ICECUBE
NEUTRINO OBSERVATORY

ICECUBE UPGRADE

ICECUBE GEN2

Probing
Neutrino Echoes
In the IceCube Upgrade

Kareem Farrag International Centre for Hadron Astrophysics

20th November, 2024, for the 2nd Annual Conference of Transformative Research Areas (A)

A01: Neutrino

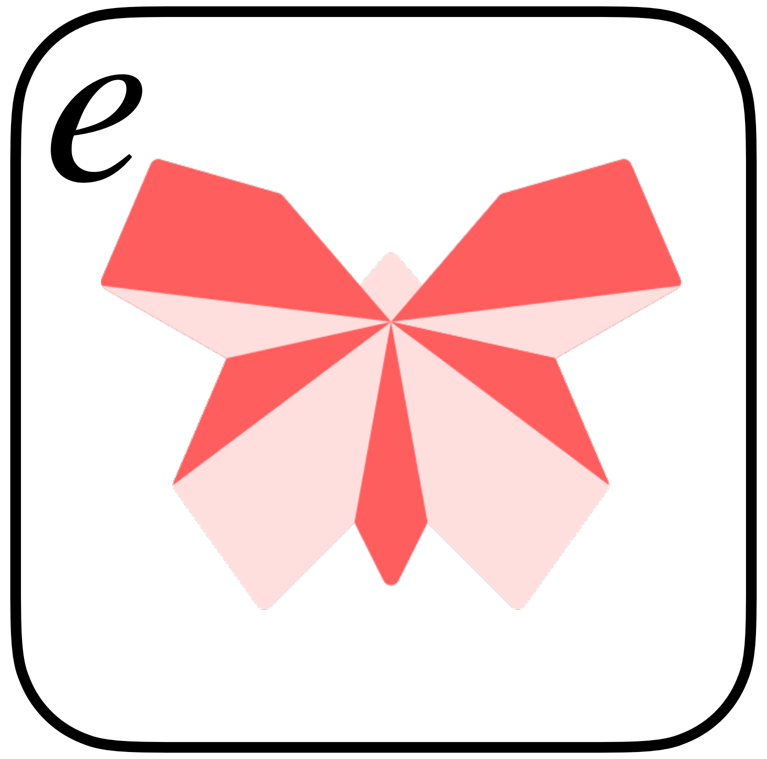
千葉大学
ハドロン宇宙国際研究センター
ICEHAP
International Center for Hadron Astrophysics

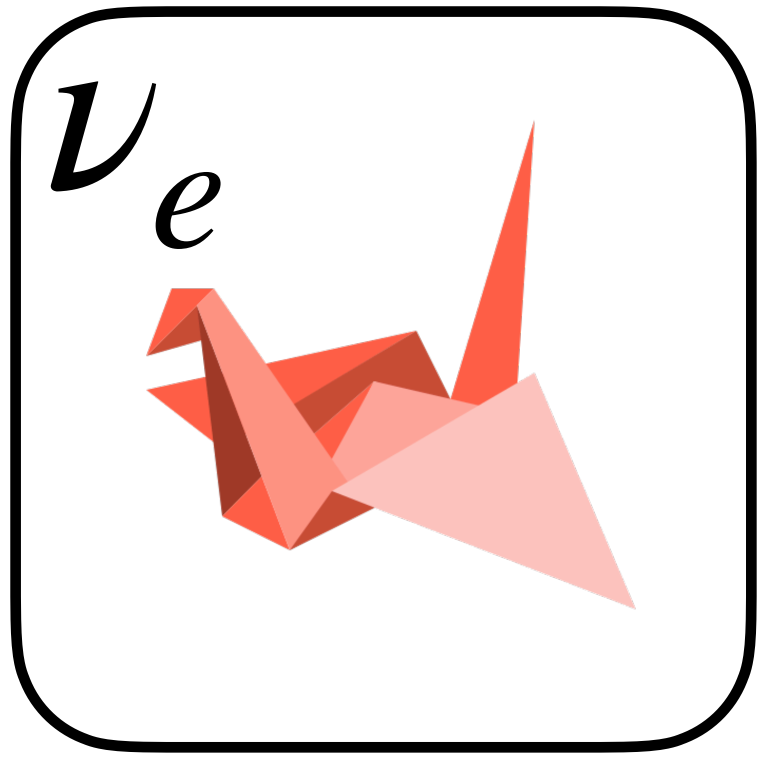
* cosmology/BSM provides tighter constraints

Tau neutrinos are the least studied

CODATA/PDG

$\frac{\sigma(m_e)}{m_e} \sim 3.9 \times 10^{-9}$



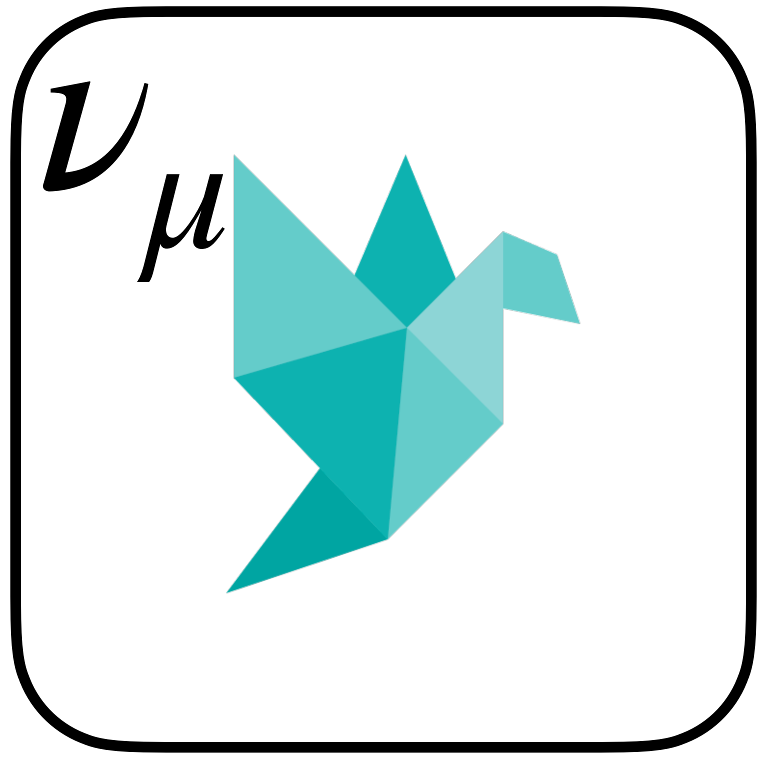


$m_{\nu_e} < 2.2\ eV/c^2$

KATRIN

PDG (g-2)

$\frac{\sigma(m_\mu)}{m_\mu} \sim 2.8 \times 10^{-9}$

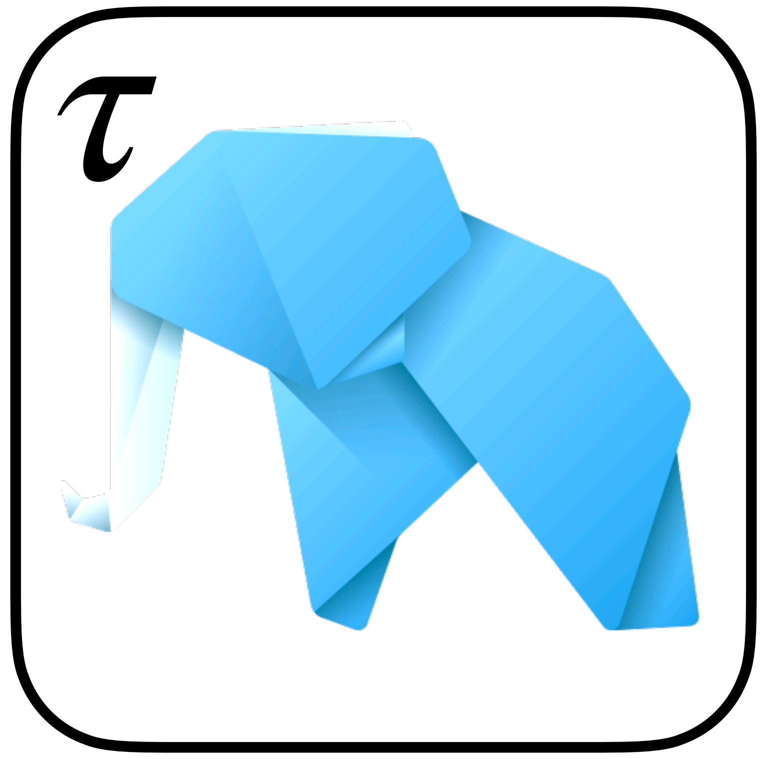


$m_{\nu_\mu} < 0.19\ MeV/c^2$

π decay/Osc.

PDG (B factory)

$\frac{\sigma(m_\tau)}{m_\tau} \sim 6.8 \times 10^{-5}$



$m_{\nu_\tau} < 18.2\ MeV/c^2$

OPERA/ALEPH (τ decay)

LEP/Tevatron

$\frac{\sigma(m_W)}{m_W} \sim 1.5 \times 10^{-4}$

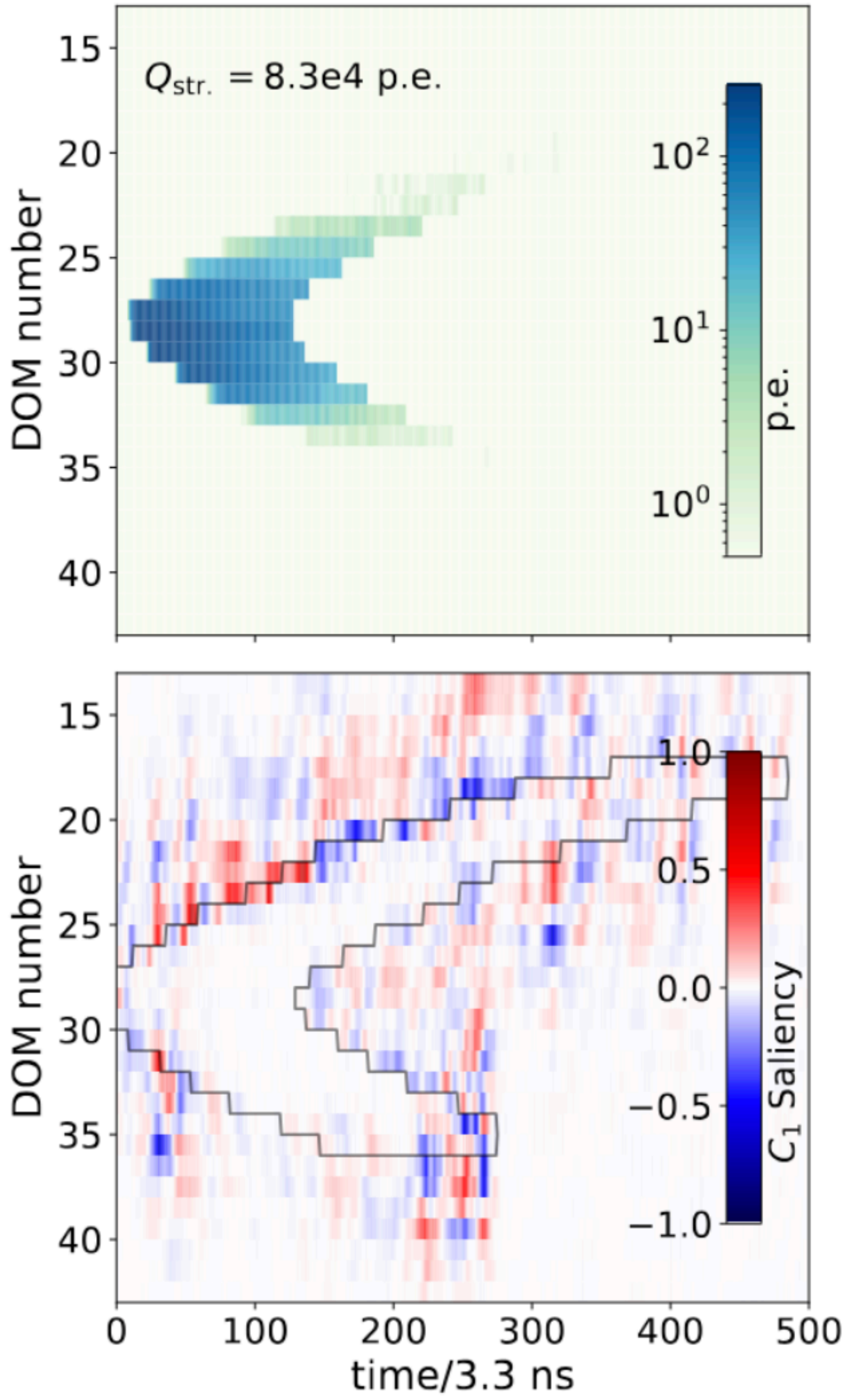
$\frac{\sigma(m_Z)}{m_Z} \sim 2.3 \times 10^{-5}$

LEP

* cosmology/BSM provides tighter constraints

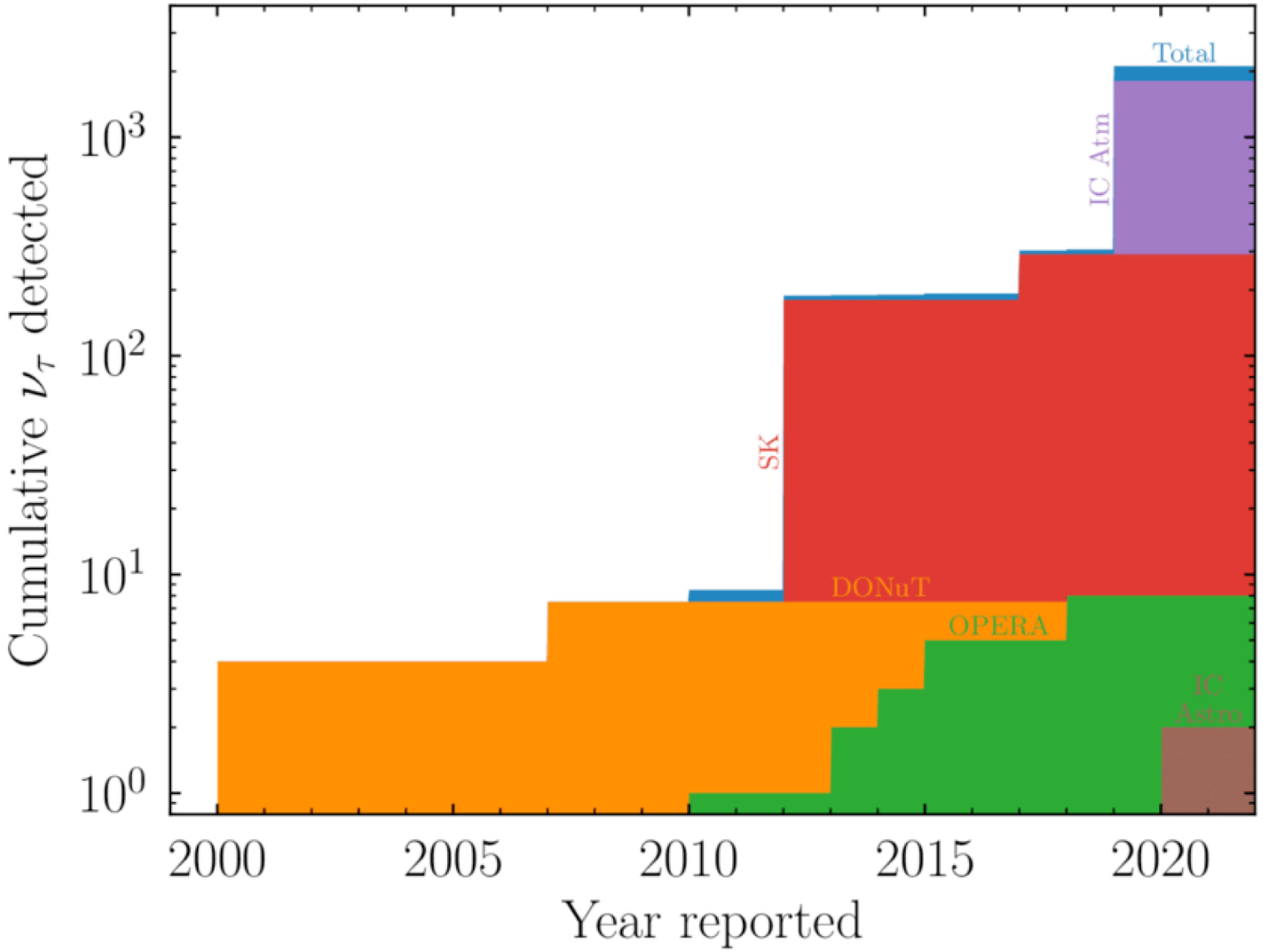
In IceCube we recently saw seven ν_τ

- 9.7 years of data
- Seven ν_τ candidates identified using convolutional neural network with parent neutrino energies between [20 TeV, 1 PeV]
- 0.5 event expected background dominated by ν_e, ν_μ
- Absence of astrophysical ντ ruled out at the 5σ level
- Flux measurement consistent with astrophysical neutrino flux measurements and neutrino oscillations



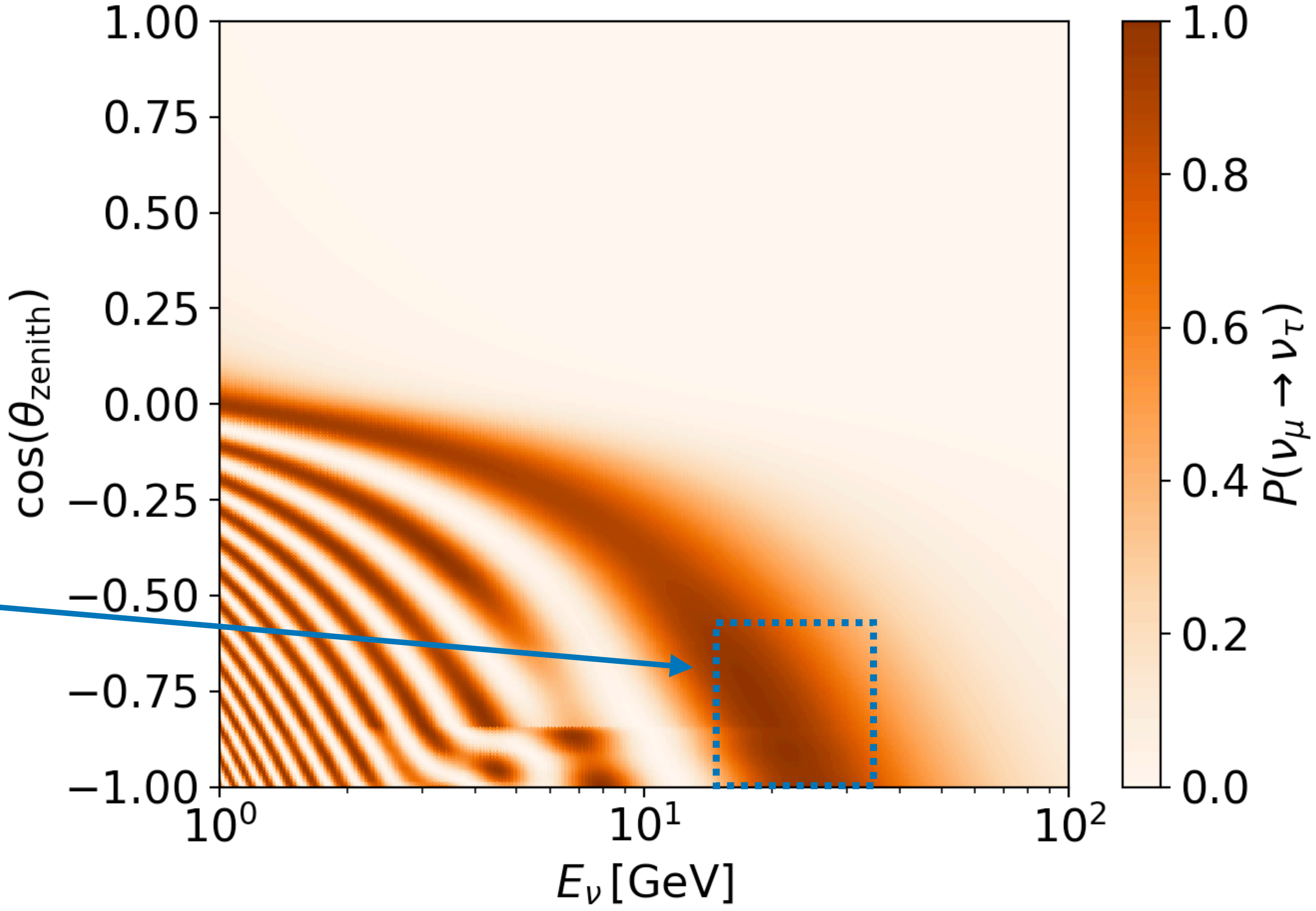
Atmospheric Mixing means we might expect $(\nu_e : \nu_\mu : \nu_\tau) \sim (1 : 1 : 1)$

- To date, ~ 2000 ν_τ candidates have been seen across all experiments over the past two decades, with only O(20) being verified on an event by event basis



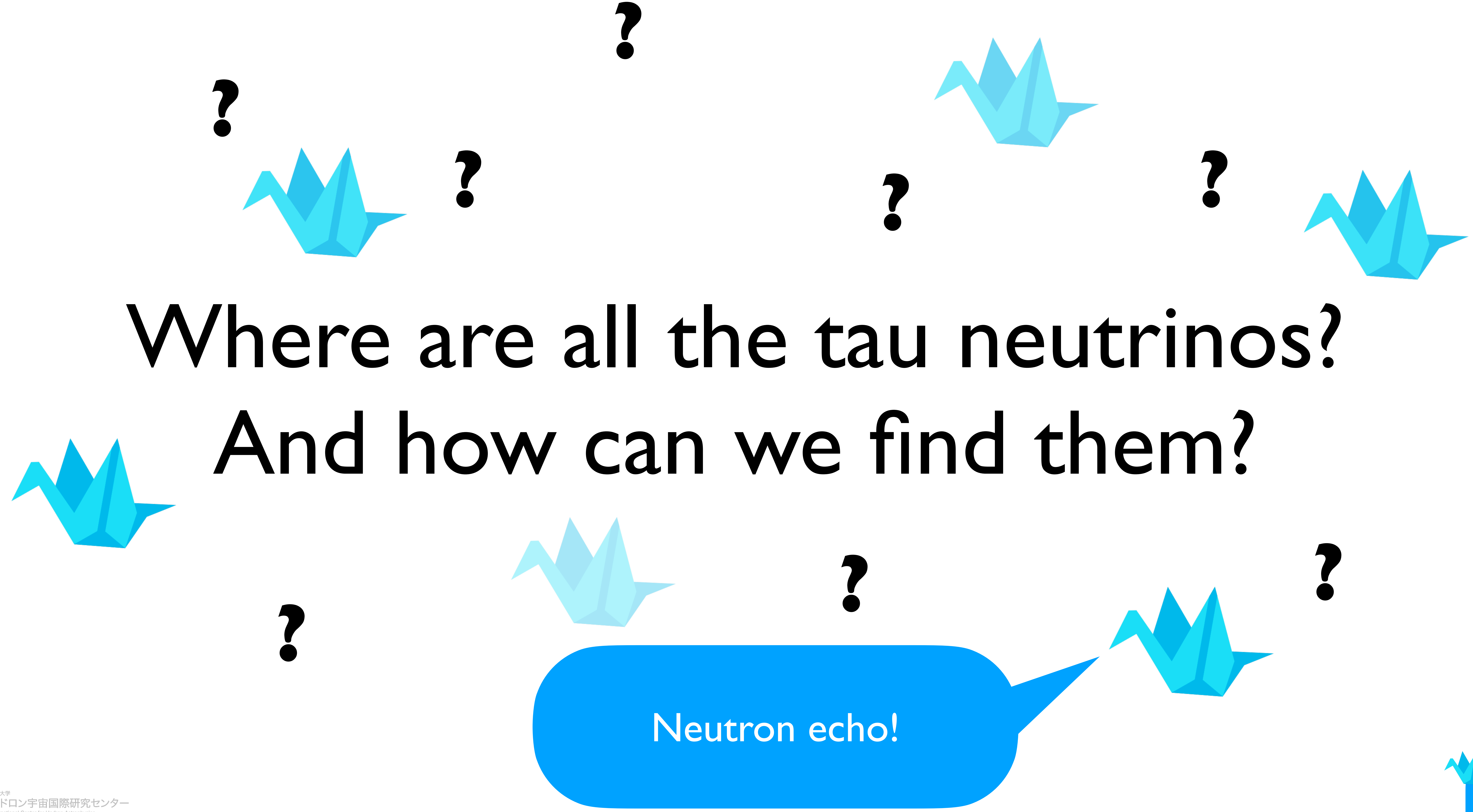
Atmospheric Mixing means we might expect $(\nu_e : \nu_\mu : \nu_\tau) \sim (1:1:1)$

- We should see from atmospheric oscillation almost equal amounts of $\nu_e : \nu_\mu : \nu_\tau$,
- Large ν_τ appearance at ~ 20 GeV, right in the DeepCore energy range



Where are all the tau neutrinos?
And how can we find them?

Where are all the tau neutrinos?
And how can we find them?



IceCube Upgrade - Deploying in 2025!


Credit: N. Shimizu/ICEHAP

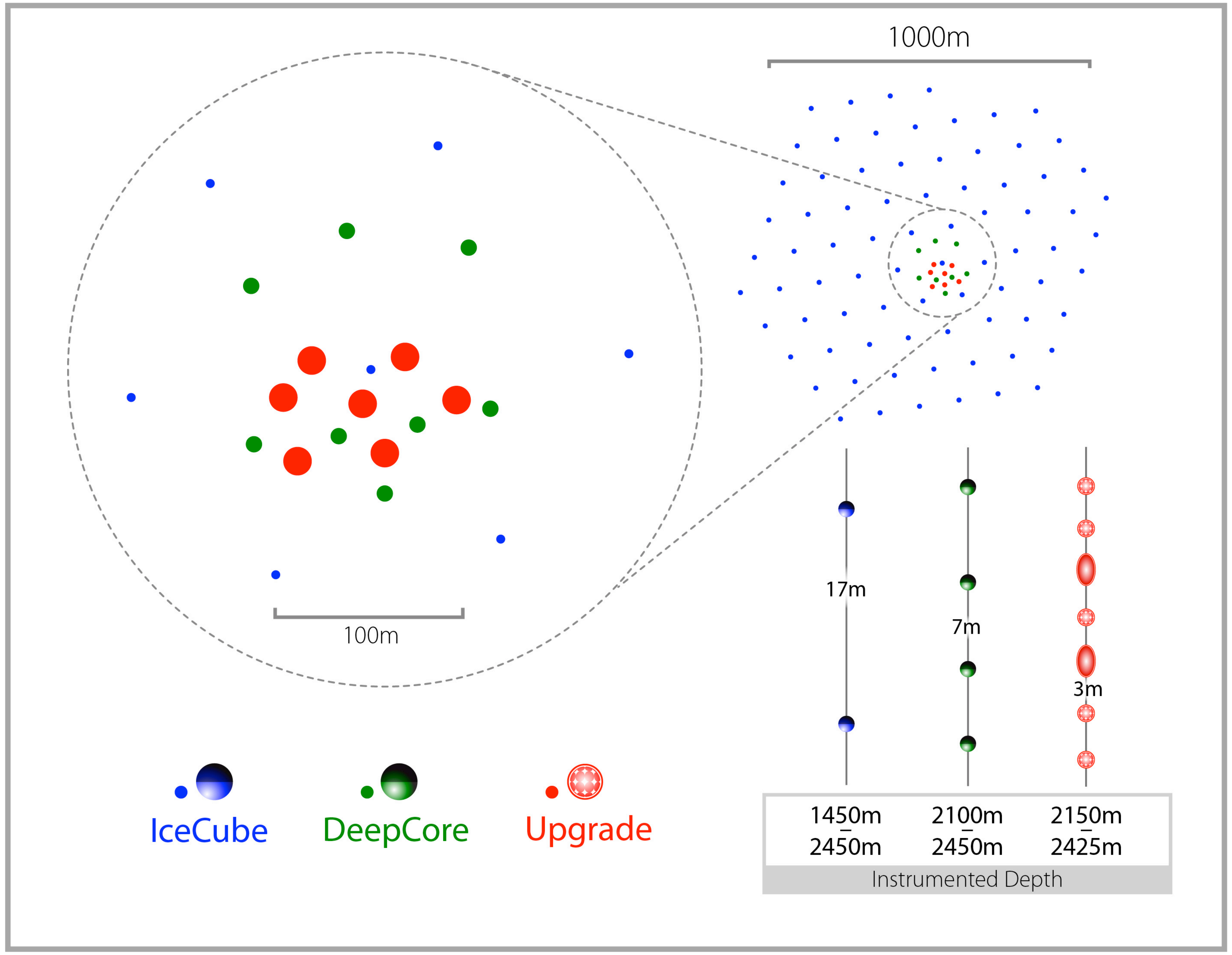
D-Egg

2x 8” HQE PMTs & dia. 30 cm

Developed in Chiba

~ 300 D-Eggs

D-Egg Posters by Y.Morii, Y.Kobayashi, R.Hmaid




Credit: S. Niedworok/DESY

mDOM

24x 3” PMTs & dia. 36 cm

Developed in Germany

~ 400 mDOMs

IceCube Upgrade - Deploying in 2025!

Chiba Team

D-Eggs on their way to the South Pole!

See Next talk by T. Tsuji
Y. Kasai for Gen-2
Prototype

Poster on FOM by
T.Kobayashi

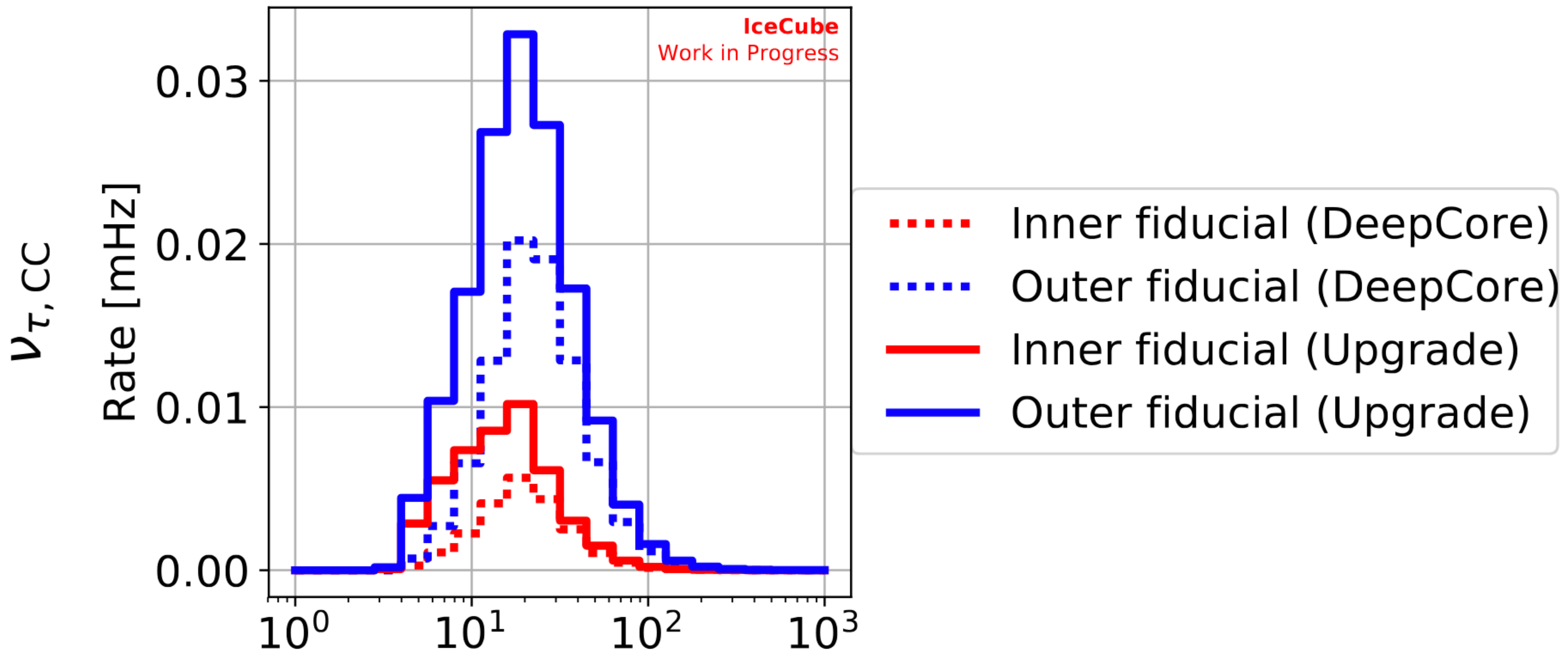
IceCube Upgrade - Deploying in 2025!

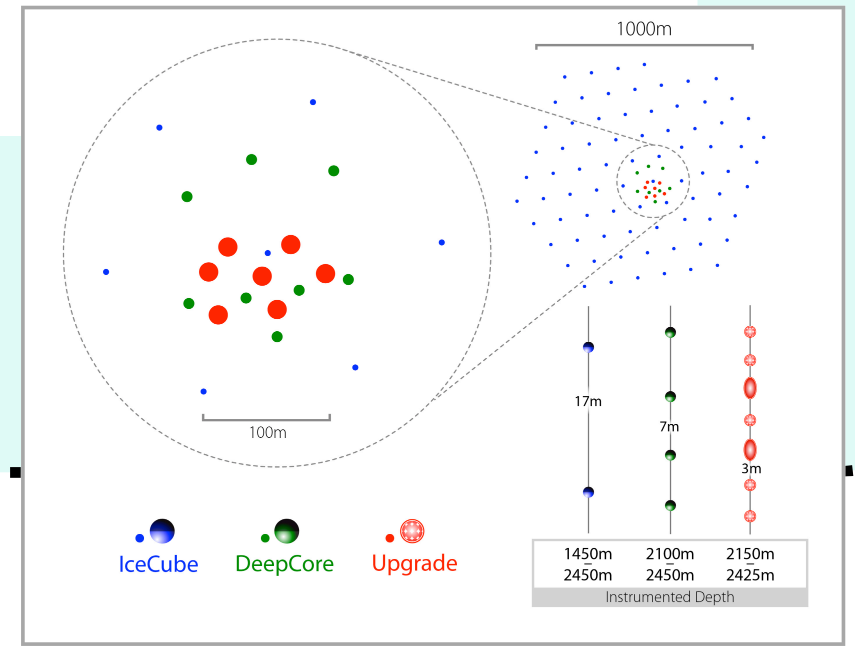
In particular for $\nu_\tau \ CC$:

Up to 2x better
energy reconstruction thanks to
10 x effective photocathode area per
unit volume

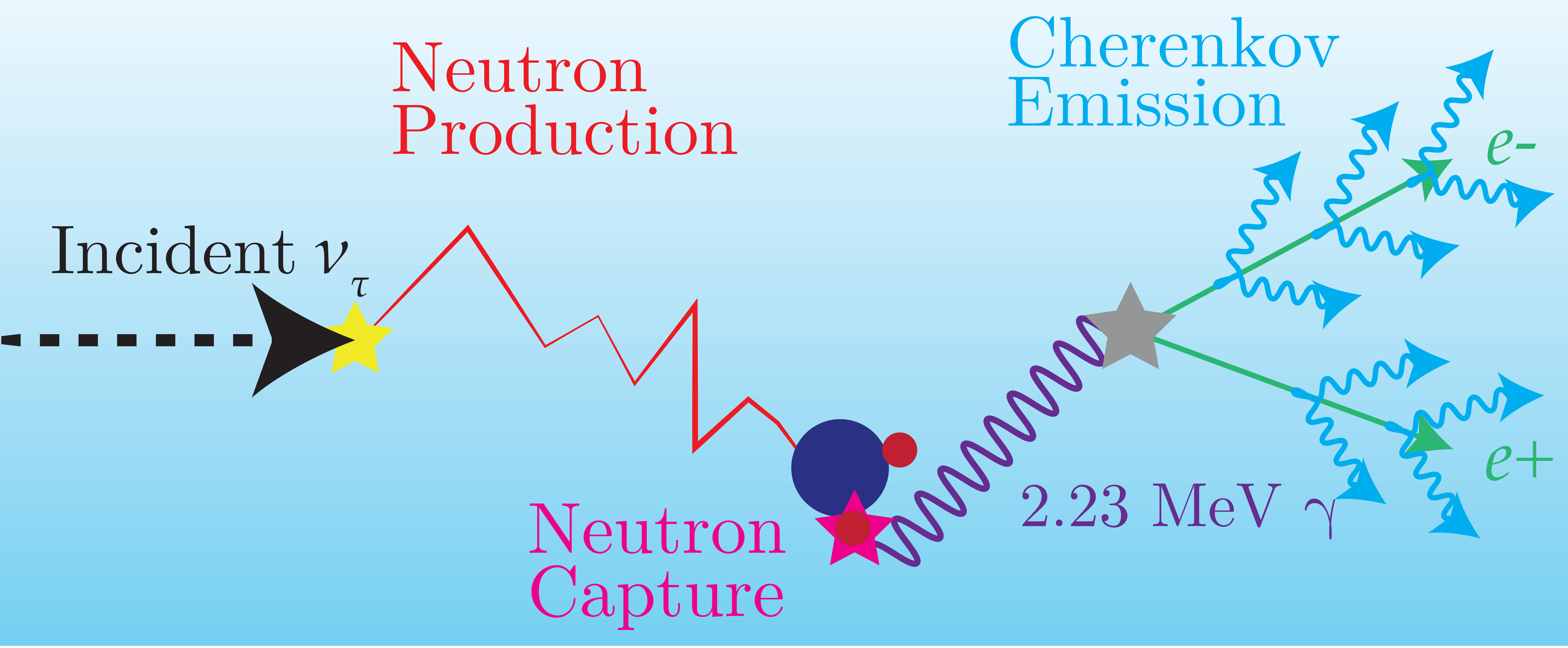
3x or better angular resolution

Inner = Cylinder(r=50m, h=275m)
Outer=Cylinder(r=145m, h=275m)





Neutron Echo



Incident ν_τ

Neutron Production

Neutron Capture

2.23 MeV γ

Cherenkov Emission

e-

e+

We need to understand some key features about the microphysics

Neutron Capture

Gamma emission

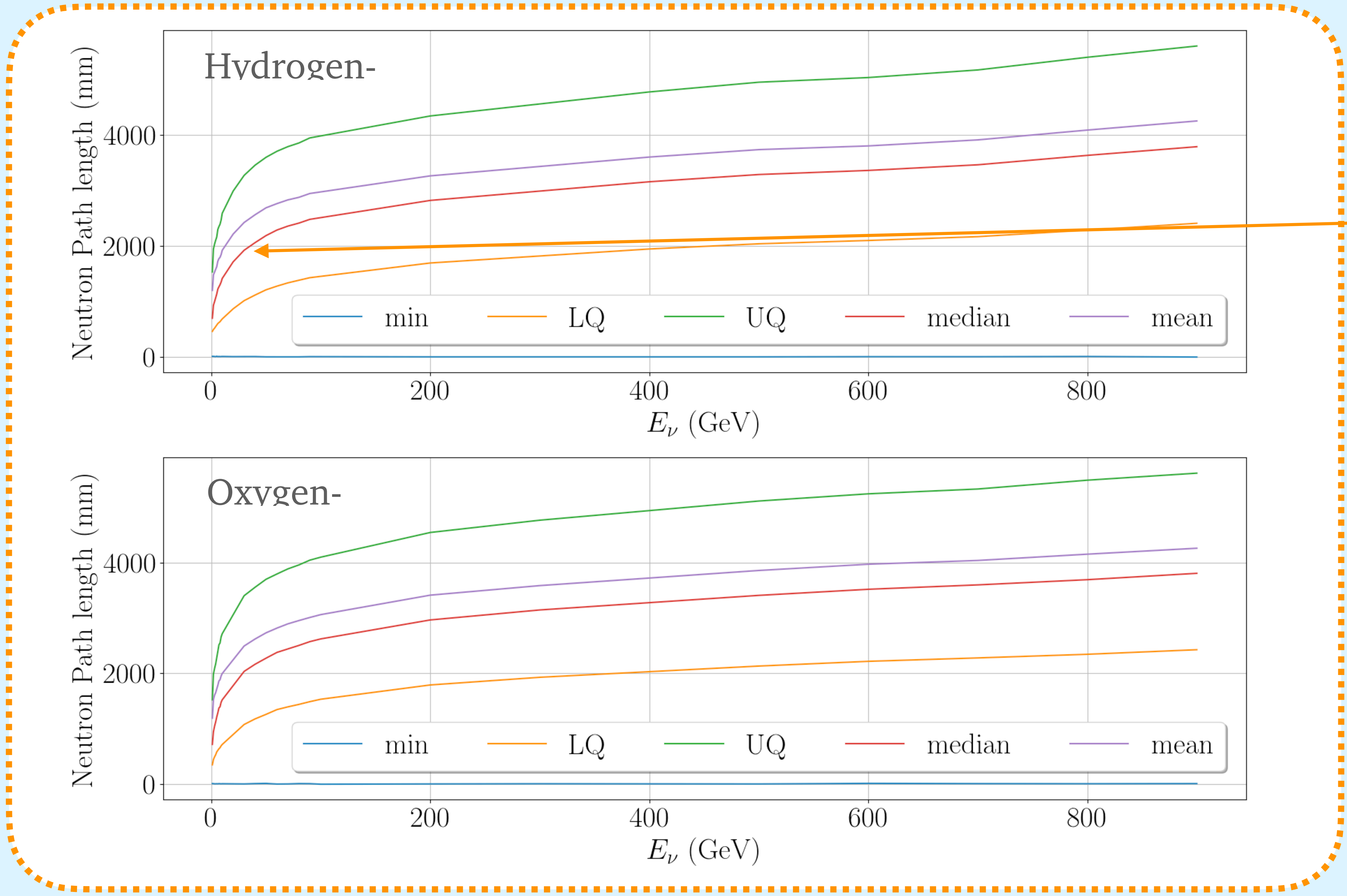
Cherenkov emission

We need to understand some key features about the microphysics

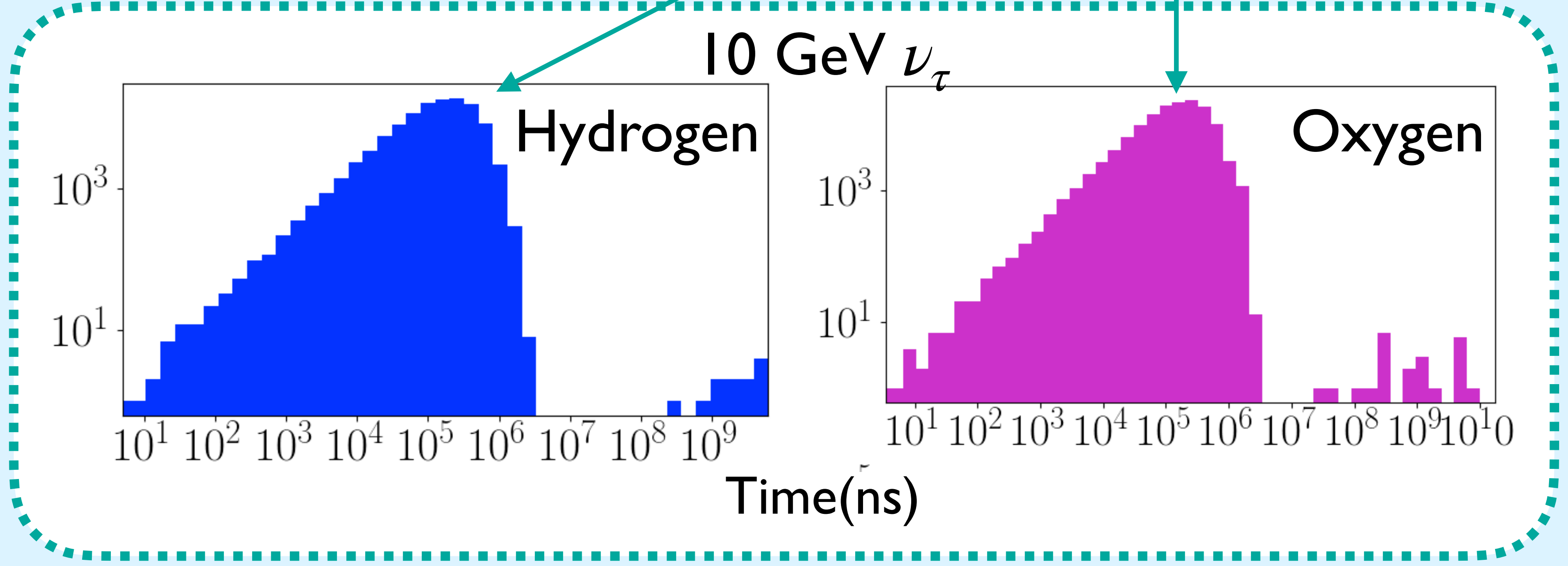
Neutron Capture

Gamma emission

Cherenkov emission



- From ν_τ interactions simulated with GENIEv3 and GEANT4, we found that neutrons peak capture time occurs around $\gtrsim$1m metres from the neutrino vertex above ~O(10 GeV) 220μs after the primary neutrino interaction as expected

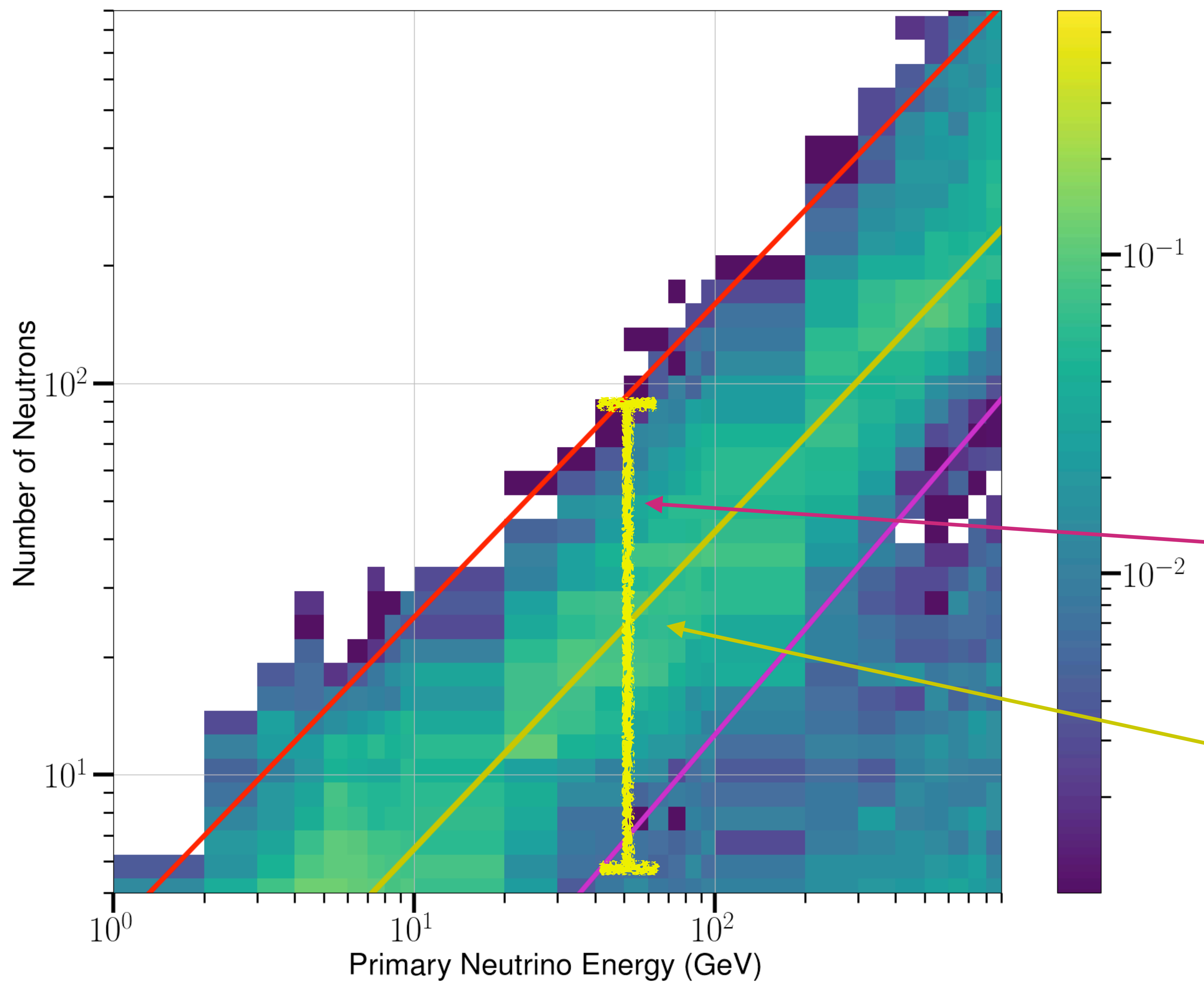


We need to understand some key features about the microphysics

Neutron Capture

Gamma emission

Cherenkov emission



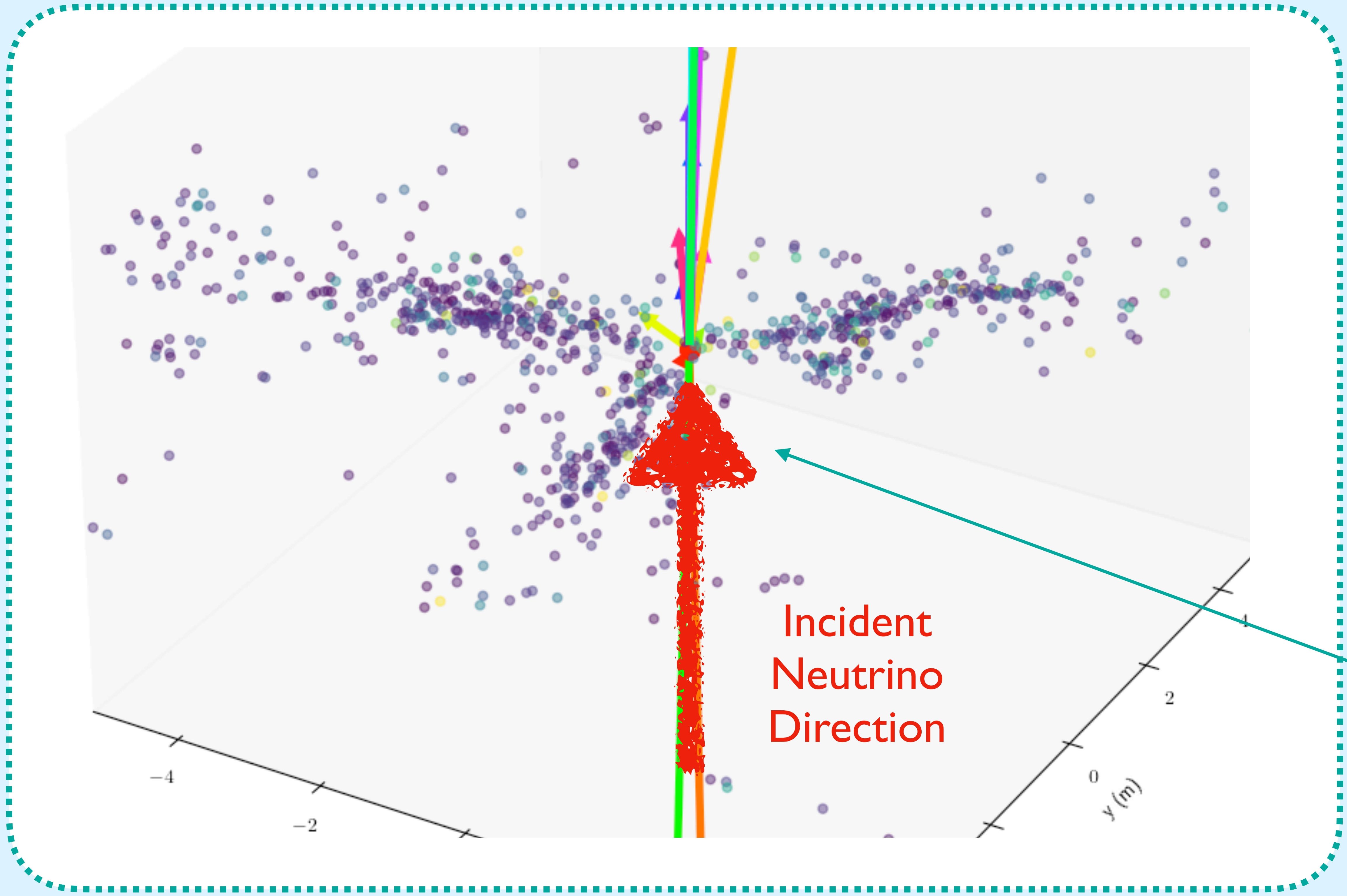
- From ν_τ interactions simulated with GENIEv3 and GEANT4, we found that neutrons peak capture time occurs around >1m metres from the neutrino vertex above 10GeV 220μs after the primary neutrino interaction as expected

- Due to the decay products + systematic uncertainty, per neutrino interaction, the neutron multiplicity (according to simulation varies by an order of magnitude)

Fit (yellow): $\langle N_N \rangle = \left(\frac{E_\nu}{GeV}\right)^{0.81}$

We need to understand some key features about the microphysics

Neutron Capture Gamma emission Cherenkov emission



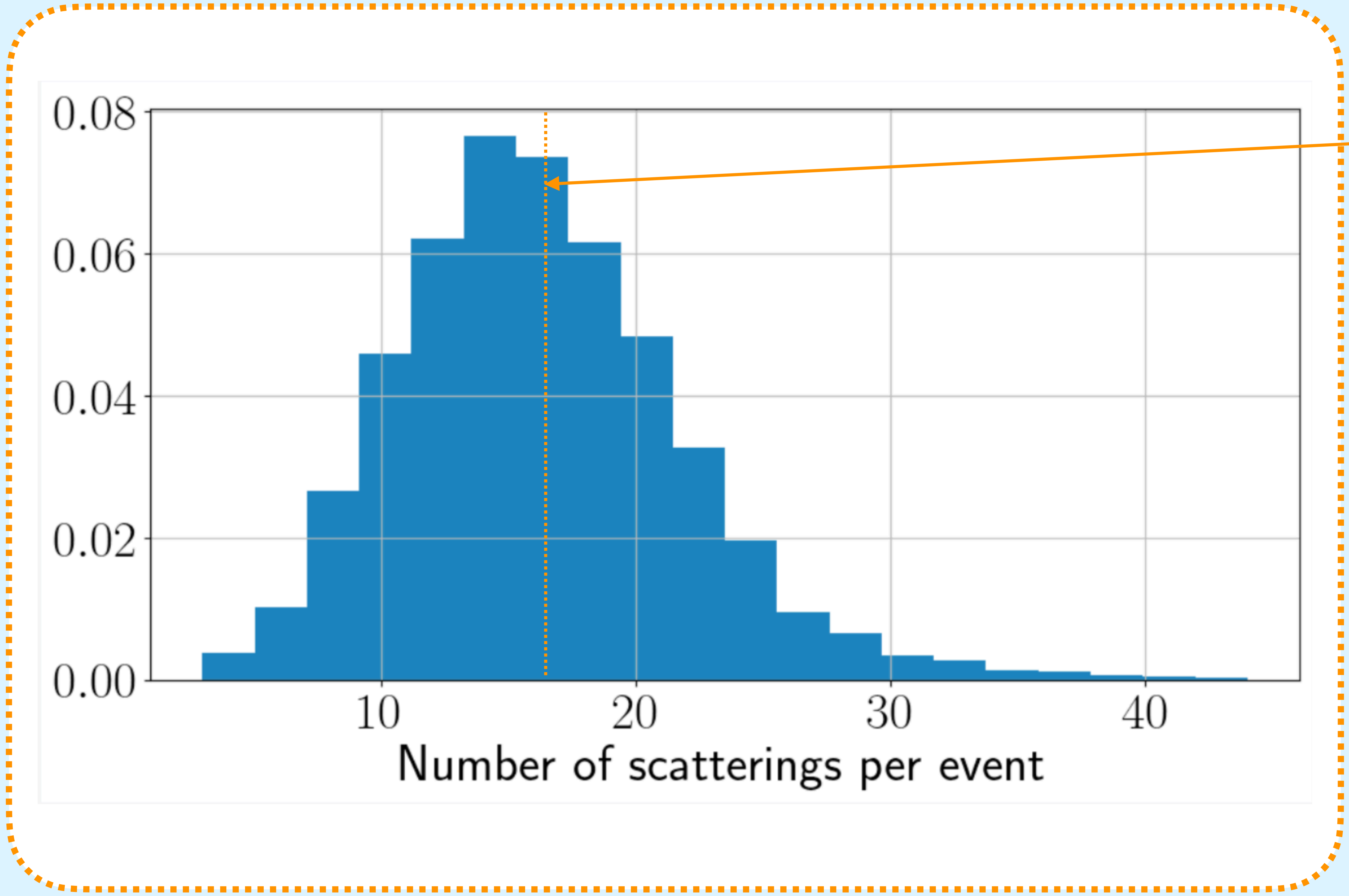
- From ν_τ interactions simulated with GENIEv3 and GEANT4, we found that neutrons peak capture time occurs around >1m metres from the neutrino vertex above 10GeV 220μs after the primary neutrino interaction as expected
- Thanks to the decay products per neutrino interaction, the neutron multiplicity (according to simulation varies by an order of magnitude)
- Finally, we learn that the neutron captures tend to Jacobian peak with respect, particularly at higher energy to the primary neutrino vertex

We need to understand some key features about the microphysics

Neutron Capture

Gamma emission

Cherenkov emission



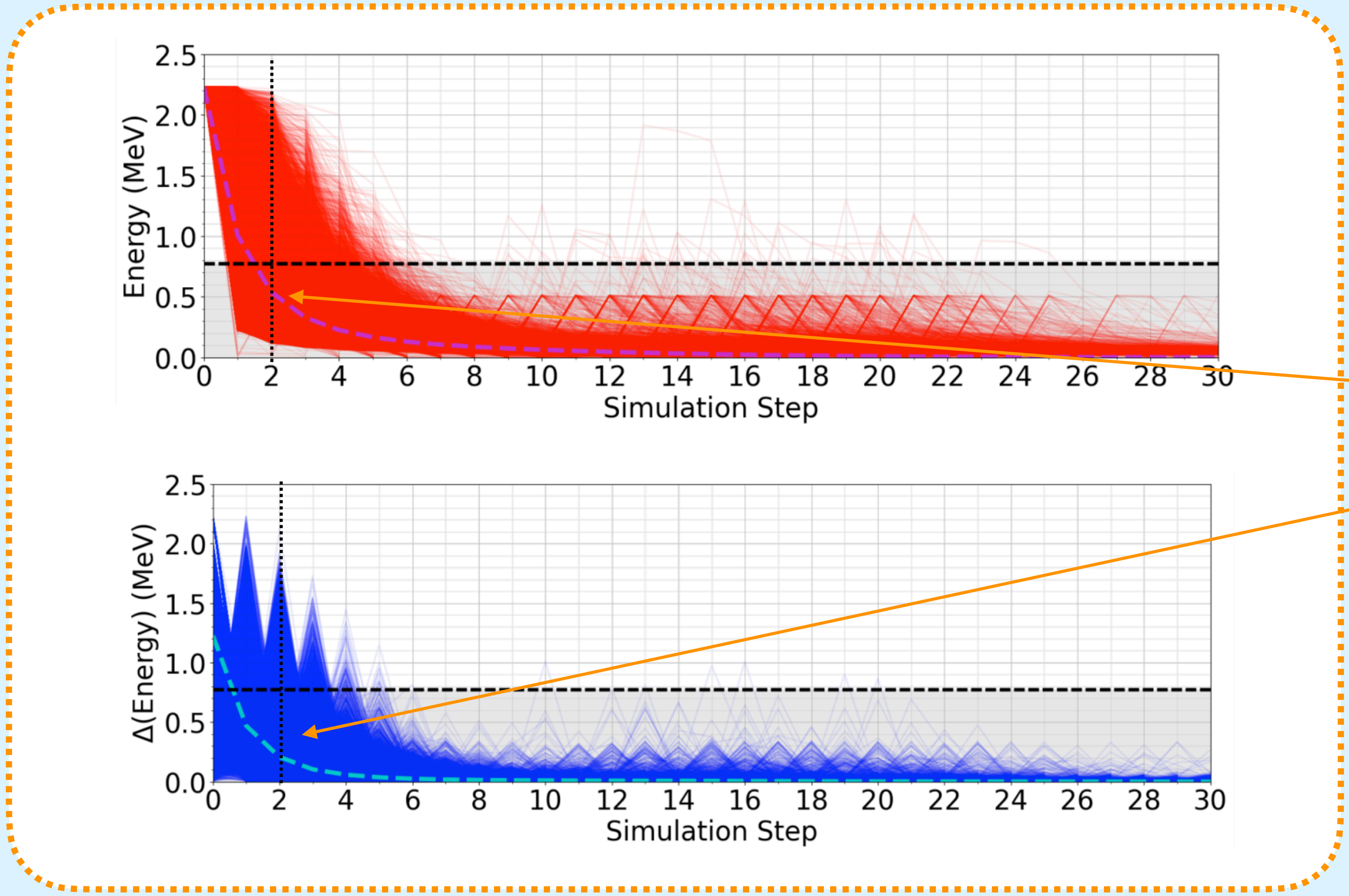
- Simulating 2.2 MeV gammas in GEANT4 in-ice, we find that each gamma undergoes a median of ~16 scatterings in ice before they are completely absorbed over ~50cm

We need to understand some key features about the microphysics

Neutron Capture

Gamma emission

Cherenkov emission



- Simulating 2.2 MeV gammas in GEANT4 in-ice, we find that each gamma undergoes a median of ~16 scatterings in ice before they are completely absorbed over ~50cm

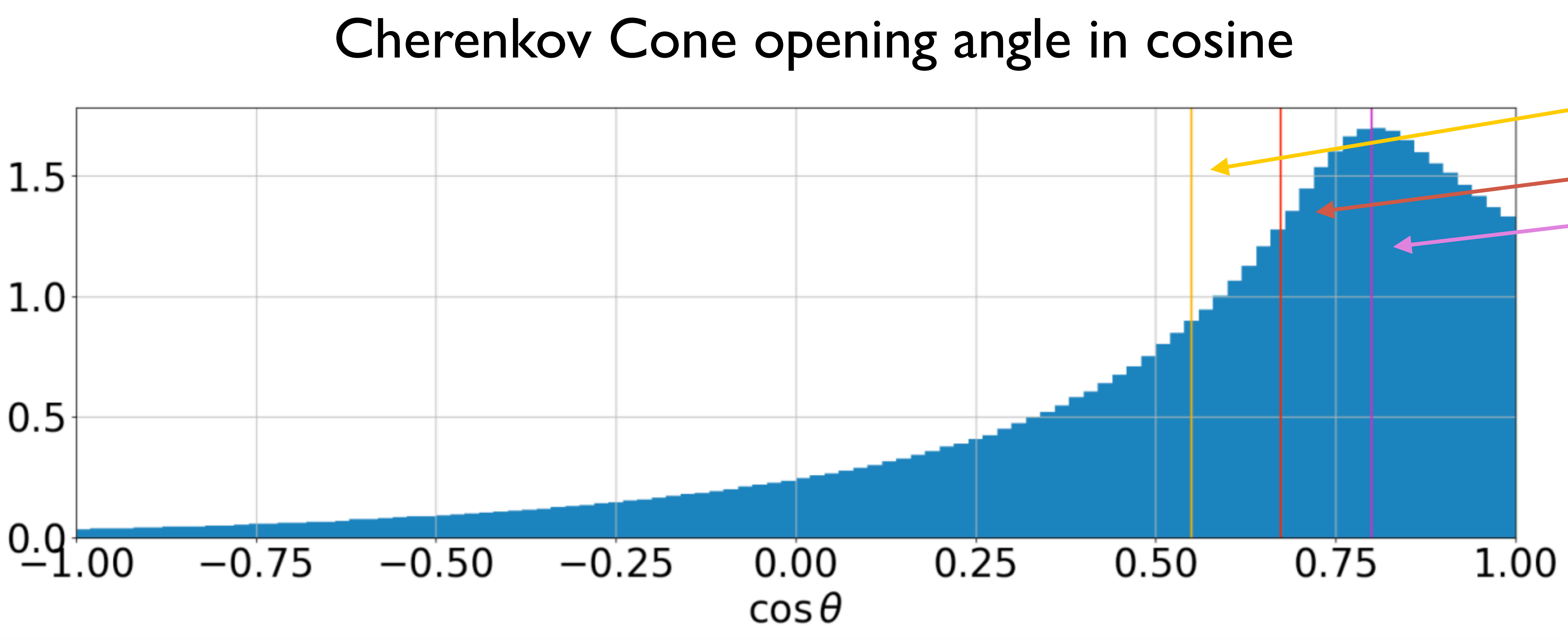
- However, typically only the first two scatterings appear to produce e with enough energy to emit Cherenkov radiation ⇒ ~2 e emissions typically expected per gamma

We need to understand some key features about the microphysics

Neutron Capture

Gamma emission

Cherenkov emission



Mean	Median	Mode
57°	48°	37°

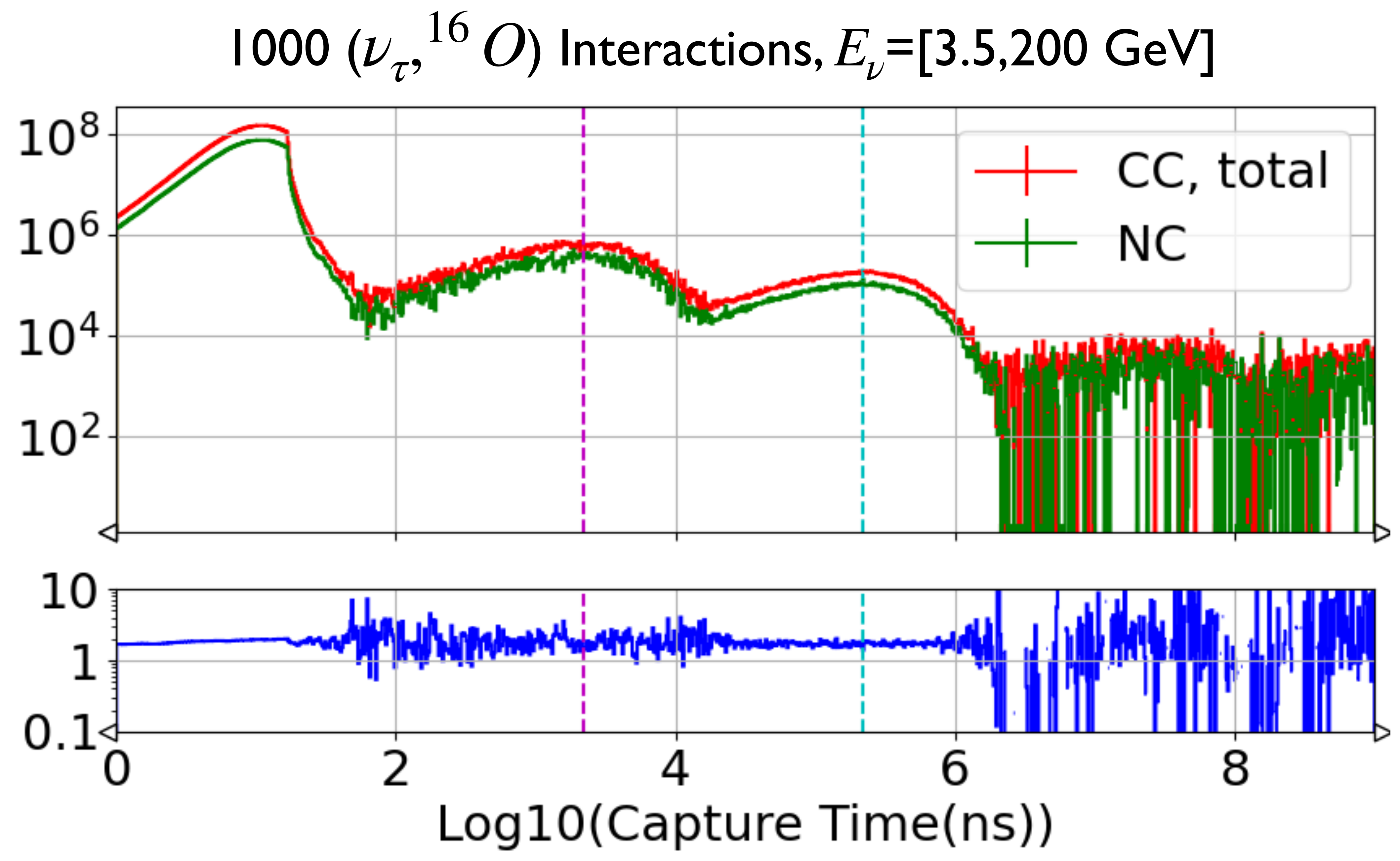
- In ice, the mean opening angle of the Cherenkov cone from a single 2.2 MeV gamma is ~57° with a long tail for photons ranging between [300,600nm]

We need to understand some key features about the microphysics

Neutron Capture

Gamma emission

Cherenkov emission



- As in the case of high energy, at GeV - TeV energies, the timing of photons at their production from GEANT4 contains three key peaks corresponding to the prompt, muon decay and neutron echo emissions*

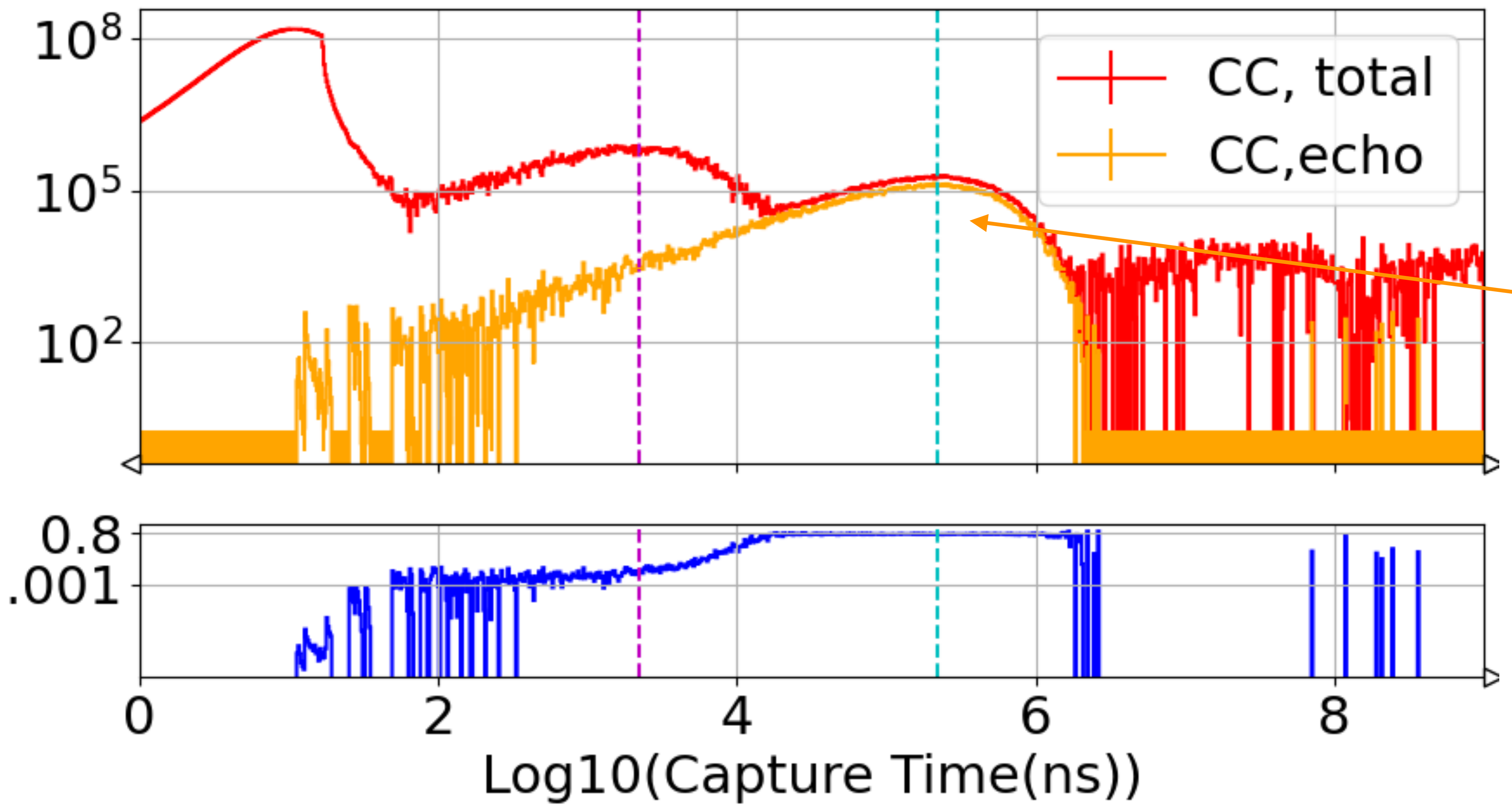
We need to understand some key features about the microphysics

Neutron Capture

Gamma emission

Cherenkov emission

1000 $(\nu_\tau, {}^{16}O)$ Interactions, E_ν=[3.5,200 GeV]



- As in the case of high energy, at GeV - TeV energies, the timing of photons at their production from GEANT4 contains three key peaks corresponding to the prompt, muon decay and neutron echo emissions*

- We calculated the fraction of photons that occur due to the photons that are produced after neutron captures - approximately 80% are due to the neutron echo between [20μs, 1ms]

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Neutron Capture

Gamma emission

Cherenkov emission

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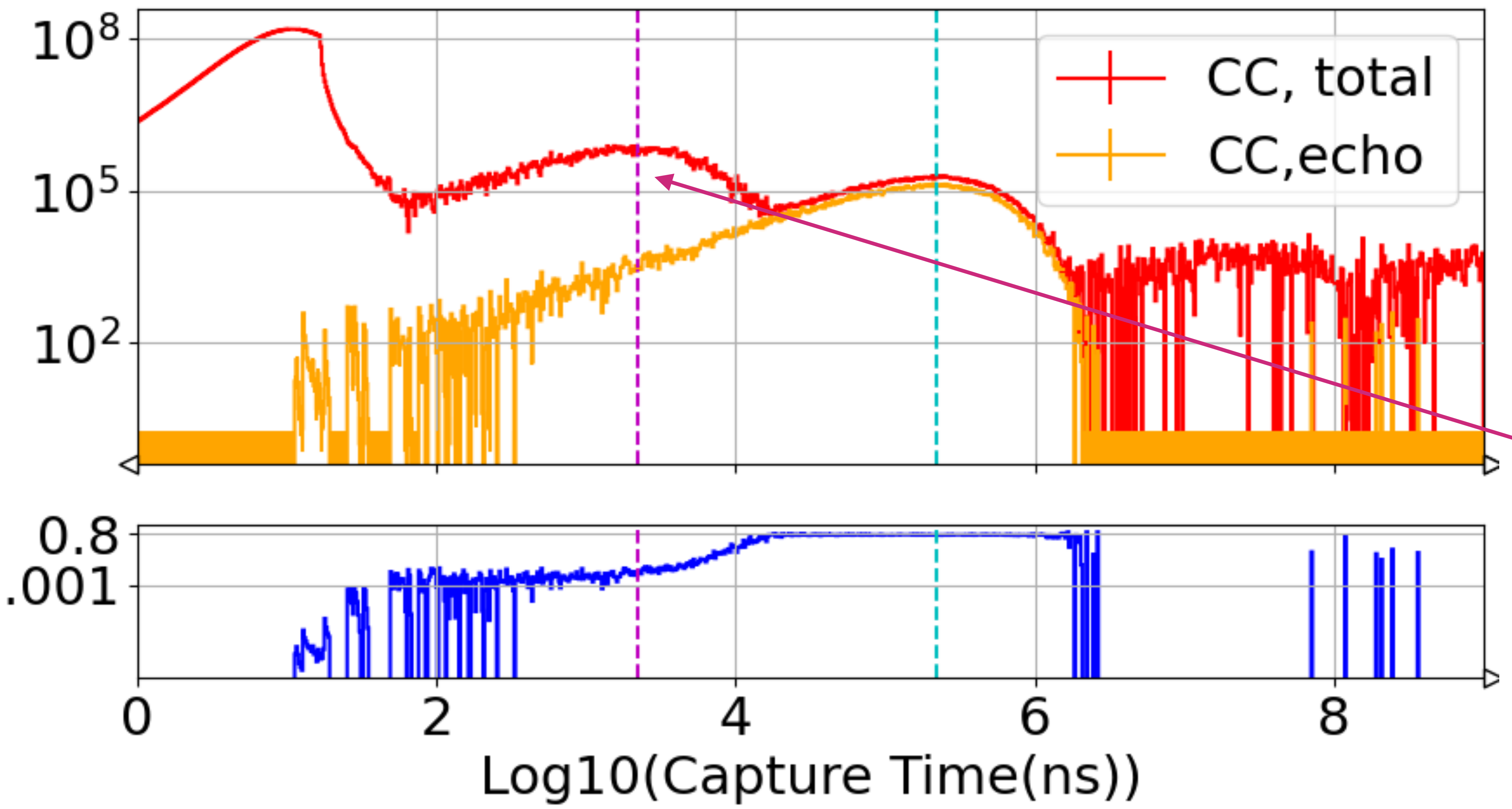
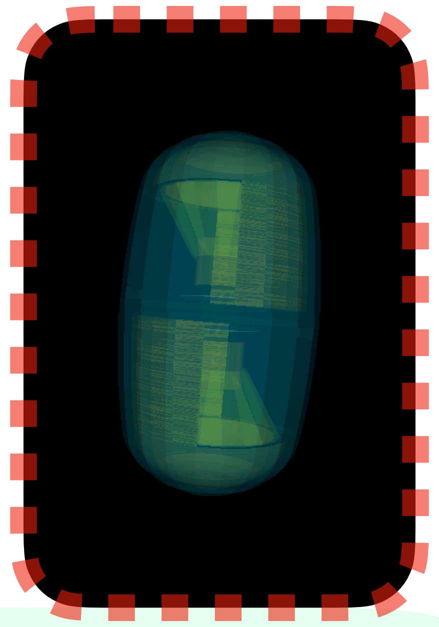


- As in the case of high energy, at GeV - TeV energies, the timing of photons at their production from GEANT4 contains three key peaks corresponding to the prompt, muon decay and neutron echo emissions*

- We calculated the fraction of photons that occur due to the photons that are produced after neutron captures - approximately 80% are due to the neutron echo between [20μs, 1ms]

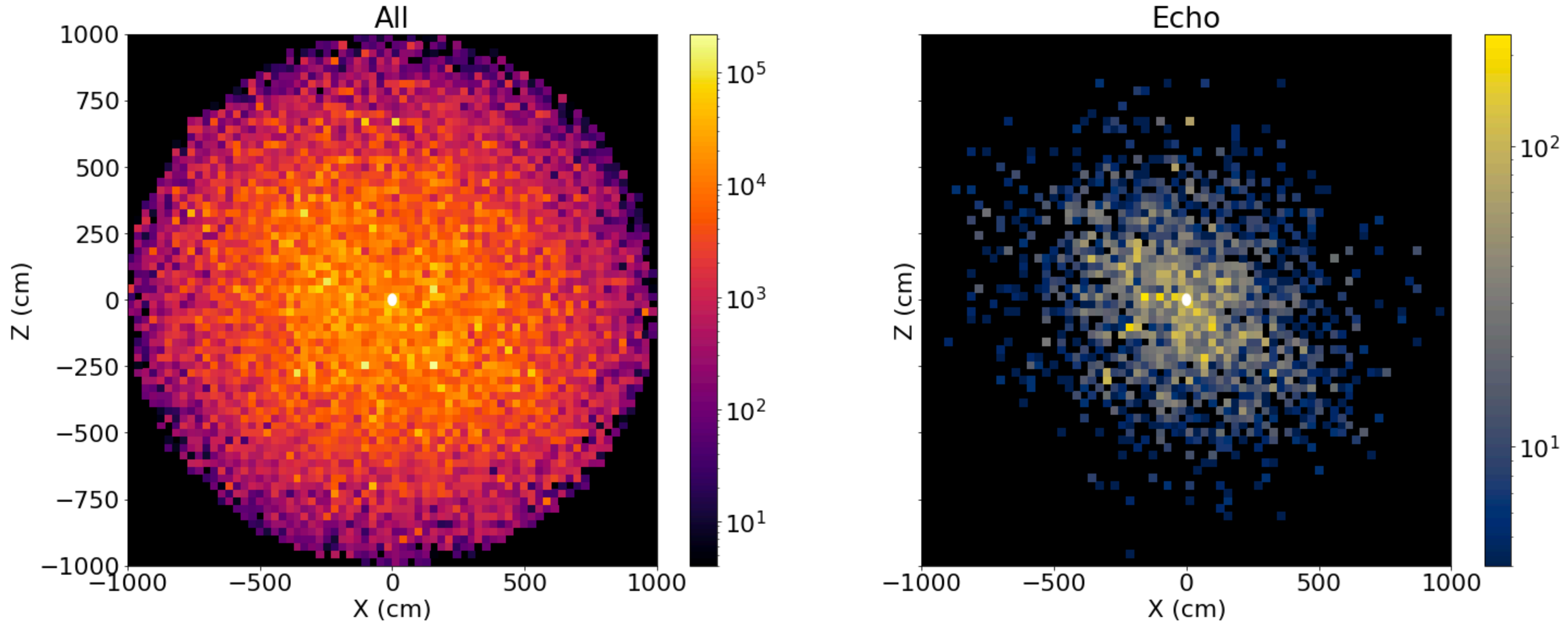
- The muon decay peak occurs around O(few) μs in ice, which overlaps with the after-pulsing time frame of the DEgg - this may make it difficult to distinguish from noise

Simulated echo photons

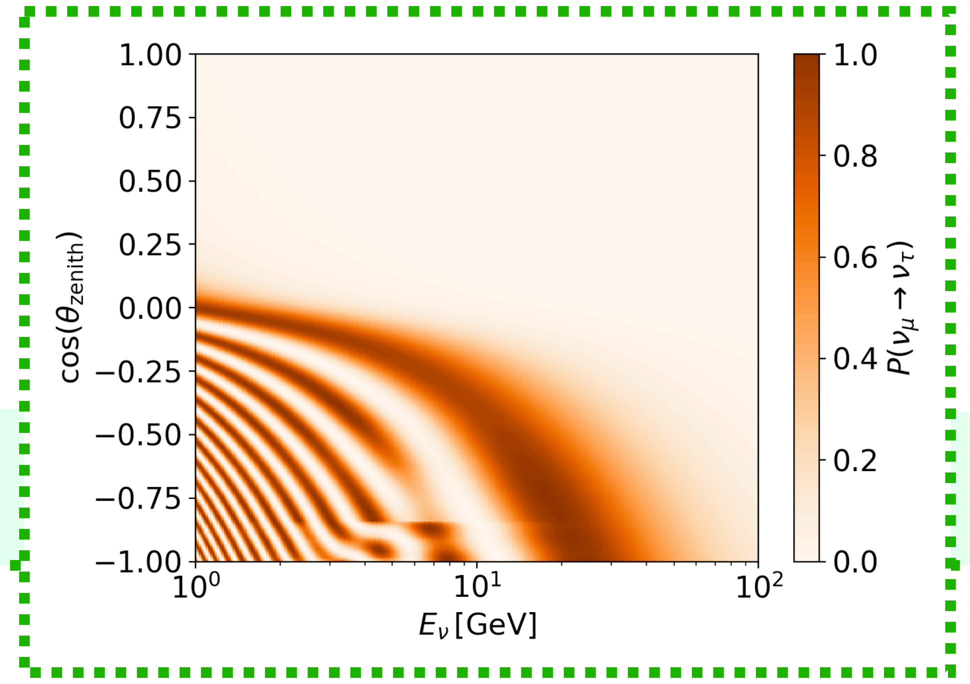


- We simulate 80000 tau neutrinos in GENIEv3, then interact them inside a 10m sphere of ice surrounding a DEgg implemented into GEANT4
- The plots on the right show the number of photons that hit either photocathode of the Egg, from both prompt and echo emissions
- A factor of 1000 less photons at O(μs) time scales are expected to hit the D-Egg

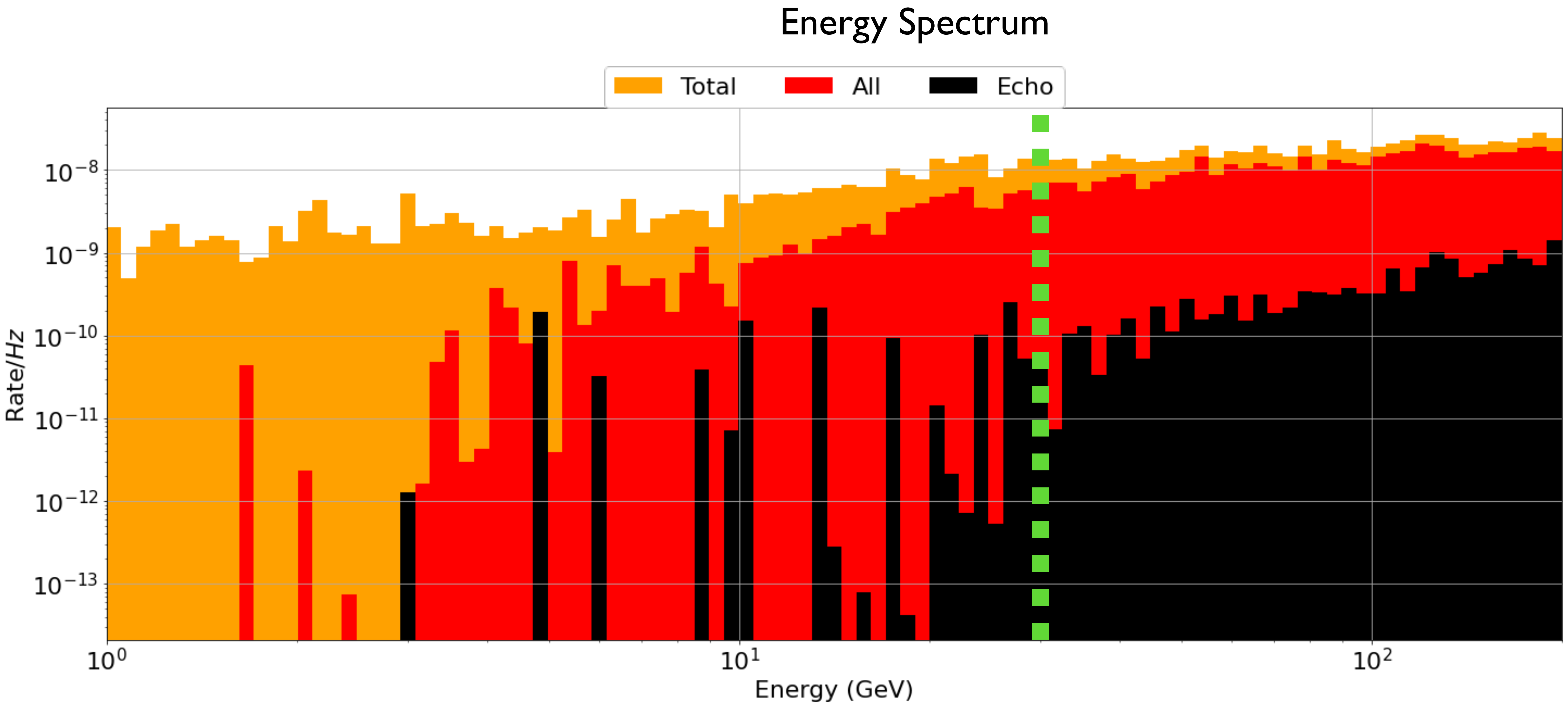
Number of neutron echo photons from ν_τ interaction vertex between E_ν=[1,200 GeV] that hit a DEgg implemented in GEANT4



Energy Spectrum

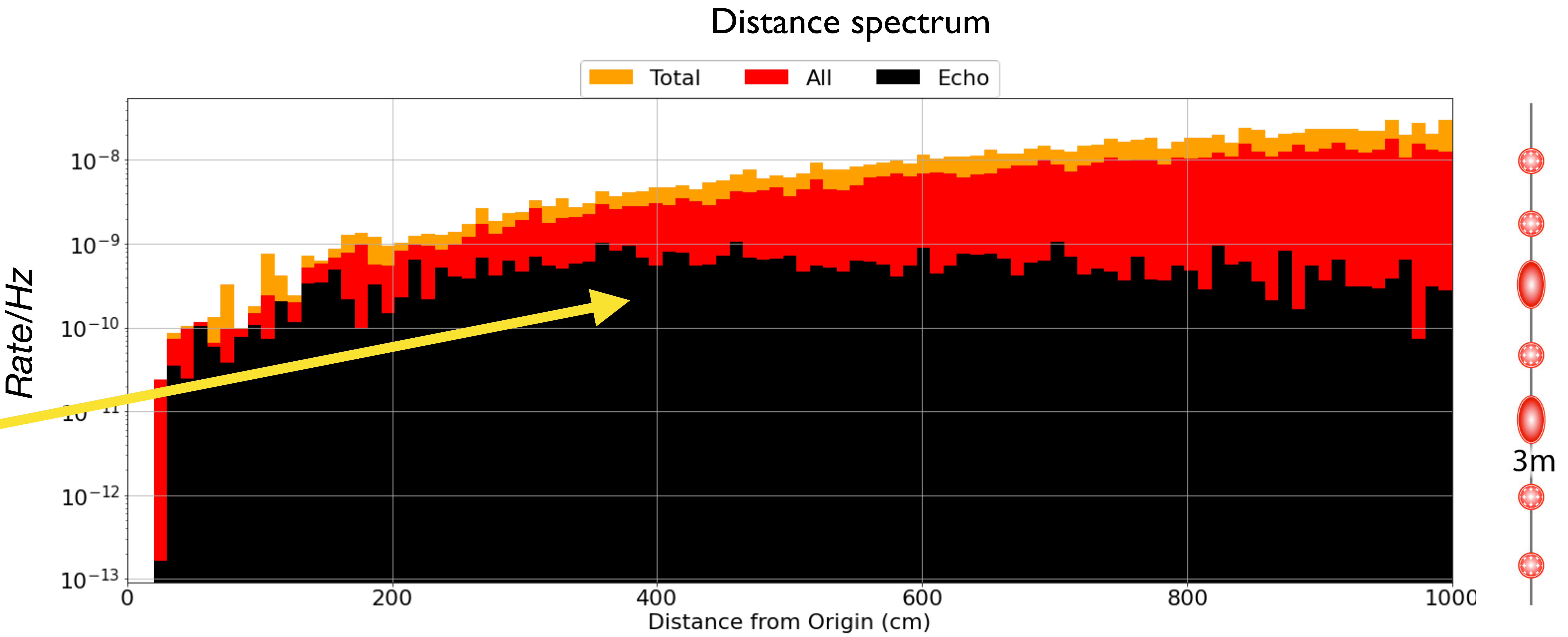


- Left plot shows the total energy spectrum for the interactions, detected events and detectable echoes per 10m sphere and D-Egg
- The Detectable echoes with >3PE appear as low as ~ few GeV, but the largest contribution comes from neutrinos above ~ O(20 GeV)

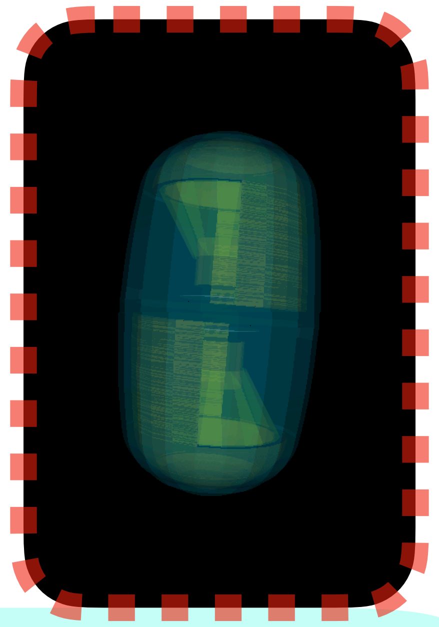


Distance spectrum

- String separation between modules is of the typical scales where the echo is detetectable (around 2-7m) so coincident measurement along strings could be a powerful tool to optimise echo detection - we are simulating now!



Estimated Echo Rates



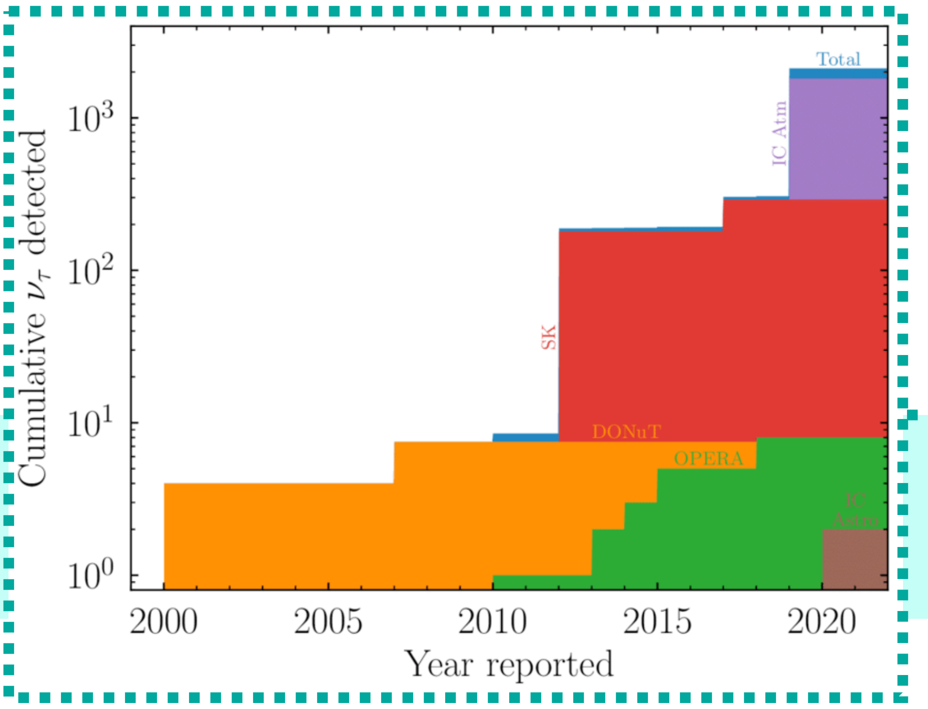
- By simulating the atmospheric neutrino flux using MCEq and propagating them to the detector using nuSQuIDS, we can compute the following estimated rates for the ~300 DEggs to be deployed in the IceCube Upgrade

$\nu_\tau + \bar{\nu}_\tau$ detection rate (>3PE) per year ~

4808

$\nu_\tau + \bar{\nu}_\tau$ echo detection rate (>3 PE) per year ~

145

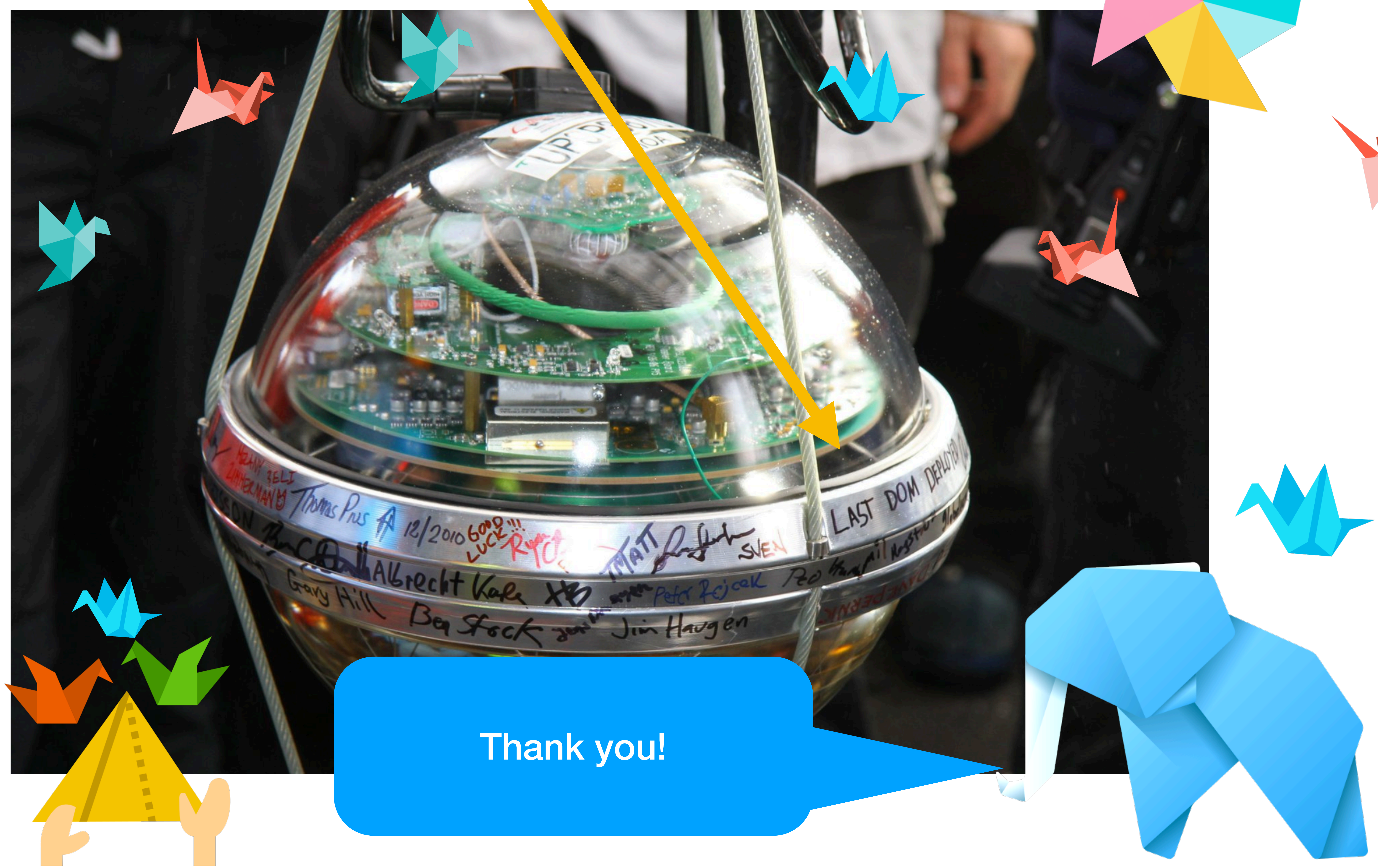


Summary

- We investigated the physics behind the neutron echo in Ice as part of the effort to increase the number of tau neutrinos measured in the upcoming IceCube Upgrade experiment
- We estimate around **145 echo events** could be detected per year, and are currently simulating the neutron echo to figure out feasible signals and a trigger scheme
- The IceCube Upgrade experiment deployment is already underway - detectors have already in transit to the South Pole as we speak
- We are conducting experiments to verify the DEgg, one of the Upgrade modules, is capable to measure the echo signal

We want to catch as many neutrinos we can (including ν_τ!)
That's why we are upgrading our detector

(Not) the last optical module to be deployed!



Backup

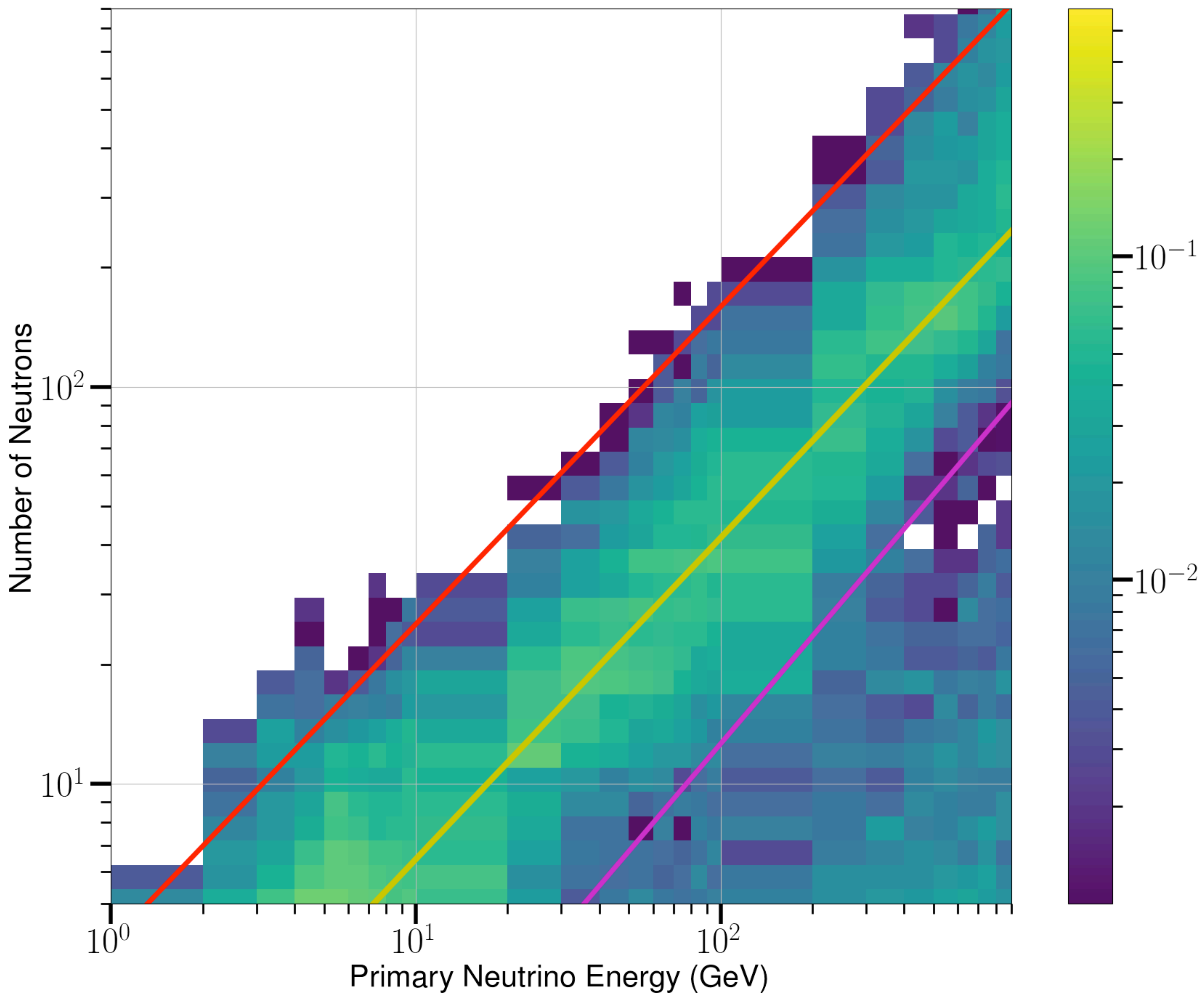
Neutron Multiplicity for ν_τ

- Plot shows number of neutrons produced as a function of neutrino energy

- Fit (yellow) corresponds to

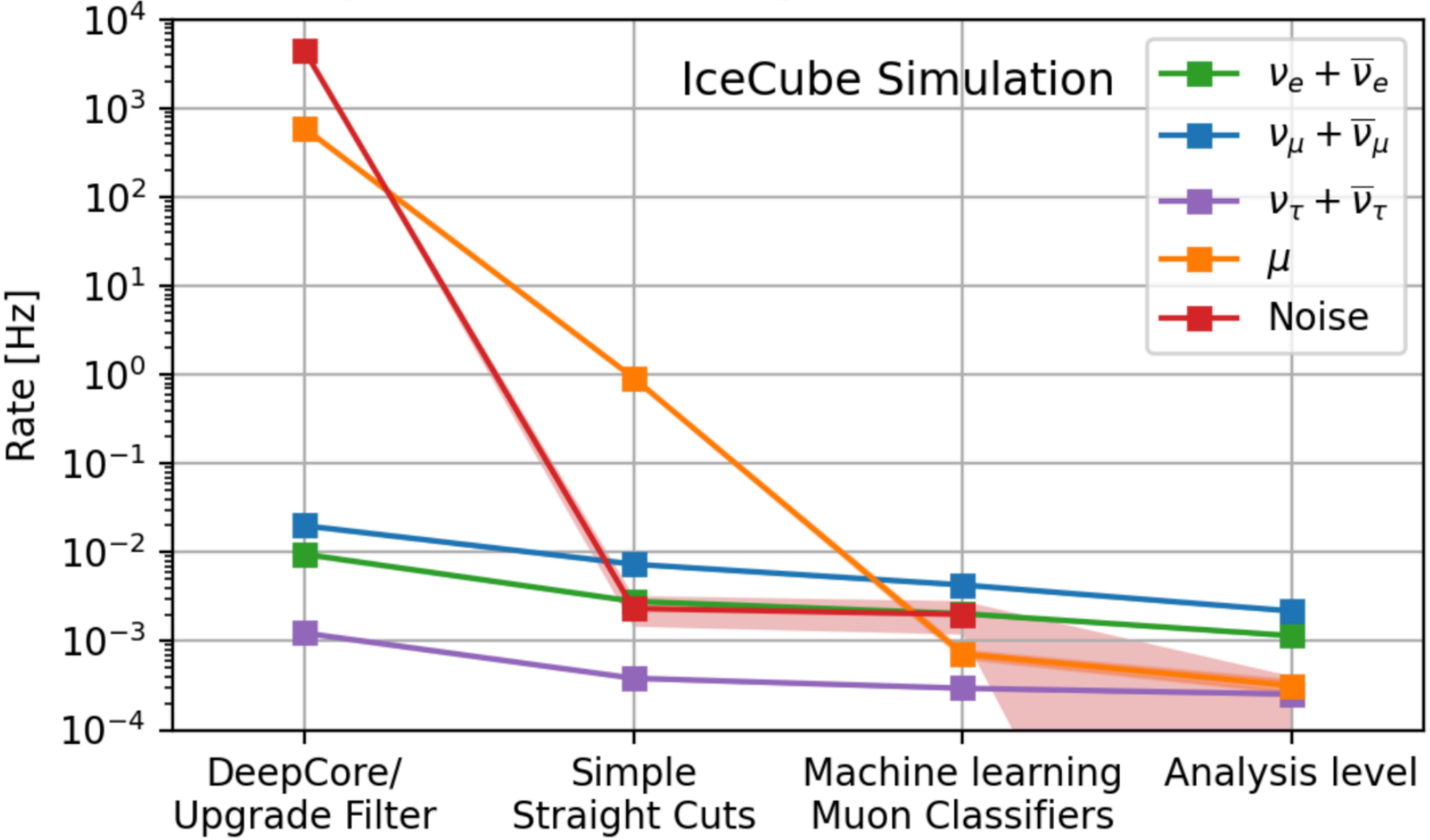
$$\langle N_N \rangle = \left(\frac{E_\nu}{GeV} \right)^{0.81}$$

D-Egg



Eller, Philipp, et al. "Sensitivity of the IceCube Upgrade to Atmospheric Neutrino Oscillations." *arXiv preprint arXiv:2307.15295* (2023).

Deepcore+Upgrade rates



https://journals.aps.org/prd/abstract/10.1103/PhysRevD.105.012009

Uncertainties and Challenges - GENIE

- GENIE has over 150 theoretical and experimental systematics!
- Hadronization is modelled using AGKY model → low invariant mass (W<2.3 GeV) hadronization is simulated by the KNO scaling-based phenomenological model. Lower than ν_τ CC threshold
- For High Invariant Mass PYTHIA handles the hadronization. Error on the multiplicity are of the order of 40-50% at 10 GeV
- Total neutrino cross sections uncertainties are within ~5-10% for $E_\nu \in [10,100]$ GeV
- Nuclear corrections are relevant in the GeV-TeV energy range

An example of
One uncertainty!

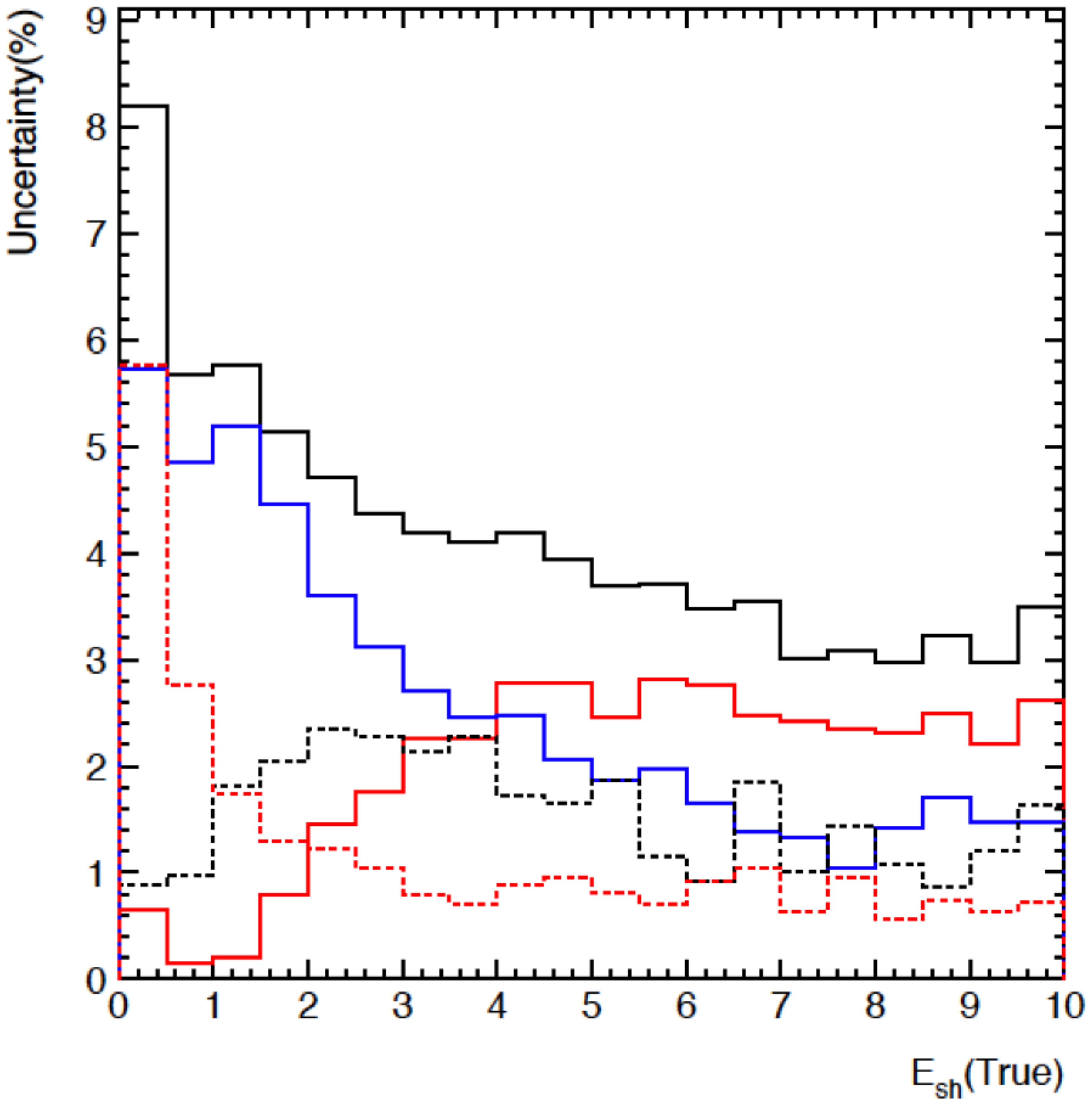


Figure 10: Total uncertainty from all sources (solid black). Contributions from intranuke assumptions (blue), `INTRANUKE` input (dashed red), hadronization model (solid red), and formation zone (dashed black).

https://journals.aps.org/prd/abstract/10.1103/PhysRevD.105.012009

Uncertainties and Challenges - GEANT

- GEANT misses some features specifically to do with tau decay
  - τ polarisation
  - Tau decays are treated as point like without resonances (ie processes that produce intermediaries are not included by default $\tau \rightarrow \rho, a_1$)
- Overall these effects cause about **6% dimmer Cherenkov signals**
- As for the hadronization scheme, this uses the FTFP_BERT_HP model - this has uncertainties for H and O with respect to their multiplicities of about ~40%
- As for gamma events, using BERT model number of gamma-rays generated by neutron inelastic scattering reactions is one is small
- To improve our simulation, we already started to implement more robust modelling of the tau decay using the TAUOLA/PYTHIA8 Decay procedure

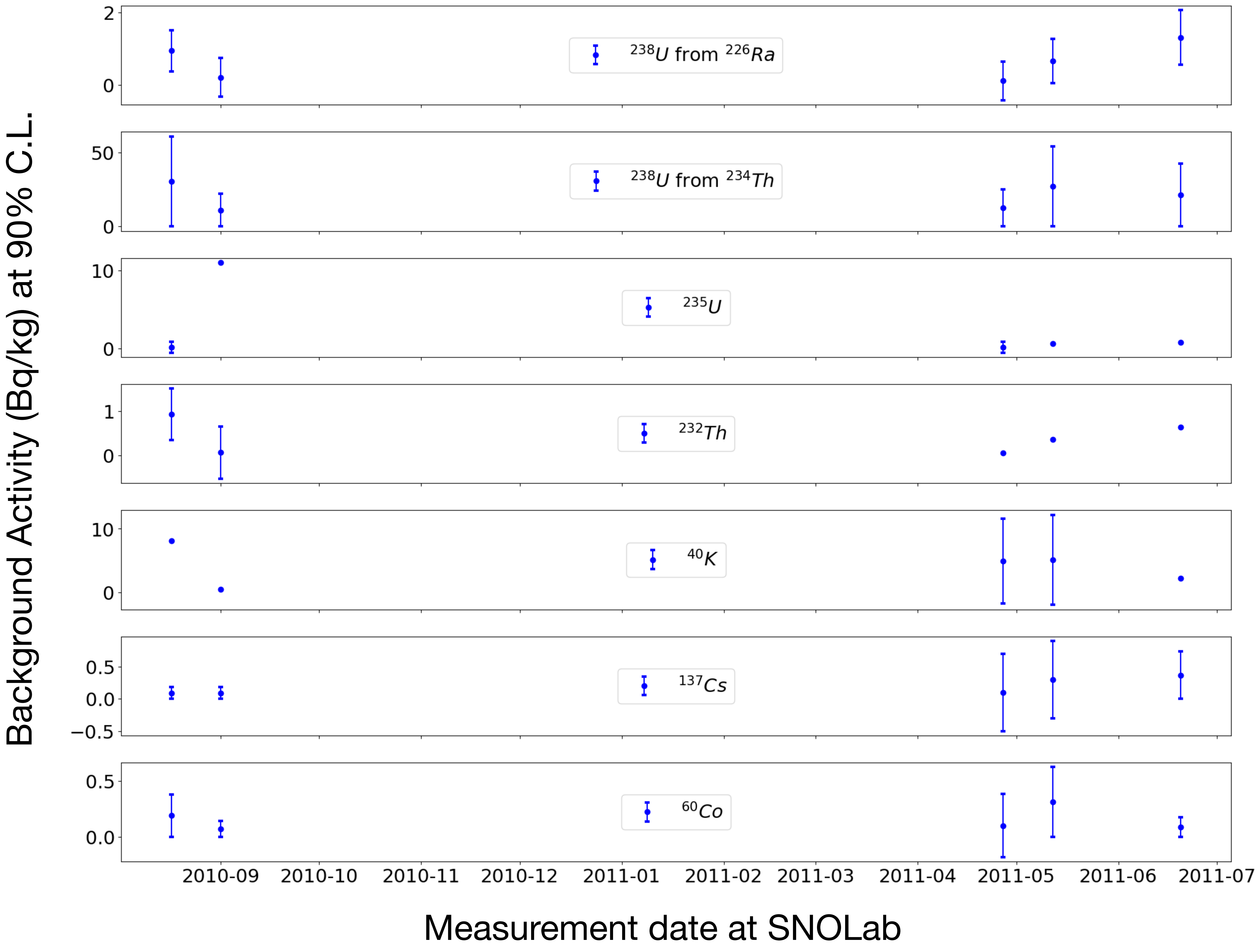
Backgrounds

- Strings 8 to 41 samples measured at the SNO lab low background HPGe detectors (as well as in lab samples and nearby IceCube samples)
- Each sample was measured between July 2010 - August 2012 each between 1.8 and 11.5 days
- Water was sampled from the bottom of the hole (clearer ice) but extraction exposed to compounds in the drill system - only upper limits available

Radioactive Backgrounds measured for IC cores

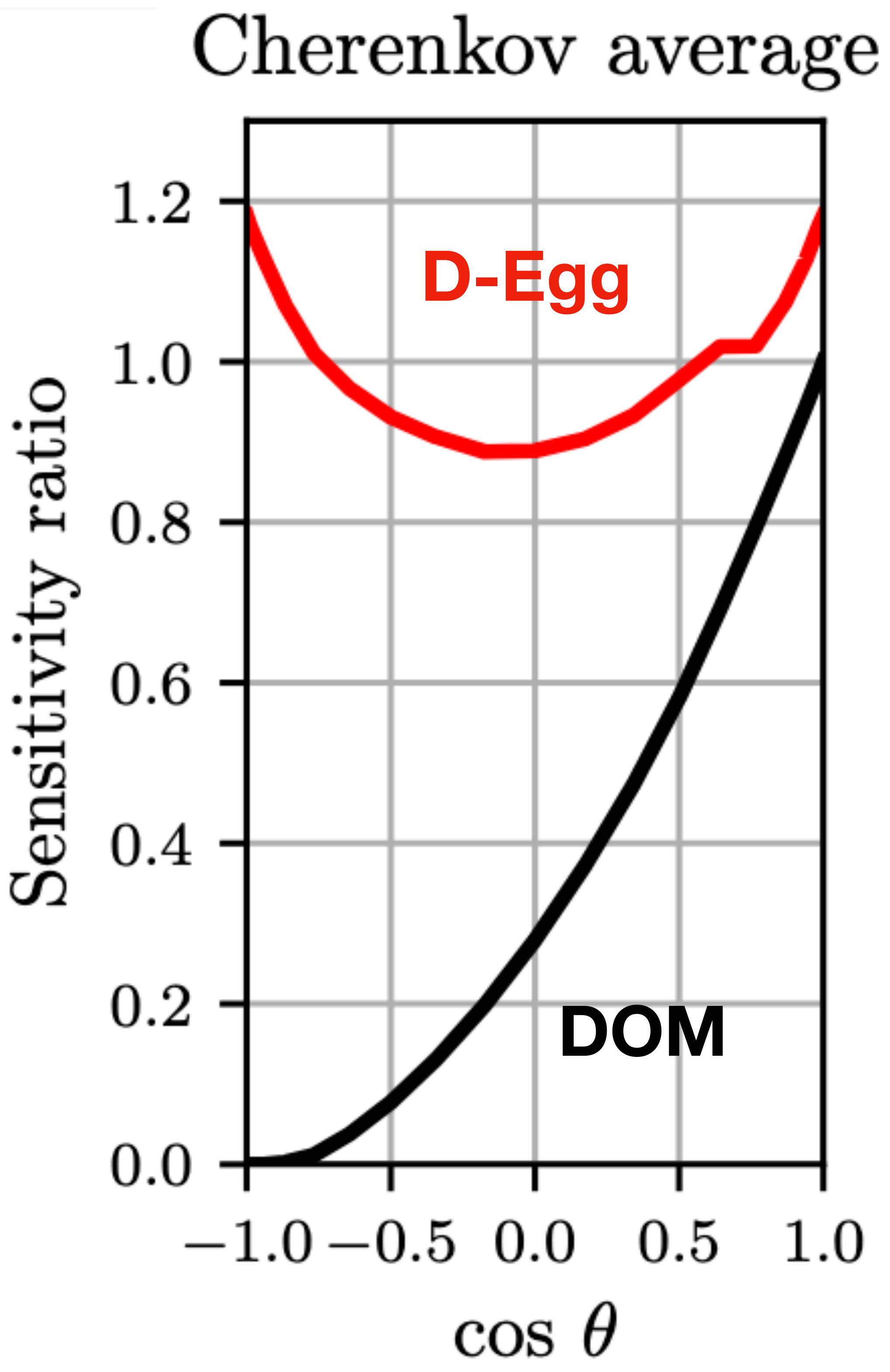
- From measurements dominant backgrounds from natural radioactivity occurs due to ${}^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He$ and ${}^{40}K$ ~ 40 Bq/kg

- If decay occurs in equilibrium, gamma rays of energy 186.1keV (${}^{226}Ra$), 295.21 and 351.92 keV (${}^{214}Pb$) and 0.61, 1.120, 1.76 and 2.20421 MeV (${}^{214}Bi$)

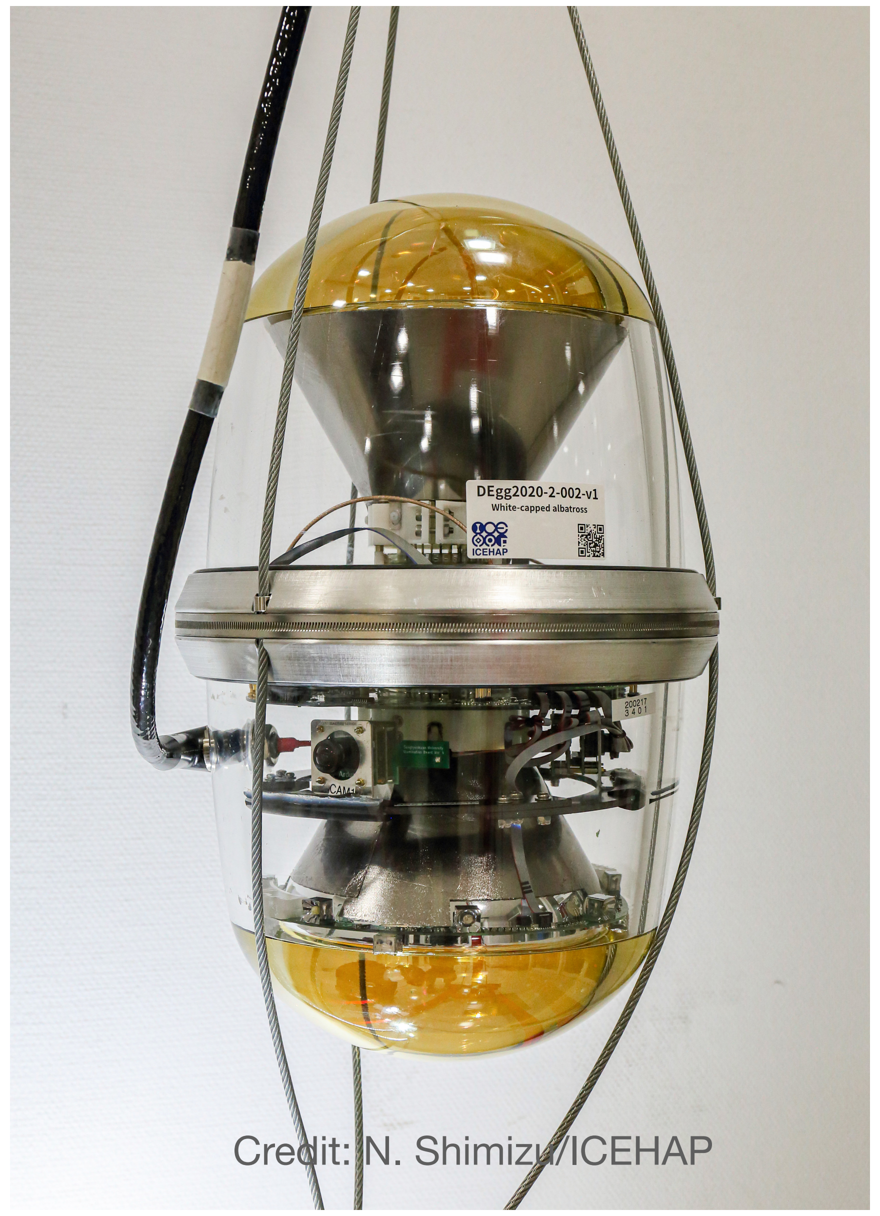


D-Egg

- ~ 300 mDOMs
- 2 8” PMTs with High Quantum Efficiency
- Waveform continuously digitized using a 14-bit ADC with an operation frequency of 240 MHz without any dead time after pulse shaping of the analog front-end circuit on the mainboard.



Effective Area



Credit: N. Shimizu/ICEHAP

D-Egg

2x 8” HQE PMTs & dia. 30 cm

Developed in Chiba

~ 300 D-Eggs

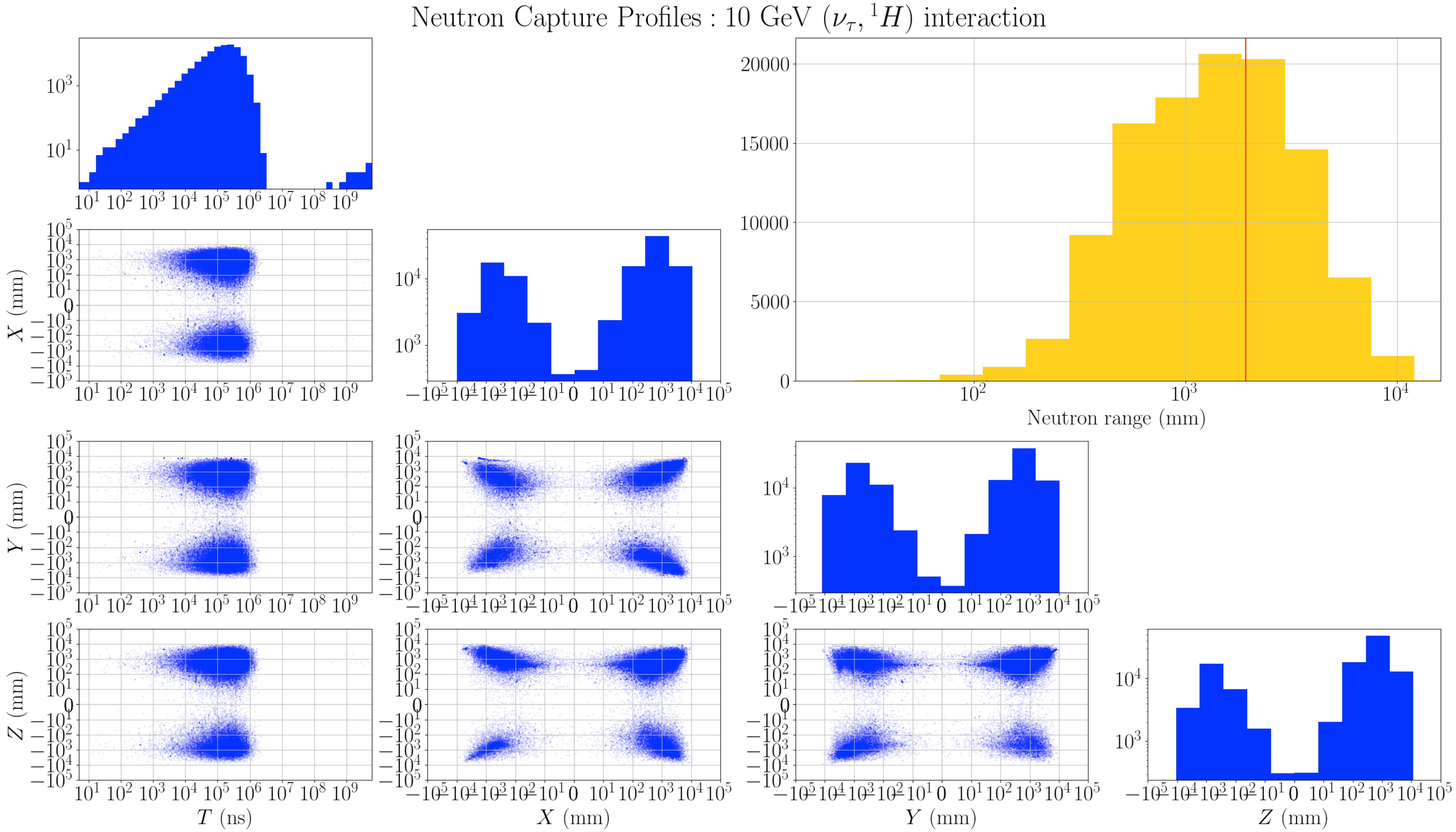
D-Egg can continuously read data

- D-Egg FPGA temporarily stores the digitized data in the buffer in the FPGA and outputs a signal when the data exceeds a programmable trigger level.

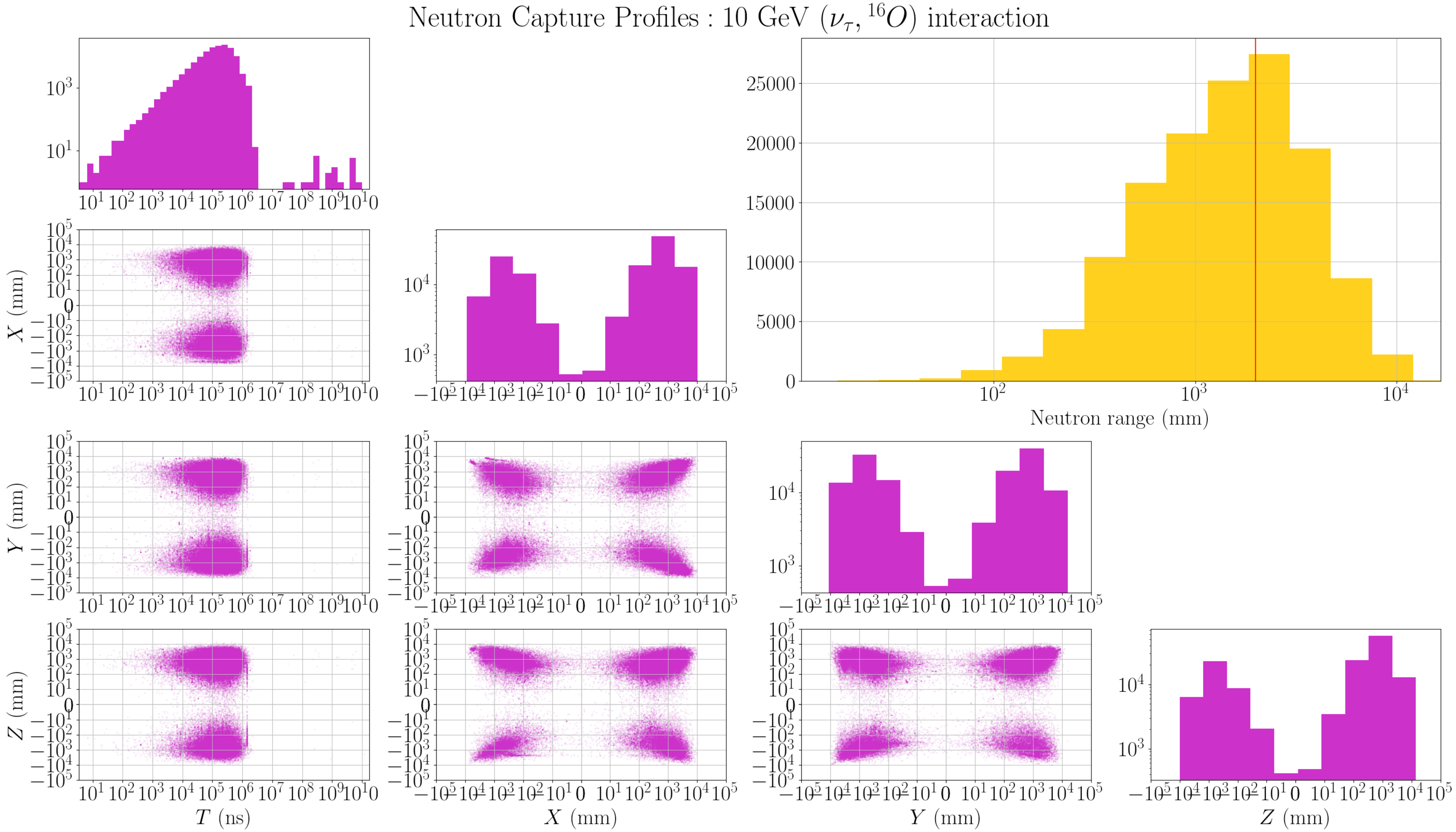
- The outputs are automatically transferred to an external onboard 2 Gbit DDR3 SDRAM which can store hundreds of milliseconds long waveforms.

- Several additional data processing, such as data compression or the charge extraction for the waveforms, are performed inside the module in order to remain within the bandwidth limits of the several-kilometer-long main cable.

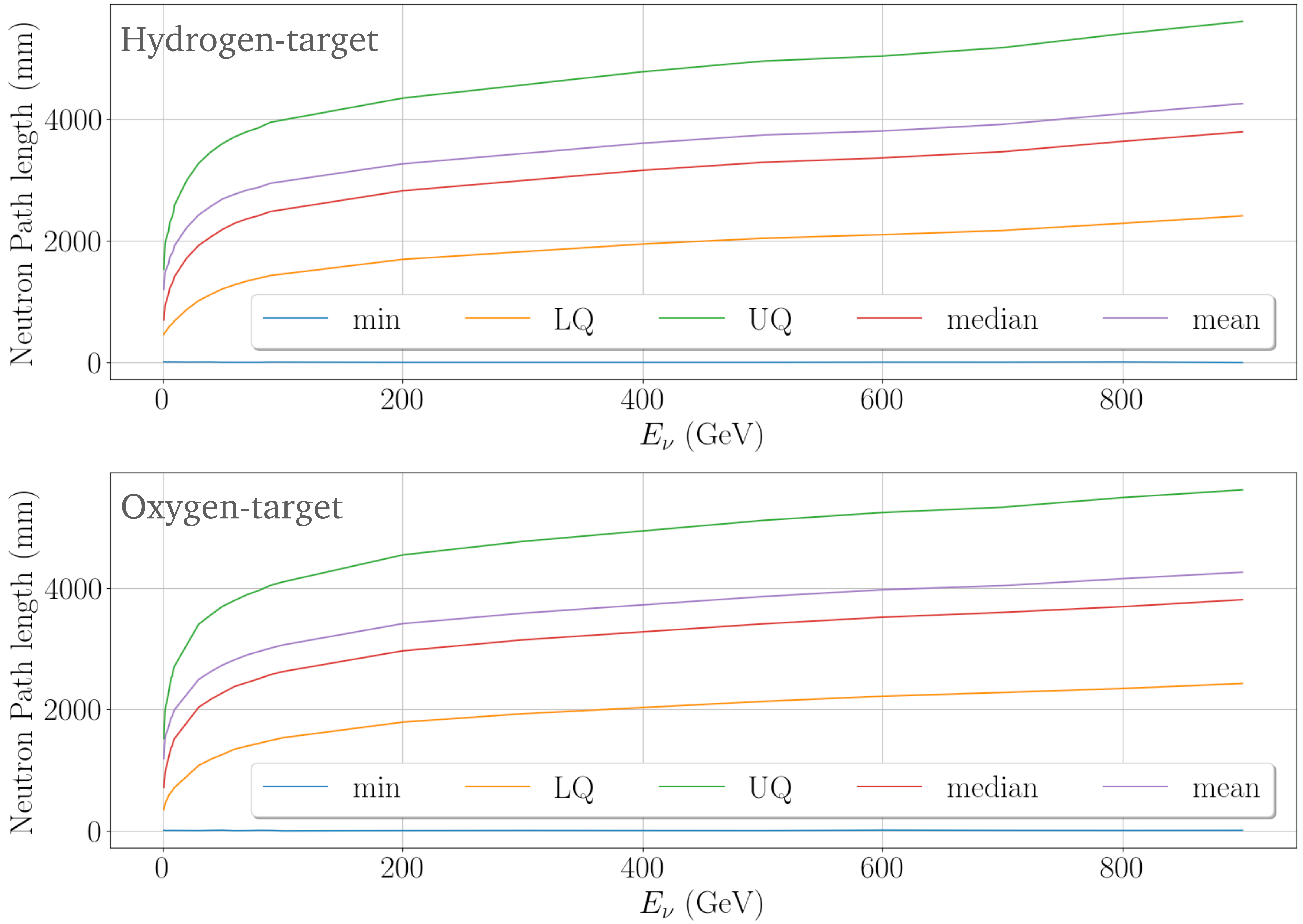
Late light emission expected ~200μs

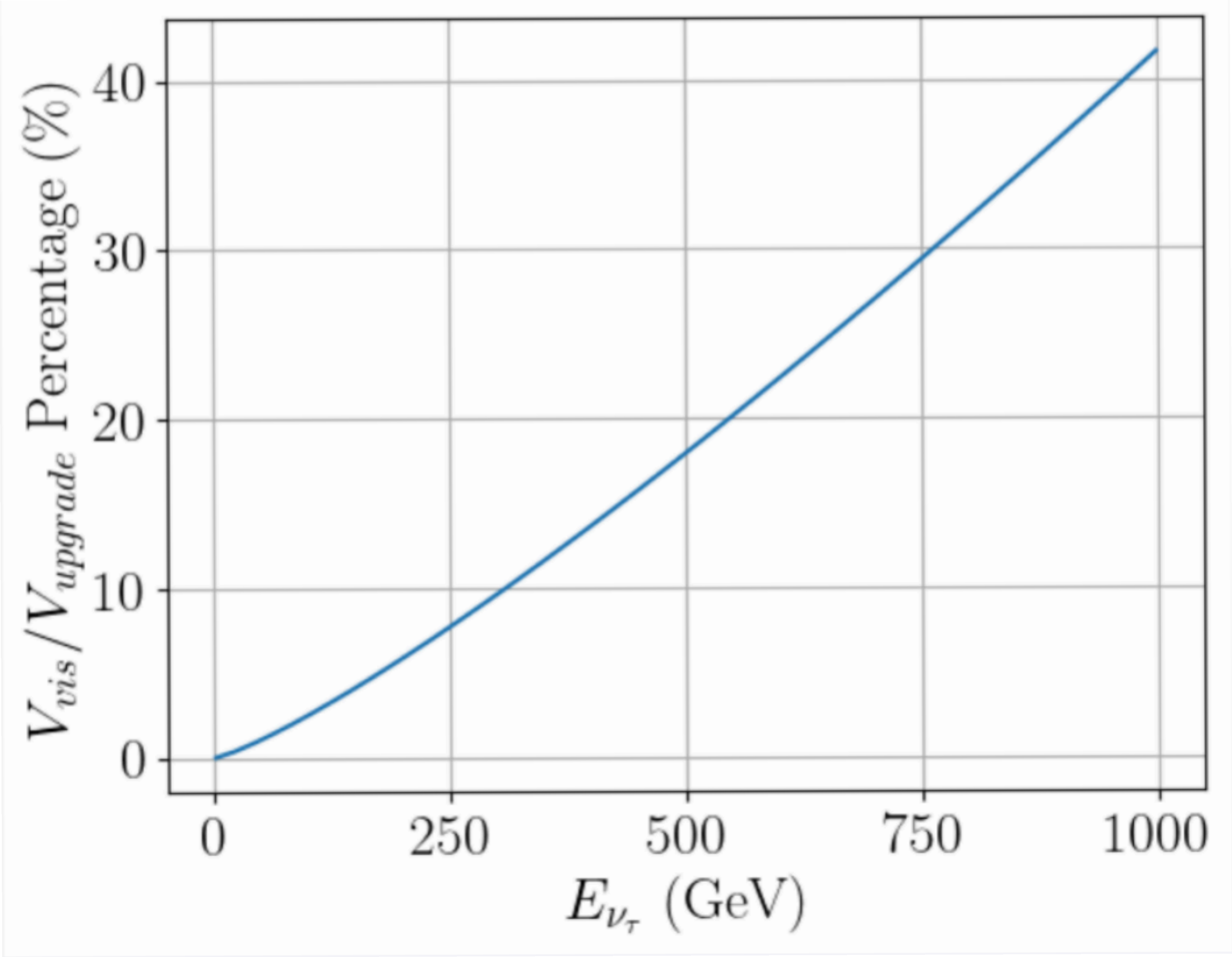


Late light emission expected ~200µs

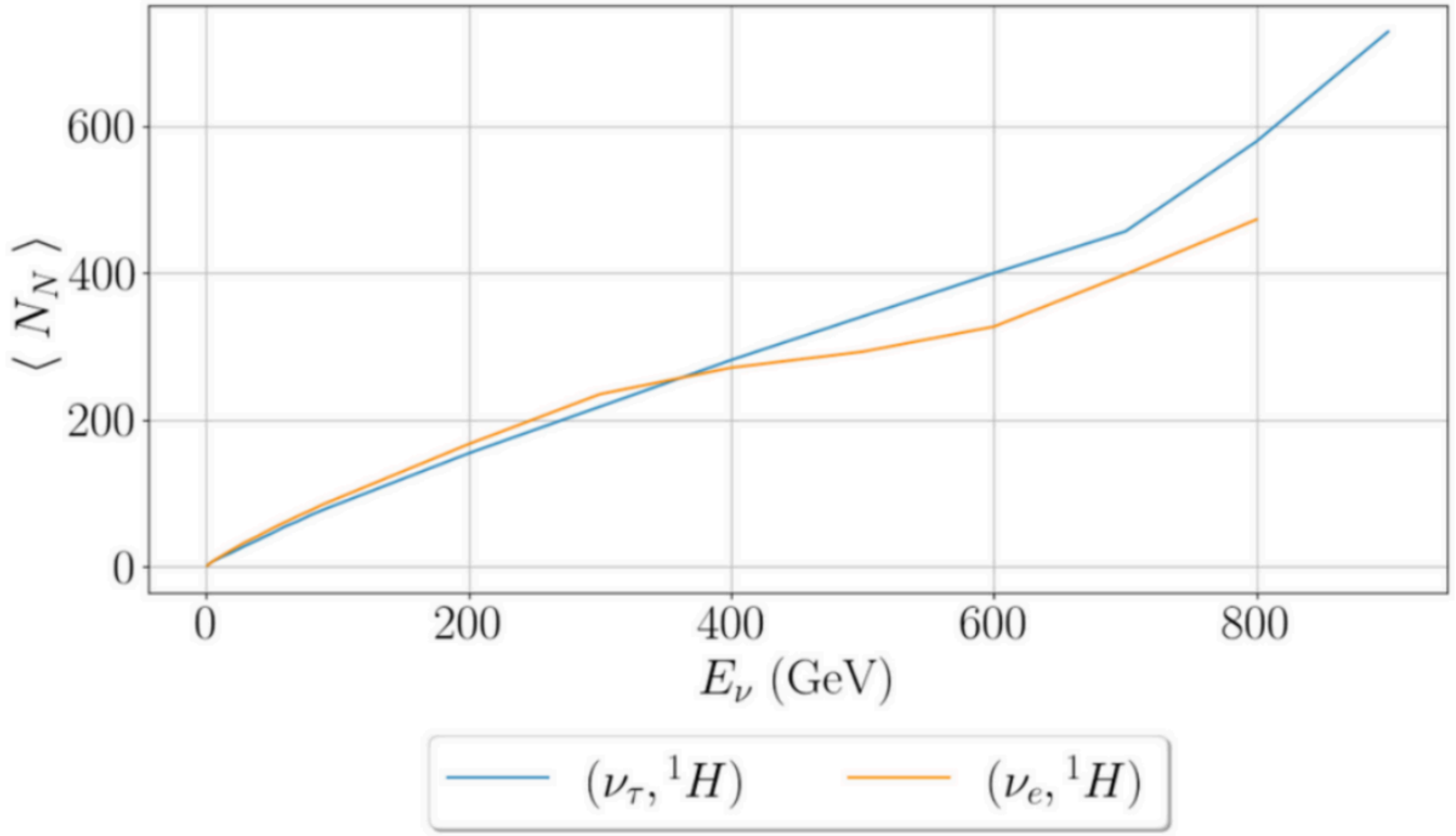


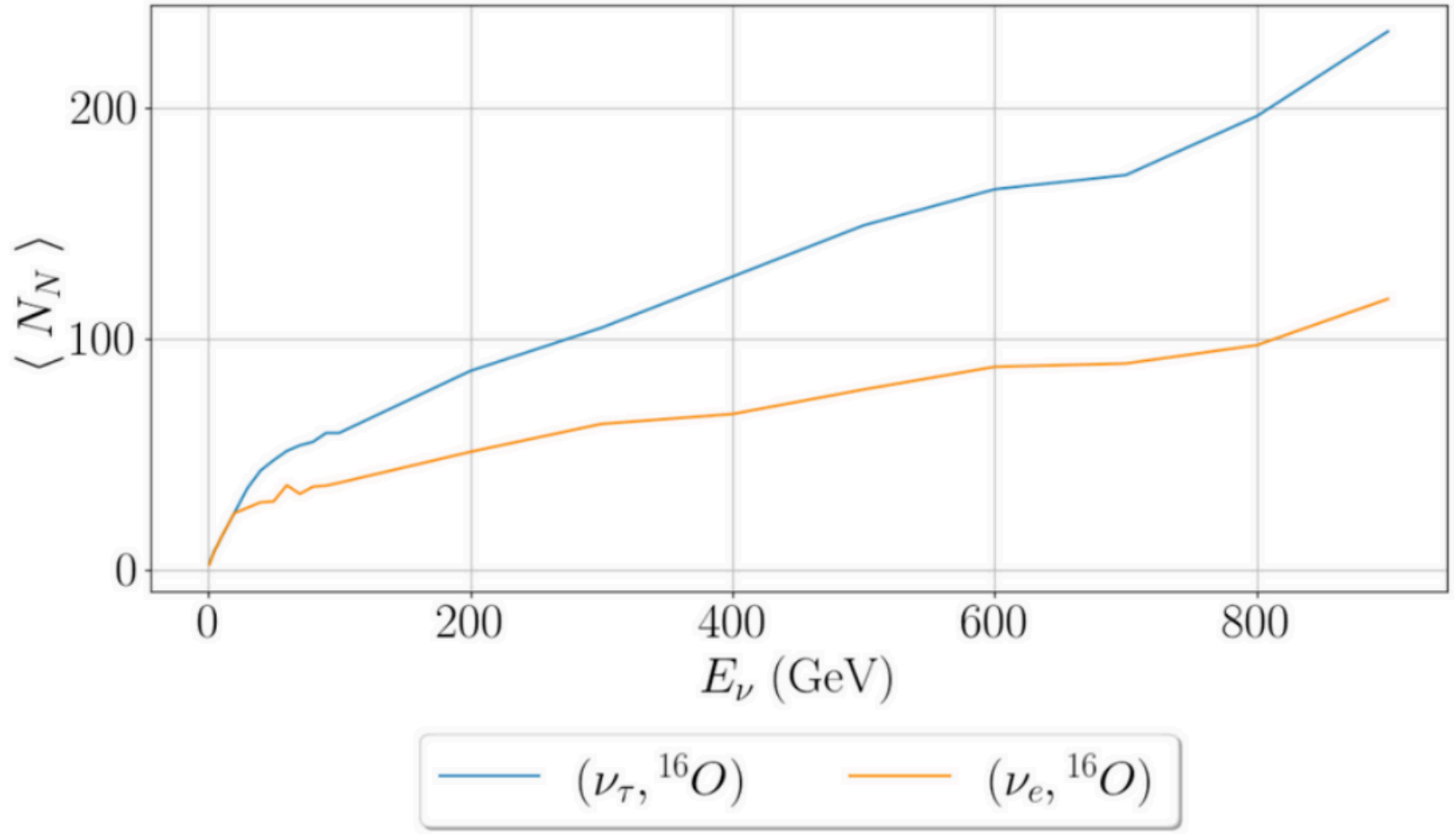
Neutron Echo with Upgrade





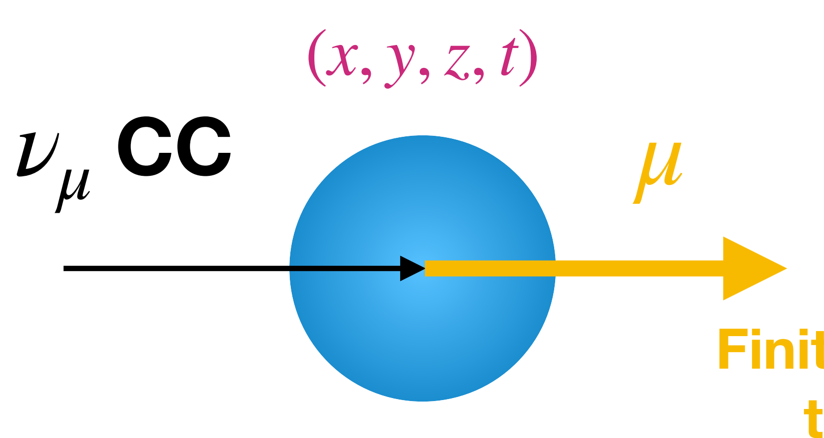
Preliminary comparison with ν_e





Credit: A. Ishihara

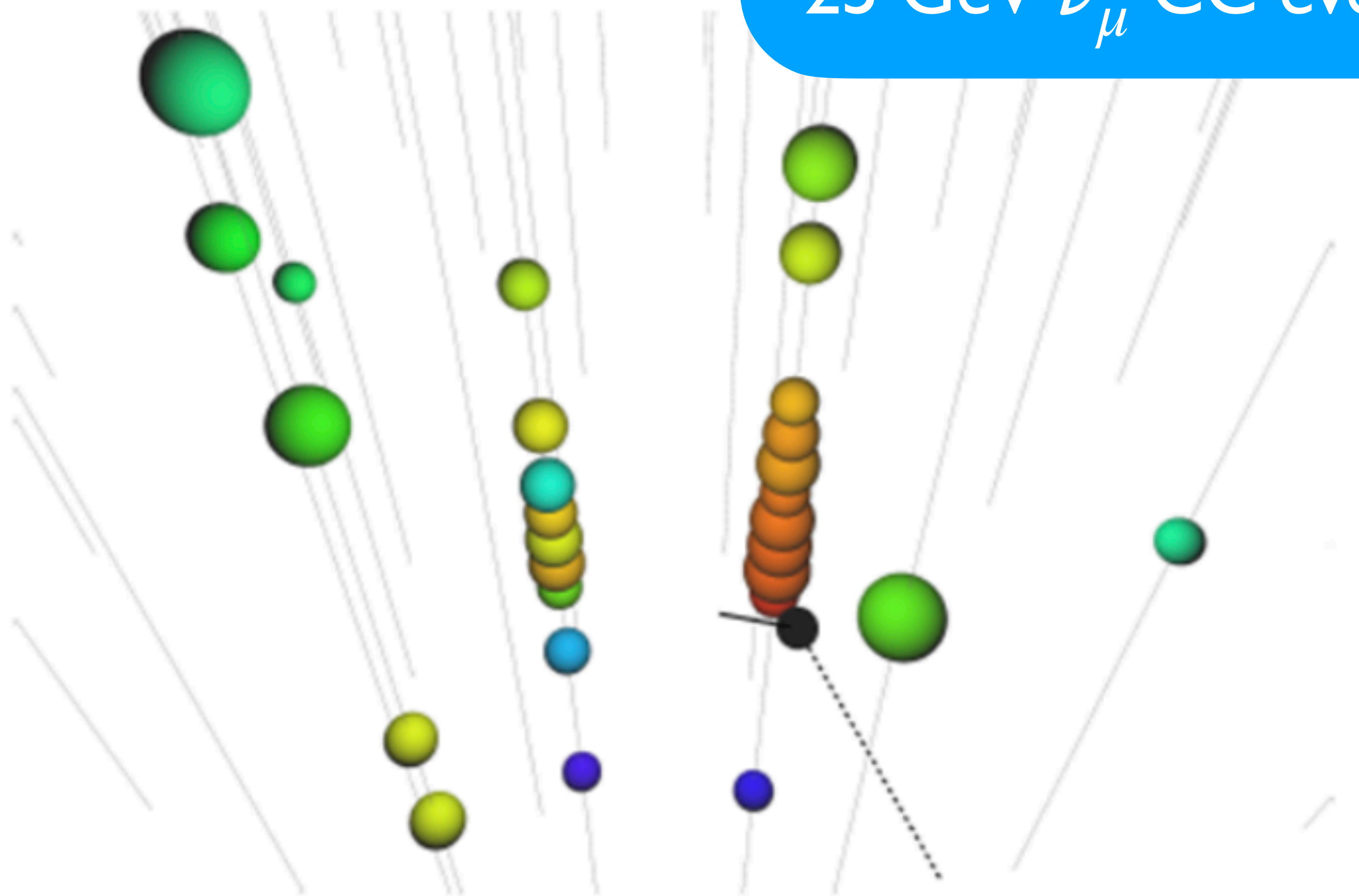
Deepcore



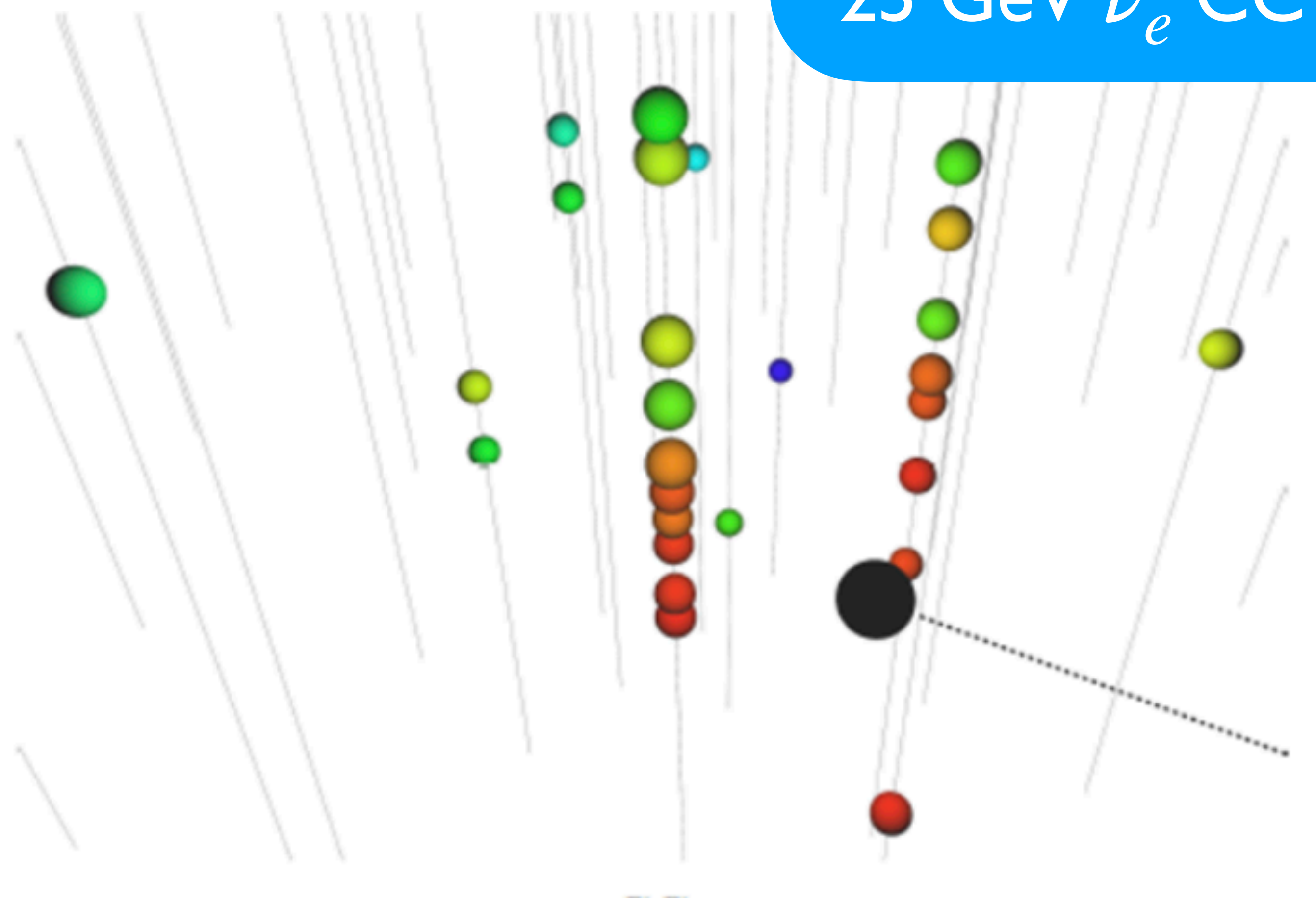
Initial cascade energy E

Finite muon track θ, ϕ, L

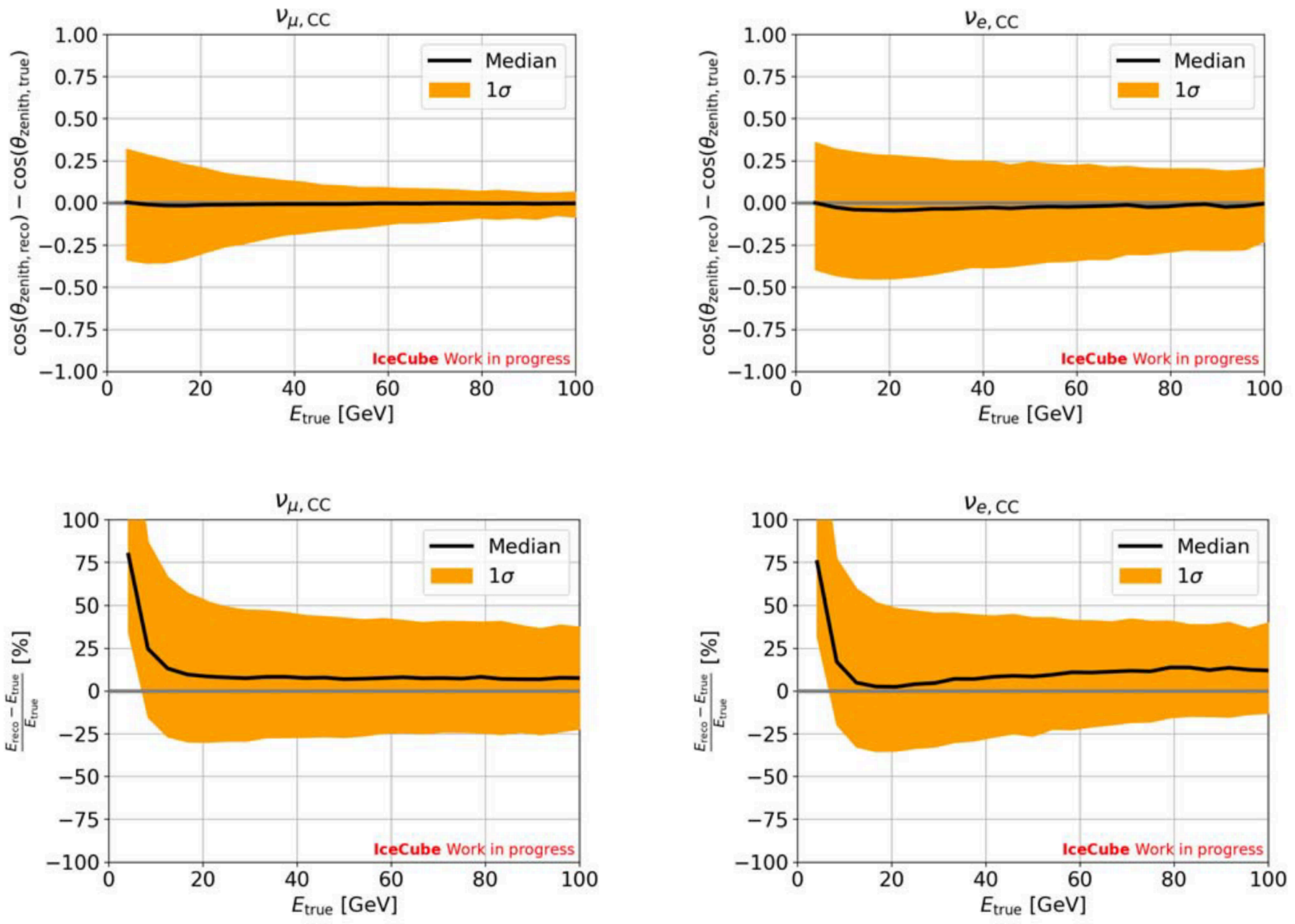
25 GeV ν_μ CC event



25 GeV ν_e CC event

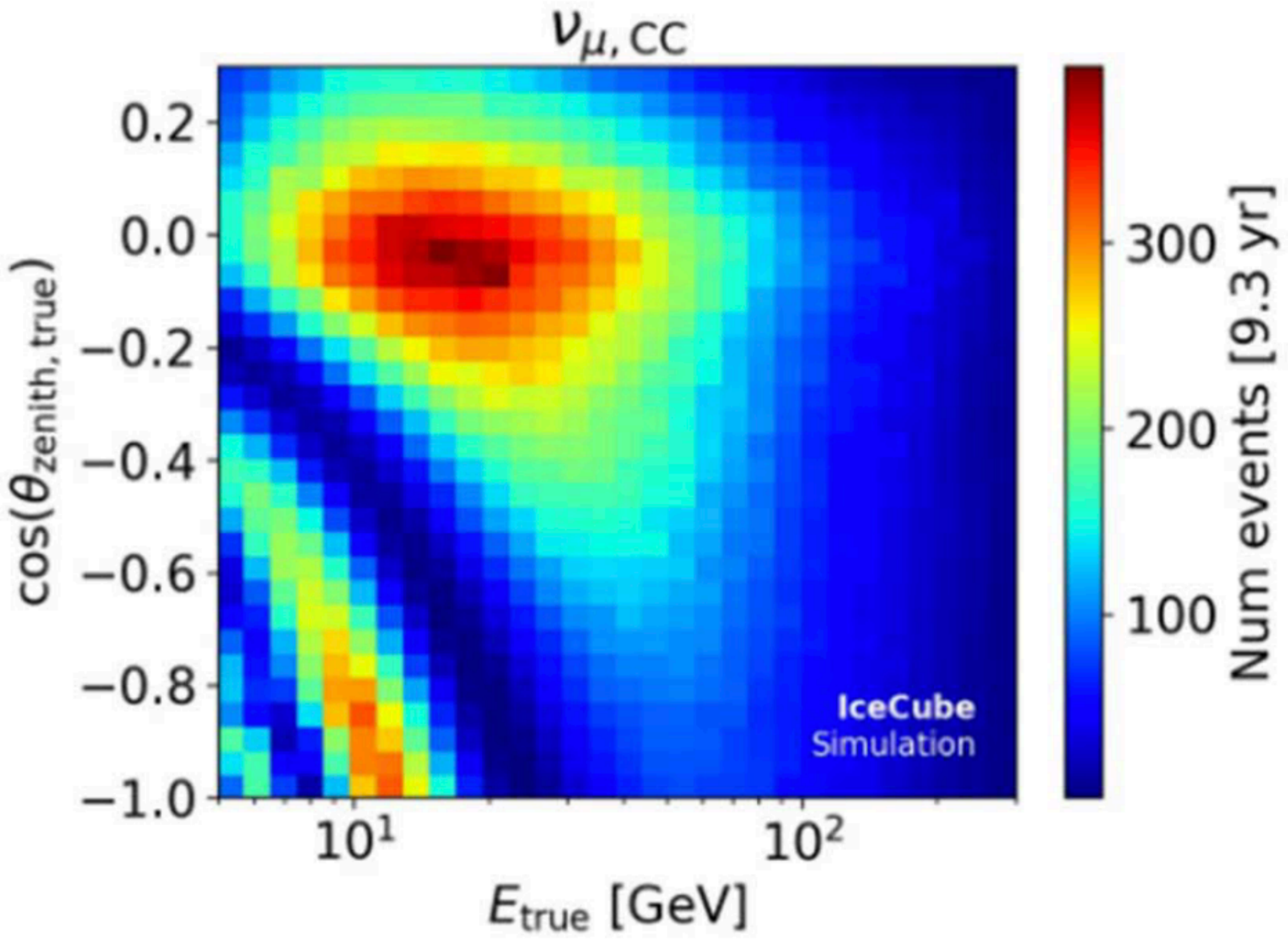


Reco Resolution



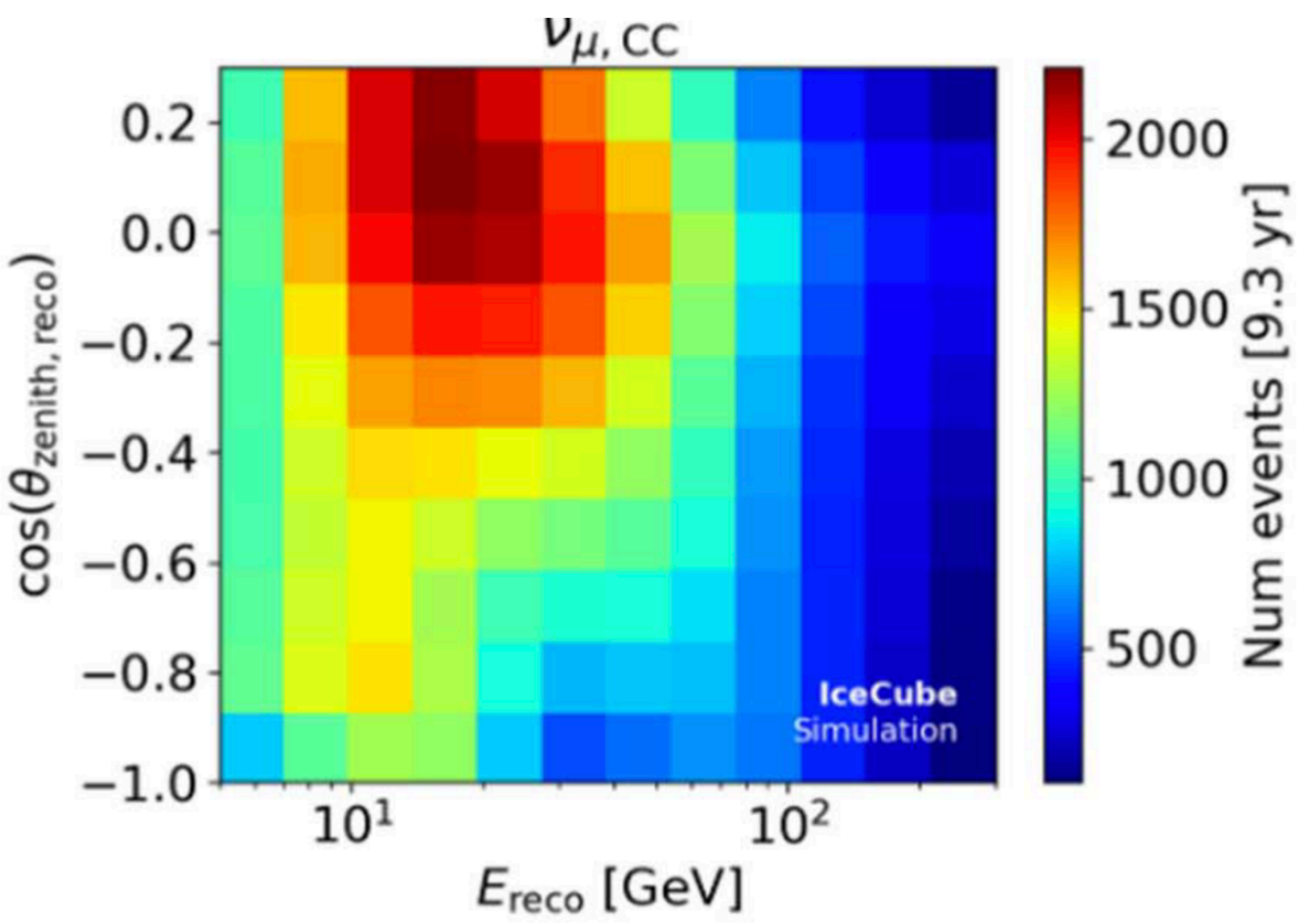
Credit: A. Ishihara

Deepcore Event Resolution



Truth information shows
Oscillation features

Event selection: Proceedings of NuFact2021 https://pos.sissa.it/402/062/pdf



Oscillation features smeared by detector
Resolution and finite binning

Reconstruction: https://arxiv.org/abs/2203.02303

PDG

Tau branching ratios

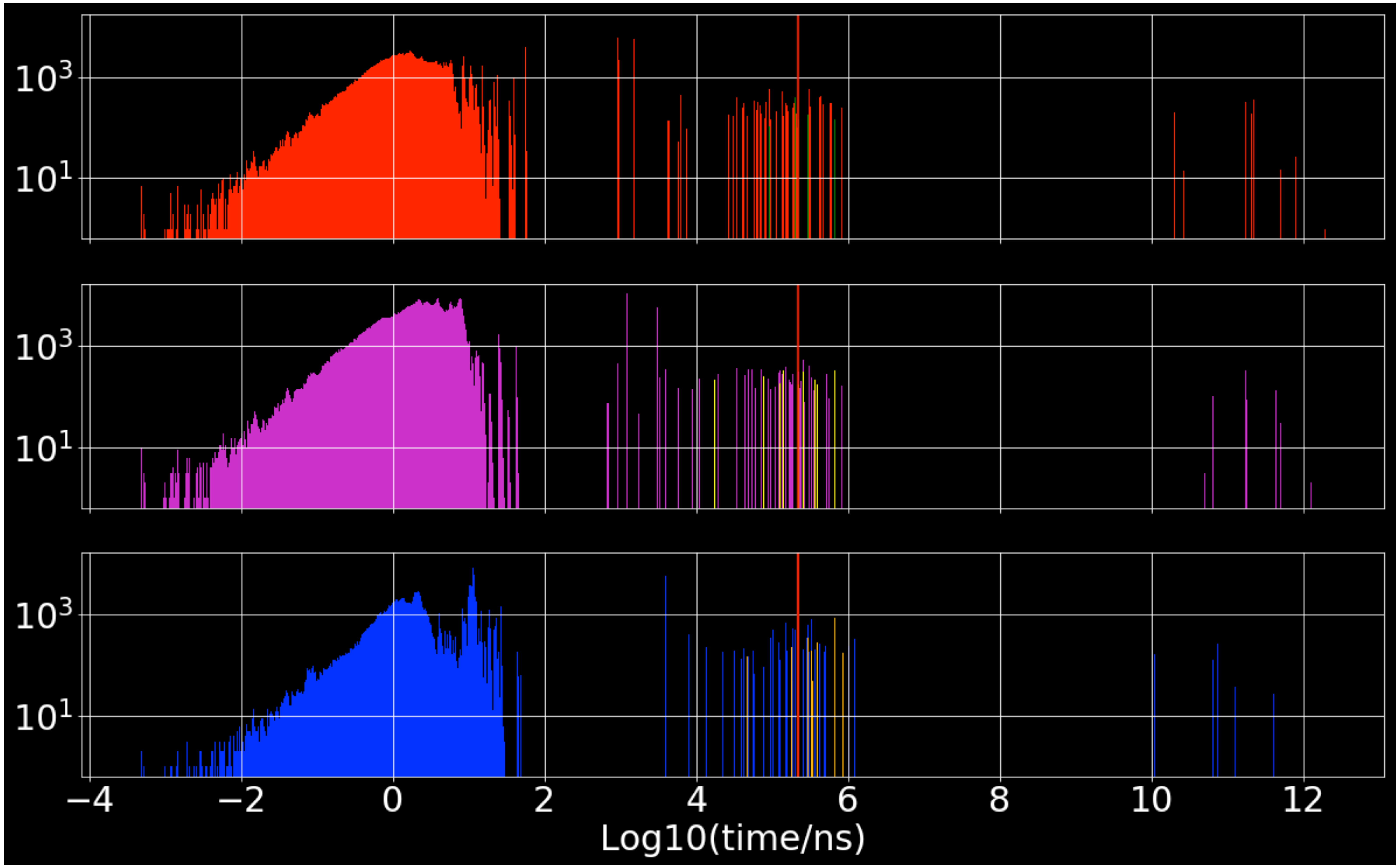
$\pi^-\bar{K}^0\nu_\tau$	0.8384 ± 0.0138
$K^-K^0\nu_\tau$	0.1486 ± 0.0034
$\pi^-\bar{K}^0\pi^0\nu_\tau$	0.3817 ± 0.0129
$K^-\pi^0K^0\nu_\tau$	0.1500 ± 0.0070
$\pi^-\bar{K}^0 2\pi^0\nu_\tau$ (ex. K^0)	0.0263 ± 0.0226
$\pi^-K^0_SK^0_S\nu_\tau$	0.0235 ± 0.0006
$\pi^-K^0_SK^0_L\nu_\tau$	0.1081 ± 0.0241
$\pi^-\pi^0K^0_SK^0_S\nu_\tau$	0.0018 ± 0.0002
$\pi^-\pi^0K^0_SK^0_L\nu_\tau$	0.0325 ± 0.0119
$\bar{K}^0h^-h^-h^+\nu_\tau$	0.0247 ± 0.0199
$\pi^-\pi^-\pi^+\nu_\tau$ (ex. K^0, ω)	8.9868 ± 0.0513
$\pi^-\pi^-\pi^+\pi^0\nu_\tau$ (ex. K^0, ω)	2.7404 ± 0.0710
$h^-h^-h^+2\pi^0\nu_\tau$ (ex. K^0, ω, η)	0.0981 ± 0.0356
$\pi^-K^-K^+\nu_\tau$	0.1435 ± 0.0027
$\pi^-K^-K^+\pi^0\nu_\tau$	0.0061 ± 0.0018
$\pi^-\pi^0\eta\nu_\tau$	0.1389 ± 0.0072
$K^-\eta\nu_\tau$	0.0155 ± 0.0008
$K^-\pi^0\eta\nu_\tau$	0.0048 ± 0.0012

$\mu^-\bar{\nu}_\mu\nu_\tau$	17.3937 ± 0.0384	1.0000
$e^-\bar{\nu}_e\nu_\tau$	17.8175 ± 0.0399	1.0000
$\pi^-\nu_\tau$	10.8164 ± 0.0512	1.0000
$K^-\nu_\tau$	0.6964 ± 0.0096	1.0000
$\pi^-\pi^0\nu_\tau$	25.4941 ± 0.0893	1.0000
$K^-\pi^0\nu_\tau$	0.4328 ± 0.0148	1.0000
$\pi^-2\pi^0\nu_\tau$ (ex. K^0)	9.2595 ± 0.0964	1.0021
$K^-2\pi^0\nu_\tau$ (ex. K^0)	0.0647 ± 0.0218	1.0000
$\pi^-3\pi^0\nu_\tau$ (ex. K^0)	1.0429 ± 0.0707	1.0000
$K^-3\pi^0\nu_\tau$ (ex. K^0, η)	0.0478 ± 0.0212	1.0000
$h^-4\pi^0\nu_\tau$ (ex. K^0, η)	0.1118 ± 0.0391	1.0000

Cherenkov photon Timing distributions

1 GeV neutrino events (Hydrogen Primary)

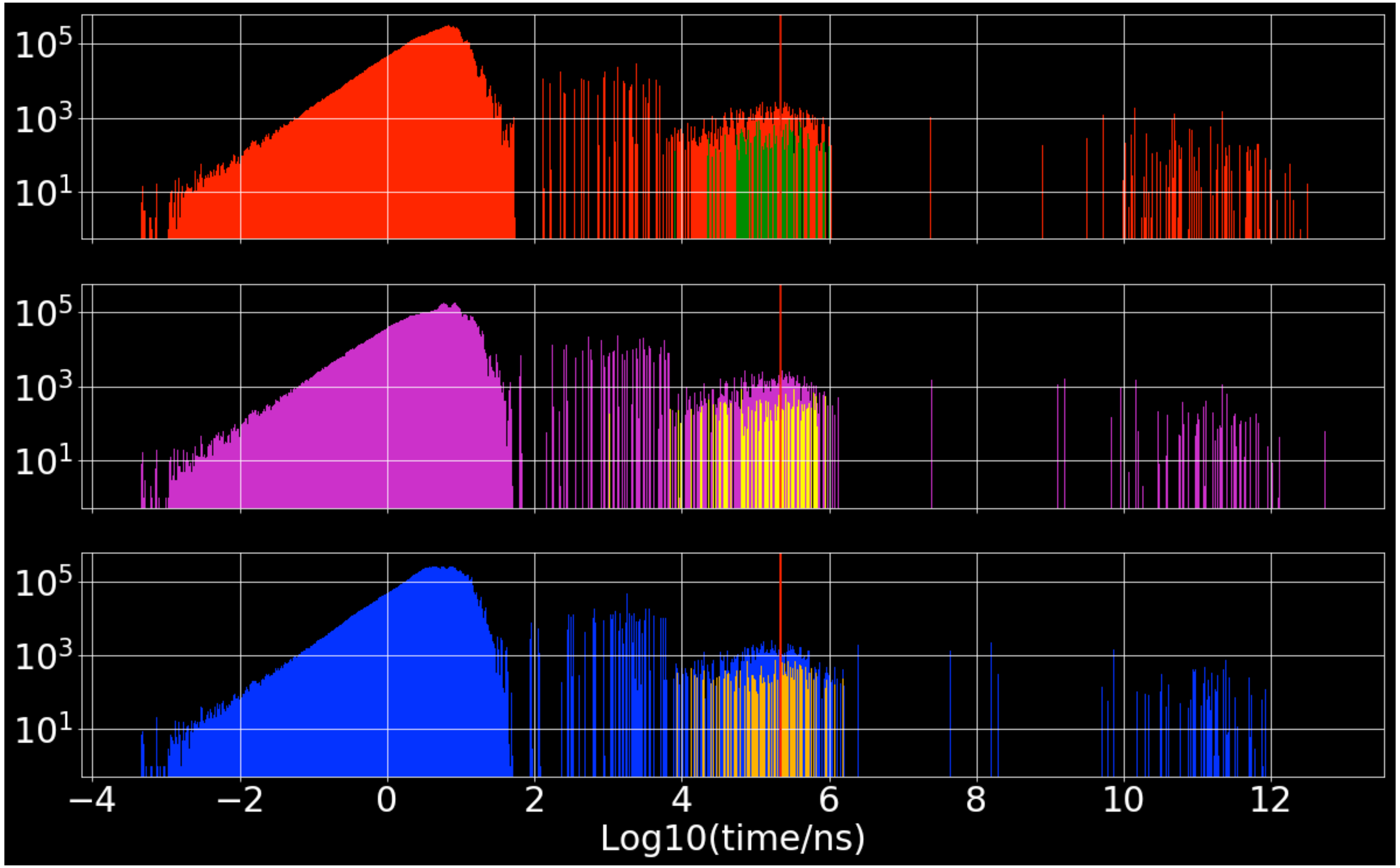
- Timing distribution of 100 stacked events of nue (red), numu (purple) and nutau (blue) on log axis



Cherenkov photon Timing distributions

5 GeV neutrino events (Hydrogen Primary)

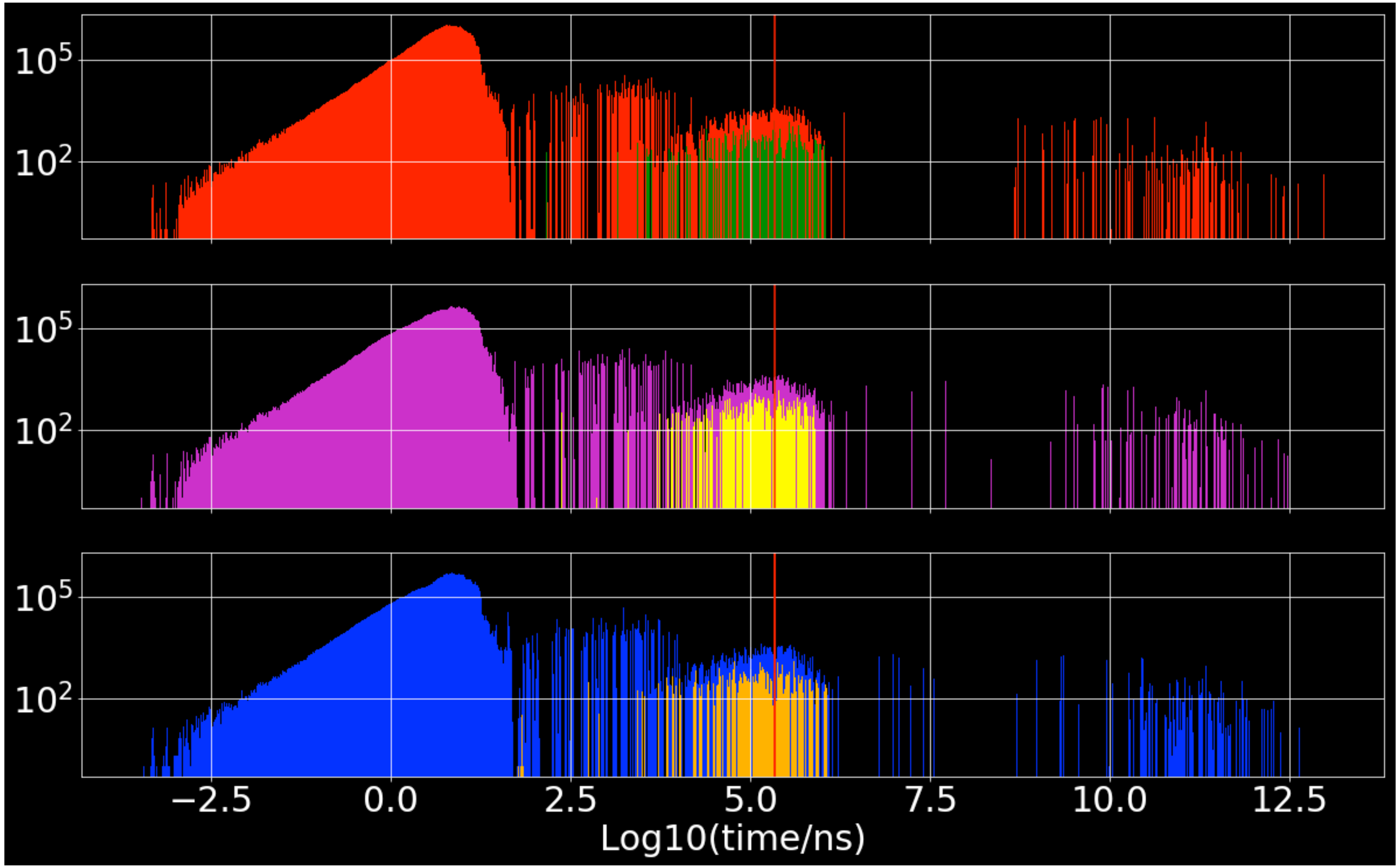
- Timing distribution of 100 stacked events of nue (red), numu (purple) and nutau (blue) on log axis



Cherenkov photon Timing distributions

10 GeV neutrino events (Hydrogen Primary)

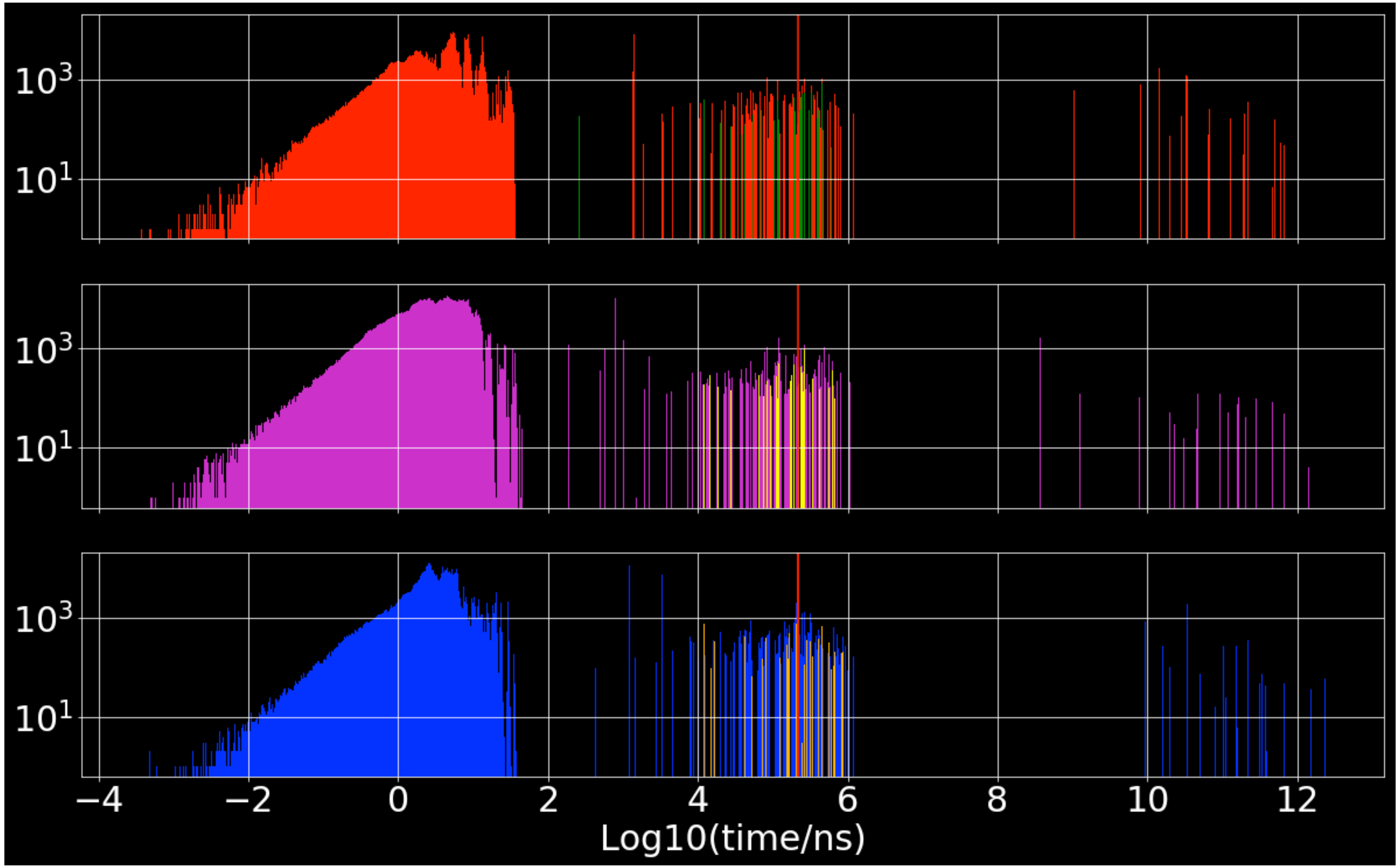
- Timing distribution of 100 stacked events of nue (red), numu (purple) and nutau (blue) on log axis



Cherenkov photon Timing distributions

1 GeV neutrino events (Oxygen Primary)

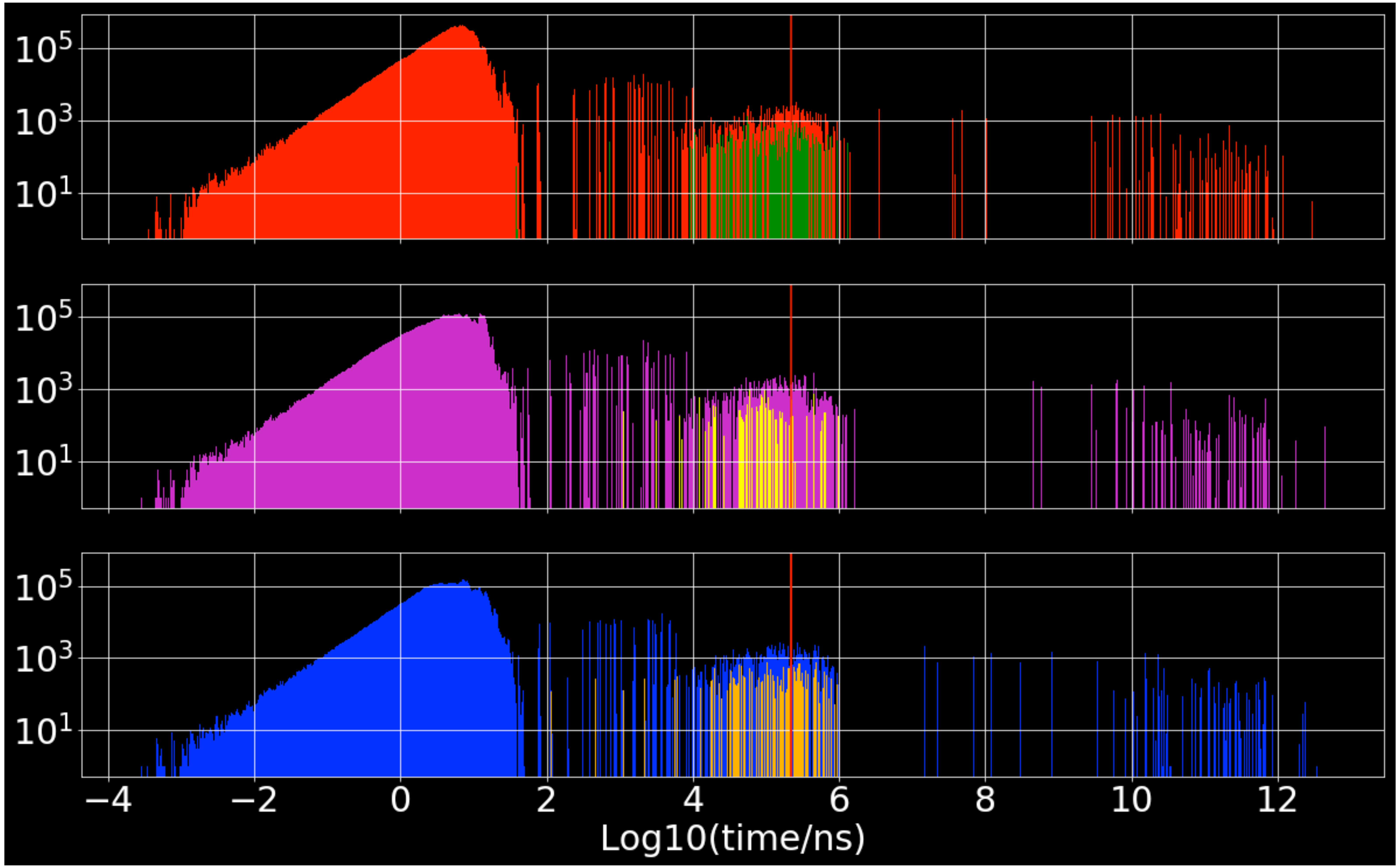
- Timing distribution of 100 stacked events of nue (red), numu (purple) and nutau (blue) on log axis



Cherenkov photon Timing distributions

5 GeV neutrino events (Oxygen Primary)

- Timing distribution of 100 stacked events of nue (red), numu (purple) and nutau (blue) on log axis



Cherenkov photon Timing distributions

10 GeV neutrino events (Oxygen Primary)

- Timing distribution of 100 stacked events of nue (red), numu (purple) and nutau (blue) on log axis