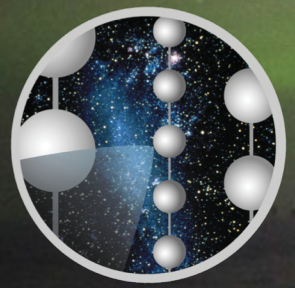
Particle physics with atmospheric neutrinos at IceCube/DeepCore

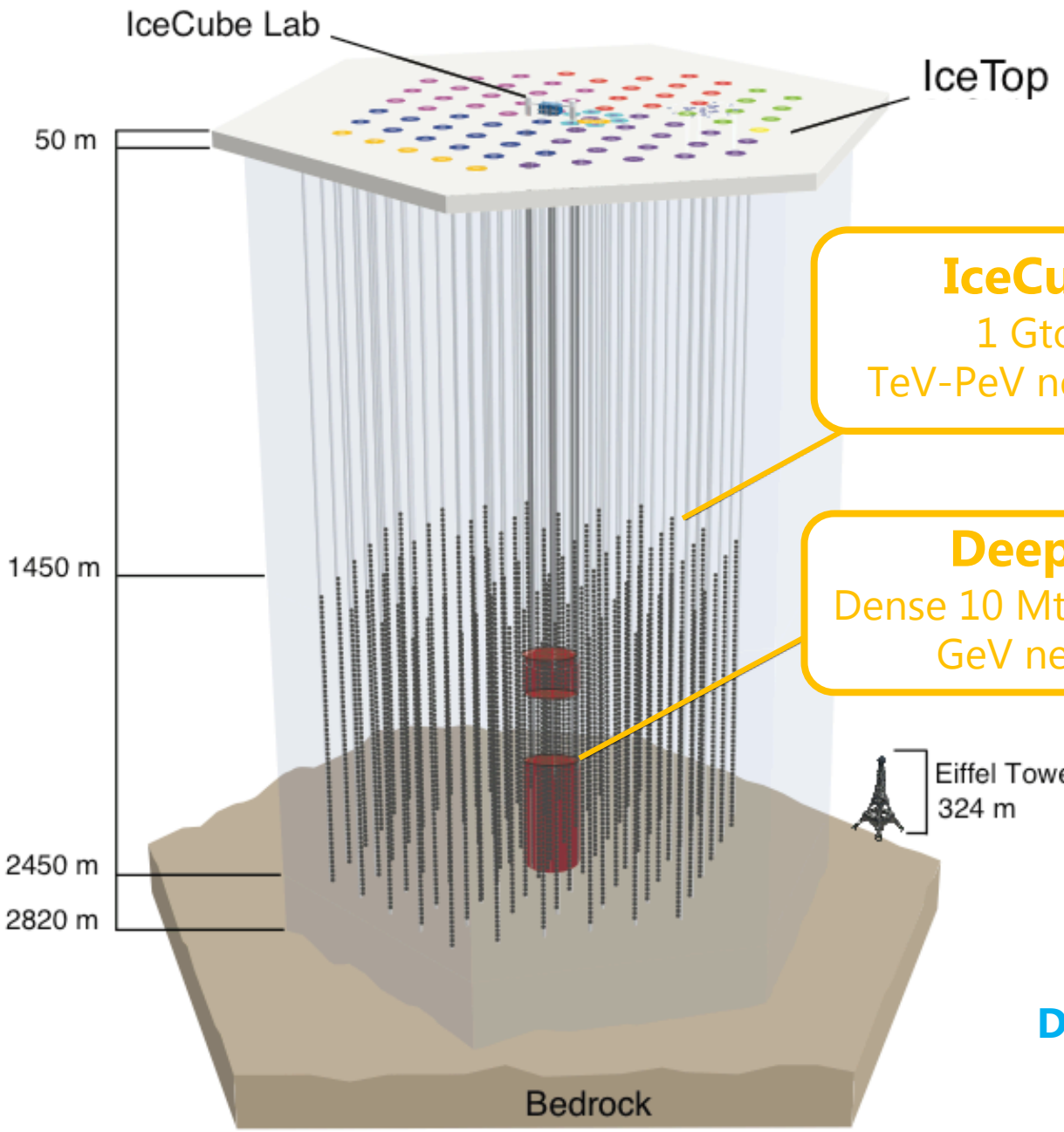
Tom Stuttard for the IceCube collaboration
Niels Bohr Institute

Neutrino 2022

CARLSBERG FOUNDATION



IceCube
South Pole Neutrino Observatory



IceCube
1 Gton
TeV-PeV neutrinos

DeepCore
Dense 10 Mton sub-array
GeV neutrinos

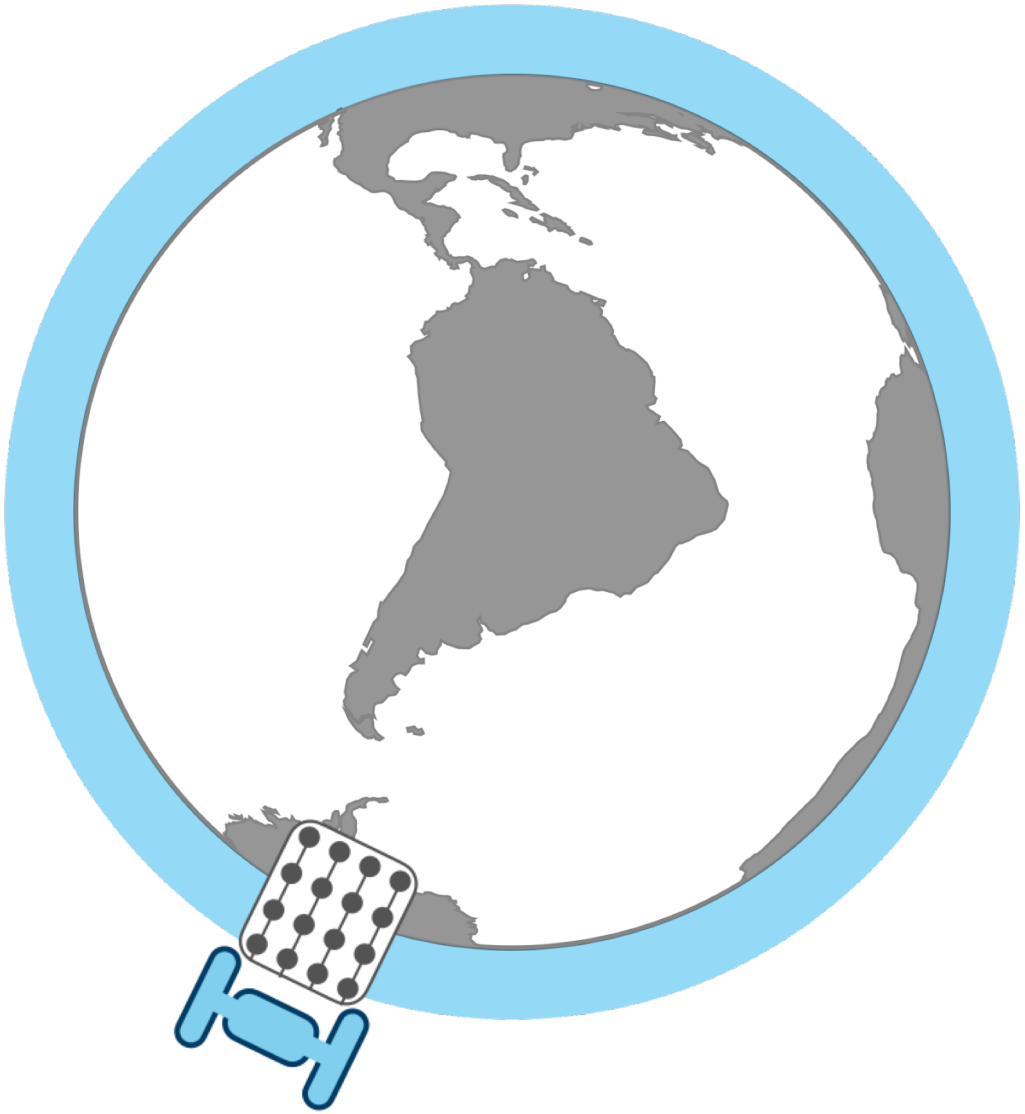
IceCube
South Pole Neutrino Observatory

5160 PMTs in glacial ice
(natural detection medium)

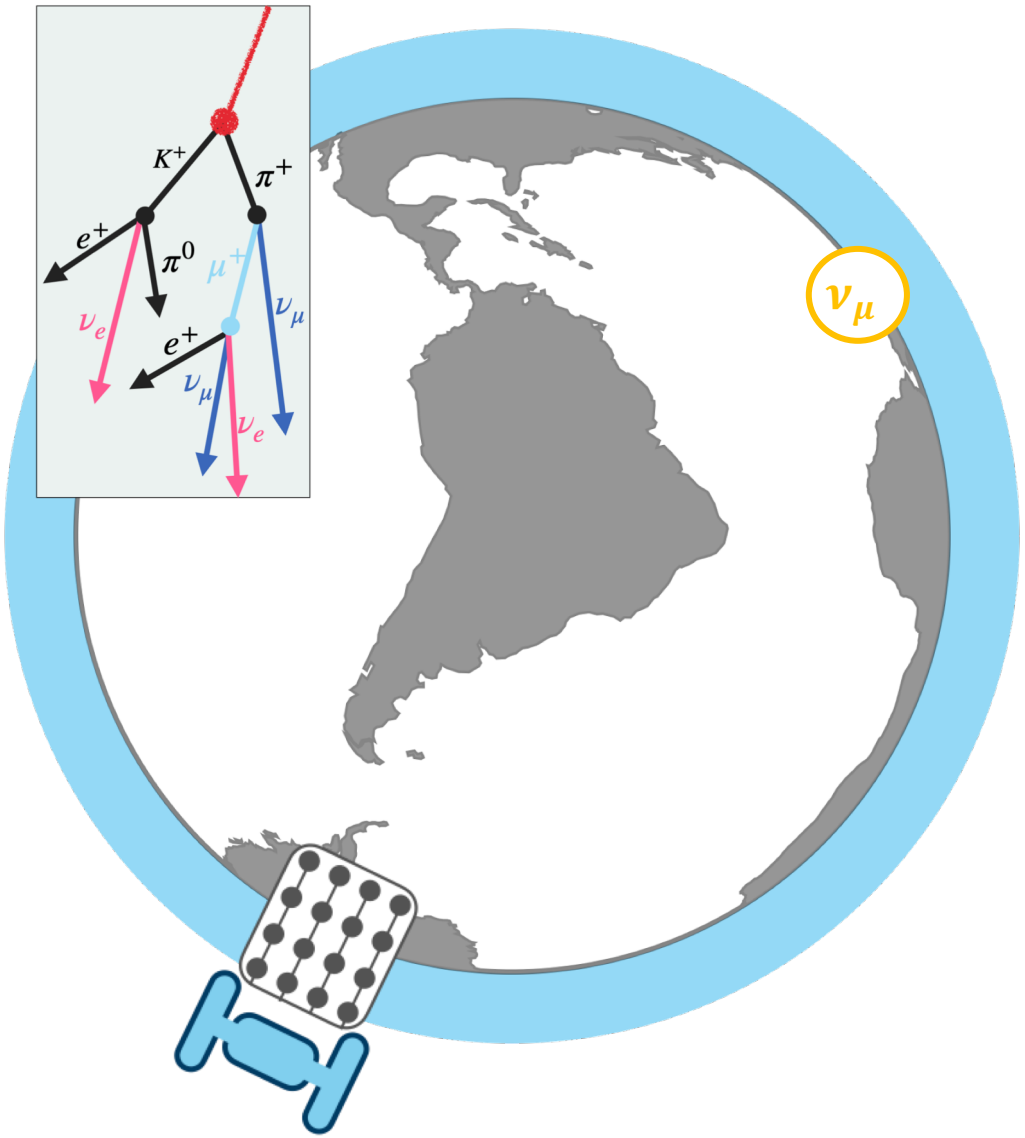
Designed to discover high energy astrophysical ν

Also detects large flux of atmospheric ν

Atmospheric neutrinos in IceCube

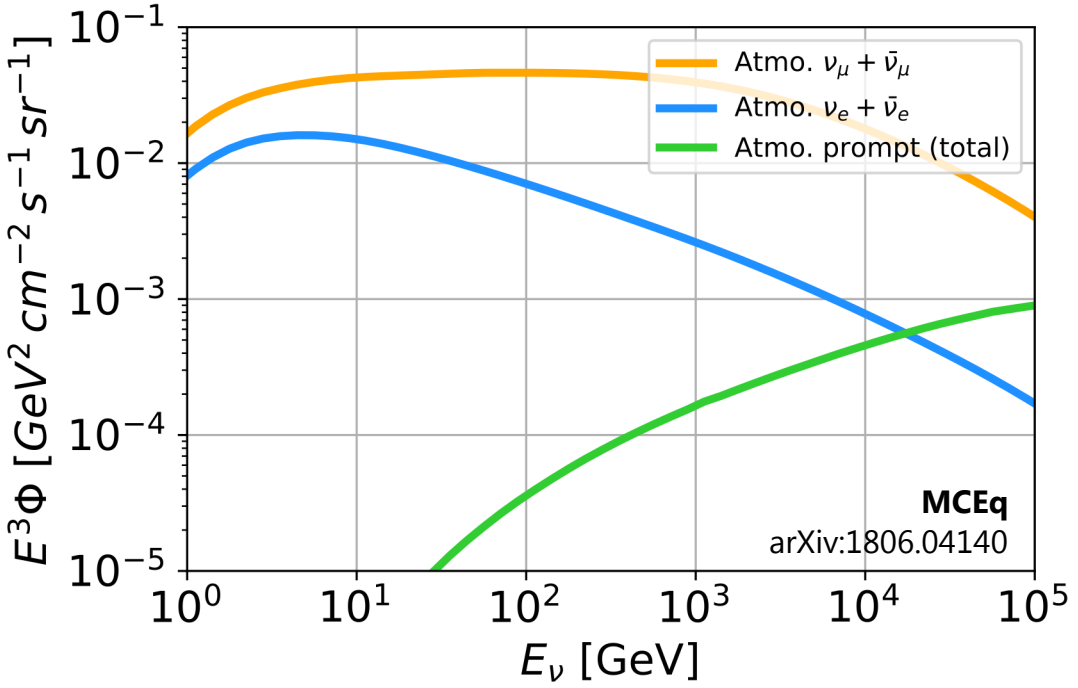


Atmospheric neutrinos in IceCube

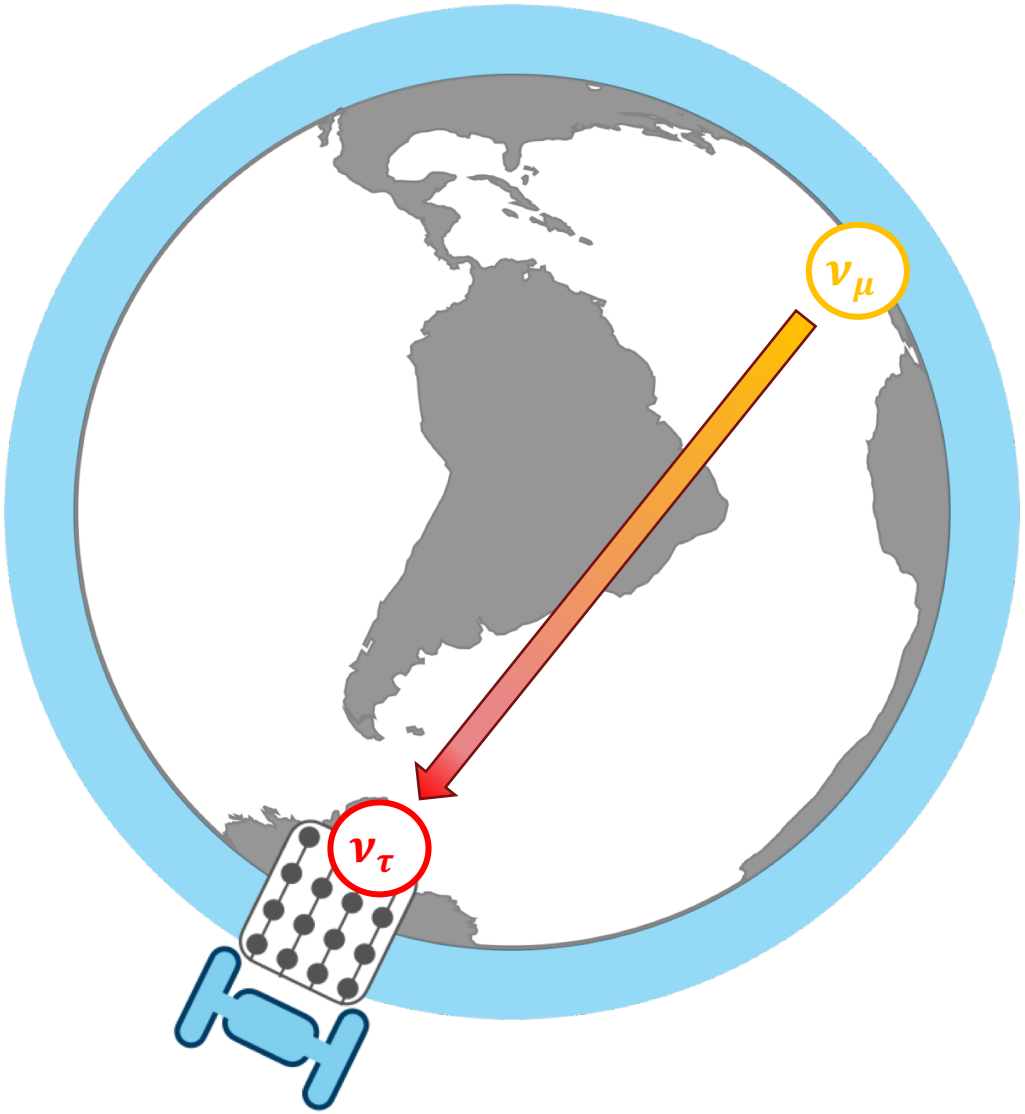


(1) Cosmic rays interact in the atmosphere and produce air showers

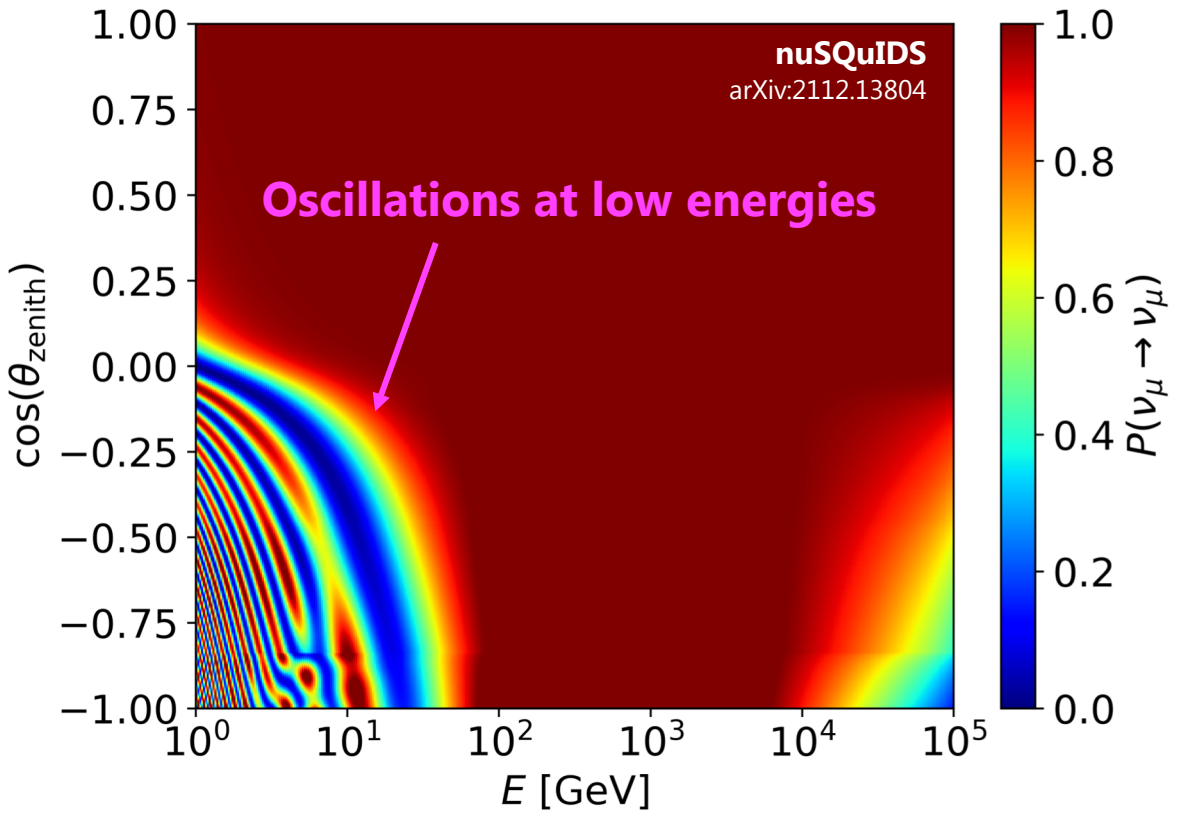
→ **Large flux of high energy neutrinos**



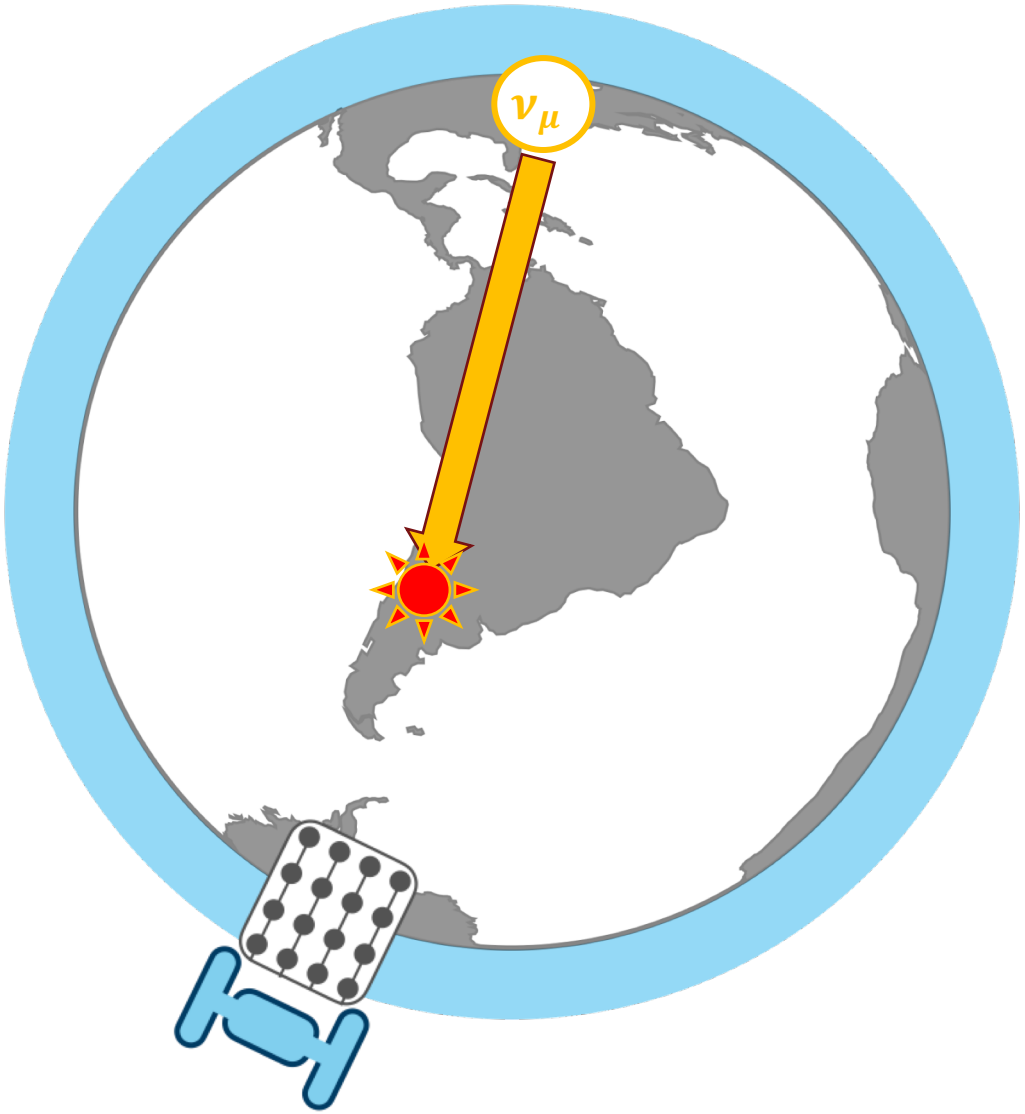
Atmospheric neutrinos in IceCube



(2) Neutrinos propagate across the Earth



Atmospheric neutrinos in IceCube



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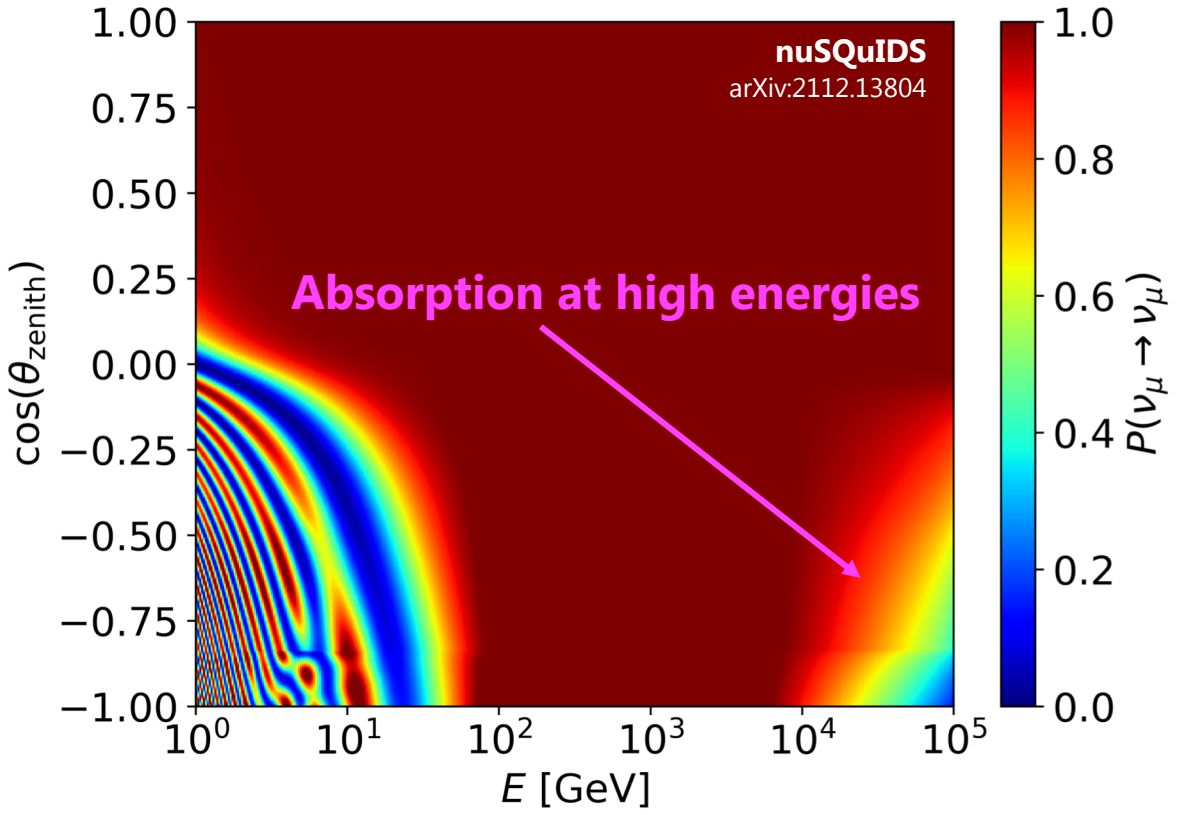
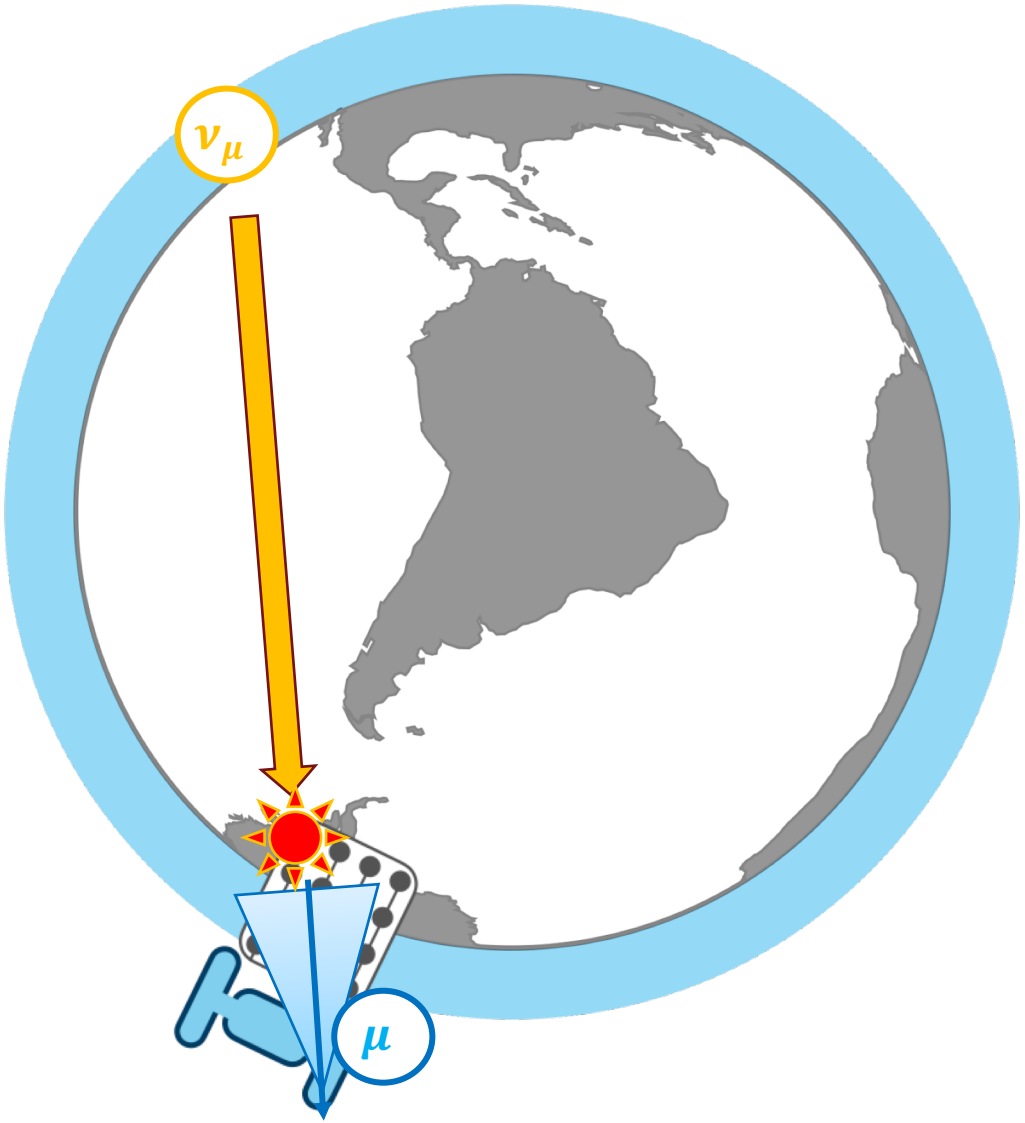


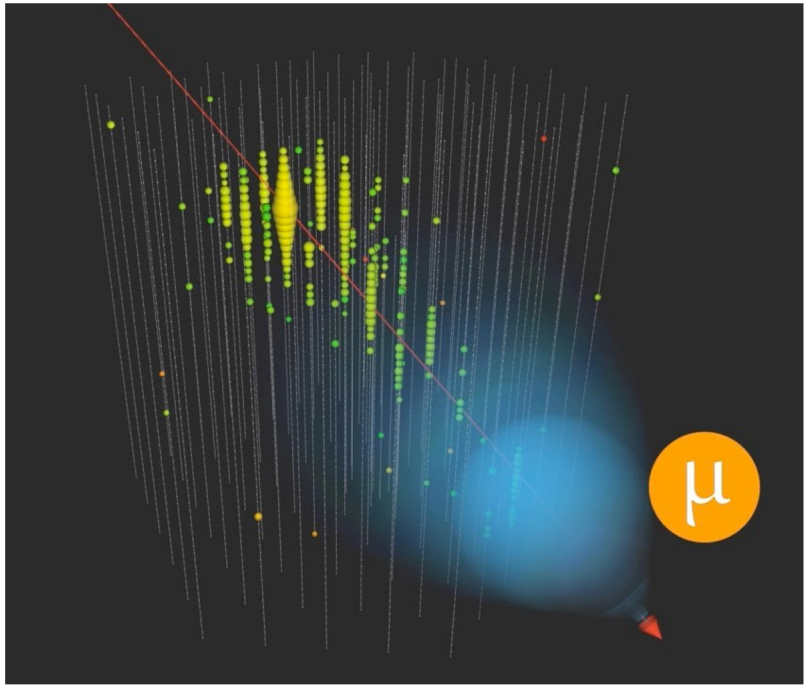
Atmospheric neutrinos in IceCube



(3) Detection via Cherenkov emission from products of $\nu - N$ interactions

Predominantly Deep Inelastic Scattering (DIS)

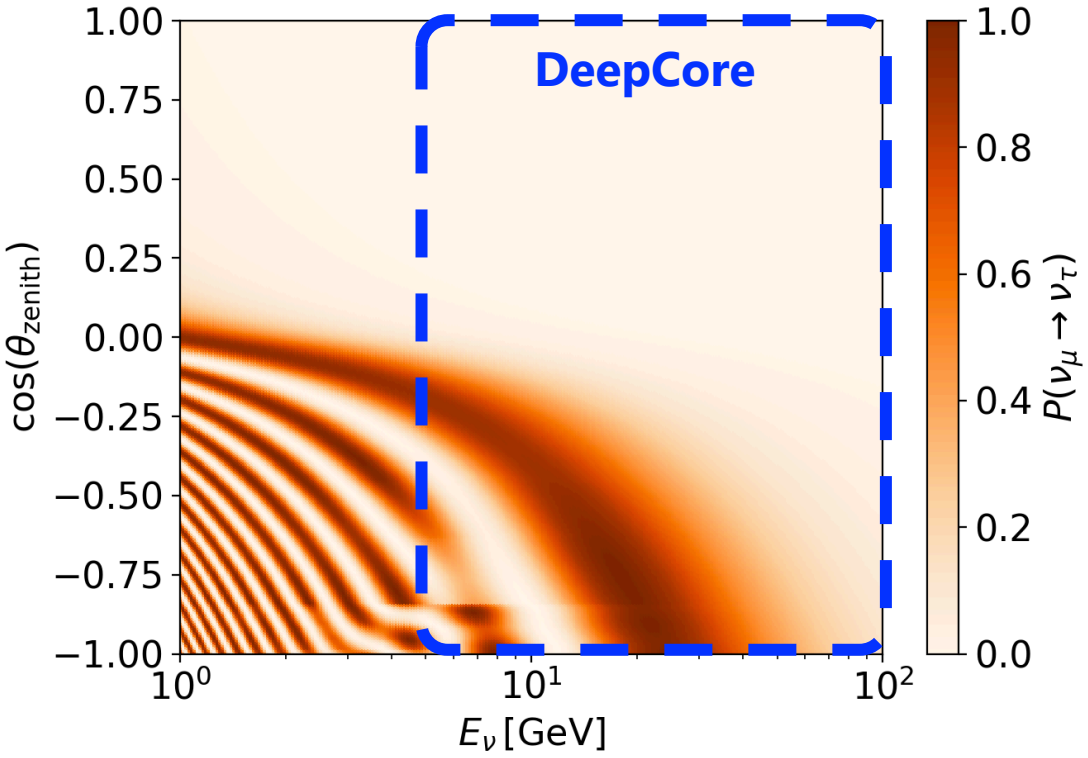
"Tracks" from secondary μ
"Cascades" from secondary e, τ and hadrons

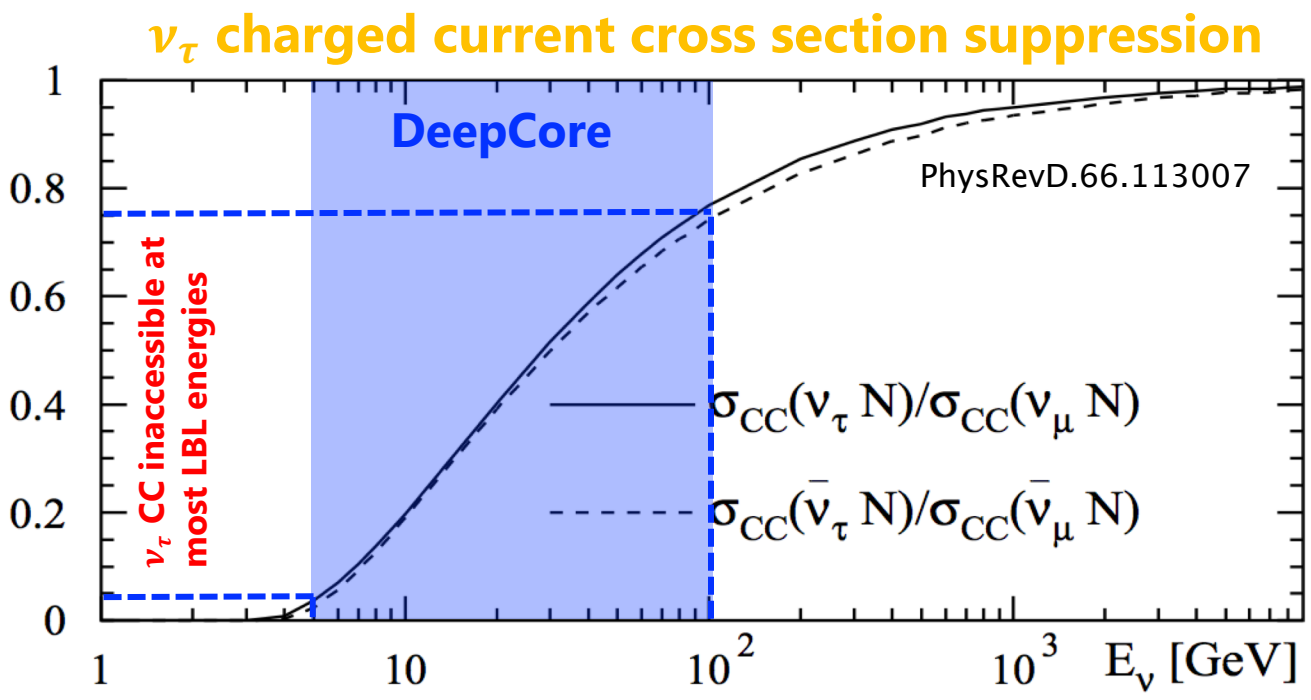


Neutrino oscillations

Atmospheric neutrino oscillations in IceCube-DeepCore

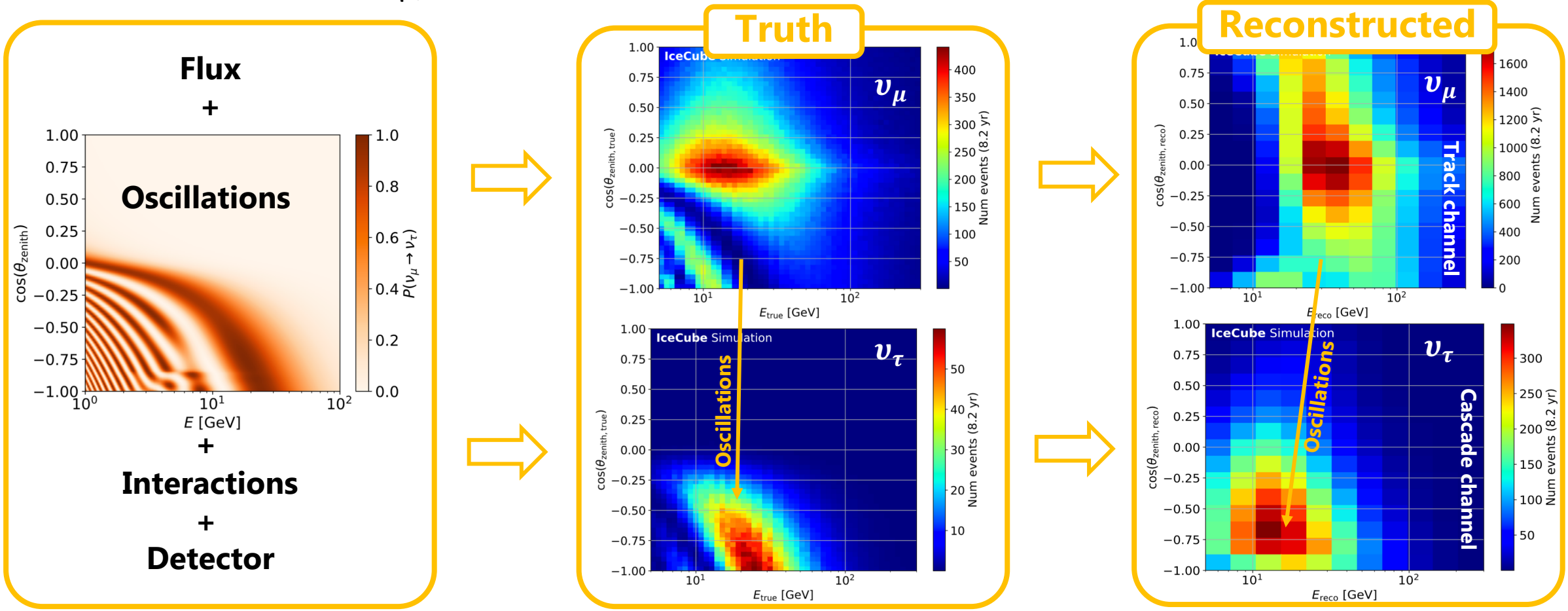
- $\mathcal{O}$(20 GeV) Earth-crossing $\boldsymbol{\nu_\mu}$ **near maximally oscillate to** $\boldsymbol{\nu_\tau}$
  - Same L/E as LBL accelerators but in DIS regime and with very different systematics
  - Observe both ν_μ and ν_τ **(above the** $\boldsymbol{\nu_{\tau,CC}}$ **kinematic threshold, ~3.5 GeV)**





Measuring oscillations

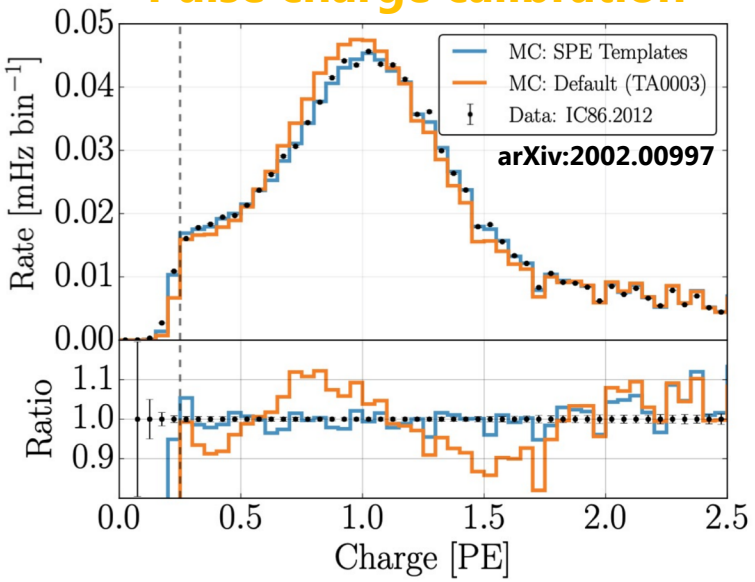
- Measure **3D distortions in reconstructed [energy, zenith, PID]**
  - Robust against systematic uncertainties
  - PID discriminates $\nu_{\mu,CC}$ interactions vs all other flavours/channels



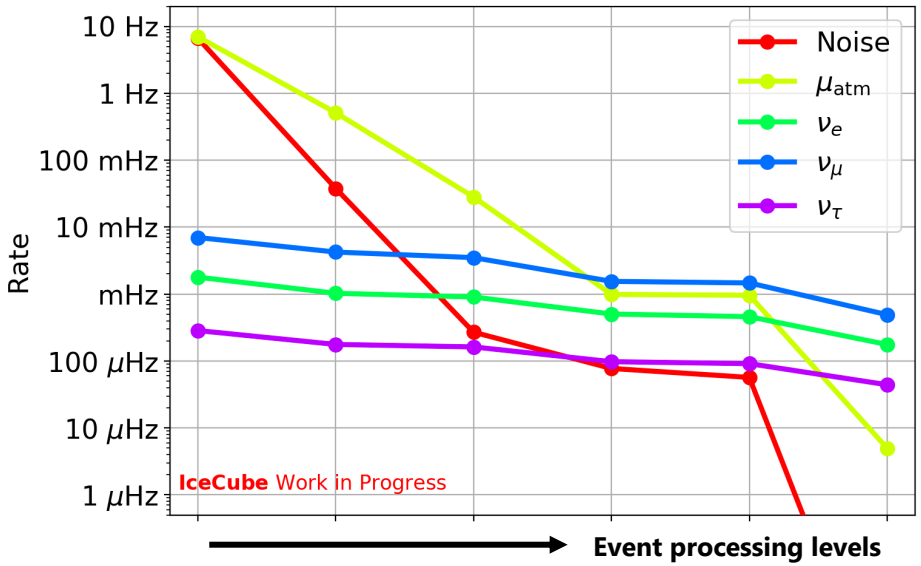
A new generation of oscillation analyses

- **8+ years of detector livetime → $\mathcal{O}(10^5)\,\nu$**
  - GeV and TeV data samples
- **Major improvements in all elements of analysis chain**
  - Calibration, systematic uncertainties, simulations, background rejection, reconstruction
- **Focus on making analyses robust to systematics**
  - Charge-independent data samples, off-signal regions, data-driven background classification, ….

Pulse charge calibration

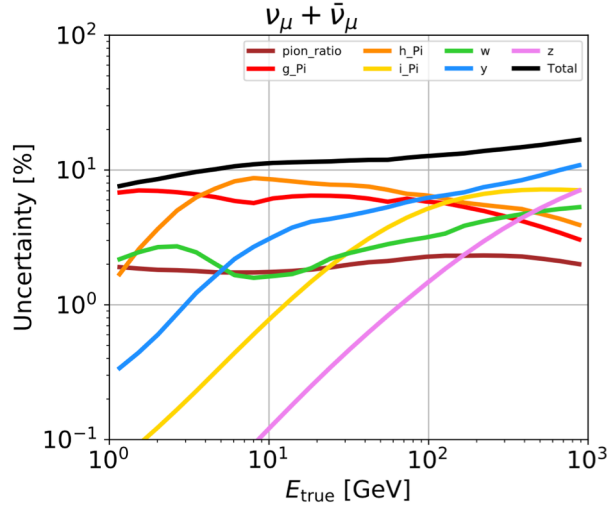


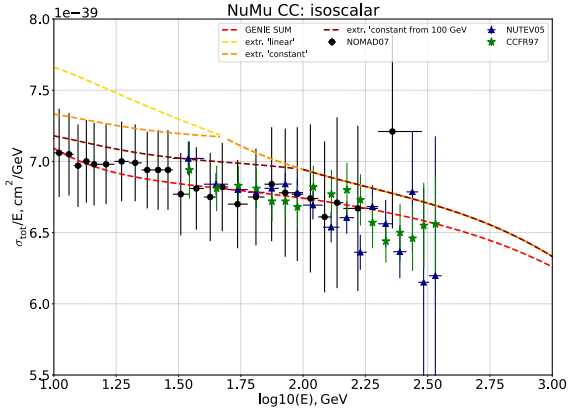
DeepCore background rejection

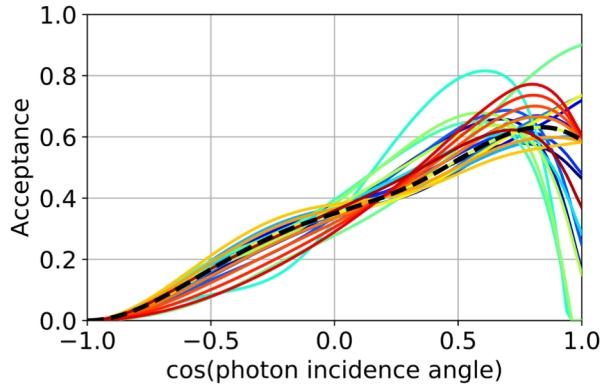


Systematic uncertainties

- **Flux**
  - Account for primary CR spectrum and hadronic model uncertainties
  - Use MCEq to re-compute flux with modified meson production
  - Meson re-interaction and atmospheric density variations uncertainties
- **Cross sections** → *smallest impact*
  - Axial mass uncertainty for resonance and quasielastic events
  - Continuous transformation between GENIE and CSMS DIS cross sections
  - Propagation of PDF uncertainties to DIS cross sections
- **Detector/ice properties** → *largest impact*
  - Individual charge calibration for every PMT
  - Detailed modelling of ice stratigraphy and anisotropy
  - Dedicated MC perturbing PMT and ice properties (bulk and drill column)
    - 6-D hypersurfaces fitted per analysis bin to give continuous distributions
  - Radioactive decay noise and charge calibration uncertainties
- **~40 systematic uncertainties in total**

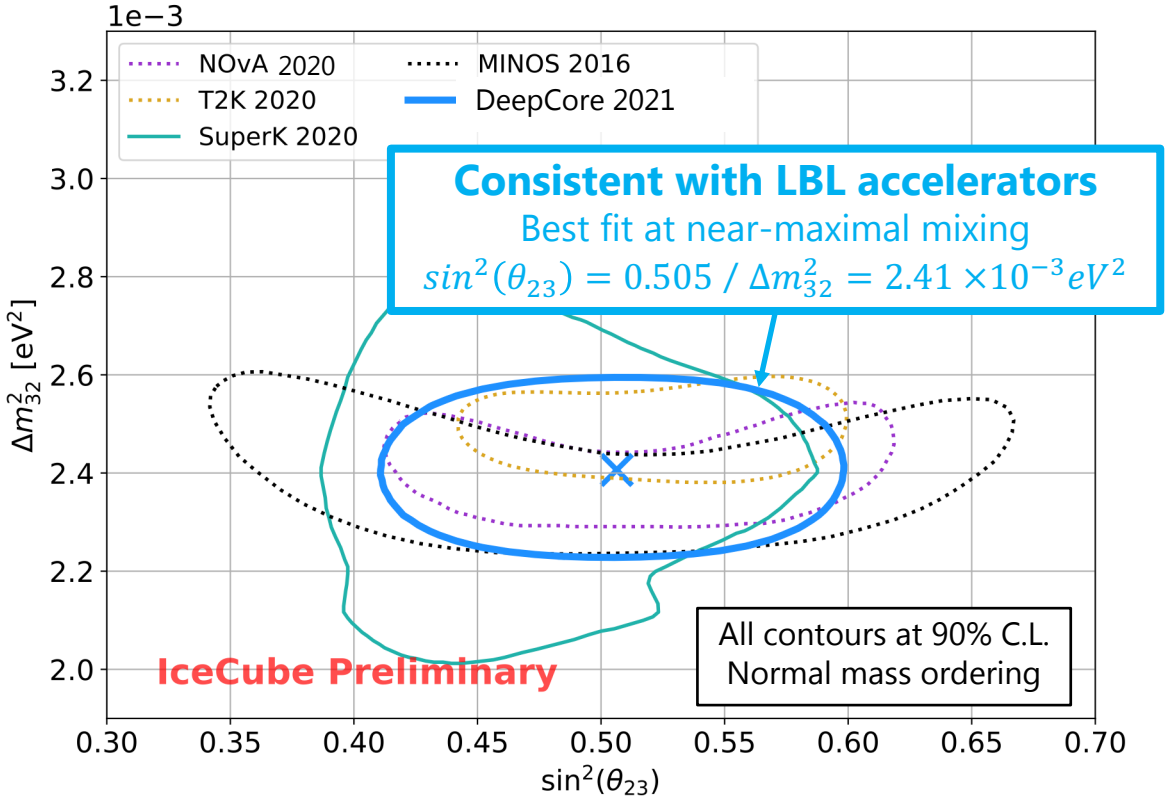


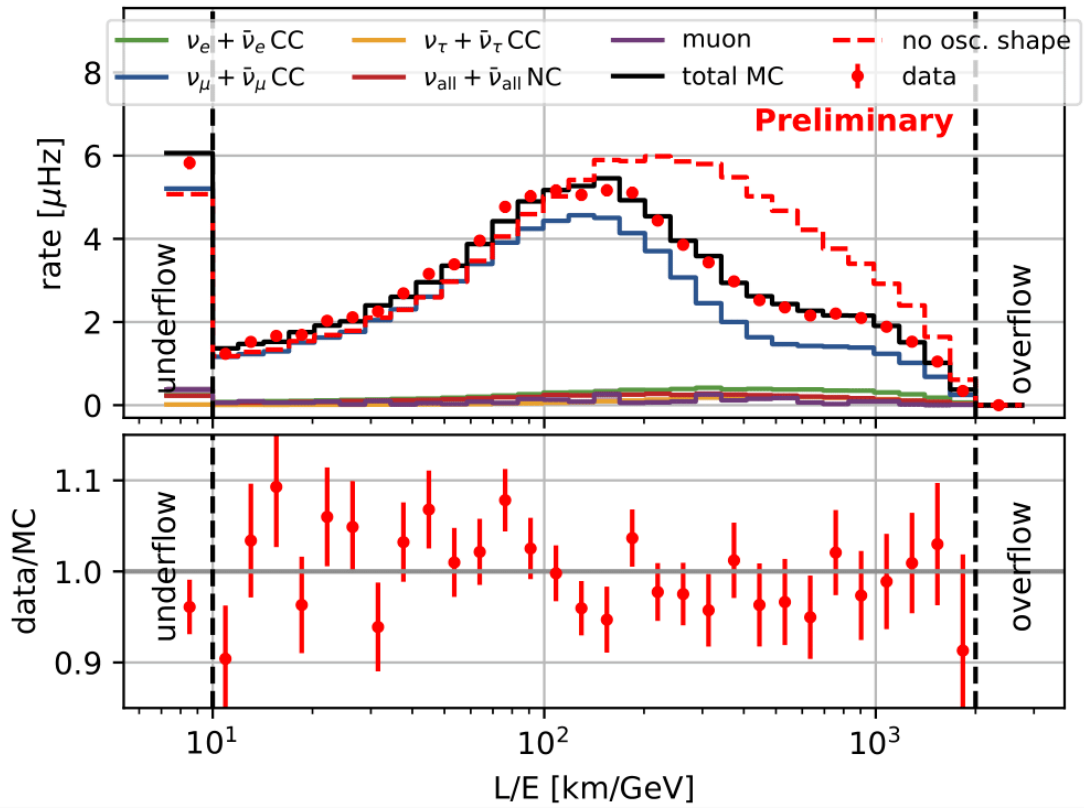




ν_μ disappearance: Latest results

- New measurement of ν_μ **disappearance with 8 years of IceCube data**
  - Uses a **"golden" sub-sample of ~23,000 track-like events**
  - Clean events with low levels of photon scattering → robust to ice modelling



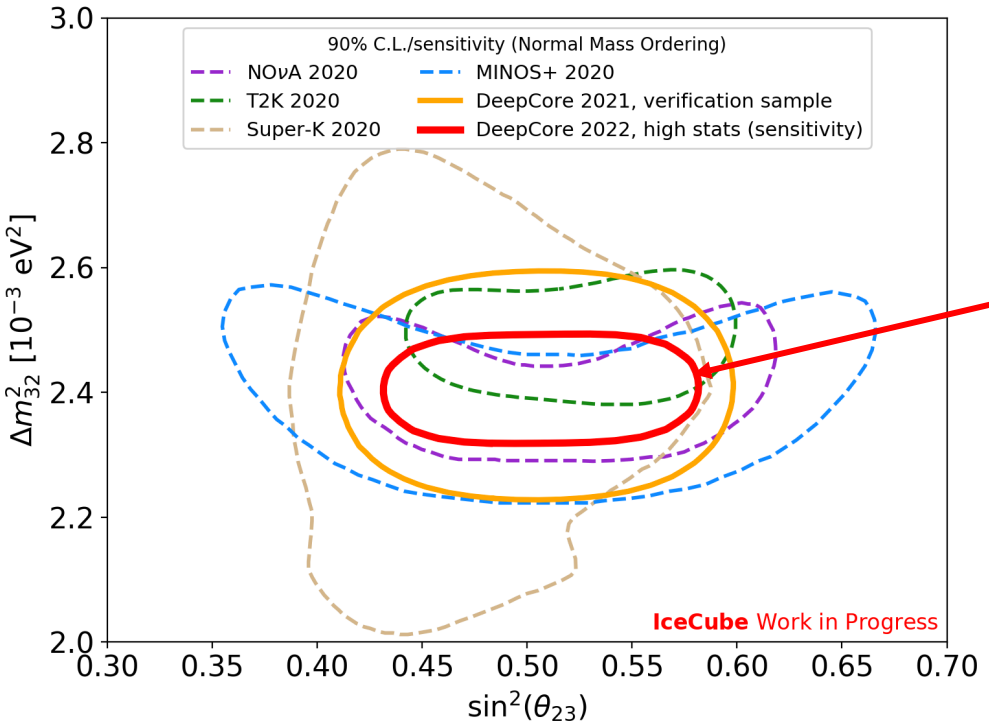


Posters DT01-606, DT01-095

Neutrino oscillations: Upcoming results

- Suite of analyses underway with a **new, high statistics data sample**
  - All flavours, state-of-the-art reconstruction and background rejection
- Observe ν_μ **disappearance and corresponding** ν_τ **appearance**

Atmospheric mixing parameter sensitivity



Sensitivity competitive with LBL accelerators

~210,000 neutrinos (0.7% background) → high stats and purity

Posters DT01-606, DT01-095

Neutrino oscillations: Upcoming results

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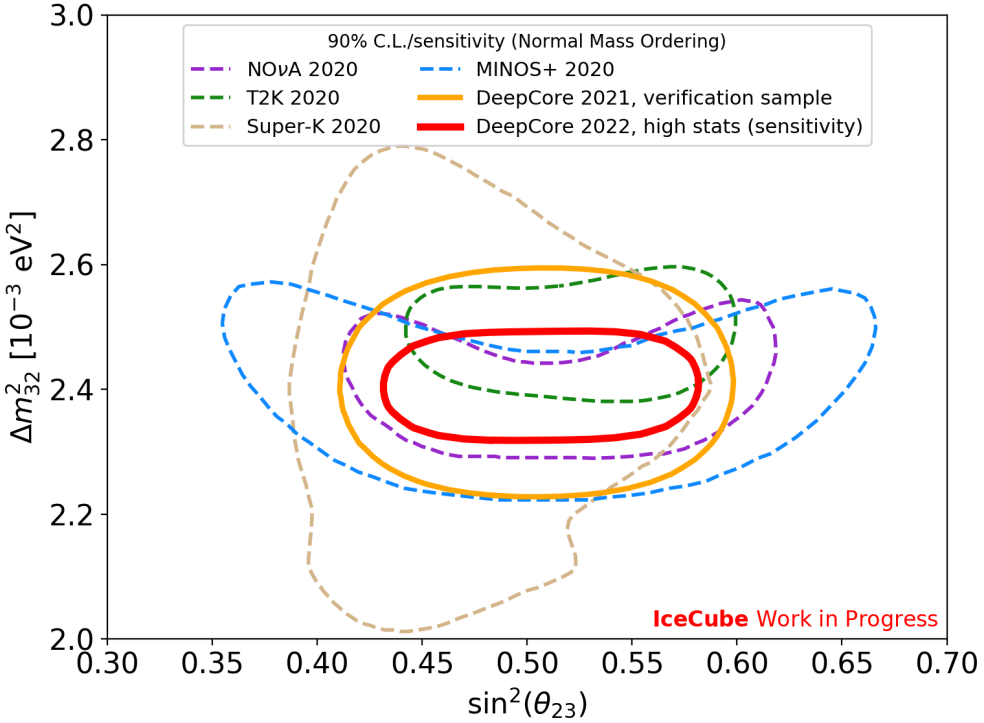
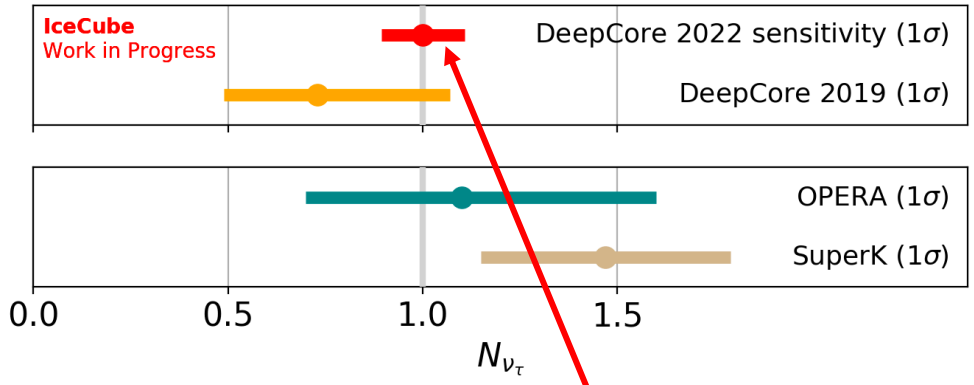


ν_τ normalization sensitivity



Expecting world-leading 11% precision

~9,700 $\nu_{\tau,CC}$ events expected

Signal is statistical excess of upgoing cascades with suppressed cross section

Tests PMNS unitarity and $\nu_{\tau,CC}$ cross section

Non-Standard Interactions

Non-Standard Interactions (NSI)

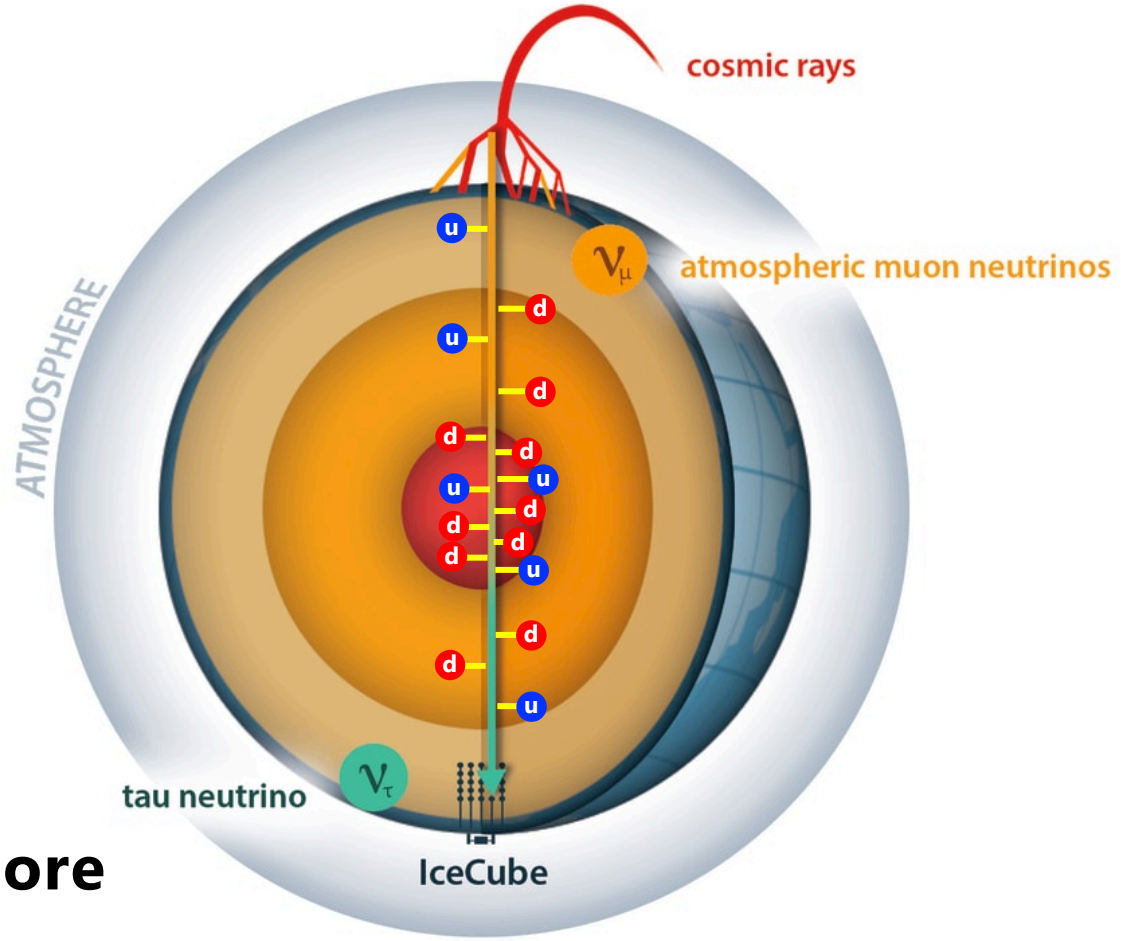
- Neutrinos traversing matter experience modified oscillations due to coherent elastic forward scattering with electrons

- **New neutrino-quark interactions** could result in **additional matter effects**

- Can parameterise via a **generic matter potential matrix**

$$H_{\text{mat+NSI}} = V_{CC}(x) \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix}$$

- Strong effects for ν crossing the **Earth's core**



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$\mathcal{O}$(GeV) DeepCore all-flavor samples give sensitivity to all NSI matrix elements

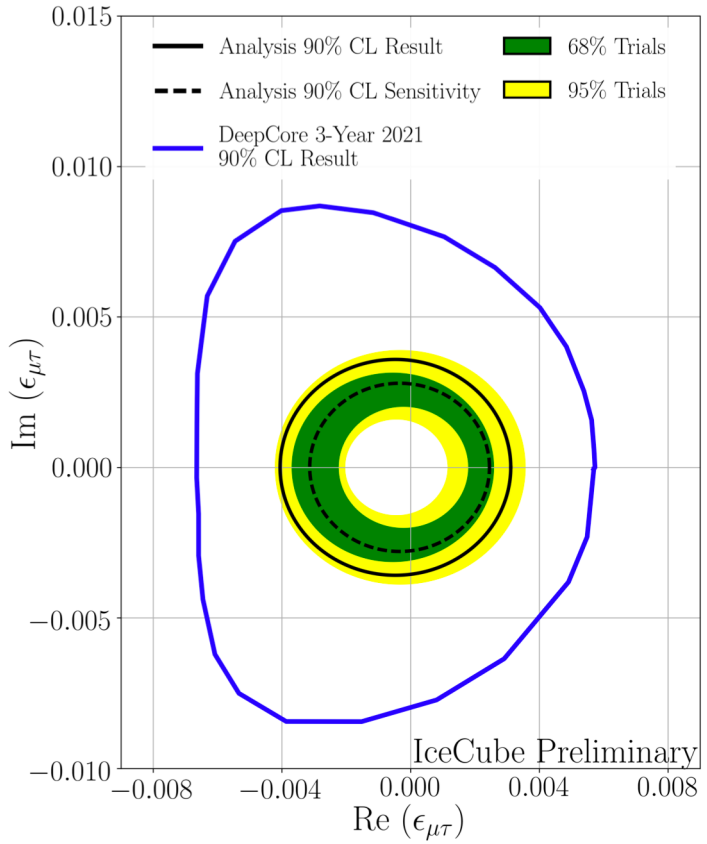
$$H_{\text{mat+NSI}} = V_{CC}(x) \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

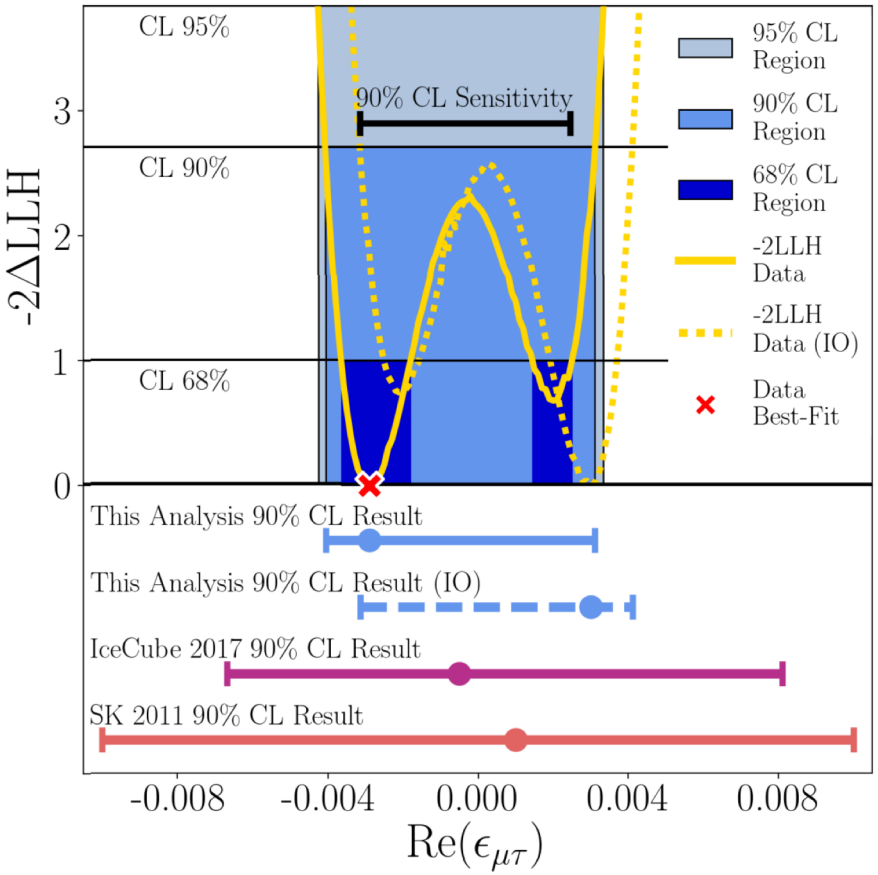
$\mathcal{O}$(TeV) IceCube track samples (IceCube) have strong sensitivity to $\epsilon_{\mu\tau}$

Latest IceCube NSI results

arXiv:2201.03566
Poster DT15-777

- Recent NSI search using 300,000 ν_μ events in the 0.5 – 10 TeV energy range
  - Results consistent with no NSI
  - **Strong limits set on $\epsilon_{\mu\tau}$ (real and imaginary components)**





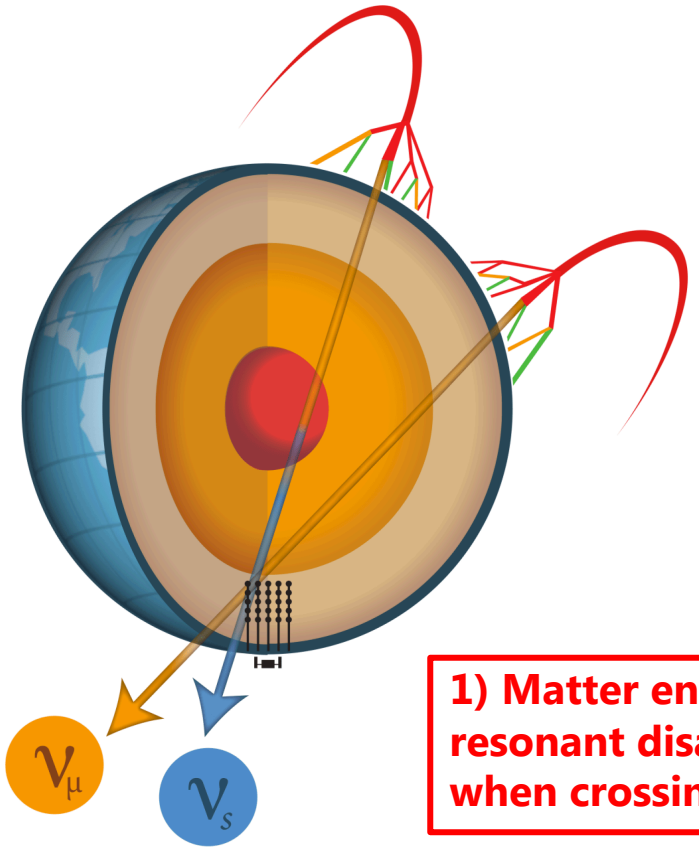
$$\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

Sterile neutrinos

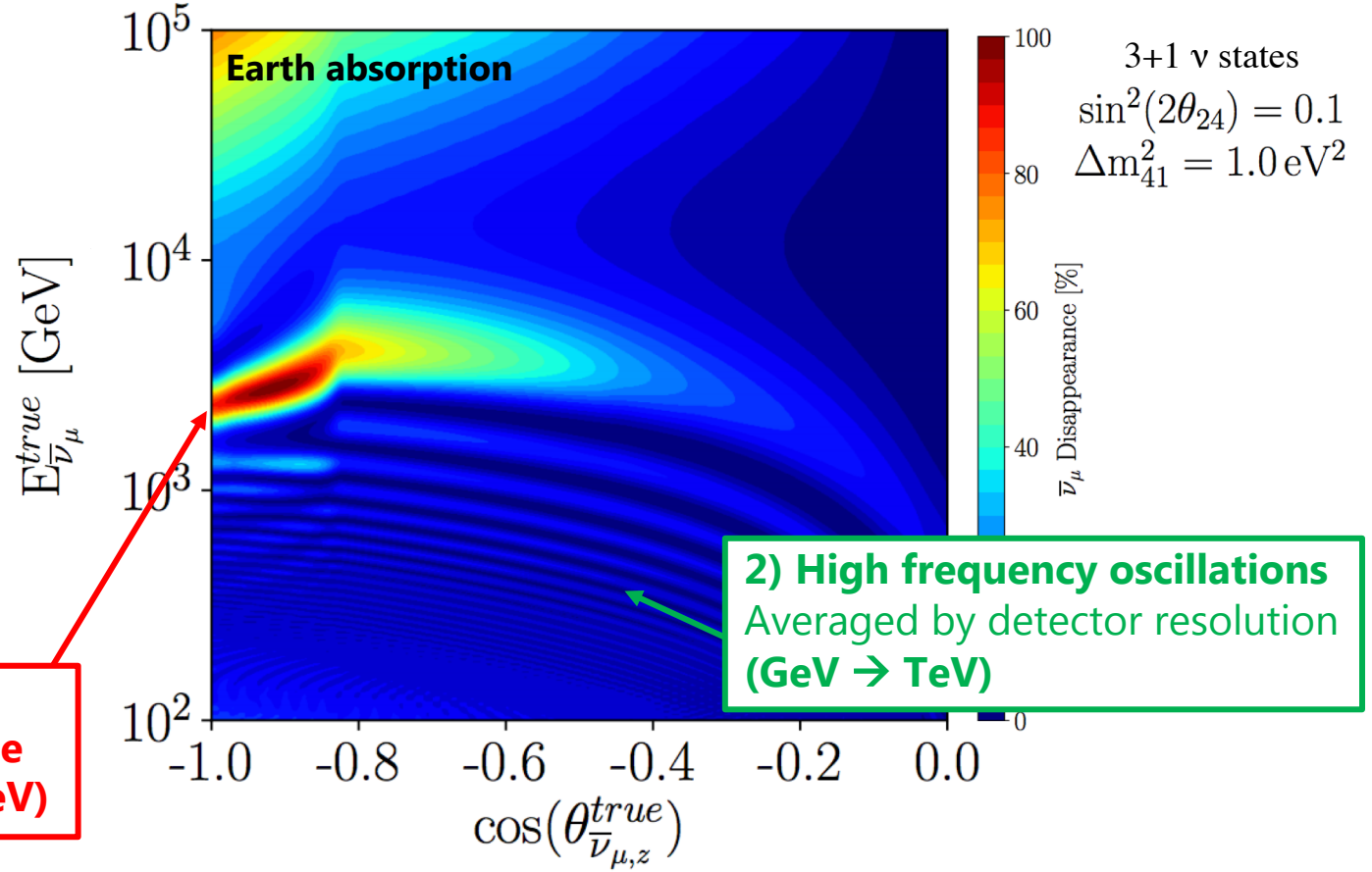
arXiv:2005.12942, 2005.12943

Sterile neutrinos

- Anomalies in short baseline appearance data → eV sterile neutrinos?
- If so, should be corresponding signals in atmospheric $\bar{\nu}_\mu$ disappearance
  - **Recent high statistics searches consistent with standard 3ν paradigm**



1) Matter enhanced resonant disappearance when crossing core (TeV)

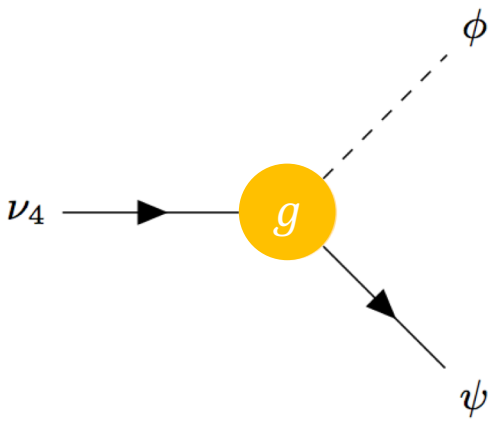


2) High frequency oscillations
Averaged by detector resolution
(GeV → TeV)

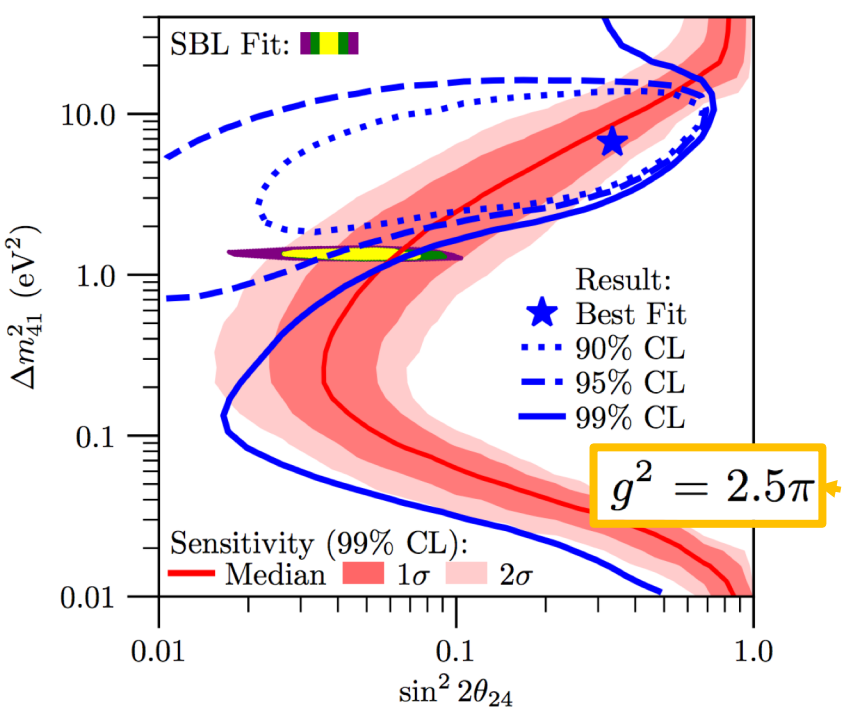
Unstable sterile neutrinos

arXiv:2204.0061
Poster DT14-250

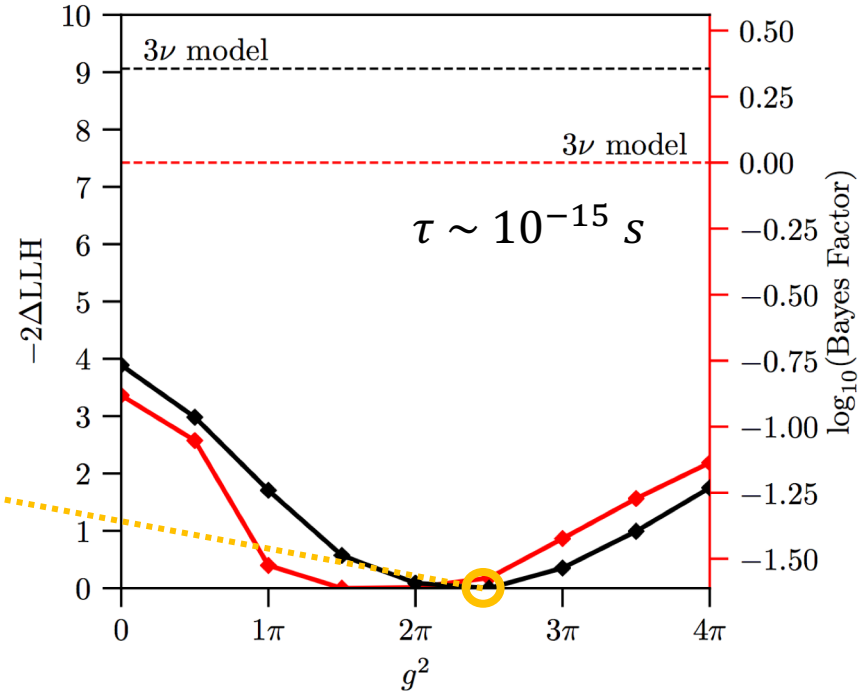
- Major tensions emerge in global fits to eV steriles
  - Suggested resolution: **Unstable sterile state (ν_4)** → decays over long baselines?
- IceCube sterile search extended to include decay:
  - Preferred to regular 3+1 scenario, but **not strongly preferred over 3ν paradigm**
  - Does not match preferred region from short baseline data



$$\tau = \frac{16\pi}{g^2 m_4}$$



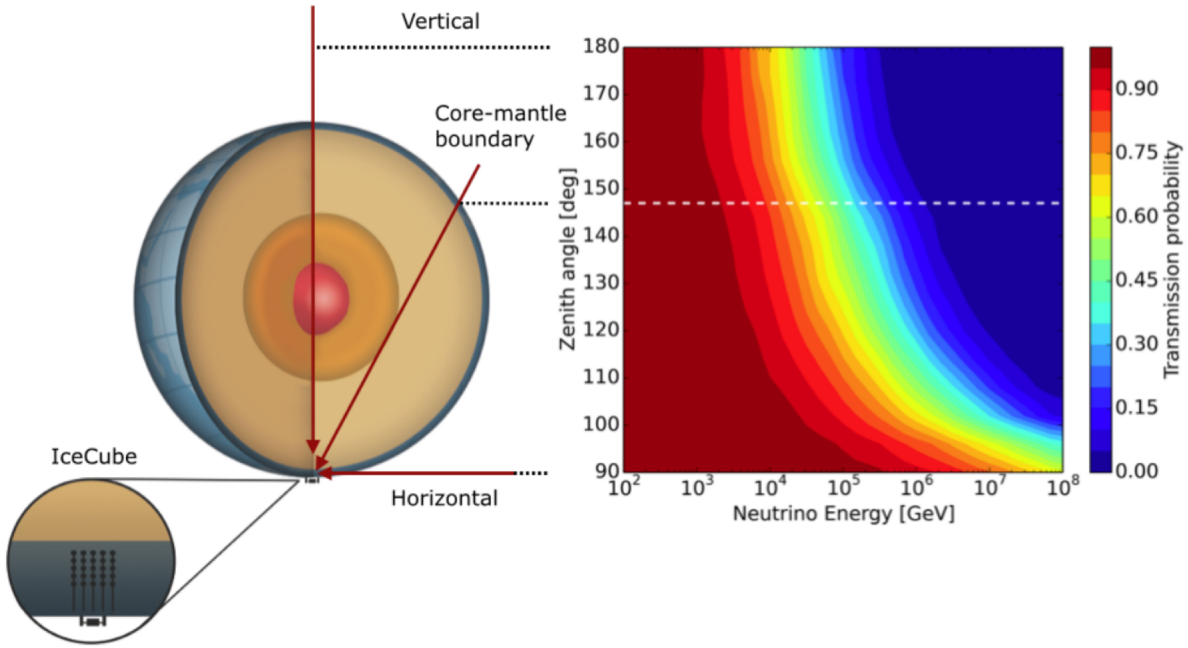
$g^2 = 2.5\pi$



Neutrino interactions

Cross section

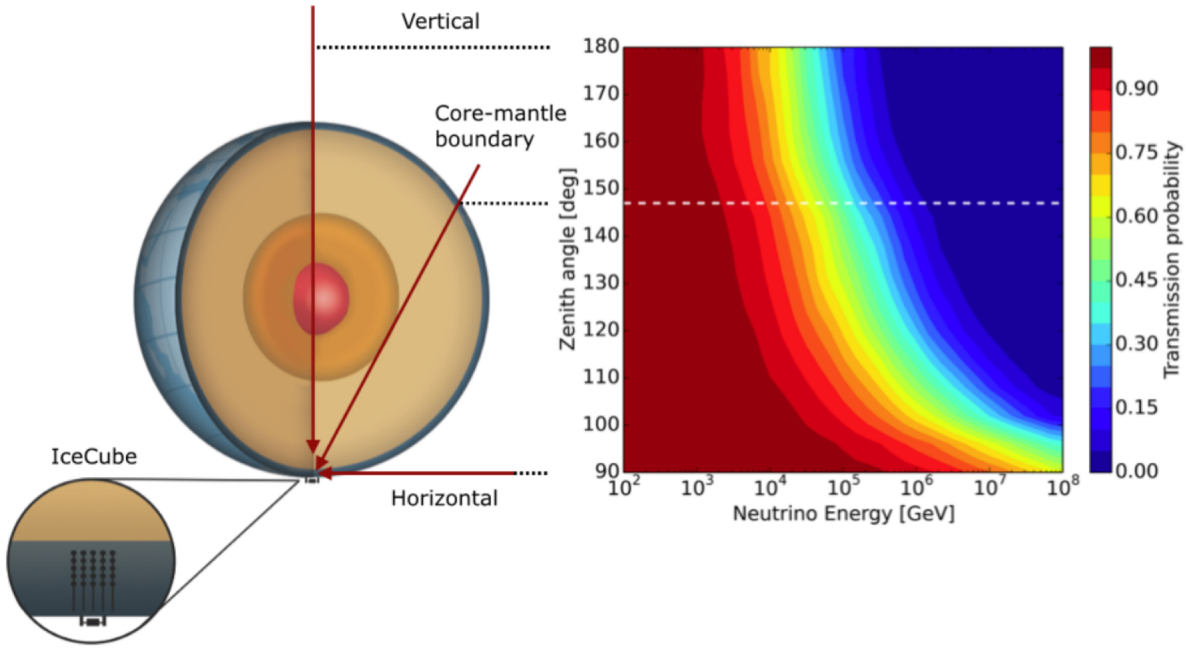
- Absorption becomes significant for ν crossing the Earth when E $\gtrsim 10^4$ GeV
- Can measure the $\nu - N$ DIS cross section by observing this deficit

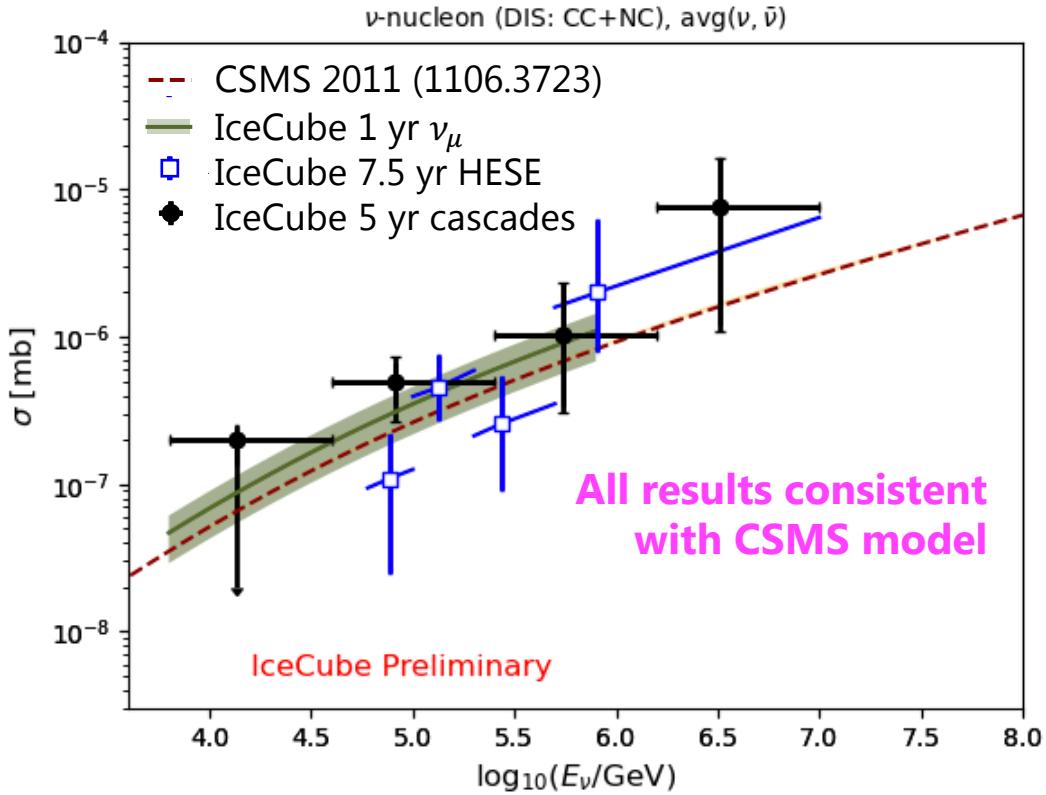


IceCube: arXiv:1711.08119, 2011.03560
See also Bustamante & Connolly (arXiv:1711.11043)

Cross section

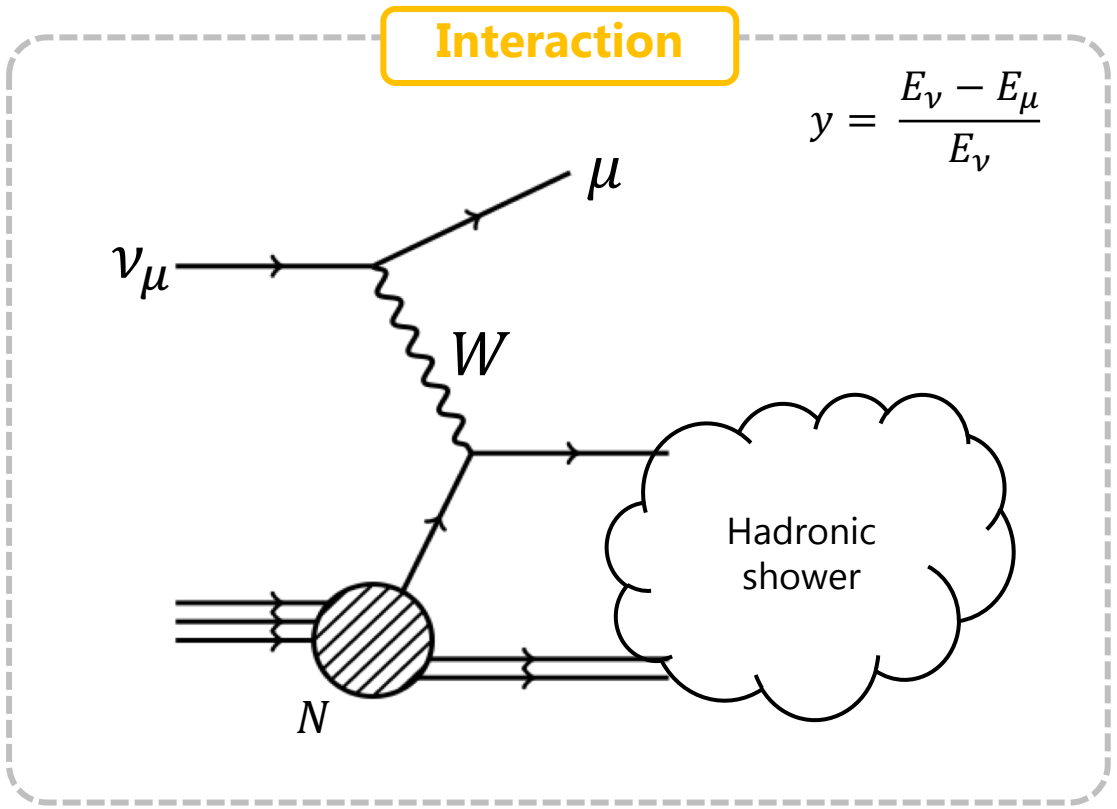
- Absorption becomes significant for ν crossing the Earth when E $\gtrsim 10^4$ GeV
- Can measure the $\nu - N$ DIS cross section by observing this deficit
  - Orders of magnitude above accelerator measurement energies
  - Range of IceCube measurements: TeV-PeV, all flavours, CC and CC+NC





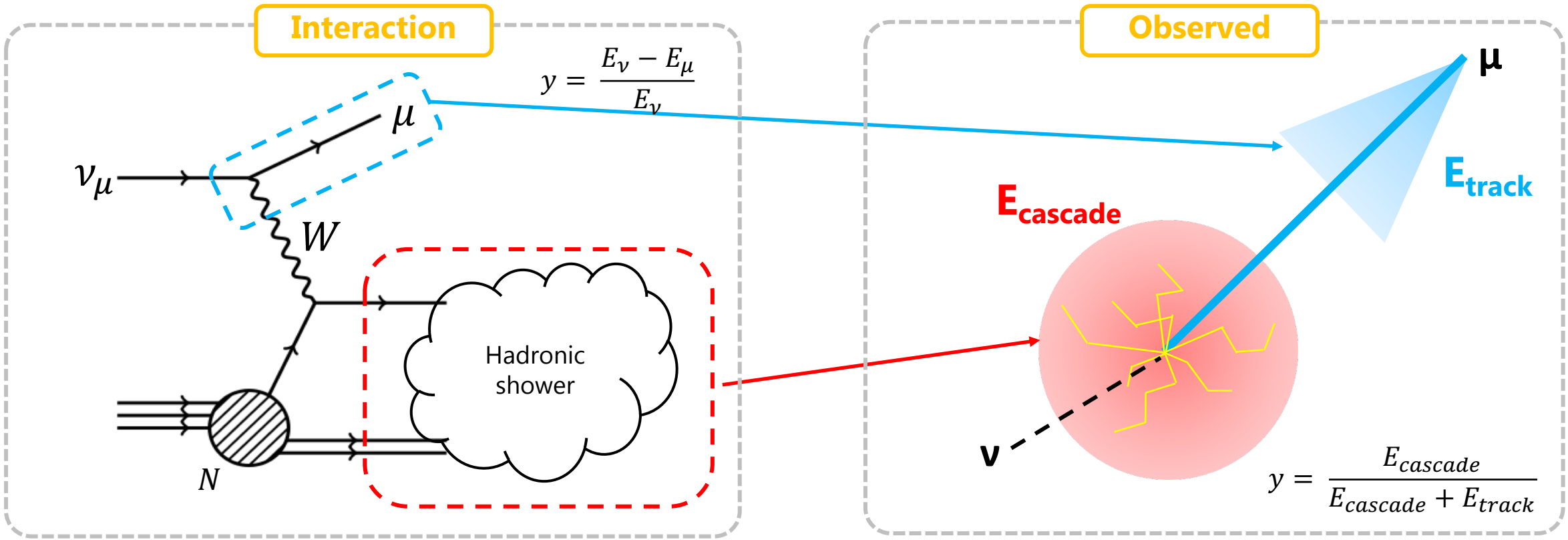
Inelasticity

- Inelasticity, y, in a ν DIS interaction is the fraction of energy transferred to the target nucleus



Inelasticity

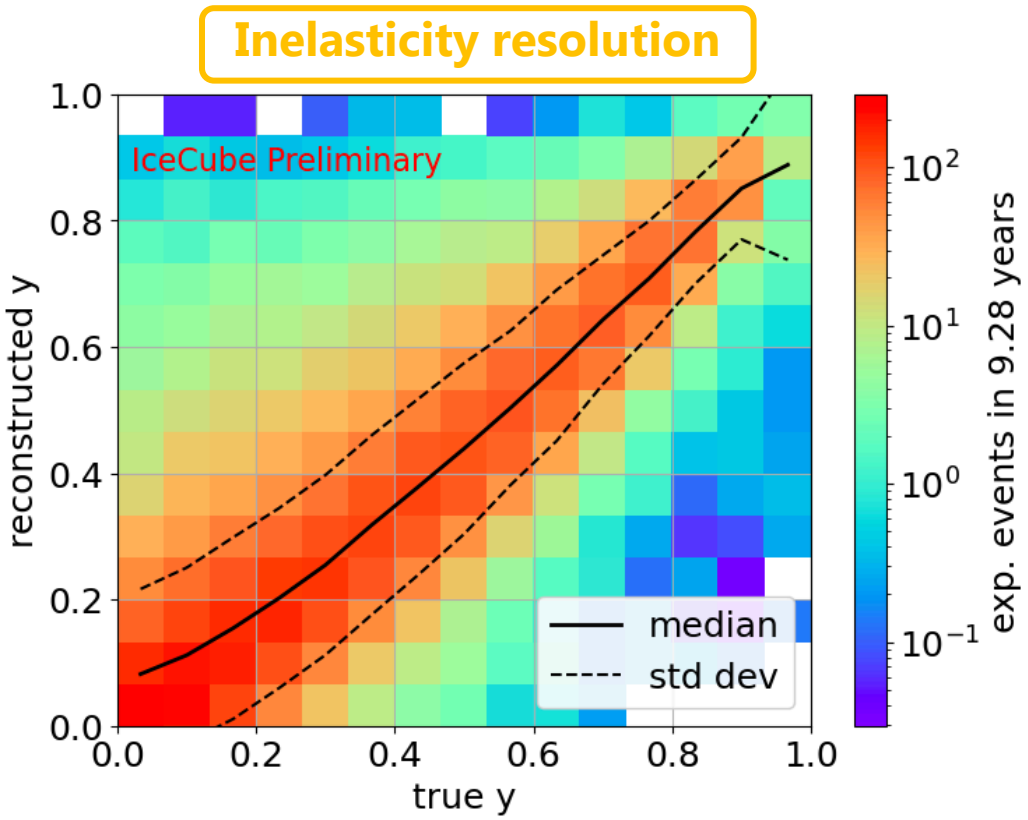
- Inelasticity, y, in a ν DIS interaction is the fraction of energy transferred to the target nucleus
- For $\nu_{\mu,CC}$ events, can reconstruct inelasticity from the energies of the reconstructed muon (track) and hadronic shower from the nucleus (cascade)

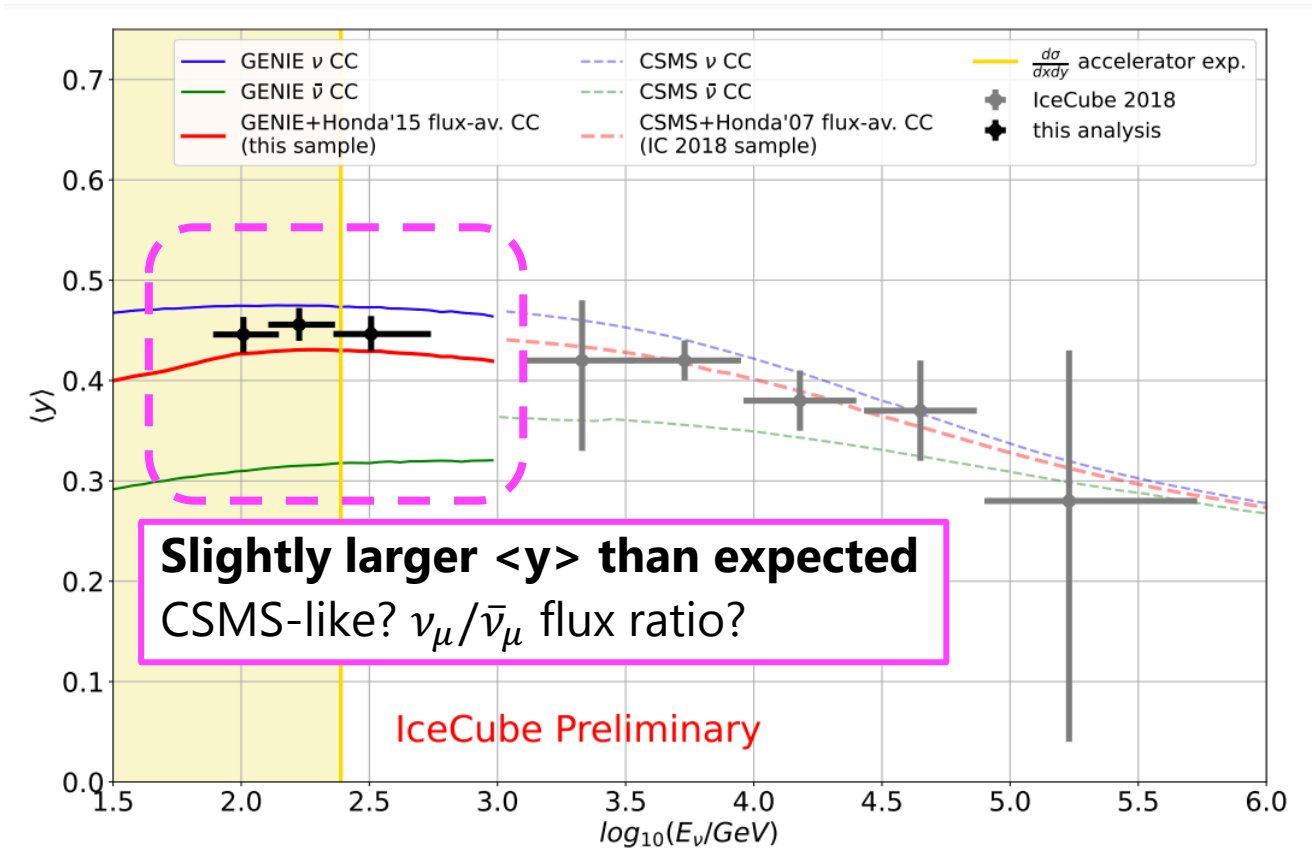


Poster MT05-086

Low energy inelasticity measurement

- New measurement of inelasticity using DeepCore (100 GeV – 1 TeV)
  - Compare to cross section model predictions
  - y differs for ν_μ and $\bar{\nu}_\mu$ → cannot distinguish so measure flux-averaged <y>





Summary

- Neutrino telescopes are potent and unique particle physics laboratories
  - High stats, high energy, large baselines, dense matter, all flavours, …
- Broad neutrino oscillation measurement program
  - Atmospheric mixing parameter measurements becoming competitive with accelerators
  - World-leading ν_τ and BSM oscillation sensitivity
- IceCube data tests DIS interactions at GeV and TeV scales
  - Data consistent with current models
- Next-generation detectors on the way → see talk by Nahee Park
  - IceCube Upgrade → low energy oscillation physics (deployment in 2025/6)
  - IceCube Gen2 → Proposed 8 Gton high energy extension for next-gen astronomy

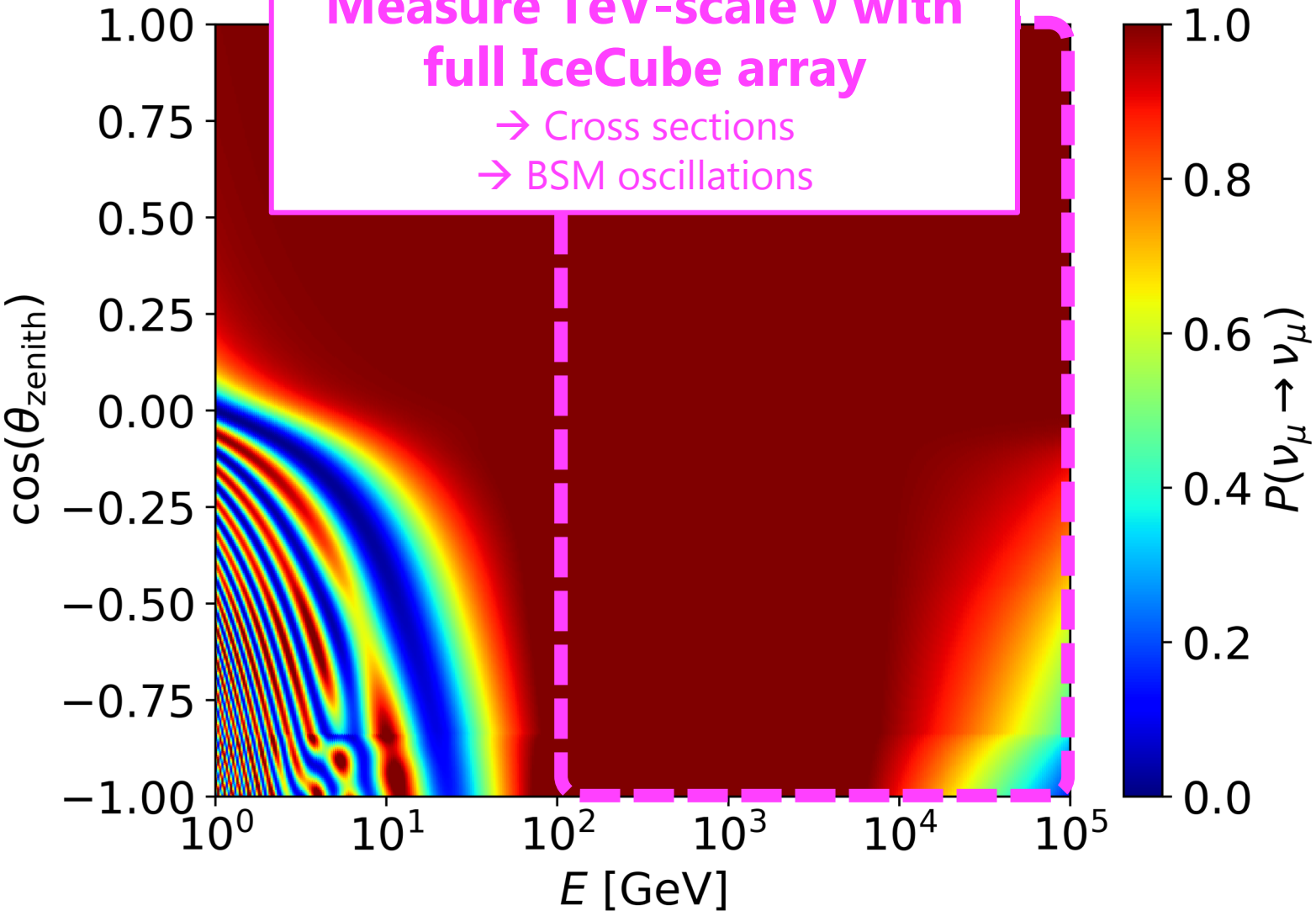
Thank you

IceCube vs DeepCore

Measure TeV-scale ν with full IceCube array

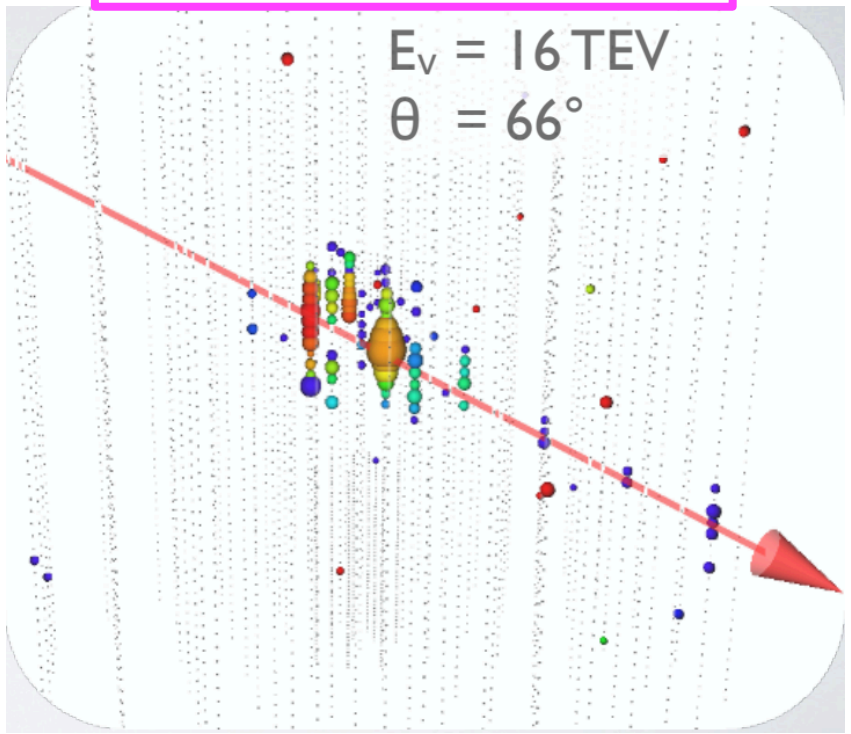
→ Cross sections

→ BSM oscillations



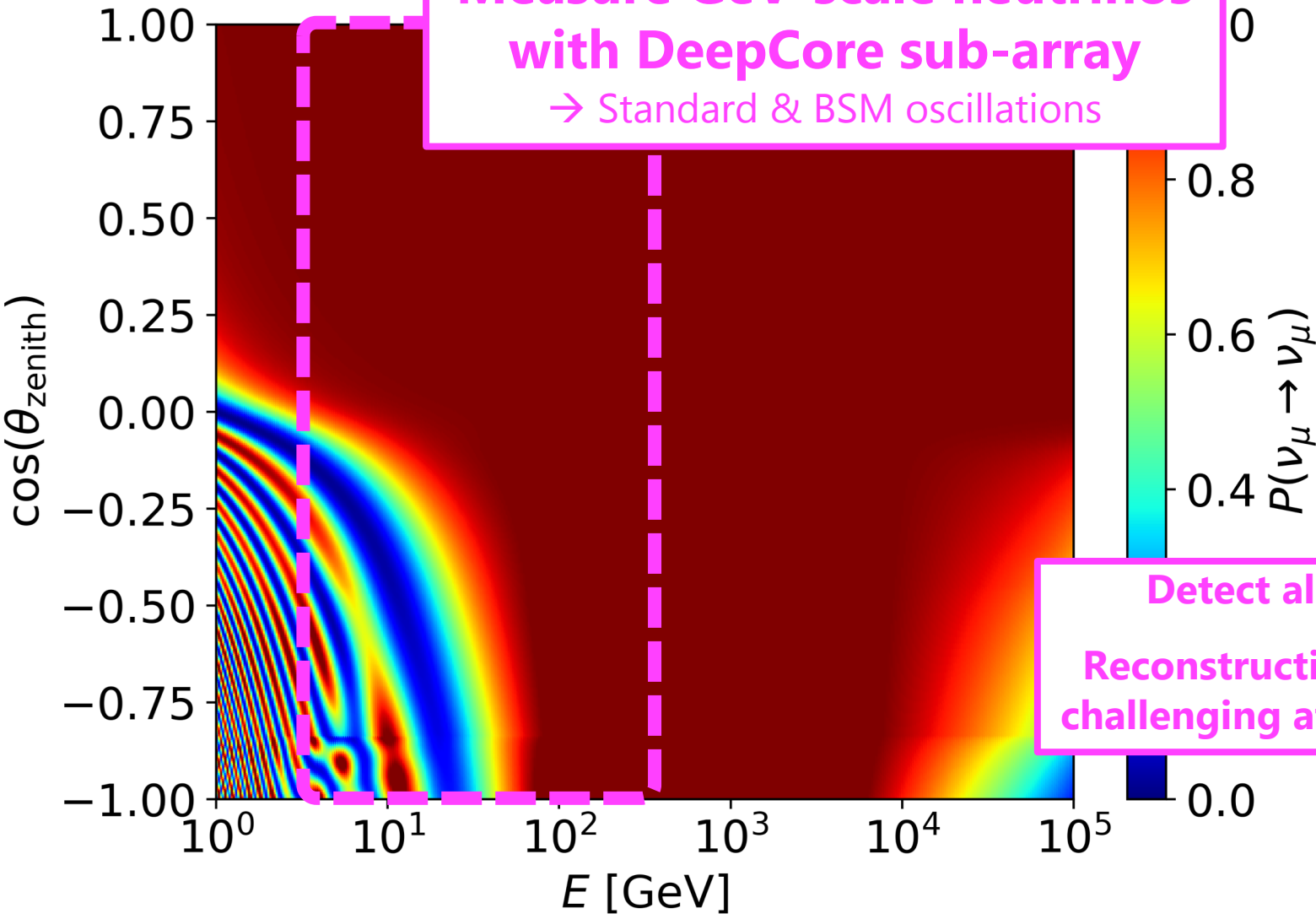
ν_μ dominate flux

Bright, km-scale events



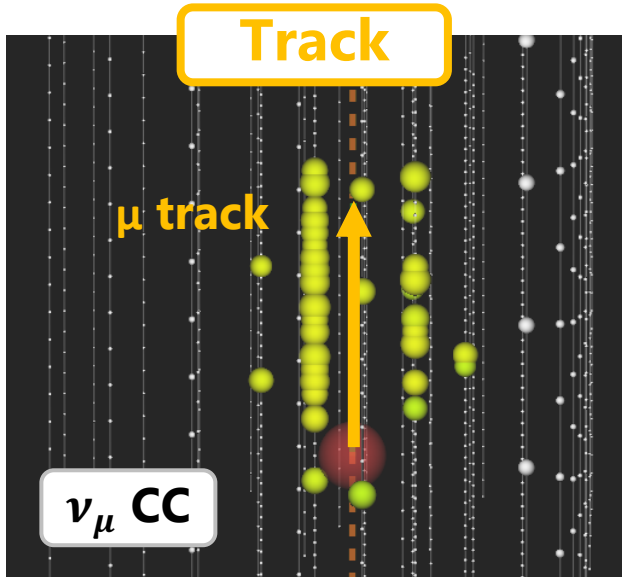
IceCube vs **DeepCore**

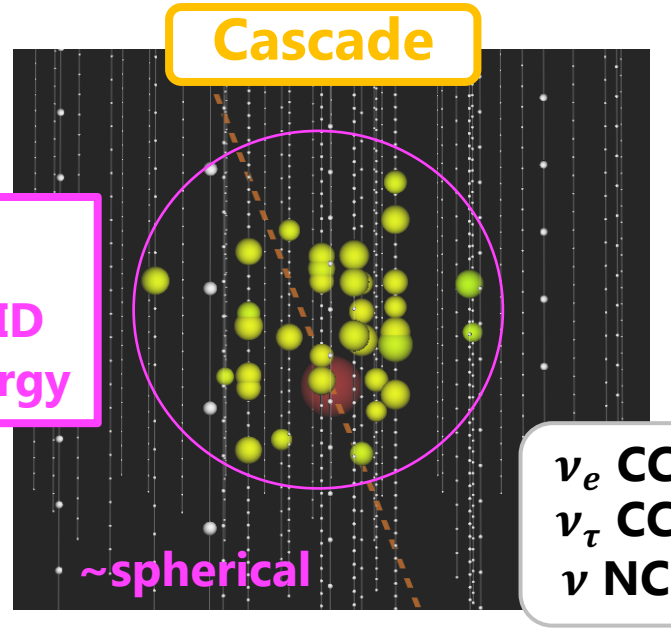
Measure GeV-scale neutrinos with DeepCore sub-array
→ Standard & BSM oscillations



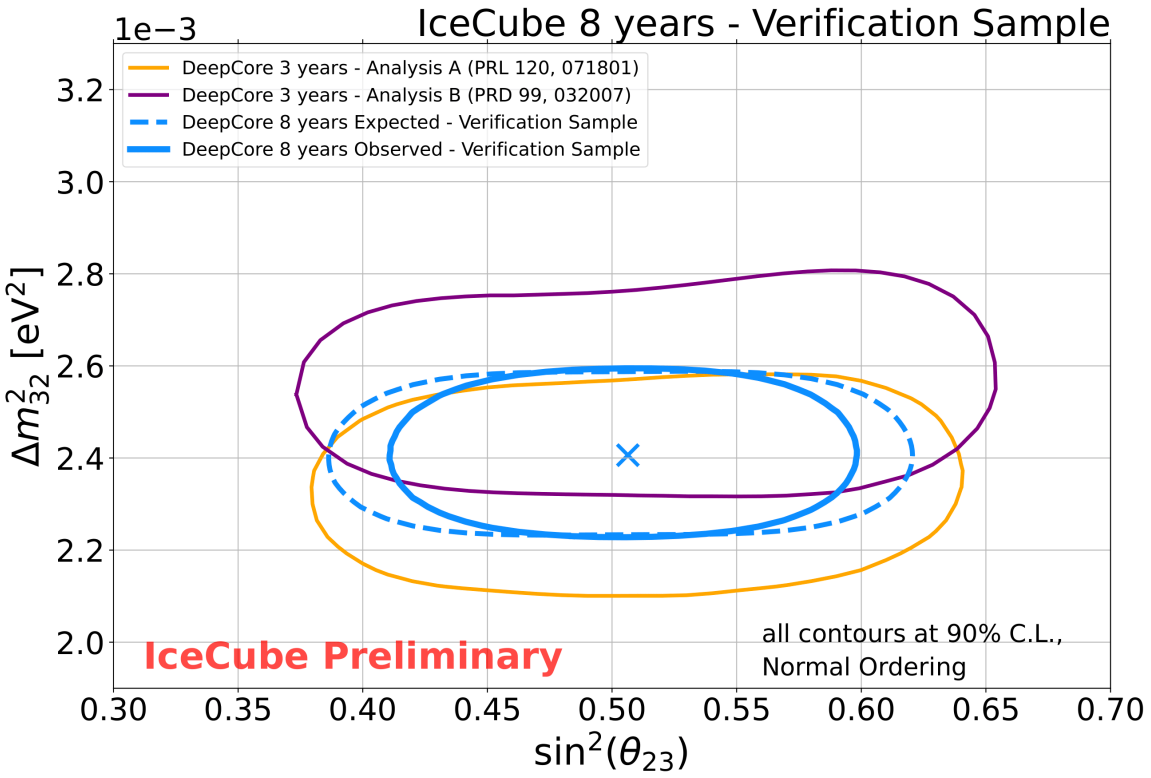
Detect all flavors

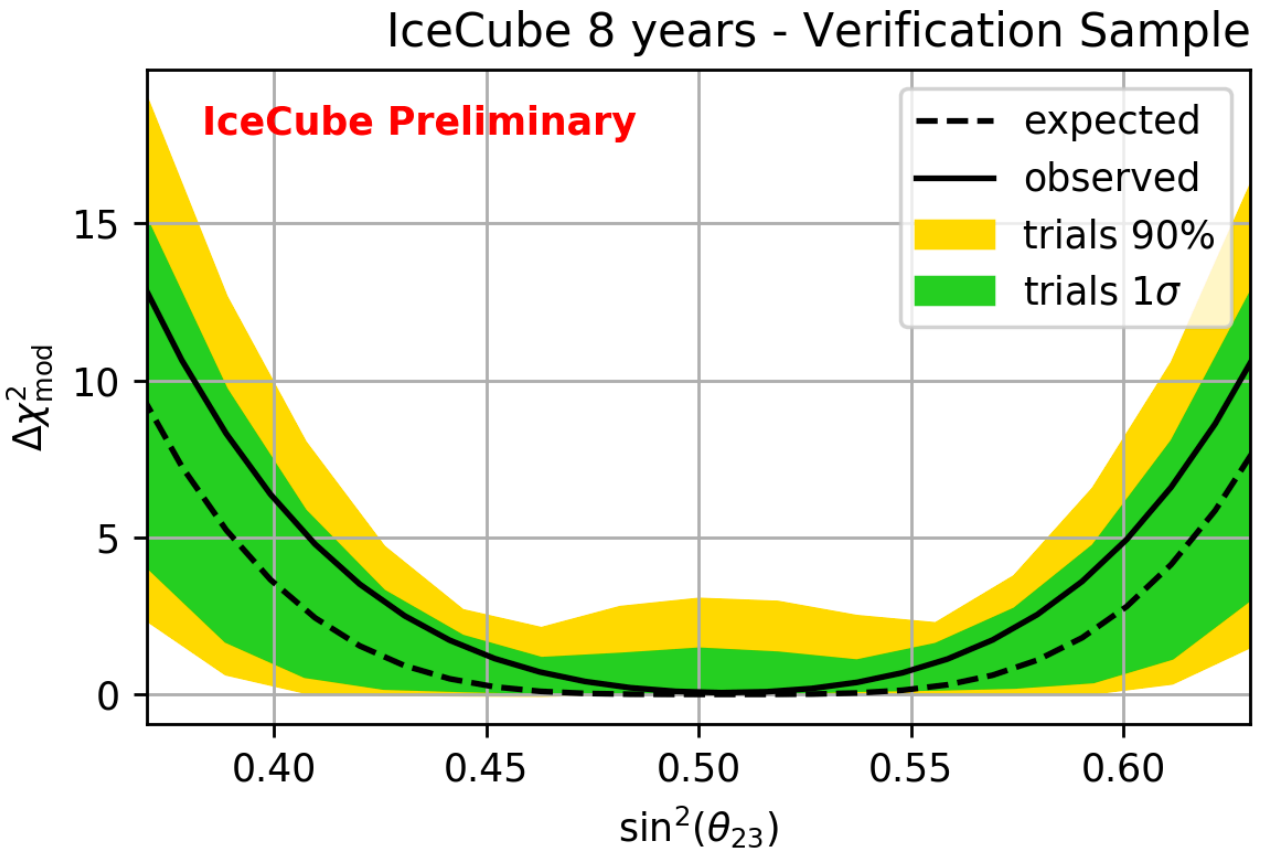
Reconstruction and PID challenging at low energy



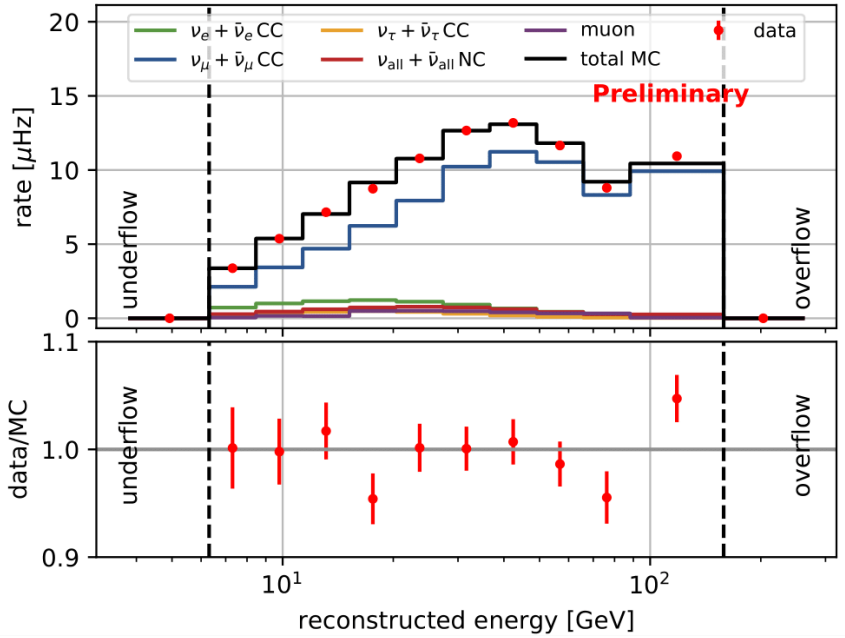


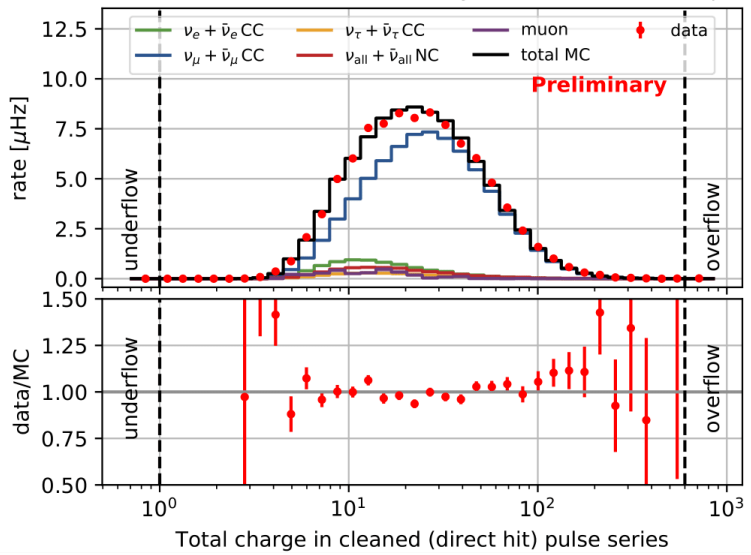
8 year oscillation result – supporting plots

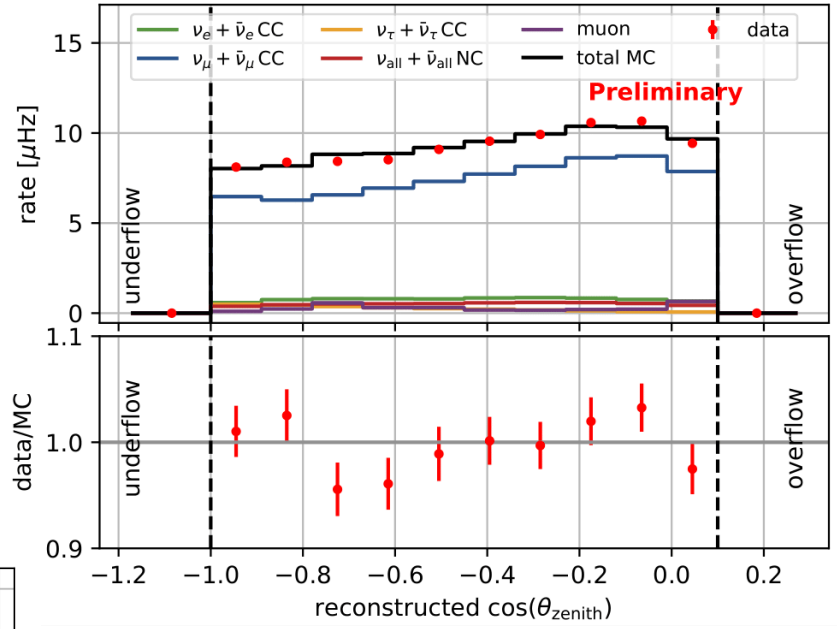




8 year oscillation result – supporting plots

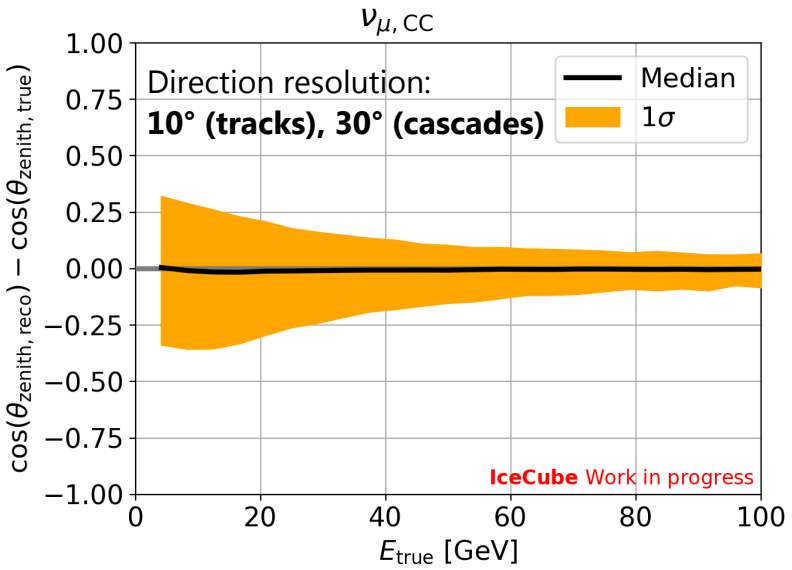


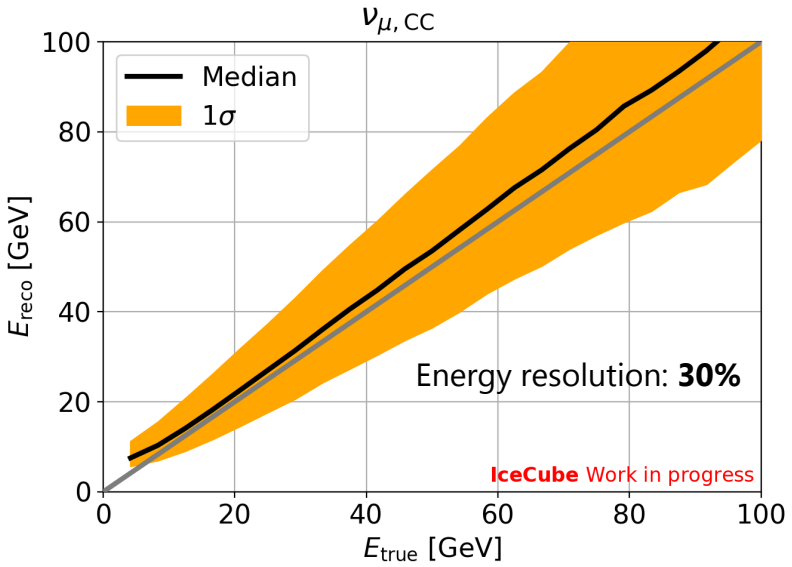


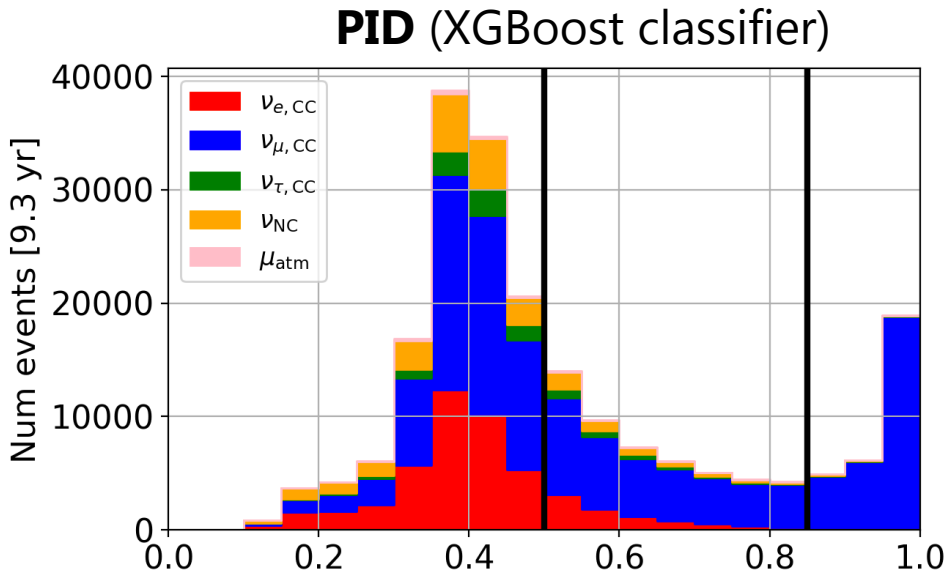


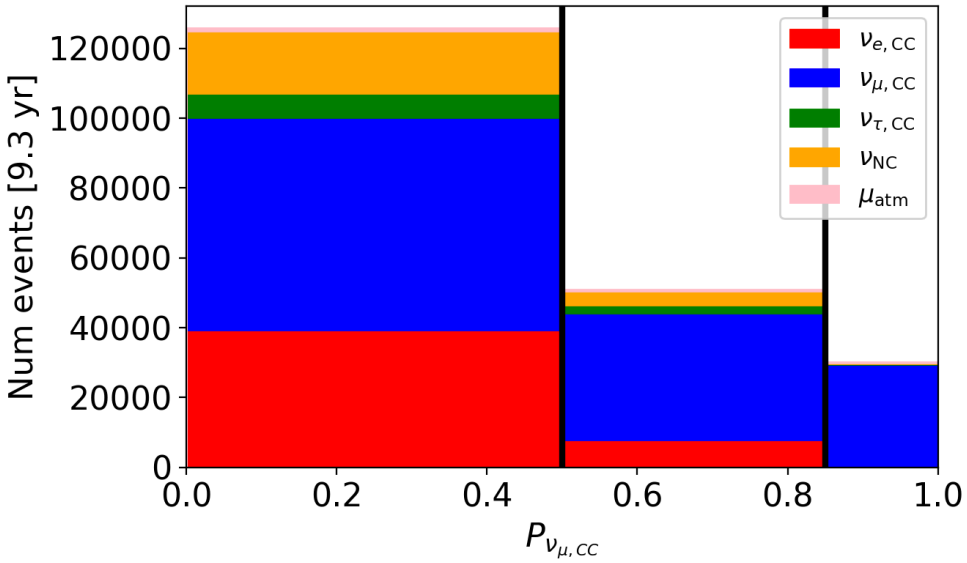
arXiv:2203.02303

DeepCore reconstruction and PID





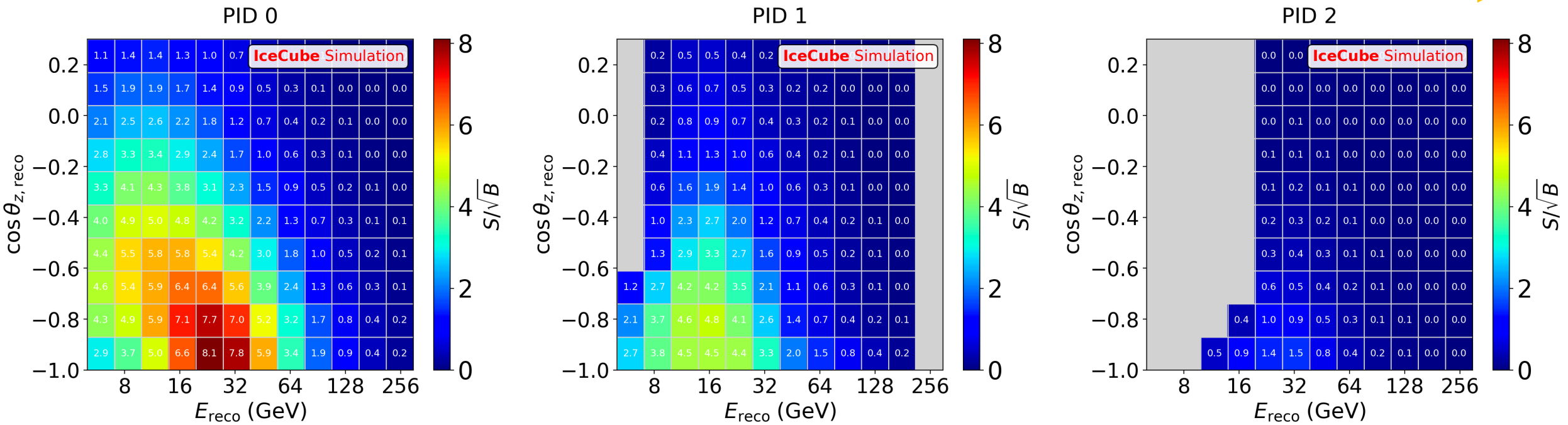




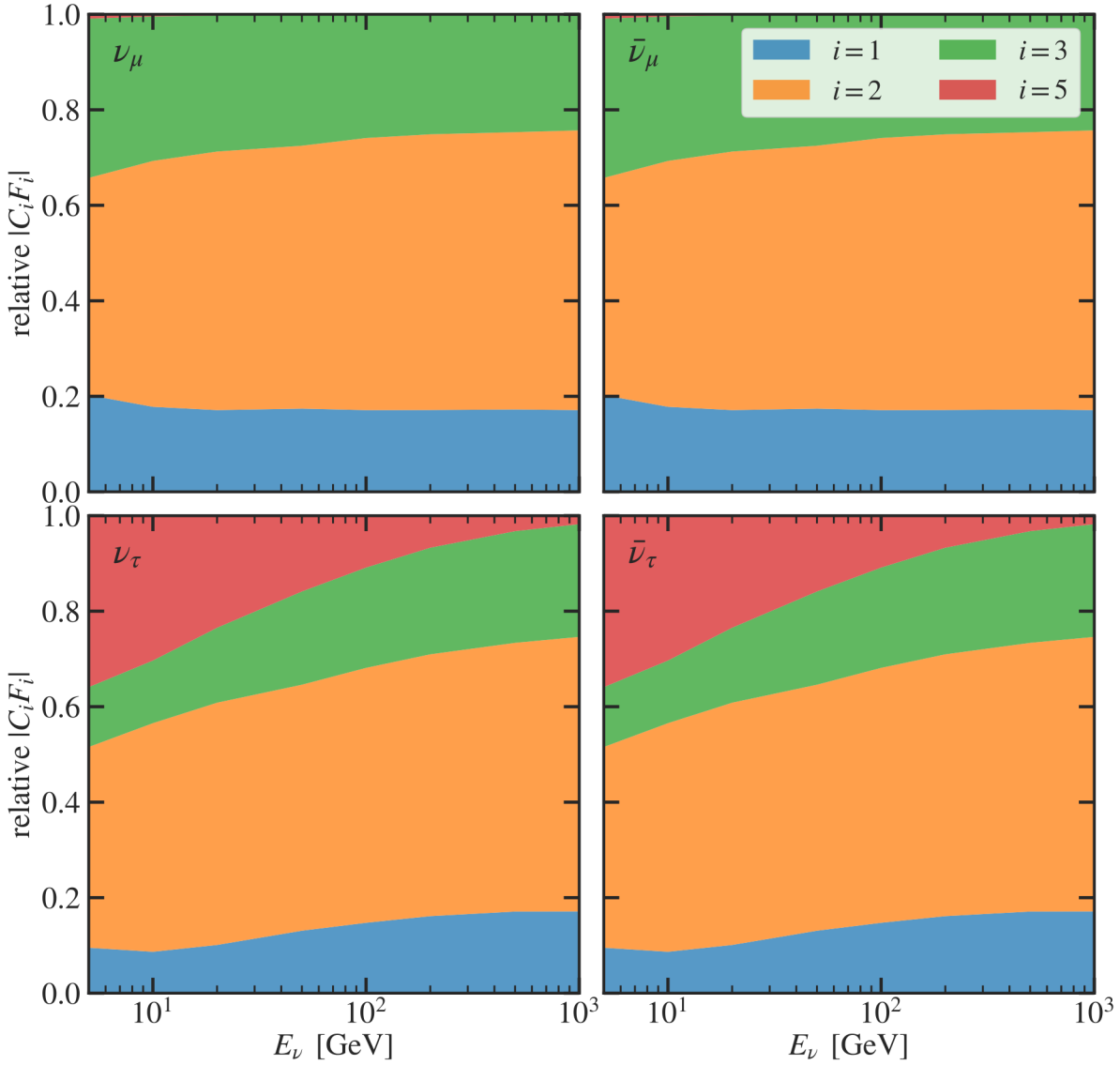
ν_τ appearance signal

- Cannot individually identify $\nu_{\tau,CC}$ events in DeepCore from other cascade-like signals ($\nu_{e,CC}, \nu_{NC}$)
- ν_τ appearance signal is statistical excess in upgoing, ~20 GeV cascades
  - Consistent with ν_μ disappearance signal (simultaneously fit) and $\nu_{\tau,CC}$ cross section
  - Other cascade event types are predominantly horizontal

PID bins of increasing $\nu_{\mu,CC}$ purity



Comparing ν_μ and ν_τ DIS cross sections (LO)

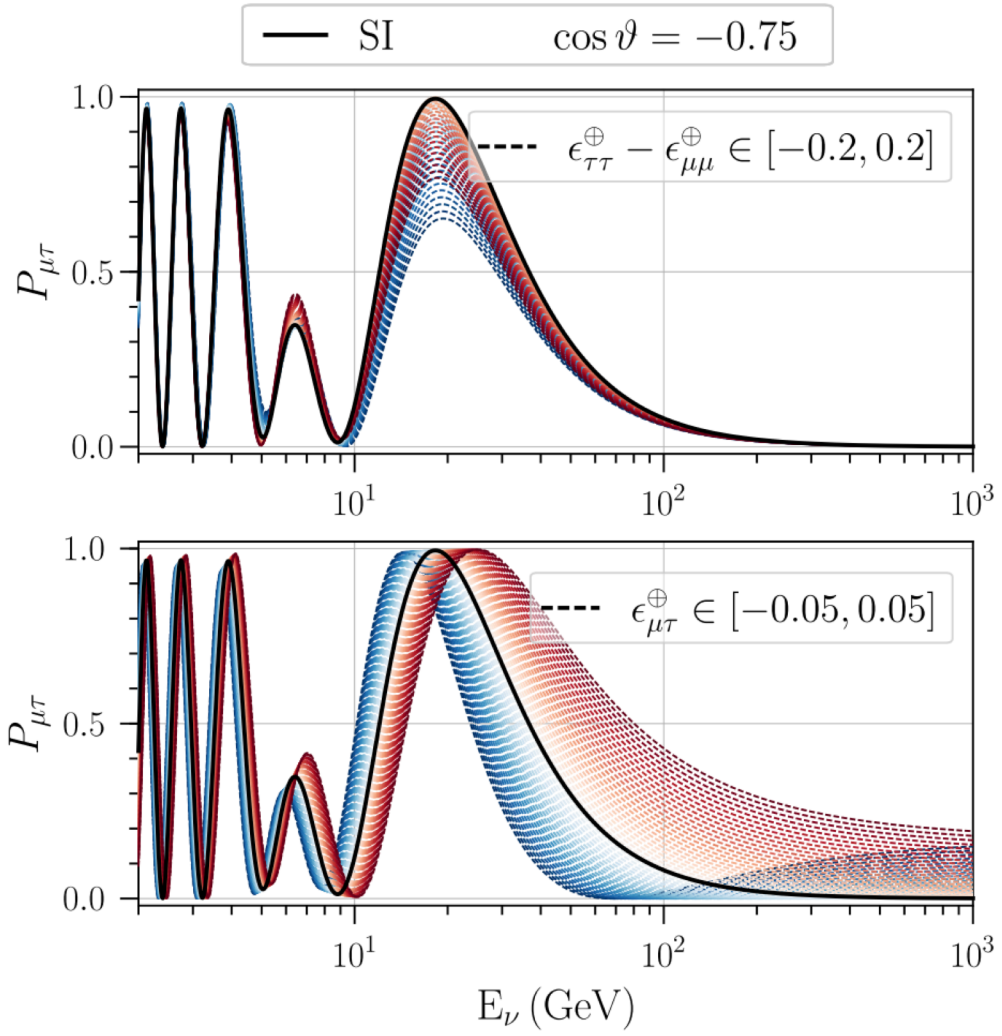


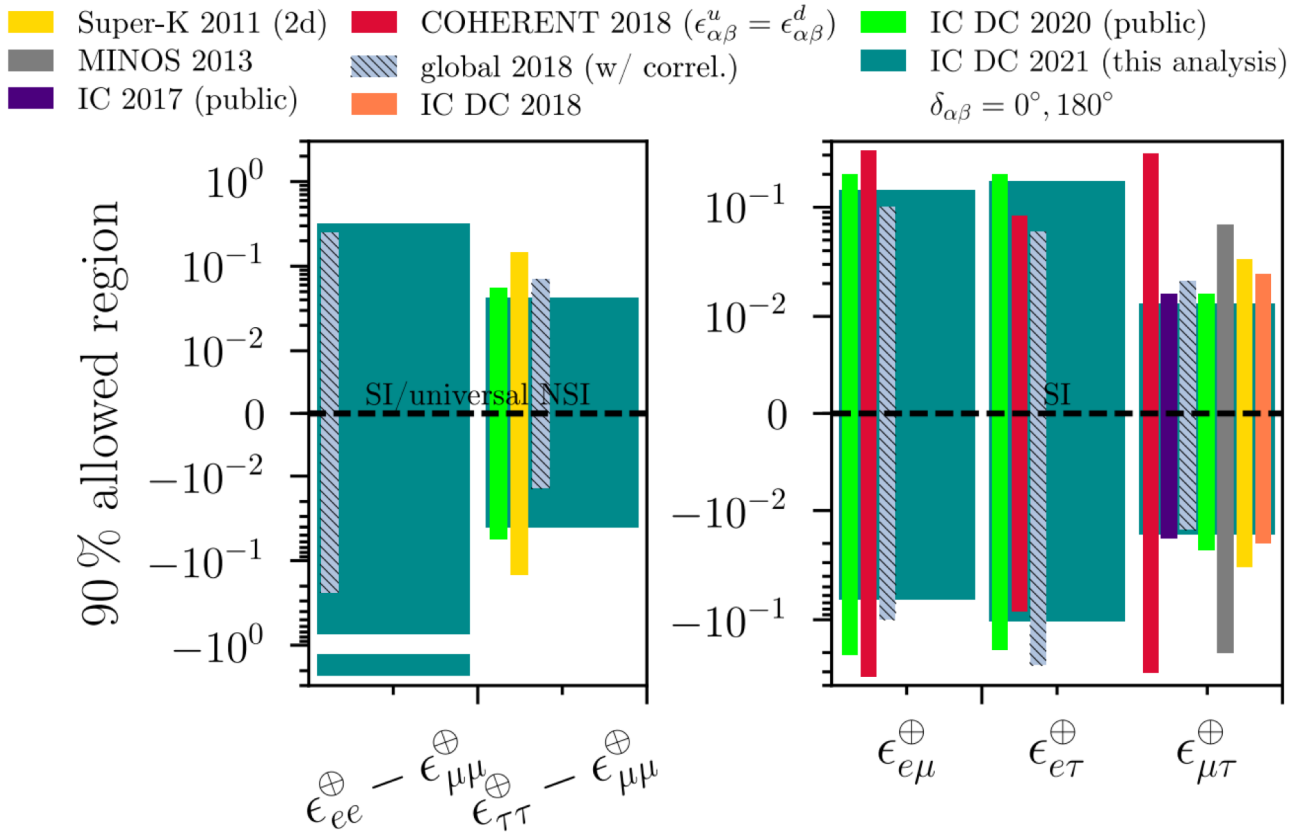
CTEQ66 PDFs

$$\frac{d^2\sigma^{\nu/\bar{\nu}}}{dxdy} = \frac{G_F^2 M_N E_\nu}{\pi(1+Q^2/M_W^2)^2}\left\{(y^2x + \frac{m_l^2 y}{2E_\nu M_N})F_1(x,Q^2) + \left[(1-\frac{m_l^2}{4E_\nu^2}) - (1+\frac{M_N x}{2E_\nu})y\right]F_2(x,Q^2)\right.$$
$$\left. \pm \left[xy(1-\frac{y}{2}) - \frac{m_l^2 y}{4E_\nu M_N}\right]F_3(x,Q^2) + \frac{m_l^2(m_l^2+Q^2)}{4E_\nu^2 M_N^2 x}F_4(x,Q^2) - \frac{m_l^2}{E_\nu M_N}F_5(x,Q^2)\right\}$$

DeepCore NSI

arXiv:2106.07755

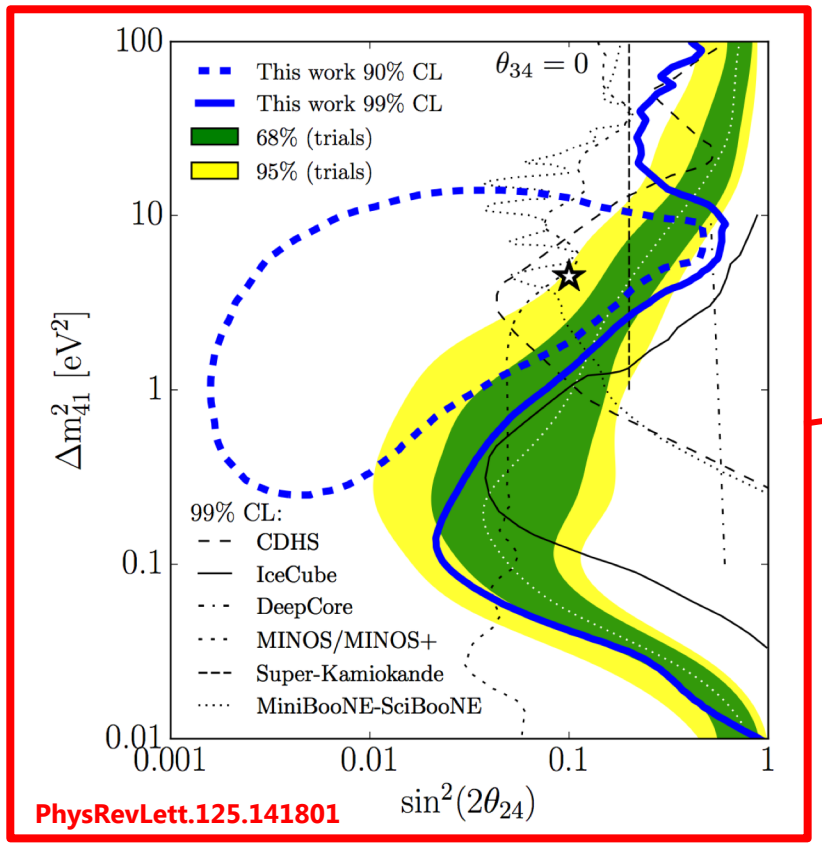


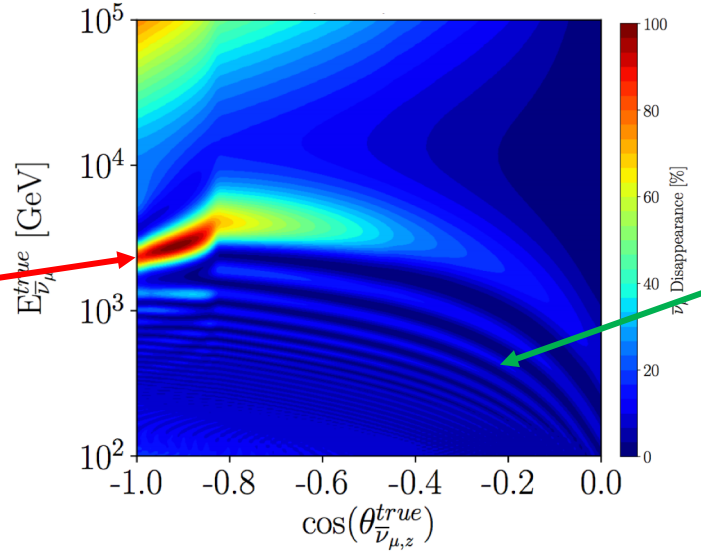


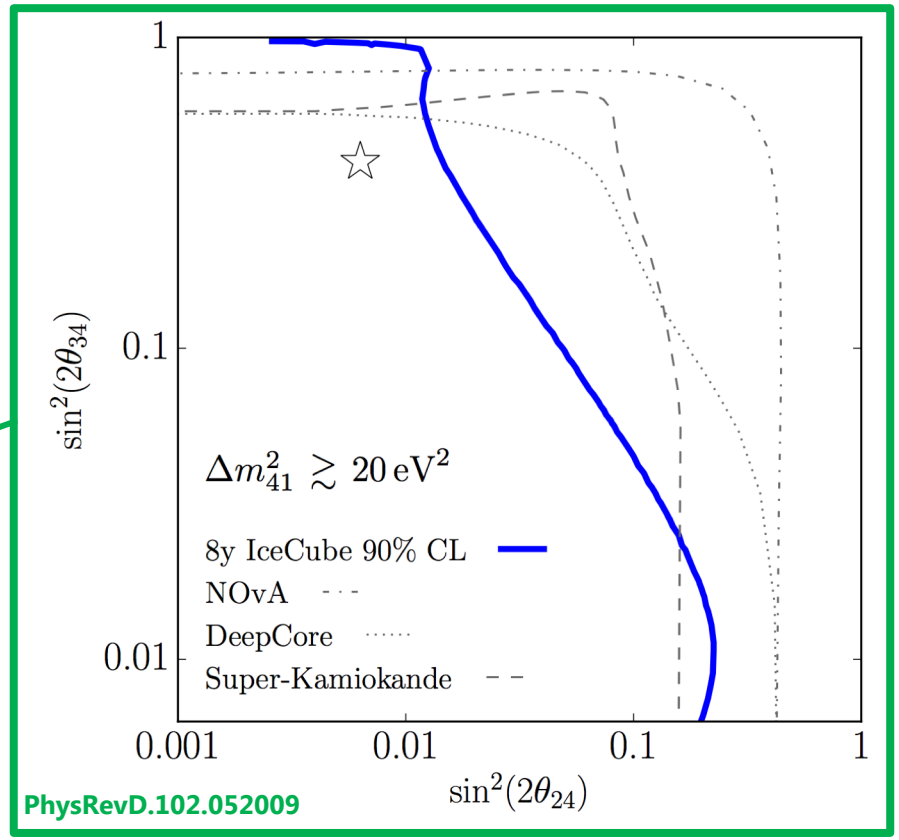
arXiv:2005.12942, 2005.12943

Sterile neutrino results

- 8 yr IceCube (high energy) results (300,000 ν_μ)

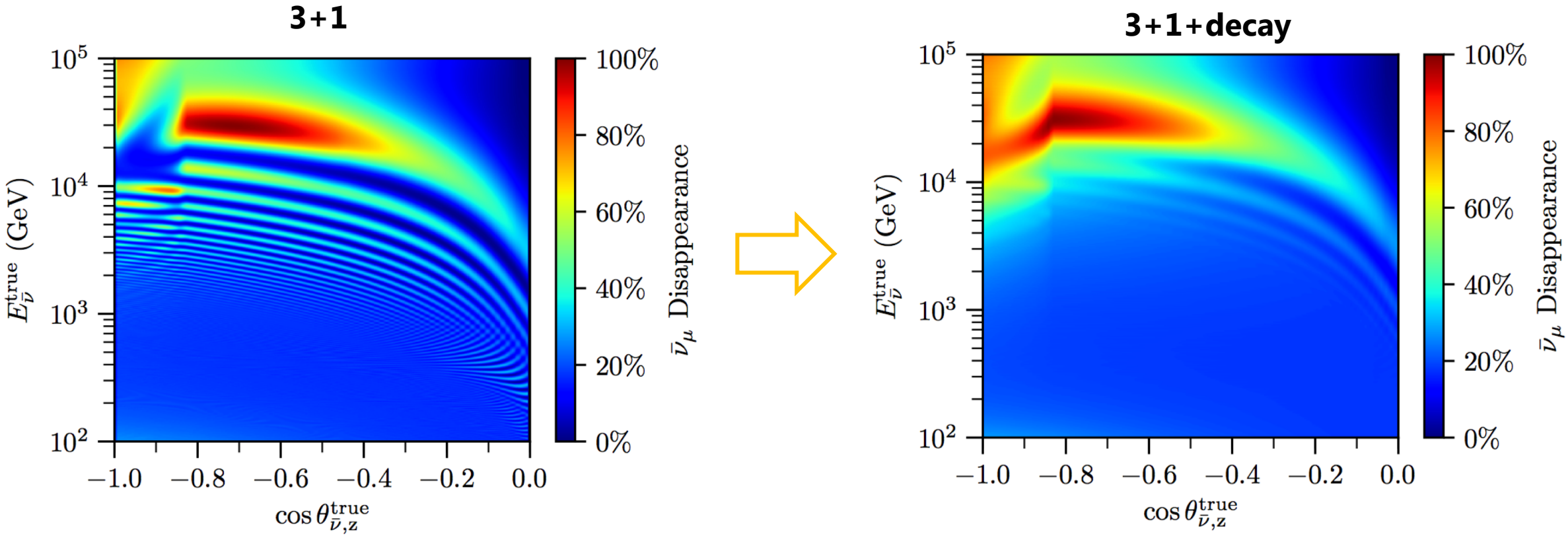






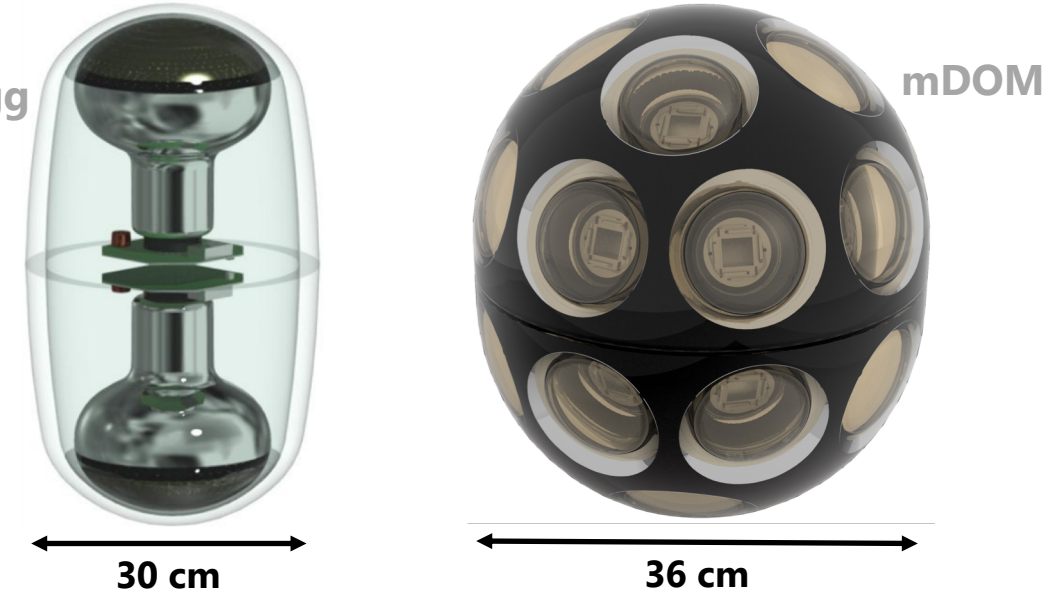
- Consistent with no sterile → increased tension with short baseline anomalies

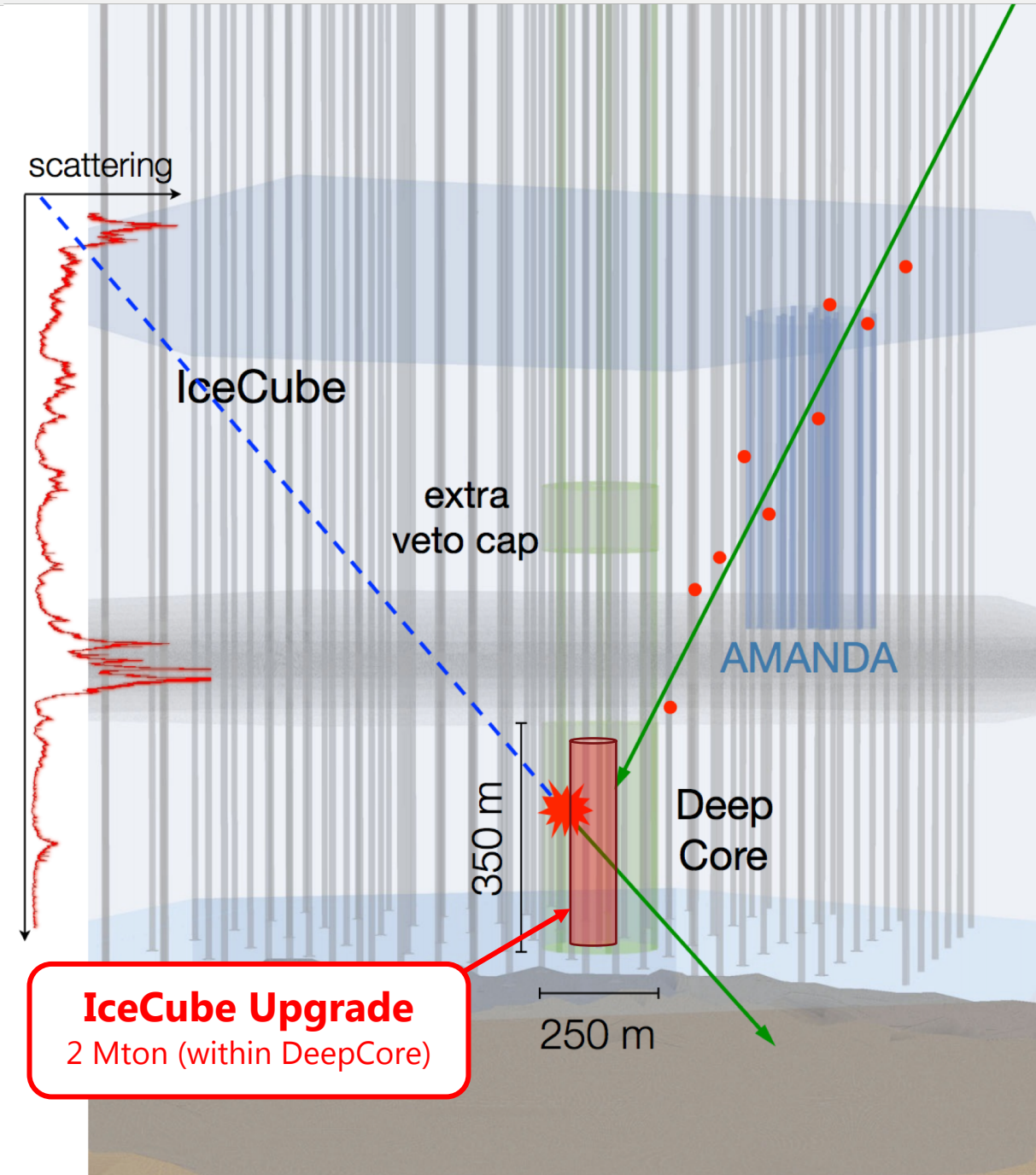
Unstable sterile neutrino – supporting plots



The IceCube Upgrade

- **Low-energy extension to IceCube**
  - Deployment in **2025/6**
  - **Drop threshold to 1 GeV**
- 700 multi-PMT sensors
- Improved detector/ice calibration

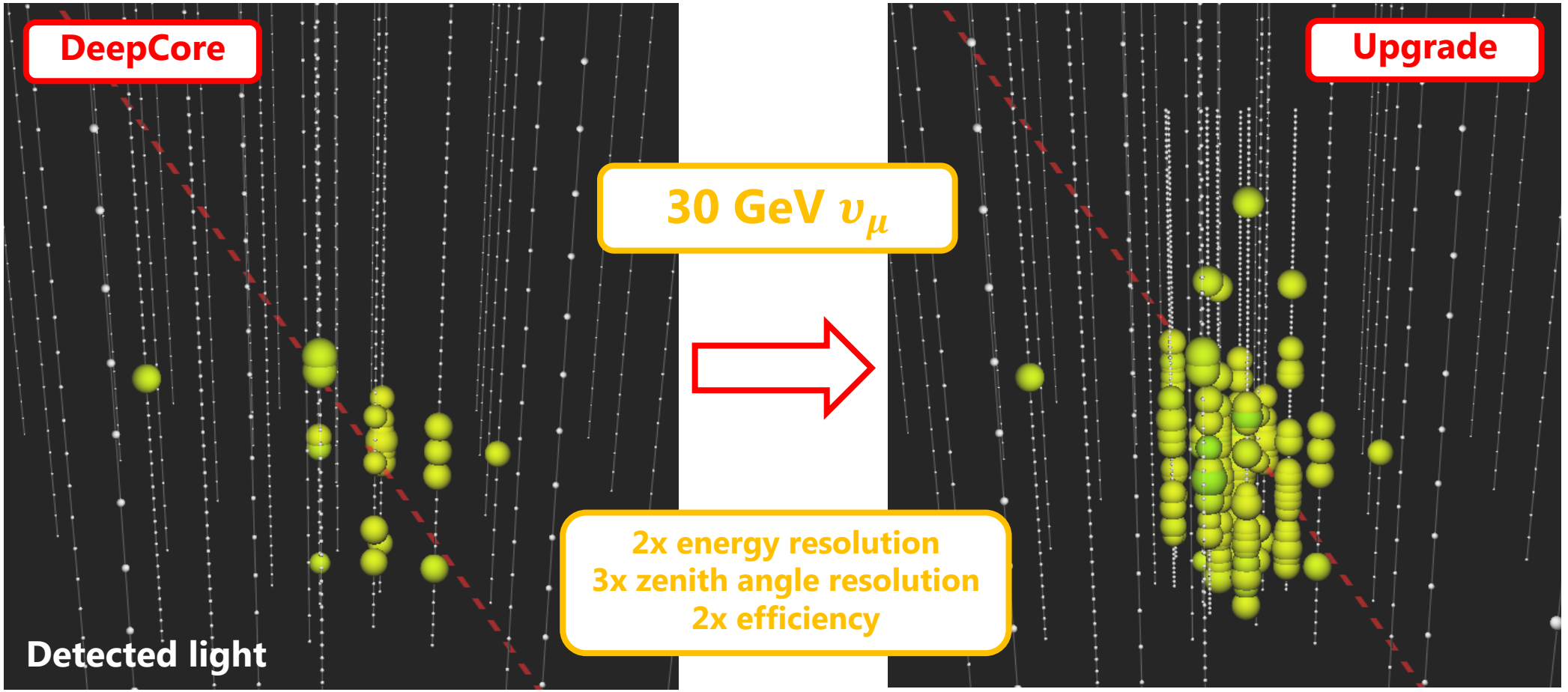




arXiv:1908.09441

IceCube Upgrade: Increased photocathode density

- **Dense instrumentation** in 2 Mton core
  - Large increase in photocathode density → sensitive down to ~**1 GeV neutrinos**



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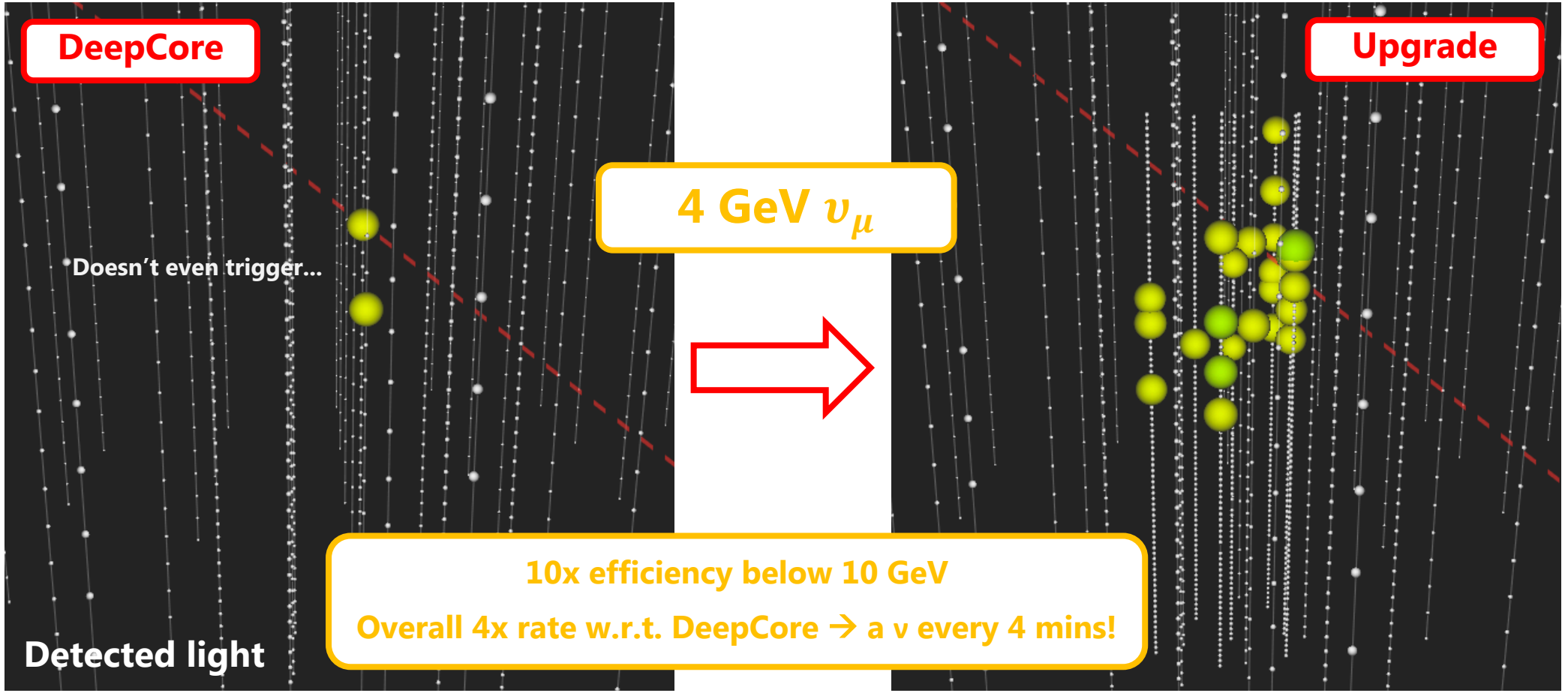
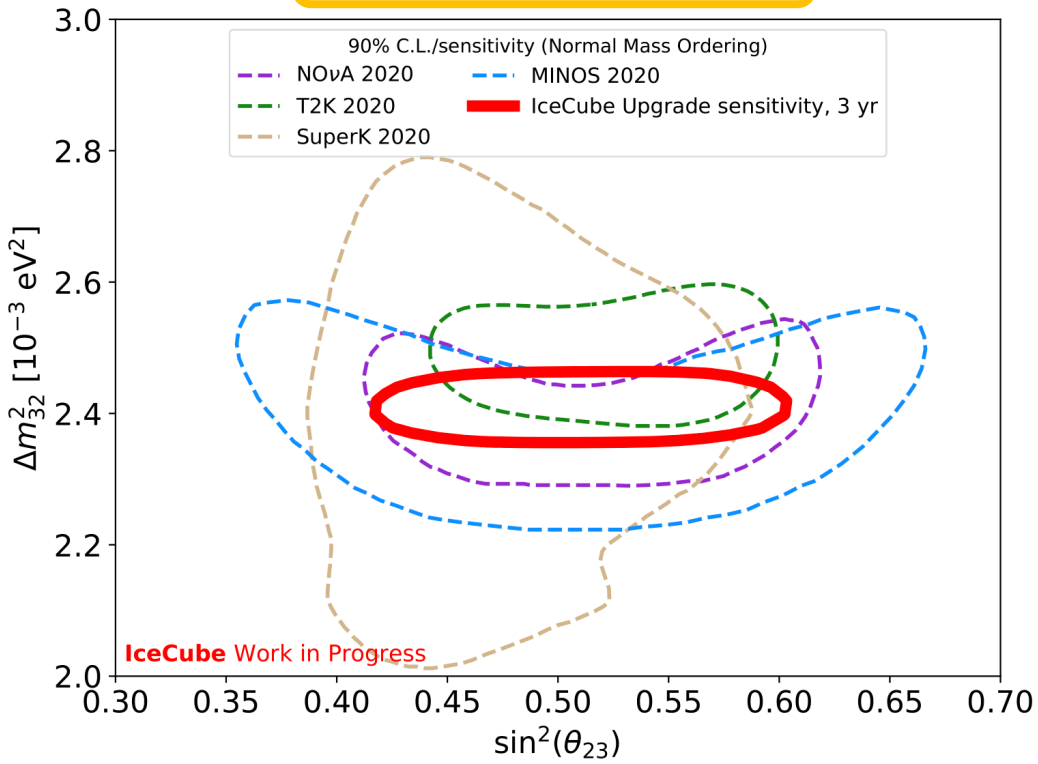


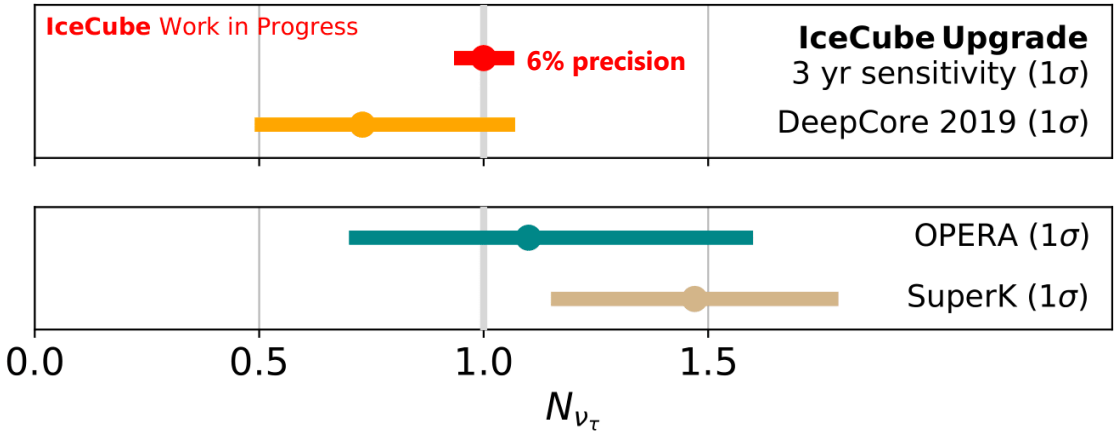
Poster DT01-691

IceCube Upgrade: Oscillation sensitivities

ν_μ disappearance



ν_τ appearance

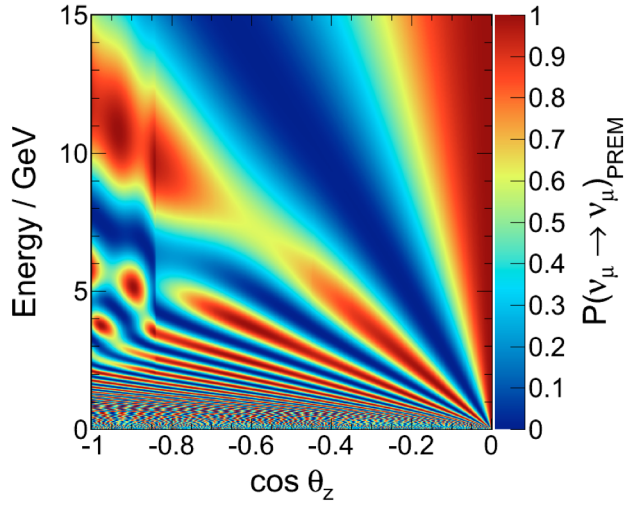


Note: Projections use preliminary analysis tools and make conservative assumptions

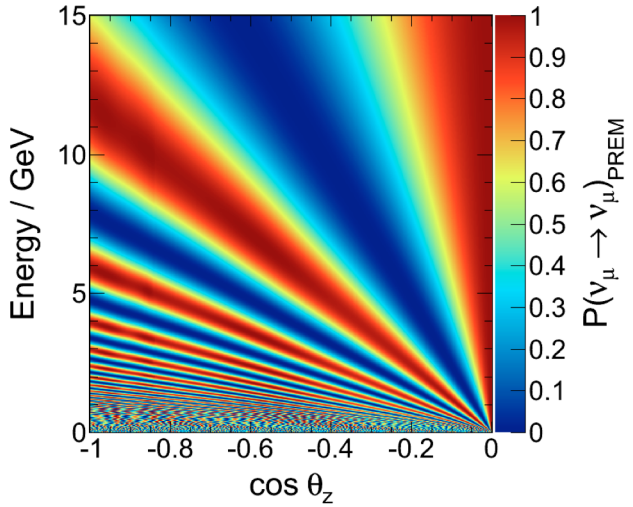
NMO with the IceCube Upgrade (+JUNO)

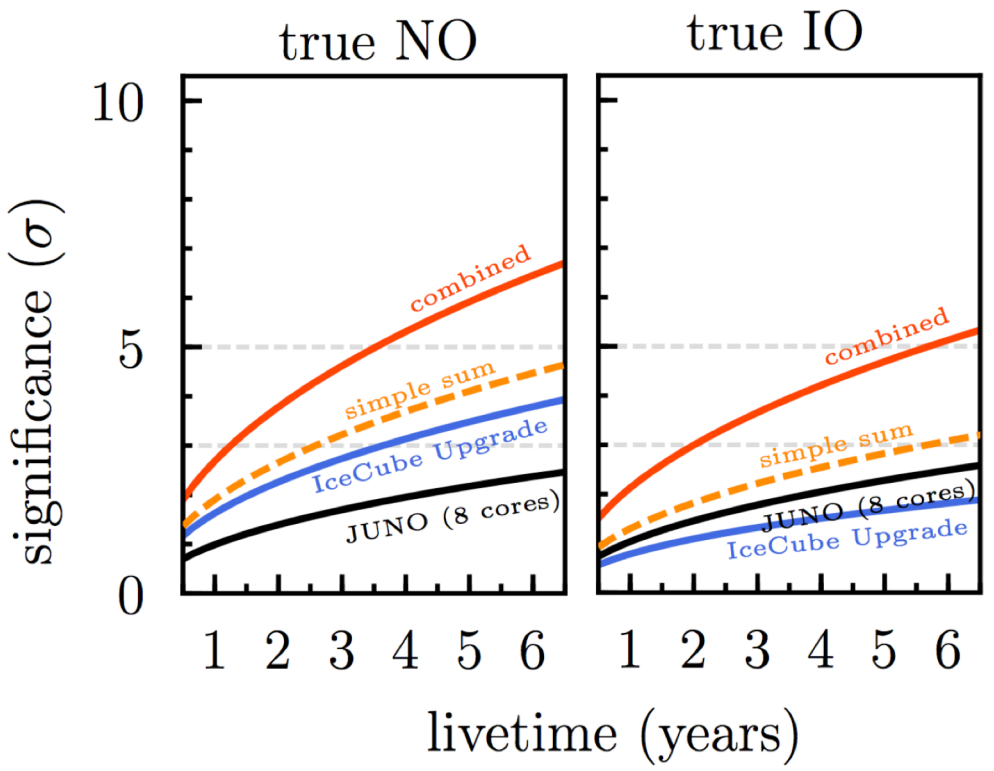
arXiv:1911.06745

NO



IO





Strong mass ordering sensitivity with Upgrade alone

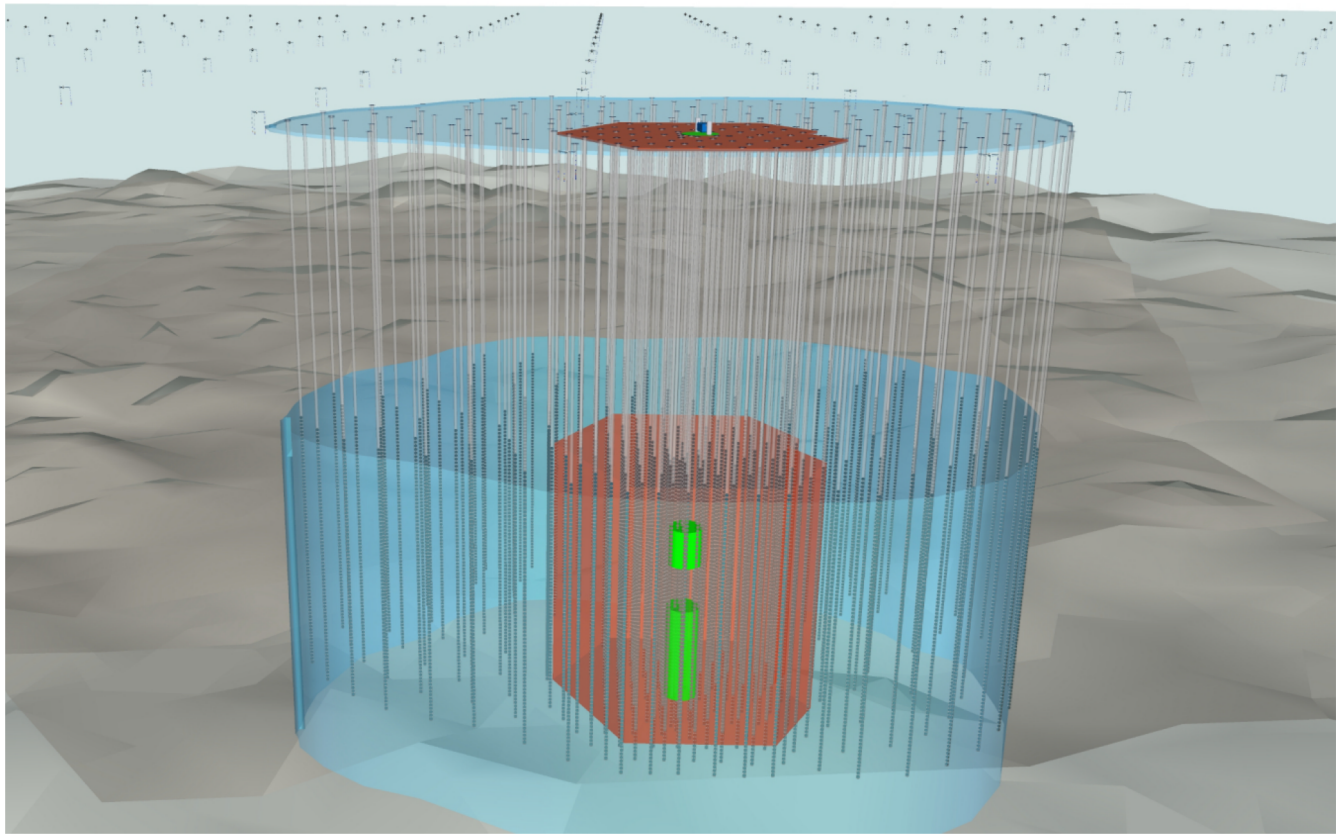
Even better when combined with JUNO

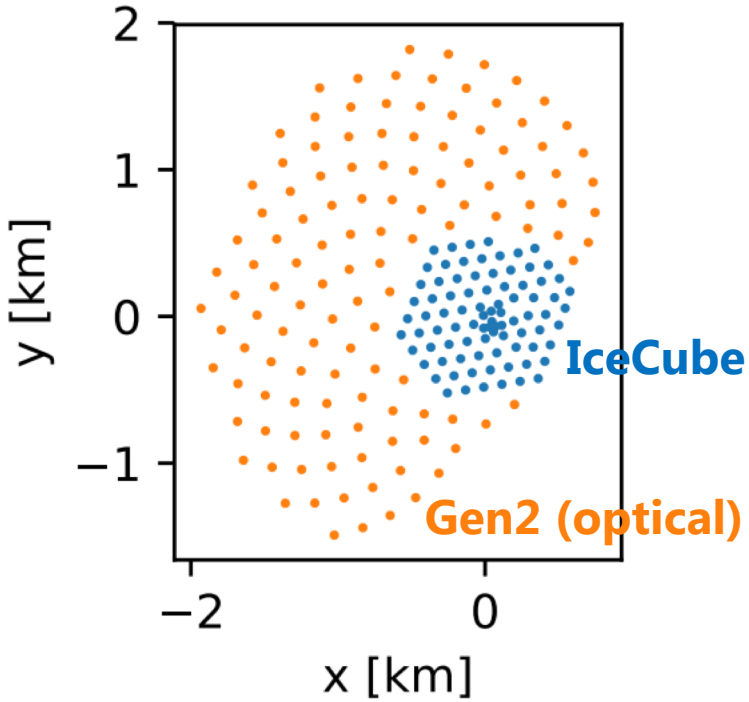
Note: Projections use preliminary analysis tools

arXiv:2008.04323

IceCube-Gen2

- Proposed extension to **high energy array (8 Gton, 2033)**
  - Addition of **radio array** increases energy reach by orders of magnitude (**EeV**)
- Next-generation high energy neutrino astronomy and particle physics





Gen2 full scope

arXiv:2008.04323