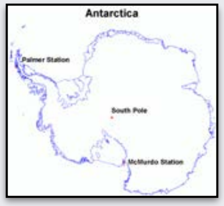
Astrophysical ν_τ with IceCube

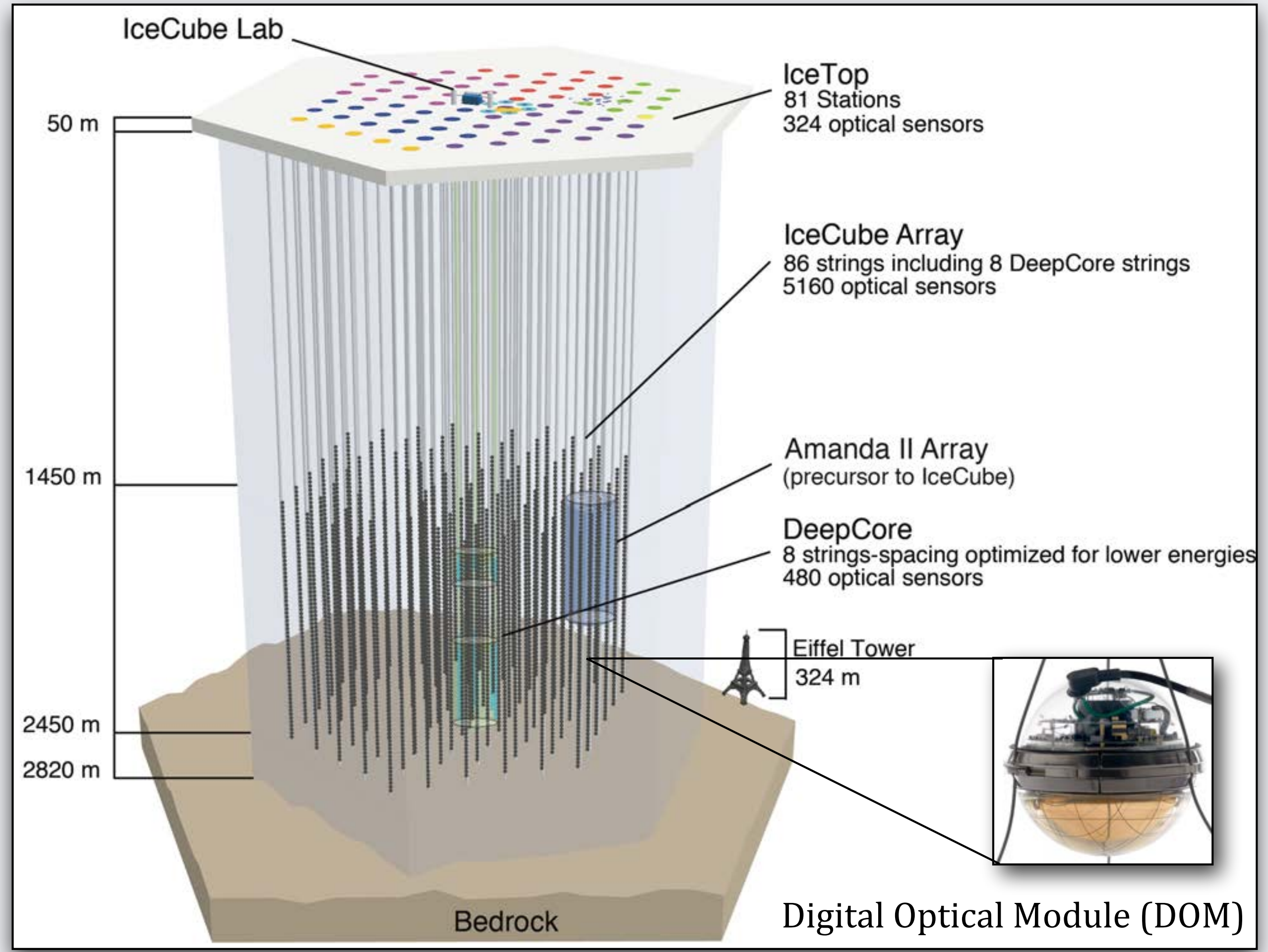
TeVPA 2021
Chengdu, China

Doug Cowen
Penn State

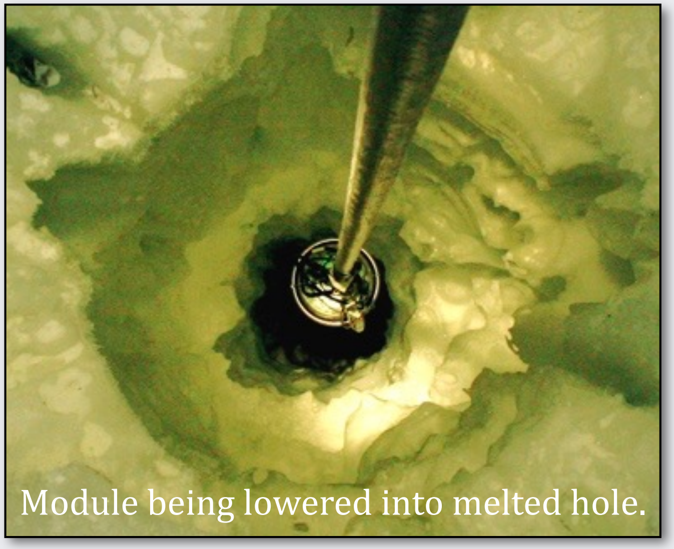


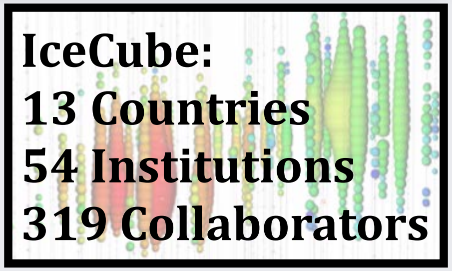
The IceCube+DeepCore Detector

- 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.



Neutrinos in IceCube: Sources

- Atmospheric tau neutrinos
  - cosmic rays (mainly protons) interact in the earth's atmosphere
  - creating ν_μ that oscillate $\rightarrow \nu_\tau$
  - IceCube threshold $E_\nu \sim 5$ GeV, $E_\nu^{\text{atm.}} < \sim 10$ TeV; $E_\nu \approx 10^{9-12}$ eV

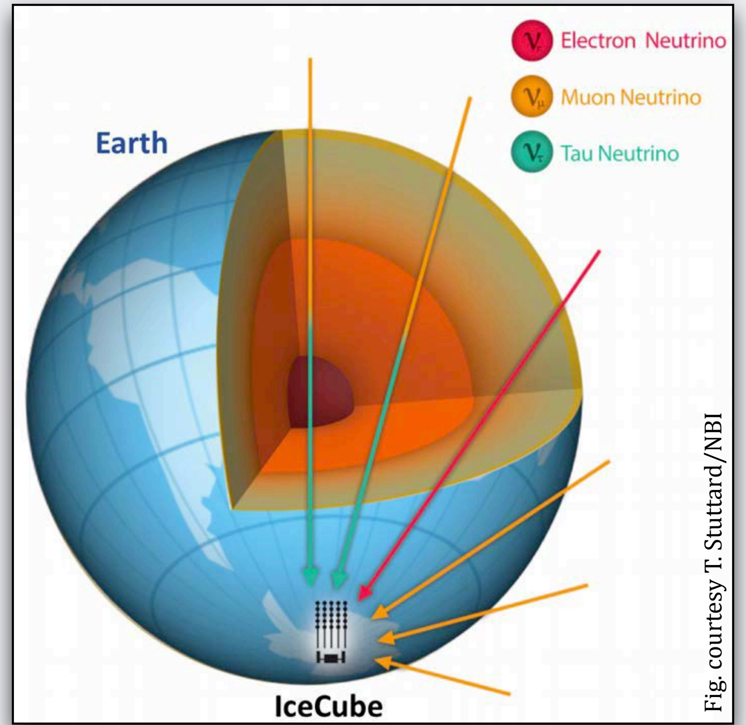


Fig. courtesy T. Stuttard/NBI

- Astrophysical high energy neutrinos
  - created in cosmic accelerators, e.g., in particle jets created by black holes
  - Evident at $E_\nu > \sim 10$ 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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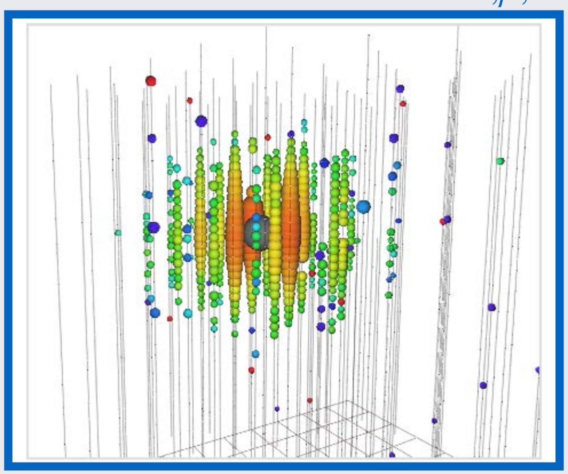
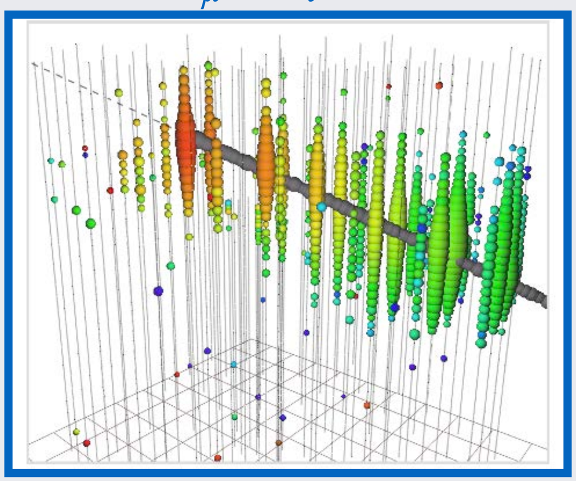
At higher energies, neutrino flavors can be distinguished:

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



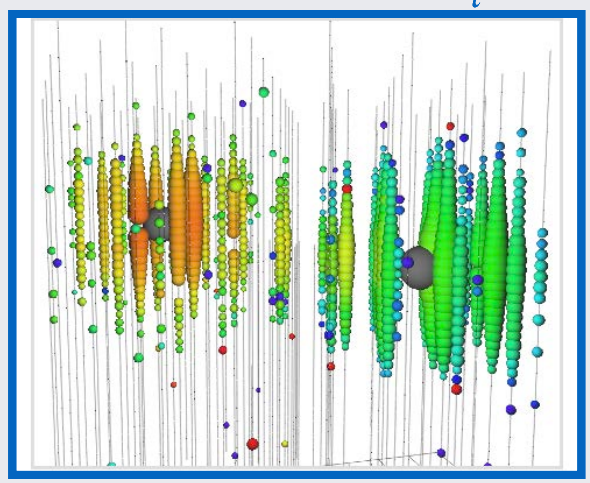
$\sigma_E \sim 11\,\%$

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

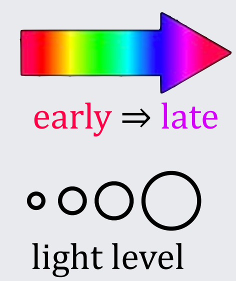


$\sigma_\phi \sim 2^\circ$

Double cascade: ν_τ^{CC}



$L_\tau \sim 50$ m/PeV



Astrophysical ν: $E_\nu > \sim 10$ TeV

- 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

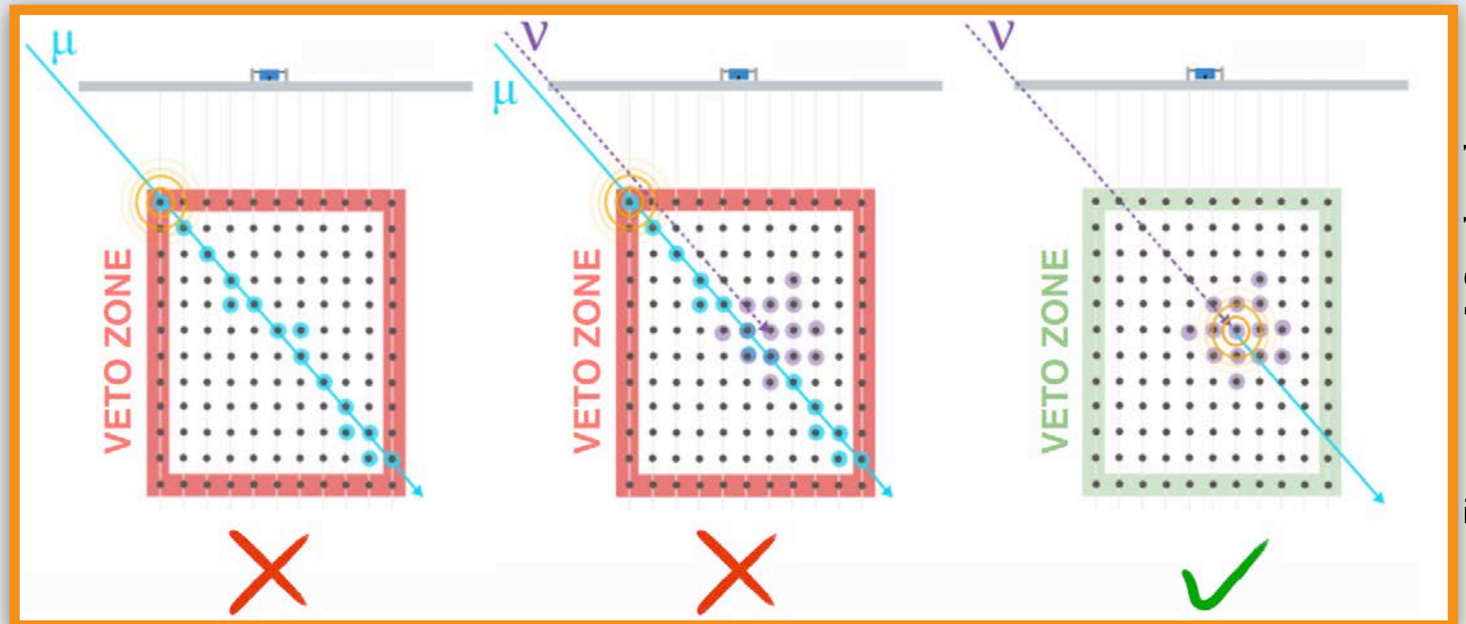


Fig. courtesy J. Stachurska

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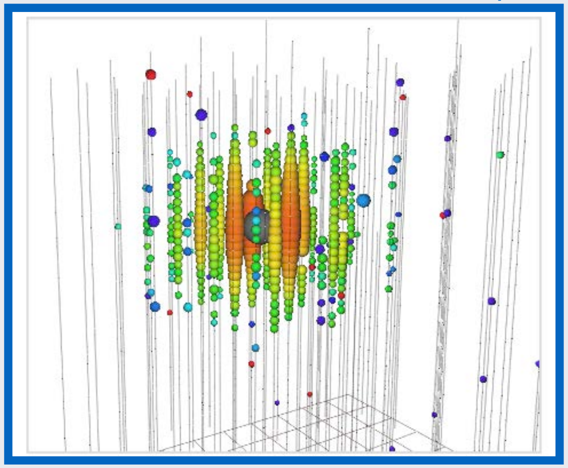
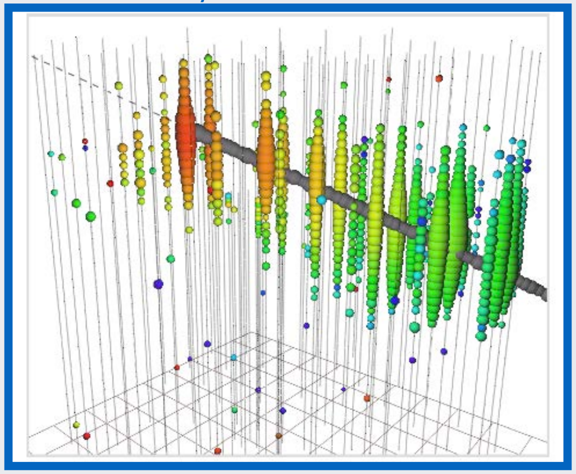
Single cascade: $\nu_e^{CC}, \nu_{e,\mu,\tau}^{NC}$



$\sigma_E \sim 11\ \%$

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



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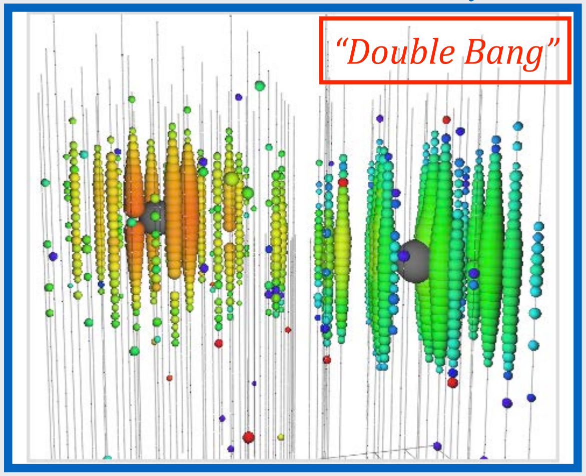
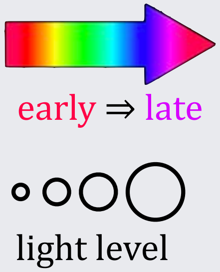
Double cascade: ν_τ^{CC}



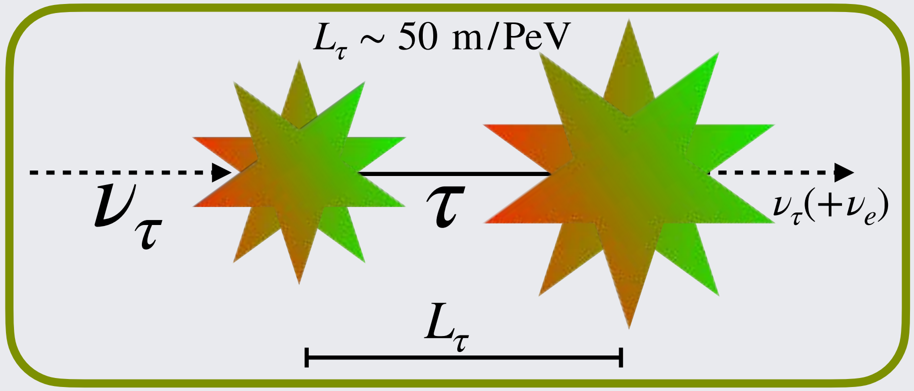
$L_\tau \sim 50$ m/PeV



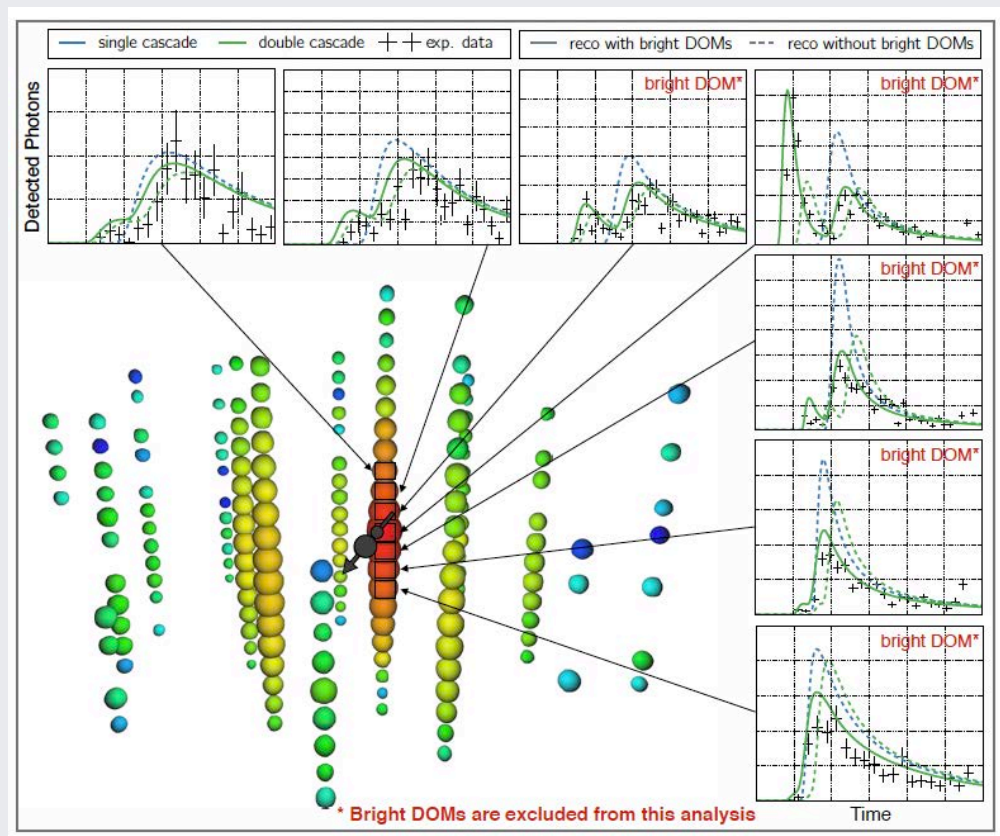
Astrophysical ν_τ

- Measurements to date:
  - Search for 1-2 clean "double pulse" waveforms and/or a "two-cascade" signature
  - $\sim 2\ \nu_\tau$ candidates found:
    - Assuming
      - 1:1:1 flavor ratio at earth
      - $\Phi(\nu) \propto E_\nu^{-2.87}$ (IceCube msmt.)

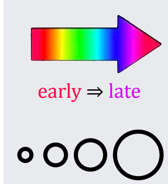
    expect 1.5 signal and 0.8 background in 7.5 yrs
    - Notes:
      - Estimate that 98% and 76% of events like the two seen are ν_τ–induced
      - Index of -2.87 softest measured by IceCube



Candidate event



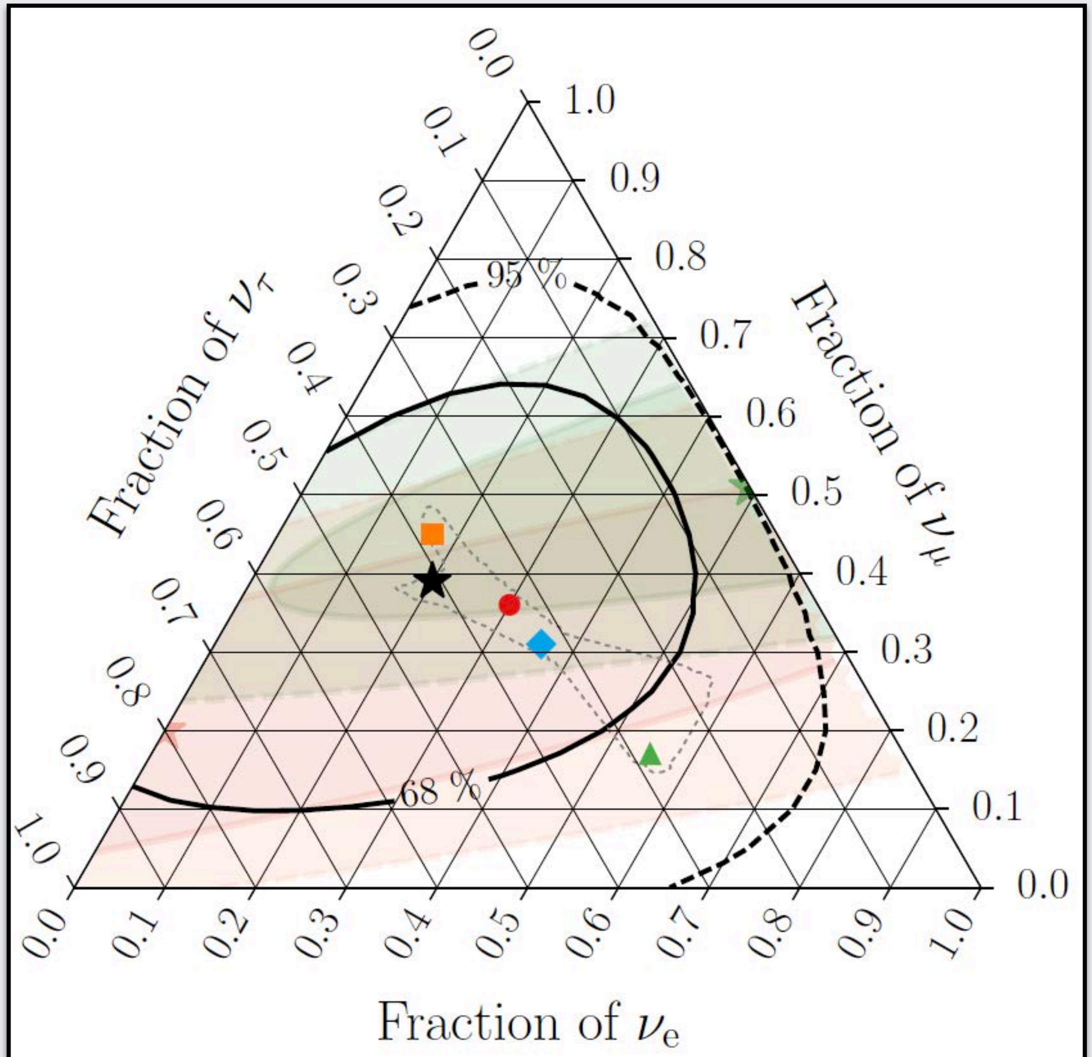
J. Stachurska Thesis (Humboldt U./Berlin; arXiv:2011.03561 [hep-ex]

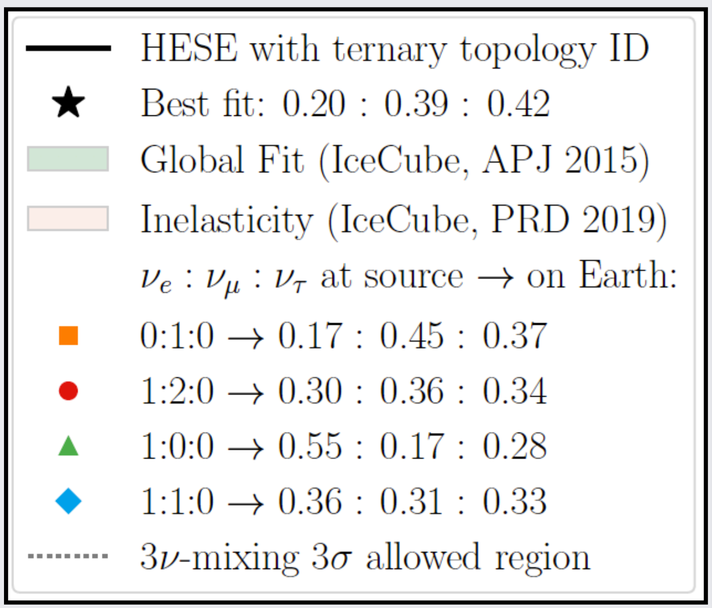


Astrophysical ν_τ

- 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"

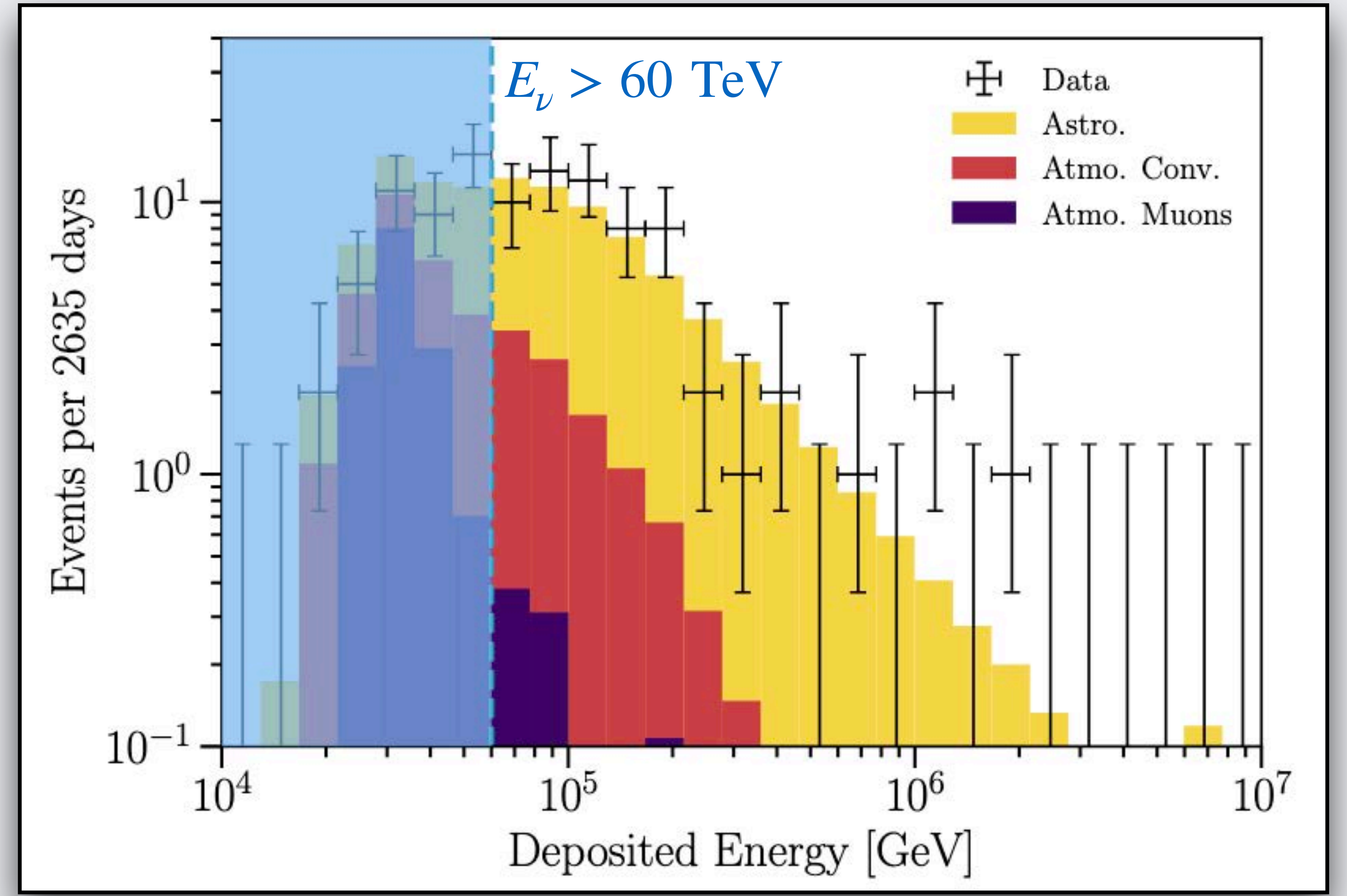




arXiv:2011.03561 [hep-ex]

Next Steps: Upcoming ν_τ^{astro} Measurement

- Waiting for a clean "double bang" would require much patience: $E_{\nu_\tau} > \sim$ PeV are rare.



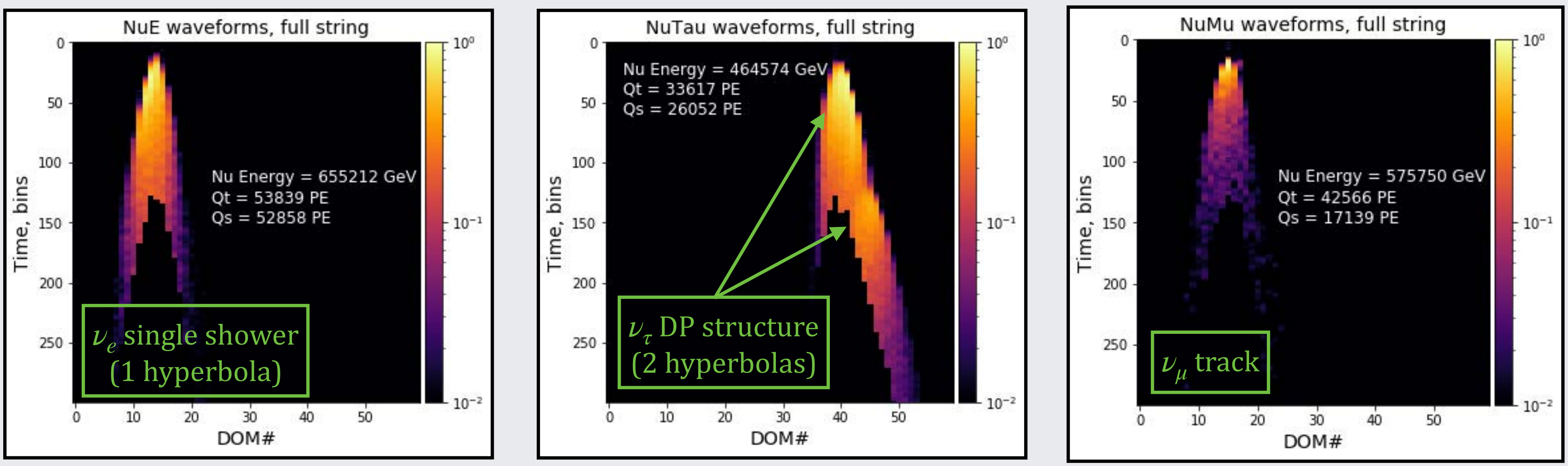
R. Abbasi et al. (IceCube Collaboration)
Phys. Rev. D 104, 022002

Upcoming 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)



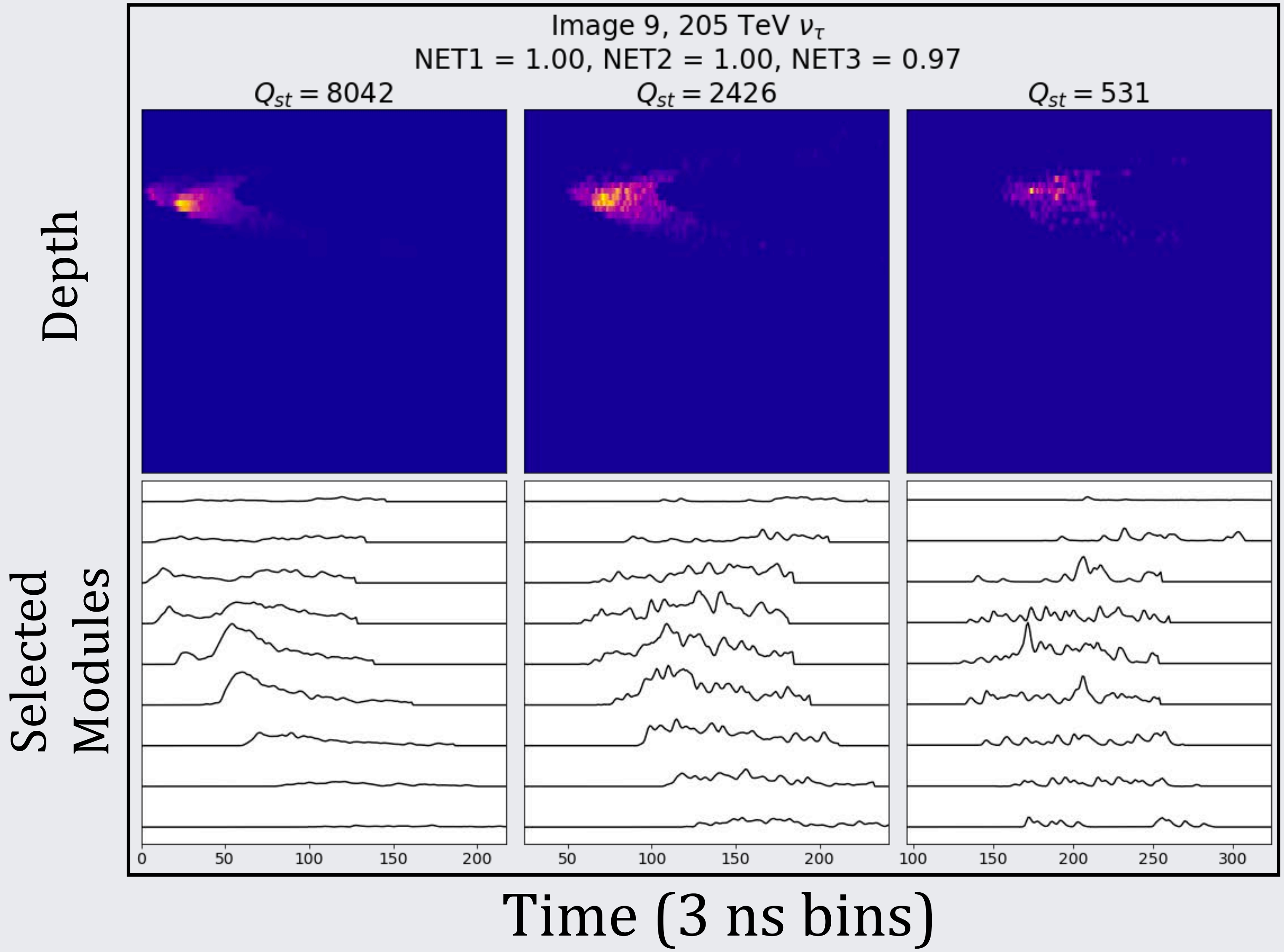
Module number ($\propto$ Depth)

Qt: total charge
Qs: string charge

Upcoming Astrophysical ν_τ Measurement

Simulated ~200 TeV ν_τ.

Data from most illuminated string and its two nearest neighbors:



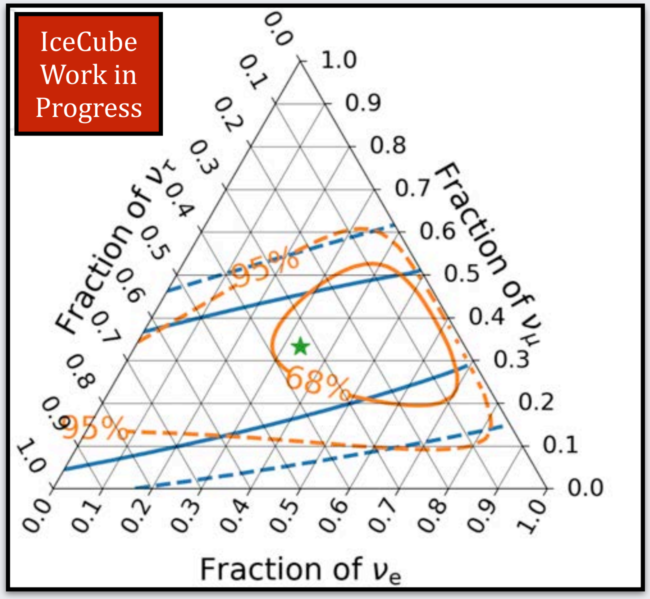
(Note: axes swapped from previous slide's figures.)

Upcoming Astrophysical ν_τ Measurement

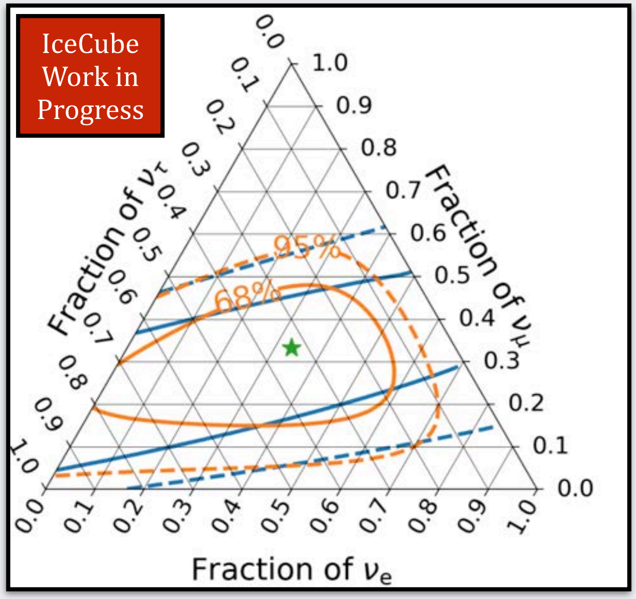
- Preliminarily predict $\sim 4.8 \pm 0.1$ ν_τ^{CC} on background of $\sim 0.4 \pm 0.06$ events (HESE flux; stat. errors only)
  - $\sim$10 years livetime
  - background dominated by $\nu_{e,\mu}^{\text{astro}}$ and prompt ν^{atm}
  - systematic effects appear to have minimal impact
- With $\sim$5 events, can rule out no–ν_τ^{astro} at high confidence
  - $\sim$50% chance to reach 5σ
- 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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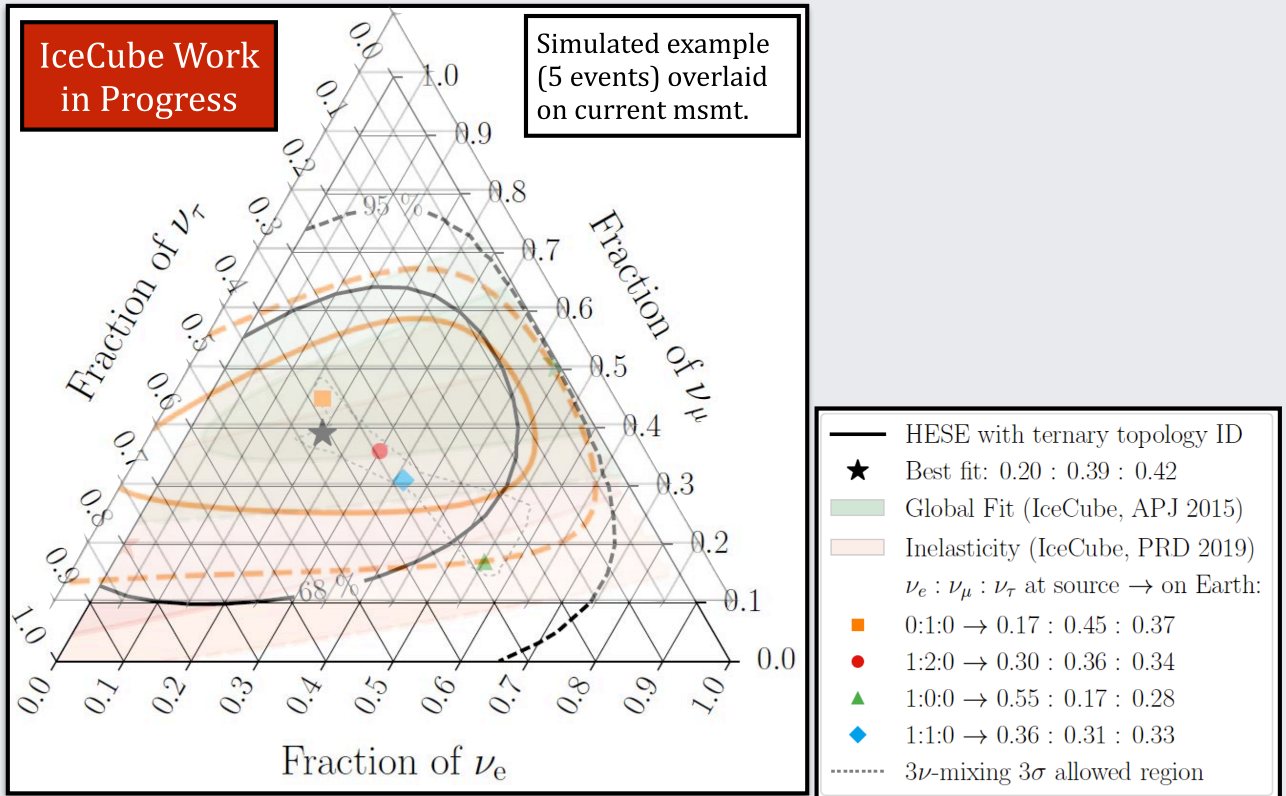


Overlaid plot lacks full systematic treatment

Conclusions

- IceCube is unique in its broad sensitivity to ν_τ (and τ)
  - ~6 orders of magnitude in E_{ν_τ} (and E_τ): 10 GeV $\leftrightarrow$ 10 PeV
  - ~20 orders of magnitude in L_{ν_τ} : $\sim R_{\mathrm{earth}} \leftrightarrow \ \sim 4 \times 10^9$ ly
- IceCube makes both exclusive $\nu_\tau^{\mathrm{astro}}$ and inclusive ν_τ^{atm} measurements
  - Exclusive: $\nu_\tau^{\mathrm{astro}} \rightarrow \tau \rightarrow$ double pulse
    - Likely to soon have world's largest (exclusive) ν_τ appearance sample
    - $\nu_\tau^{\mathrm{astro}}$ are powerful probes of
      - ultra-long baseline, ultra-high energy ν oscillations
      - astrophysical accelerator ν production scenarios
      - new physics
    - Very early days for $\nu_\tau^{\mathrm{astro}}$...but maturing rapidly!

Thanks!

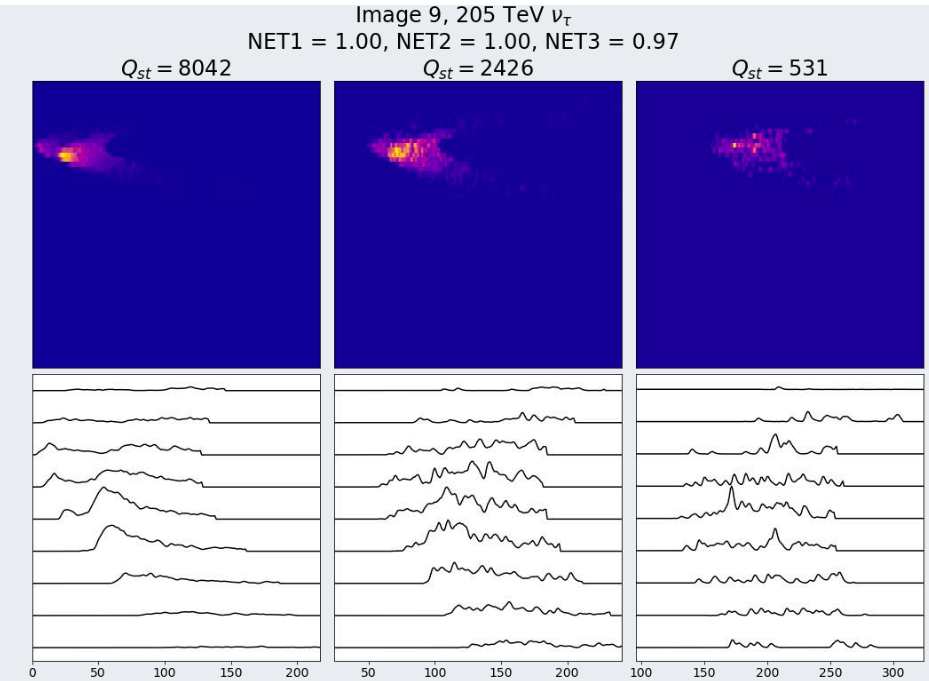
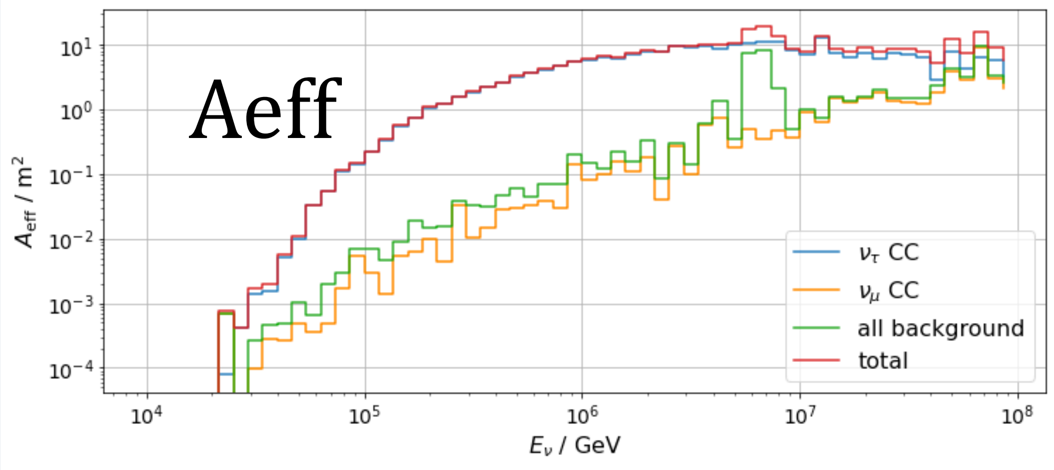
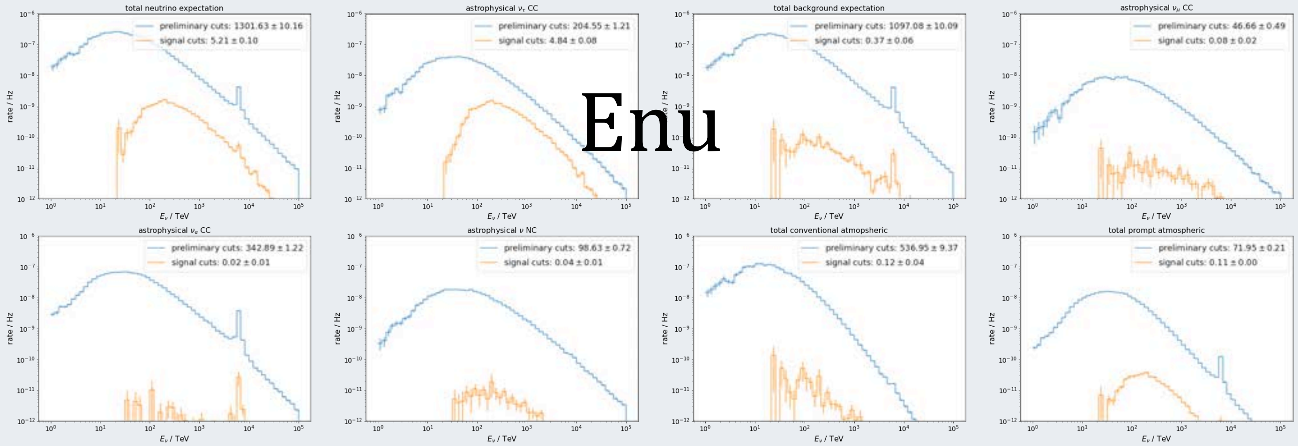


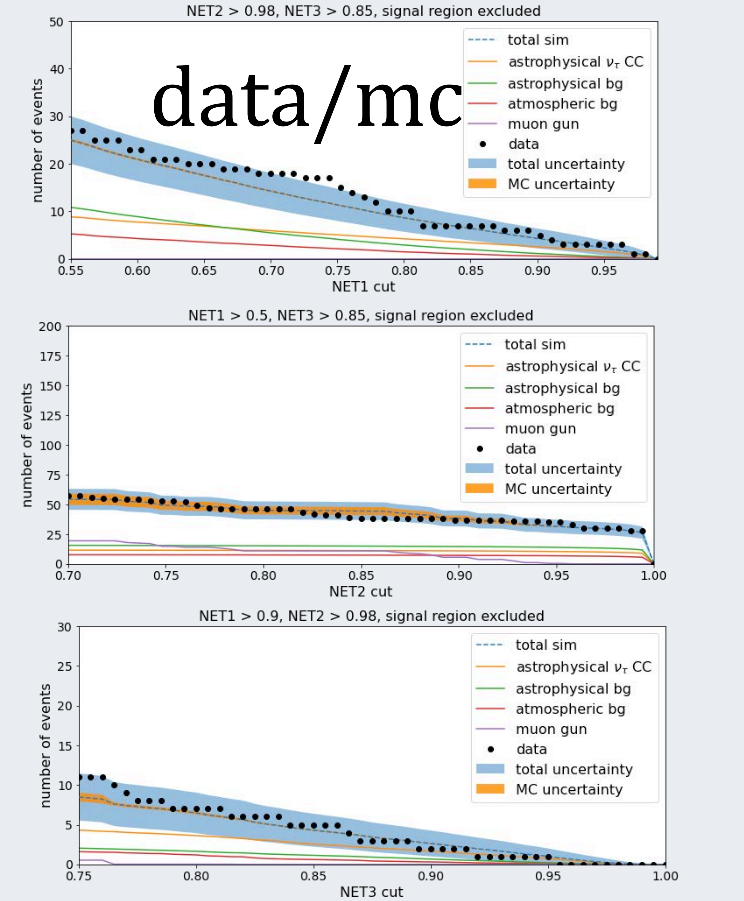
Image 9, 205 TeV ν_τ
NET1 = 1.00, NET2 = 1.00, NET3 = 0.97
$Q_{st} = 8042$
$Q_{st} = 2426$
$Q_{st} = 531$



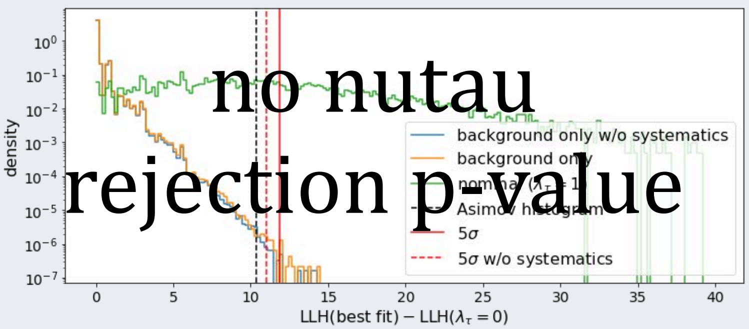
Aeff
A_{eff} / m^2
E_ν / GeV
ν_τ CC
ν_μ CC
all background
total



Enu
total neutrino expectation
astrophysical ν_τ CC
total background expectation
astrophysical ν_μ CC
astrophysical ν_e CC
astrophysical ν NC
total conventional atmospheric
total prompt atmospheric
preliminary cuts
signal cuts
rate / Hz
E_ν / TeV



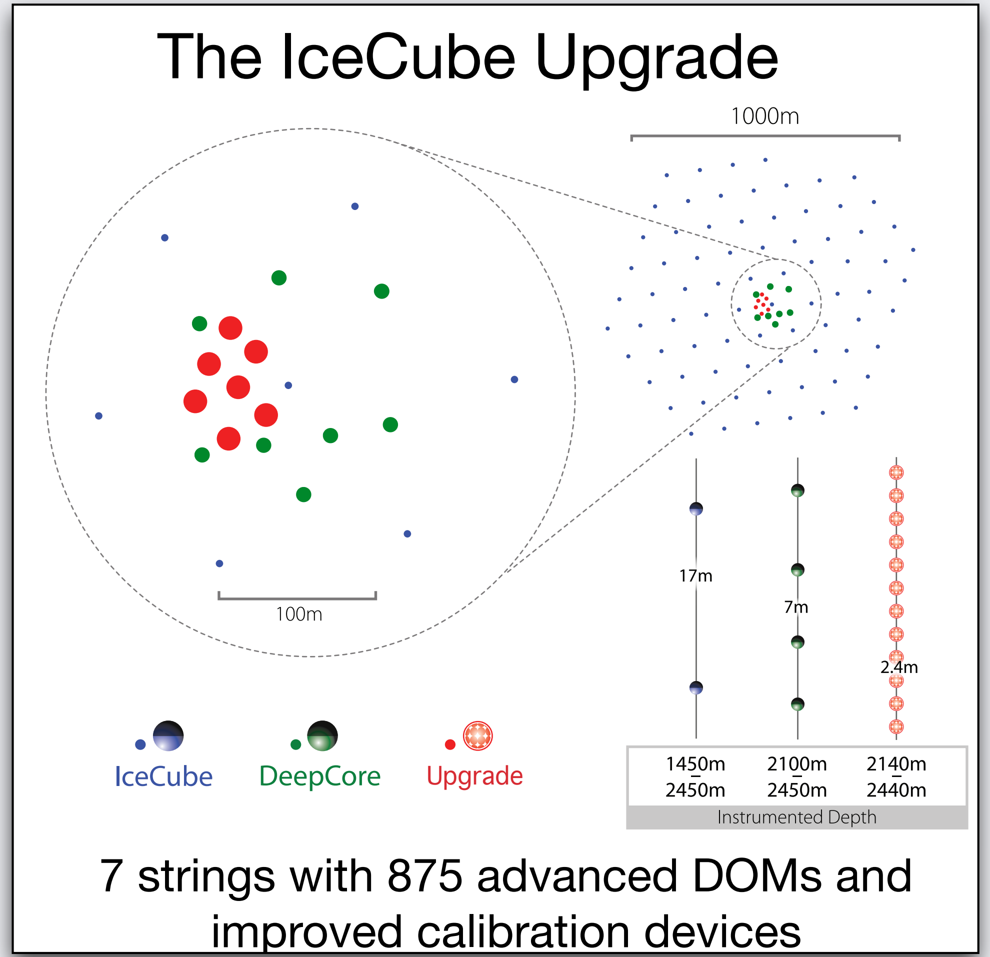
data/mc
NET2 > 0.98, NET3 > 0.85, signal region excluded
NET1 cut
NET1 > 0.5, NET3 > 0.85, signal region excluded
NET2 cut
NET1 > 0.9, NET2 > 0.98, signal region excluded
NET3 cut
number of events
total sim
astrophysical ν_τ CC
astrophysical bg
atmospheric bg
muon gun
data
total uncertainty
MC uncertainty



no nutau rejection p-value
density
LLH(best fit) − LLH($\lambda_\tau = 0$)
background only w/o systematics
background only
5σ
5σ w/o systematics

IceCube Prospects

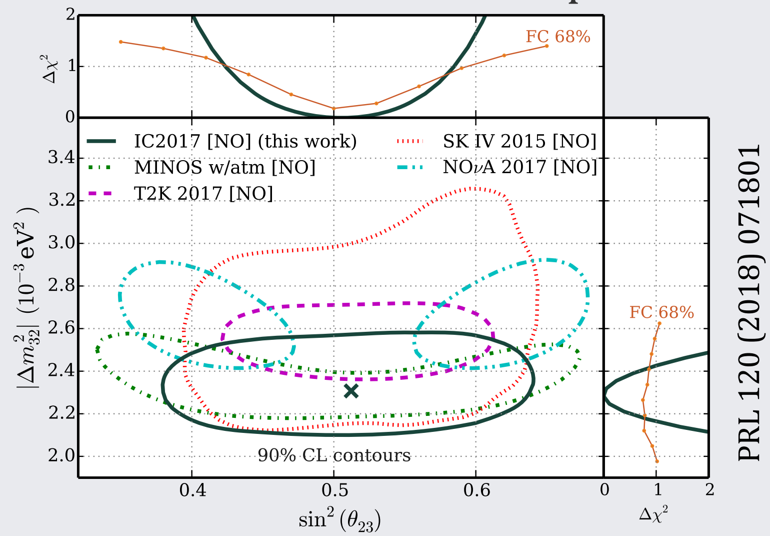
- IceCube Upgrade
  - Will improve both low and high energy neutrino measurements
  - Important step towards the "Gen-2" experiment that will improve IceCube's capabilities by ~10x



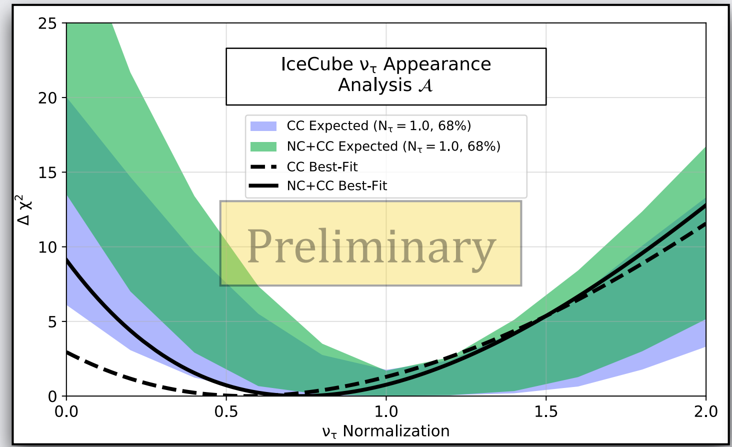
IceCube: Neutrino Particle Physics

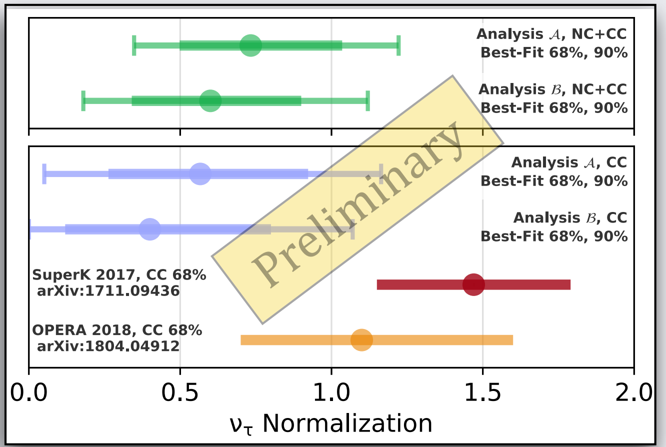
- Only detector in the world that can perform atmospheric ν oscillation studies at high energies
- Megaton-scale detector confers enormous statistical power

ν_μ “disappearance” results competitive with dedicated accelerator-based ν experiments



ν_τ “appearance” results currently competitive and soon will be world-leading; tests unitarity





8-Year DeepCore ν_μ Disappearance