Dark Matter Annihilation from Nearby Ultra-compact Micro Halos to Explain the Tentative Excess at $\sim$1.4 TeV in DAMPE data

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(Dated: December 6, 2017)

The tentative 1.4 TeV excess in the e^+e^- spectrum measured by The DArk Matter Particle Explorer (DAMPE) motivates the possible existence of one or more local dark matter concentrated regions. In particular, Ultra-compact Micro Halos (UCMHs) seeded by large density perturbations in the early universe, allocated within 0.3 kpc from the solar system, could provide the potential source of electrons and positrons produced from dark matter annihilation, enough to explain the DAMPE signal. Here we consider a UCMH with density profile assuming radial in-fall and explore the preferred halo parameters to explain the 1.4 TeV "DAMPE excess". We find that typical parameter space of UCMHs can easily explain the "DAMPE excess" with usual thermal-averaged annihilation cross section of WIMP. The fraction of dark matter stored in such UCMHs in the Galactic-scale halo can be reduced to as small as $O(10^{-5})$, well within the current cosmological and astrophysical constraints.

PACS numbers:

INTRODUCTION

The DArk Matter Particle Explorer (DAMPE; [1, 2]) is the first Chinese space mission for astronomical study, it was successfully launched from Jiuquan Satellite Launch Center on December 17, 2015. It has already surveyed the full sky four times and collected almost two-year cosmic rays data continuously. Recently, the DAMPE collaboration has published the positron-electron energy spectrum as the first scientific results from DAMPE, which extends the direct detection of electron energy spectrum with a spaceborne detector to 4.6 TeV [3].

The DAMPE measurement has unprecedentedly high energy resolution, low particle background, and well controlled instrumental systematics. Although the majority of the spectrum can be fitted by a smoothly broken power-law model with a spectral break at E$\sim$0.9 TeV, a tentative peak at $\sim$1.4 TeV in e^+e^- total spectrum has been claimed [3]. The excess of the e^+e pairs at 1.4 TeV is approximately 2.5×10^{-8} GeV^{-1} s^{-1} sr^{-1} m^{-2} from the detected electron-positron energy spectrum of DAMPE [4]. Since the first publication there have been extensive discussion on the possible theoretical explanation and observational constraints on the explanations of the "DAMPE excess" with both particle origin or astrophysical origin. [5–19].

In the DAMPE data, the electron and positron excess events occur only in one energy bin around 1.4 TeV. Such sharp peak in e^+e^- energy spectrum is unexpected because high energy electrons quickly lose energy through synchrotron radiation and inverse Compton scattering while propagating in the Milky Way. The localized feature in the energy spectrum of the excess events hints a nearby source of the high energy electrons and positrons. If explained by DM, the source of such energetic and monochromatic electrons and positrons has to be closed to the solar system.

The Ultra-compact Micro Halos (UCMHs) have been proposed as a potential dark matter formed structure, whose cosmological and astrophysical constraints are widely discussed in different areas [20–22]. UCMHs can be collapsed and formed in the early universe from mechanisms e.g. phase-transitions in the early universe, inflation, and topological defects like cosmic strings [20, 23]. As UCMHs intrinsically have denser dark matter density with a steeper density profile than the standard NFW profile of DM subhalo, and higher chance to survive from tidal stripping in the Galactic halo, they may offer unique opportunities to provide strongest DM annihilation/decay signals nearby solar system. One would expect to observe stronger radiation and higher flux of cosmic rays including high-energy positron-electron pairs, gamma rays, and neutrinos from UCMHs than the center of the Milky Way. On the other hand, these small mass UCMHs might not have accreted enough baryonic matter to provide observable signal in radio and gamma ray.

In this letter, we study the possibility of attributing the excess of the "DAMPE excess" to the DM annihilations in the vicinity of the solar system. We consider one or more UCMHs nearby as the cosmic ray source [24–26], where e^+e^- flux is produced through the pair annihilation of dark matter particle. We explore if such scenario could explain the DAMPE signal with the limits on the abundance of these primordial UCMHs structures.There is an apparent link between annihilation cross-section

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of a hypothetical WIMP and the abundance fraction of UCMHs themselves in the Galactic halo. A large population of UCMHs could be easily unobservable with a small WIMP annihilation cross-section. If we assume all DAMPE observed 1.4 TeV signal comes from dark matter annihilation in the UCMHs, this would mean that we could set upper limits on the UCMH abundance (given a mass range and the distance to the structure) via annihilation cross-sections will simply return more and more permissive bounds the more refined the annihilation search becomes. In this framework, we could use multi-frequency emissions from the UCMHs to determine what independent limits can be placed on UCMH abundance in the future.

We calculate the properties of the UCMH, including its mass and radius, as a function of its distance to the Earth. In Sec. II, we first introduce the profile of UCMHs. In Sec. III, we study the parameters of UCMHs to explain the 1.4 TeV e^+e^- excess measured by DAMPE.

UCMHS' MODEL

There are many possible mechanisms to trigger the formation of UCMHs, such as sizable density fluctuations at small scales. A over-dense region can efficiently accumulate DM particles after matter-radiation equaltity. The accretion process will stop when dynamical friction becomes important. We take the cut off in accretion to be the beginning of star formation. Thus the current properties of UCMH nowadays is determined by the profile at $z \sim 10$. Note, that the core of UCMHs are dense and safe from tidal perturbations during the evolution [27].

Such UCMHs, if exists, can induce interesting astrophysical signatures. The UCMHs are formed through radial in-fall [22, 28], indicating the density profile of UCMH as

$$\rho_{UCMH}(z,r) = \frac{3f_\chi M_{UCMH}(z)}{16\pi R_{UCMH}^{3/4}(z) r^{9/4}}, \tag{1}$$

f_χ is the dark matter fraction, $M_{UCMH}(z)$ is the mass of UCMH at redshift z, and r is the distance away from the center of UCMH. The effective radius of UCMH, $R_{UCMH}(z)$, is obtained from numerical simulations [29, 30]

$$R_{UCMH}(z) = 0.019\mathrm{pc}\left(\frac{1000}{1+\mathrm{z}}\right)\left(\frac{\mathrm{M_{UCMH}(z)}}{\mathrm{M}_\odot}\right)^{1/3}. \tag{2}$$

The radial in-fall approximation breaks down when angular momentum of infalling gas becomes important. The scaling behavior, $r^{-9/2}$, in Eq. 1 is truncated at a cut-off radius r_c [20],

$$\frac{r_{c,ang}}{R_{UCMH}(0)} = 2.9\times10^{-7}\left(\frac{1000}{1+z_{coll}}\right)^{2.43}\left(\frac{M_{UCMH}(0)}{M_\odot}\right)^{-0.06} \tag{3}$$

where z_{coll} is the redshift when the UCMH collapsed, which we take to be around 1000 as the smallest allowed redshift of collapse. The density is approximately constant when $r < r_c$.

At the meanwhile, if DM annihilation cross section is sizable, such process is not negligible when DM density is high. This imposes an additional modification to the DM profile considered above, i.e. an upper limit on DM density,

$$\rho_{c,ann}(t) = \frac{m_\chi}{(t-t_i)\langle\sigma v\rangle}, \tag{4}$$

where m_χ is the mass of a dark matter particle. t_i is taken to be the time of matter-radiation equlibrium, i.e. $t_i = t(z_{eq}) = 59$Myr. t is the taken to be 13.799Gyr for UCMHs nearby. $\langle\sigma v\rangle$ is the thermally-averaged annihilation cross section of the dark matter particle.

Thus the truncation of the UCMH profile is determined by the competition between $r_{c,ang}$ and $r_{c,ann}$, i.e. $r_c = \max(r_{c,ann}, r_{c,ang})$. Take typical averaged-thermal annihilation cross section as a benchmark, $\langle\sigma v\rangle = 3\times10^{-26}\mathrm{cm}^3/\mathrm{s}$, and set $m_\chi = 1.4$ TeV, we find that as long as UCMH mass is larger than 1.67×10^9g, r_c is always determined by $r_{c,ann}$.

The full piecewise expression of the density of an UCMH at some radius r will be:

$$\rho_{UCMH}(r) = \begin{cases} \rho_c,\ 0 \le r \le r_c \\ \rho_c(\dfrac{r}{r_c})^{-9/4},\ r_c < r \le R_{UCMH}(z) \\ 0,\ r > R_{UCMH}(z) \end{cases} \tag{5}$$

where ρ_c is determined by the UCMH profile in Eq. 1 at $r = r_c$. Further, since we are focused on UCMHs nearby the solar system, these UCMHs should have already stopped accretion process, and z is set to be 10, i.e. the redshift when star formation happens.

ELECTRON-POSITRON PAIRS EXCESS ON 1.4 TEV

Due to the existence of galactic magnetic field, e^+e^- does not follow a straight line. Their flux after injection from a source can be described by the transport equation,

$$\frac{\partial n}{\partial t} = D(E)\,\nabla^2 n + Q_s(E)\delta(\vec{x}-\vec{x}_s) \tag{6}$$

where $D(E)$ is the spatial diffusion coefficient. We take $D(E) \simeq 10^{29}\mathrm{cm}^2/\mathrm{s}$ for 1.4 TeV e^+e^- propagating in our galaxy. This gives the travel distance of these electrons as $\lambda \sim$O(1) kpc. In order to achieve the peak structure in the observed electron positron flux, the source needs to be nearby the solar system, i.e. $R < 0.3$ kpc. In this regime, the stationary solution of the transport equation, neglecting energy loss processes, can be written as

$$n_e(R,E) = \frac{Q_e(E)}{4\pi\, R\, D(E)} \tag{7}$$

The 1.4 TeV peak observed at DAMPE indicates the radial energy density distribution of electrons as $w_e \simeq 1.2 \times 10^{-8}\mathrm{erg/cm^3}$ [4]. This translates to the source injection power as,

$$\begin{aligned}\dot{Q} = \quad & 5\times 10^{32}\mathrm{erg/s}\left(\frac{\mathrm{R}}{0.1\mathrm{kpc}}\right)\left(\frac{\mathrm{D(E)}}{10^{29}\mathrm{cm^2/s}}\right) \\ & \times \left(\frac{w_e}{1.2\times 10^{-18}\mathrm{erg/cm^3}}\right)\end{aligned} \tag{8}$$

Now we use source injection power to extract the properties of the nearby UCMH which gives the observed e^+e^- flux.

FIND THE SUITABLE MASS OF AN UCMH TO FIT THE ELECTRON-POSITRON PAIRS EXCESS

We only focus on the $e^{\pm}$ annihilation channel with velocity-averaged cross section $\langle\sigma v\rangle = 3\times10^{-26}$ cm^3 s^{-1}. Then, the annihilation rate per dark matter particle is

$$\frac{\rho_{UCMH}(r)}{m_\chi} \times \langle\sigma v\rangle. \tag{9}$$

The total annihilation rate in the volume $dV = 4\pi r^2 dr$ is obtained by multiplying Eq. 9 by the total number of particles in the volume:

$$\left(\frac{\rho_{UCMH}(r)}{m_\chi}\langle\sigma v\rangle\right) \times \left(\frac{\rho_{UCMH}(r)}{2m_\chi}dV\right). \tag{10}$$

Note that the factor of two in the denominator comes from the fact that there are two particles involved in every annihilation interaction.

As the density profile is piecewise, this integral also needs to be integrated by parts:

$$\begin{aligned} I &= \int_V dV \rho^2_{UCMH}(r) \\ &= \left(\int_0^{r_c} + \int_{r_c}^{R^0_{UCMH}}\right) 4\pi r^2 \rho^2_{UCMH}(r) dr \\ &= \int_0^{r_c} 4\pi r^2 \rho_c^2 dr + \int_{r_c}^{R^0_{UCMH}} 4\pi \rho_c^2 r_c^{9/2} r^{-5/2} dr, \end{aligned} \tag{11}$$

Then by equating the continuous rate $\dot{Q}$ of monoenergetic electrons and positrons to the total annihilation rate of WIMPs from a UCMH,

$$\dot{Q} = \frac{\langle\sigma v\rangle}{2m_\chi^2} I \times 2E_0, \tag{12}$$

where E_0=1.4 TeV is the proposed energy of each e± pairs produced by WIMPs' annihilation.

Combining Eqs. 1, 2, 8 & 12, we can calculate the mass of the UCMH, the effective radius of the UCMH and the angular separation of the UCMH we observe, if the distance from the Earth to it is given. For example, if $R = 100$pc, the nowadays mass of the UCMH is obtained in terms of solar mass $M_\odot$,

$$M^0_{UCMH} = 2.5\times 10^{33}\mathrm{g} \approx 1.3 M_\odot. \tag{13}$$

If $R = 300$pc, we get

$$M^0_{UCMH} = 7.5\times 10^{33}\mathrm{g} \approx 3.8 M_\odot. \tag{14}$$

The relation between the distance to the UCMH and the mass of this UCMH is shown in Fig. 1. We see that as the distance to this UCMH increases, its mass required to produce sufficient annihilation e± flux increase accordingly. In Fig. 2, we show how the effective radius of such UCMH changes as the distance to it changes. And given the effective radius and the distance to the UCMH, we can estimate the angular separation of this compact object, which is shown in Fig. 3.

One natural question to study is the fraction of DM stored in the UCMHs. Assuming small density perturbation at O(10^{-5}) to start with, the numerical simulations indicates a very low probability to generate an over-dense regime in order to explain DAMPE excess at 1.4 TeV [4]. On the other hand, in Fig. 4, we show the fraction of DM stored in UCMHs in order to have at least one UCMH at certain distance away from the solar system. We see that UCMH scenario provide a very natural explanation to the DAMPE excess. Here we set the mean DM density around solar system $\bar{\rho}_\chi = 0.4\mathrm{GeVcm^{-3}}$. Given the distance to the UCMH, R, we can obtain the mass of this UCMH and thus the fraction

$$f(R) = \frac{M^0_{UCMH}}{M_\chi(R)} = \frac{3M^0_{UCMH}}{4\pi\bar{\rho}_\chi R^3}. \tag{15}$$

DISCUSSION

The tentative peak at 1.4 TeV in e^+e^- spectrum measured by DAMPE motivates the possibility of dark matter annihilation in nearby structure. The diffusion of cosmic-ray electrons and positrons can easily smear the sharp peak structure in the energy spectrum across kpc propagation scale. Thus an over-dense regime near the solar system is motivated by the sharp structure at TeV electron spectrum. Ordinary collisionless cold dark matter in subhalos of the Milky Way cannot easily produce such over dense objects. On the other hand, UCMHs are natural consequences of moderate density perturbations in the early universe. A nearby UCMH may serve as a

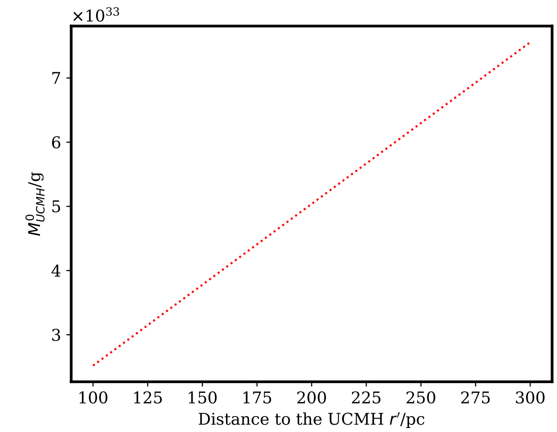

FIG. 1: The relation between the mass of UCMHs and the distance to the UCMH

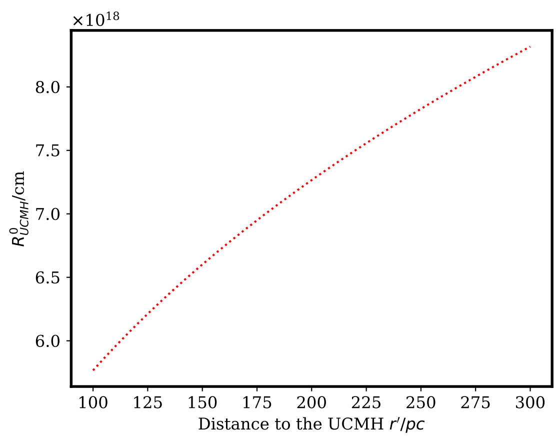

FIG. 2: The relation between the effective radius of UCMHs and the distance to the UCMH

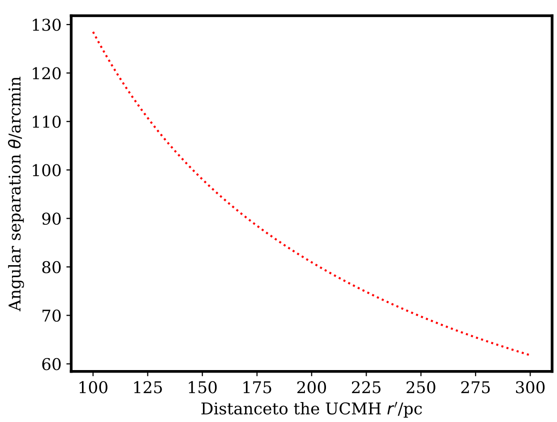

FIG. 3: The relation between the effective angular separation of UCMHs and the distance to the UCMH

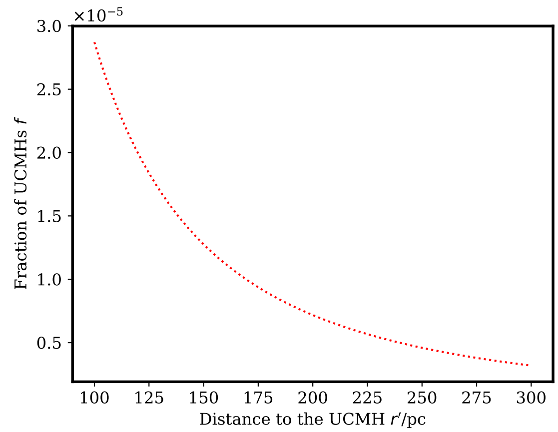

FIG. 4: The fraction of UCMHs and the distance to the UCMH

potential dark matter object to explain the e^+e^- excess measured by DAMPE.

With simple assumptions, such as radial in-fall approximation, the parameters of UCMH profiles are correlated with each other and only few intrinsic parameters are remained to be determined, including $\{M_{UCMH}, f_\chi, \langle\sigma v\rangle\}$. Assuming conventional thermal-averaged WIMP annihilation cross section, we have determined the M_{UCMH} as a function of the distance between the target UCMH and the solar system. Furthermore, we find that with reasonable choice of model parameters, only a small fraction of DM allocated in the object of UCMHs can induce enough annihilation signal (from one or more UCMHs) near the solar system to explain the DAMPE signal.

UCMH seeded by cosmic strings could produces UCMHs with considerably larger central cores and has less constraints from multiwavelength observations. The gamma ray from bremsstrahlung and inverse Compton radiation when electron positron are produced is inevitable. Using Fermi satellite along with DAMPE gamma-ray deata sets for such source search in gamma ray in the context of DAMPE excess will be further studied in the future work.

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