Project 1. One Neutrino to Bring Them All. What Can We Learn from the KM3NeT Extreme-Energy Event?

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1 Introduction

In February 2025, the KM3NeT collaboration announced the observation of a neutrino with a record energy of 220 PeV [1] (the topography of the event can be seen at figure 1). At the same time, the IceCube experiment – with a significantly larger effective volume and exposure – has not reported any neutrinos with such high energies.

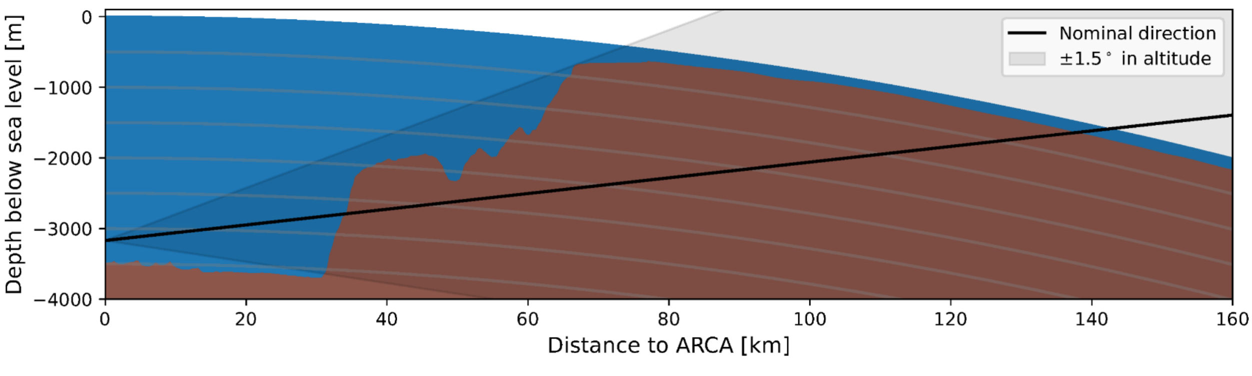

Figure 1: Illustration of the KM3NeT event topography

The project aims to evaluate the probability of such an outcome. We model detector efficiencies and effective areas, and obtain estimates of the neutrino flux in the isotropic flux model. We also perform a joint-fit analysis with the data from IceCube, both with non-detection in the > 100 PeV range and with the data from the $\approx$ PeV region.

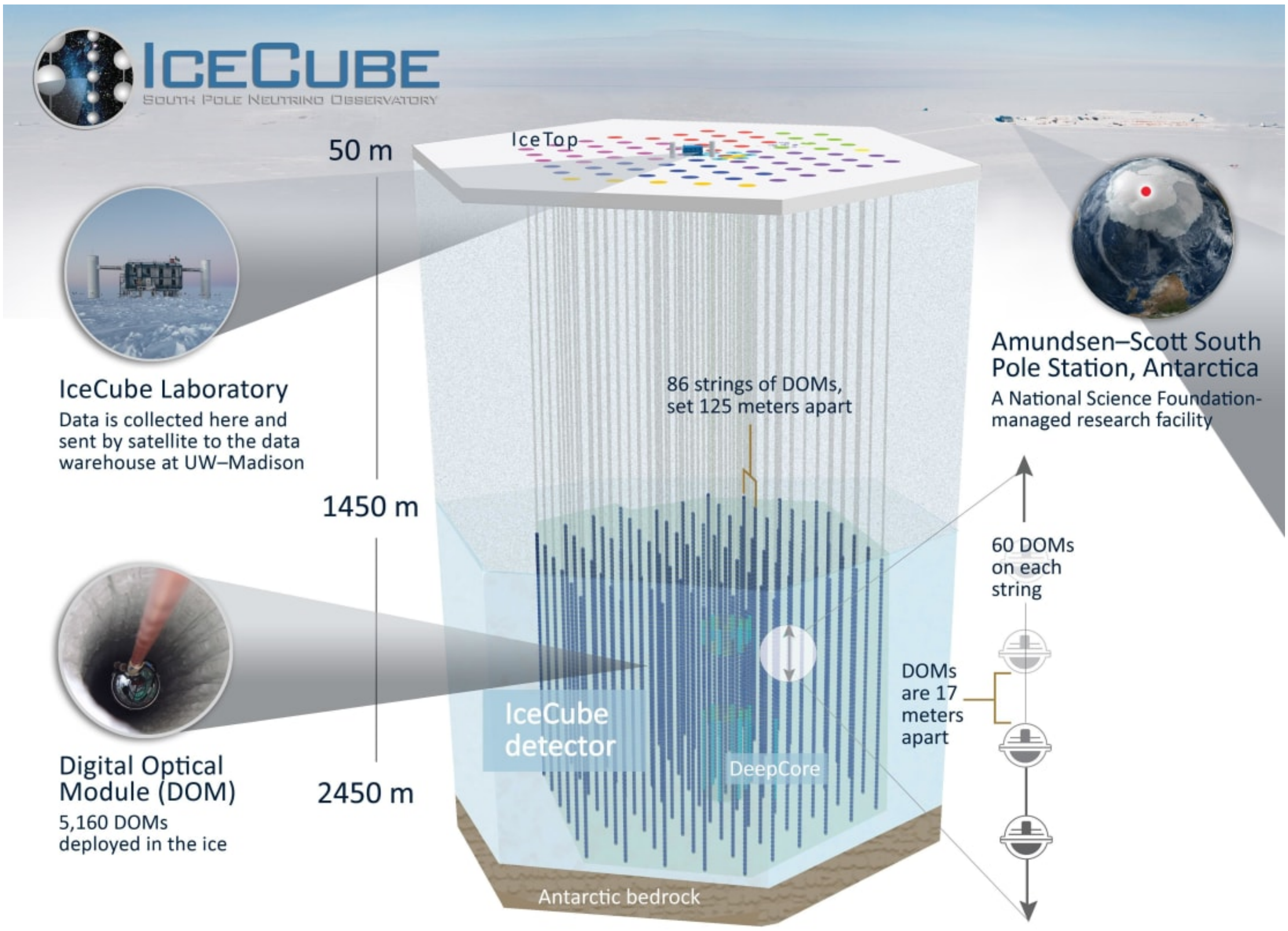

Figure 2: IceCube geometry illustration

2 Detector models

The general idea of the detector model is as follows. We assume that the detector looks for Cherenkov light from high-energy muon tracks born in the interaction of muon neutrino with the Earth. Cherenkov light cone must reach the detector, so the muon must reach the point defined by the angle of the Cherenkov cone. We assume an ad-hoc cutoff on the minimum energy of detected muons of 1TeV. As the analysis deals with PeV neutrinos, this has no significant impact and partly accounts for detection efficiency. The length of the muon path is defined by the pair-production energy losses (see the school's lectures :)).

$$-\frac{dE_\mu(\mathrm{GeV})}{dx(\mathrm{m})} = 0.5 \cdot 10^{-3} \times E_\mu(\mathrm{GeV}). \tag{1}$$

Neutrino must interact with matter via the $\nu_\mu + p/n \to \mu + X$ process before the detector and closer than the maximum muon path. This gives us a simple analytical expression for detector efficiency:

$$\mathrm{Eff} = \exp(-\sigma n(L - l_{max})) - \exp(-\sigma n L), \tag{2}$$

where L is the neutrino path to detector and l_{max} is the maximum muon path in matter. Neutrino interaction cross-sections are taken from [2]. We forgo the neutrino energy resolution entirely, as it is not as important for the flux analysis and very hard to estimate with any degree of accuracy due to light absorption in the medium and photomultiplier efficiency.

We then model the detector geometry and the neutrino path length, accounting for the different materials along the path (rock, water, and ice). The resulting dependence of detection efficiency on the incoming neutrino angles is presented in figure 3.

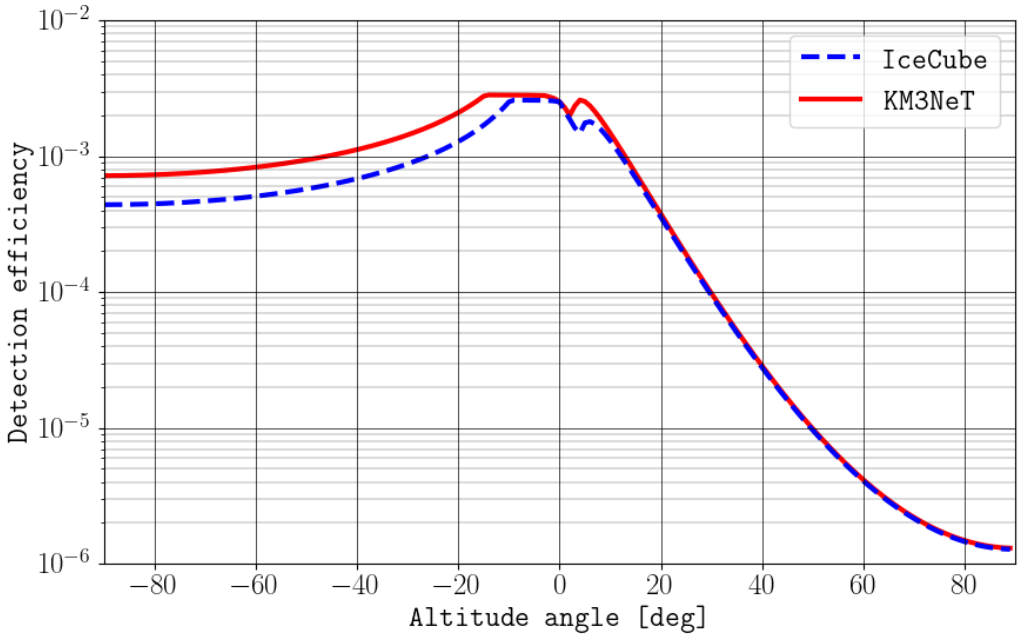

Figure 3: Dependence of detection efficiency on altitude angle for both KM3NeT (solid red line), and IceCube (dashed blue line) experiments. Energy is fixed at 100 PeV.

We also present the effective area dependence on neutrino energy for both the KM3NeT and IceCube detectors (figure 4), as well as a comparison with the real KM3NeT effective area (figure 5) taken from the open collaboration data.

We note a very good agreement with the real effective area, within a factor of 3. We overestimate the real data because of imperfect trigger and muon detection in the real world.

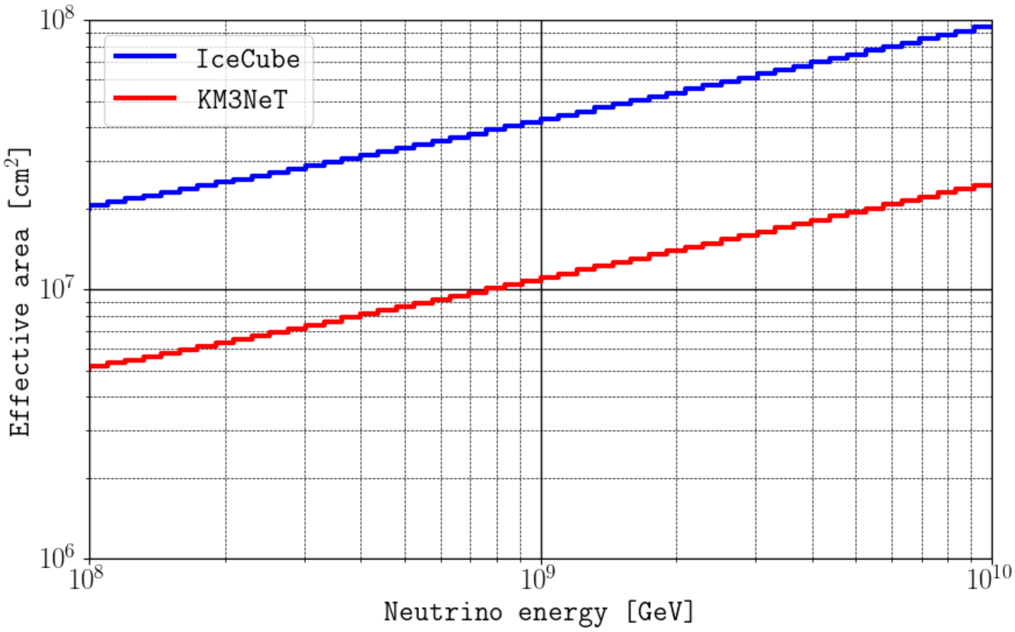

Figure 4: Naive estimation of KM3NeT and IceCube effective areas with respect to muon neutrinos. The red line and the blue lines correspond to the KM3NeT and IceCube, respectively.

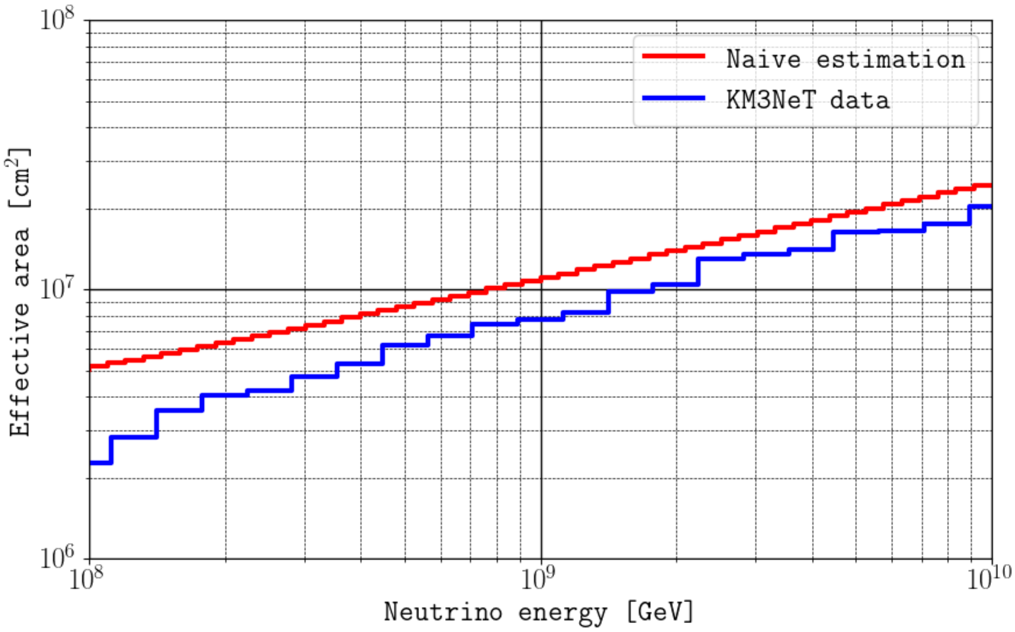

Figure 5: KM3NeT effective area with respect to muon neutrinos. The red line represents a naive estimation, the blue line corresponds to the KM3NeT data [3].

3 Isotropic flux model

The simplest neutrino flux model is isotropic with a customary E^{-2} spectrum. We estimate this flux based on the single event in KM3NeT via maximum likelihood. The number of expected events in the detector is

$$\bar{n} = \int_{E_{min}}^{E_{max}} \Phi \cdot E^{-2} \cdot A_{\rm eff}(E) \cdot 4\pi \cdot T \cdot dE. \tag{3}$$

We then estimate the flux assuming Poisson statistics for the number of arrived events and get

$$\Phi_{\rm KM3NeT} = 3.8^{+12.7}_{-3.2} \cdot 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}. \tag{4}$$

The error is 90% CL following the Neumann error estimation method [4]. Figure 6 7 shows the confidence interval calculation. This error accounts for the fact that KM3NeT stopped the observation after just one event, and the estimator is unbiased.

This value agrees with the published flux of $\Phi = 5.8^{+10.1}_{-3.7} \cdot 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}.

3.1 IceCube non-observation

If one accounts for the IceCube non-observation of any events in this energy range in the 9 years of operation, it is possible to perform a joint-fit estimation of the flux and the probability of such an outcome. One should get 1 event in the KM3Net and 0 events in IceCube. This joint fit results in an estimate of

$$\Phi_{\rm KM3+IC} = 9.8^{+13.2}_{-4.5} \cdot 10^{-10} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}. \tag{5}$$

For this flux, the expected number of events in KM3NeT is $n_{\rm KM3} = 0.025$ and in IceCube $n_{\rm IC} = 0.97$. The probability of such an outcome is 0.009. This results in an upward fluctuation of approximately 2σ.

We also provide a Bayesian goodness-of-fit analysis. One wants to check that this power-law spectrum can describe both datasets. The tension is computed using the posterior predictive check approach. The joint probability is

$$p_{pcc} = \iint P(\Phi, \gamma) \cdot \mathcal{L}_{IC} \cdot \mathcal{L}_{KM3NeT} \cdot d\Phi d\gamma \tag{6}$$

Here the prior distribution of variables is taken to be uniform. We than convert this probability to a z-score using the one-tail convention. This results in a tension of 2.4σ, which roughly corresponds to the frequentist approach.

3.2 Extension to lower energies

It is also possible to do a single power law fit to both the KM3NeT event and IceCube events in the PeV region (GOLD and BRONZE type events are used here). We treat the flux and spectral index as unknowns and estimate them in a similar way. This procedure yields a flux and spectral index of

$$\Phi_{\text{KM3+IC low}} = 2.1 \cdot 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}, \gamma = -2.3, \tag{7}$$

but a probability of 0.001. This also coincides with the KM3NeT collaboration estimates within the errors [5].

4 Conclusions

We estimate the detection probability and effective areas for KM3NeT and IceCube detectors. They are in good agreement with detailed calculation result provided by KM3NeT. We also provide estimates of neutrino flux with the assumption of an isotropic model. The flux obtained from only the KM3NeT event is unrealistically large. The estimates are also prone to big uncertanties, rooted in the fact that this is a single observation of a rare Poisson process. We provide a detailed error calculation that takes this into account.

The joint-fit for both IceCube and KM3NeT shows that this event (in this model) can be a fluctuation of 2σ significance. If lower energy IceCube events are taken into account, the probability of such an outcome remains very low, even with an arbitirary power law spectrum.

We believe that this analysis hints at a non-isotropic nature of this event. Possible explanations could be sources with flaring activity, like radio blazars or other similar objects.

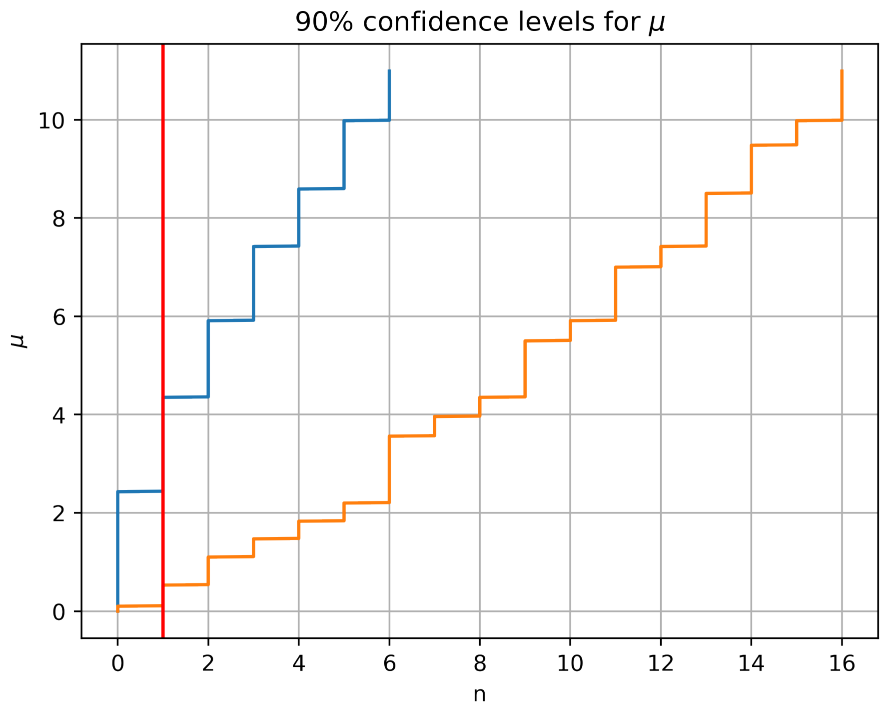

Figure 6: Confidence Levels for different number of expected events μ vs. the number of events n.

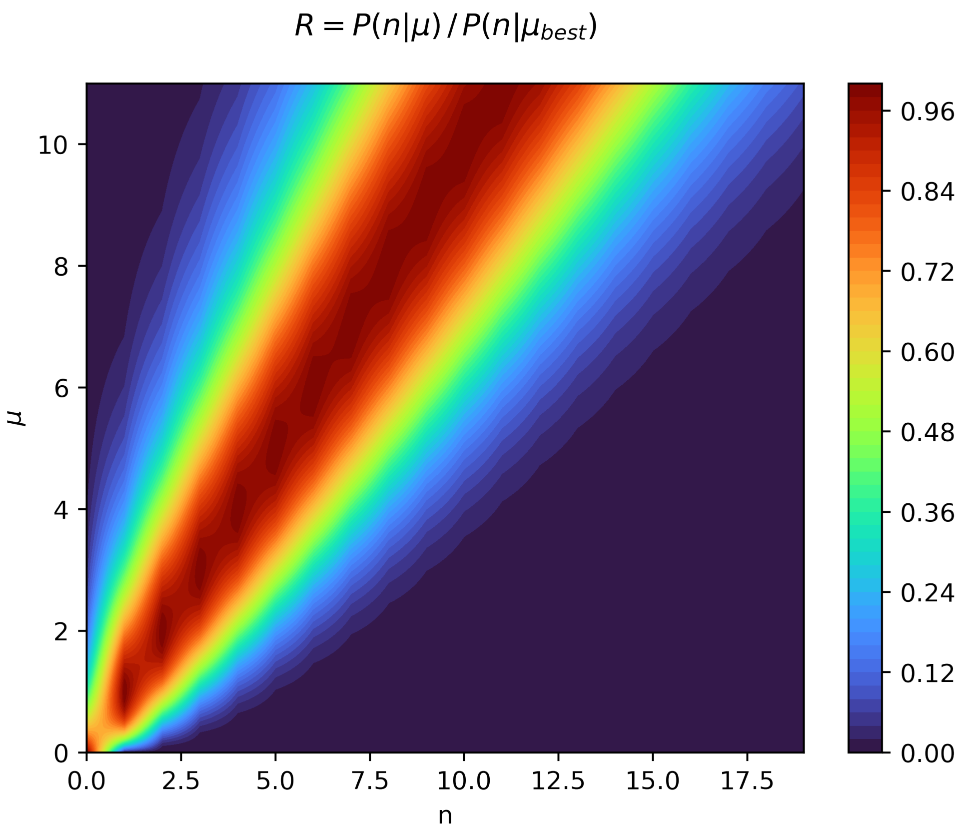

Figure 7: R-parameter dependency on μ and n.

References

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