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The direct detection of boosted dark matter at high energies and PeV events at IceCube

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Abstract. We study the possibility of detecting dark matter directly via a small but energetic component that is allowed within present-day constraints. Drawing closely upon the fact that neutral current neutrino nucleon interactions are indistinguishable from DM-nucleon interactions at low energies, we extend this feature to high energies for a small, non-thermal but highly energetic population of DM particle χ, created via the decay of a significantly more massive and long-lived non-thermal relic ϕ, which forms the bulk of DM. If χ interacts with nucleons, its cross-section, like the neutrino-nucleus coherent cross-section, can rise sharply with energy leading to deep inelastic scattering, similar to neutral current neutrino-nucleon interactions at high energies. Thus, its direct detection may be possible via cascades in very large neutrino detectors. As a specific example, we apply this notion to the recently reported three ultra-high energy PeV cascade events clustered around $1-2\,\mathrm{PeV}$ at IceCube (IC). We discuss the features which may help discriminate this scenario from one in which only astrophysical neutrinos constitute the event sample in detectors like IC.

Keywords: dark matter theory, neutrino detectors, ultra high energy photons and neutrinos

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Contents

1 Introduction

The nature and origin of dark matter (DM) remains one of the principal unanswered questions in physics. While theoretical biases have served as a guide for searches and model-building, in principle, very little is known about its nature and properties. Specifically, the DM mass can span the range 10^{-15}–10^{15} GeV, and its interaction cross-section with nucleons and annihilation cross-section into SM particles can lie in the range 10^{-76}–10^{-41} cm^2 [1].

Since the bulk of DM is known to be non-relativistic, its direct detection has focussed on its low-energy coherent scattering off nuclei, leading to nuclear recoils which have energies of a few keV, making them very challenging to detect over backgrounds. In general, most efforts have been directed towards exploring the parameter space spanned by thermal DM masses in the 10–100 GeV range with weak-scale interaction cross-sections with nucleons. Recent experiments have, however, significantly constrained this space for such particles (also called WIMPS).[1] When combined with results from indirect DM searches and colliders, it is fair to say that credible reasons for seriously considering "non-WIMP" and possibly non-thermal candidates for DM exist (for a review, see [3]). In addition, we note that Big Bang Nucleosynthesis (BBN) constraints derived from the primordial Helium and Deuterium abundances [4], indicate that the number of effective relativistic species is $N_{\mathrm{eff}} = 3.56 \pm 0.23$. Constraints derived from observations of the Cosmic Microwave Background (CMB) by the Planck experiment [5] similarly favor the presence of some "dark radiation" over and above the three standard model neutrinos, with $N_{\mathrm{eff}} = 3.30 \pm 0.27$. Significantly, when combined, these two sets of constraints with very different origins rule out the presence of a full sterile neutrino, $\Delta N_{\mathrm{eff}} = 1$ at $> 99\%$ C.L, whereas the absence of any additional neutrino coupled relativistic species is disfavoured at $> 98\% C.L.$ [4]. Relativistic non-thermal DM particles could be one possible way of resolving this [6].

The possibility that DM may be a multi-particle sector has, of course, been extensively studied in the literature under various assumptions. Due to the reasons mentioned above, it is possible that the bulk of this sector may comprise of non-thermal (and non-relativistic) components, and may also contain a small component that may be relativistic and highly energetic. In what follows, we focus on the detection of DM via this component. Specifically, we explore the possibility of directly detecting DM in existing large neutrino detectors at energies much higher than presently considered. After further motivating this idea, we explore

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[1] For recent reviews, see [1, 2].

its consequences qualitatively and quantitatively when specifically applied to the recently announced IceCube (IC) PeV events.

We note that coherent elastic neutrino-nucleus scattering [7], a process not yet experimentally observed due to the very small nuclear recoil measurement required to detect it, is expected to be an irreducible background for future DM direct detection experiments [8]. Thus DM and neutral current (NC) neutrino interactions mimic each other at low energies. One can expect that this analogy holds with rising energies, and in particular at the highest energies at which neutrinos are presently detected.

In the present work, we assume DM to be primarily non-thermal[2] with its bulk comprised of a very massive relic ϕ (with mass m_ϕ and a lifetime τ_ϕ greater than the age of the Universe) which decays preferentially to another much lighter DM particle χ (as opposed to decaying to standard model (SM) daughters). This leads to a small but significant population of ultra-high energy relativistic DM particles, non-thermally created in the narrow energy region spanning m_ϕ.

Drawing closely upon the similarity between neutrino NC and DM interactions, we further assume that χ interacts with SM particles with cross-sections much smaller than standard weak interactions via the exchange of a heavy gauge boson which connects the SM and DM sectors. The assumption of a small strength interaction between DM and SM is of course empirically required, and the assumption about the existence of a heavy neutral guage boson provides a simple way to implement it. At high energies, this will result in deeply inelastic interactions (DIS) of DM with SM particles, and mimic UHE neutrino-nucleon NC interactions [10, 11] in a detector like IC, creating cascades which are indistinguishable from those created by neutrinos.

In what follows, we quantitatively implement the above proposal of looking for DM at high energies in neutrino detectors by performing a flux and cross-section calculation. While the approach is generic, it can be modified in specific ways to perform a broader and more general study, vis a vis choices of a mediator (scalar versus a vector boson, for instance), coupling strengths , masses etc [12]. Our choices below are pertinent to our chosen application, which are the recently observed PeV IC events. We calculate the DM-nucleon cross section at high energies in analogy with the neutrino-nucleon NC cross-section. We then focus on the three PeV events in IC, and assuming that their cascades originate in DM interactions with ice nuclei, we determine the ramifications for DM mass and flux which result from this. Finally, we discuss the general features that would distinguish this scenario from others in which all the events in IC -like detectors are due to neutrino scattering.

2 Neutral-current scattering of a relativistic dark matter species with nuclei

We assume that the DM sector consists of at least two particle species with the following properties:

- A co-moving non-relativistic real scalar species ϕ, with a mass of $\mathcal{O}(10\,\mathrm{PeV})$, which is unstable but decays with a very large lifetime to χ, and does not have any decay channels to SM particles. We call this species the PeV Dark Matter (PDM), and it comprises the bulk of present-day DM.

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[2] Unitarity bounds constrain particles with mass $m \gtrsim 300\,\mathrm{TeV}$ to remain out of thermal equilibrium throughout its history as discussed in [9]; in addition, we choose the lighter DM species to be non-thermal also.

- A lighter fermionic DM species (FDM), χ with mass $m_\chi \ll m_\phi$, which we assume is produced in a monochromatic pair when the PDM decays, i.e., $\phi \to \bar{\chi}\chi$, each with energies of $m_\phi/2$.[3]

The lifetimes for the decay of heavy DM particles to standard model species are strongly constrained ($\tau \gtrsim 10^{27}$–10^{28}s) by diffuse gamma-ray and neutrino observations [13, 14]. However, since in our scenario ϕ does not decay to SM particles, constraints relevant here are only those based on cosmology, which limits the total relativistic particle density of the universe at the respective epochs, independent of what those particles are, and are significantly weaker. Specifically, these include limits from the observed CMB anisotropies [15], light nuclei abundances during Big-Bang Nucleosynthesis (BBN) [4, 16] and from structure formation (see, e.g., [17] for a review).[4] Consistent with these constraints, and with present-day relic abundance considerations, we assume that the PDM decays with a lifetime of $\tau_\phi \gtrsim 10^{17}$s, i.e., greater than the lifetime of the universe. Additionally, the lighter (and stable) FDM species is assumed to be produced only non-thermally, via the decay of the long-lived PDM. Its contribution to the DM mass density is thus expected to be small.

The FDM flux is composed of galactic and extragalactic components of comparable magnitudes [18]. Thus, the total flux $\Phi = \Phi^{\mathrm{G}} + \Phi^{\mathrm{EG}}$, where, Φ^{G} and Φ^{EG} respectively represent the galactic and extra-galactic components of this flux [18, 19]):

$$\Phi^{\mathrm{G}} = \int_{E_{\min}}^{E_{\max}} \mathrm{d}E_\chi \, D_{\mathrm{G}} \frac{\mathrm{d}N_\chi}{\mathrm{d}E_\chi}, \tag{2.1}$$

and,

$$\begin{aligned}\Phi^{\mathrm{EG}} &= \frac{\Omega_{DM}\,\rho_{\mathrm{c}}}{4\pi\, m_\phi\, \tau_\phi} \int_{E_{\min}}^{E_{\max}} \mathrm{d}E_\chi \int_0^\infty \mathrm{d}z\, \frac{1}{H(z)} \frac{\mathrm{d}N_\chi}{\mathrm{d}E_\chi}\left[(1+z)E_\chi\right] && \text{(2.2a)}\\ &= D_{\mathrm{EG}} \int_{E_{\min}}^{E_{\max}} \mathrm{d}E_\chi \int_0^\infty \mathrm{d}z\, \frac{1}{\sqrt{\Omega_\Lambda + \Omega_{\mathrm{m}}(1+z)^3}} \times \frac{\mathrm{d}N_\chi}{\mathrm{d}E_\chi}\left[(1+z)E_\chi\right], && \text{(2.2b)}\end{aligned}$$

with

$$D_{\mathrm{G}} = 1.7 \times 10^{-8} \left(\frac{1\ \mathrm{TeV}}{m_\phi}\right)\left(\frac{10^{26}\ \mathrm{s}}{\tau_\phi}\right)\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$$

and

$$D_{\mathrm{EG}} = 1.4 \times 10^{-8} \left(\frac{1\ \mathrm{TeV}}{m_\phi}\right)\left(\frac{10^{26}\ \mathrm{s}}{\tau_\phi}\right)\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}.$$

Here, z represents the red-shift of the source, $\rho_{\mathrm{c}} = 5.6 \times 10^{-6}$ GeV cm^{-3} denotes the critical density of the universe, and we have used $H(z) = H_0\sqrt{\Omega_\Lambda + \Omega_{\mathrm{m}}(1+z)^3}$, and $\Omega_\Lambda = 0.6825$, $\Omega_{\mathrm{m}} = 0.3175$, $\Omega_{DM} = 0.2685$ and $H_0 = 67.1$ km s^{-1} Mpc^{-1} from the recent PLANCK data [5]. For the two-body decay $\phi \to \bar{\chi}\chi$

$$\frac{\mathrm{d}N_\chi}{\mathrm{d}E_\chi} = 2\delta\left(E_\chi - \frac{1}{2}m_\phi\right), \tag{2.3}$$

where, E_χ denotes the energy of each of the produced χ particle.

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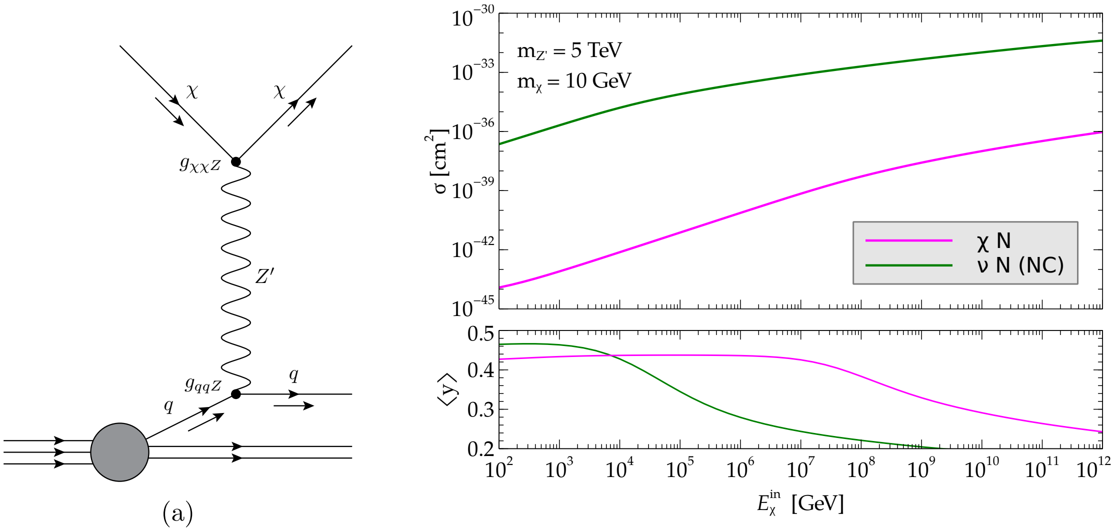
[3] As mentioned above, the choice of a PeV scale mass for DM and subsequent choices of couplings and a mediator is based on our application below to recent IC events, but they are representative of a concept that may have broader applicability.

[4] BBN is also sensitive to the electron-positron pair production rate in DM annihilation, but for both the PDM and FDM these interaction strengths are tiny.



(a)

(b)

Figure 1. (a) Interaction of the incoming TeV mass DM particle χ with a nucleus, mediated by a heavy non-standard boson Z'. (b) The χN DIS interaction cross-section and the corresponding $\langle y(E)\rangle$ are shown for the benchmark value of m_χ and $m_{Z'}$. The overall normalisation to the χN cross-section is set by the product of coupling constants G, and is here arbitrarily chosen to be $G = 0.05$. The real magnitude of G will be determined by comparing event rates to those seen at IC in the succeeding section. For comparison, the νN neutral current cross-section and the corresponding $\langle y\rangle$ are also shown.

The FDM interacts with the nucleus within the IceCube detector via a neutral current interaction mediated by a beyond-SM heavy gauge boson, Z' (figure 1a) that couples to both the χ and quarks and gluons.

For both the $\chi\chi Z'$ and qqZ' interactions we assume the interaction vertex to be vector-like, with hitherto undetermined coupling constants $g_{\chi\chi Z}$ and g_{qqZ} respectively.[5] The DIS cross-section for $\chi N \to \chi X$ is then computed in the lab-frame, with the product $G = g_{\chi\chi Z} g_{qqZ}$ as the undetermined parameter, over a broad range of incoming FDM energies, 100 GeV $\leq E_\chi^{\rm in} \leq$ 10 PeV, using tree-level `CT10` parton distribution functions [22]. We set the Z' mass to be 5 TeV. For Z' with mass $\geqslant$ 2.9 TeV, the couplings $g_{\chi\chi Z}$ and g_{qqZ} are largely unconstrained by collider searches [23], thus are limited only by unitarity.[6]

Since the IC can only measure the deposited energy $E^{\rm dep}$ for neutral current events, it is important to determine the nature of the inelasticity parameter, relating the deposited

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[5] We have deliberately tried to avoid limiting the scenario to any particular theoretical model in order to focus solely on the phenomenological signatures of the two-sector DM that we have discussed here. Theoretical models that encompass our DM spectrum have been discussed in the literature in terms of Z or Z' portal sectors with the Z' vector boson typically acquiring mass through the breaking of an additional U(1) gauge group at the high energies (see e.g., [20, 21]).

[6] We note here that due to the presence of $\chi\chi Z'$ vertex, the possibility that Z'-bremsstrahlung affects the two-body $\phi \to \chi\chi$ decay and thus the energies of the outgoing χ-particles becomes worth considering. We have verified by means of explicit calculations that, for the value of the parameters G^2 and τ_ϕ that we require in order to fit the predicted events from χN NC scattering with IC observations (see section 3.1), Z' bremsstrahlung-included decay rate is about 5% of the total decay rate and therefore negligible. A presentation of the full computation is beyond the scope of this paper, but closely follows a similar computation made in [24].

energy to the incoming particle energy (E_χ^{in}):

$$y = \frac{E_\chi^{\text{in}} - E_\chi^{\text{out}}}{E_\chi^{\text{in}}} = \frac{E^{\text{dep}}}{E_\chi^{\text{in}}}\,, \tag{2.4}$$

where, E_χ^{out} represents the energy of the outgoing χ in the scattering process. The DIS differential cross-section with respect to the inelasticity parameter is then expressed as

$$\frac{\mathrm{d}\sigma}{\mathrm{d}y}(E_\chi^{\text{in}}, y) = G^2 f(E_\chi^{\text{in}}, y)\,. \tag{2.5}$$

The results for the total cross-section and the mean inelasticity parameter,

$$\langle y(E_\chi^{\text{in}})\rangle = \frac{1}{\sigma(E_\chi^{\text{in}})}\int_0^1 \mathrm{d}y\, y \frac{\mathrm{d}\sigma(E_\chi^{\text{in}}, y)}{\mathrm{d}y}\,,$$

are shown in figure 1b.

3 The IC events: characteristics and possible origins

Prior to applying our proposal, we recapitualte the basic observations and features of the IC data below.

The observation of ultra-high energy (UHE, $E_\nu \geq 30\,\text{TeV}$) neutrino events at IceCube (IC) [25, 26] is one of the most striking of recent experimental results in all of physics. When statistically buttressed by imminent additional observations by IC and other high energy neutrino observatories like ANTARES [27], AUGER [28] and the upcoming KM3NET [29] they promise to open hitherto unprecedented windows of understanding on the highest energy processes in our Universe. In IC, neutrino detection occurs via weak charge and neutral current (CC and NC respectively) interactions with nucleons in ice, resulting in the deposition of visible energy in the form of Cerenkov radiation. Observed events are categorized into two distinct types:

- ν_μ CC and a subset of ν_τ CC interactions produce *tracks* of highly energetic charged leptons traversing a significant length of the detector, while
- ν_e CC, a subset of ν_τ CC and NC interactions of all three flavors produce *cascades* characterized by their collective light deposition in a bulbous signature distributed around the interaction vertex.

Additionally, in spite of the belief that sources do not produce ν_τ, the flavour ratios for neutrinos are rendered close to $1 : 1 : 1$ at earth due to oscillations over large distance scales. In this situation, cascade events are expected to constitute about 75–80% of the total observed sample [30]. The background to these events is provided by the rapidly falling atmospheric neutrino flux and the muons created in cosmic-ray showers in the atmosphere.

The 988-day IC data reveals 37 events (9 track, 28 cascades) with energies between 30 TeV and 2 PeV, consistent with a diffuse neutrino flux given by

$$E^2\phi_\nu(E) = 0.95 \pm 0.3 \times 10^{-8}\ \text{GeV cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}, \tag{3.1}$$

in the energy range 60 TeV–3 PeV, where ϕ_ν represents the per-flavor flux. A purely atmospheric/cosmic-ray shower origin of these events is rejected at the 5.7σ level.

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We mention three characteristics of the event sample which will be pertinent to our work below: *a*) the three highest energy events are closely clustered, with energies of 1 PeV, 1.1 PeV and 2.1 PeV, *b*) there are no events between 400 TeV and 1 PeV, a gap which can be statistically realised in 43% of continuous power-law spectrum predictions [25, 26] , and *c*) there are no events beyond 2 PeV, although 3 events are expected between 3–10 PeV for an unbroken E^{-2} spectrum.[7]

The precise origin of these events is as yet unknown. There is weak evidence of a slight Galactic bias in the directionality, but the overall distribution over the entire sample is consistent with a diffuse isotropic flux. Possible astrophysical sources including both from within our galaxy [34–40] and from outside the galaxy [41–48] have been considered as explanations for the origin of these high energy particles. Some models of astrophysical sources, e.g., for galaxy clusters [49] and starburst galaxies [50], also predict a break in the neutrino spectrum at energies above ~ 1 PeV consistent with IC observations. In addition, the possibility that such UHE events might originate from the decay/annihilation of super-heavy DM into standard model particles has also been investigated [19, 51–54].

3.1 PeV events: fitting the DM-prediction to the IC observation

We next determine the values of the parameters G^2 and τ_ϕ that fits the number of DM events from our prediction with the IC PeV events. The energy at which the χ flux should peak is determined by requiring that the event rates peak at around 1.1 PeV; in turn, this requires that the flux peak at around energies of

$$E_{\text{peak}} = 1.1 / \left[\langle y \rangle \big|_{E_\chi^{\text{in}} = 1.1\,\text{PeV}} \right] = 2.53 \ \text{PeV},$$

which implies, $m_\phi = 5.06$ PeV.

The total number of events in a given IC bin increases proportionally with the incident flux and the interaction rate of the incident particles with the ice nuclei relevant to the corresponding bin energies. Since, in addition, the FDM flux $\Phi \propto \tau_\phi^{-1}$ [eq. (2.1) and (2.2)] and $\mathrm{d}\sigma/\mathrm{d}y \propto G^2$ [eq. (2.5)], the ratio G^2/τ_ϕ of the undetermined parameters G and τ_ϕ can be ascertained by normalising the number of events predicted due to the FDM flux at deposited energies $E^{\text{dep}} \geqslant 1$ PeV against those seen at the IC. We find that for a reasonable decay lifetime of $\tau_\phi = 5 \times 10^{21}$s, we need to set $G = 0.047$ to obtain the 3 PeV+ events from the FDM flux seen over the 988-day IC runtime. The values of the parameters thus determined are well within the allowed parameter-space, given constraints on the coupling constant from perturbativity and on the lifetime from model independent considerations for heavy DM decaying to relativistic particles: $\tau_\phi \geq 10^{18}$s [55]. The corresponding nature of the FDM extragalactic flux is shown in figure 2. The bigger the value of τ_ϕ, the larger would G need to be, to match the IC PeV+ event rate, with the upper bound to the coupling constant and, by consequence, the upper bound to τ_ϕ, being set by unitarity limits on G.

3.2 Sub-PeV events: neutrinos from extra-galactic sources

While the events corresponding to deposited energies $E_{\text{dep}} \geqslant 1$ PeV are accounted for by the FDM flux, the sub-PeV events up to 400 TeV are consistent with a power-law flux of incident particles, and are, likely, representative of a diffuse flux of neutrinos from extra-galactic sources. The term “best-fit” has limited validity at this point in time since given

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[7] This expectation is due to the Glashow resonance [31–33].

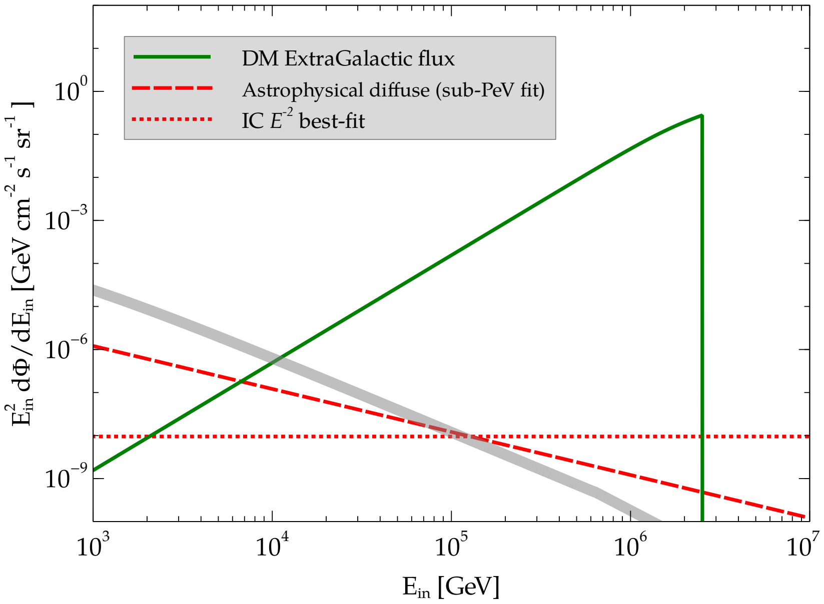

Figure 2. The TeV-scale diffuse neutrino flux and the extra-galactic FDM flux at PeV+ energies for decay lifetime $\tau_\phi = 5 \times 10^{21}$s. The thick light-gray curve indicates the estimated conventional atmospheric $\nu_\mu + \bar{\nu}_\mu$ flux [58].

the limited statistics, it is at present unclear if the flux is truly diffuse and extra-galactic, or a superposition of individual extended sources or a combination of these alternatives [56]. Indeed, using only the sub-PeV events to determine the best-fit $E^{-\alpha}$ spectrum, we find that the IC observation is closely matched by a more steeply falling astrophysical flux spectrum than that in eq. (3.1), i.e., the best-fit is instead given by (figure 2)[8]

$$\mathrm{d}\Phi_{\mathrm{astro}}/\mathrm{d}E_{\mathrm{in}} = 1.21 \times 10^{-3} E^{-3.0}\ \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}. \tag{3.2}$$

We note here that while eq. (3.2) represents the best possible fit to the sub-PeV events from a power-law, any soft spectra with index $\alpha \leqslant 2.5$ and appropriate normalization would be compatible with the data, within a 1σ confidence level, although with slightly poorer goodness-of-fit measures. Due to the softness of the spectral shape, the astrophysical flux drops to below the single-event threshold at energies higher than 400 TeV, rendering it naturally consistent with the lack of events at subsequent energies up to the PeV. The FDM flux itself does not contribute appreciably to the sub-PeV event-rate (see figure 3).

We note here that the gap in the event-spectrum between 400 TeV–1 PeV is not yet statistically significant and, therefore, a diffuse astrophysical flux with less steep spectra $\alpha \approx 2$–2.3 would also be consistent with the sub-TeV event-spectra should this gap fill up in the future.

4 Discussion and conclusions

Given present-day constraints on DM, it is possible that it may not be WIMP-like and thermal in nature. In the scenario proposed in this paper, we have focussed on the possible direct

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[8] Theoretically we can encounter a flux spectrum that is softer than E^{-2}. See e.g., [57].

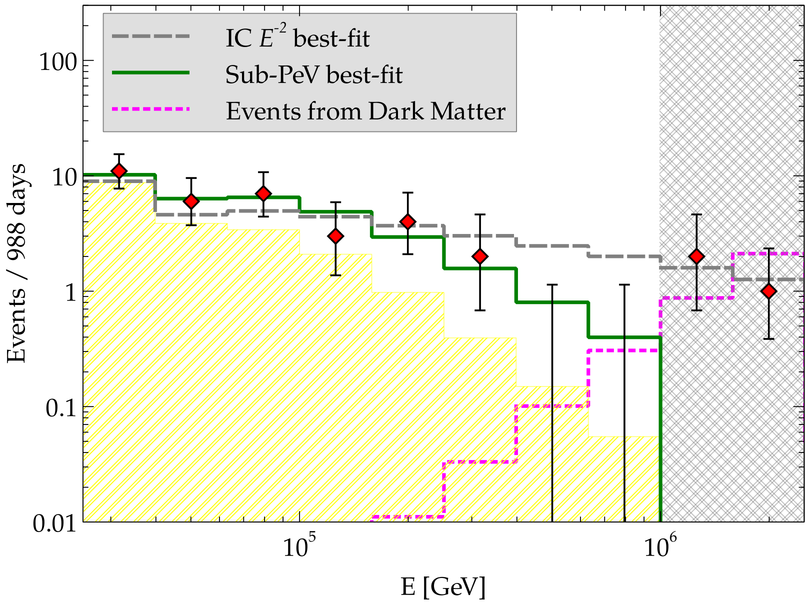

Figure 3. Predicted and observed total event rates at the IceCube. The gray shaded region represents energies at which we expect events predominantly from the DM sector. The green line shows event-rate predictions from our best fit flux to the sub-PeV event-rates observed at IC, with the flux given by eq. (3.2). The event rates predicted due to the IC best-fit E^{-2} flux (gray dashed line) and the observed data (red diamonds) are shown. The IC-estimate for the atmospheric background events is shown as the yellow shaded region.

detection of high energy DM particles. Such particles cannot form the bulk of DM, which must be non-relativistic, but may be a small population that lends itself to detection via methods different from those currently implemented at current DM detectors. One possible way such a component could exisit at and around a specific high energy, would be due to its creation by the decay of another significantly more massive non-thermal DM relic. If the lighter DM particle interacts with nucleons, its cross-section at high energies may be detectable as neutrino-like cascades in a massive detector like IC. Using the neutrino-nucleon NC deep inelastic cross-section as a guiding analogy, we have applied this to the cluster of three $\sim$ PeV events seen at IC.

Thus, this cluster of three events has a different origin from the remainder of the IC event sample, which we assume to be primarily astrophysical extra-galactic neutrinos. It results in a softer astrophysical spectral best-fit than the one which includes the full-event sample. In this picture, the gap currently seen in the data between 400 TeV–1 PeV is physical, and the result of two distinct spectra. While it may partially get filled in or otherwise modified due to future data, it would remain as a demarcating feature between 2 fluxes of different origins, a UHE neutrino flux with a softer than currently estimated spectrum, and a DM flux that generates cascade interactions in the detector. Additionally, the PeV events should continue to cluster in the 1–3 PeV region, with a galactic bias [19] due to the fact that about half of the DM induced PeV flux contribution is expected to be galactic. We note that at present 2 of the 3 events appear to come from the direction of the galaxy. This scenario also provides a natural explanation for the lack of events beyond 3 PeV. Other recent proposals, in addition to certain models of astrophysical sources referred to previously, which also account for the cut-off at PeV energies are discussed in [51, 52, 59–63].

It is also to be noted that DM induced events will for the most part not contain energetic muon tracks, and will mostly be cascade-like. Thus, over time, if the IC sample contains a mixture of such events along with an astrophysical neutrino event component, the overall data will manifest a deficit in the ratio of muon track to cascades compared to the standard IC expectation of $1:3$.

Additionally, for DM events in the 1–3 PeV range, some extra-galactic contribution of cascades could come from the Northern hemisphere, because the lower DM-matter cross-section does not cause their flux to attenuate significantly in the earth at PeV energies, unlike neutrinos. These predictions separate the present scenario from other DM induced indirect detection proposals [51, 52]), and can be tested as IC gathers more data.

In conclusion, we have studied the possibility of detecting DM using large neutrino detectors, via a relativistic and high energy component that may exist in addition to the bulk of non-relativistic DM. As a specific example of the concept, we have applied it to recent events reported by IC, and also pointed out testable features of the scenario which can be used, with future data, to rule it out.

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