Search for Heavy Neutral Lepton Production and Decay with IceCube DeepCore

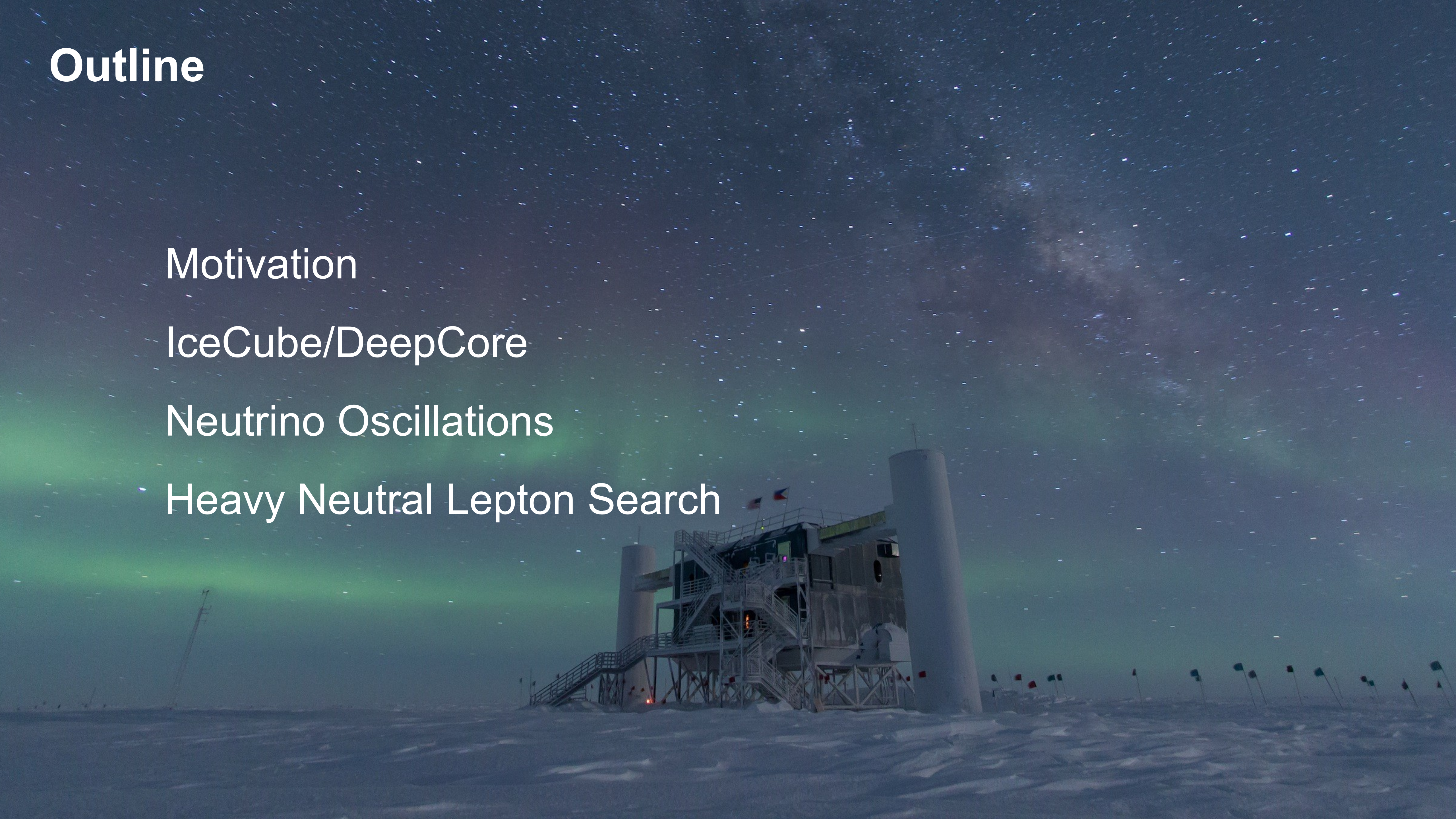
Leander Fischer
ICHEP Bologna, 09.07.2022

HELMHOLTZ

ICECUBE

DESY.

Outline



Motivation

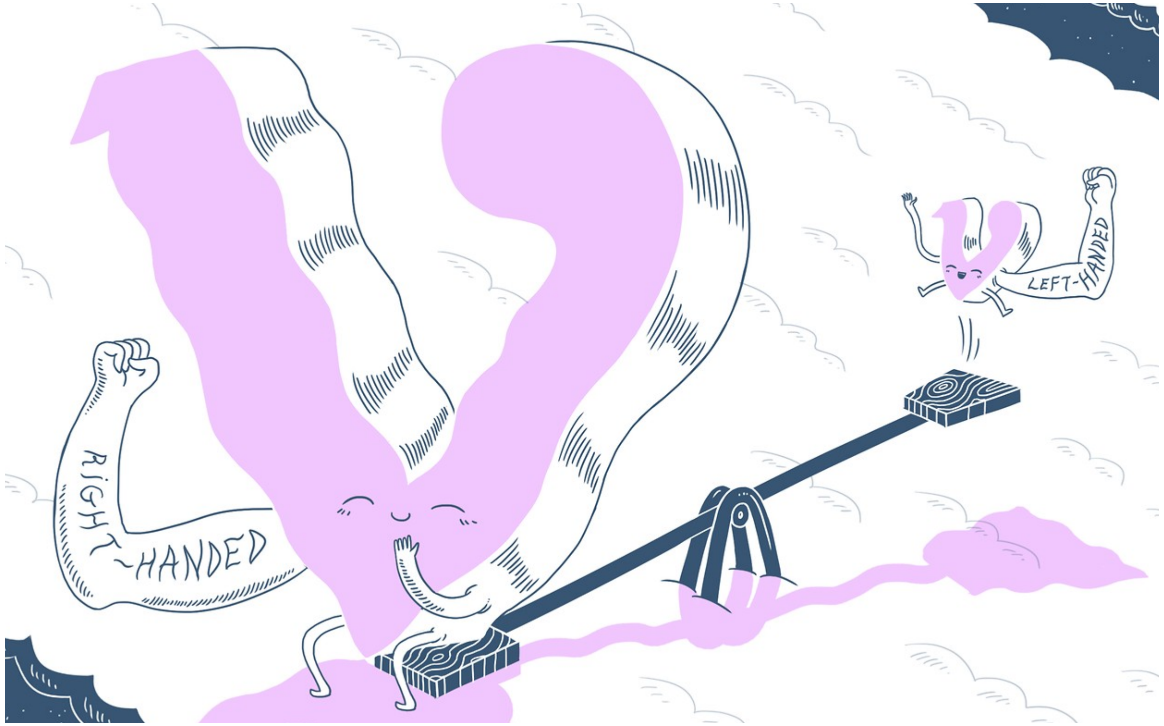
IceCube/DeepCore

Neutrino Oscillations

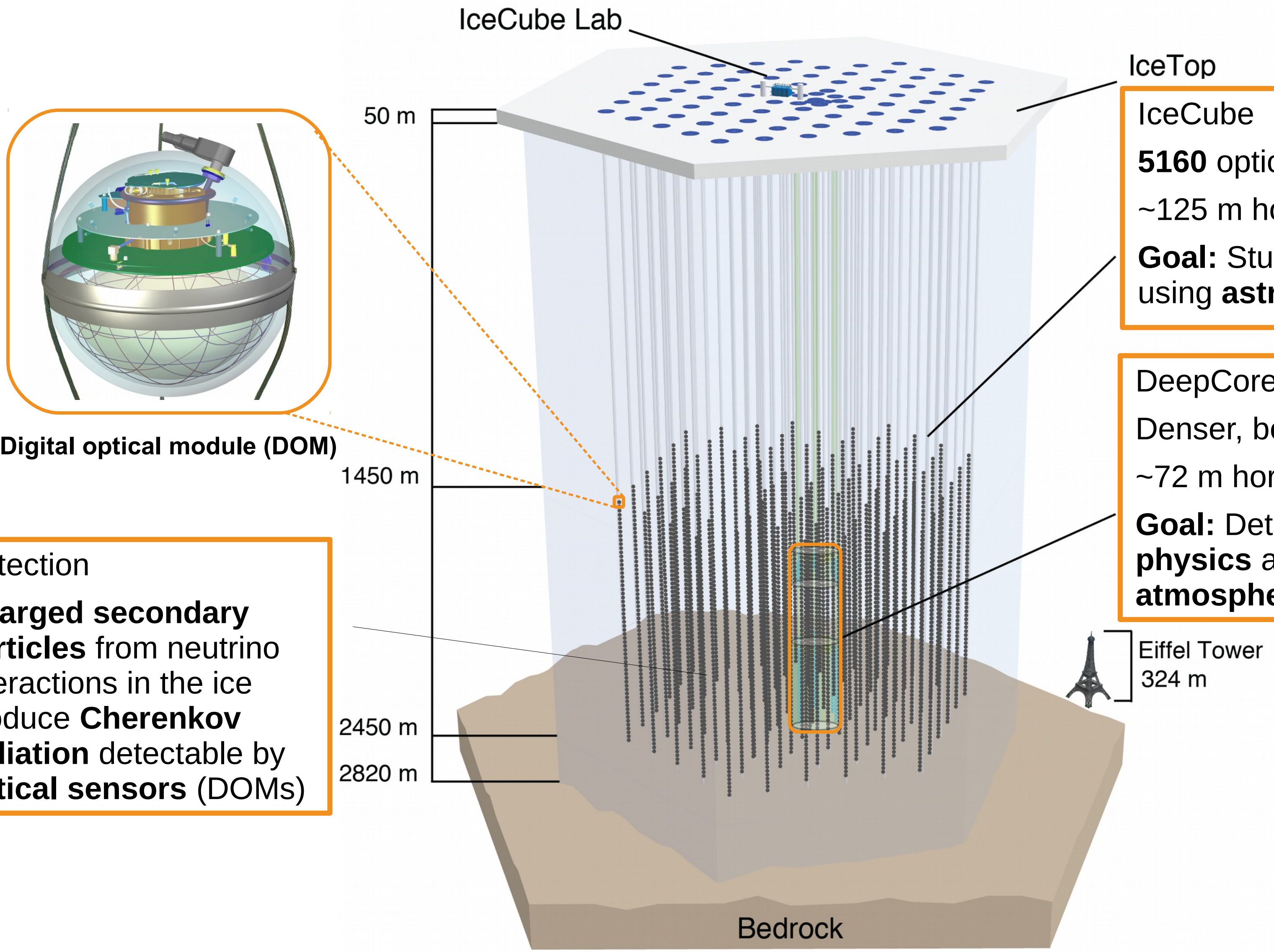
Heavy Neutral Lepton Search

Motivation

- Observation of neutrino oscillations proves that (at least two) neutrinos have mass:
  - SM extensions including **RH (sterile) neutrinos** provide a good explanation to the origin of neutrino masses (e.g. through seesaw mechanism)
- These **Heavy Neutral Leptons (HNLs)** could also explain many other open questions in cosmology and particle physics
  - Matter-antimatter asymmetry (leptogenesis) arxiv:10.1142
  - Dark matter arxiv:9303287v1
  - Anomalies in oscillation experiments arxiv:1906.02106v3



IceCube and DeepCore



Detection

Charged secondary particles from neutrino interactions in the ice produce **Cherenkov radiation** detectable by **optical sensors** (DOMs)

IceCube

5160 optical sensors in **1 km^3** volume (**1Gton**)

~125 m horizontal, ~17 m vertical spacing

Goal: Study **sources** and **flux properties** using **astrophysical neutrinos**

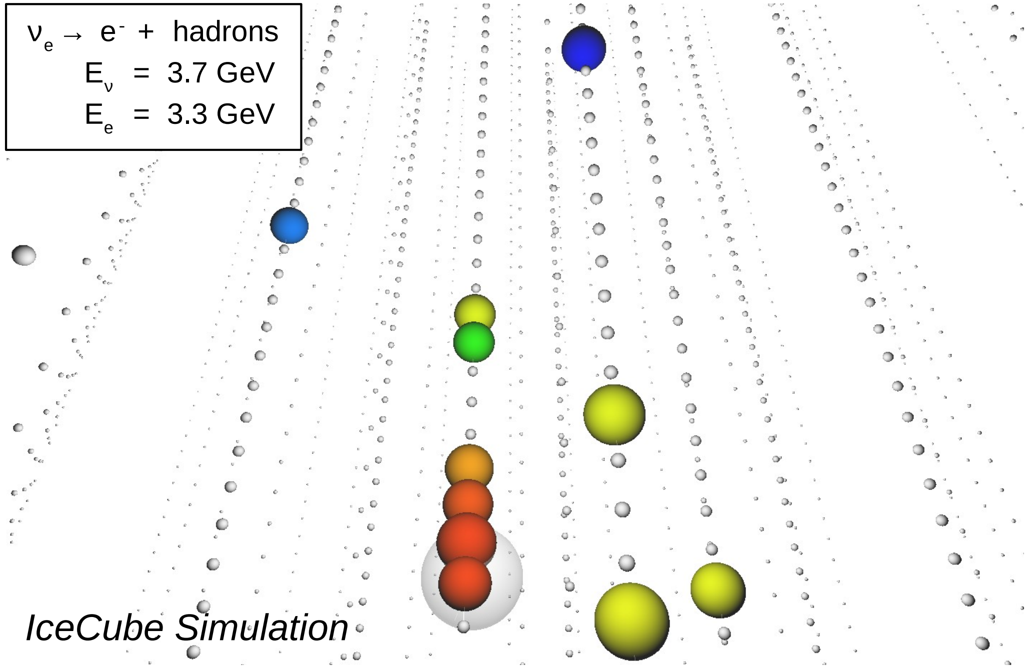
DeepCore

Denser, better instrumented sub-array (**10Mton**)

~72 m horizontal, ~7 m vertical spacing

Goal: Determine neutrino properties and perform **particle physics** analyses, **dark matter searches**, and more with **atmospheric neutrinos**

(Very) Low Energy Event Topologies



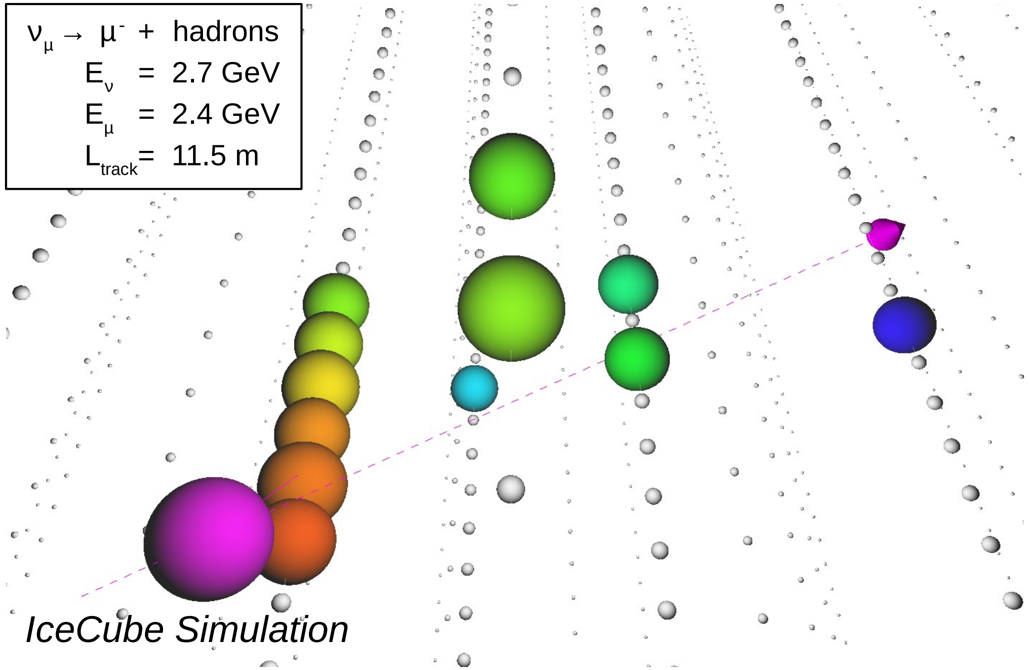
$\nu_e \rightarrow e^- + \text{hadrons}$

$E_\nu = 3.7$ GeV

$E_e = 3.3$ GeV

Cascade

(ν_e/ν_τ Charged- and all ν Neutral-Current)



$\nu_\mu \rightarrow \mu^- + \text{hadrons}$

$E_\nu = 2.7$ GeV

$E_\mu = 2.4$ GeV

$L_{track} = 11.5$ m

Track

(ν_μ Charged-Current)

3 Flavor Neutrino Oscillations

$$U^{3x3}_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

Can be parameterized as 3 mixing angles and 1 CP phase

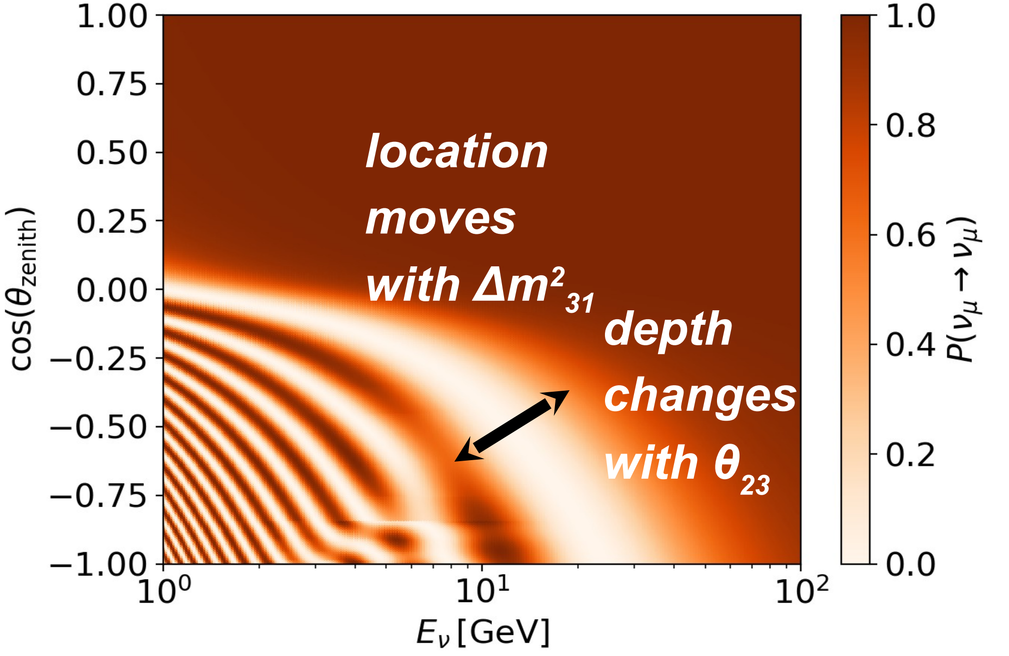
- Flavor eigenstates (ν_α) are superposition of mass eigenstates (ν_κ)

Flavor (e, μ, τ)

$$|\nu_\alpha\rangle = \sum U^*_{\alpha\kappa} |\nu_\kappa\rangle$$

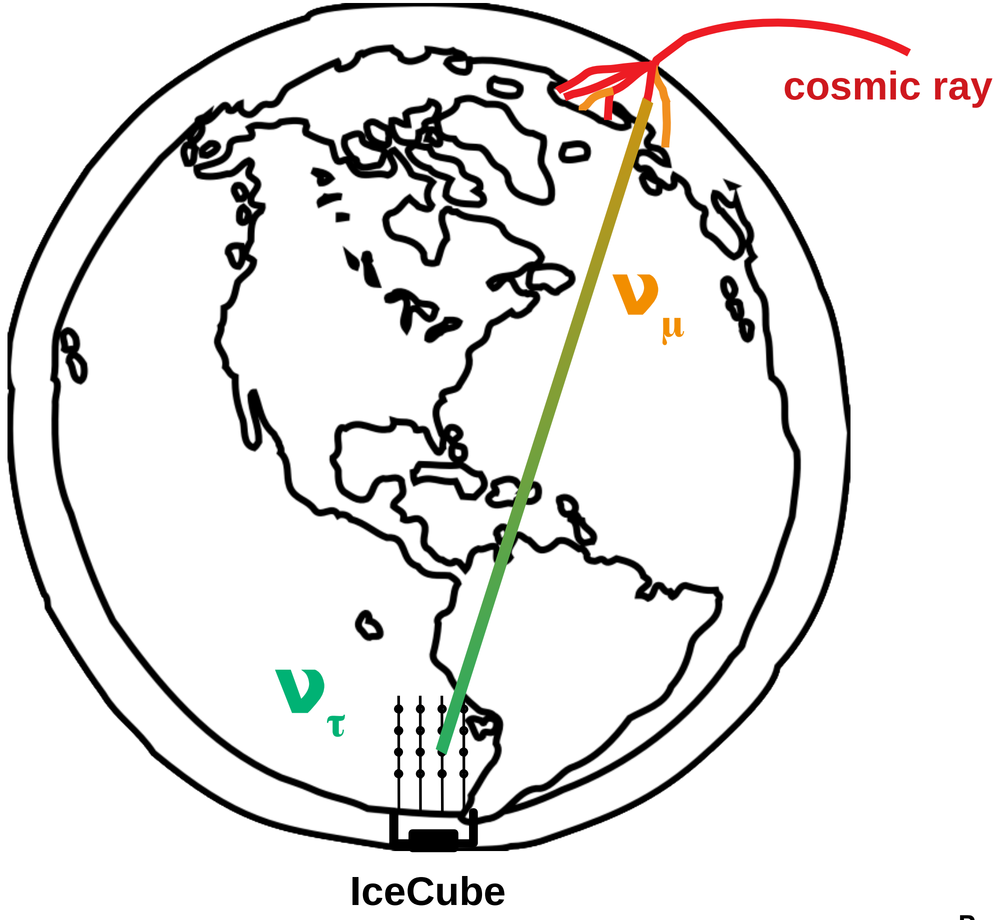
Mass (1, 2, 3)

- Neutrinos produced in the atmosphere propagate through earth and oscillate into other flavors (depending on squared mass splittings and mixings)



location moves with Δm^2_{31}

depth changes with θ_{23}



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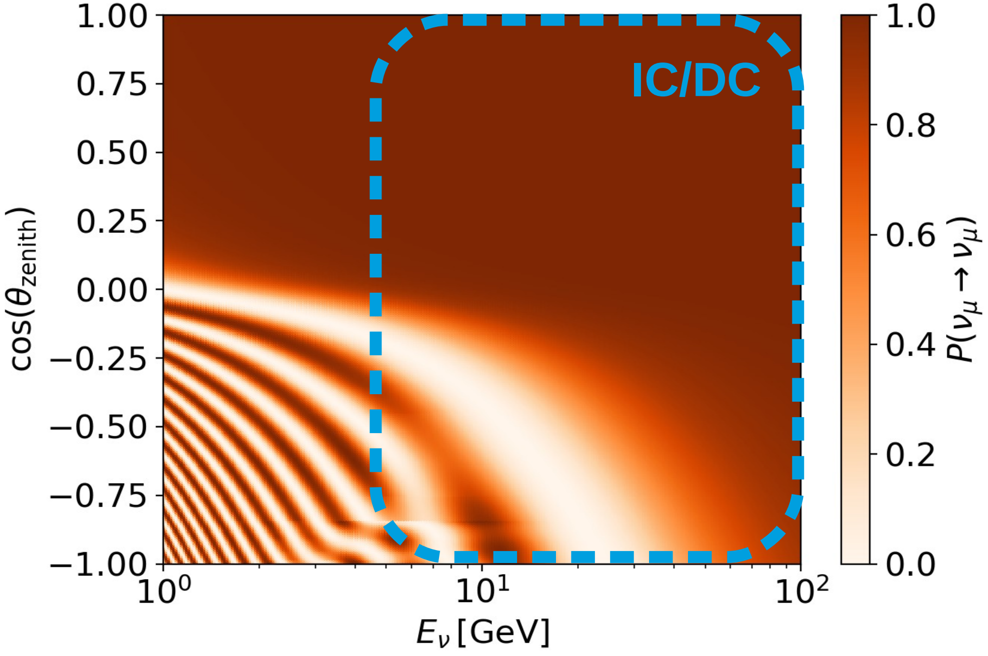
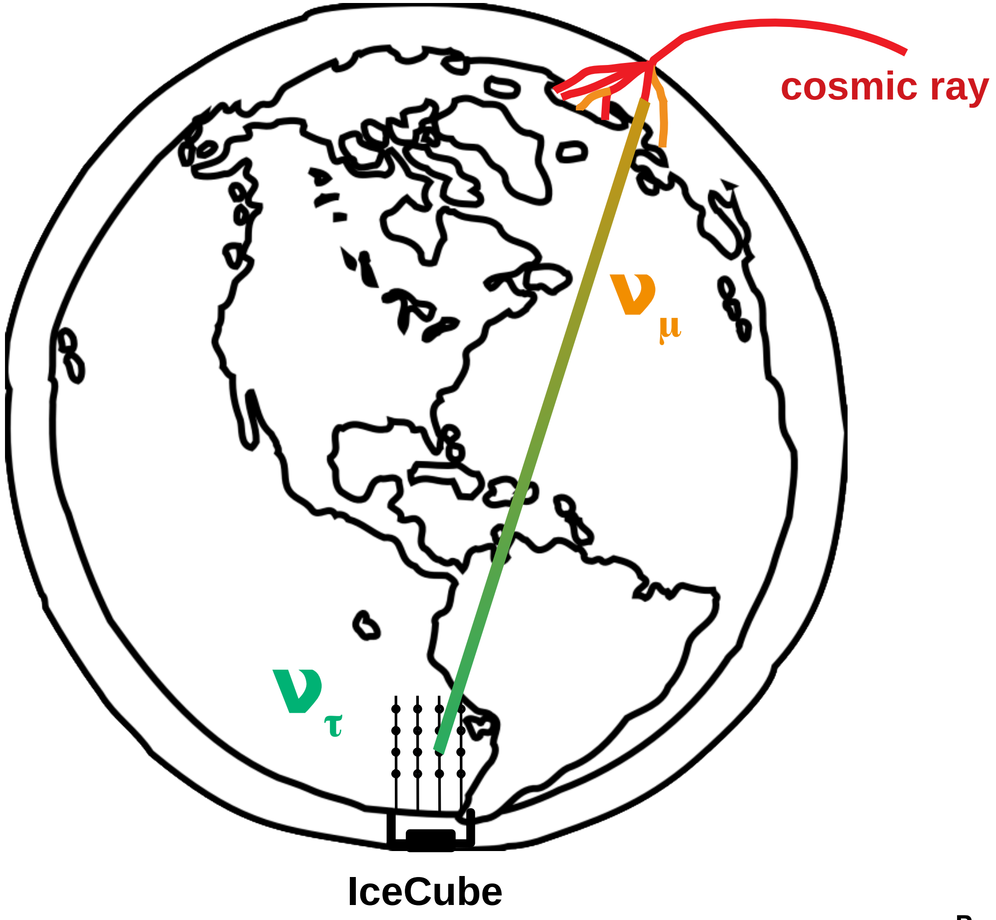
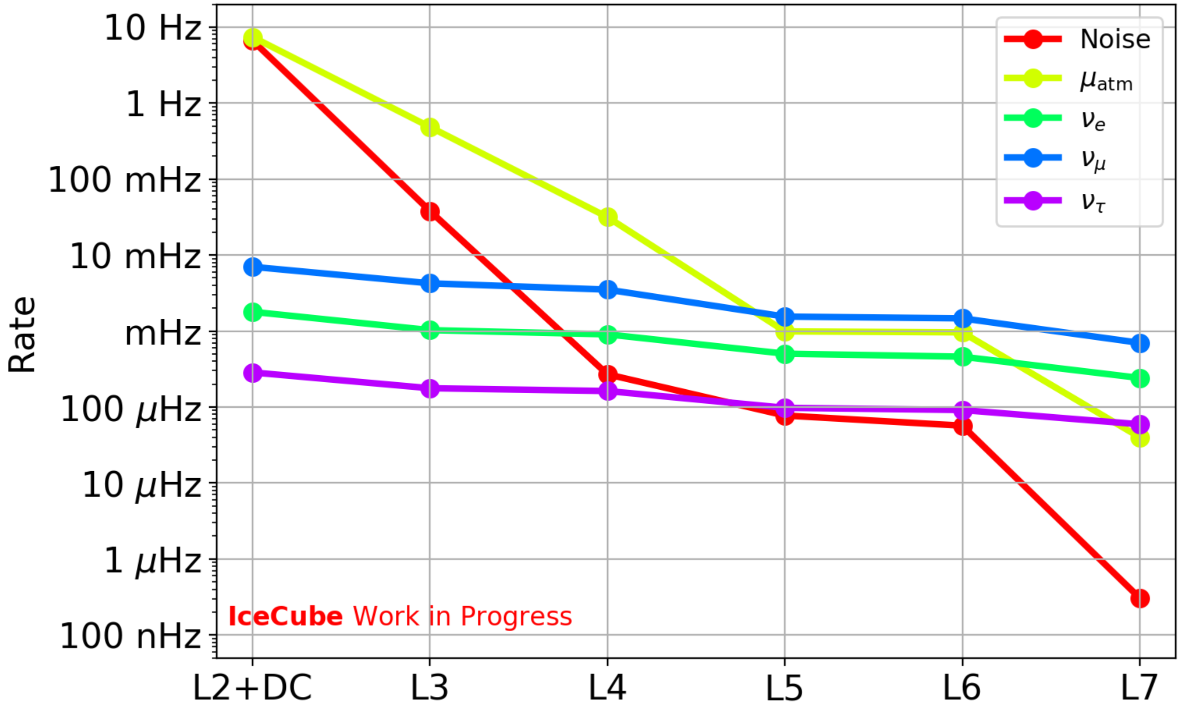




10 Year Data Sample

- Energy in range **5 GeV – 300 GeV**, mostly coming through earth, **up-going** (cos(θ) < 0.3)
- **Very low** atmospheric **muon** and **noise contamination**



Event type	Events (10 years)	Fraction
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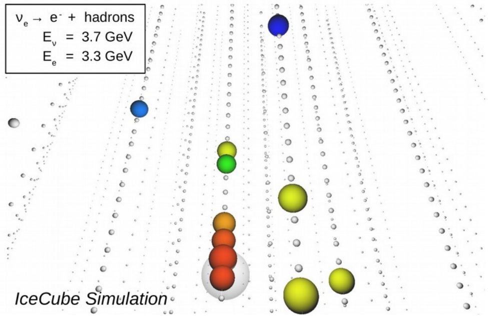
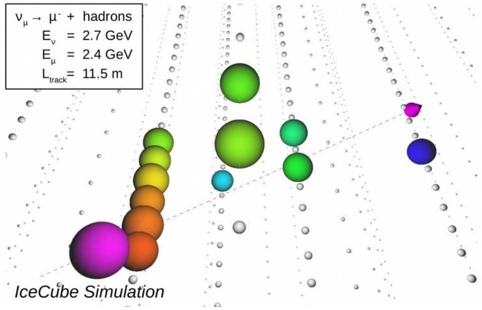
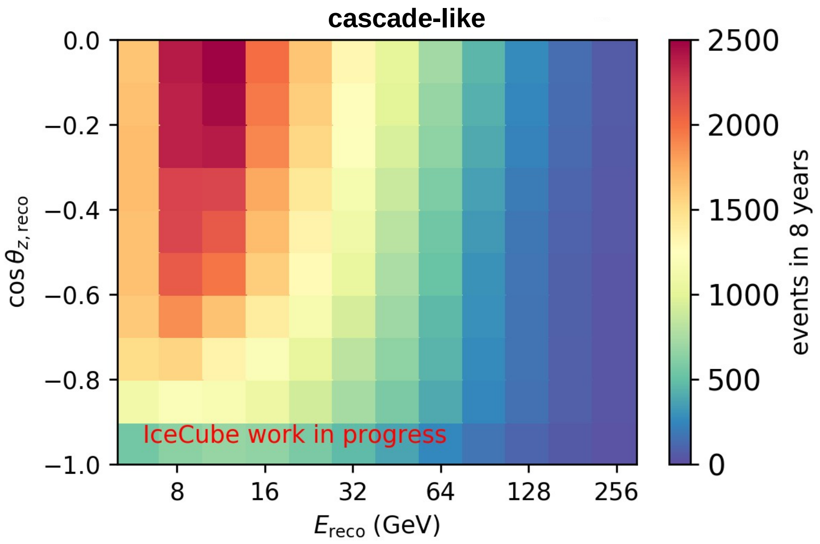
ν-NC	22245 ± 51	10.6%
$\mu_{atm.}$	1463 ± 87	0.7%
Noise	~ 0	<0.03%
Total	**209346 ± 182**	

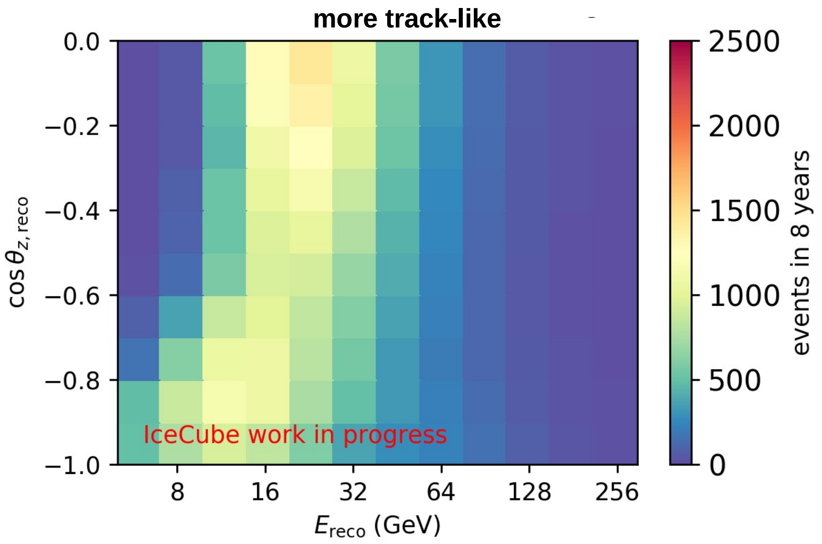
Measuring Oscillations with IceCube/DeepCore

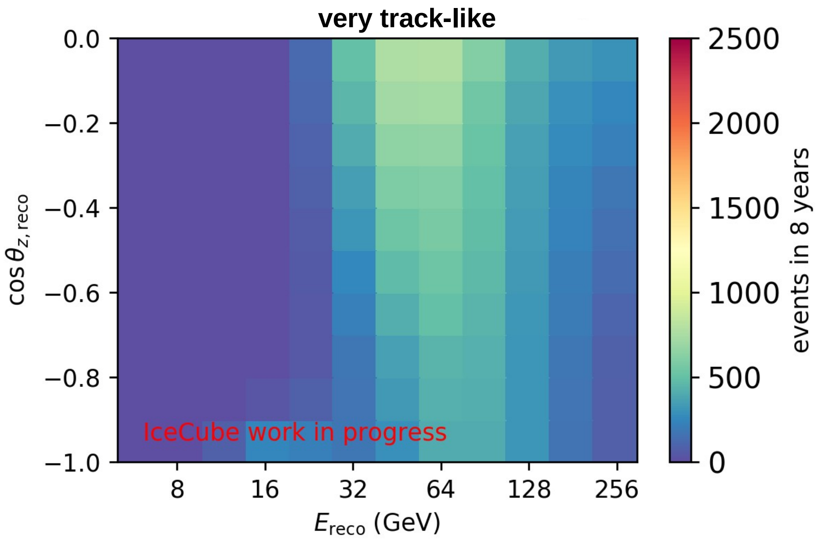
- Observe distortions in 3-d analysis bins (energy, zenith, PID)
- PID aims to distinguish ν_μ-CC (tracks) from other events (cascades)







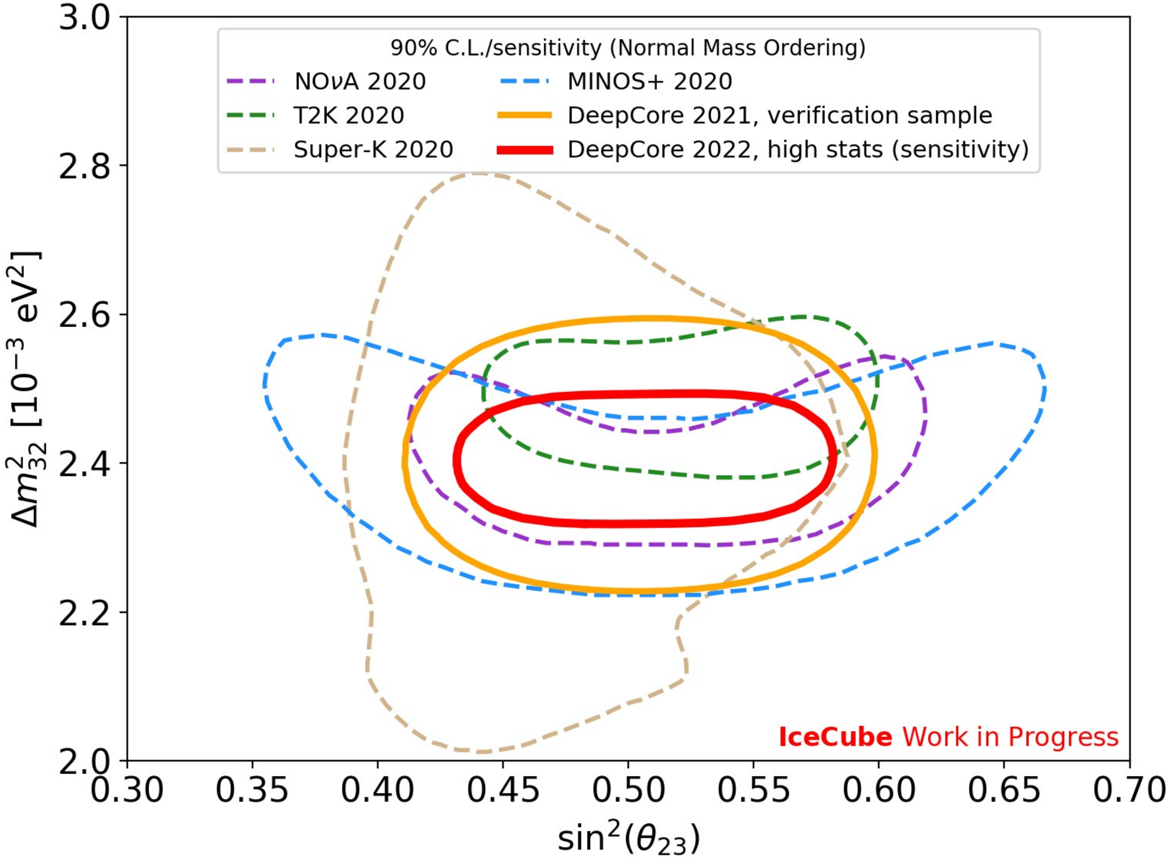


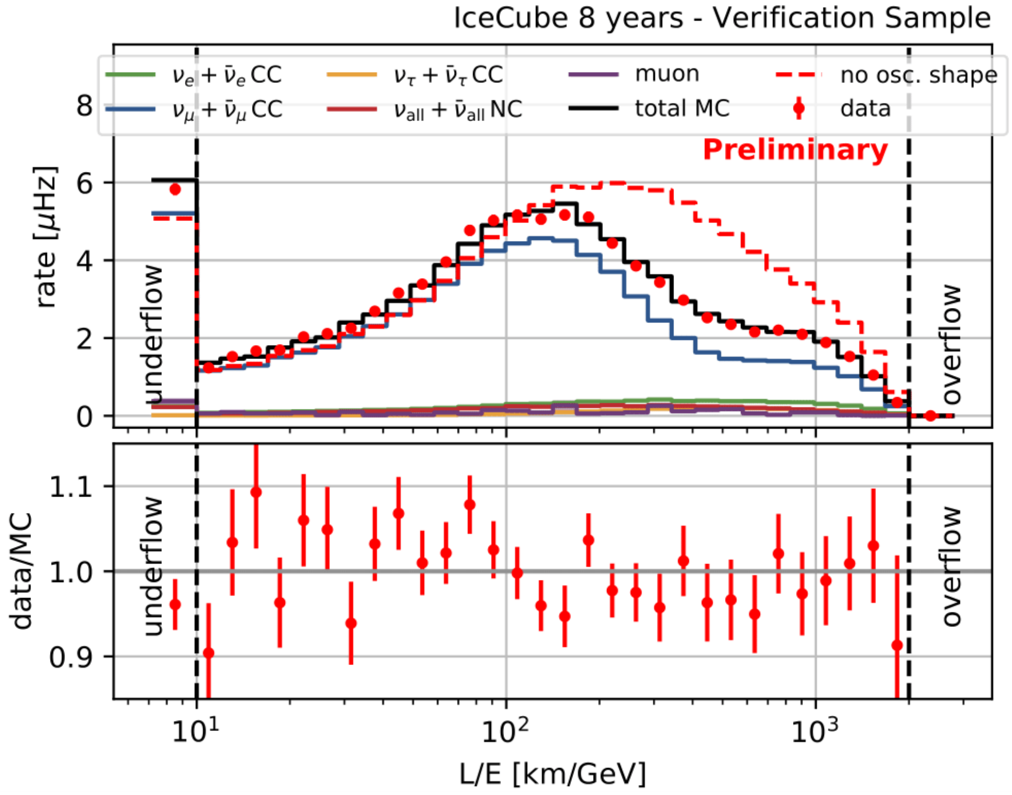


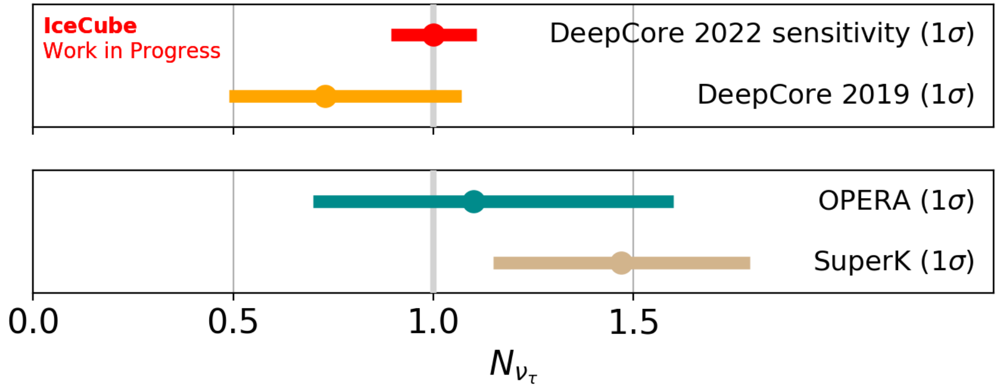
Measuring Oscillations: Latest and Upcoming Results

- Latest atmospheric neutrino mixing results using “golden” sub-sample (yellow):

$$\sin^2(\Theta_{23}) = 0.505,\ \Delta m_{32}^2 = 2.41\text{e-}3\ \text{eV}^2$$







Heavy Sterile Neutrino (HNL) Model

- Additional fourth **heavy mass state ν_4**

Flavor (e, μ, τ, s)

Mass (1, 2, 3, 4)

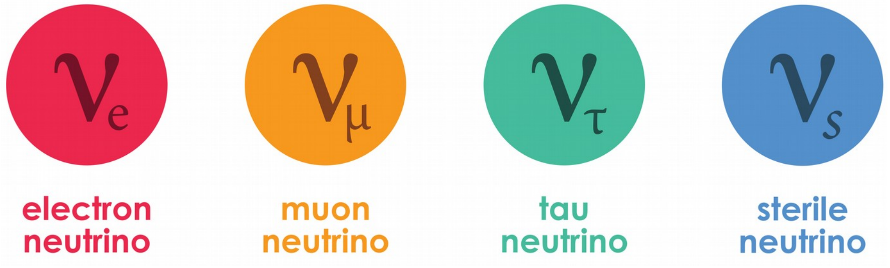
$$|\nu_\alpha\rangle = \sum U^{*}_{\alpha\kappa} |\nu_\kappa\rangle$$

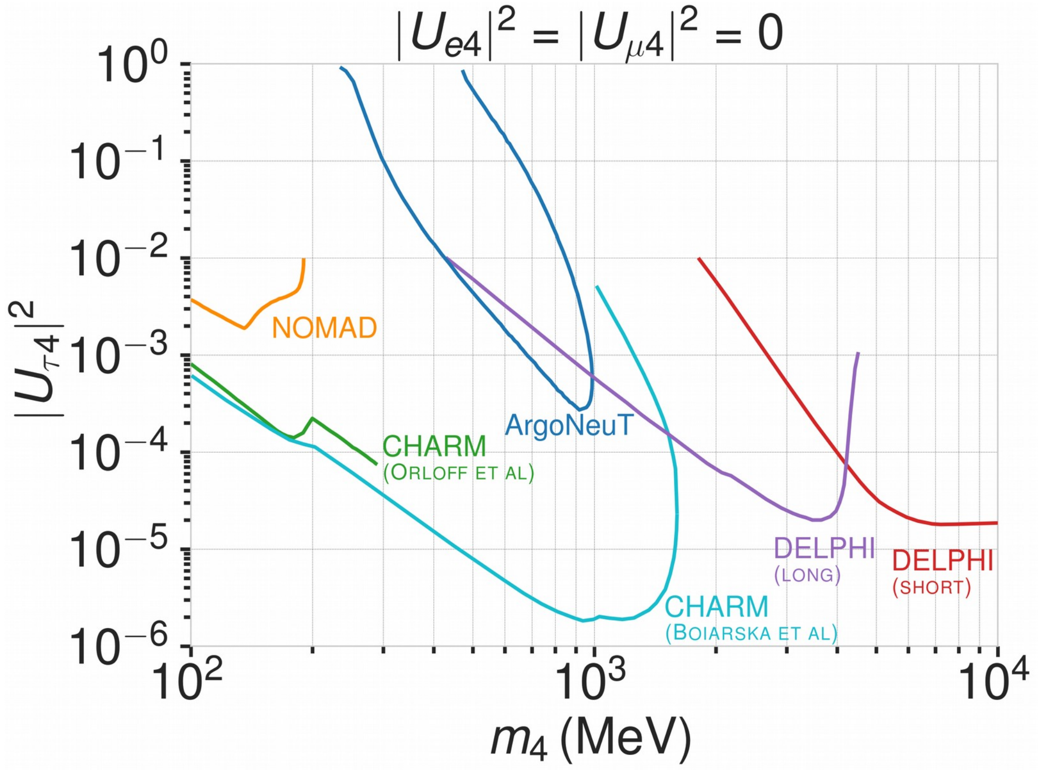
$$U^{4x4}_{PMNS}$$

- Mixing with Standard Model neutrinos through extended **4x4 mixing matrix** (3 new mixing angles, 2 new CP phases)

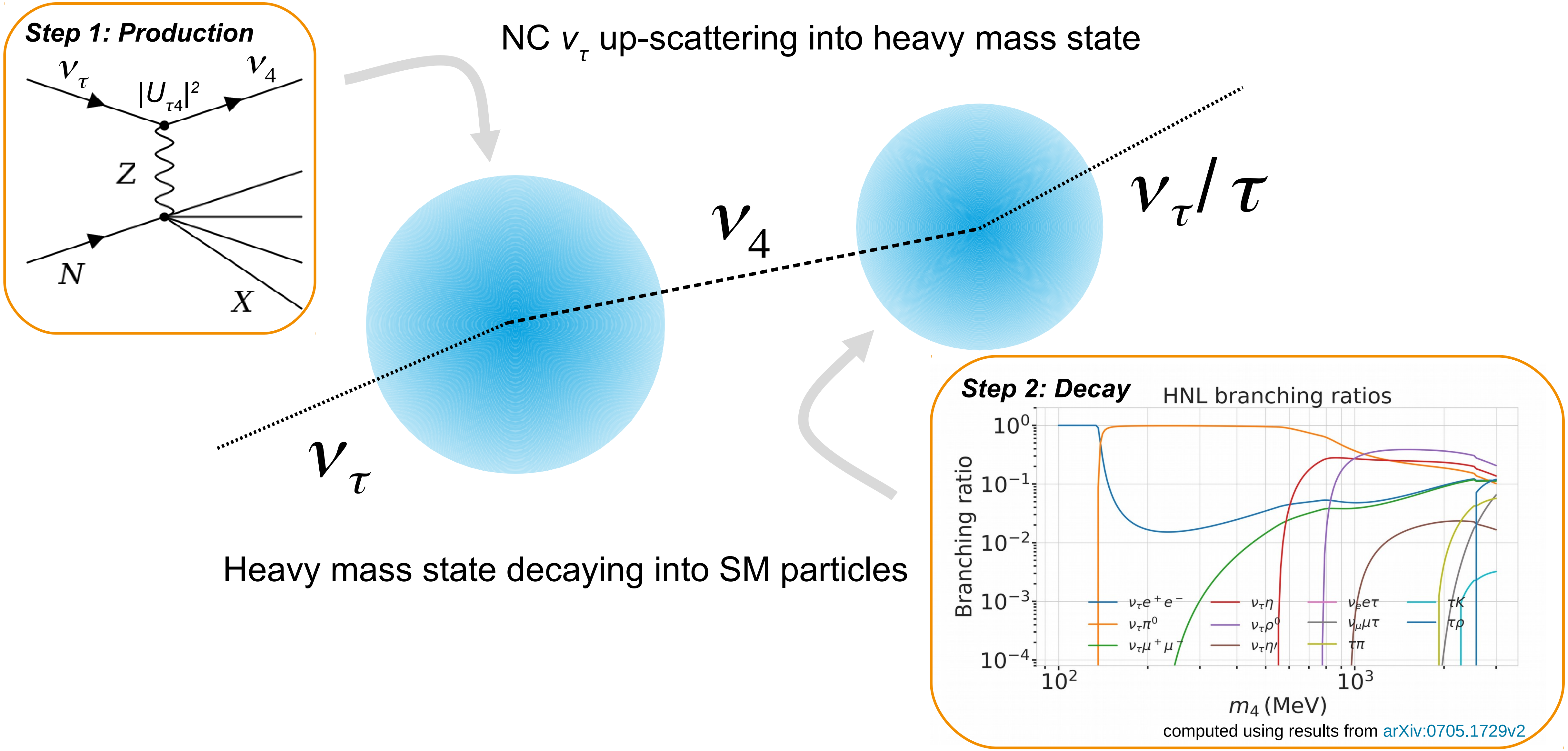
- Neutrino oscillations deliver atmospheric ν_τ beam

→ focus on $|U_{\tau4}|^2$ mixing, other parameters already very well constrained: $O_e(10^{-5}\text{-}10^{-7})$, $O_\mu(10^{-6}\text{-}10^{-9})$ around 1 GeV mass





HNL Event Signature – Double Cascade



Step 1: Production

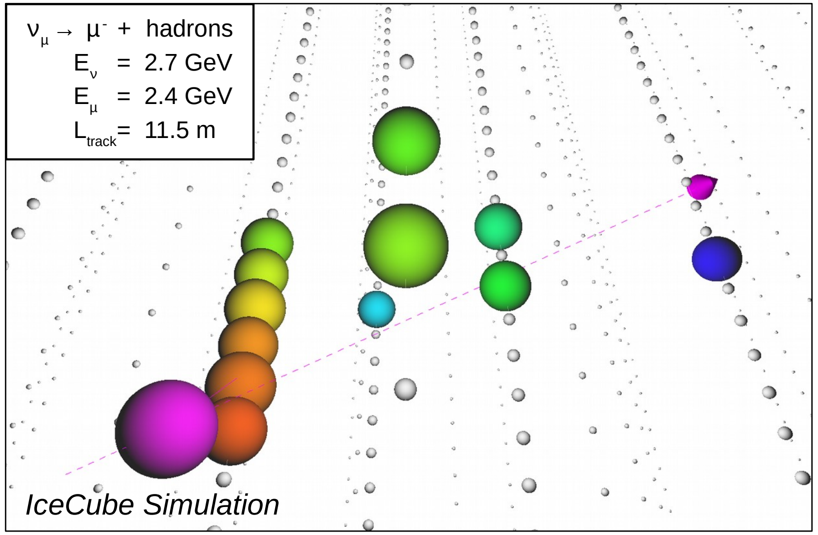
NC ν_τ up-scattering into heavy mass state

Heavy mass state decaying into SM particles

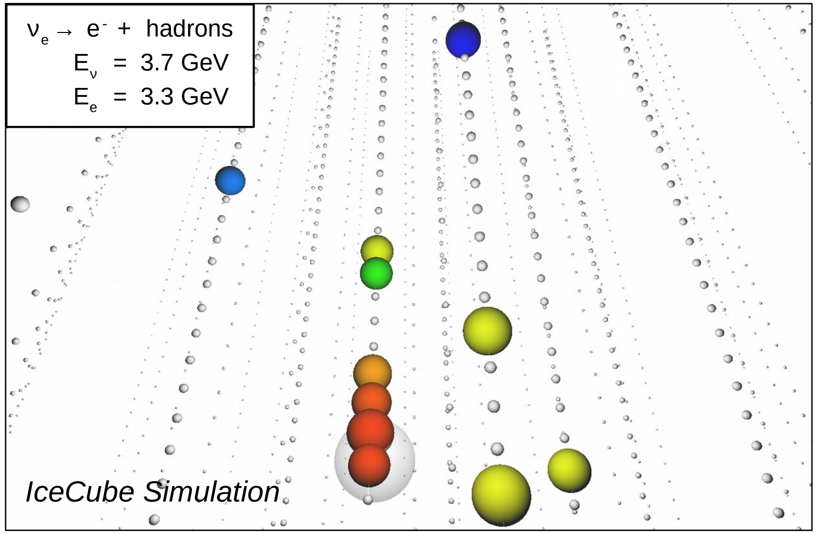
Step 2: Decay

computed using results from arXiv:0705.1729v2

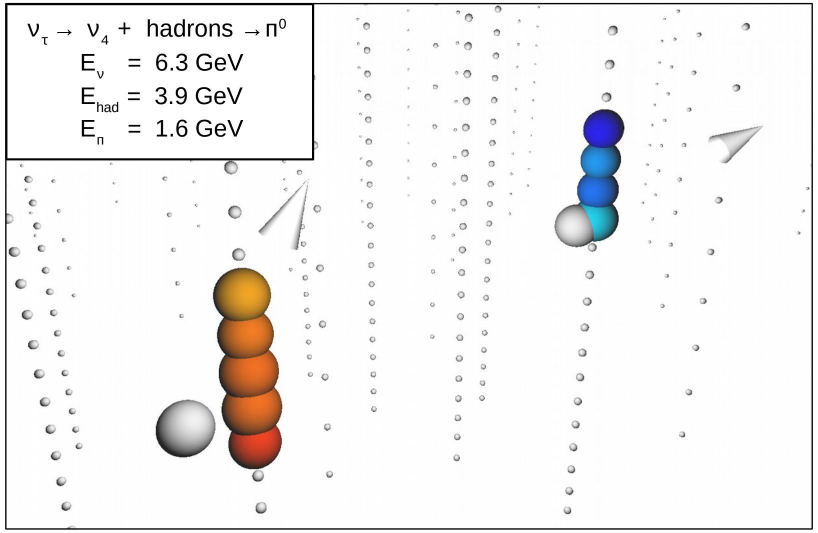
(Very) Low Energy Event Topologies



Track
(ν_μ-CC)

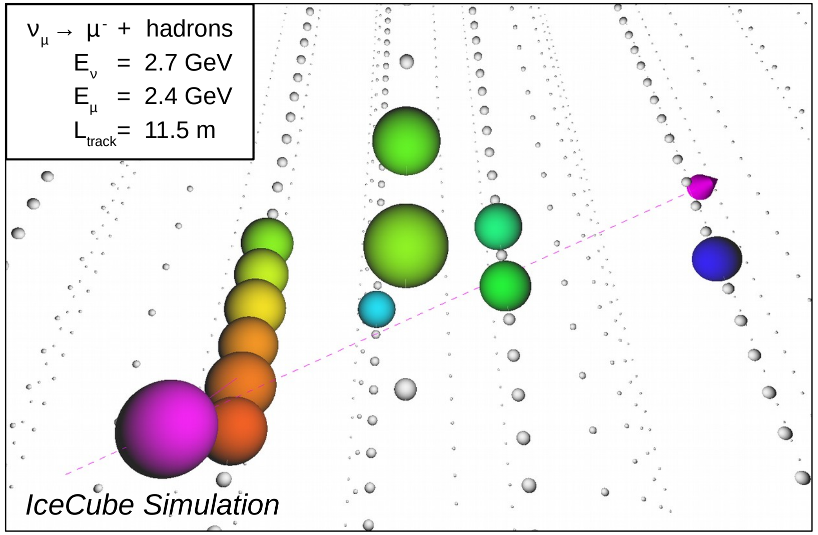


Cascade
(ν_e/ν_τ-CC and all ν NC)

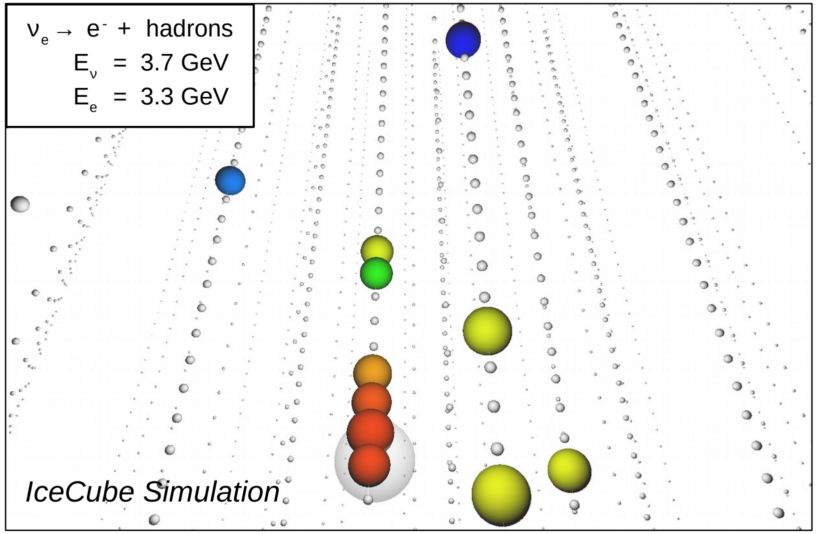


Double Cascade
(HNL)

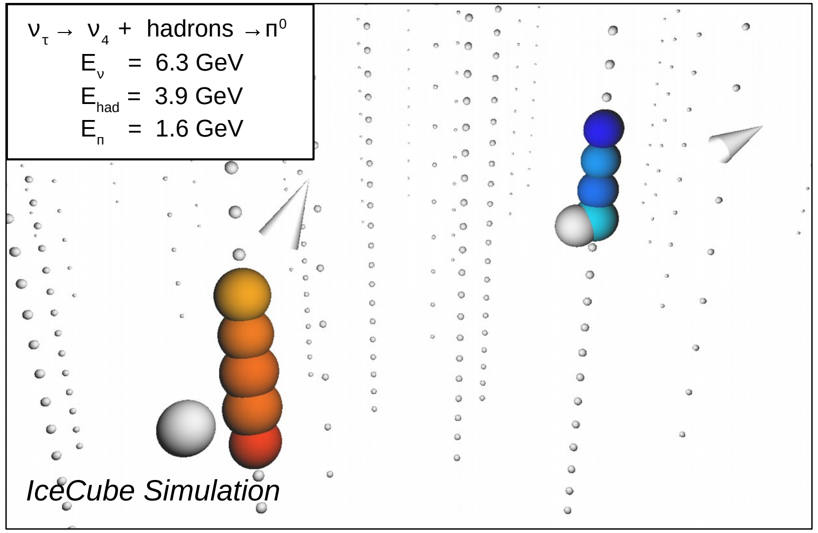
(Very) Low Energy Event Topologies



Track
(ν_μ-CC, ideal case)



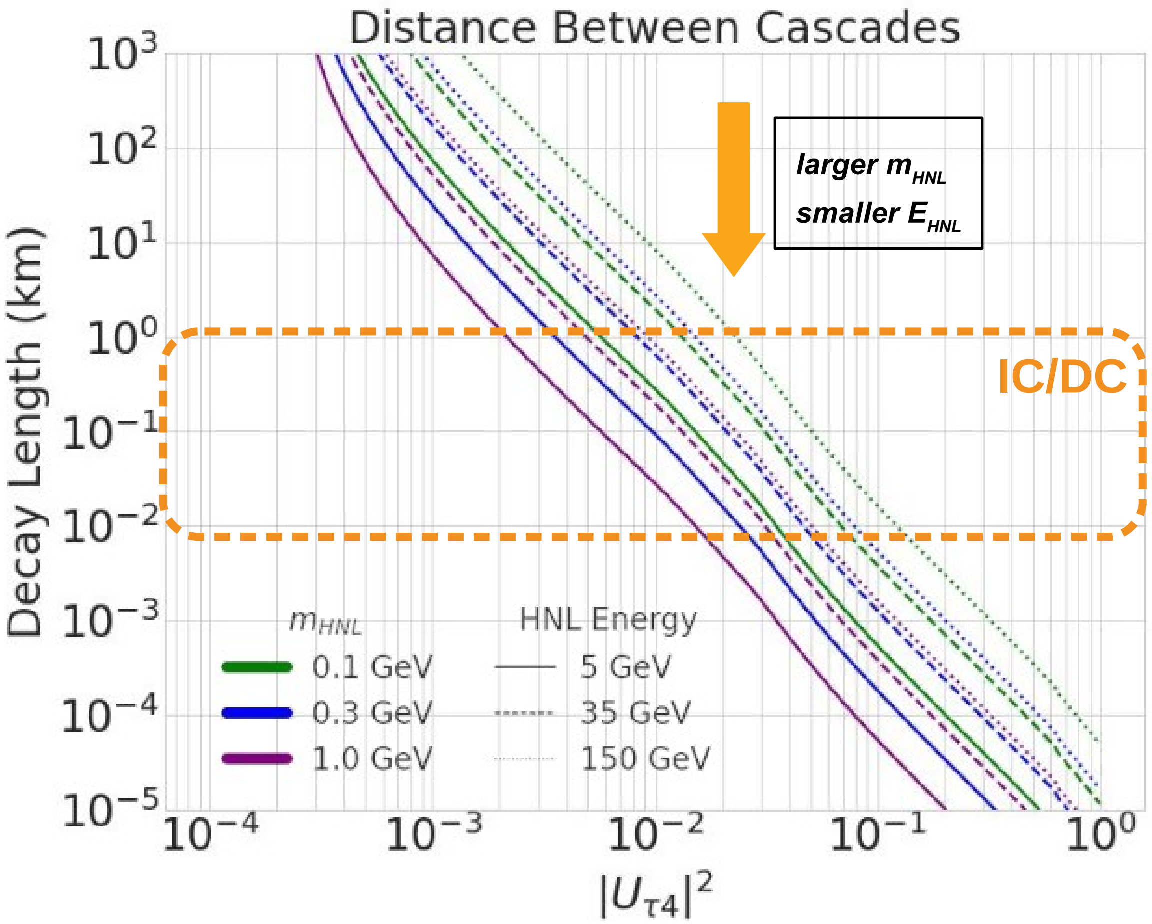
Cascade
(ν_e/ν_τ-CC, all ν NC,
some ν_μ-CC, many HNL)



Double Cascade
(HNL, ideal case)

HNL Analysis

- Oscillated atmospheric ν_τ events (~2.5 k in 10 years) provide opportunity to look for HNL events
- Dedicated HNL signal simulation (ν_τ - production channel) is being refined
- Low energy double cascade reconstruction is being optimized



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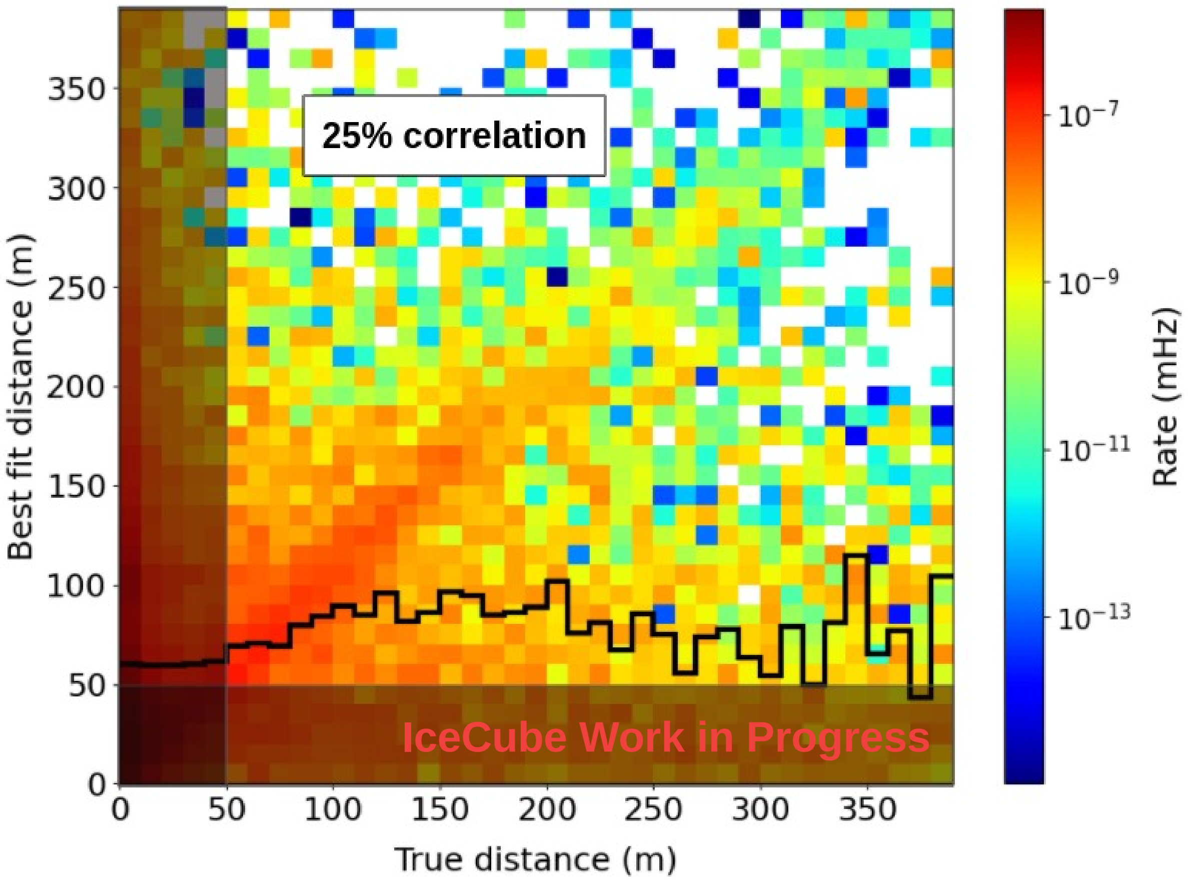
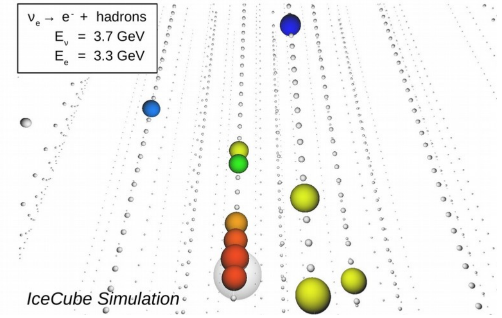
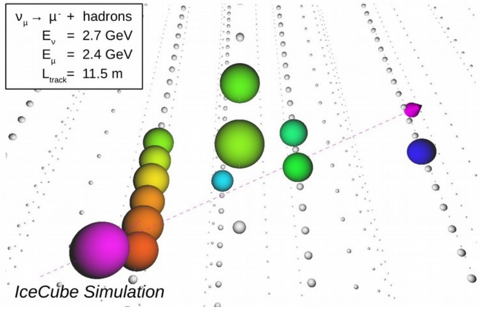
- Takeaway:
  - Few HNLs resolvable as double cascades (model effects/low energy/detector sparsity)
  - Intrinsic background (other flavors) can mimic double cascade signature (detector sparsity)
  - Isolating pure double-cascade is quite challenging

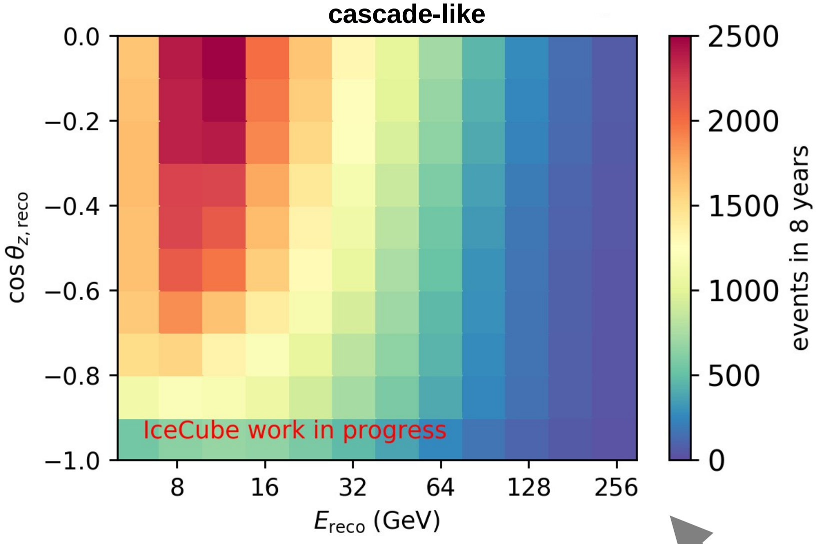
Reco vs. True Decay Length

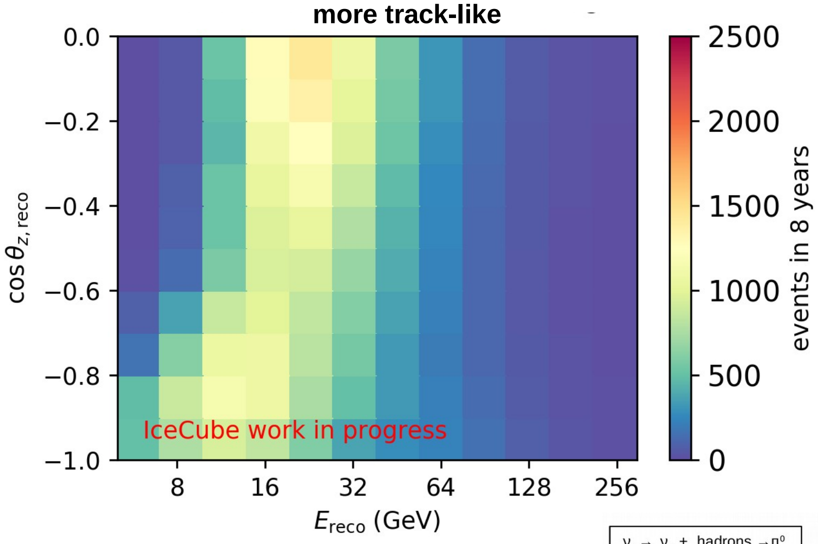


HNL Analysis Principle



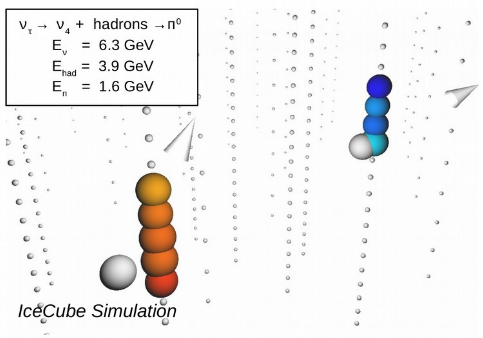



cascade-like


more track-like

double cascade-like

?



HNL Analysis Outlook

- Increasing $|U_{\tau 4}|^2$ increases HNL *signal* events on top of SM neutrino *background*

  → test $|U_{\tau 4}|^2$ for a few discrete HNL masses

  → produce first (ever) IceCube HNL result using 10 years of data

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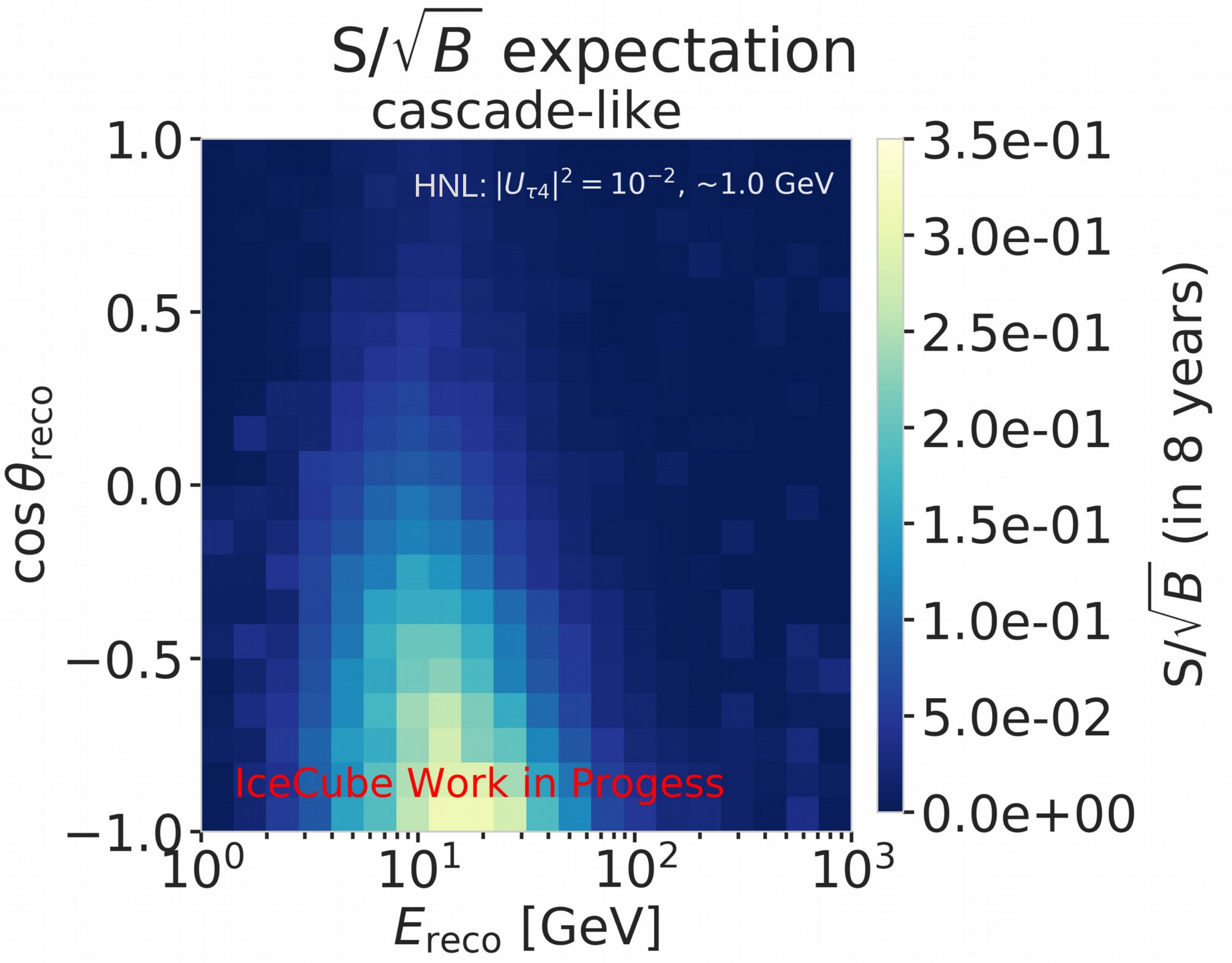
- Preliminary expectation for $|U_{\tau4}|^2=10^{-2}$, m_{HNL}=1 GeV:
  - Approximately 73%, 25%, and 2% would end up in the standard oscillation cascade-, more track-, and very track-like bin



Backup

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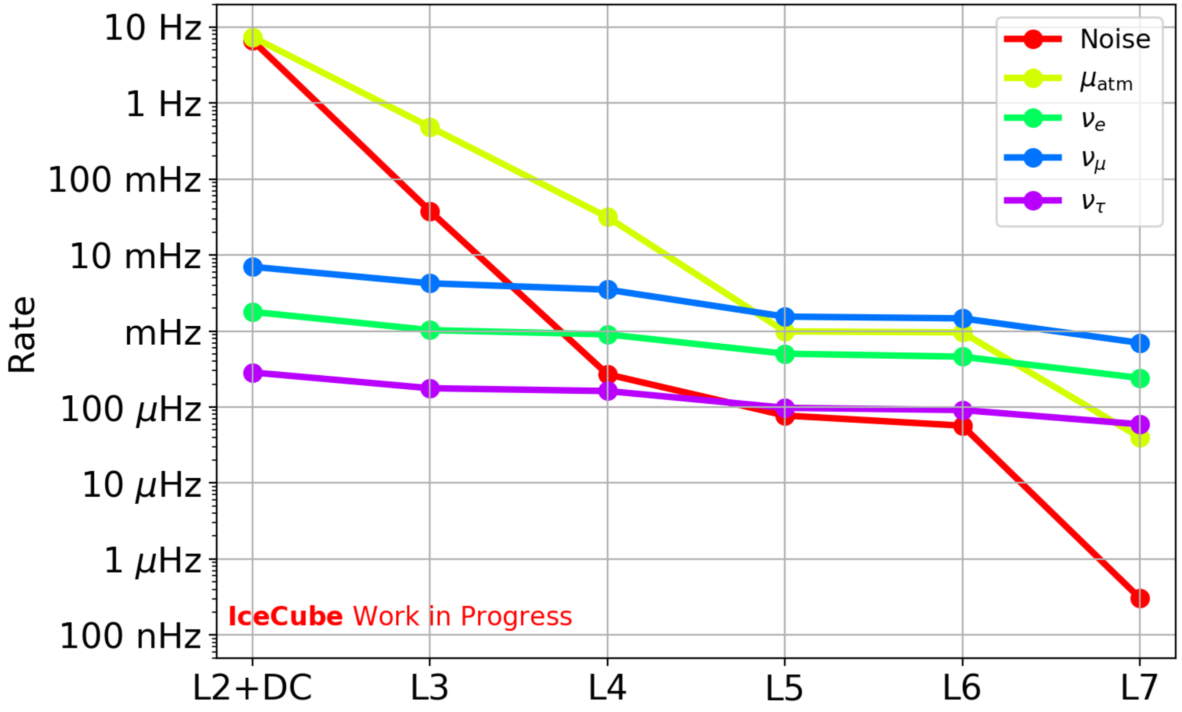

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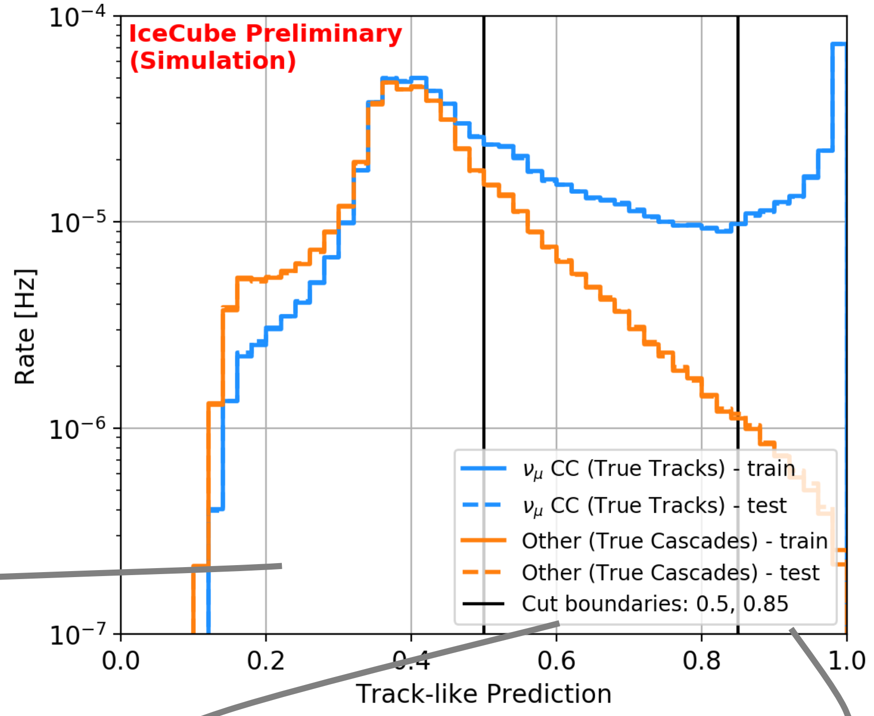
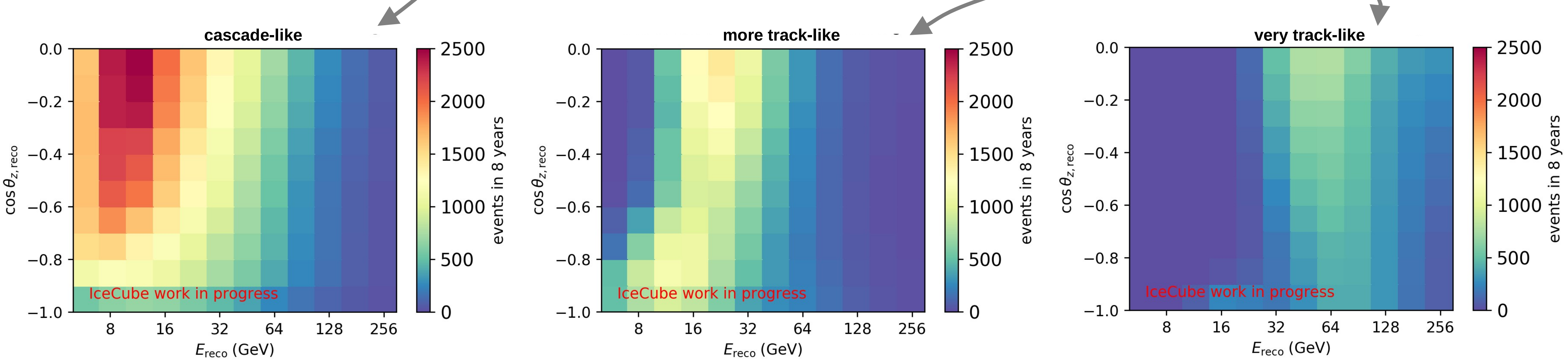
16%/72%/12% from $v_e/v_\mu/v_\tau$

Measuring Oscillations – PID

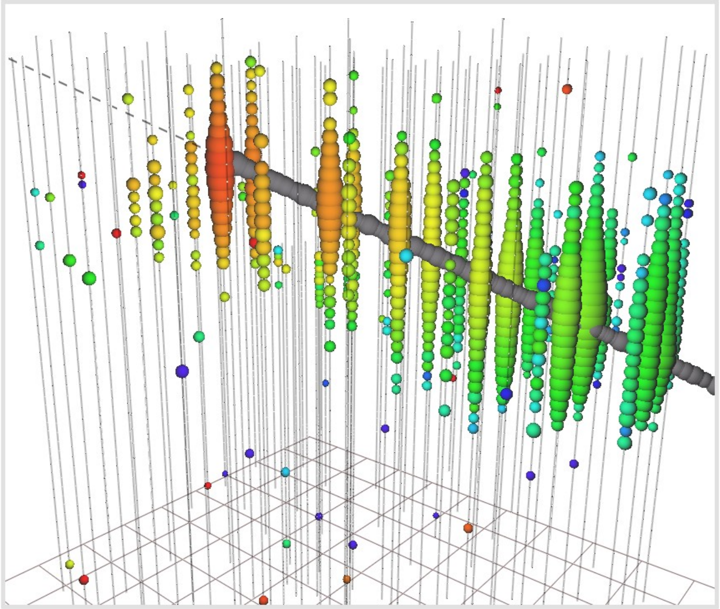
- BDT to distinguish tracks and cascades
  - Trained on reconstructed quantities like energy, tracklength and track, cascade
  - Trained on up-going, un-oscillated events





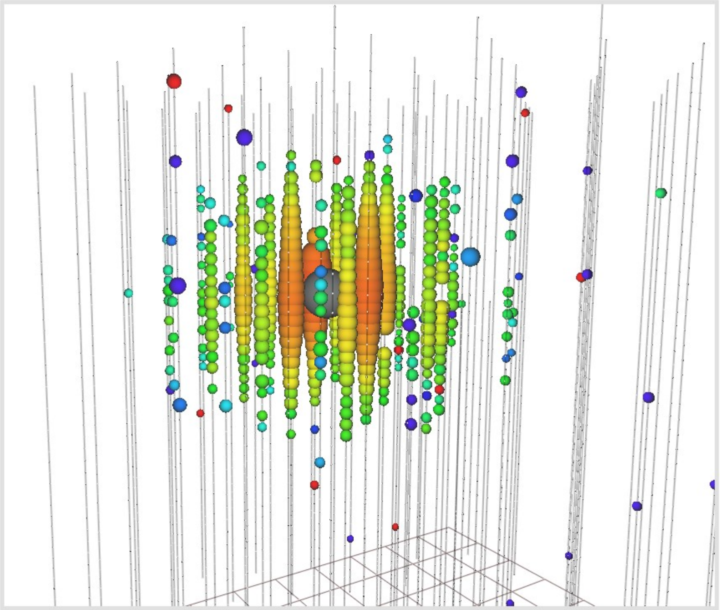
Measuring Oscillations – PID

~PeV energies!!



$$\nu_\mu + N \rightarrow \mu^- + X$$

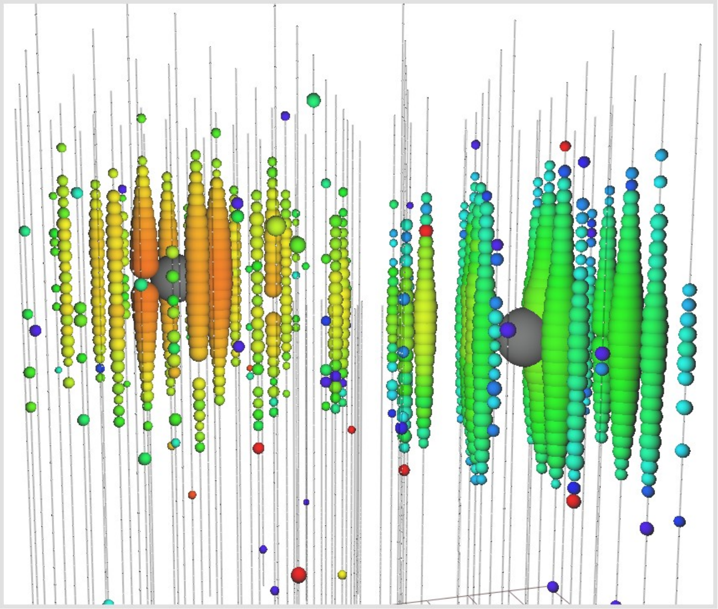
Track



$$\nu_x + N \rightarrow \nu_x + X$$

$$\nu_e + N \rightarrow e^- + X$$

Cascade



$$\nu_\tau + N \rightarrow \tau^- + X$$

$$\tau^- \rightarrow \nu_{\mu,e} + \mu^-/e^- + \nu_\tau \text{ or}$$

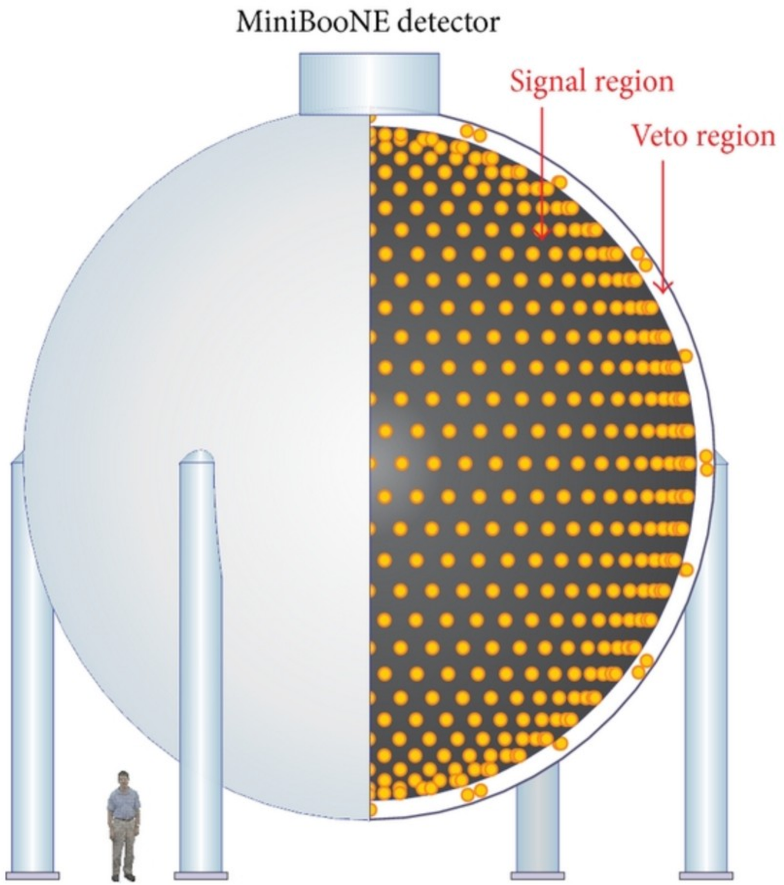
$$\tau^- \longrightarrow \nu_\tau + \pi^-/K^- + X$$

Double Cascade

MiniBooNE

- Most experimental results are consistent with oscillations in three neutrinos
  - **But:** There are unexplained experimental anomalies like the MiniBooNE low energy excess (LEE)

- **MiniBooNE**:
  - Intense neutrino beam (Booster Neutrino Beam, Fermilab)
  - Pure mineral oil (CH_2) Cherenkov/scintillation detector
  - Measured $\nu_e/\bar{\nu}_e$ CCQE events from ν_μ beam



MiniBooNE Detector

MiniBooNE low energy excess

- 18.75 x 10^{20} protons-on-target (neutrino mode)
- Total excess of 638.0+-132.8 electron-like events (4.8σ)
- Energy range: 200 MeV < E < 1250 MeV

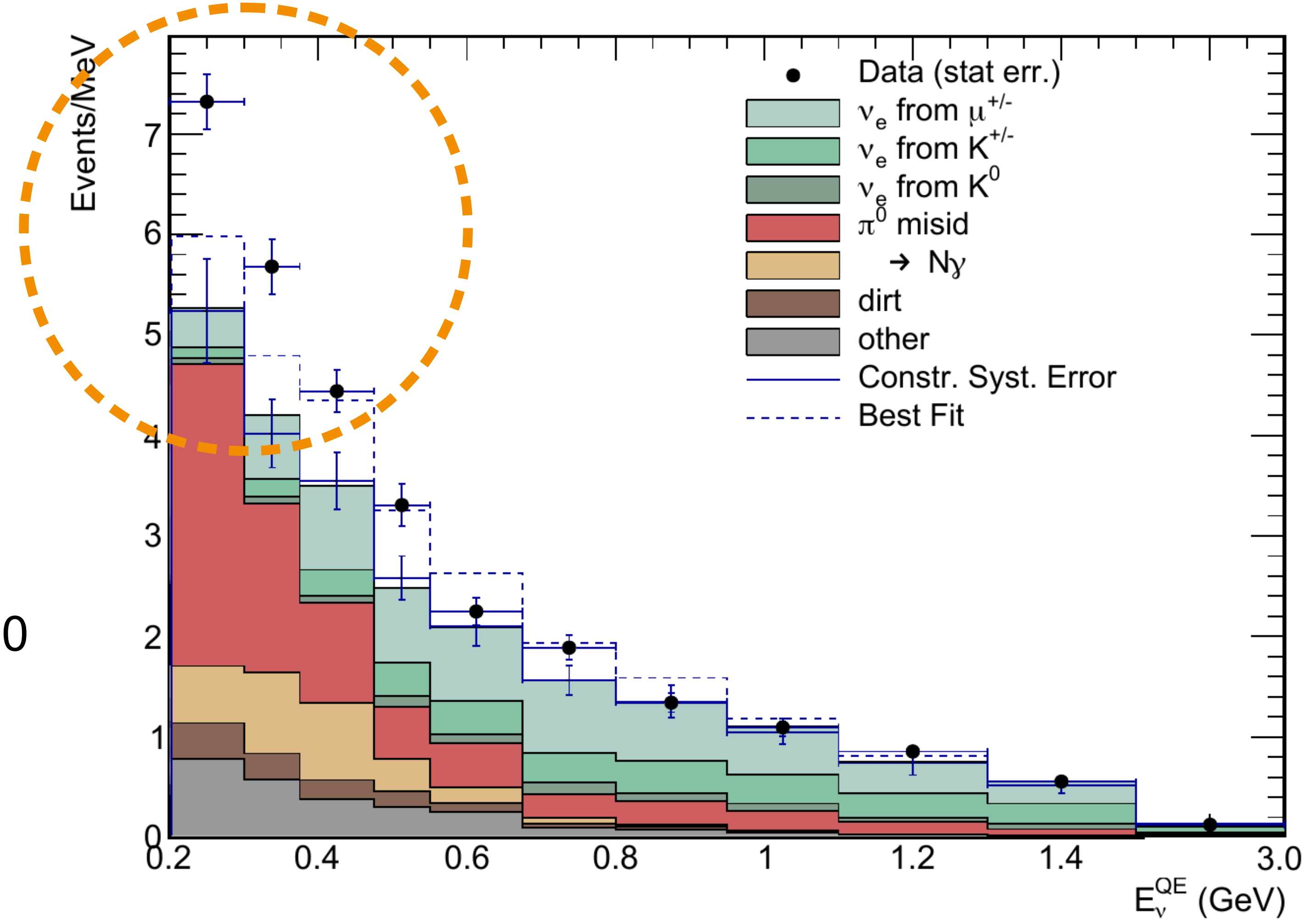


Table based reconstruction

- Poissonian likelihood:

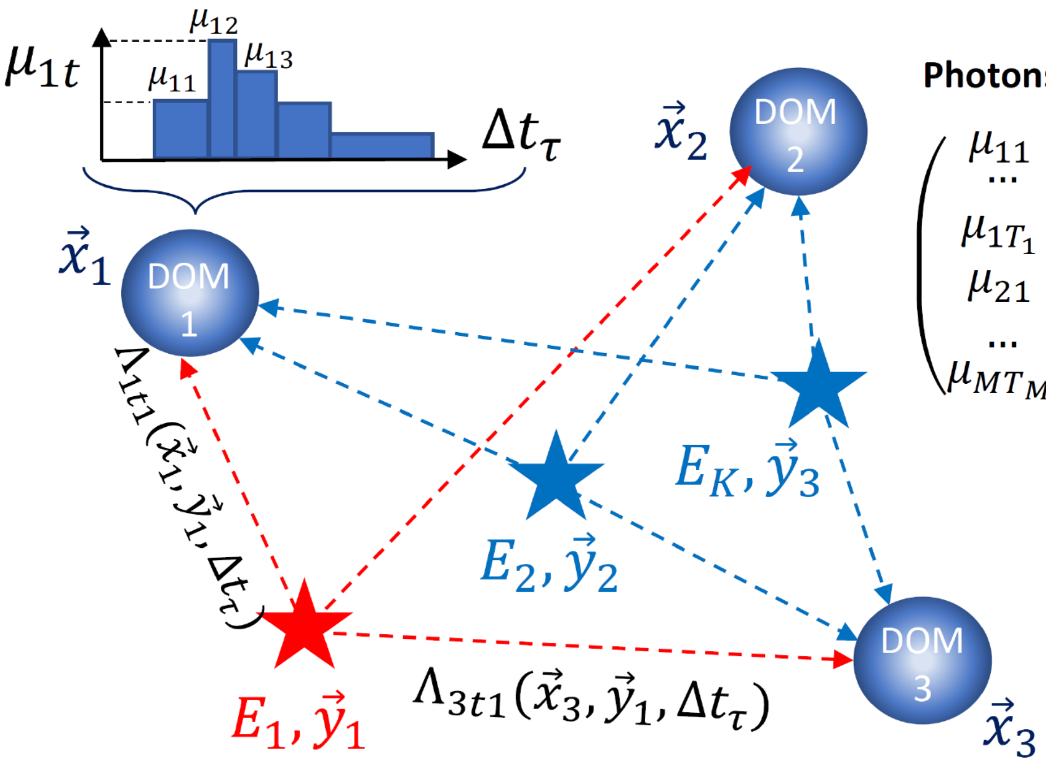
DOMs

exp. γ

$$\mathrm{LLH}_{\mathrm{mp}} = \sum_{i}^{M} \sum_{\tau}^{T_i} \left[N_{i\tau} \cdot \log(\mu_{i\tau}) - \mu_{i\tau} + \log\left(\Gamma(N_{i\tau} + 1)\right)\right]$$

obs. γ

times



Photons $\mu_{i\tau}$ in DOM $i = 1, \dots, M$ and bin $\tau = 1, \dots T_i$:

$$\begin{pmatrix}\mu_{11}\\ \cdots \\ \mu_{1T_1}\\ \mu_{21}\\ \cdots \\ \mu_{MT_M}\end{pmatrix} = \begin{pmatrix}\Lambda_{111} & \cdots & \Lambda_{11K}\\ \vdots & \ddots & \vdots\\ \Lambda_{1T1} & \cdots & \Lambda_{1TK}\\ \Lambda_{211} & \cdots & \Lambda_{21K}\\ \vdots & \ddots & \vdots\\ \Lambda_{MT1} & \cdots & \Lambda_{MTK}\end{pmatrix} \begin{pmatrix}E_1\\ \cdots\\ E_K\end{pmatrix} + \begin{pmatrix}n_1\\ \cdots\\ n_K\end{pmatrix}$$

● **DOMs**
★ **cascade-like energy loss**
★ **muon-like energy loss**

Likelihood

- **Poissonian** likelihood:
  - Compare number of observed PE (**n**) per DOM per time slice to expected number (**y**) for given event hypothesis

$$p(n/\mu)=\frac{\mu^n\cdot e^{-\mu}}{n!}$$

total expected charge = expected + noise

$$L=\prod_{i\in DOMs}\prod_{j\in time\,bins}\frac{(\mu_{i,j}+\rho_{i,j})^{n_{i,j}}\cdot e^{-(\mu_{i,j}+\rho_{i,j})}}{n_{i,j}!}$$

Negative Logarithm (function to minimize)

$$\ln(L)=\sum_{i\in DOMs}\sum_{j\in time\,bins}n_{i,j}\cdot\ln(\mu_{i,j}+\rho_{i,j})-\mu_{i,j}-\rho_{i,j}-\ln(n_{i,j}!)$$