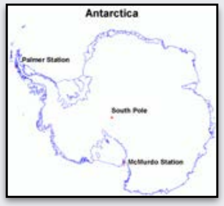
All ν_τ's, Great and Small

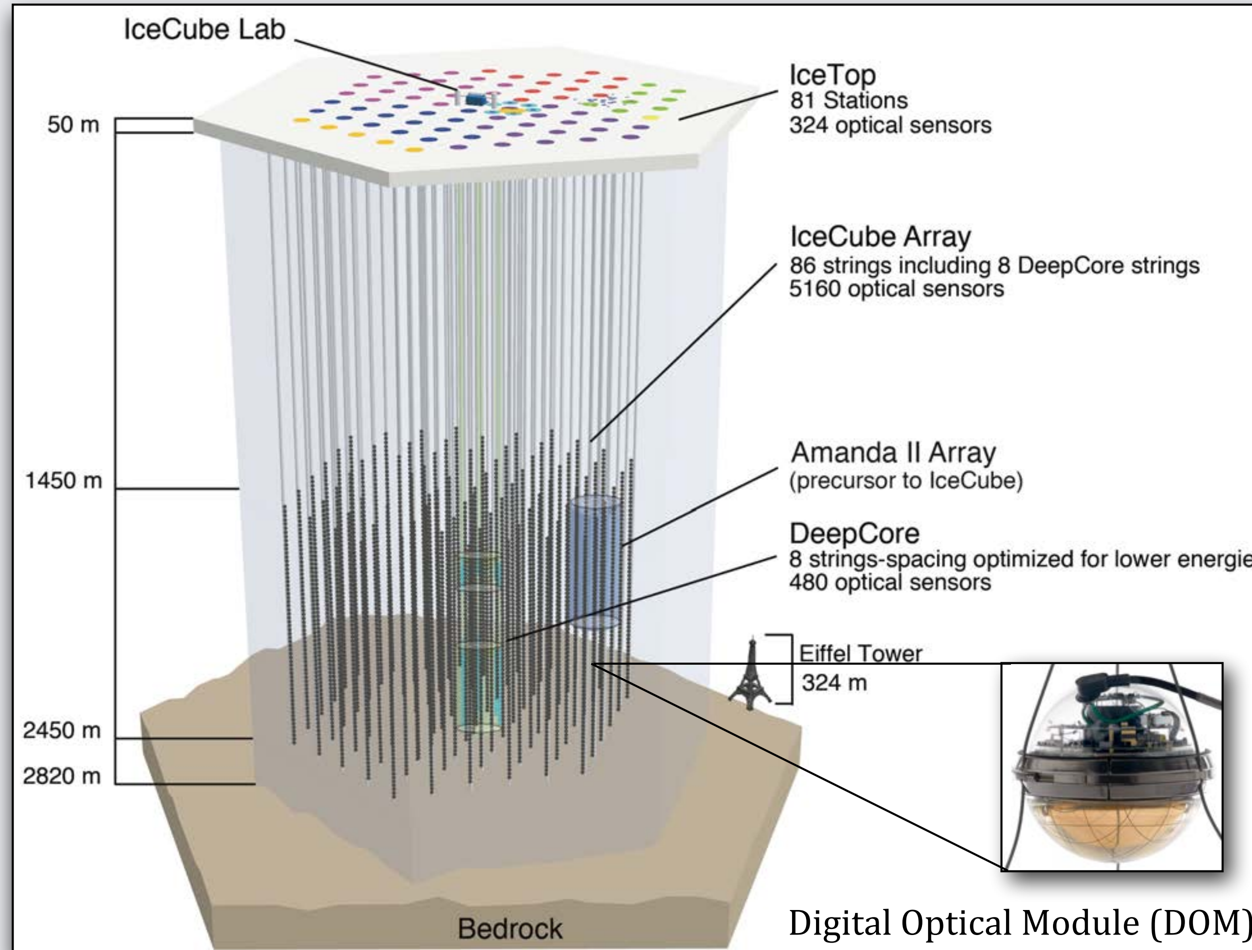
Tau Neutrino Physics with IceCube
Spanning Six Orders of Magnitude in Energy

Doug Cowen
Penn State



The IceCube+DeepCore Detector

- IceCube built in 2010 to map the ν sky at $E_\nu \sim 1$ TeV
  - Find astrophysical ν
  - Find astrophysical ν sources
  - Help solve mystery of UHECR
- Enhanced with DeepCore
  - more densely instrumented region for DM and atm. ν osc.



Digital Optical Module (DOM)


Module being lowered into melted hole.

IceCube:
13 Countries
54 Institutions
319 Collaborators

Neutrinos in IceCube: Sources

- Atmospheric neutrinos
  - cosmic rays (mainly protons) interact in the earth's atmosphere
  - resulting particle showers include ν's
  - IceCube threshold $E_\nu \sim 5$ GeV, $E_\nu^{\text{atm.}} < \sim 10$ TeV; $E_\nu \approx 10^{9-12}$ eV

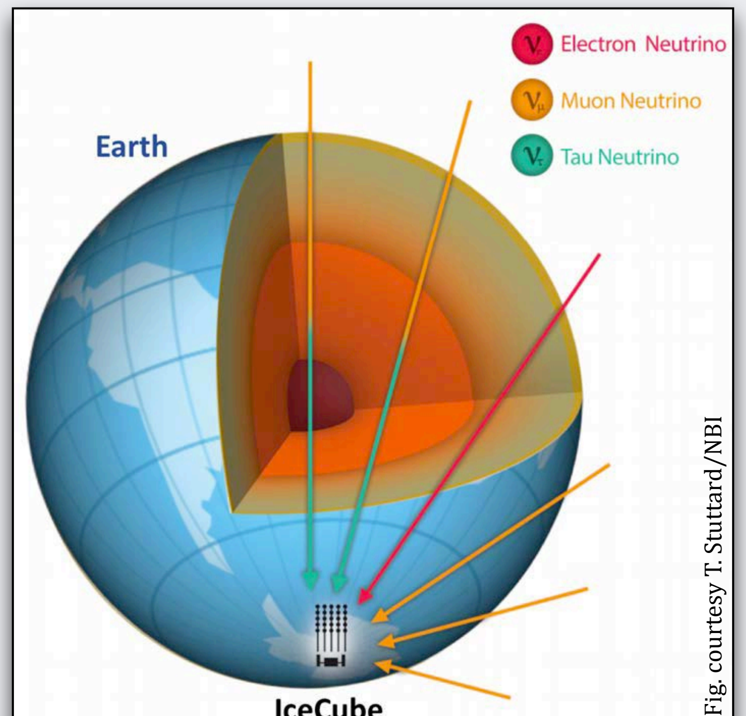


Fig. courtesy T. Stuttard/NBI

- 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
    - IceCube has seen PeV-scale (10^{15} eV) ν's

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

Fig. courtesy DESY/Zeuthen

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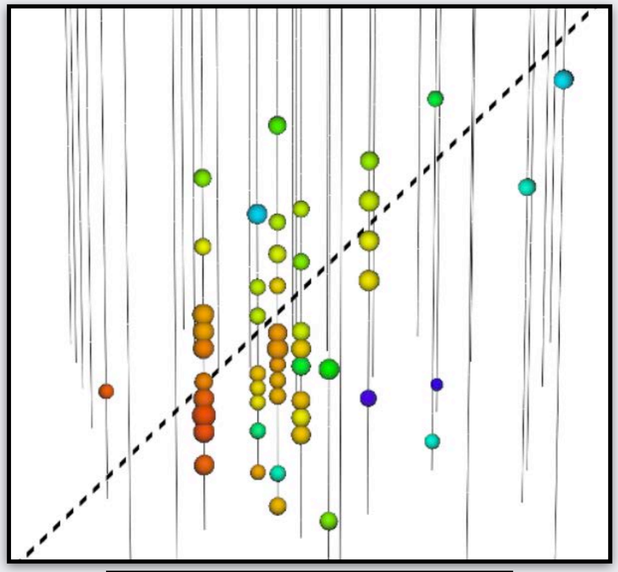
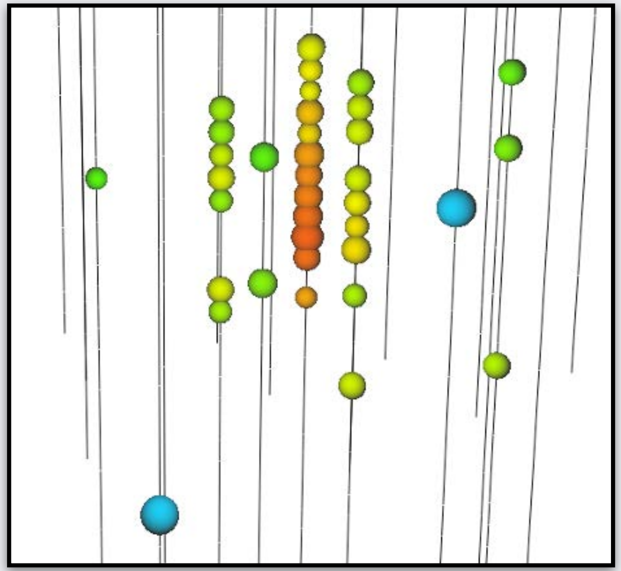
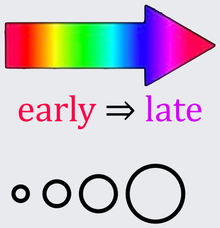
ν_μ^{CC} ("track") interactions can be distinguished from other ν ("cascade") interactions, but not so easily by eye.



Simulated 25 GeV muon



Simulated 25 GeV cascade



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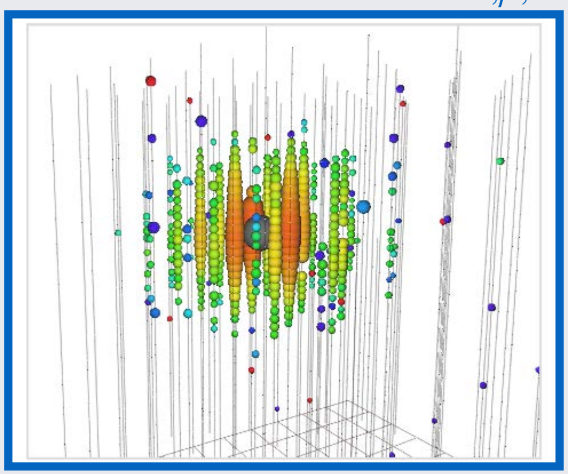
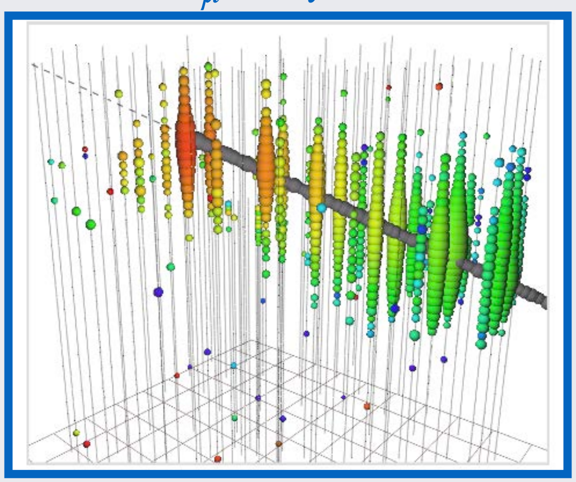
At higher energies, neutrino flavors can be distinguished:

Single cascade: $\nu_e^{CC}, \nu_{e,\mu,\tau}^{NC}$



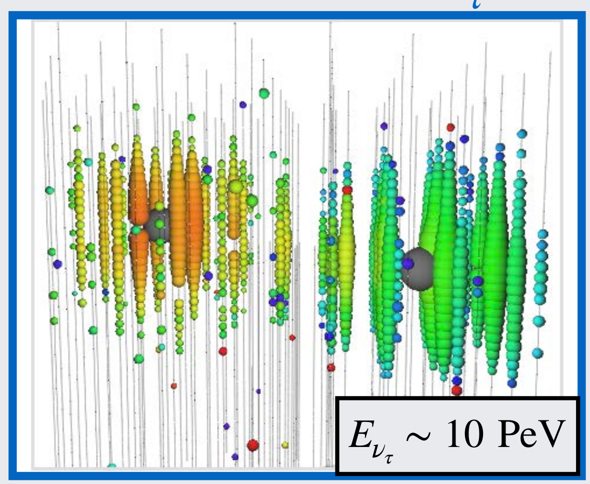
$\sigma_E \sim 11\ \%$

Track: $\nu_\mu^{CC}, \nu_\tau^{CC}(\tau \to \mu)$

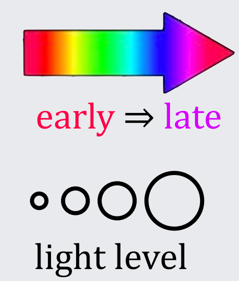


$\sigma_\phi \sim 2^\circ$

Double cascade: ν_τ^{CC}



$L_\tau \sim 50$ m/PeV



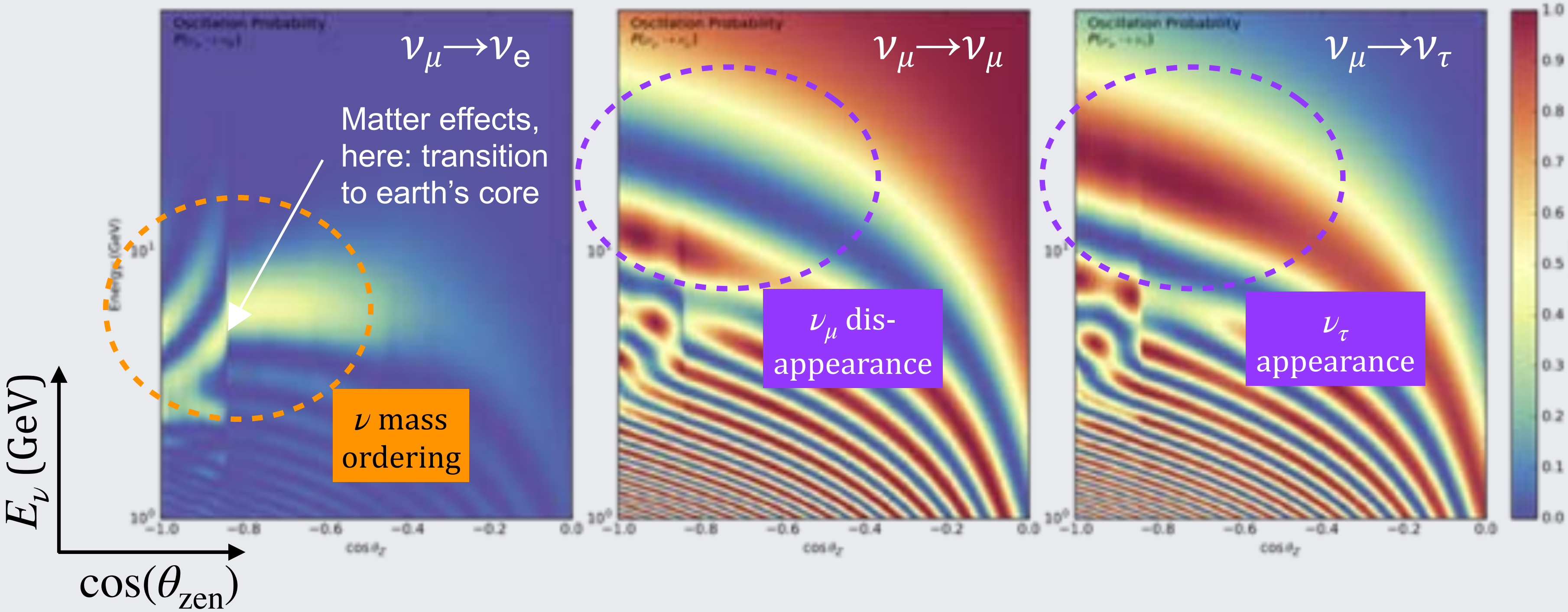
Atmospheric ν_τ

- Atmospheric ν's arise mainly from the decay of light mesons
  - At production, expect flux ratio of roughly $(\nu_e : \nu_\mu : \nu_\tau) :: (1 : 2 : 0)$
    - No ν_τ there.

- ν_τ arise from ν oscillations as they cross the earth:

$$P_{\nu_\mu \to \nu_\tau} \approx \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2 L_\nu}{E_\nu}\right)\frac{[\mathrm{eV}^2][\mathrm{km}]}{\mathrm{GeV}}$$

  - E.g., $P(\nu_\mu \to \nu_\tau) \approx 100\,\%$ for $E_\nu \approx 25$ GeV, $L_\nu \approx D_{\mathrm{earth}}$



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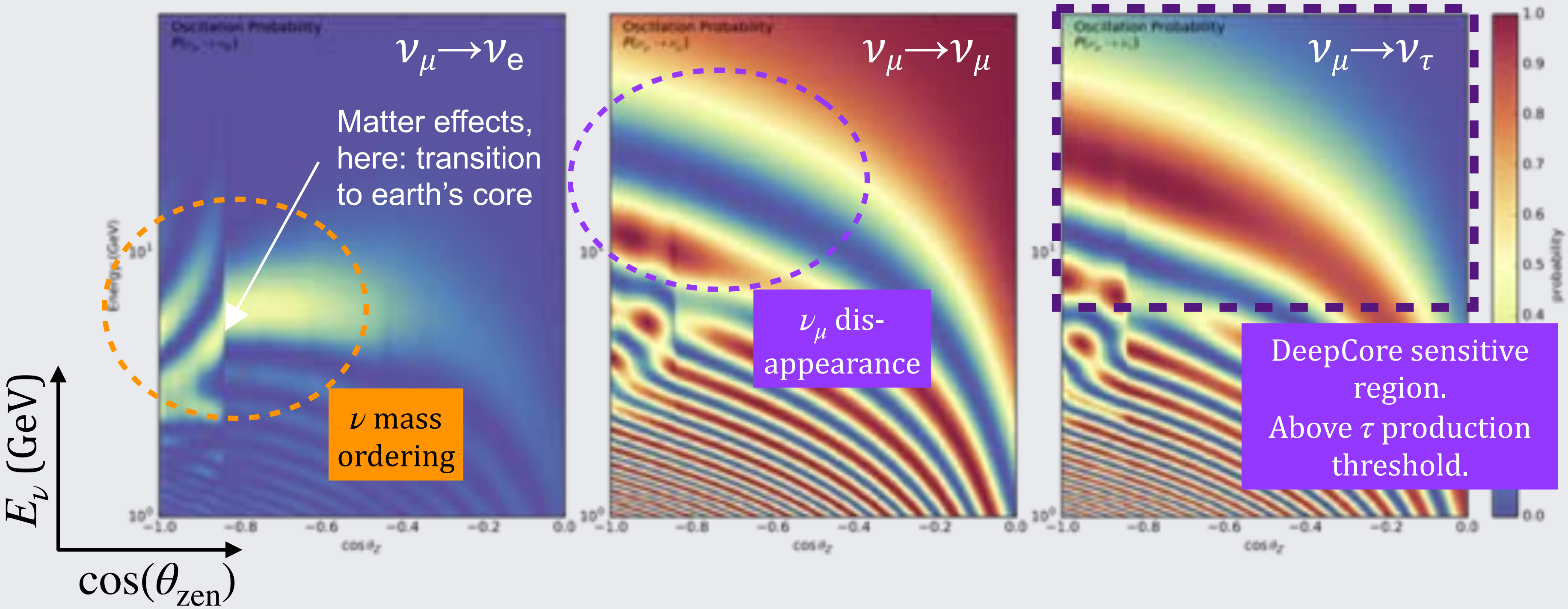
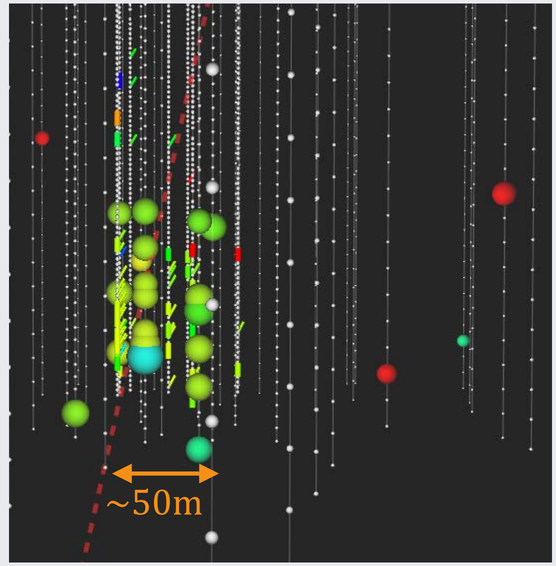


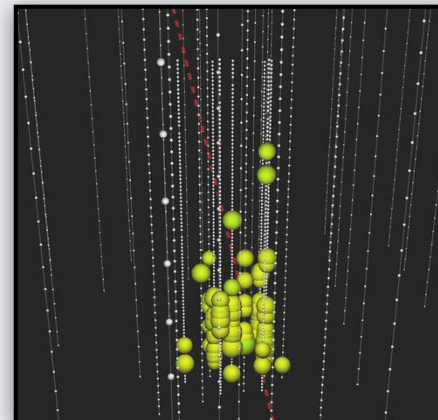
Atmospheric ν_τ Reconstruction

- Atm. ν_τ will produce particle showers in the detector
- We reconstruct the energy & direction of these showers, and can distinguish them from track-like events
- Look for excess of upward-going, shower-like interactions around 20 GeV

21 GeV ν_τ (sim.)

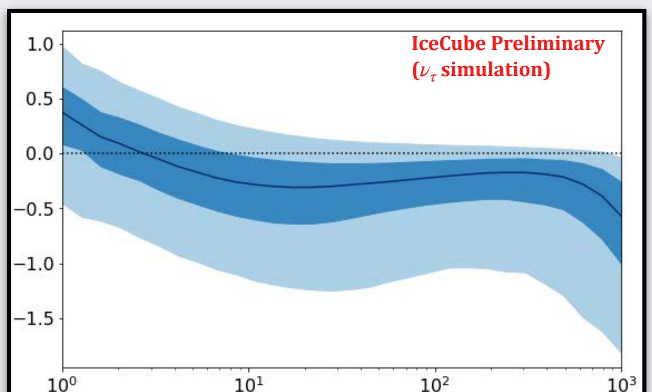


IceCube/DeepCore



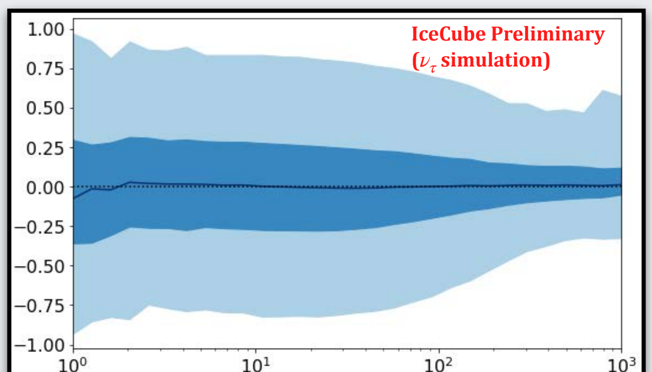
IceCube/Upgrade
(N_γ *much* larger)

$\log(E_{\mathrm{reco}}^{\mathrm{cscd}}) - \log(E_{\mathrm{true}}^{\mathrm{cscd}})$ (GeV)



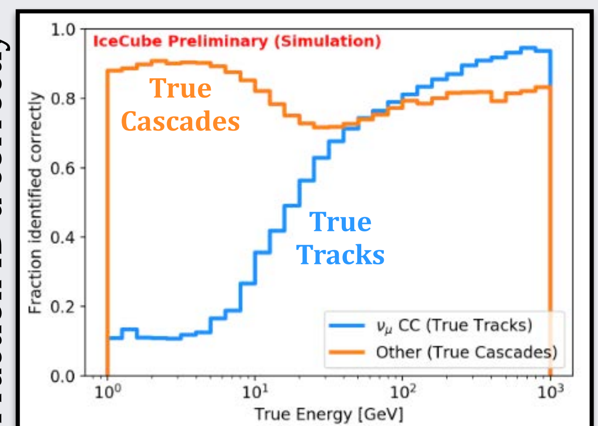
$E_{\mathrm{true}}^{\mathrm{cscd}}$ (GeV)

$\cos(\theta_{\mathrm{reco}}^{\mathrm{zen}}) - \cos(\theta_{\mathrm{true}}^{\mathrm{zen}})$



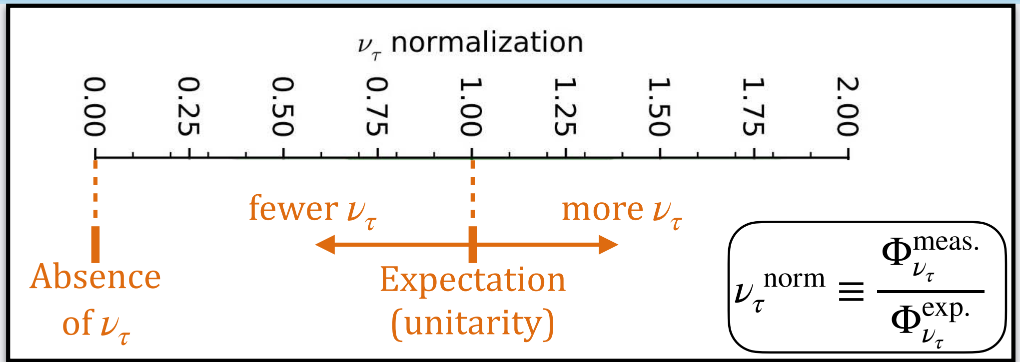
$E_{\mathrm{true}}^{\mathrm{cscd}}$ (GeV)

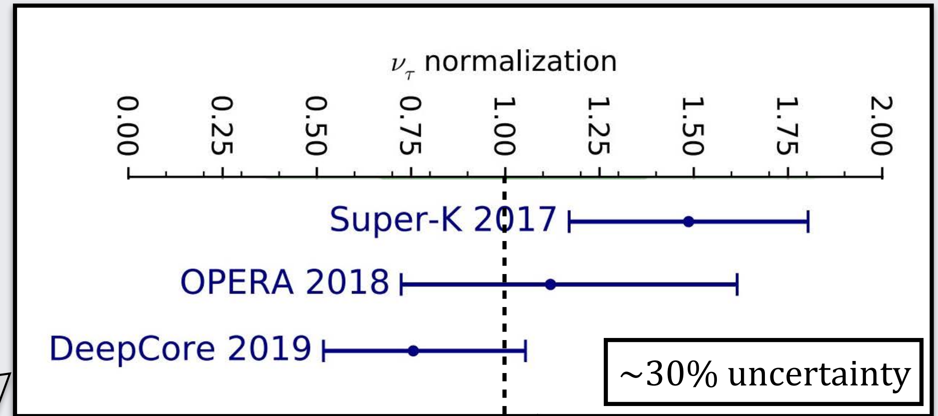
Fraction ID'd correctly



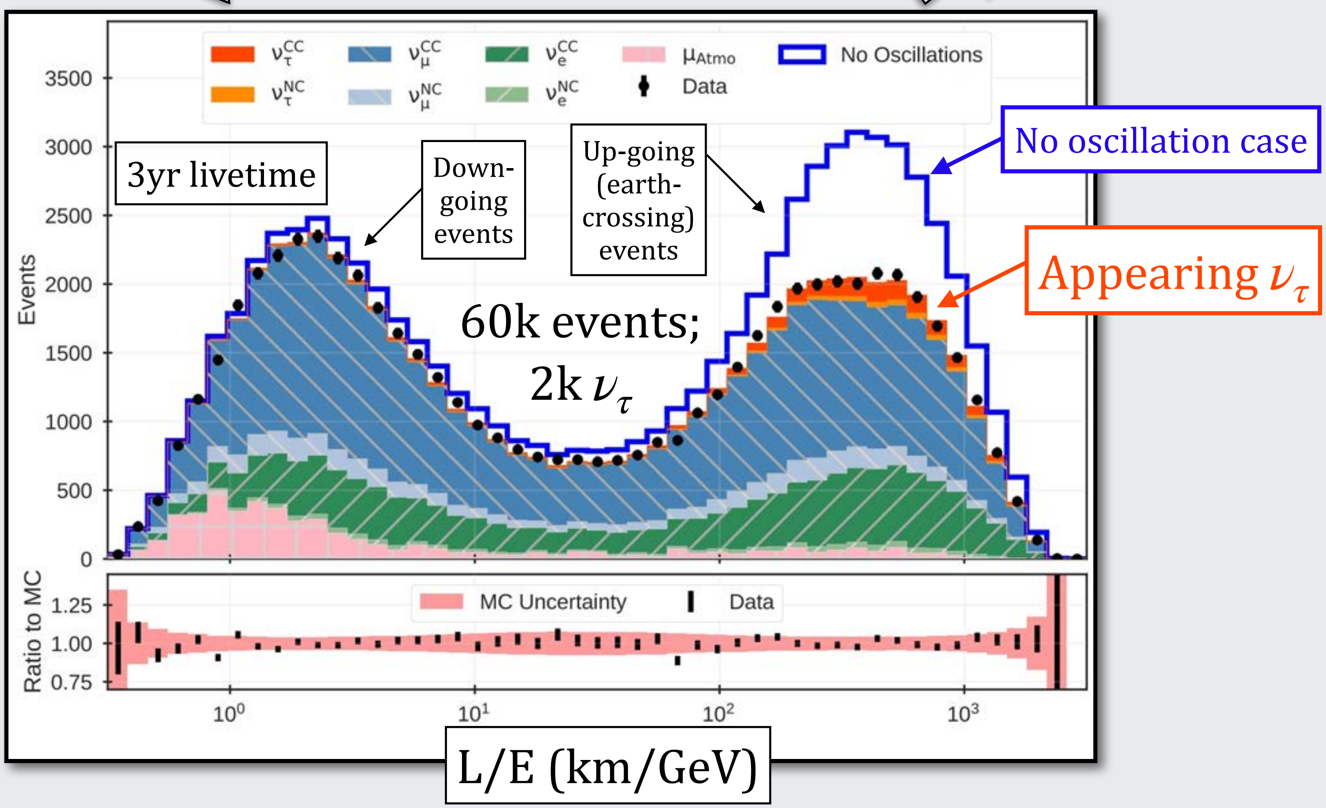
$E_{\mathrm{true}}^{\mathrm{total}}$ (GeV)

First IceCube ν_τ Appearance Measurement

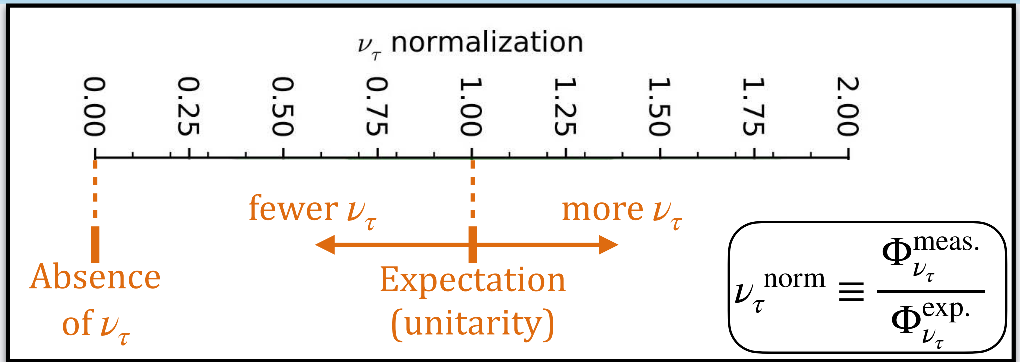


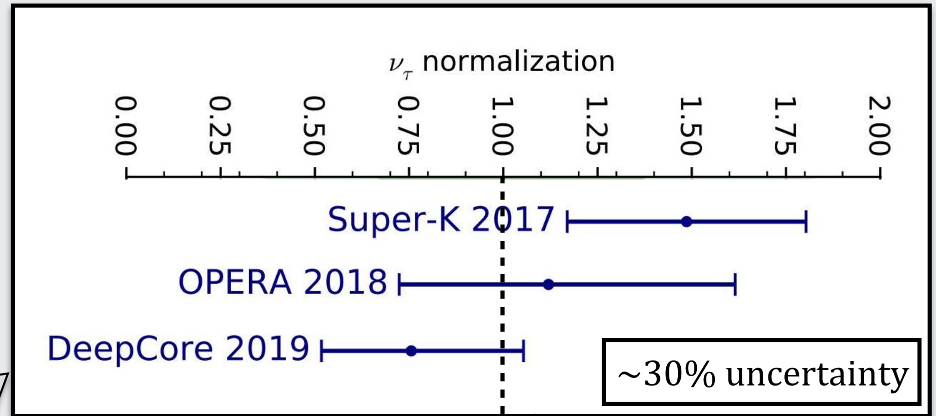


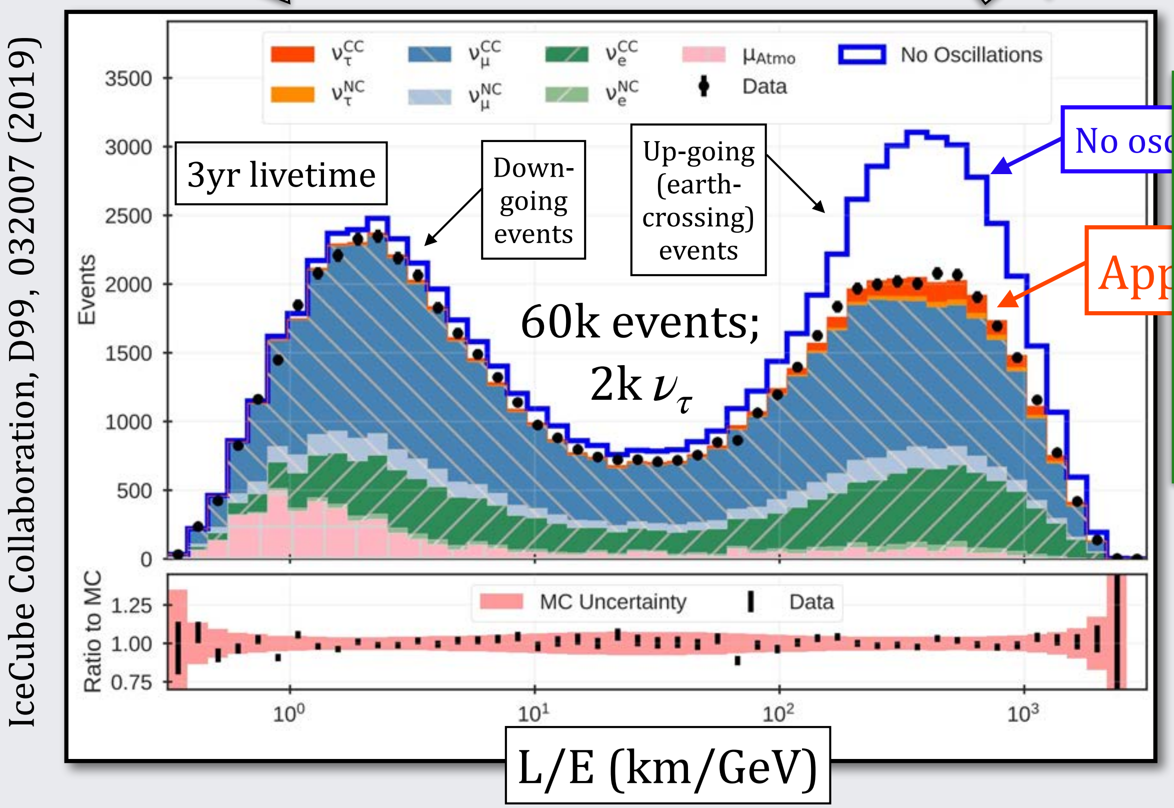
IceCube Collaboration, D99, 032007 (2019)

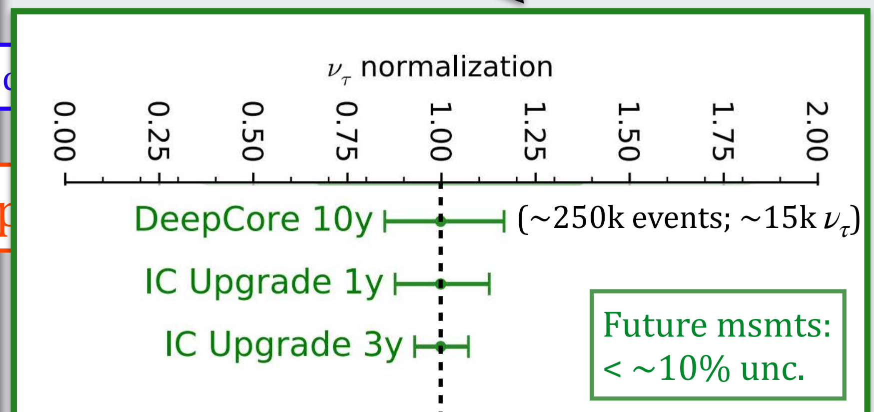


Future IceCube ν_τ Appearance Measurements









Astrophysical ν: $E_\nu > 10^{13-14}$ eV

- ν mainly from $\pi^\pm$ decay in astrophysical beamdumps
- Needle in a haystack!
  - 10^{11} atmospheric μ/yr,
  - 10^{5} atmospheric ν/yr, and
  - 10^{1} astrophysical ν/yr
- Beat down atm. μ using part of detector as veto (see below)
- Separate atm. ν from astrophys. ν using E_ν, spatiotemporal concidence, and/or event topology

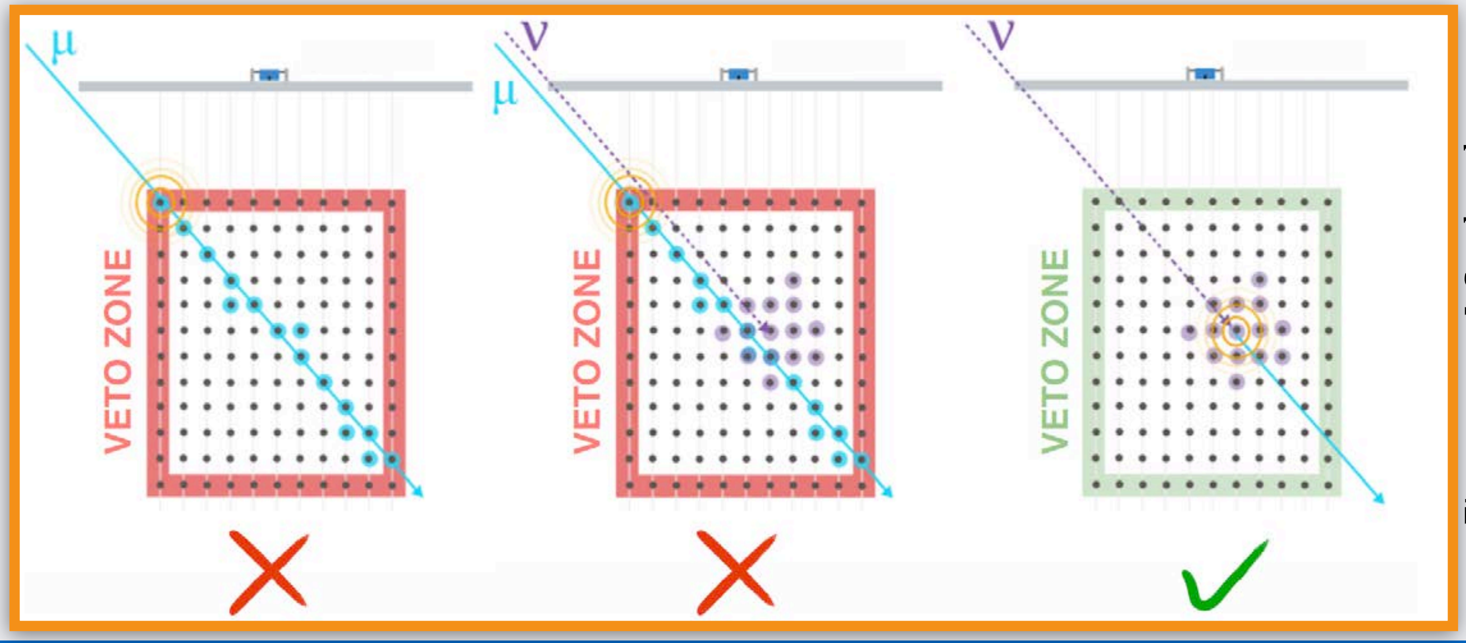


Fig. courtesy J. Stachurska

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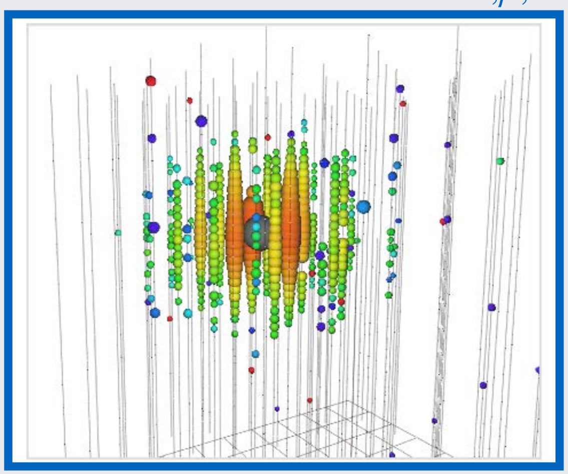
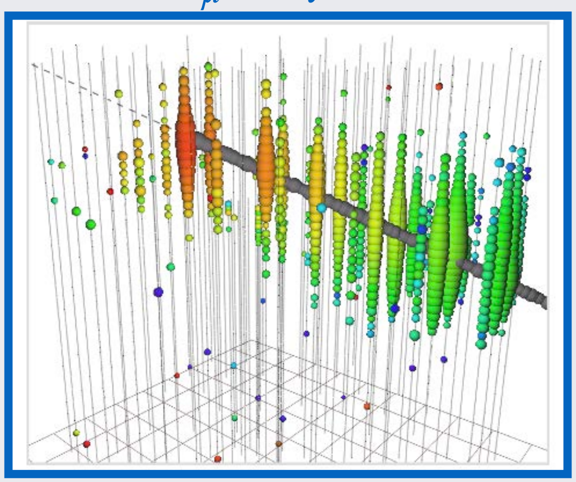
Single cascade: $\nu_e^{CC}, \nu_{e,\mu,\tau}^{NC}$



$\sigma_E \sim 11~\%$

Track: $\nu_\mu^{CC}, \nu_\tau^{CC}(\tau \to \mu)$



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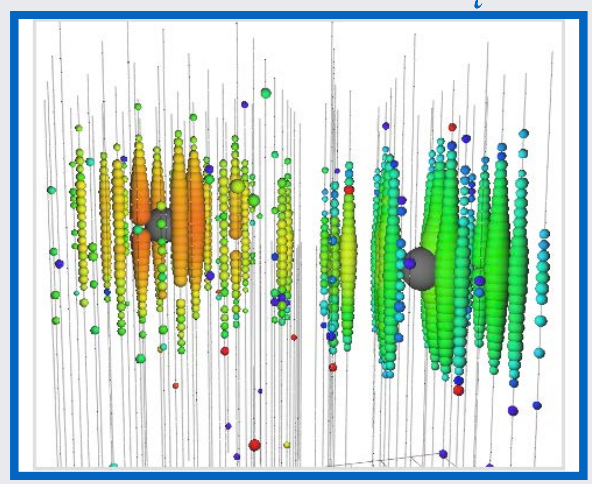
Double cascade: ν_τ^{CC}



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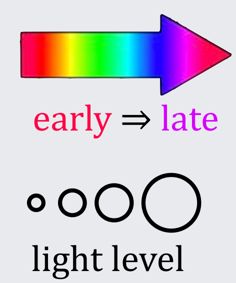
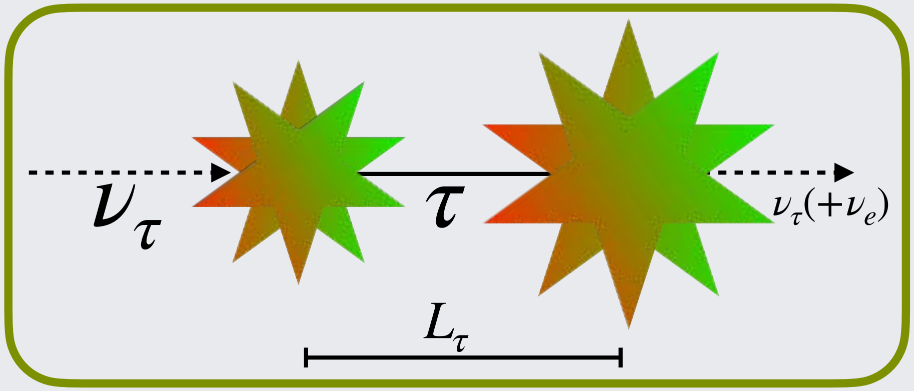
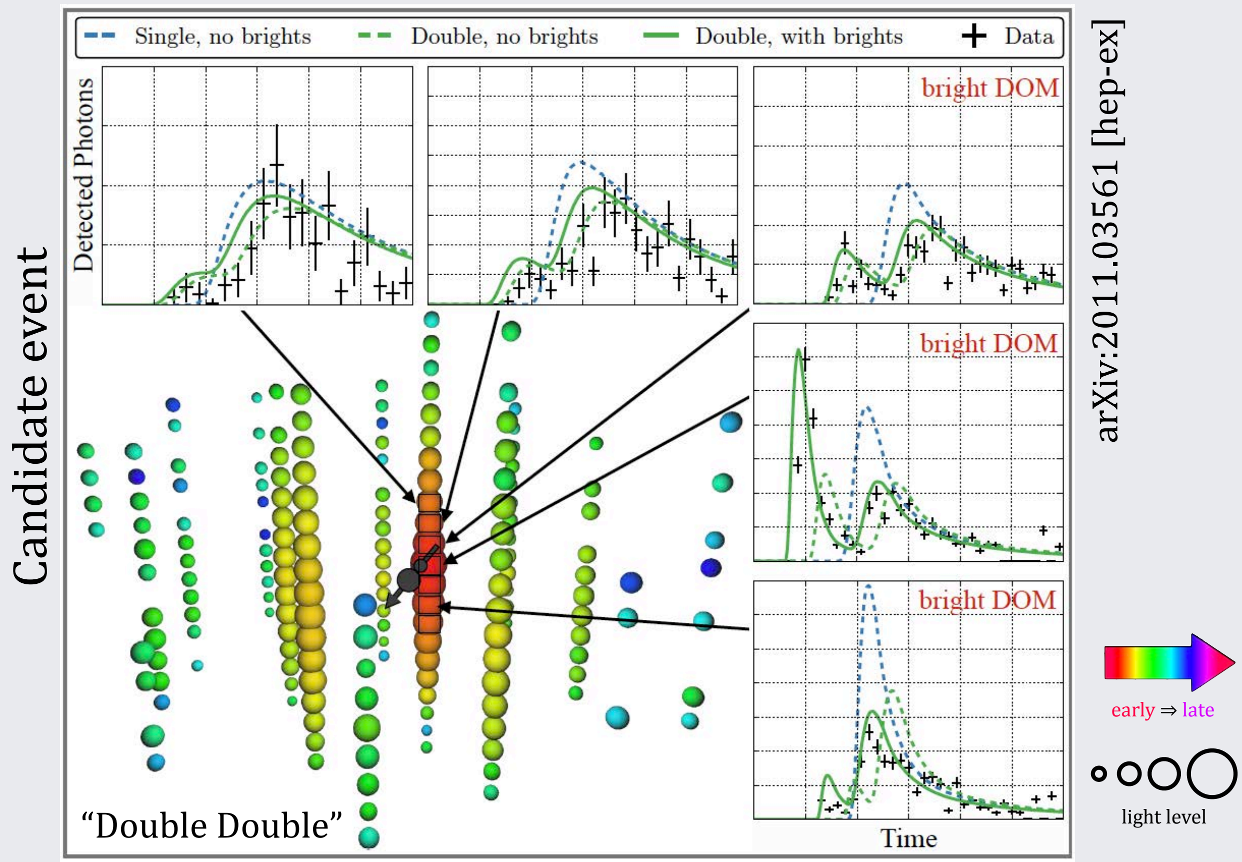


Astrophysical ν_τ

- Measurements to date:
  - Search for clean "double pulse" waveforms arising from "two-cascade" signature
  - Two ν_τ candidates found:
    - With
      - 1:1:1 flavor ratio at earth
      - $\Phi(\nu) \propto E_\nu^{-2.87}$

    expect 1.5 signal + 0.8 background in 7.5 yrs
    - (Estimate that 98% and 76% of events like the two seen are ν_τ–induced)



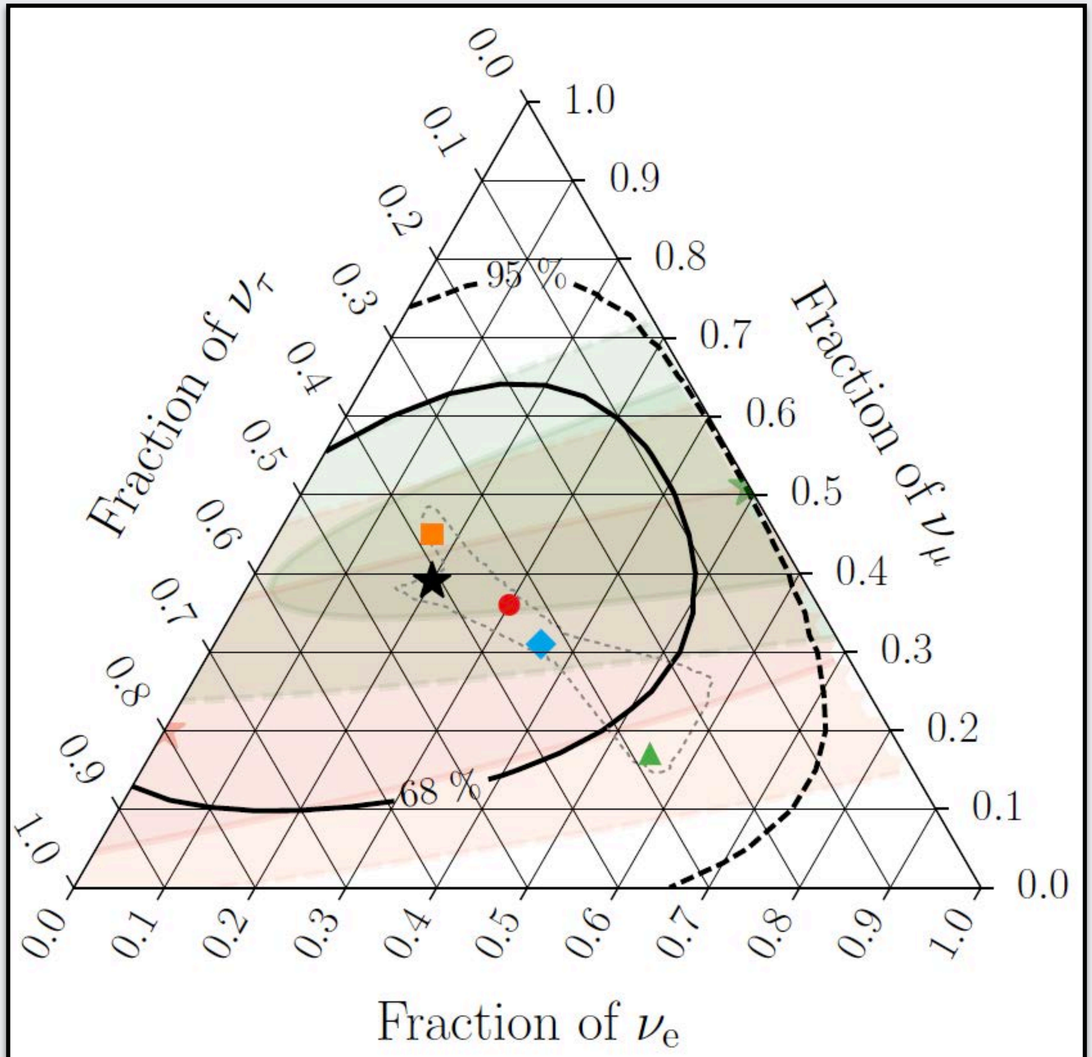


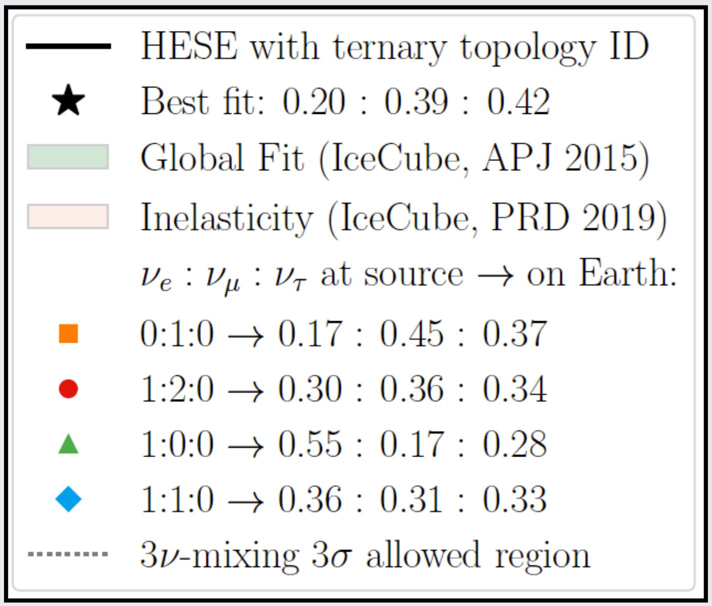
arXiv:2011.03561 [hep-ex]

Astrophysical ν_τ

- Joint flavor analysis:
  - First time best fit point with $(\Phi_{\nu_e}, \Phi_{\nu_\mu}, \underline{\text{and}}\ \Phi_{\nu_\tau}) \neq 0$
  - First probe of ν flavor oscillations over cosmic baselines & at the TeV scale
  - Rules out no-$\nu_\tau^{\text{astro.}}$ hypothesis at 2.8σ

“Flavor Triangle”





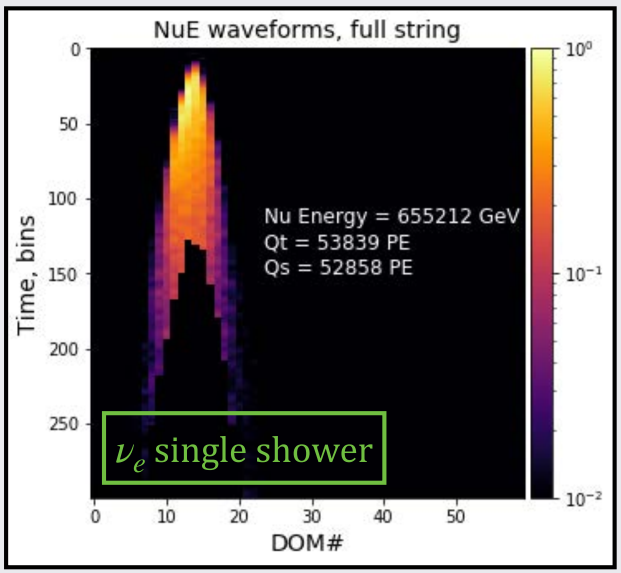
arXiv:2011.03561 [hep-ex]

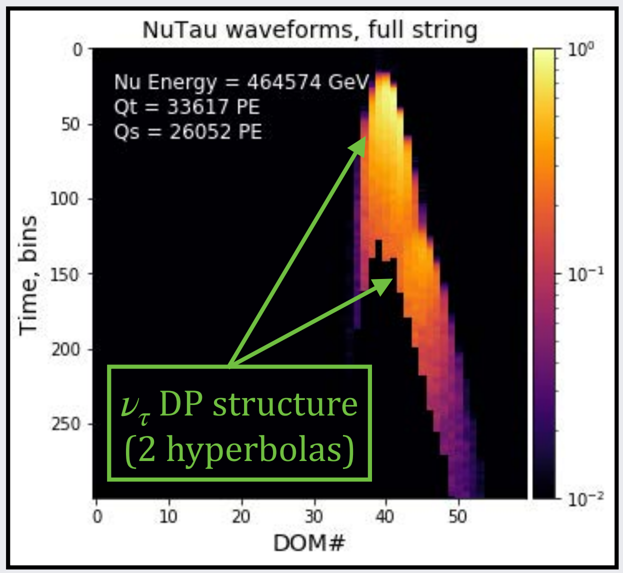
Future Astrophysical ν_τ Measurement

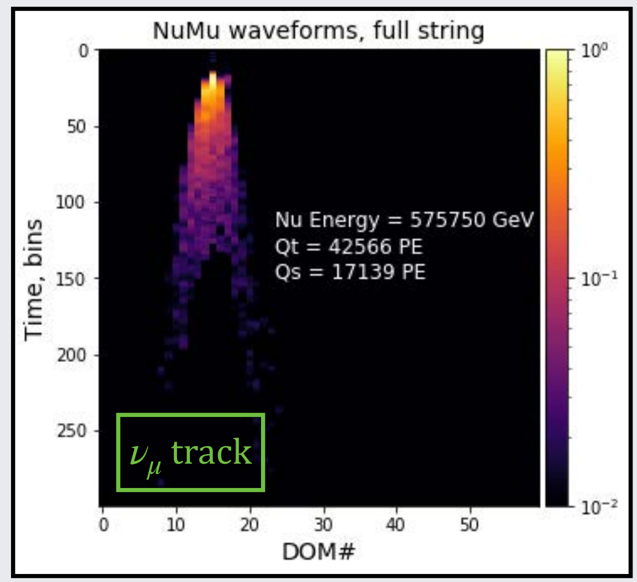
- Waiting for a clean “double bang” would require much patience: $E_{\nu_\tau} > \sim$ PeV are rare.
- Instead use more plentiful “double pulse” ν_τ events at lower threshold energies: $E_{\nu_\tau} > \sim 50$ TeV

- Follow in footsteps of previous analyses, but look for DP signature on 3 strings (180 vs. 1–2 modules)
  - Render each string into a 2-D image
  - Identify DP signal(s) using deep convolutional neural networks

time (3ns bins)







Module number ($\propto$ Depth)

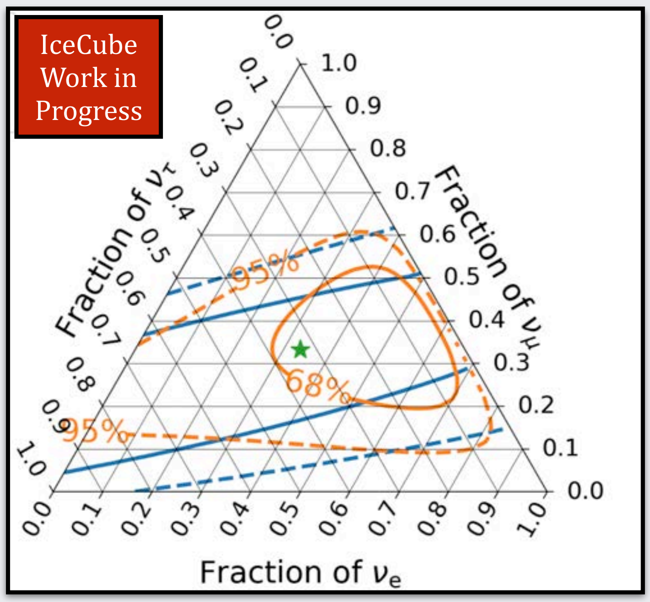
Qt: total charge
Qs: string charge

Future Astrophysical ν_τ Measurement

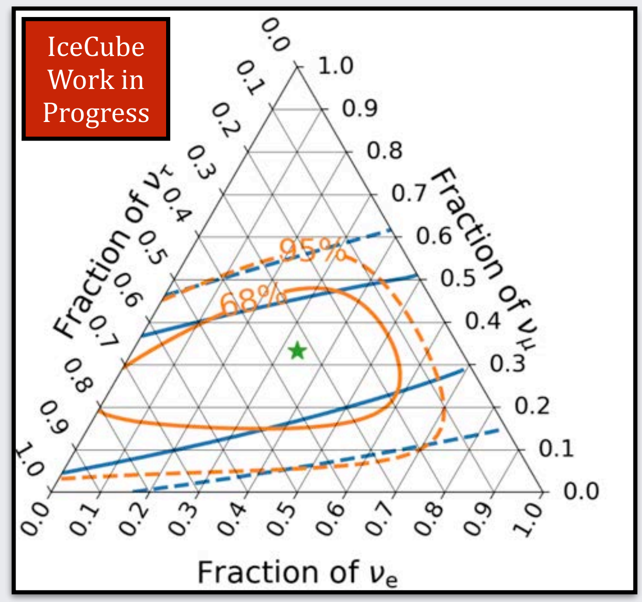
- Preliminarily predict ~5.5 ν_τ^{CC} on background of ~0.3 events
  - 10 years livetime
  - background dominated by other–flavor astrophysical ν
  - systematic effects appear to have minimal impact
- With ~5 events, can rule out no–$\nu_\tau^{\text{astro.}}$ at high confidence
- May be able to better constrain astrophysical neutrino “flavor triangle”
- Also: Exploring supra-PeV ν_τ producing kms-long τ tracks
  - Potentially distinguishable from μ tracks (smoother: $m_\tau \gg m_\mu$)

After opening the box, here’s what the triangle plot might look like for two selected values of events seen:

2 events seen



5 events seen



★ Source $\nu_e : \nu_\mu : \nu_\tau$ = 1:2:0 → ~1:1:1 at det.

Blue lines from IceCube Collaboration, Phys. Rev. D 99, 032004

Orange lines lack full systematic treatment.

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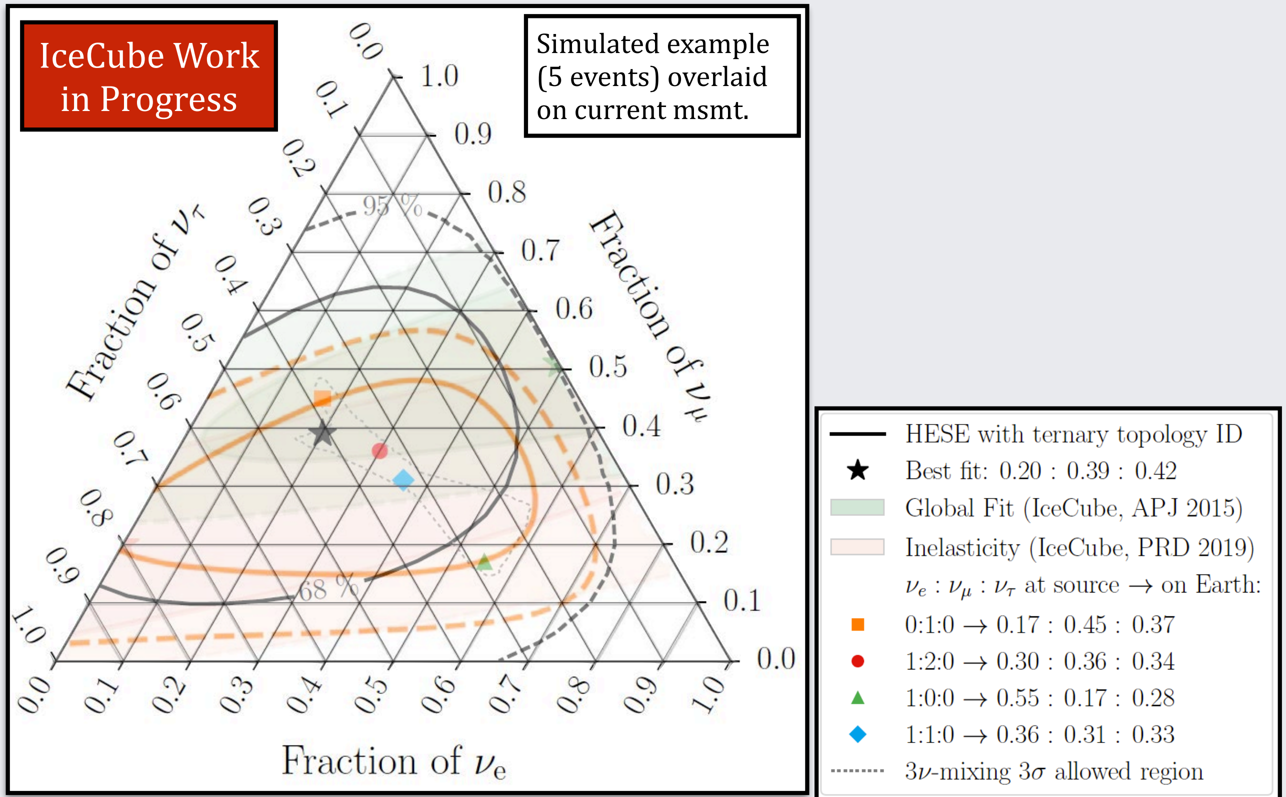

Overlaid plot lacks full systematic treatment

Conclusions

- IceCube is unique in its broad sensitivity to ν_τ and τ
  - ~6 orders of magnitude in E_{ν_τ} and E_τ
  - ~20 orders of magnitude in L_{ν_τ}
- IceCube makes both inclusive and exclusive measurements of ν_τ and τ
  - Inclusive: $\nu_\mu^{\text{atm}} \rightarrow \nu_\tau^{\text{atm}}$ appearance with world's largest sample (thousands of ν_τ and τ)
    - Fundamental ν oscillation measurement
    - Current measurement in agreement with standard ν osc. picture; future measurements will have compelling sensitivity to non-standard physics
  - Exclusive: $\nu_\tau^{\text{astro}} \rightarrow \tau \rightarrow$ double pulse, not with world's largest sample *(yet)*
    - Powerful probe of ultra-long baseline, ultra-high energy ν oscillations, and of astrophysical accelerator ν production scenarios
    - Very early days for ν_τ^{astro}...but maturing rapidly!


Thanks!