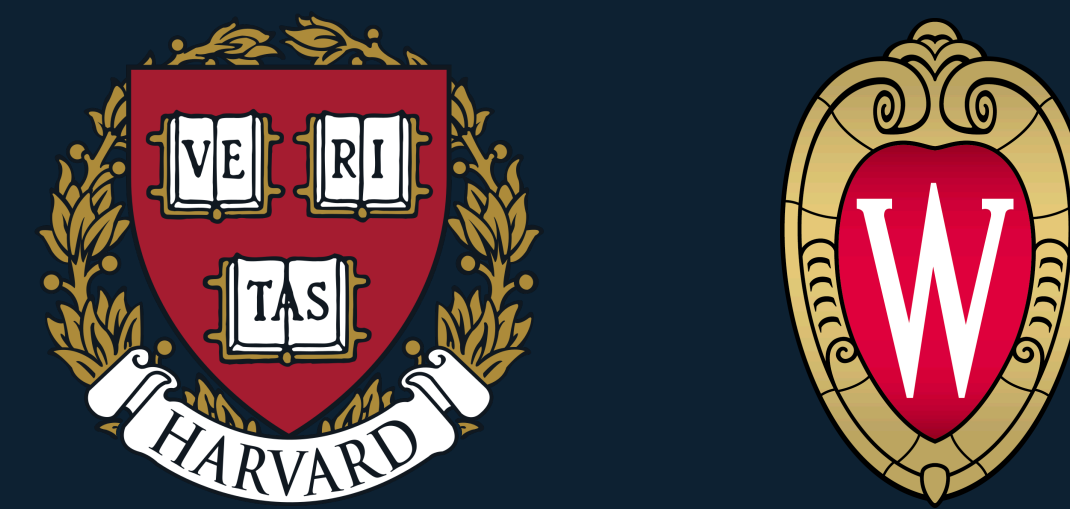


# Detecting EeV tau neutrinos at PeV energies with IceCube



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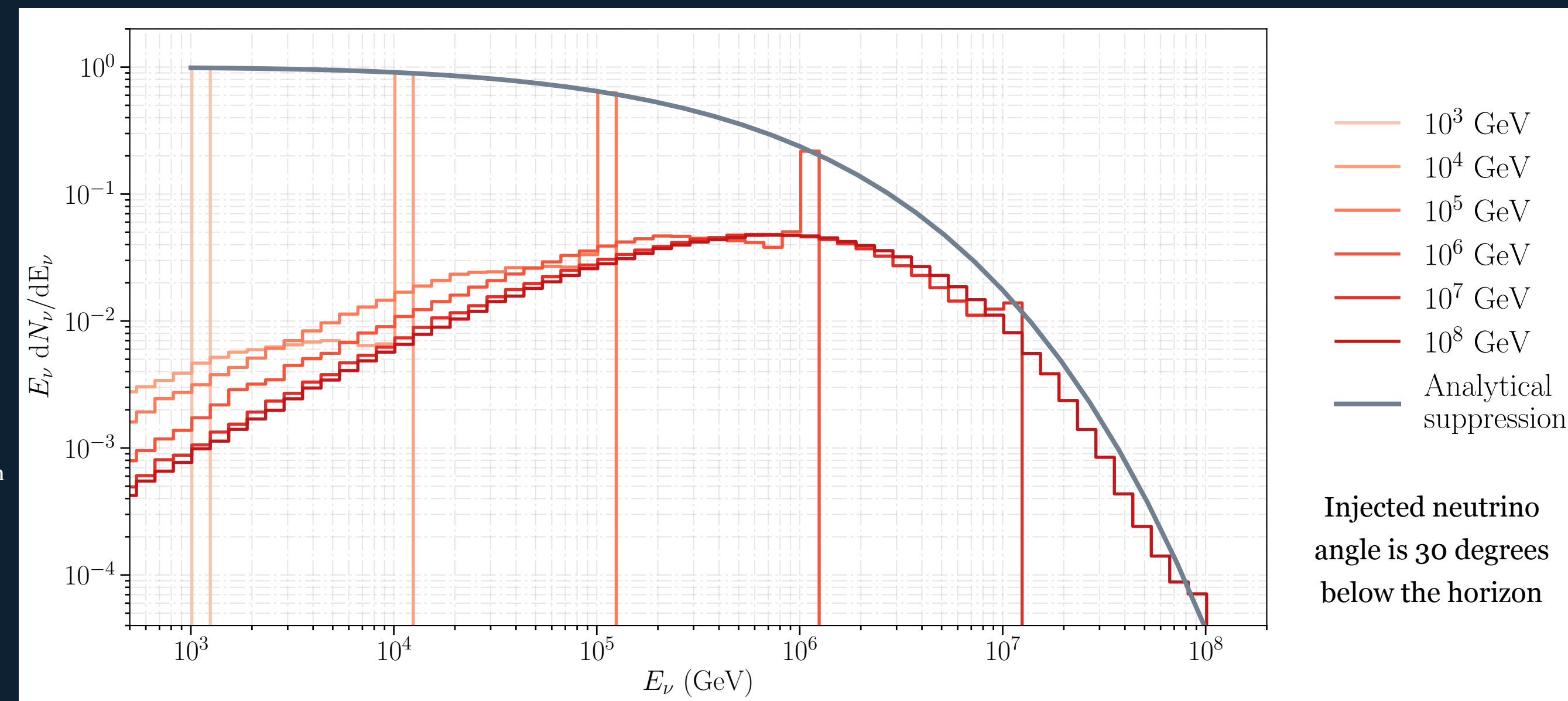
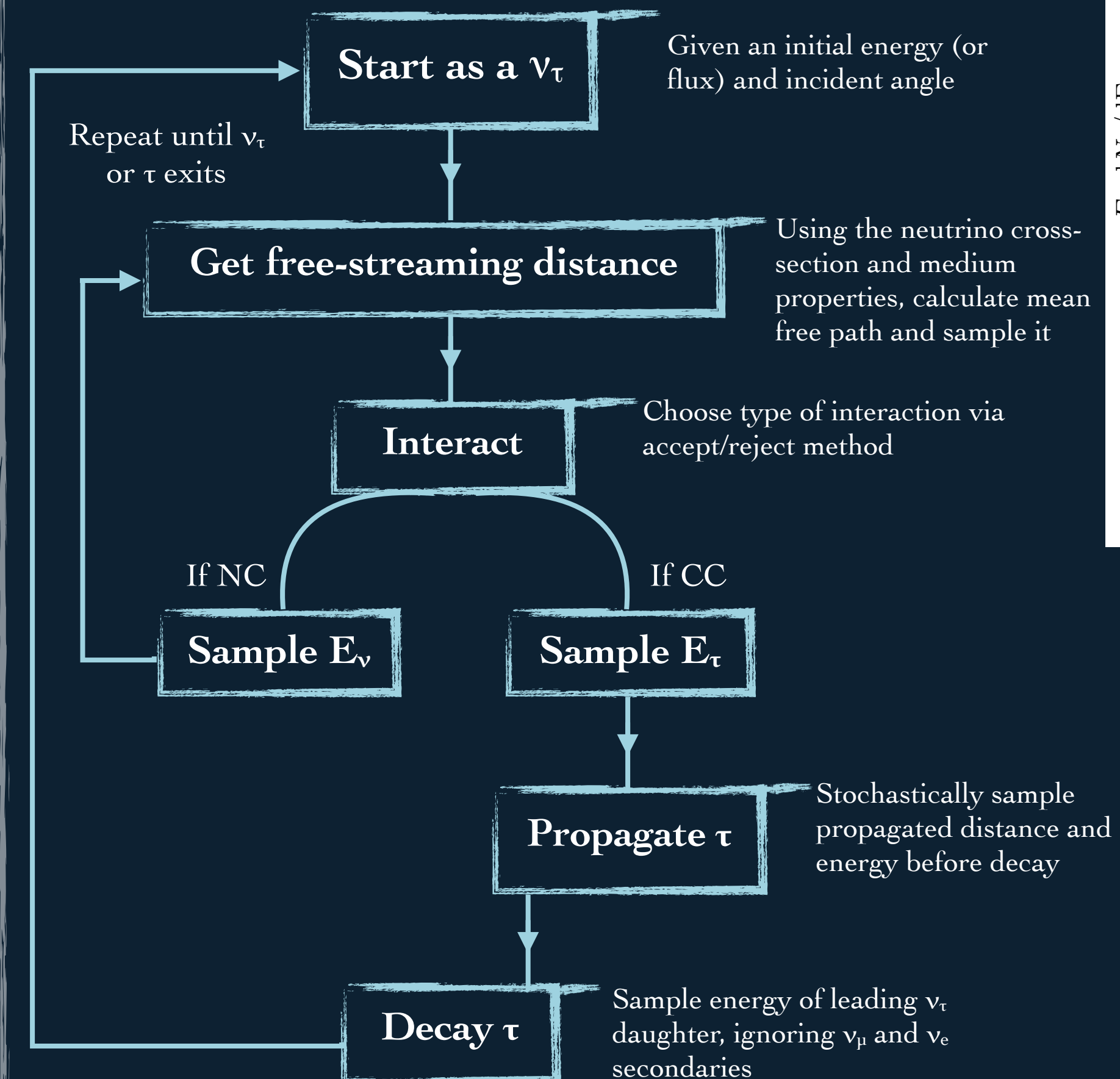
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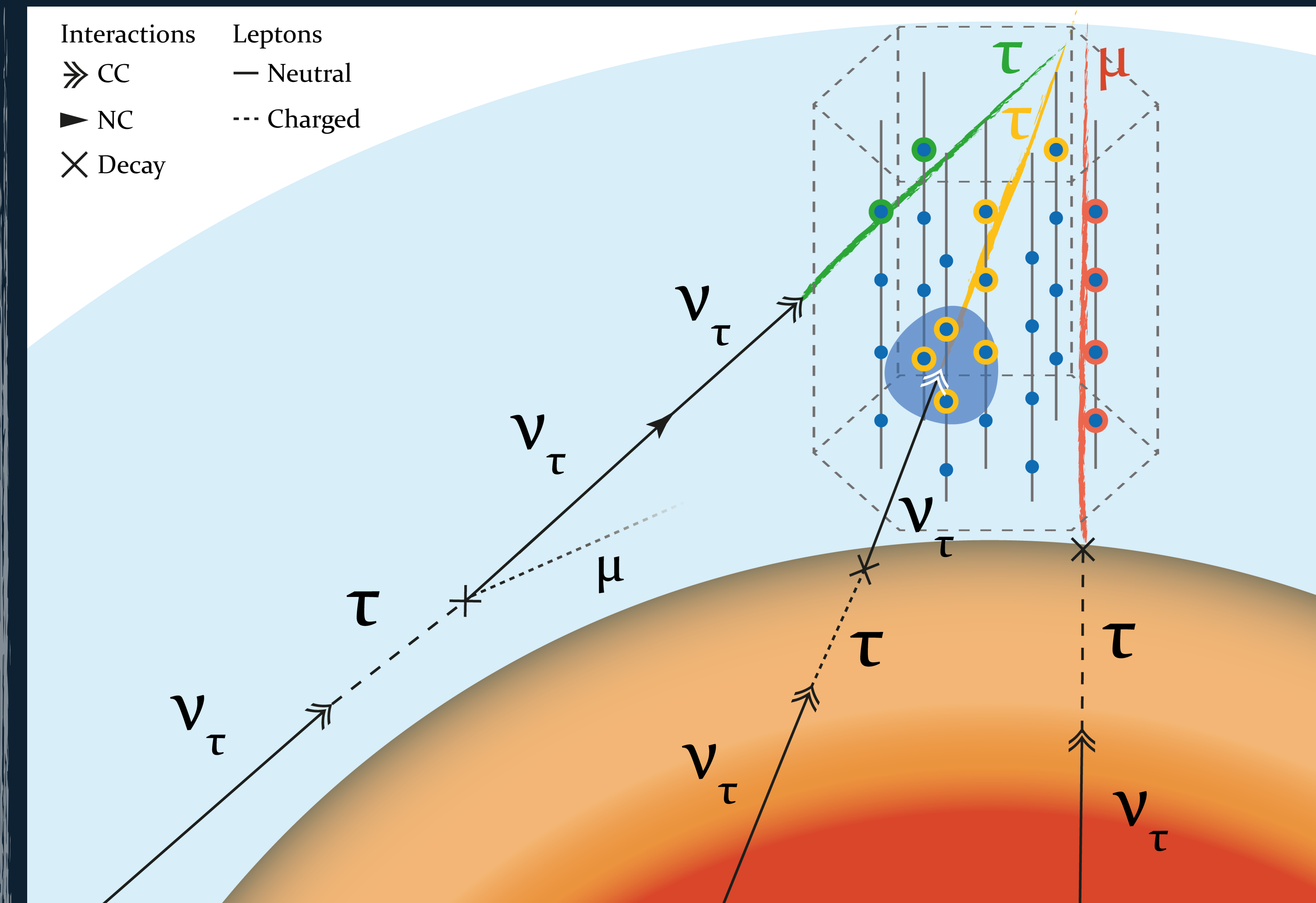
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**TauRunner MC** is a python package developed for this work. Its algorithm is illustrated below:



Secondary neutrino intensities calculated with TauRunner by injecting a set of initial monochromatic energies 30 degrees below the horizon. Spikes in each spectrum are the fraction of neutrinos that did not interact.



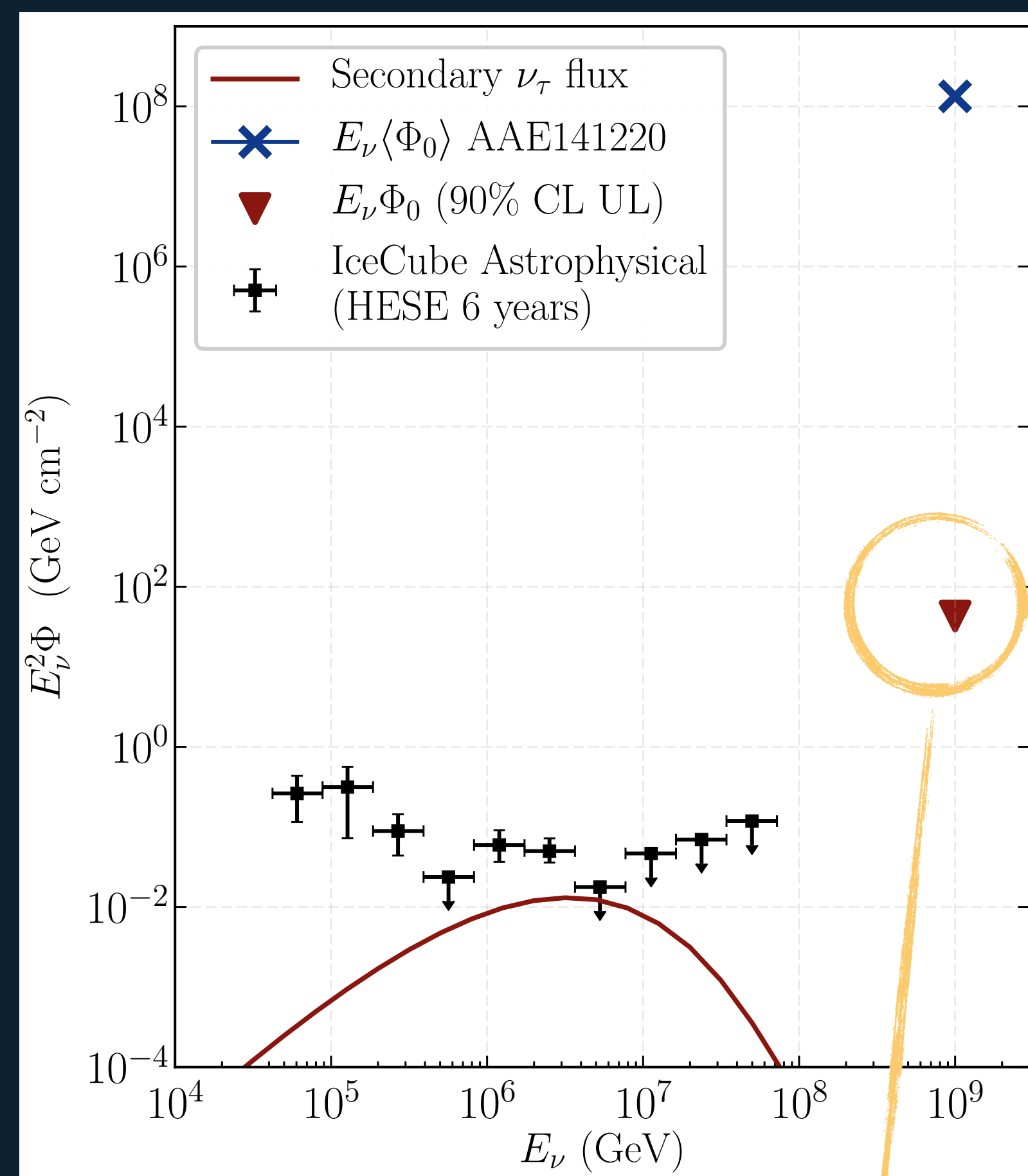
**Event Signatures from Earth-traversing ~EeV  $\nu_\tau$**

**Green:** CC-interaction just outside the detector manifests as an upward-going  $\tau$  track, possible at energies at or above 10 PeV.

**Yellow:** CC-interaction where the vertex is contained in the detector. A cascade is seen followed by an outgoing  $\tau$  track.

**Red:** Muons created as a byproduct of tau decay 18% of the time. In that case, a muon track can be seen if the interaction happens a few km from the detector.

## What it means for ANITA



Number of events detected by ANITA is given by:

$$N_\nu = \int dE_\nu dE'_\nu \Phi(E_\nu) \frac{dN}{dE'_\nu}(E_\nu, E'_\nu) \xi_{acc}(E'_\nu) \Delta T,$$

Maximum allowed incident flux

Earth-emerging secondary flux (top-left panel)

**Required  $\nu_\tau$  flux to produce the 2014 ANITA event overshoots IceCube limits by 6 orders of magnitude:**

- ANITA reported 2 anomalous events seemingly emerging at angles steeper than 30 degrees below the horizon with energies  $\mathcal{O}(1)$  EeV assuming a  $\nu_\tau$  interpretation [1].
- EeV neutrinos traveling through Earth have a mean interaction length of  $\mathcal{O}(100)$  km [2,3]. The  $\tau$  has a significantly short lifetime causing it to decay before losing too much energy. This implies a secondary flux of  $\nu_\tau$  [4] that can be detected by IceCube.
- Using the guaranteed secondary  $\nu_\tau$  flux, we set an upper limit (maroon arrow) on the time-integrated incident EeV flux. We find it to be in severe tension with the required Standard Model flux to produce the ANITA event (blue X) integrated over the same time period and in the same direction.

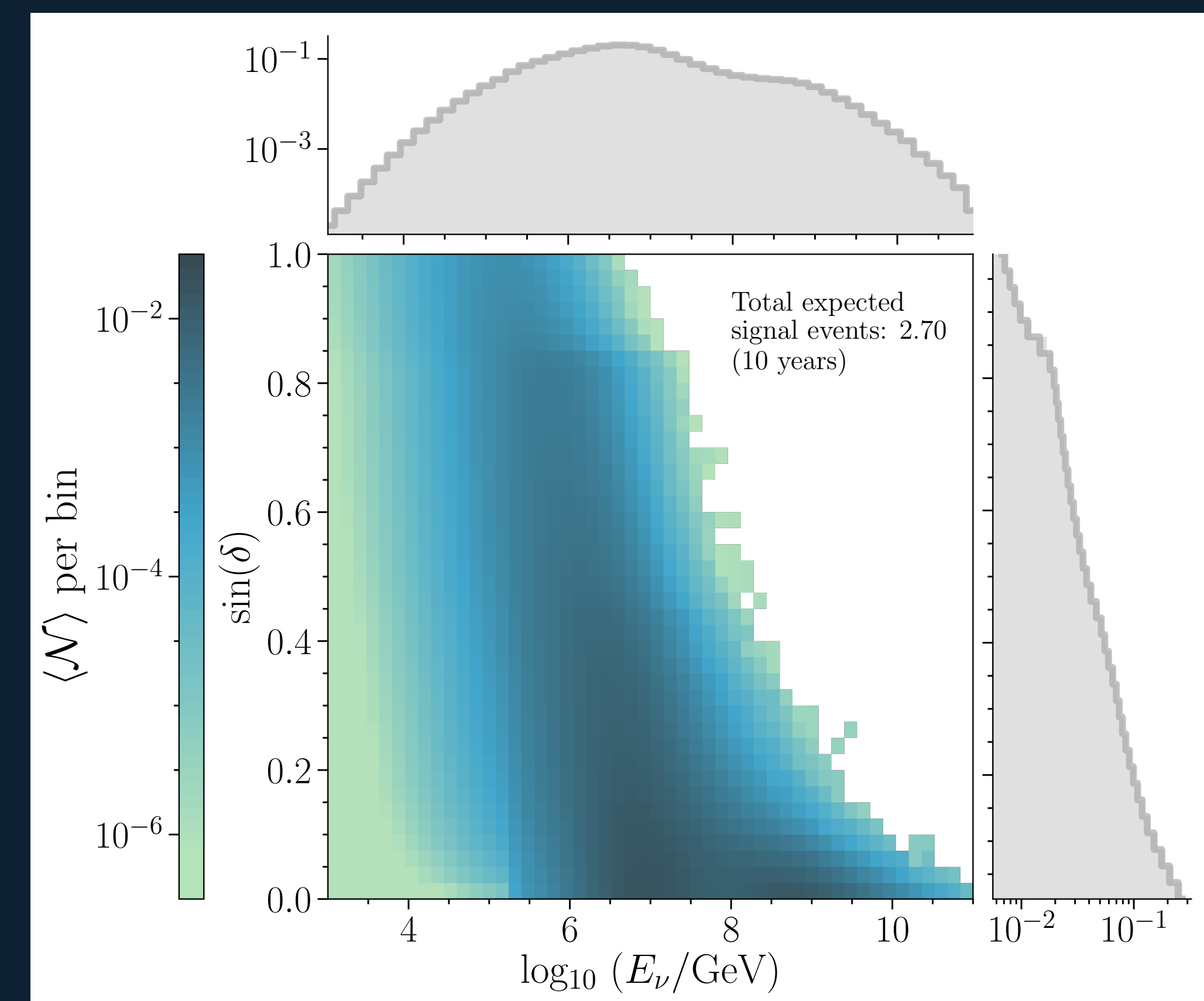
Using the constrained normalization given by the maroon arrow above, we find the maximum allowed number of events to be less than  $10^{-6}$ .

AAE141220 cannot be caused by localized emission under Standard Model assumptions

## What it means for GZK detection

GZK neutrinos are produced in the interactions of  $>10^{19}$  eV cosmic-rays with CMB photons. This undetected GZK flux should be isotropic at Earth. But searches have been limited to small solid angles, specifically looking for Earth-skimming neutrinos, where the probability of detecting a tau after a single neutrino interaction in Earth is optimized.

**GZK neutrinos traversing Earth arrive at IceCube with O(PeV) energies for most incident angles. By looking through the Earth, IceCube can open up the search for GZK neutrinos to the entire sky.**



Expected distribution of events from GZK neutrinos at IceCube, with 10 years of data. We propagate a model-independent fit from [5] assuming a cosmic-ray composition that is dominated by protons. The Earth-skimming contribution represents only about one third of the total expectation. The majority of events are expected at around 10 PeV in true neutrino energy.

## References

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