Astrophysical Tau Neutrinos

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

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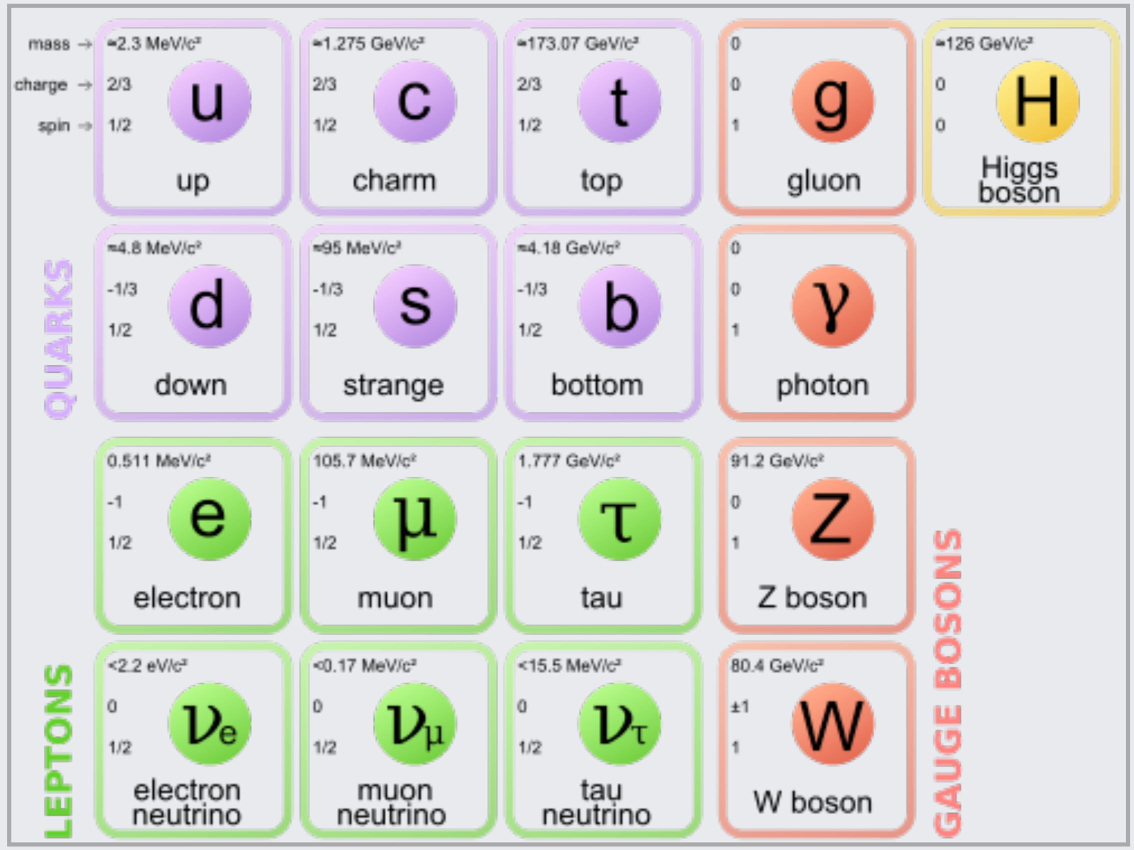
Mainz May 2024

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

Neutrinos: The Basics

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



graphic: wikipedia

The large m_τ suppresses direct ν_τ production.

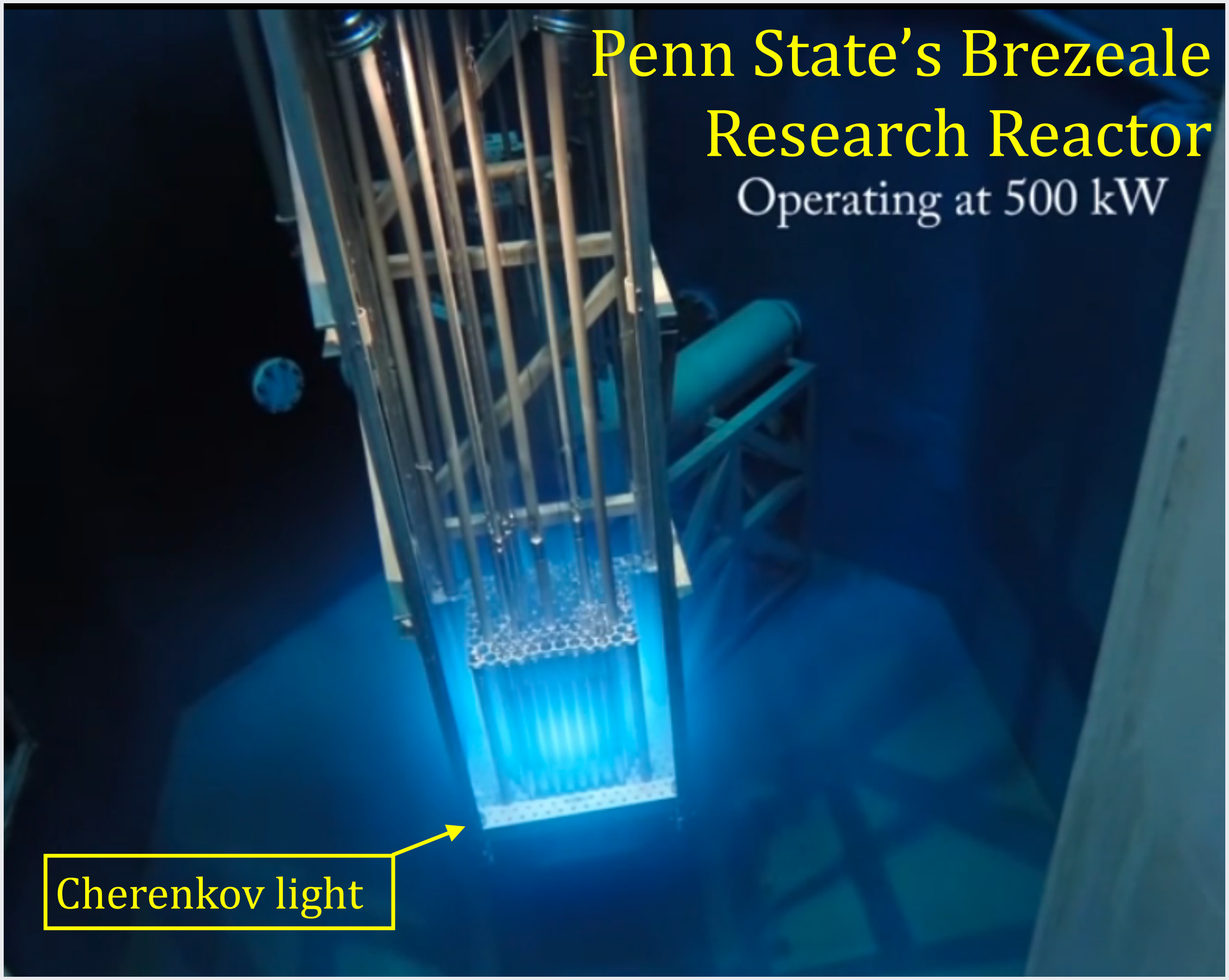
ν_τ are even harder to see than your average super-shy neutrino.

ν_τ mainly arise through neutrino oscillations.

Detecting Neutrinos: Cherenkov Light

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

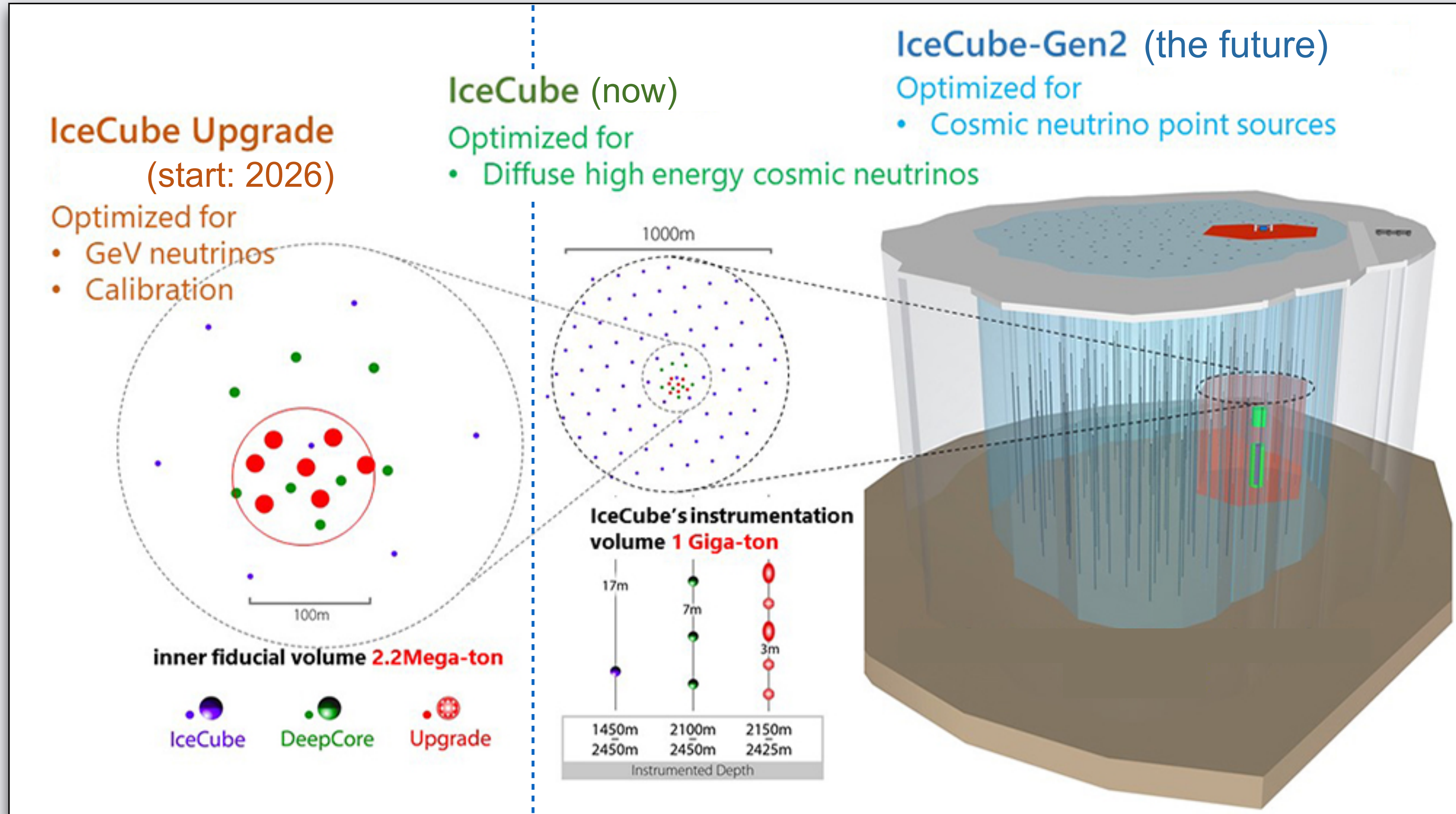
Electromagnetic equivalent of a sonic boom.



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

The IceCube Detector

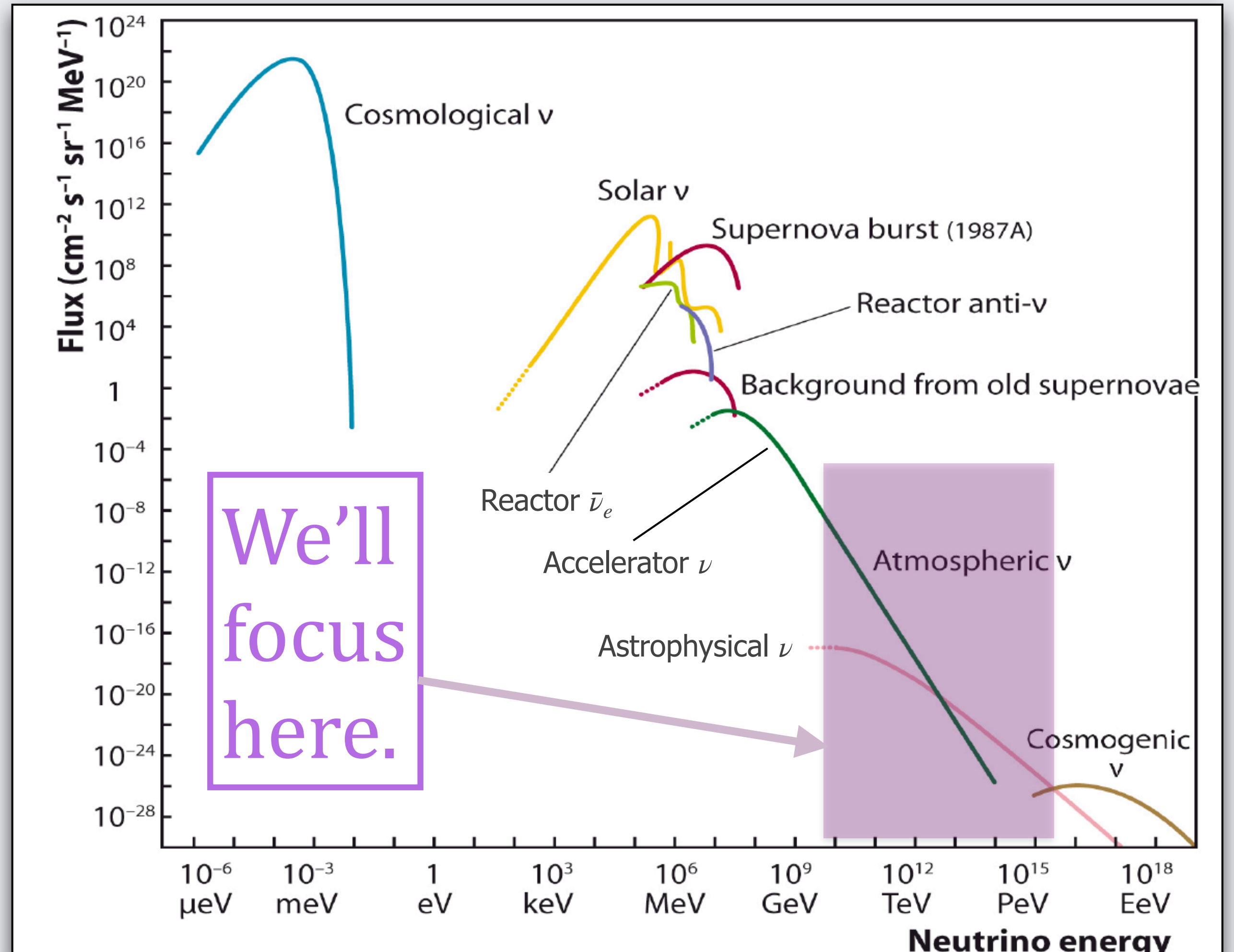
← atmospheric astrophysical →



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

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)

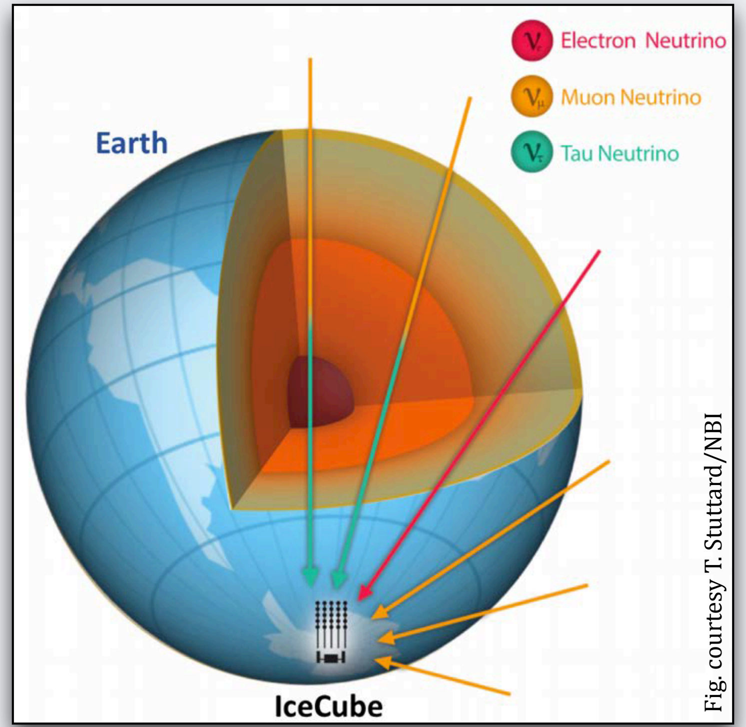


Fig. courtesy T. Stuttard/NBI

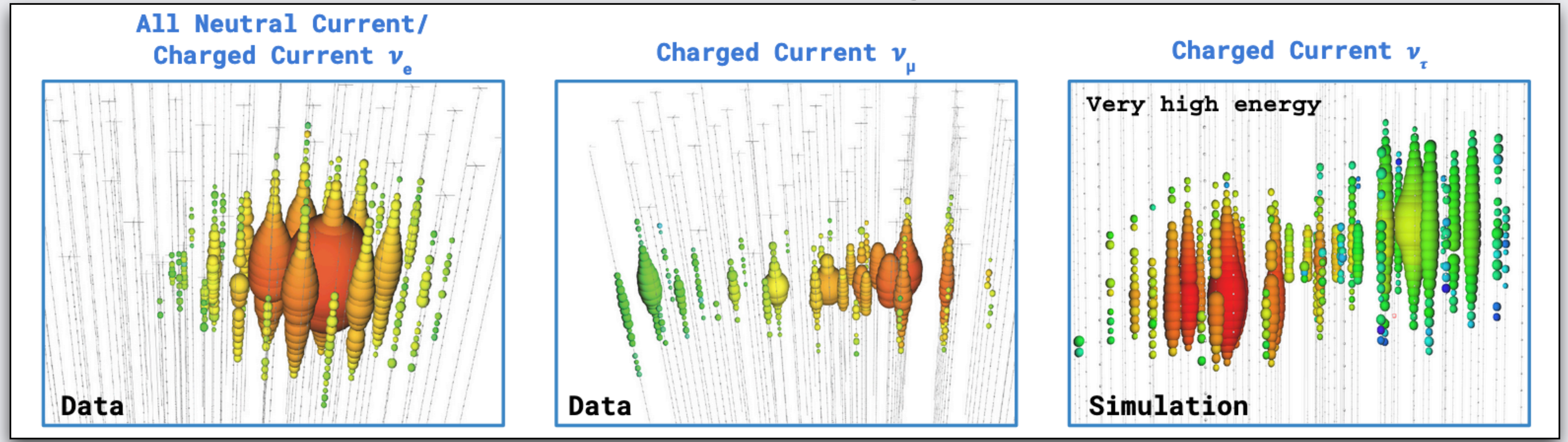
- Astrophysical high energy neutrinos
  - created in cosmic accelerators, e.g., in particle jets created by black holes
  - Evident at $E_\nu > \sim 50$ TeV in IceCube
    - Also seen: PeV-scale (10^{15} eV) ν's (incl. Glashow Resonance)

Fig. courtesy DESY/Zeuthen

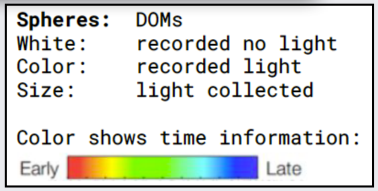
ν^{astro} in IceCube

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

Event morphologies

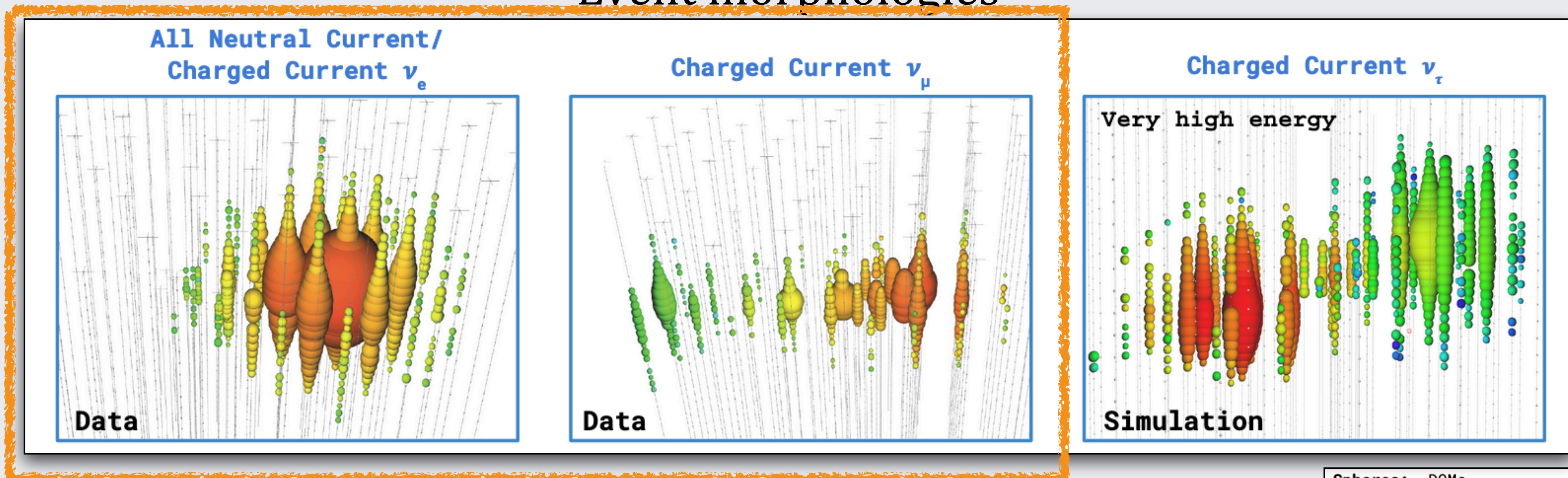


At higher energies, neutrino flavors can be readily distinguished—sometimes.

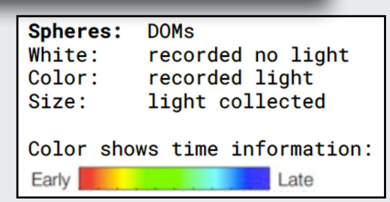


ν^{astro} in IceCube

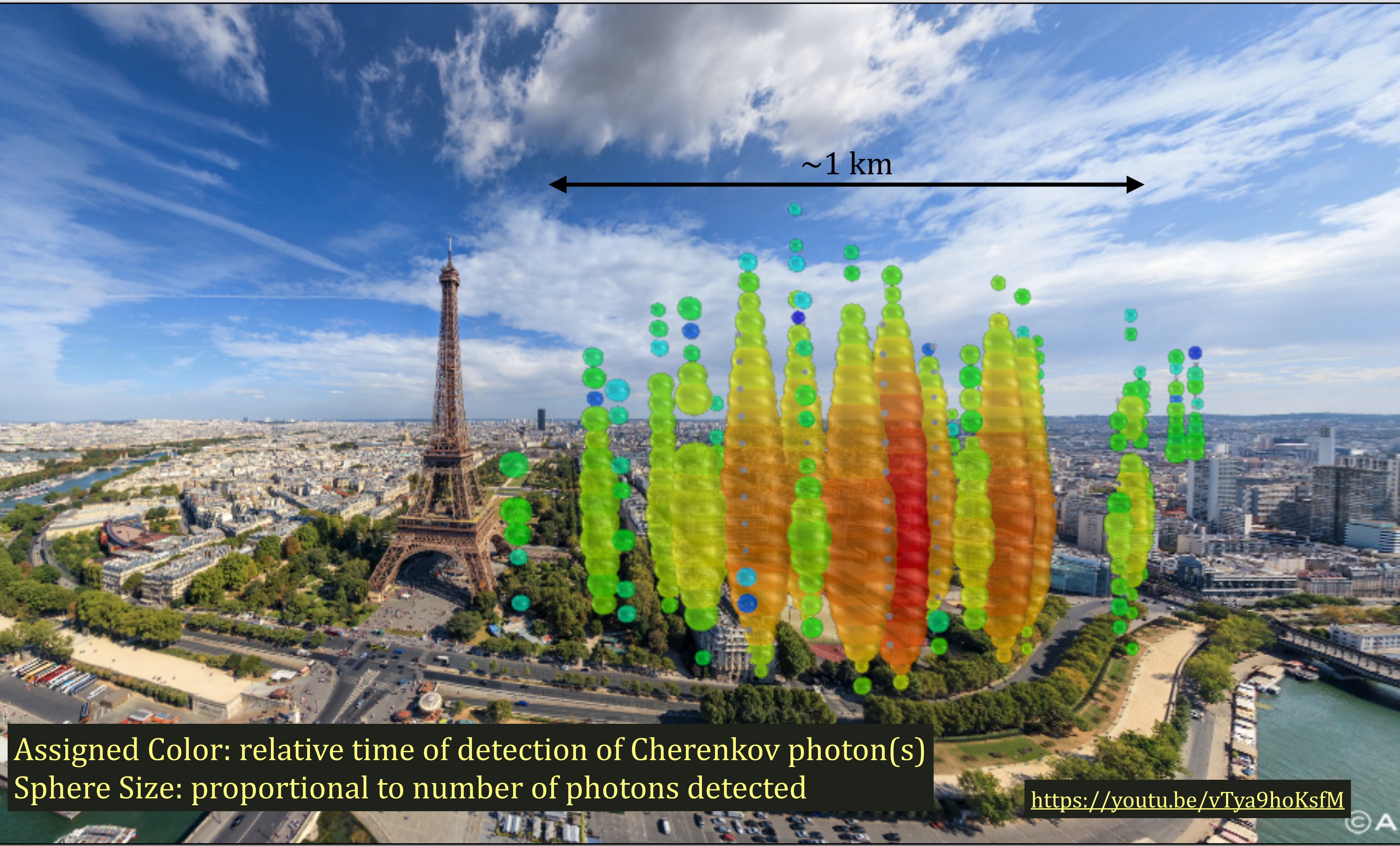
Event morphologies



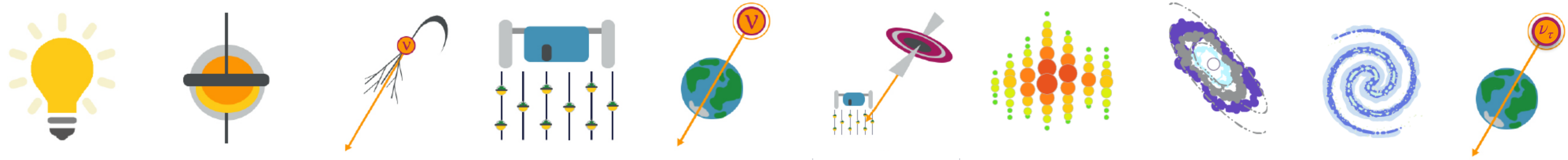
IceCube has focused on track & cascade morphologies, as ν_τ^{astro} are exceedingly challenging to distinguish.



Event Size

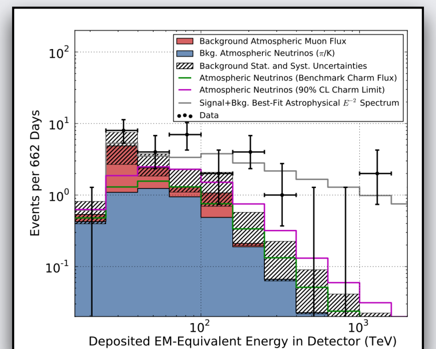

~1 km
Assigned Color: relative time of detection of Cherenkov photon(s)
Sphere Size: proportional to number of photons detected
https://youtu.be/vTya9hoKsfM

IceCube Discovery Timeline

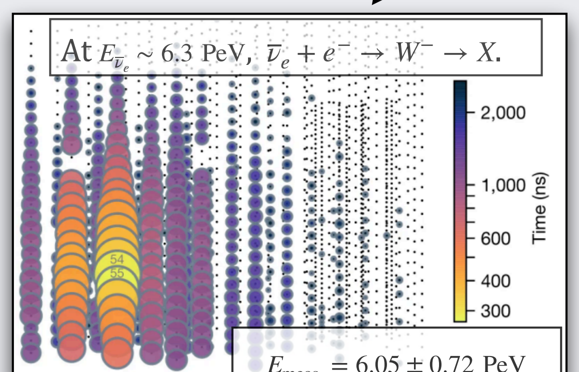


- **1988** — Telescope in the Ice Envisioned
- **2000** — AMANDA Completed
- **2001** — Atmospheric Neutrinos Detected
- **2011** — IceCube Completed
- **2013** — Astrophysical Neutrinos Discovered
- **2018** — First Source TXS 0506+056 Identified
- **2021** — Glashow Resonance Neutrino Identified
- **2022** — Second Source NGC 1068 Identified
- **2023** — Third Source Milky Way Identified
- Seven Astrophysical ν_τ Observed

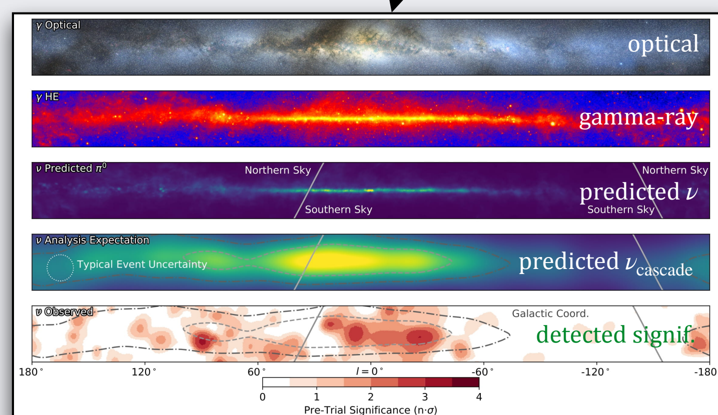
See this talk!



https://arxiv.org/abs/1311.5238



Nature 591 (2021)



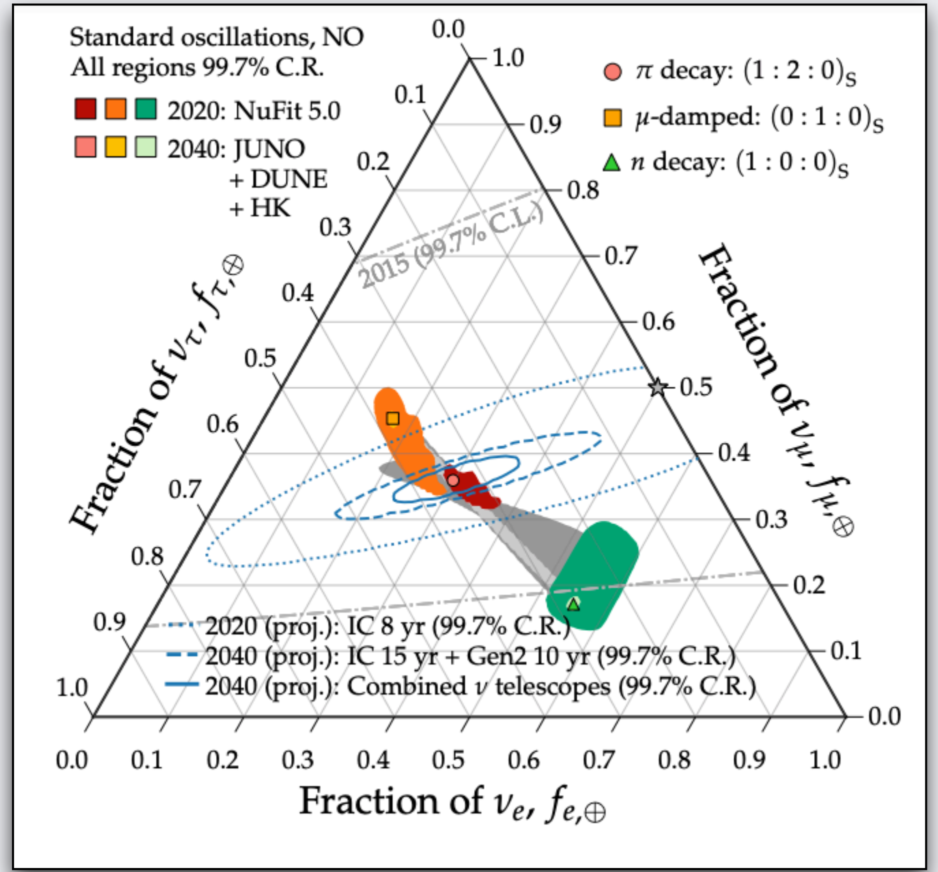
Science 380, 6652 (2023)

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)

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

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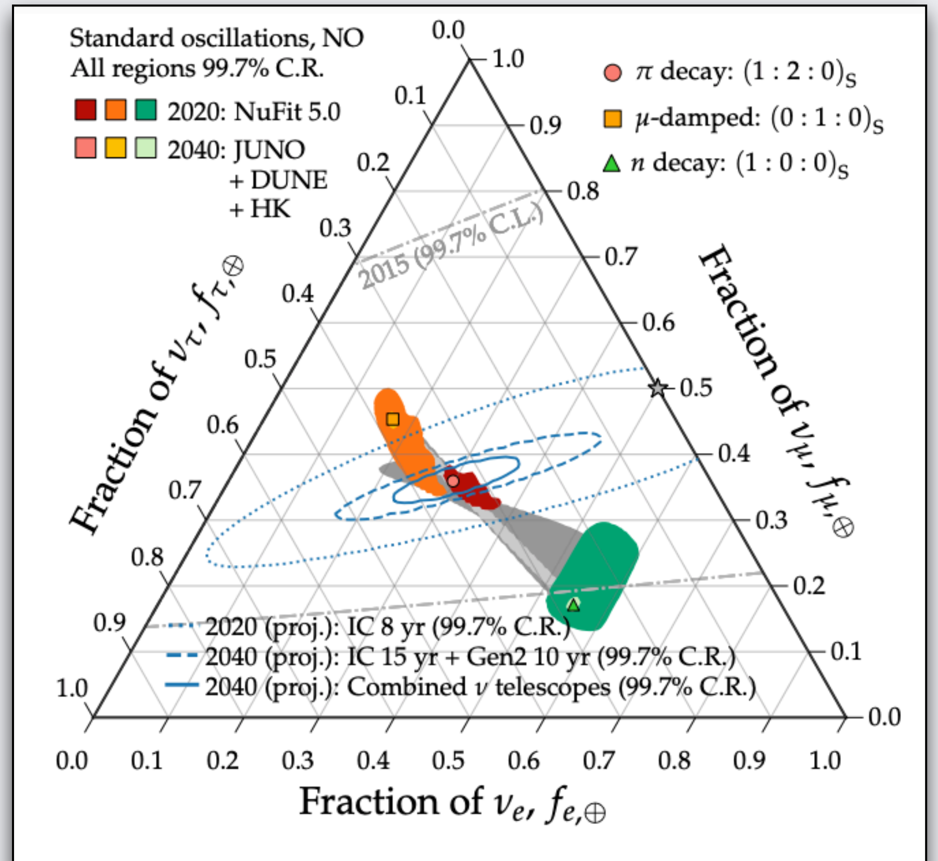
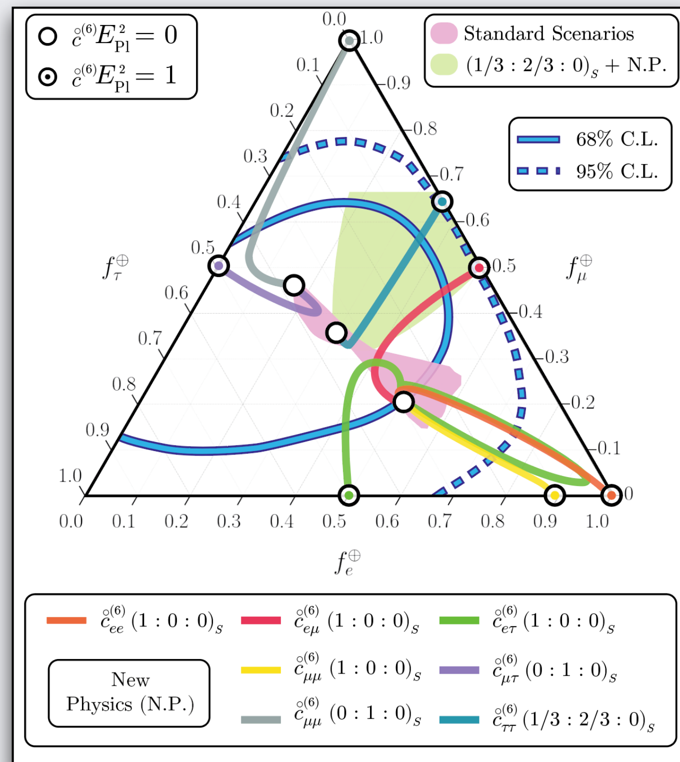


https://arxiv.org/abs/2012.12893

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

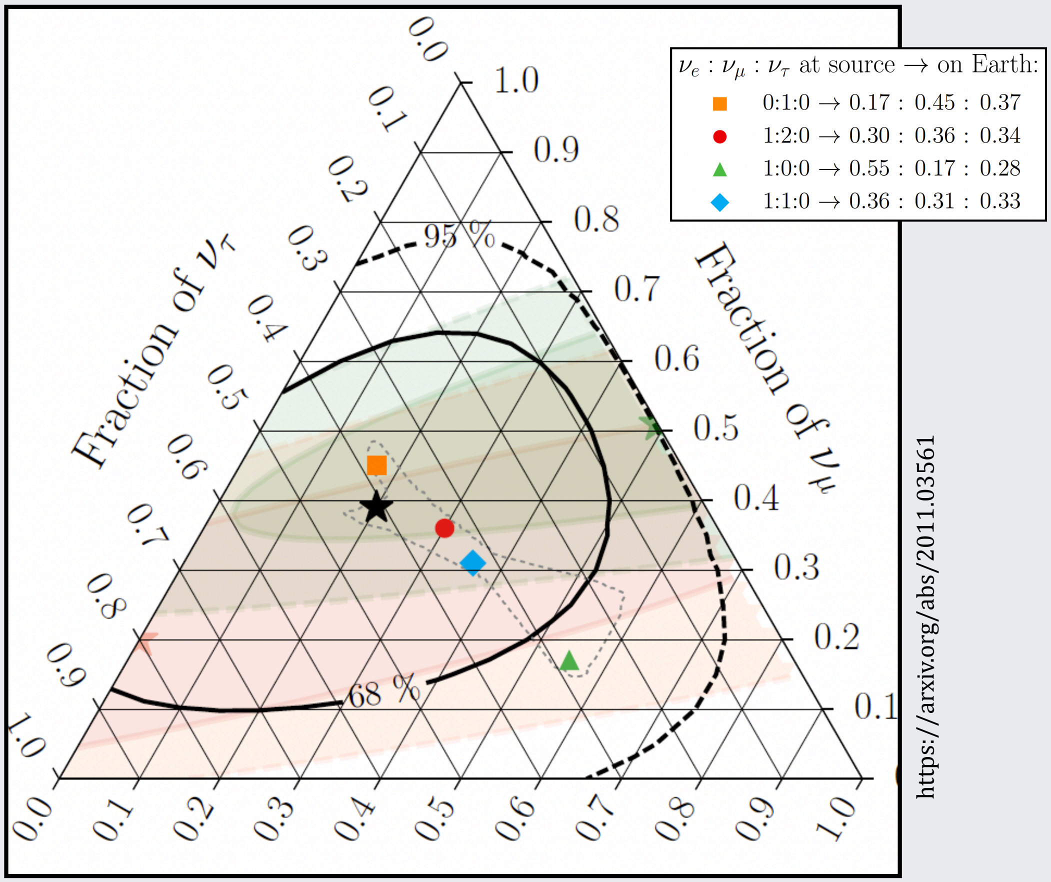


Nat. Phys. 18, 1287–1292 (2022)

Example: Effect of quantum gravity.

Importance of Flavor ID for ν^{astro}

Status quo (2020):



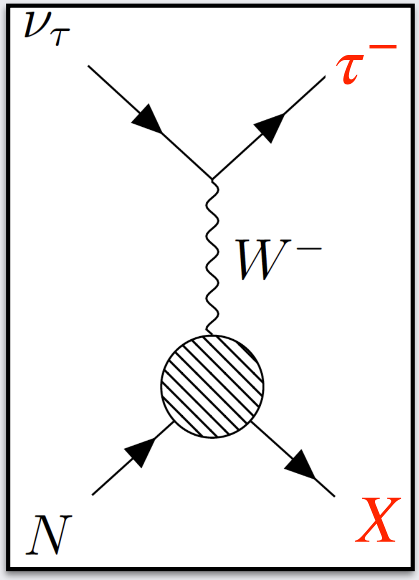
Measured flavor composition of IceCube HESE events. ★ is best fit point, consistent with presence of all 3 flavors, but ν_τ flux only weakly constrained.

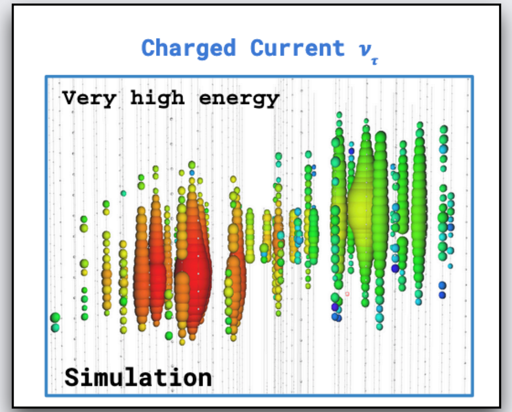
Identification of ν_τ would:

- help shrink contour (and maybe reveal new physics);
- enable studies of ν_τ (and τ) behavior at ultrahigh energies;
- give access to very high astrophysical purity ν;
- confer bragging rights for largest exclusive sample of ν_τ.

Searching for Astrophysical ν_τ

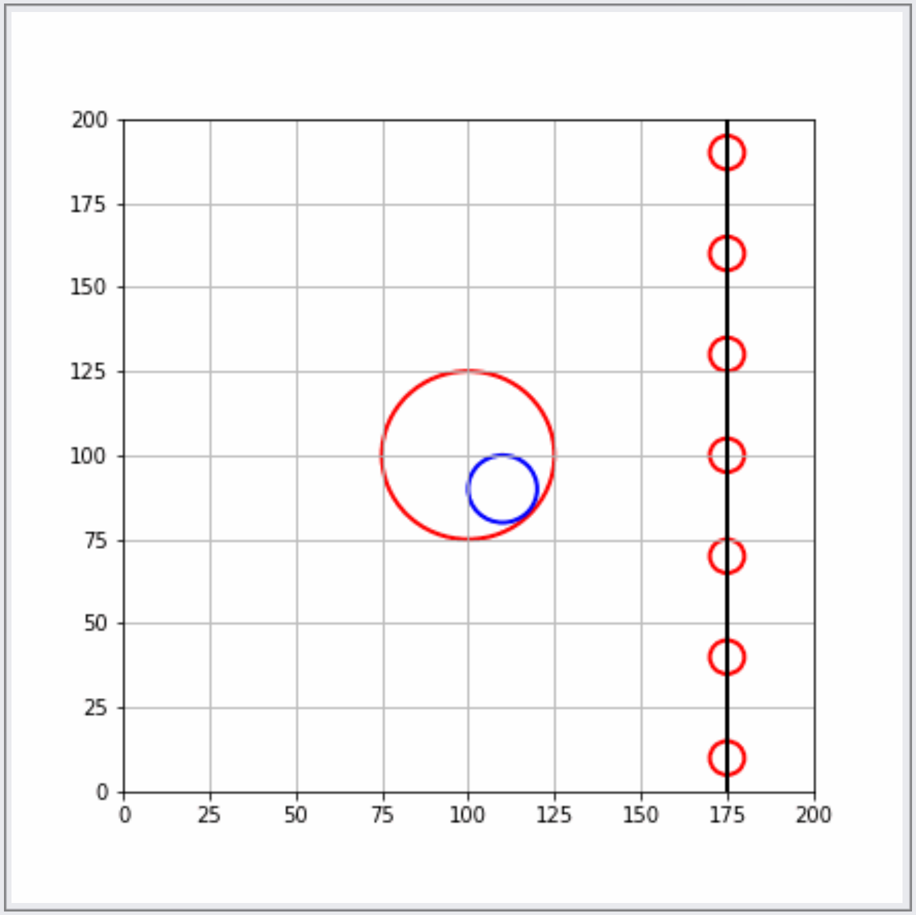
- ν_τ identification
  - Exclusive channel: "Double Bang"
    - $L_\tau > \sim 50\text{m}$ to distinguish two showers (X and $\tau \to (e, h)$)
      - But $L_\tau \simeq 50\text{m} \cdot (E_\tau\ /\text{PeV})$:
        - So need high energy. And favorable interaction vertex. And direction. Etc.
      - 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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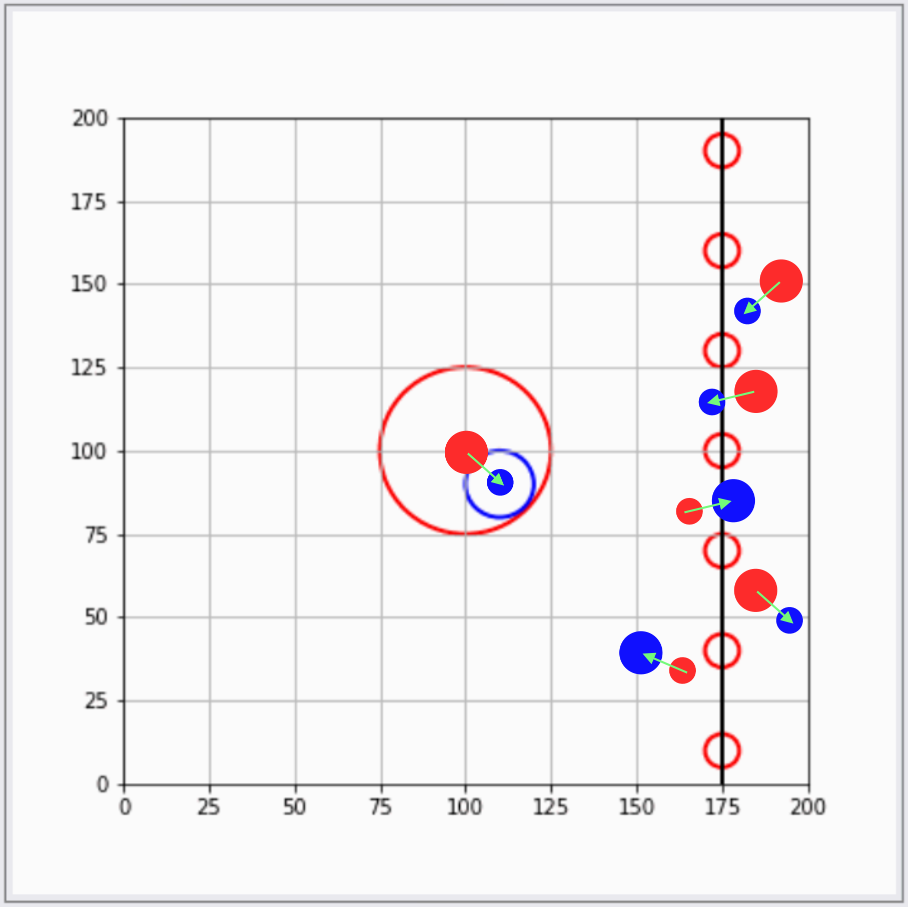
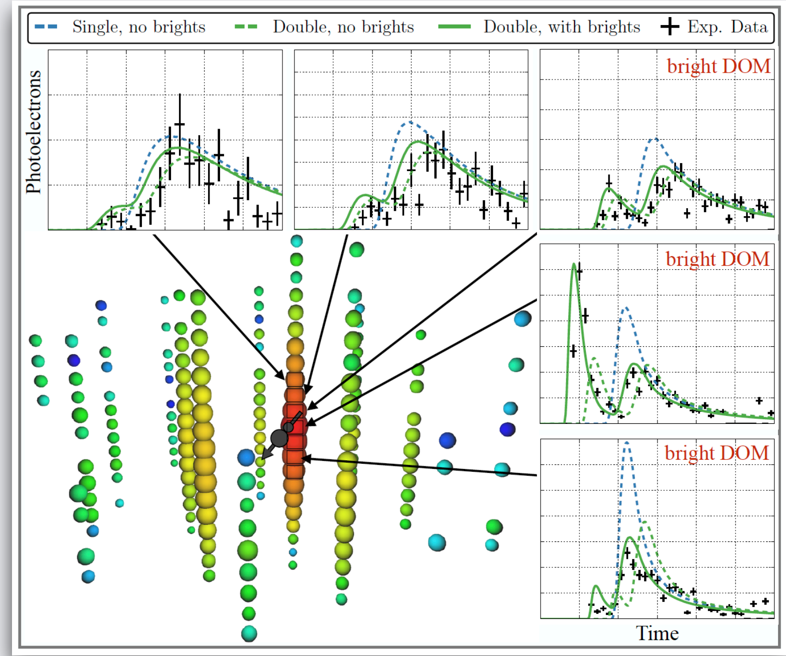


DOM (Digital Optical Module)

There's a large phase space for ν_τ signatures.

Searching for Astrophysical ν_τ

- ν_τ identification
  - Inclusive 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 ν_τ^{astro}

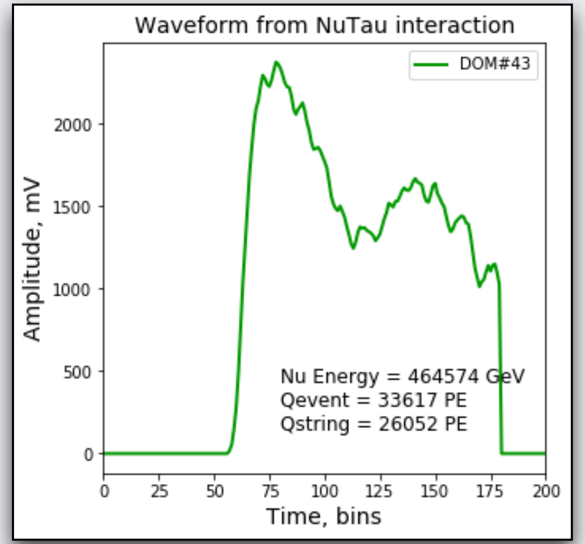


Eur. Phys. J. C 82, 1031 (2022)

*HESE: High-Energy Starting Event

Searching for Astrophysical ν_τ

- Challenge: Grow N_{ν_τ}, reduce N_{bkgd}
  Leverage: $(\phi_\nu^{\text{astro.}} \cdot \sigma_{\nu N}) \propto E_\nu^{-1}$
  - <u>Exclusive</u> 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



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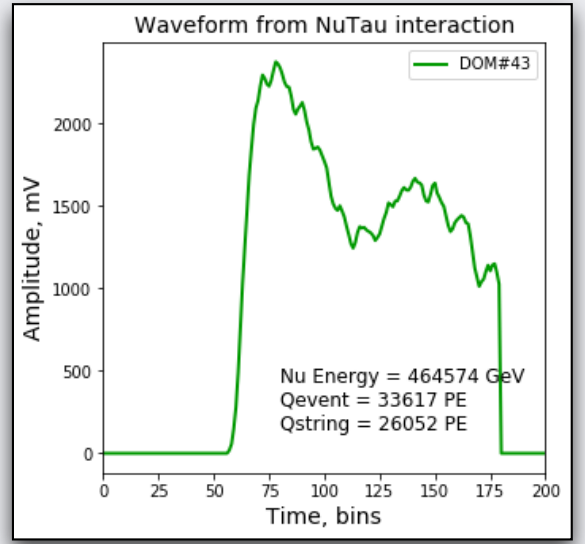
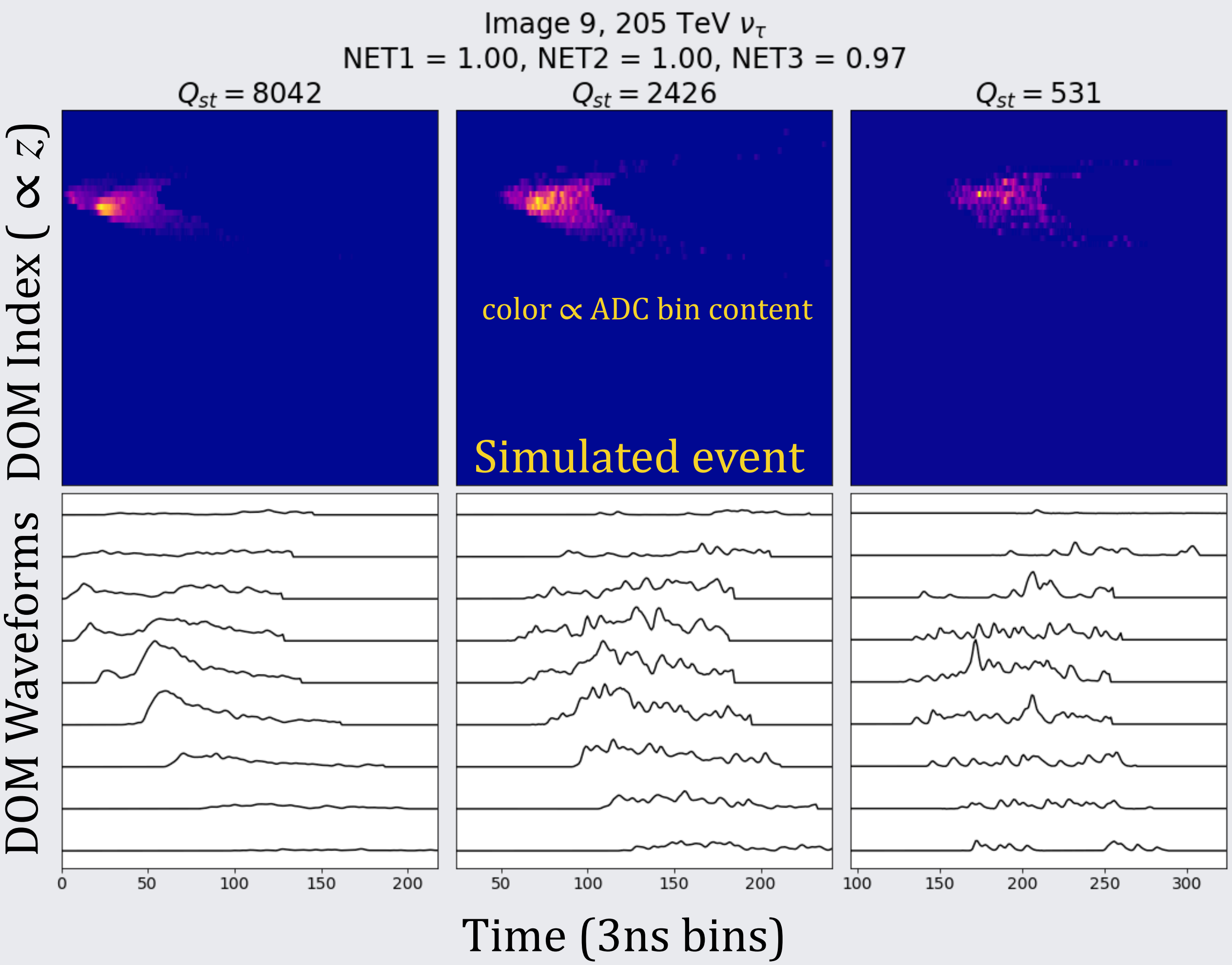


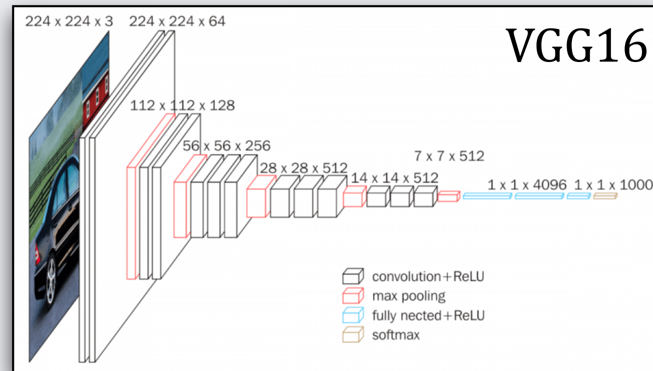
    - Current analysis
      - Look for signature across 180 DOMs on 3 strings w/neural networks (spoiler alert: "Double Pulse" a bit of a misnomer)
      - High S/N achieved…

Searching for Astrophysical ν_τ: CNNs

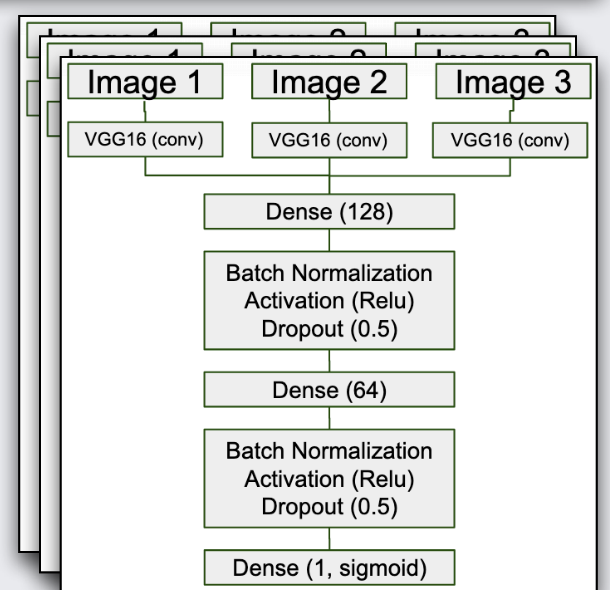
- ν_τ DP with up to 180 modules
  - Create 2d images, one per string



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



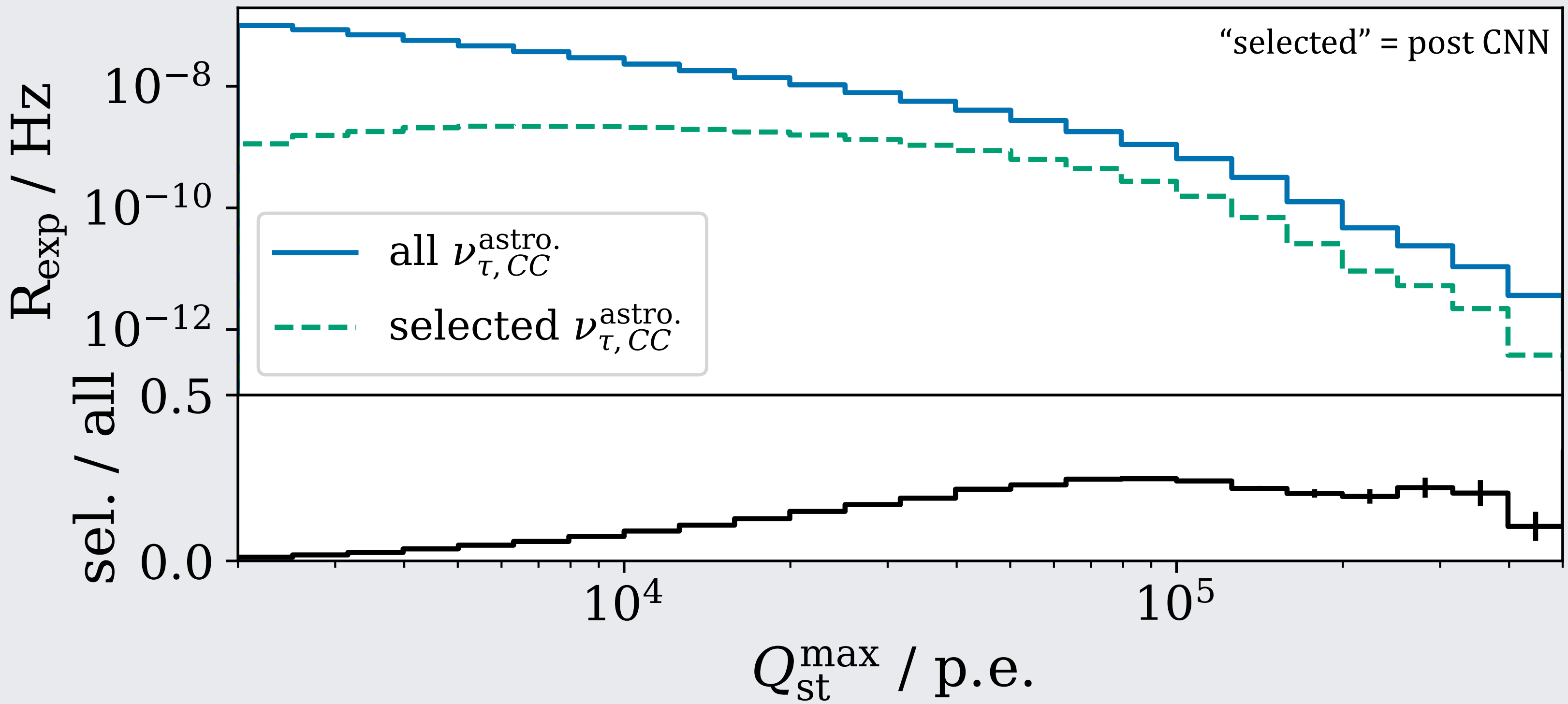
Simonyan & Zisserman, 1409.1556



$3 \times$ VGG16'

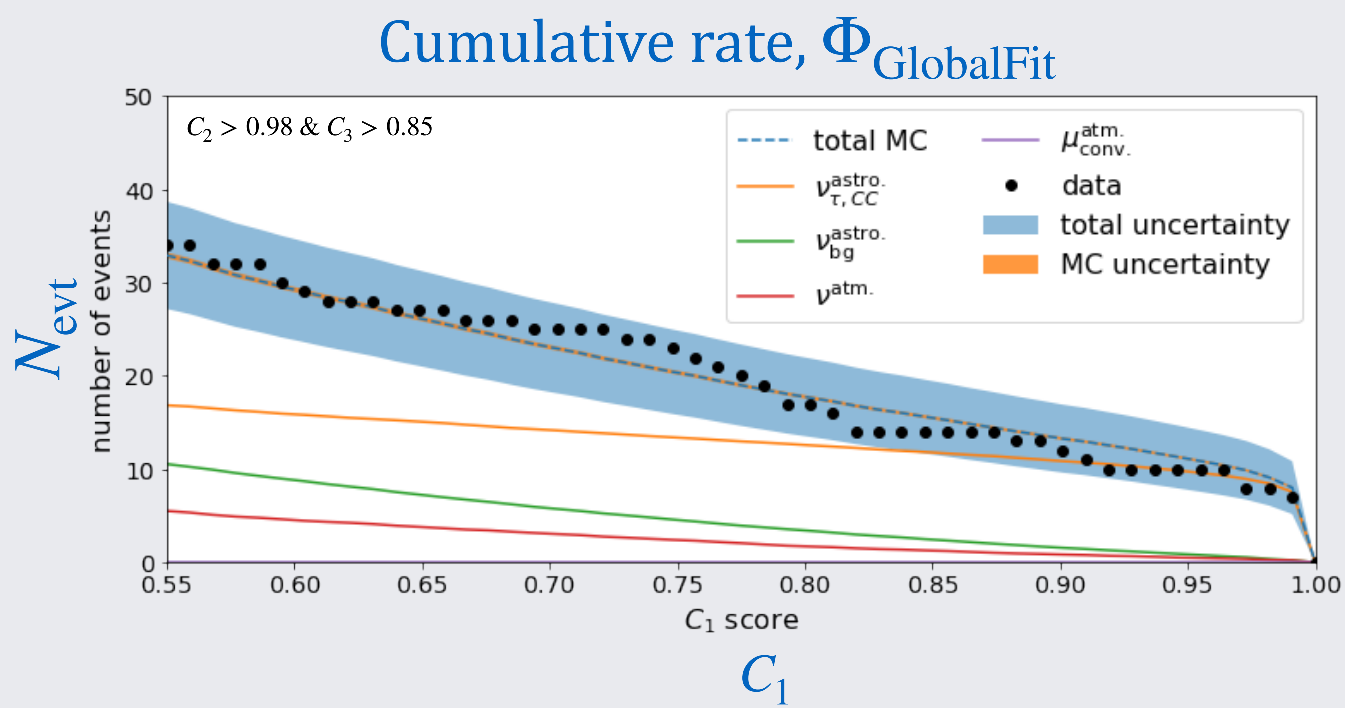
Searching for Astrophysical ν_τ: $Q_{\rm str}^{\rm max}$

- 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



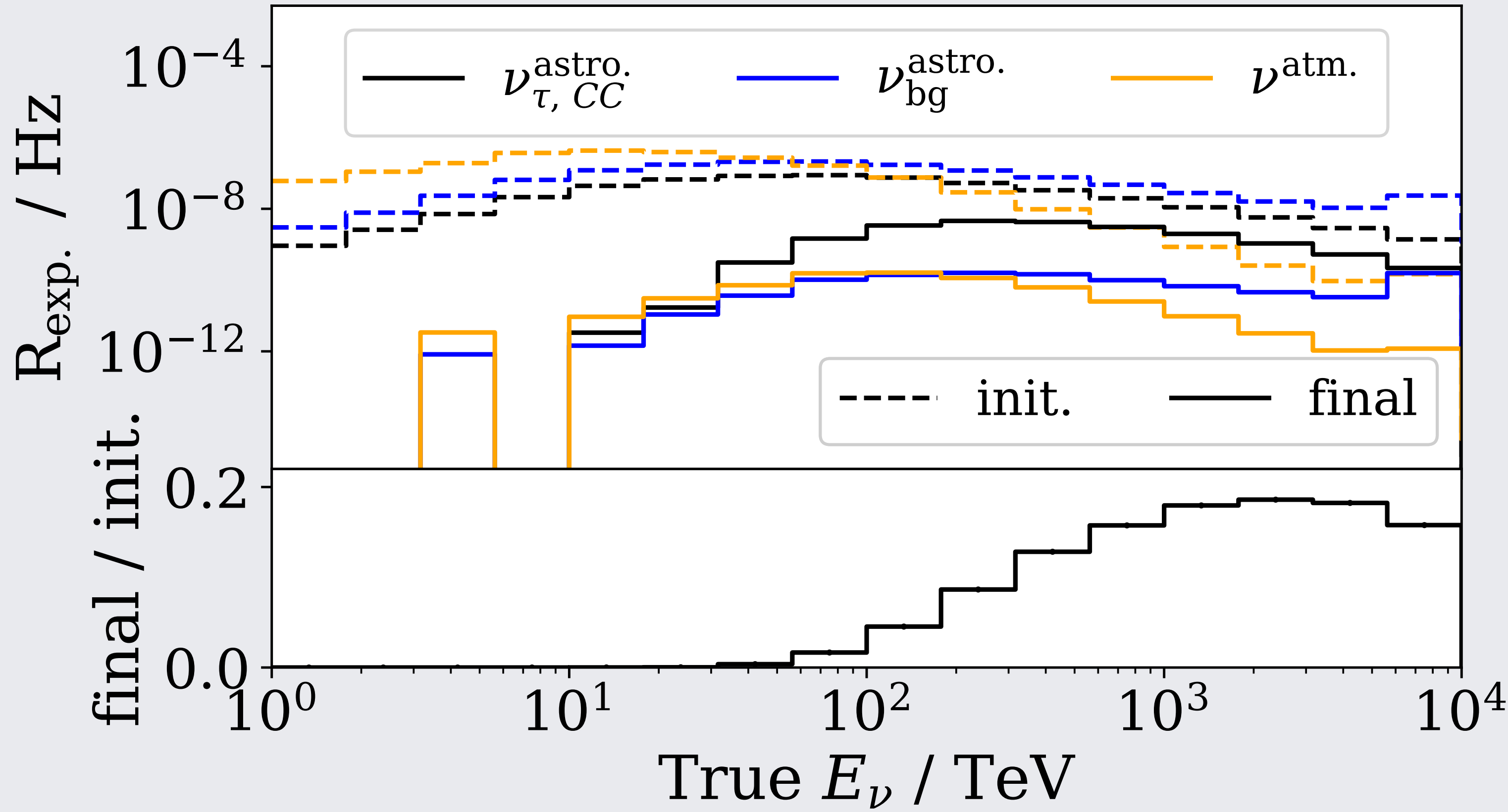
Searching for Astrophysical ν_τ: CNNs

- Trained 3 independent CNNs
  - $C_1 \geq 0.99$: ν_τ^{CC} vs. ν_e^{CC}, ν_x^{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
  - $\nu_{\text{astro.}}$ and $\nu_{\text{atm.}}$
    - Sub-dominant: $\mu_\downarrow$
- Off-signal region Data-MC agreement is good for $C_{1,2,3}$



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

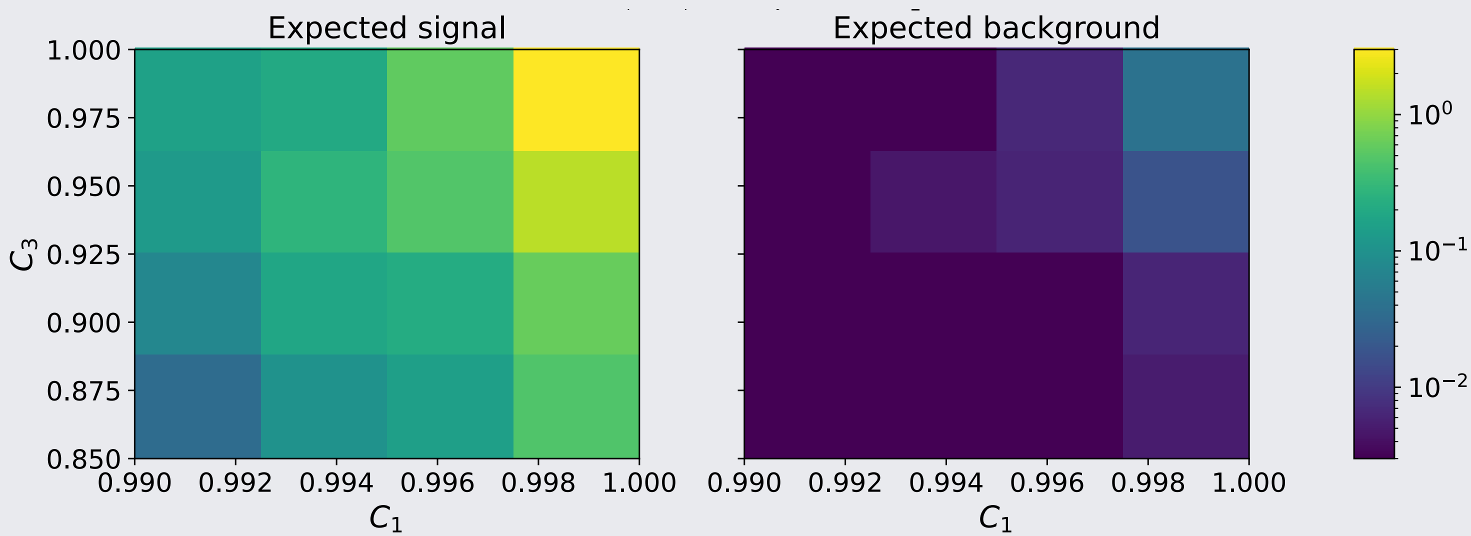
	$\nu_{\text{other}}^{\text{astro}}$	$\nu_{\text{conventional}}^{\text{atm}}$	$\nu_{\text{prompt}}^{\text{atm}}$	μ^{atm}	all background
initial	400 ± 0.7 (490 ± 0.8)	580 ± 7	72 ± 0.1	8400 ± 110	9450 ± 110 (9540 ± 110)
final	0.3 ± 0.02 (0.2 ± 0.01)	0.1 ± 0.008	0.1 ± 0.001	0.005 ± 0.004	0.5 ± 0.02 (0.4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

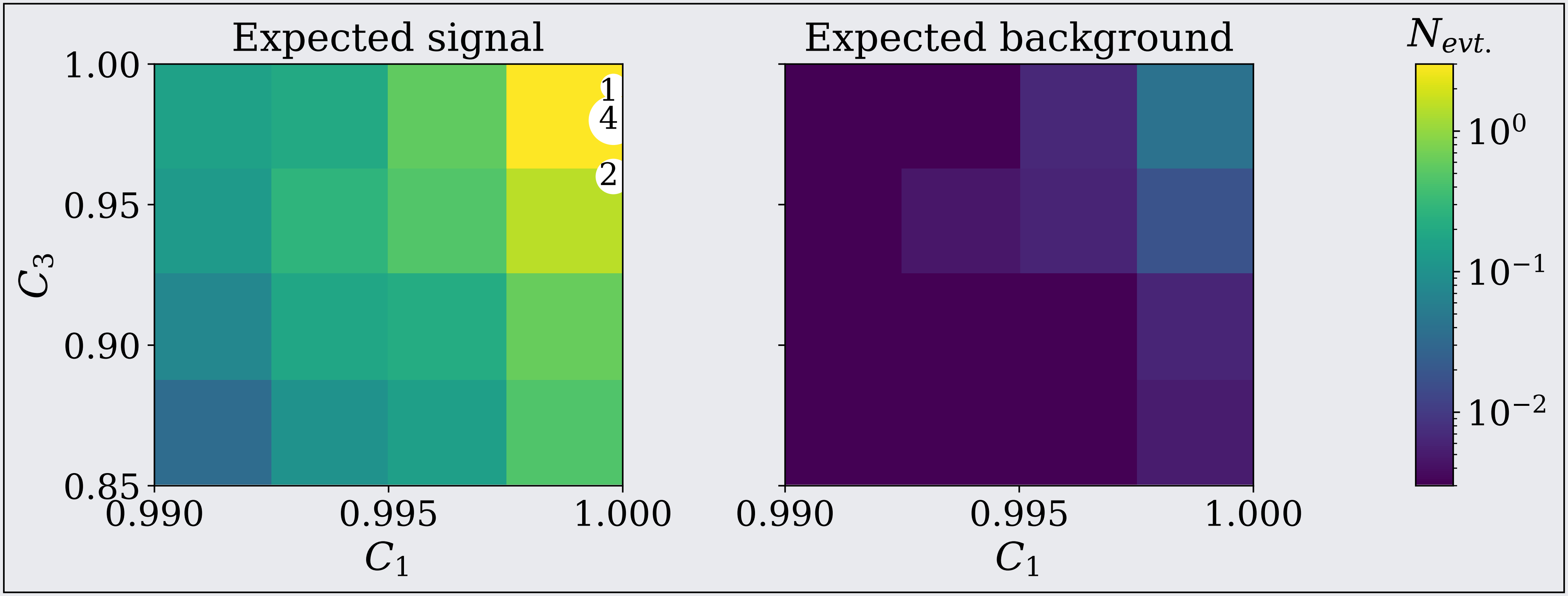
Astrophysical ν_τ: Results

- 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 new. 3 events old (1 of which previous ν_τ candidate).

Events tend to interact near strings.

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

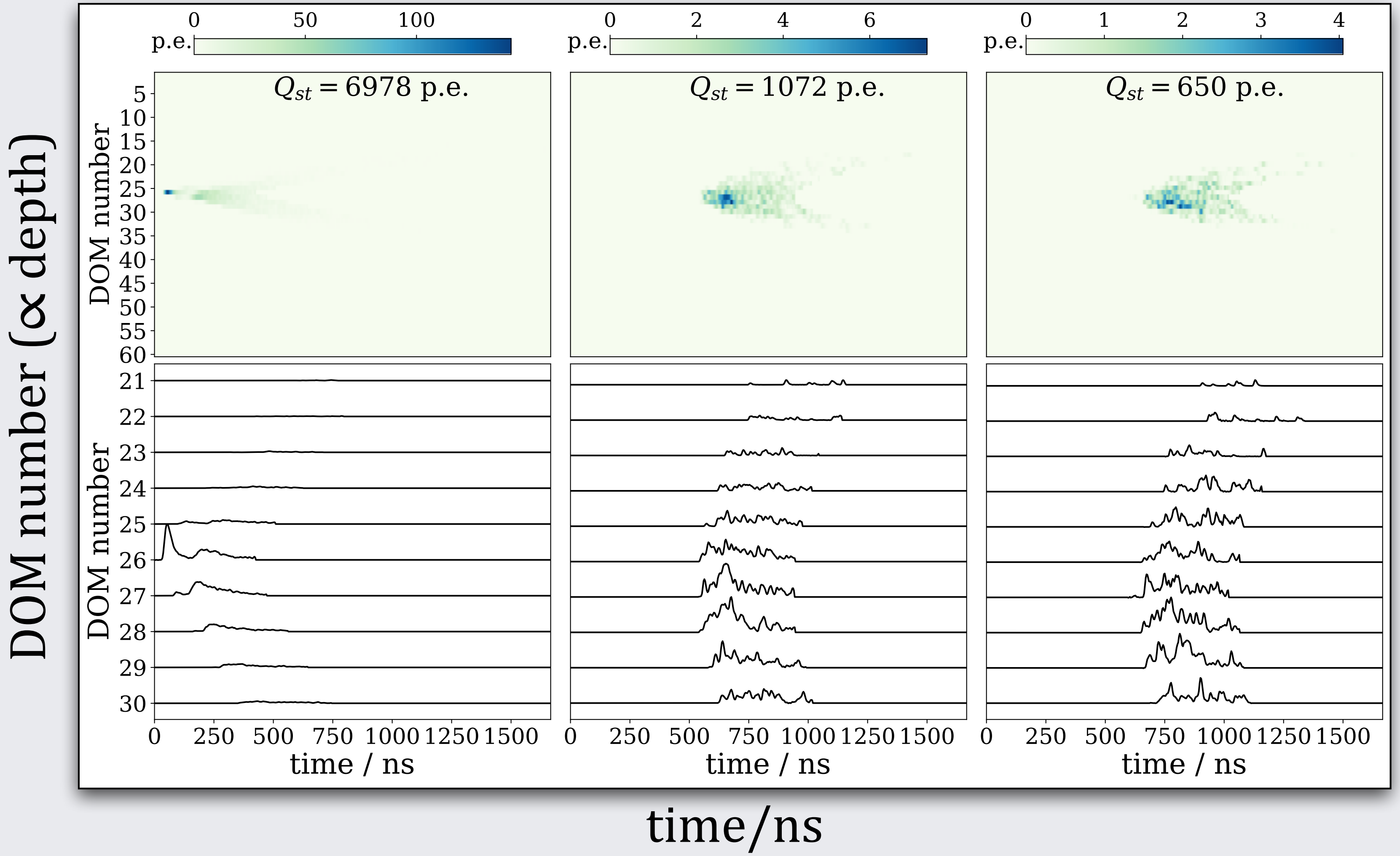
Summary →

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

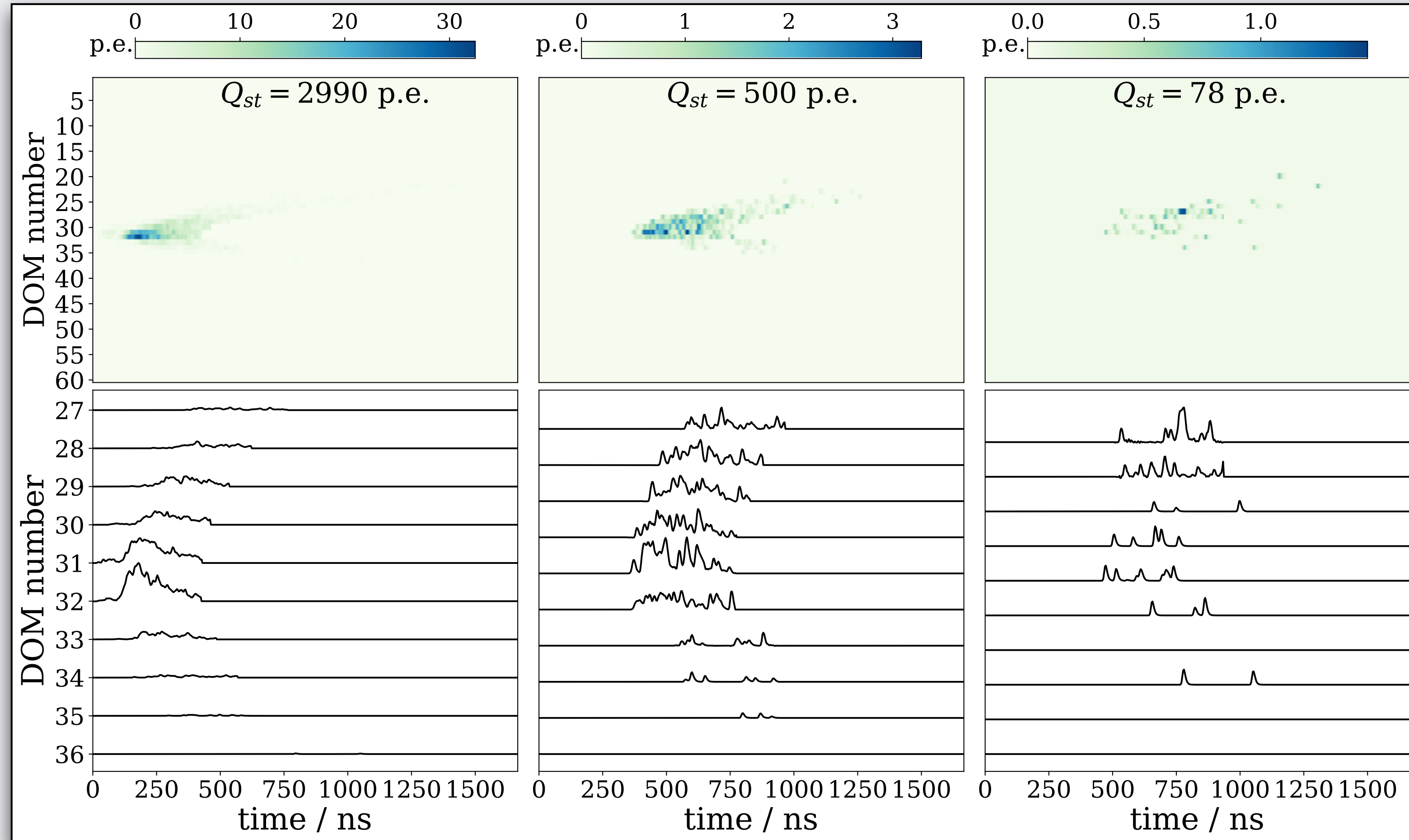
Here's "Double Double," an old event & prior ν_τ candidate:



Gratifying to find this event again.

Event Pic: Unclear DP Signature

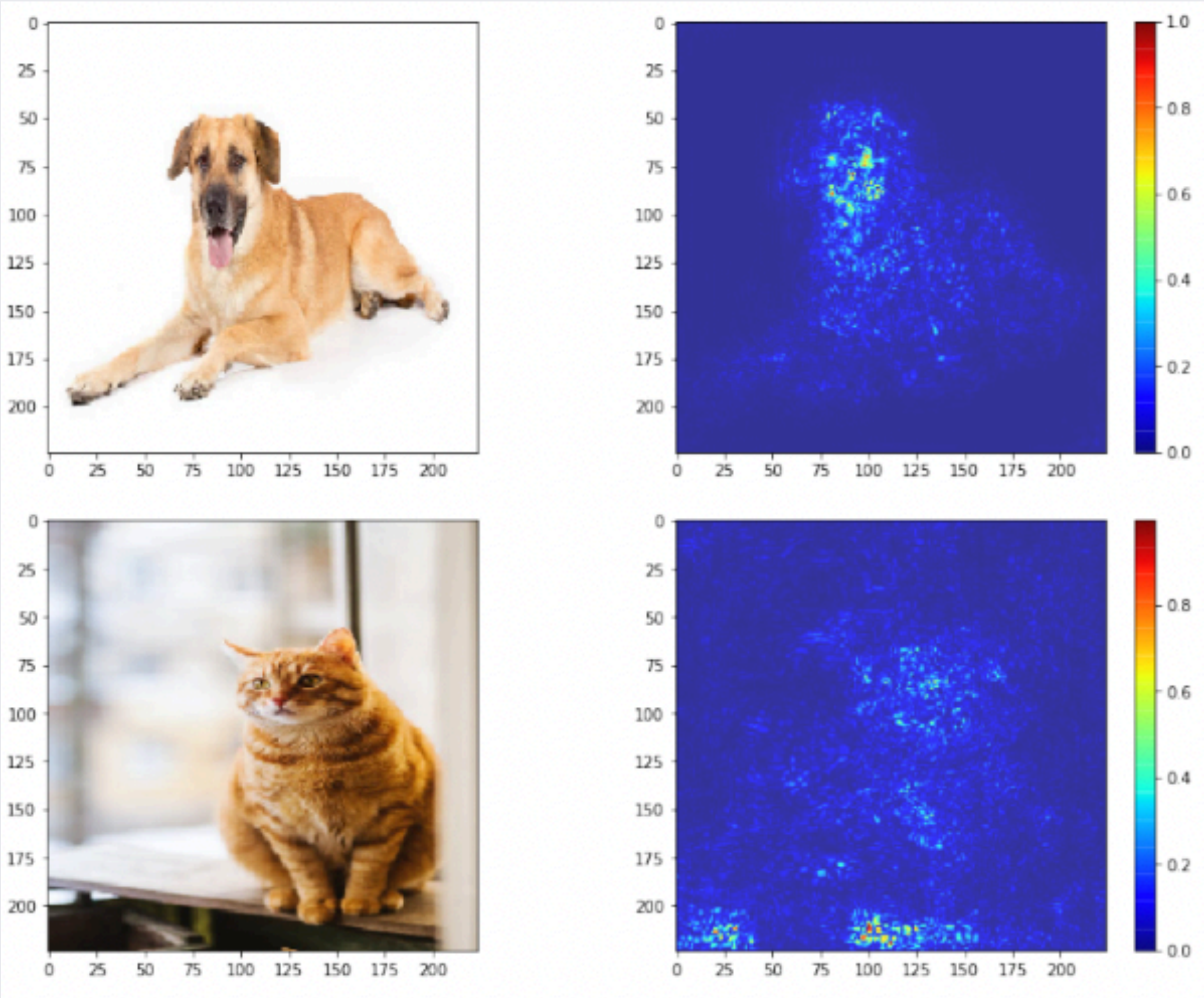
Here's "Barn Owl," another new event:



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.



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

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

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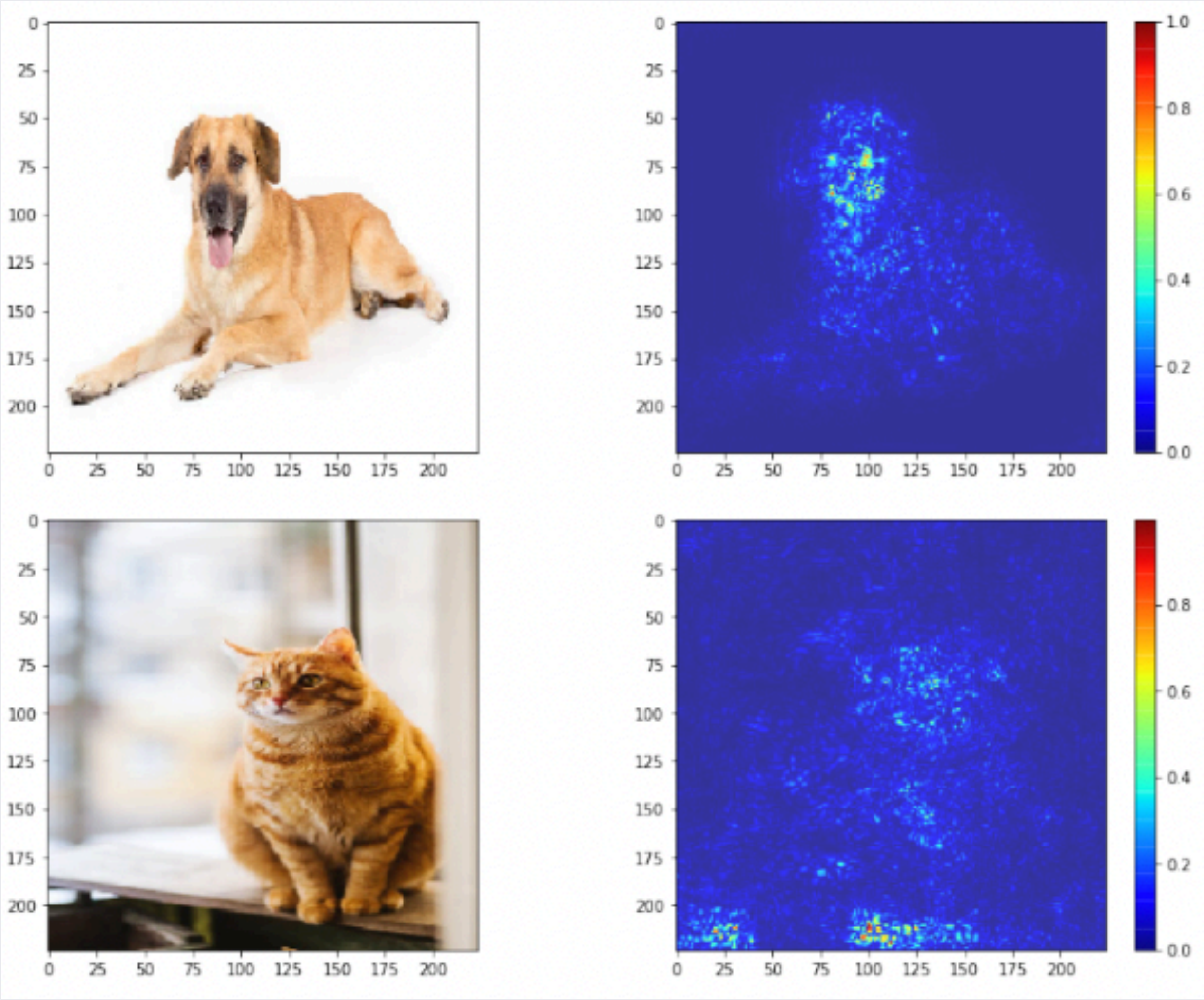

https://usmanr149.github.io/urmlblog/cnn/2020/05/01/Salincy-Maps.html

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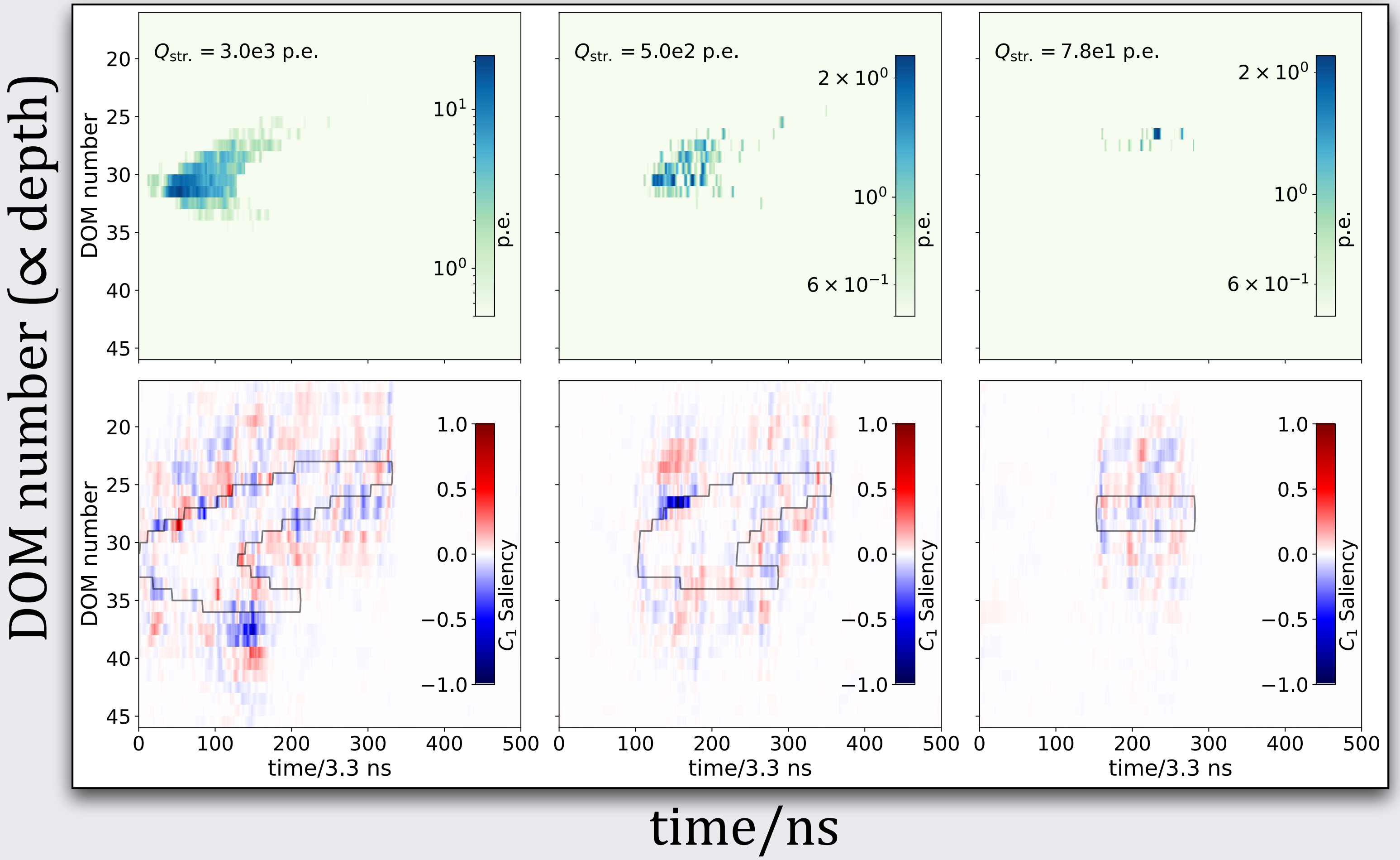
(Evidently, the training sample had many of its cats sitting on tables.)

Event Pics w/Saliency Maps

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



Measured light levels in each of 3 strings.

Saliency:

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

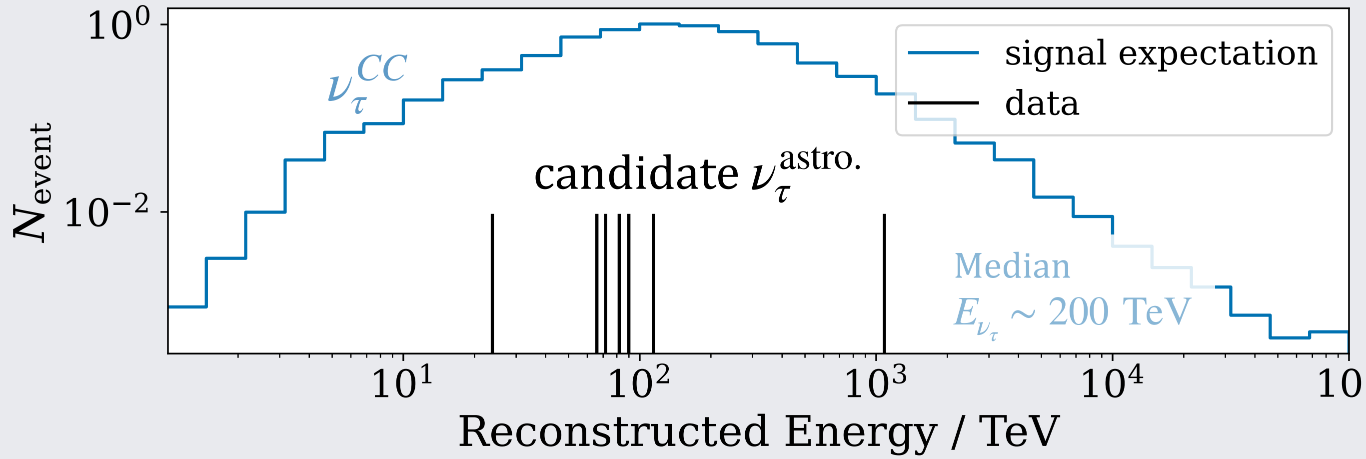
- light↑, C_1↑
- light↓, C_1↑

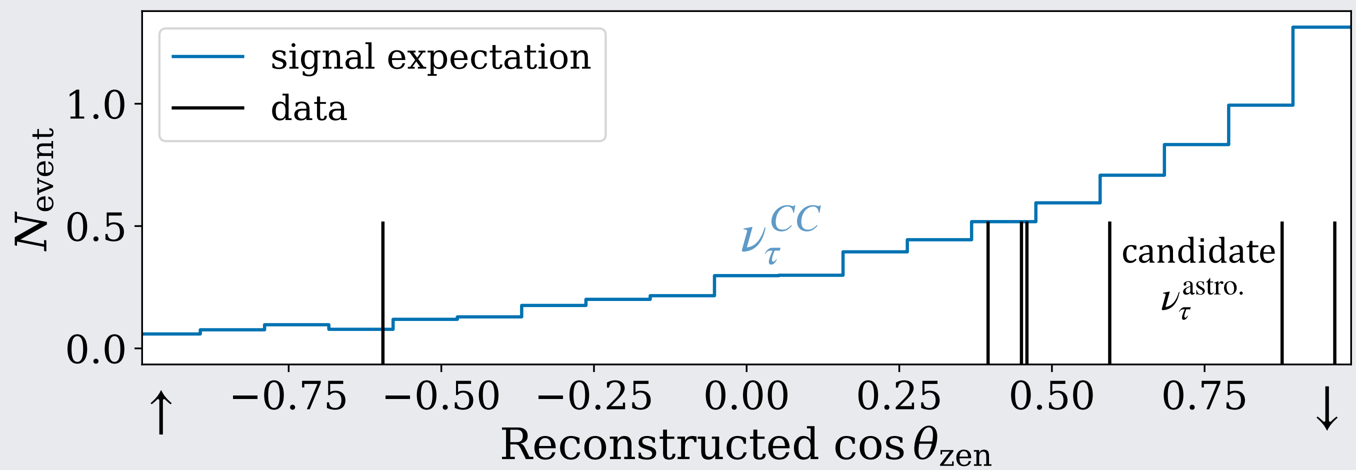
Contours: where light level $\rightarrow 0$.

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

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

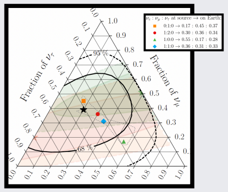




(IceCube's "GlobalFit" flux assumed above.)

Conclusions: What's Next?

- Used just 3 (of 86) strings. Using more strings would:
  - Improve bkgd rejection ⇒ relax cuts, more signal
    - Possibly start excluding some source acceleration mechanisms



- 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