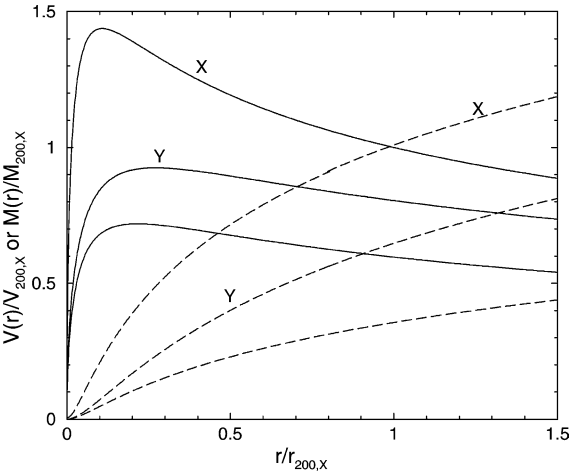

Fig. 1. Solid (dashed) curves represent respectively from up to down the rotation curves (mass profiles) for the X halo which is from the NFW profile in the CCDM model, the Y halo in the DCDM model, and the case in which X decays into relativistic particles. The x-axis (y-axis) is in unit of r_{200} of the X halo (V_{200} for solid curves and M_{200} for dashed curves).

most X particles have decayed into Y particles many gigayears ago and the Y DM halo has been virialized. Otherwise, one should treat the recoil velocities in a more proper way as considered in Ref. [12] to estimate the resulting halo profile. Hence we can see that we have found out the allowed parameter space which is consistent with current observation data and justified the method we used. In short, the fraction of remaining X particles in the recently formed Y DM halo is tiny and given by $\xi_X \sim 10^{-9}$, and they are decaying at the present epoch to produce the observed UHECR flux [18]. Furthermore, the possible distortions of the ionization history of the Universe caused by the energy injection from decays of these relatively short-lived X particles have been recently discussed and the superheavy DCDM model is able to provide a good fit to the current CMB anisotropy and polarization data [29]. On the other hand, the scenario proposed in Ref. [11], where $\xi_X = 1$ and $\tau_X \sim t_0$, would produce unacceptably large flux of UHECR unless the relativistic particles produced from the X decay involve some exotic quarks and leptons which are weakly interacting and may generate UHECR at an acceptable level by interacting with the interstellar medium when propagating to the Earth.

4. Phenomenological implications

We have shown that the KR model that has attempted to explain the presence of UHECR with energies beyond the GZK cutoff can easily provide a DCDM solution for the problem of subgalactic structure formation in the CCDM model. In the DCDM model in which X DM decay into relativistic particles [11], not only halo core density is lowered but also small dwarf galaxies are darkened due to core expansion and subsequent quenched star formation. It has also been argued that presently observed dwarf spheroidal galaxies with lower velocity dispersions were resulted from decaying dark matter and subsequent core expansion in a small fraction of halos with high velocity dispersions [30]. This model predicts that the small-scale power at higher redshift is enhanced compared to the CDM model as well as the gas fraction in clusters should decrease with redshift. The latter can be tested by X-ray and Sunyaev–Zel'dovich effect observations. However, this model has been criticized for that the reduction in the central density of clusters of galaxies due to X DM evaporation might be too large to be compatible with observations and could even be harmful to the halo substructure formation [12]. It has been pointed out that this excessive reduction can be remedied if X particles decay into non-relativistic stable massive Y DM, and shown that the Y DM provides well fits to the rotation curves of low-mass galaxies and does not necessarily produce a significant reduction of the central DM density of certain dwarf spheroidals [12]. Undoubtedly, detailed numerical simulations of the subgalactic structure formation in the DCDM model versus high-quality observations on the properties of subhalos and X-ray/Sunyaev–Zel'dovich effect of clusters would test the DCDM model and should differentiate the two scenarios. Remarkably, the subhalo astrophysics at kpc scales may provide a hint to understand the mass difference between X and Y in the KR model at energy scale of grand unification.

To test models of superheavy particles directly in terrestrial particle accelerators is quite impossible. However, the particle spectra and the arrival directions of UHECR produced from decays of superheavy particles in the Galactic halo can provide crucial tests. Superheavy particles decay into ultra high-energy quark and lepton jets which fragment predominantly into photons with a small admixture of protons [18,19]. Although UHECR observations seem to show a subdominant photon flux [31], the photon flux with energies near the GZK cutoff may be attenuated in the cascading of the jets in the radio background and intergalactic magnetic fields [22]. The ultra high-energy neutrino flux accompanying the UHECR has been calculated [17,18,32] to be much higher than the proton flux due to the long mean free path and high multiplicity of neutrinos produced in high-energy hadronic jets. This neutrino flux is near the detection limit of the on-going AMANDA neutrino experiment and will be severely constrained by the upgraded AMANDA and next generation neutrino telescope IceCube. Because of the off-center location of the Solar system in the Galactic halo, some amount of anisotropy in the arrival directions of UHECR is expected [22]. Recently it was claimed that no significant deviation from isotropy is found, based on the data from the SUGAR and the AGASA experiments taken a 10-year period with nearly uniform sky coverage [33]. This may be overturned due to insufficient statistics. It is likely that the signal of the predicted anisotropy will have to wait to be tested by the upcoming Pierre Auger Observatory.

As pointed out by KR [19], instanton mediated decay processes typically lead to multiparticle final states. Thus X particle decays will produce a relatively large number of quark jets with a fairly flat energy distribution and rather hard leptons as compared to typical perturbative decays of superheavy particles. This may leave a distinct signature in the predicted UHECR spectrum which may help in distinguishing the KR model from other DCDM models. Furthermore, in the KR model which has $\delta \lesssim 1$, the energy of the relativistic Y particle is about $m_X/2$ and the flux of Y particles in the Solar vicinity is approximately given by $n_X R_{\rm halo}/\tau_X \sim 10^{-5} n_X$, where $R_{\rm halo} \sim 100$ kpc is the size of the Galactic halo. This flux is about two orders of magnitude lower than the local flux of typical halo DM which is estimated as $n_X v_X \sim 10^{-3} n_X$ (where v_X is about 300 km/s). If the Y particle interacts weakly with ordinary matter, it may scatter with the target nucleus with mass m_N in a cryogenic detector and deposit a huge amount of energy of order $m_N(1-\delta)^{-2}$ in the detector. This deposit energy is much larger than that of a typical halo DM particle which is about $m_N v_X^2$. This may give a new thought to the direct

detection of halo DM. Unfortunately, since the local number density of X is $n_X \sim (\mathrm{GeV}/m_X)\,\mathrm{cm}^{-3}$ strongly suppressed by the mass of X and X is weakly interacting, the direct search for halo X particles or the indirect search for high-energy neutrinos from decaying X particles captured in the Sun or the Earth in current experiments are elusive [34]. However, it is worth noting that the fluxes of X-induced high-energy neutrinos from the Sun and the Earth are expected to be similar, though they are relatively low, to those considered in a different context of annihilation of strongly interacting superheavy DM which are predominantly tau neutrinos with a flat energy spectrum of events at about few TeV [35] and distinguishable from the energy spectrum of high-energy neutrinos induced by neutralino DM [36].

5. Conclusions and discussions

In conclusion we have discussed the implication of the Kuzmin–Rubakov's decaying superheavy dark matter model for generating cosmic rays with energies beyond the Greisen–Zatsepin–Kuzmin cutoff to the subgalactic structure formation of the Universe. The model involving a new $SU(2)_X$ gauge interaction and two left-handed $SU(2)_X$ fermionic doublets $\mathbf{X}$ and $\mathbf{Y}$ can easily accommodate decaying dark matter scenarios for solving the cuspy halo problem inherent in the collisionless cold dark matter model. Intriguingly, the longevity of X particles due to instanton mediated decays may explain the presence of a small cosmological constant as well.

The drawback is that we require the near-degeneracy of X and Y particle masses. However, this may have recourse to physics at the relevant high energy scale. In order to obtain the near mass degeneracy between X and Y particles, we assume that at high energies there is a symmetry, for example, an exchange symmetry between X and Y, that makes their masses equal. Small mass differences could be generated by radiative corrections from symmetry breaking terms arising via threshold corrections near grand unification scale or even from stringy effects near Planck scale. For example, consider a term $\lambda_1\mathcal{L}_1$ which contains X and other heavy fields. The one-loop correction lifts X mass by a factor of $\lambda_1^2/16\pi^2 m_X$, giving rise to $\delta \sim 10^{-2}$ for $\lambda_1 \sim 1$. To get an even smaller δ, we may use the idea of collective breaking of symmetries. Instead of using one single coupling to break the symmetry, we introduce another similar coupling $\lambda_2\mathcal{L}_2$ in such a way that each coupling by itself preserves sufficient amount of symmetry such that the mass degeneracy between X and Y is exact at one-loop level. It is only when the simultaneous presence of both symmetry breaking terms the mass degeneracy will be lifted. Therefore, the radiative corrections which lift the mass degeneracy of X and Y are necessarily proportional to both λ_1 and λ_2. Hence, this mass degeneracy splitting effect occurs at two-loop level and is of order $\lambda_1^2/16\pi^2$ which is sufficiently small even for $\lambda_1 \sim \lambda_2 \sim 1$. An alternative mechanism for generating a small mass difference between X and Y particles is closely related to the result of instanton effects considered here. The mass relation between X and Y may be slightly modified by non-perturbative mass renormalization due to instanton-induced counterterms, similar to instanton-generated quark masses considered in QCD physics [37].

It is quite interesting to link different astrophysical and cosmological problems in a single particle model at grand unification scale. Future observations of dark matter halos and ultra high-energy cosmic rays, halo dark matter experimental search, and future CMB anisotropy and polarization measurements will test the decaying dark matter models and shed light on the mass degeneracy of X and Y.

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