Measurement of Astrophysical Tau Neutrinos by IceCube

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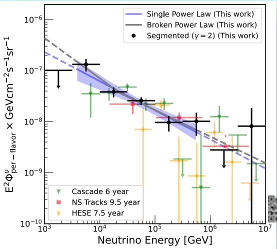
1. Motivation

Energetic ν^{astro} exist:

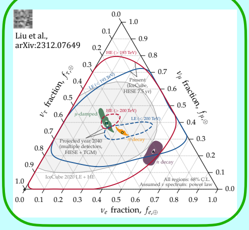


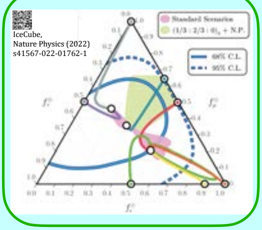
See all flavors?

Missing flavor(s)?

Standard oscillations ⇒ $\nu_e:\nu_\mu:\nu_\tau \sim 1:1:1$

New physics ⇒ $\nu_e:\nu_\mu:\nu_\tau \neq 1:1:1$





IceCube has detected ν_μ^{astro} (long μ) & $\bar{\nu}_e^{\text{astro}}$ (Glashow resonance).

What about ν_τ^{astro}?

- Seen by IceCube at 2.8σ in inclusive analysis (1).
- Here we describe a high-signif. *exclusive* ν_τ^{astro} analysis (2).

2. ν_τ Channels in IceCube

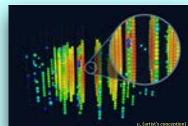
Expect ν_τ^{astro} in IceCube data, but they're hard to isolate:

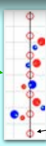
Detection Channels

L_τ (50m/PeV)	$\sim E_{\nu_\tau}$	Channel Name	Detection Status
$> \sim 50$m	> few PeV	Double Bang	Very rare; unseen
10–20m	~100 TeV	Double Cascade	Visible (incl. & excl.)
$\mathcal{O}(\mu m)$	~10 GeV	ν_τ appearance	Visible (incl. only)

Sparse detector

Varied signatures





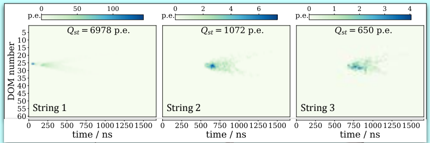
ν_τ interaction → τ decay

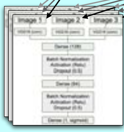
Size of solid circle ∝ energy deposition

Digital Optical Module

3. ν_τ Detection; Expected (S,B)

A) Require shower-like, bright events.
B) Create images of 3 brightest neighboring strings.
C) Train 3 CNNs to distinguish ν_τ^{astro} from bkgds.





3 × VGG16*⇒$C_{1,2,3}$ CNN scores:
ν_τ vs. $[(\nu_e, \nu_{NC}), \nu_\mu, \mu_1]$
*arXiv:1409.1556

Expected ν_τ^{astro} signal

	$\nu_{\tau,CC}^{\text{astro}}$
initial	160 ± 0.2 (190 ± 0.3)
final	6.4 ± 0.02 (4.0 ± 0.02)

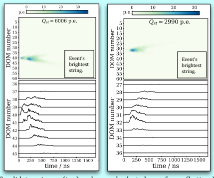
Expected Bkgs.

	$\nu_{\text{other}}^{\text{astro}}$	$\nu_{\text{conventional}}^{\text{atm}}$	$\nu_{\text{prompt}}^{\text{atm}}$	μ^{atm}	all background
initial	400 ± 0.7 (490 ± 0.8)	580 ± 7	72 ± 0.1	8400 ± 110	9450 ± 110 (9540 ± 110)
final	0.3 ± 0.02 (0.2 ± 0.01)	0.1 ± 0.008	0.1 ± 0.001	0.005 ± 0.004	0.5 ± 0.02 (0.4 ± 0.02)

Tables show expectations for two–GlobalFit (HESE)–of four flux msmts.
Summary: 4–8 ν_τ^{astro} on ~0.5 bkgd. Biggest bkgd: Other-flavor ν^{astro}.

4. Results

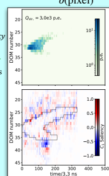
9.7 yr livetime: 7 candidate ν_τ^{astro}, some with clear double pulse waveforms, others without:



Candidate ν_τ image (top) and several selected waveforms (bottom) with visible double-pulse structure (right) and without (left).

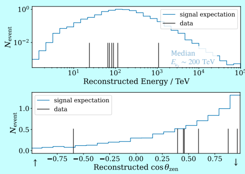
Use *saliency* to grasp what CNNs are using.

$$S(C_1) = \frac{\partial(C_1)}{\partial(\text{pixel})}$$



Candidate ν_τ image (top) and C_1 CNN score saliency map (bottom) showing importance of overall event structure (line indicates where $N_{\text{p.e.}} \to 0$).

Candidate ν_τ^{astro} look as expected.



Checks: Performed numerous data-driven tests (forced light-level changes) and tests of CNN robustness (e.g., adversarial attacks).

Only changes well outside realm of systematic uncertainties had any impact.

We rule out $\Phi(\nu_\tau^{\text{astro}}) = 0$ at 5.1σ.

ν_τ^{astro} References

1. IceCube, EPJC **82** (2022) 11, 1031
2. IceCube, PRL **132** (2024) 15, 151001

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