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IceCube neutrinos, decaying dark matter, and the Hubble constant

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Cosmological parameters deduced from the *Planck* measurements of anisotropies in the cosmic microwave background are at some tension with direct astronomical measurements of various parameters at low redshifts. Very recently, it has been conjectured that this discrepancy can be reconciled if a certain fraction of dark matter is unstable and decays between recombination and the present epoch. Herein we show that if the superheavy relics have a branching into neutrinos $\mathcal{B}_{X\to\nu\bar\nu} \sim 5\times 10^{-8}$, then this scenario can also accommodate the recently discovered extraterrestrial flux of neutrinos, relaxing the tension between IceCube results and *Fermi* LAT data. The model is fully predictive and can be confronted with future IceCube data. We demonstrate that in 10 years of observation IceCube will be able to distinguish the mono-energetic signal from X decay at the 3σ level. In a few years of data taking with the upgraded *IceCube-Gen2* enough statistics will be gathered to elucidate the dark matter–neutrino connection at the 5σ level.

We propose an explanation for the origin of IceCube neutrinos [1] assuming heavy decaying dark matter, which is characterized by a lifetime and a comoving number density that may resolve the tension between *Planck* data and low redshift astronomical measurements [2]. The ensuing discussion will be framed in the context of dissipative dark matter. We consider a multicomponent hidden sector, with strong self interactions, featuring a massless dark photon which mixes with the ordinary photon and a dark Z' which mixes with the Z. The dark photon induces a one-loop photon wave function mixing term $\epsilon F^{\mu\nu}F'_{\mu\nu}$ [3]. Early universe cosmology and galactic structure considerations constrain the dark photon mixing strength, $\epsilon \lesssim 10^{-9}$ [4]. Bounds on the $Z-Z'$ mixing angle are less restrictive [5].

Cosmic Neutrinos— Recently, the IceCube Collaboration reported the discovery of extraterrestrial neutrinos [1]. By establishing a strict veto protocol, the collaboration was able to isolate 36 events in 3 years of data, with energies between 30 TeV $\lesssim E_\nu \lesssim$ 2 PeV. These events follow the expected spectral shape ($\propto E_\nu^{-2}$) of a Fermi engine, and are consistent with an isotropic distribution in the sky. A purely atmospheric explanation of the data can be excluded at 5.7σ.

At $E_\nu^{\rm res} \simeq 6.3$ PeV, one expects to observe a dramatic increase in the event rate for $\bar\nu_e$ in ice due to the Glashow resonance in which $\bar\nu_e e^- \to W^- \to$ shower greatly increases the interaction cross section [6]. The hypothesis of an unbroken power law $\propto E_\nu^{-\alpha}$ then requires $\alpha \gtrsim 2.45$ to be consistent with data at 1σ [7]. More recently, the IceCube search technique was refined to extend the neutrino sensitivity to lower energies $E_\nu \gtrsim 10$ TeV [8]. A fit to the resulting data, assuming a single unbroken power law and equal neutrino fluxes of all flavors, finds a softer spectrum

$$\Phi^{\rm per\,flavor}_{\rm IceCube}(E_\nu) = 2.06^{+0.4}_{-0.3}\times 10^{-18}\left(\frac{E_\nu}{10^5\ {\rm GeV}}\right)^{-2.46\pm0.12} \times {\rm GeV^{-1}\,cm^{-2}\,sr^{-1}\,s^{-1}} \quad (1)$$

and already mildly excludes the benchmark spectral index $\alpha = 2$.

The neutrino flux in (1) is exceptionally high by astronomical standards, with a magnitude comparable to the Waxman-Bahcall bound [9]. A saturation of this bound can only be achieved within astrophysical environments where accelerator and target are essentially integrated. Potential candidate sources are discussed in [10]. These powerful sources produce roughly equal numbers of π^0, π^+ and π^- in the proton-proton beam dump. The π^0 accompanying the $\pi^\pm$ parents of IceCube neutrinos decay into γ-rays, which are only observed indirectly after propagation in the extragalactic radiation fields permeating the universe. These γ-rays initiate inverse Compton cascades that degrade their energy below 1 TeV. The relative magnitudes of the diffuse γ-ray flux detected by *Fermi* LAT [11] can then be used to constrain the spectral index, assuming the γ-rays produced by the π^0's accompanying the $\pi^\pm$ escape the source. Figure 1 shows that only a relatively hard injection spectrum is consistent with the data. Indeed, if IceCube neutrinos are produced through

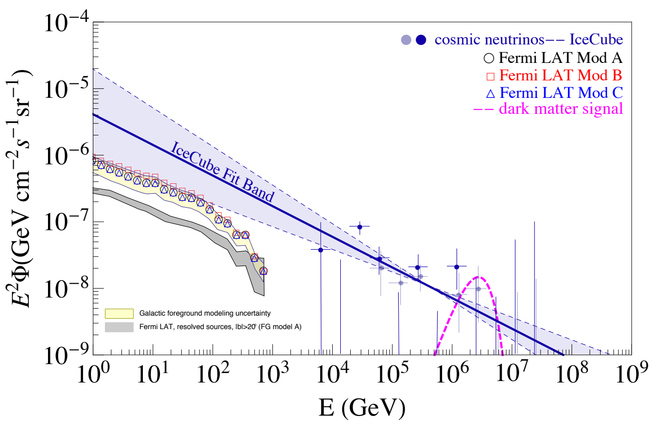

FIG. 1. The open symbols represent the total extragalactic γ-ray background for different foreground (FG) models as reported by the Fermi LAT Collaboration [11]. For details on the modeling of the diffuse Galactic foreground emission in the benchmark FG models A, B and C, see [11]. The cumulative intensity from resolved *Fermi* LAT sources at latitudes $|b| > 20^\circ$ is indicated by a (grey) band. The solid symbols indicate the neutrino flux (per flavor) reported by the IceCube Collaboration. The blue points are from the data sample of the most recent IceCube analysis [8]. The light grey data points are from the 3-year data sample of [1], shifted slightly to the right for better visibility. The best fit to the data (extrapolated down to lower energies), is also shown for comparison [8]. The dashed line indicates the mono-energetic signal from dark matter decay. Note that a plotting of $E^2\Phi = EdF/(d\Omega\, dA\, dt\, d\ln E)$ versus $\ln E$ conserves the area under a spectrum even after processing the electromagnetic cascade. Thus, the area of the π^0 contribution to the diffuse γ-ray spectrum (total diffuse γ-ray flux provides an upper bound) implies the low energy cutoff (upper bound) to the $\pi^\pm$ origin of the neutrinos.

pp collisions in optically thin extragalactic sources, the γ-rays expected to accompany the neutrinos saturate the *Fermi* LAT flux for $\alpha \approx 2.2$ [12]. The overall isotropy of the observed arrival directions and the fact that a PeV event arrives from outside the Galactic plane disfavor a Galactic origin. Moreover, for the Galactic hypothesis one must consider another important caveat, namely that the expected photon flux in the PeV range [13] has been elusive [14].

The difficulties so far encountered in modeling the production of IceCube neutrinos in astrophysical sources fueled the interest in particle physics inspired models. By far the most popular model in this category is the decay of a heavy massive ($\sim$ few PeV) relic that constitute (part of) the cold dark matter (CDM) in the universe [15]. The lack of events in the vicinity of the Glashow resonance, implies the spectrum should decrease significantly at the energy of a few PeV. Spectra from dark matter decays always exhibit a sharp cutoff determined by the particle mass. Furthermore, the 3 highest energy events appear to have identical energies, up to experimental uncertainties. A line in the neutrino spectrum would be a smoking gun signature for dark matter. If the heavy relic also decays into quarks and charged leptons, the mono-energetic neutrino line may be accompanied by a continuous spectrum of lower-energy neutrinos, which can explain both the PeV events and some of the sub-PeV events. All of these considerations appear to be in agreement with the data [16]. Even much heavier relic particles, with masses well above a PeV, can generate the required neutrino spectrum from their decays if their lifetime is much shorter than the present age of the universe [17]. The spectrum of neutrinos is modified by a combination of redshift and interactions with the background neutrinos, and the observed spectrum can have a cutoff just above 1 PeV for a broad range of the relic particle masses. In this Letter we will reexamine the idea of a dark matter origin for IceCube events.

H_0 Measurements— Another, seemingly different, but perhaps closely related subject is the emerging tension between direct astronomical measurements at low redshift and cosmological parameters deduced from temperature fluctuations in the cosmic microwave background (CMB). Strictly speaking, the TT, TE, EE spectra recorded by the *Planck* spacecraft when combined with polarization maps (lowP) describe the standard spatially-flat 6-parameter ΛCDM model $\{\Omega_b h^2, \Omega_{\rm CDM} h^2, \Theta_s, \tau, n_s, A_s\}$ with high precision: *(i)* baryon density, $\Omega_b h^2 = 0.02225 \pm 0.00016$; *(ii)* CDM density, $\Omega_{\rm CDM} h^2 = 0.1198 \pm 0.0015$; *(iii)* angular size of the sound horizon at recombination, $\Theta_s = (1.04077 \pm 0.00032) \times 10^{-2}$; *(iv)* Thomson scattering optical depth due to reionization, $\tau = 0.079 \pm 0.017$; *(v)* scalar spectral index, $n_s = 0.9645 \pm 0.0049$; *(vi)* power spectrum amplitude of adiabatic scalar perturbations, $\ln(10^{10} A_s) = 3.094 \pm 0.034$ [18]. *Planck* data also constrain the Hubble constant $h = 0.6727 \pm 0.0066$, the dark energy density $\Omega_\Lambda = 0.6844 \pm 0.0091$, the amplitude of initial density perturbations $\sigma_8 = 0.831 \pm 0.013$, and the mass density parameter $\Omega_m = 0.3156 \pm 0.0091$.[1] Unexpectedly, the H_0 inference from *Planck* observations deviates by more than 2.5σ from the previous interpretation of the Hubble Space Telescope (HST) data (based on over 600 cepheids in host galaxies and 8 samples of SNe Ia) which leads to $h = 0.738 \pm 0.024$, including both statistical and systematic uncertainties [19]. A separate study by the Carnegie Hubble program using mid-infrared calibration of the cepheid distance scale based on data from NASA's Spitzer Space Telescope yields $h = 0.743 \pm 0.021$ [20]. Besides, the interpretation of gravitational lensing time delay measurements of the system RXJ1131-1231 points to $h = 0.787^{+0.043}_{-0.045}$ [21].

The tension between the CMB based determination of the Hubble constant and the h value inferred from direct low redshift measurements is intriguing and deserves further attention. On the one hand, the underly-

[1] Throughout we adopt the usual convention of writing the Hubble constant at the present day as $H_0 = 100\ h$ km s^{-1} Mpc^{-1}.

ing source of discrepancy could be some systematic uncertainty in the calibration [22]. On the other hand, it could trace a deficiency of the concordance model of cosmology. In the spirit of [23], it has been recently conjectured that *Planck*-inspired ΛCDM paradigm can be reconciled with HST measurements if a subdominant fraction f_X of CDM is unstable and decays rather quickly with respect to the present Hubble time [2]. The width of the unstable component Γ_X, normalized to H_0, is an independent parameter of the model. By forcing the X particles to decay after recombination Γ_X/H_0 is bounded from above. Moreover, the X is assumed to decay (dominantly) into invisible massless particles of the hidden sector and hence does not produce too many photons. A joint fit to *Planck*, supernova, and HST data reveals that the base ΛCDM model, with $\Gamma/H_0 = 0$, is outside the 2σ likelihood contours in the (Γ_X, f_X) plane [2]. The data instead favor $0.05 \lesssim f_X \lesssim 0.10$. The mean value and 1σ error derived from a maximum likelihood analysis are $h = 0.716 \pm 0.020$ [2]. Interestingly, within the same parameter range the model could also alleviate the emerging tension with the cluster data. (See, however, [24].) For example, for $f_X \simeq 0.10$ and $\Gamma_X/H_0 \simeq 2000$ the corresponding values of $\Omega_m \simeq 0.25$ and $\sigma_8 \simeq 0.80$ [2] are marginally consistent with the 2σ allowed contours by the *Planck* cluster mass scale [25] and the extended ROSAT-ESO Flux Limited X-ray Galaxy Cluster Survey (REFLEX II) [26]. For smaller values of f_X and or Γ_X/H_0 the values of Ω_m and σ_8 move closer to the base ΛCDM model [2]. Next, in line with our stated plan, we take $f_X \simeq 0.07$ and $\Gamma_X/H_0 \simeq 1500$ as benchmarks and investigate what would be the CDM fraction required to decay into the visible sector to accommodate IceCube observations.

Bump-Hunting— The two main parameters characterizing the X particle are its lifetime $\tau_X \simeq 3\times10^{14}$ s and its mass m_X, which is a free parameter. We assume the neutrino produced via X decay is mono-energetic, with energy $\varepsilon_\nu = m_X/2$. The neutrino energy distribution from X decay is given by $dN_\nu/dE_\nu = N_\nu\ \delta(E_\nu - \varepsilon_\nu)$, where N_ν is the neutrino multiplicity. We further assume the dominant decay mode into the visible sector, contributing to neutrino production, is $X \to \nu\bar{\nu}$ and so $N_\nu = 2$.

The evolution of the number density of neutrinos $n_\nu(E_\nu, z)$ produced at cosmological distances in the decay of X particles is governed by the Boltzmann continuity equation,

$$\frac{\partial[n_\nu/(1+z)^3]}{\partial t} = \frac{\partial[HE_\nu n_\nu/(1+z)^3]}{\partial E_\nu} + \mathcal{Q}_\nu\,, \quad (2)$$

together with the Friedman-Lemaître equations describing the cosmic expansion rate $H(z)$ as a function of the redshift z. This is given by $H^2(z) = H_0^2\,[\Omega_m(1+z)^3+\Omega_\Lambda]$. The time-dependence of the red-shift can be expressed via $dz = -dt\,(1+z)H$. We have found that for the considerations in the present work neutrino interactions on the cosmic neutrino background can be safely neglected [27].

In (2),

$$\mathcal{Q}_\nu(E_\nu, t) = \frac{n_X(t)}{\tau_X}\,\mathcal{B}_{X\to\nu\bar{\nu}}\ \frac{dN_\nu}{dE_\nu}\,, \quad (3)$$

is the source term, $n_X(t) = Y_X\ s(t)\ e^{-t/\tau_X}$ is the number density of X, $\mathcal{B}_{X\to\nu\bar{\nu}}$ is the neutrino branching fraction, $s(t)$ is the entropy density, and

$$Y_X = 3.6\times10^{-9}\,\frac{\Omega_X h^2}{m_X/\text{GeV}} \quad (4)$$

is the comoving number density at the CMB epoch. By solving (2) we obtain the (all flavor) neutrino flux at present epoch t_0,

$$\begin{aligned}\Phi(E_\nu) &= \frac{c}{4\pi} n_\nu(E_\nu, 0) \quad (5)\\ &= \frac{c}{4\pi}\frac{N_\nu Y_X s(t_0)}{\tau_X E_\nu}\mathcal{B}_{X\to\nu\bar{\nu}}\ \frac{e^{-t_*/\tau_X}}{H(t_*)}\bigg|_{1+z(t_*)=\varepsilon_\nu/E_\nu},\end{aligned}$$

with $s(t_0) \simeq 2.9\times10^3\ \text{cm}^{-3}$.

Maximization of (5) yields the energy relation for the peak in the spectrum,

$$E_\nu^{\text{peak}} \simeq \frac{1}{2}\ \frac{m_X/2}{1+z(\tau_X)}\,, \quad (6)$$

which sets the mass of the X. Since $z(\tau_X) \simeq 140$ to accommodate the PeV peak in IceCube's neutrino spectrum we take $m_X \simeq 560$ PeV. Now, from (4) we obtain $Y_X \approx 5.4\times10^{-20}$. Finally, we normalize the cosmic neutrino flux per flavor using (1). The intensity of the mono-energetic signal at the peak is taken as 60% of the flux reported by the IceCube Collaboration, yielding a neutrino branching fraction $\mathcal{B}_{X\to\nu\bar{\nu}} \sim 5\times10^{-8}$ into all three flavors. The width, an output of the Boltzmann equation, is shown in Fig. 1. It is evident that the mono-energetic neutrino spectrum is in good agreement with the data. In particular, the flux suppression at the Glashow resonance, $\Phi(E_\nu^{\text{res}})/\Phi(E_\nu^{\text{peak}}) \simeq 0.011$, is consistent with data at 1σ.

The model is fully predictive and can also be confronted with *Fermi* LAT data. It is reasonable to assume that $\mathcal{B}_{X\to e^+e^-} \approx \mathcal{B}_{X\to\nu_e\bar{\nu}_e} \approx \mathcal{B}_{X\to u\bar{u}} \approx \mathcal{B}_{X\to d\bar{d}}$. About 1/3 of the energy deposited into either $u\bar{u}$ or $d\bar{d}$ is channeled into γ-rays via π^0 decay and about 1/6 of the energy is channeled into electrons and positrons. As previously noted, the γ-rays, electrons, and positrons trigger an electromagnetic cascade on the CMB, which develops via repeated e^+e^- pair production and inverse Compton scattering. As a result of this cascade the energy gets recycled yielding a pile up of γ-rays at GeV $\lesssim E_\gamma \lesssim$ TeV, just below the threshold for further pair production on the diffuse optical backgrounds. We have seen that under very reasonable assumptions the energy deposited into neutrinos is comparable to the energy deposited into the electromagnetic cascade. Therefore, the neutrino energy density at the present epoch,

$$\omega_\nu = \int E_\nu\ n_\nu(E_\nu, 0)\ dE_\nu = 2.5\times10^{-11}\ \text{eV cm}^{-3}, \quad (7)$$

TABLE I. Event rates (yr^{-1}) at IceCube for $E_\nu^{\min} = 1$ PeV.

$E_\nu^{\max}$/PeV	spectrum $\propto E_\nu^{-2.46}$			X decay spectrum		
	ν_e	ν_μ	ν_τ	ν_e	ν_μ	ν_τ
2	0.20	0.18	0.20	0.25	0.23	0.25
3	0.27	0.24	0.27	0.46	0.41	0.46
4	0.31	0.27	0.30	0.58	0.51	0.56
5	0.34	0.29	0.32	0.66	0.56	0.62

provides reliable estimate of the cascade energy density ($\omega_{\rm cas} \sim \omega_\nu$), which is bounded by *Fermi* LAT data to not exceed $\omega_{\rm cas}^{\max} \sim 5.8 \times 10^{-7}$ eV cm^{-3} [28]. We conclude that the γ-ray flux associated with the neutrino line is found to be about 4 orders of magnitude smaller than the observed flux in the *Fermi* LAT region.

We now turn to discuss the possibility of distinguishing the neutrino line from an unbroken power-law spectrum without the neutrino line, with future IceCube data. The value of the spectral index is determined by the "low energy" events. Following the best IceCube fit we adopt a spectrum $\propto E_\nu^{-2.46}$. We assume that the IceCube events below 1 PeV have an astrophysical origin. Indeed, the steep spectrum $\propto E_\nu^{-2.46}$ may suggest we are witnessing the cutoff of TeV neutrino sources running out of power. Using the IceCube aperture for the high-energy starting event (HESE) analysis [1] we compute the event rate per year above 1 PeV for both the neutrino flux given in (1) and that of (5). The results are given in Table I. As expected, the predictions from X decay are in good agreement with existing data. Because of the smeared energy-dependence of muon tracks, in what follows we will only consider cascades and double bang topologies initiated by charged current interactions of electron and tau neutrinos, as well as all neutral current interactions processes. We identify the events coming from the power law spectrum $\mathcal{N}_{\rm B}$ with background and adopt the standard bump-hunting method to establish the statistical significance of the mono-energetic signal. To remain conservative we define the noise $\equiv \sqrt{\mathcal{N}_{\rm B} + \mathcal{N}_{\rm S}}$, where $\mathcal{N}_{\rm S}$ is the number of signal events. In 10 years of operation the total detection significance,

$$S_{\rm det} = \frac{\mathcal{N}_{\rm S}}{\sqrt{\mathcal{N}_{\rm B} + \mathcal{N}_{\rm S}}}\,, \tag{8}$$

would allow distinguishing the neutrino line from a statistical fluctuation of a power law spectrum $\propto E_\nu^{-2.46}$ at the 3σ level. Note that the shape of the distribution with energy conveys additional information allowing one to distinguish the line signal from fluctuations of a power-law background. The proposed *IceCube-Gen2* extension plans to increase the effective volume of IceCube by about a factor of 10 [29]. This facility will not only increase the HESE sensitivity but also improve the energy resolution for muon tracks. In a few years of operation *IceCube-Gen2* will collect enough statistics to elucidate the dark matter–neutrino connection with $S_{\rm det} > 5\sigma$.

We end with an observation: IceCube data can also be fitted by a neutrino line peaking at $E_\nu \sim 20$ TeV superimposed over a power law spectrum ($\propto E_\nu^{-2}$) of astrophysical neutrinos [30]. By duplicating our discussion for $m_X \sim 1$ PeV it is straightforward to see that the model can also accommodate this neutrino line.

Conclusions— We have shown that the PeV flux of extraterrestrial neutrinos recently reported by the IceCube Collaboration can originate through the decay of heavy dark matter particles with a mass $\simeq 560$ PeV and a lifetime $\simeq 3 \times 10^{14}$ s. On a separate track, the tension between *Planck* data and low redshift astronomical measurements can be resolved if about 7% of the CDM component at CMB epoch is unstable. Assuming that such a fraction of quasi-stable relics is responsible for the IceCube flux we determined the neutrino branching fraction, $\mathcal{B}_{X\to\nu\bar\nu} \sim 5 \times 10^{-8}$. The model has no free parameters and will be tested by future IceCube data. Indeed 10 years of data taking will be required to distinguish the neutrino line from an unbroken power-law spectrum at the 3σ level. The upgraded *IceCube-Gen2* will collect enough statistics to elucidate the dark matter–neutrino connection at the 5σ discovery level in a few years of operation.

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