ν_τ Appearance
(And ν_μ Disappearance)
with IceCube

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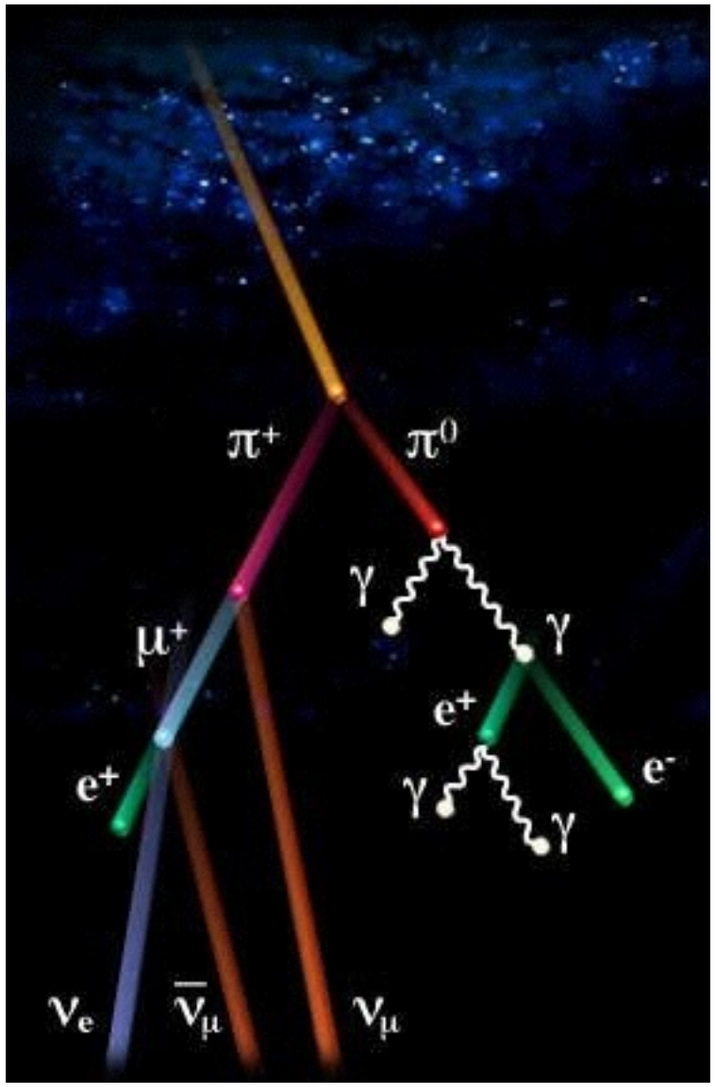
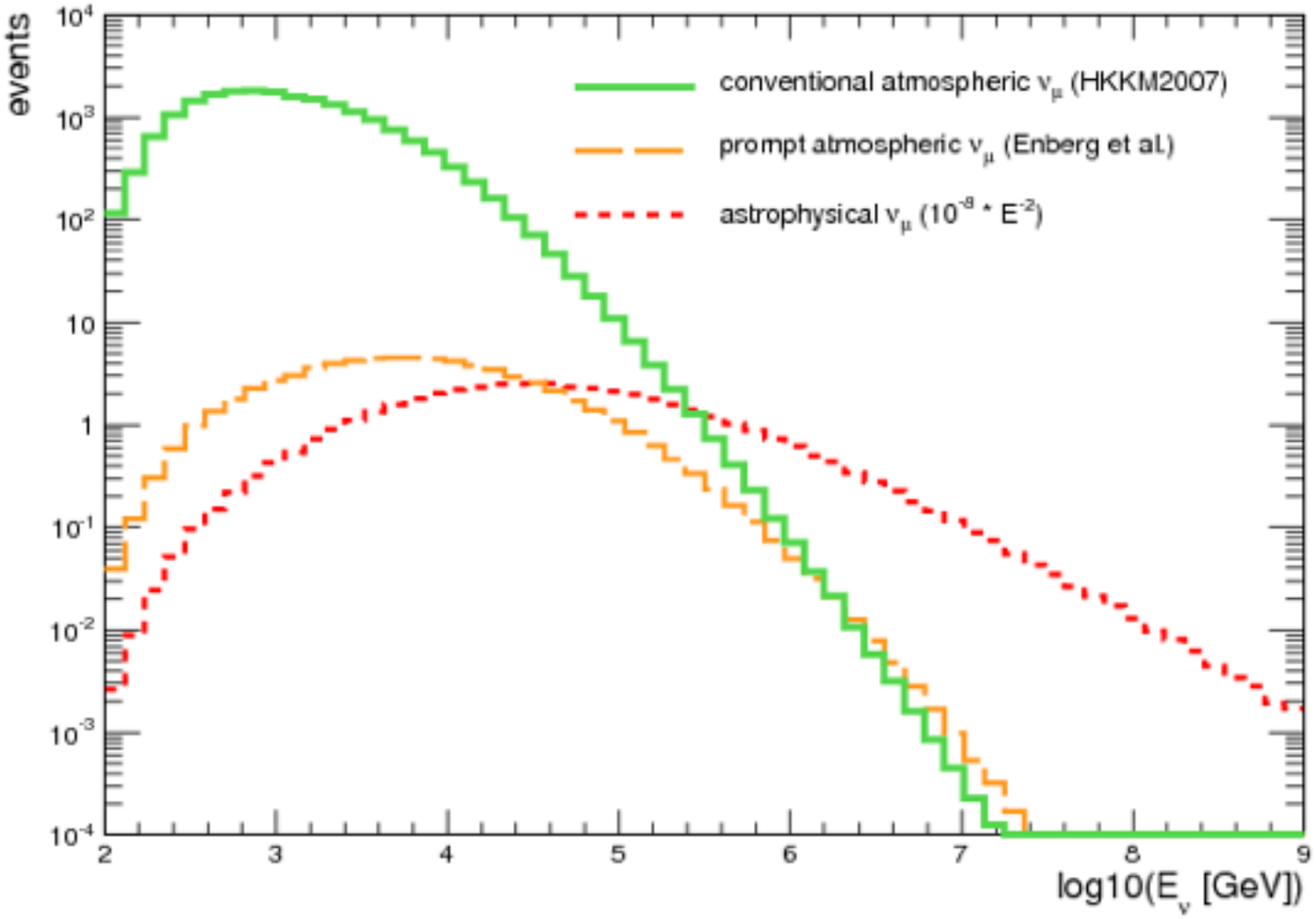
Neutrino Mixing

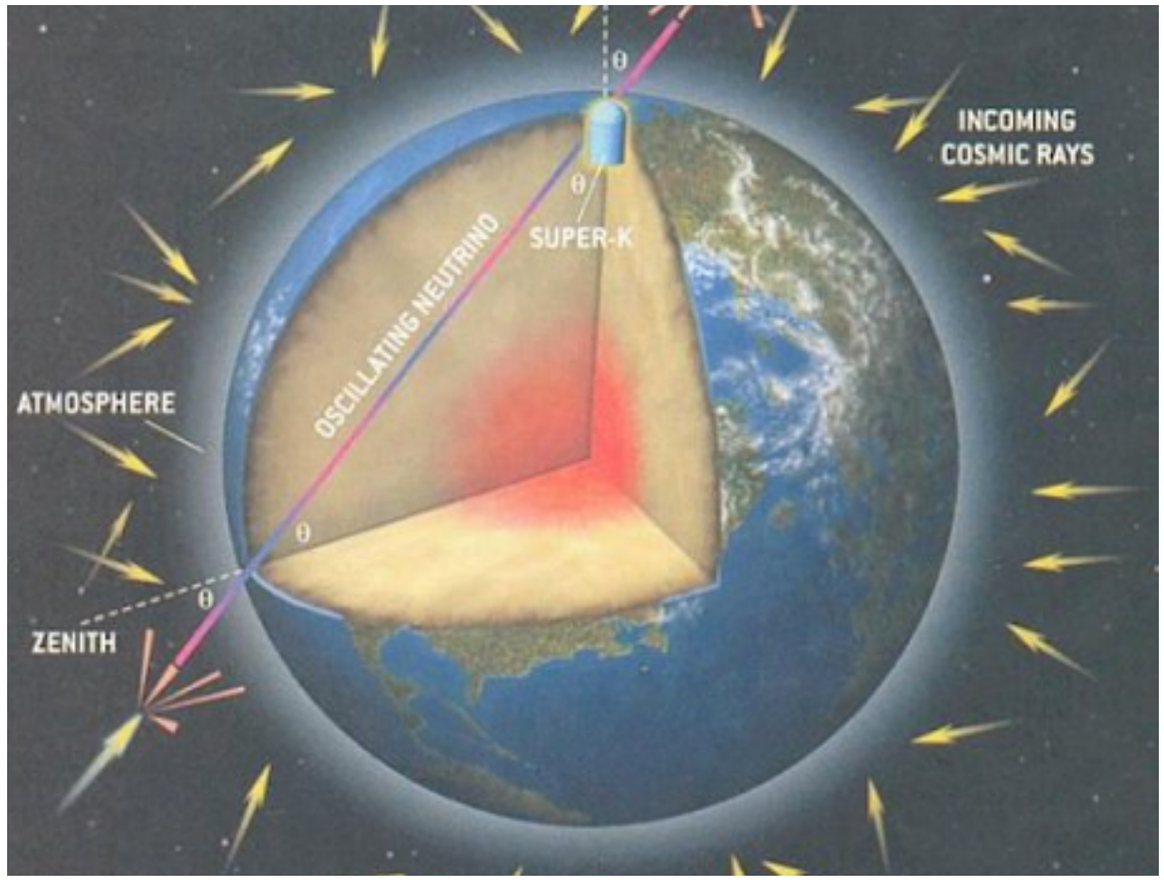
- Want to find and measure ν_τ
- Atmospheric neutrinos are mostly ν_μ
- PMNS Matrix provides mixing between flavor eigenstates
- Can oscillate to ν_τ for right combination of L/E



$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} . \quad P_{\nu_\mu \to \nu_\tau} = |\langle \nu_\tau | \nu_\mu(t) \rangle|^2 = \left| \sum_i U^*_{\mu i} U_{\tau i} e^{-i m_i^2 L/2E} \right|^2$$

L/E

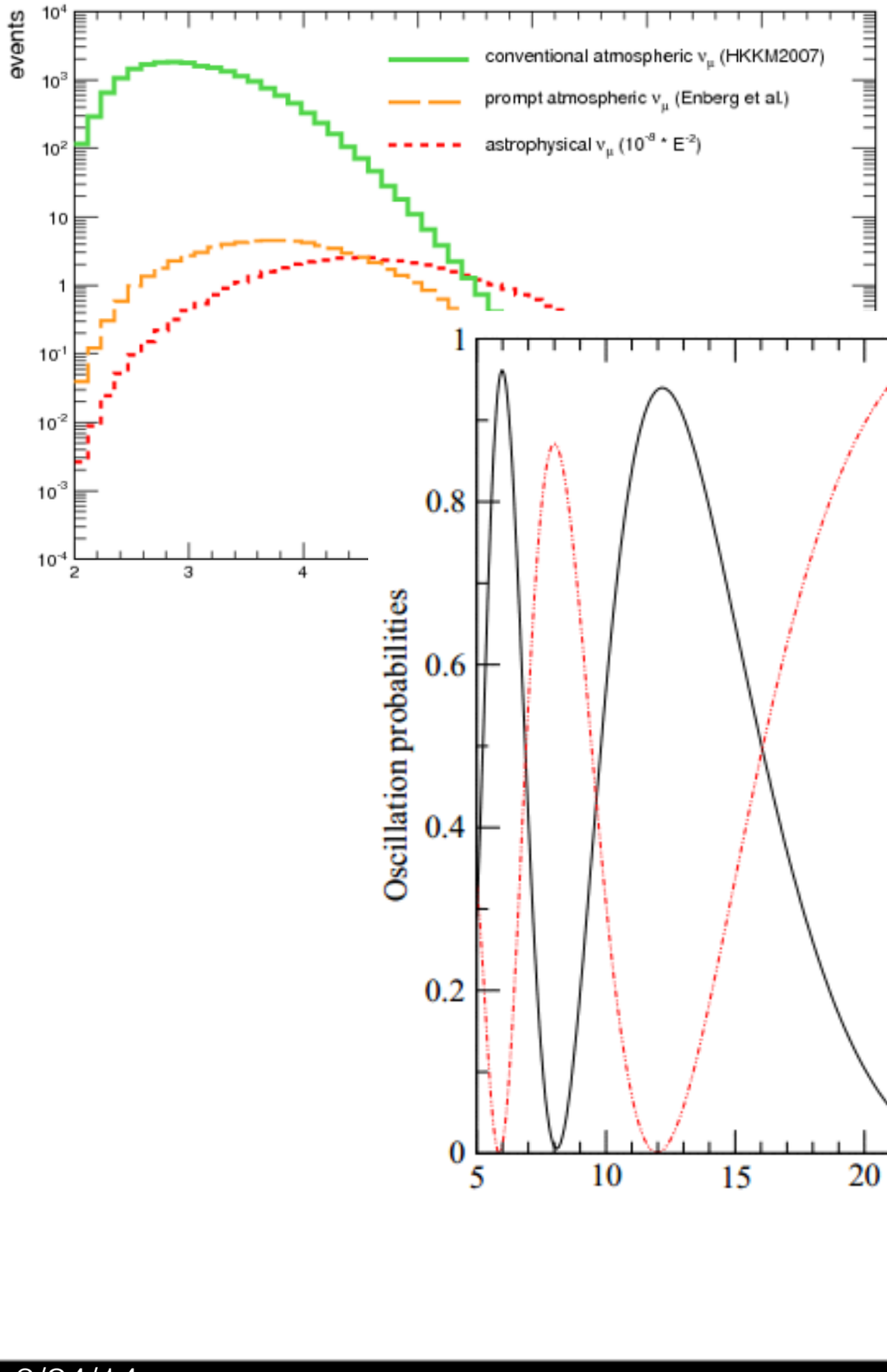


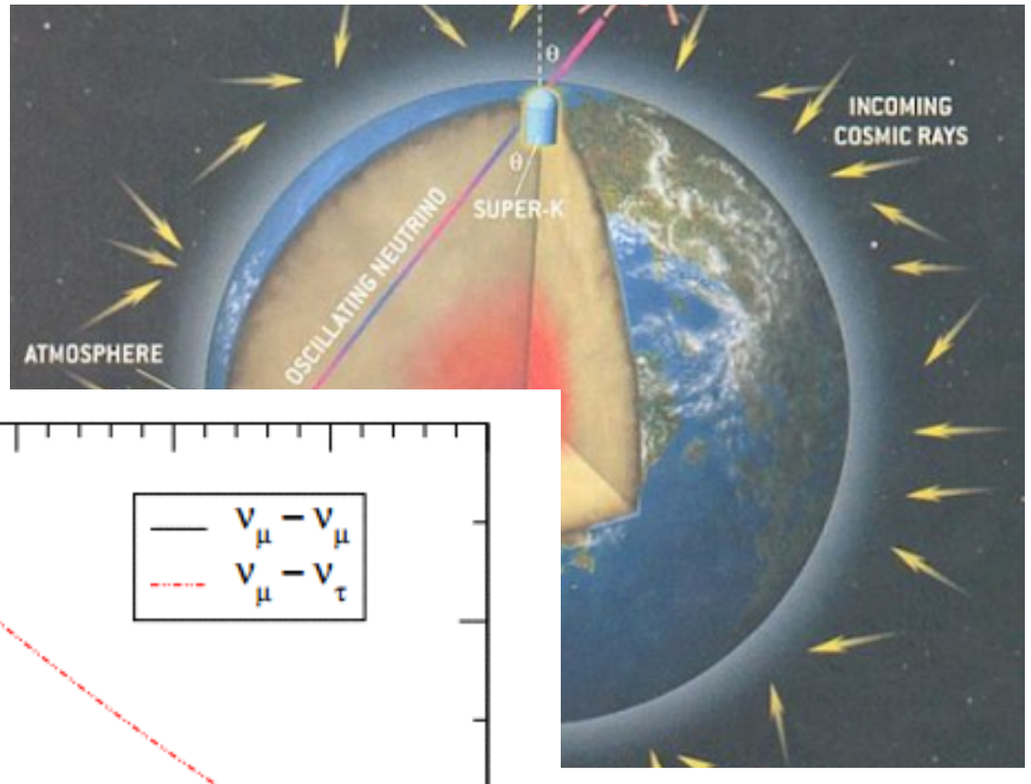


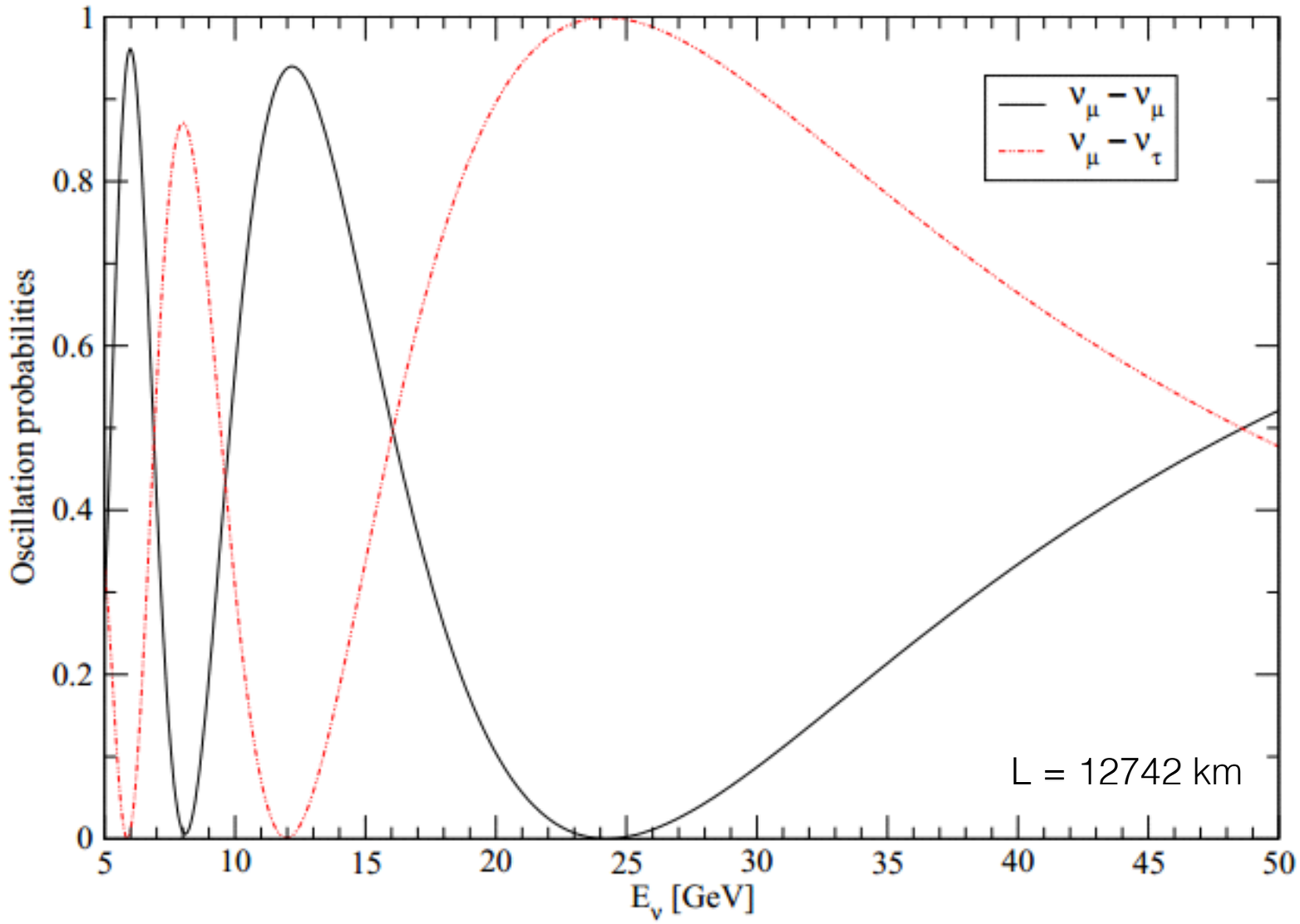
Lots of energies, baselines available for atmospheric neutrinos!

What does the oscillation probability look like?

L/E

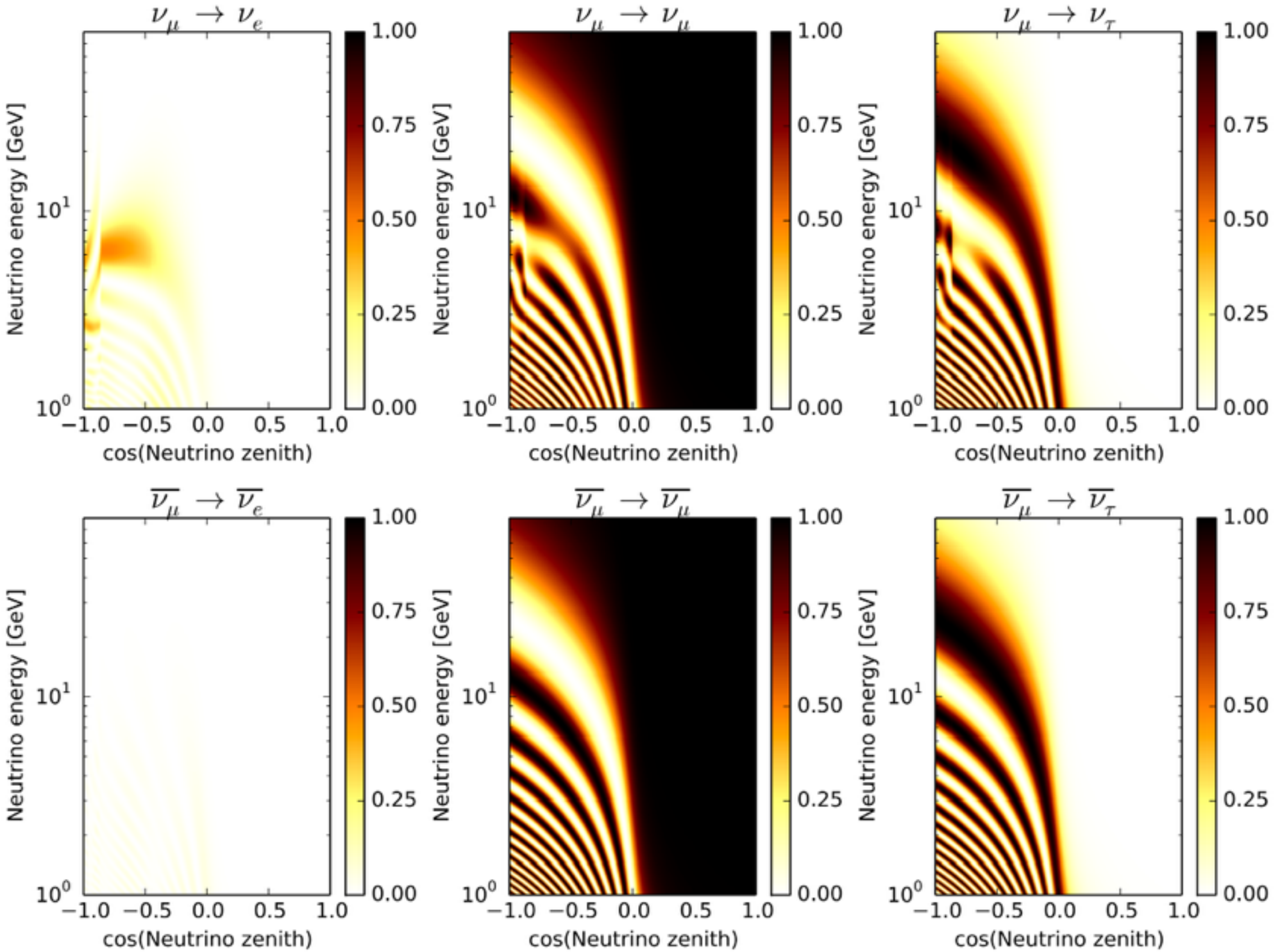




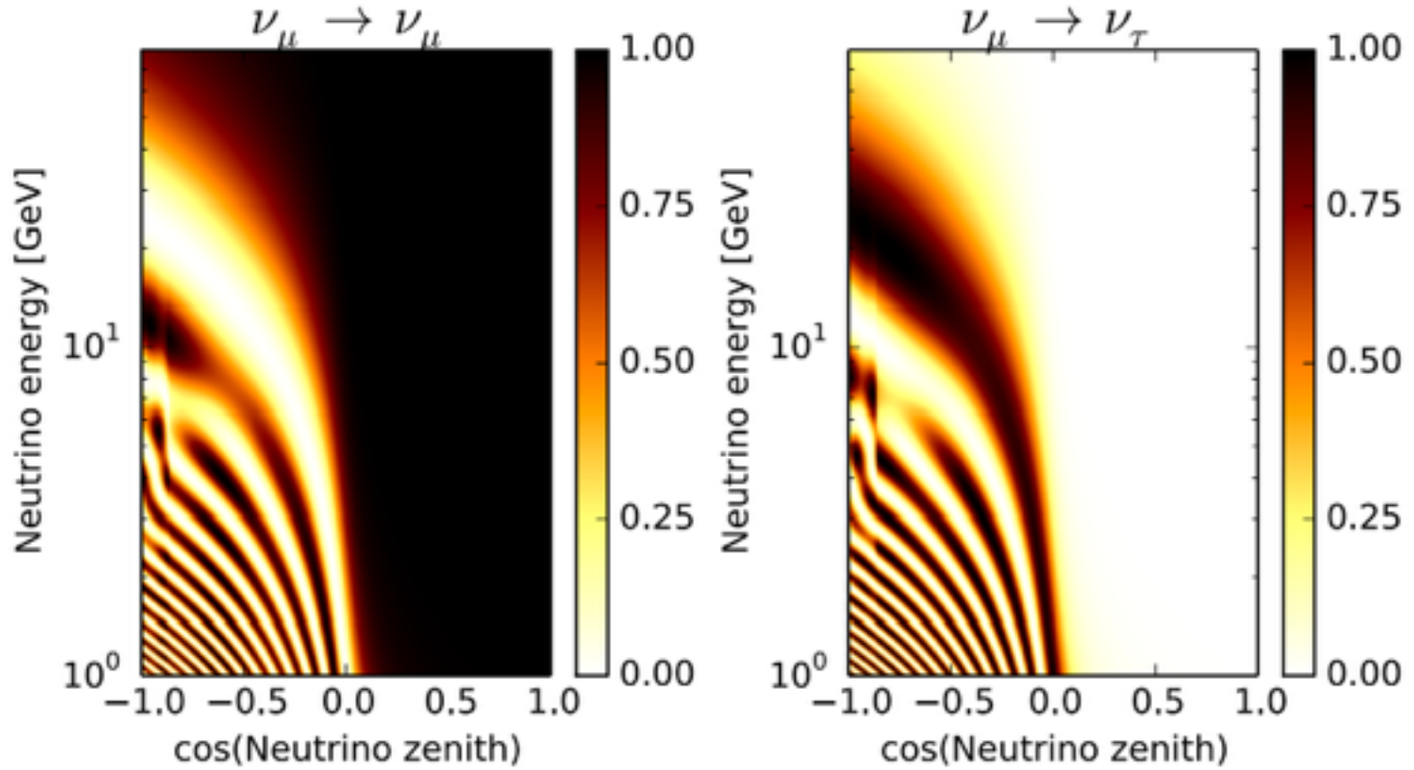


Atmospheric neutrino oscillations and tau neutrinos in ice
Arxiv:1004.3519

ν_μ Oscillations



ν_μ Oscillations

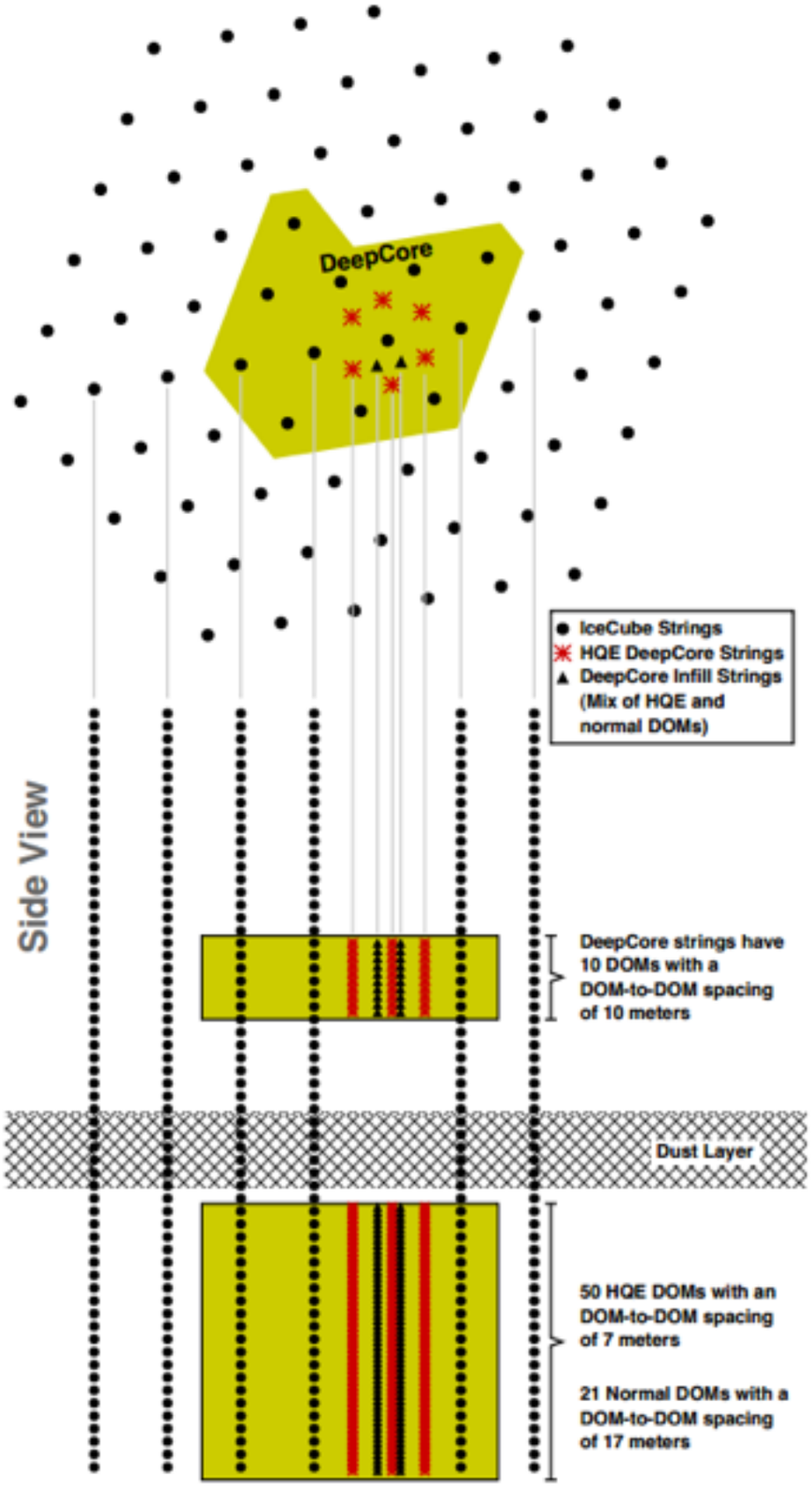


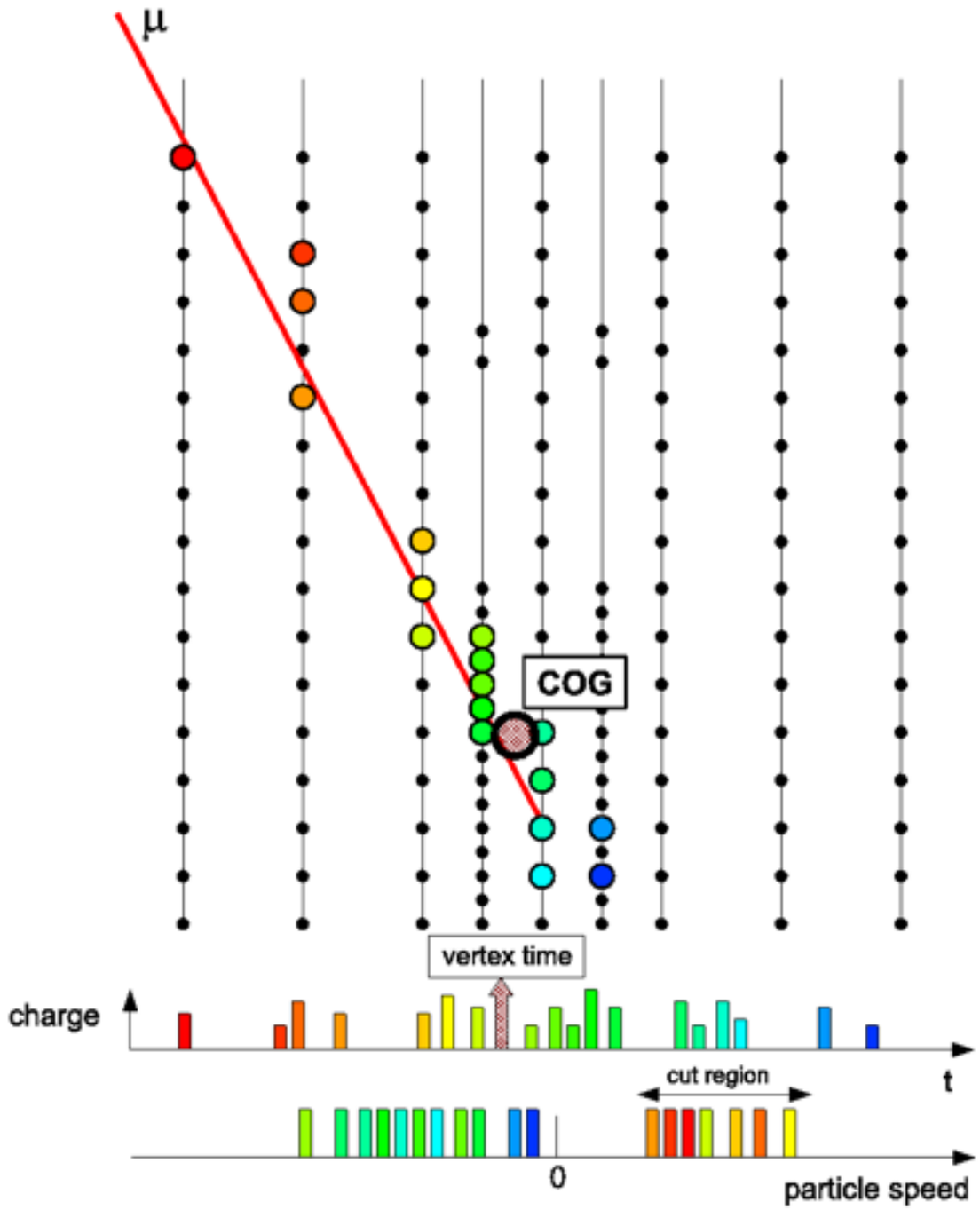
Looking for tracks:
ν_μ Disappearance

Looking for showers:
ν_T Appearance

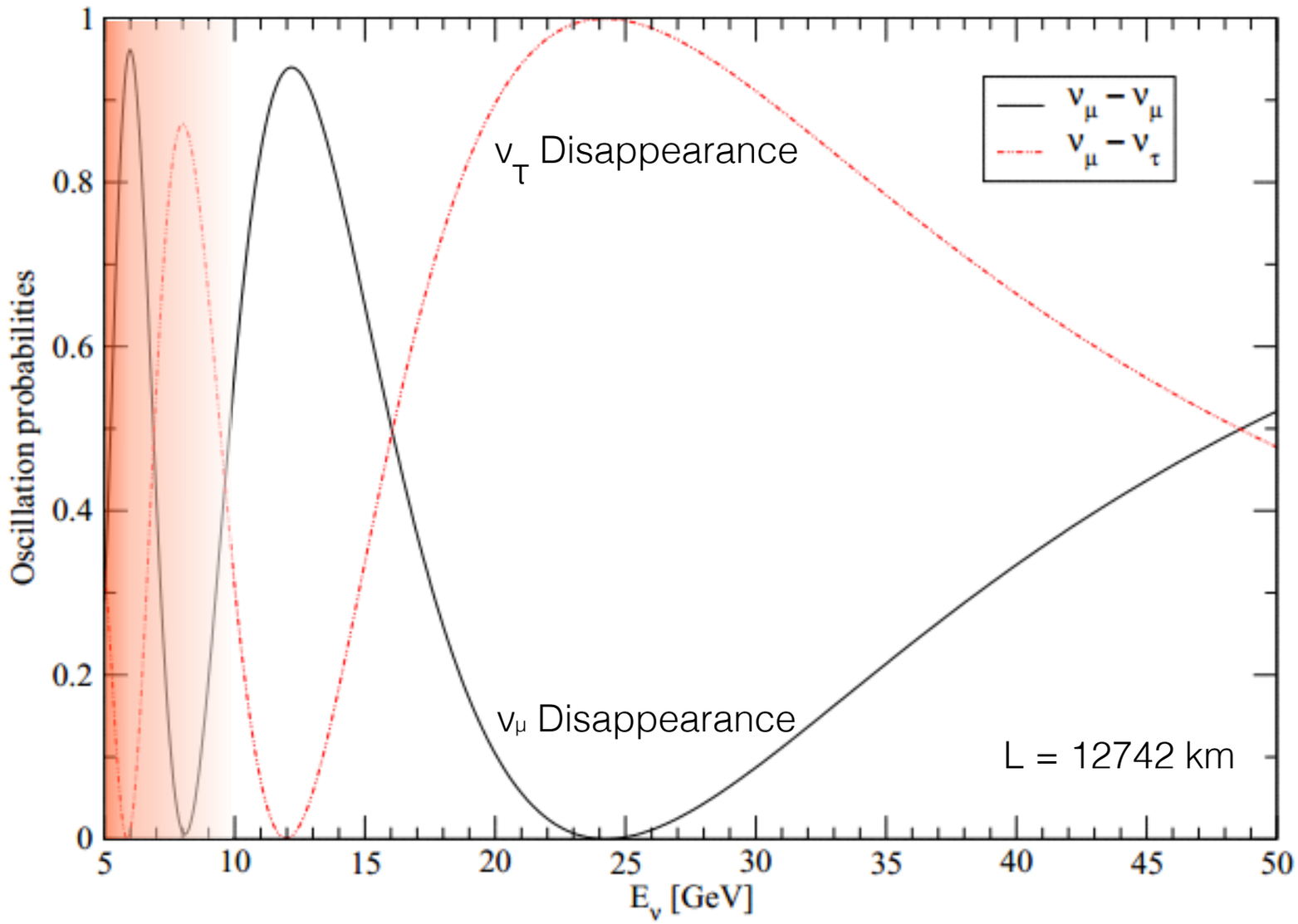
Appearance and Disappearance in IceCube

DeepCore


DeepCore
IceCube Strings
HQE DeepCore Strings
DeepCore Infill Strings
(Mix of HQE and
normal DOMs)
Side View
DeepCore strings have
10 DOMs with a
DOM-to-DOM spacing
of 10 meters
Dust Layer
50 HQE DOMs with an
DOM-to-DOM spacing
of 7 meters
21 Normal DOMs with a
DOM-to-DOM spacing
of 17 meters


μ
COG
vertex time
charge
t
cut region
0
particle speed

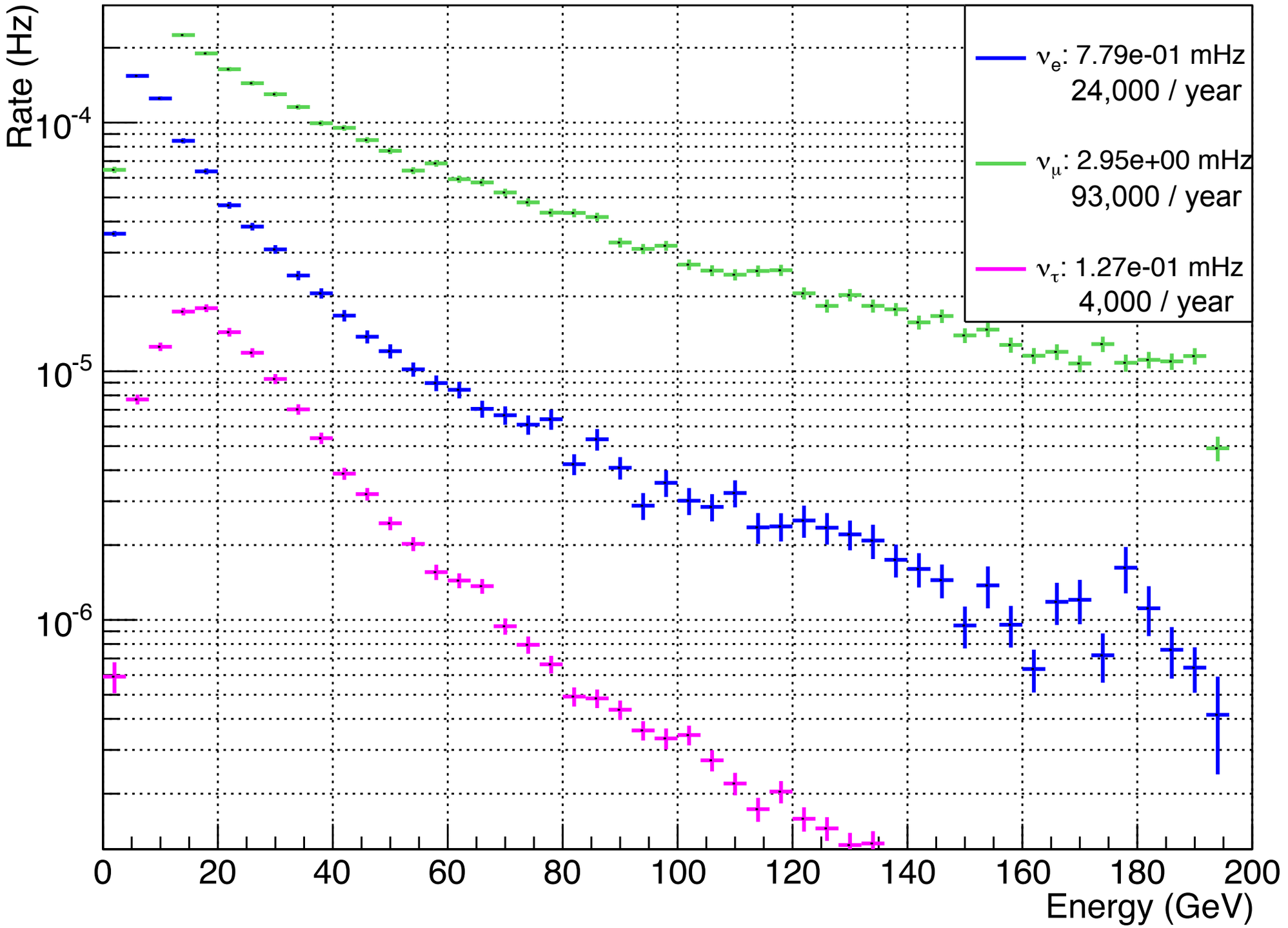
Oscillations in IceCube



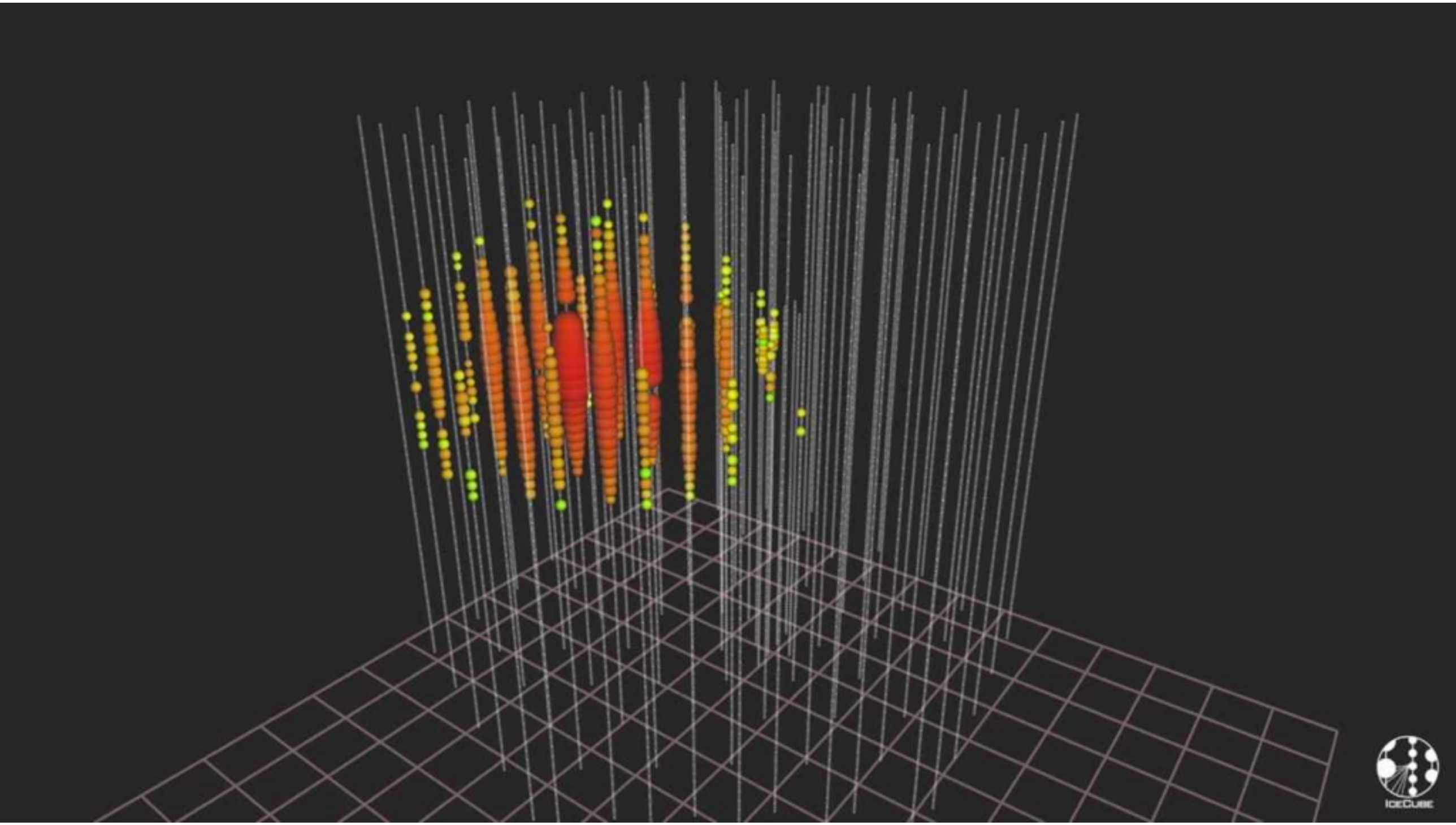
IceCube/DeepCore's low energy threshold is ~10 GeV

ν_e, ν_μ, ν_τ look very similar near the threshold…

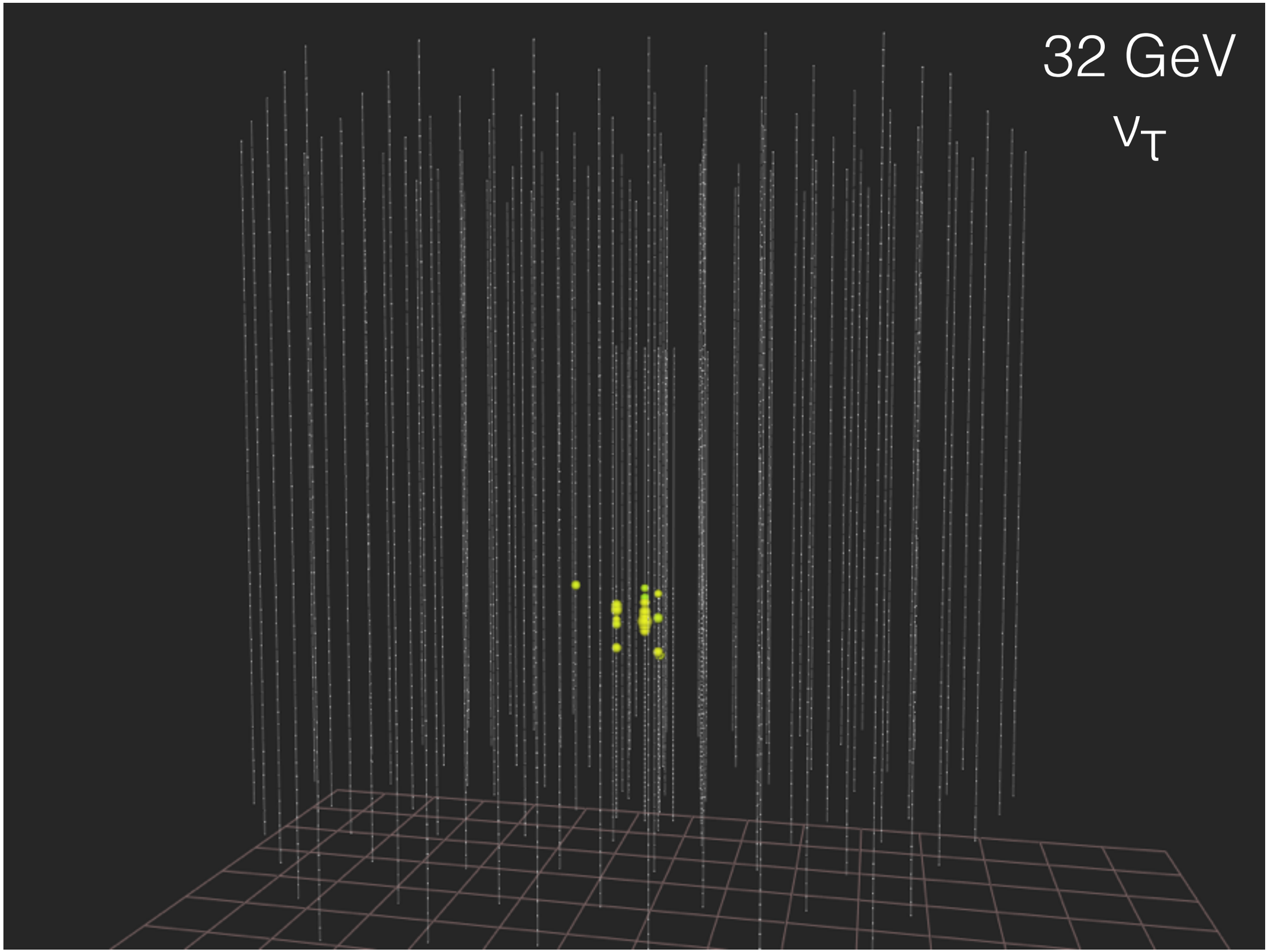
IceCube Energy Spectra



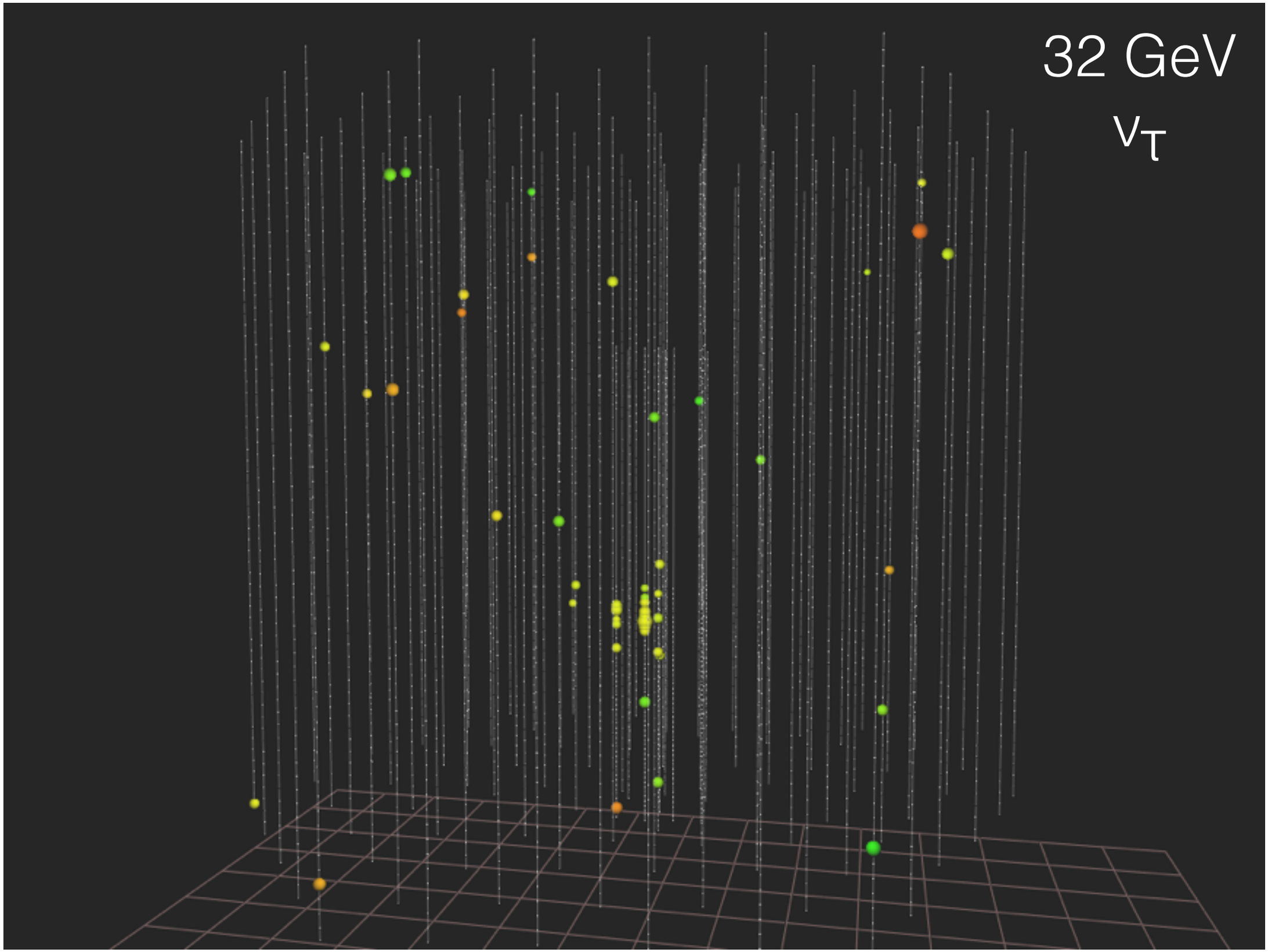
IceCube Events



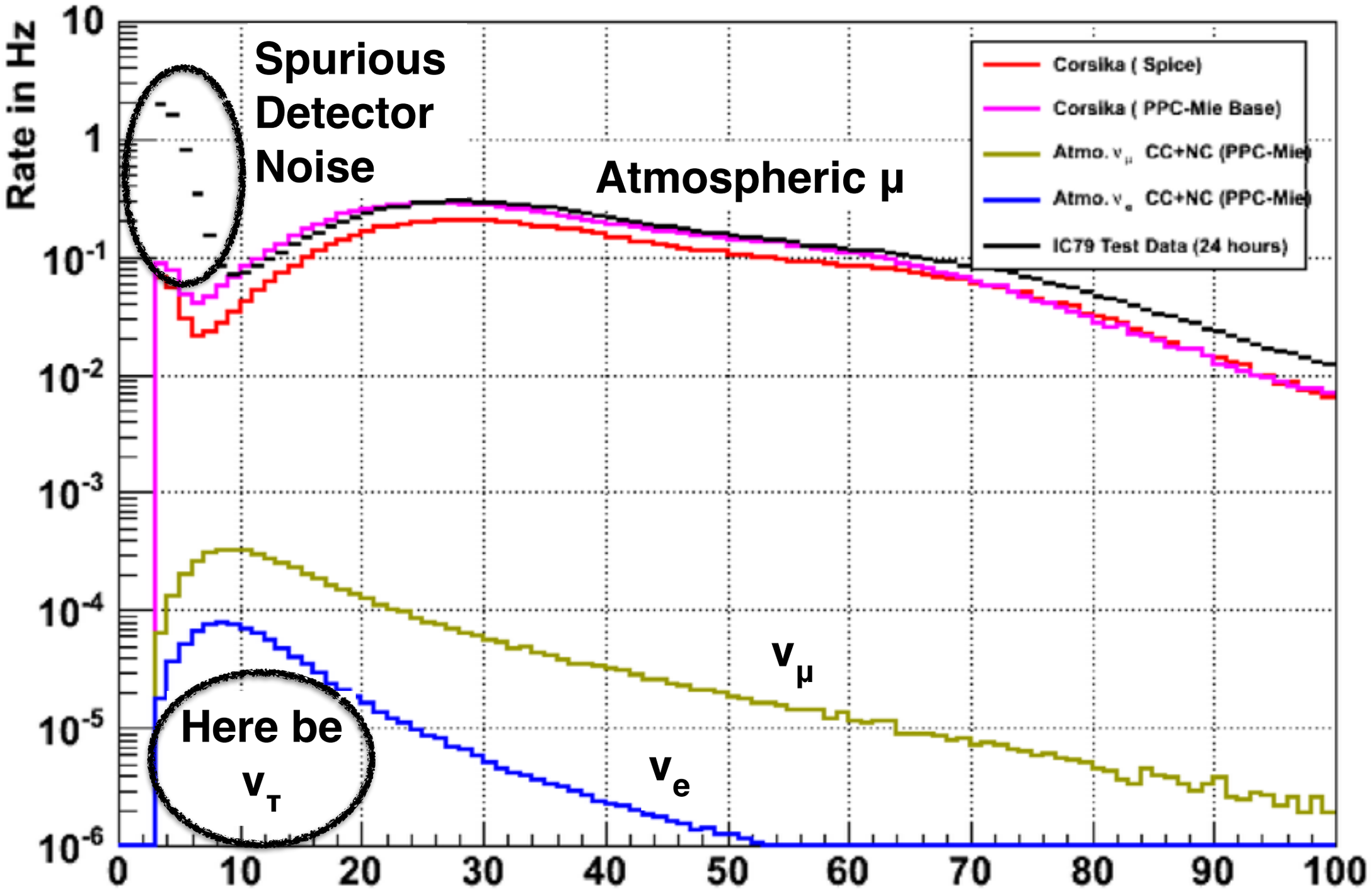
Tau Appearance Events



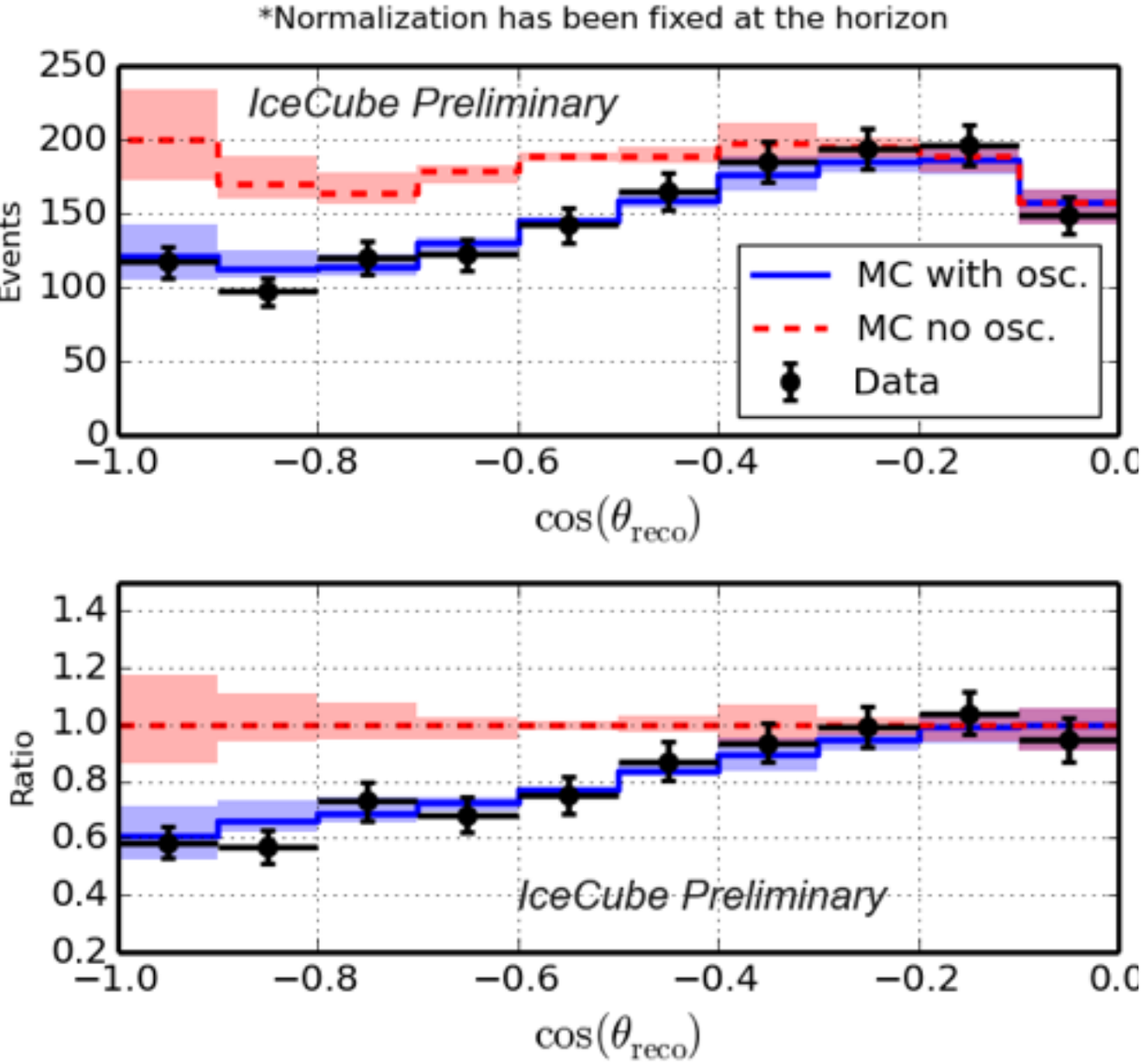
Tau Appearance Events

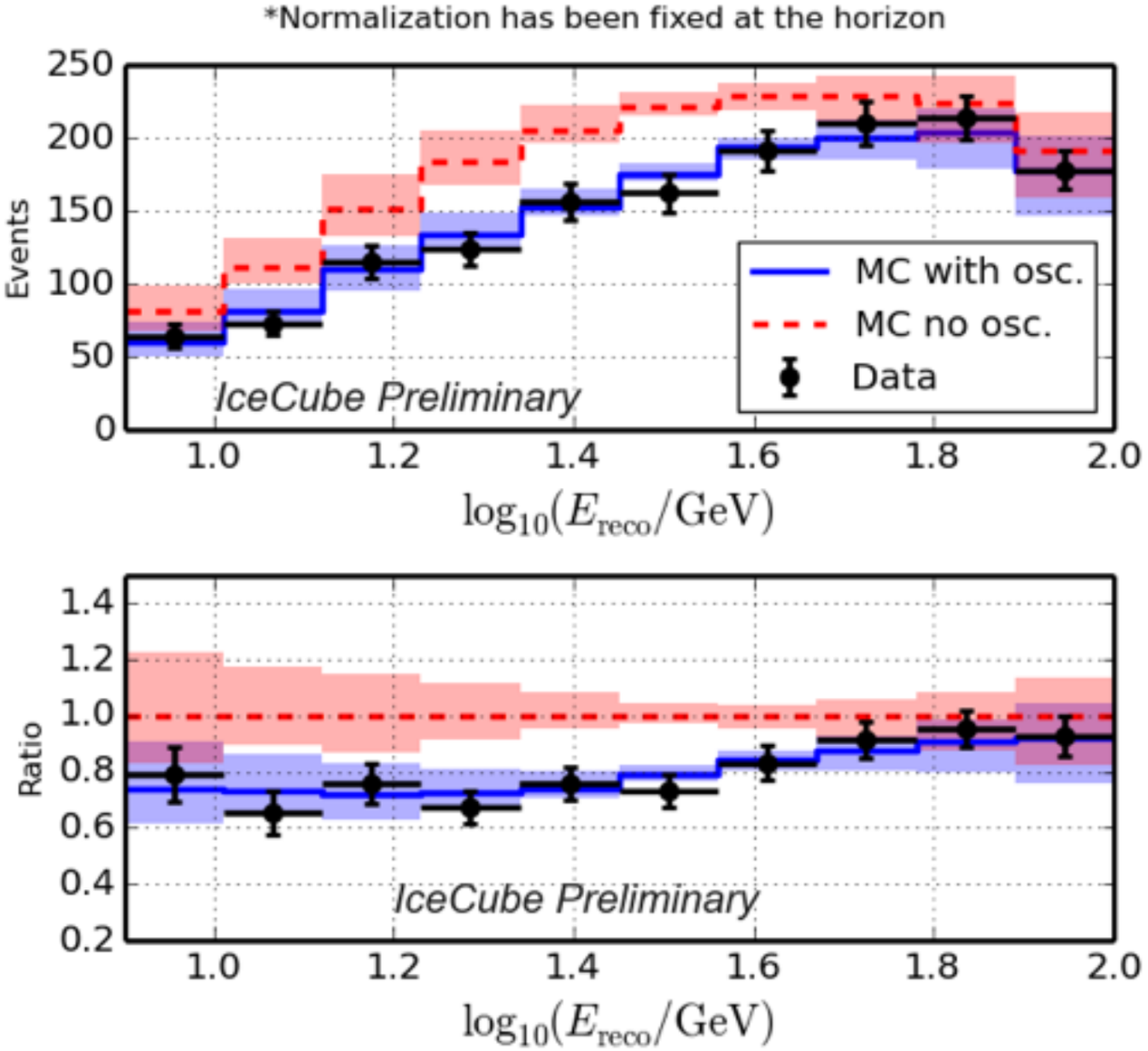


ν_τ Oscillation Backgrounds

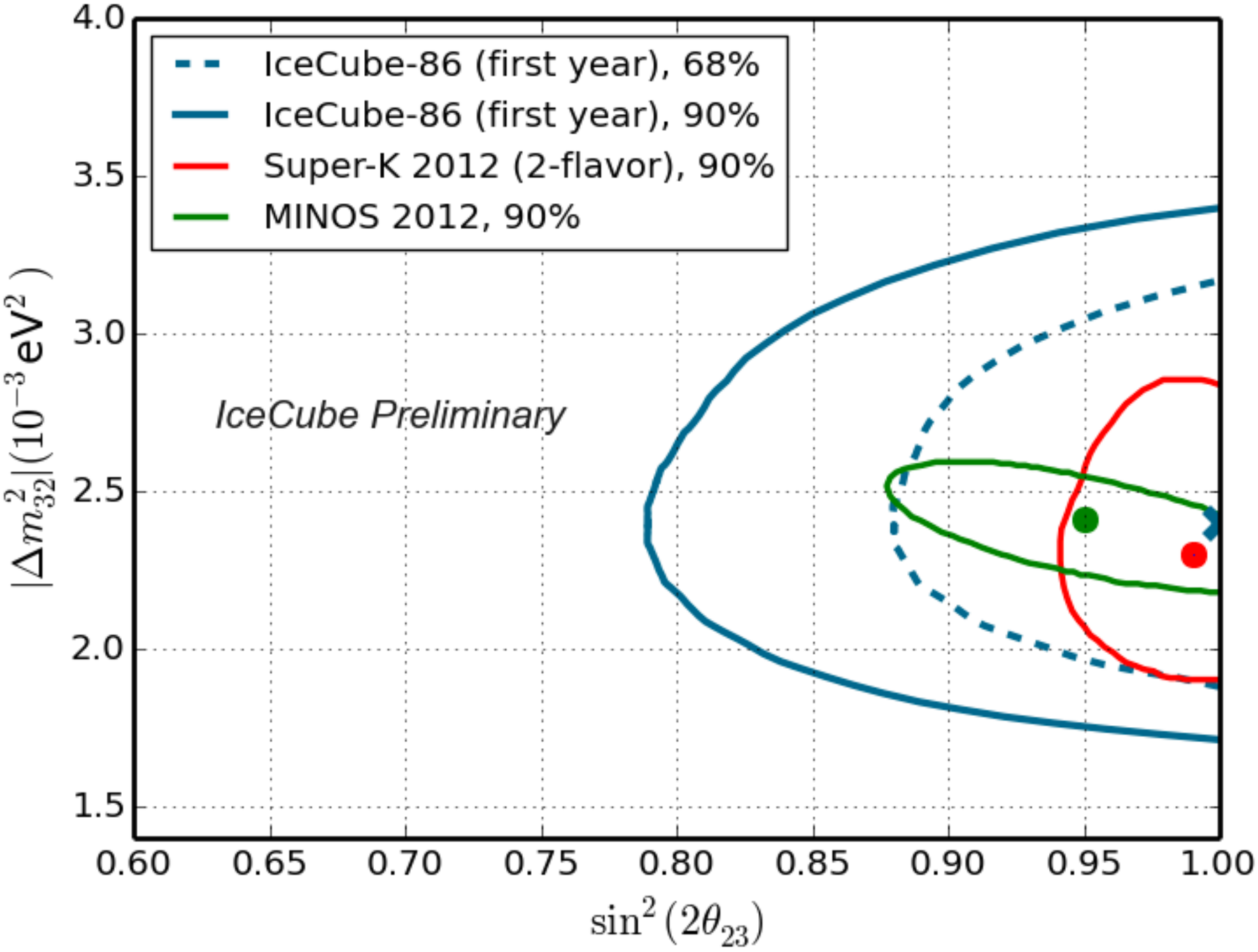


ν_μ Disappearance



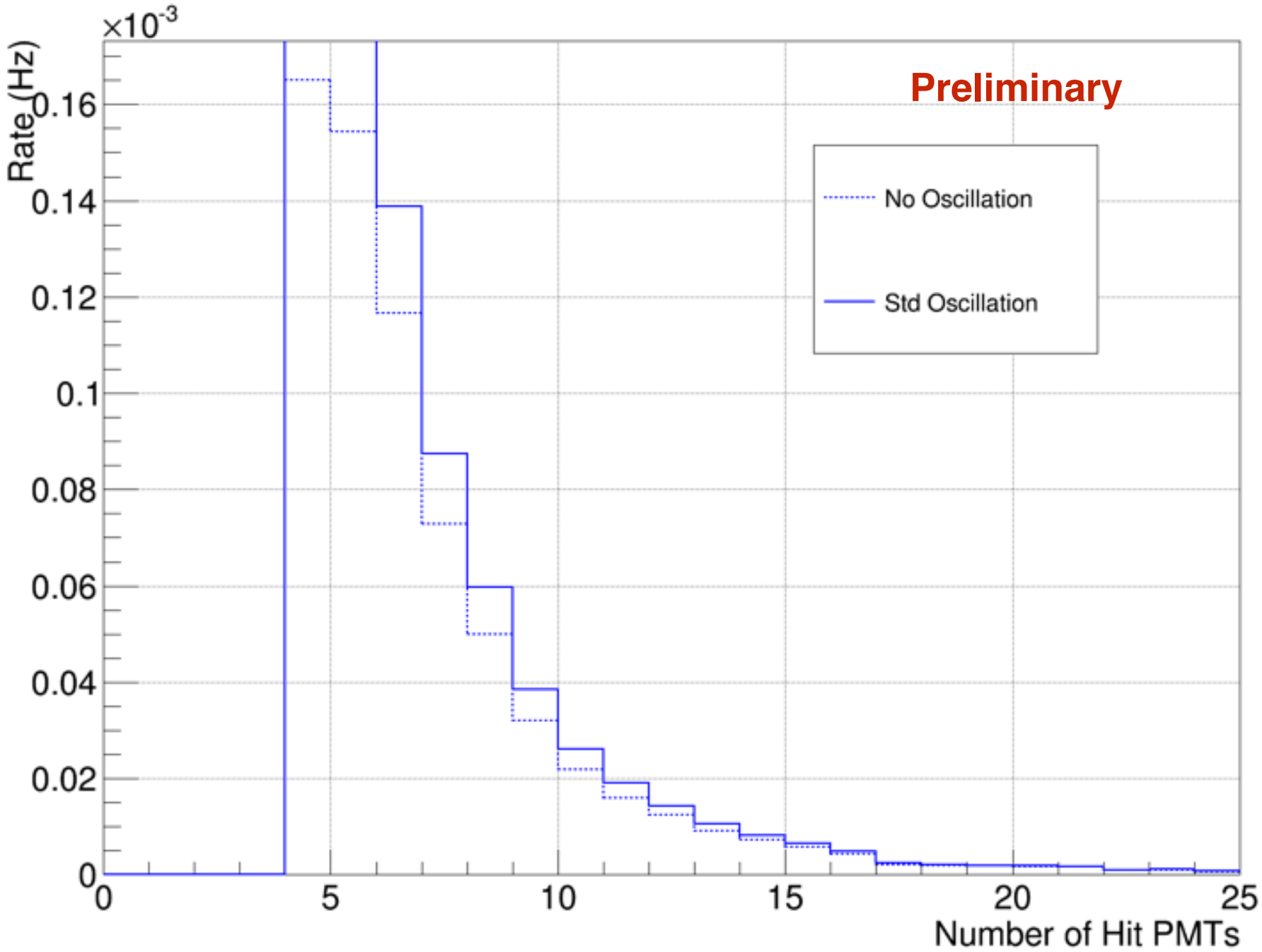


ν_μ Disappearance



But what about v_τ?

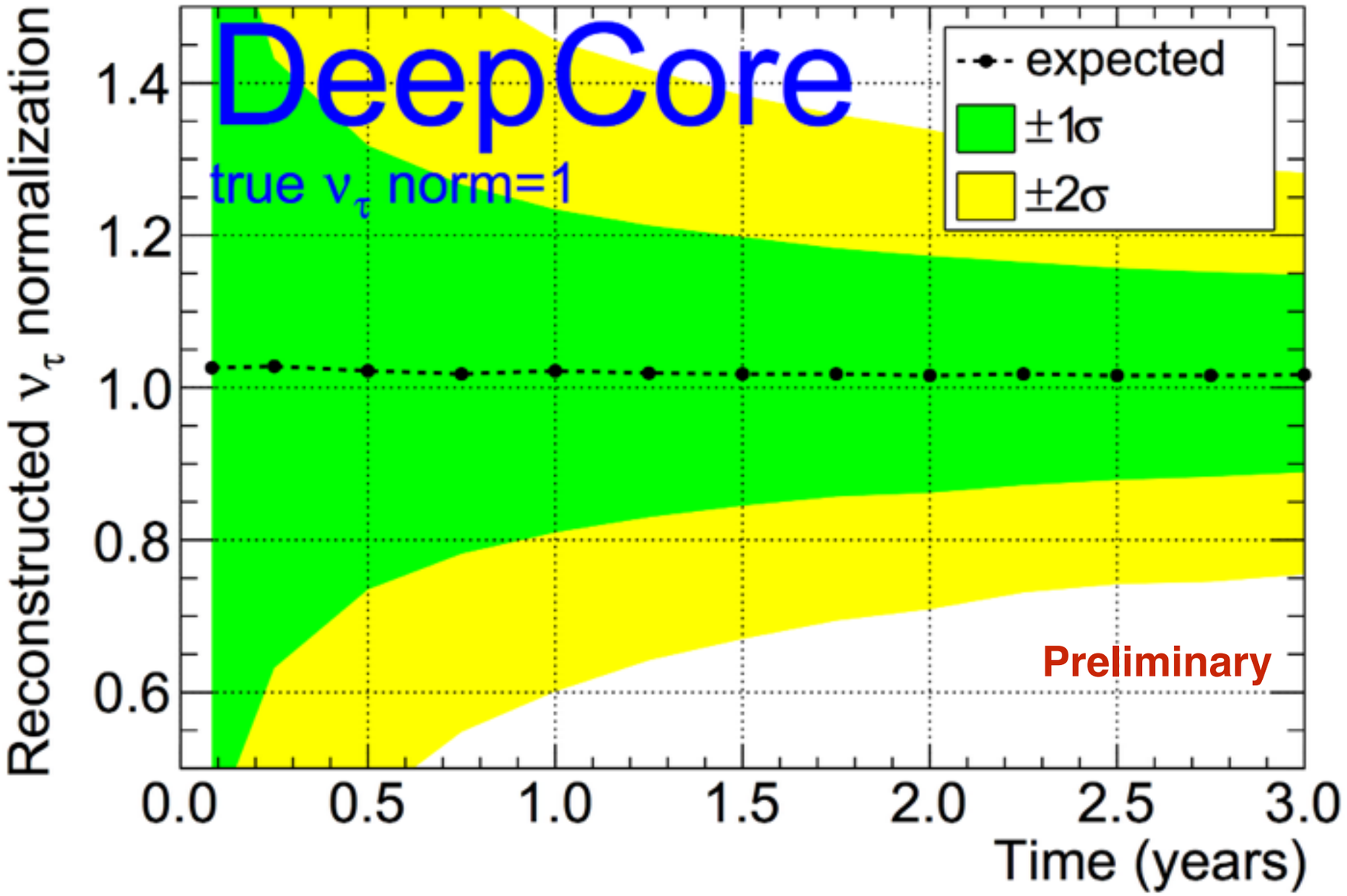
ντ Appearance



Oscillation signature in IceCube will be an excess of dim events

Work is currently ongoing

ντ Appearance



DeepCore can potentially measure ν_τ normalization at high σ

Work is currently ongoing

Appearance in Other Experiments

ν_τ Appearance in OPERA

OPERA has 5 years of livetime and has seen 3 ν_τ candidates

No $\nu_\mu \rightarrow \nu_\tau$ ruled out at 3.4σ.

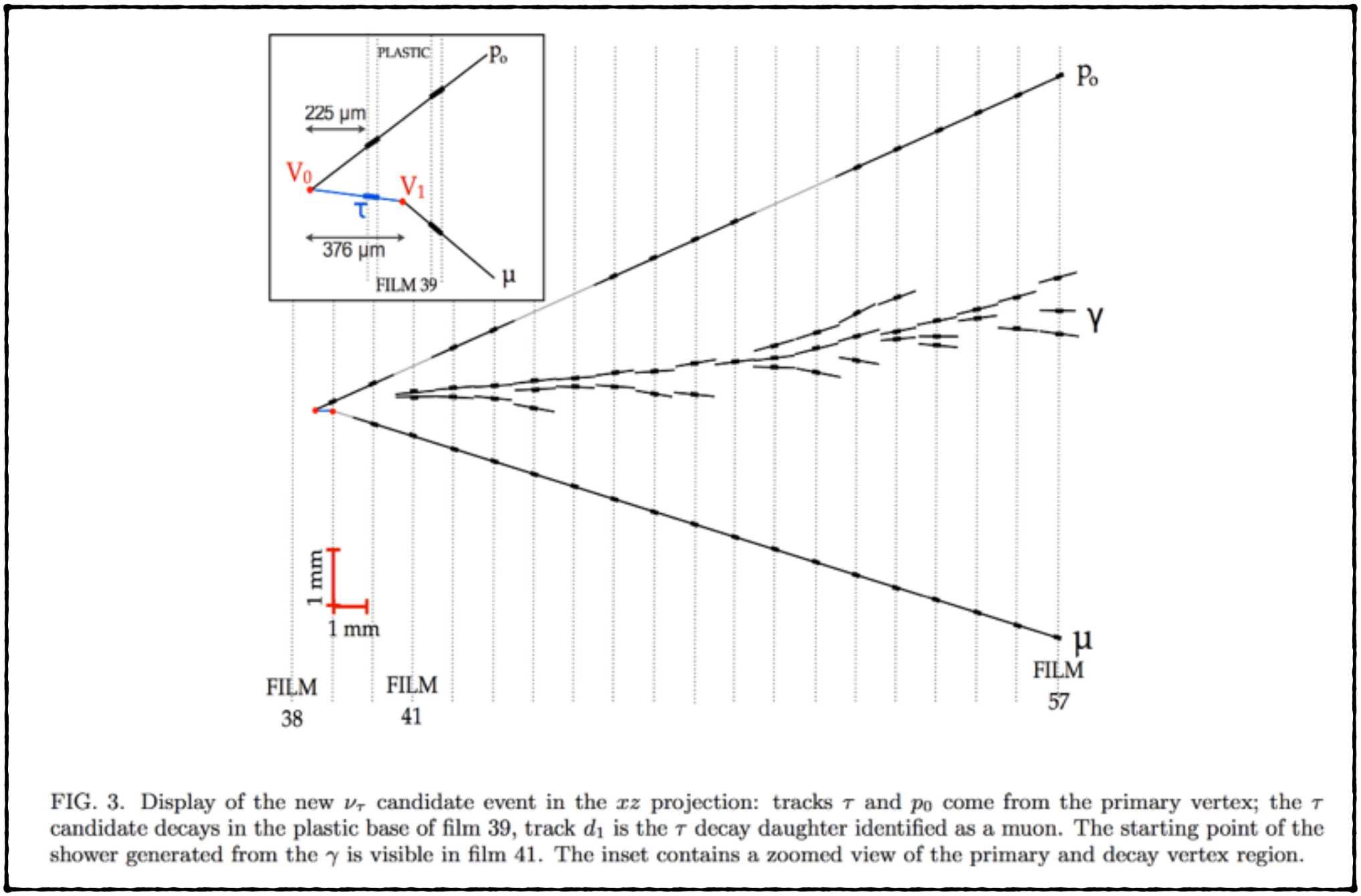


FIG. 3. Display of the new ν_τ candidate event in the xz projection: tracks τ and p_0 come from the primary vertex; the τ candidate decays in the plastic base of film 39, track d_1 is the τ decay daughter identified as a muon. The starting point of the shower generated from the γ is visible in film 41. The inset contains a zoomed view of the primary and decay vertex region.

Evidence for νμ → ντ appearance in the CNGS neutrino beam with the OPERA experiment
Arxiv:1401.2079v1

ν_τ Appearance in SuperK

SuperK has 12 years of livetime and has seen ~180 ν_τ candidates

No $\nu_\mu \rightarrow \nu_\tau$ ruled out at 3.8σ.

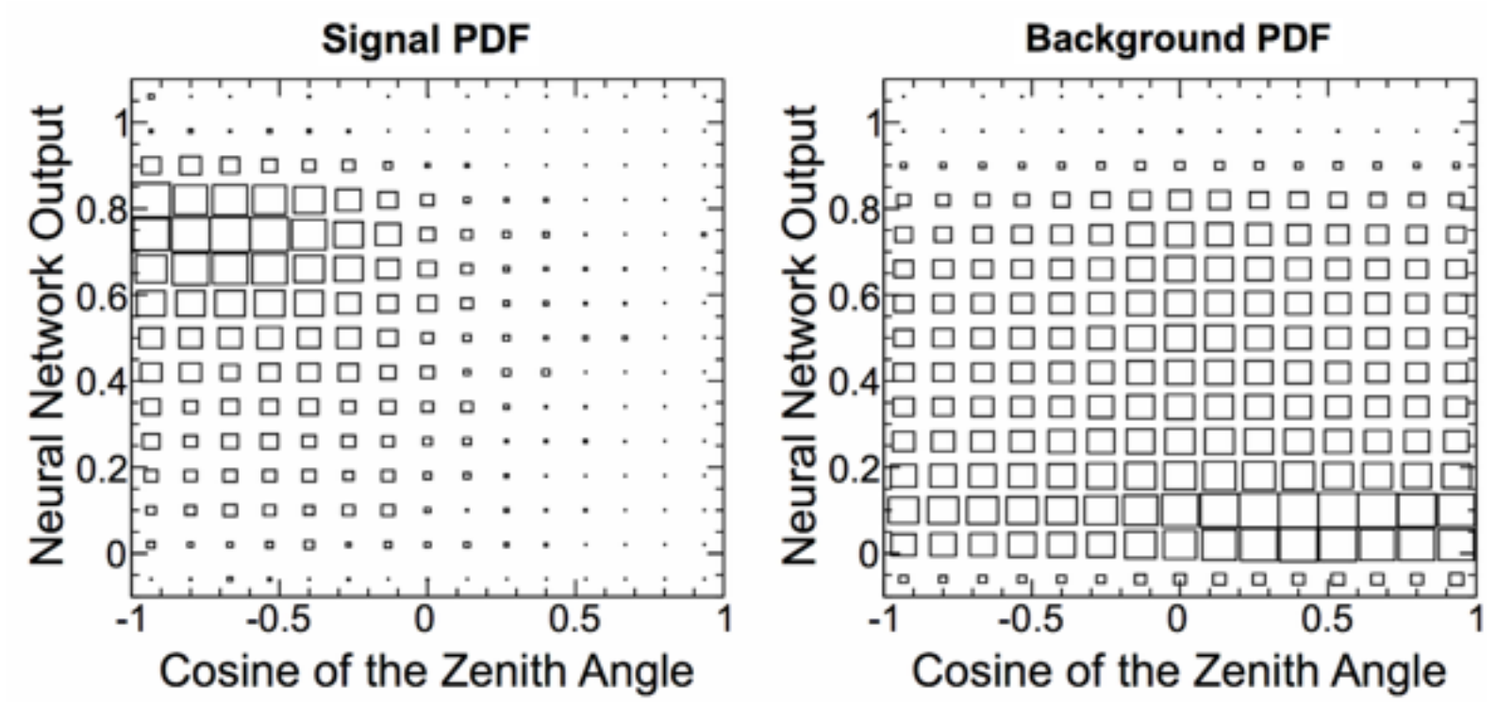
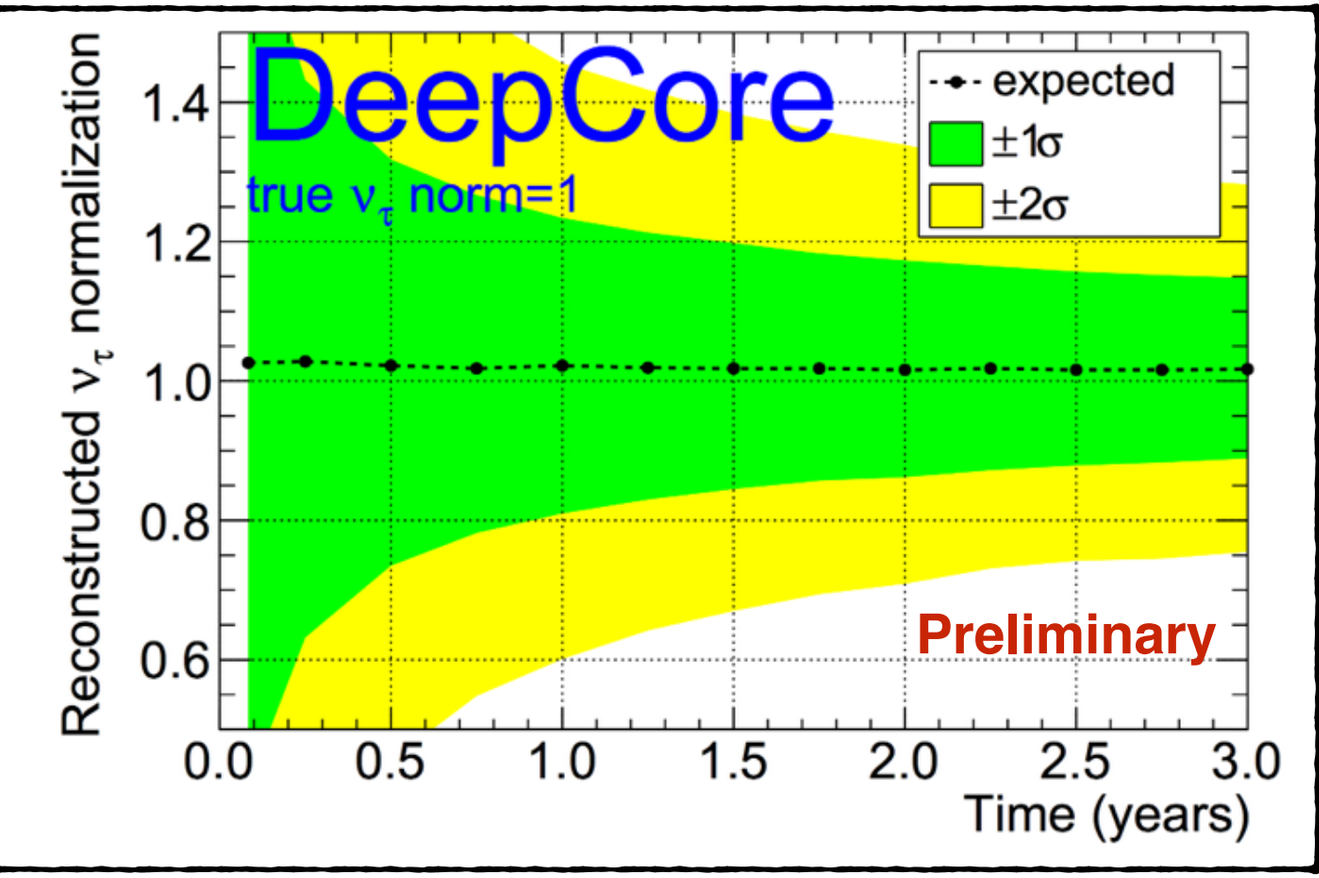


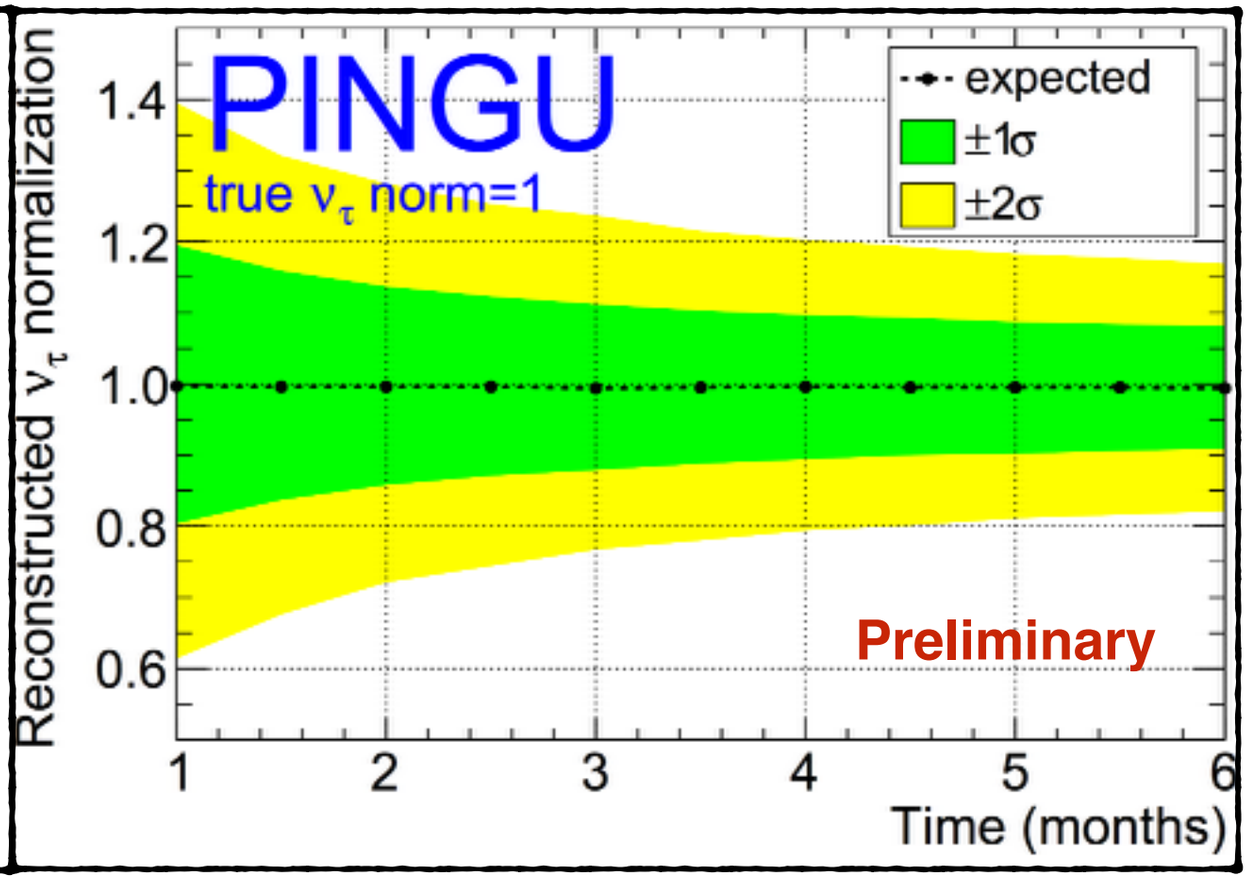
FIG. 2. Histograms of the PDFs of both tau signal (left) and atmospheric background (right). The vertical axis is the output of the NN, the horizontal axis the cosine of the event zenith direction. Upward going events are to the left, downward going to the right. The tau signal appears in the upward-going tau-like region.

Evidence for the Appearance of Atmospheric Tau Neutrinos in Super-Kamiokande
Arxiv:1206.0328

ν_τ Appearance in PINGU

If approved and built, PINGU (IceCube-DeepCore upgrade) should reach DeepCore's sensitivity within months





Conclusions

- Muon neutrinos have been measured with IceCube
  - Newer, more competitive analyses on their way!
- Tau neutrinos are currently being identified
- DeepCore should be sensitive enough for a competitive measurement
- Other experiments already have results (but don't have the statistics of IceCube)