Tau Neutrinos with IceCube

Third-Generation ν_τ (and τ) Physics
Spanning over Five Orders of Magnitude in Energy

Doug Cowen
Penn State

Mascot Observations

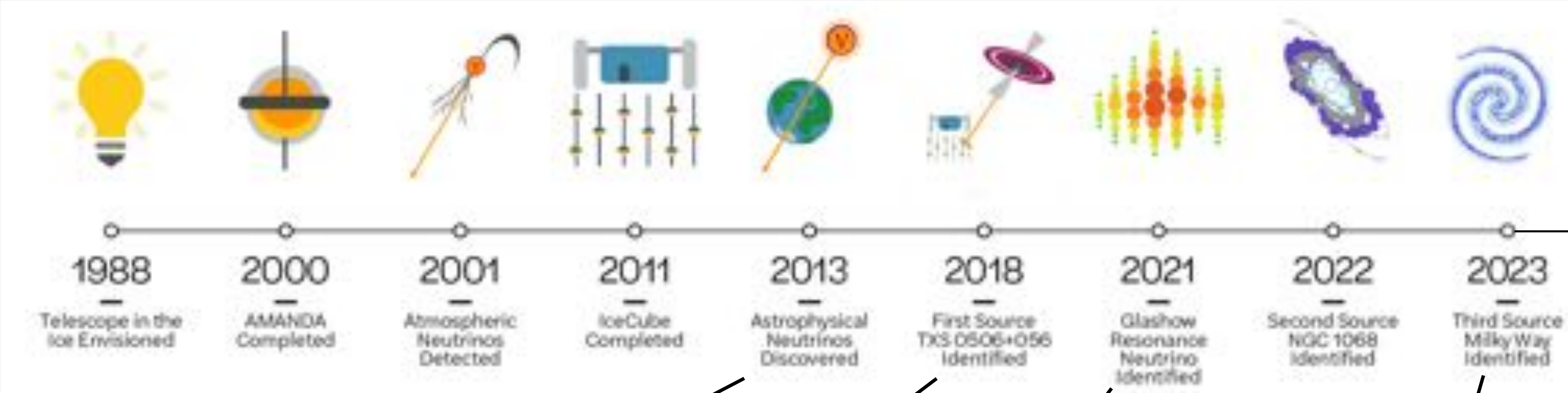
Penn State's "Nittany Lion"

Has teeth but does not need to show them.

U. of Louisville's Cardinal

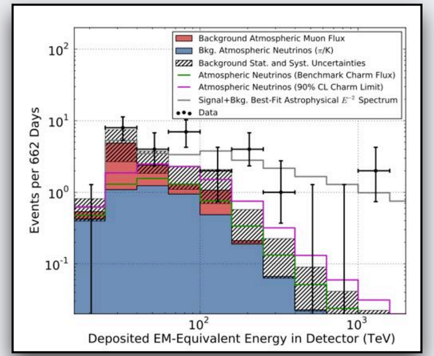
Anatomically incorrect. Birds don't have teeth.

IceCube Discovery Timeline

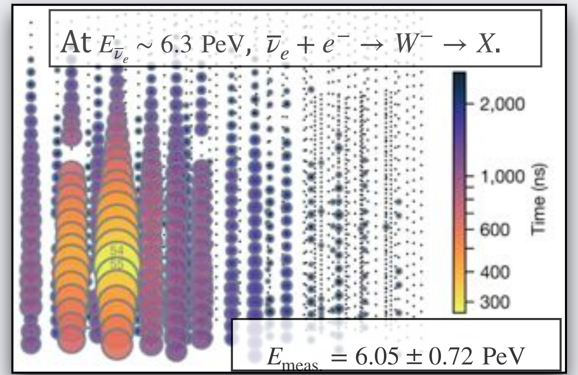


Seven Astrophysical ν_τ Observed

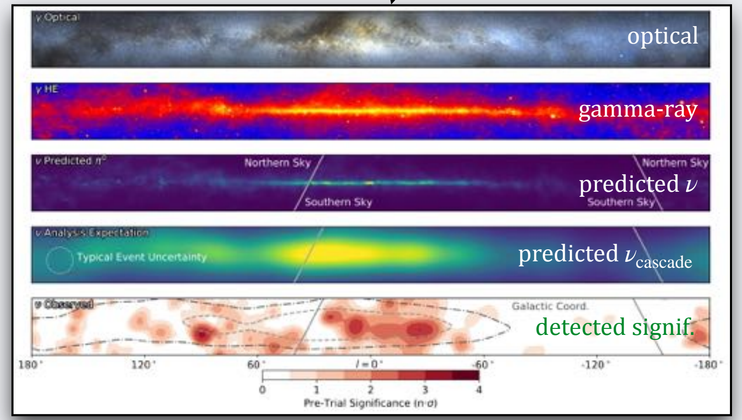
See this talk!



https://arxiv.org/abs/1311.5238

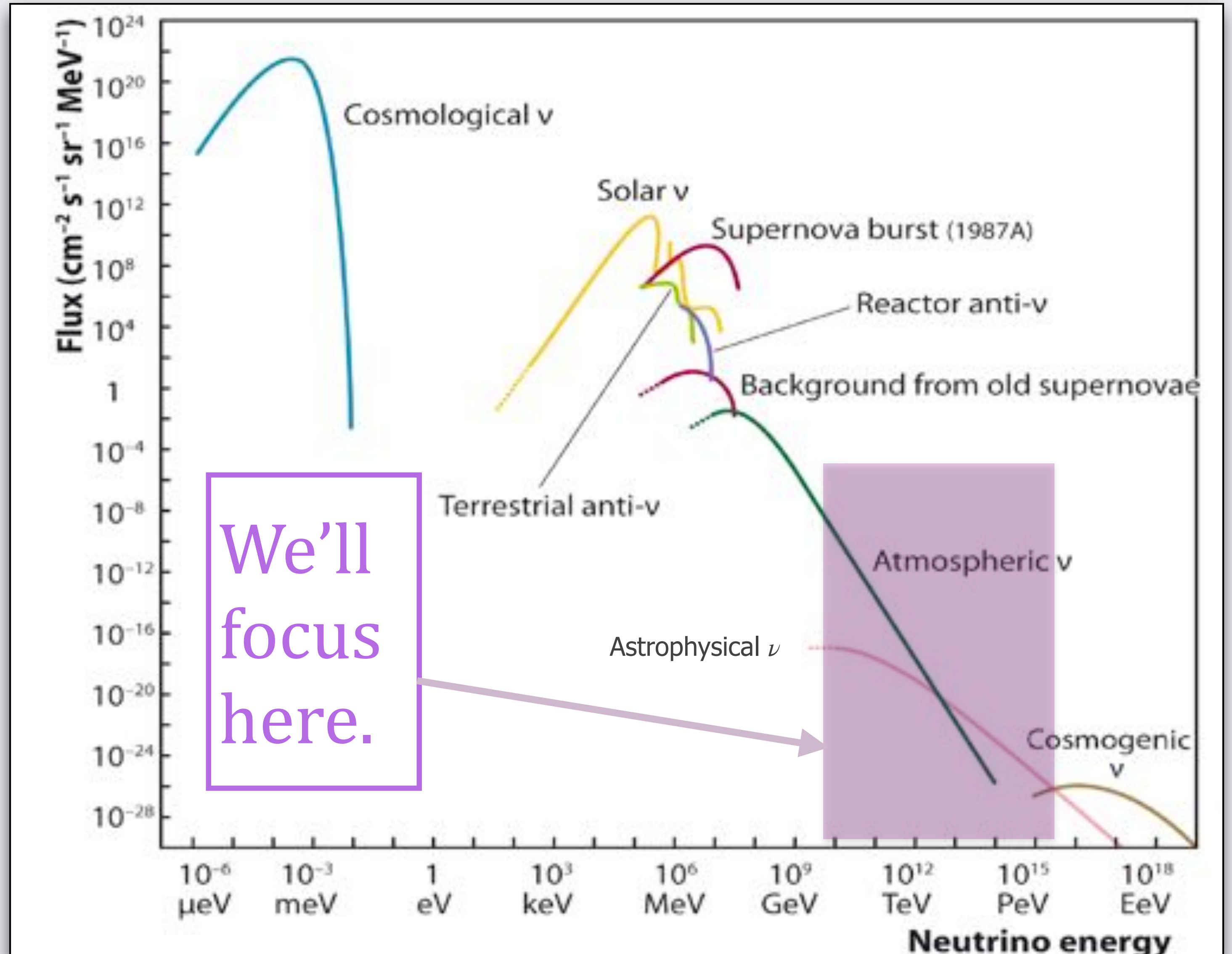


Nature 591 (2021)



Science 380, 6652 (2023)

Sources of ν_τ in IceCube



The challenge:

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

(per 10 years).

Sources of ν_τ in IceCube

- Atmospheric neutrinos
  - Created when cosmic rays hit atm.
  - Resulting particle showers make $\nu_{e,\mu}$ with $E_\nu \approx 10^{9-12}$ eV
  - For $(E_\nu, L_\nu) \sim (20 \text{ GeV}, d_E)$, $P(\nu_\mu \to \nu_\tau) \sim 1$
- Astrophysical high energy neutrinos
  - Created in cosmic accelerators
  - IceCube sees at $E_\nu > \sim 50$ TeV
  - Expect $\nu_e : \nu_\mu : \nu_\tau \sim 1:1:1$ under standard oscillation picture

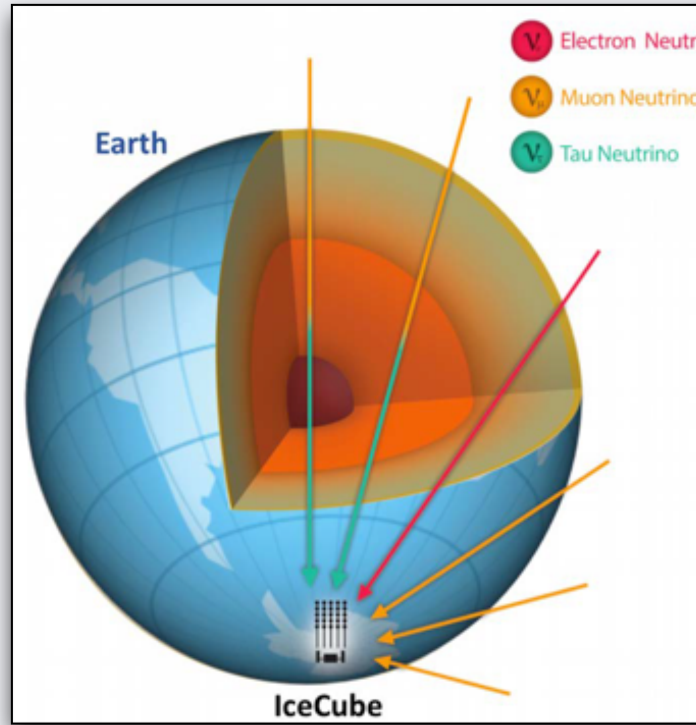
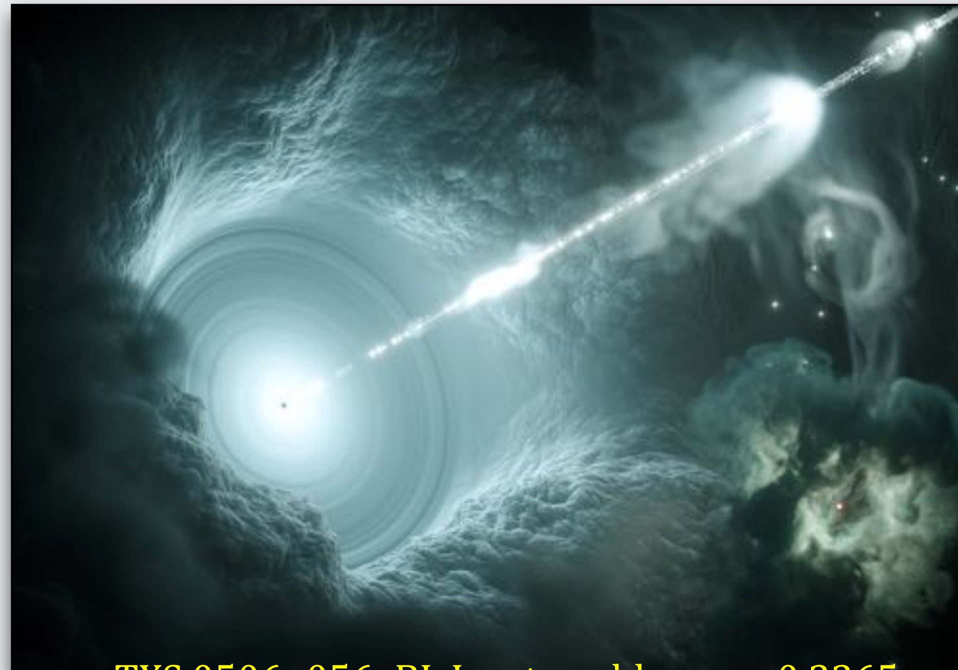


Fig. courtesy T. Stuttard/NBI


TXS 0506+056: BL Lac-type blazar, z=0.3365
Fig. courtesy DESY/Zeuthen

Sources of ν_τ in IceCube

- Atmospheric neutrinos
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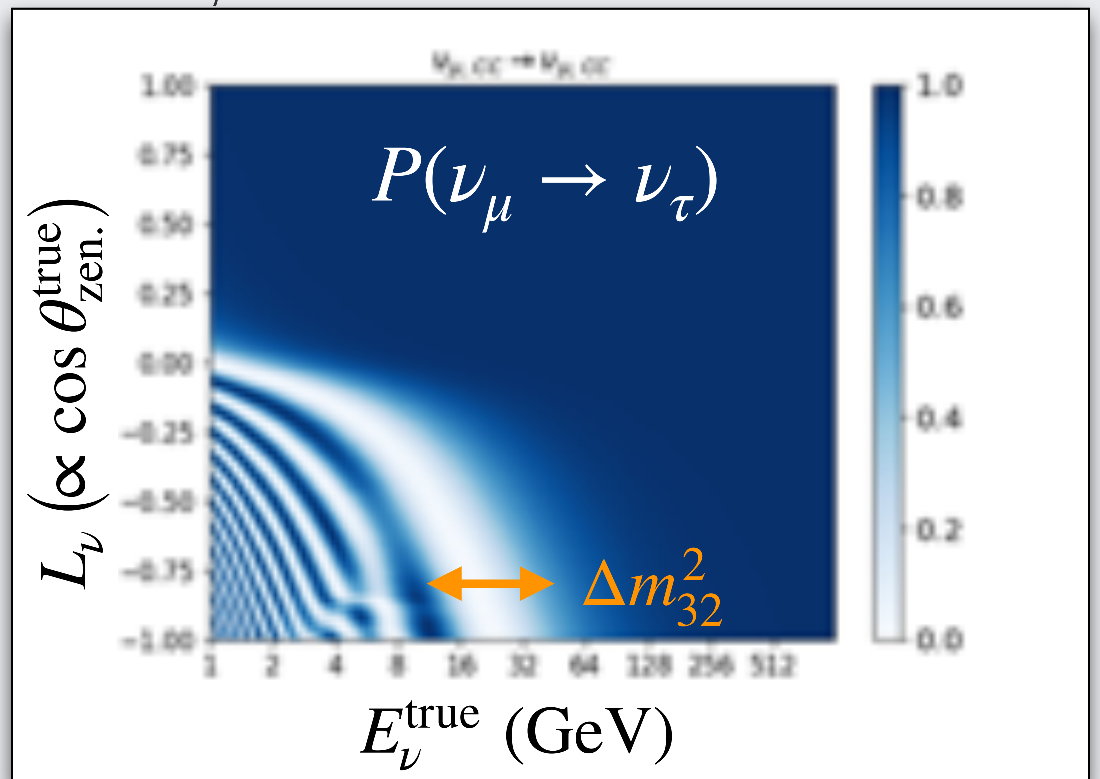
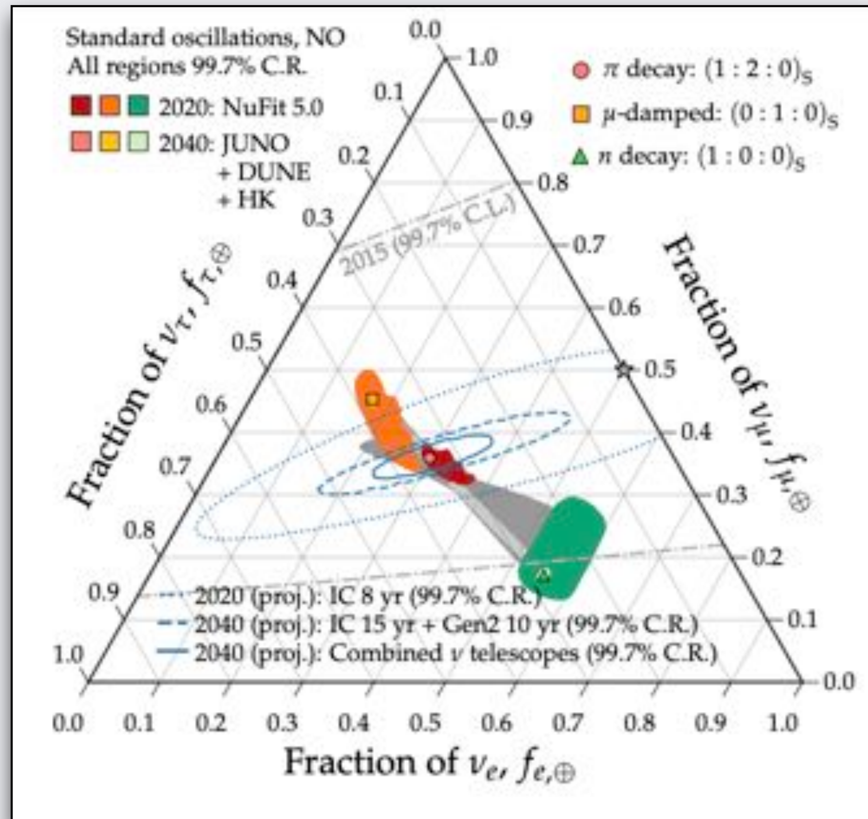
  - Resulting particle showers make $\nu_{e,\mu}$ with $E_\nu \approx 10^{9-12}$ eV
  - For $(E_\nu, L_\nu) \sim (20 \text{ GeV}, d_E)$, $P(\nu_\mu \to \nu_\tau) \sim 1$

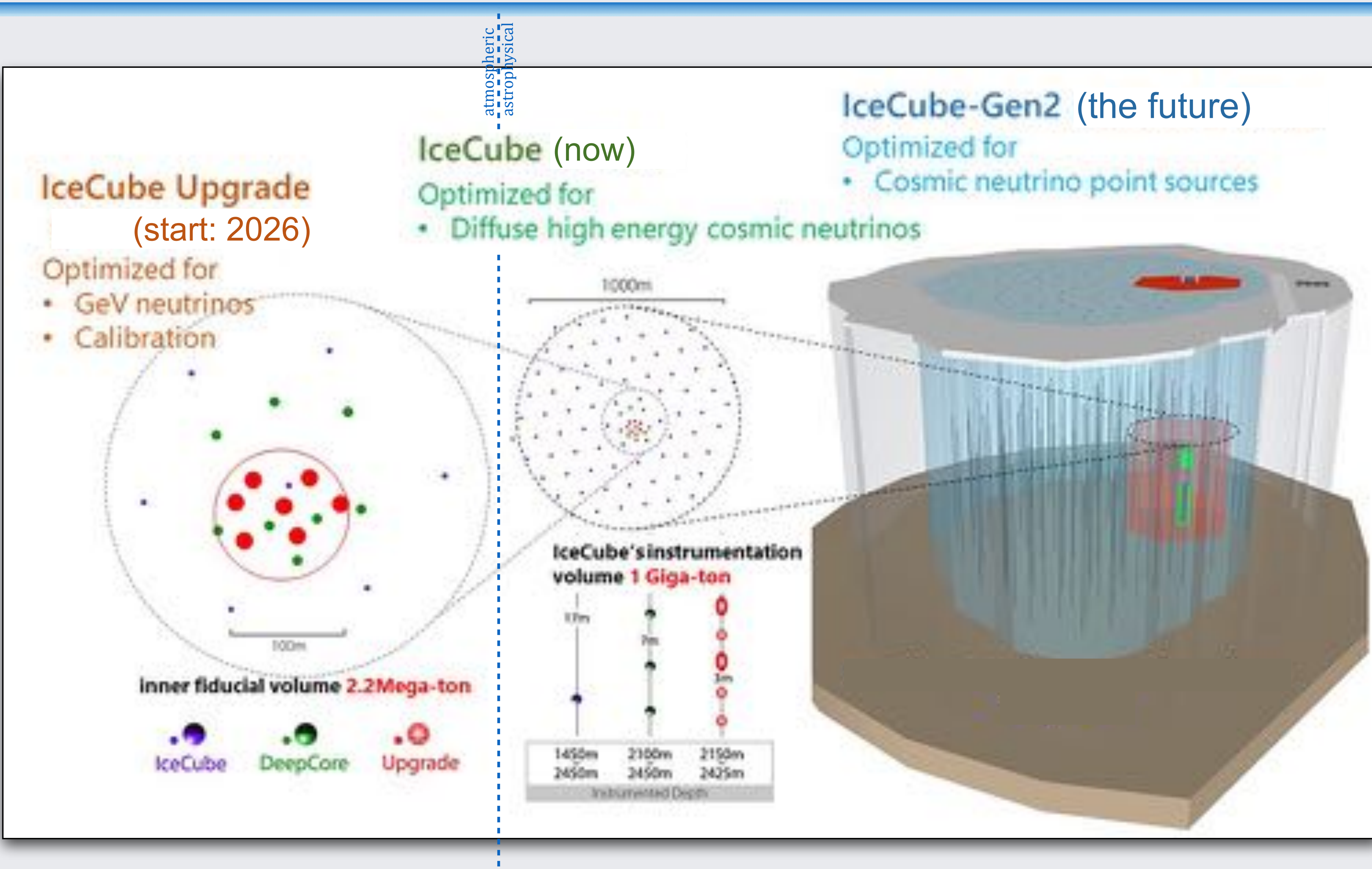


- Astrophysical high energy neutrinos
  - Created in cosmic accelerators
  - IceCube sees at $E_\nu > \sim 50$ TeV
  - Expect $\nu_e : \nu_\mu : \nu_\tau \sim 1:1:1$ (std. ν osc., independent of sources' $\nu_e : \nu_\mu : \nu_\tau$)



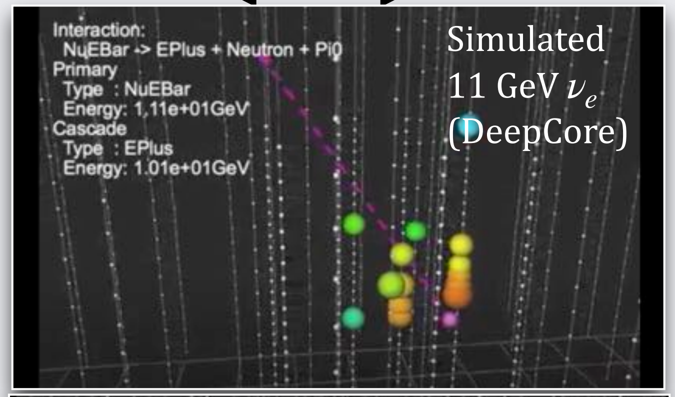
https://arxiv.org/abs/2012.12893

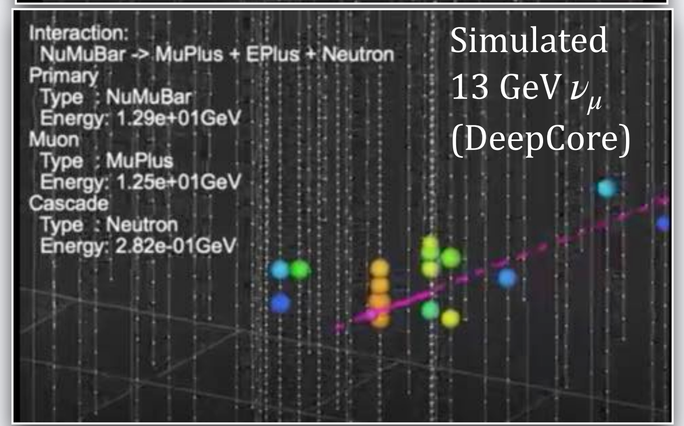
The IceCube Detector

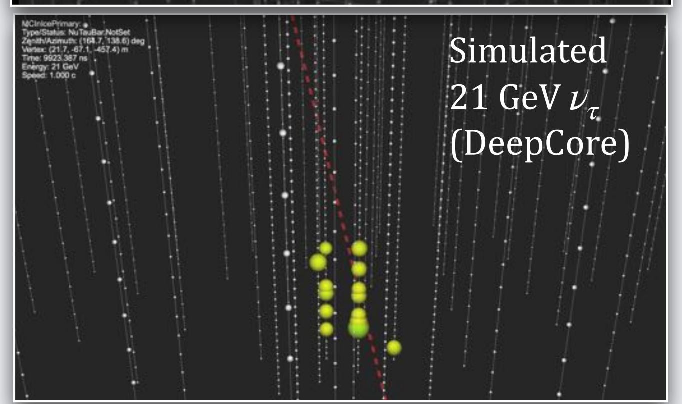


ν_τ Signatures in IceCube

~100 m







Event morphologies

ν^{atm} ↙

ν^{astro} ↘

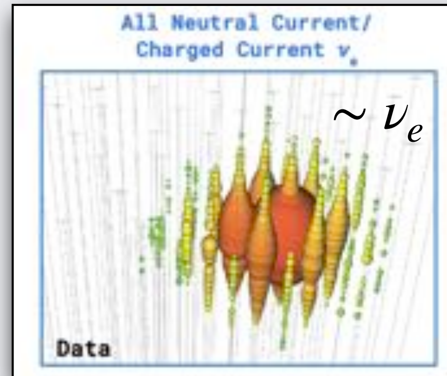
At $\mathcal{O}$(10 GeV), only $\nu_\uparrow$ oscillate.

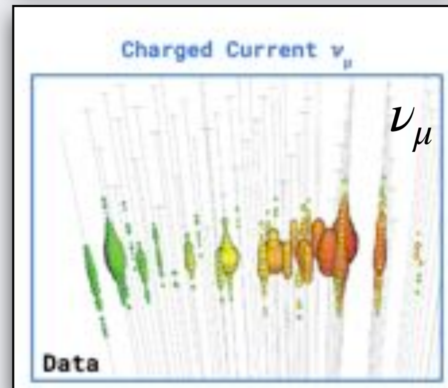
At $\mathcal{O}$(100 TeV):
- see both $\nu_{\uparrow,\downarrow}$
- $\lambda^{\nu}_{\text{int}} \sim d_{\text{Earth}}$
- ν_τ regeneration

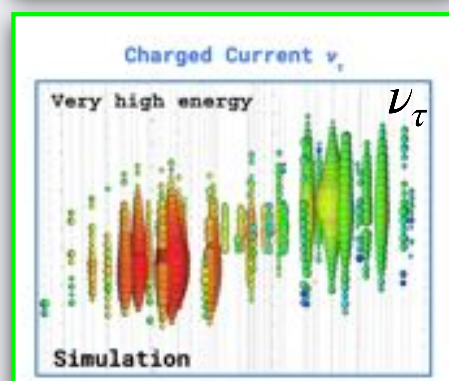
Spheres:	DOMs
White:	recorded no light
Color:	recorded light
Size:	light collected

Color shows time information:
Early — Late

~1 km



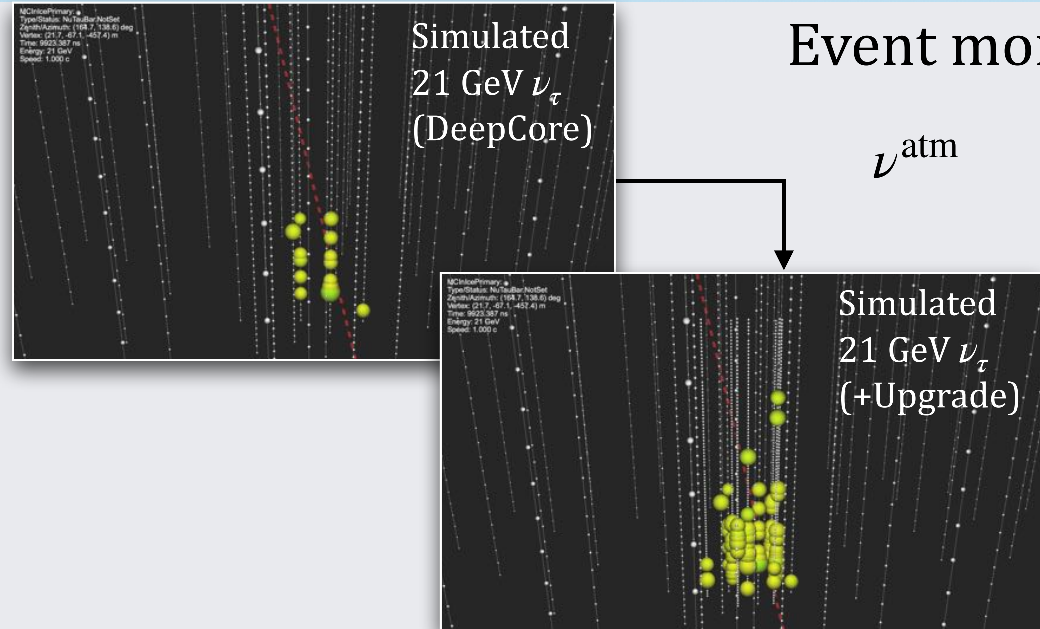




$E_{\nu_\tau} \sim$ PeV

(L_τ = 50 m/PeV)

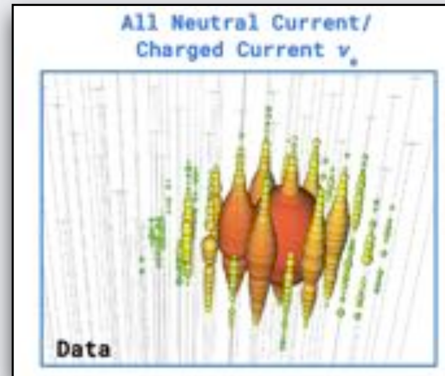
ν_τ Signatures in IceCube

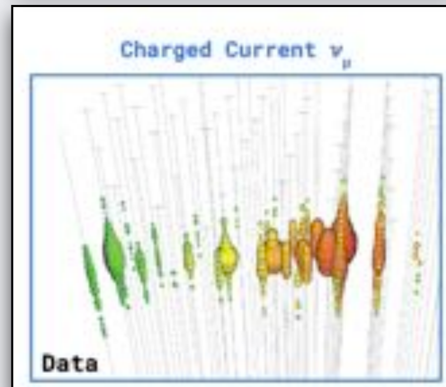


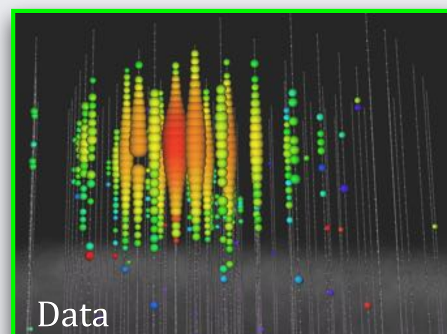
Event morphologies

ν^{atm} | ν^{astro}

~1 km



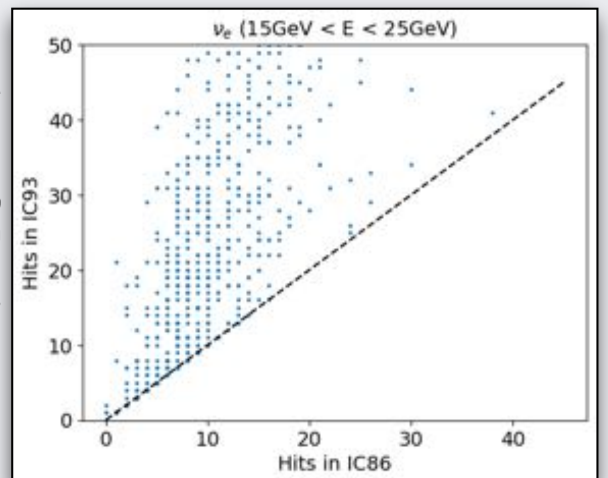




At ~200 TeV, $\nu_{e,\tau}$ look very similar *by eye*.

With Upgrade ("IC93") expect ~3x more photons for ν^{atm}:

Hits (+Upgrade)



Hits (DeepCore)

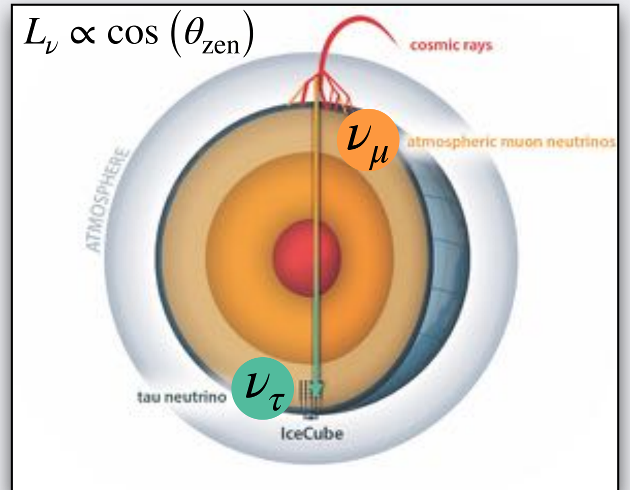
Spheres:	DOMs
White:	recorded no light
Color:	recorded light
Size:	light collected

Color shows time information:

Early — Late

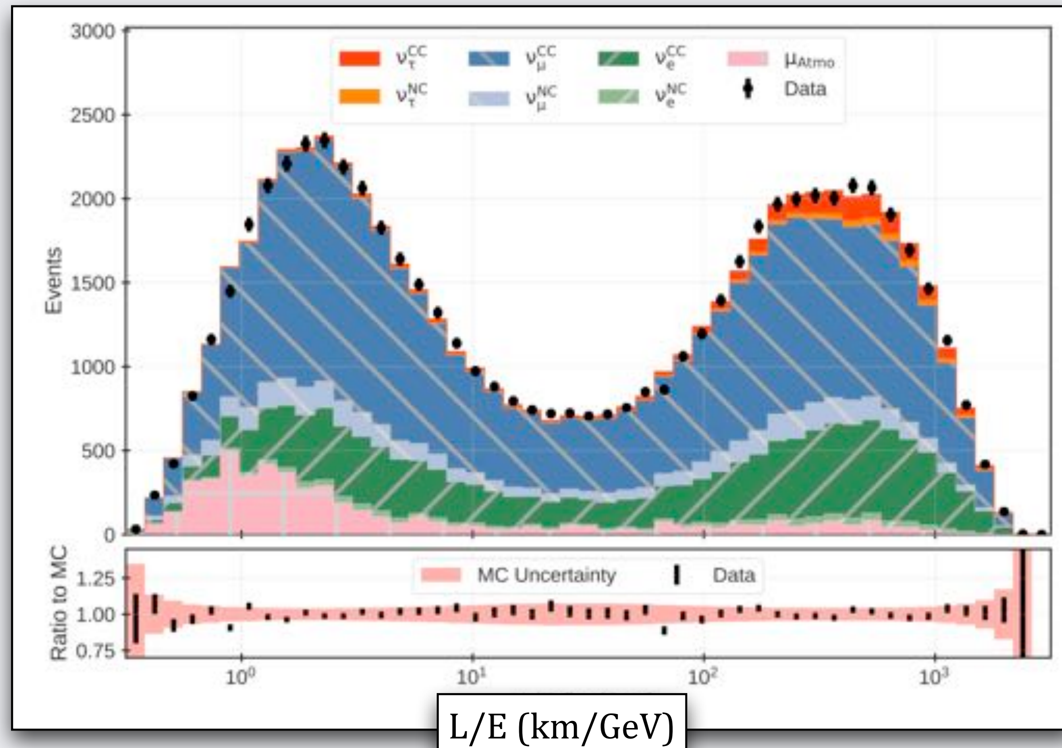
Atmospheric Tau Neutrinos

$E_\nu \sim \mathcal{O}(10\ \mathrm{GeV})$



$$P(\nu_\mu \to \nu_\tau) = \sin^2(2\theta_{23}) \sin^2\left(1.27\frac{\Delta m_{32}^2 L}{E}\right)$$

- Inclusive analysis:
  - Look for excess of cascade-like events: "ν_τ appearance"

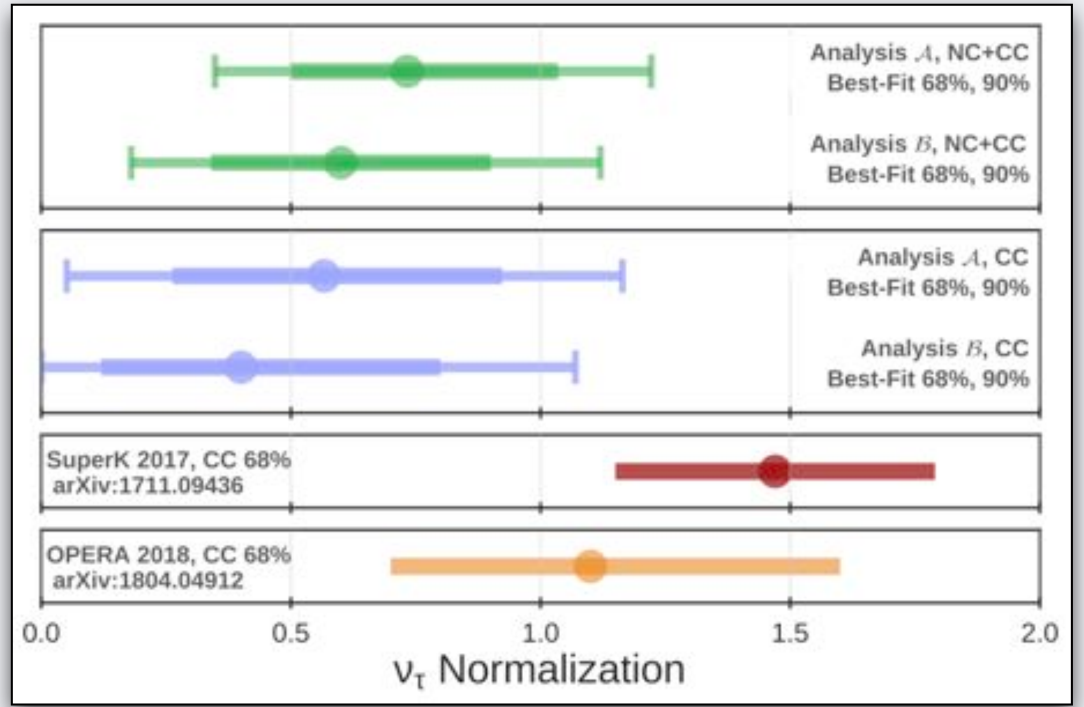


PRD 99, 032007 (2019)

Atmospheric Tau Neutrinos

- Inclusive analysis:
  - Measure $\nu_\tau^{\text{norm}} \equiv \nu_\tau^{\text{meas.}} / \nu_\tau^{\text{pred.}}$
- ν_τ^{norm} sensitive to new physics:
  - "non-unitarity" $(\nu_\mu \rightarrow \nu_s)$
  - unexpected $\sigma_{\nu_\tau N}$ cross section behavior

3 years of data



PRD 99, 032007 (2019)

All consistent with standard oscillations @30% level.

Atmospheric Tau Neutrinos

- Inclusive analysis:
  - Measure $\nu_\tau^{\text{norm}} \equiv \nu_\tau^{\text{meas.}} / \nu_\tau^{\text{pred.}}$
- ν_τ^{norm} sensitive to new physics:
  - "non-unitarity" $(\nu_\mu \to \nu_s)$
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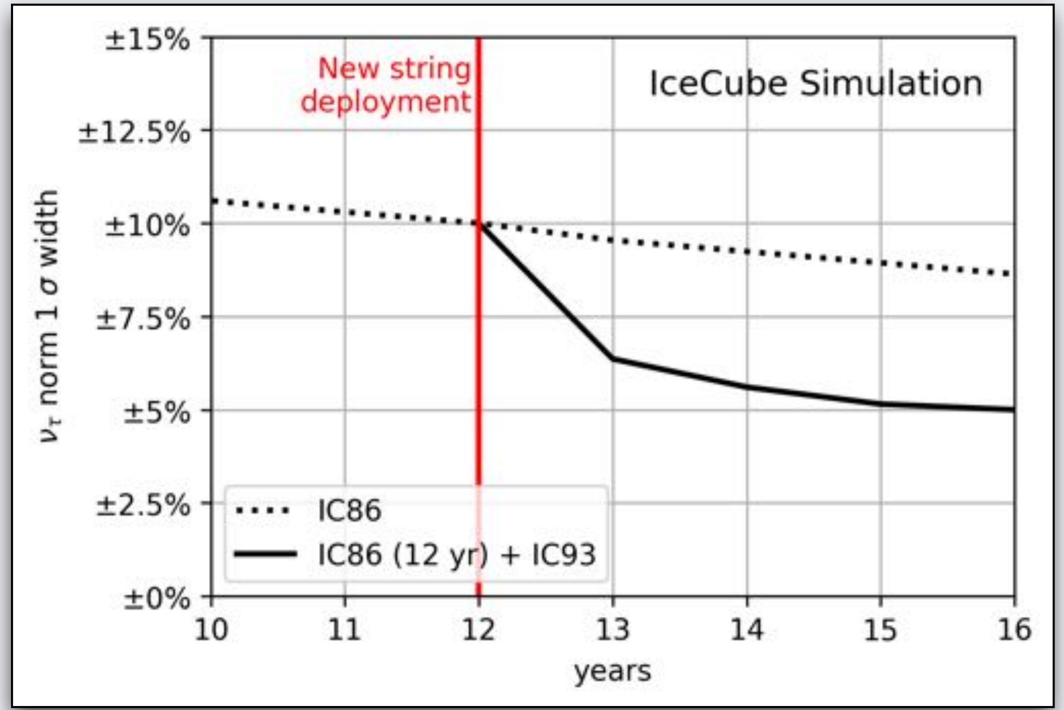
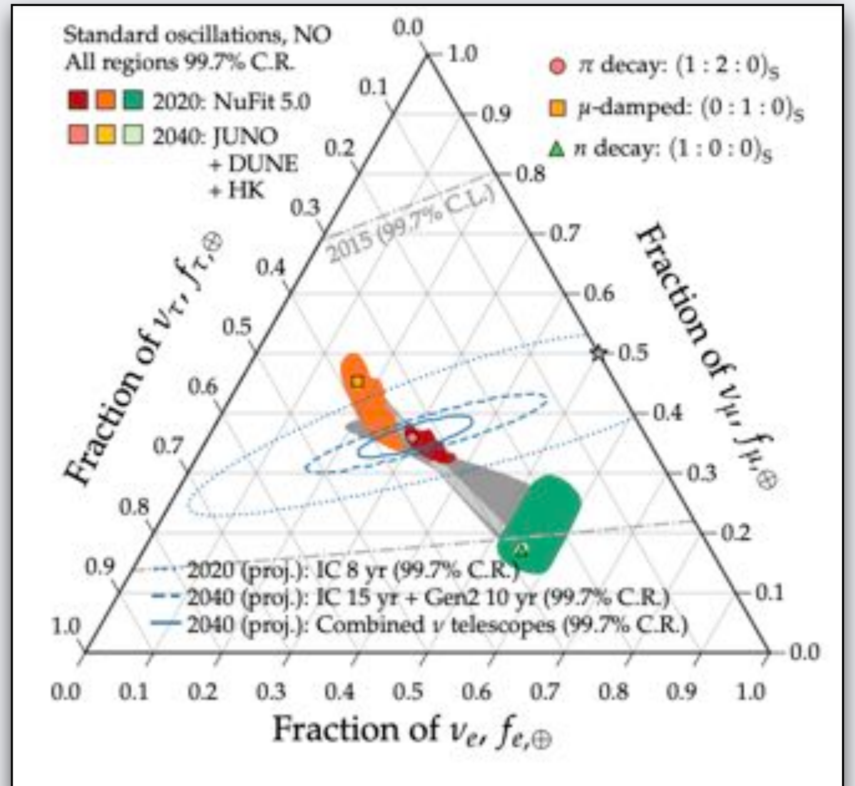


Have data now for ~10% msmt.; Upgrade → ~5%.

Astrophysical Tau Neutrinos

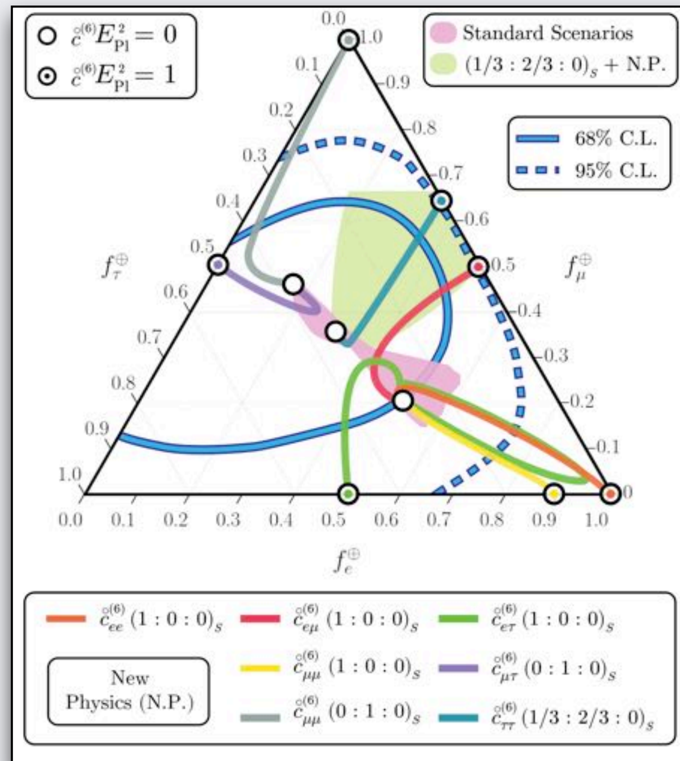
$E_\nu \sim \mathcal{O}(100\ \text{TeV})$



https://arxiv.org/abs/2012.12893

For standard oscillations over astrophysical distances, expect $\nu_e : \nu_\mu : \nu_\tau \sim 1 : 1 : 1$, and to see some ν_τ, independent of source's $\nu_e : \nu_\mu : \nu_\tau$ ...

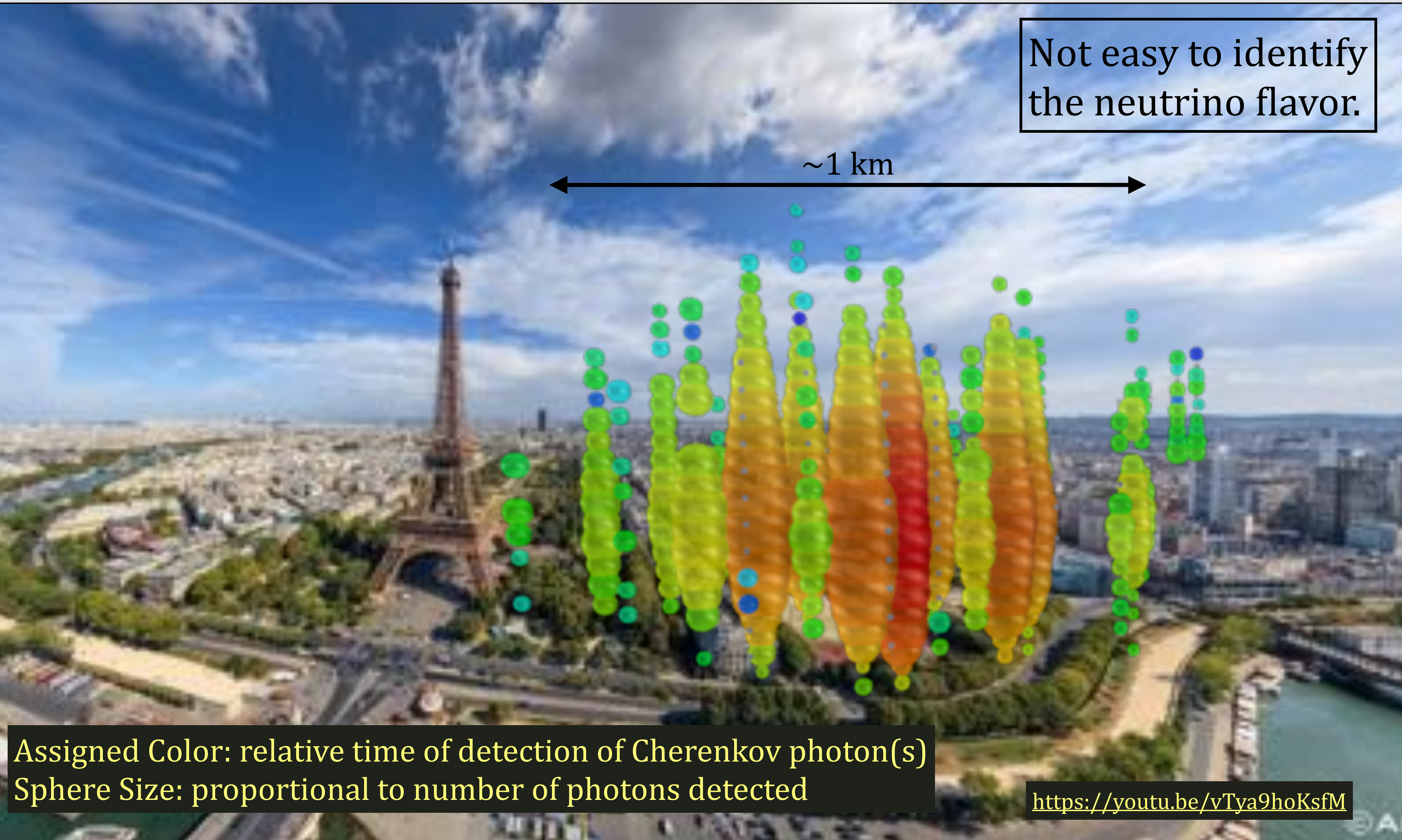
...while strong deviations from $1 : 1 : 1$ could signify new physics:



Nat. Phys. 18, 1287–1292 (2022)

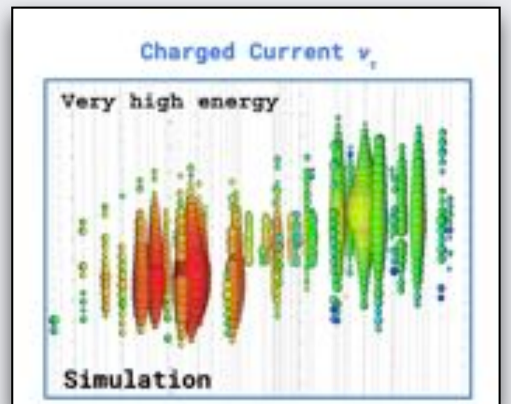
Example: Effect of quantum gravity.

These Events are Huge



Astrophysical Tau Neutrinos

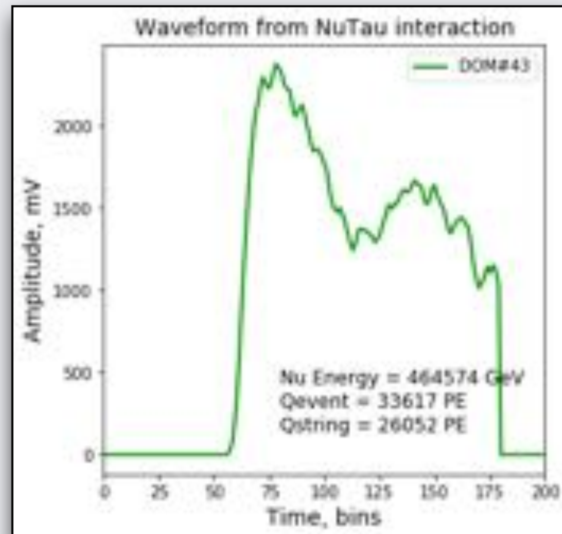
- Previous IceCube msmts. looked for ν_τ via
  - "Double bang":



$L_\tau \simeq 50\text{m} \cdot E_\tau$ /PeV. Severely limited phase space. Not yet seen.

$$\nu_\tau \to W\tau$$
$$W \to X$$
$$\tau \longrightarrow (e,h)$$

- Double cascade:



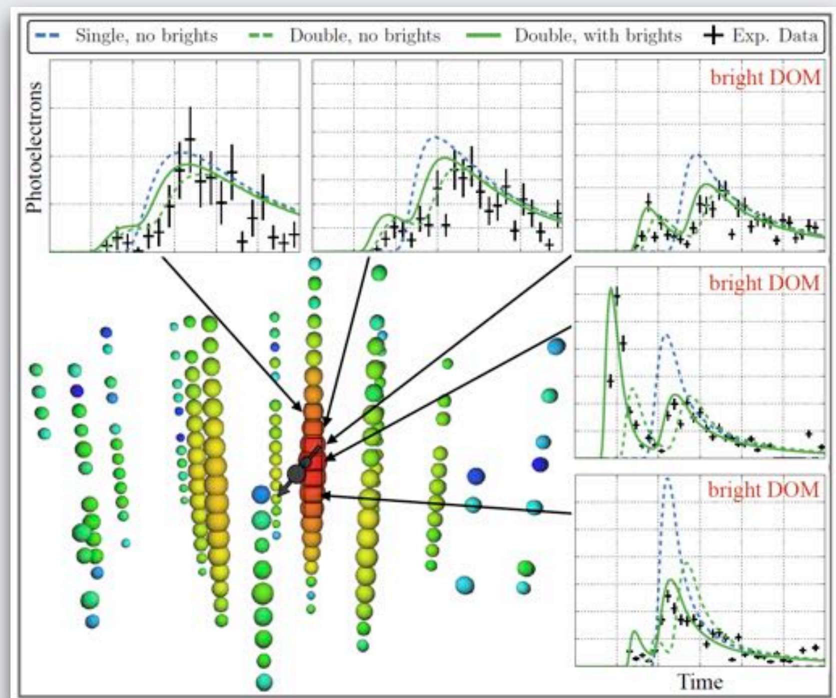
Search for ν_τ-induced waveforms on 1-2 DOMs.

Candidate ν_τ seen, but at low significance.

Note: $(\phi_\nu^{\text{astro.}} \cdot \sigma_{\nu N}) \propto E_\nu^{-1}$, so lowering energy threshold will increase signal level.

Astrophysical Tau Neutrinos

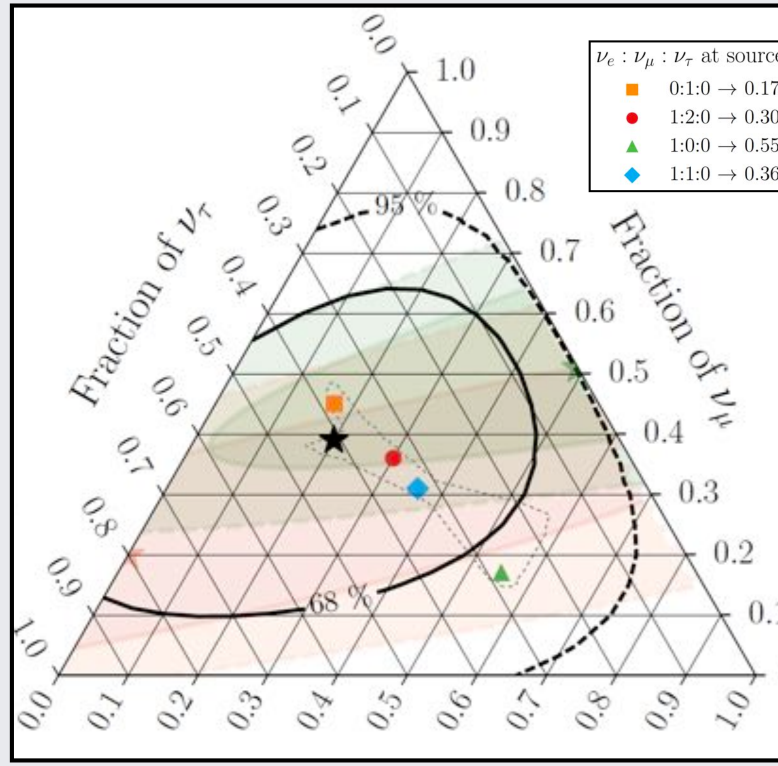
- Also inclusively with "HESE" 60-event sample:
  - LLH-based fit classified 41 single cascades, 2 double cascades, & 17 tracks



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

Candidate ν_τ: "Double Double"

- Excluded null hypothesis ($\Phi_{\nu_\tau} = 0$) at 2.8σ

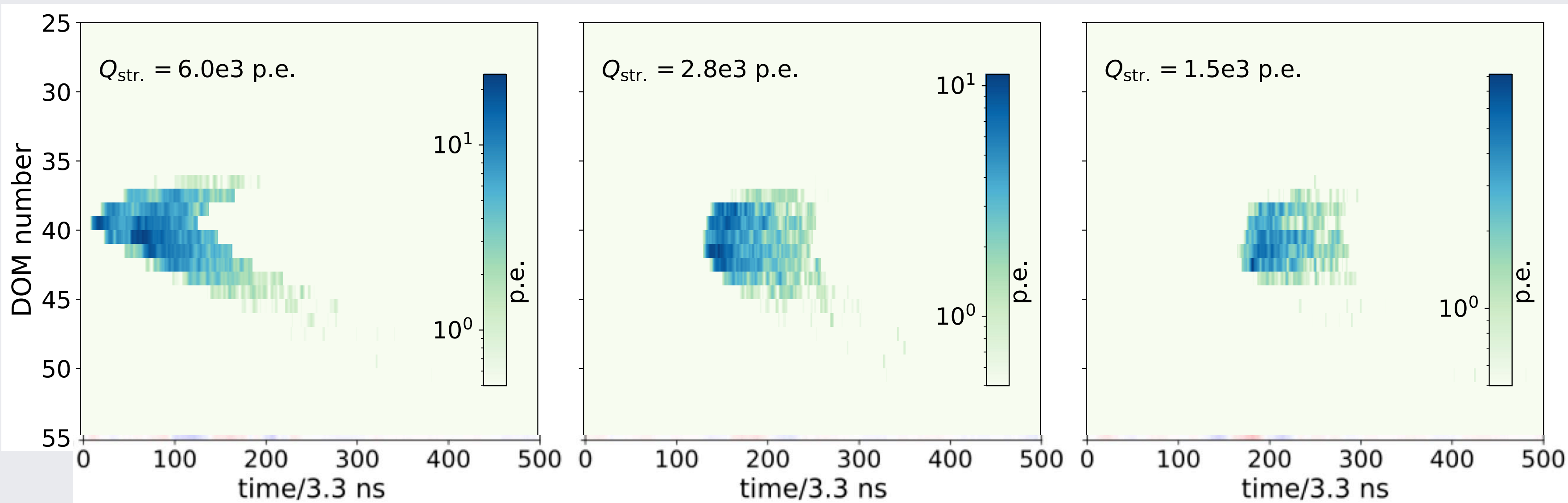


Eur. Phys. J. C 82, 1031 (2022)

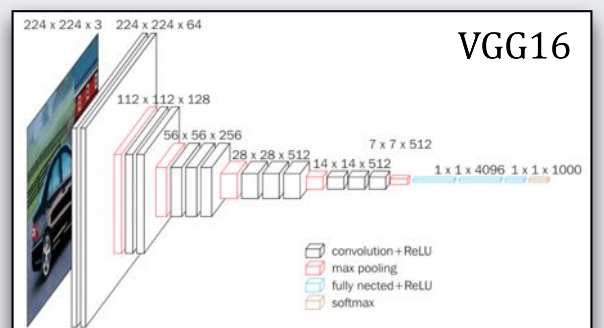
Measured flavor composition of IceCube HESE events. ★ is best fit point, consistent with presence of all 3 flavors, but ν_τ flux only weakly constrained.

Astrophysical Tau Neutrinos

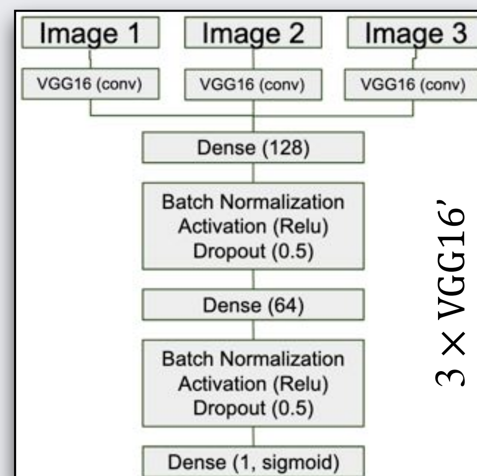
- Current (exclusive) measurement starts with 2-d images, one per string:



- Then it trains CNN (VGG16) to distinguish signal from background.



Simonyan & Zisserman, 1409.1556



Astrophysical Tau Neutrinos

- Expected 4–8 ν_τ on a bkgd. of ~0.5 with 9.7 years of data; predicted ~50% chance of excluding null hypothesis of $\Phi_{\nu_\tau}^{\mathrm{astro}} = 0$ at $> 5\sigma$
  - (S,B) levels depend on chosen $\Phi_\nu^{\mathrm{astro}}$; assume 1:1:1 flavor ratio
    - IceCube has 4 $\Phi_\nu^{\mathrm{astro}}$ msmts.; use one w/least-significant exclusion of null hypothesis
- Main contributors to the ~0.5 background events
  - $\nu_{\mathrm{other}}^{\mathrm{astro}}$: Dependent on chosen Φ_ν (IceCube msmts.)
  - 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^{astro} interactions; on-shell W; Earth-crossing $\nu_e, \nu_\mu \to \nu_\tau$

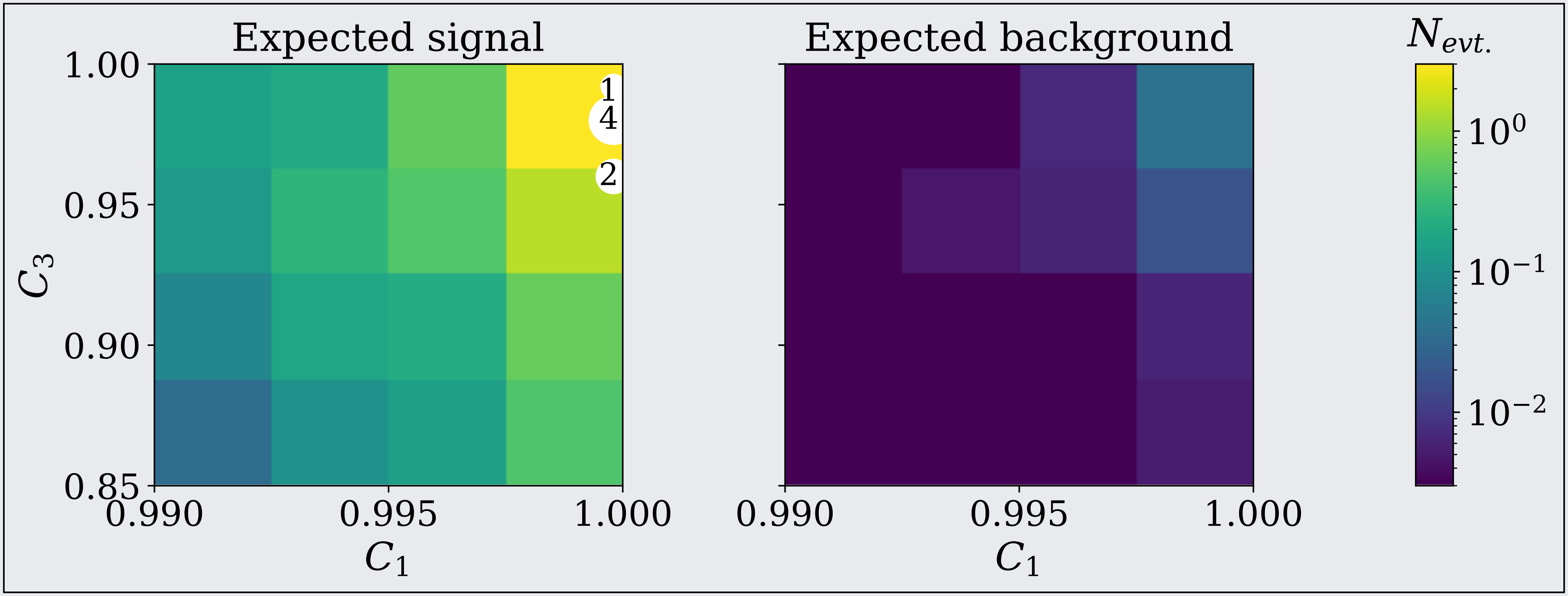
	Signal	Backgrounds				
	$\nu_{\tau,CC}^{\mathrm{astro}}$	$\nu_{\mathrm{other}}^{\mathrm{astro}}$	$\nu_{\mathrm{conventional}}^{\mathrm{atm}}$	$\nu_{\mathrm{prompt}}^{\mathrm{atm}}$	μ^{atm}	all background
initial	160 ± 0.2 (190 ± 0.3)	400 ± 0.7 (490 ± 0.8)	580 ± 7	72 ± 0.1	8400 ± 110	9450 ± 110 (9540 ± 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).

*From charm decays.

Searching for Astrophysical ν_τ

Opening the box, we saw 7 events.



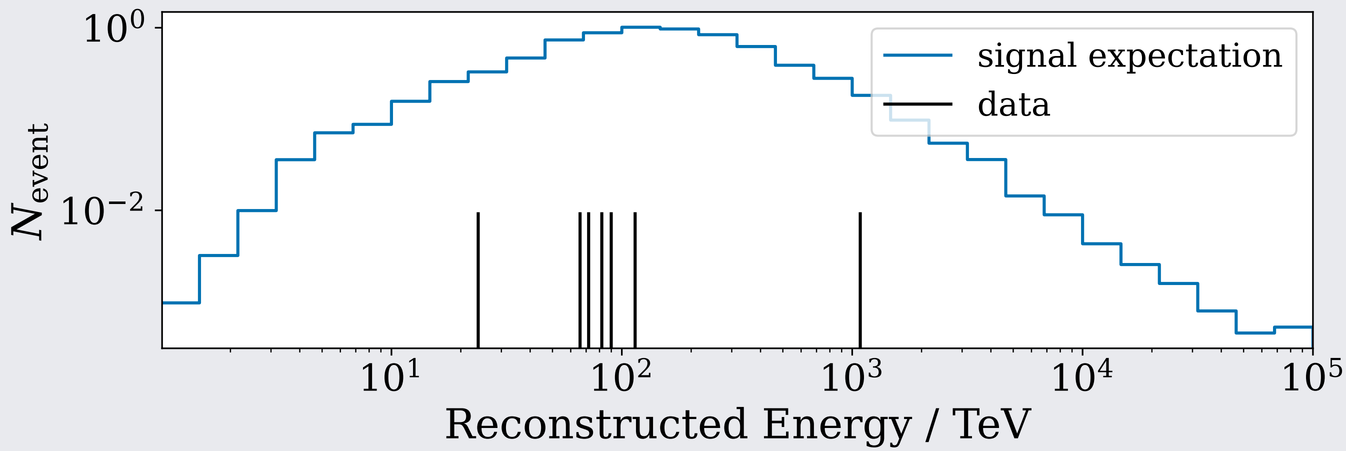
4 events are brand new.

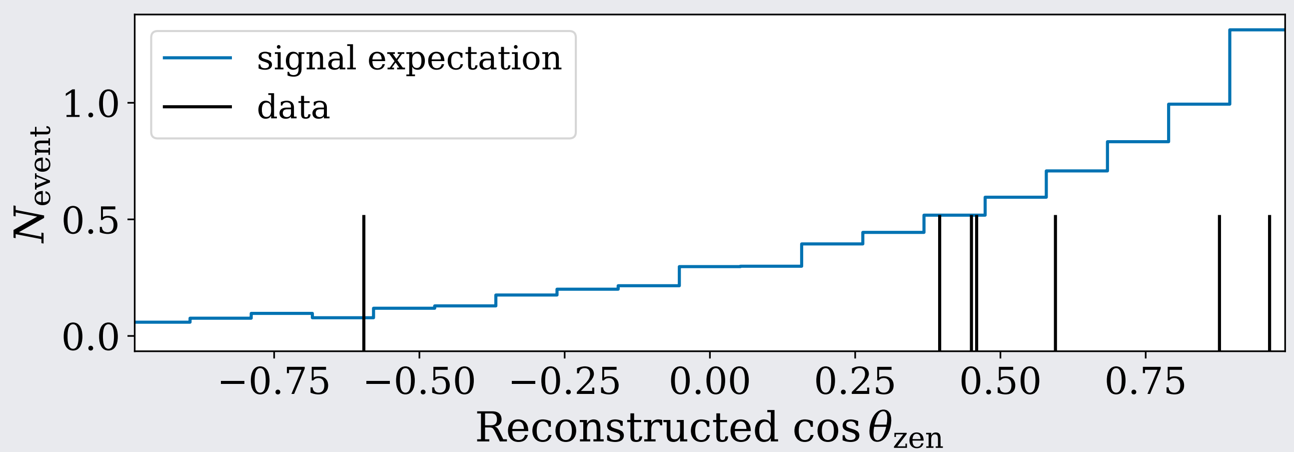
3 events are old; 1 of which had been identified as a ν_τ candidate.

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

Post-Unblinding Checks

- Apply single-pulse reco. to
  - simulated ν_τ
  - candidate ν_τ
- Good data–MC agreement…
  - …but take numbers with a grain of salt
- Event vertices (see backup)
  - Over-clustered but consistent with stat. fluctuation
  - Loosening C_1 score
    - admits 12 total events without visible clustering
    - retains high significance level





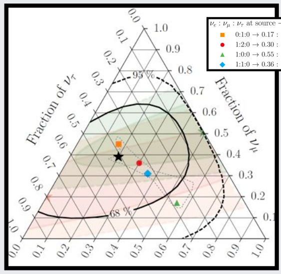
(IceCube's "GlobalFit" flux assumed above.)

$\nu_\tau^{\rm astro}$ Conclusions: Exclusion of Null Hypothesis

- For IceCube's *GlobalFit* flux, exclude $\phi(\nu_\tau^{\rm astro}) = 0$ at 5.1σ
  - Other fluxes: 5.2σ, 5.2σ, 5.5σ (*Inelasticity*, *Diffuse*, *HESE*)
  - Measured $\phi(\nu_\tau^{\rm astro})$ is consistent with all four $\phi(\nu^{\rm astro})$
- Alternatively, this is a 40%-level confirmation of the standard oscillation picture: $7 \pm \sqrt{7}$ events.
- Also, since $\nu_\tau^{\rm atm}$ negligible at these E_ν
  - Detection of energetic ν_τ powerfully confirms IceCube's earlier $\nu^{\rm astro}$ discovery.

ν_τ^{astro}: What's Next?

- Used just 3 (of 86) strings. Using more strings would:
  - Improve bkgd rejection, allowing for relaxation of cuts→more signal
    - Improve $\phi(\nu_\tau^{\text{astro}})$ 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 ν_τ reconstruction for direction, E,...
  - Study parameters of highest-energy ν_τ and τ ever detected
    - L_τ, energy asymmetry, ...
  - Use high-astrophysical-purity ν_τ to look for point sources

Conclusions

- IceCube has world-leading sensitivity to atmospheric $\nu_\mu \rightarrow \nu_\tau$ oscillations
  - Current ~30% measurement with 3 yrs DeepCore
  - Future measurements will have sensitivity to new physics
    - ~10% measurement with ~decade of DeepCore: already have these data
    - ~5% measurement with ~3 years Upgrade: deployment in 2025/26
- IceCube has world's only sample of astrophysical ν_τ
  - New analysis yielded considerable sensitivity boost: 5σ-level achieved!
  - Future analyses will further increase sample and exploit physics content
    - Enhance sensitivity to astrophysical source acceleration environment
    - Study the most energetic τ leptons available
    - Search for new 3rd-generation physics

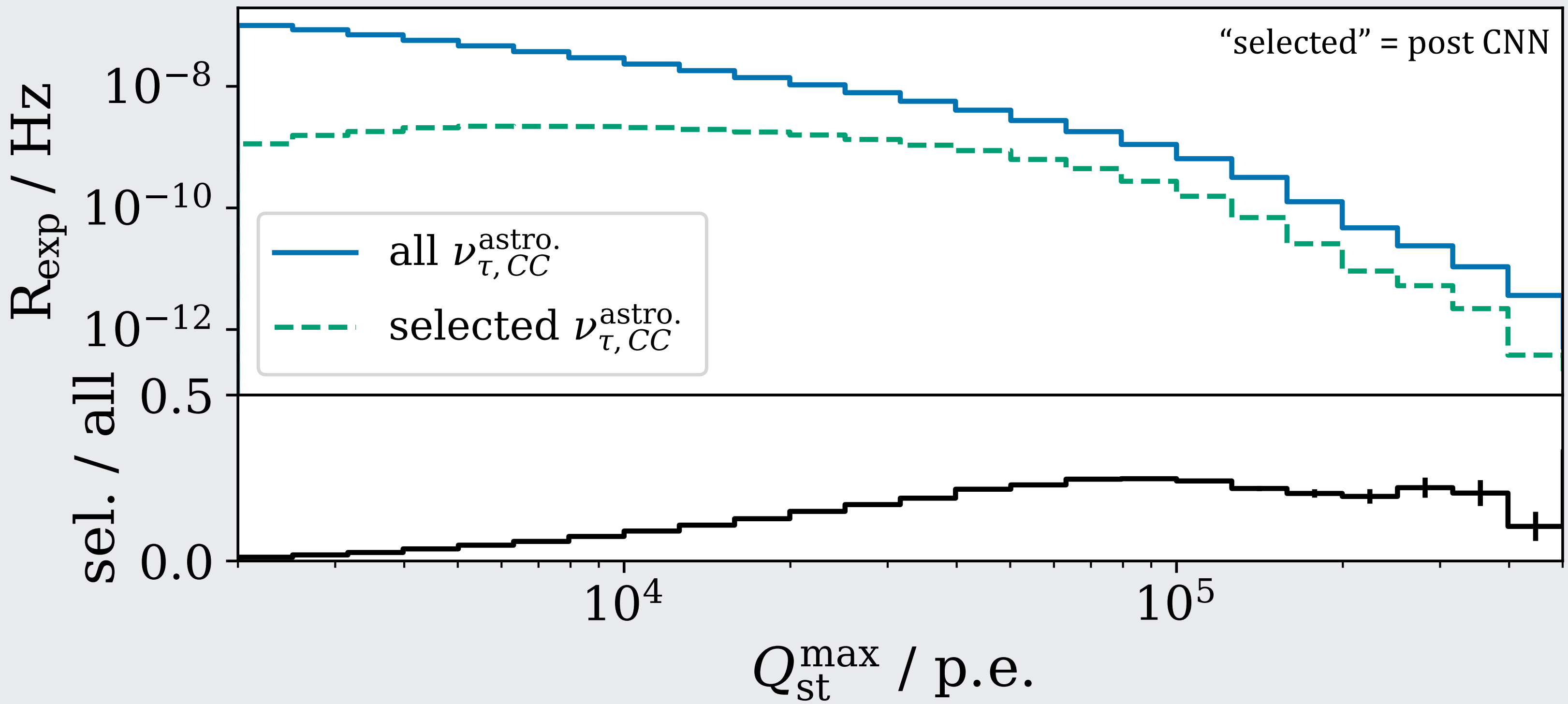
IceCube Collaboration

Spring 2022 Collaboration Meeting, Brussels, Belgium

Backup

Searching for Astrophysical ν_τ

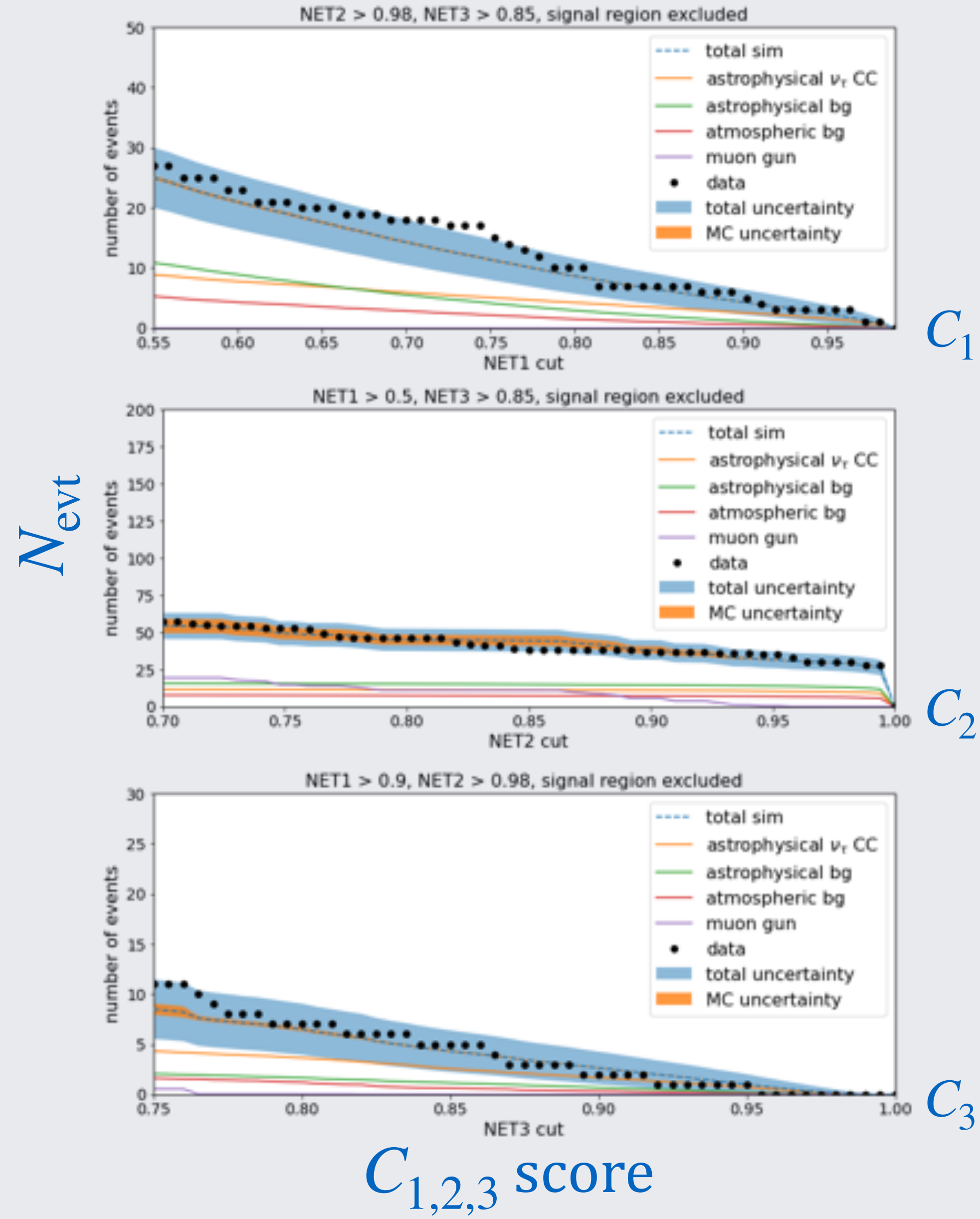
- Initial ν_τ DP selection criteria
  - Require ≥ 2000 p.e. on highest-charge string and ≥ 10 p.e. on two neighbors
  - Require cascade topology
- After initial criteria, have ~300x more background than signal



Searching for Astrophysical ν_τ

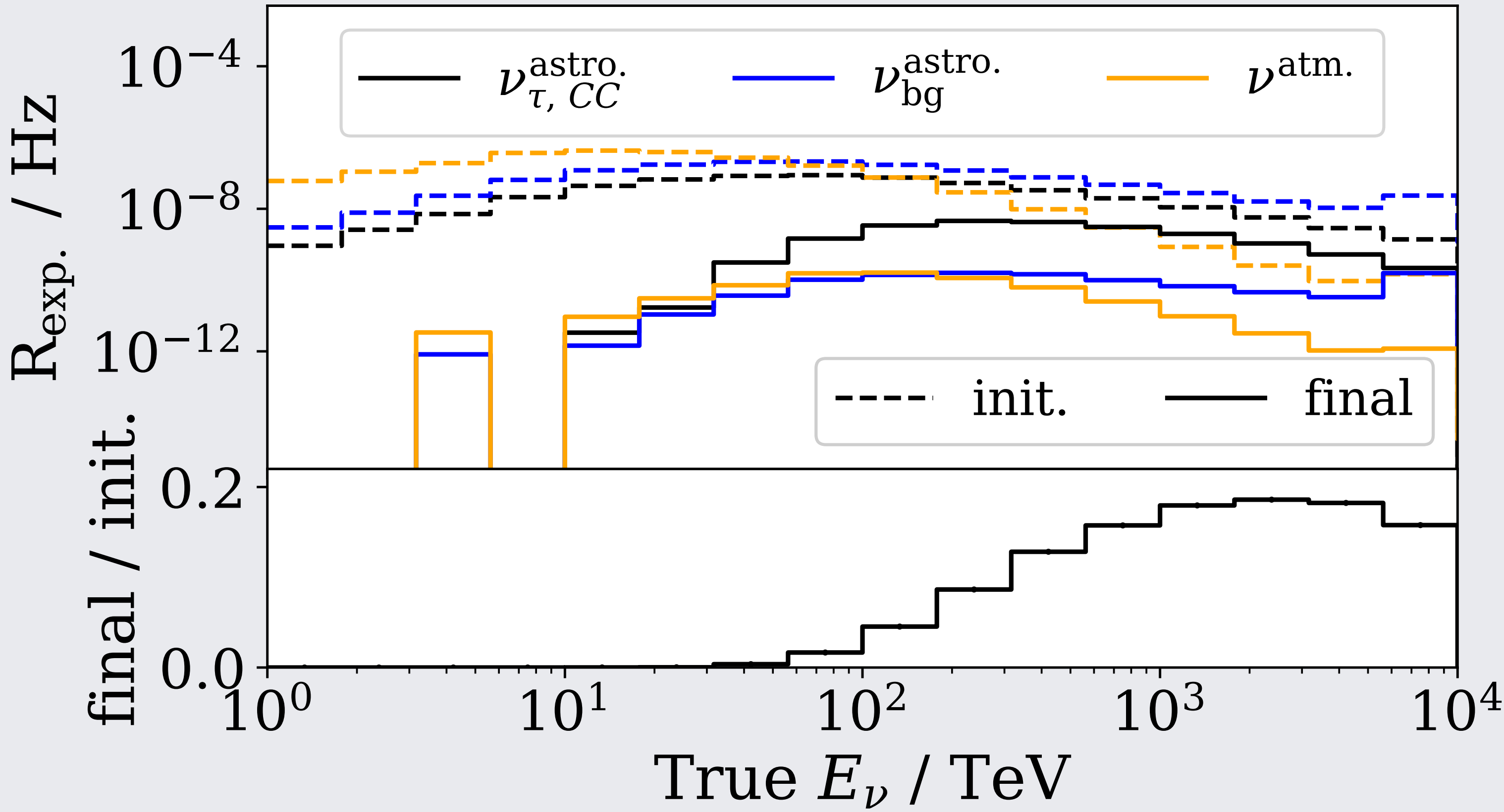
- Trained 3 independent CNNs
  - C_1: DP vs. SP (ν_τ^{CC} vs. ν_e^{CC}, ν_x^{NC})
  - C_2: DP vs track (ν_τ^{CC} vs. $\mu_\downarrow$)
  - C_3: DP vs Track (ν_τ^{CC} vs. ν_μ^{CC})
- $C_1 \geq 0.99,\ C_2 \geq 0.98,\ C_3 \geq 0.85$
  - Gives S/N ~ 14.
- Backgrounds
  - Dominant: $\nu_{\text{astro.}}$ and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



Searching for Astrophysical ν_τ

- E_{ν_τ} spectrum:



- After final (CNN) 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

- Backgrounds/Systematics in more detail: Charm
  - Charm: $\nu_e^{\text{astro}} \to eW;\ W \to cs$ (and $\nu_{\text{NC}}^{\text{astro}}; Z \to c\bar{c}$)
    - $\lambda_{\text{charm}} \simeq \mathcal{O}(\text{m}),\ \ E_{\text{dep.}} \simeq 10^{12-14}$ 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.
      - 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.)

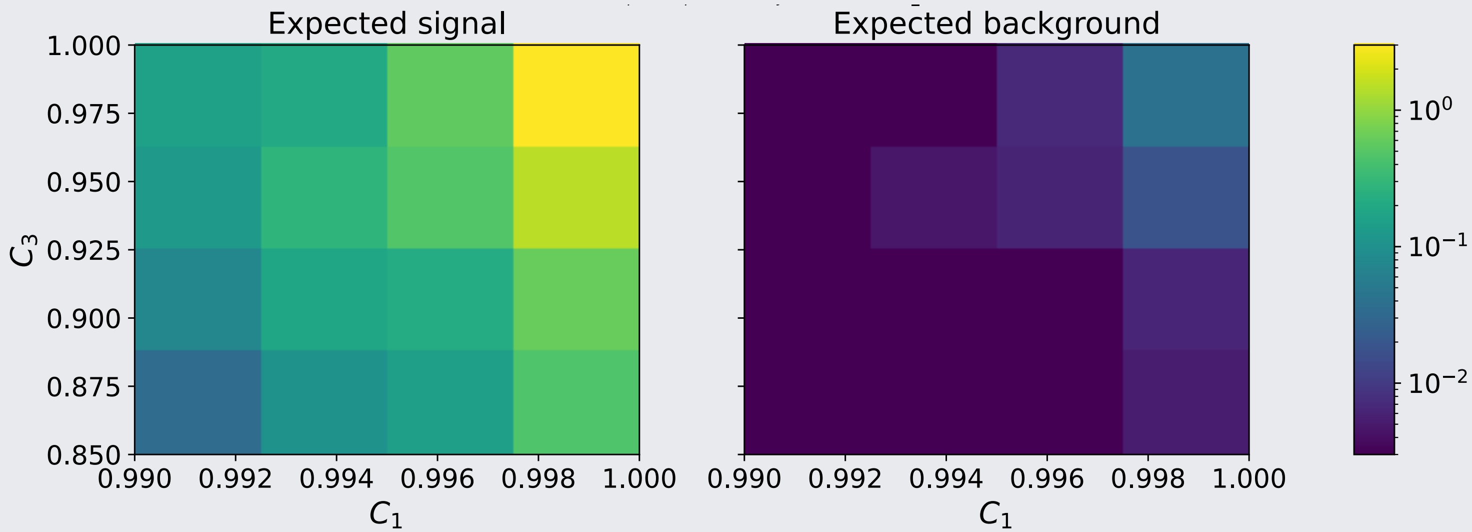
Searching for Astrophysical ν_τ

- Backgrounds/Systematics, cont'd:
  - $\mu_\downarrow, \mu_{\mathrm{DIS}}$ $(\mu + X \to \nu_\mu + X')$: 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)

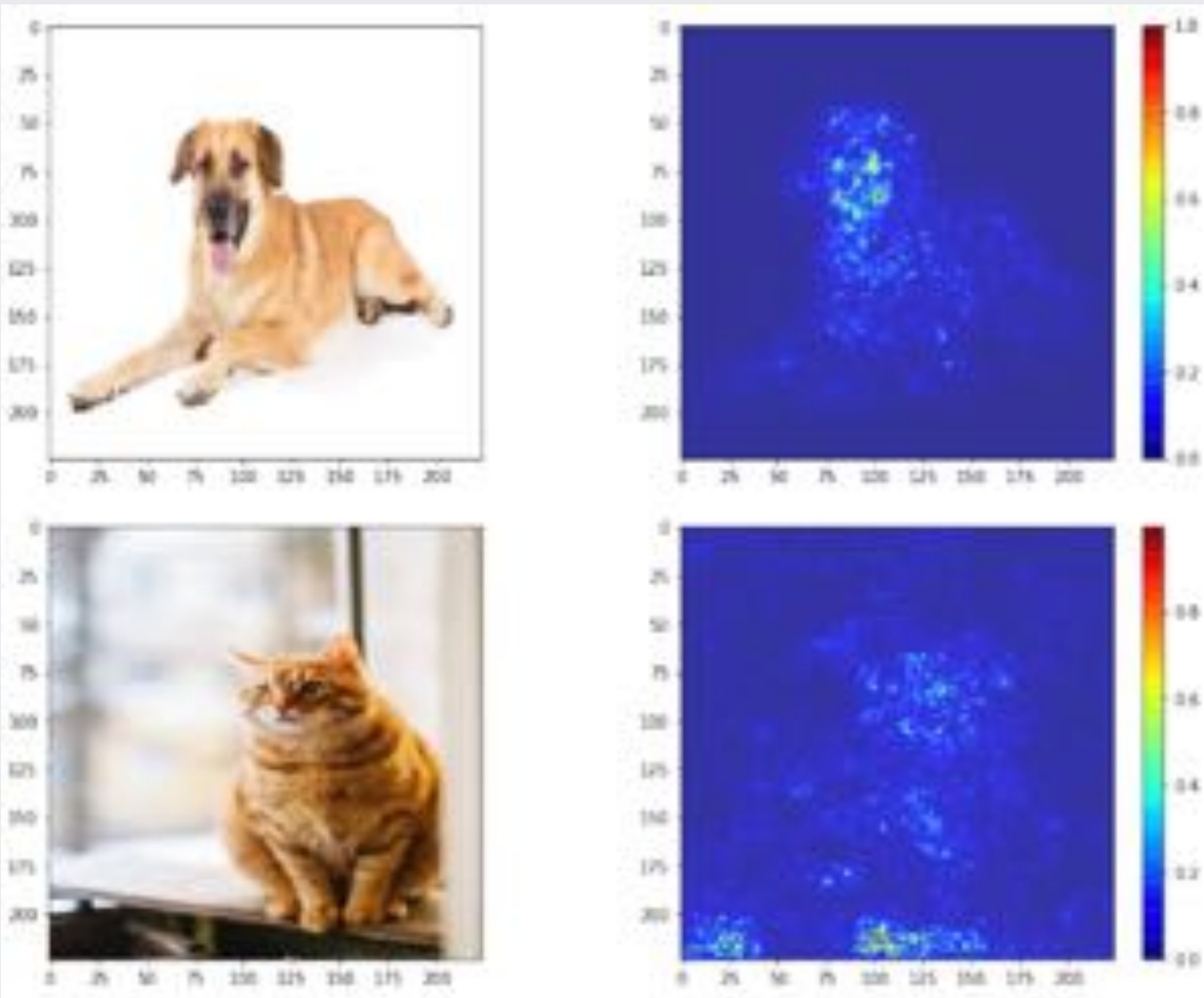
Searching for Astrophysical ν_τ

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



CNN Robustness: 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.



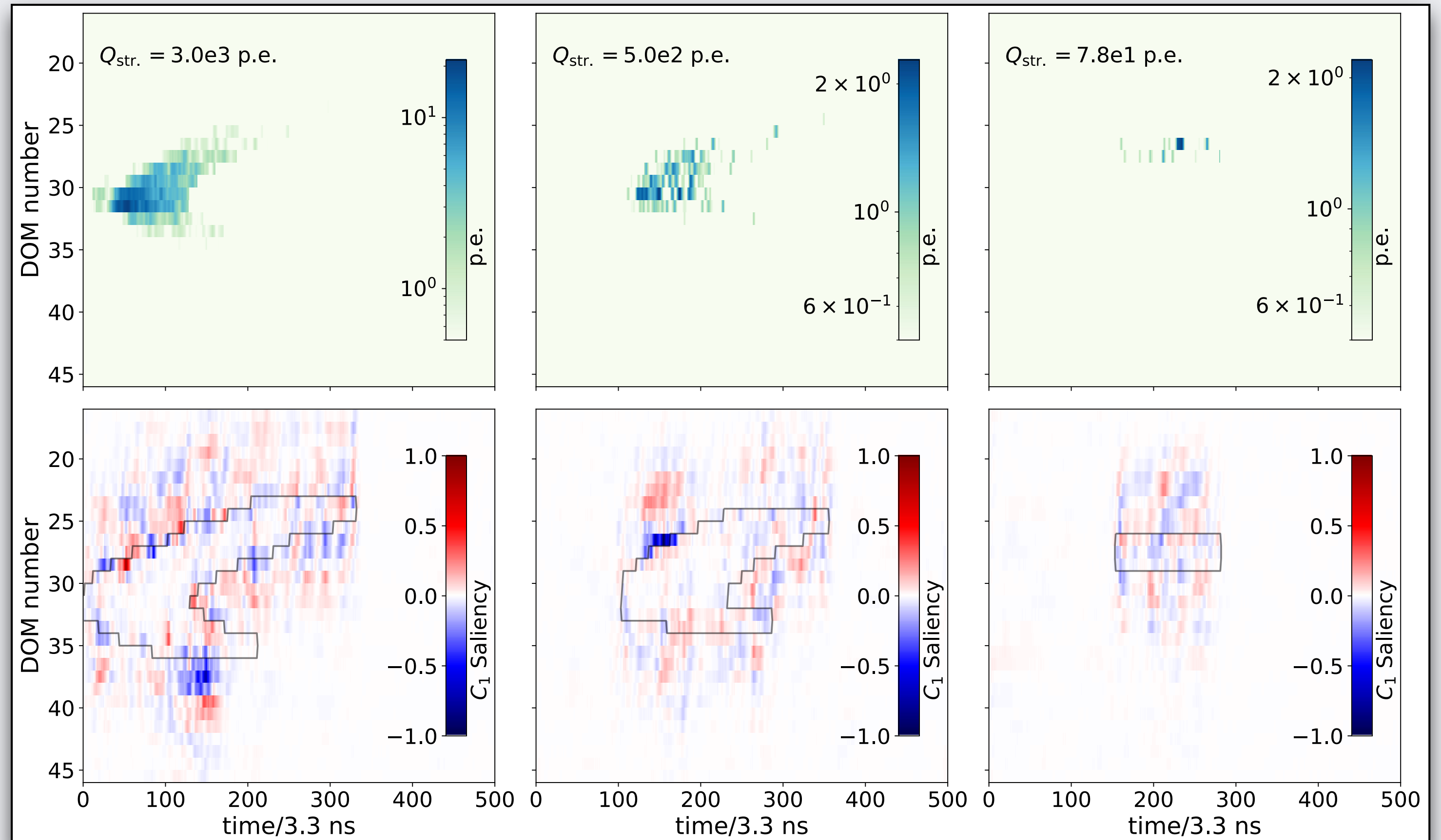
https://usmanr149.github.io/urmlblog/cnn/2020/05/01/Salincy-Maps.html

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.)

Event Pics w/Saliency Maps

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

DOM number (∝ depth)



time/ns

Measured light levels in each of 3 strings.

Saliency:

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

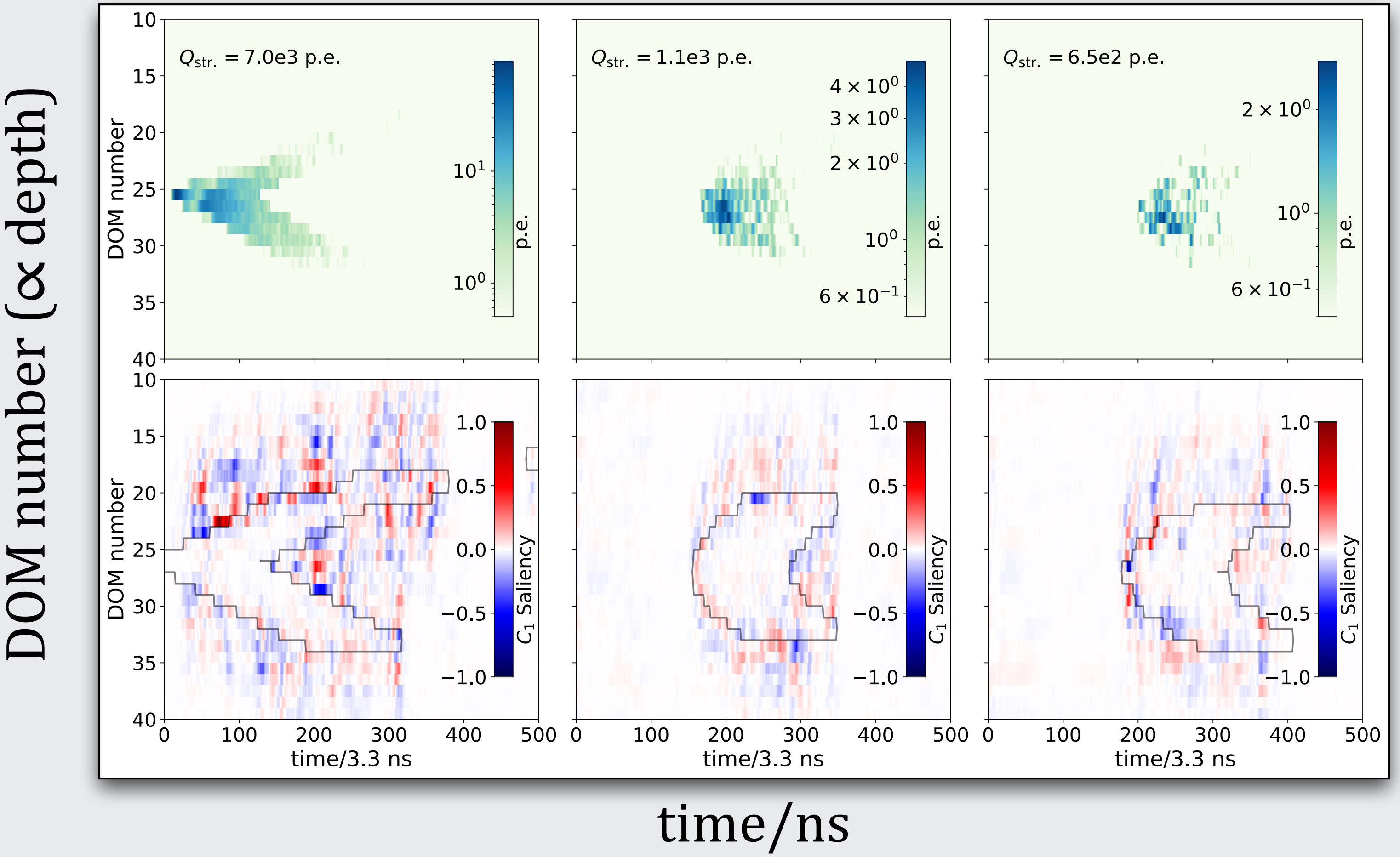
- light↑, C_1↑
- light↓, C_1↑

Contours: where light level → 0.

Large $S(C_1)$ show where & when light-level change most effectively changes C_1.
Bright pixels with small $S(C_1)$ show where C_1 is less sensitive to light-level changes.
Generally, $S(C_1)$ shows C_1 sensitive to overall event shape.

Event Pics w/Saliency Maps

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



(Gratifying to see this event again.)

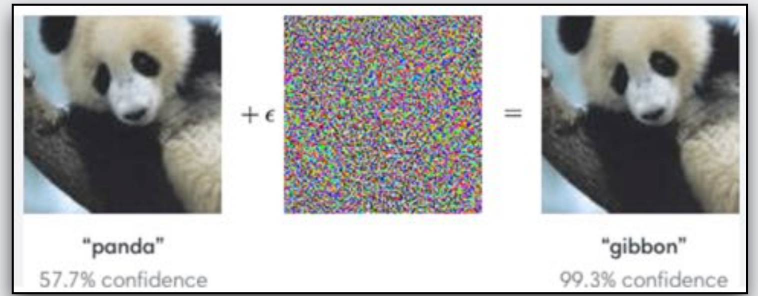
All event pics in backup.

CNN Robustness

- Data-driven tests
  - Randomly scale pre-CNN data events' light levels within known uncertainties
    - Use patterns to mimic detector systematics (module efficiency, ice properties) with ~6M pseudo-data events
    - Estimated signal→background migration probability: $< 0.3\% \pm 0.08\,\%$ in all cases (< 0.02 signal events)
    - Estimated background→signal: $< 0.002\% \pm 0.0002\,\%$ (<0.2 background events)
      - Adding in 0.2 background events modestly reduces significance
      - Analysis already includes these systematics, estimated from MC; replacing one estimate with the other would not impact the final result.

CNN Robustness

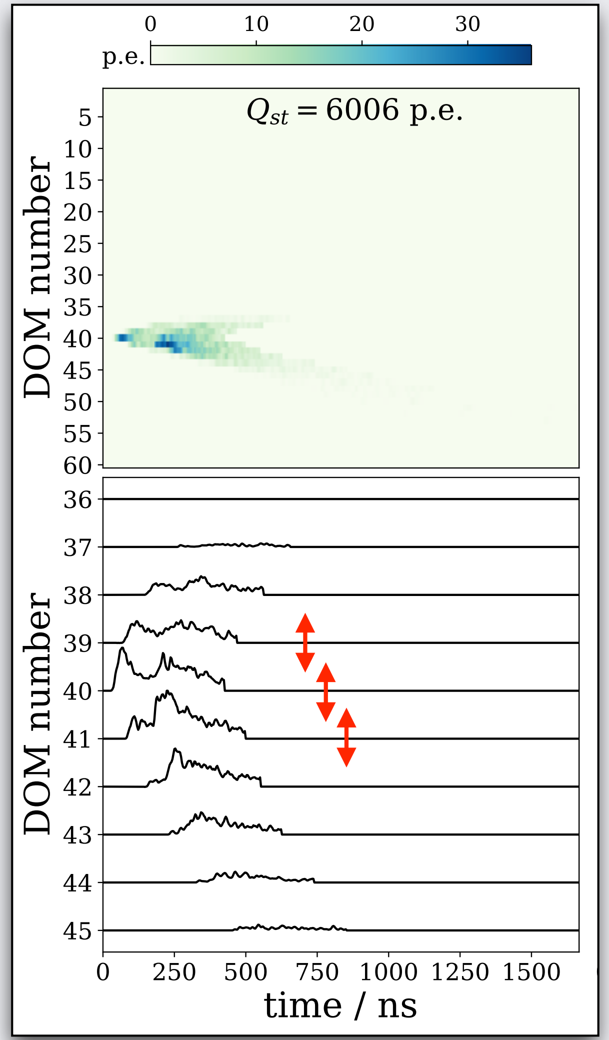
- For 7 candidate signal events:
  - Manually merged double pulse waveforms, manually shifted light arrival times: CNN response unchanged
  - "Adversarial Attack" (DeepFool): Find closest decision boundary and compute perturbation required to cross it
    - Only with pixel variations outside uncertainties could one event could be forced to migrate
    - 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; changes required to get $B \rightarrow S$ migration outside uncertainties
  - Attacked 634 simulated ν_e, allowing pixels to change $\pm 10\,\%$, and only 1 $\nu_e \rightarrow \nu_\tau$

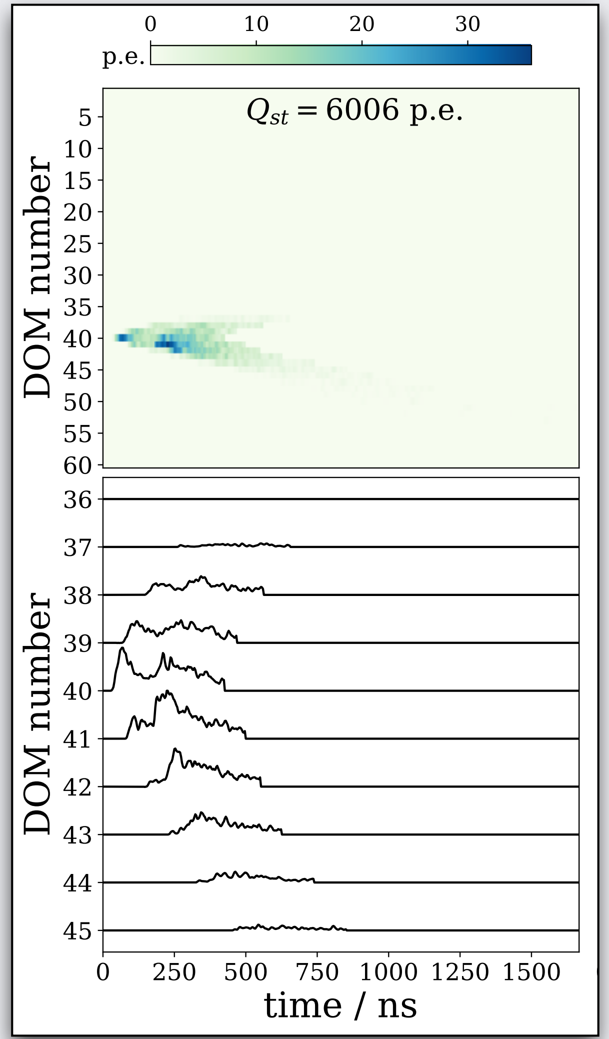
Data-Driven Systematic Checks

- 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

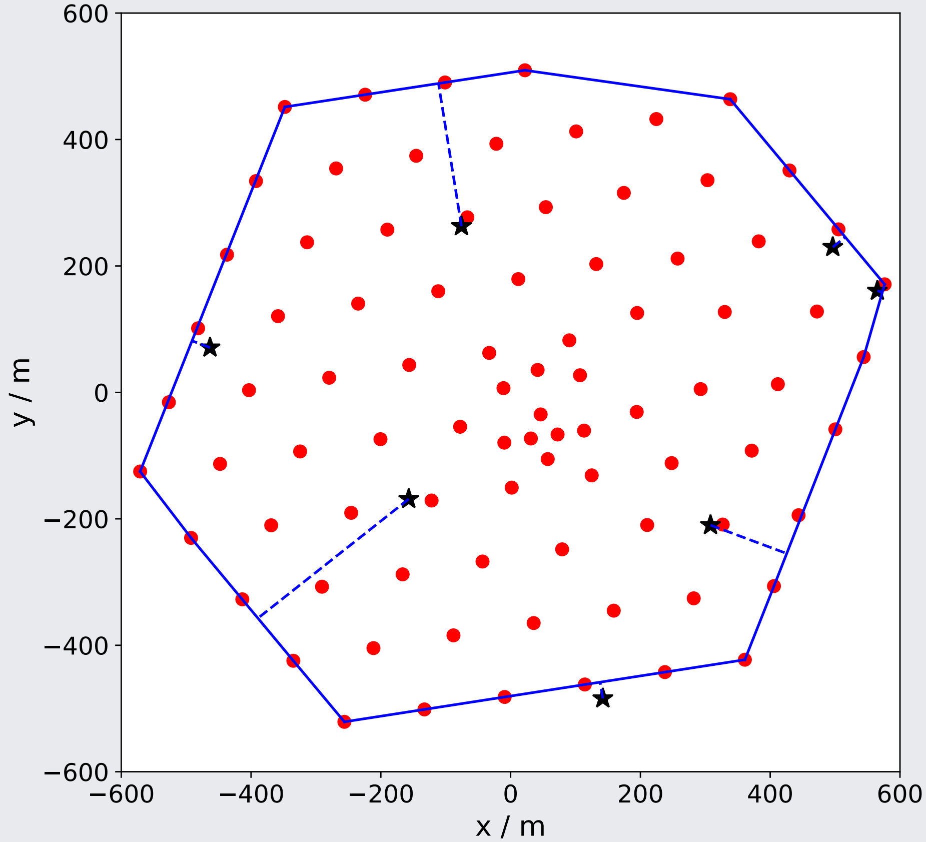


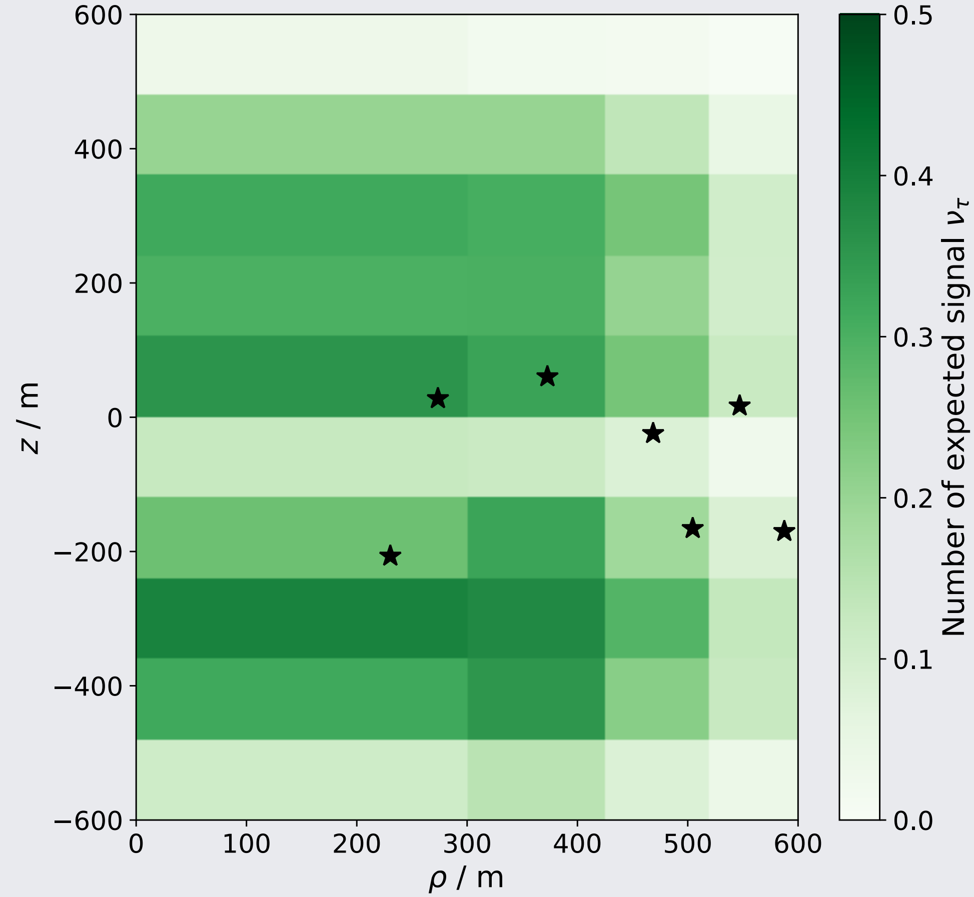
Data-Driven Systematic Checks

- 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.

Post-Unblinding Checks

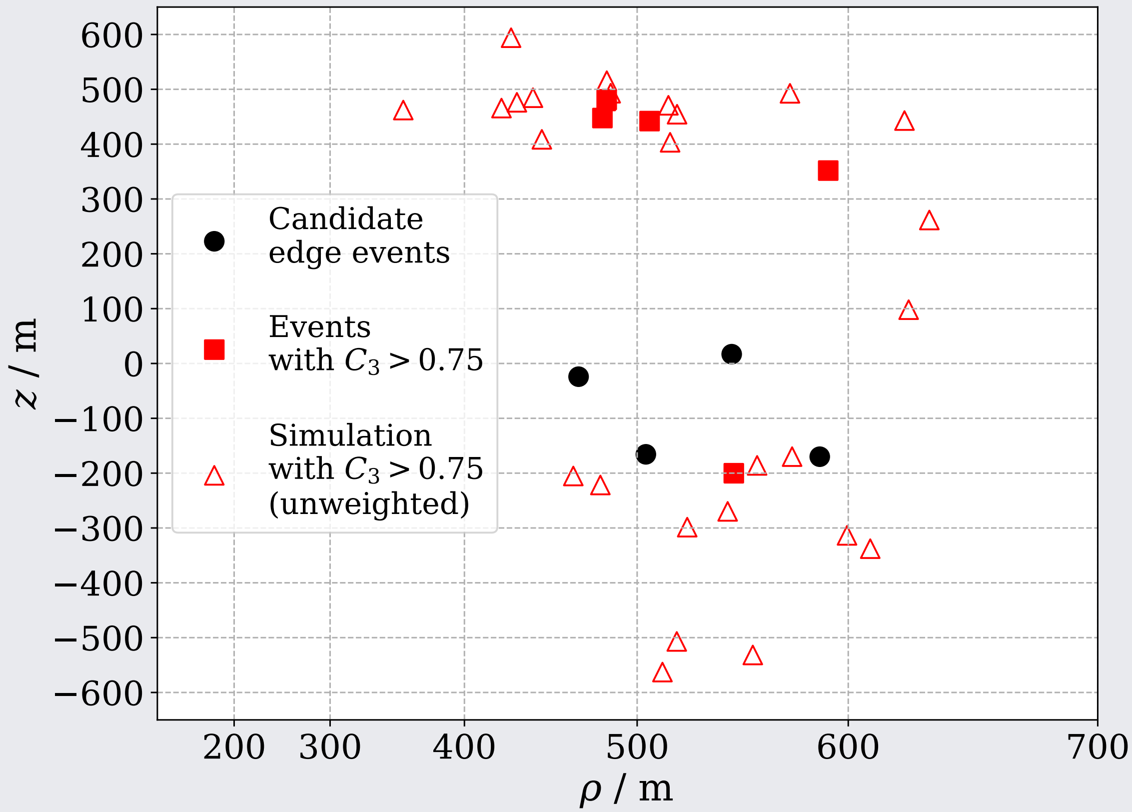
- The event vertex distribution did not look as uniform as expected
  - Several events' highest charge string was near detector's edge
  - More clustered in z above and below the "dust band"
    - A ~3σ-ish effect, depending on assumptions





Event Vertex Distribution

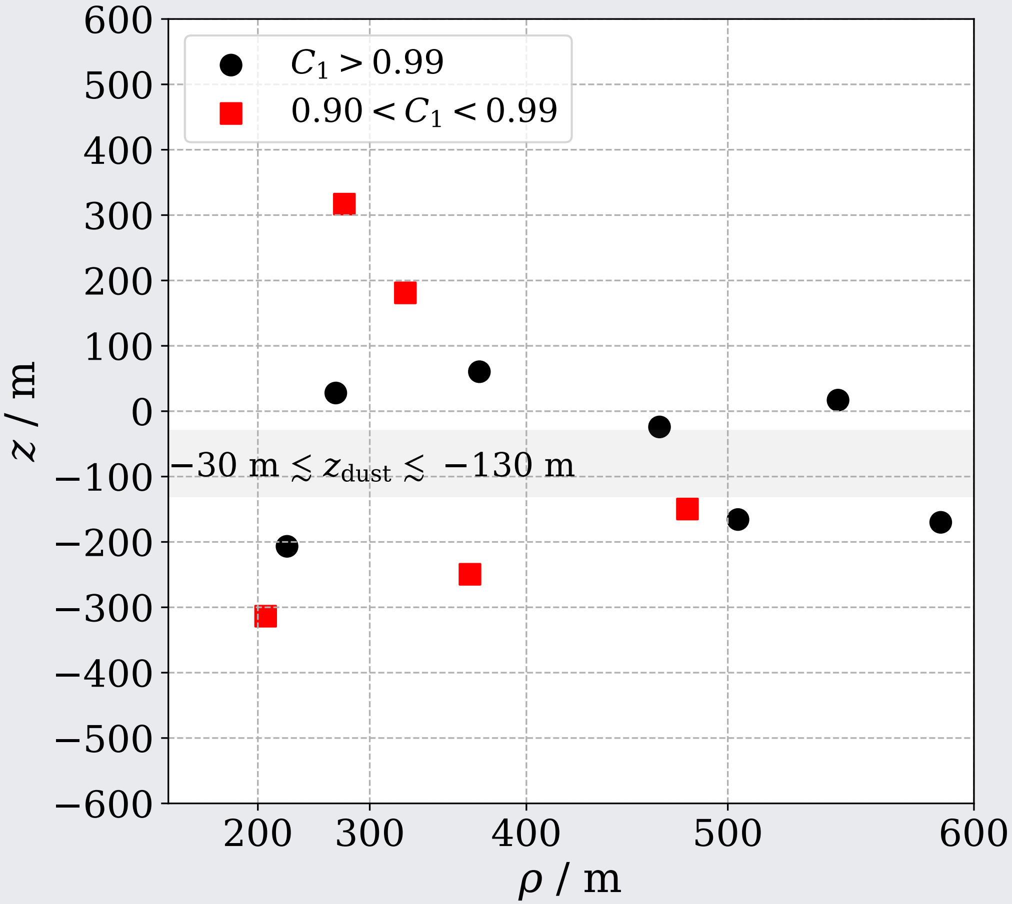
- Geometry: There's a lot of physical volume near the edge
- Loosening CNN scores $C_{2,3}$ $(\nu_\tau^{CC}$ vs. $(\nu_\mu^{CC}, \mu))$ adds new events mostly at top of detector
  - Very unlikely all 4 edge events are μ: $p_{KS}(C_3 > 0.75) = 0.1$ $[p_{KS}(C_3 > 0.85) = 0.004]$



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

Event Vertex Distribution

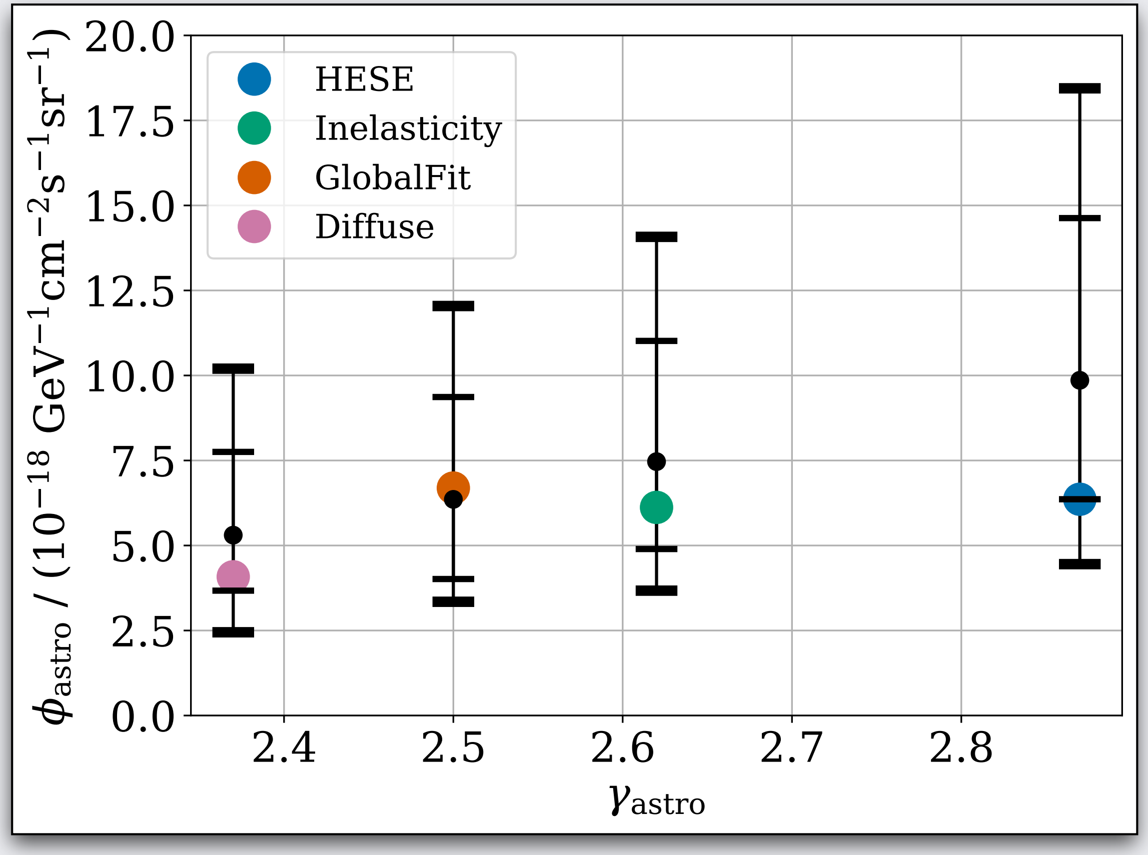
- Loosening C_1 score (ν_τ^{CC} vs. (ν_e^{CC}, ν_x^{NC}))
  - Expected 9.4 ν_τ and 2.9 bkgd events
  - Saw 12 (see figure)
- New events more evenly distributed in (ρ, z)
- Note: The 12 events would also exclude null hypothesis of $\phi(\nu_\tau^{astro}) = 0$ at high significance.



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:

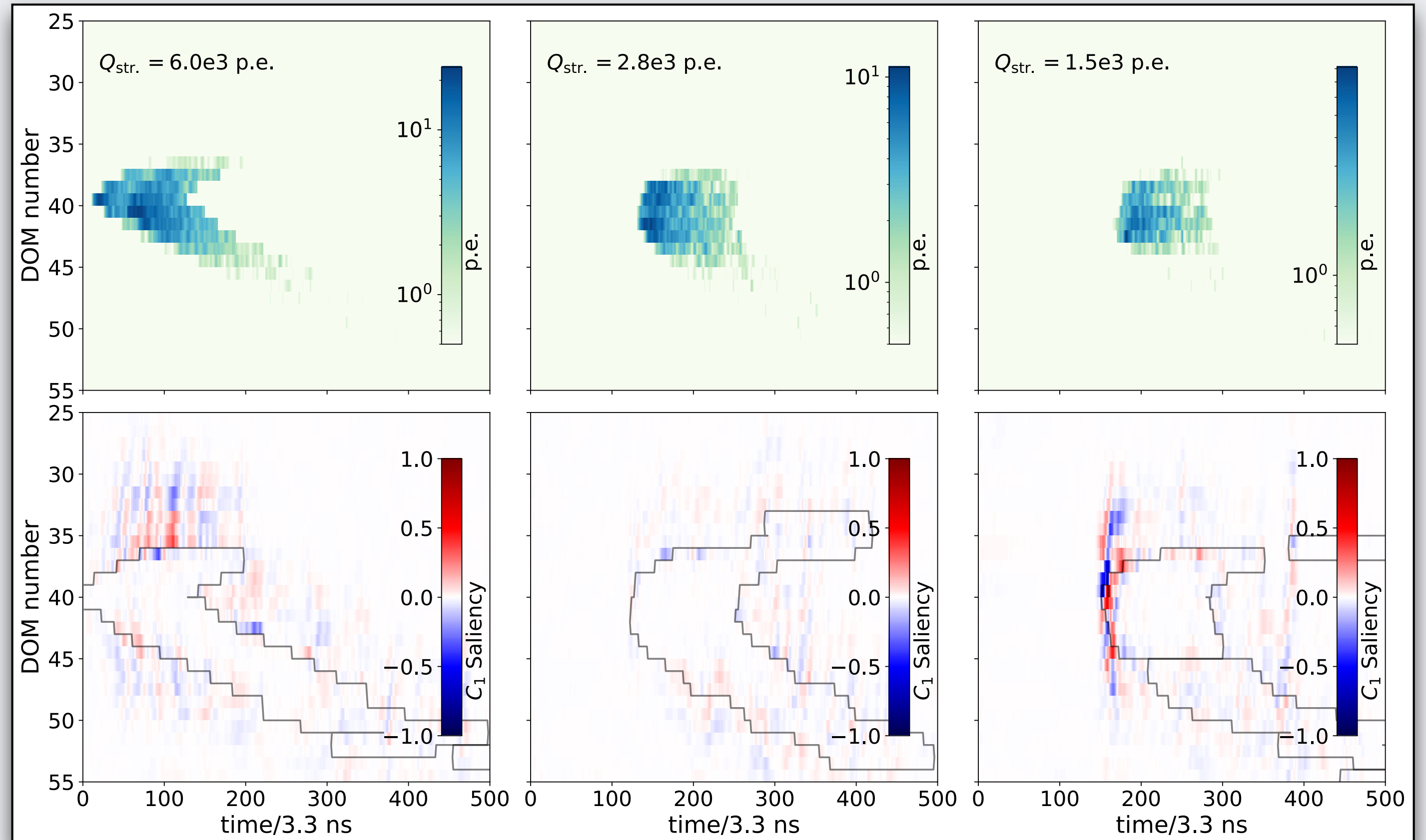


Excellent agreement with all four IceCube (non-ν_τ) measured fluxes.

Event Pics w/Saliency Maps

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

DOM number (∝ depth)

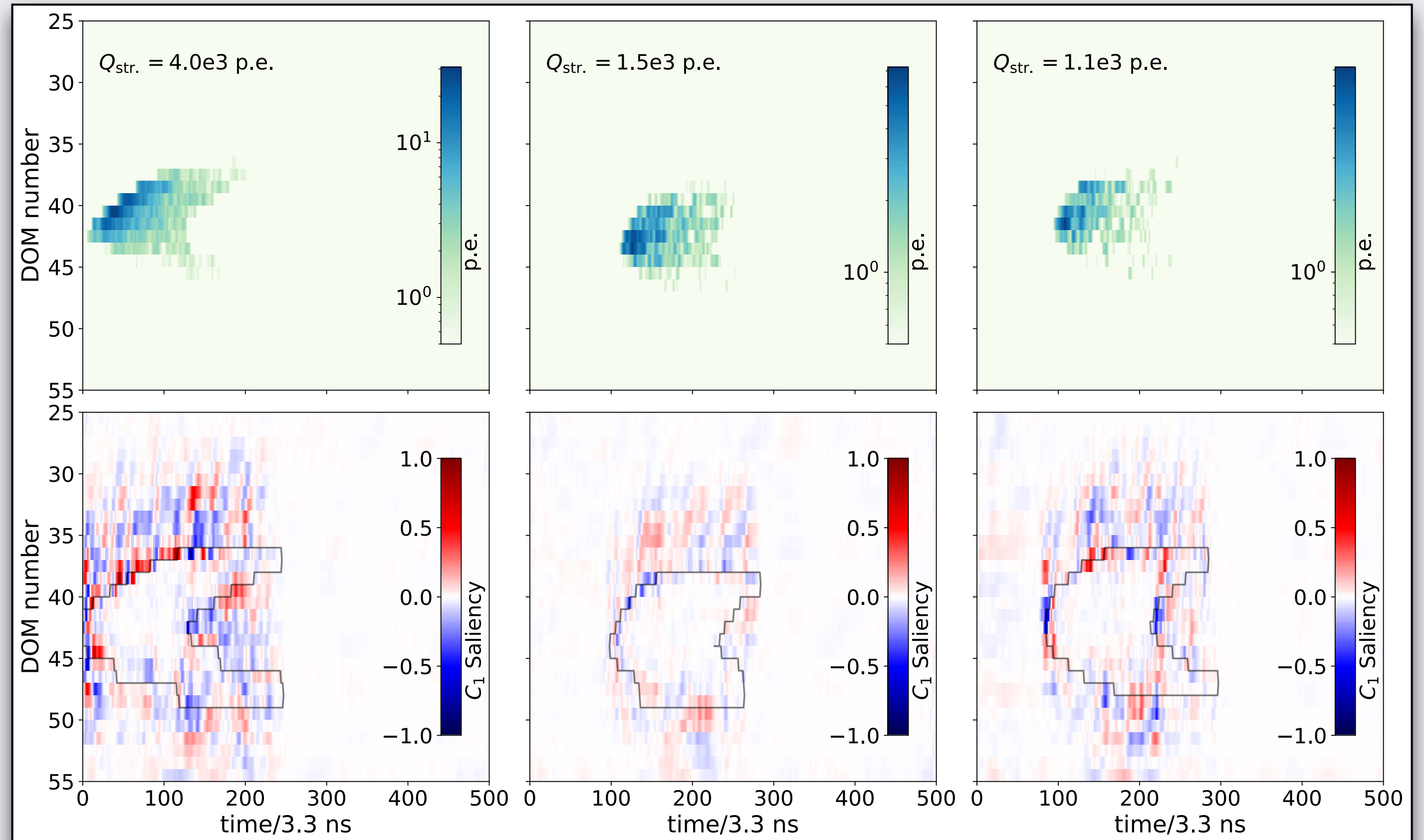


time/ns

Event Pics w/Saliency Maps

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

DOM number (∝ depth)

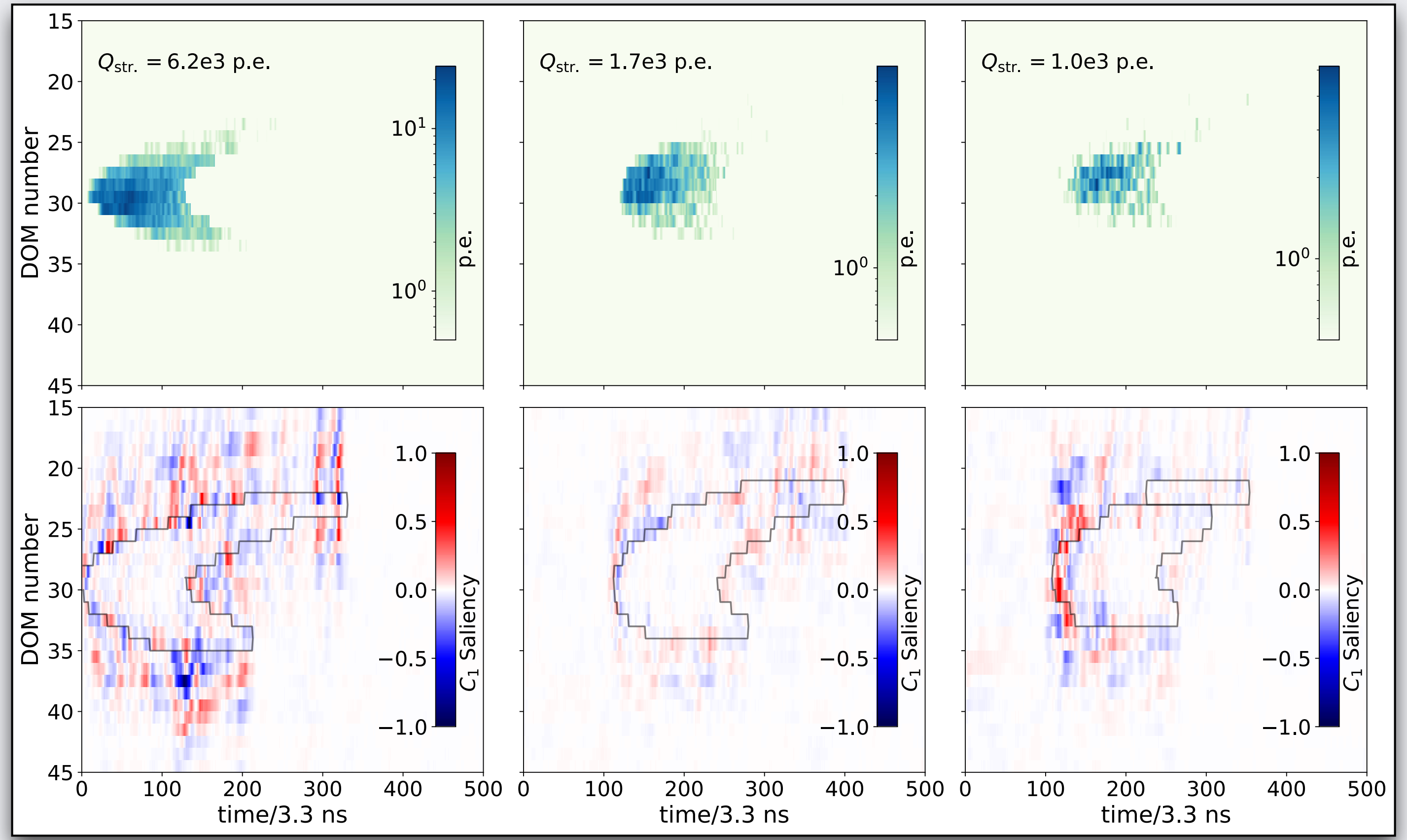


time/ns

Event Pics w/Saliency Maps

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

DOM number (∝ depth)

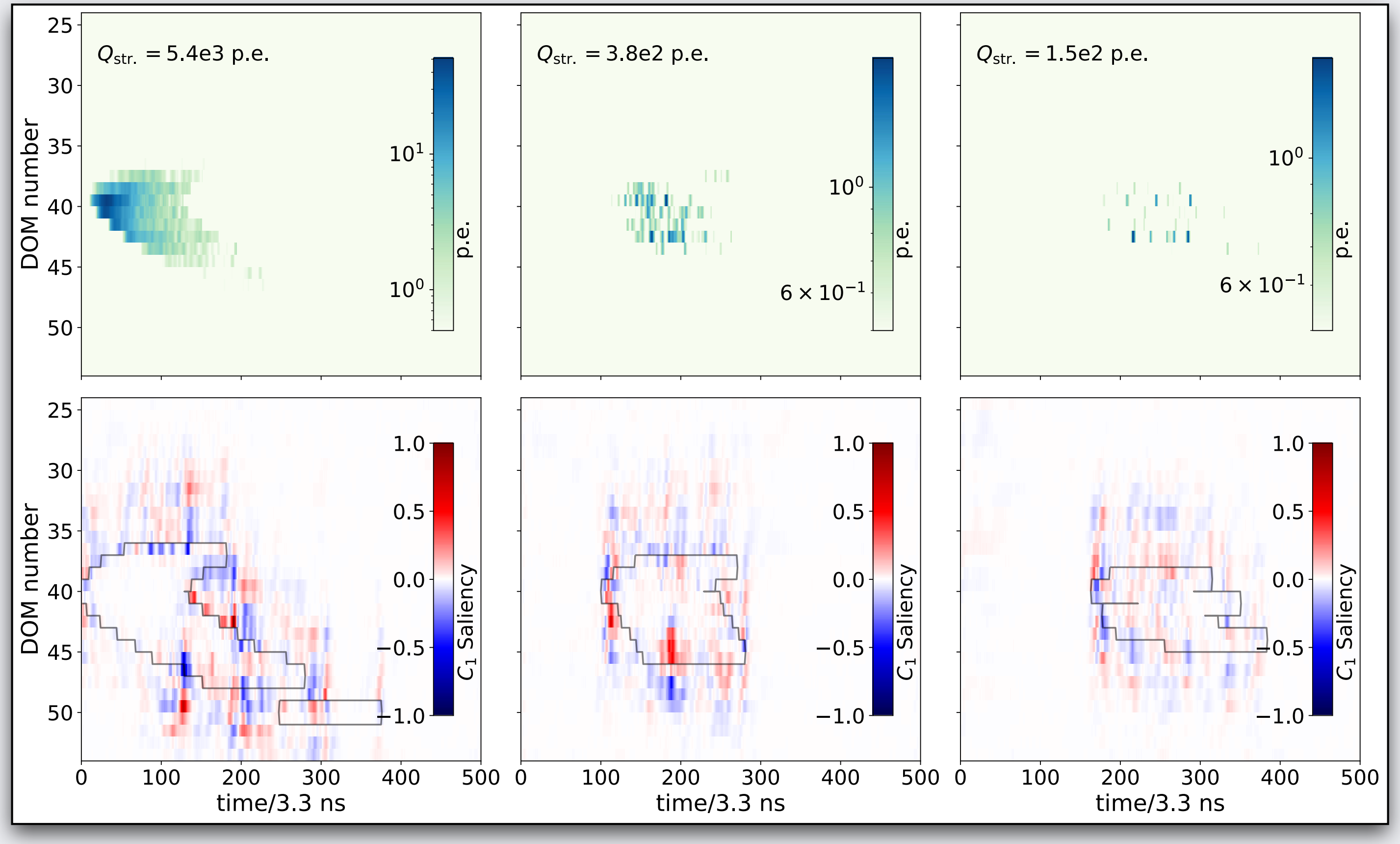


time/ns

Event Pics w/Saliency Maps

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

DOM number (∝ depth)

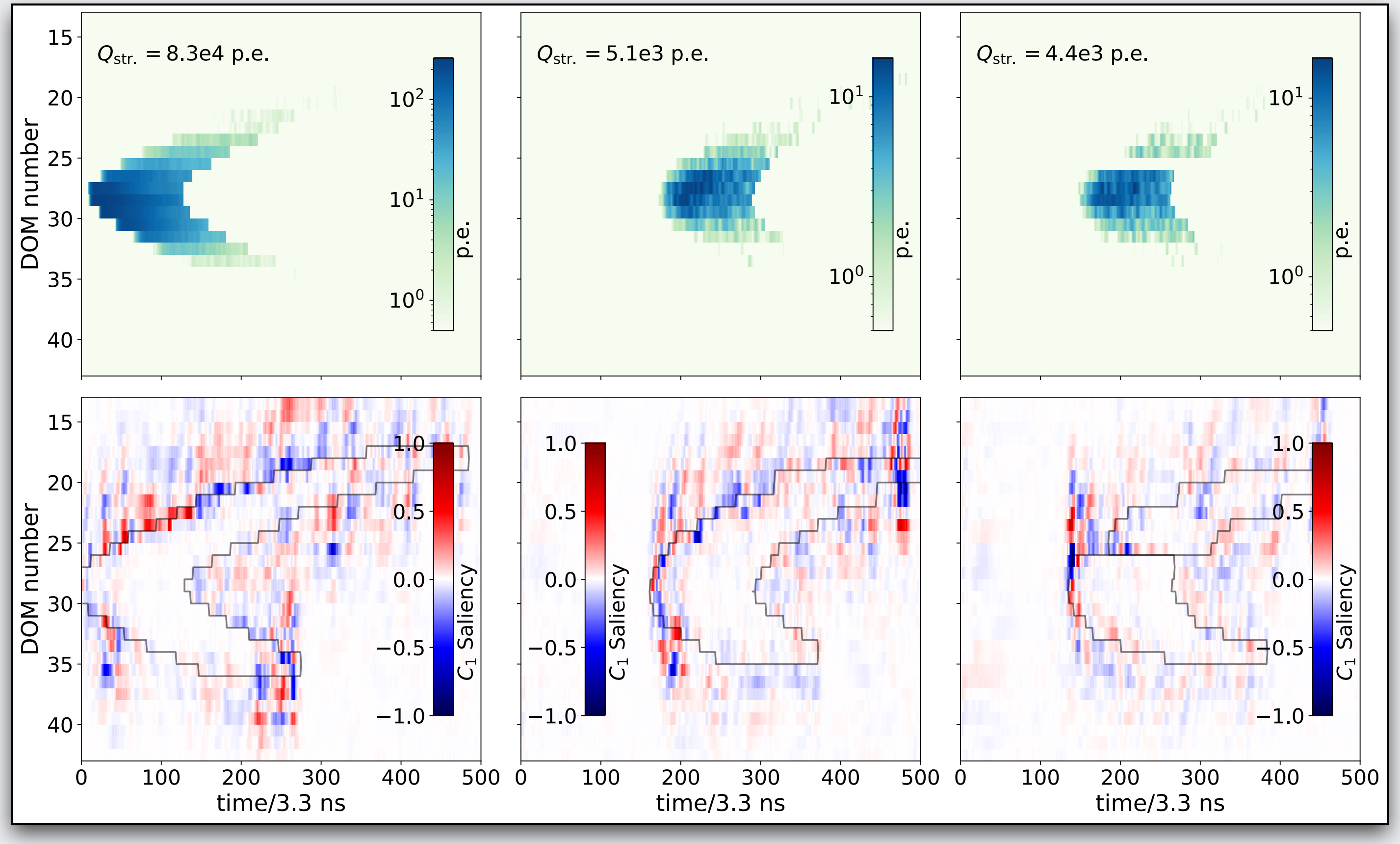


time/ns

Event Pics w/Saliency Maps

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

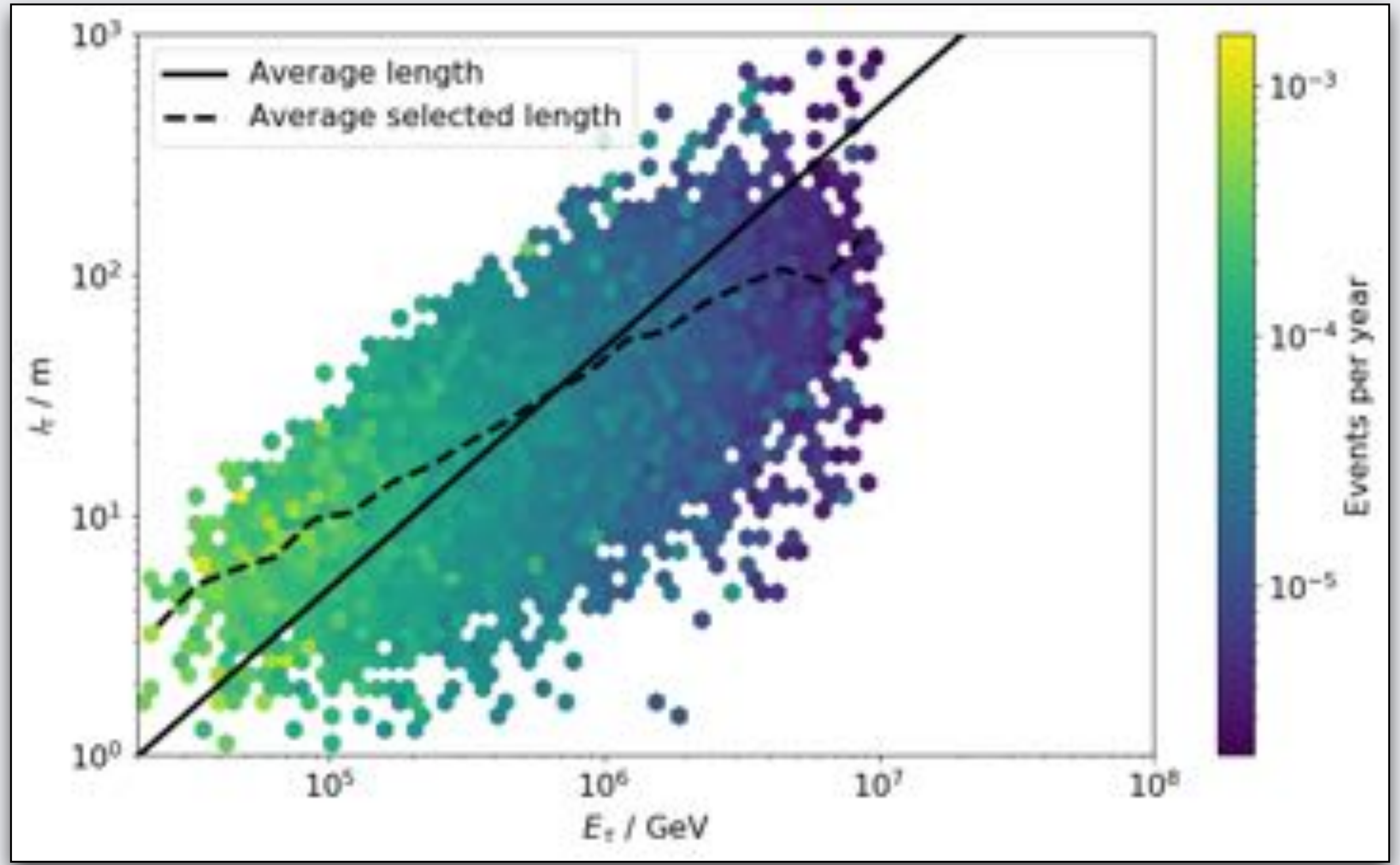
DOM number (∝ depth)



time/ns

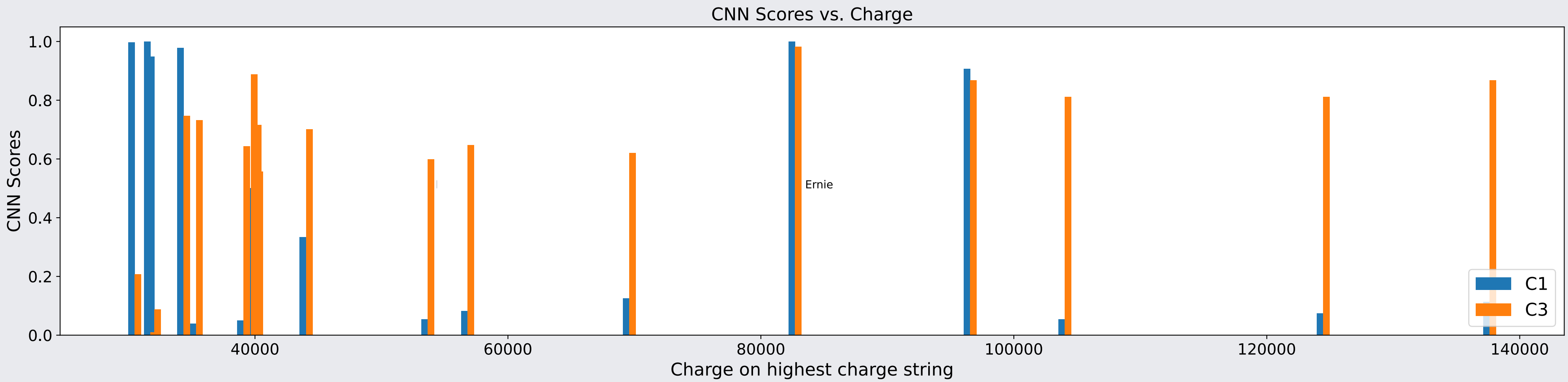
L_τ vs. E_τ

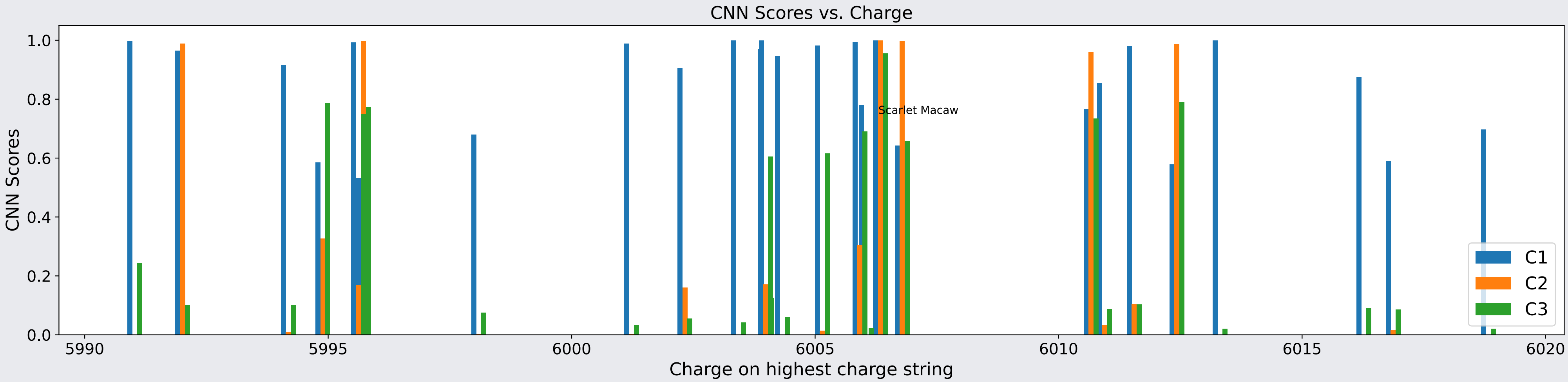
Analysis prefers events with τ's with above-average lifetimes:



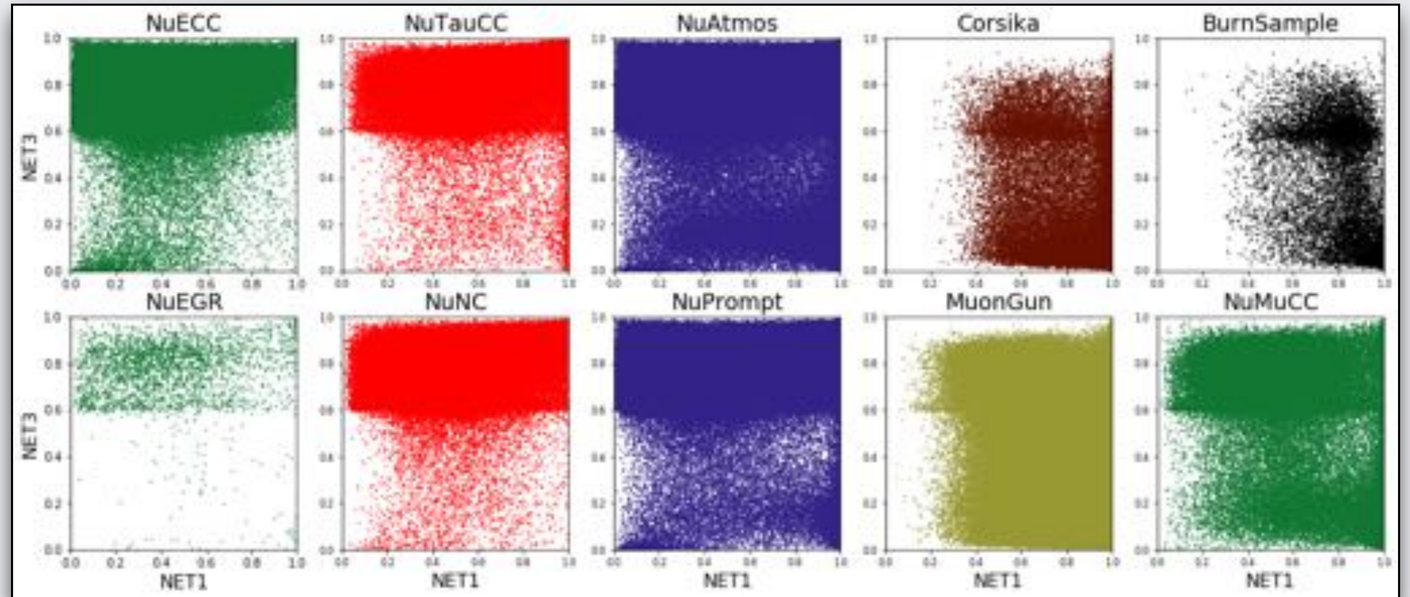
CNN Scores vs. Charge

- High charge is neither sufficient nor necessary

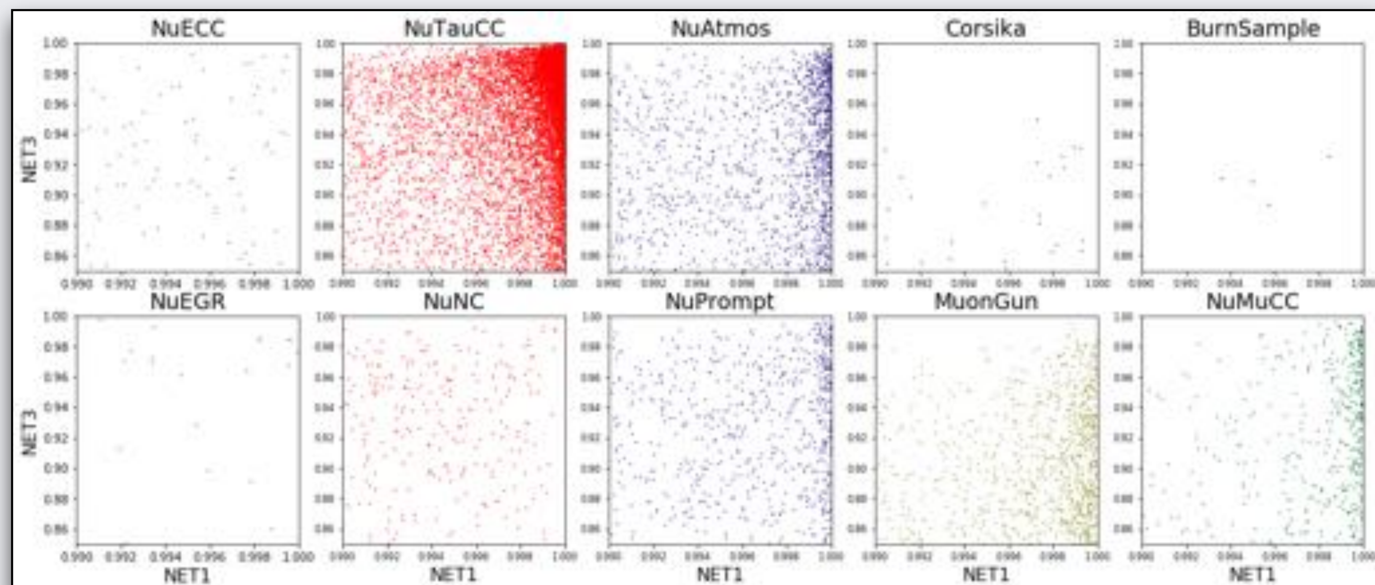




C_3 vs. C_1 (Q_{str} > 2000 p.e.)



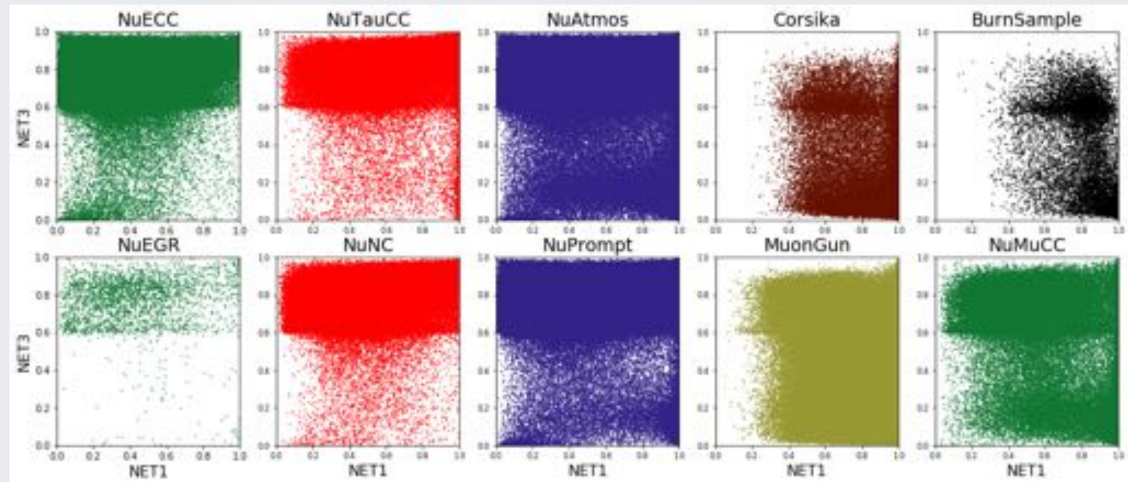
Unweighted



Unweighted

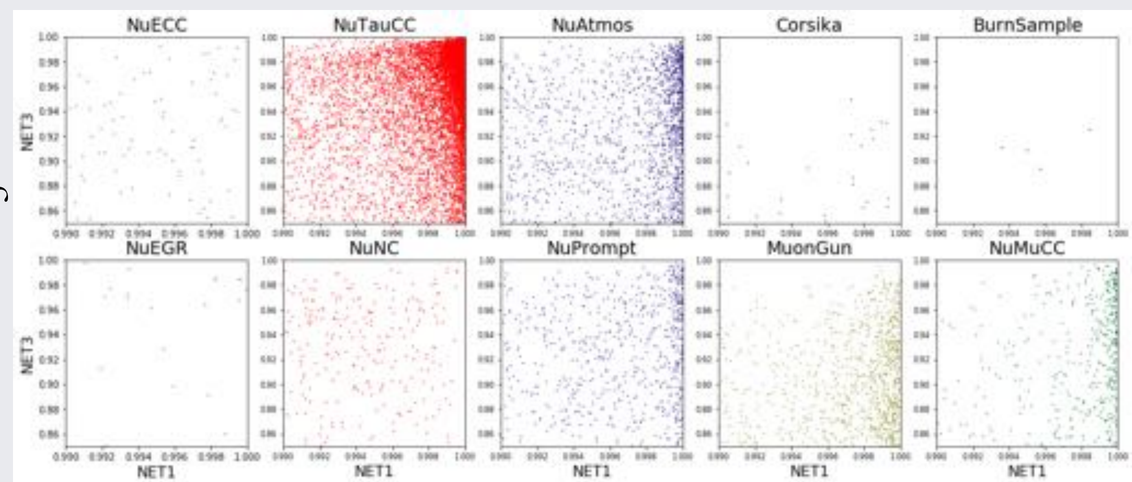
Searching for Astrophysical ν_τ

- Trained 3 independent CNNs
  - C_1: DP vs. SP (ν_τ^{CC} vs. $\nu_e^{\mathrm{CC}}, \nu_x^{\mathrm{NC}}$)
  - 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: $\nu_{\mathrm{astro.}}$ and $\nu_{\mathrm{atm.}}$
  - Sub-dominant: $\mu_\downarrow$
- 3 separate CNNs worked better than 1 all-purpose CNN



$0 \le C_3 \le 1$

$0 \le C_1 \le 1$

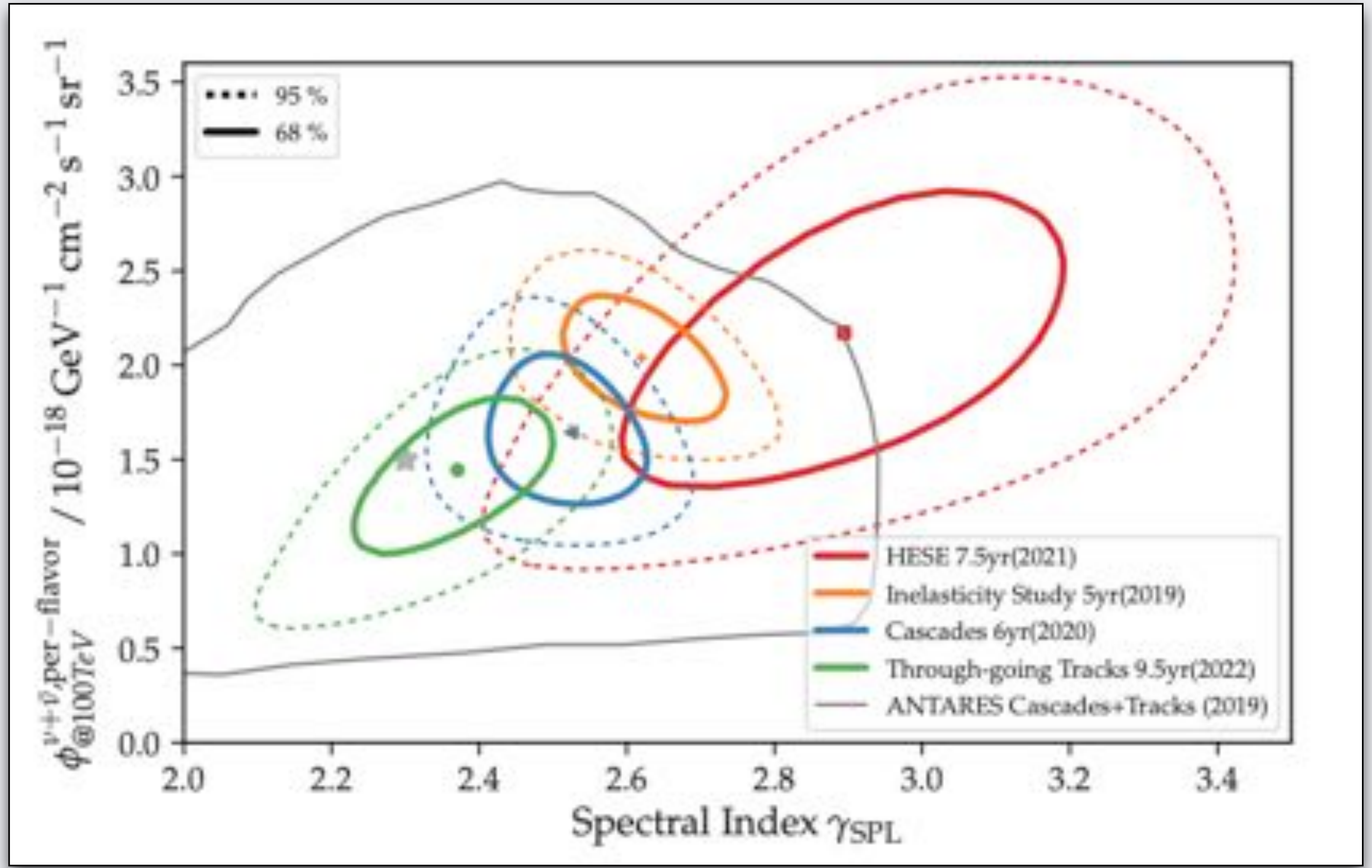


$0.85 \le C_3 \le 1$

$0.99 \le C_1 \le 1$

(Events not weighted.)

IceCube Fluxes

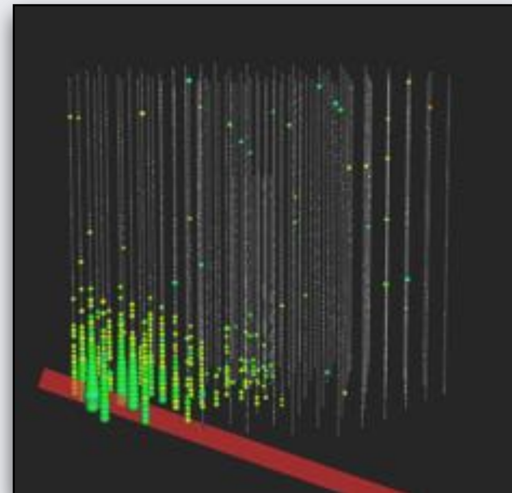


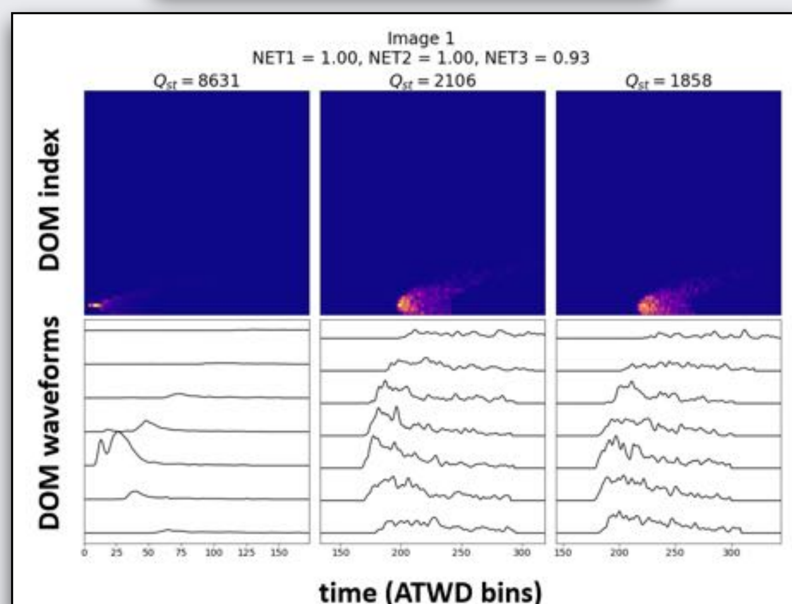
https://arxiv.org/pdf/2203.08096

Searching for Astrophysical ν_τ

- Backgrounds, cont'd:
  - $\mu_\downarrow$: sub-dominant but presented low-hanging background fruit
    - "Corner-clippers" could look like ν_τ DP, only 1/200 yrs., but nevertheless:
      - Add requirement $C_3 \geq 0.95$ if highest-charge string at outer edge.
      - Reduced background to 1/2,000yrs, at a cost of 15% of the expected signal.
    - Saw excess edge events in pre-defined bkgd region
      - Would have failed CNN criteria, but had highly asymmetric light deposition pattern
      - Asymmetry cut reduced this excess by 10x, at cost of 3% of signal

"Corner-clipper" background.
Intrinsically rare; made 10x rarer.

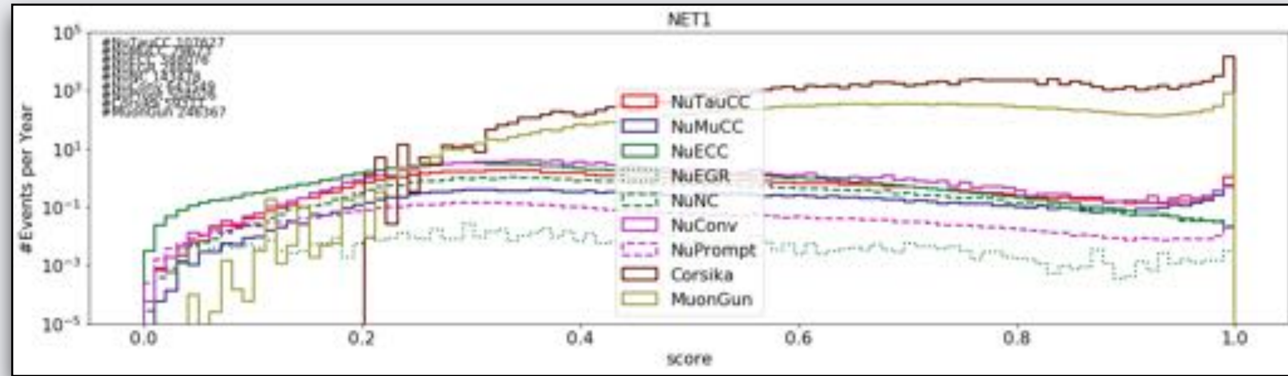




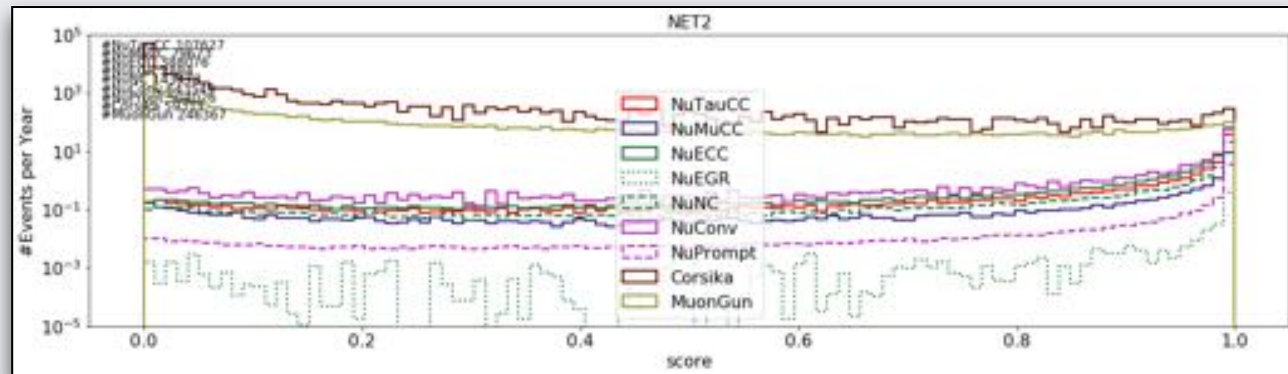
Searching for Astrophysical ν_τ

- Backgrounds, cont'd:
  - μ_{DIS}: $\mu + X \rightarrow \nu_\mu + X'$
    - Initial μ deposits light, followed by light from hadronic shower
    - Not directly simulated
    - At $E > 100$ TeV expect $N_\mu^{\text{atm.}} \simeq N_{\nu_\mu}^{\text{atm.}}$, but μ will lose energy traveling through atmosphere and ice
      - Conservatively doubled estimated background from $\nu_{\mu,\text{atm.}}^{\text{CC}}$

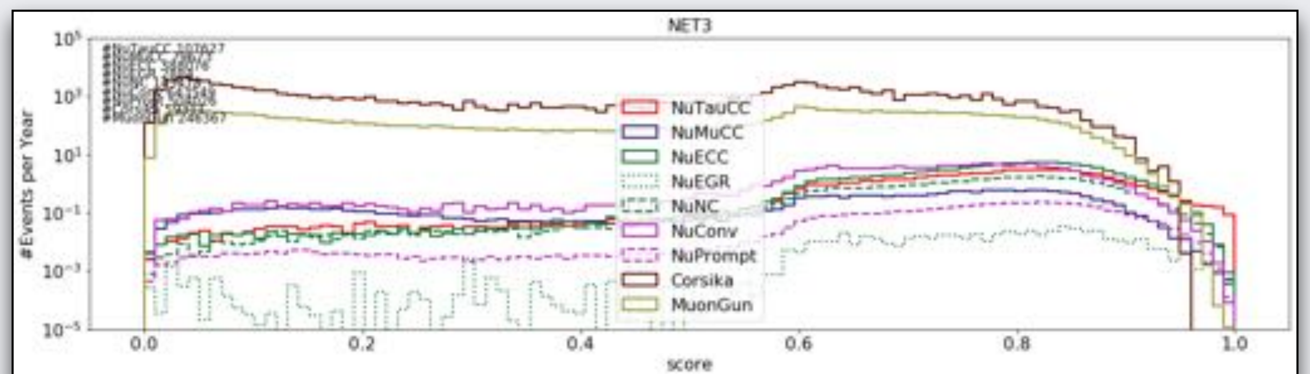
CNN Scores (Q_{str} > 2000 p.e.)



C_1:
Cascade vs. ν_τ

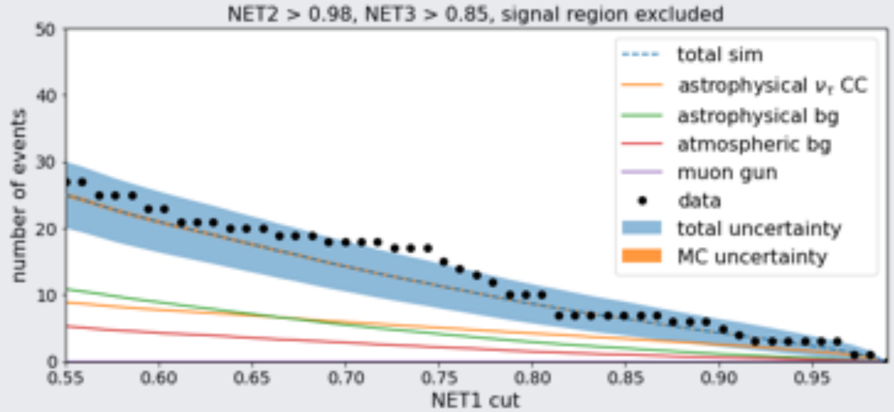


C_2:
$\mu_\downarrow$ vs. ν_τ

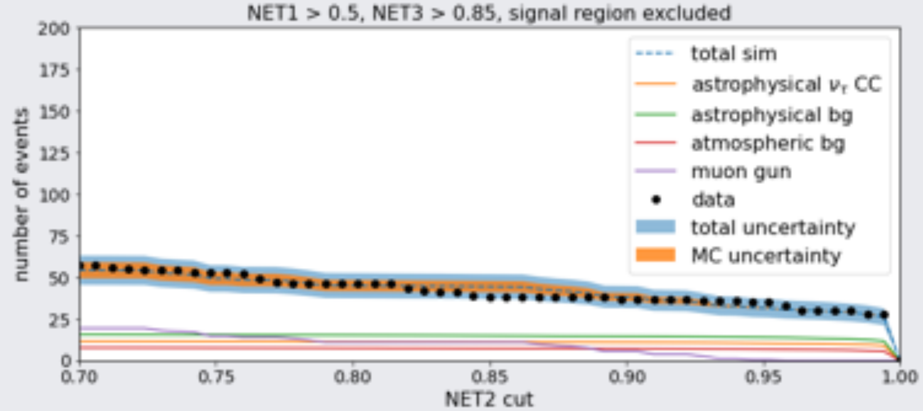


C_3:
ν_μ vs. ν_τ

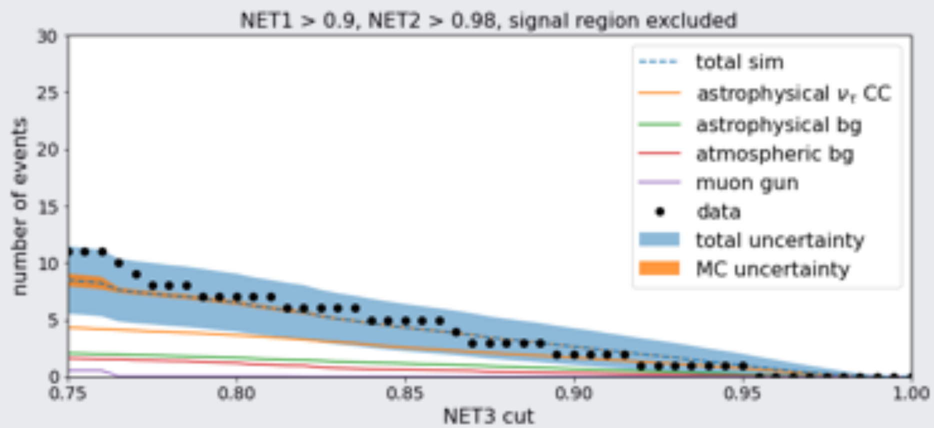
Cumulative $C_{1,2,3}$ (ϕ_{HESE} assumed)



C_1:
Cascade vs. ν_τ



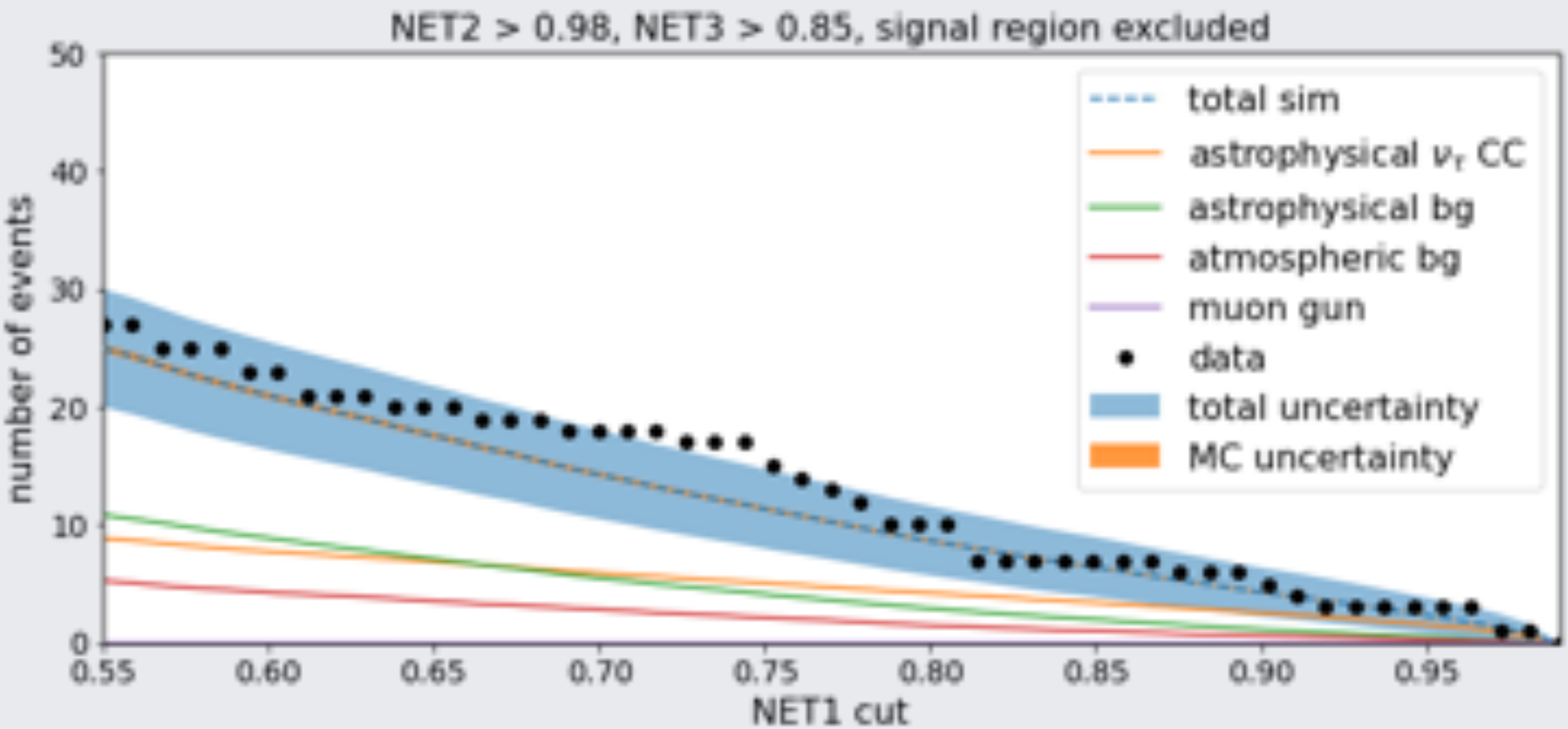
C_2:
$\mu_\downarrow$ vs. ν_τ



C_3:
ν_μ vs. ν_τ

Cumulative $C_{1,2,3}$ (ϕ_{HESE} assumed)

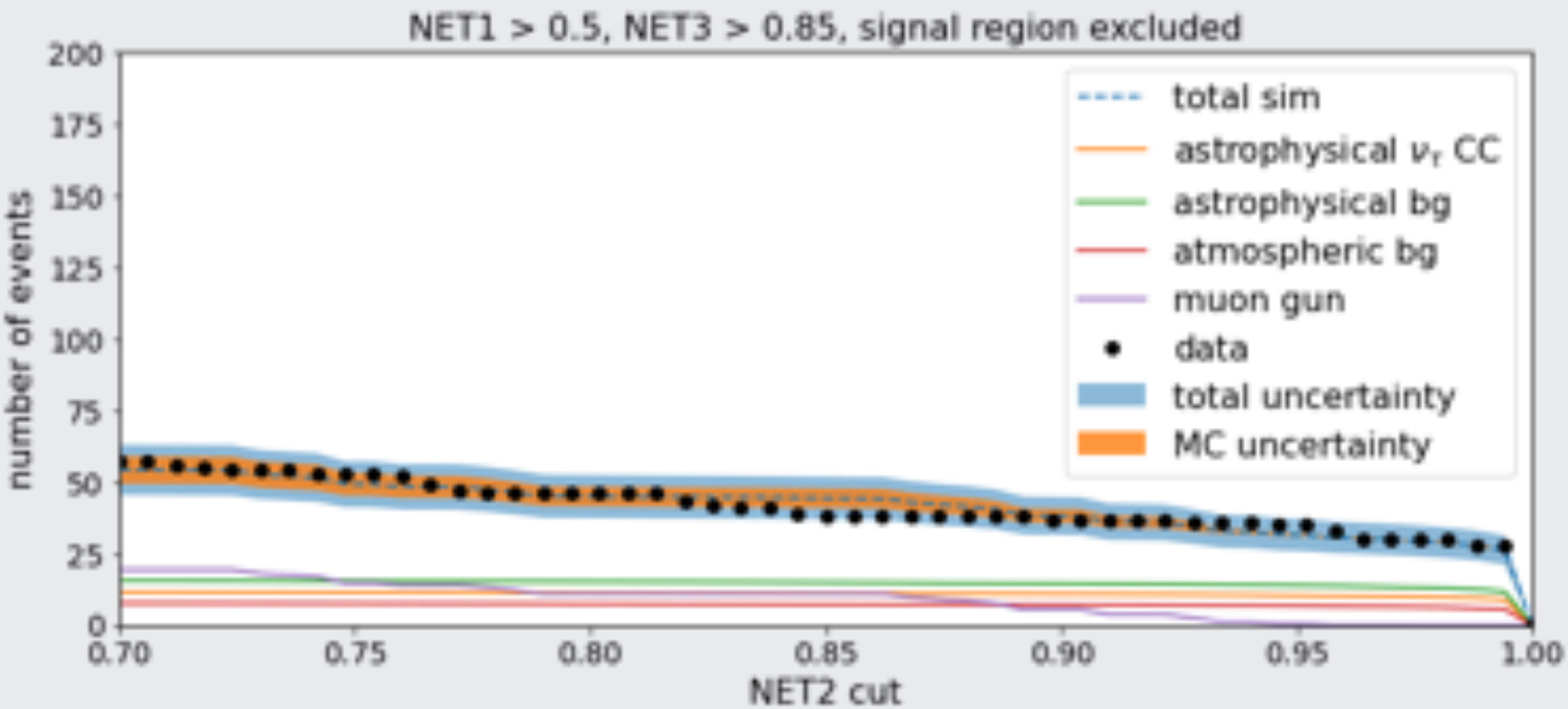
C_1: Cascade vs. ν_τ



Roughly equal numbers of astrophys. ν_τ^{CC} & $(\nu_e^{\text{CC}}, \nu_x^{\text{NC}})$

Cumulative $C_{1,2,3}$ (ϕ_{HESE} assumed)

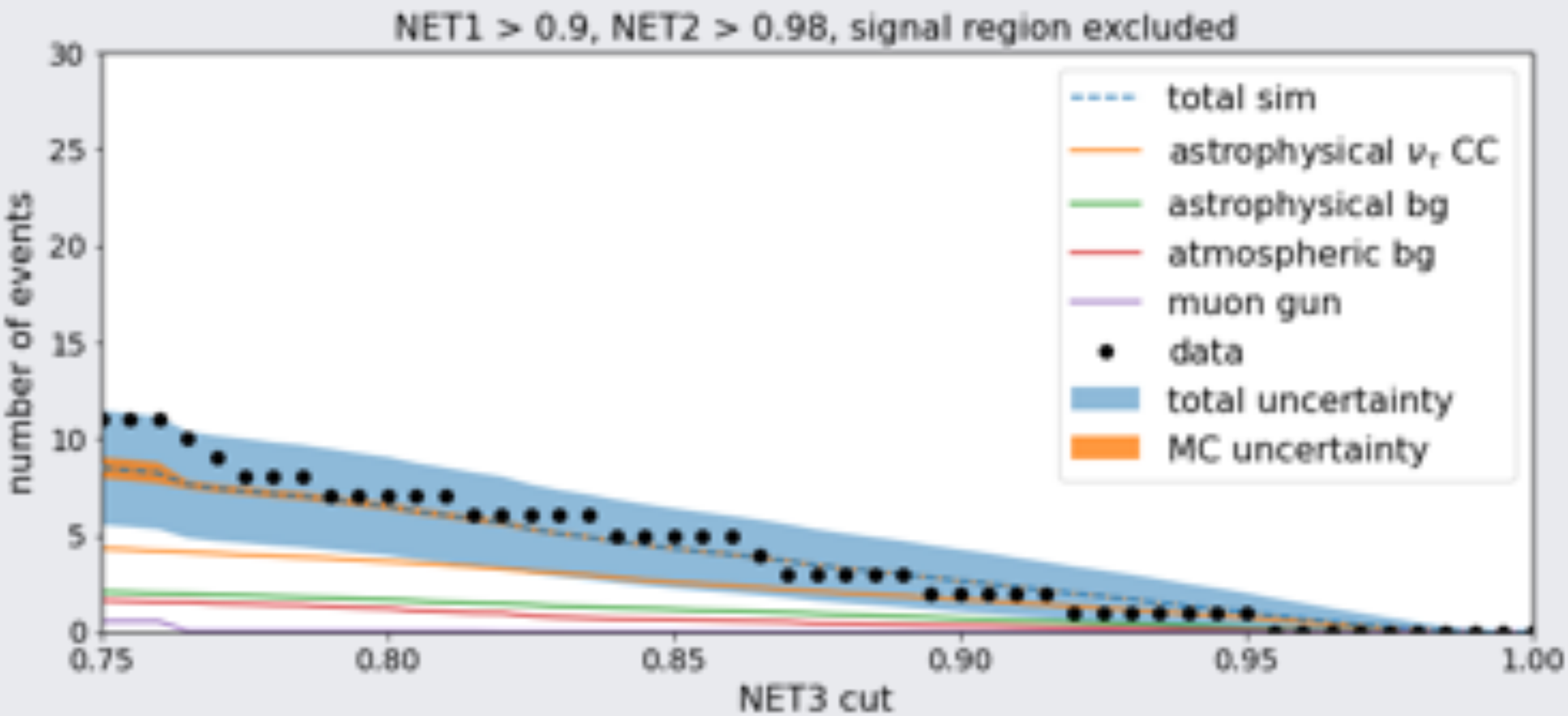
C_2: $\mu_\downarrow$ vs. ν_τ



Roughly equal numbers of $\mu_\downarrow$, $\nu_{\mathrm{astro}}^{\mathrm{bkgd}}$

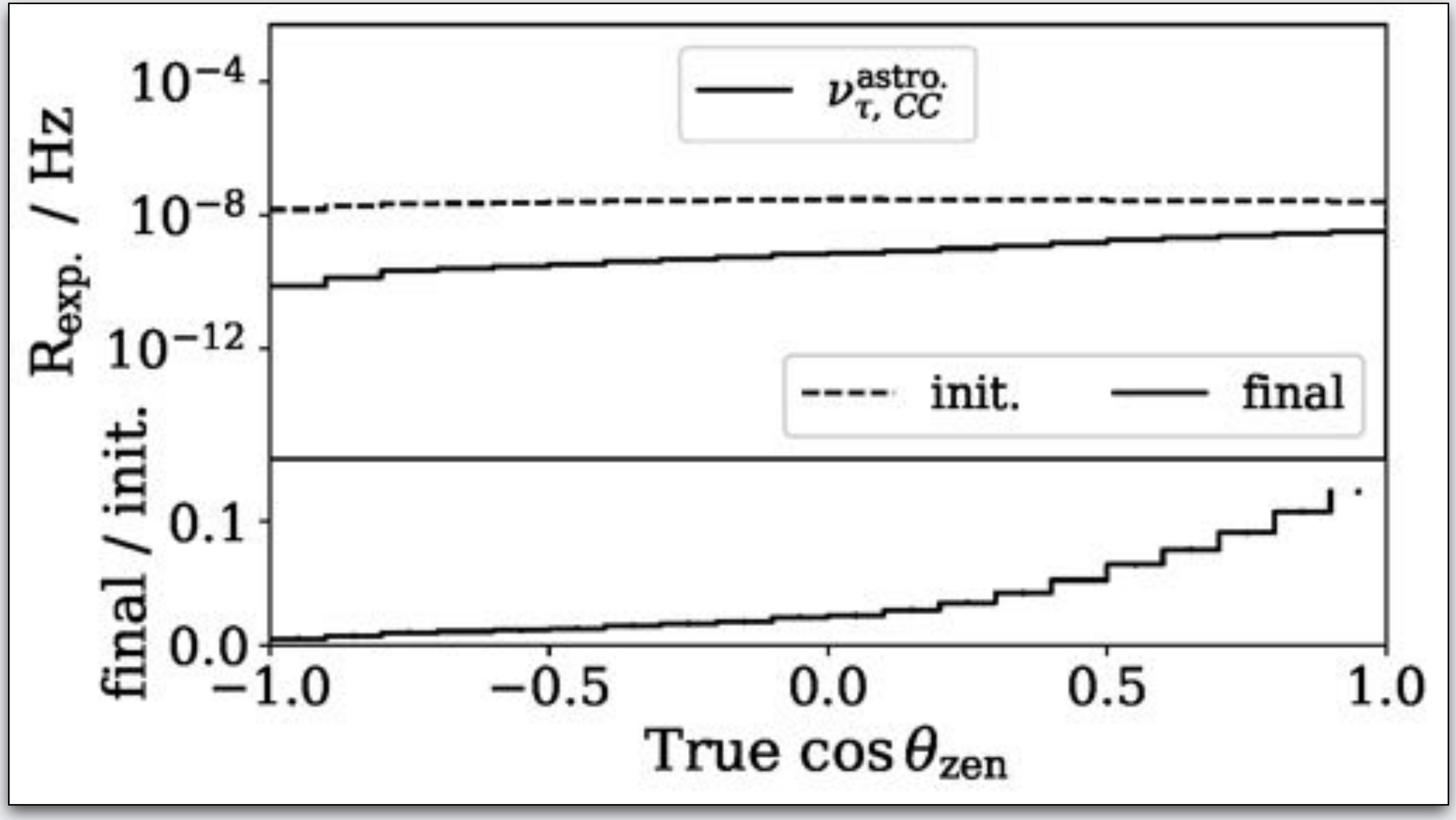
Cumulative $C_{1,2,3}$ (ϕ_{HESE} assumed)

C_3: ν_μ vs. ν_τ



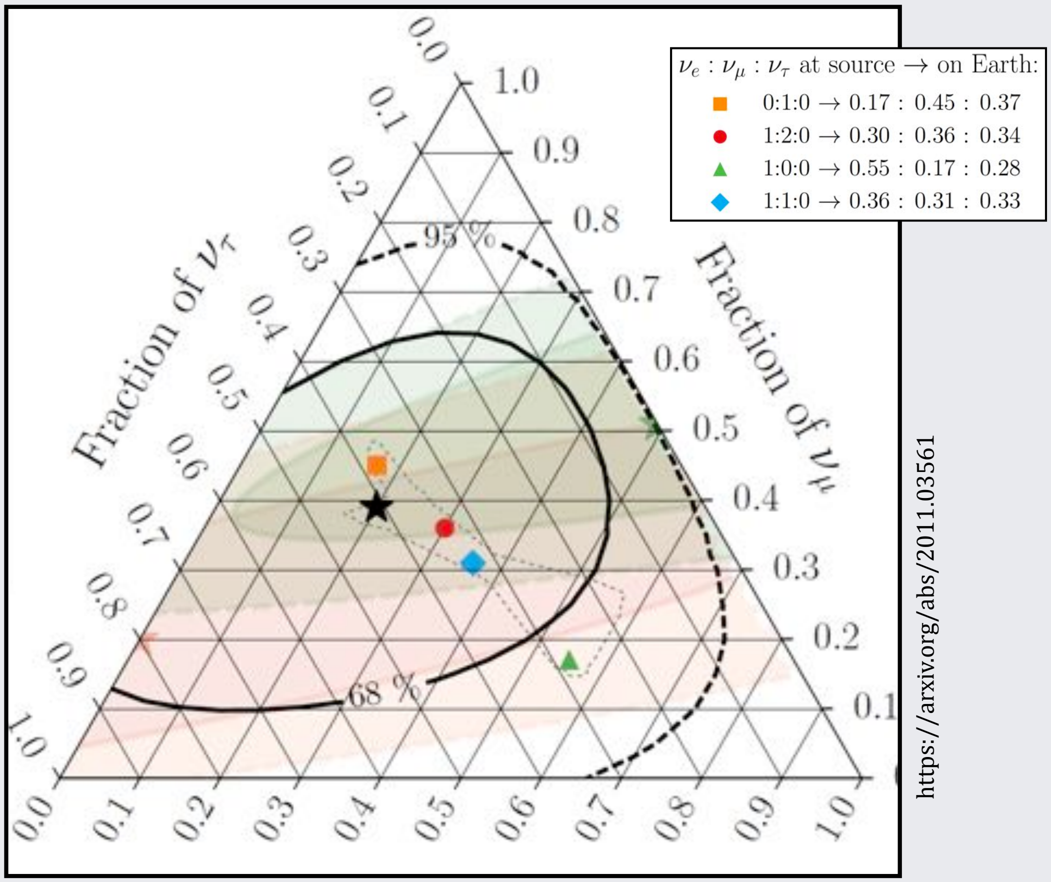
Mostly astrophysical ν_τ but not in signal region

Signal ν_τ mostly downgoing



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.

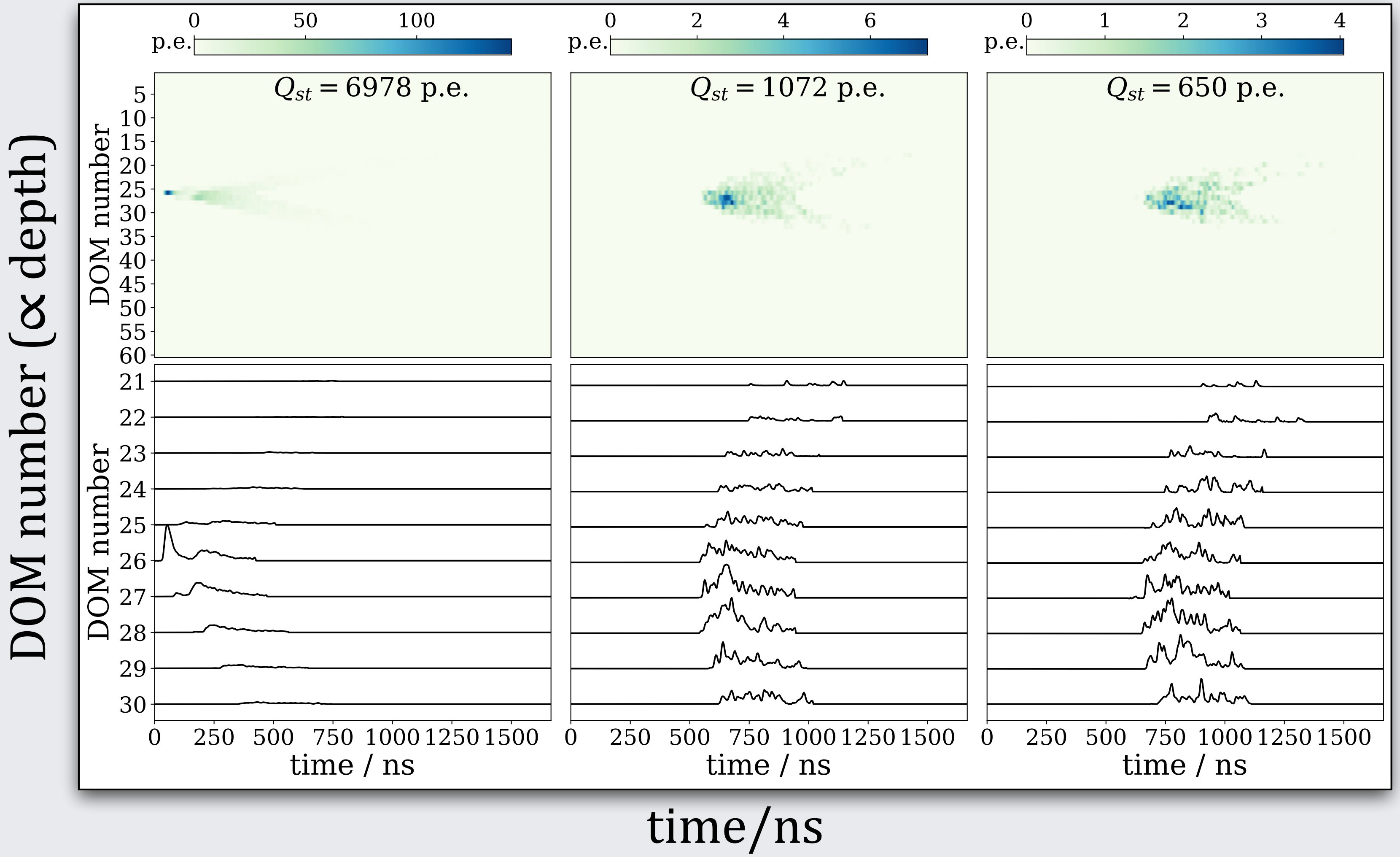
Better identification of ν_τ would help to shrink the contour and maybe signpost new physics.

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.

Event Pics

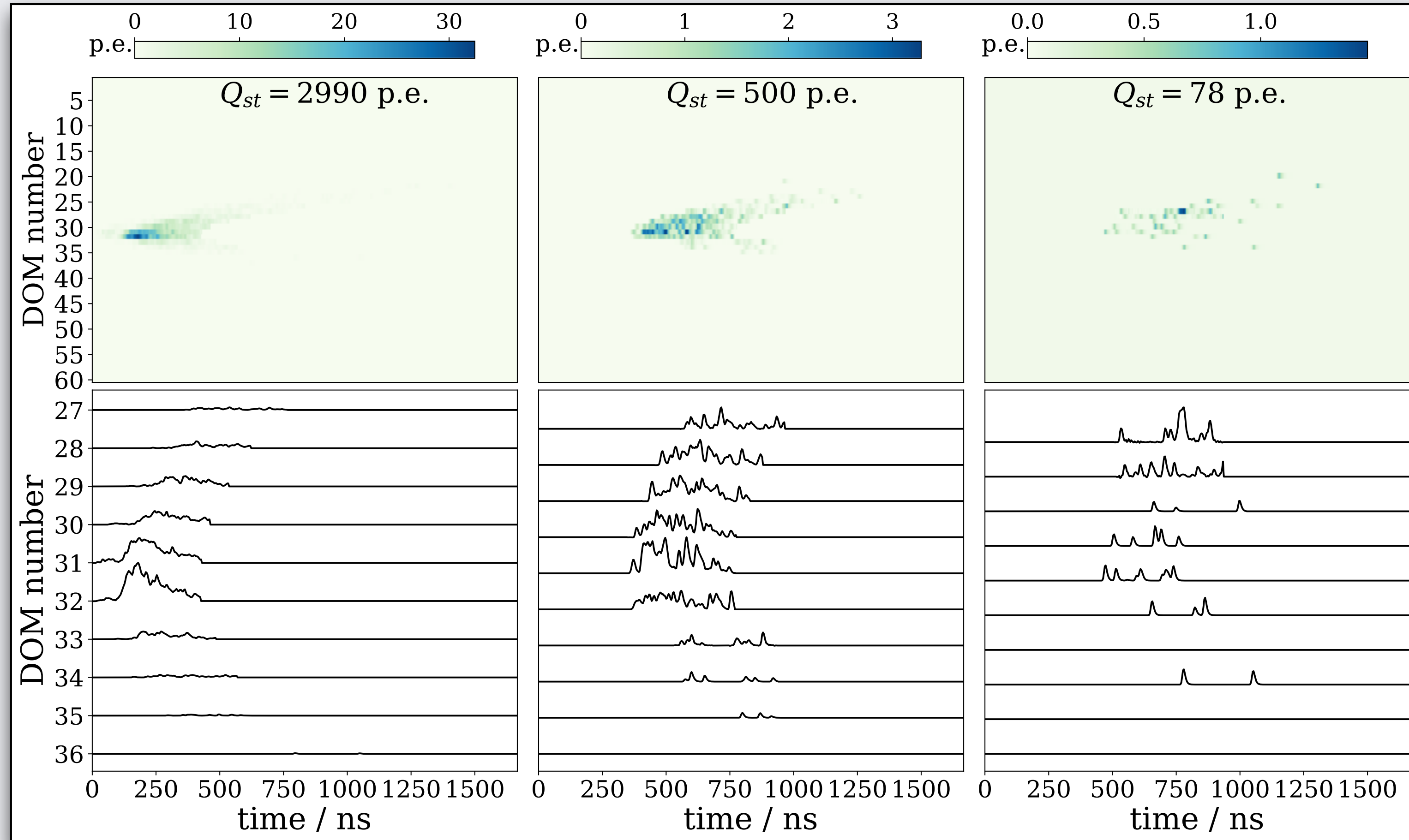
Here's "Double Double," an old event & prior ν_τ candidate:



Gratifying to find this event again.

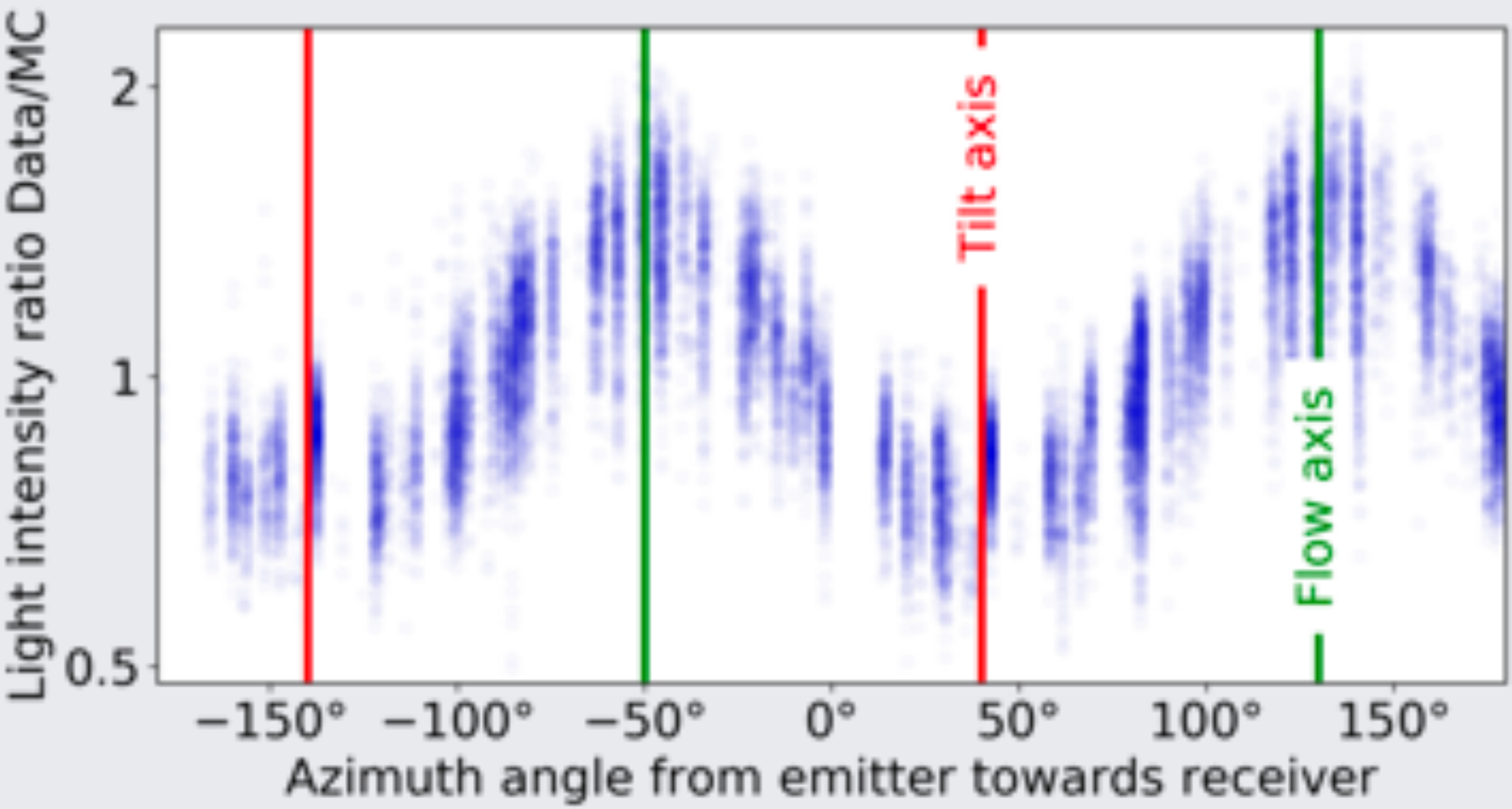
A Less Obvious Event Pic

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



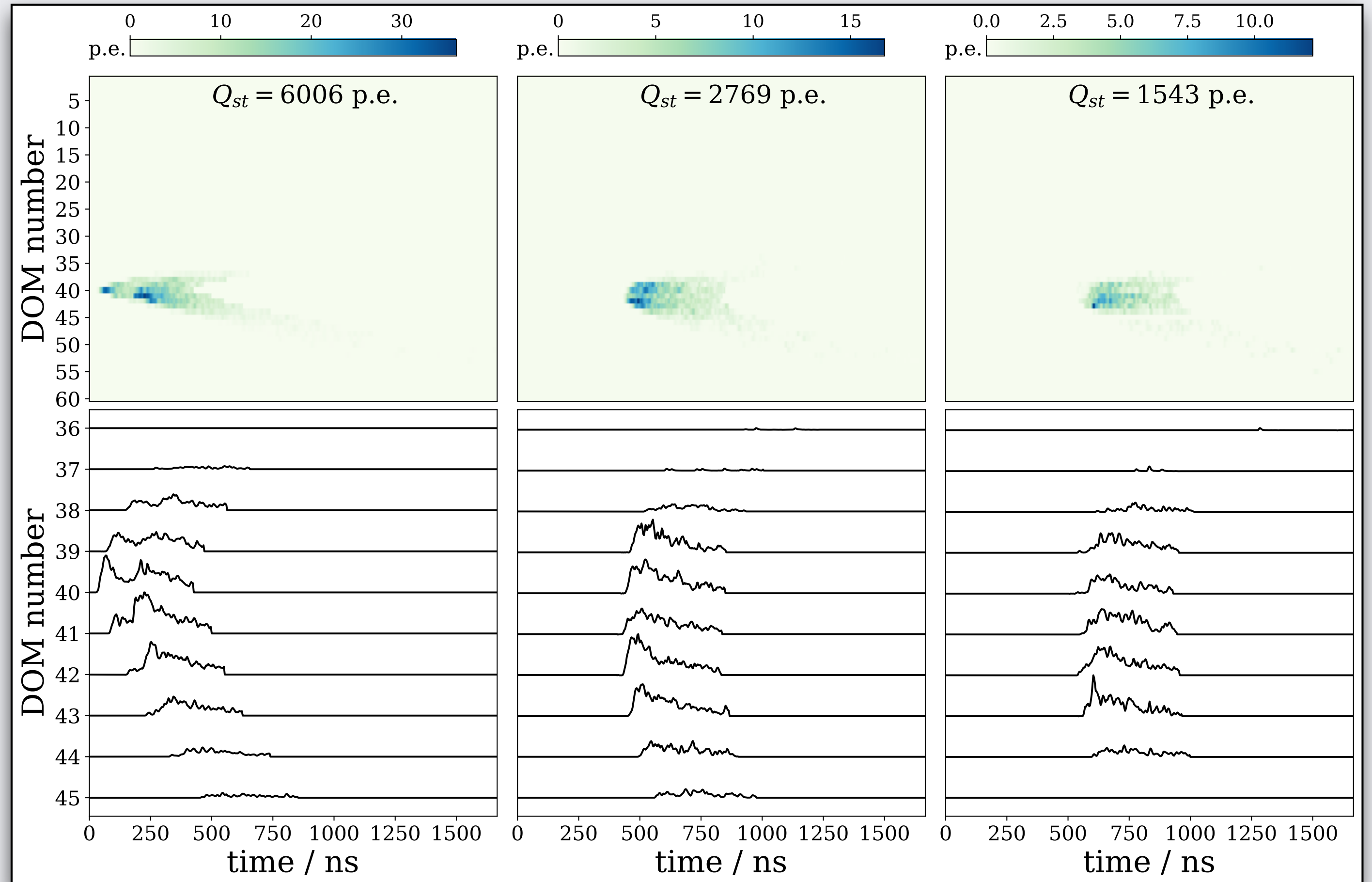
No clear double pulse waveform. What makes it a ν_τ^{astro} candidate? To better understand CNN, use saliency maps.

Ice Optical Properties: Birefringence



Event Pics

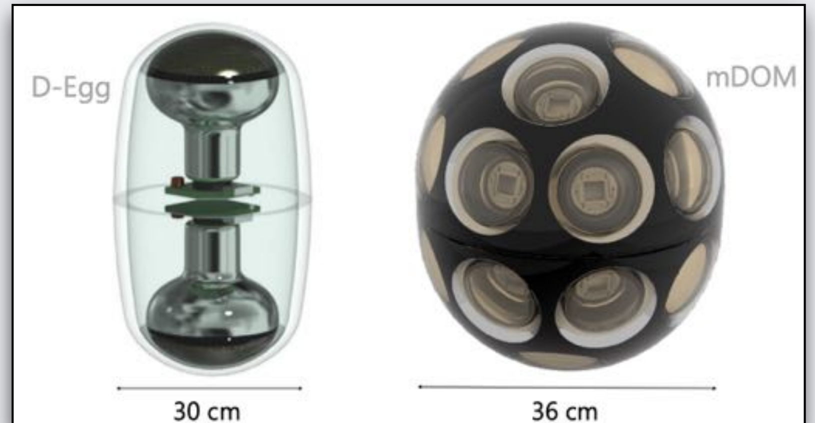
Here's "Scarlet Macaw," a new event:

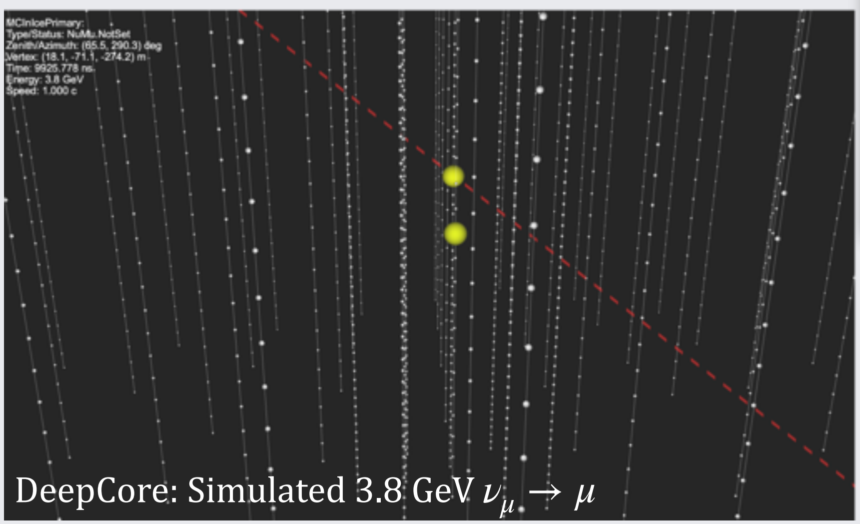


Clear double pulse structure. Detected in 2019 (too recent for previous analyses to have seen).

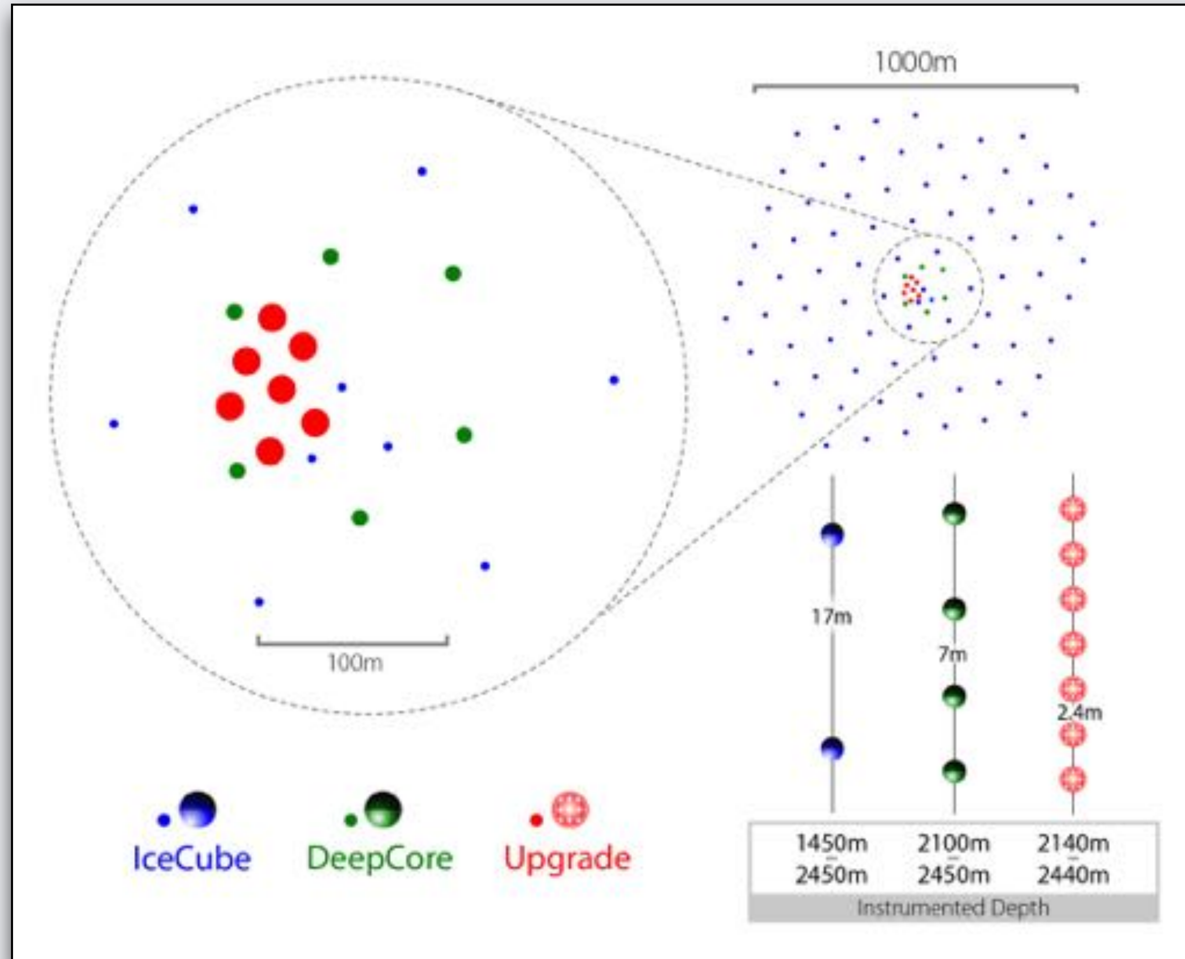
The IceCube Upgrade

- 7 new strings with new modules



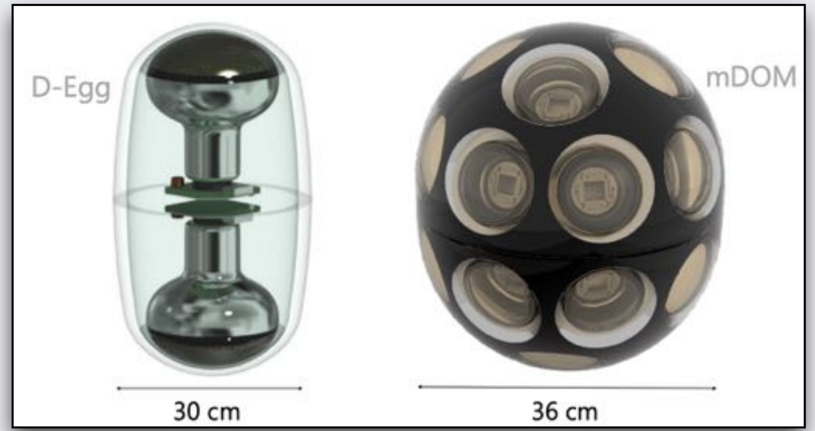


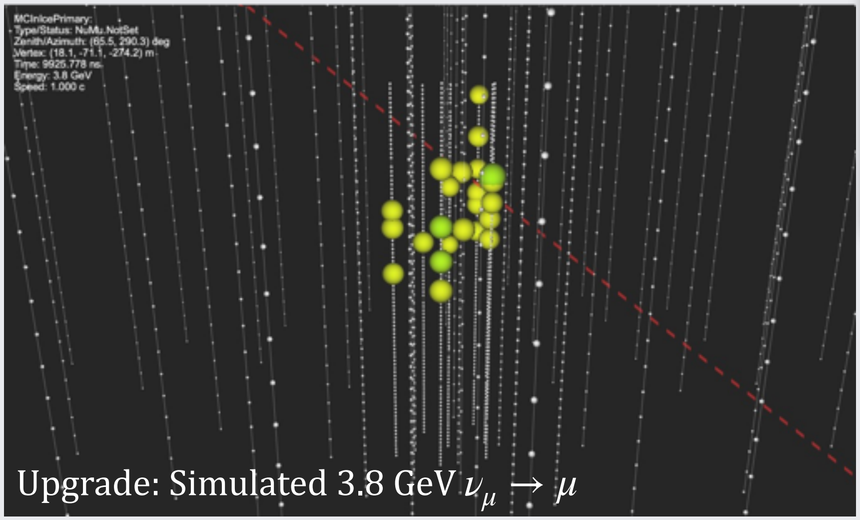
DeepCore: Simulated 3.8 GeV $\nu_\mu \rightarrow \mu$



The IceCube Upgrade

- 7 new strings with new modules





Upgrade: Simulated 3.8 GeV $\nu_\mu \rightarrow \mu$