IceCube Events from Decaying Dark Matter with Neutrino Portal

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IceCube has observed several PeV neutrino events whose astrophysical origin has not been identified. In this proceeding, we discuss heavy decaying dark matter may be responsible for these neutrinos. Dark matter χ is constructed to communicate with standard model particles through the neutrino-portal interaction. We calculate both total and differential decay width for the dominant three-body decay of dark matter and show that to fit the data, the required mass is around $\mathcal{O}(10 \text{ PeV})$ and lifetime is about 10^{28} s .

Keywords: IceCube; dark matter; neutrino.

1. Introduction

Recently, IceCube collaboration has fully identified 3 PeV neutrino cascade events during its 4-year observation.^{1–5} One more PeV track event was also observed but its energy has not been determined yet. Together with other ~ 50 events in the energy range $\mathcal{O}(30 \text{ TeV}) - \mathcal{O}(1 \text{ PeV})$, IceCube is able to claim that there is more than 6σ significance to support the astrophysical origin of these events.

Astrophysical sources that can be responsible for these high energy neutrino events include supernova remnants, active galactic nuclei, and gamma-ray bursts. It is usually assumed that these sources inject some primary protons with specific spectra and then consider the resulting neutrino flux from proton-proton or proton-gamma interaction. Assuming astrophysical flux arrives isotropically with equal flavor,

$$\Phi_\nu = \phi \left(\frac{E}{100 \text{ TeV}} \right)^{-\gamma}, \quad (1)$$

IceCube has given the best-fit values with three-year data,

$$\gamma = 2.5 \pm 0.09, \quad \phi = 6.7^{+1.1}_{-1.2} \times 10^{-18} [\text{GeV s sr}]^{-1} \text{cm}^{-2}.$$

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The central value for γ has shifted to 2.58 with preliminary results based on four-year data. With such a large index γ , although such astrophysical explanations can not be fully excluded, it is also expected that there should be accompanied with large gamma-ray flux which is highly constrained by Fermi-LAT experiment. Moreover, a large γ indicate a smaller flux at high energy, which may not be consistent with this multi-PeV track events mentioned above.

In this contribution, we discuss a possibility that these very high energy PeV neutrino events could come from dark matter decay.

2. Decaying Dark Matter with Neutrino Portal

The most straightforward way to implement decaying dark matter is just to introduced a heavy right-handed neutrino, N , which couples to standard model particles only through the neutrino-portal interaction,

$$\delta\mathcal{L} = y\bar{L}\tilde{H}N, \quad (2)$$

where $L = (\nu \ l)^T$ is a left-handed SM $SU(2)$ lepton doublet, H is the SM Higgs doublet. If $y \sim 10^{-29}$ and $m_N \sim \text{PeV}$, we might be able to produce the right amount of neutrino flux through $N \rightarrow \nu h, \nu Z, e^\pm W^\mp$ decay channels. Since these are all two-body decay, the primary neutrino flux has δ -function distribution, a sharp spectral that may not be favored by the observed neutrino events.

In our proposal,⁶ we have the dominant decay modes from three-body-decay which can provide a broad spectrum, see Ref. 7 for similar discussion. We consider a hidden sector with another Higgs field Φ and a Dirac fermion DM χ associated $U(1)_X$ gauge symmetry. Their $U(1)_X$ charges are assigned as follows^a:

$$(Q_\Phi, Q_\chi) = (1, 1).$$

We have the following renormalizable and gauge-invariant Lagrangian including just one singlet right-handed neutrino N and one lepton flavor:

$$\begin{aligned} \mathcal{L} = & \mathcal{L}_{\text{SM}} + \frac{1}{2}\bar{N}i\not{D}N - \left(\frac{1}{2}m_N\bar{N}^cN + y\bar{L}\tilde{H}N + \text{h.c.} \right) - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{1}{2}\sin\epsilon X_{\mu\nu}F_Y^{\mu\nu} \\ & + D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi, H) + \bar{\chi}(i\not{D} - m_\chi)\chi - (f\bar{\chi}\Phi N + \text{h.c.}), \end{aligned} \quad (3)$$

where $X_{\mu\nu} = \partial_\mu X_\nu - \partial_\nu X_\mu$ is the field strength for $U(1)_X$ gauge field X_μ , $F_Y^{\mu\nu}$ is for SM hypercharge $U(1)_Y$, and ϵ is the kinetic mixing parameter.

Both electroweak and $U(1)_X$ symmetries are spontaneously broken: $\langle H \rangle = (0, v_H/\sqrt{2})^T$, $\langle \Phi \rangle = v_\phi/\sqrt{2}$. Here $v_H \simeq 246\text{GeV}$ is the same as SM value but v_ϕ might be taken as a free parameter. In the unitarity gauge, we replace the scalar

^aA similar setup with different dark charge assignments has been considered for the AMS02 positron excess.⁸

fields with

$$H \rightarrow \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_H + h(x) \end{pmatrix} \quad \text{and} \quad \Phi \rightarrow \frac{v_\phi + \phi(x)}{\sqrt{2}}. \quad (4)$$

When N is much heavier than χ , we integrate it out to obtain an effective operator,

$$\frac{yf}{m_N} \bar{\chi} \Phi H^\dagger L + h.c., \quad (5)$$

which would make χ decay possible but long-lived if yf/m_N is sufficiently small, around 10^{-36}GeV^{-1} . This is not a problem since y and f is technically natural in the sense that vanishing y and f gives symmetries that protect χ from decay.

If $m_\chi \gg v_\phi$, the dominant decay channel is the following one, $\chi \rightarrow \phi h \nu$:

$$\frac{\Gamma_3(\chi \rightarrow \phi h \nu)}{\Gamma_2(\chi \rightarrow h \nu, \phi \nu)} \simeq \frac{1}{16\pi^2} \frac{m_\chi^2}{v_\phi^2 + v_H^2} \gg 1, \quad (6)$$

because we actually have an enhancement from heavy m_χ even though there is a phase space suppression. Other three-body-decay channels are also equally important:

$$\chi \rightarrow \phi/Z' + h + \nu, \quad \phi/Z' + Z + \nu, \quad \phi/Z' + W^\pm + l^\mp,$$

with branching ratios 1 : 1 : 2 due to the Goldstone boson equivalence theorem.

3. Numeric Results

In Fig. 1 we show the neutrino spectra. The neutrino flux is composed of galactic and extragalactic contributions,

$$\left. \frac{d\Phi_\nu^G}{dE_\nu} \right|_{E_\nu=E} = \frac{1}{4\pi} \sum_i \Gamma_i \int_0^\infty dr \frac{\rho_\chi^G(r')}{m_\chi} \left. \frac{dN_\nu^i}{dE_\nu} \right|_{E_\nu=E}, \quad (7)$$

where Γ_i is partial decay width for channel i , dN_ν^i/dE_ν is the neutrino spectrum at production, $r' = \sqrt{r_\odot^2 + r^2 - 2r_\odot r \cos \theta}$, r is the distance to DM decay point, $r_\odot \simeq 8.5 \text{kpc}$ and θ is the observation angle.

$$\left. \frac{d\Phi_\nu^{EG}}{dE_\nu} \right|_{E_\nu=E} = \frac{\rho_c \Omega_\chi}{4\pi m_\chi} \sum_i \Gamma_i \int_0^\infty \frac{dz}{\mathcal{H}} \left. \frac{dN_\nu^i}{dE_\nu} \right|_{E_\nu=(1+z)E}, \quad (8)$$

where E' is red-shifted to E as $E' = (1+z)E$, the critical energy density $\rho_c = 5.5 \times 10^{-6} \text{GeV/cm}^3$ and $\Omega_\chi \simeq 0.27$ is DM χ 's fraction. $\mathcal{H}$ is the Hubble parameter.

Next, we compare our model predictions with IceCube four-year data.⁵ To parameterize the possible astrophysical neutrino fluxes at low energy, we consider

Fig. 1. Neutrino spectra from DM χ decay with $m_\chi \sim 5$ PeV and lifetime $\tau_\chi = 1/\Gamma \sim 2 \times 10^{28}$ s. The left panel shows individual contribution of different final states from χ 's decay, ν and h/ϕ , respectively. The right panel presents the galactic and extragalactic neutrino flux.

Fig. 2. Compare with preliminary results based on 4-year data, with $J_0^{\text{BPL}} = 5.6 \times 10^{-8} \text{ GeV/cm}^2/\text{s/sr}$ and $\tau_\chi \sim 1.5 \times 10^{28}$ s (left), and $J_0^{\text{UPL}} = 2.1 \times 10^{-8} \text{ GeV/cm}^2/\text{s/sr}$ and $\tau_\chi \sim 2 \times 10^{28}$ s (right).

either a broken power law (BPL) or unbroken power law (UPL),

$$E_\nu^2 \frac{d\Phi_{\text{bkg}}}{dE_\nu} = J_0^{\text{BPL}} \left(\frac{E_\nu}{100 \text{ TeV}} \right)^{-\gamma_1} \exp \left(-\frac{E_\nu}{E_0} \right), \quad (9)$$

$$E_\nu^2 \frac{d\Phi_{\text{bkg}}}{dE_\nu} = J_0^{\text{UPL}} \left(\frac{E_\nu}{100 \text{ TeV}} \right)^{-\gamma_2}, \quad (10)$$

where the first one has an exponential cut-off at energy scale E_0 which is chosen to be 125 TeV. As shown in Fig. 2, we illustrate with DM χ decay with $m_\chi \sim 5$ PeV and lifetime $\tau_\chi = 1/\Gamma \sim 2 \times 10^{28}$ s.

We also checked that the resulting gamma-ray flux is consistent with the current astrophysical bounds.

4. Conclusion

We have discussed a decaying dark matter model that can explain the IceCube PeV events, based on an extra $U(1)_\chi$ dark gauge symmetry and right-handed neutrino portal interactions. The dominant decay channel for dark matter χ is the three-body final state with a SM Higgs, a dark Higgs, and a neutrino ($\chi \rightarrow \phi + h + \nu$). We show that resulting neutrino flux has a spectrum that is consistent with the IceCube observation. Together with astrophysical flux for lower energy events, we fit IceCube data around 100 TeV $\sim$ 2 PeV if DM mass is about $m_\chi \sim$ 5PeV and its lifetime is $\tau_\chi \sim 2 \times 10^{28}$ sec.

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