Ultrahigh energy neutrino absorption by neutrino dark matter

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If the dark matter in the Universe consists of massive neutrinos ($m_{\nu_i} \simeq 30-100$ eV, $i = \mu, \tau$), a cosmic ray ν_i of ultrahigh energies may be absorbed at large redshifts, or even while crossing galactic halos, due to their annihilation with the dark matter neutrinos. These processes can become very important for $E_\nu \simeq M_Z^2/2m_\nu \simeq 5-10\times 10^{19}$ eV, for which the Z-exchange cross section is resonant, and may lead to a dip in the cosmic ray neutrino spectrum. I compute all the relevant contributions to the ν cross section and use them to evaluate the absorption redshift at ultrahigh energies and to analyze the absorption probability at large redshifts as well as in halos of galaxies. If the determination of the neutrino spectrum at those energies were to become experimentally feasible, the observation of the features discussed here would provide a clear indication of the nature of the dark matter.

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I. INTRODUCTION

Many sources of ultrahigh energy (UHE) neutrinos, $E_\nu > 10^{16}$ eV, have been proposed in the past. Neutrinos can be produced in astrophysical objects by the decay of pions or kaons produced in the interaction of accelerated protons and nuclei with ambient protons and photons. The acceleration sources could be shocks of supernova explosions, pulsars, the active nuclei of Seyfert galaxies and quasars [active galactic nuclei (AGN)], a bright phase of galaxy formation, etc. [1]. The UHE neutrinos could also result from the decay of very heavy exotic particles, such as long-lived relics from the big bang [2], or, for instance, by ultraheavy particle emission from saturated superconducting cosmic strings [3] (see, however, [4]), by mini-black-hole evaporation [5], by cusp radiation from ordinary cosmic strings [6], etc.

The hadronic component of cosmic rays (CR's) has been observed in air shower arrays up to energies $\sim 10^{20}$ eV, and experiments are being done and planned to continue the exploration of the spectrum in the range $10^{20}-10^{21}$ eV. Although the CR composition is not completely established, one expects that if there is a proton component up to the maximum observed CR energies, the associated neutrino spectrum due to photopion production at the source will extend up to $E_\nu \sim E_p^{\max}/20$, i.e., at least up to 5×10^{18} eV (the π has typically $\langle E_\pi \rangle \simeq 0.2E_p$ and the mean neutrino energy is $E_\pi/4 \simeq E_p/20$). Furthermore, if the cosmic ray protons have a component originating from distant sources beyond the local cluster of galaxies, their interactions with the cosmic microwave photons would not only produce a secondary neutrino flux [7], but also give rise to the Greisen-Zatsepin-Kuzmin [8] cutoff in the proton spectrum at $E_p \sim 10^{20}$ eV (starting at 3×10^{19} eV, the photopion production threshold for 3 K background photons). Hence, even if no CR nucleons were observed much above 10^{20} eV, it may still be that the CR-induced neutrino flux extends significantly beyond 10^{19} eV and arises from extragalactic cosmic rays. The other possibilities mentioned above, involving (more exotic) nonastrophysical sources, can produce important fluxes of neutrinos extending even up to $10^{25}-10^{28}$ eV.

Another very important aspect of neutrinos is the existence of a cosmic neutrino background, resulting from early decoupling just before the time of nucleosynthesis, which is expected to have an average density at present of $n_\nu + n_{\bar\nu} \simeq 108$ cm^{-3} for each flavor. This has led to the nice possibility of explaining the dark matter (DM) problem just by invoking a small neutrino mass $m_{\nu_i} = 92\Omega_{\nu_i} h^2$ eV (h is Hubble's constant in units of 100 km/s Mpc, $0.4 < h < 1$). If this is actually the case, large enhancements in the ν_i (and $\bar\nu_i$) density are expected around galaxies to account for the dark halos responsible for the observed flatness of galaxy rotation curves. For example, if we take for the halo density the usual parametrization

$$\rho_h(r) = \frac{\rho_0}{1+(r/r_c)^2}, \tag{1.1}$$

where for our Galaxy the estimated central density is $\rho_0 \simeq 0.014\ M_\odot/\text{pc}^3$ and the core radius of the halo is $r_c \simeq 7.9$ kpc [9], then the neutrino number density inside the core of our Galaxy will be

$$n_\nu = n_{\bar\nu} \simeq 4\times 10^6/m_{50}\ \text{cm}^{-3},$$

i.e., a factor $\sim 10^5$ larger than the average relic ν density ($m_{50} \equiv m_\nu/50$ eV). Hereafter, $\Omega_{\nu_i} \simeq 1$ will be taken, assuming that at present 10–20 % of the DM neutrinos are in galactic halos, while the rest are distributed more smoothly, as suggested by numerical simulations [10].

I consider here the possible attenuation that the DM neutrinos may produce in the cosmic neutrino fluxes. As was shown many years ago by Weiler [11], the smooth DM neutrino background can attenuate neutrinos produced at large redshifts. I reanalyze those processes, taking into account all the contributions to the cross section responsible for the CR ν absorption, and also show that the DM neutrinos clustered around galaxies may attenu-

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ate the CR neutrinos crossing dark halos. Since the "target" neutrinos are massive, many of the electroweak channels for neutrino-antineutrino annihilation become sizable for $E_\nu \gtrsim 10^{19}$ eV ($\sigma_{\nu\bar{\nu}} \gtrsim 10^{-34}$ cm^2) and there is a special enhancement at the pole of the Z resonance, i.e., at an energy

$$E_{\rm res} = \frac{M_Z^2}{2m_\nu} \simeq 8\times 10^{19}\ \text{eV}/m_{50}\ ,$$

at which $\sigma_{\nu\bar{\nu}} \simeq 5\times 10^{-31}$ cm^2. These processes could cause strong absorption of the neutrinos with energies close to $E_{\rm res}$, a value that may still be inside the cosmic ray neutrino continuum. Unlike the case considered here, if the background neutrinos were massless, the effects would be much less important, since the annihilation would become resonant only at energies $E_\nu \simeq 10^{25}$ eV [11,12].

If the neutrino fluxes are of astrophysical origin, i.e., arising from light meson decays, one expects fluxes of ν_μ and ν_e (and the antineutrinos) in the ratio 2:1, with no sizable flux of ν_τ's. Hence, in the case in which the DM consists of ν_τ mass eigenstates, the resonant ν_μ absorption will be suppressed by the ν mixing factor $\sin^2\theta_{\mu\tau}$. More important effects would be expected if the dark matter is composed of muon neutrinos ($m_{\nu_\mu} > m_{\nu_\tau}$) and, although this is not the outcome of models with a common heavy Majorana mass, a heavier ν_μ can naturally result in scenarios of radiatively generated neutrino masses [13]. If the UHE neutrino fluxes are instead due to exotic particle decays, it is plausible that there will be comparable fluxes of the different flavors, and the ones most affected by absorption will be those of the same flavor as the DM neutrinos.

In Sec. II the relevant cross sections for neutrino annihilation are computed. Section III discusses the attenuation of cosmological neutrinos at high redshifts, while Sec. IV considers their possible attenuation in dark halos. Further discussion is given in Sec. V.

II. NEUTRINO ANNIHILATION CROSS SECTION

Because the target neutrinos are nonrelativistic, they will be evenly distributed between left- and right-handed chiralities. If neutrinos are Dirac particles, the sterile components ν_R and $\bar{\nu}_L$ will not contribute to the CR ν absorption, while if neutrinos are Majorana, ν_L and $\bar{\nu}_R$ are just the two (active) components of the neutrino and, hence, the absorption is twice that in the Dirac case. I will consider here the case of Majorana ν's, keeping in mind that the absorption will be halved in the Dirac ν case.

The total center-of-mass (c.m.) energy squared for the annihilation of a CR neutrino of energy E_ν in the lab frame, the Earth, in which the DM neutrinos (of mass m_ν) are almost at rest, is just $s \simeq 2m_\nu E_\nu$. If the annihilations were instead with massless thermal neutrinos ($T = 1.9$ K), s would be five orders of magnitude smaller and, since the cross section is correspondingly reduced (below the Z peak, $\sigma_{\nu\bar{\nu}} \propto s$), these other processes are in general negligible when compared with the annihilations with the massive ones.

Figure 1 shows the total neutrino absorption cross section as a function of the energy of the CR neutrino impinging on the DM one, together with the contribution of the different channels. The most important process is Z exchange in the s channel (long-dashed line), which has resonant behavior. The corresponding cross section is (omitting hereafter the helicity labels of the initial state neutrinos and neglecting the ν flavor mixings for simplicity)

$$\sigma_Z(\nu_i\bar{\nu}_i \to f\bar{f}) = \sum_f \frac{2G_F}{3\pi} n_f s P_Z [t_3^2(f) - 2t_3(f)Q_f s_W^2 + 2Q_f^2 s_W^4]\ , \qquad (2.1)$$

where the sum is over all fermions with $m_f < \sqrt{s}/2$, with charge Q_f, isospin $t_3(f)$, and $n_f = 1(3)$ for leptons (quarks), and their masses were neglected. In Eq. (2.1),

$$P_Z \equiv \frac{M_Z^4}{(s - M_Z^2)^2 + \Gamma_Z^2 M_Z^2}$$

and $s_W^2 \equiv \sin^2\theta_W \simeq 0.23$. Note that the annihilation (2.1) also includes the production of neutrinos, with a 20% branching ratio, and although this is not exactly an absorption process, the secondary ν fluxes it produces are depleted in energy with respect to the primary flux so that, for a typical power-law initial spectrum, the associated "pileup" effect may be neglected and the process will also appear as an absorption. This approximation is also especially appropriate for the study of the attenuation of the neutrino fluxes with energies in the resonance region, to which we pay particular attention below.

In addition to the s-channel Z exchange, the t-channel Z exchange contributes to $\nu_i\bar{\nu}_j \to \nu_i\bar{\nu}_j$ (short-long dashes), with

$$\sigma_Z^t(\nu_i\bar{\nu}_j \to \nu_i\bar{\nu}_j) = \frac{G_F^2}{2\pi} s F_1\left[\frac{s}{M_Z^2}\right]\ , \qquad (2.2)$$

where $F_1(y) = [y^2 + 2y - 2(1+y)\ln(1+y)]/y^3$, while the

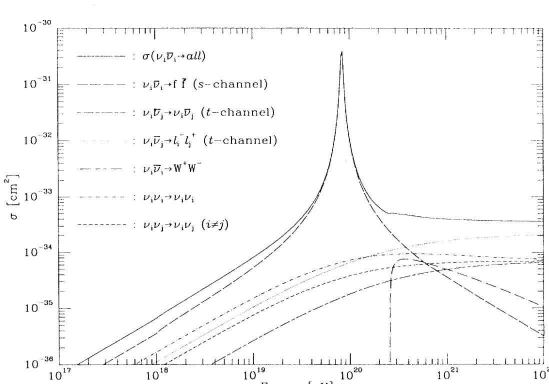

FIG. 1. Total $\nu_i\bar{\nu}_i$ annihilation cross section (continuous line) and individual contributions to the different neutrino processes, as a function of the cosmic ray neutrino energy E_ν (times $m_{50} \equiv m_\nu/50$ eV).

interference of s and t channels (for $i=j$) is

$$\sigma_Z^{st}(\nu_i\bar{\nu}_i \to \nu_i\bar{\nu}_i) = \frac{G_F^2}{2\pi}\frac{P_Z(s-M_Z^2)}{M_Z^2} s F_2\left[\frac{s}{M_Z^2}\right], \quad (2.3)$$

with $F_2(y)=[3y^2+2y-2(1+y)^2\ln(1+y)]/y^3$.

Another relevant process, which becomes very important at energies beyond the Z peak, is the t channel W exchange (dotted line), with

$$\sigma_W(\nu_i\bar{\nu}_j \to l_i\bar{l}_j) = \frac{2G_F^2}{\pi} s F_1\left[\frac{s}{M_W^2}\right]. \quad (2.4)$$

Note that this interaction will be the most important process for the attenuation of the UHE neutrinos with a flavor different from that of the DM ones. If they are both of the same flavor, $i=j$, one must also include the interference of the processes (2.1) and (2.4), that is

$$\sigma_{WZ}(\nu_i\bar{\nu}_i \to l_i\bar{l}_i) = \frac{2G_F^2}{\pi}(s_W^2-\tfrac{1}{2}) \times \frac{P_Z(s-M_Z^2)}{M_Z^2} s F_2\left[\frac{s}{M_W^2}\right]. \quad (2.5)$$

For $E_\nu > 2M_W^2/m_\nu$, the annihilation into W^+W^- pairs is kinematically allowed, proceeding both through t-channel lepton exchange and s-channel Z exchange; it gives (dot–long-dashed line)

$$\sigma(\nu_i\bar{\nu}_i \to W^+W^-) = \frac{G_F^2 s\beta}{12\pi}\left[\frac{\beta^2 M_W^4}{(s-M_Z^2)^2}(12+20y+y^2) + \frac{2M_W^2}{(s-M_Z^2)y^2}\left[24+28y-18y^2-y^3+\frac{48}{\beta y}(1+2y)L\right] + \frac{1}{y^2}\left[y^2+20y-48-\frac{48}{\beta y}(2-y)L\right]\right], \quad (2.6)$$

with $y\equiv s/M_W^2$, $\beta\equiv\sqrt{1-4/y}$, and $L\equiv\ln((1+\beta)/(1-\beta))$. There is also annihilation into Z pairs for $E_\nu > 2M_Z^2/m_\nu$, giving

$$\sigma(\nu_i\bar{\nu}_i \to ZZ) = \frac{G_F^2 M_Z^2 \beta}{\pi(y-2)}\left[\frac{2}{y}-1+\frac{4+y^2}{2y^2\beta}L\right], \quad (2.7)$$

where $y\equiv s/M_Z^2$. This cross section has a similar qualitative behavior to the W pair production one, but is numerically smaller by a factor of ~ 5. For simplicity the process $\nu\bar{\nu}\to ZH$ was not included, but it will also contribute above the (unknown) threshold for Higgs production.

All (anti)neutrino flavors may also scatter elastically off DM (anti)neutrinos by t-channel Z exchange, with the cross section (short dashes)

$$\sigma(\nu_i\nu_j \to \nu_i\nu_j) = \frac{G_F^2 M_Z^2}{2\pi}\frac{s}{s+M_Z^2}, \quad i\neq j, \quad (2.8)$$

while for $i=j$ there is also the contribution of the u channel, giving (dot–short-dashed line)

$$\sigma(\nu_i\nu_i \to \nu_i\nu_i) = \frac{G_F^2 M_Z^2}{2\pi}\left[\frac{s}{s+M_Z^2} + \frac{2M_Z^2}{2M_Z^2+s} \times \ln\left[1+\frac{s}{M_Z^2}\right]\right]. \quad (2.9)$$

We again neglect the secondary ν flux that this process produces.

The sum of all the contributions to the ν_i cross section, shown by the full line in Fig. 1, determines the absorption probability of the neutrino flux with the same flavor i as the DM neutrinos. On the other hand, if the CR neutrino flavor differs from that of the DM, the absorption will be due to the processes in Eqs. (2.4), (2.2), and (2.8).

III. ABSORPTION BY THE COSMIC DM ν BACKGROUND

As was shown in the previous section, the $\nu\bar{\nu}$ annihilation cross section reaches a maximum of 5×10^{-31} cm^2 at the Z resonance peak. However, even UHE neutrinos of this energy are not absorbed by the diffuse background of DM neutrinos if they are of noncosmological origin. In fact, the corresponding mean free path

$$l_\nu = (n_\nu \sigma_{\nu\bar{\nu}})^{-1} \simeq 4\times10^{28}\ \text{cm}$$

is just above the present size of the horizon, $H_0^{-1}\simeq 10^{28}$ cm.

If, instead, the UHE neutrinos are produced at large redshifts, the effects of absorption are much more important [11]. In this case one must take into account that the DM ν density increases as $(1+z)^3$, and also that the UHE ν energy is affected by redshift, $E(z)=(1+z)E_0$. As long as redshifts $z<10^5$ are considered, the DM neutrinos will still be nonrelativistic and the cross sections obtained in the previous section can still be used with $s=2m_\nu E_\nu(z)$. Taking this into account, the absorption time can be computed as a function of redshift for a given present neutrino energy E_0:

$$\tau_\nu(z,E_0) \equiv \{c n_\nu(z)\sigma_{\nu\bar{\nu}}[s=2m_\nu(1+z)E_0]\}^{-1}. \quad (3.1)$$

The lowest redshift at which absorption of the UHE neutrinos becomes important, $z_{\rm abs}$, can be obtained by equating the absorption time to the Hubble time of the Universe H^{-1}, which is, in the matter-dominated era $z<z_{\rm eq}\simeq 2\times10^4\ h^2$,

$$H^{-1}(z)=\frac{3t_0}{2(1+z)^{3/2}} , \qquad (3.2)$$

with $t_0=2.1\times10^{17}\ h^{-1}$ s the present age of the Universe. The resulting absorption redshift is plotted as a function of the present ν energy E_0 in Fig. 2. If a source produced UHE neutrinos at redshifts z_* with energy $E_*=(1+z_*)E_0$, the neutrino absorption by the DM ν background will be sizable as long as $z_*>z_{\rm abs}(E_0)$. The resonant effect in the annihilation cross section is apparent in the figure, and may lead to sizable absorption for redshifts as low as $z_{\rm min}\simeq2$ and, for present energies,

$$E_0\lesssim\frac{E_{\rm res}}{z_{\rm min}+1}\simeq3\times10^{19}\ {\rm eV}/m_{50}$$

(actually, the resonant absorption is also affected by the fact that, due to the redshift, the annihilation stays resonant only for a fraction of an expansion time). In particular, if a high-redshift quasar or a bright phase of galaxy formation produced UHE neutrinos at a redshift of, say, $z_*=5$, the neutrinos with present energy $(1-3)\times10^{19}$ eV$/m_{50}$ would have been significantly absorbed. The effect becomes even stronger for sources at larger redshifts, and the Universe becomes completely opaque to UHE ν's of the same flavor as the DM neutrinos for $z\gtrsim200$. Figure 2 also shows, with dotted lines, the absorption redshift for CR neutrinos with a flavor different from that of the DM ones. It follows that the "horizon" of UHE neutrinos is constrained in this case to $z\lesssim(2\times10^2)-10^3$.

In Fig. 3, the transmission probability for neutrinos produced at time t_*,

$$\mathcal{P}(E_0)=\exp\left[-\int_{t_*}^{t_0}dt\ \tau^{-1}(z(t),E_0)\right] , \qquad (3.3)$$

is shown for $z(t_*)=5$ and 20, where $z(t)=(t_0/t)^{2/3}-1$, and the features just discussed can be seen. Figures 2 and 3 are for $h=0.5$, while the absorption is somewhat reduced for larger values of h.

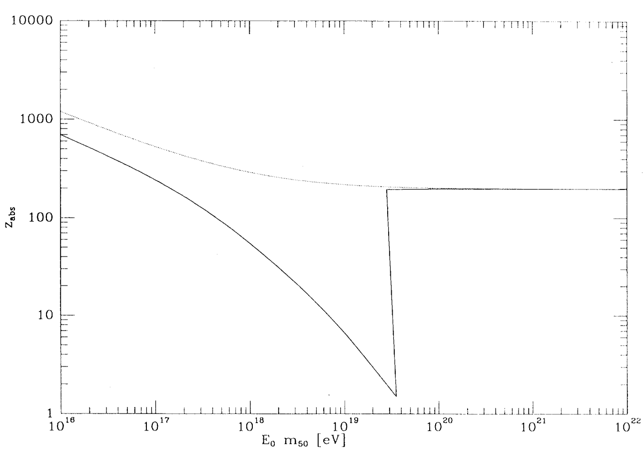

FIG. 2. Absorption redshift for neutrinos of the same flavor as the DM ones (solid line) and for those of different flavor (dotted line), as a function of the present neutrino energy E_0, taking $h=0.5$.

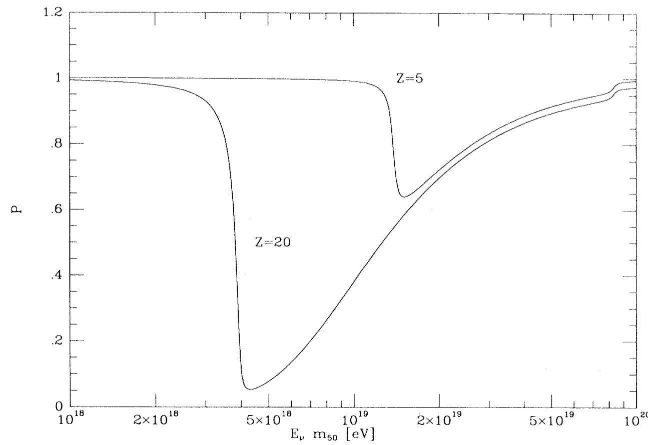

FIG. 3. Transmission probability as a function of E_0 for neutrinos produced at redshifts $z=5$ and $z=20$, for $h=0.5$.

IV. ABSORPTION BY NEUTRINO HALOS

If massive neutrinos constitute the DM, it is also possible that the large enhancement in the ν density in galactic halos may lead to a sizable absorption of UHE neutrinos. The relevant quantity to consider here is the ν column density that an UHE neutrino has to cross while traversing the halo. For extragalactic neutrinos, absorption can occur both in the halo of our Galaxy and in the halo around the source. In particular, if the ν source is in the center of a galaxy (such as on AGN), with a halo density described by Eq. (1.1), the UHE neutrinos will cross a column density

$$N_\nu=N_{\bar\nu}=\frac{\pi}{4}\frac{\rho_0 r_c}{m_\nu}$$

$$\simeq1.8\times10^{30}\left[\frac{\rho_0}{0.1\ M_\odot/{\rm pc}^3}\right]\frac{r_{10}}{m_{50}}\ {\rm cm}^{-2} \qquad (4.1)$$

on their way out of the source, with $r_{10}\equiv r_c/10$ kpc. The probability for the UHE neutrinos to cross through the halo without annihilating with the DM ones is then

$$\mathcal{P}(E_\nu)=e^{-N\sigma_{\nu\bar\nu}(E_\nu)} . \qquad (4.2)$$

This "transmission" probability is shown as a function of E_ν in Fig. 4, assuming that the source is at $z=0$ and for $m_\nu=50$ eV [for $z\neq0$, the dip in the spectrum due to the absorption at the source would be correspondingly redshifted to $E=E_{\rm res}/(1+z)$]. The three curves correspond to

$$X\equiv\rho_0 r_c\ [(M_\odot/{\rm pc}^3){\rm kpc}]^{-1}=0.1\ ,\ 1\ ,\ {\rm and}\ 10\ ,$$

spanning the range expected for DM halos of nondwarf galaxies ($X\simeq0.1$ for our Galaxy, and it is expected to increase in early-type galaxies. In particular, ellipticals are generally more massive and compact than spirals). From Fig. 4 we see that the halo of our own Galaxy can only marginally absorb neutrinos coming from the other side of the Galaxy with energies close to the resonance value.

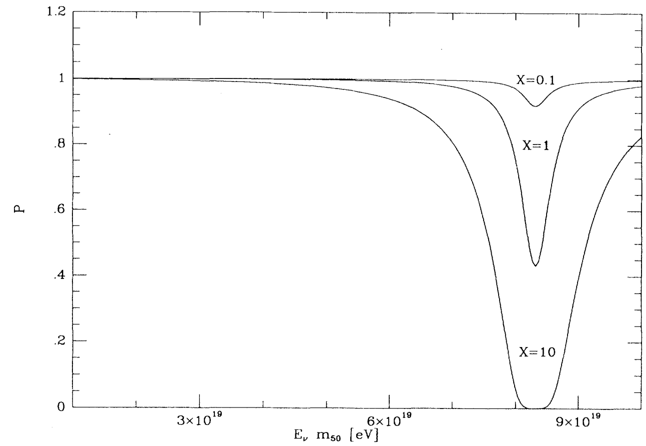

FIG. 4. Transmission probability for a neutrino leaving from the center of a halo with density given by Eq. (1.1) and for $X \equiv \rho_0 r_c/(M_\odot/\mathrm{pc}^3\,\mathrm{kpc})=0.1$, 1, and 10, as a function of the neutrino energy.

One should keep in mind, however, that fits to halo densities without assuming a "minimal halo" lead to significantly larger column densities than the usually quoted ones, that rely on that assumption. We also note that in rich clusters, where AGN are likely to be found, the DM density might be smeared to Mpc scales (tidal forces between nearby galaxies can strip individual galactic halos), and although the average DM density of the cluster ($\lesssim 10^{-3}\ M_\odot/\mathrm{pc}^3$) is lower than in galactic halo models, the DM column density of the cluster could also correspond to $X \gtrsim 0.1$.

One can obtain an upper bound for the absorption that a halo made of neutrinos can produce by considering the "maximum neutrino halo" allowed by the Tremaine-Gunn phase-space constraint [14]. If the halo is modeled as an isothermal sphere [15] with velocity dispersion

$$\sigma=\sqrt{\langle v_x^2\rangle}=\sqrt{\langle v_y^2\rangle}=\sqrt{\langle v_z^2\rangle}$$

(related to the circular velocity of rotation curves by $v_c=\sqrt{2}\sigma$), the Tremaine-Gunn constraint is

$$\frac{\rho_0}{m_\nu^4(2\pi\sigma^2)^{3/2}}<\frac{g_\nu}{h^3}\ , \tag{4.3}$$

leading to

$$\rho_0 r_c < 4.0 g_\nu m_{50}^4 \sigma_{200}^3 r_{10}\ \frac{M_\odot}{\mathrm{pc}^3}\ \mathrm{kpc}\ , \tag{4.4}$$

where g_ν is the number of occupied spin states contributing to the DM density, i.e., $g_\nu=1$ if just one flavor of left-handed neutrinos contributes and $\sigma_{200}\equiv\sigma/(200$ km/s). It is then clear that to have significant absorption, i.e., $X \gtrsim 1$, large values of m_ν would be preferable, and the effects can be expected to be more important in halos where the dispersion velocities are large. (We should note, however, that if phase-space anisotropies were allowed, the bound in Eq. (4.4) would be looser [16].)

In the isothermal sphere model, the following relation holds

$$\rho_0 r_c=\frac{9\sigma^2}{4\pi G_N r_c}\simeq 0.67\frac{\sigma_{200}^2}{r_{10}}\ \frac{M_\odot}{\mathrm{pc}^3}\ \mathrm{kpc}\ , \tag{4.5}$$

where G_N is Newton's constant, from which we see that values of X of order unity seem quite reasonable for the expected ranges of σ ($\lesssim 300$ km/s) and r_c (1–10 kpc). (Actually, Eq. (4.5) defines the King radius r_c, sometimes called core radius since $\rho(r_c)\simeq\rho_0/2$, but Eq. (1.1) is not a good fit to $\rho(r)$ for the isothermal sphere at $r \gg r_c$ [15].)

V. DISCUSSION

It was shown that DM neutrinos can give rise to a sizable absorption of UHE neutrinos with energies close to the Z resonance value. If the absorption happened at high redshifts ($z>2$) because of annihilations with the smoothly distributed cosmic neutrino background, there would be a dip in the UHE ν spectrum that should appear at the redshifted energies

$$\frac{E_{\mathrm{res}}}{1+z}\lesssim E \lesssim \frac{E_{\mathrm{res}}}{3}\ .$$

If the source produces neutrinos at a very early epoch, $z \gtrsim 300$, the absorption of the UHE neutrinos will be total. It was also shown that UHE ν's may be absorbed while crossing halos of very massive galaxies, leading to a dip in the spectrum around $E_{\mathrm{res}}\simeq 8\times10^{19}\ \mathrm{eV}/m_{50}$. Although it is unlikely that a high-redshift astrophysical source be powerful enough to individually produce large UHE ν fluxes, it could be that the sum over large z sources does lead to a sizable ν flux [17], but in this case the dip in the spectrum will be somewhat smeared due to the difference in the energies of the dips for each individual redshifted source. On the other hand, if the absorption is produced in halos around sources at small z (that need not be so powerful since they are closer), also, their combined fluxes will show the dip at E_{res}, but the absorption may be reduced by the contribution of sources surrounded by halos with DM column density not sufficiently large to produce a sizable absorption ($X \ll 1$).

On the observational side, we know that no UHE neutrinos have yet been detected, although neutrino astronomy is still in its infancy. At $E_\nu \gtrsim 10^{15}$ eV, one should take into account the fact that the Earth is no longer transparent to neutrinos [18], but, on the other hand, the atmospheric ν flux induced by hadronic cosmic rays drops to very low values at ultrahigh energies. Neutrinos of UHE should produce giant horizontal air showers by interacting deep in the atmosphere or in the crust of the Earth, and the nonobservation of these showers has already been used to set bounds [19] on energetic neutrinos from AGN [20]. Other methods proposed for UHE neutrino detection are acoustic detection and the observation of radio waves generated by the showers of charged particles produced in dielectric media (the Antarctic ice or even the surface of the Moon) [21]. These techniques could allow for much larger detector sizes (as required for UHE ν detection) than those of the present Cherenkov detectors. In the near future, large optical Cherenkov detectors deep in the sea [Deep Underground Muon and Neutrino Detector (DUMAND)] or in the ice [Antarctic Muon and Neutrino Detector Array (AMANDA)] remain a promising tool for UHE ν searches. It is not clear whether detection methods sensitive to the features of the UHE neutrino spectrum discussed here will become available (provided that ν fluxes of 10^{20} eV exist), but certainly a positive determination of these effects would have far-reaching consequences, giving an indication in favor of neutrino dark matter, even pointing to a value for the neutrino mass, in addition to providing information regarding the UHE neutrino sources themselves.

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