Neutrino source searches and a realtime neutrino alert stream in the southern sky with IceCube starting tracks

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1. Introduction

Highlights

- New method in IceCube to look for starting track events
- Atmospheric neutrinos rejected in southern sky while astrophysical neutrinos are retained
- Realtime alert stream with lower energy neutrinos
- Improvement to IceCube's sensitivity to southern sky neutrino sources

The **IceCube Neutrino Observatory** is an **array of digital optical modules (DOMs)** in a cubic kilometer of Antarctic ice that observes Cherenkov light from relativistic particles. IceCube's **astrophysical neutrino signal** is buried beneath a **background of atmospheric muons and atmospheric neutrinos** created in cosmic ray air showers.

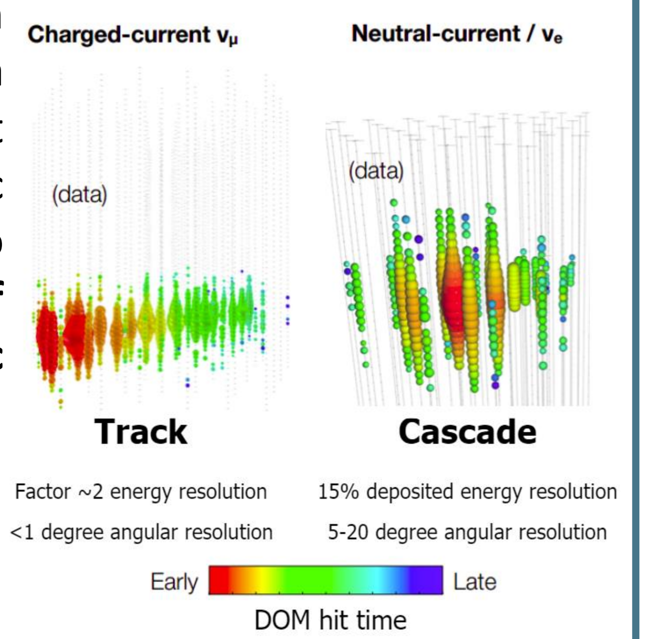


Figure 1: Common IceCube morphologies. The selection described in the poster looks for tracks left by muons.

Looking for starting events rejects atmospheric muon and neutrino events in the southern sky by vetoing atmospheric neutrino events accompanied by an incoming muon [1,2].

The following highlights the methods for a new IceCube **starting track event selection** and its advantages for astrophysical neutrino source searches.

2. Starting Track Event Selection Method

IceCube is **sparsely instrumented** relative to lower energy neutrino detectors, so incoming atmospheric muons can sneak past layers of the detector and mimic starting events

Previous IceCube starting event selections use a static fiducial cut [3,4], the following method generates a **dynamic veto definition** for each event

Dynamic Incoming Muon Veto

Given a incoming track reconstruction hypothesis:

1. Find first point along track where light seen by DOMs is well described by track hypothesis
2. Split the track into **muon region** and **dark region** (Fig. 2)
3. Calculate the probability that DOMs in the dark region did not see light if event was an incoming muon, $\mathbf{p_{miss}}$ (Fig. 3)

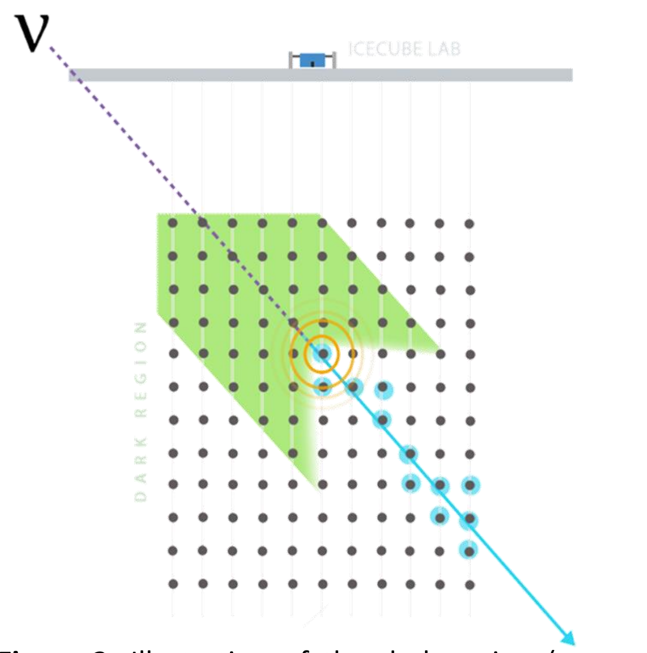


Figure 2: Illustration of the dark region (green shaded region) and muon region (blue DOMs).

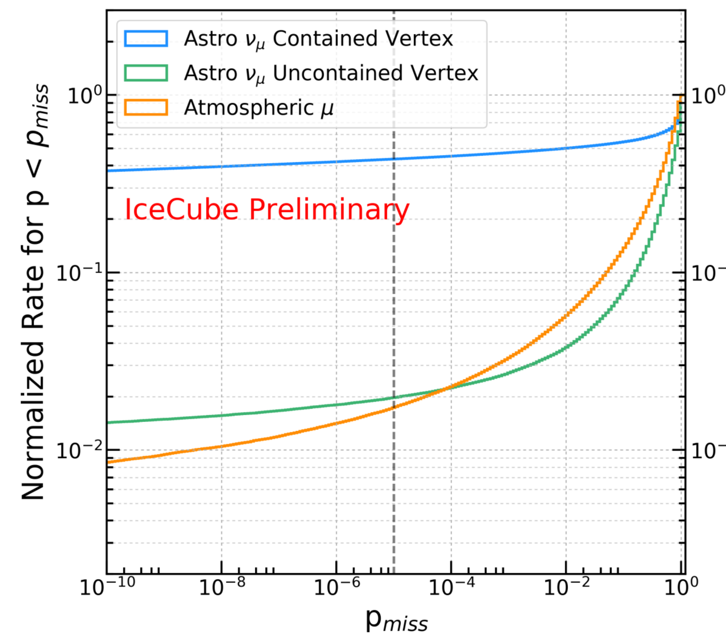


Figure 3: Normalized cumulative distribution of p_{miss}. A value approaching 1 implies that if the event was incoming, it was likely that old not deposit light in the dark region DOMs. Our signal, starting tracks, is shown in blue and exhibits a very different behavior to our main background of atmospheric muons in orange. An initial cut is made at 10^{-5} shown by the dashed line. Astrophysical events weighted assuming flux from [3].

3. Final Level Starting Track Event Selection

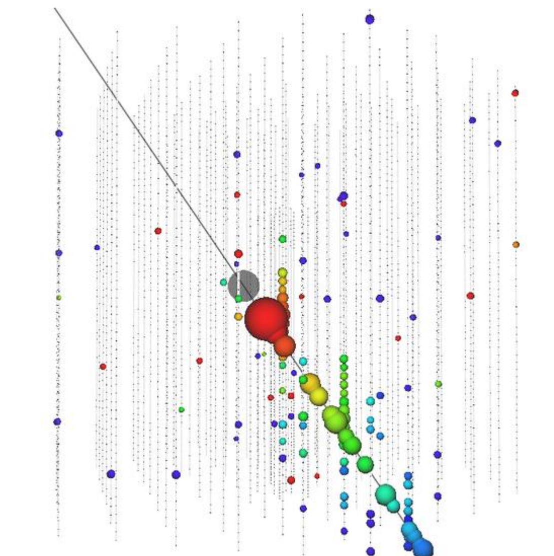


Figure 4: Starting track candidate event showing the reconstructed energy losses which are used in the BDT. The size of the losses is relative to the reconstructed energy of the loss.

BDT

p_{miss} and other variables fed to a **Boosted Decision Tree** (BDT)

Other important inputs in the BDT are:

- Fraction of charge in the first reconstructed stochastic loss (Fig. 4)
- Distance of reconstructed interaction position to edge of the detector

(per year)	Atmo μ	Atmo ν_μ	Astro ν_μ	Astro ν_e	Astro ν_τ
South (θ ≤ 80°)	1.6	91.7	17.8	1.7	4.9
North (θ > 80°)	0.3	829.4	30.9	0.7	4.8

Table 1: Starting track event selection final level per year event rates. The atmospheric neutrino suppression was modeled using methods similar to [2]. The astrophysical rate was calculated assuming the flux from [3], and a flavor ratio of 1:1:1.

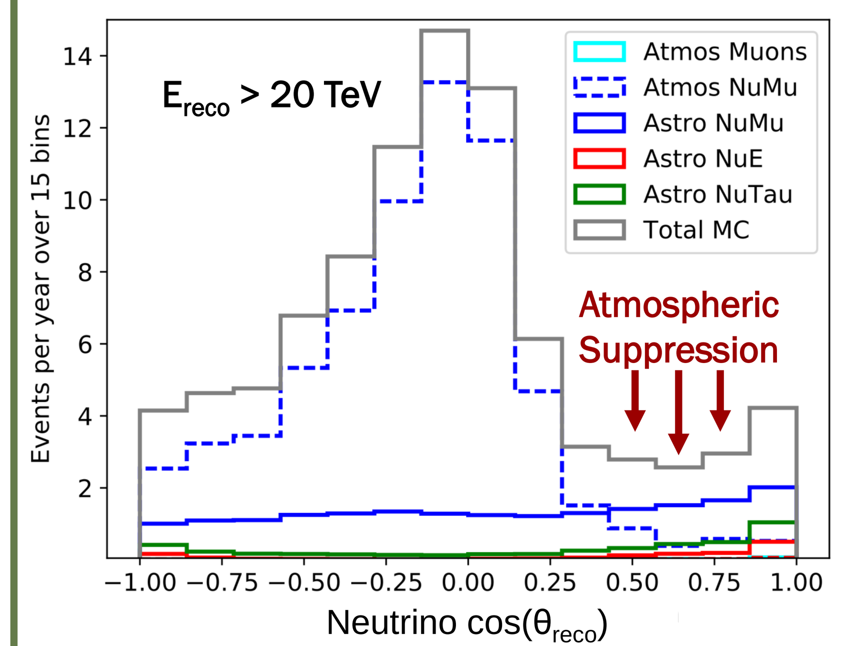


Figure 5: Starting track cosine zenith distribution for events with a reconstructed energy > 20 TeV. Positive value of cosine zenith are in the southern sky (cos(θ) = -sin(δ)).

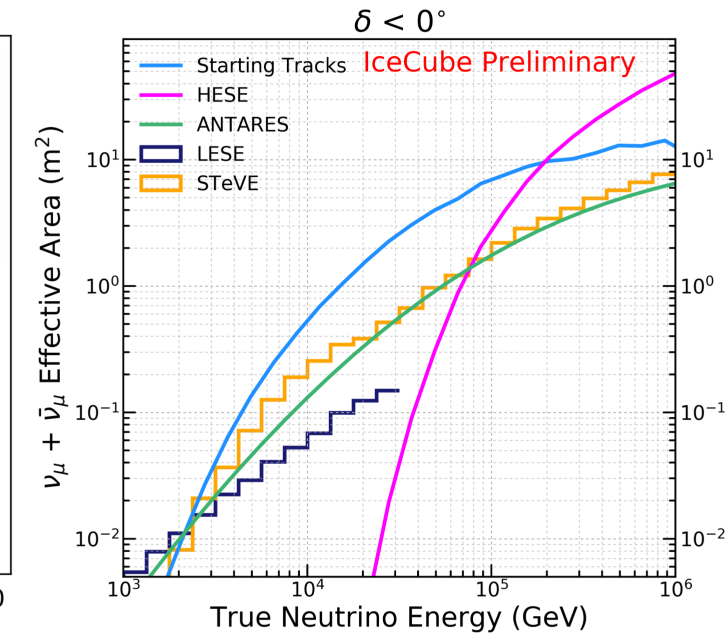
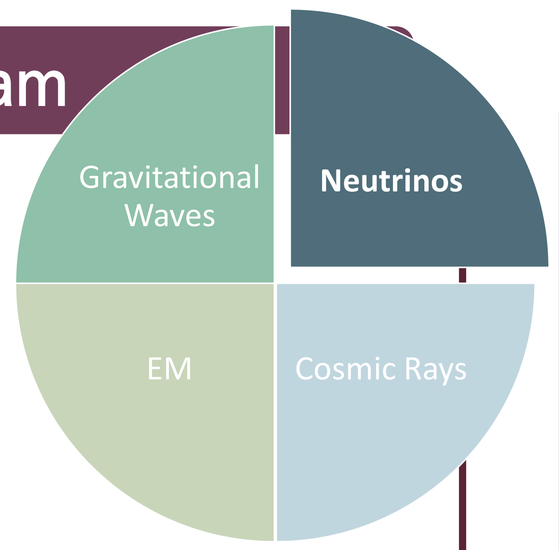


Figure 6: Starting track $\nu_\mu + \bar{\nu}_\mu$ effective area compared to other southern sky neutrino samples. HESE effective area from [4], Antares effective area from [5], and LESE and STeVE effective area from [6].

4. Starting Track Realtime Alert Stream



Neutrino alert follow-up used to find the TXS 0506+056 results [7]

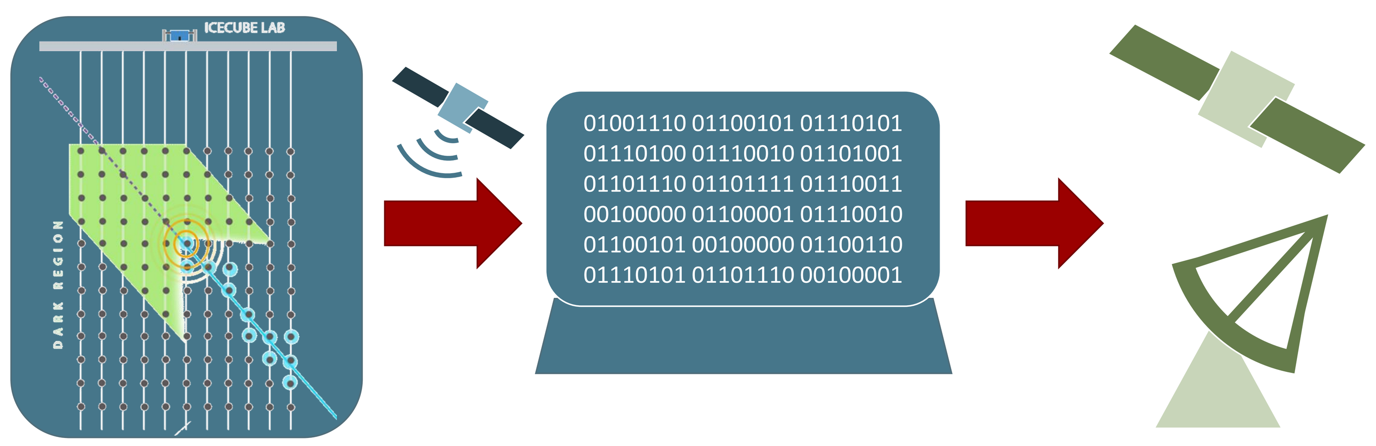
IceCube "gold" alerts have **Signalness > 50%**, which occurs at $\mathbf{E_{reco} \geq 10}$ **TeV** for starting track alerts [8]

$$Signalness(E,\delta) = \frac{N_{signal}(E,\delta)}{N_{signal}(E,\delta) + N_{bg}(E,\delta)}$$

Galactic transients may not have the power to create neutrinos with energies up to 100 TeV, so starting track alert stream ideal

	Atmospheric μ	Atmospheric ν_μ	Astrophysical ν_μ (with signalness > 50%)
South Pole Filter	16.8 per day	7.5 per year	5.5 per year
Alert Stream	0 MC Events	4.8 per year	3.7 per year

Table 2: Starting track south pole filter and final event stream rates assuming the astrophysical flux from [3]. Candidate events are selected by the filter and sent north to be processed by the full event selection. Events that pass the full selection will then be sent to our partners for follow-up.



5. Starting Track Time-Integrated Neutrino Source Searches

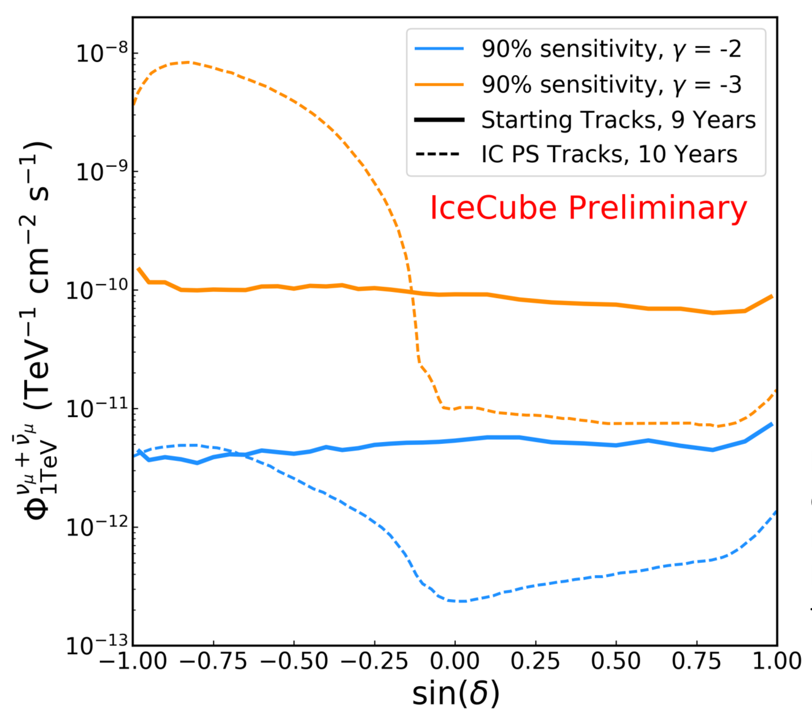


Figure 7: Point source sensitivities across all declinations. The starting track selection has improved sensitivities compared to the IceCube 10 year point source search [11] in the southern sky especially for softer spectra.

With starting tracks we plan to look for neutrino sources using the following methods:

- All-Sky Source Search
- Galactic and Extragalactic Source Catalog
- Galactic Source Stacking
- Galactic Plane Template (Fermi π^0 [9] and KRAγ [10])

Previous 10 year point source analysis [11] applied high energy cuts in southern sky

Starting tracks improve southern sky source sensitivity especially for softer spectra (Fig. 7) or for sources with energy cutoffs

For Galactic Plane Template (KRAγ [10]): expect a signal of 13.8 neutrinos over a background of 50.8 atmospheric neutrinos in 9 years (for $\delta_{reco} < -15°$ and $E_{reco} > 10$ TeV)

6. Conclusion and Outlook

Starting tracks promising for studying southern sky neutrino sources

Realtime neutrino alerts with a lower energy threshold coming to multimessenger astrophysics community

Starting track method could be applied in IceCube-Gen2 [12]

- Larger volume helps capture more neutrinos
- Less dense array means incoming muons can travel farther through the detector without depositing light in DOMs
- New array geometry would help this method by reducing "alleyways" for muons to sneak through detector

References:

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