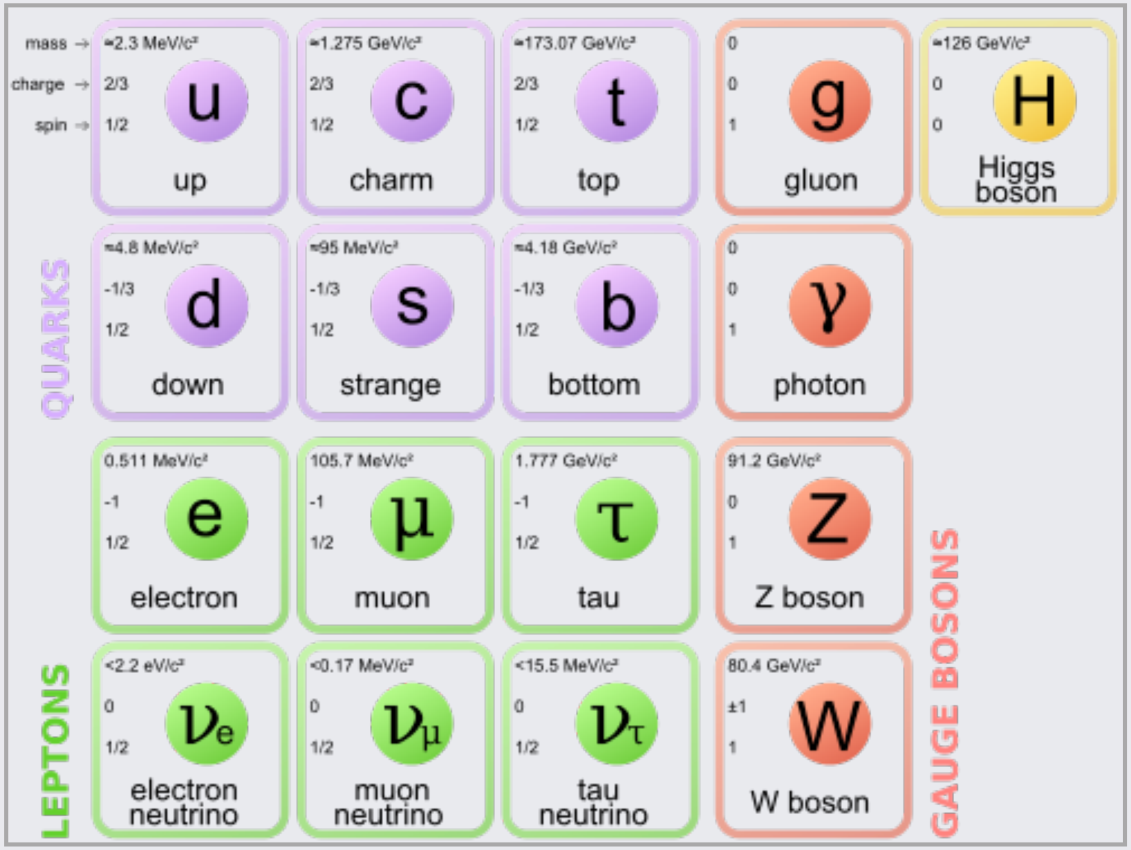
Astrophysical Tau Neutrinos

The first high-significance measurement of the highest-energy tau neutrino candidates ever observed

Doug Cowen
Penn State

Neutrinos: The Basics

- Fundamental
- Light
- Ubiquitous
- Apparently stable
- Tri-flavored
- Penetrating



graphic: wikipedia

The large m_τ suppresses direct ν_τ production.

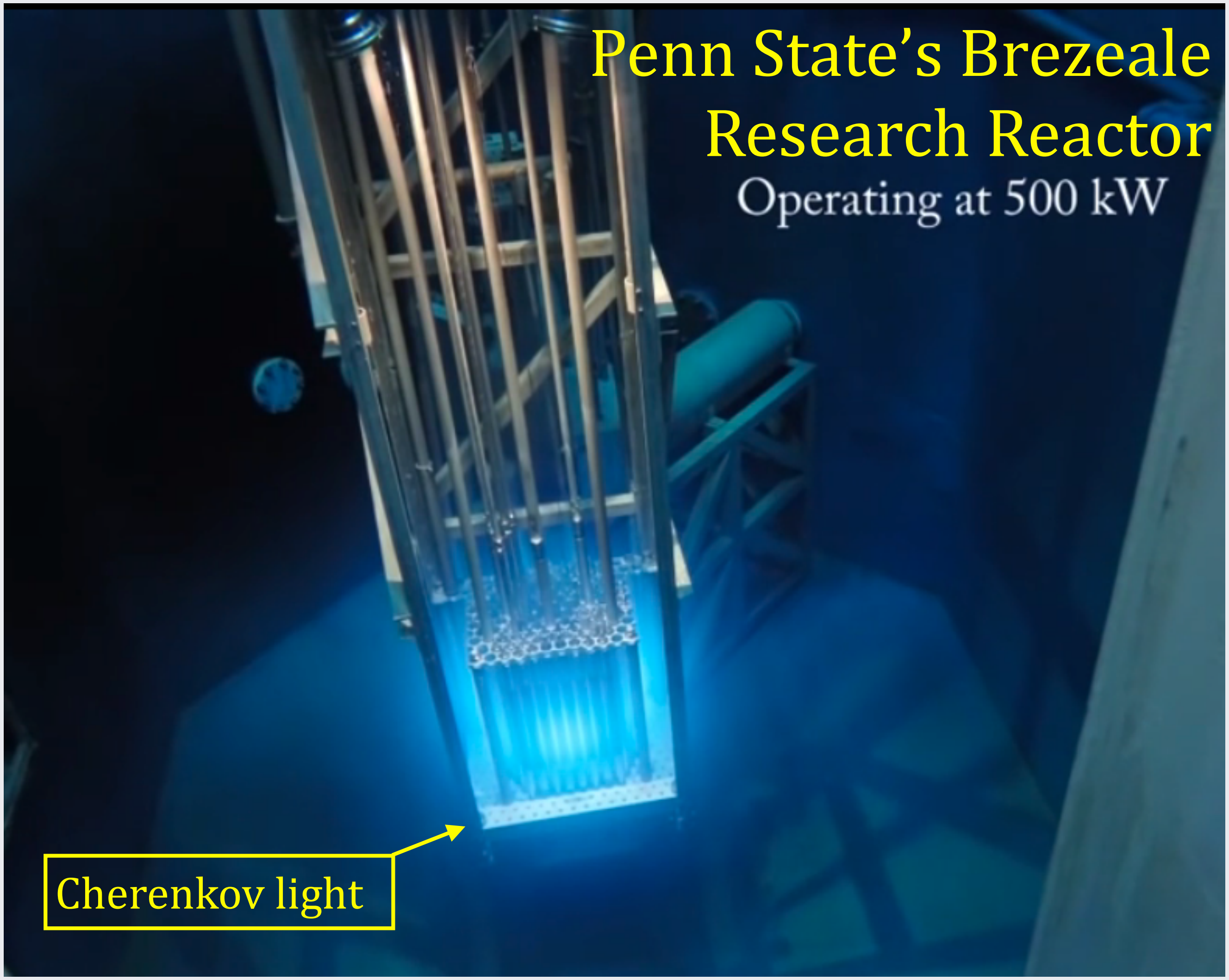
ν_τ are even harder to see than your average super-shy neutrino.

ν_τ mainly arise due to neutrino oscillations.

Detecting Neutrinos: Cherenkov Light

When a charged particle moves faster than light in a medium, it emits Cherenkov light.

Electromagnetic equivalent of a sonic boom.

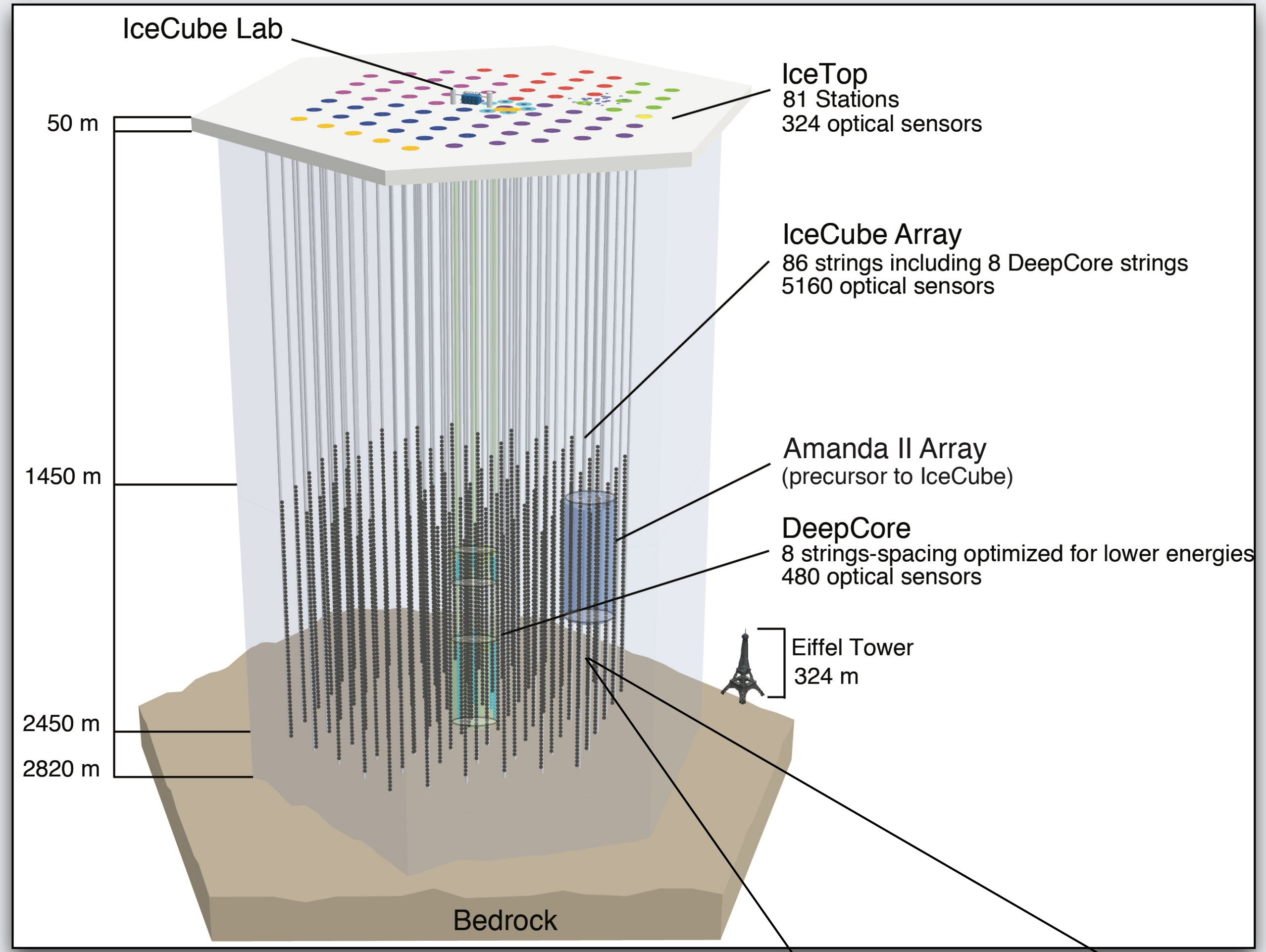


This is the operating principle of many real-time neutrino detectors.

Detecting Neutrinos with IceCube

- IceCube built in 2010 to map the neutrino sky at $E_\nu \sim 1$ TeV
  - ✓ Find astrophysical ν
  - ✓✓✓ Find astrophysical ν sources
  - ✓ Help solve mystery of ultrahigh energy cosmic rays
    - $E_{CR} \sim 10^{21}$ eV exist!
- Enhanced with more densely instrumented core region for DM and atm. ν osc. studies

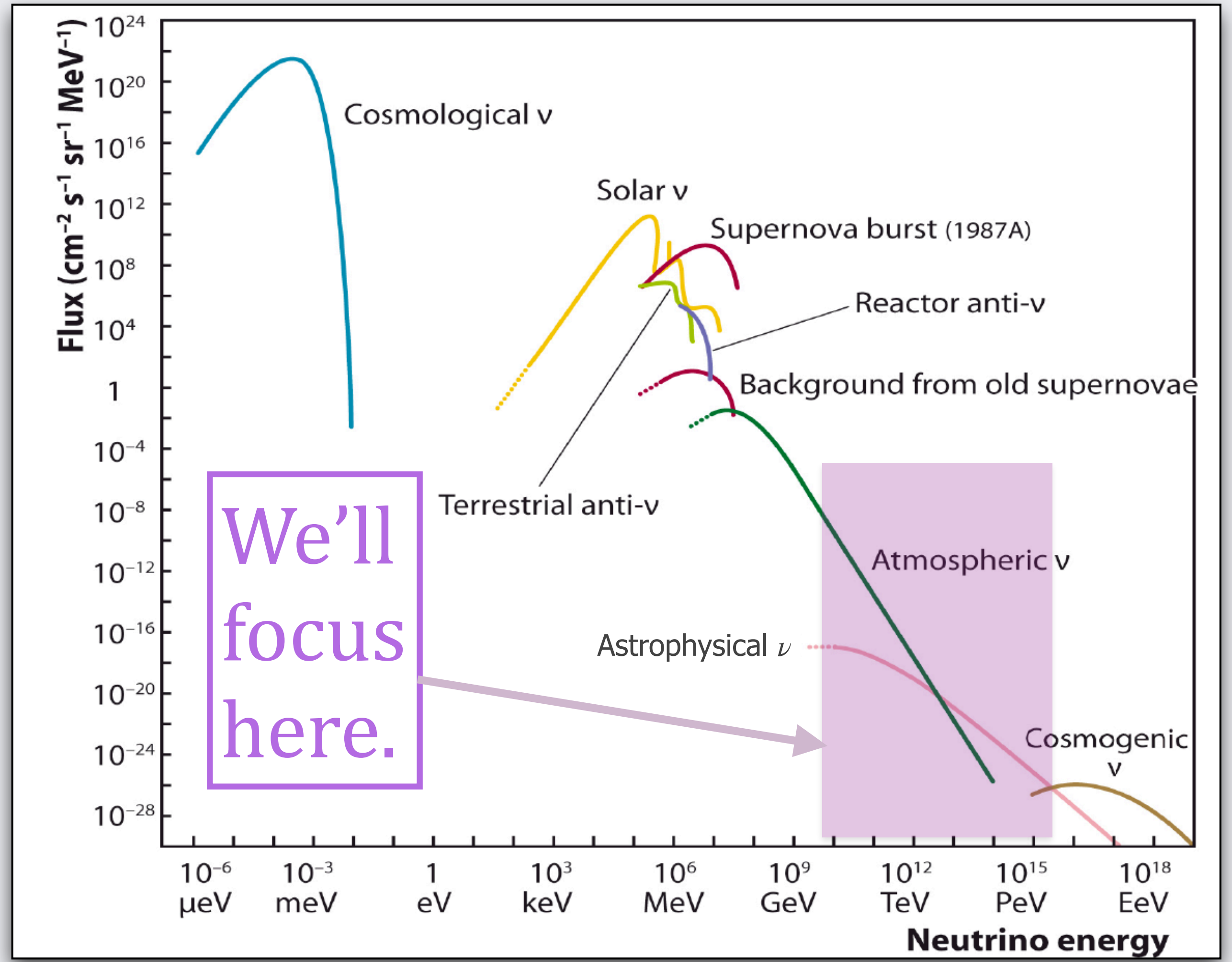
Module being lowered into melted hole.



Digital Optical Module (DOM)

Neutrinos in IceCube

Many possible neutrino sources:



The challenge (in numbers, 10 yrs):

- $\sim 10^{12}$ triggers ($\mu_{\downarrow}$)
- $\sim 10^{6}$ ν_{atm}
- $\sim 10^{2}$ ν_{astro}

Neutrinos in IceCube: Sources

- Atmospheric neutrinos
  - cosmic rays (e.g., protons) interact in the earth's atmosphere
  - resulting particle showers include ν's
  - See at ~1 GeV < E_ν < ~1 TeV in IceCube ($E_\nu \approx 10^{9-12}$ eV)

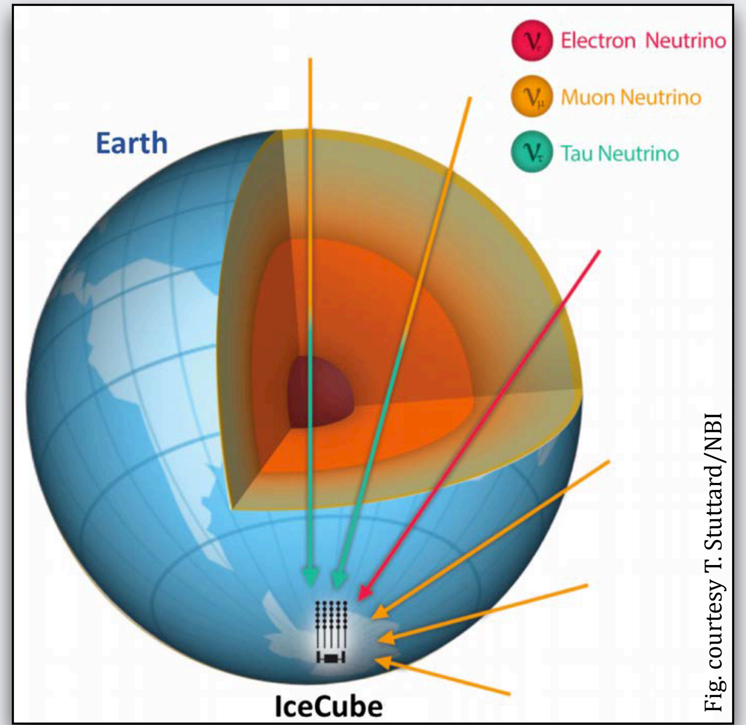
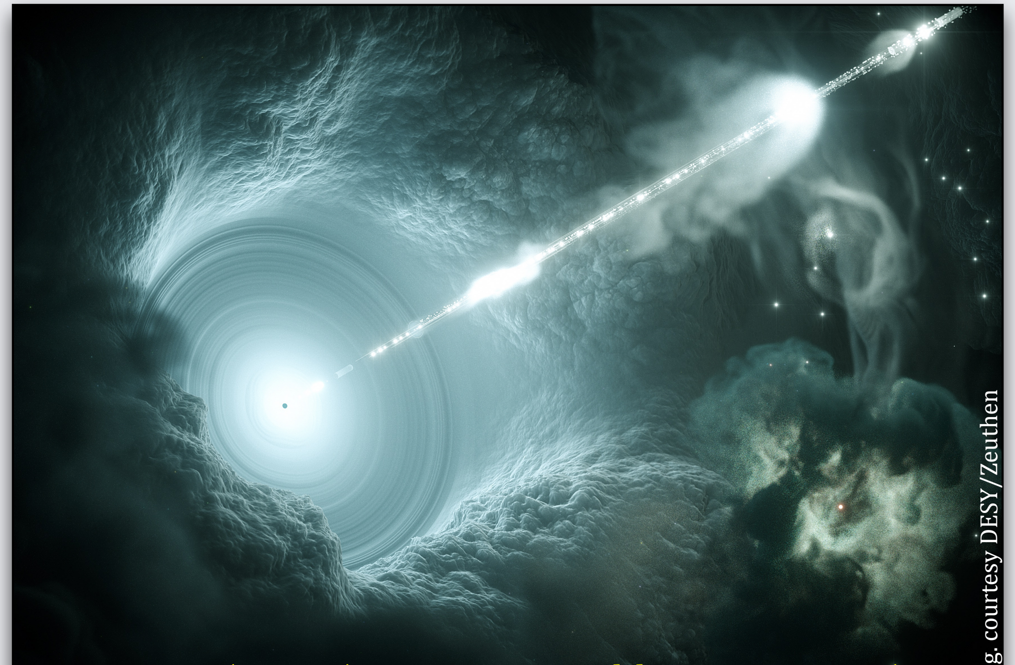


Fig. courtesy T. Stuttard/NBI

- Astrophysical high energy neutrinos
  - created in cosmic accelerators, e.g., in particle jets created by black holes
  - Evident at $E_\nu > \sim 50$ TeV in IceCube
    - Also seen: PeV-scale (10^{15} eV) ν's



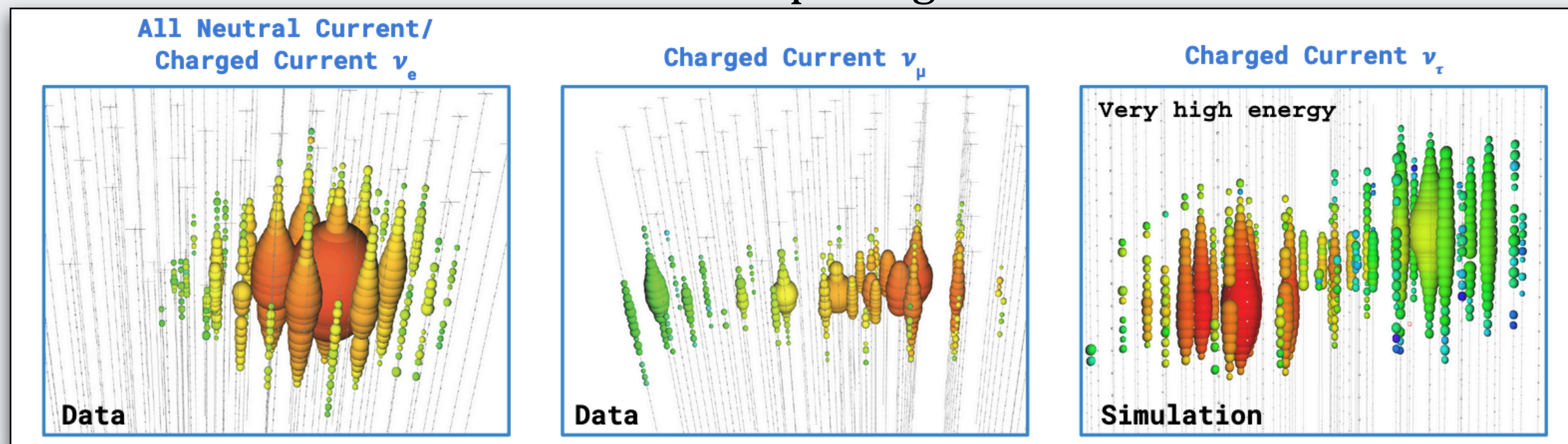
TXS 0506+056: BL Lac-type blazar, z=0.3365

Fig. courtesy DESY/Zeuthen

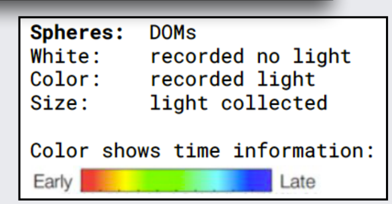
ν^{astro} in IceCube

- Motivations:
  - Study ν properties at highest E_ν and longest baselines
  - Uncover source production mechanism(s)
  - Gain sensitivity to new physics

Event morphologies

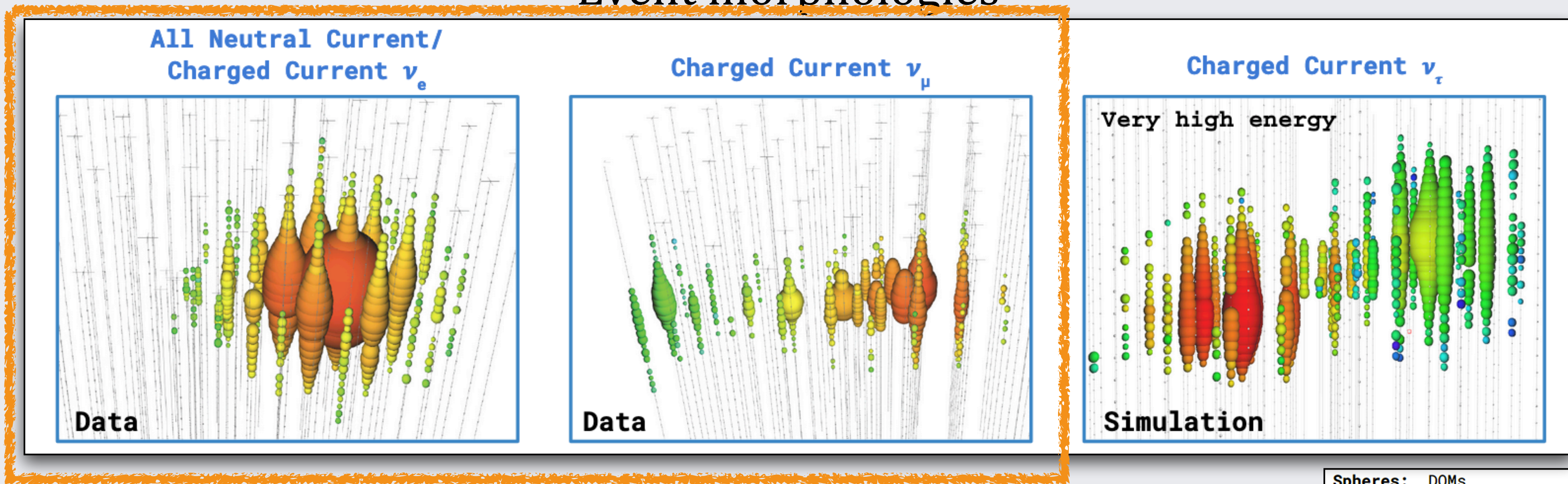


At higher energies, neutrino flavors can be readily distinguished—sometimes.

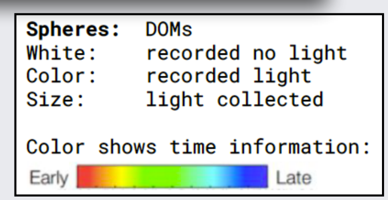


ν^{astro} in IceCube

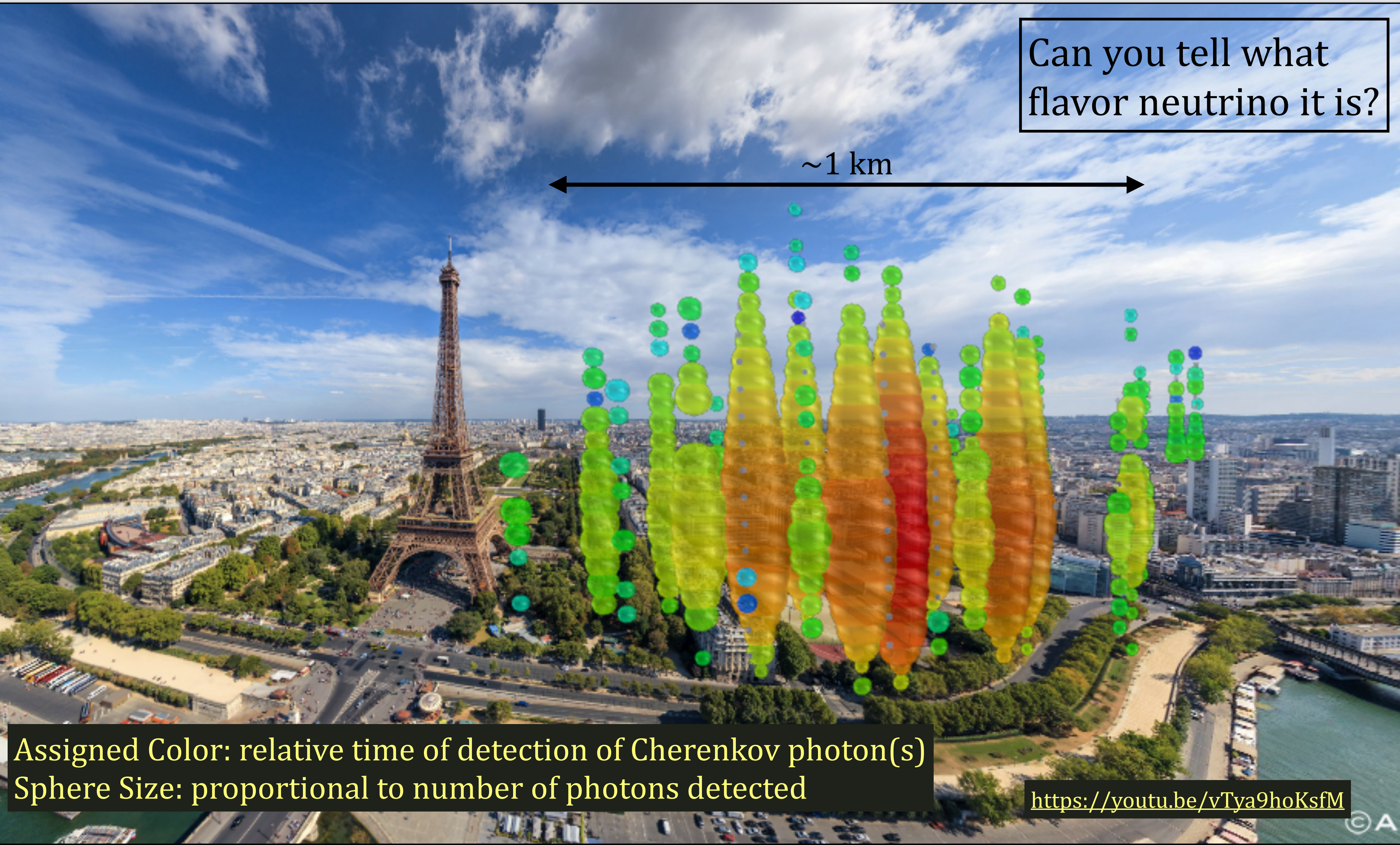
Event morphologies



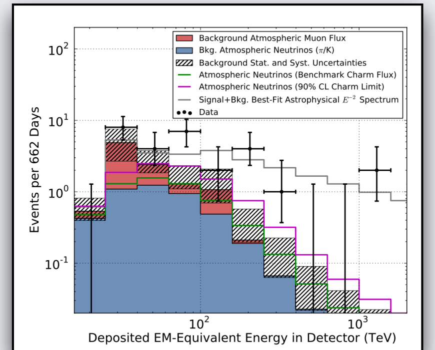
IceCube has focused on track & cascade morphologies, as $\nu_\tau^{\mathrm{astro}}$ are exceedingly challenging to distinguish.



These Events are Big

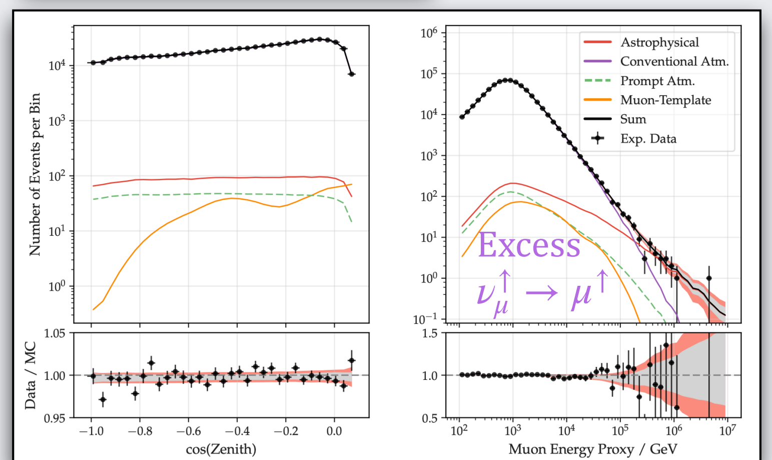


Some IceCube Discoveries



https://arxiv.org/abs/1311.5238

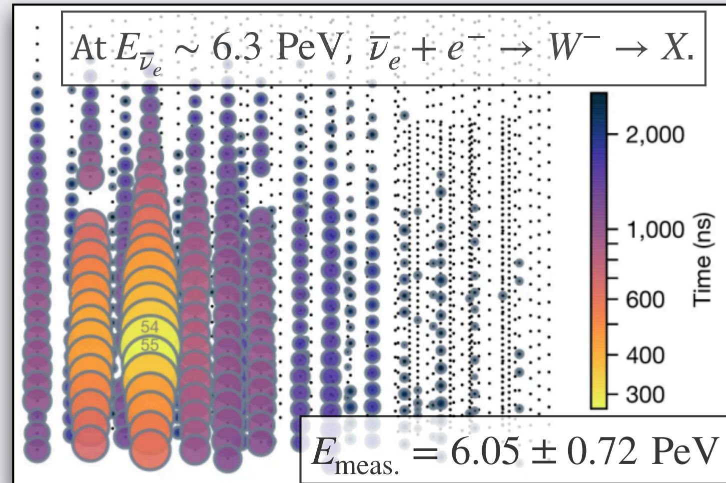
Discovery of diffuse ν^{astro}



https://arxiv.org/abs/2111.10299

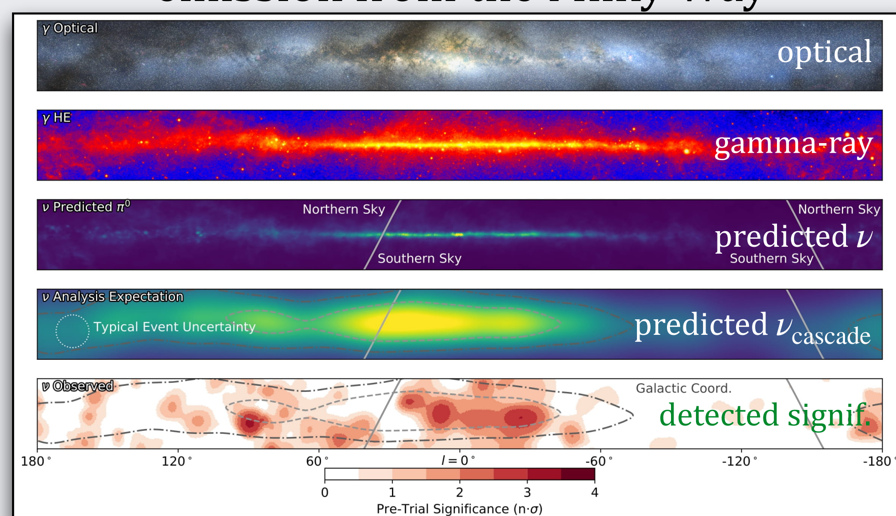
Discovery of ν^{astro} source

Evidence for Glashow Resonance



Nature 591 (2021)

Evidence for high-energy ν emission from the Milky Way



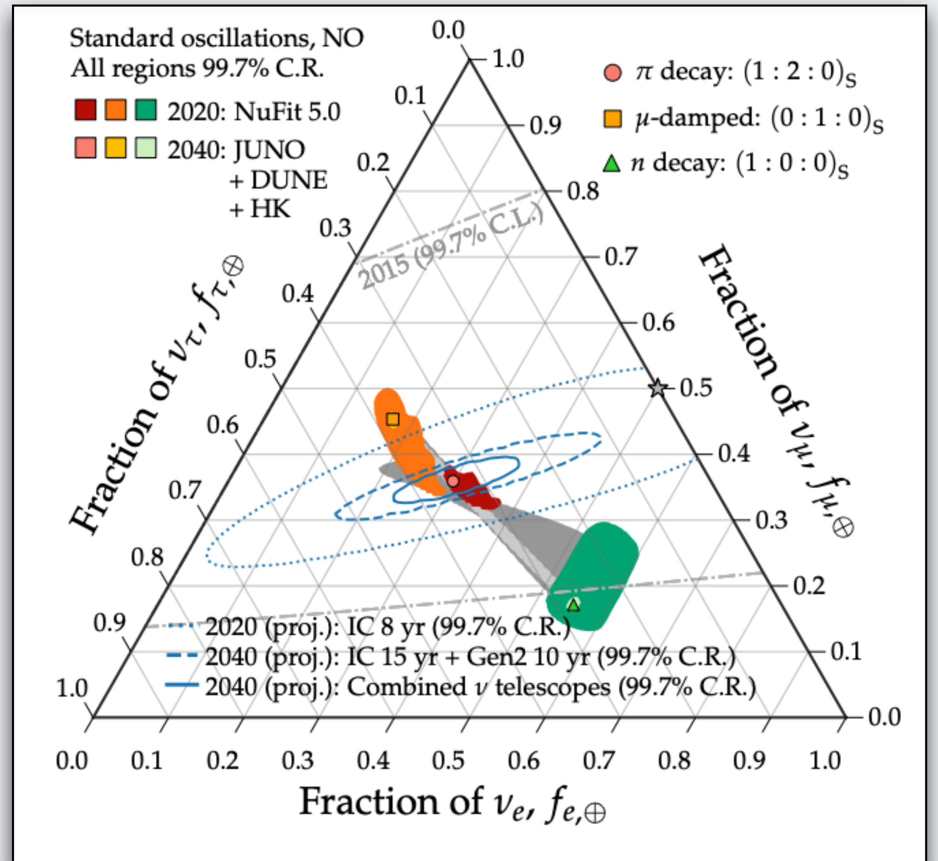
Science 380, 6652 (2023)

IceCube and Tau Neutrinos

- Standard ν oscillations:
  - Predict ~1:1:1 flavor ratio for ν^{astro}
    - Numerous ν_τ should be in IceCube data
- Flavor ratio can be *somewhat* altered by production mechanism
- Flavor ratio can be *dramatically* altered by new physics (e.g., quantum gravity)

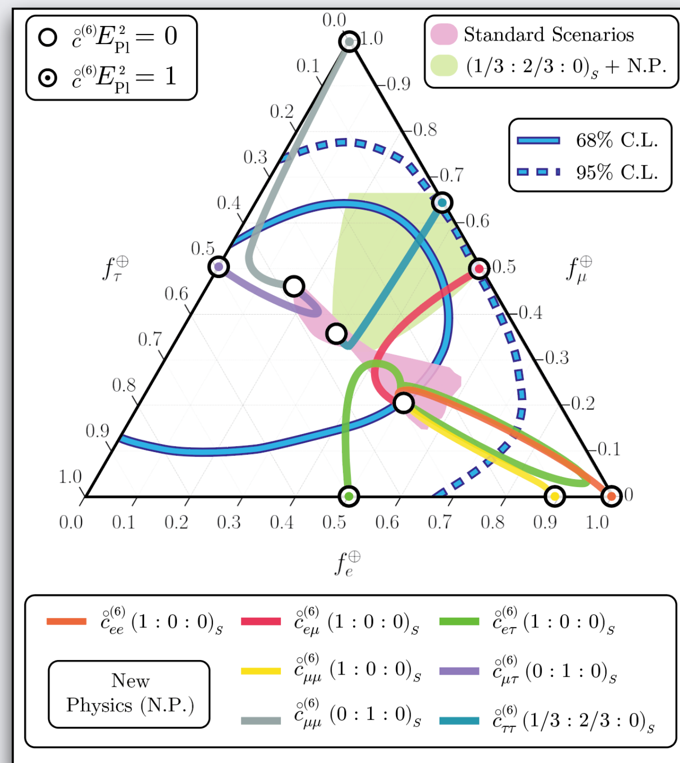
Importance of Flavor ID for ν^{astro}

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

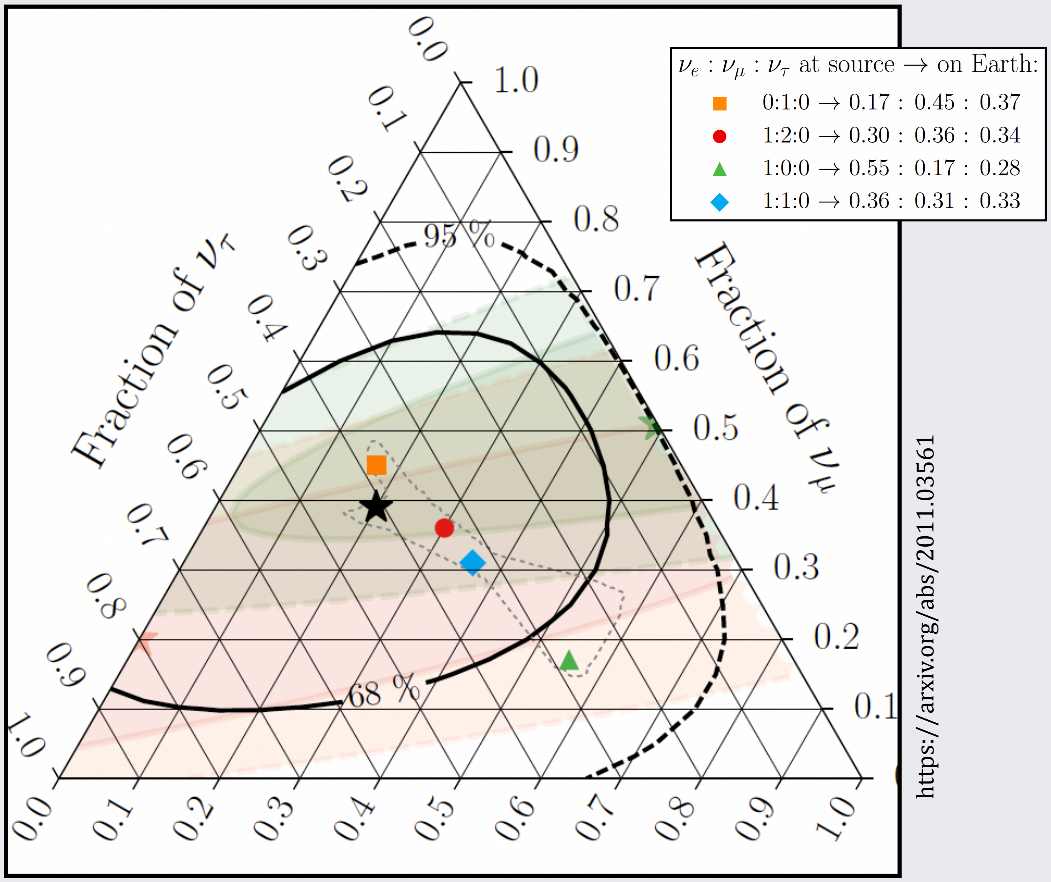


Nat. Phys. 18, 1287–1292 (2022)

Example: Effect of quantum gravity.

Importance of Flavor ID for ν^{astro}

Status quo:

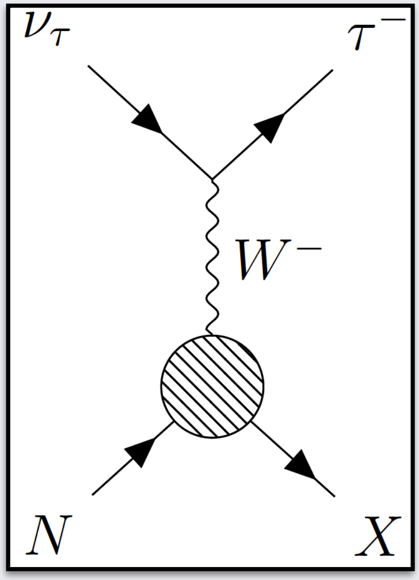


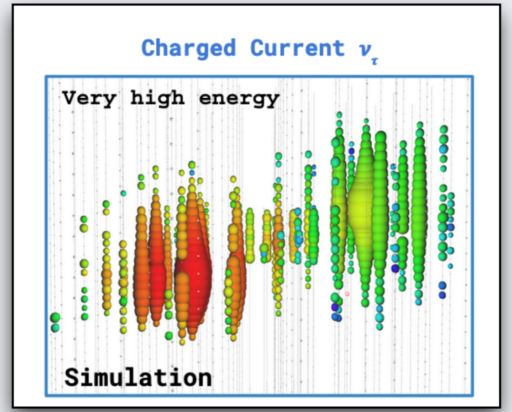
Measured flavor composition of IceCube HESE events. ★ is best fit point, consistent with presence of all 3 flavors, but ν_τ flux only weakly constrained.

To shrink the contour, need better identification of ν_τ .

Searching for Astrophysical ν_τ

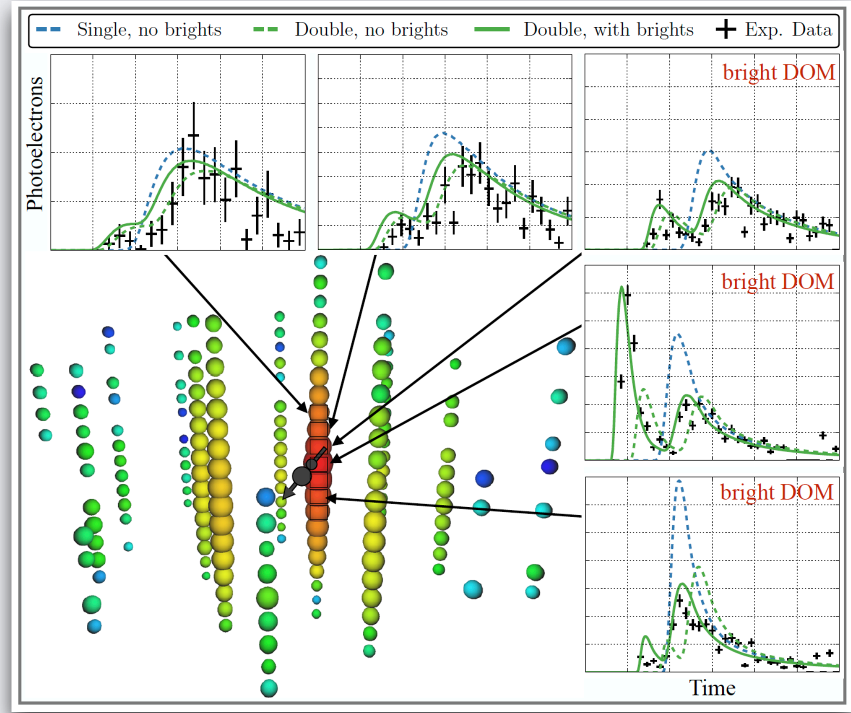
- ν_τ identification
  - Exclusive channel: "Double Bang"
    - $L_\tau > \sim 50\text{m}$ to distinguish two showers (diagram: X and $\tau \to (e, h)$)
      - But $L_\tau \simeq 50\text{m} \cdot E_\tau$ /PeV:
        - So need high energy. And favorable interaction vertex. And direction. Etc.
      - Upshot: Very limited phase space. None found yet.





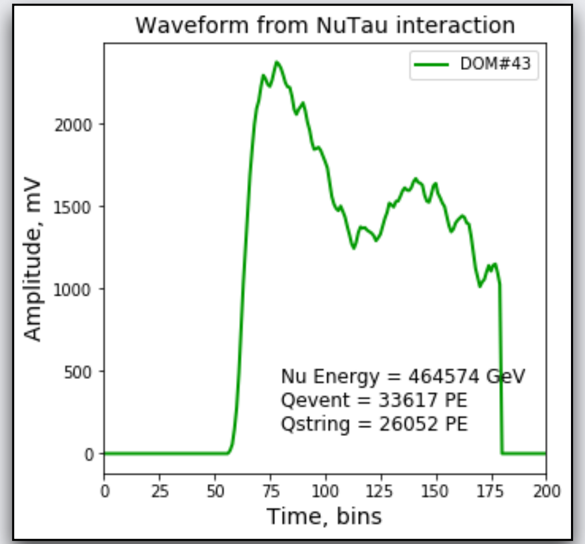
Searching for Astrophysical ν_τ

- ν_τ identification
  - Inclusive channel: "Double Cascade"
    - Classify 60 "HESE" events as single cascades, double cascades, or tracks; require high ν_τ purity with low $\nu_{e,\mu,\tau}$ mis-ID
    - Saw 41 single cascades, 2 double cascades, 17 tracks
      - One of the two double cascades ("double double") shown in figure
    - 2.8σ exclusion of null hypothesis (i.e., of no ν_τ^{astro})



Searching for Astrophysical ν_τ

- Challenge: Grow N_{ν_τ}, reduce N_{bkgd}
  - Exclusive channel: “Double Pulse” (DP)
    - $L_\tau \sim 10\text{–}50$ m to distinguish two showers in individual module light-arrival waveforms
      - Identify DPs in one or more modules
      - Decreasing E_ν increases event count: $(\phi_\nu^{\text{astro.}} \cdot \sigma_{\nu N}) \propto E_\nu^{-1}$
    - Previous IceCube analyses
      - Looked for 1–2 modules with waveforms having clean DP signatures
      - Candidate ν_τ seen, but at low S/N



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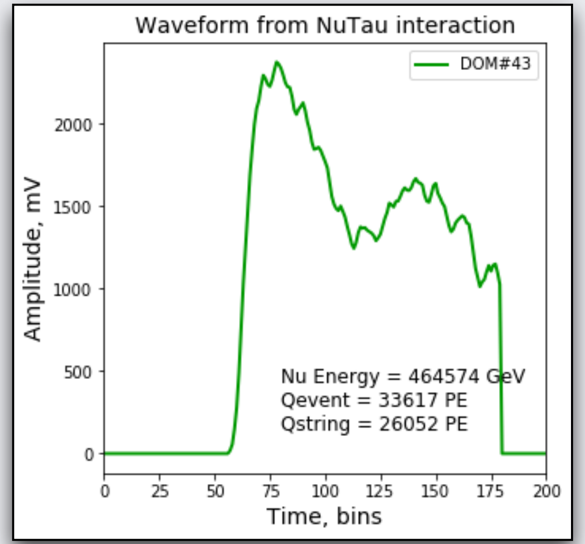
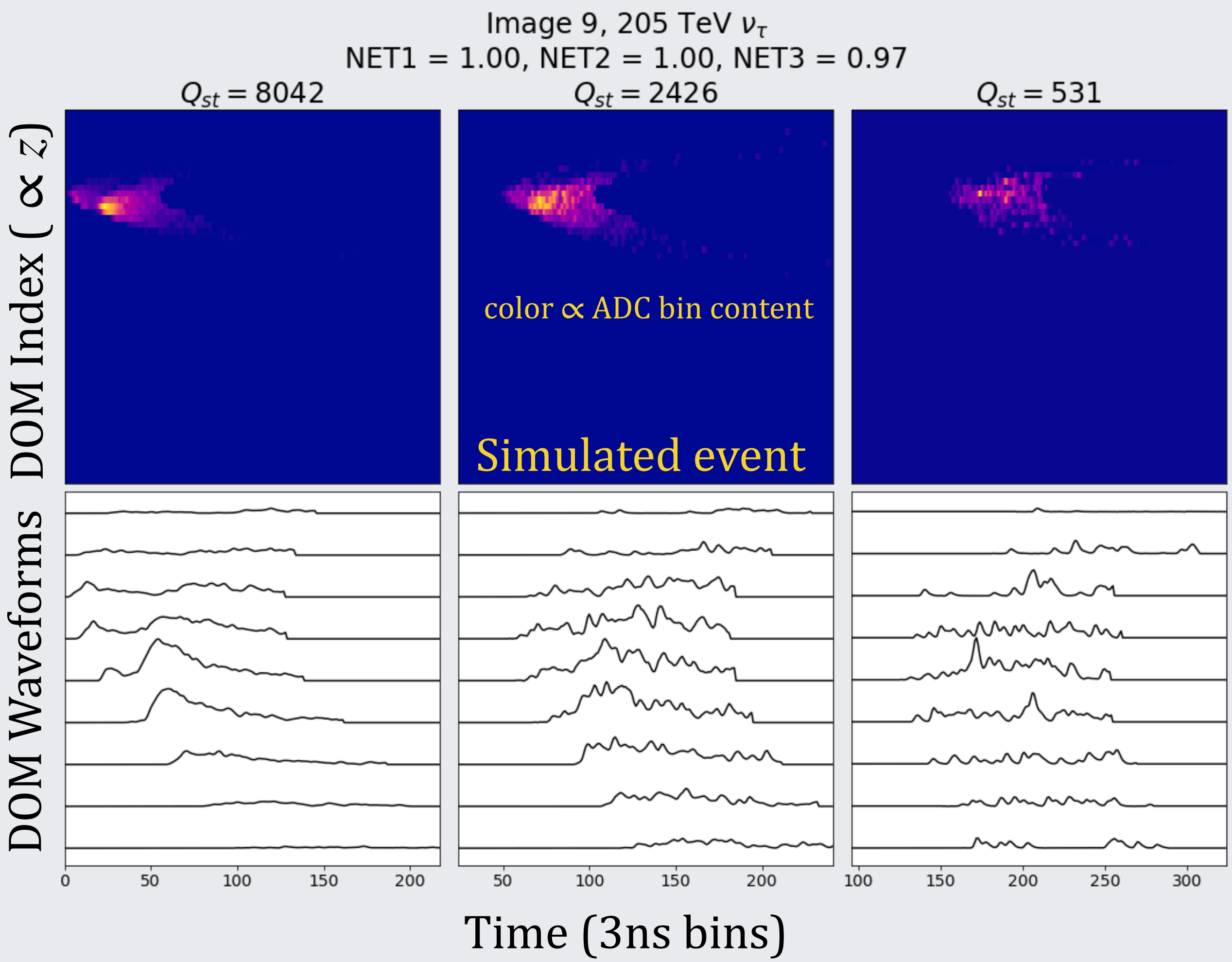
    - Current analysis
      - Look for DPs across 180 modules on 3 strings w/neural networks
      - High S/N achieved…

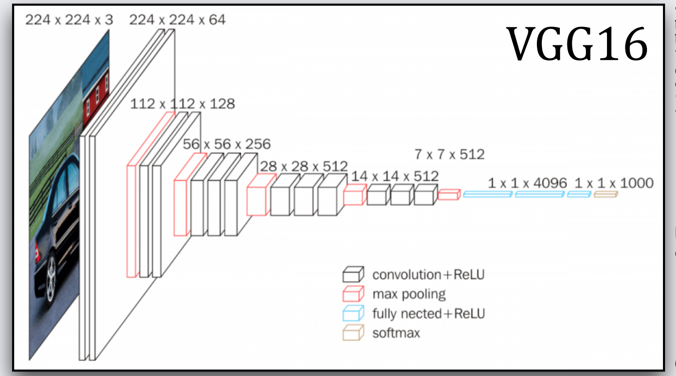


Searching for Astrophysical ν_τ

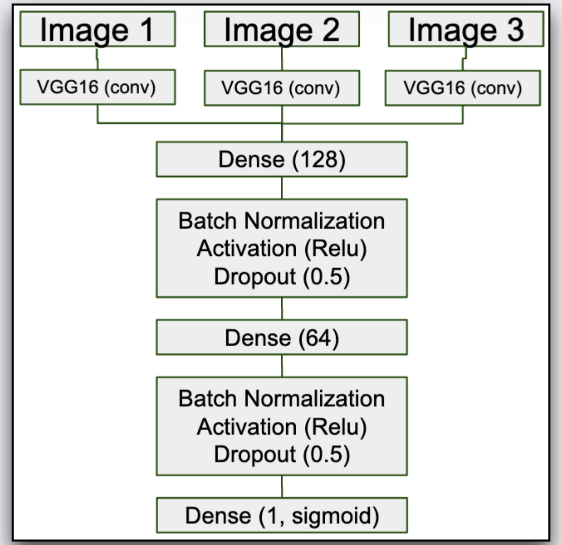
- ν_τ DP with up to 180 modules
  - Create 2d images, one per string



- Train convolutional neural network (CNN) to find signal and reject background



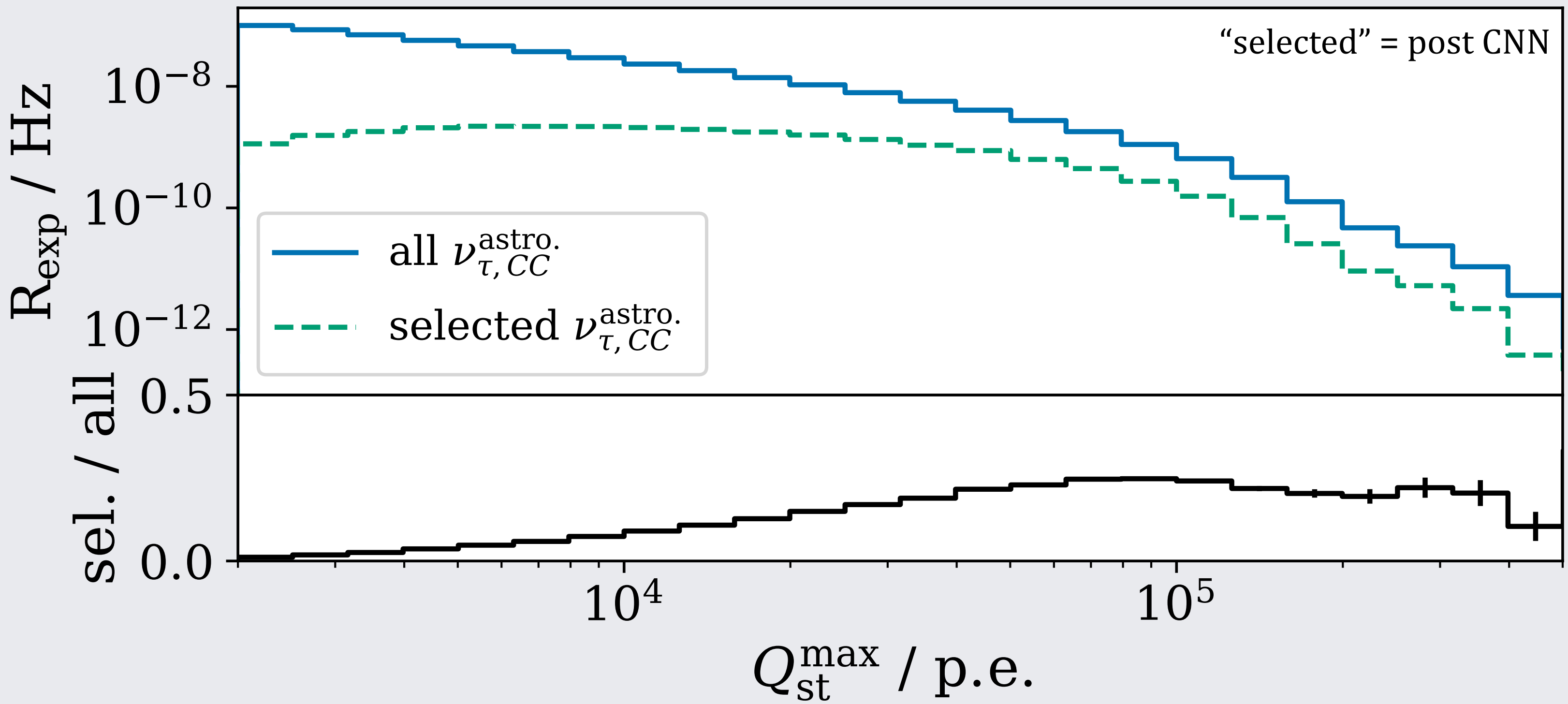
Simonyan & Zisserman, 1409.1556



$3 \times$ VGG16'

Searching for Astrophysical ν_τ

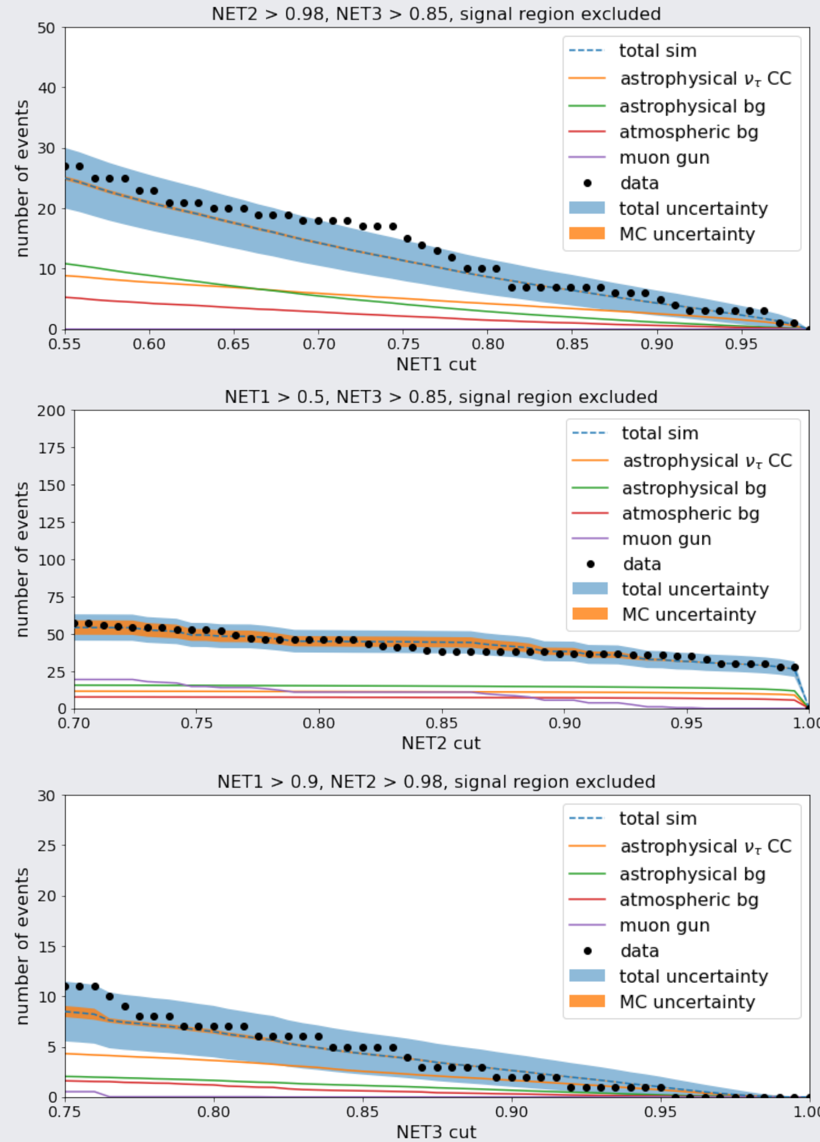
- Initial ν_τ DP selection criteria
  - Require ≥ 2000 p.e. on highest-charge string and ≥ 10 p.e. on two neighbors
  - Require cascade topology
- After initial criteria, have ~300x more background than signal



Searching for Astrophysical ν_τ

- 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
- Off-signal region Data-MC agreement is good for $C_{1,2,3}$

Cumulative rate; signal region excluded



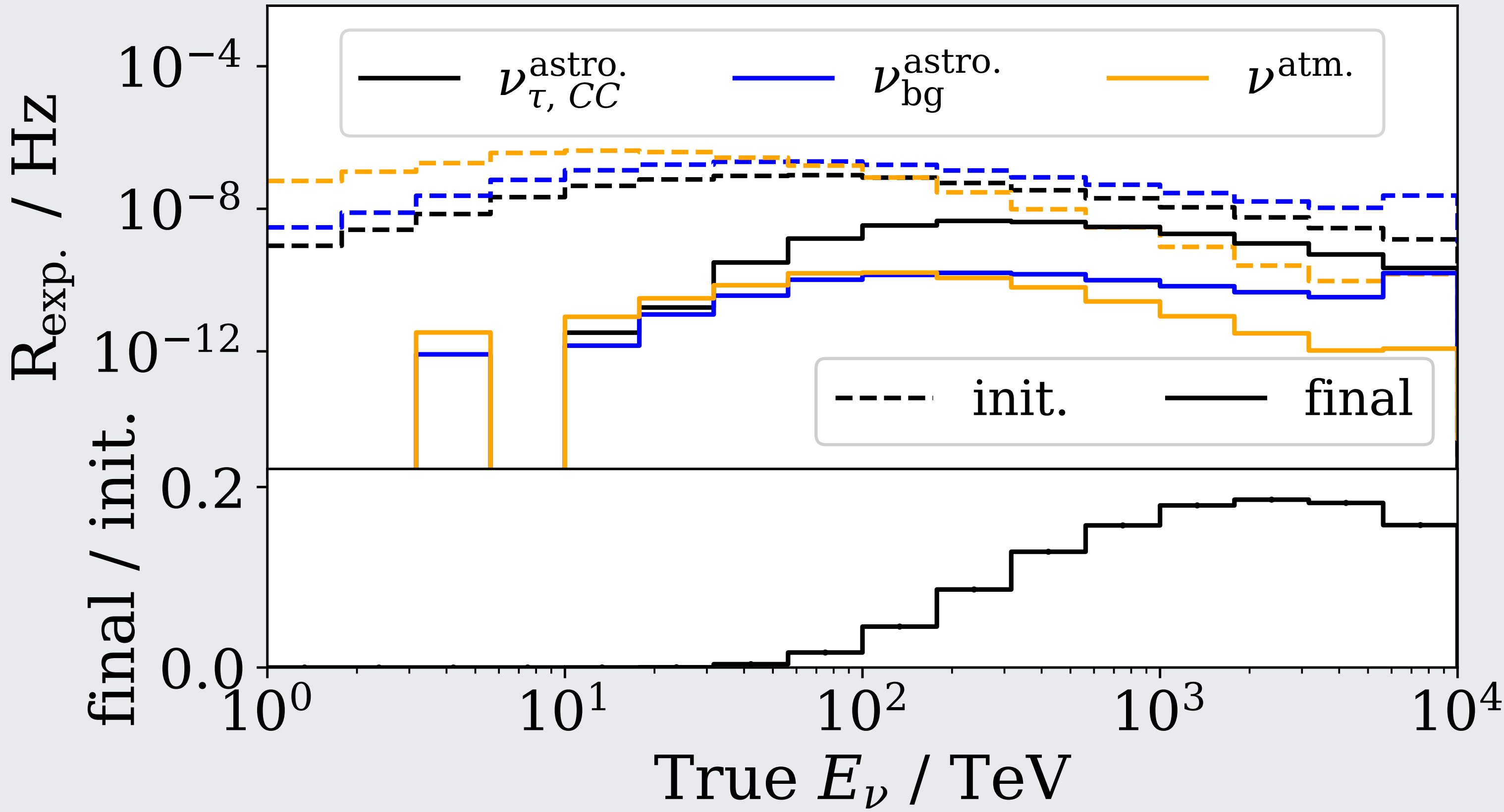
N_{evt}

C_1 C_2 C_3

$C_{1,2,3}$ score

Searching for Astrophysical ν_τ

- 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

Searching for Astrophysical ν_τ

- 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
- Contributors to the ~0.5 background events:
  - ν^{astro}: IceCube has 4 flux measurements
    - use one giving least-significant exclusion of null hypothesis
  - ν^{atm}: Conventional flux (Honda et al.; IceCube msmts.); possible prompt flux (Bhattacharya et al.; IceCube exclusion)
  - $\mu_\downarrow$: Only conventional (prompt not yet seen)
  - Other: Charm in ν_e, on-shell W, Earth-crossing $\nu_e, \nu_\mu \to \nu_\tau$

Searching for Astrophysical ν_τ

- 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
    - Double pulse from first shower of e and second shower due to 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 morphology may be sufficiently different from ν_τ that new CNN could reject.)

Searching for Astrophysical ν_τ

Signal — Backgrounds

	$\nu^{\rm astro}_{\tau,CC}$	$\nu^{\rm astro}_{\rm other}$	$\nu^{\rm atm}_{\rm conventional}$	$\nu^{\rm atm}_{\rm prompt}$	$\mu^{\rm atm}$	all background
initial	160 ± 0.2 (190 ± 0.3)	400 ± 0.7 (490 ± 0.8)	580 ± 7	72 ± 0.1	8400 ± 110	9450 ± 110 (9540 ± 110)
final	6.4 ± 0.02 (4.0 ± 0.02)	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)

IceCube's GlobalFit flux assumed (HESE flux in parentheses).

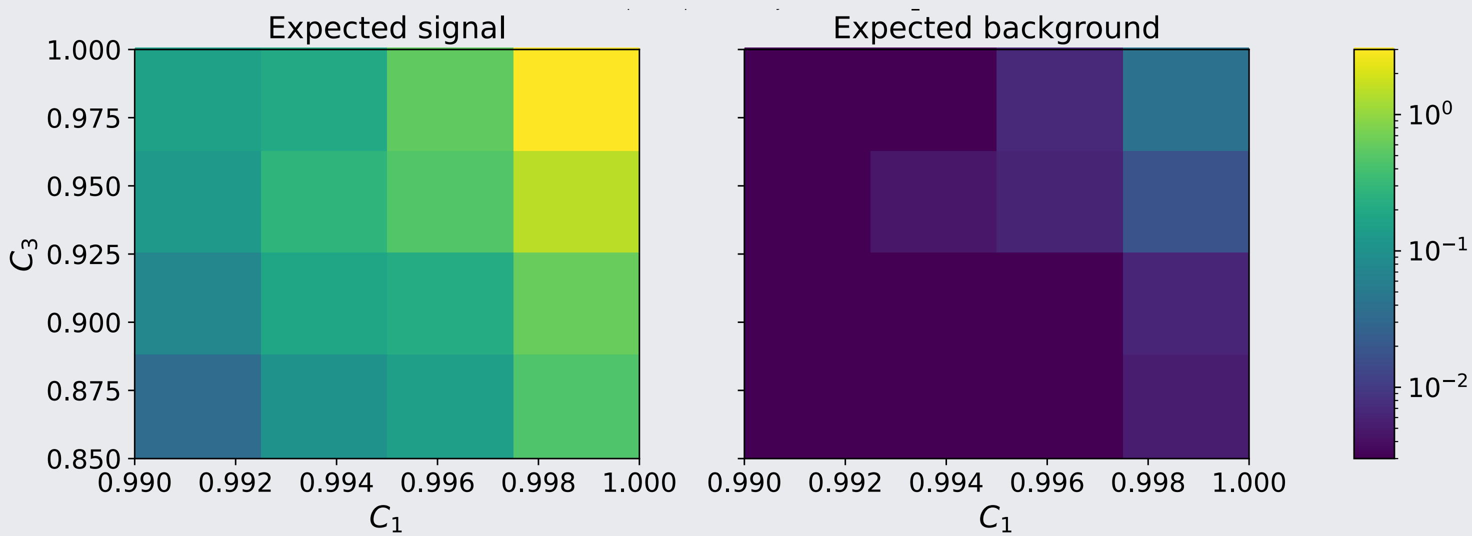
Searching for Astrophysical ν_τ

- Backgrounds/Systematics, cont'd:
  - $\mu_\downarrow, \mu_{\text{DIS}}$ $(\mu + X \to \nu_\mu + X')$: considerably smaller than ν^{astro}
  - Impact of detector-related systematics all found to be small. Included uncertainties in:
    - bulk ice scattering & absorption
    - hole ice scattering & absorption
    - DOM efficiencies
  - 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 $\nu_e, \nu_\mu \to \nu_\tau$**

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

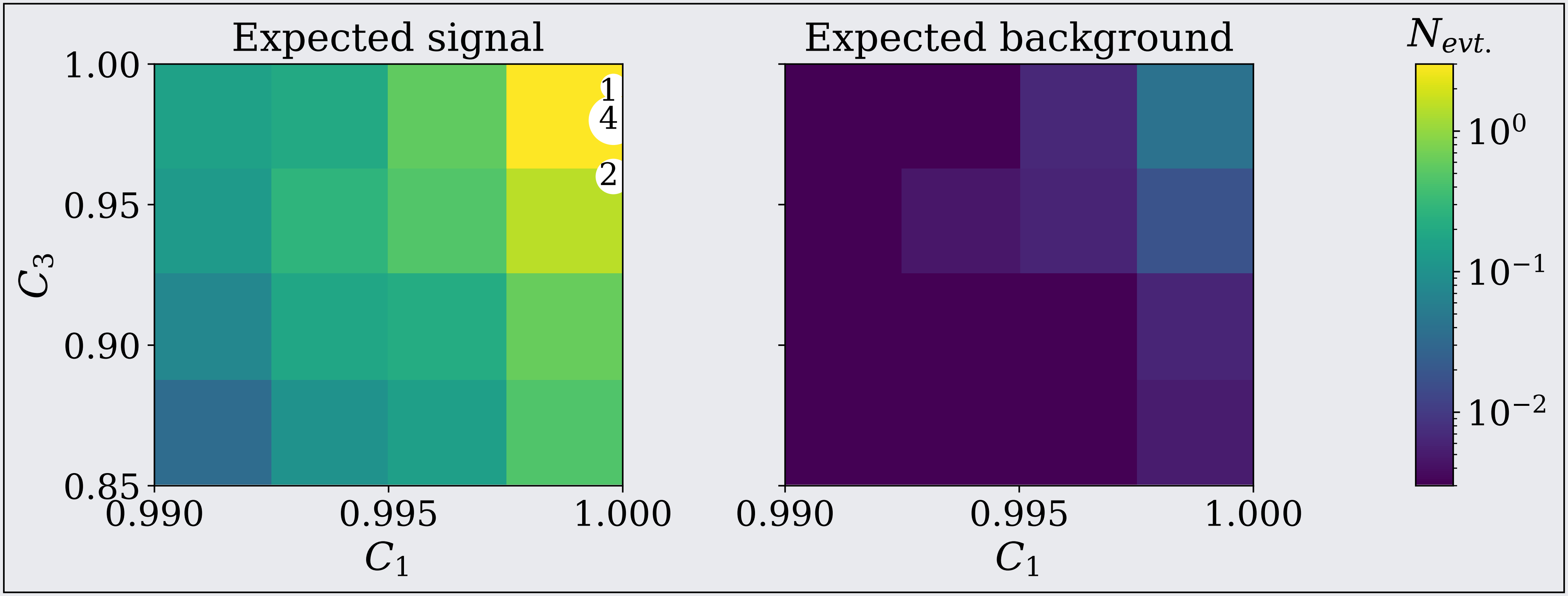
Searching for Astrophysical ν_τ

- Confidence intervals calculation (Feldman & Cousins)
  - Test statistic $\mathrm{TS}(\lambda_\tau) = \ln L(\hat{\lambda}_\tau) - \ln L(\lambda_\tau)$
    - where $\lambda_\tau = \dfrac{\phi_{\nu_\tau,\text{ astro.}}}{\phi^{\text{nominal}}_{\nu_\tau,\text{ astro.}}}$ and $\hat{\lambda}_\tau$ maximizes Poisson-based LLH across 16 bins in (C_3, C_1) space:



Searching for Astrophysical ν_τ

Opening the box, we saw 7 events!



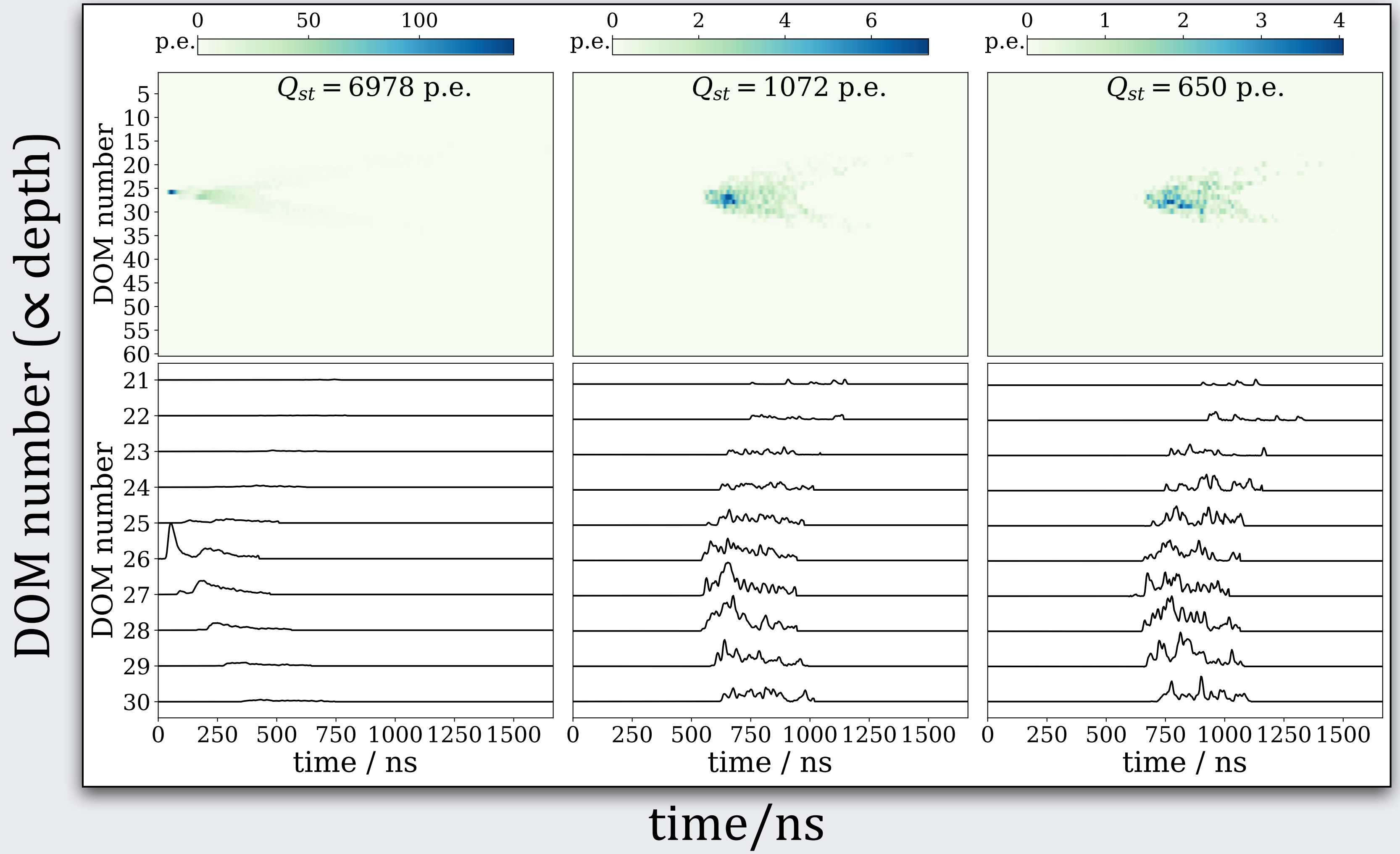
4 events are brand new.

3 events are old; 1 of which had been identified as a ν_τ candidate.

Tau-ness: $P_\tau(i) = n_s(i)/(n_s(i) + n_b(i)) \rightarrow (0.90 - 0.92,\ 0.94 - 0.95)$

Event Pics

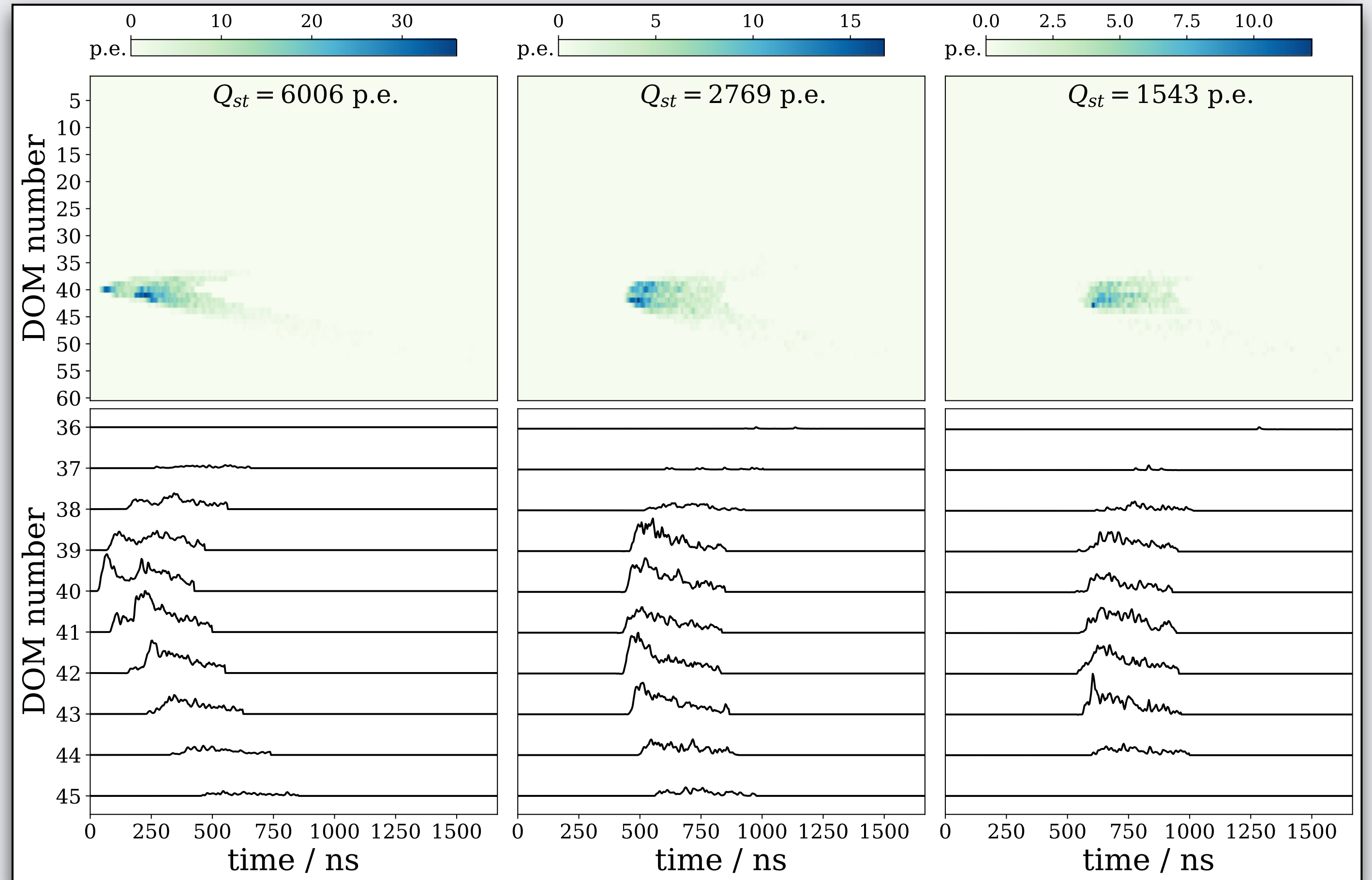
Here's "Double Double," an old event & prior ν_τ candidate:



Gratifying to find this event again.

Event Pics

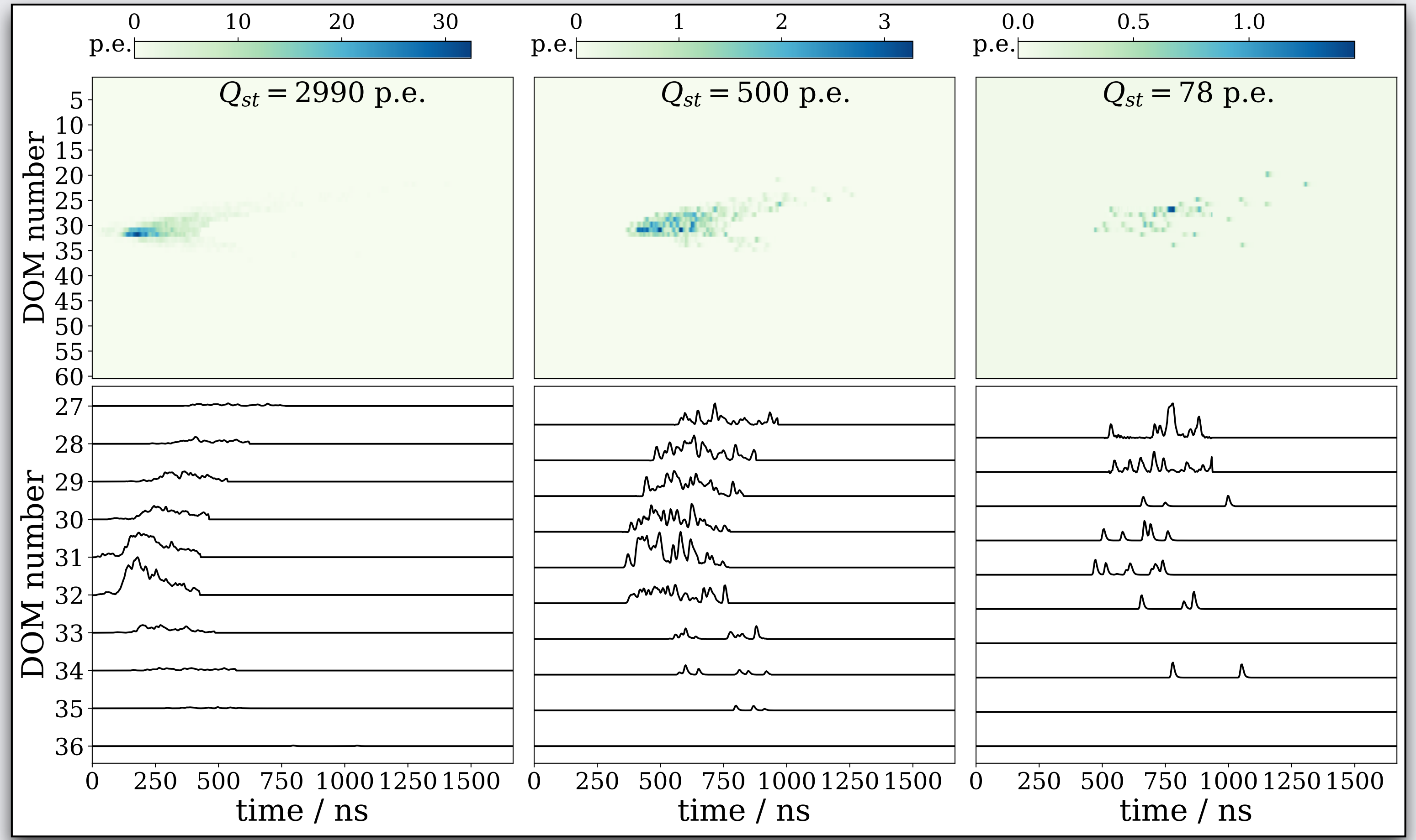
Here's "Scarlet Macaw," a new event:



Clear double pulse structure. Detected in 2019 (too recent for previous analyses to have seen).

A Less Obvious Event Pic

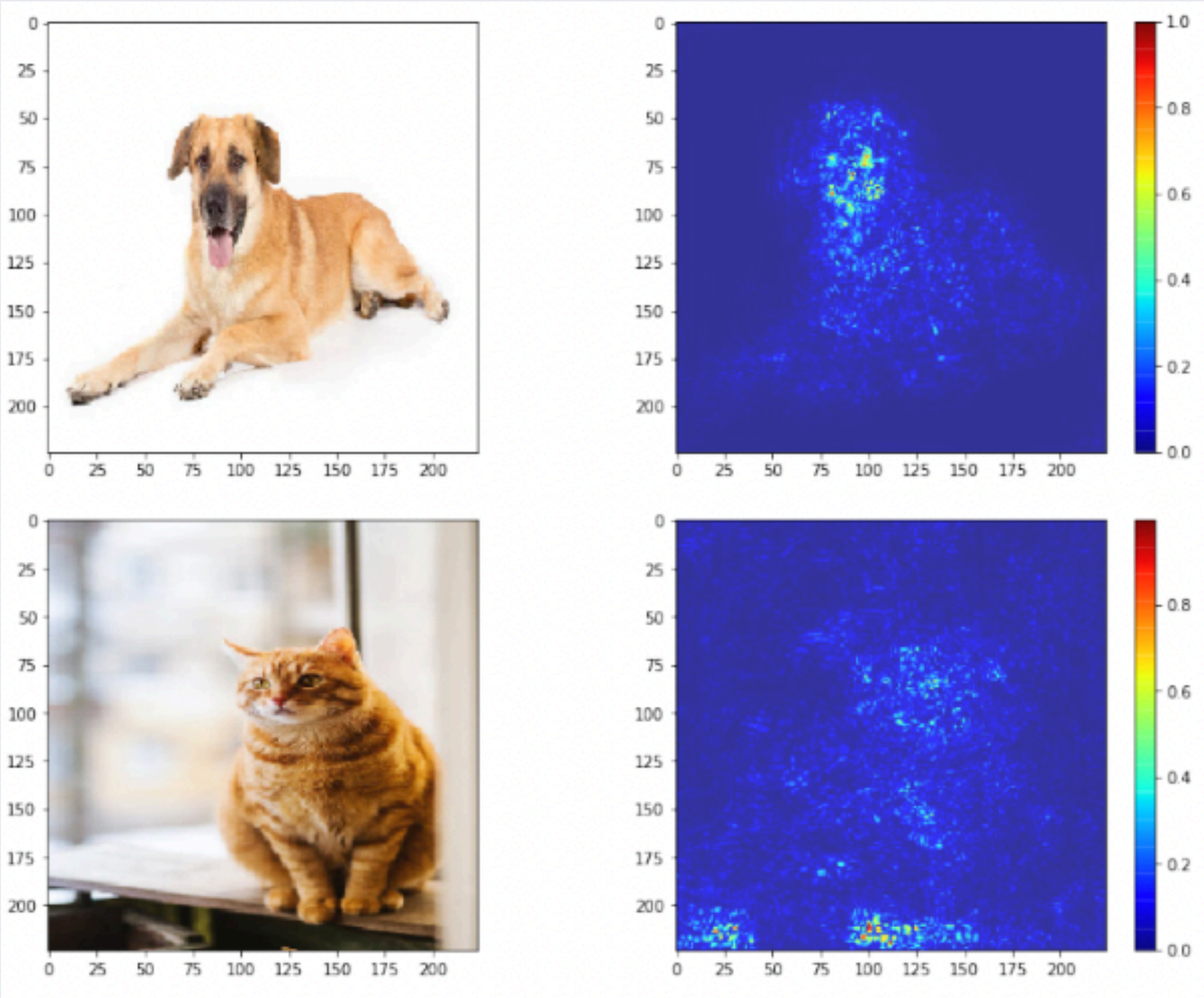
Here's "Barn Owl," another new event:



No clear double pulse structure. What makes it a ν_τ^{astro} candidate?

Saliency Maps

Saliency maps "rank the pixels in an image based on their contribution to the final score from a Convolution Neural Network."

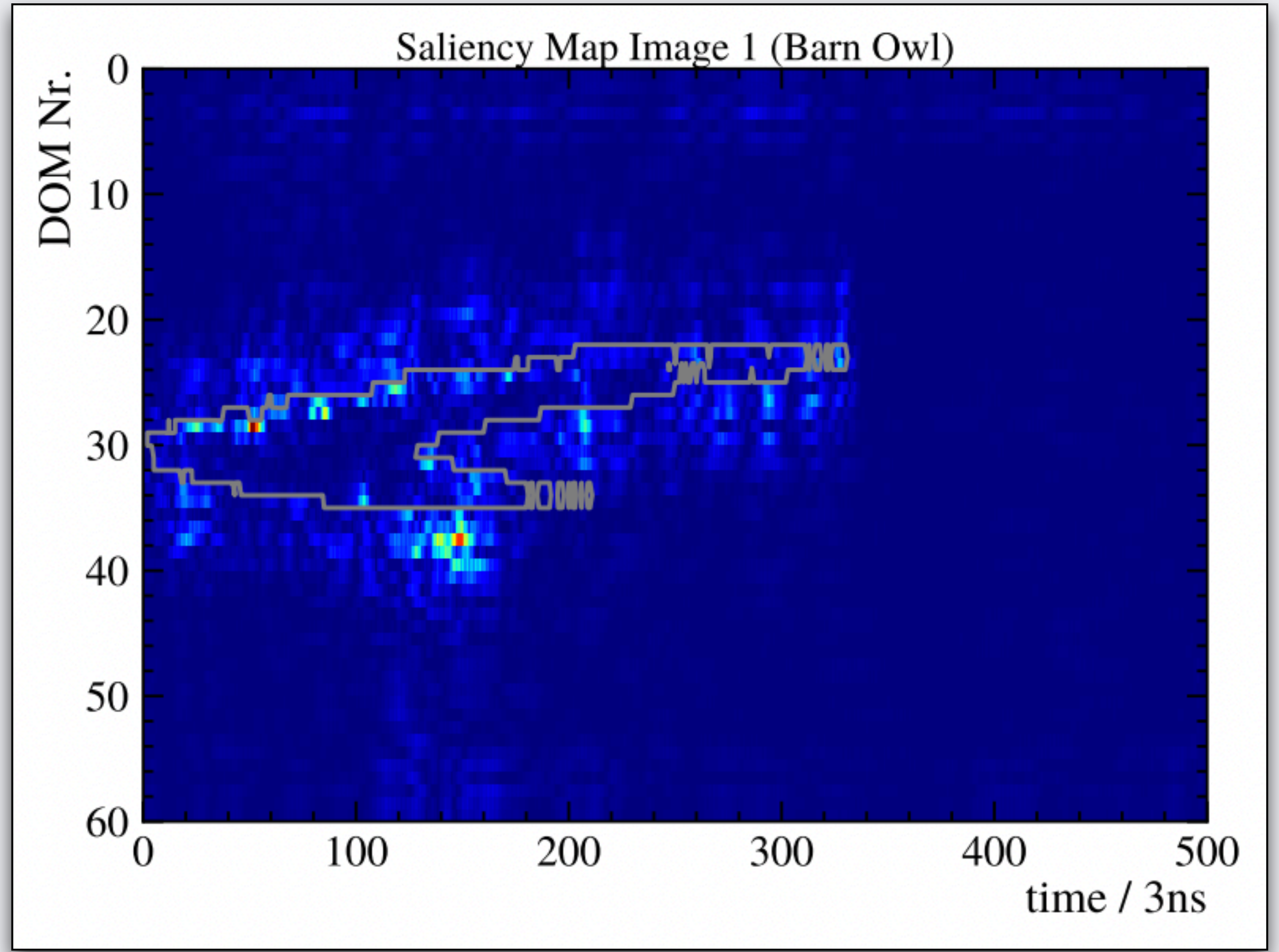


These saliency maps show what parts of the photos the CNN finds most useful for identifying the dog in the dog photo, and the cat in the cat photo.
(Evidently, the training sample had many of its cats sitting on tables.)

https://usmanr149.github.io/urmlblog/cnn/2020/05/01/Salincy-Maps.html

Saliency Maps

Here's a saliency map for Barn Owl.



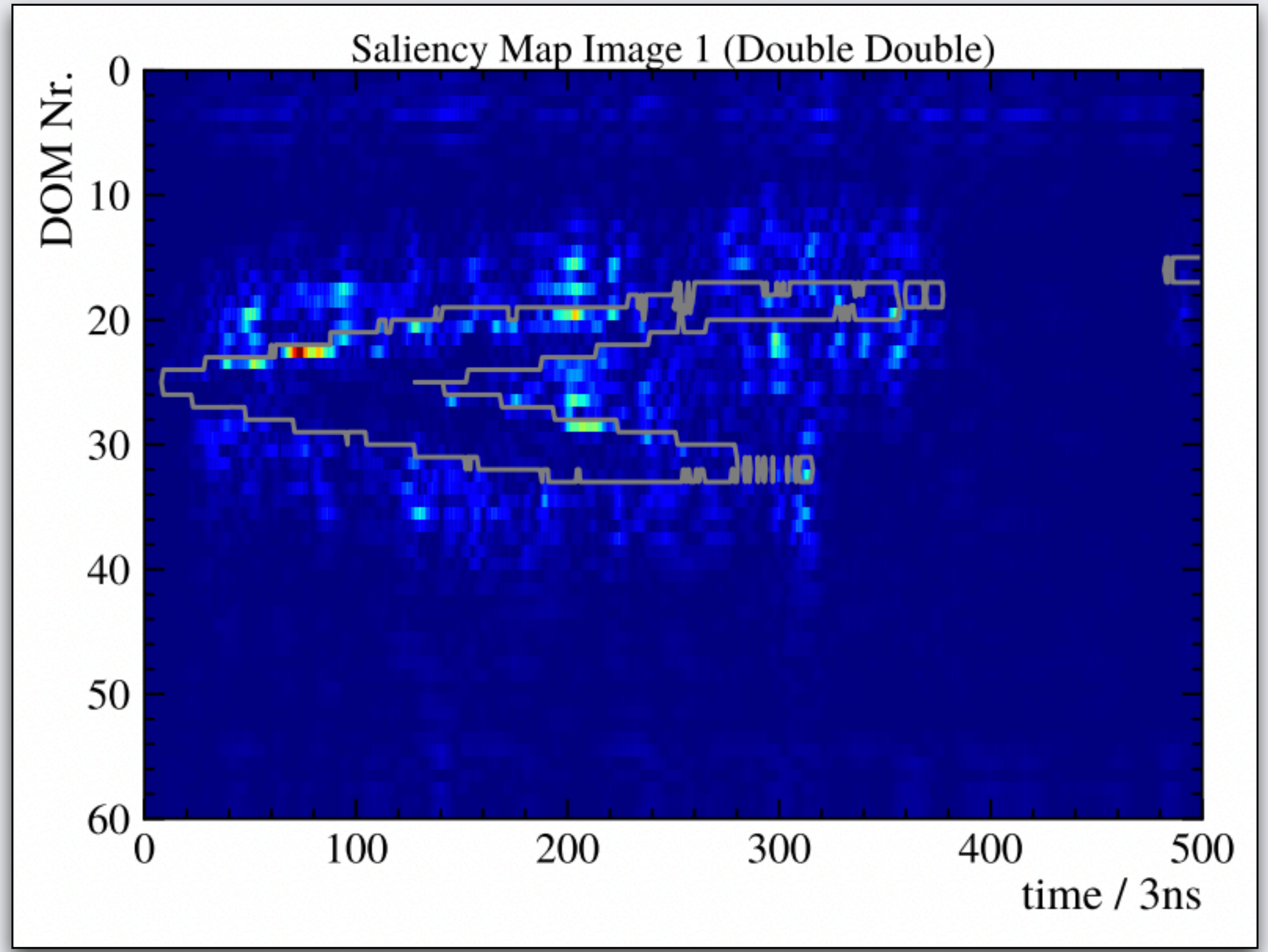
The CNN C_1 is using the leading edge light from the two ν_τ^{astro} candidate's cascades.

It also expects there to be places where there is no light.

(The silver line shows the boundary outside of which no light was detected.)

Saliency Maps

Here's a saliency map for the event Double Double.



Again, we see that the leading edge light is what matters. Also implies that double pulse waveforms may not be so important.

Tested this hypothesis: intentionally smoothed DP waveforms; CNN scores remained high.

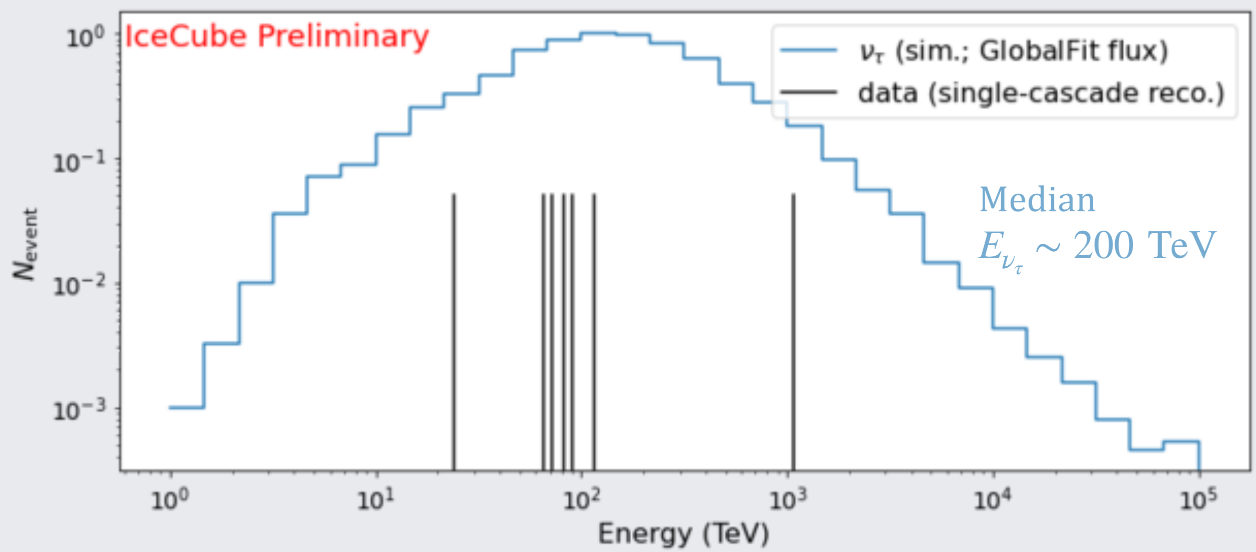
Machine learning is less biased than physicist-engineered selection criteria!

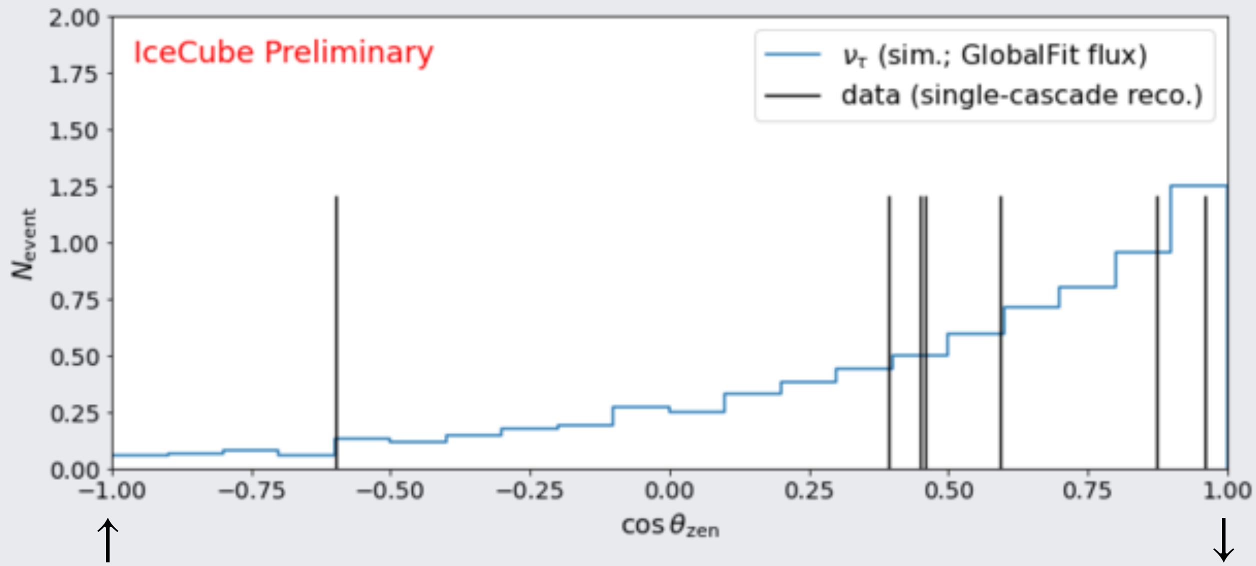
Post Unblinding Checks

- Explicit reconstruction of ν_τ's $(x, y, z, E, \theta, \phi)$ 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
- Instead, checked candidate ν_τ w/existing reco.
  - Tuned for *single-pulse* events (e.g., ν_e)

Post-Unblinding Checks

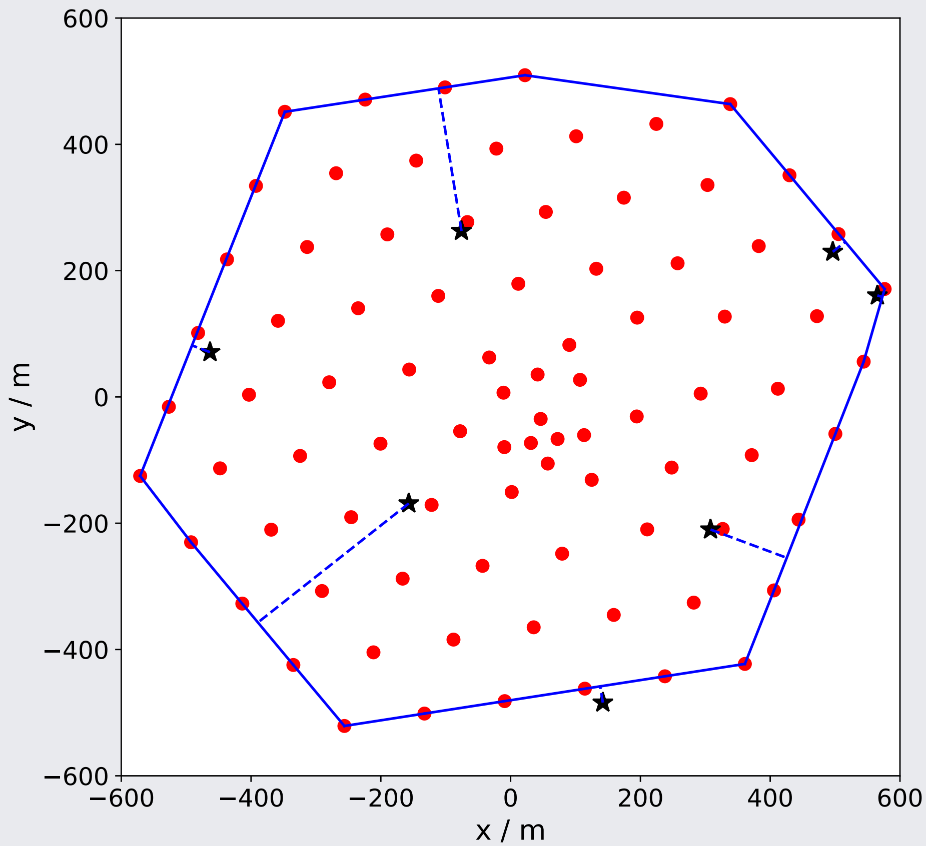
- Apply single-pulse reco. to
  - simulated ν_τ
  - candidate ν_τ
- Good data–MC agreement…
  - …but take actual numbers with a big grain of salt

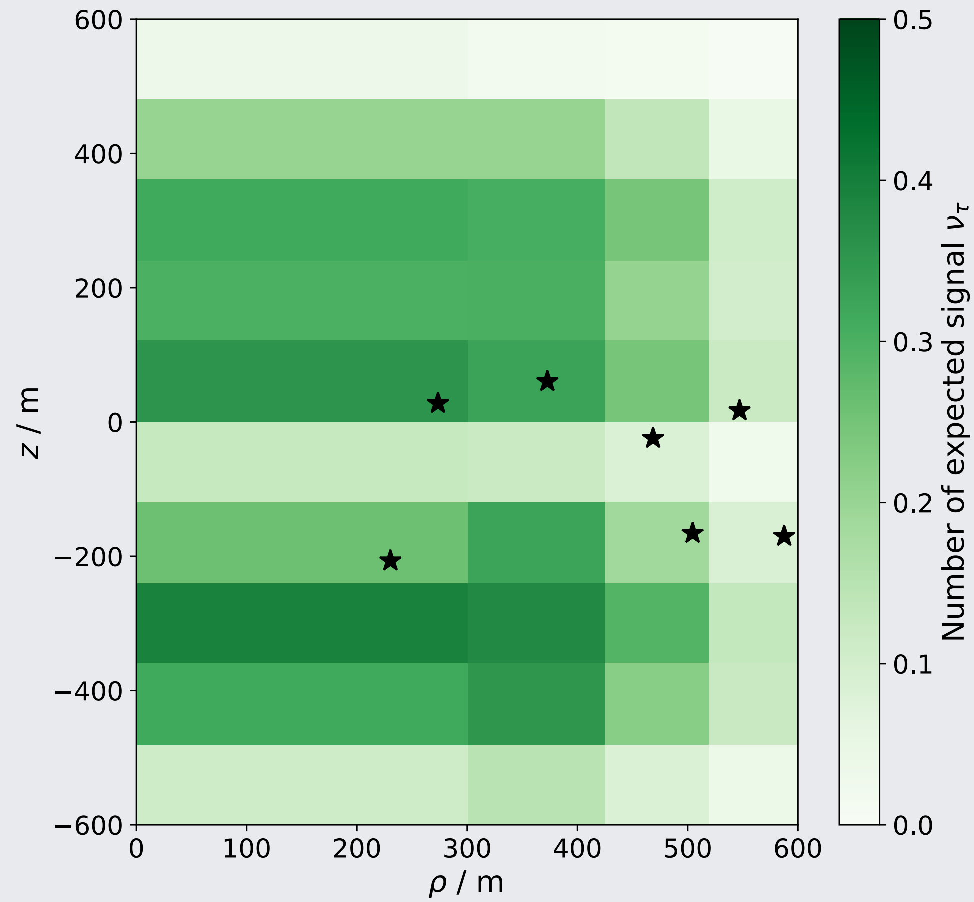




Post-Unblinding Checks

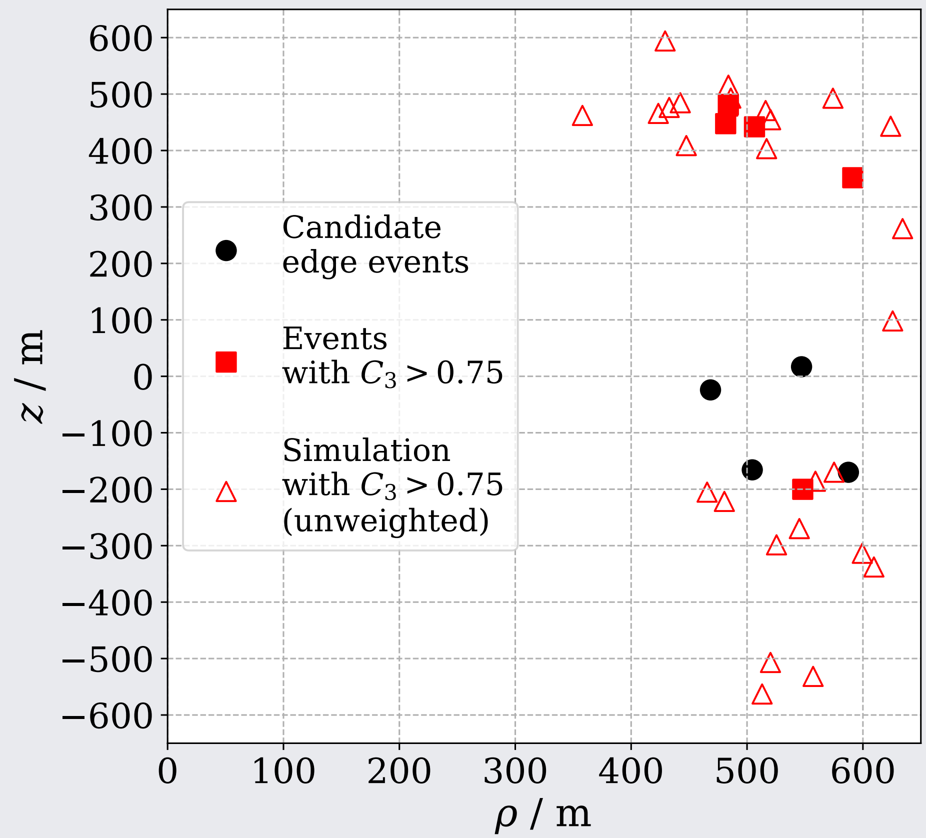
- The event vertex distribution did not look as uniform as expected
  - Several events' highest charge string was near detector's edge
  - More clustered in z above and below the "dust band"
    - A ~3σ-ish effect, depending on assumptions





Event Vertex Distribution

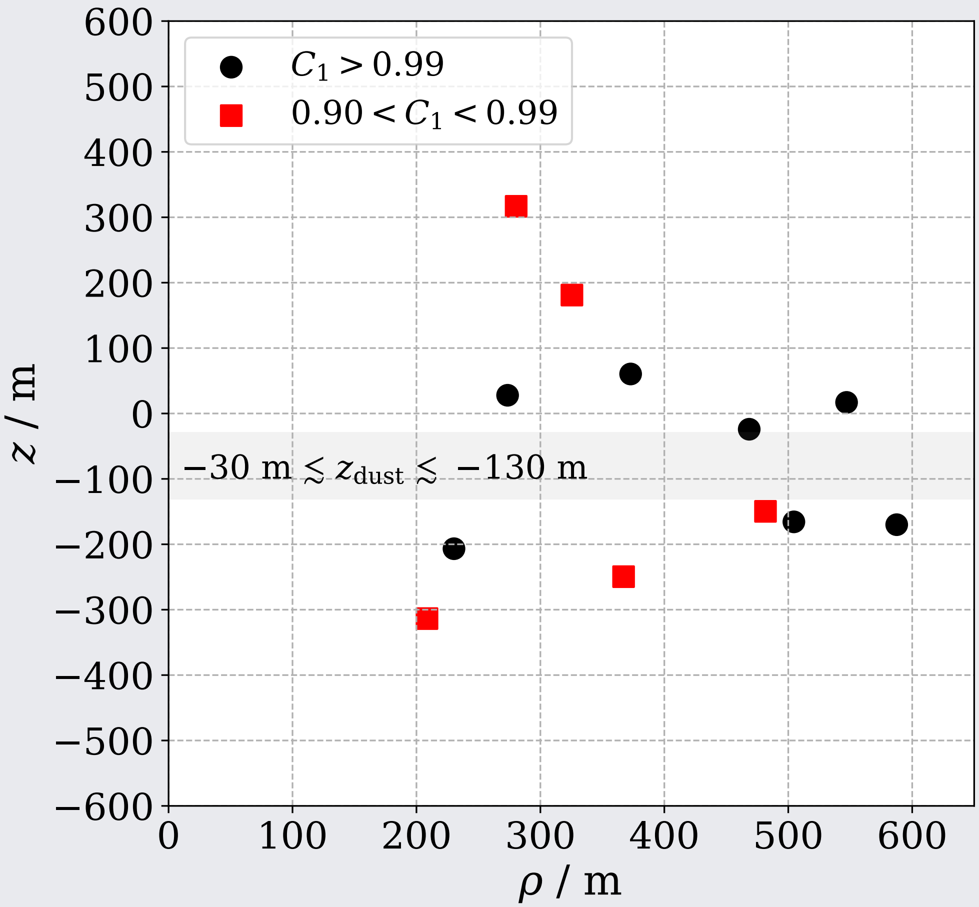
- Geometry: There's a lot of physical volume near the edge
- Loosening CNN scores $C_{2,3}$ (ν_τ^{CC} vs. (ν_μ^{CC}, μ)) adds new events mostly at top of detector
  - Very unlikely all 4 edge events are μ: $p_{KS}(C_3 > 0.75) = 0.1$ [$p_{KS}(C_3 > 0.85) = 0.004$]



- One of the four events reconstructs as outward-going
  - Likely ν: absence of light on ~0.5 km path toward vertex

Event Vertex Distribution

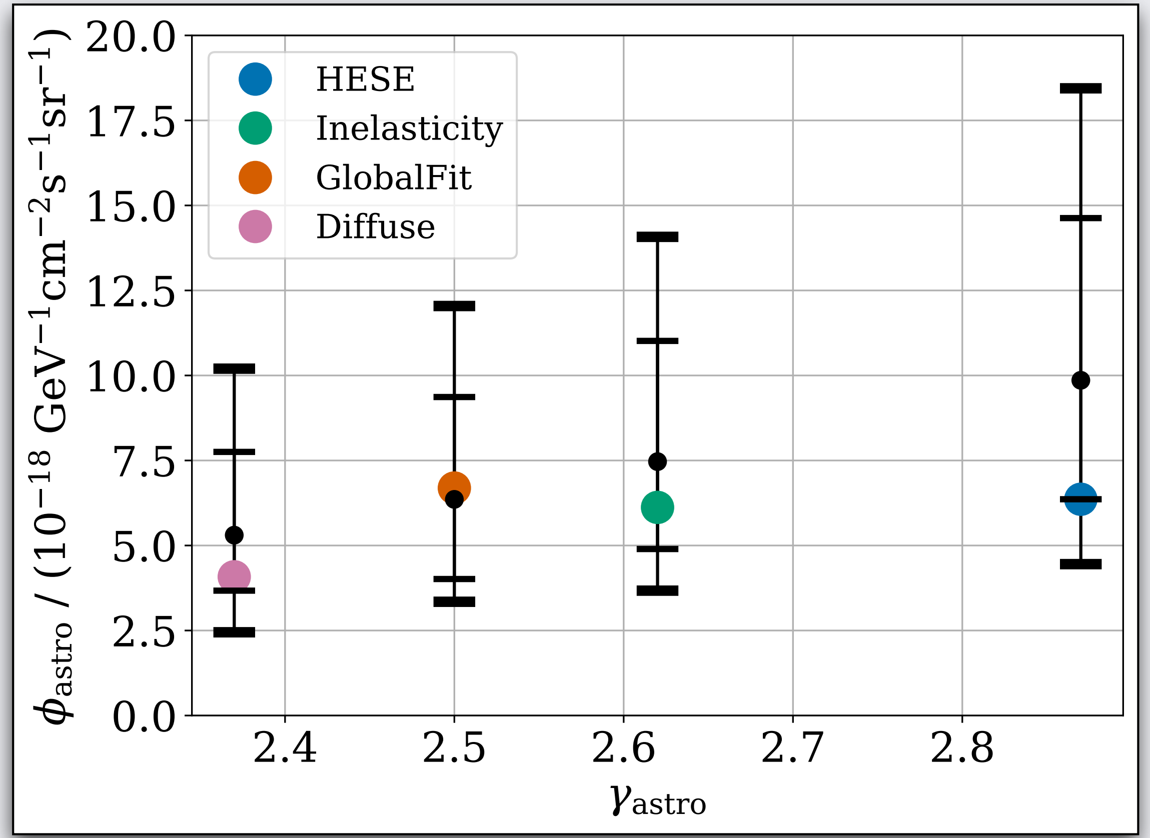
- Loosening C_1 score (ν_τ^{CC} vs. (ν_e^{CC}, ν_x^{NC}))
  - Expected 9.4 ν_τ and 2.9 bkgd events
  - Saw 12 (see figure)
- New events more evenly distributed in (ρ, z)
- Note: The 12 events would also exclude null hypothesis of $\phi(\nu_\tau^{\text{astro}}) = 0$ at high significance.



Conclusions: The 7 candidates' vertex distribution is an unfortunate statistical fluctuation, and the edge events are inconsistent with cosmic ray muons.

Conclusions: Fitted ν_τ Fluxes

$\phi = \phi_0 E^{-\gamma}$; fix γ, fit for ϕ_0:



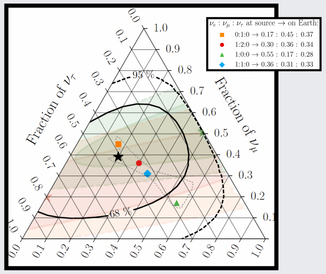
Excellent agreement with all four IceCube (non-ν_τ) measured fluxes.

Conclusions: Exclusion of Null Hypothesis

- For IceCube's *GlobalFit* flux, exclude $\phi(\nu_\tau^{\mathrm{astro}}) = 0$ at 5.1σ
  - Other fluxes: 5.2σ, 5.2σ, 5.5σ (*Inelasticity*, *Diffuse*, *HESE*)
  - Expected bkgd (and expected signal) depend on assumed flux
    - Pre-unblinding, decided to use flux giving least significant exclusion
      - Instead, could have used most significant result & corrected for trials
- Alternatively, this is a 40%-level confirmation of the standard oscillation picture $(7 \pm \sqrt{7})$
- ν_τ^{atm} negligible at these E_ν
  - Detection of energetic ν_τ powerfully confirms IceCube's earlier ν^{astro} discovery.

Conclusions: What's Next?

- Used just 3 (of 86) strings. Using more strings would:
  - Improve bkgd rejection, allowing for relaxation of cuts→more signal
    - Improve current $\nu_\tau^{\mathrm{astro}}$ flux measurement
    - Update "triangle plot" with ν_τ information
      - Search for new physics (e.g., quantum gravity)
      - Identify likely astrophysical-source acceleration scenarios; maybe exclude some



- Apply a dedicated reco. for direction, E,…
  - Use high-astrophysical-purity ν_τ to look for point sources
  - Study parameters of the ν_τ and τ themselves
    - L_τ, energy asymmetry, …

IceCube Collaboration

Spring 2022 Collaboration Meeting, Brussels, Belgium