

## Constraints on ultracompact minihalos using neutrino signals from gravitino dark matter decay \*

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**Abstract** Ultracompact dark matter minihalos (UCMHs) would be formed during the early universe if there were large density perturbations. If dark matter can decay into particles described by the standard model, such as neutrinos, these objects would become potential astrophysical sources of emission which could be detected by instruments such as IceCube. In this paper, we investigate neutrino signals from nearby UCMHs due to gravitino dark matter decay and compare these signals with the background neutrino flux which is mainly from the atmosphere to obtain constraints on the abundance of UCMHs.

**Key words:** dark matter — early universe — dark matter halos

### 1 INTRODUCTION

Structure formation is one important research field in cosmology. According to the theory, the cosmic structures observed at present originated from earlier density perturbations with amplitude  $\delta\rho/\rho \sim 10^{-5}$  and this has been confirmed by many studies. On the other hand, primordial black holes would be formed if there were large density perturbations ( $\delta\rho/\rho > 0.3$ ) in the early universe (Green & Liddle 1997). Recently, Ricotti & Gould (2009) found that if the amplitude of density perturbations was between the above values, a new kind of dark matter structure called ultracompact dark matter minihalos (UCMHs) would be formed. Compared with classical dark matter halos, the formation time for these objects is earlier ( $z \sim 1000$ ) and the density profile is steeper ( $\rho(r) \sim r^{-2.25}$ ). If dark matter is in the form of weakly interacting massive particles (WIMPs), such as the neutralino, it can annihilate into particles described by the standard model, such as photons, positrons or neutrinos (Jungman et al. 1996; Bertone et al. 2005). Moreover, because the dark matter annihilation rate is proportional to the square of the number density, UCMHs would become

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one kind of potential astrophysical source of emission (Scott & Sivertsson 2009; Bringmann et al. 2012; Yang et al. 2013a,b). In addition to annihilation, decay is another important approach for detecting dark matter signals. This is especially crucial for those dark matter candidates that do not annihilate. A famous example is gravitino dark matter which in some supergravity models is the lightest supersymmetric particle (Bertone et al. 2005). Although compared with annihilation, the decay rate is proportional to the number density instead of the number density squared, decay is still very important for cosmological probes of dark matter particles which do not have annihilation channels. Yang et al. (2013c) have investigated the gamma-ray flux from nearby UCMHs due to dark matter decay. Through comparing with observations, they obtained constraints on the abundance of UCMHs for different decay channels, lifetimes and density profiles of the Milky Way. They found that the strongest constraint comes from the  $b\bar{b}$  channel with dark matter mass  $m_\chi = 100\text{GeV}$ , and the fraction of UCMHs is  $f_{\text{UCMHs}} \sim 5 \times 10^{-5}$ .

Besides high energy photons, the other kind of important product of dark matter decay is neutrinos which are usually accompanied by photons. The advantage of neutrino detection is that neutrinos can propagate through space without attenuation due to their very weak interaction with other particles. Therefore, compared with other particles (e.g. electrons and positrons) the orientation of corresponding sources can be directly confirmed. When neutrinos propagate through a medium, such as ice, muons ( $\mu$ ) can be produced by the charged current interaction and detected by a Cherenkov radiation detector. Because neutrino signals accompany the production of a gamma-ray, the study of neutrino signals would be complementary to gamma-ray observations, especially because of the larger mass of dark matter and availability of lepton channels (Sandick et al. 2010; Abbasi et al. 2011; Ackermann et al. 2011). In this paper, we will investigate neutrino signals from UCMHs due to dark matter decay. As we have not observed any excess of neutrino flux compared with atmospheric neutrino flux, we get constraints on the abundance of UCMHs.

This paper is organized as follows. The neutrino flux from nearby UCMHs due to dark matter decay is studied in Section 2. In Section 3, we obtain constraints on the fraction of UCMHs. We conclude with discussions in Section 4.

## 2 THE BASIC QUALITY OF UCMHS AND POTENTIAL NEUTRINO SIGNALS DUE TO DARK MATTER DECAY

After the formation of UCMHs, dark matter particles will be accreted by the radial infall. The density profile of UCMHs can be obtained through a simulation (Ricotti & Gould 2009; Scott & Sivertsson 2009),

$$\rho(r, z) = \frac{3f_\chi M_{\text{UCMHs}}(z)}{16\pi R(z)^{\frac{3}{4}} r^{\frac{9}{4}}}, \quad (1)$$

where  $M_{\text{UCMHs}}(z) = M_i \frac{1+z_{\text{eq}}}{1+z}$  is the mass of UCMHs and  $M_i$  is the mass within the scale of perturbations,

$$R(z) = 0.019 \left( \frac{1000}{z+1} \right) \left[ \frac{M_{\text{UCMHs}}(z)}{M_\odot} \right]^{\frac{1}{3}} \text{ pc}$$

is the radius of UCMHs at redshift  $z$  and  $f_\chi = \frac{\Omega_{\text{CDM}}}{\Omega_{\text{CDM}} + \Omega_{\text{b}}} = 0.83$  (Komatsu et al. 2011).

The muons produced in the detector through the charged current interactions are called contained events. Their flux can be written as (Erkoca et al. 2009; Yang et al. 2013b)

$$\frac{d\phi_\mu}{dE_\mu} = \int_{E_\mu}^{m_\chi} dE_\nu \frac{d\phi_\nu}{dE_\nu} \frac{N_A \rho}{2} \left[ \frac{d\sigma_\nu^P(E_\nu, E_\mu)}{dE_\mu} + (p \rightarrow n) \right] + (\nu \rightarrow \bar{\nu}), \quad (2)$$

where  $N_A = 6.022 \times 10^{23}$  is Avogadro's number and  $\rho$  is the density of the medium,  $d\sigma_{\nu, \bar{\nu}}^{p,n}/dE_\mu$  are the weakly scattering charged-current cross sections for neutrinos and antineutrinos scattering

with protons and neutrons,  $d\phi_\nu/dE_\nu$  is the differential flux of a neutrino from UCMHs due to dark matter decay,

$$\frac{d\phi_\nu}{dE_\nu} = \frac{1}{d^2} \times \frac{1}{m_\chi \tau} \left( \sum B_F \frac{dN_\nu^F}{dE_\nu} \right) \int \rho(r) r^2 dr, \quad (3)$$

where  $dN_\nu/dE_\nu$  is the neutrino number per dark matter decay and  $B_F$  is the branching ratio of every decay channel.  $m_\chi$  and  $\tau$  are the dark matter mass and lifetime respectively, and  $d$  is the distance of UCMHs.

In this paper, we consider the gravitino ( $\psi_{\frac{3}{2}}$ ) in the dark matter decay model. The gravitino is the lightest supersymmetric particle and it can decay into particles described by the standard model by breaking R-parity symmetry (Steffen 2009). There are three-body and two-body decay models for gravitino particles and the three-body decay models can supply one of the explanations for positron excess observed by the PAMELA experimental payload and *Fermi* spacecraft (Bajc et al. 2010). In this paper, we mainly consider the model  $\psi_{\frac{3}{2}} \rightarrow l^+ l^- \nu$ . Here,  $l$  could be  $\mu$  or  $\tau$ . Because the observation and identification of  $\nu_\mu$  is easier than that of  $\nu_\tau$ , we mainly consider the  $\mu(\nu_\mu)$  channel. On the other hand, the second muon neutrino can also be produced through the decay of  $\mu$  which is from three-body decay. Although the contribution of this process is much smaller than that from the primary case, we also include it in our calculations. For the neutrino spectrum of these decay channels, we use the forms which have been given in Erkoca et al. (2010b).

Besides the contained events, the flux of the muons produced before arriving at the detector are called upward events (Erkoca et al. 2009; Yuan et al. 2010),

$$\frac{d\phi_\mu}{dE_\mu} = \int_{E_\mu}^{m_\chi} dE_\nu \frac{d\phi_\nu}{dE_\nu} \frac{N_A \rho}{2} \left[ \frac{d\sigma_\nu^P(E_\nu, E_\mu)}{dE_\mu} + (p \rightarrow n) \right] R(E_\mu) + (\nu \rightarrow \bar{\nu}), \quad (4)$$

where  $R(E_\mu)$  is the muon range or stopping distance at which muons can propagate in matter until their energy is below the threshold of the detector  $E_\mu^{\text{th}}$  and it is given by  $R(E_\mu) = \frac{1}{\beta \rho} \ln\left(\frac{\alpha + \beta E_\mu}{\alpha + \beta E_\mu^{\text{th}}}\right)$  (Sandick et al. 2010), with  $\alpha$  corresponding to the ionization energy loss and  $\beta$  accounts for the bremsstrahlung pair production and photonuclear interactions.

For neutrino detection, the main background is from the atmosphere. The angle-averaged atmospheric flux (ATM) is in the form of (in units of  $\text{GeV}^{-1} \text{km}^{-2} \text{yr}^{-1} \text{sr}^{-1}$ ) (Erkoca et al. 2010a)

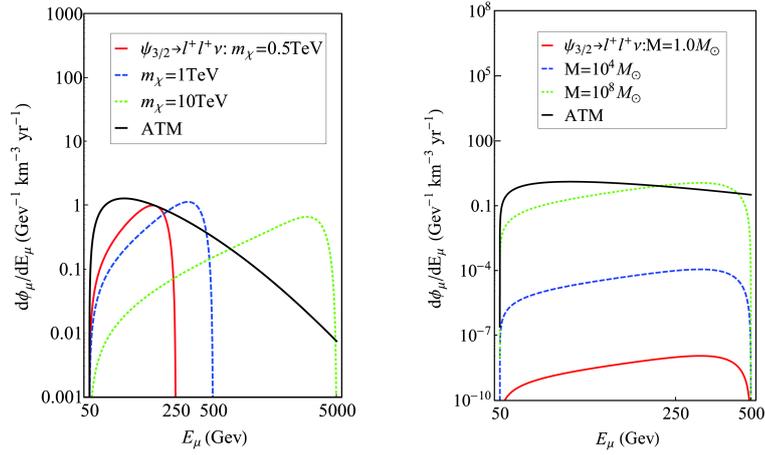
$$\left( \frac{d\phi_\nu}{dE_\nu d\Omega} \right)_{\text{ATM}} = N_0 E_\nu^{-\gamma-1} \times \left[ \frac{a}{b E_\nu} \ln(1 + b E_\nu) + \frac{c}{e E_\nu} \ln(1 + e E_\nu) \right], \quad (5)$$

where  $a = 0.018$ ,  $b = 0.024$ ,  $c = 0.0069$ ,  $e = 0.00139$ ,  $\gamma = 1.74$  and  $N_0 = 1.95(1.35) \times 10^{17}$  for  $\nu(\bar{\nu})$ .

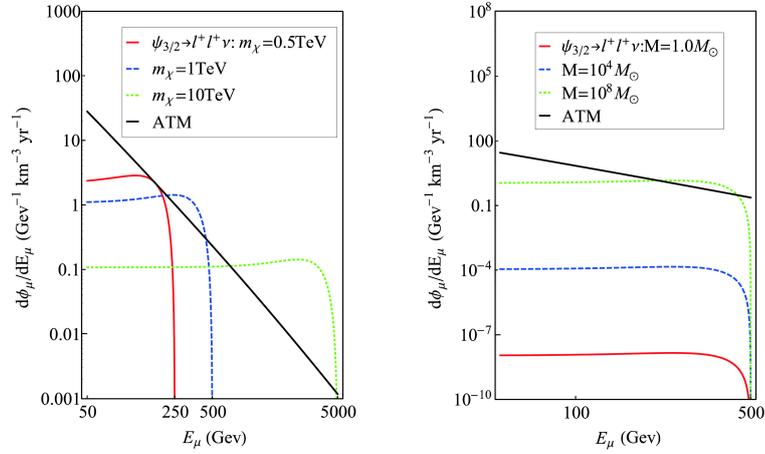
In Figures 1 and 2, the neutrino flux from nearby UCMHs ( $d_{\text{UCMHs}} = 1 \text{ kpc}$ ) is shown for different dark matter masses. For these results, we set the dark matter decay rate to be  $\Gamma = 10^{-26} \text{s}^{-1}$  and treat the distribution of neutrino flavors at Earth as 1:1:1 which is due to vacuum oscillation during propagation. From these figures, it can be seen that for a fixed mass of UCMHs, the flux would exceed the ATM for a larger dark matter mass. For a fixed mass of dark matter, the flux has exceeded the ATM for bigger UCMHs. Similar results can also be found in our other work (Yang et al. 2013b) where the neutrino signals from UCMHs due to dark matter annihilation are considered.

### 3 CONSTRAINTS ON THE ABUNDANCE OF UCMHs

After the formation of UCMHs, one of the important questions is about their abundance in our universe. According to the above discussions, this issue can be resolved through studying the different observational results that have been presented (Bringmann et al. 2012; Yang et al. 2013b,a,c; Josan & Green 2010; Yang et al. 2011a,b). In the previous work, we found constraints on the abundance of



**Fig. 1** The potential neutrino flux for the upward events from nearby UCMHs due to gravitino decay. The distance of UCMHs is  $d = 1$  kpc and the decay rate is  $\Gamma = 10^{-26} \text{ s}^{-1}$ . *Left*: the neutrino flux for a fixed mass of UCMH of  $M_{\text{UCMHs}} = 10^8 M_{\odot}$  and dark matter mass of  $m_{\chi} = 0.5 \text{ TeV}$  (solid),  $1 \text{ TeV}$  (long-dashed line) and  $10 \text{ TeV}$  (short-dashed line). The neutrino flux from the atmosphere is also shown (thick solid line). *Right*: the neutrino flux for a fixed dark matter mass of  $m_{\chi} = 1 \text{ TeV}$  and the mass of UCMHs  $M_{\text{UCMHs}} = 1 M_{\odot}$  (solid line),  $10^4 M_{\odot}$  (long-dashed line) and  $10^8 M_{\odot}$  (short-dashed line). The neutrino flux from the atmosphere is also shown (thick solid line).

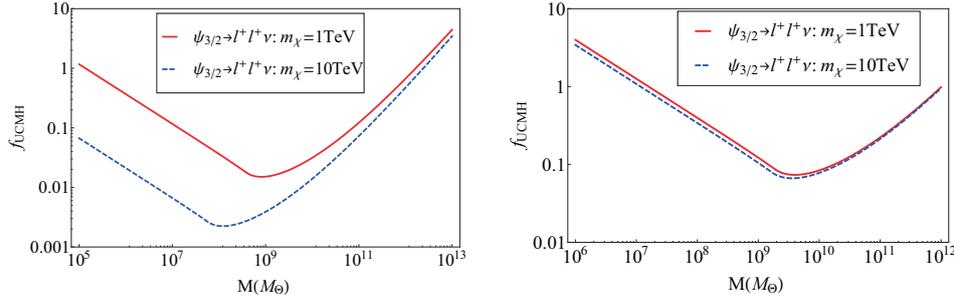


**Fig. 2** The potential neutrino flux for contained events from nearby UCMHs due to the gravitino decay. The parameters are the same as in Fig. 1.

UCMHs by considering neutrino signals due to dark matter annihilation (Yang et al. 2013b). In this section, we will investigate the fraction of UCMHs in the case of dark matter decay.

Following previous works (e.g. Bringmann et al. 2012), we assume that UCMHs are distributed uniformly and their abundance is the same everywhere in our universe. The mass has the form of a delta function which means that all of these objects have the same mass. Therefore, the fraction of UCMHs can be written as (Josan & Green 2010)

$$f_{\text{UCMH}} = \frac{M_{\text{UCMH}}}{M_{\text{DM,MW}}(< d)}, \quad (6)$$



**Fig. 3** The constraints on the abundance of UCMHs using the potential neutrino signals, contained events (right) and upward events (left). We have chosen the dark matter mass  $m_\chi = 1$  TeV (solid line) and 10 TeV (dashed line) and set the decay rate to be  $\Gamma = 10^{-26} \text{ s}^{-1}$ .

where  $M_{\text{DM,MW}}(< d)$  is the dark matter mass of the Milky Way within the distance  $d$  and in this work we use the Navarro-Frenk-White profile for the dark matter halo.

In Section 2, it can be seen that the neutrino flux would exceed the ATM for some cases. During an exposure time of ten years, considering contamination from the atmospheric background, the minimal number of muons from UCMHs for a fixed distance and  $2\sigma$  statistical significance can be derived as  $N_{\text{UCMHs}}/\sqrt{N_{\text{UCMHs}} + N_{\text{ATM}}} = 2$ , where  $N_{\text{UCMHs}}$  can be obtained by integration

$$N_{\text{UCMHs}} = \int_{E_\mu^{\text{th}}}^{E_{\text{max}}} \frac{d\phi_\mu}{dE_\mu} F_{\text{eff}}(E_\mu) dE_\mu, \quad (7)$$

where  $F_{\text{eff}}(E_\mu)$  is the effective volume  $V_{\text{eff}}$  and  $A_{\text{eff}}$  is the effective area of the detector for the contained and upward events respectively. For IceCube, we ignore the energy dependence and accept that  $V_{\text{eff}} = 0.04 \text{ km}^3$  and  $A_{\text{eff}} = 1 \text{ km}^2$ . The final results are shown in Figure 3.

From these results it can be seen that the strongest constraint is  $f_{\text{UCMHs}} \sim 2 \times 10^{-3}$  for the dark matter mass  $m_{\text{DM}} = 10$  TeV of the upward events. For the case of contained events, the constraints are weaker and the strongest constraint is  $f_{\text{UCMHs}} \sim 0.1$ . So, the upward events are much more applicable for the constraints on UCMHs and the limits will be stronger for a larger dark matter mass. On the other hand, compared with dark matter annihilation cases, these constraints are weaker. However, like we mentioned in the above sections, if the dark matter particles do not annihilate, dark matter decay will be important, so these results are still very significant.

## 4 DISCUSSION

The UCMHs would be formed if there are large density perturbations during an earlier epoch and then their cosmological abundance becomes an important issue. In previous works, the main limits are from research about gamma-ray flux due to dark matter annihilation within UCMHs. In our recent works, we considered constraints from the neutrino flux due to dark matter annihilation and gamma-ray flux due to dark matter decay (Yang et al. 2013c,b).

In this work, we extended these works and investigated the neutrino flux from nearby UCMHs due to the decay of gravitino particles. The decay modes of gravitinos include two-body and three-body decays. The latter can also provide one of the explanations for an excess of positrons (or positrons plus electrons) which has been observed recently by the PAMALA experimental payload and *Fermi* spacecraft. In this work, we mainly considered the three-body decay mode. This decay mostly produces leptons, therefore, neutrinos will be plentiful. We calculated the neutrino flux from nearby UCMHs due to the decay of dark matter and compared that with signals from the atmosphere which are the main background of neutrino detection. We found that for a larger dark matter mass or

UCMHs, the final flux would exceed the ATM. These results are similar to the cases of dark matter annihilation (Yang et al. 2013b).

On the other hand, because we have not observed any excess of neutrino flux from nearby unknown sources, the abundance of UCMHs can be constrained. We considered an exposure time of ten years for neutrino observation and signals with  $2\sigma$  statistical significance to calculate limits on the fraction of UCMHs. In this work, we also assumed that the distribution of these objects is uniform in the universe. We found that the strongest limits on the abundance of UCMHs is  $f_{\text{UCMHs}} \sim 10^{-3}$ . One should note that these results depend on the dark matter mass. From Figure 3, it can be seen that the limits will be stronger for a larger dark matter mass. Moreover, the final constraints are stronger for upward events compared with contained events. The other important parameter is the dark matter decay rate.

In this paper, we have used a conservative value of  $\Gamma = 10^{-26} \text{ s}^{-1}$  for our research. There are many works where the constraints on the decay rate of a gravitino are obtained. Huang et al. (2012) used the *Fermi* observations of nearby galaxy clusters to derive constraints on this parameter. They found that the limit on the lifetimes of a gravitino from observations of these clusters is  $\tau(1/\Gamma) \sim 2 \times 10^{26} \text{ s}$  and it is mostly independent of the dark matter mass. The limits obtained from signals are different and the lifetime becomes smaller with an increase in dark matter mass.

For future neutrino observations, such as KM3Net, because their effective area and volume will be improved, it is expected that constraints on the abundance of UCMHs will be much stronger.

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