Astrophysical Tau Neutrinos

The first high-significance measurement of the most energetic tau neutrino candidates ever observed

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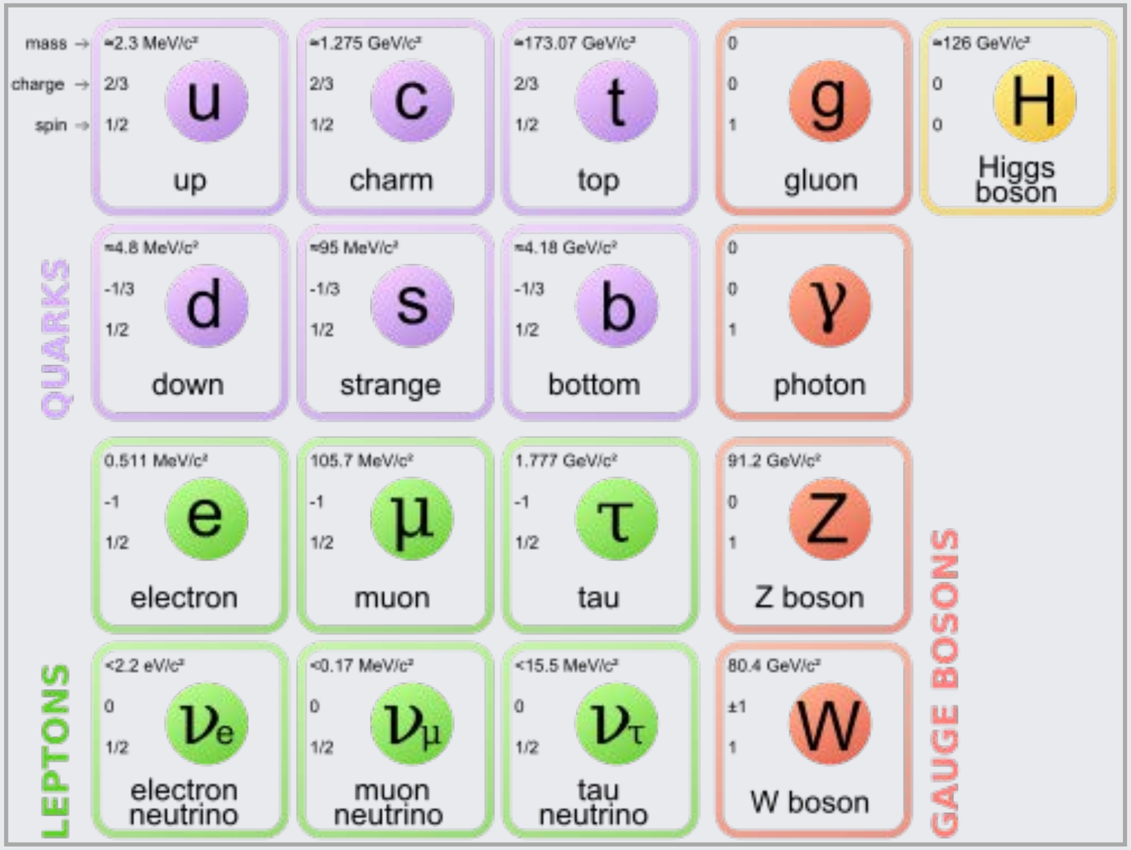
Neutrinos: The Basics

https://www.particlezoo.net/collections/leptons

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



graphic: wikipedia

The large m_τ suppresses direct ν_τ production.

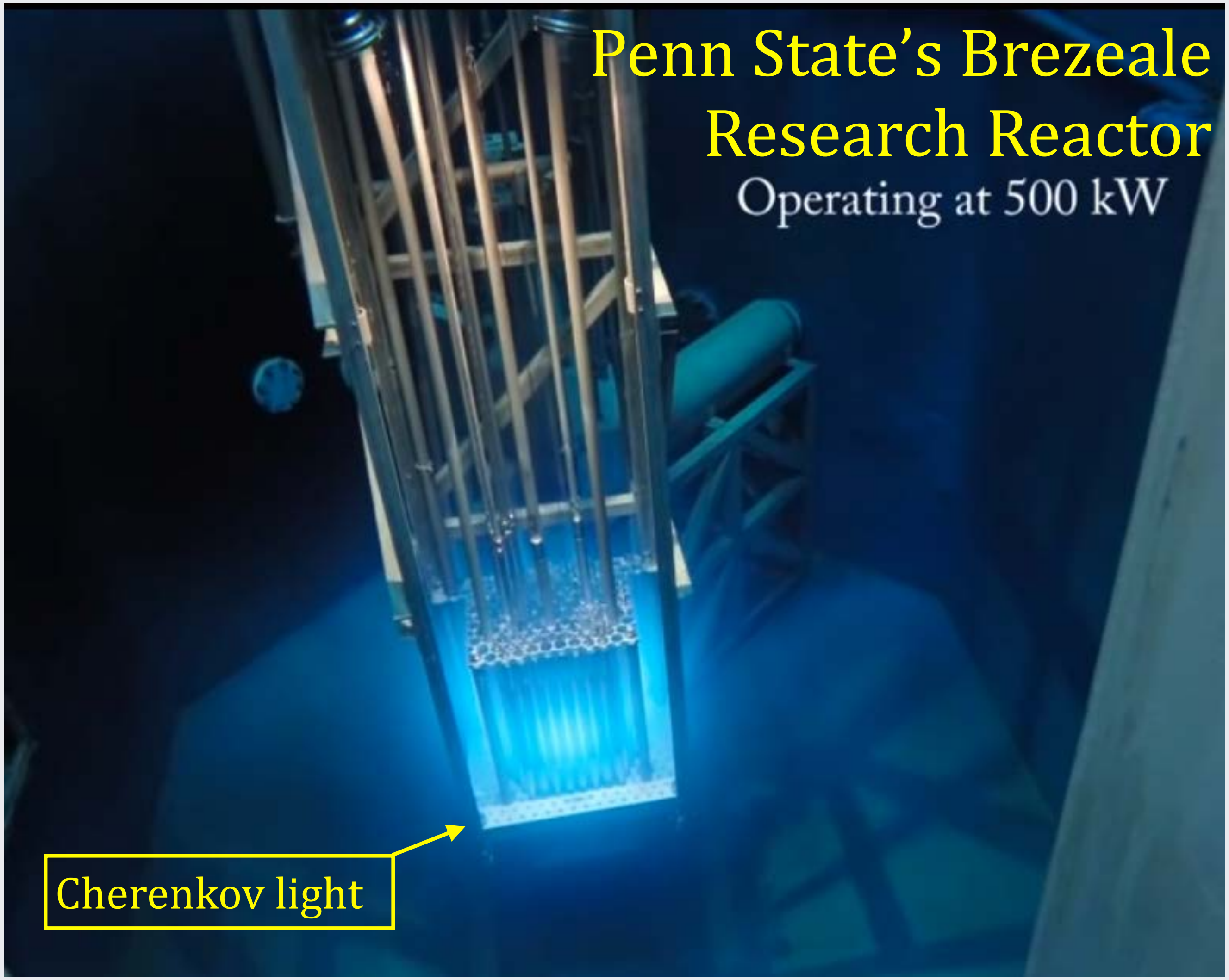
ν_τ are even harder to see than your average super-shy neutrino.

ν_τ mainly arise through neutrino oscillations.

Detecting Neutrinos: Cherenkov Light

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

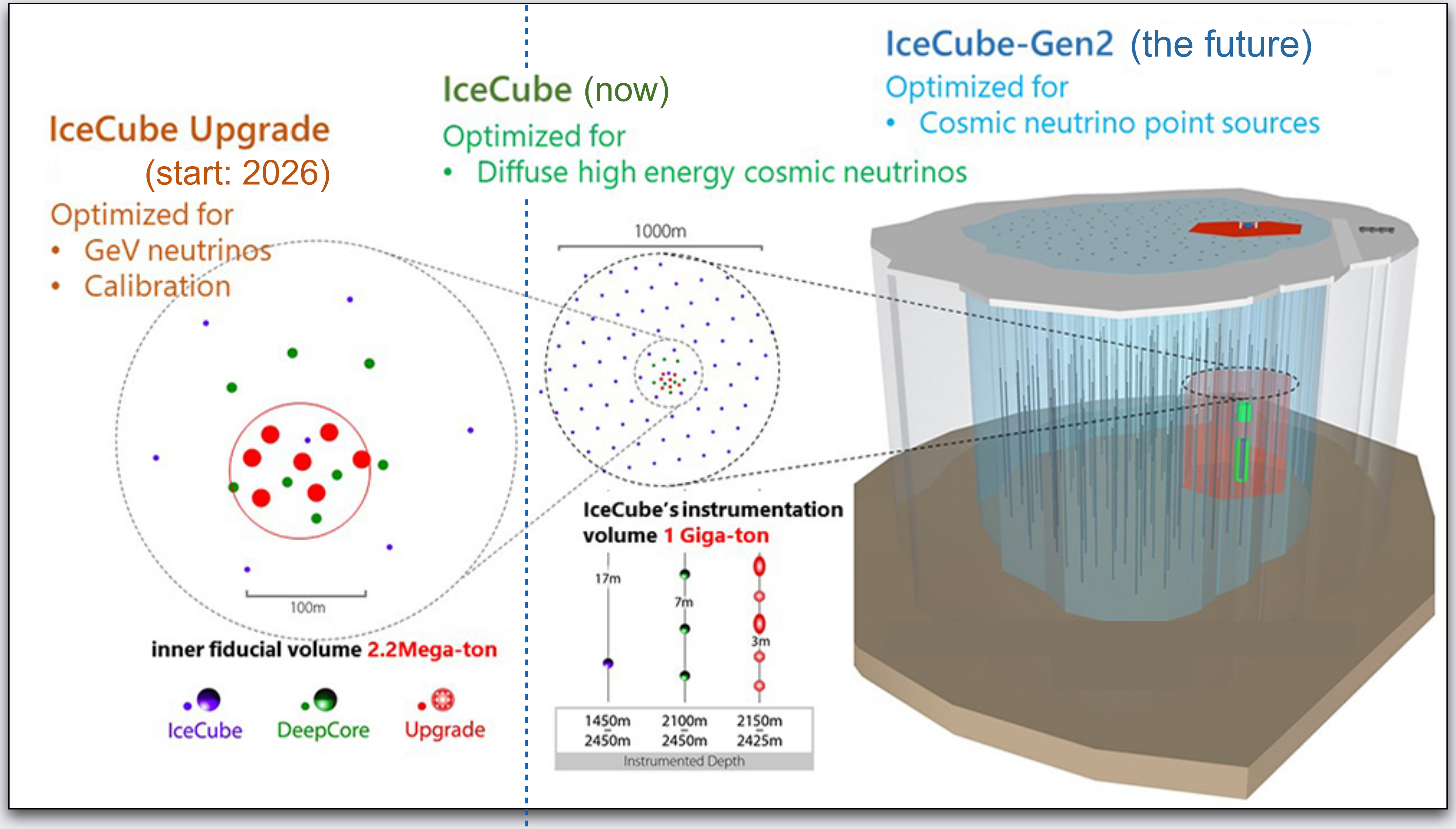
Electromagnetic equivalent of a sonic boom.



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

The IceCube Detector

← atmospheric astrophysical →



IceCube Upgrade (start: 2026)

Optimized for
- GeV neutrinos
- Calibration

IceCube (now)

Optimized for
- Diffuse high energy cosmic neutrinos

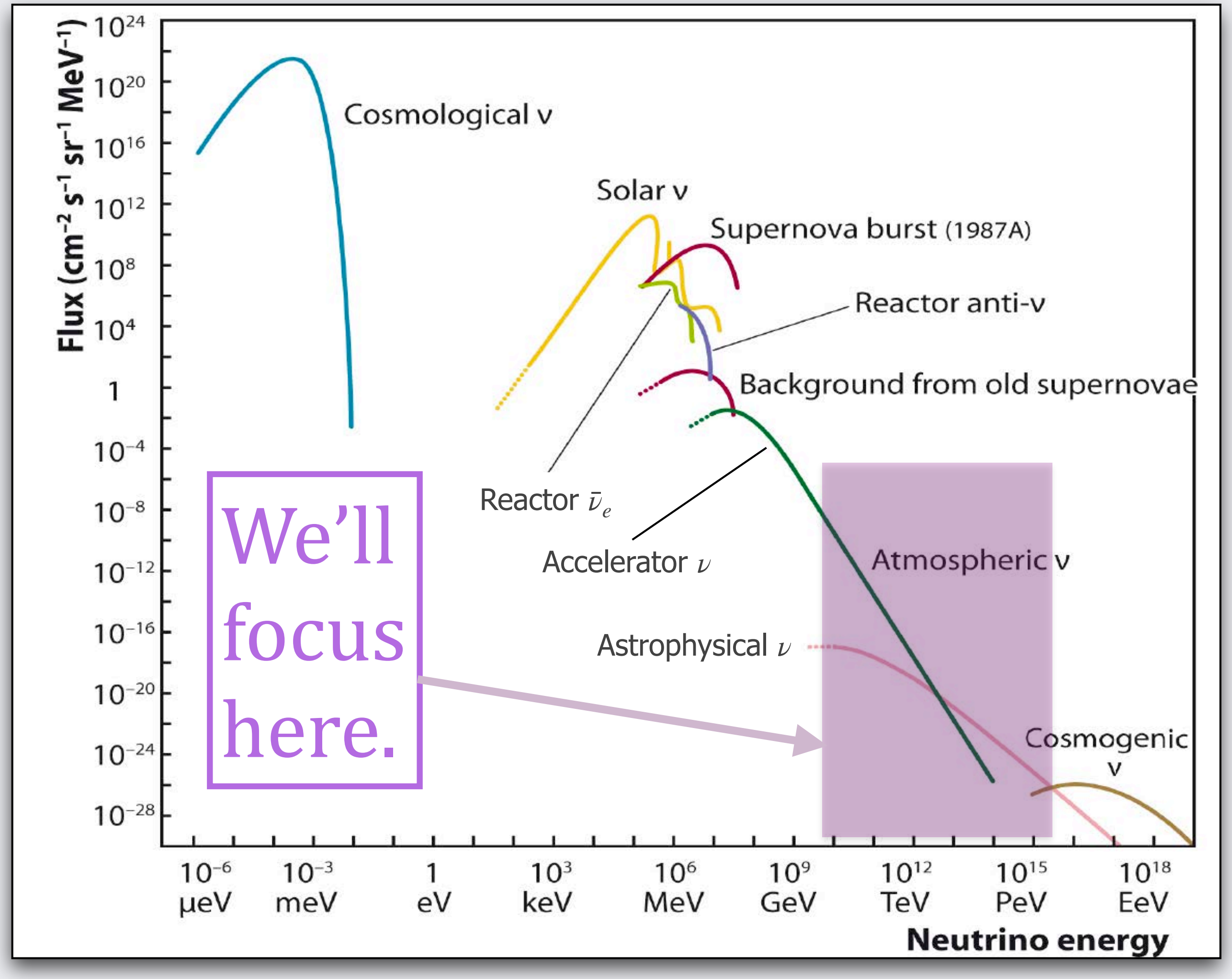
IceCube-Gen2 (the future)

Optimized for
- Cosmic neutrino point sources

(Yes, I have been to the South Pole.)

Neutrinos in IceCube

Many possible neutrino sources:



We'll focus here.

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)

- 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 (incl. Glashow Resonance)

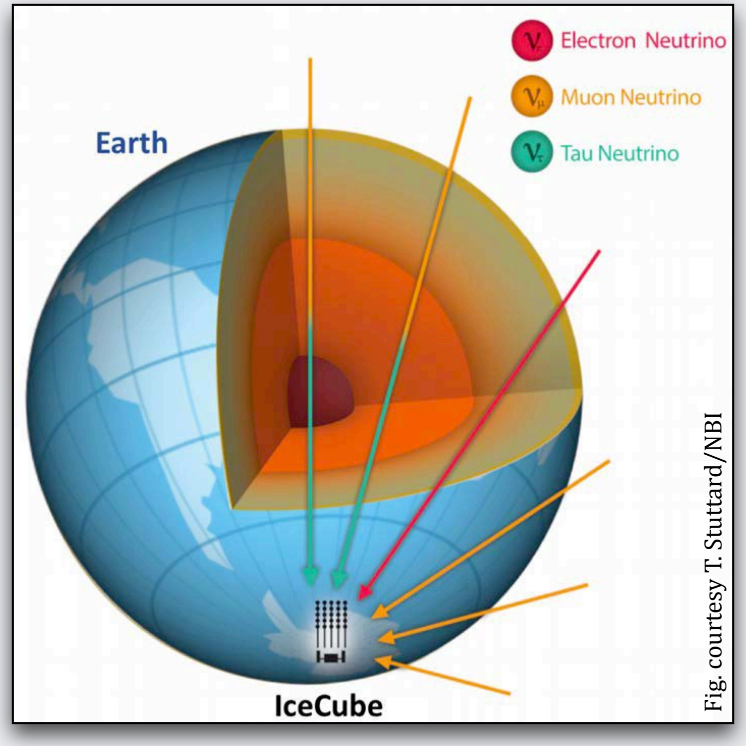


Fig. courtesy T. Stuttard/NBI

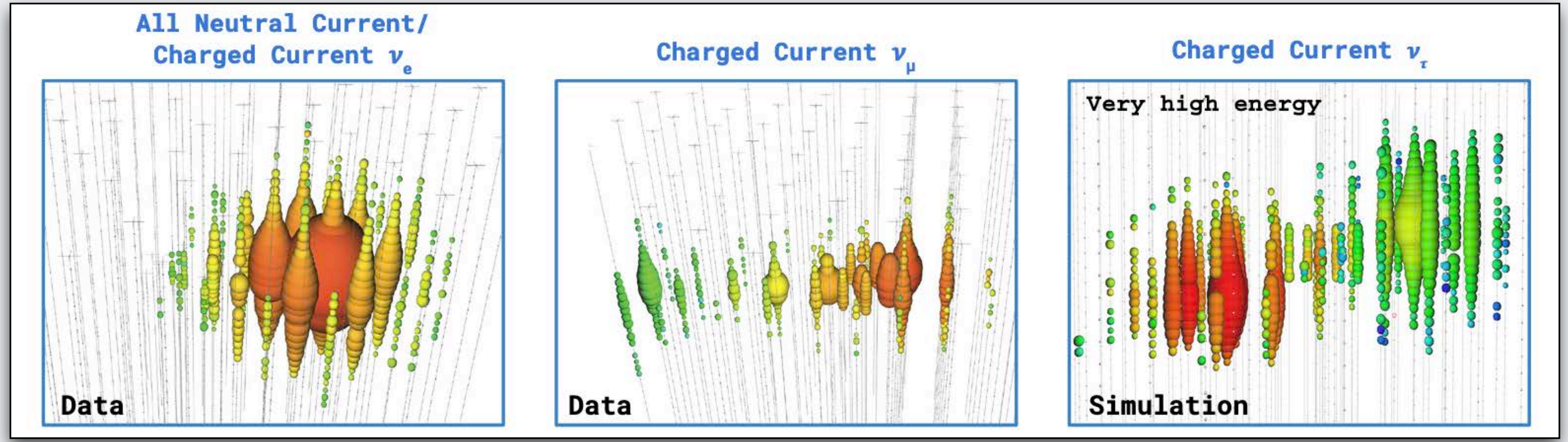
TXS 0506+056: BL Lac-type blazar, z=0.3365

Fig. courtesy DESY/Zeuthen

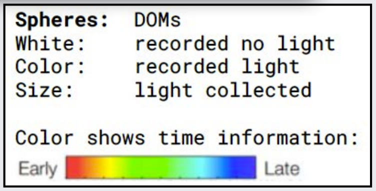
ν^{astro} in IceCube

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

Event morphologies

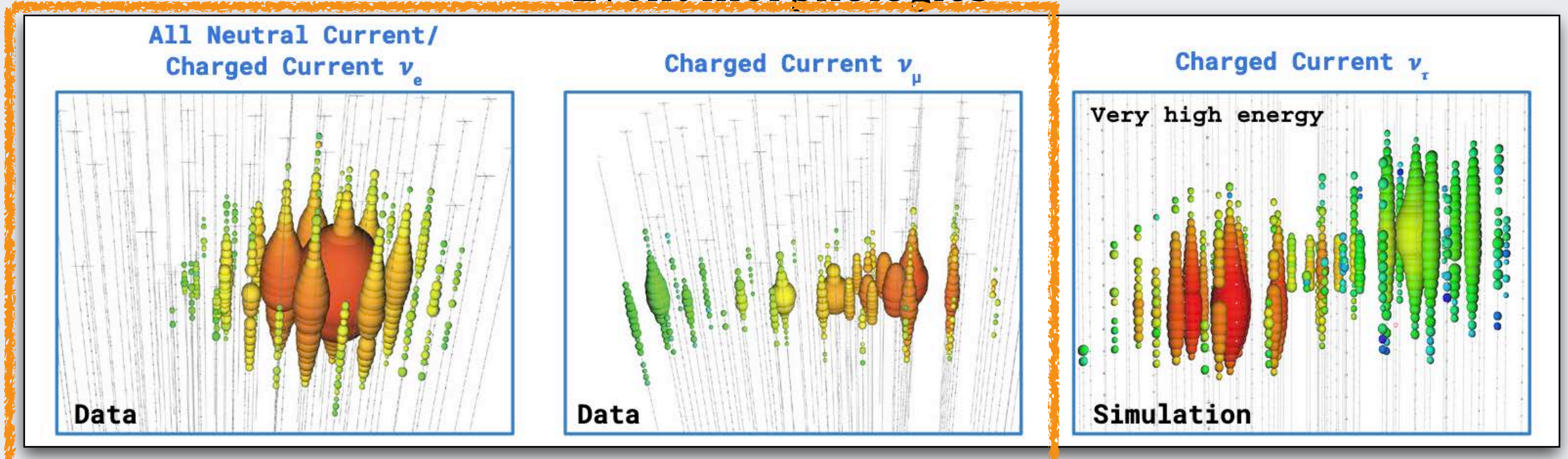


At higher energies, neutrino flavors can be readily distinguished—sometimes.

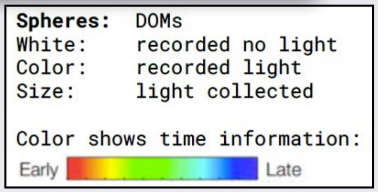


ν^{astro} in IceCube

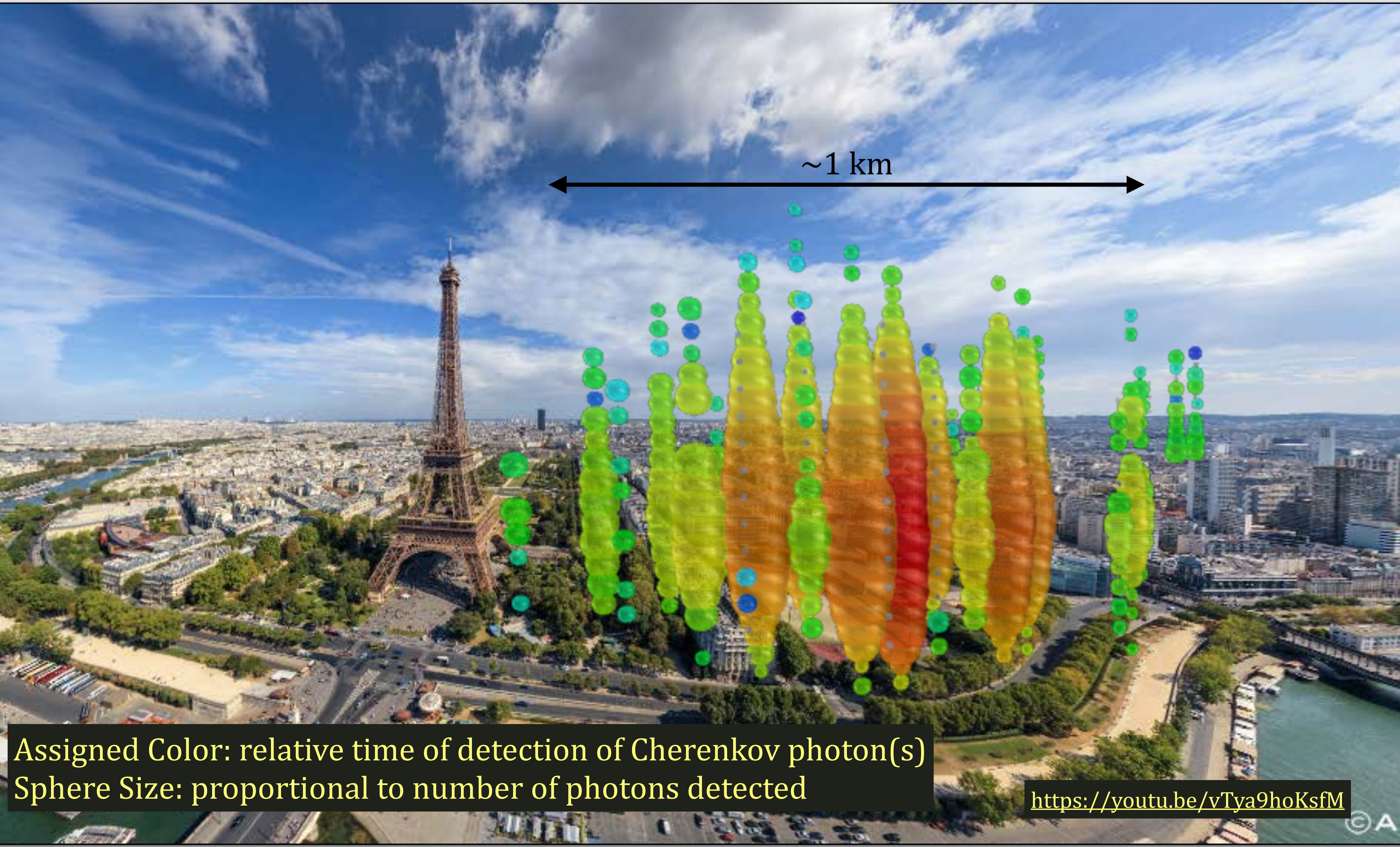
Event morphologies



IceCube has focused on track & cascade morphologies, as ν_τ^{astro} are exceedingly challenging to distinguish.



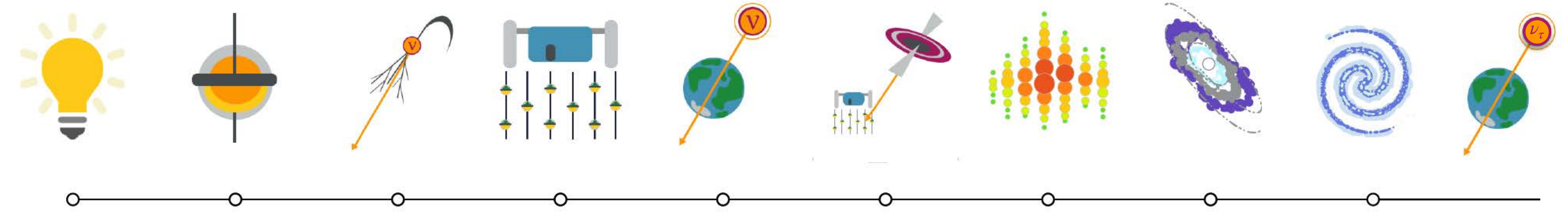
ν_e^{cc}? ν_τ^{cc}? ν^{nc}?



Assigned Color: relative time of detection of Cherenkov photon(s)
Sphere Size: proportional to number of photons detected

https://youtu.be/vTya9hoKsfM

IceCube Discovery Timeline



1988 — Telescope in the Ice Envisioned

2000 — AMANDA Completed

2001 — Atmospheric Neutrinos Detected

2011 — IceCube Completed

2013 — Astrophysical Neutrinos Discovered

2018 — First Source TXS 0506+056 Identified

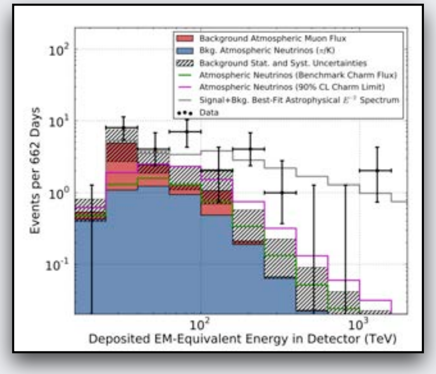
2021 — Glashow Resonance Neutrino Identified

2022 — Second Source NGC 1068 Identified

2023 — Third Source Milky Way Identified

— Seven Astrophysical ν_τ Observed

See this talk!



https://arxiv.org/abs/1311.5238

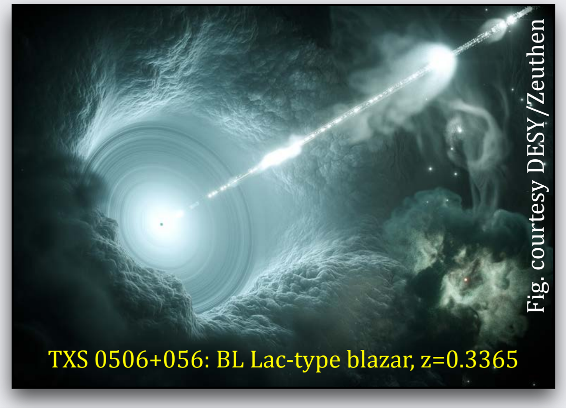
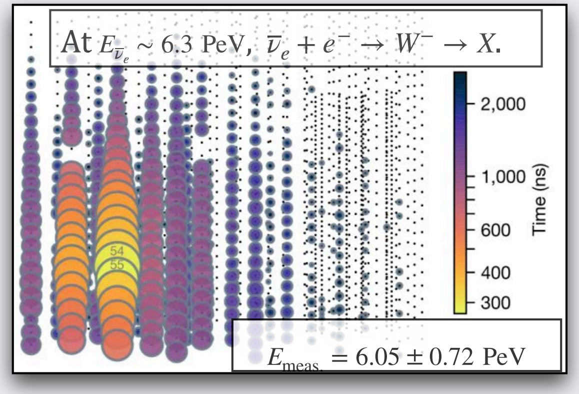


Fig. courtesy DESY/Zeuthen

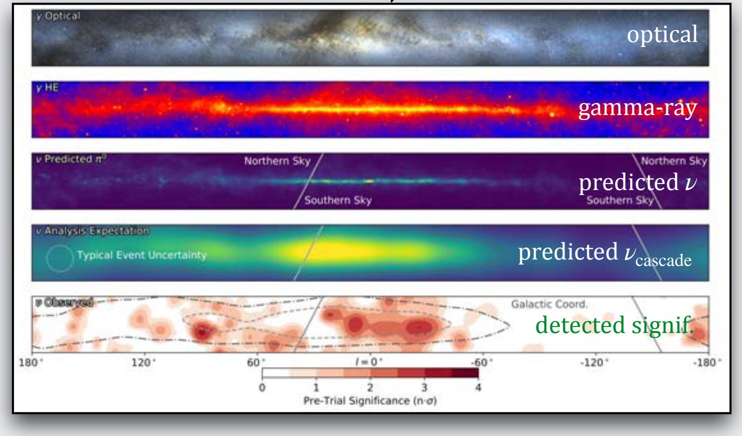
TXS 0506+056: BL Lac-type blazar, z=0.3365



At $E_{\bar{\nu}_e} \sim 6.3$ PeV, $\bar{\nu}_e + e^- \to W^- \to X$.

$E_{\text{meas.}} = 6.05 \pm 0.72$ PeV

Nature 591 (2021)



Science 380, 6652 (2023)

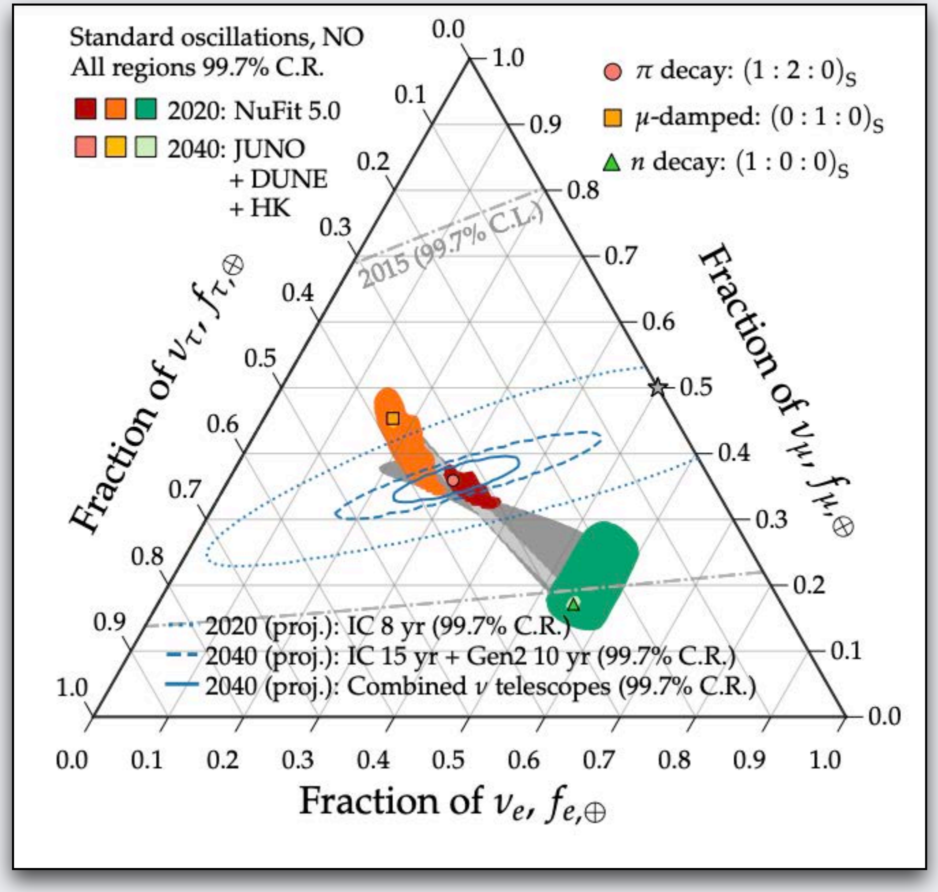
IceCube and ν^{astro}

- Standard ν oscillations:
  - Predict ~1:1:1 flavor ratio for ν^{astro} at Earth
    - 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)

Doug Cowen/Penn State/dfc13@psu.edu

Importance of Flavor ID for ν^{astro}

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

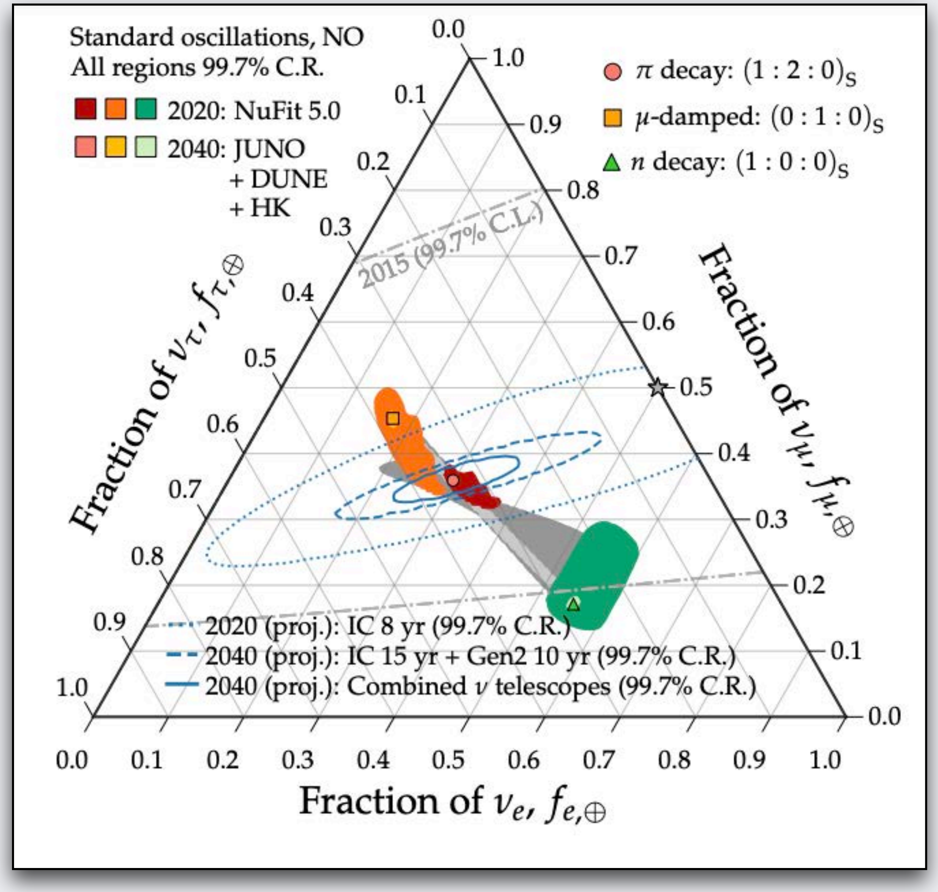


https://arxiv.org/abs/2012.12893

Importance of Flavor ID for ν^{astro}

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

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



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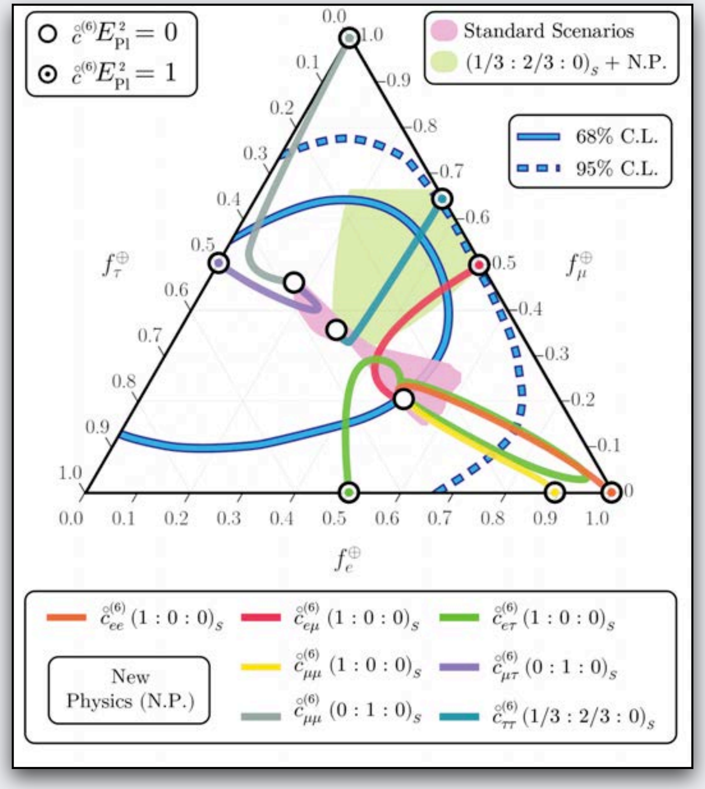
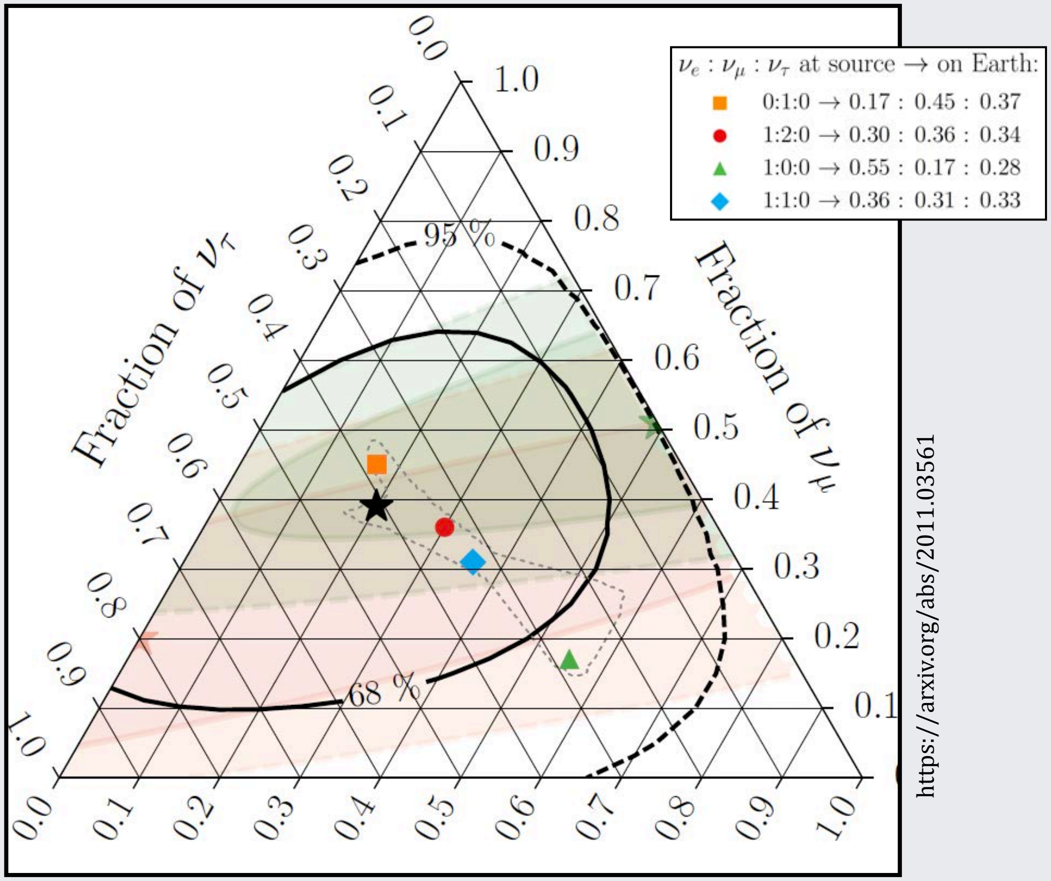


Nat. Phys. 18, 1287–1292 (2022)

Example: Effect of quantum gravity.

Importance of Flavor ID for ν^{astro}

Status quo (2020):



https://arxiv.org/abs/2011.03561

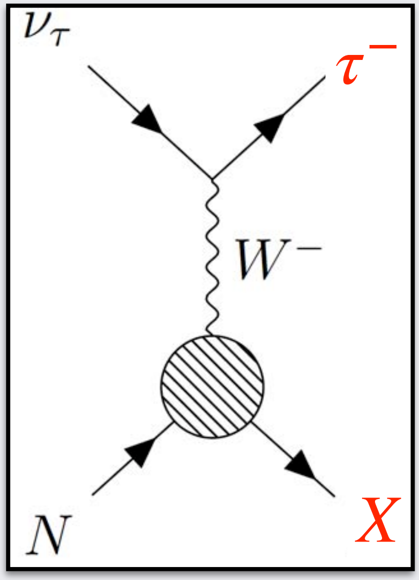
Measured flavor composition of IceCube HESE events. ★ is best fit point, consistent with presence of all 3 flavors, but ν_τ flux only weakly constrained.

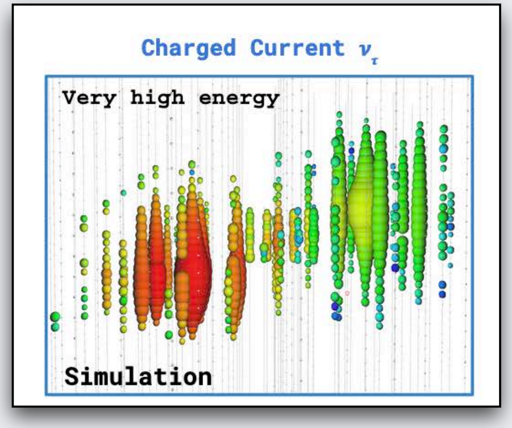
Better identification of ν_τ would help to shrink the contour and maybe signpost new physics.

Also:
- Study ν_τ (and τ) behavior at ultrahigh energies;
- Leverage their very high astrophysical purity;
- Get bragging rights with the largest exclusive sample of ν_τ.

Searching for Astrophysical ν_τ

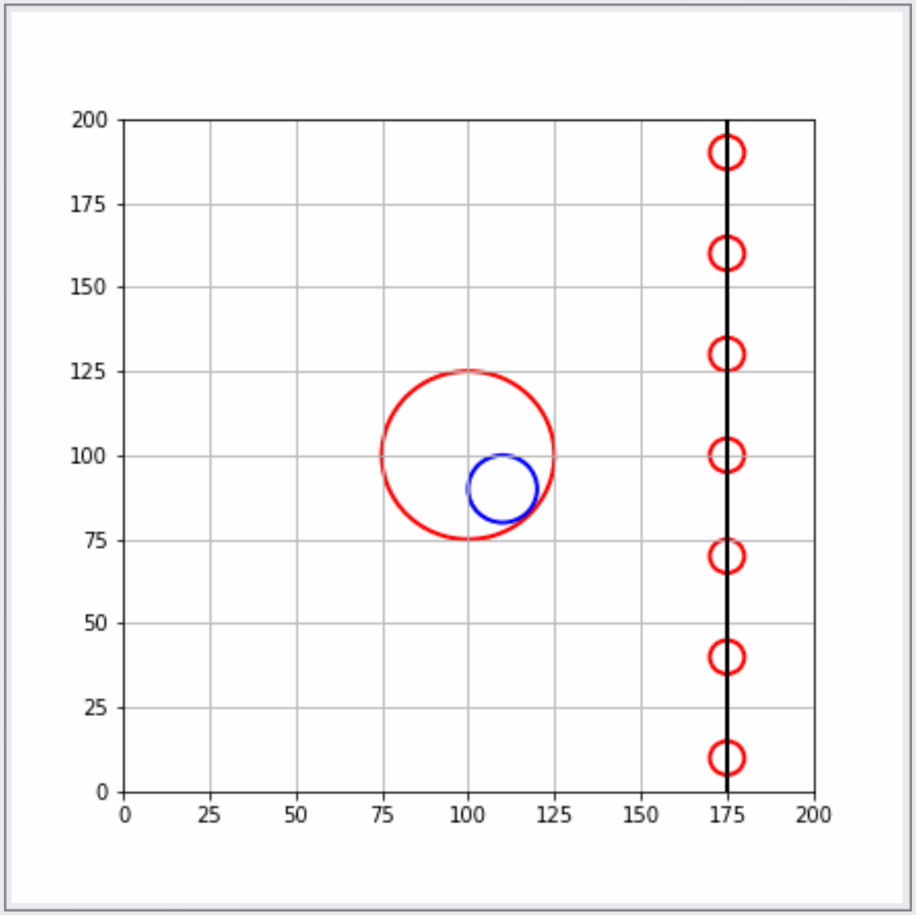
- ν_τ identification
  - Exclusive channel: “Double Bang”
    - $L_\tau > \sim 50\text{m}$ to distinguish two showers (X and $\tau \rightarrow (e, h)$)
      - But $L_\tau \simeq 50\text{m} \cdot (E_\tau\ /\text{PeV})$:
        - So need high energy. And favorable interaction vertex. And direction. Etc.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





Searching for Astrophysical ν_τ

At lower energies, the two ν_τ cascades are closer together. Here's a spiffy custom animation to help visualize, made by yours truly in collaboration with Dr. Chat G.P.T. IV:



○ DOM (Digital Optical Module)

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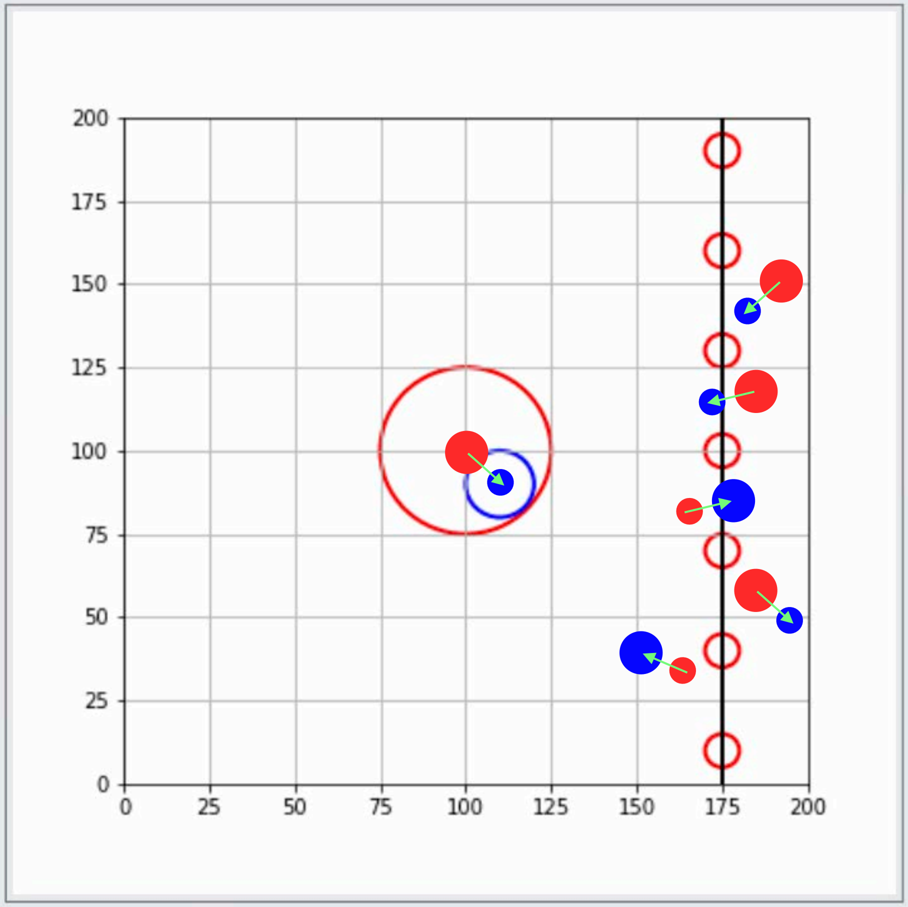
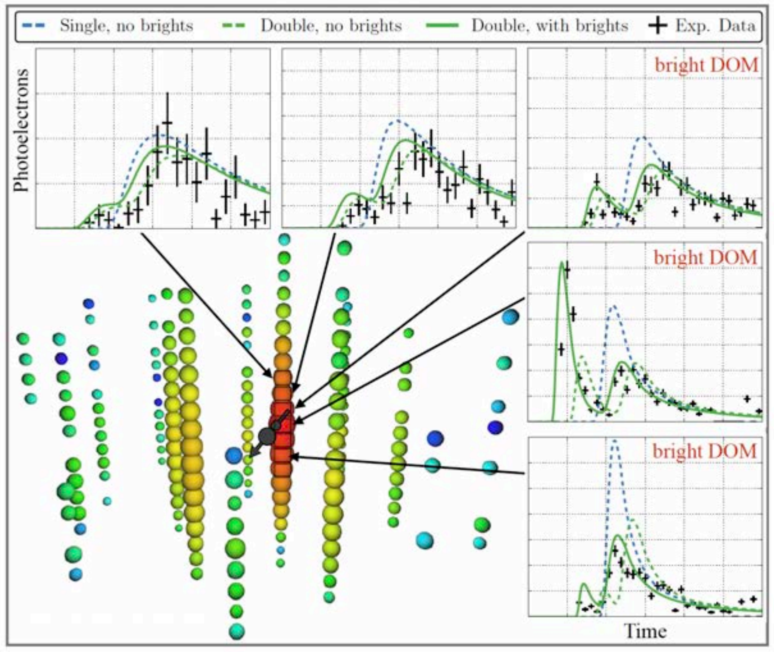


○ DOM (Digital Optical Module)

There's a large phase space for ν_τ signatures.

Searching for Astrophysical ν_τ

- ν_τ identification
  - <u>Inclusive</u> channel: “Double Cascade”
    - 60 well-contained HESE* events
    - Classified as
      41 single cascades,
      2 double cascades,
      17 tracks
      - “Double-double”→
    - 2.8σ exclusion of no $\nu_\tau^{\mathrm{astro}}$



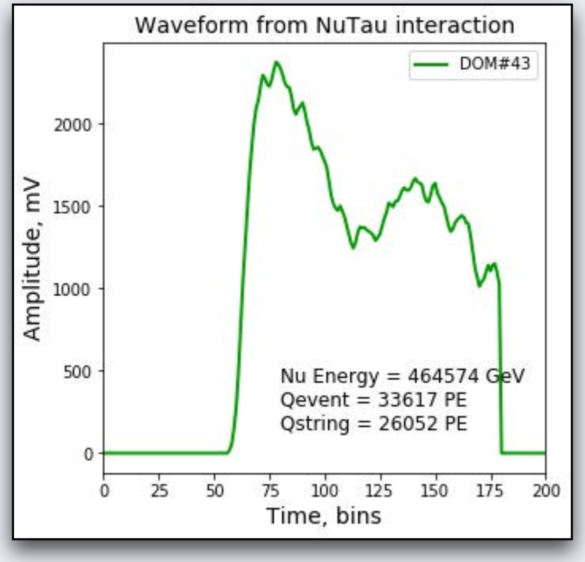
Eur. Phys. J. C 82, 1031 (2022)

*HESE: High-Energy Starting Event

Searching for Astrophysical ν_τ

- Challenge: Grow N_{ν_τ}, reduce N_{bkgd}

  Leverage: $(\phi_\nu^{\text{astro.}} \cdot \sigma_{\nu N}) \propto E_\nu^{-1}$
  - Exclusive channel: “Double Pulse”
    - $L_\tau \sim 10-50$ m to distinguish two showers in DOM waveform(s)
      - Identify DPs in one or more DOMs
    - Previous IceCube analyses
      - Looked for 1–2 modules with waveforms having clean DP signatures
      - Candidate ν_τ seen, but at low S/N



Searching for Astrophysical ν_τ

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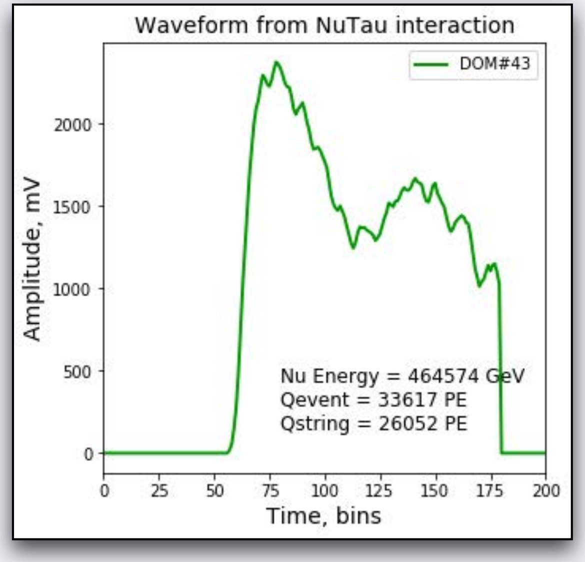
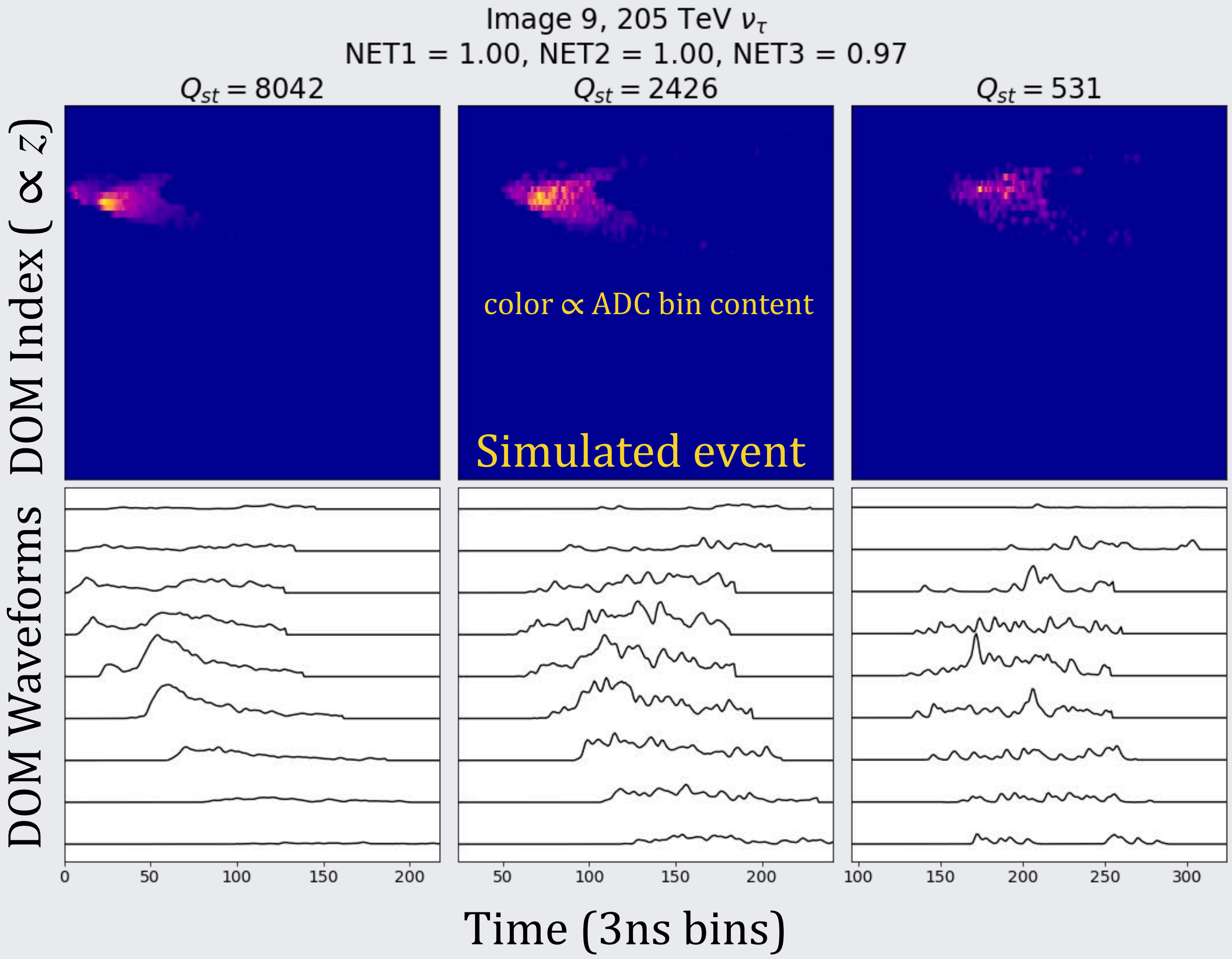
  Leverage: $(\phi_\nu^{\text{astro.}} \cdot \sigma_{\nu N}) \propto E_\nu^{-1}$
  - Exclusive channel: "Double Pulse"
    - $L_\tau \sim 10{-}50$ m to distinguish two showers in DOM waveform(s)
      - Identify DPs in one or more DOMs
    - Current analysis
      - Look for signature across 180 DOMs on 3 strings w/neural networks (spoiler alert: "Double Pulse" a bit of a misnomer)
      - High S/N achieved…



Searching for Astrophysical ν_τ: CNNs

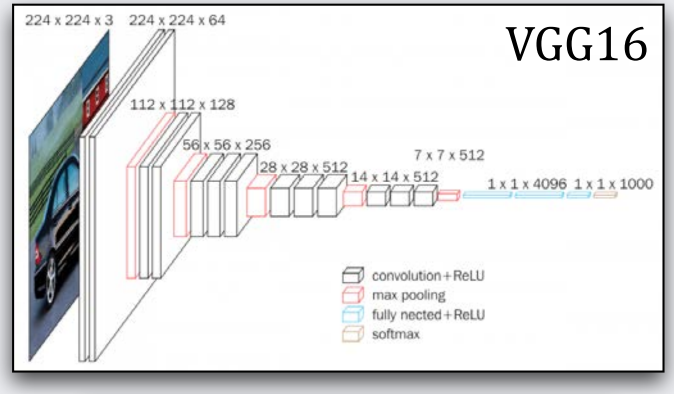
- ν_τ DP with up to 180 modules
  - Create 2d images, one per string

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



color ∝ ADC bin content

Simulated event



VGG16

Simonyan & Zisserman, 1409.1556

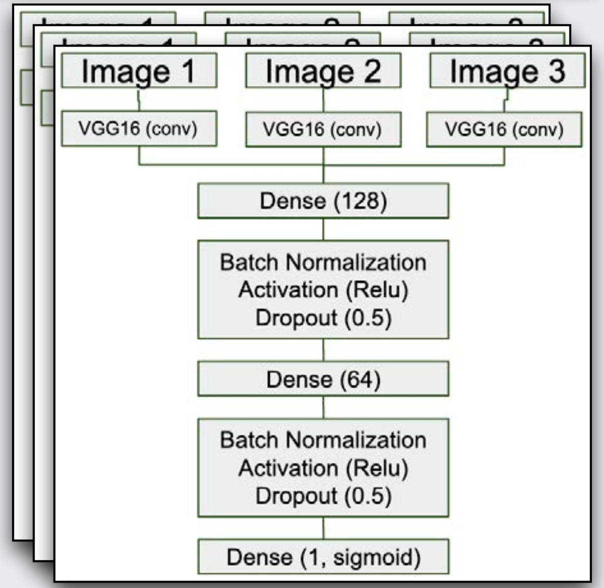
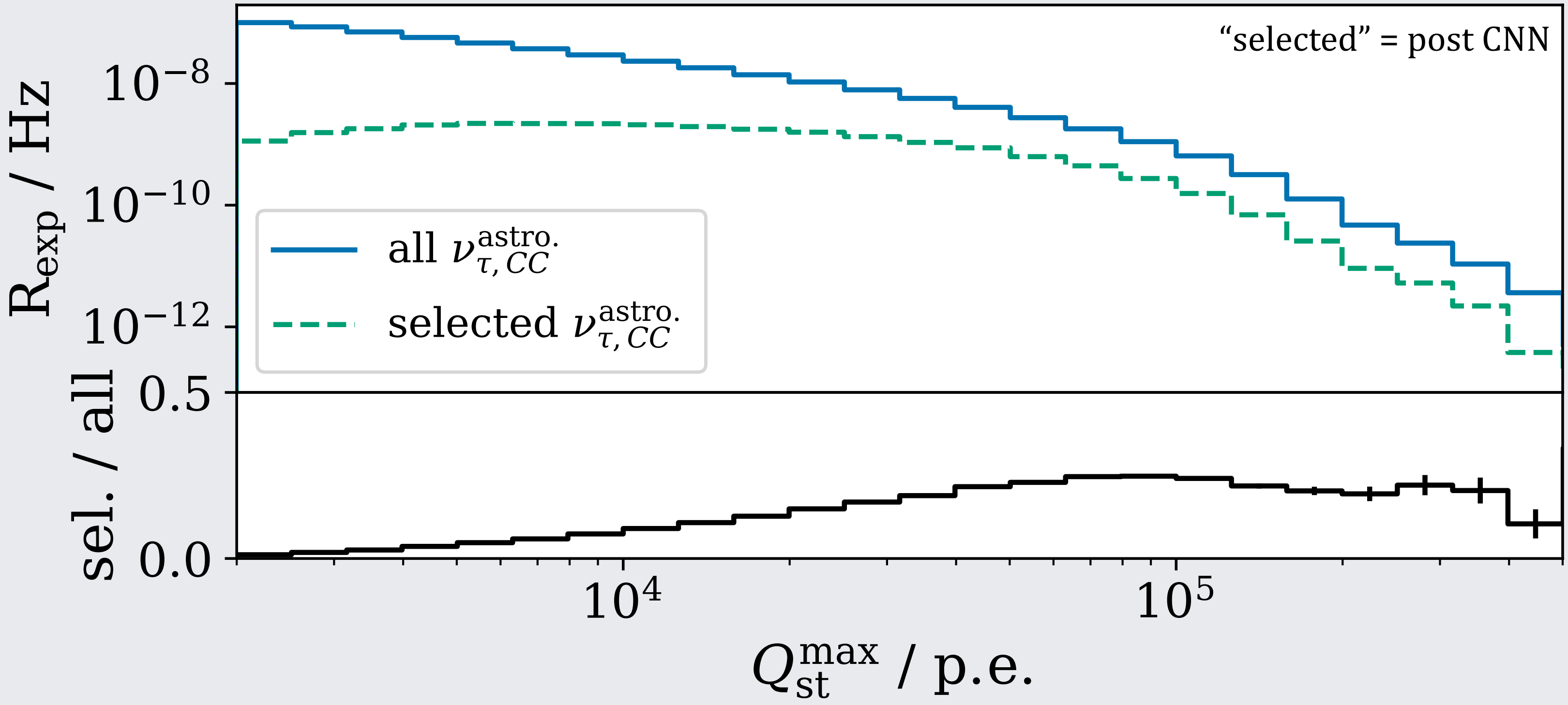


Image 1
Image 2
Image 3
VGG16 (conv)
VGG16 (conv)
VGG16 (conv)
Dense (128)
Batch Normalization
Activation (Relu)
Dropout (0.5)
Dense (64)
Batch Normalization
Activation (Relu)
Dropout (0.5)
Dense (1, sigmoid)

3 × VGG16'

Searching for Astrophysical ν_τ: $Q_{\text{str}}^{\text{max}}$

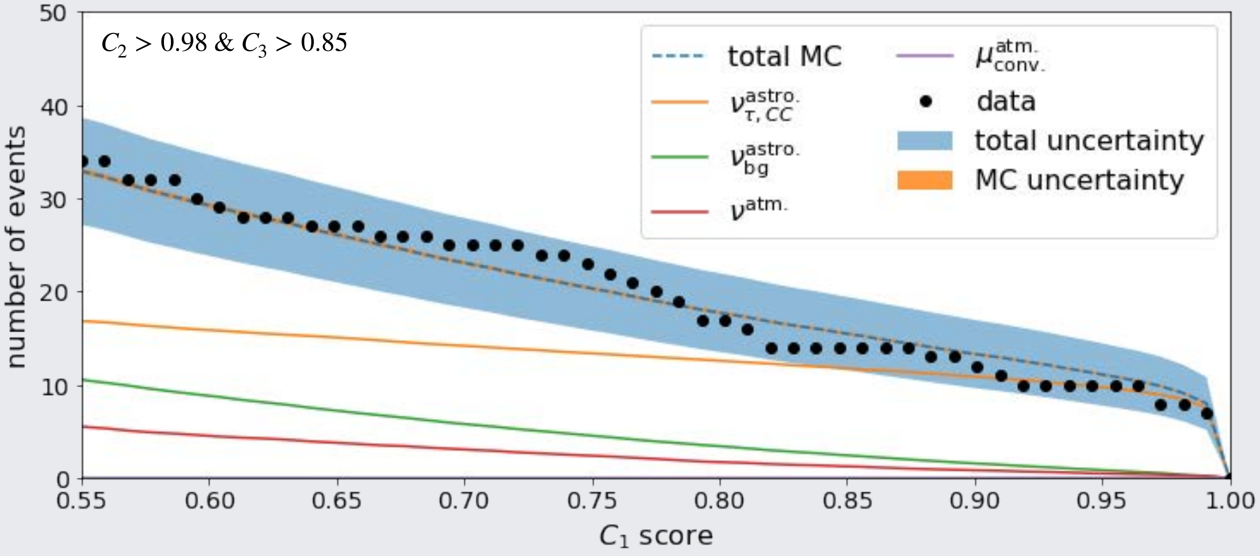
- Initial ν_τ DP selection criteria
  - Require ≥ 2000 p.e. on highest-charge string and ≥ 10 p.e. on two neighbors
  - Require cascade topology
- After initial criteria, have ~300x more background than signal



Searching for Astrophysical ν_τ: CNNs

- Trained 3 independent CNNs
  - $C_1 \geq 0.99$: ν_τ^{CC} vs. $\nu_e^{\mathrm{CC}}, \nu_x^{\mathrm{NC}}$
  - $C_2 \geq 0.98$: ν_τ^{CC} vs. $\mu_\downarrow$
  - $C_3 \geq 0.85$: ν_τ^{CC} vs. ν_μ^{CC}
- Gives S/N ~ 14.
- Backgrounds
  - $\nu_{\mathrm{astro.}}$ and $\nu_{\mathrm{atm.}}$
    - Sub-dominant: $\mu_\downarrow$
- Off-signal region Data-MC agreement is good for $C_{1,2,3}$

Cumulative rate, $\Phi_{\mathrm{GlobalFit}}$

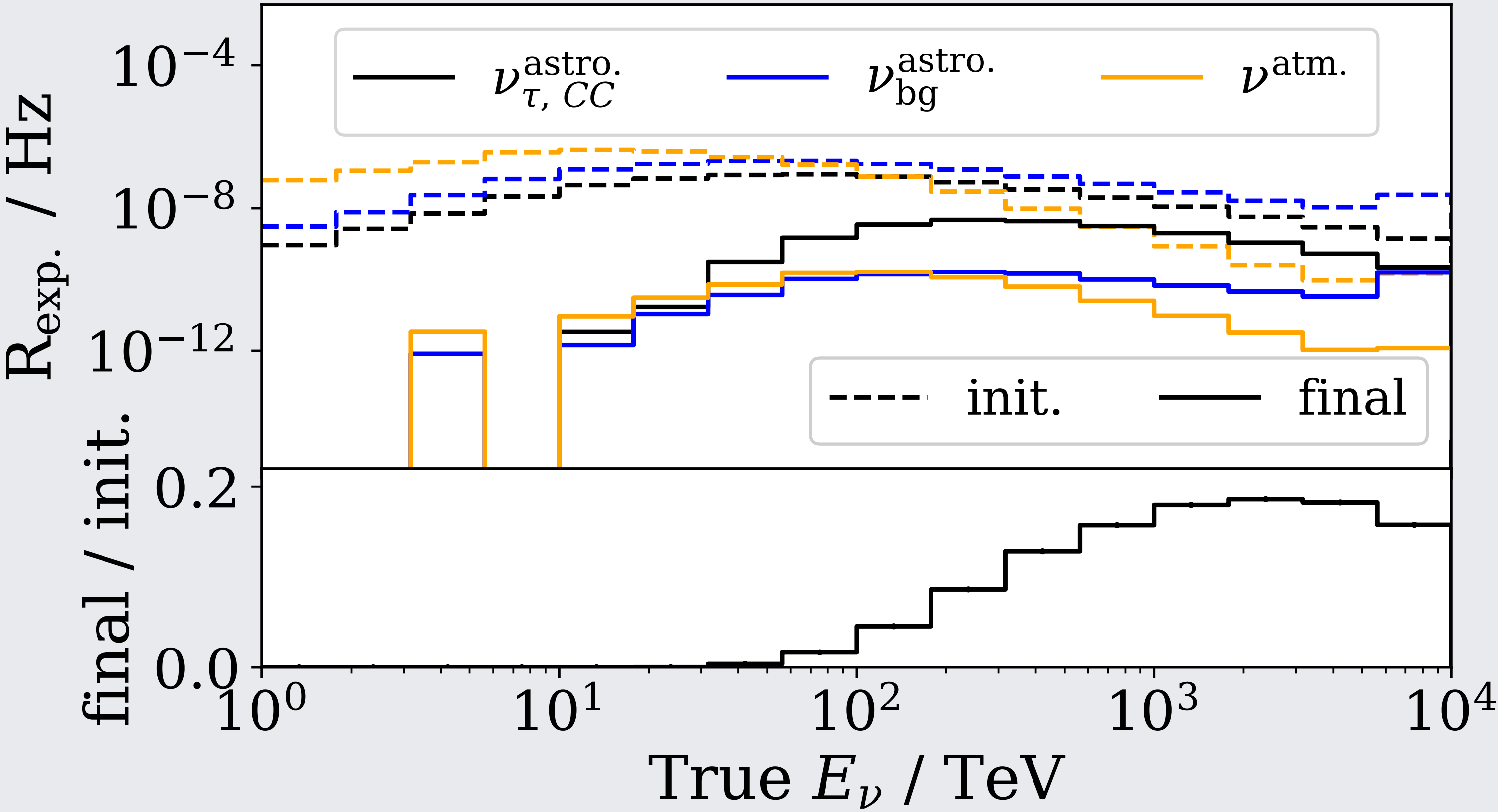


N_{evt}

C_1

Searching for Astrophysical ν_τ: $E_{\nu_\tau}^{\mathrm{true}}$

- E_{ν_τ} spectrum:



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

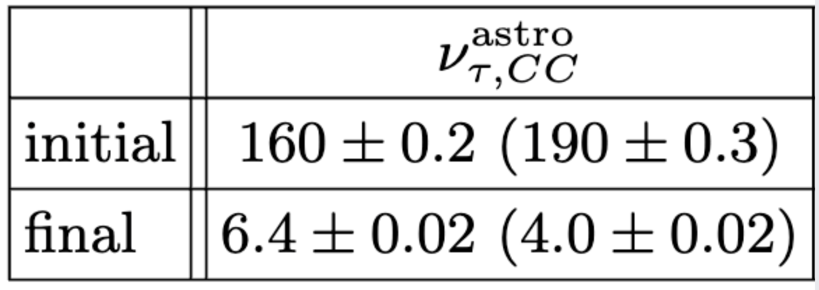
Searching for Astrophysical ν_τ: S & B

- 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 flux giving least-significant exclusion of null hypothesis
    - (Conservative: Typically, we use most-significant exclusion & trials-correct)
  - ν^{atm}: Conventional flux (Honda et al.; IceCube msmts.); possible prompt* flux (Bhattacharya et al.; IceCube exclusion)
  - $\mu_\downarrow$: Only conventional (prompt* not yet definitively measured)
  - Other: ν^{astro}–induced charm; on-shell W; Earth-crossing $(\nu_e, \nu_\mu) \rightarrow \nu_\tau$

*From atmospheric charm decays.

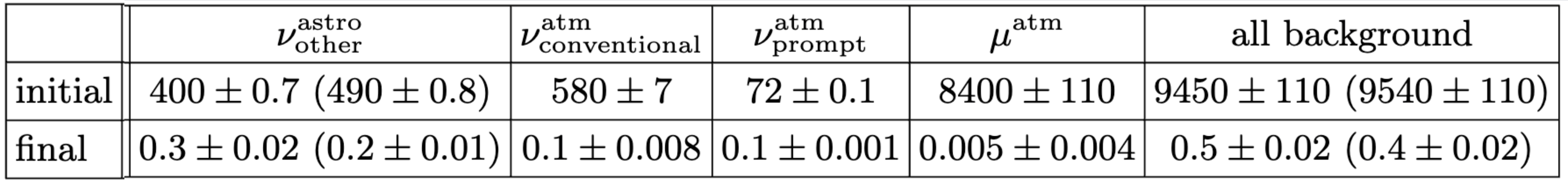
Searching for Astrophysical ν_τ: S & B

Signal



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

Backgrounds



	$\nu_{\text{other}}^{\text{astro}}$	$\nu_{\text{conventional}}^{\text{atm}}$	$\nu_{\text{prompt}}^{\text{atm}}$	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)

IceCube's *GlobalFit* (*HESE*) flux assumed.

Note: ν^{atm} can be rejected by accompanying $\mu_\downarrow$.
This "self-veto" effect was *not* included in background estimates above.

Searching for Astrophysical ν_τ: Charm

- Backgrounds/Systematics in more detail: Charm
  - Charm: $\nu_e^{\text{astro}} \rightarrow eW;\ W \rightarrow cs$ (and $\nu_{\text{NC}}^{\text{astro}}; Z \rightarrow c\bar{c}$)
    - $\lambda_{\text{charm}} \simeq \mathcal{O}(\text{m}),\ E_{\text{dep.}} \simeq 10^{12-14}$ 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^{astro} bkgd.
      - Plus small correction to account for newest PDFs
    - Added to estimated background *after unblinding*
      - (Future improvement: Charm event morphology may be sufficiently different from ν_τ that new CNN could reject.)

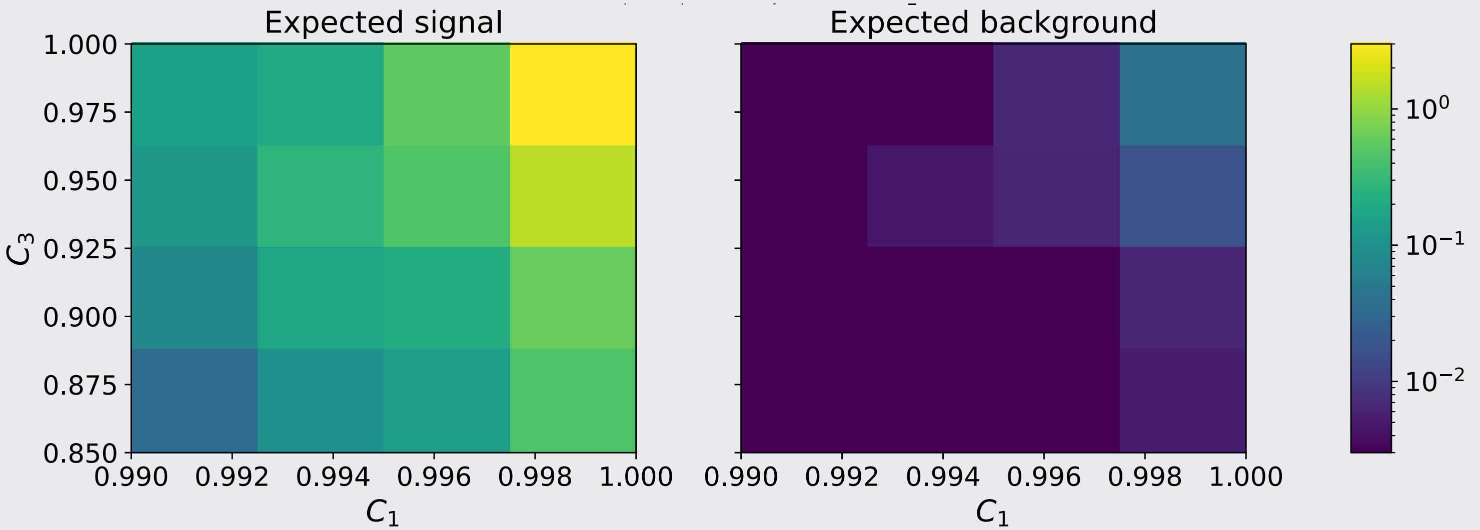
Searching for Astrophysical ν_τ: Other Bkgds.

- 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. Uncertainties in the following items were modeled via randomly fluctuating non-ν_τ fluxes within their expected range:
    - 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)

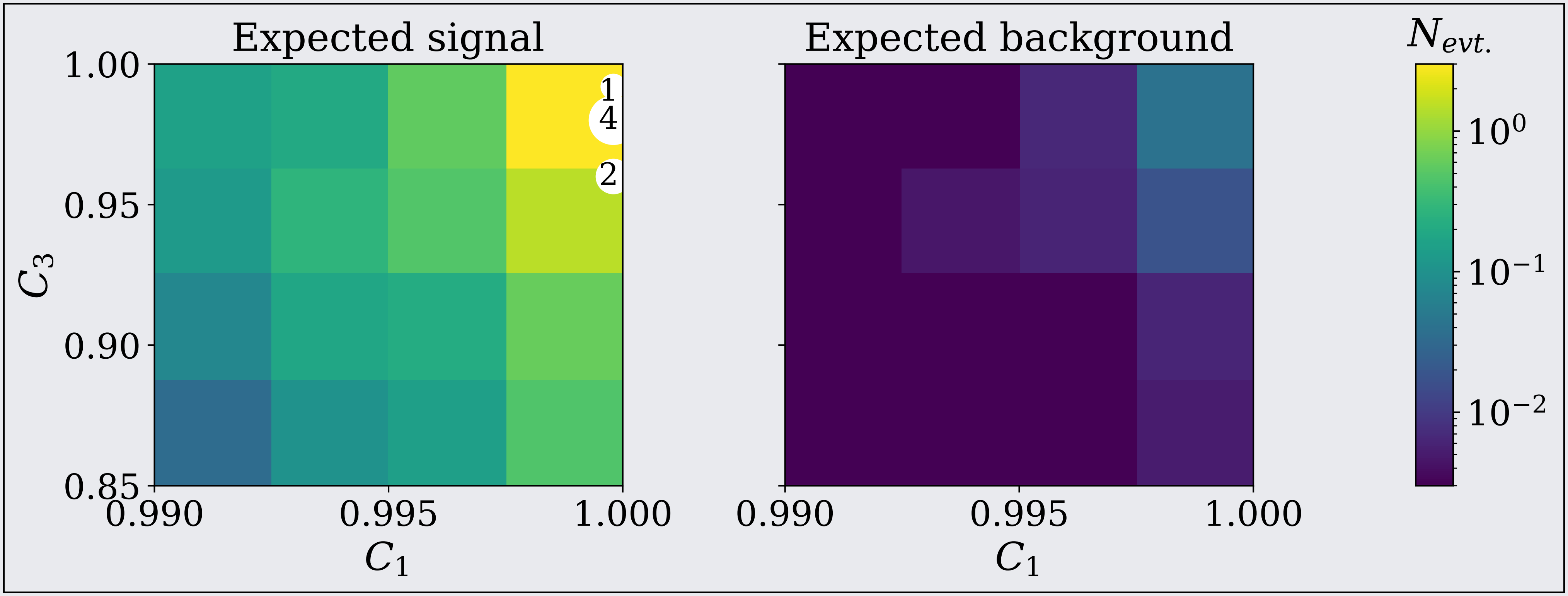
Astrophysical ν_τ: Results

- 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:



Astrophysical ν_τ: Results

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

Astrophysical ν_τ: Results

- For IceCube's *GlobalFit* flux, exclude $\phi(\nu_\tau^{\text{astro}}) = 0$ at 5.1σ
  - Other fluxes: 5.2σ, 5.2σ, 5.5σ (*Inelasticity*, *Diffuse*, *HESE*)
- Also a 40%-level confirmation of the standard oscillation picture
  - $\left(7 \pm \sqrt{7}\right)$ ν_τ's
- Powerful confirmation of IceCube's 2013 ν^{astro} discovery
  - ν_τ^{atm} negligible at these E_ν

Accepted for publication by PRL.
https://arxiv.org/abs/2011.03561

Post-Unblinding Checks

- Event displays
- Saliency maps
- Reconstructed data vs. MC: E_{ν_τ}, $\cos(\theta_{\text{zen}})$, vertex
- Data-driven tests
  - $\mathscr{P}$(S↔B) under forced light-level variations

- CNN scores’ robustness
  - With 7 ν_τ candidates:
    - Adversarial attacks
    - Manually smooth DP waveforms
    - Forced arrival time shifts
      - Randomly
      - Dust band focused
  - With backgrounds:
    - Adversarial attacks on data
    - Adversarial attacks on ν_e^{astro} MC

Summary →

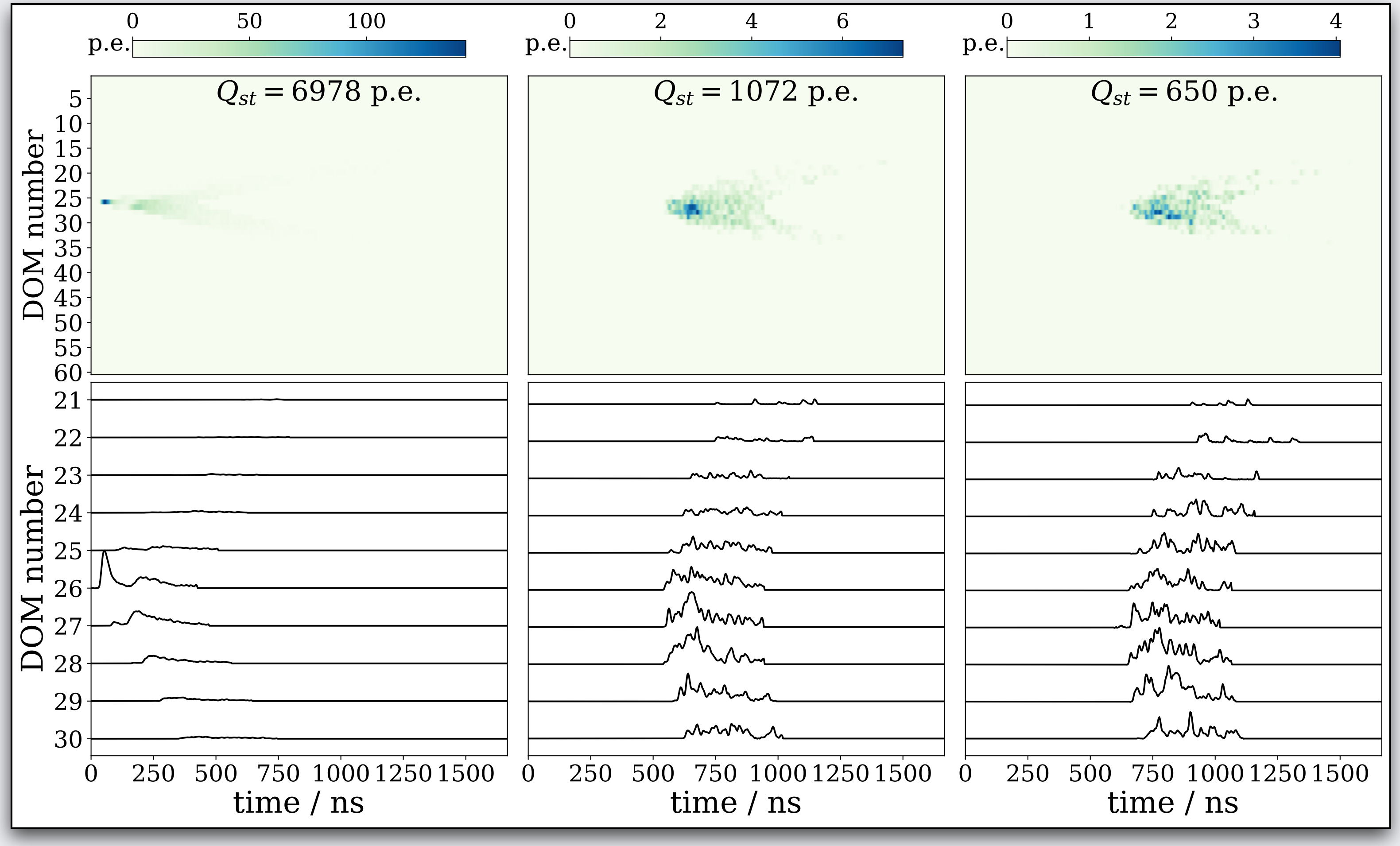
Post-Unblinding Checks: Summary

- CNNs sensitive to overall event structure, not just to a few DP waveforms
- Reconstructed distributions look fine
- Induced $S \leftrightarrow B$ migration probabilities small & consistent with MC estimates
- CNN scores very robust
  - Only alterations (e.g., using *DeepFool*) outside expected ranges produce noticeable change

Event Pics: Clear Double Pulse Signature

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

DOM number (∝ depth)

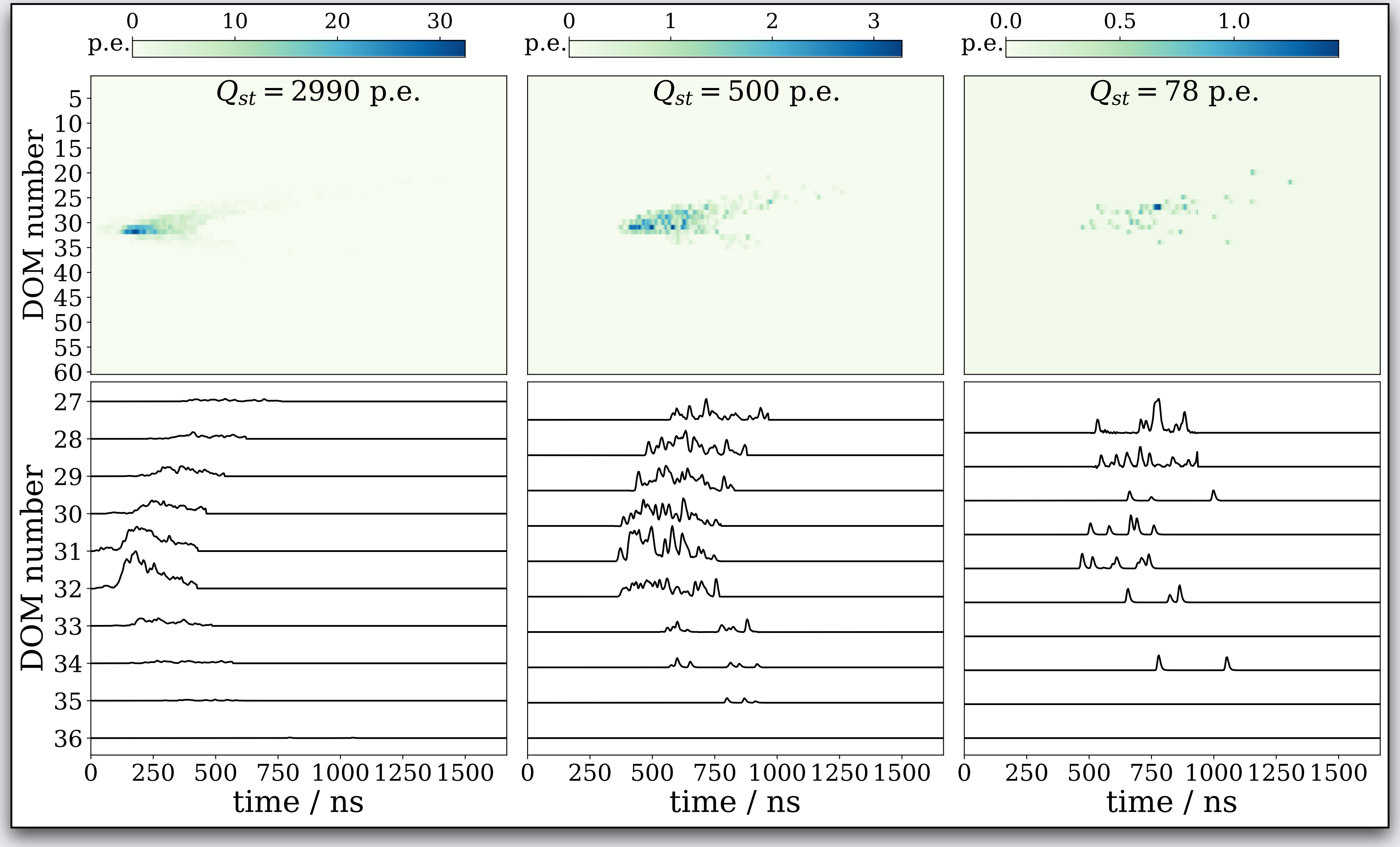


time/ns

Gratifying to find this event again.

Event Pic: Unclear DP Signature

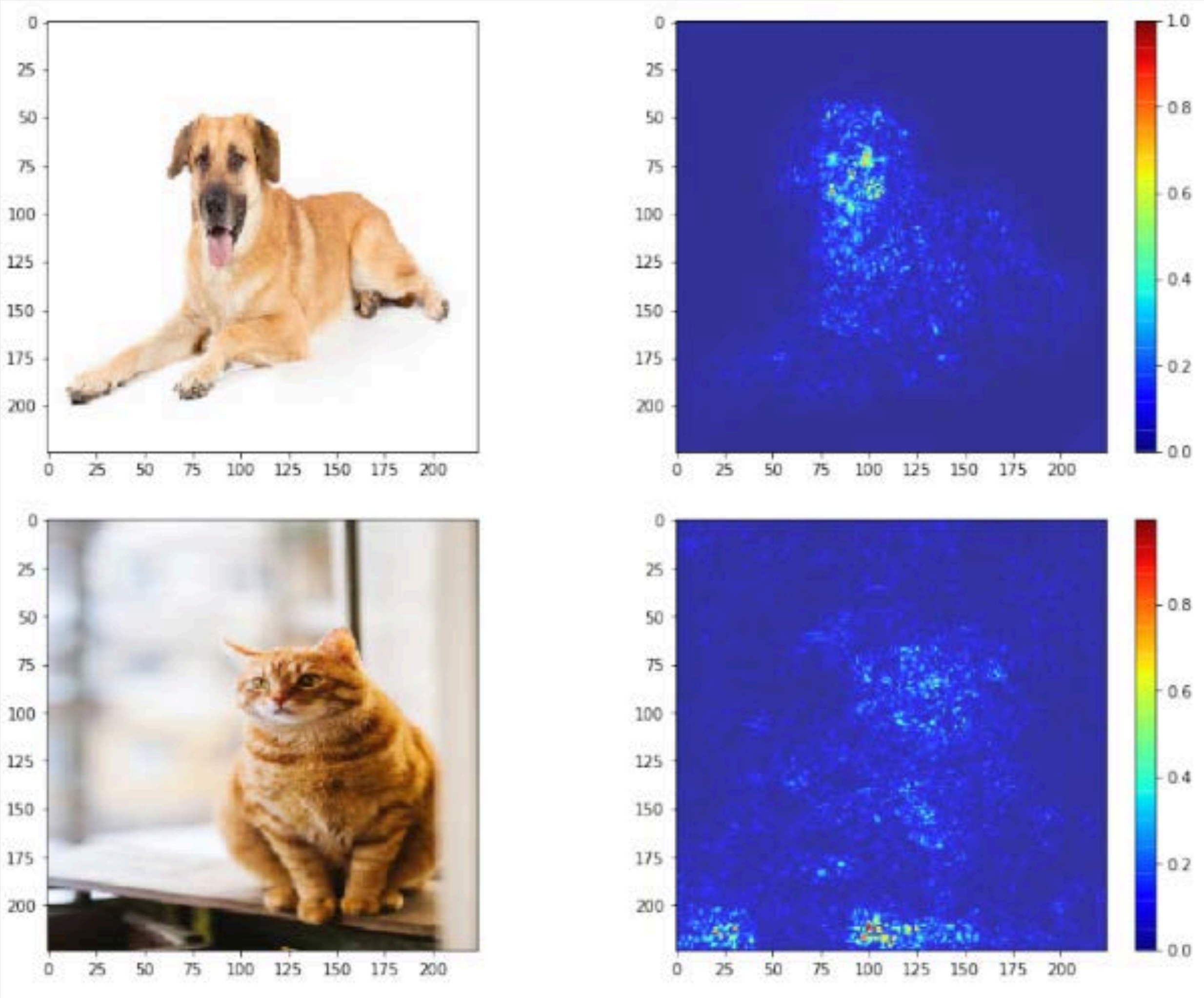
Here's "Barn Owl," another new event:



No clear DP waveform! Use *saliency maps* to see 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 CNN." Saliency = gradient of CNN score vs. pixel content.

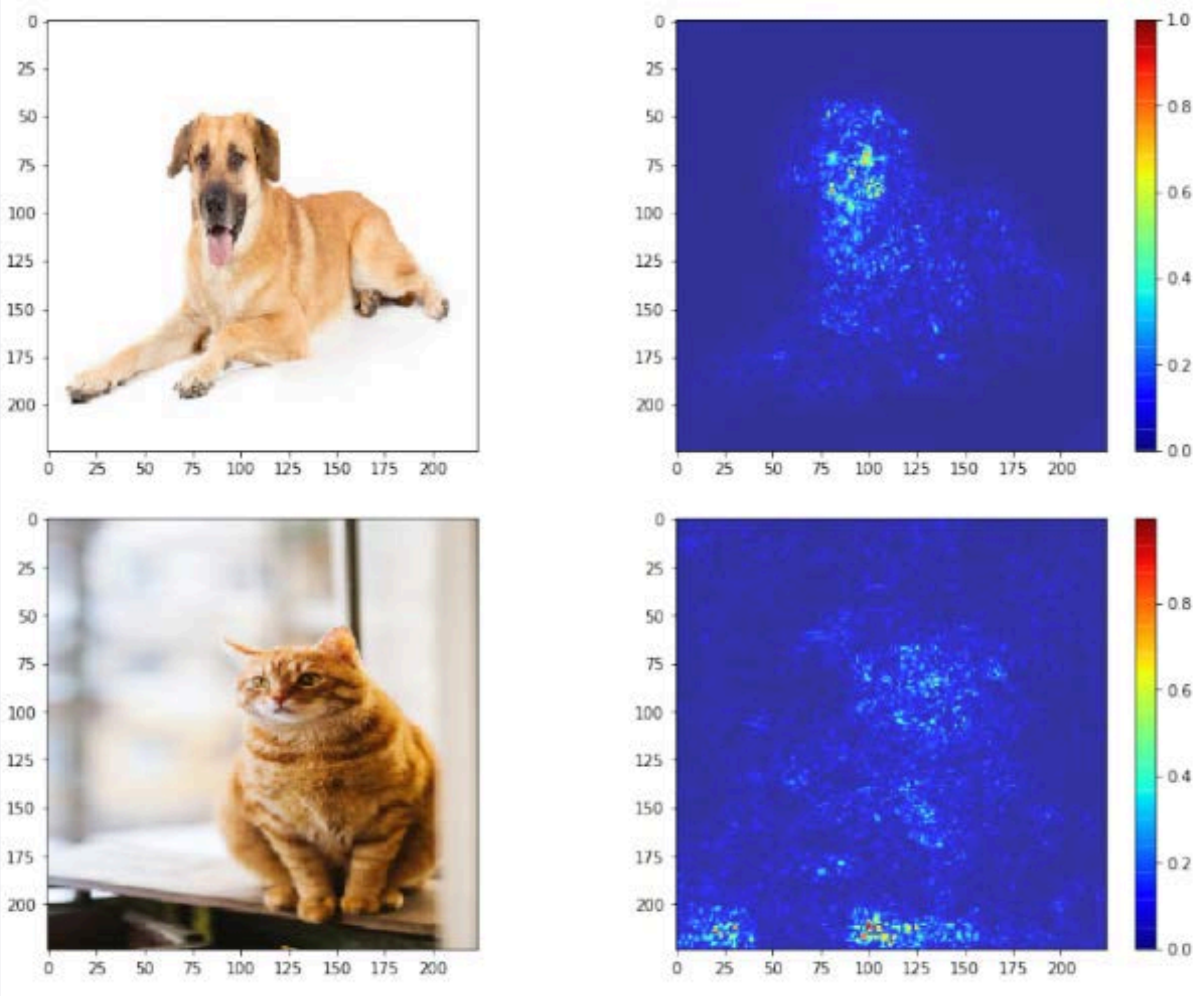


https://usmanr149.github.io/urmlblog/cnn/2020/05/01/Salincy-Maps.html

Maps show parts of the photos CNN is most sensitive to in identifying the dog or cat in photos.

Saliency Maps

Saliency maps “rank the pixels in an image based on their contribution to the final score from a CNN.” Saliency = gradient of CNN score vs. pixel content.



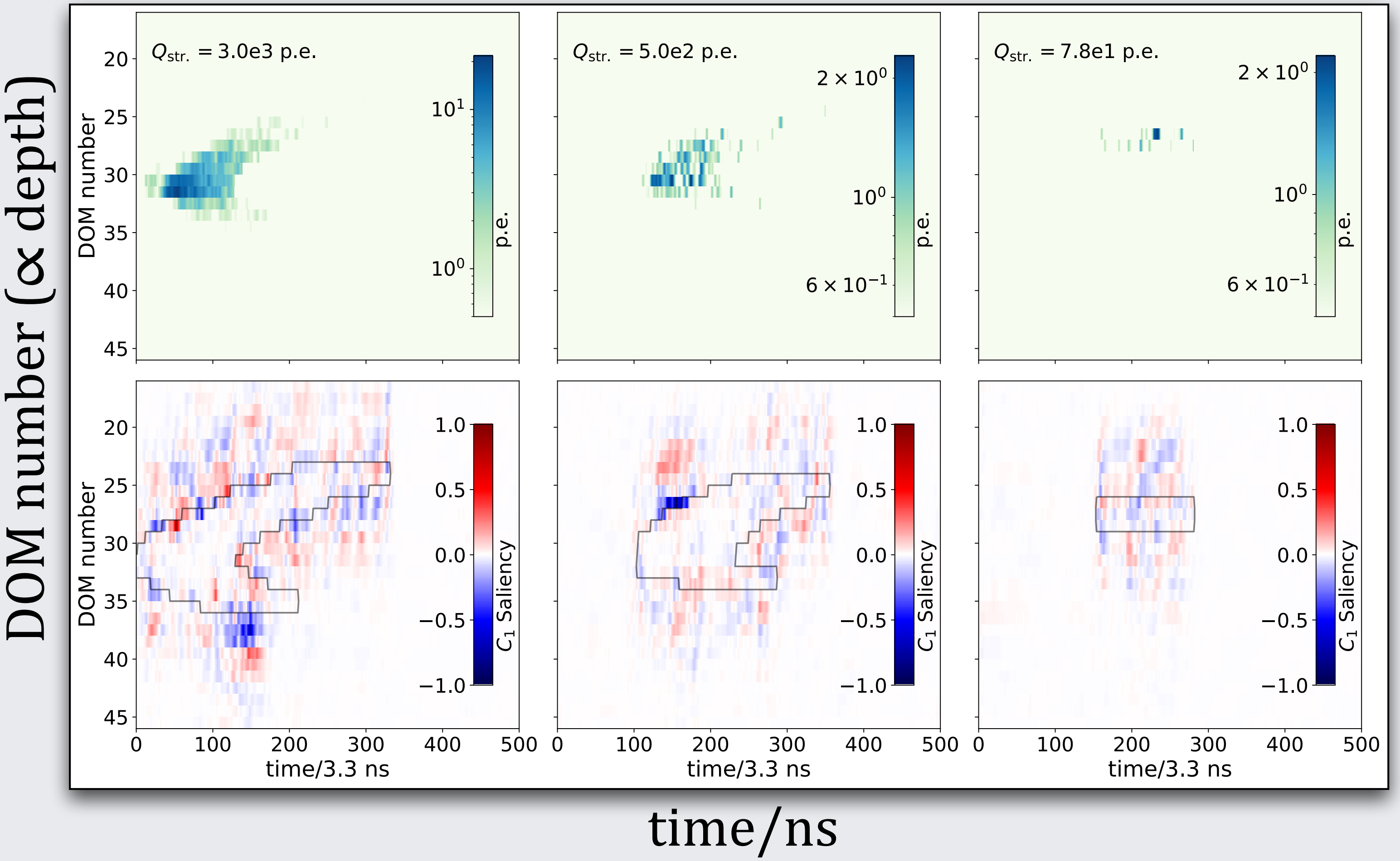
https://usmanr149.github.io/urmlblog/cnn/2020/05/01/Salincy-Maps.html

Maps show parts of the photos CNN is most sensitive to in identifying the dog or cat in photos.

(Evidently, the training sample had many of its cats sitting on tables.)

Event Pics w/Saliency Maps

“BarnOwl,” with log Q_{str} and saliency maps:



Measured light levels in each of 3 strings.

Saliency:

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

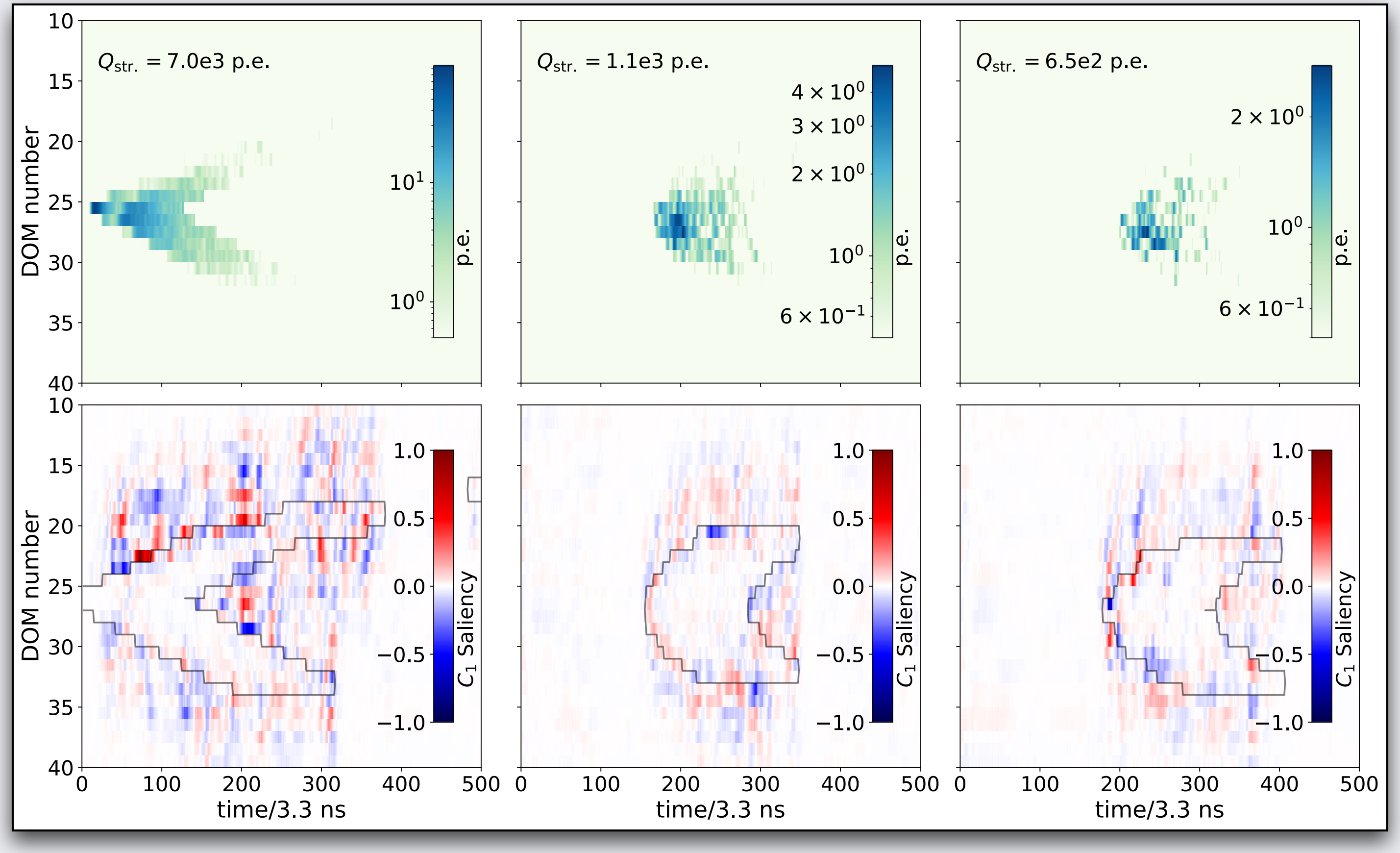
- light↑, C_1↑
- light↓, C_1↑

Contours: where light level → 0.

Large $S(C_1)$: where/when Δ(light) → ΔC_1. (Bright pixels can have small $S(C_1)$.) Generally, $S(C_1)$ shows C_1 sensitive to overall event shape.

Event Pics w/Saliency Maps

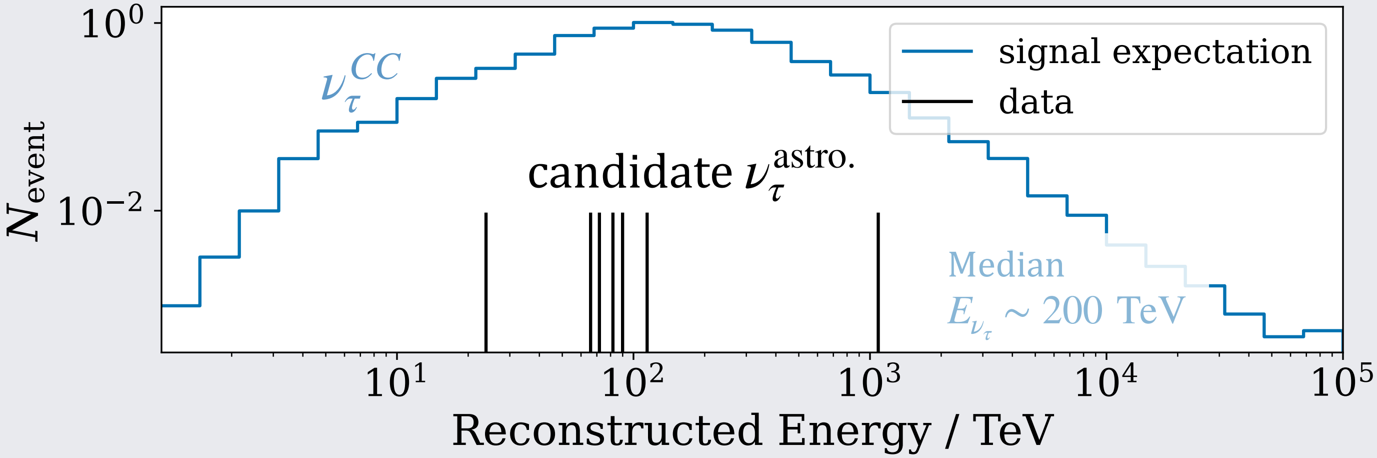
DoubleDouble, with log $Q_{\rm str}$ and saliency maps:

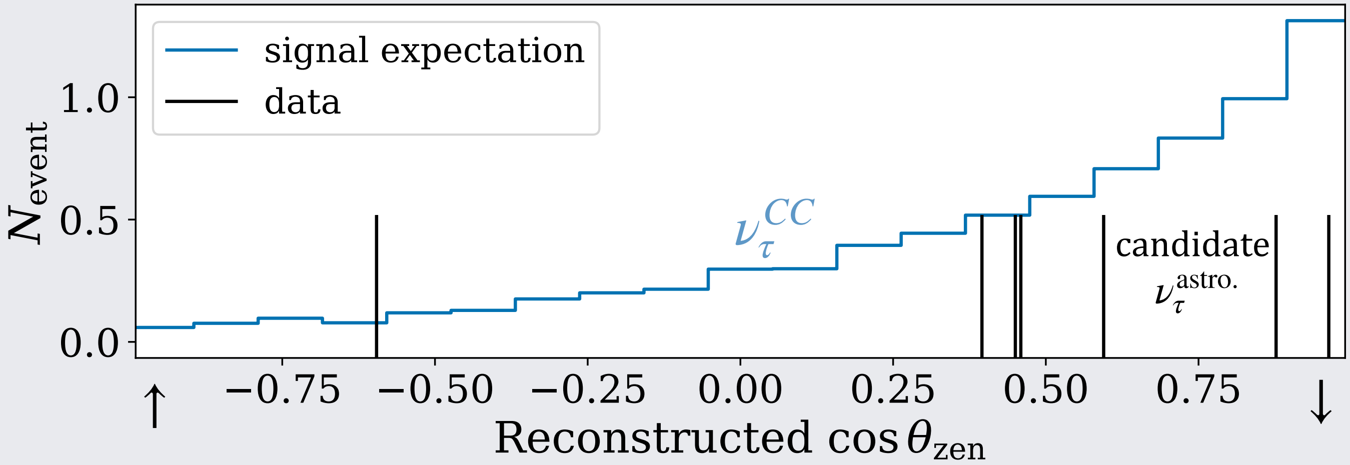


All event pics in backup.

Post-Unblinding Checks: $E_\nu^{\text{reco.}}$, $\cos\theta_{\text{zen.}}^{\text{reco.}}$

- Single-pulse reco.
- Good data–MC agreement…
  - …but take numbers w/ grain of salt

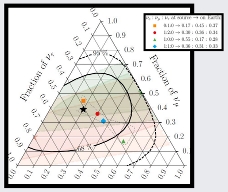




(IceCube's "GlobalFit" flux assumed above.)

Conclusions: What's Next?

- Used just 3 (of 86) strings. Using more strings would:
  - Improve bkgd rejection ⇒ relax cuts, more signal
    - Improve our $\Phi(\nu_\tau^{\text{astro}})$ measurement (see backup)
    - Update "triangle plot" with ν_τ information



      - Search for new physics (e.g., quantum gravity)
      - Identify likely astrophysical-source acceleration scenarios; start excluding some
- Apply a dedicated reco. for direction, E,…
  - Study parameters of the ν_τ and τ themselves
    - Inelasticity, L_τ, energy asymmetry, …
  - Look for ν_τ^{astro} point sources
- $\lambda_s^{\text{sea}} > \lambda_s^{\text{ice}}$:
  - KM3NeT, P-ONE,… should have larger effective volume per string

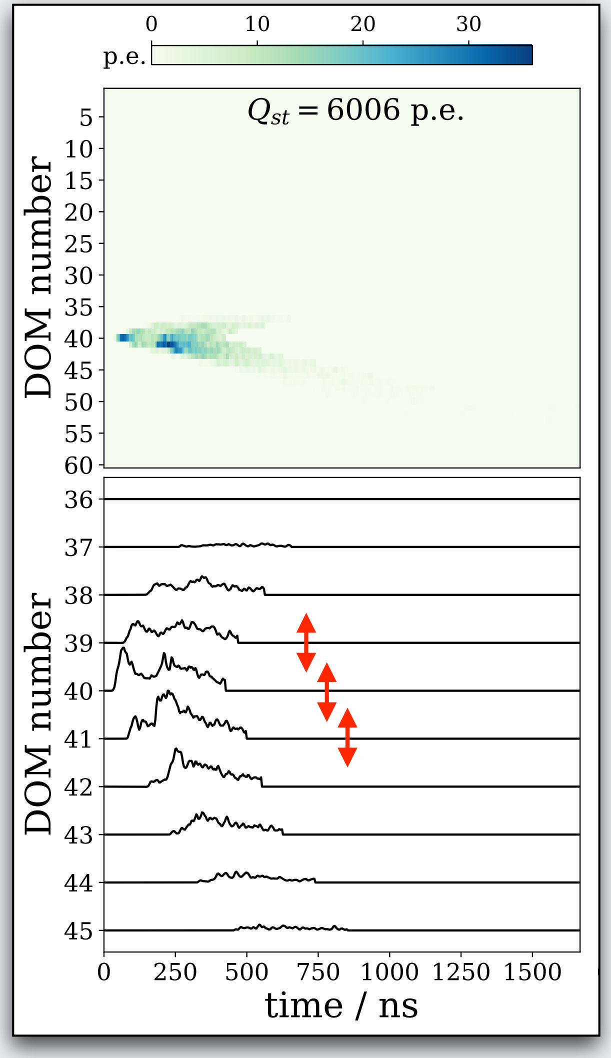
IceCube Collaboration

Spring 2022 Collaboration Meeting, Brussels, Belgium

Backup

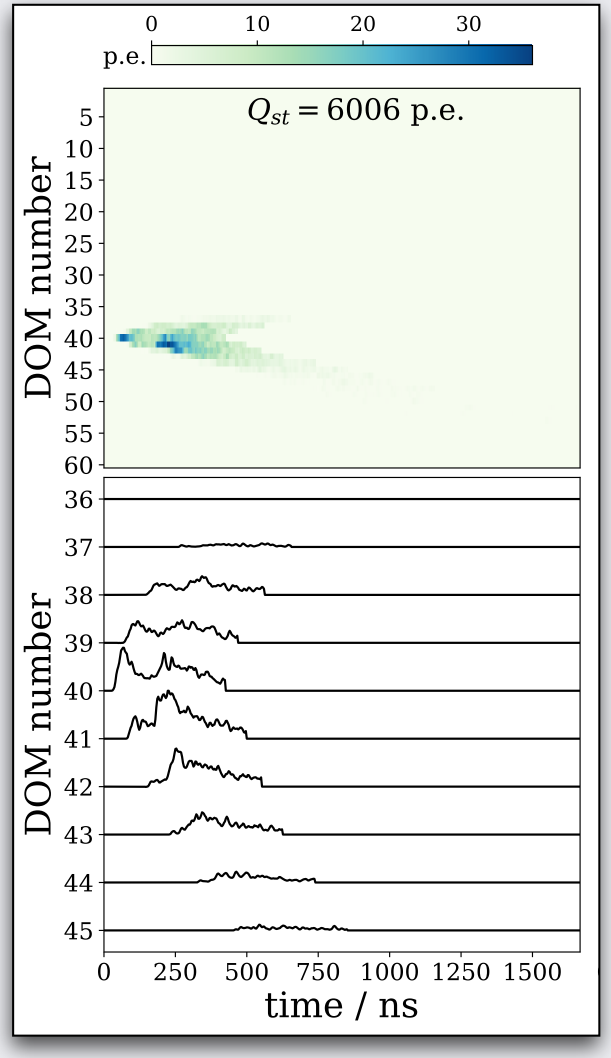
Data-Driven Systematic Checks

- Starting point: 8,188 events
  - Use 8,175 at slight distance signal box edge
- Vary waveforms to estimate migration probability
  - Procedure:
    - Apply variation randomly to each event,
    - evaluate CNN scores,
    - calculate migration probabilities.
    - Repeat 750 times/event. ~6M trials for bkgd; ~5k for signal.



Data-Driven Systematic Checks

- Variations studied:
  - DOMEff: scale waveforms w/ $\sigma = \pm 10\,\%$
  - Ice absorption and scattering: scale in groupings in z: every 3, 4, 5 DOMs (every 51m, 68m, 85m) w/ $\sigma = \pm 20\,\%$
  - Ice scattering: shift times in groups of 4 DOMs with $\sigma = \pm 10$ ns
  - Ice birefringence: scale all 120 DOMs in 2nd and 3rd strings w/ central value dependent on azimuth w/ $\sigma = \pm 20\,\%$
    - Note: scaling inverted from expectation: MC did not have full birefringence but data does

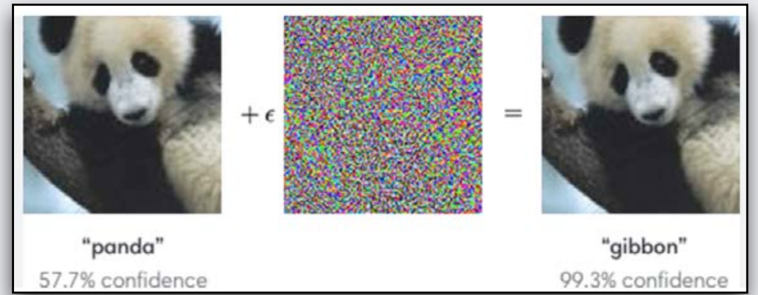


Data-Driven Systematic Checks

- Outcomes:
  - Migration out of signal box:
    - Very unlikely: $< 0.3\% \pm 0.08\,\%$ in all cases (< 0.02 signal events)
  - Migration into signal box:
    - Also very unlikely: $< 0.002\% \pm 0.0002\,\%$ (<0.2 background events)
      - Adding in 0.2 background events would modestly reduce our significance.
      - Current analysis already includes these systematics, estimated from MC
        - Replacing one estimate with the other (so as not to double count) would not impact the final result.

Other CNN Robustness Studies

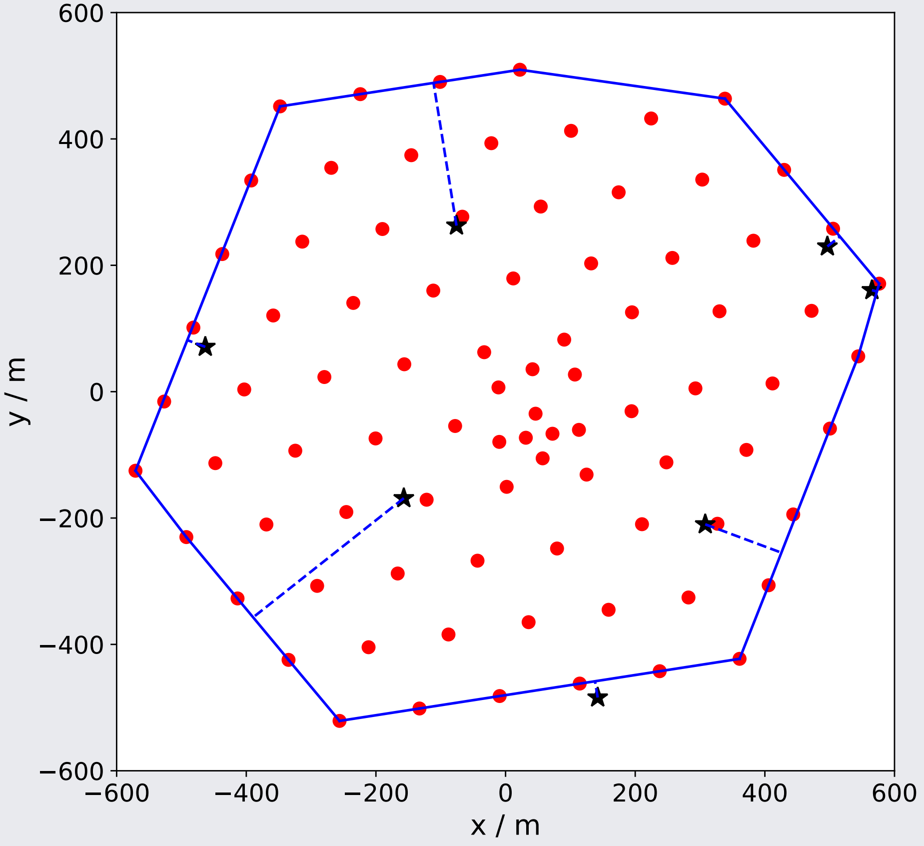
- For 7 candidate events:
  - Smoothed prominent double pulse waveforms: 0 migrated.
  - Shift pixel arrival times by up to 100 ns: scores unaffected (estimated timing unc.: 20 ns)
  - All DOMs in dust layer: ± 300 ns shifts, or outright from event, did not change CNN response
  - "Adversarial Attack" (DeepFool): Find closest decision boundary and compute the perturbation required to cross it
    - Only one event could be forced to migrate, provided average change across all pixels was $\geq 2.5\,\%$, well outside our uncertainties
    - With random $\pm 10\,\%$ pixel variations, 10^4 trials/event, one candidate event had $(2.1 \pm 0.14)\,\%$ migration probability

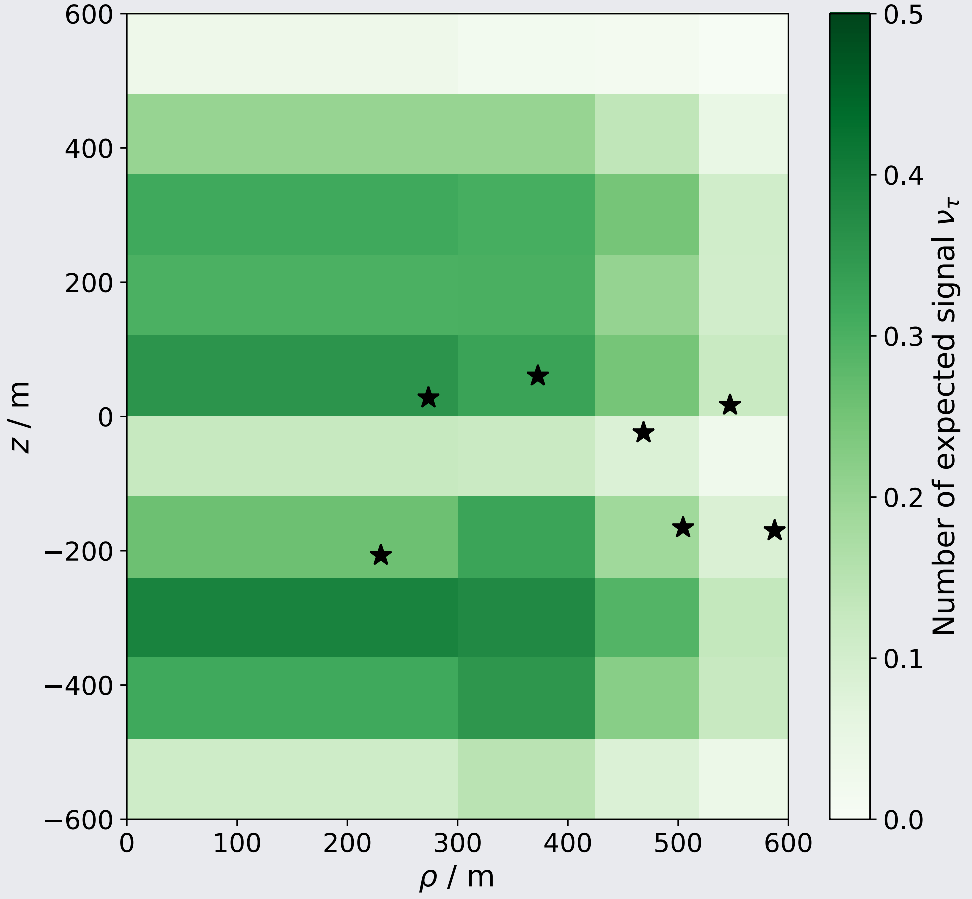


- For background events:
  - Attacks did not reveal any exceptionally susceptible region, and changes required to get $B \to S$ migration were outside uncertainties
  - Attacked 634 simulated ν_e, allowing pixels to change $\pm 10\,\%$, and only 1 $\nu_e \to \nu_\tau$

Post-Unblinding Checks

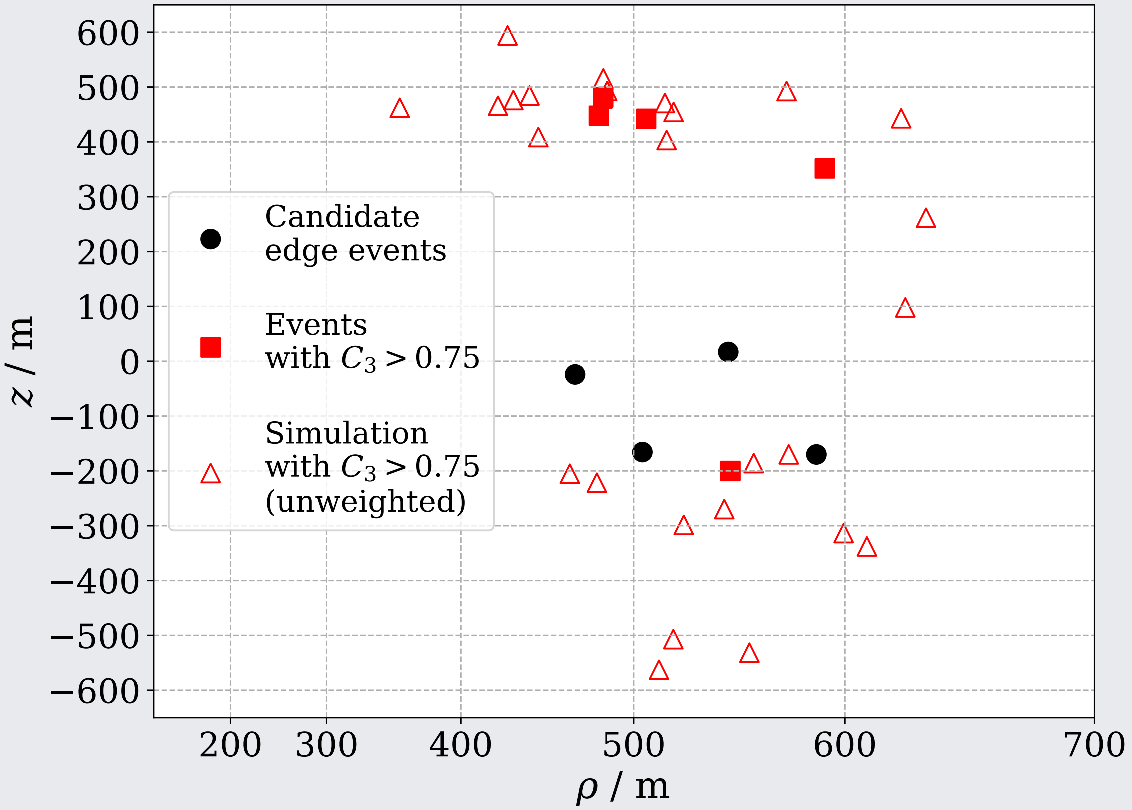
- The event vertex distribution did not look as uniform as expected
  - Several events' highest charge string was near detector's edge
  - More clustered in z above and below the "dust band"
    - A ~3σ-ish effect, depending on assumptions





Event Vertex Distribution

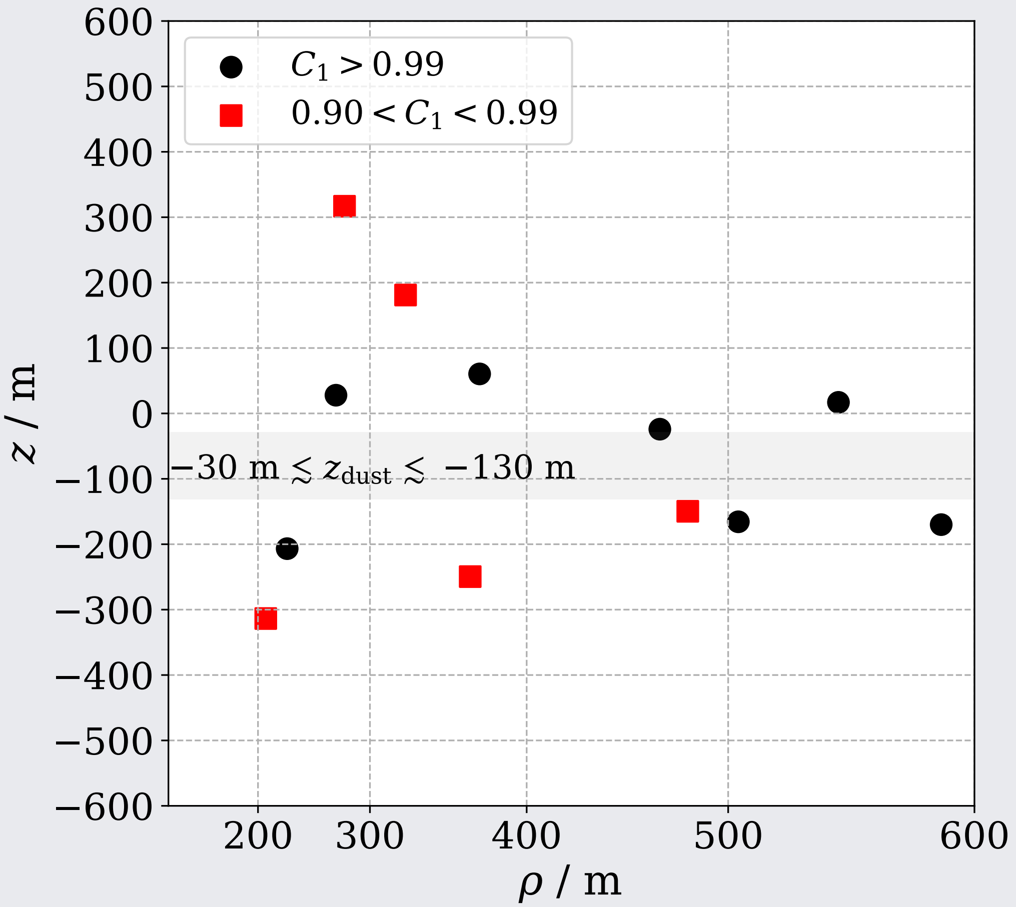
- Geometry: There's a lot of physical volume near the edge
- Loosening CNN scores $C_{2,3}$ $(\nu_\tau^{\mathrm{CC}}$ vs. $(\nu_\mu^{\mathrm{CC}}, \mu))$ adds new events mostly at top of detector
    - Very unlikely all 4 edge events are μ: $p_{\mathrm{KS}}(C_3 > 0.75) = 0.1$ $[p_{\mathrm{KS}}(C_3 >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



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

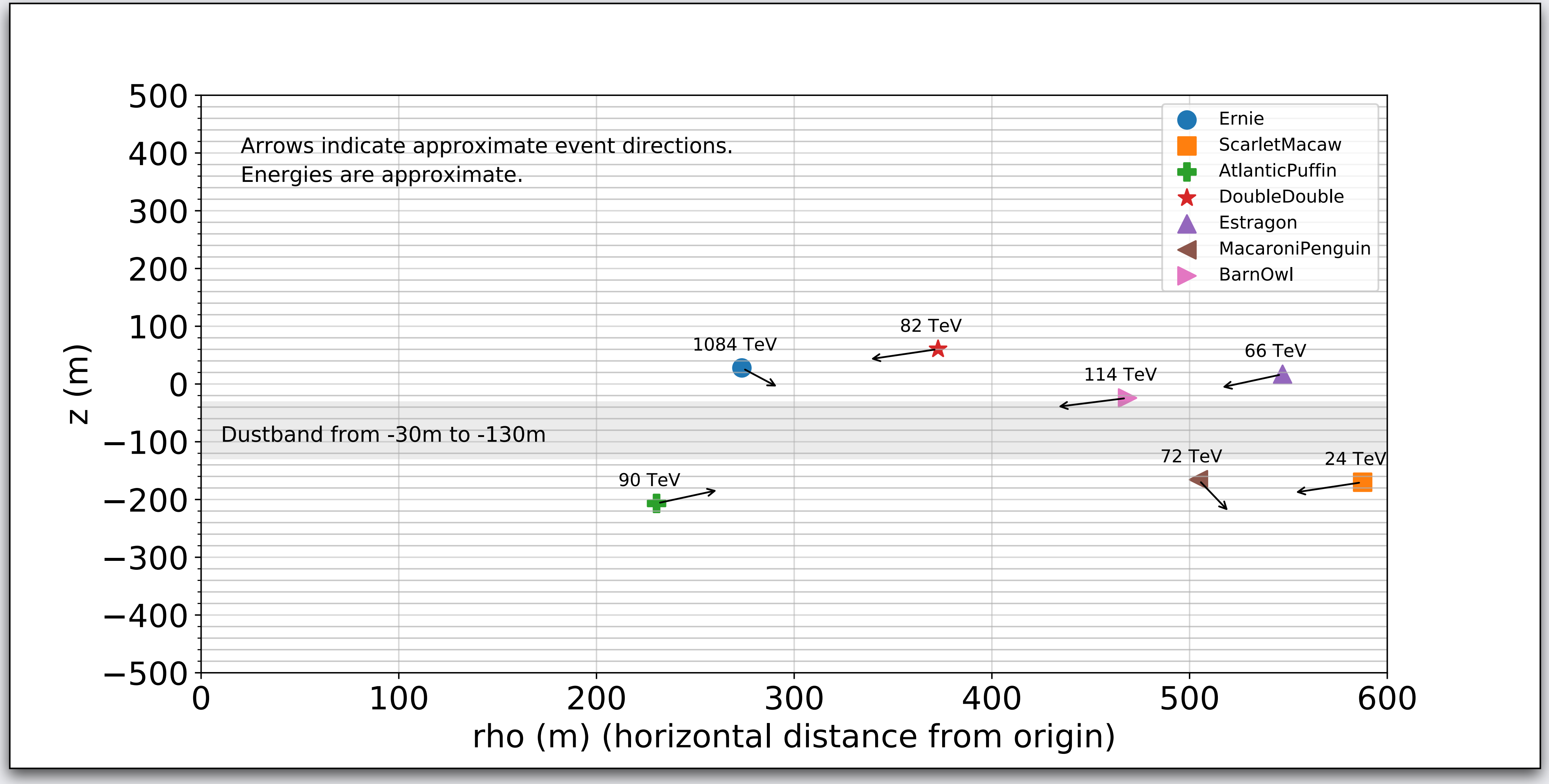
Event Vertex Distribution

- Loosening C_1 score (ν_τ^{CC} vs. $(\nu_e^{\mathrm{CC}}, \nu_x^{\mathrm{NC}})$)
  - 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 $\phi(\nu_\tau^{\mathrm{astro}}) = 0$ at high significance.



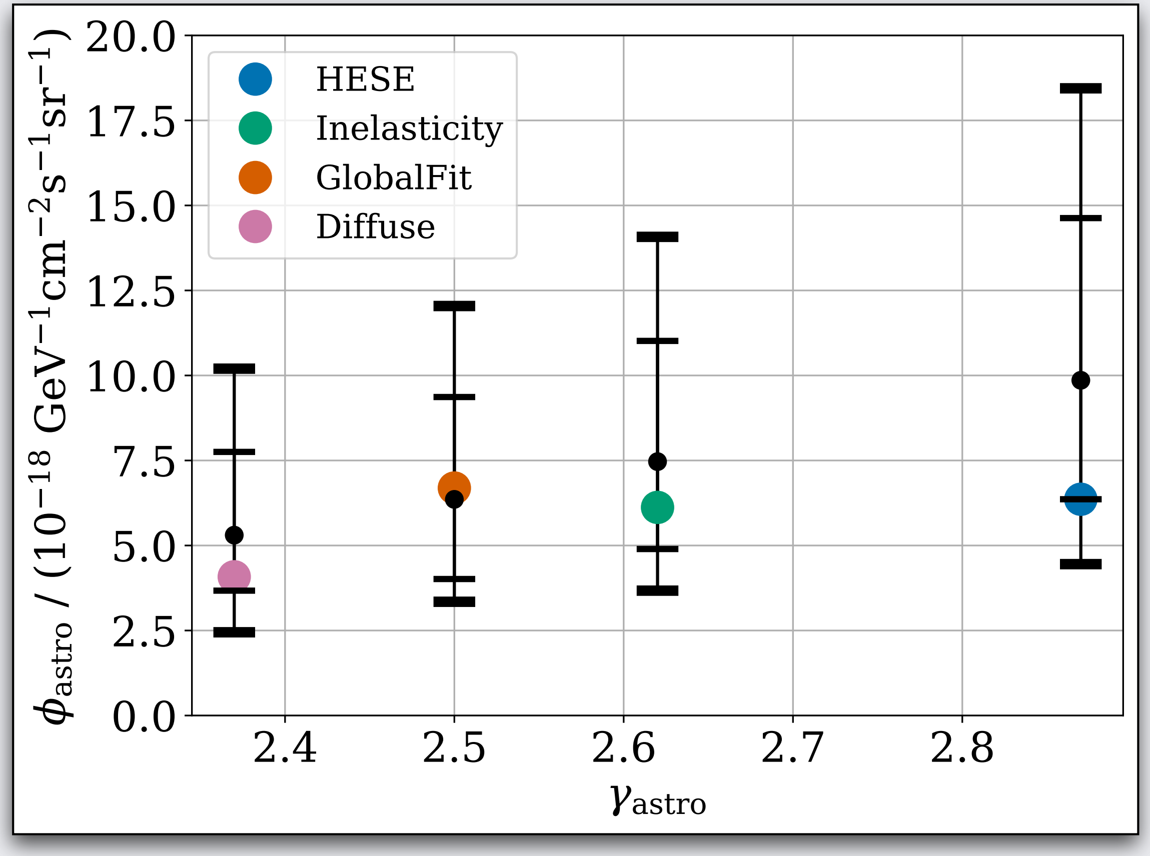
Conclusions: The 7 candidates' vertex distribution is an unfortunate statistical fluctuation, and the edge events are inconsistent with cosmic ray muons.

Event Vertex & Direction Distribution



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.

Self-Veto Effect

If included, would reduce est. ν^{atm} bkgd. by ~1.5-2x.

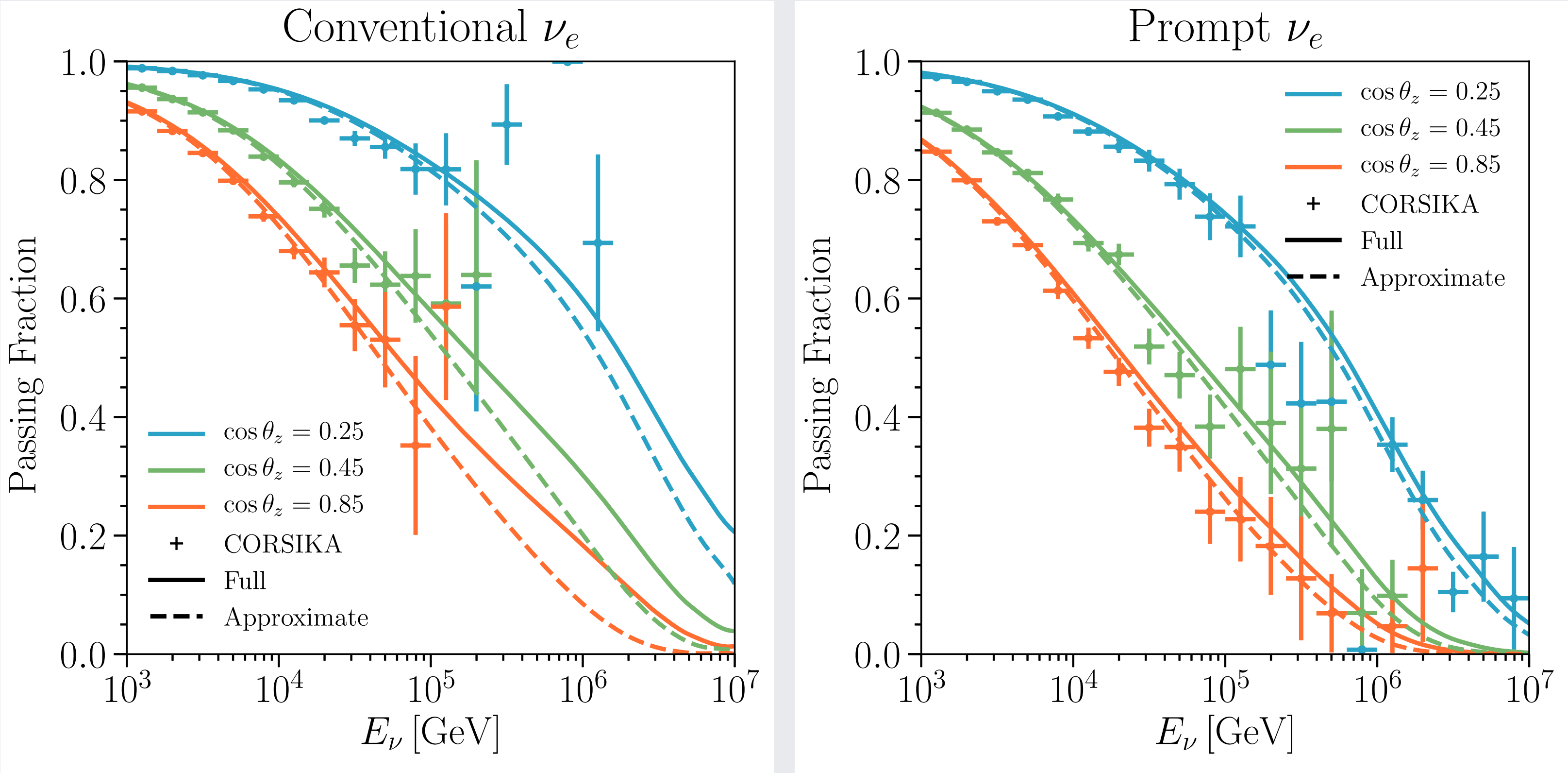


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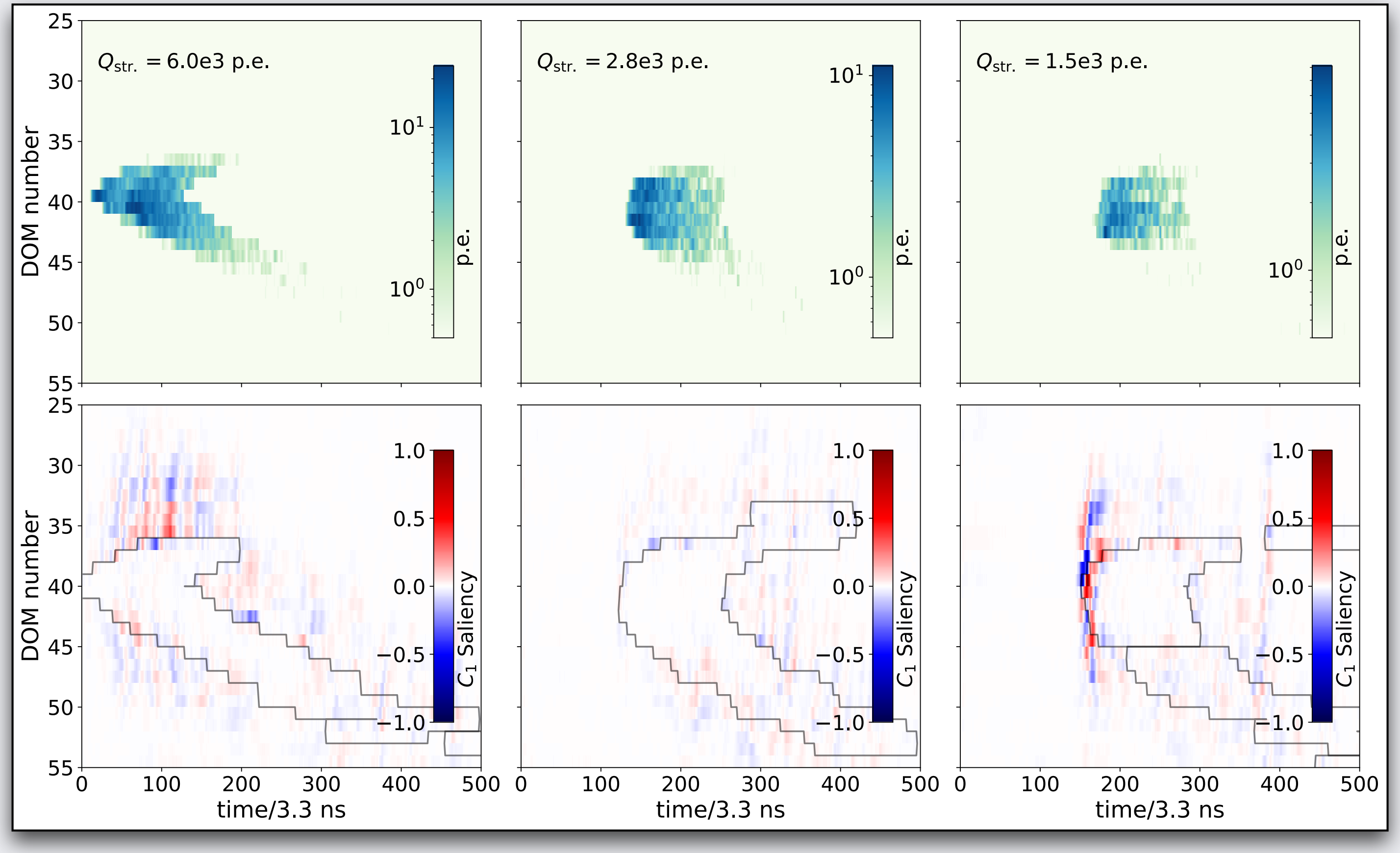
FIG. 3. ***Passing fractions: effect of approximations on the energy of the shower giving rise to uncorrelated muons.*** Results are shown for three values of $\cos\theta_z$ (from top to bottom): 0.25 (blue), 0.45 (green), and 0.85 (orange); with the approach of this work (solid), Eq. (9), where the energy carried by the neutrino parent is subtracted from the rest of the shower which produces the muons to be triggered (i.e., $E_{\rm CR} - E_p$), and without this subtraction (dashed), Eq. (5), considering the cumulative muon yield from a shower with energy $E_{\rm CR}$. Results from the `CORSIKA` simulation are shown as crosses, with statistical error bars only. In all cases, the H3a primary cosmic-ray spectrum [22], the SIBYLL 2.3 hadronic-interaction model [27, 28] and the MSIS-90-E atmosphere-density model at the South Pole on July 1, 1997 [25, 26] are used, and $d_{\rm det} = 1.95$ km in ice and $\mathcal{P}_{\rm light}(E_\mu^{\rm f}) = \Theta(E_\mu^{\rm f} - 1\,{\rm TeV})$ are assumed. *Left panel:* Conventional ν_e passing fraction. *Right panel:* Prompt ν_e passing fraction.

A 2x decrease in ν^{atm} would increase significances by about 0.3σ

Event Pics w/Saliency Maps

ScarletMacaw, with log Q_{str} and saliency maps:

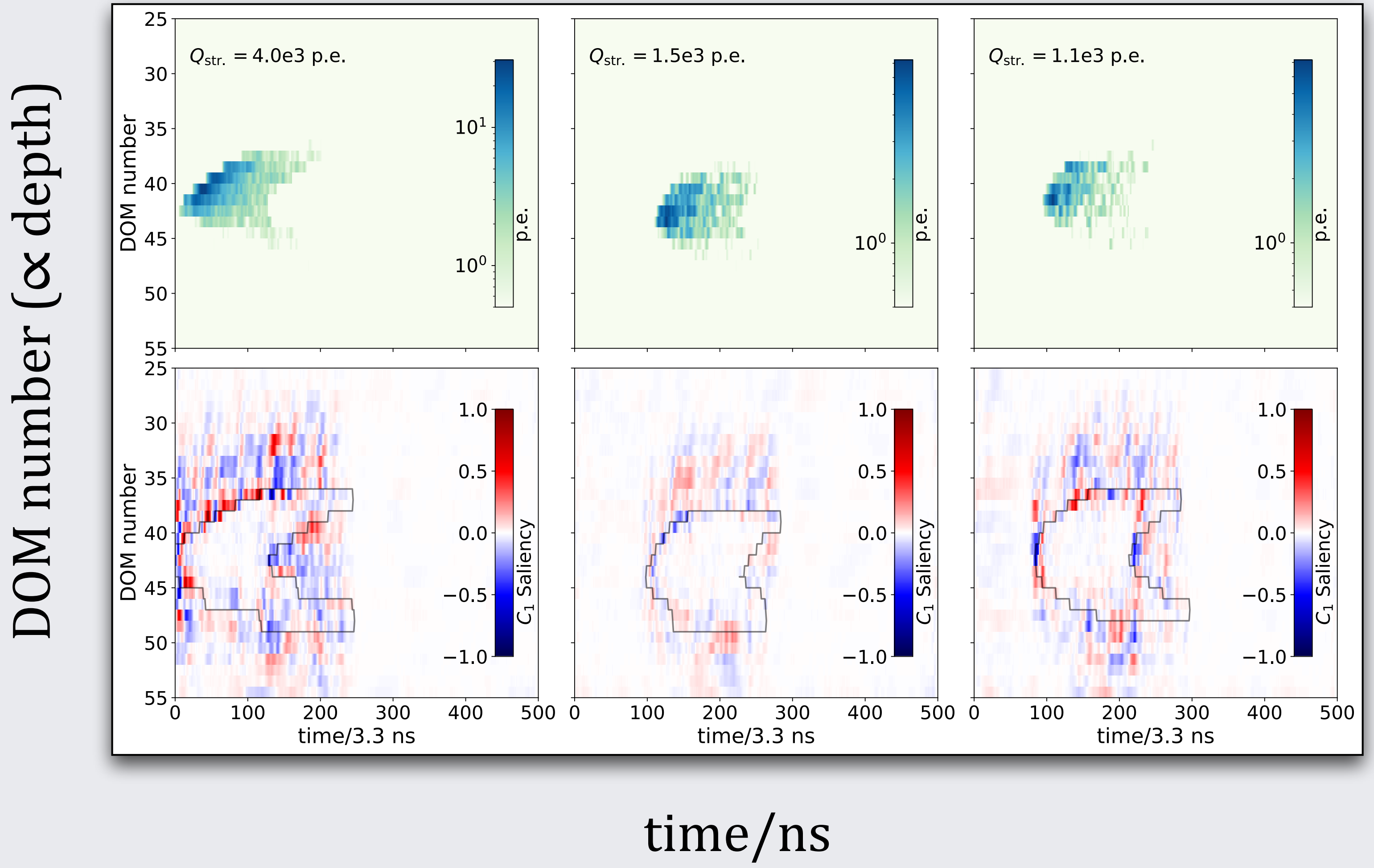
DOM number (∝ depth)



time/ns

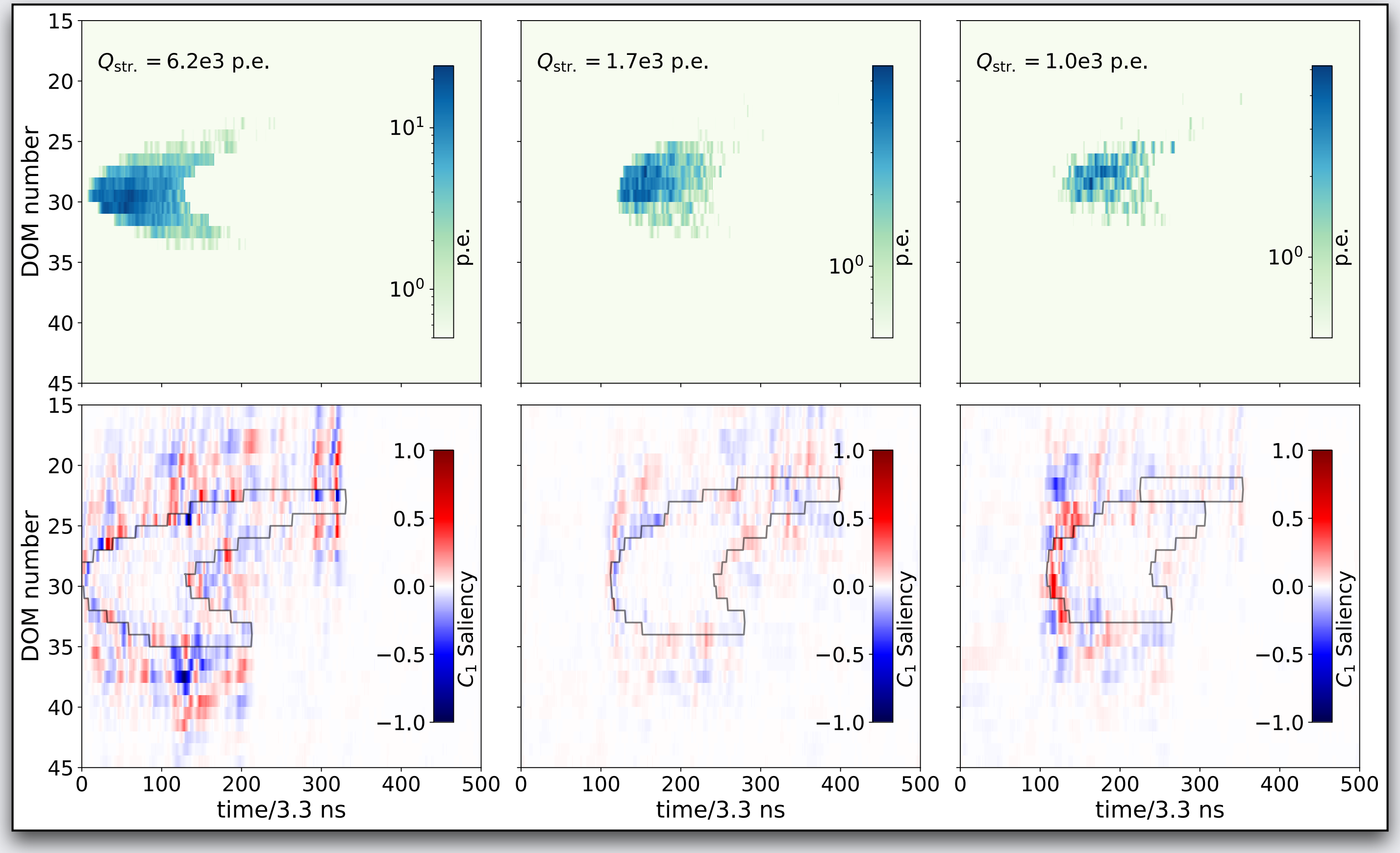
Event Pics w/Saliency Maps

AtlanticPuffin, with log Q_{str} and saliency maps:



Event Pics w/Saliency Maps

Estragon, with log Q_{str} and saliency maps:



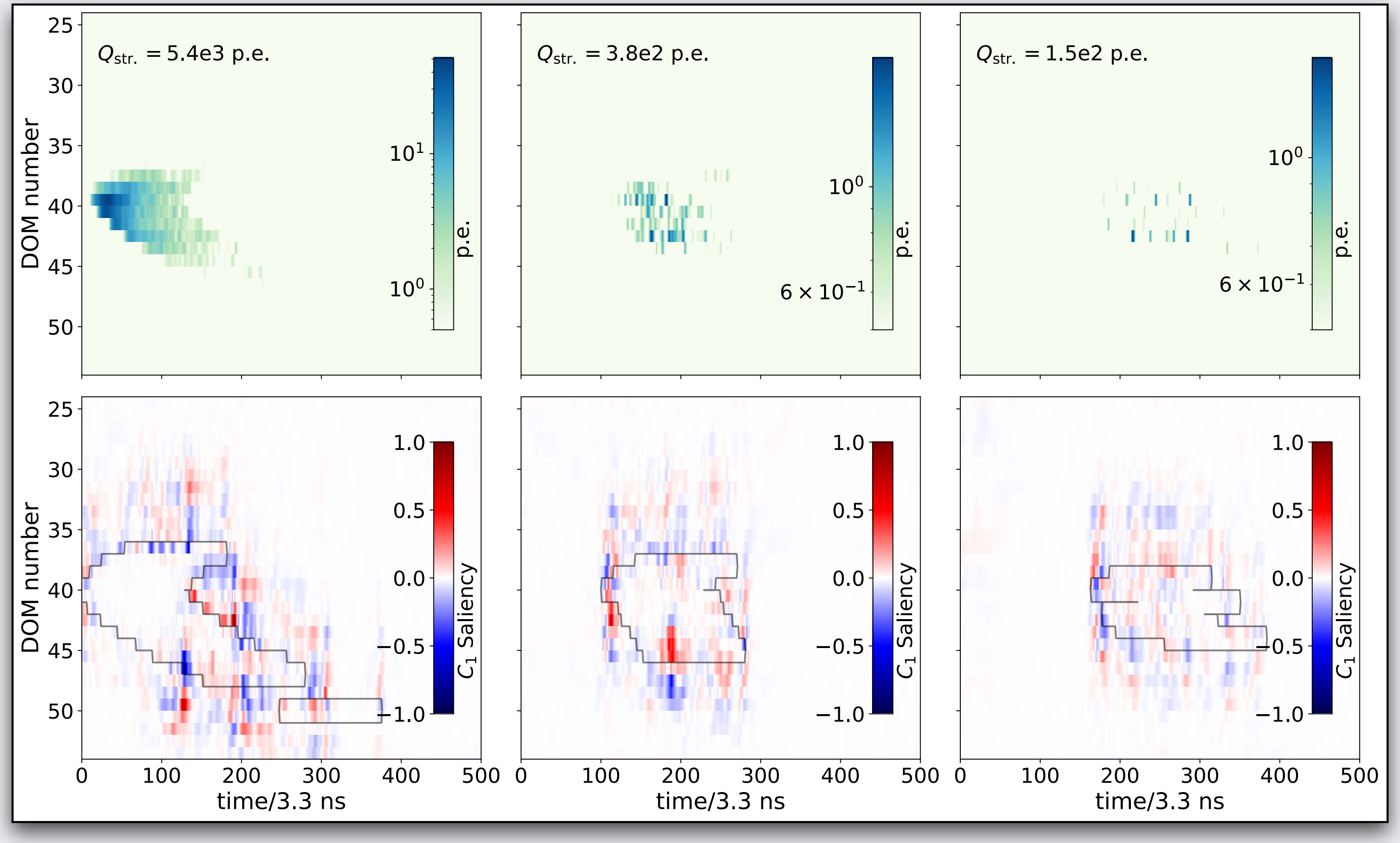
DOM number (∝ depth)

time/ns

Event Pics w/Saliency Maps

MacaroniPenguin, with log Q_{str} and saliency maps:

DOM number (∝ depth)

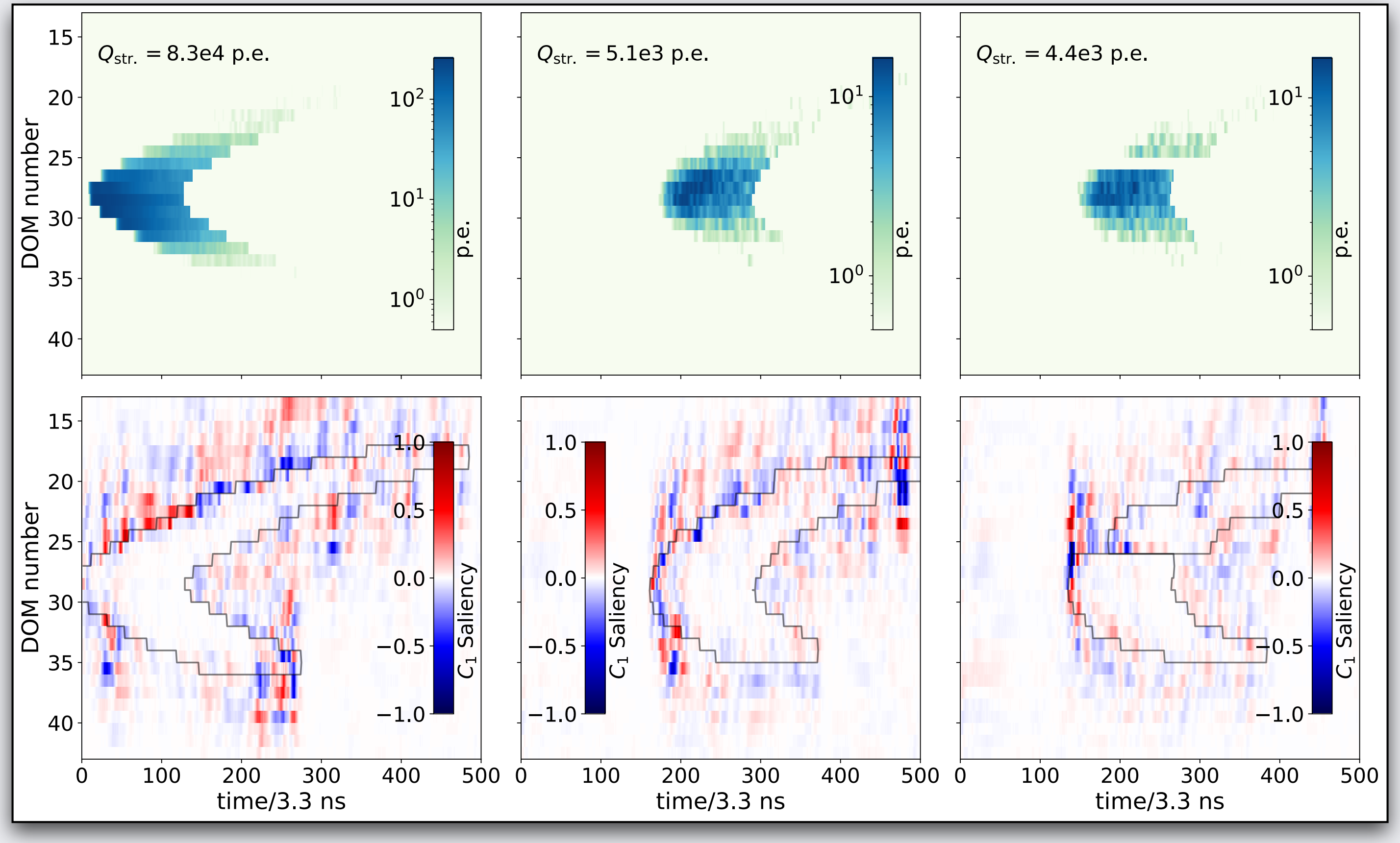


time/ns

Event Pics w/Saliency Maps

Ernie, with log Q_{str} and saliency maps:

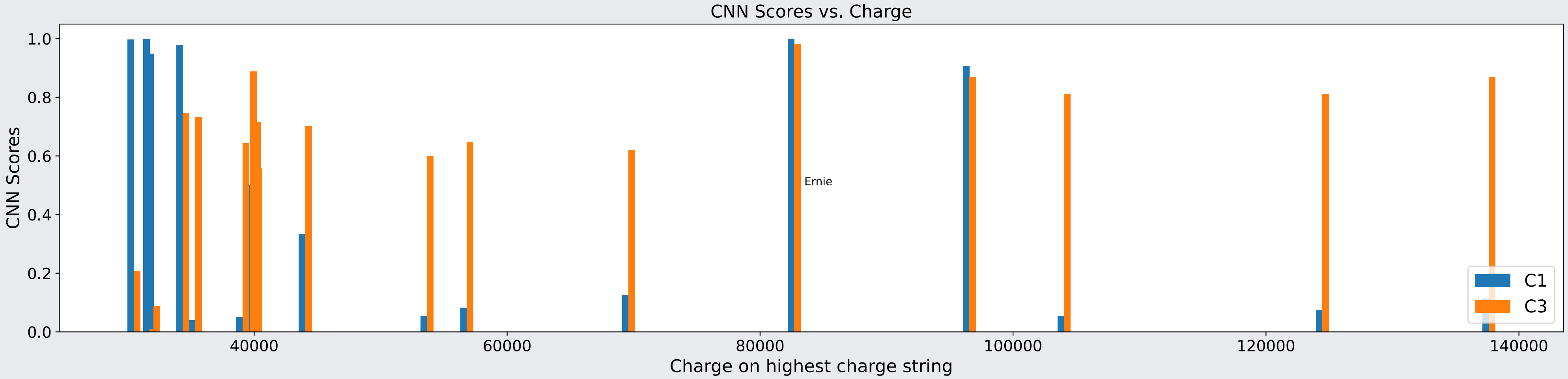
DOM number (∝ depth)

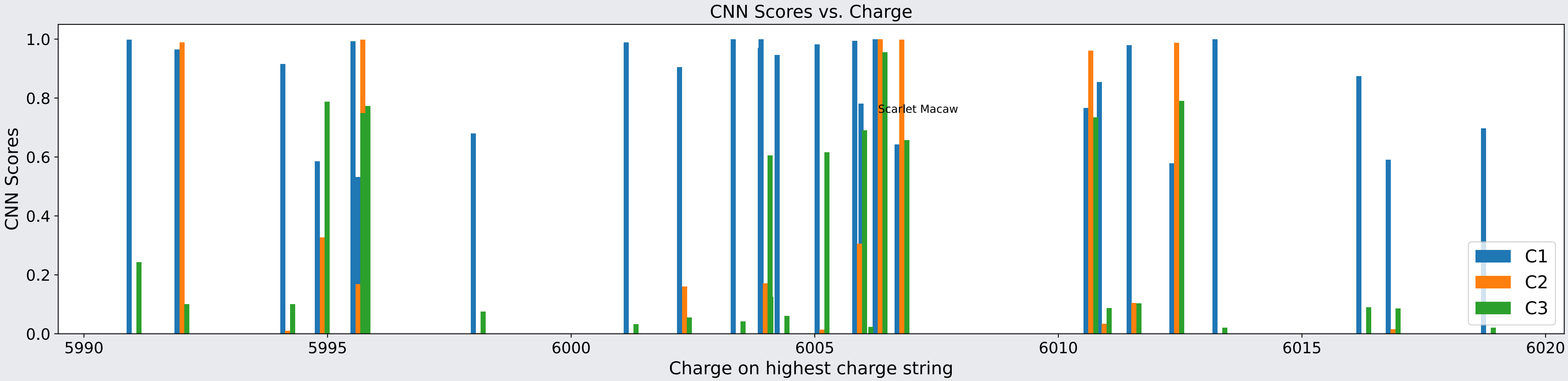


time/ns

CNN Scores vs. Charge

- High charge is neither sufficient nor necessary





L_τ vs. E_τ

Analysis prefers events with τ's with above-average lifetimes: