Interpretations of the IceCube neutrino excess

M. Kachelrieß
Institutt for fysikk, NTNU, Trondheim, Norway

Abstract. The IceCube Collaboration announced 2012 evidence for the first detection of extraterrestrial neutrinos. Meanwhile, the discovery of a extraterrestrial neutrino flux of surprisingly large magnitude has been established. I discuss a selection of possible sources for these neutrinos and their signatures, concentrating on the neutrino yield from collisions of cosmic ray nuclei with gas and the possibility that Galactic sources can explain the IceCube excess. I review also the cascade bound on extragalactic neutrinos and its consequences as well as the possibility that decays of PeV dark matter are the origin of the IceCube excess.

1. Introduction
High energy (HE) neutrinos are produced by cosmic rays (CR) interacting with gas or photons in their sources, and with cosmic microwave and other background photons during propagation. Alternatively, HE neutrinos may be produced in annihilations or decays of dark matter particles. Any process involving hadronization leads mainly to the production of pions, and the ratio of charged and neutral pions produced is fixed by isospin symmetry. The production of neutrinos is thus intimately tied to the one of photons, and both depend in turn on the flux of primary CRs. This connection allows one to estimate the minimal size of detector able to detect HE neutrinos as $\sim 1\, \text{km}^3$.

The IceCube neutrino observatory has been the first detector reaching this size, being thus able to test this paradigm. In 2013, the IceCube collaboration announced evidence for the first detection of extraterrestrial neutrinos at the 4$\sigma$ confidence level [1]. This announcement followed the observation of two PeV neutrino cascades [2]. The 3-year data set consists of 37 events with deposited energy in the range between 30 TeV and 2 PeV, while 15.0 background events are expected from atmospheric muons and neutrinos. In the most recent analysis [3], the energy threshold applied was reduced to 1 TeV. The determined excess of events (denoted “IceCube excess” in the following) is consistent with a diffuse intensity (summed over flavors) at the level of

$$\Phi_{\nu}(E) = 20.6^{+4}_{-3} \left( E_\nu / 10^{14} \, \text{eV} \right)^{-2.46^{+0.12}_{-0.12}} \, \text{eV cm}^{-2} \text{sr}^{-1} \text{s}^{-1}.$$

The basic information contained in these events can be summarised by the energy spectrum, the arrival directions and the flavor composition of these events:

Energy spectrum: The energy threshold used in different analyses has been continuously reduced, reaching 1 TeV in the most recent analysis [3]. At the same time, the slope of the neutrino energy spectrum assuming an unbroken power-law $dN/dE \propto E^{-\alpha}$ in the whole energy range has become steeper, and deviates now with $\alpha = -2.46 \pm 0.12$ clearly from $\alpha = -2$. Since the intensity at $\gtrsim 10^{14} \, \text{eV}$ remained unchanged, the intensity at lower energies increased, putting pressure on extragalactic neutrino models.
However, this change of the spectral index is driven by the addition of the low-energy neutrinos: In particular, if the deposited-energy threshold is raised to 60 TeV (corresponding to a sensitivity for $E_\nu > 100$ TeV), then the analysis [3] finds that the spectral index hardens to $2.26 \pm 0.35$, compatible with the previous high-energy result. This may indicate that above $E_\nu \sim 100$ TeV a different source population dominates the neutrino flux. Since the maximal energy of neutrinos produced via pion production in $pp$ interactions is approximately 10% of the energy of the proton primary, the corresponding break in the CR primary energy would correspond to $E_{CR} \sim 1$ PeV. Thus the hardening of the neutrino spectrum may be associated with the Galactic CR knee and a transition to extragalactic neutrinos.

Arrival directions: No statistically significant clustering of the arrival directions has been observed, although an overdensity of events close to the Galactic center and, less pronounced, towards the Galactic plane exists.

Flavor composition: After the discovery of large $\nu_\mu-\nu_\tau$ mixing, it was often taken for granted that the small oscillation length (of order 10 pc for $E_\nu \sim 10^{15}$ eV) together with $\nu_e:\nu_\mu:\nu_\tau = 1:2:0$ at generation leads to flavor equipartition at observation, $\nu_e:\nu_\mu:\nu_\tau = 1:1:1$. There exist however several examples of neutrino sources where at least in some energy range significant deviations from this canonical flavor ratio from pion decay can be expected [4, 5]. Specific examples are the cases where the neutrino spectrum is dominated by neutron [5] or kaon decays [6] or influenced by muon damping [7]. In the diffuse flux, one should however expect that these deviations are washed out. For a detailed discussion of the various possibilities see [8, 9].

The analysis [10] found that the ratio of track/shower events in the IceCube's 3-year data favors $\nu_e : \nu_\mu : \nu_\tau = 1:0:0$ at generation at the 92% C.L. However, the recent analysis [11] performed by the IceCube collaboration finds that the track/shower ratio is consistent with flavor equipartition at observation. The discrepancy between these two results was explained by a partial classification of CC events as showers and the not accounted systematic uncertainty of the muon background in [10].

2. Galactic sources
2.1. Neutrino yield in CR interactions with gas
The Galactic neutrino flux contains a guaranteed component which is produced by CRs interacting with gas during their confinement in a CR halo. This minimal Galactic neutrino flux has been discussed since the late 1970s [12].

The observed 2 PeV neutrino event requires proton energies above 20 PeV. However, already at $10^{15}$ eV protons represent only a subdominant fraction of the primary CR flux compared to helium and heavier nuclei [13]. Moreover, the composition of the CR flux becomes increasingly heavier in the energy range between the knee at $E_k \approx 4$ PeV and $10^{17}$ eV. Since the maximal neutrino energy in nucleus-proton collisions is a factor $A$ lower than in $pp$ interactions ($A$ being the nuclear mass number), the required minimal CR energy to explain the IceCube events increases compared to $pp$ processes. This implies in turn that the number of potential scattering events, and thus secondary fluxes, is drastically reduced, because the CR spectrum is steeply falling, $I(E) \propto E^{-3.1}$ above the knee [13]. Therefore it is essential to account correctly for the elemental composition of the Galactic CR flux, if one aims at relating the neutrino intensity required to explain the IceCube excess to the primary CR intensity.

Reference [14] quantified the neutrino yield from nucleus-proton collisions using up-to-date simulation tools for the relevant hadron production processes and including information on the elemental composition of the CR flux around and above the knee region. The simulations were based on the event generator QGSJET-II-04 [15] which includes relevant results from run I of LHC [16]. In this section, we summarise some results of this study.

Explanations for the origin of the knee fall in two main categories. First, the knee may correspond to the maximum rigidity to which CRs can be accelerated by the dominant population
of Galactic CR sources [17, 18]. Second, the knee energy may correspond to the rigidity at which the CR Larmor radius \( r_L \) is of the order of the coherence length \( l_c \) of the turbulent magnetic field in the Galactic disk. As a result, a transition from large-angle to small-angle scattering or Hall diffusion is expected, the energy dependence of the confinement time changes which in turn induces a steepening of the CR spectrum [19, 20, 21]. Both possibilities lead to a rigidity-dependent sequence of knees at \( ZE_k \), a behavior first suggested by Peters [22]. In contrast to models in category 1, those of category 2 predict both the position of the knee and the rigidity dependent suppression of the different CR components for a given model of the Galactic magnetic field [21].

Various models which describe the elemental composition of the total CR flux have been developed. The poly-gonato model [23] is a fit of rigidity-dependent knees at \( E = ZE_k \) to measurements of the total CR intensity. Below and above \( E = ZE_k \), the fluxes of individual CR nuclei are assumed to follow power-laws \( \phi_A(E) = K_A^1 E^{-\gamma_A} \) and \( \phi_A(E) = K_A^2 E^{-\gamma_A} \) which are smoothly interpolated. The fluxes are assumed to steepen by a common amount, \( \gamma_A = \gamma_A^1 + \delta \) with \( \delta \approx 2.1 \), for more details see [23]. The steepening of the CR intensity around the knee is very pronounced in this model, \( \delta \approx 2 \), and as a result the composition is heavier than suggested by KASCADE-Grande data. The resulting neutrino intensity \( I_\nu(E) \) is shown in Fig. 1, where we assumed that the CR nuclei cross the grammage \( X = 30 \text{ g/cm}^2 \); this value corresponds for primary protons with energy 1 PeV to the interaction depth \( \tau_{pp} = 1 \). Above few hundred TeV, the intensity is dominated by the proton contribution and is strongly decreasing with energy as \( I_\nu(E) \sim E^{-4.7} \). Therefore the expected neutrino energy distribution disagrees with the neutrino spectrum suggested by the IceCube excess, in particular with the two PeV events.

The Hillas model [18] and its variants belong to the category 1, associating the knee with the maximal rigidity achievable in the dominant population of Galactic CR sources. Moreover, the Hillas model assumes that the ankle signals the transition from Galactic to extragalactic CRs. Therefore, an additional population of Galactic CR sources must exist (“the component B” of Ref. [18]) which fills the gap between the knee and the ankle. Thus the Hillas model contains two Galactic components. Each population is assumed to contain five elemental groups and cuts off at a characteristic rigidity. We present here results for the new parametrisation H3a given in Tab. 3 of Ref. [24]. The intensity of Galactic neutrinos in this model is shown in Fig. 1, which is again dominated by the proton contribution; its shape is very similar to the neutrino intensity of the poly-gonato model.

Finally, Ref. [14] considered a parametrisation of the CR flux motivated by the recent results of Ref. [21]; There, the escape of CRs from our Galaxy was studied calculating trajectories of individual CRs in models of the regular and turbulent Galactic magnetic field. For a coherence length \( l_c \approx (2−5) \text{ pc} \) of the turbulent field and a reduced turbulent magnetic field, a knee-like structure at \( E/Z = \text{few} \times 10^{15} \text{ eV} \) was found, which is sufficiently strong to explain the knee and the energy spectra of different groups of CR nuclei as determined by KASCADE and KASCADE-Grande. The resulting neutrino intensity for \( X = 30 \text{ g/cm}^2 \) is shown in Fig. 2 together with the individual contribution from five elemental groups. The suppression of the neutrino intensity above the knee is less pronounced as in the previous models, since the decrease of the CR escape time \( \tau_{esc}(E) \) slows down around \( E/Z \approx 10^{16} \text{ eV} \) for a weak turbulent field. In the energy range between \( 10^{13} \text{ eV} \) and \( 10^{16} \text{ eV} \), the neutrino intensity scales as \( I_\nu(E) \propto E^{-3.2} \).

In summary, [14] found that the neutrino intensity below \( 10^{14} \text{ eV} \) reflects the slope of protons and agrees therefore in all three models. In contrast, the exact position of the “neutrino knee” and the slope of neutrino intensity above this break depends on the nuclear composition and is therefore model dependent: A comparison of the neutrino intensity in the three models is shown in Fig. 1. Finally, one may yet ask which of the three composition models considered is the more realistic one in the light of recent CR data. Comparing e.g. the CR spectra predicted
by the poly-gonato model to the intensities of individual groups of CR nuclei up to 10^{17} eV, measured by the KASCADE and KASCADE-Grande experiments, already an inspection by eye indicates that this model predicts a too heavy composition above the knee. The Hillas model of Ref. [24] describes well the average composition (represented e.g. by ln(A)) but fails to reproduce the up-turn of the light component around 10^{17} eV observed by KASCADE-Grande. By contrast, such an up-turn around $E/Z \approx 10^{16}$ eV is the characteristic feature of the escape model [21]. As a result, the intensity of individual groups of CR nuclei measured by KASCADE and KASCADE-Grande is well reproduced in this model [21].

![Figure 1](image1.png)  
**Figure 1.** A comparison of the total neutrino spectra $E^{2.6}I(E)$ predicted for $X = 30 \text{ g/cm}^2$ by the three CR models.

![Figure 2](image2.png)  
**Figure 2.** Total neutrino spectrum $E^{2.6}I(E)$ and individual contributions of five elemental groups for $X = 30 \text{ g/cm}^2$ in the escape model.

### 2.2. Neutrinos from Galactic sea CRs

The slight over-density of the neutrino events in a region close to the Galactic center and towards the Galactic plane invites to speculations about a (partly) Galactic origin of these events. We consider first the guaranteed contribution from Galactic sea CRs.

The gas distribution in the Galactic disk can be modeled as $n(z) = N \exp(-(z/z_{1/2})^2)$ with $N \approx 0.3 \text{ cm}^{-3}$ at $R_\odot$ (increasing to $N \approx 10 \text{ cm}^{-3}$ at the GC) and $z_{1/2} = 0.21 \text{ kpc}$. Integrating the interaction probability, $\int dln n_{\text{CR}}(E) \sigma_{\text{inel}}^{pp}(E)$, with $\sigma_{\text{inel}}^{pp}(E) \approx 60 \text{ mb}$ results in the maximal interaction depth of $\tau \approx 0.005$ towards the GC. At the reference energy $E_\ast = 1 \text{ PeV}$, all three parametrisations predict a neutrino intensity around $\tau_{\nu} E_{\nu}^{2.6} I_{\nu}(E_\ast) \sim 10 \text{ GeV}^{1.6} \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$, corresponding to $E_{\nu}^2 I_{\nu} \sim 0.1 \times \text{ eV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$. Thus even in the direction of the largest expected intensity, the predicted neutrino intensity due to diffuse Galactic CR interactions is about two orders of magnitude too small compared to the IceCube excess. Moreover, the neutrino events should be concentrated within $|b| \leq 1^\circ$ [25], reflecting the very slim Galactic plane, which is much narrower than the latitude distribution of the IceCube events.

### 2.3. Neutrinos from Galactic CR sources

We consider next the neutrino flux produced close to recent CR sources. The propagation of CRs on distances $l > \text{ few} \times l_{\text{coh}}$ can be approximated by diffusion [26]. For $l_{\text{coh}} \sim 10 \text{ pc}$ as found in Ref. [27] for the Galactic disk, the diffusion approach is marginally justified for the time scales, $10^3$ to $10^4 \text{ yr}$, we consider.

Galactic accelerators able to produce CRs with energies $10^{16} \text{ eV}$ have typically only short life-times: For instance, the highest energy particles produced by a supernova remnant (SNR)
are thought to escape at the end of the Sedov phase after few 100 yrs. Approximating therefore the accelerator as a bursting source, the number density \( n_{\text{CR}}(E, r) = dN/(dE dV) \) of CRs at the distance \( r \) is given by

\[
n_{\text{CR}}(E, r) = \frac{Q(E)}{\pi^{3/2} r_{\text{diff}}^3} \exp \left[ -r^2/r_{\text{diff}}^2 \right],
\]

with \( r_{\text{diff}}^2 = 4D t \) assuming no energy losses. We use as diffusion coefficient \( D(E_\alpha) = 3 \times 10^{28} \text{cm}^2/\text{s} \) at our reference energy \( E_\alpha = 1 \text{PeV} \) and assume that the source injects instantaneously CRs with the total energy \( E_0 = 10^{50} \text{erg} \) in protons with an injection spectrum \( Q(E) = Q_0(E/E_0)^{-\alpha} \) between the minimal energy \( E_0 = 1 \text{GeV} \) and a maximal energy \( E_{\text{max}} = 10 \text{PeV} \). We choose \( \alpha = 2.0 \) suggested by shock acceleration. Then PeV CRs are concentrated within \( r_{\text{diff}} \sim 35 \text{pc} \) after 3000 yr.

The brightest spots in the Galactic neutrino sky are likely giant molecular clouds (GMC) immersed into the CR overdensities close to recent CR sources. The neutrino flux from a point source at the distance \( d \) is given by

\[
\phi_\nu(E) = \frac{c \sigma_{\text{inel}}}{4\pi d^2} \frac{M_{\text{d}}}{m_p} n_{\text{CR}}(E) Y_\nu(E),
\]

where \( Y_\nu(E) \) denotes the neutrino yield \( Y_\nu(E) = \phi_\nu(E)/[\tau(E) \phi(E)] \). Assuming as cloud mass \( M_{\text{d}} = 10^5 M_\odot \) and as distance \( d = 1 \text{kpc} \) results in the neutrino flux \( E^2 \phi_\nu(E) \simeq 140 \text{ eV cm}^{-2} \text{sr}^{-1} \). Sources of this kind would be clearly visible on the neutrino sky as seen by IceCube. Choosing as source rate \( \dot{N} \simeq 1/(30 \text{yr}) \), which coincides with the Galactic SN rate, implies that the average number \( N_\nu \) of such sources present in the Galaxy equals \( N_\nu \simeq 100 \). Using as volume of the Galactic disk \( V = 4\pi R^2 h \simeq 140 \text{kpc}^3 \), there are on average 0.5 sources within one kpc distance to an observer. We note also that the presence of GMCs close to SNRs is not unnatural, since they are born most likely in OB associations.

Any source of high-energy neutrinos produces also \( \gamma \)-rays. In Ref. [28], the 1–10 TeV \( \gamma \)-ray flux from known sources in the direction towards the GC was compared with the IceCube excess. Extrapolating the \( \gamma \)-ray flux of these sources to higher energies implies a neutrino flux which is an order of magnitude smaller than the one required to explain the IceCube excess. This discrepancy could be explained by the slower diffusion of low-energy CRs which have not yet reached GMCs and by the additional contribution from extragalactic neutrinos.

Limits on the fraction of photons in the CR flux as e.g. those of CASA-MIA, KASCADE and IceCube can be used to constrain Galactic neutrino sources [29]. However, PeV \( \gamma \)-rays can be absorbed both in sources and during propagation by pair production on star light and CMB photons. Moreover, these gamma-ray limits are biased towards the northern hemisphere. As a result, they do not exclude the case that (a fraction of) the IceCube excess has a Galactic origin.

### 3. Extragalactic sources

#### 3.1. Source types

The idea that neutrinos and photons are produced efficiently as secondaries in CR interactions close to the core of AGN dates back to the 1970’s [30]. Gamma-ray bursts (GRB) were suggested as another promising neutrino source [31]. The negative results from searches for HE neutrinos from stacked GRBs disfavors however GRBs as the main source of the IceCube excess.

Starburst galaxies have magnetic fields which are two orders of magnitude higher than the Galactic magnetic field [32]. As a consequence, in the model of Ref. [21] where the knee is caused by the escape of CRs, its position and thus the one of the neutrino knee is shifted by up too two orders of magnitude. If moreover CRs are re-accelerated in super-bubbles, the maximal energy of CRs in starburst galaxies should be increased as well. Thus normal and starburst galaxies are a promising candidate for the neutrino events in IceCube.
Figure 3. Intensity of the diffuse EGRB and neutrinos arising from pp collisions, left $\alpha = 2.3$ and right $\alpha = 2.5$.

3.2. Limits from the diffuse $\gamma$-ray background

A general upper bound on the cosmogenic neutrino flux can be derived from the observation of the extragalactic diffuse gamma-ray background (EGRB). Since the Universe acts as a calorimeter for electromagnetic radiation, accumulating it in the MeV–TeV range, the measured EGRB limits all processes during the history of the Universe that inject electromagnetic energy above the pair creation threshold. In [33], the measurement [34] of the EGRB by Fermi-LAT was used to constrain UHECR models and to limit the HE neutrino flux as $E^2\Phi_\nu(E) < \sim 40 \text{eV/(cm}^2\text{s sr)}$. Note that the best-fit value for the neutrino flux from the 2-year IceCube data saturated this bound.

Meanwhile, the Fermi collaboration presented results for 44 months of data taking, extending their measurement of the EGRB to higher energies [35]. As a result, the limits on the allowed cascade radiation and the limit on the cosmogenic neutrino flux drop by a factor $\sim 3$, i.e. to $\omega_{\text{casc}} < 2 \times 10^{-7} \text{eV/cm}^2$. Moreover, the contribution from unresolved sources is estimated to be as large as 50–80% [35]. In Fig. 3, we show the intensity of the extragalactic diffuse gamma-ray background (EGRB) together with diffuse neutrino intensity arising from pp collisions in extragalactic sources for two different values of the injection power-law $dN/dE \propto E^{-\alpha}$ of CRs with an exponential cutoff. Here, we normalised the diffuse neutrino intensity to the IceCube events and assumed as redshift evolution $\propto (1 + z)^3$ until $z = 1$.

For $\alpha = 2.3$, the resulting EGRB saturates the EGRB measurements by Fermi-LAT [35], while the predicted EGRB overshots the data for $\alpha = 2.5$. Note also that a large fraction of the EGRB may be associated to sources like mis-aligned blazars or cascades from ultrahigh energy cosmic rays which do not contribute to the IceCube neutrino excess. Thus a spectral index of neutrino spectrum as small as $-2.45$ is problematic for models which rely on neutrino production via pp collisions. Similar conclusions were presented in Ref. [36]. It is clear that the EGRB is an important constraint on any proposed extragalactic model for neutrino sources.

4. Neutrinos from top-down models

Top-down model is a generic name for all proposals in which the observed CR primaries are produced as decay products of some heavy particles $X$ with mass $m_X$ much larger than the weak scale, $m_X \gg m_W$. These $X$ particles can be either metastable or be emitted by topological defects at the present epoch.

The suggestion [37] of superheavy metastable relic particles as CR sources was originally motivated by the AGASA excess, although it was soon realized that stable or metastable particles
in this mass range are generically interesting DM candidates. The idea that PeV dark matter is responsible for the IceCube excess [38] is a natural variation of this suggestion.

What are the particle candidates for PeV DM? A well-suited candidate for PeV DM is the lightest neutralino within the scenario of superheavy supersymmetry [39]. This is a unique case where the PeV DM has weak interactions and respects perturbative unitarity despite the large mass hierarchy $m_X \gg m_Z$. Since the annihilation cross section of a (point) particle is bounded by unitarity, $\sigma_{\text{ann}} \propto 1/m_X^2$, the resulting flux of HE neutrinos for stable PeV DM is too small to be observable without an additional enhancement of the annihilation rate. The flux of HE neutrinos can be observable either if the PeV DM particle is meta-stable with suitable lifetime or the DM is much more clumpier than predicted by the simplest inflationary scenario [40].

4.1. PeV Dark Matter
Dark matter particles with masses in the PeV range constitute (part of) the CDM and, consequently, their abundance in the galactic halo is enhanced by a factor $\sim 5 \times 10^4$ above their extragalactic abundance. Therefore, the secondary fluxes from their decays are dominated by the halo component. The quotient $r_X = \Omega_X(t_0/\tau_X)$ of relic abundance $\Omega_X$ and lifetime $\tau_X$ of the $X$ particle is fixed by the HE neutrino flux. The value of $r_X$ is not predicted, but calculable as soon as a specific particle physics and cosmological model is fixed. PeV dark matter has several clear signatures:

Spectral shape: The fragmentation spectra of superheavy particles calculated by different methods and different groups agree well. This allows to consider the spectral shape as a signature of models with decays or annihilations of PeV DM particles. The predicted fragmentation spectrum, $dN/dE \propto E^{-1.9}$, at $x = E/M \lesssim 0.1$ is potentially modified by virtual electroweak Bremsstrahlung and direct neutrino production at larger $x$, cf. Fig. 4. However, it is clear that it cannot fit the observed neutrino spectrum at low energies.

Composition: Since at the end of the QCD cascade quarks combine more easily to mesons than to baryons, the main component of the HE flux are neutrinos and photons from pion decay. Therefore, a robust prediction of this model is the appearance of large photon fluxes, which are limited by experimental bounds.

Galactic anisotropy: The HE neutrino flux from PeV DM should show a galactic anisotropy [41], because the Sun is not in the center of the Galaxy. The degree of this anisotropy depends on how strong the CDM is concentrated near the Galactic center.

For a combined analysis of the arrival directions and the energy spectrum in the PeV DM scenario see e.g. [42]

5. Summary
The discovery of HE astrophysical neutrinos with energies $E > 10\text{ TeV}$ by the IceCube experiment opened a new window to the Universe—and we are waiting for a more detailed view.
Acknowledgments
I am grateful to Gwenael Giacinti, Sergey Ostapchenko and Dima Semikoz for pleasant collaborations and discussions.

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