Diffuse Astrophysical (Tau) Neutrinos

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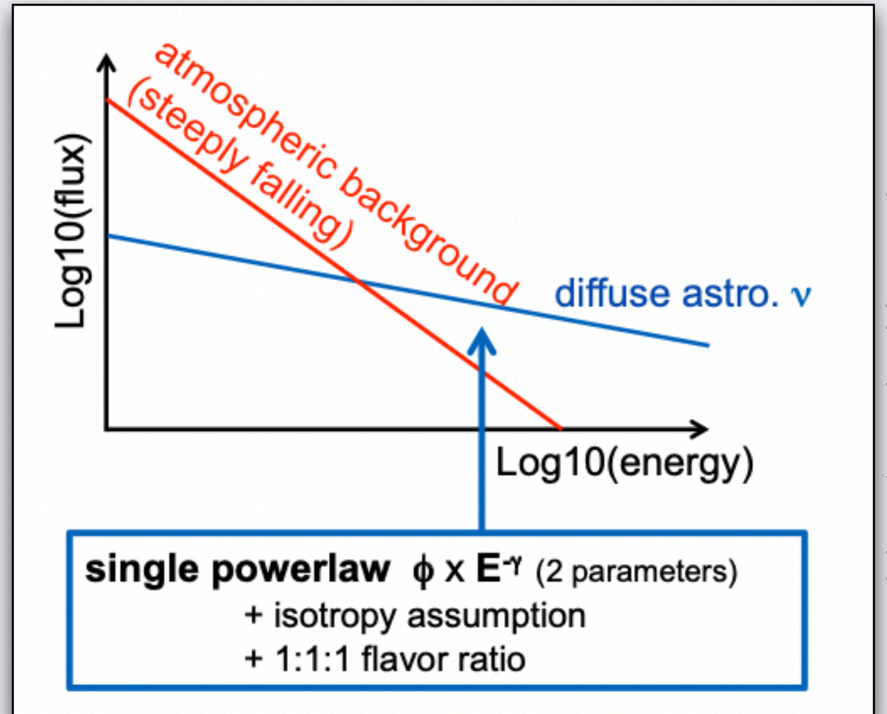
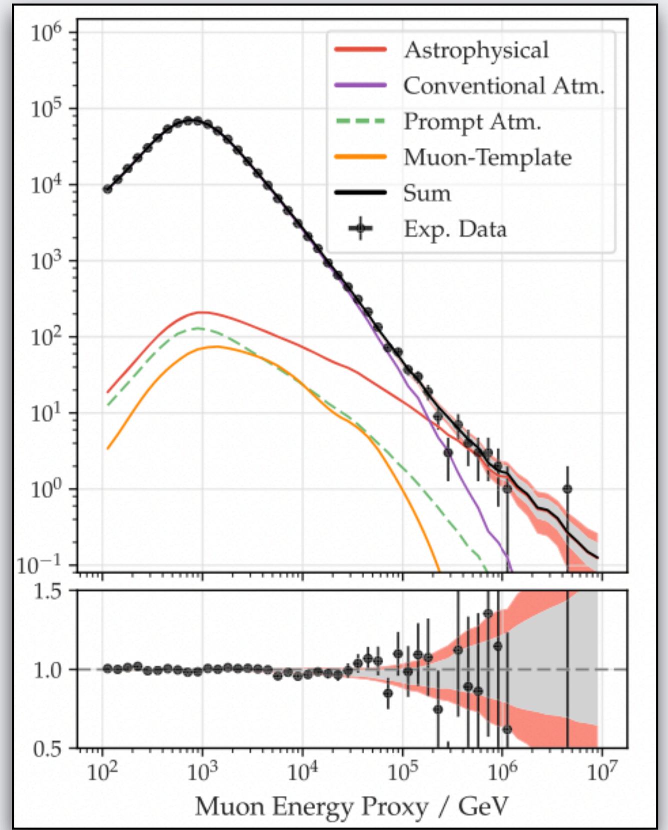
Introduction

- Diffuse ν^{astro}: excess at high E_ν
- Give insights into acceleration and propagation of high-E cosmic rays
- Possible sample slices: Contained, Upgoing, Track-like, Cascade-like, Tau-like
- Possible sources: AGNs, choked GRBs, TDEs, Starburst galaxies…

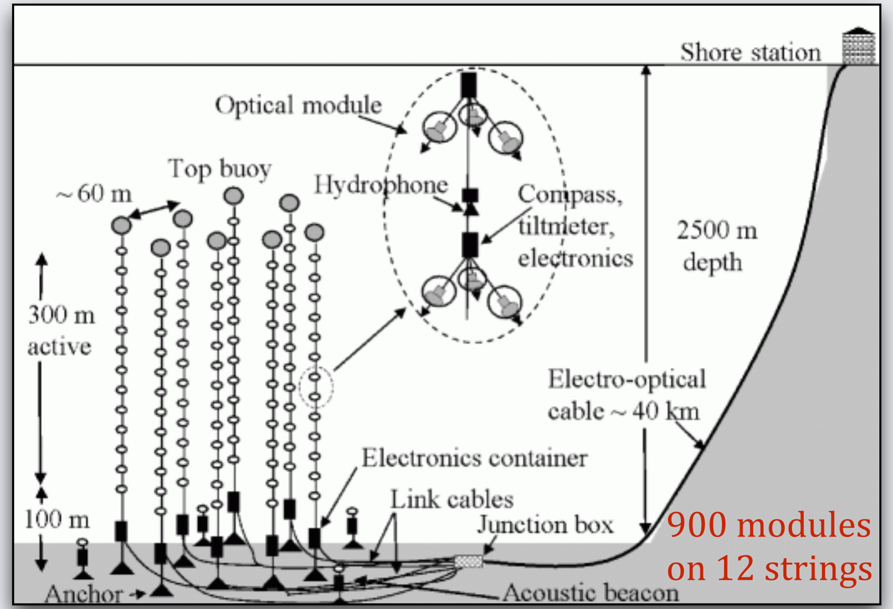


H. Niederhausen | XVIII Intl. Workshop on ν Telescopes

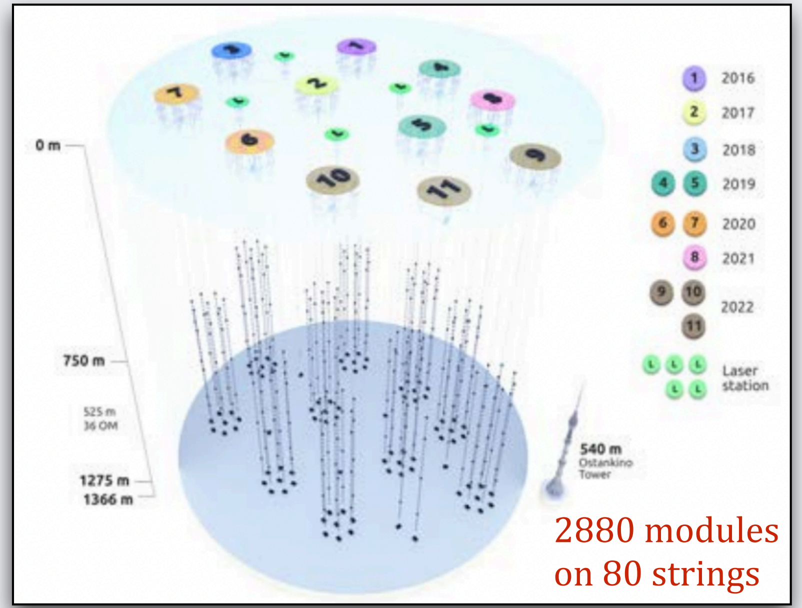


IceCube, Astrophys. J. 928, 50 (2022)

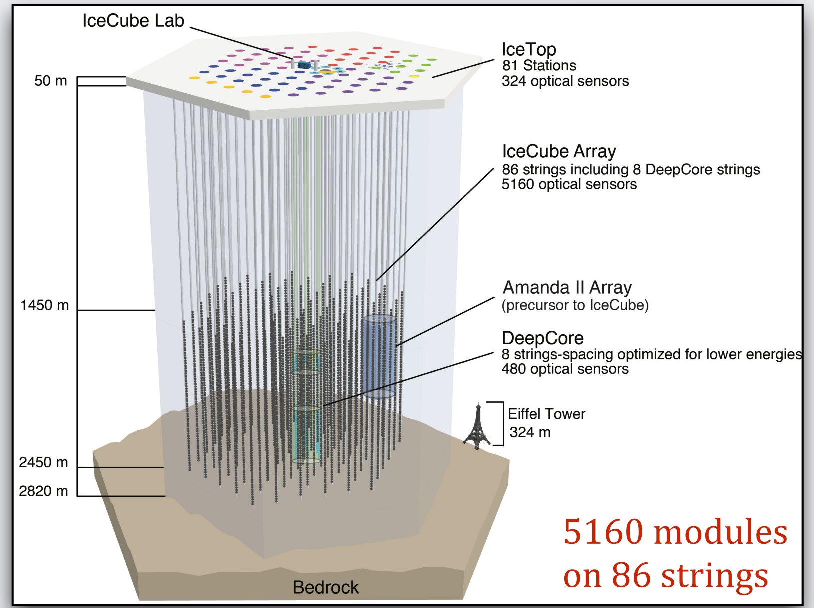
Detectors



ANTARES



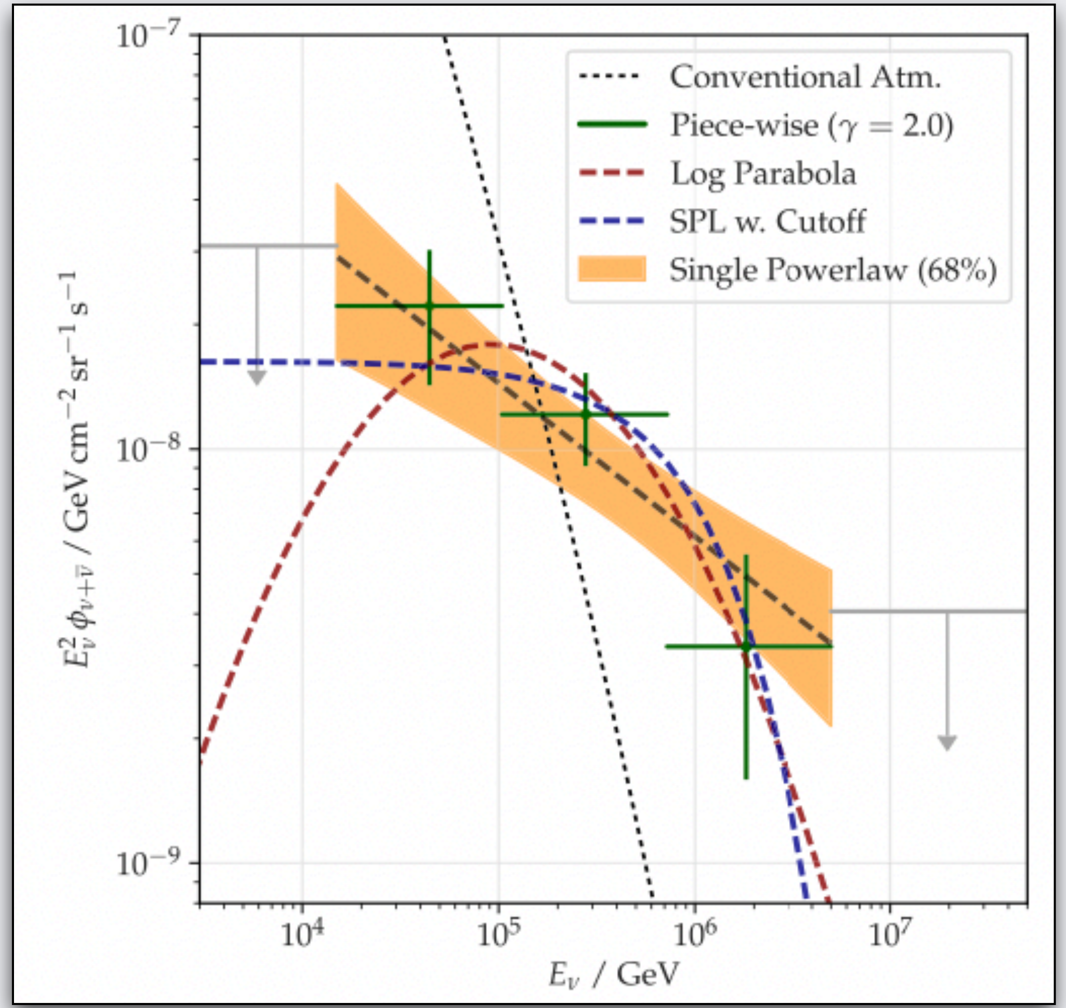
Baikal/GVD



IceCube

Diffuse High-E ν: Previous Results

- Flux consistent with single power law (SPL): $\Phi_\nu \propto \phi_0 E_\nu^{-\gamma}$
  - Also consistent with (softer) SPL-with-cutoff, log-parabola, piece-wise.
  - *In*consistent with pure ν^{atm} at $>5\sigma$ ($>3\sigma$, $>1.8\sigma$) by IceCube (GVD, ANTARES)
- Comparable energy content in γ-rays, ν's and cosmic-rays.
  - Suggests common origin(s).

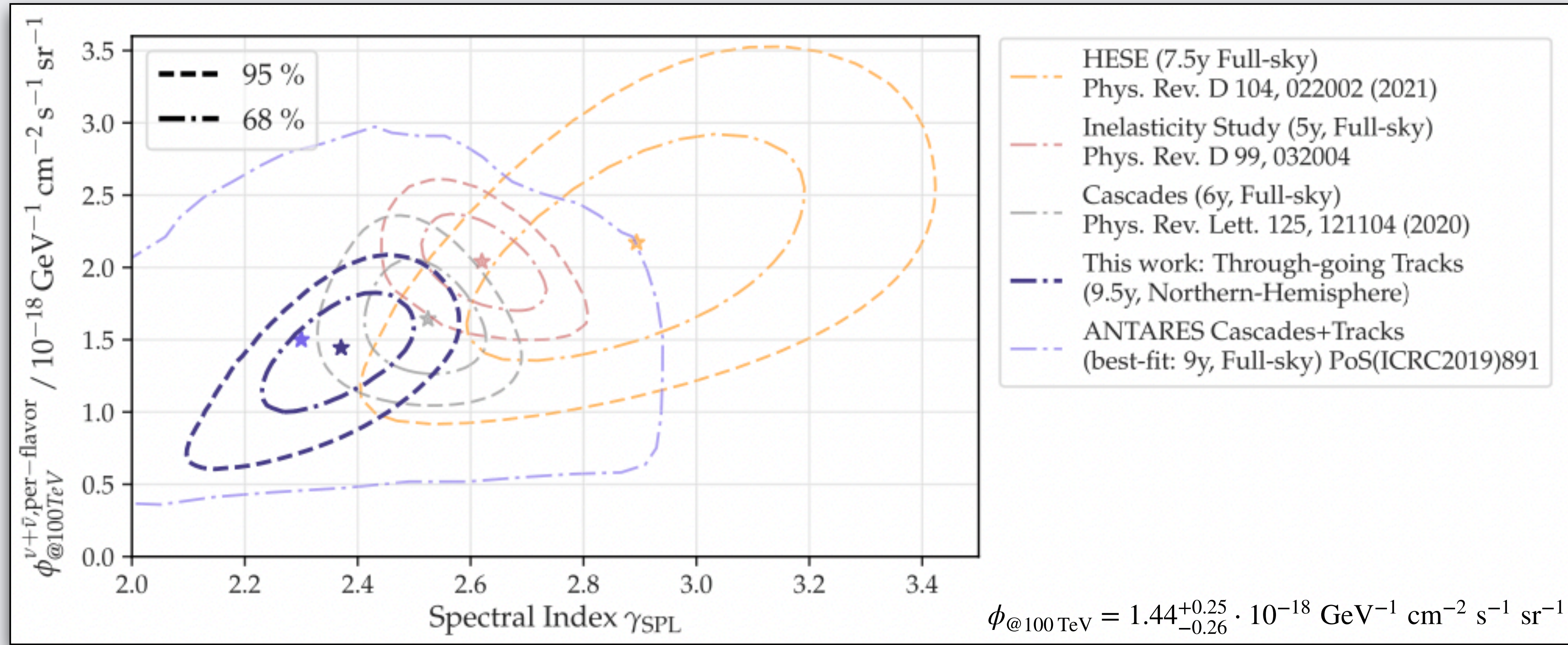


IceCube, Astrophys. J. 928, 50 (2022)

$N_{\text{evt}}(E_{\mu,\,\text{proxy}} > 200\,\text{TeV}) \sim 35$

Diffuse High-E ν: Previous Results

- Summary of ANTARES & IceCube measurements of ϕ_0, γ
  - All broadly consistent with one another

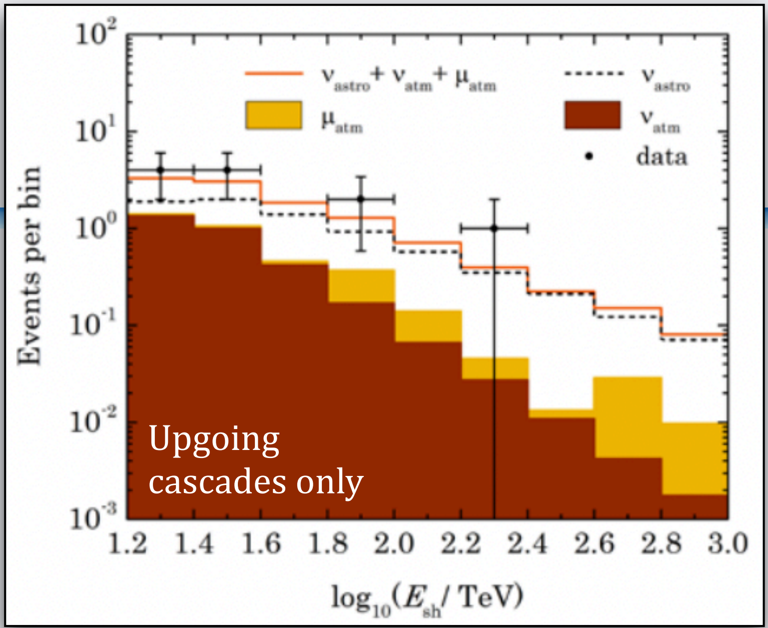


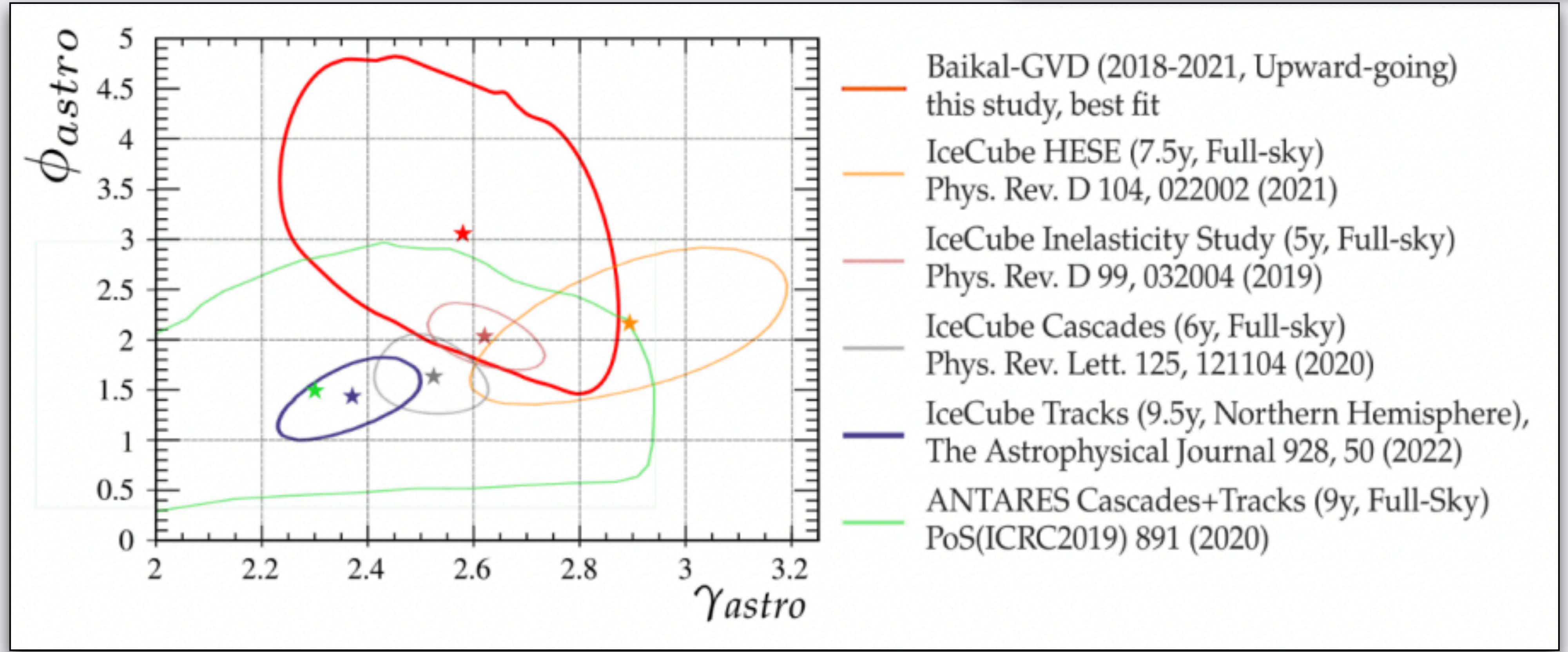
$\phi_{@100\,\mathrm{TeV}} = 1.44^{+0.25}_{-0.26} \cdot 10^{-18}\ \mathrm{GeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}}$

IceCube, Astrophys. J. 928, 50 (2022)

New Results: GVD

- Based on cascade-like events
  - Consistent with other msmts.





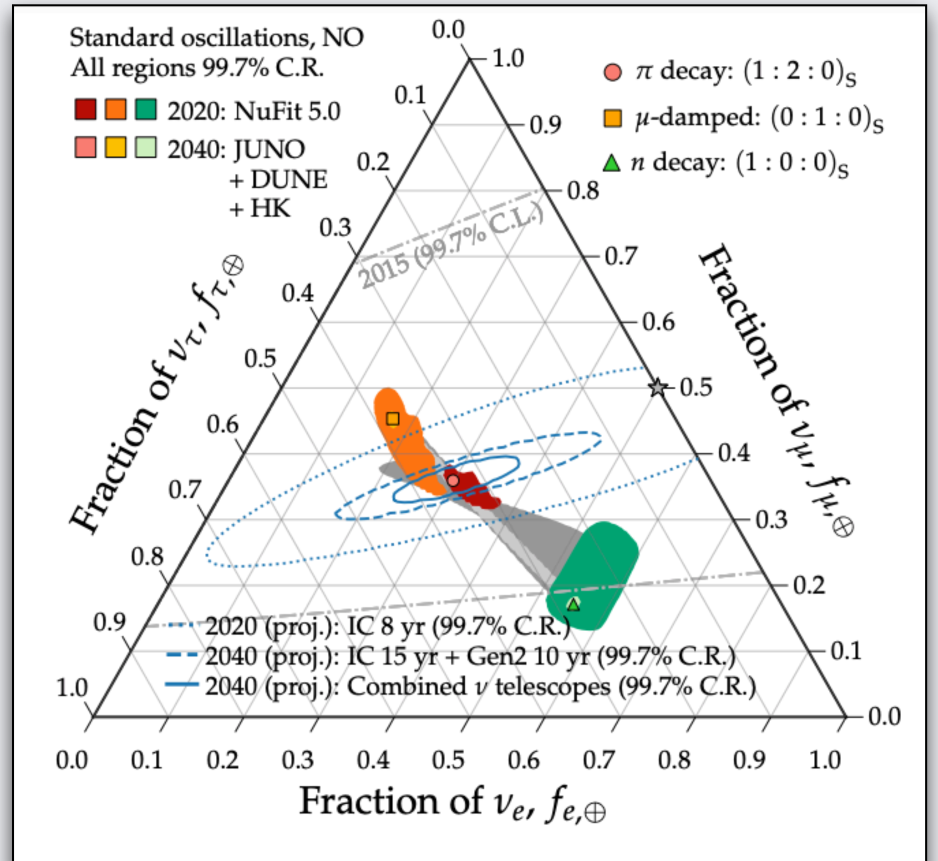
https://arxiv.org/pdf/2211.09447.pdf

ν_τ^{astro}: A New (Multi-)Messenger?

- Detection of ν_τ^{astro} is very challenging. Why bother?
  - Can help pin down flavor ratio $\nu_e : \nu_\mu : \nu_\tau$ at sources
    - More insight into acceleration environment
  - Improves access to cosmic baseline ν oscillations
    - Strong deviations from 1:1:1 at detector→new physics?

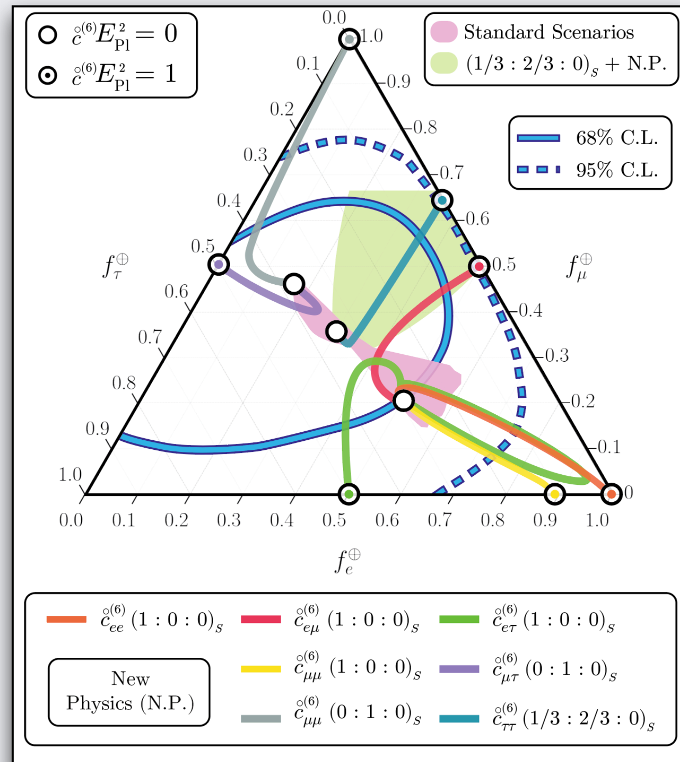
Importance of Flavor ID for ν^{astro}

At Earth, $\nu_e:\nu_\mu:\nu_\tau$ could tell us about the source…



https://arxiv.org/abs/2012.12893

…while strong deviations from 1:1:1 could mean new physics.



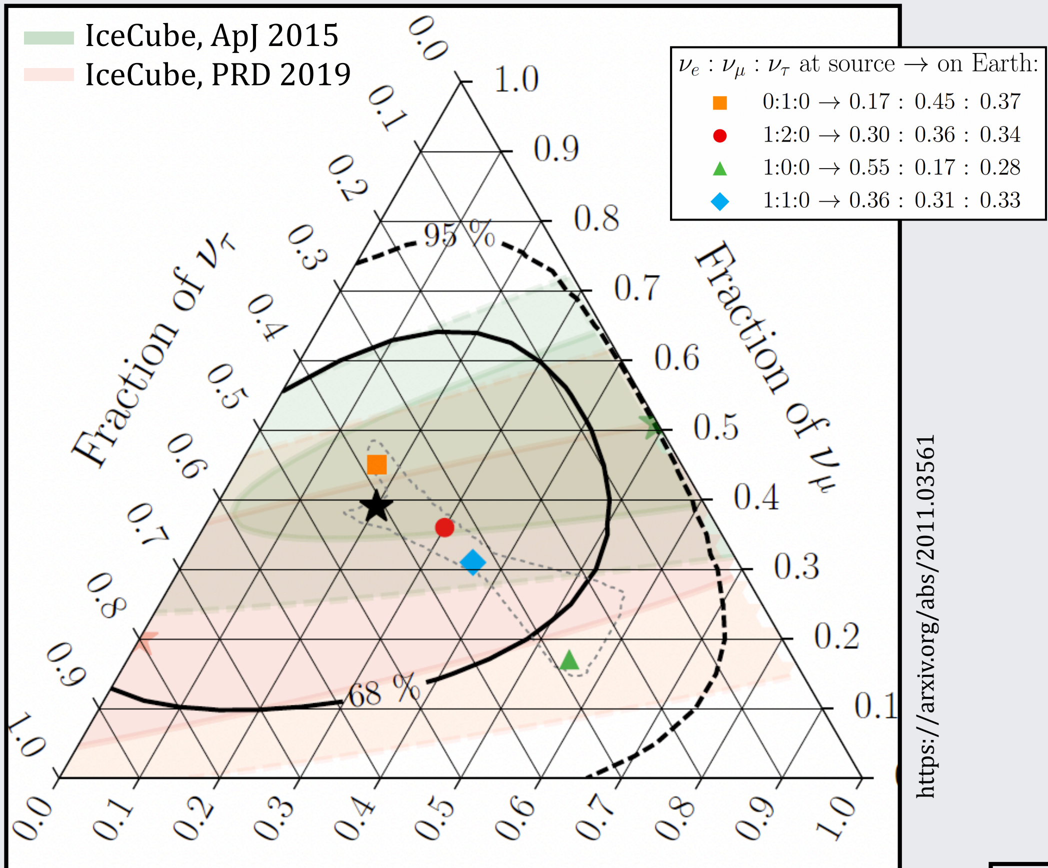
https://arxiv.org/abs/2111.04654v1

Example: Effect of quantum gravity.

For more examples, see Refs. 22-59 in IceCube, PRD 104, 022002 (2021).

Importance of Flavor ID for ν^{astro}

Status quo:



Measured flavor composition of IceCube HESE events. ★ is best fit point, consistent with presence of all 3 flavors, but ν_τ flux only weakly constrained.

To shrink the contour, need better P.I.D., certainly more than just "track" vs. "cascade."

$\nu_{\tau}^{\text{astro}}$: A New (Multi-)Messenger?

- Detection of $\nu_{\tau}^{\text{astro}}$ is very challenging. Why bother?
  - Can help pin down flavor ratio $\nu_e : \nu_\mu : \nu_\tau$ at sources
    - More insight into acceleration environment
  - Improves access to cosmic baseline ν oscillations
    - Strong deviations from 1:1:1 at detector→new physics?
- Path forward: Improve particle ID
  - From $(\nu_{e,\tau}^{\text{CC}}, \nu_{e,\mu,\tau}^{\text{NC}})$ vs. ν_{μ}^{CC}
    - "cascade" vs. "track"
  - To $(\nu_{e}^{\text{CC}}, \nu_{e,\mu,\tau}^{\text{NC}})$ vs. ν_{μ}^{CC} vs. ν_{τ}^{CC}
    - "single cascade" vs. "track" vs. "double cascade"

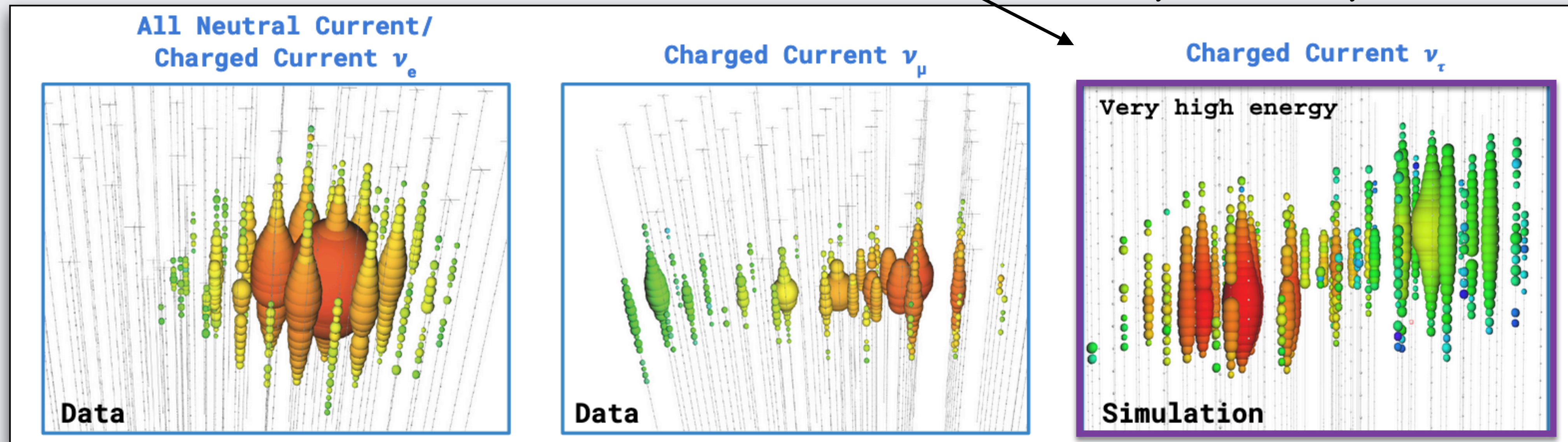
ν_τ^{astro}: Signatures

Spheres: DOMs
White: recorded no light
Color: recorded light
Size: light collected

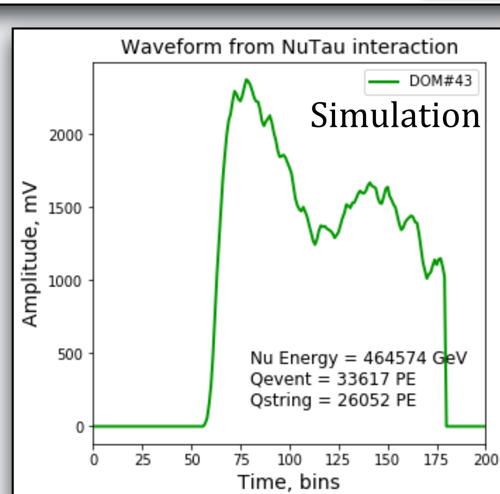
Color shows time information:
Early — Late

At high energies: "Double Bang."
Unfortunately, very rare.

$L_\tau \simeq 50\text{m} \cdot E_\tau$ /PeV

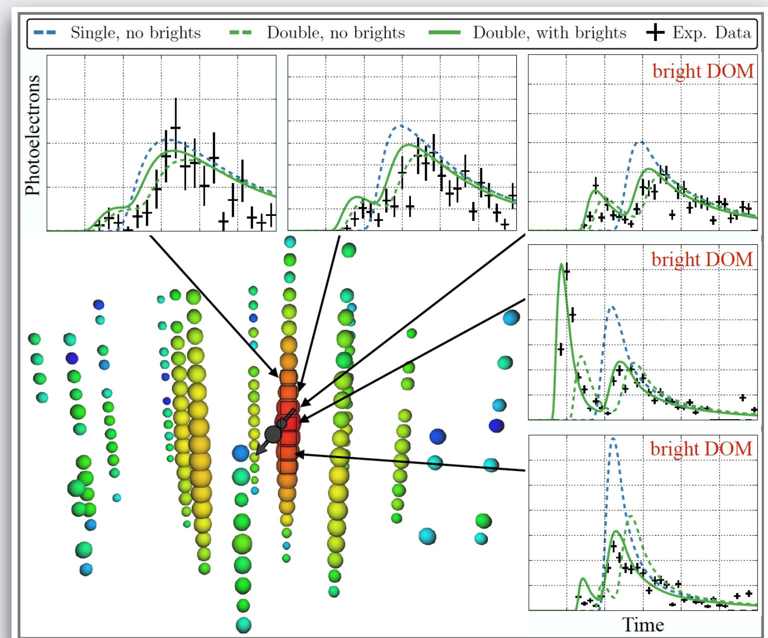


More flux at lower energies!
Look for subtler signature(s) in one or more modules.



ν_τ^{astro}: Past Results

- Previous IceCube analyses:
  - Exclusive v01
    - Seek distinct double pulse (DP) waveforms in 1–2 modules
    - Two candidate ν_τ^{astro}
  - ~Inclusive
    - Use likelihood reconstruction to classify 60 "HESE" events (with $E_{\text{dep}} > 60$ TeV) as either track, single cascade, or double cascade
      - Saw 17 tracks, 41 single cascades, 2 double cascades
- Summary of results:
  - One event (nicknamed "Double Double") appeared in all analyses
  - Background levels were $\mathcal{O}(1)$ event
  - Best exclusion of null hypothesis, $\Phi(\nu_\tau^{\text{astro}}) = 0$, was 2.8σ



IceCube, Eur. Phys. J. C 82, 1031 (2022)

"Double Double" candidate ν_τ

ν_τ^{astro}: Past Results

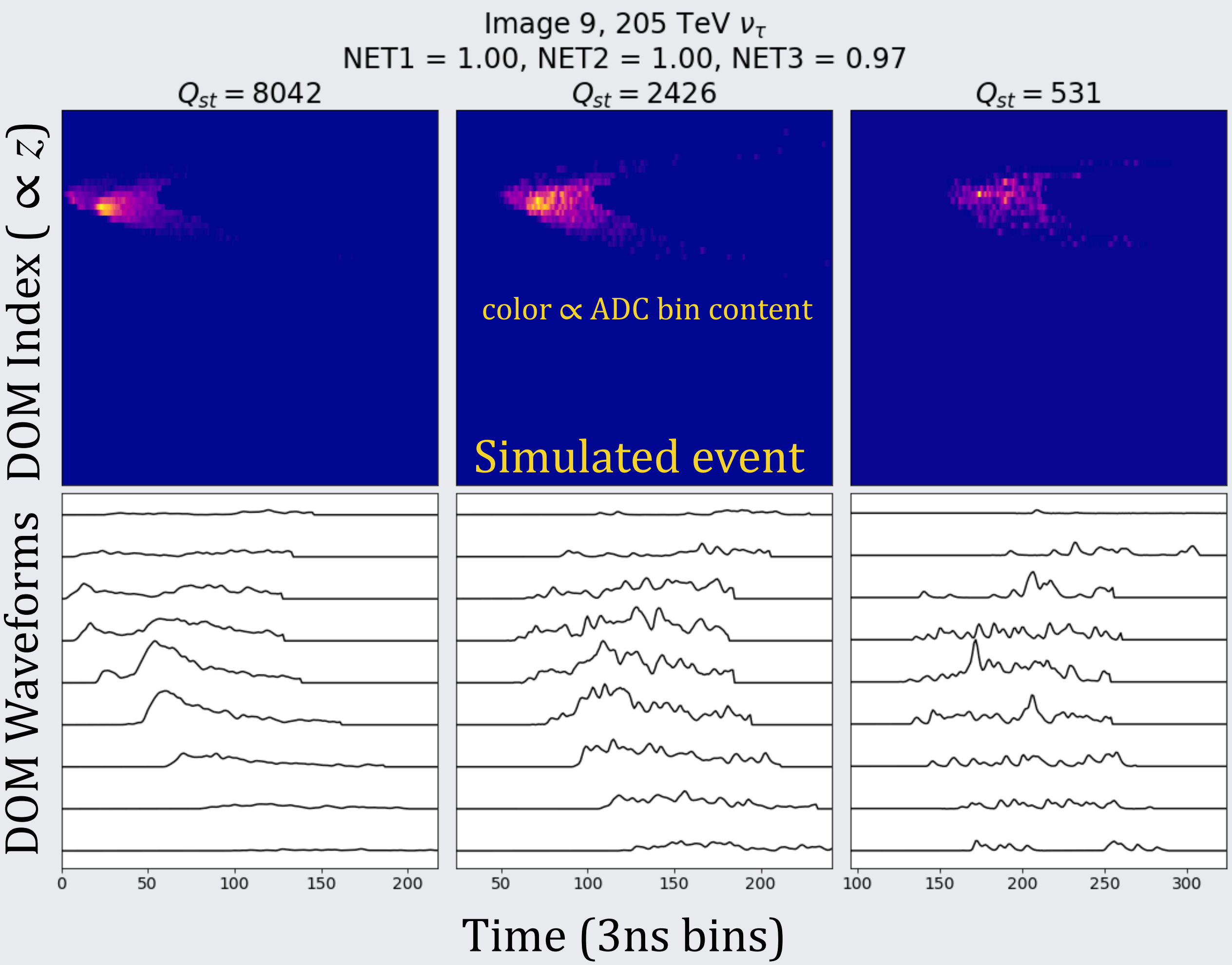
- With standard ν oscillations, expect $\gg 2\ \nu_\tau^{\text{astro}}$ in the data
- Challenge: Grow N_{ν_τ} but keep N_{bkgd} low
  - Exclusive analysis: Look for double pulse waveforms, correlations across modules & strings,…
    - $L_\tau \sim 10-50$ m to distinguish two showers in individual module light-arrival waveforms
      - Identify DPs in one or more modules
      - Lower E_ν threshold increases event count: $\phi_\nu^{\text{astro.}} \propto E_\nu^{-2.x}$
    - Previous IceCube analyses
      - Look for 1–2 modules with waveform(s) having clean DP signature(s)
      - Candidate ν_τ seen, but need higher S/N

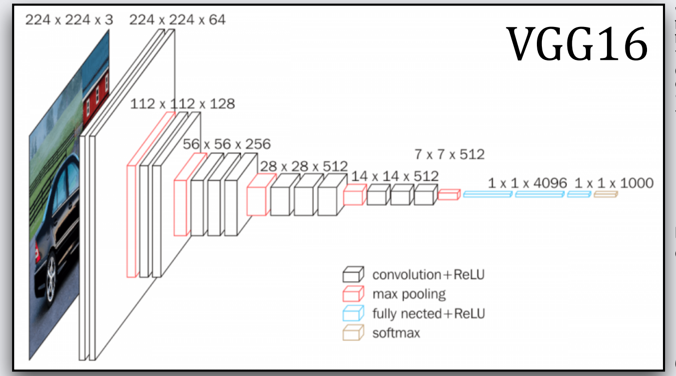
ν_τ^{astro}: New Approach

- With standard ν oscillations, expect $\gg 2\ \nu_\tau^{\text{astro}}$ in the data
- Challenge: Grow N_{ν_τ} but keep N_{bkgd} low
  - Exclusive analysis: Look for double pulse waveforms, correlations across modules & strings,…
    - $L_\tau \sim 10\text{–}50$ m to distinguish two showers in individual module light-arrival waveforms
      - Identify DPs in one or more modules
      - Lower E_ν threshold increases event count: $\phi_\nu^{\text{astro.}} \propto E_\nu^{-2}$
    - Current analysis
      - Look for DP signatures across 180 modules on 3 strings using neural networks
      - High S/N achieved…

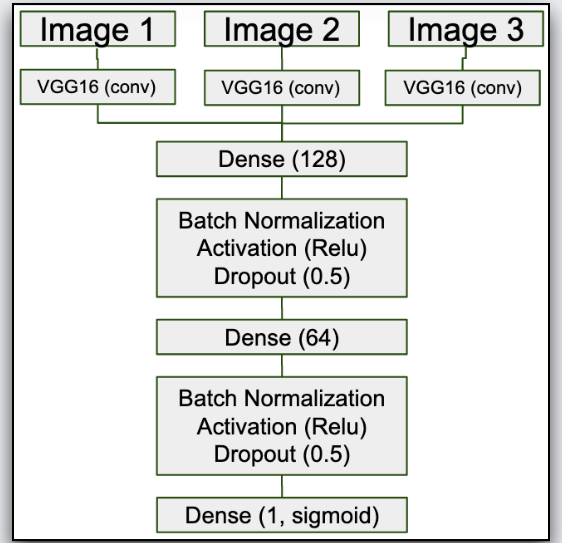
ν_τ^{astro}: Convolutional Neural Networks

- ν_τ DP with up to 180 modules
  - Create 2d images, one per string
- Train convolutional neural network (CNN) to find signal and reject background





Simonyan & Zisserman, 1409.1556

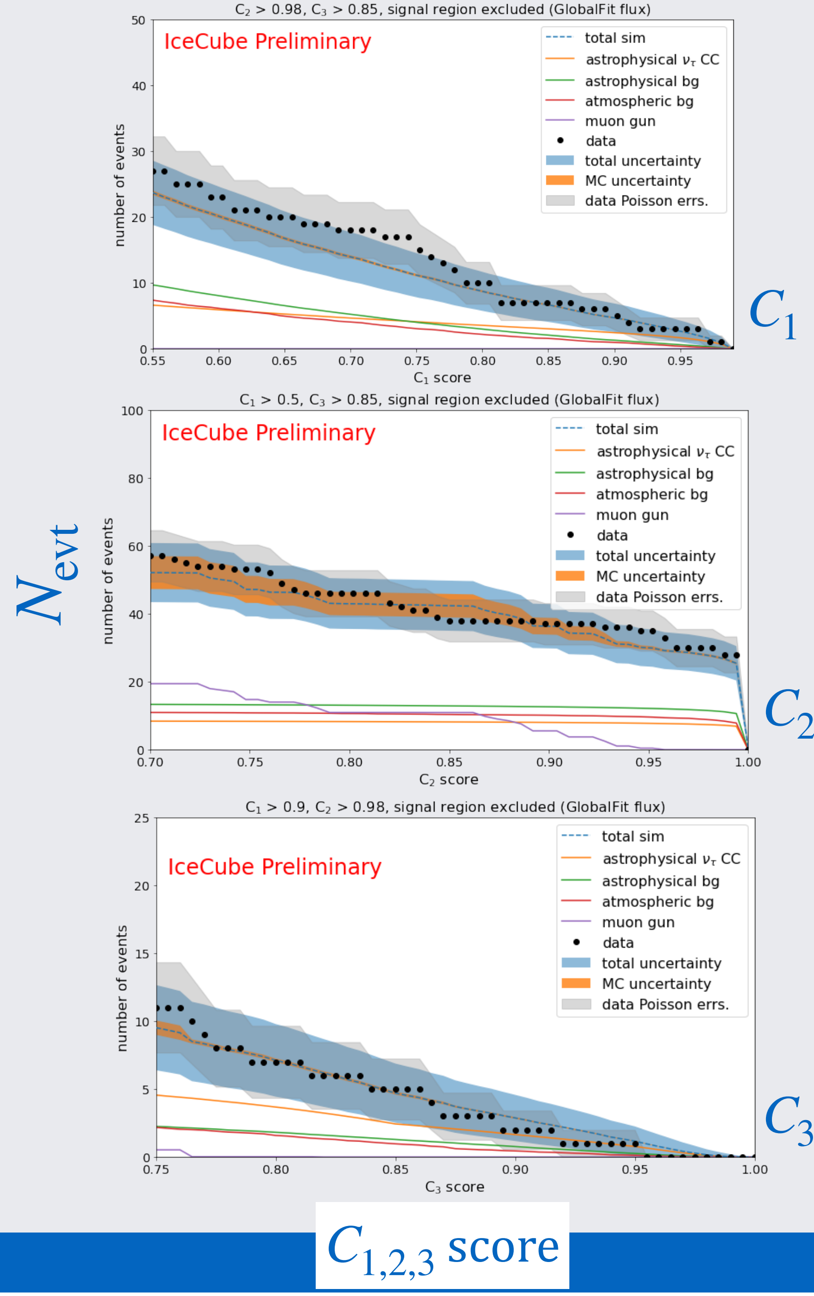


3 × VGG16'

ν_τ^{astro}: Convolutional Neural Networks

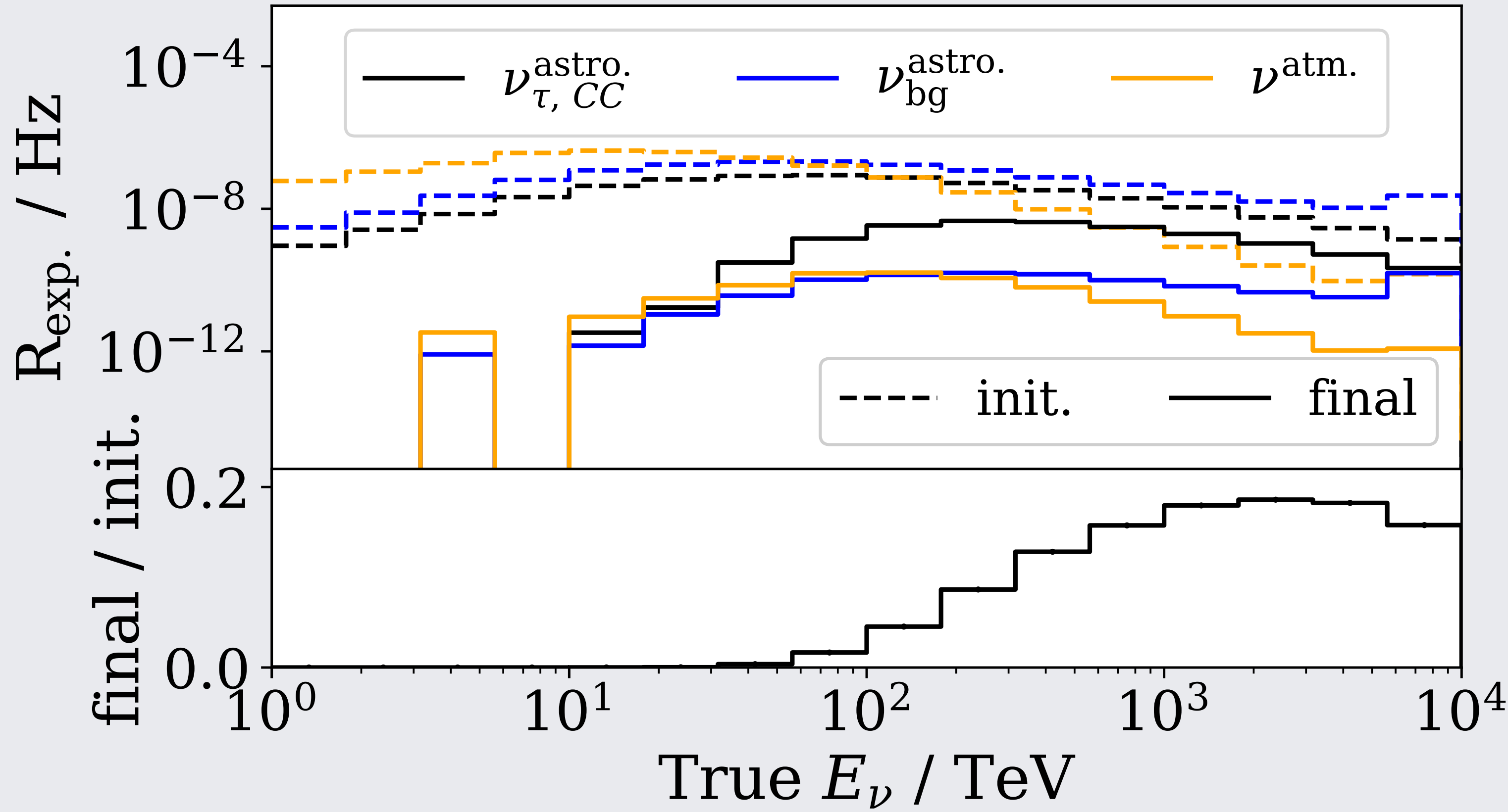
- Trained 3 independent CNNs
  - C_1: DP vs. SP (ν_τ^{CC} vs. ν_e^{CC}, ν_x^{NC})
  - C_2: DP vs track (ν_τ^{CC} vs. $\mu_\downarrow$)
  - C_3: DP vs Track (ν_τ^{CC} vs. ν_μ^{CC})
- $C_1 \geq 0.99,\ C_2 \geq 0.98,\ C_3 \geq 0.85$
  - Gives S/N ~ 14.
- Backgrounds
  - Dominant: $\nu_{\text{astro.}}$ and $\nu_{\text{atm.}}$
  - Sub-dominant: $\mu_\downarrow$
- 3 separate CNNs worked better than 1 all-purpose CNN

Cumulative rate; signal region excluded



ν_τ^{astro}: Predicted Energy Spectrum

- E_{ν_τ} spectrum:



- After final cuts, peaks at ~200 TeV
  - Lower E_{ν_τ} threshold translates to higher N_{ν_τ}
  - Peak signal efficiency at several PeV, but flux there is v. low

$\nu_{\tau}^{\text{astro}}$: Signal & Backgrounds

- Expected 4–8 ν_τ on a bkgd. of ~0.5 with 9.7 years of data
  - (S,B) levels depend on assumed astrophys. flux
  - Flavor ratio at Earth assumed to be 1:1:1
- What about the backgrounds?
  - ν^{astro}
    - IceCube has four flux measurements
    - Use one with least-significant exclusion of null hypothesis
  - ν^{atm}
    - Conventional flux (Honda et al.; IceCube msmts.)
    - Possible prompt flux (Bhattacharya et al.; IceCube exclusion)
  - Other:
    - Charm, cosmic ray muons, on-shell W, Earth-crossing $\nu_e, \nu_\mu \rightarrow \nu_\tau$

ν_τ^{astro}: Charm Background

- Backgrounds/Systematics in more detail: Charm
  - Charm: $\nu_e^{\text{astro}} \to eW;\ W \to cs$
    - $\lambda_{\text{charm}} \simeq \mathcal{O}(\text{m}), E_{\text{dep.}} \simeq 10^{12-14}$ eV
    - Two separated cascades: e + second shower if have large $(\lambda_{\text{charm}}, E_{\text{dep.}})$
    - Full charm MC: ~20% increase in ν_e^{astro} bkgd.
      - Small correction to account for MC's older PDFs
    - Added to estimated background *after unblinding*
      - (Future improvement: Charm event topology may be sufficiently different from ν_τ that new CNN could reject.)

$\nu_\tau^{\rm astro}$: Other Backgrounds/Systematics

- Backgrounds/Systematics, cont'd:
  - $\mu_\downarrow, \mu_{\rm DIS}$ $(\mu + X \to \nu_\mu + X')$: considerably smaller than $\nu^{\rm astro}$
  - Other physics processes determined to be sub-dominant:
    - On-shell W production $(\nu_e \to eW;\ \ W \to \tau\nu_\tau;\ \ \tau \to (e, h))$*
    - High-energy Earth-crossing $\nu_e, \nu_\mu \to \nu_\tau$**
  - Detector-related systematics all found to be small. Checked uncertainties in:
    - bulk ice scattering & absorption
    - hole ice scattering & absorption
    - DOM efficiencies

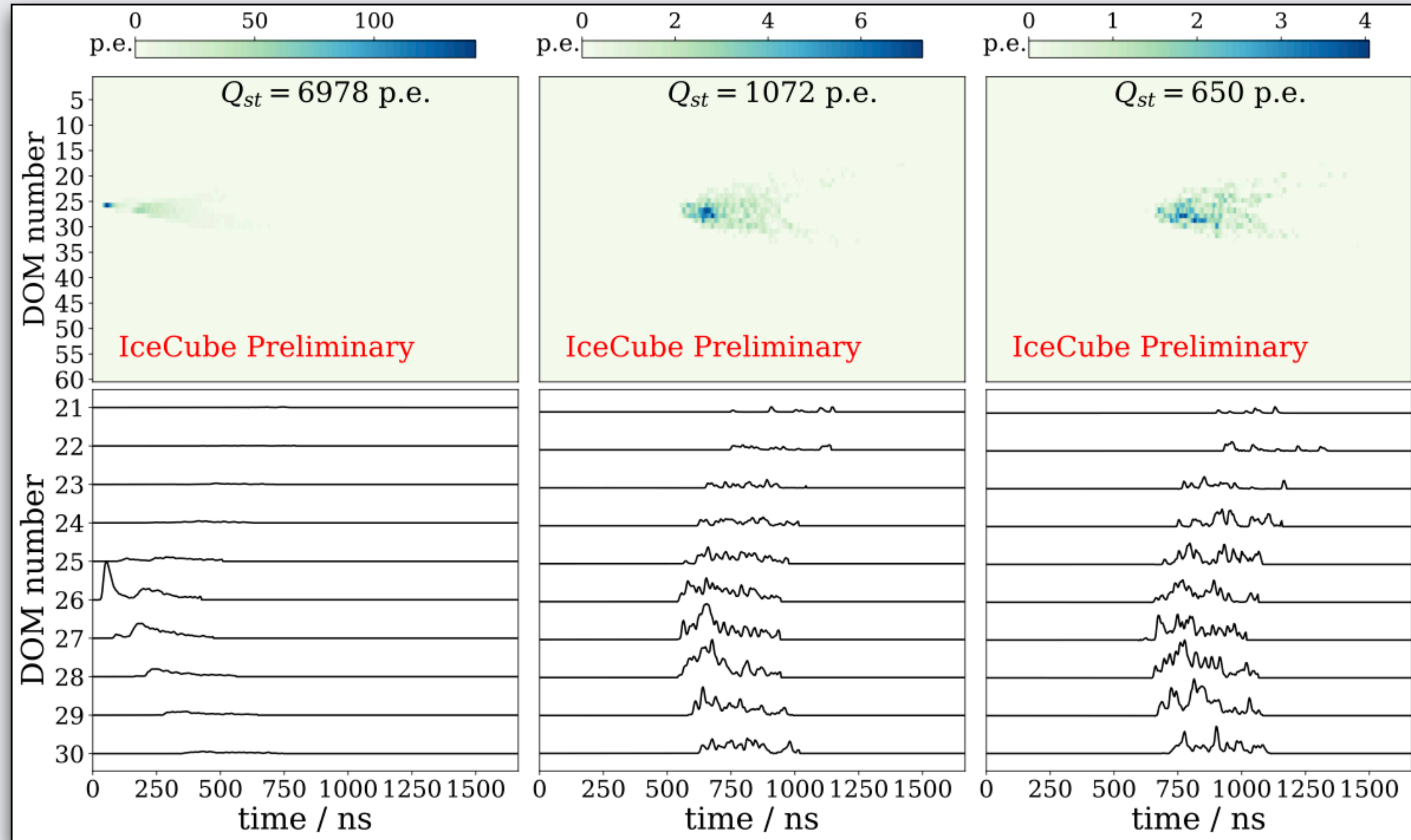
*B. Zhou and J.F. Beacom, PRD 101, 036010 (2020)
**A. G. Soto et al., PRL 128, 171101 (2022)

ν_τ^{astro}: Results

- Saw 7 candidate ν_τ^{astro} events
  - ~0.5 events estimated total background
  - 4 of 7 candidates not selected by previous analyses
  - 3 of 7 candidates previously selected
    - 1 of which was identified as a ν_τ candidate
  - $\Phi(\nu_\tau^{\text{astro}})$ consistent with measured $\Phi(\nu^{\text{astro}})$ from published analyses
    - $(\phi_0, \gamma) = [(2.23, 2.5),\ (1.36, 2.37),\ (2.12, 2.87),\ (2.04, 2.62)]$ (GlobalFit, Diffuse, HESE and Inelasticity, respectively)
- Exclusion of $\Phi(\nu_\tau^{\text{astro}}) = 0$ will be reported soon.
  - Pre-unblinding, predicted ~50% chance of ~5σ result.

ν_τ^{astro} Candidate Event Pics

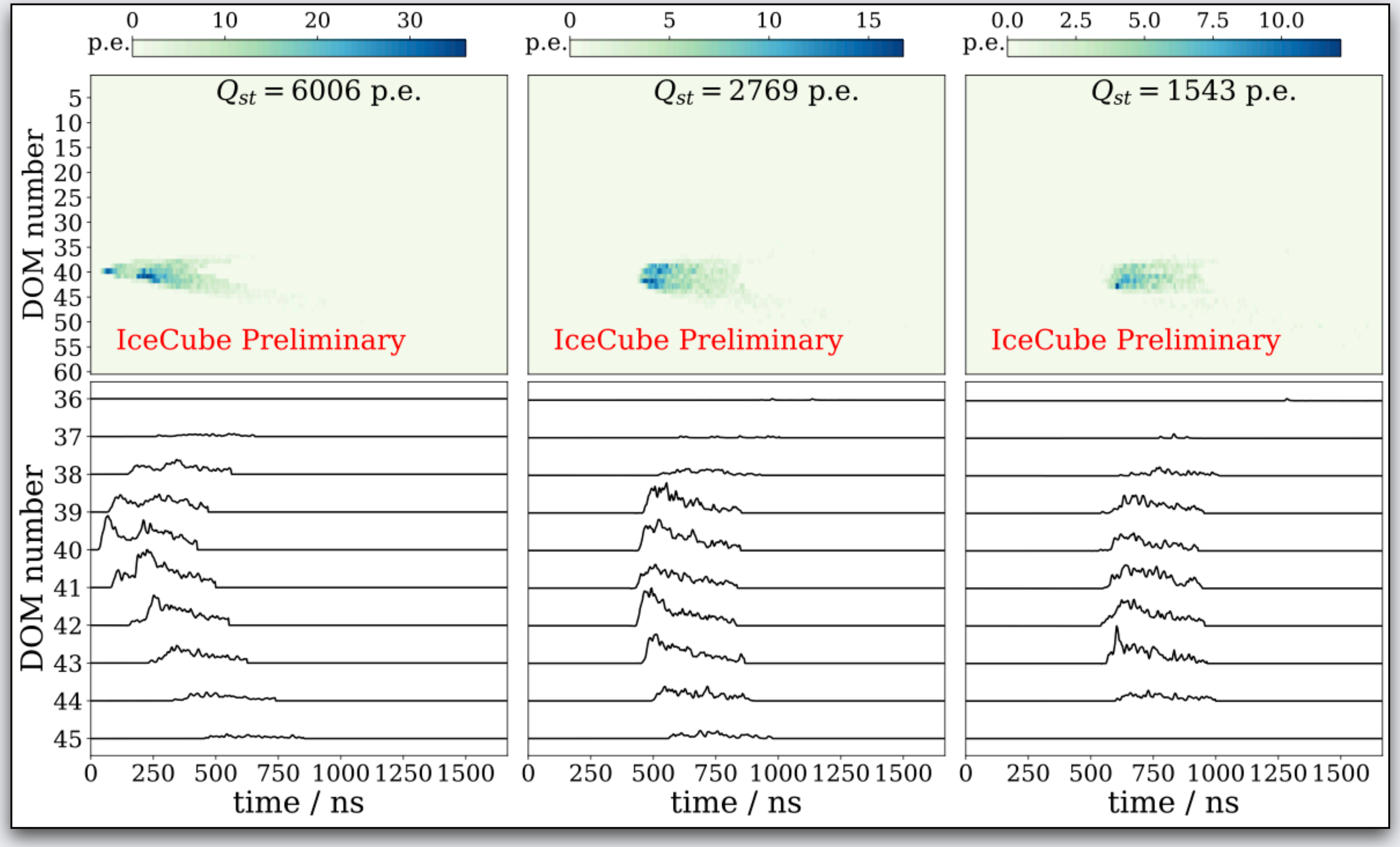
Here's "Double Double," an old event & prior ν_τ candidate:



Gratifying to find this event again.

ν_τ^{astro} Candidate Event Pics

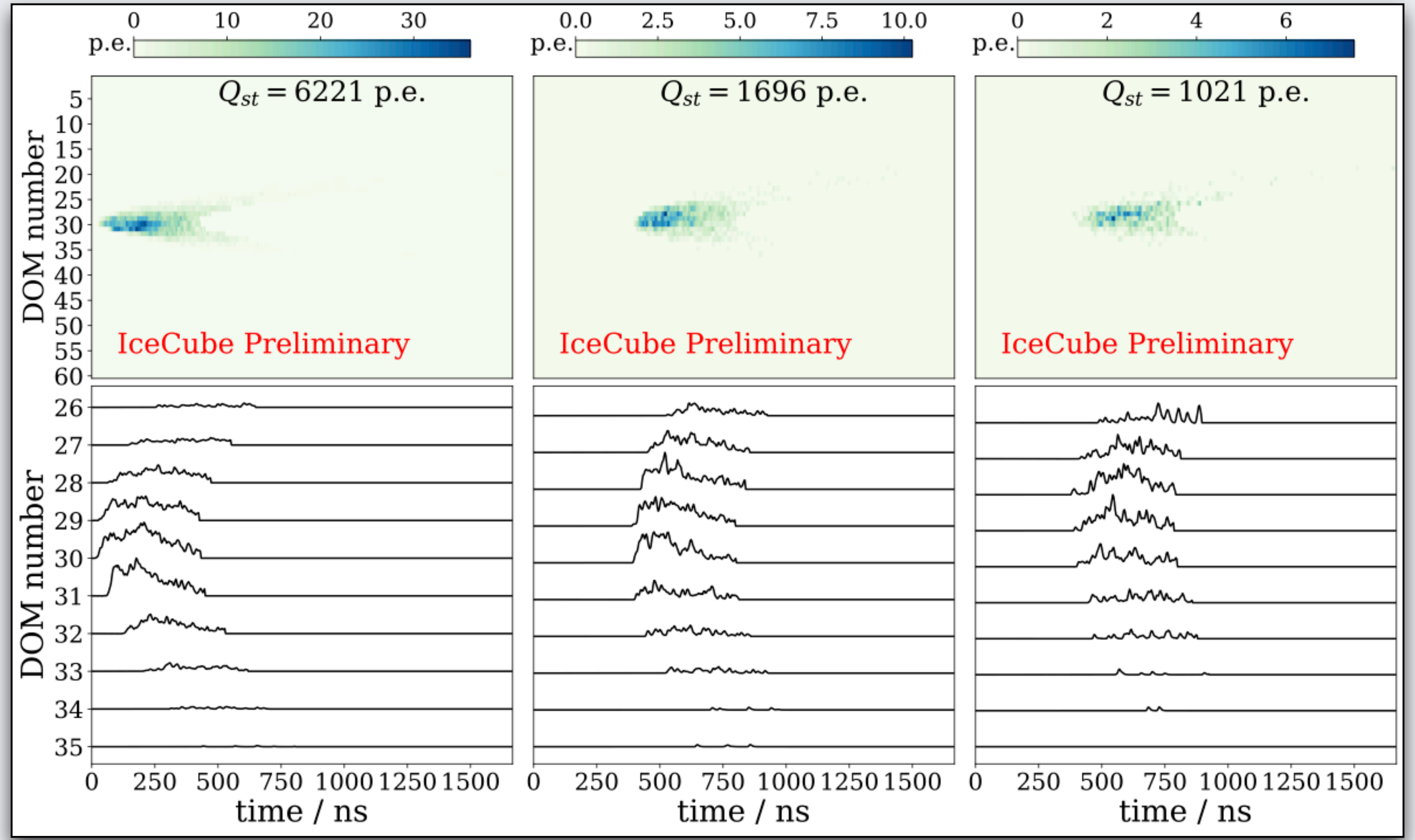
Here's "Scarlet Macaw," a new event:



Clear ν_τ signature. Detected in 2019 (too recent for previous analyses to have seen).

ν_τ^{astro} Candidate Event Pics

And here's "Estragon," an old event revealed as a ν_τ candidate:



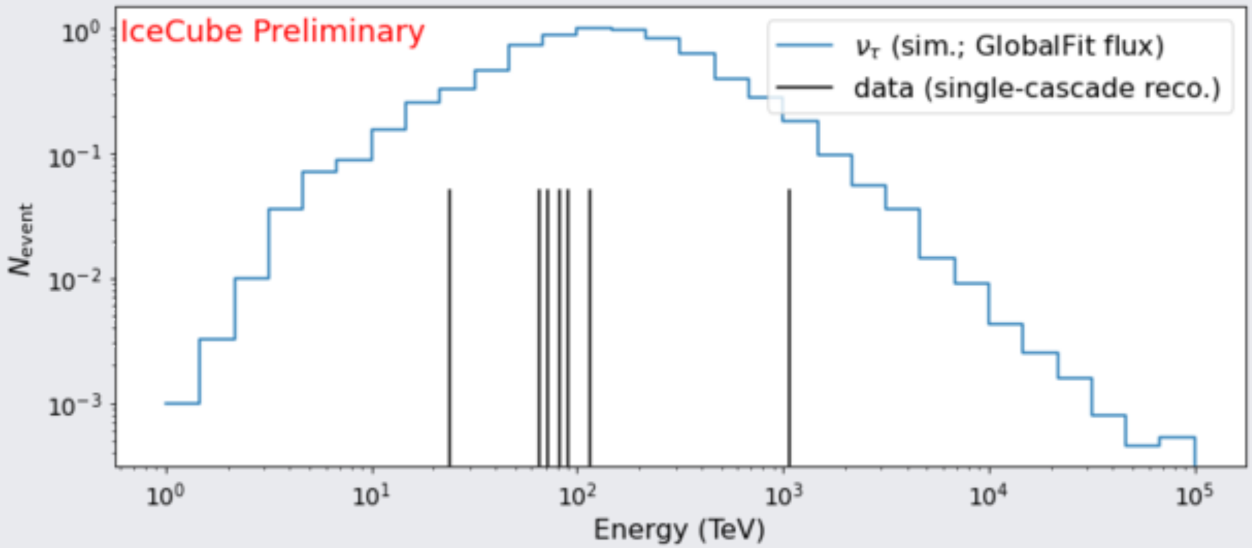
The ν_τ signature is spread out over multiple modules and strings.

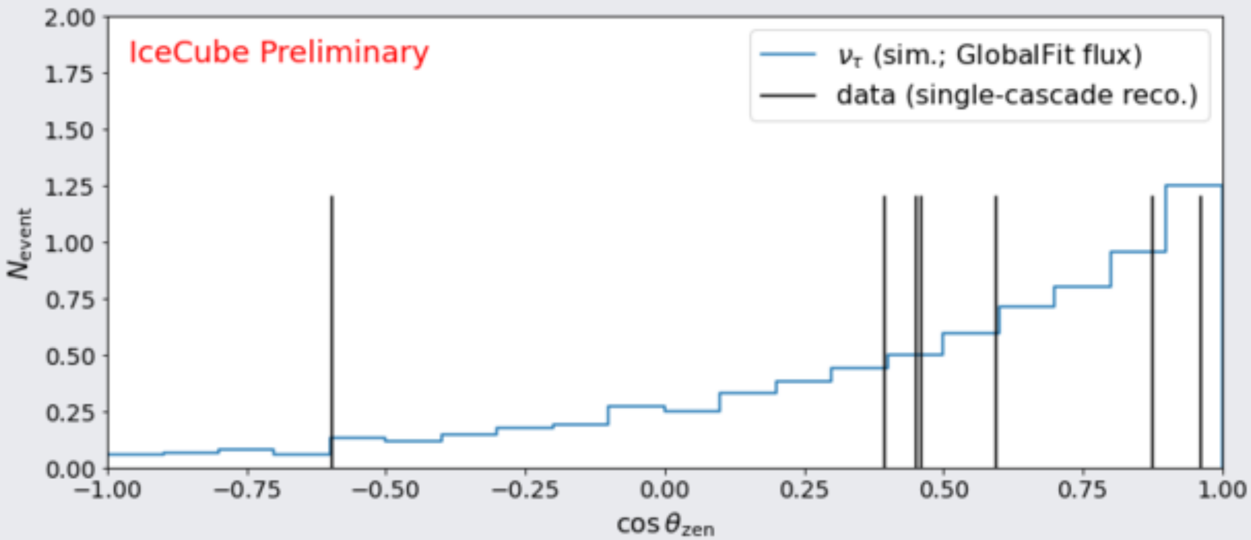
ν_τ^{astro}: Post-Unblinding Checks

- Explicit reconstruction of $(x, y, z, E, \theta, \phi)$ not part of the analysis
  - Do not (yet) have a reco. tuned for such ν_τ
    - Would have added considerable delay and complexity
    - Would have increased susceptibility to systematic uncertainties of, e.g., ice properties
- Here we checked candidate ν_τ w/existing reco.
  - Reco. was tuned for *single-pulse* events (e.g., ν_e)

ν_τ^{astro}: Post-Unblinding Checks

- Apply single-pulse reco. to
  - simulated ν_τ
  - candidate ν_τ
- Reasonably good agreement…
  - …but take actual numbers with a *big* grain of salt



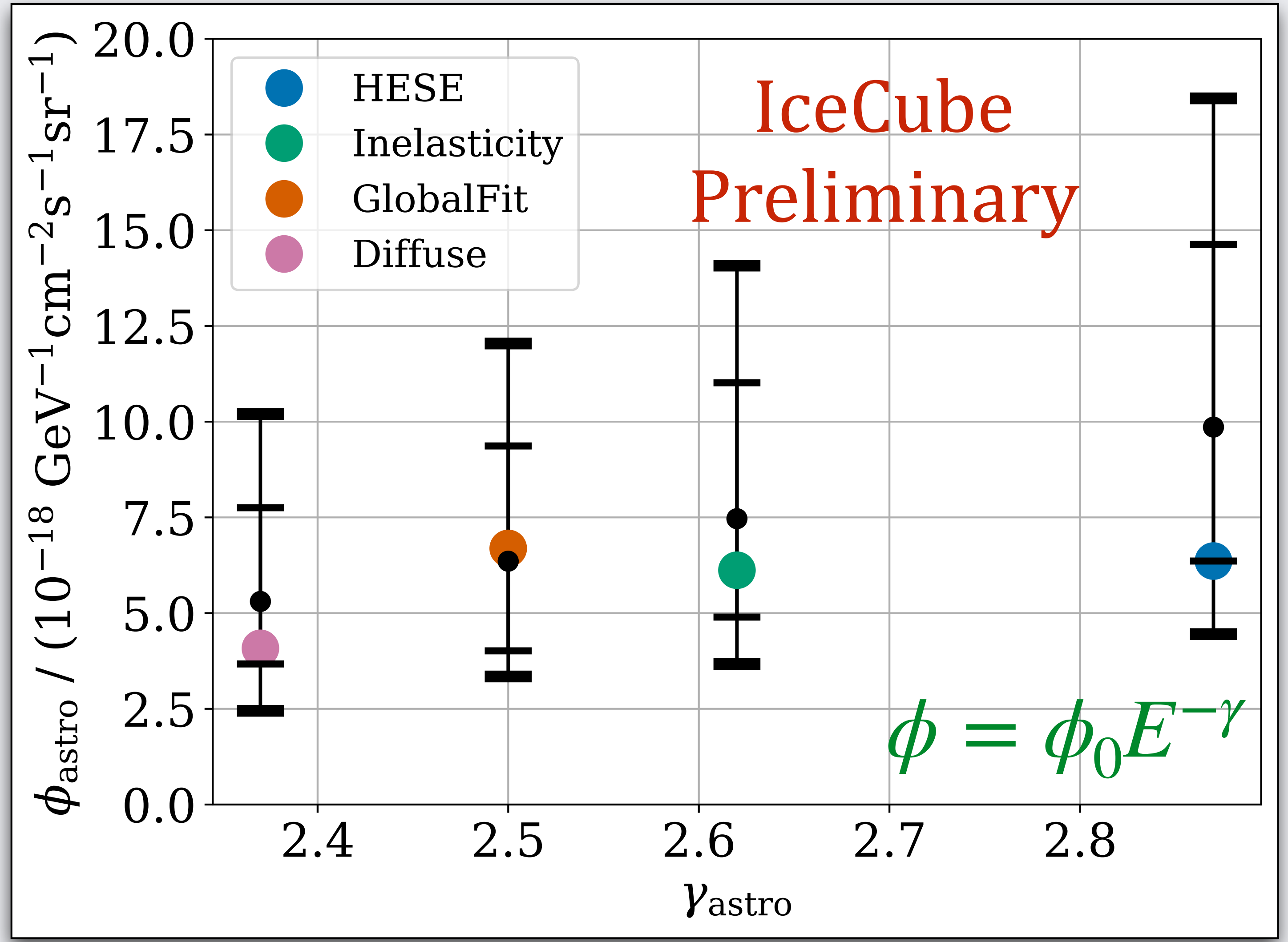


Fitted ν_τ Fluxes

With just 7 candidate ν_τ^{astro}, we fix γ and fit for ϕ_0:

Excellent agreement with previous four IceCube measurements.

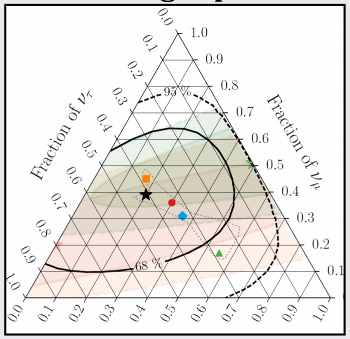
Diffuse ν_τ consistent with other flavors.



What's Next for ν_τ^{astro} ?

- Used just 3 (of 86) strings for CNNs. Using more strings may:
  - Improve bkgd rejection → relax cuts → more signal
    - Improve current ν_τ^{astro} flux measurement
- Will update "triangle plot" with ν_τ information
    - Search for new physics (e.g., quantum gravity)
    - ID likely astrophysical-source acceleration scenarios
      - exclude some?

Triangle plot



Contours will shrink

- Apply a dedicated reco. for ν_τ direction, E_{ν_τ},...
  - Use high-astrophysical-purity ν_τ to look for point sources
    - Can run neural networks in real time; generate alerts
  - Study parameters of the ν_τ themselves
    - L_τ, energy asymmetry, ...

Summary

- Diffuse ν_x^{astro}, first detected nearly a decade ago,
  - birthed high-E_ν astronomy
  - is consistent with single power law spectrum
- We can expect tighter constraints on (ϕ, γ) with improved techniques, more data and more detectors (e.g., ARCA)
- Together, diffuse & point source detections can
  - unveil astrophysical source environments
  - reveal new physics
- ν_τ can provide powerful constraints
  - astrophysical source characterization
  - cosmic baseline neutrino oscillations
- New ν_τ analysis successfully increased statistics
  - use to better constrain triangle plot, search for new physics
  - further analysis improvements in the works

IceCube Collaboration

Spring 2022 Collaboration Meeting, Brussels, Belgium