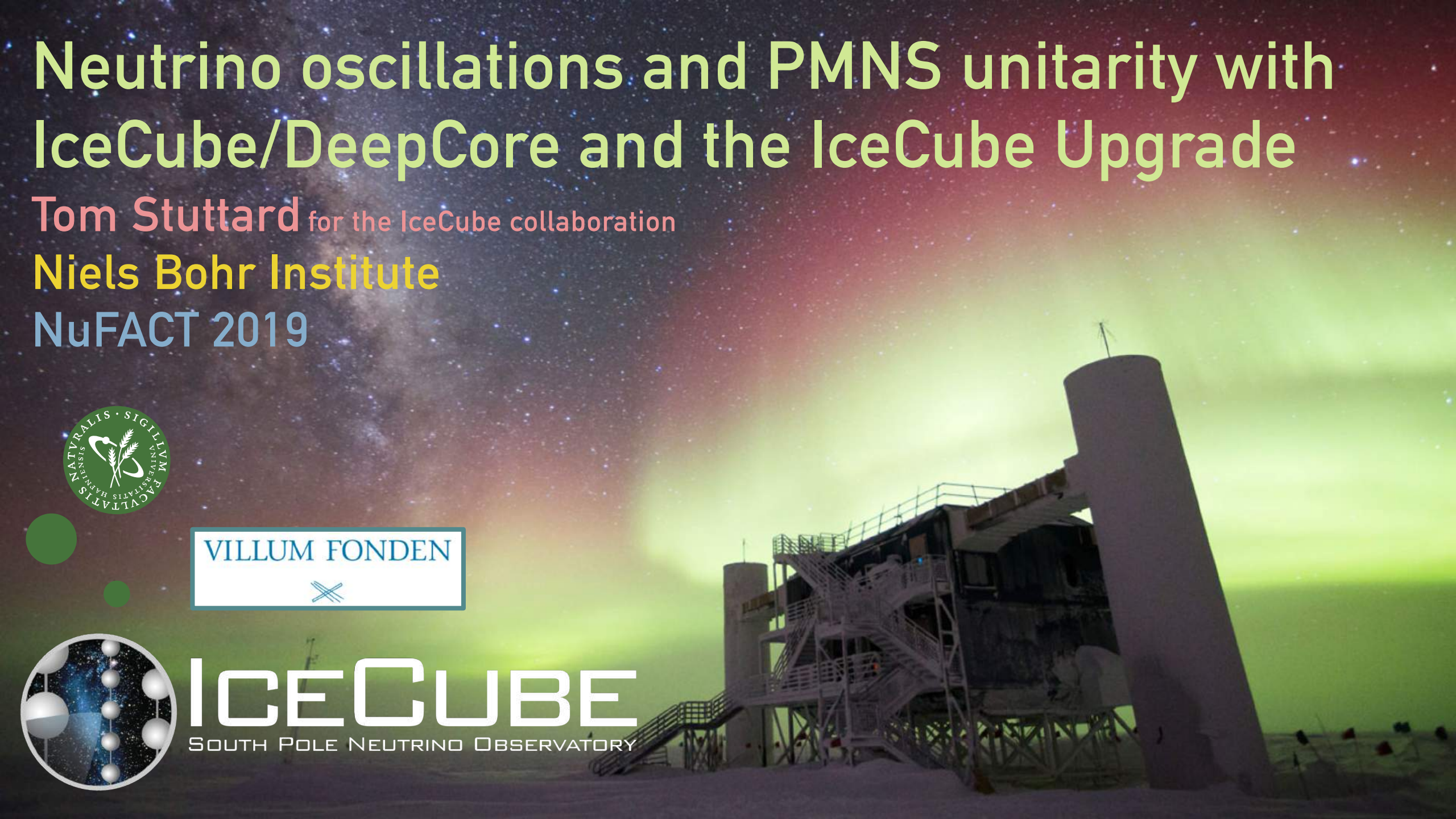
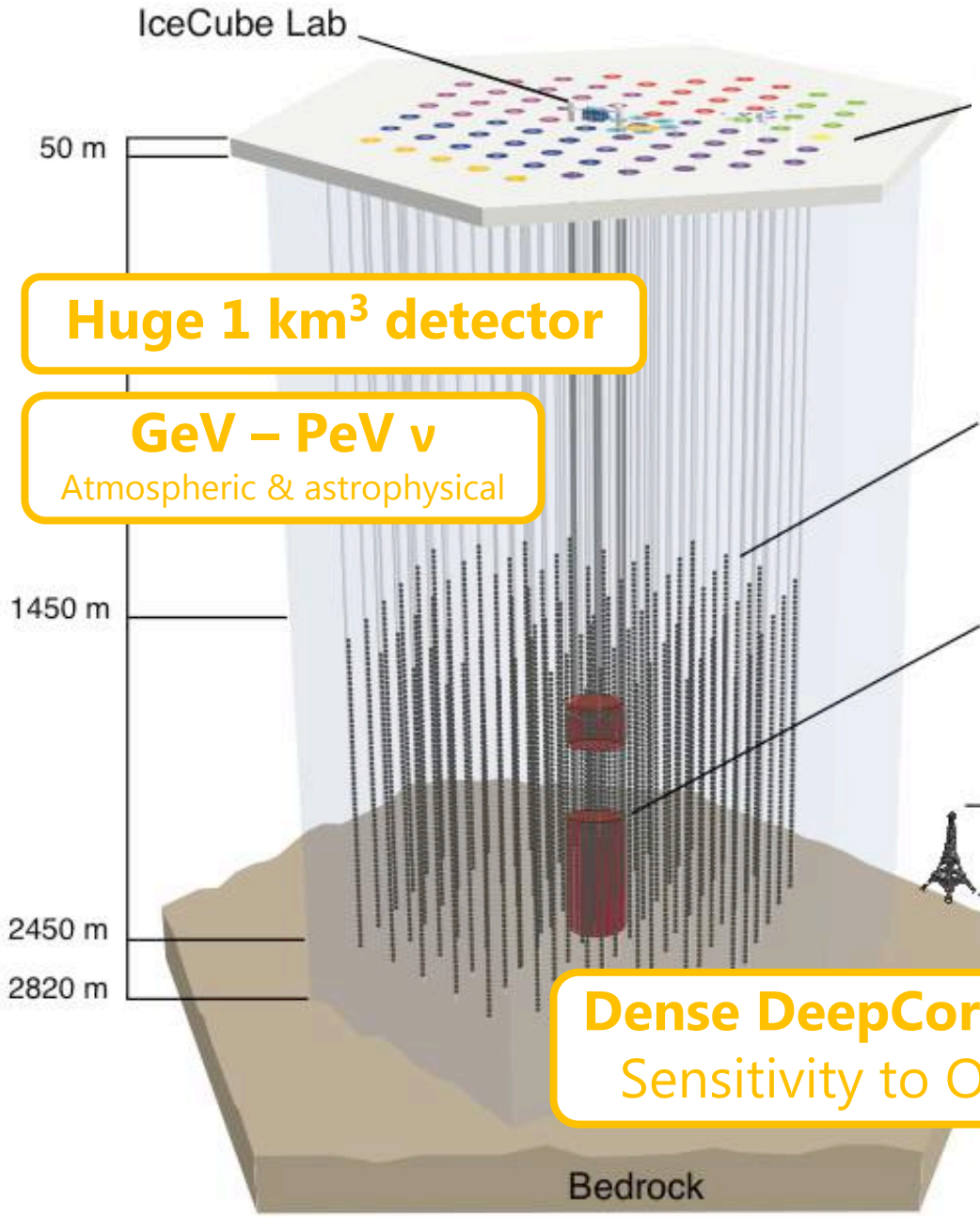
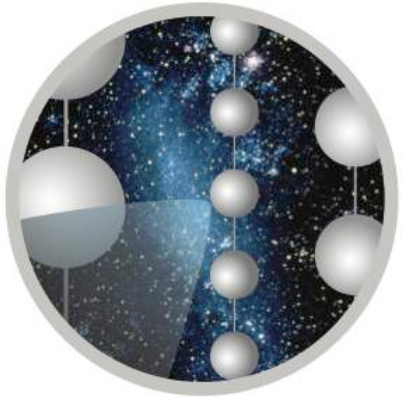
Neutrino oscillations and PMNS unitarity with IceCube/DeepCore and the IceCube Upgrade

Tom Stuttard for the IceCube collaboration
Niels Bohr Institute

NuFACT 2019







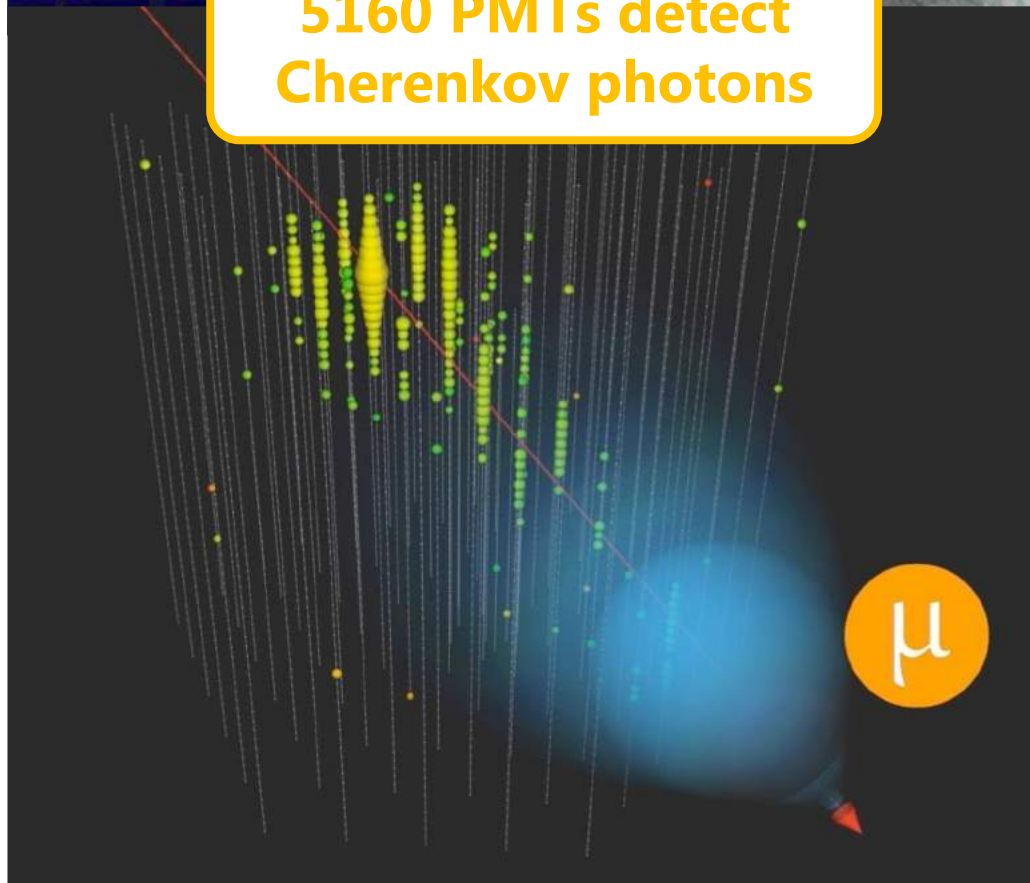
ICECUBE

Huge 1 km³ detector

GeV – PeV ν
Atmospheric & astrophysical

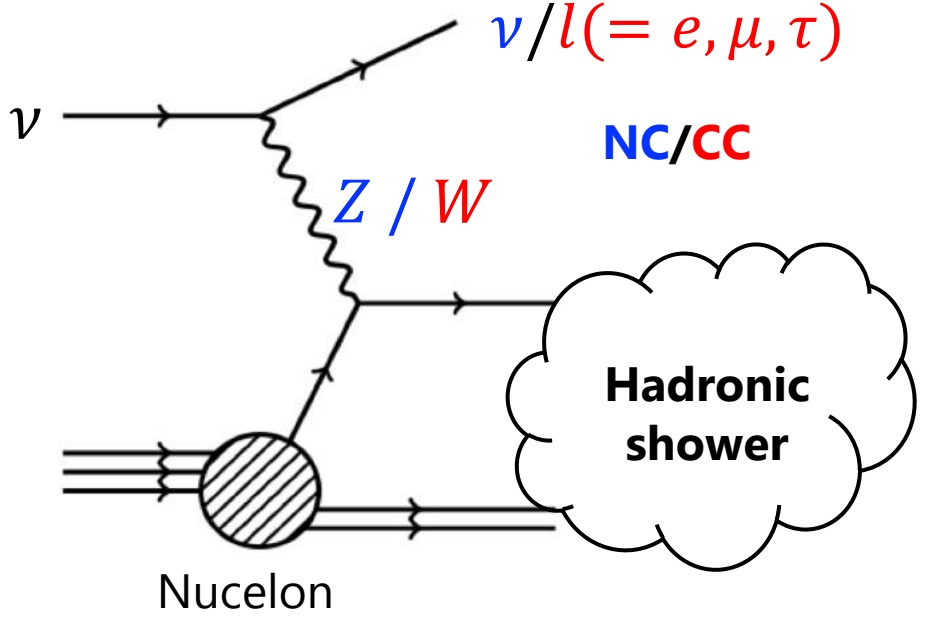
Dense DeepCore sub-array
Sensitivity to O(10 GeV) ν

5160 PMTs detect Cherenkov photons

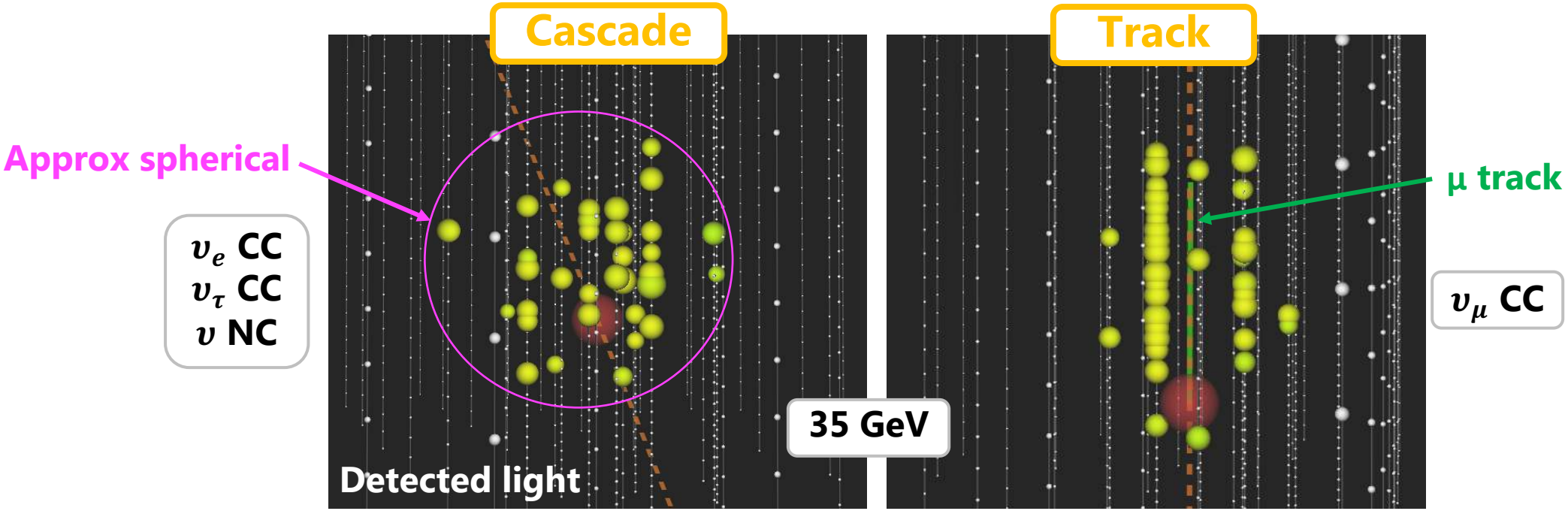


Detecting neutrinos

- Primarily detect ν-ice **Deep Inelastic Scattering** (DIS) interactions
- **Charged-** and **Neutral-Current** (CC/NC)

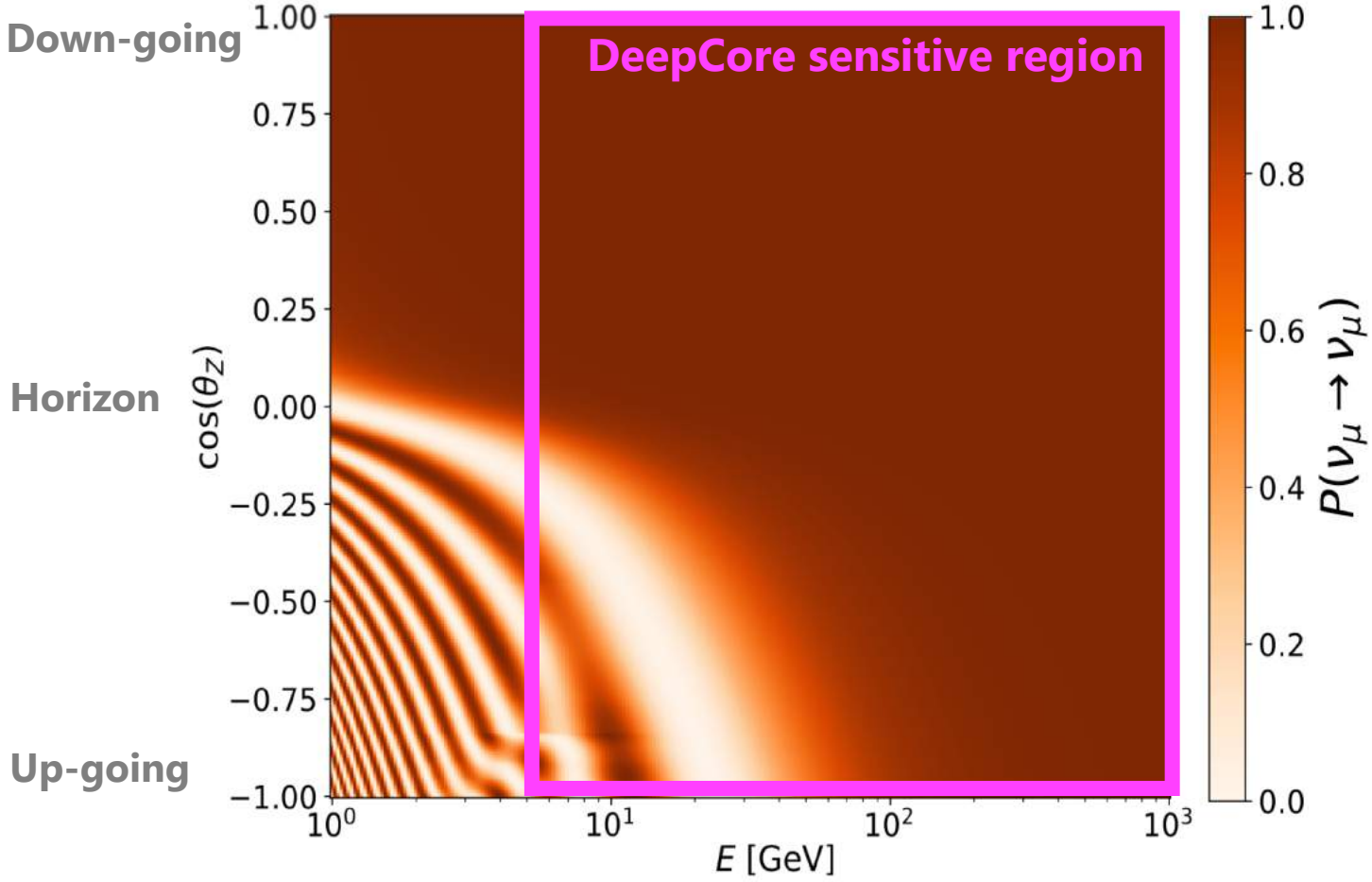


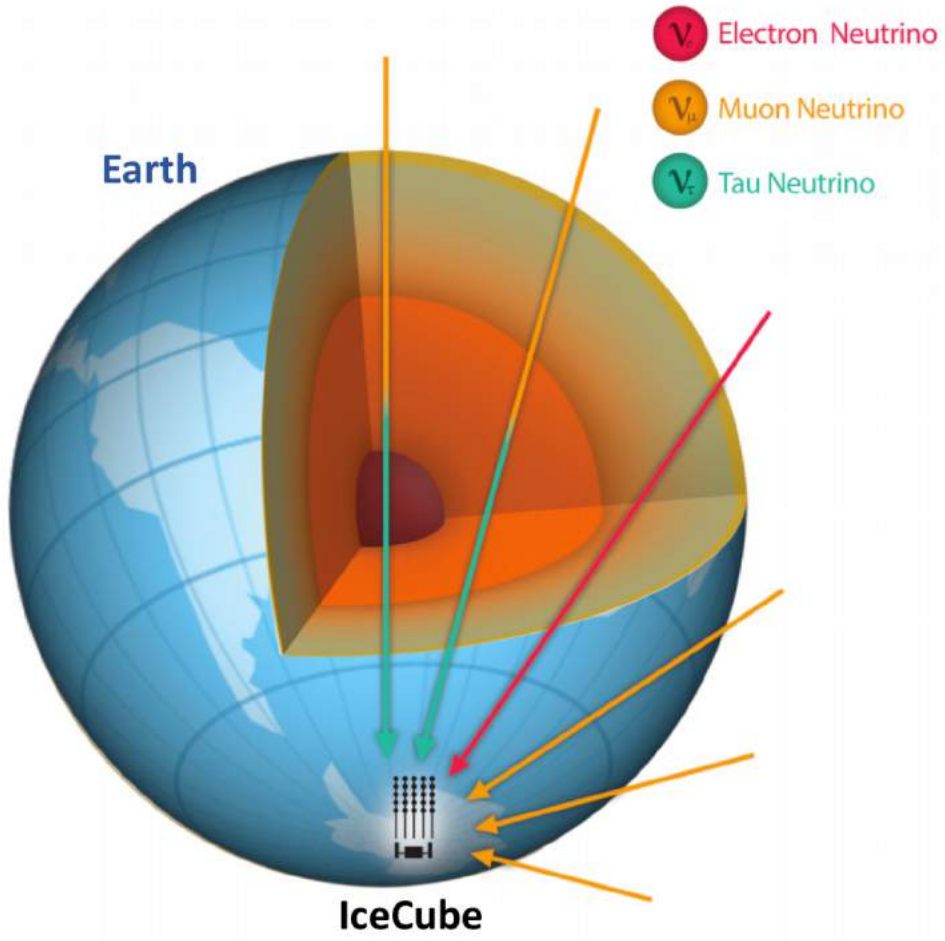
- Two event topologies @ oscillation energies:



Atmospheric neutrino oscillations in DeepCore

- mHz atmospheric neutrino detection rate @ O(10 GeV)
- Maximal ν_μ disappearance for Earth-crossing (up-going) neutrinos

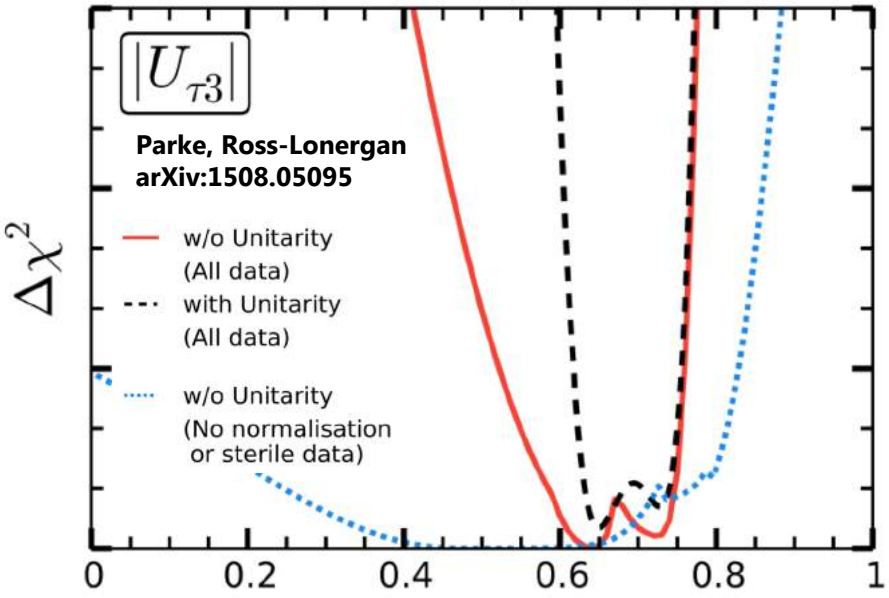


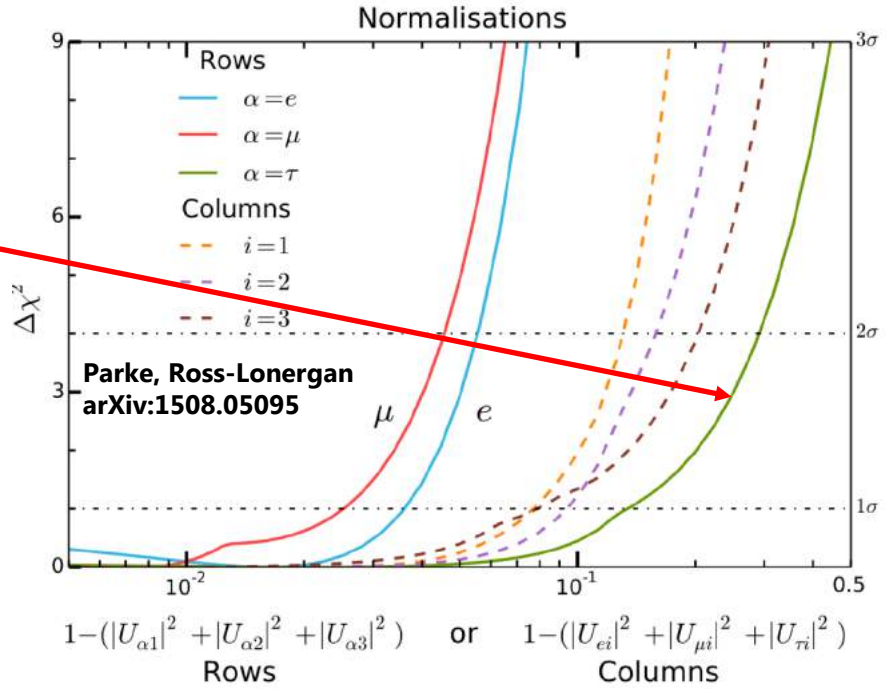


PMNS unitarity

- **PMNS** mixing matrix is **unitary** in standard oscillation picture
  - e.g. mixing between the 3 known neutrino flavours
- Additional (sterile?) states → 3x3 matrix is subset of full unitary matrix
- Test unitarity by measuring 3x3 matrix elements
  - **ν_τ elements least well measured**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \vdots \end{pmatrix} = \overbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \\ \vdots & & & \ddots \end{pmatrix}}^{\mathrm{U_{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \vdots \end{pmatrix}$$





$$-4\,\mathrm{Re}\{U^*_{\tau 3}U_{\mu 3}\,(U^*_{\tau 1}U_{\mu 1}+U^*_{\tau 2}U_{\mu 2})\}$$

ν_τ appearance

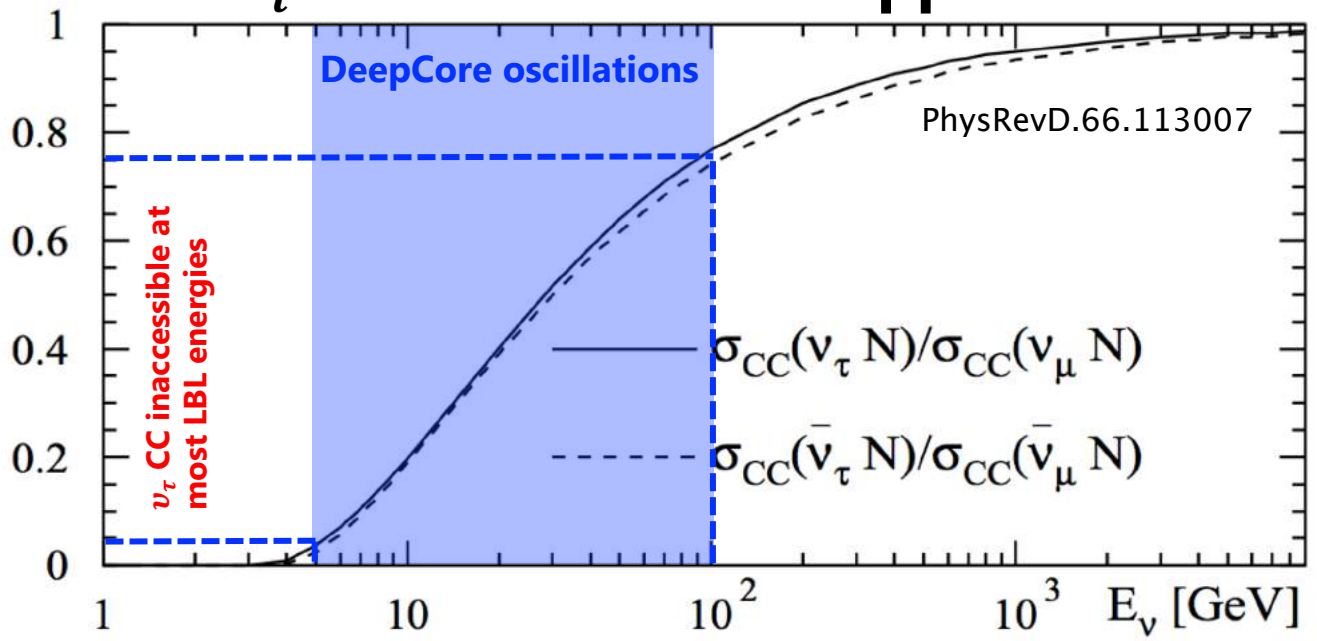
- Measure ν_τ sector via $\boldsymbol{\nu_\mu \rightarrow \nu_\tau}$ measurements (ν_τ appearance)

- **Challenging** measurement:
  - CC **cross section suppressed** by τ mass → low stats
  - Produced $\boldsymbol{\tau}$ **decays ~instantly** → PID difficult

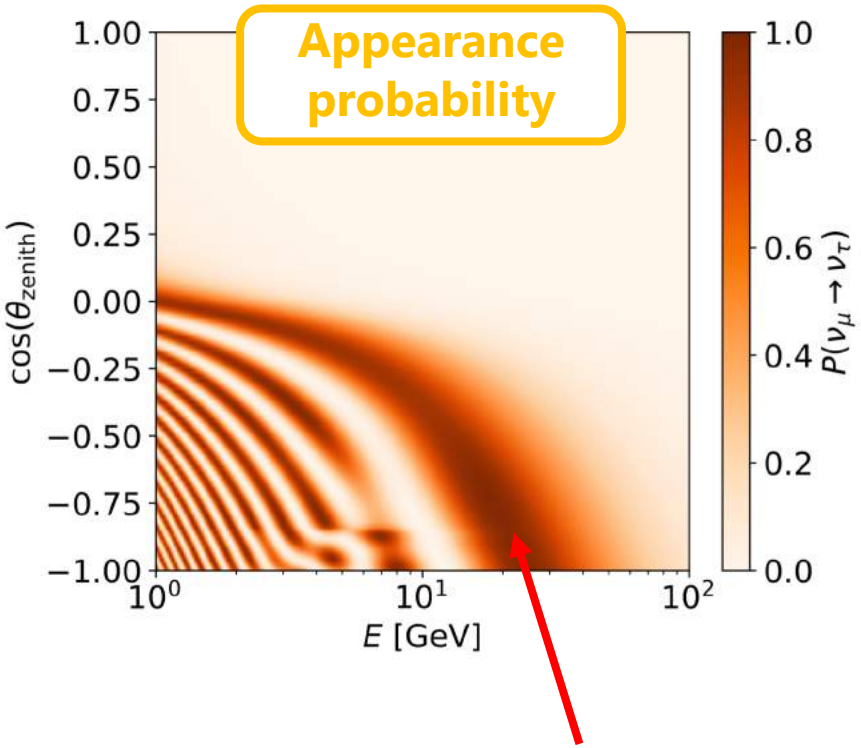
- 3 measurements to date
  - Beam: **OPERA**
  - Atmospheric: **SuperK**, **DeepCore**

- Can interpret results as:
  - PMNS elements measurement
  - ν_τ cross section measurement

ν_τ CC cross section suppression

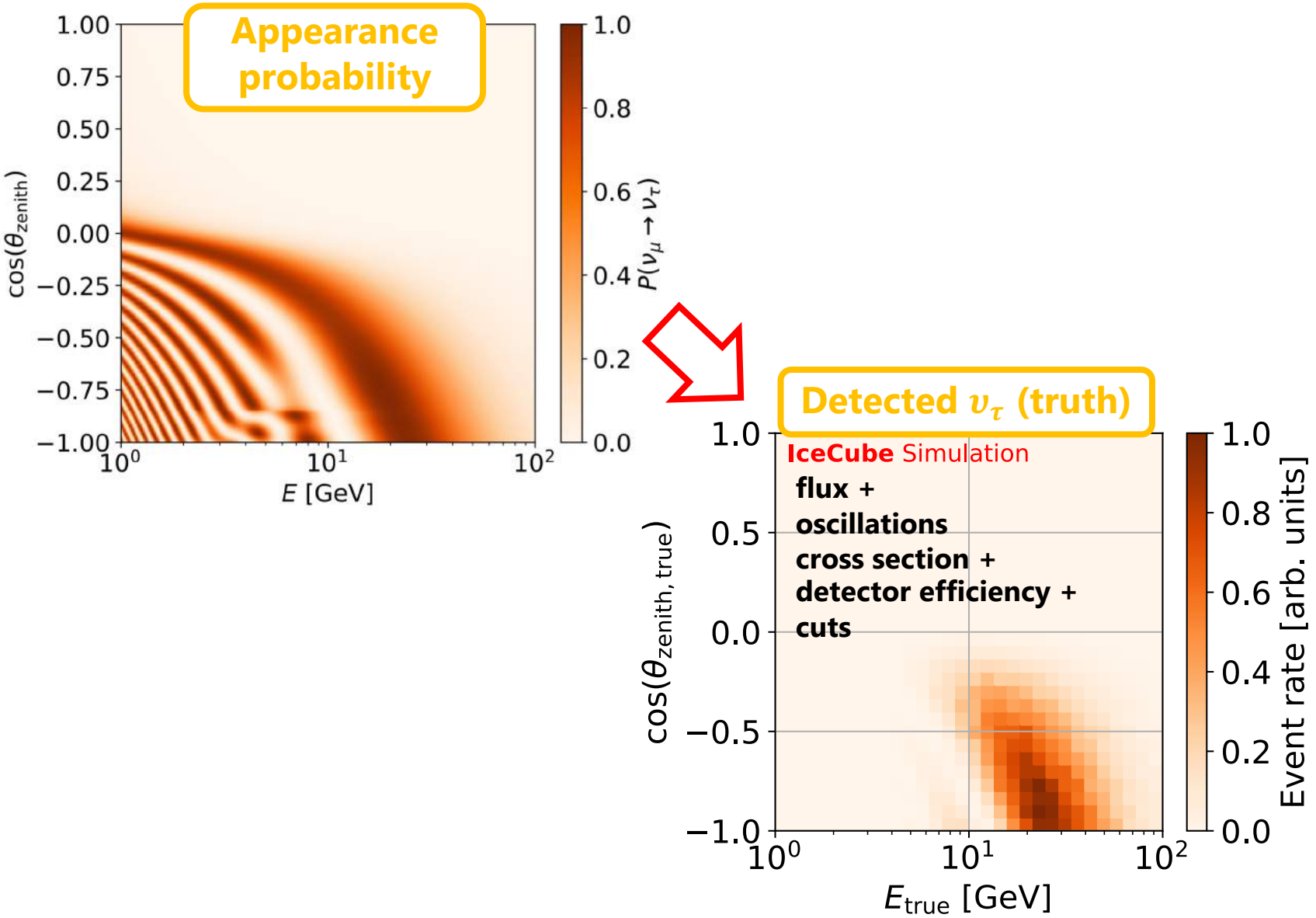


υ_τ appearance @ DeepCore

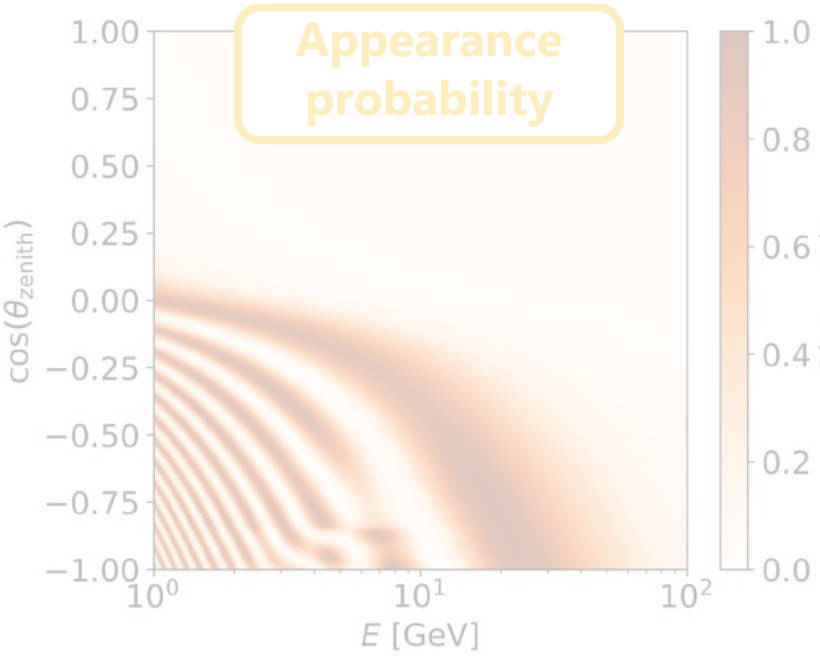


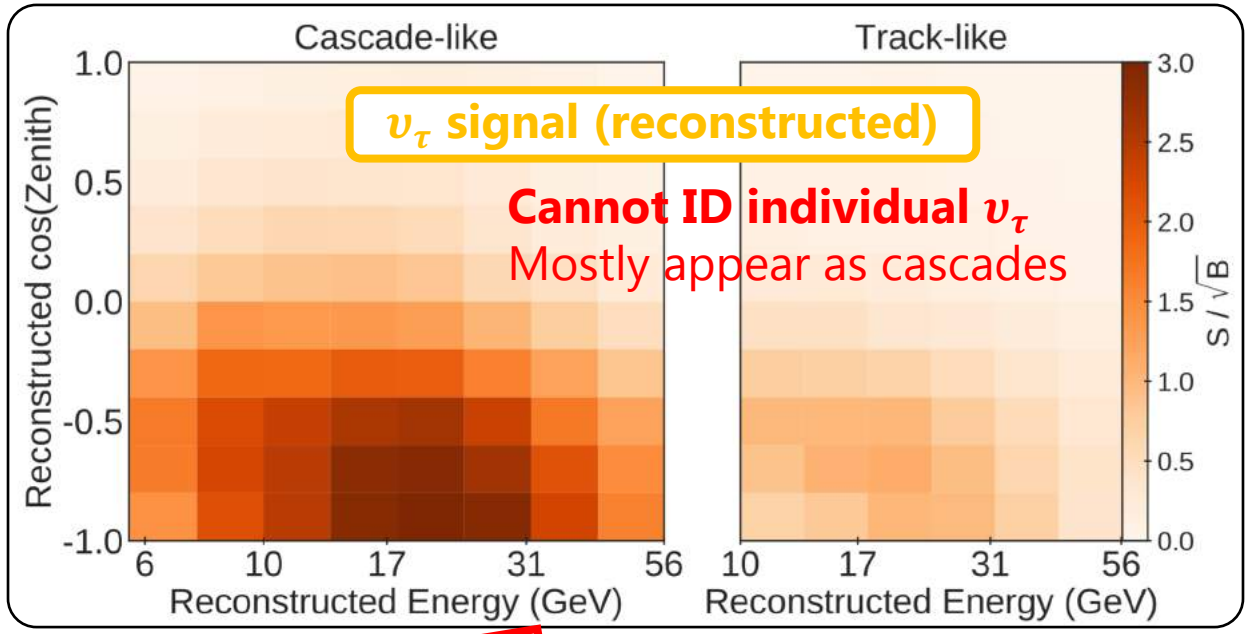
Strong $\upsilon_\mu \rightarrow \upsilon_\tau$ oscillations for Earth-crossing neutrinos

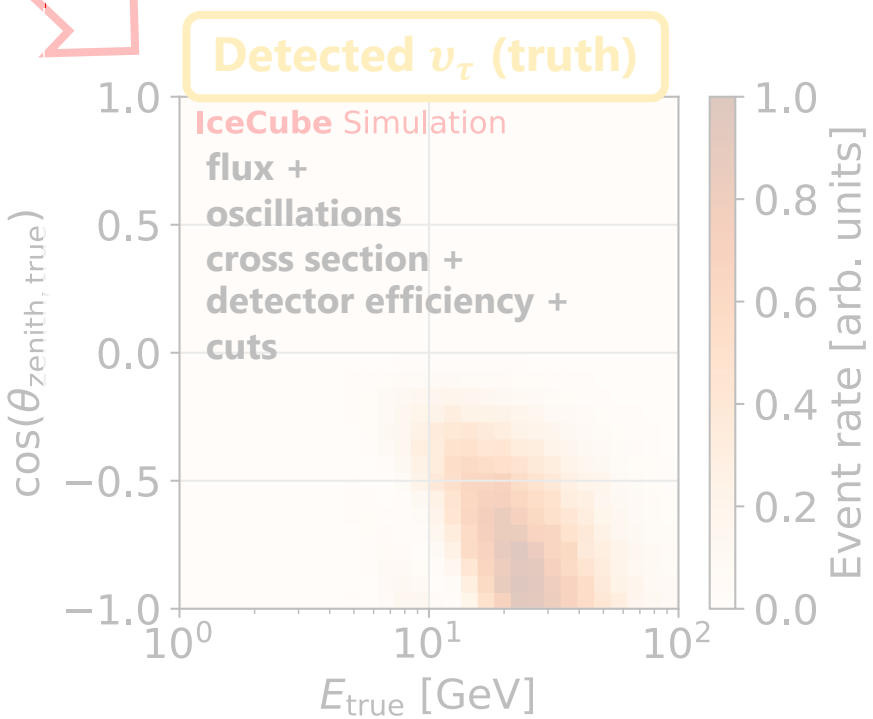
υ_τ appearance @ DeepCore



υ_τ appearance @ DeepCore







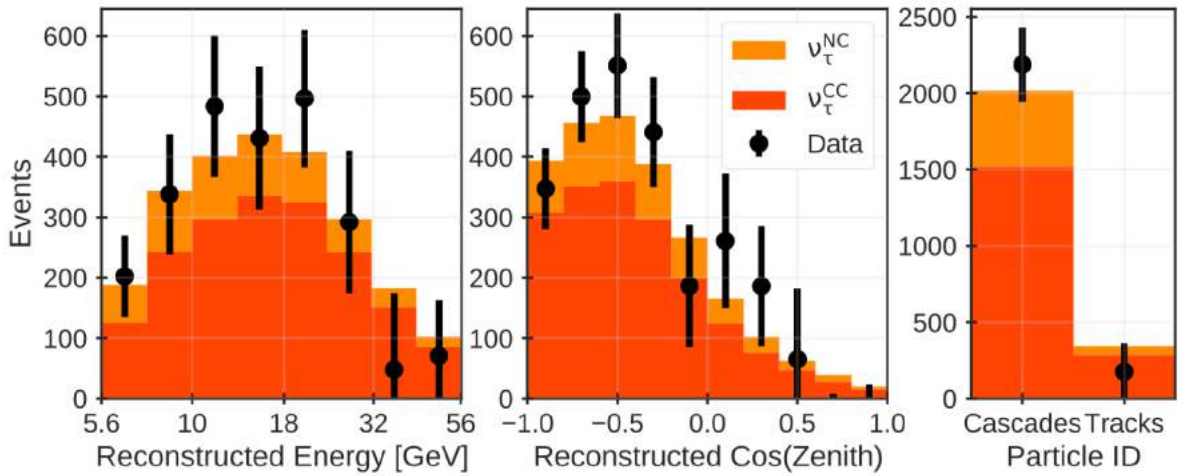
Statistically fit overall υ_τ contribution

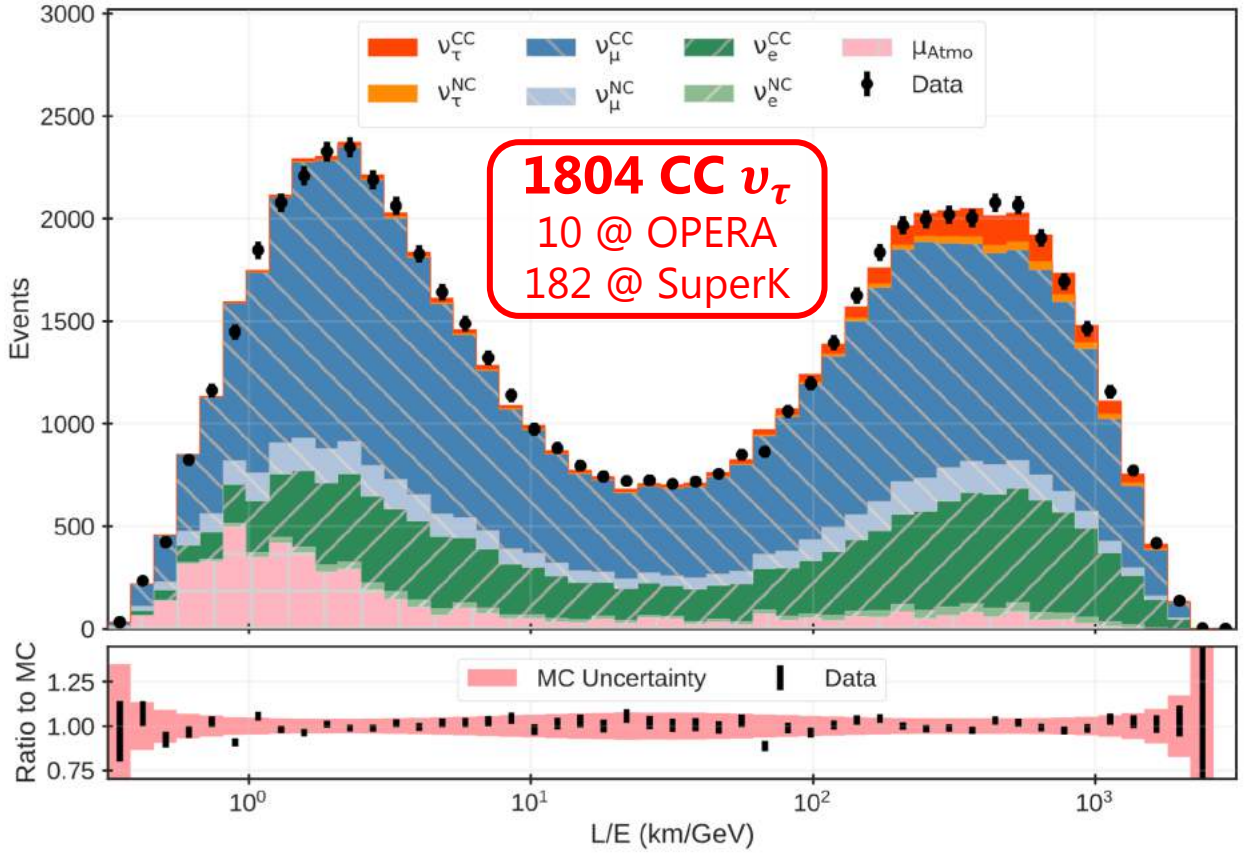
- Perform υ_μ disappearance fit
- Allow υ_τ normalisation to vary w.r.t. unitarity

DeepCore ν_τ appearance results

- 2 measurements performed with 3 years of DeepCore data [PRD 2019]

Data vs MC (best fit)

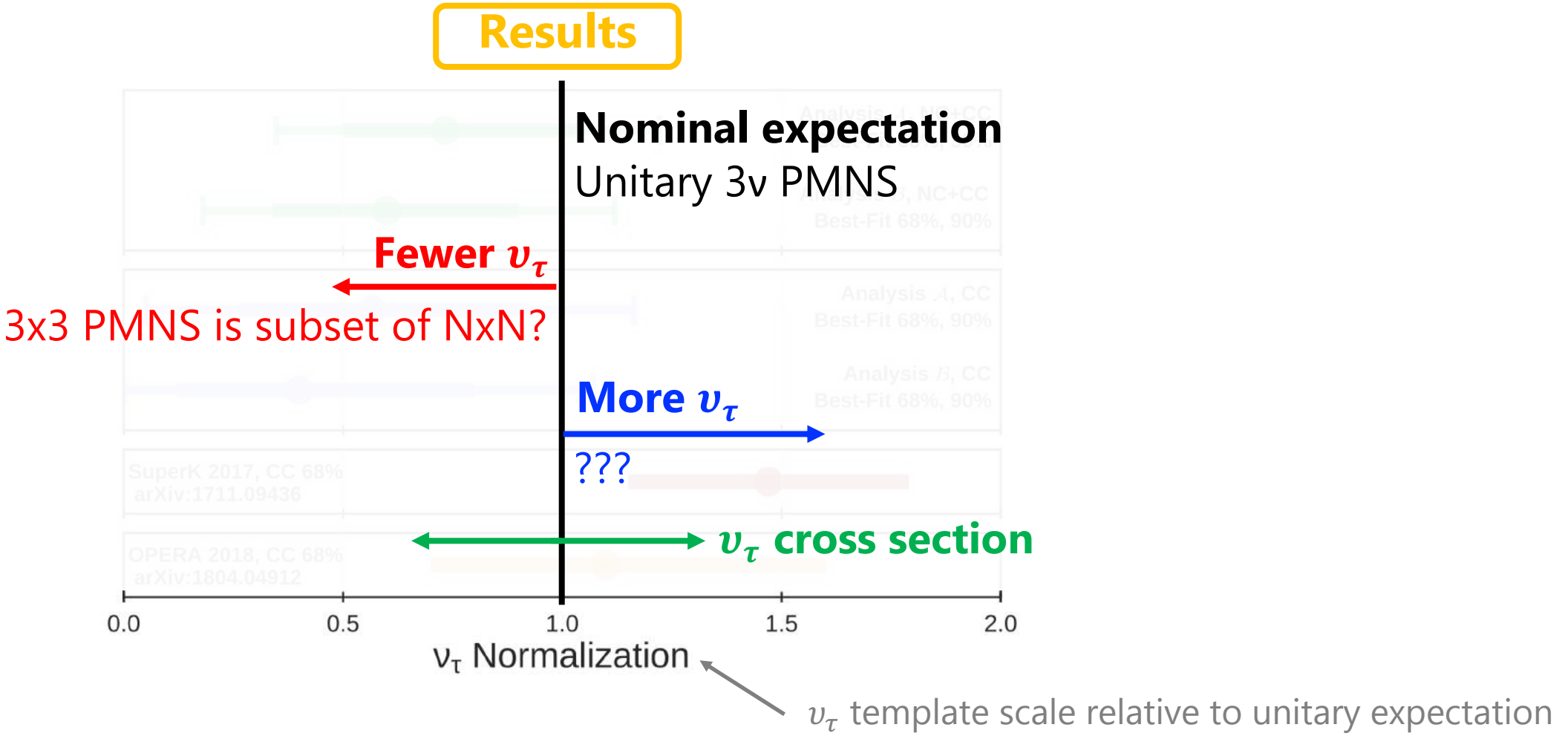




Data fit in [energy, cos(zenith), PID] space
Searching for 3D distortions (shape-only)

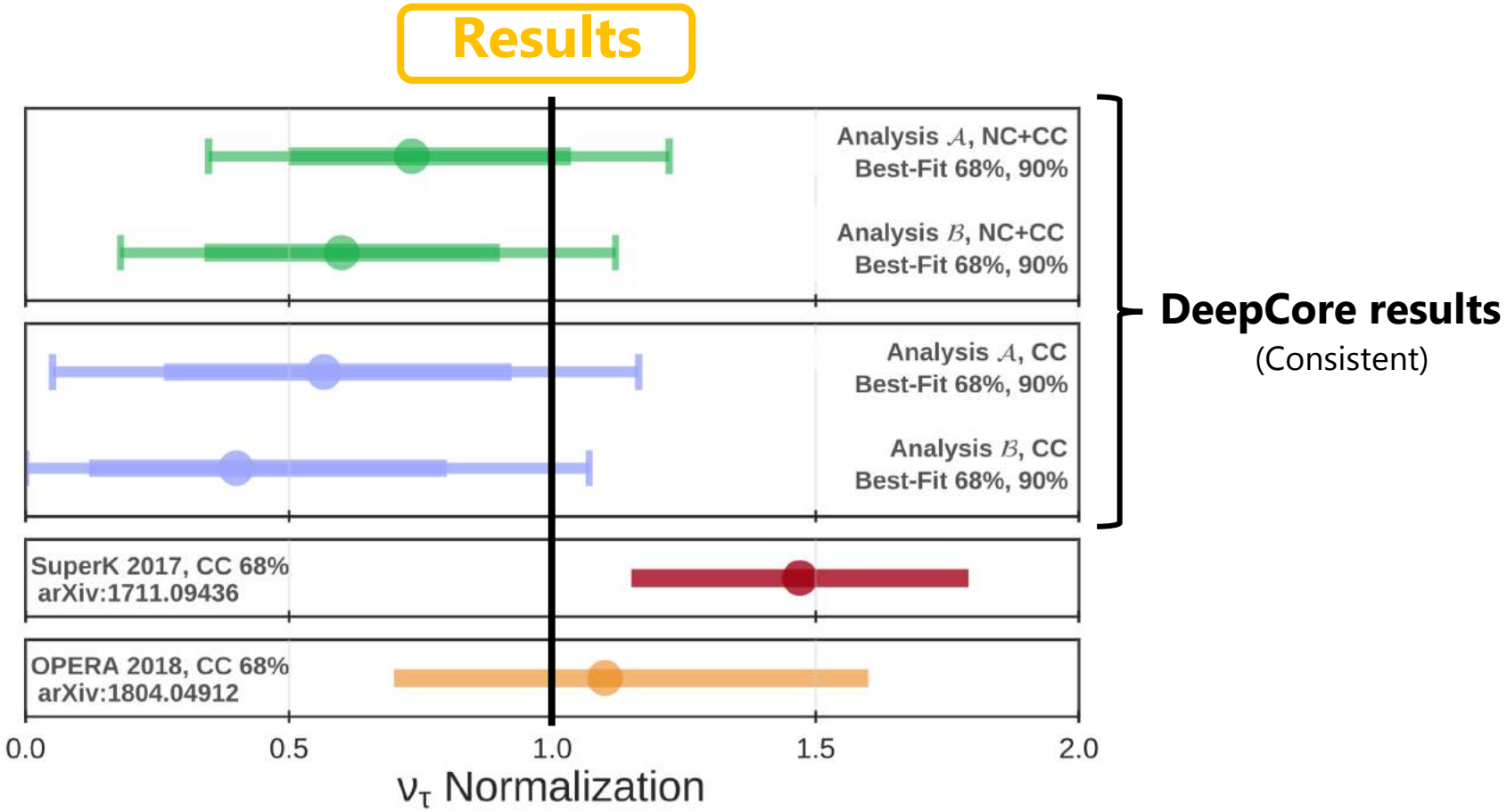
DeepCore ν_τ appearance results

- 2 measurements performed with 3 years of DeepCore data [PRD 2019]



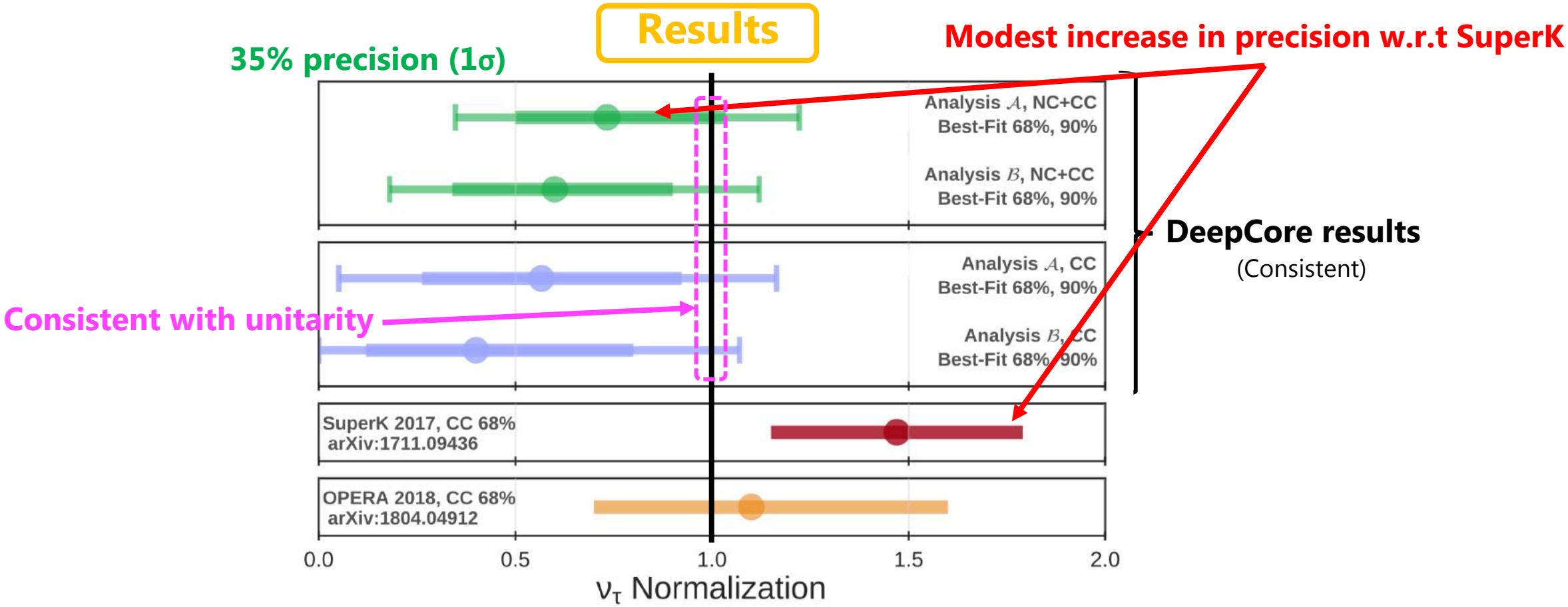
DeepCore ν_τ appearance results

- 2 measurements performed with 3 years of DeepCore data [PRD 2019]



DeepCore ν_τ appearance results

- 2 measurements performed with 3 years of DeepCore data [PRD 2019]



DeepCore ν_τ appearance results

- 2 measurements performed with 3 years of DeepCore data [PRD 2019]
  - Consistent results

Take away message

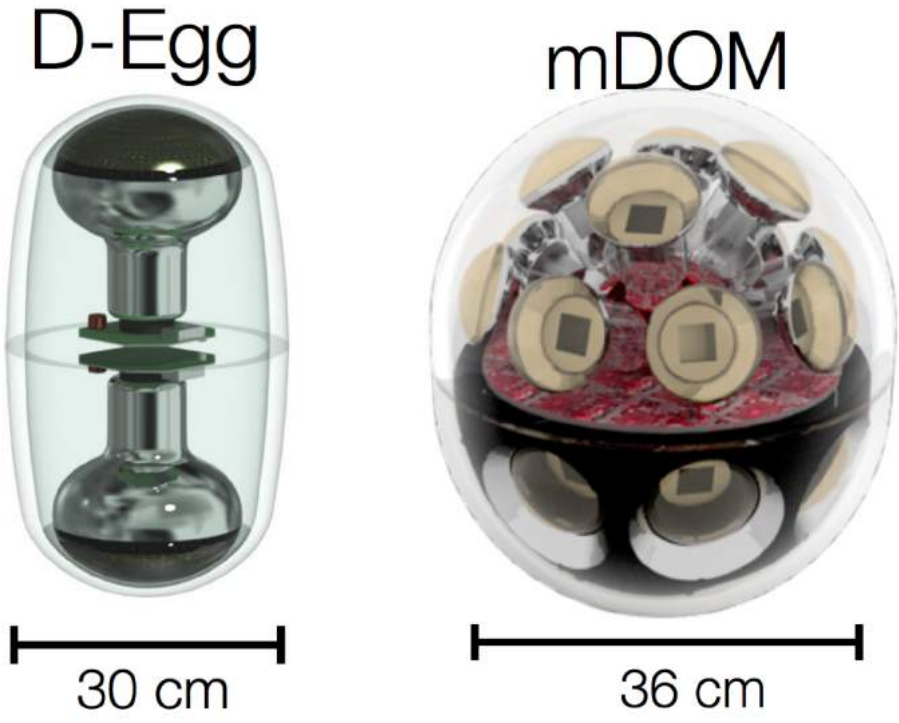
- World-leading ν_τ appearance measurement precision @ DeepCore
- Results consistent with standard oscillation picture

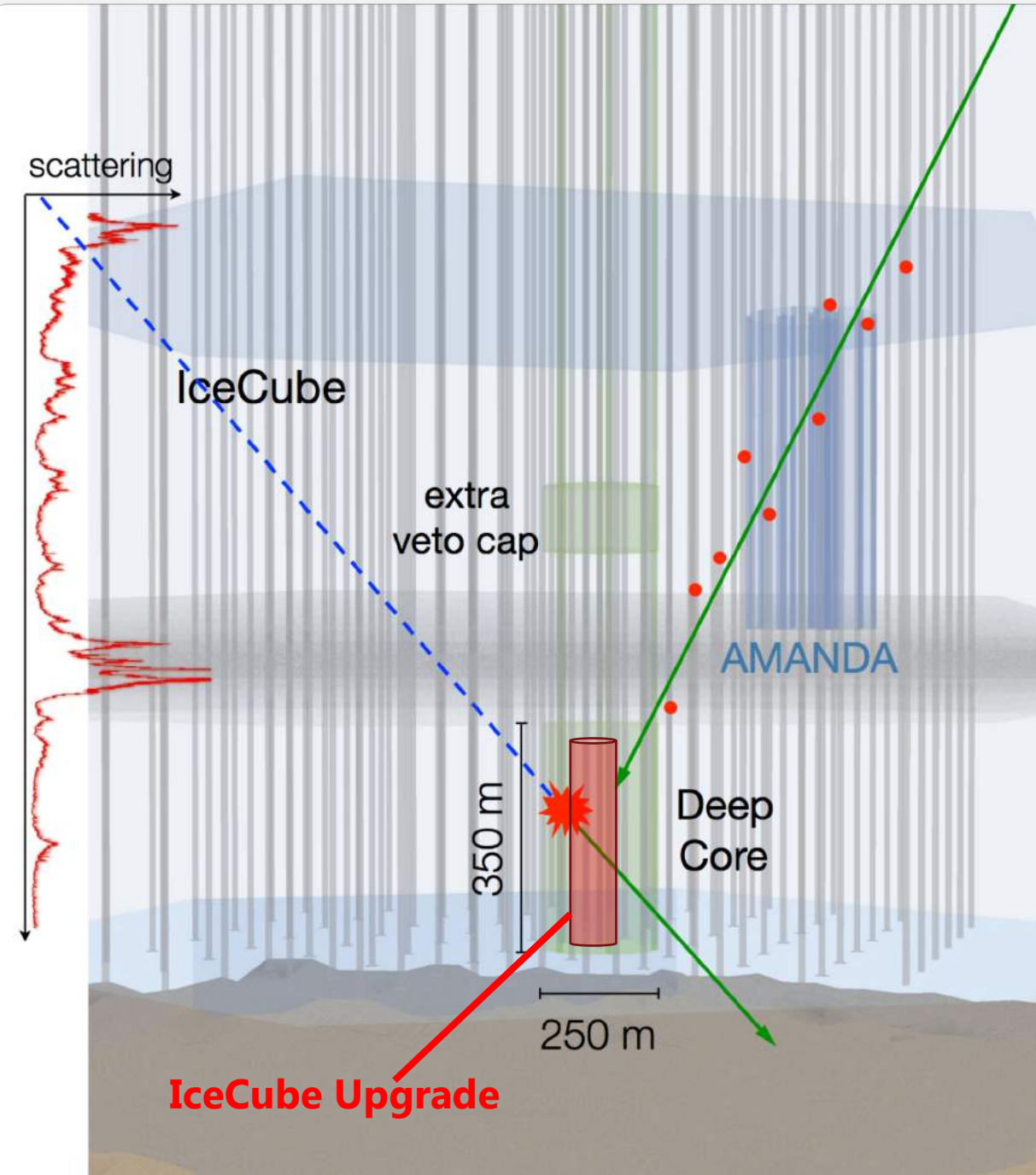
Coming soon

New measurement with >5x statistics

The IceCube Upgrade

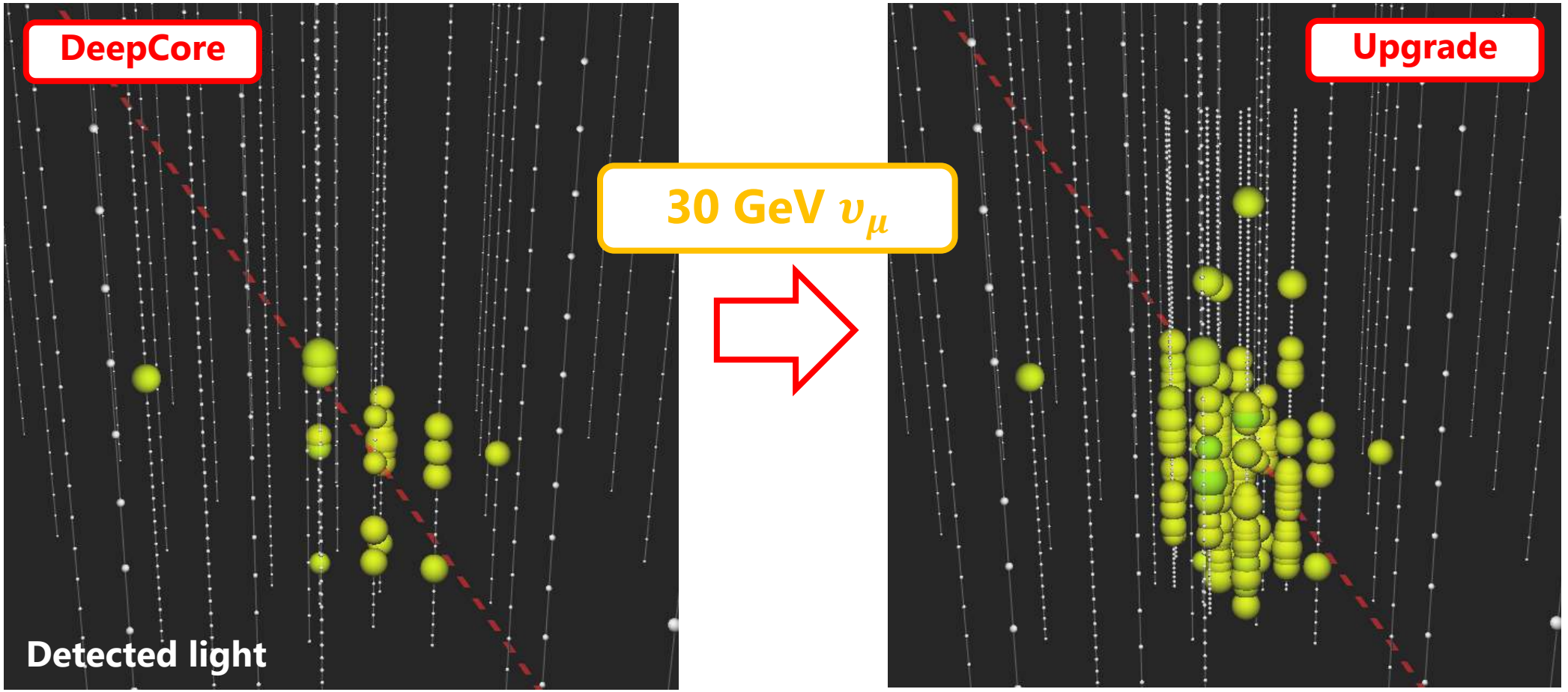
- NSF have funded a $30M extension to IceCube
  - Deployment in 2022/3
- 700 multi-PMT sensors
- Improved ice calibration





A low energy neutrino detector

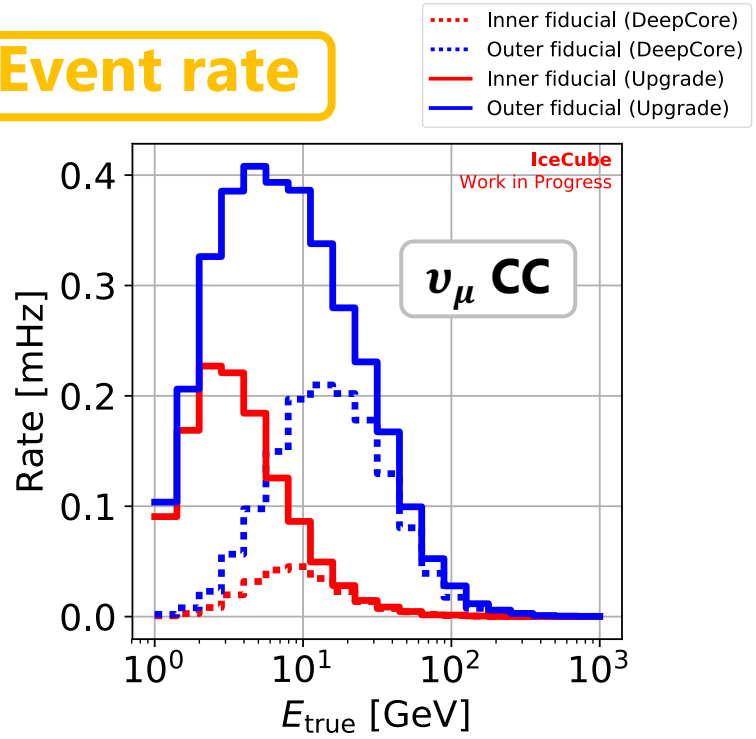
- **Dense instrumentation** in 2 Mton core
  - Large increase in photocathode density → sensitive to **1 GeV neutrinos**



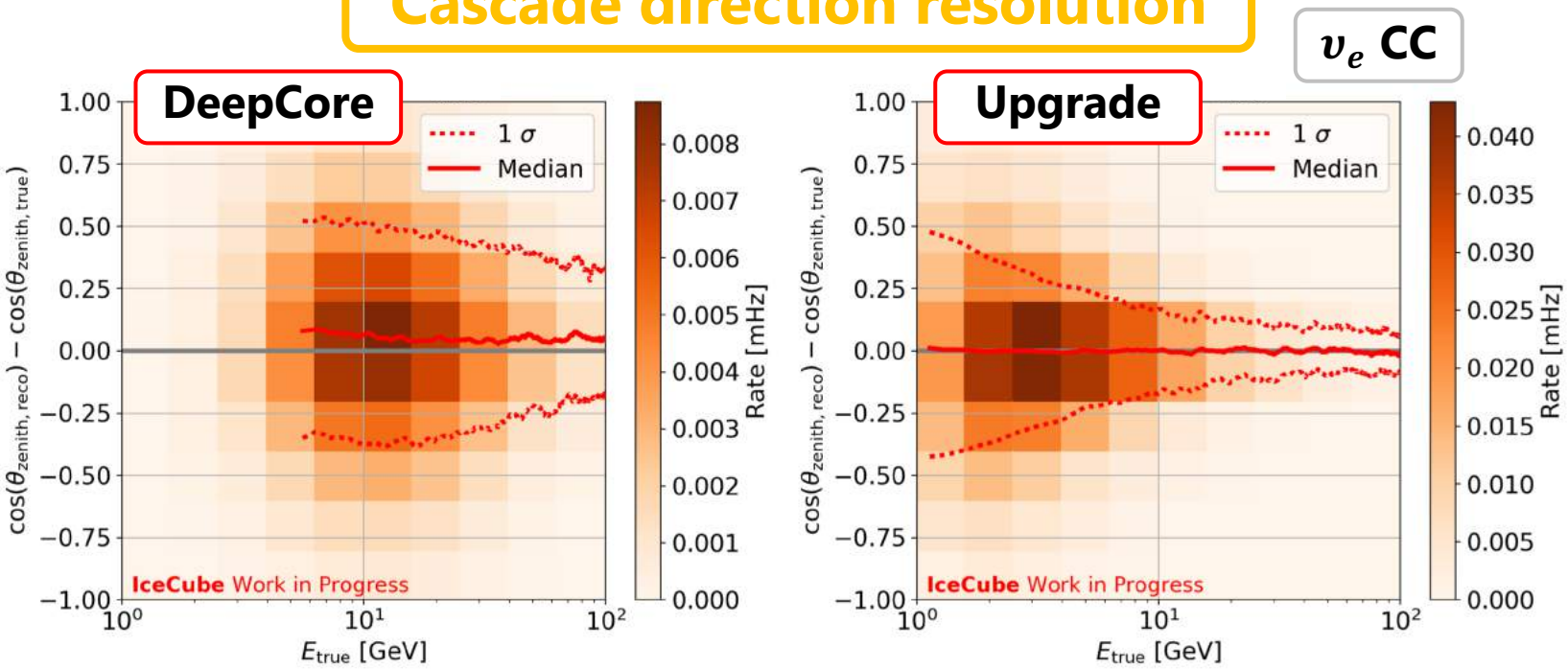
Upgrade performance

- Major improvement in detection rate and energy/direction resolution

Event rate



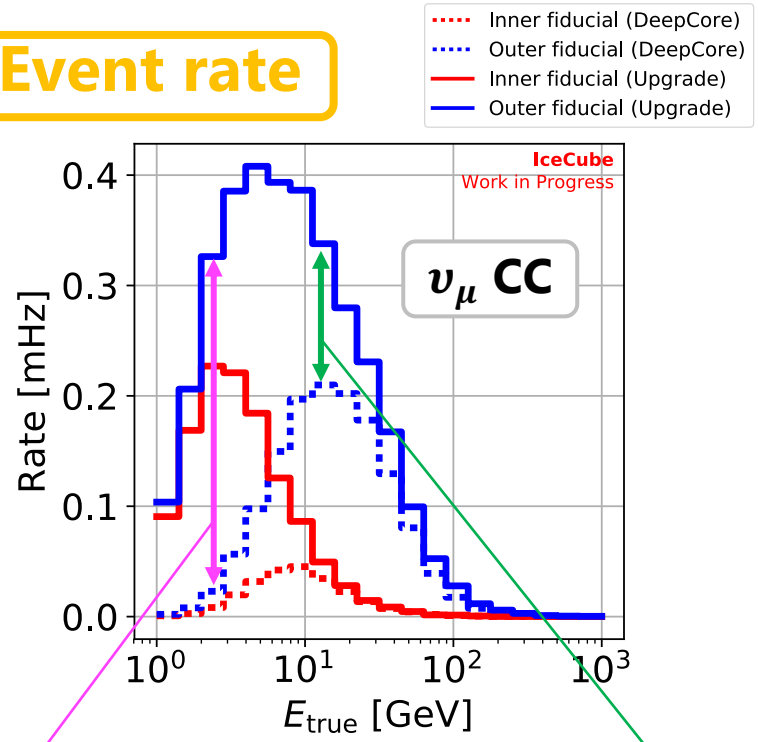
Cascade direction resolution



Upgrade performance

- Major improvement in detection rate and energy/direction resolution

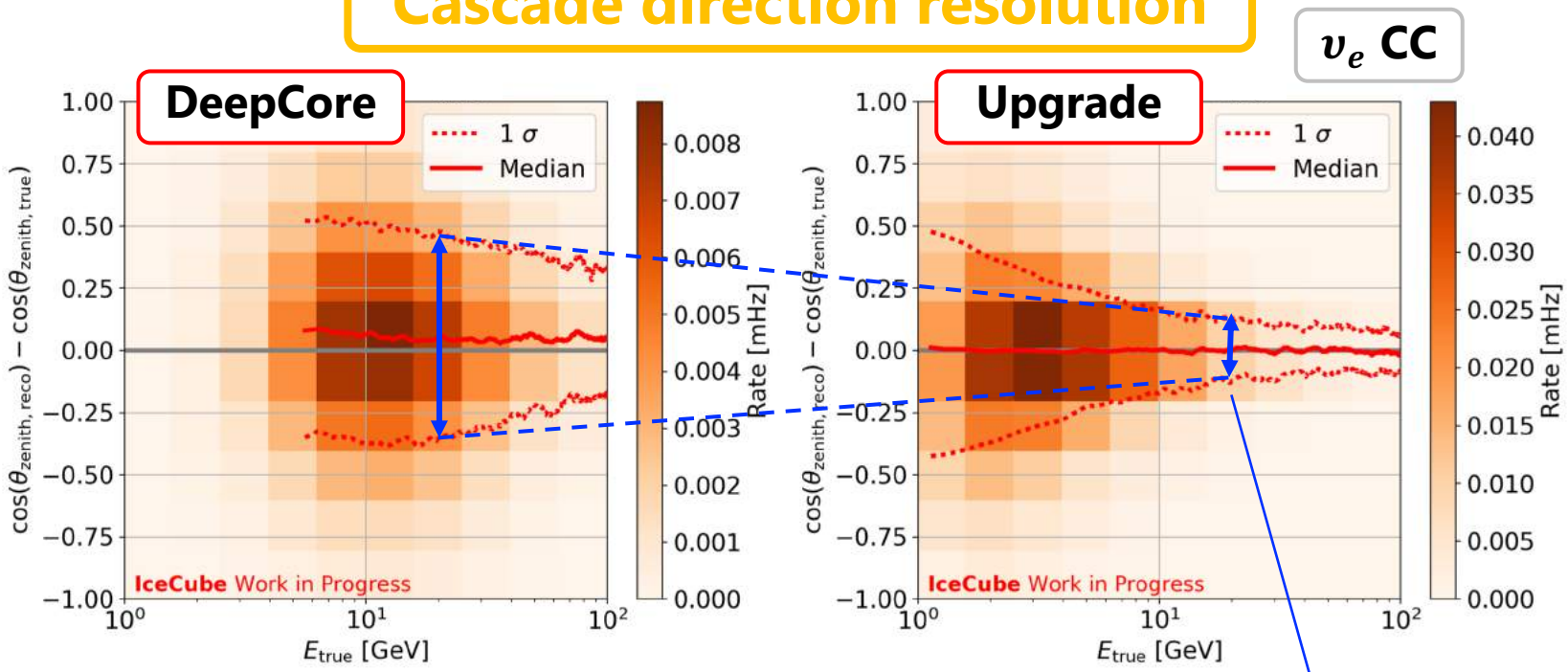
Event rate



Huge increase in <10 GeV ν rate

Enhanced rate for all oscillation energies

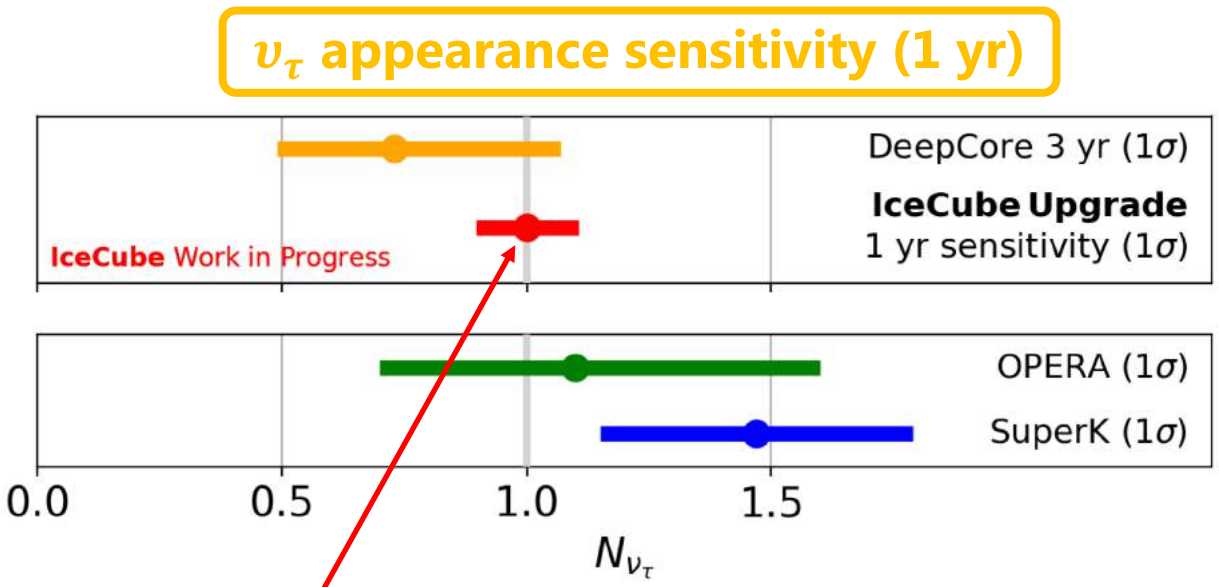
Cascade direction resolution



3x improvement @ ν_τ appearance energies

Oscillations @ the IceCube Upgrade

- ν_τ **appearance** is Upgrade **primary physics goal**
- Broad oscillation program including **mass ordering** and **BSM**

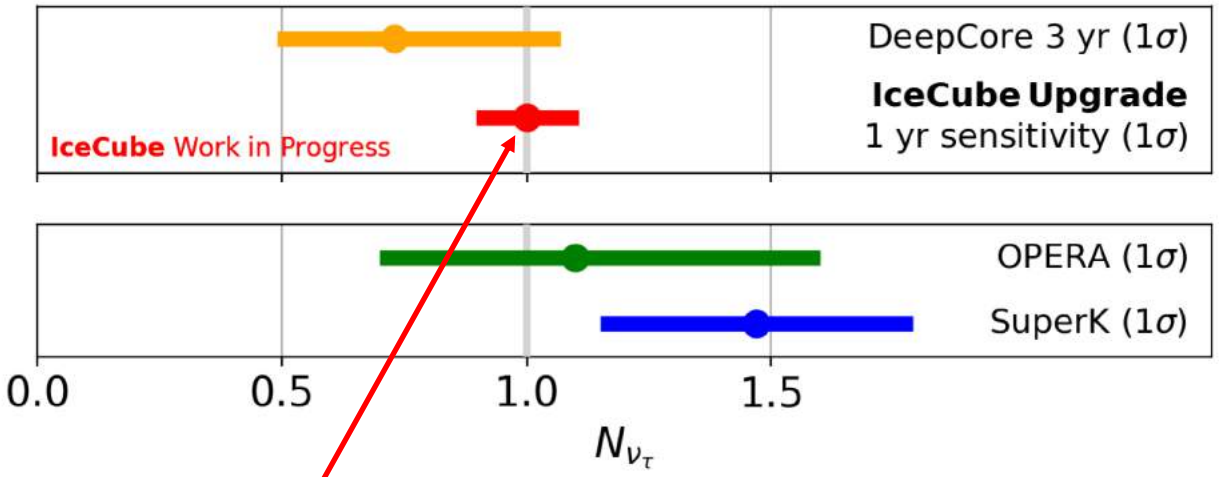


10% precision after 1 year
(6% after 3 years)

Oscillations @ the IceCube Upgrade

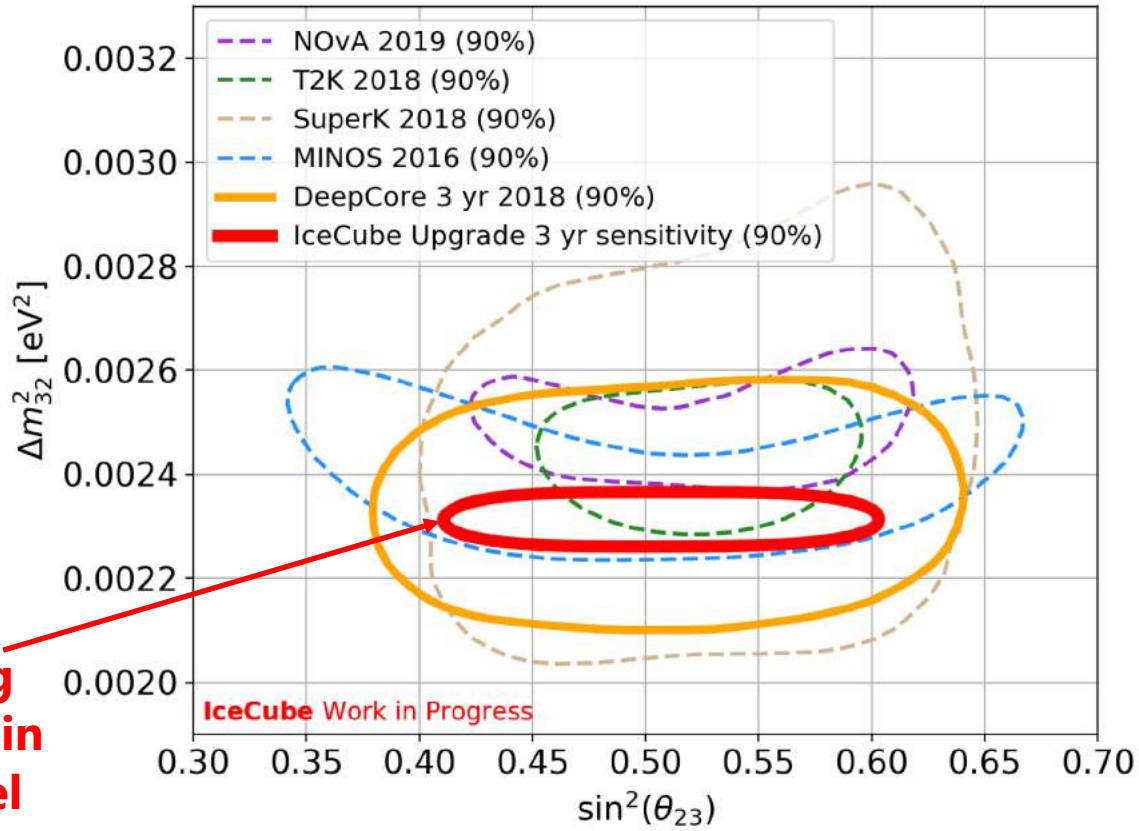
- ν_τ **appearance** is Upgrade **primary physics goal**
- Broad oscillation program including **mass ordering** and **BSM**

ν_τ **appearance sensitivity (1 yr)**



10% precision after 1 year
(6% after 3 years)

ν_μ **disappearance sensitivity (3 yr)**



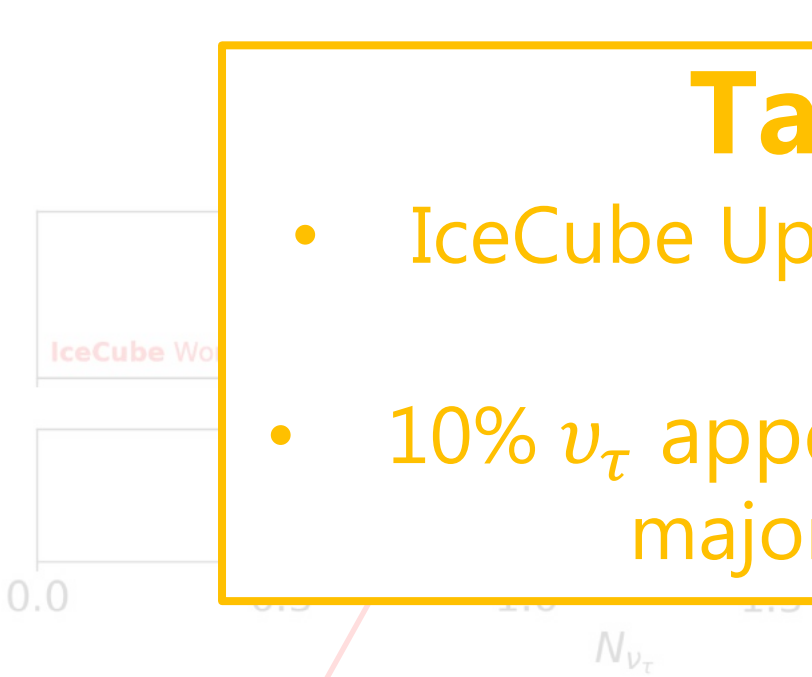
Competitive with long baseline experiments in disappearance channel

Oscillations @ the IceCube Upgrade

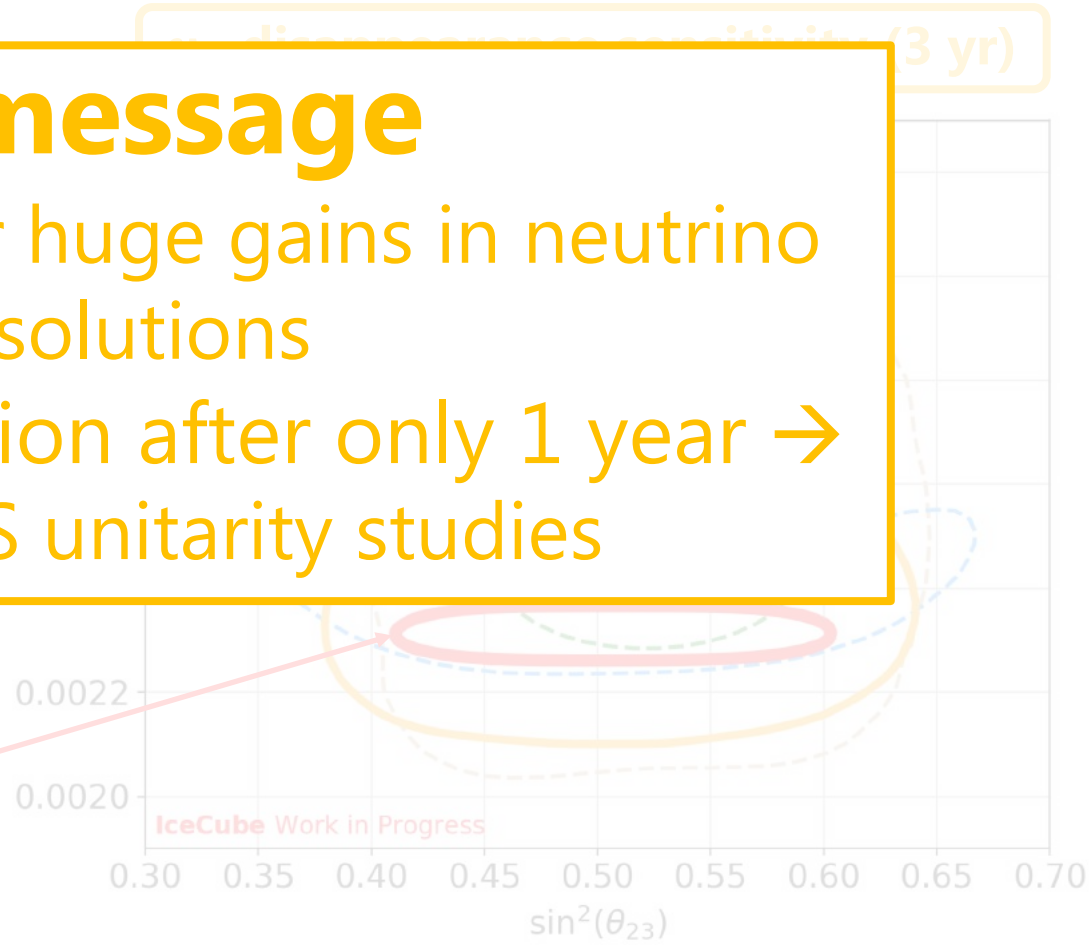
- ν_τ **appearance** is Upgrade **primary physics goal**
- Broad oscillation program including **mass ordering** and **BSM**

Take away message

- IceCube Upgrade will offer huge gains in neutrino rates and resolutions
- 10% ν_τ appearance precision after only 1 year → major leap for PMNS unitarity studies



10% precision after 1 year
(6% after 3 years)



Competitive with long baseline experiments in disappearance channel

Other IceCube BSM oscillation searches

- IceCube/DeepCore is a versatile oscillations detector
  - Large range of energies, baselines, matter profiles
- Broad BSM oscillation program

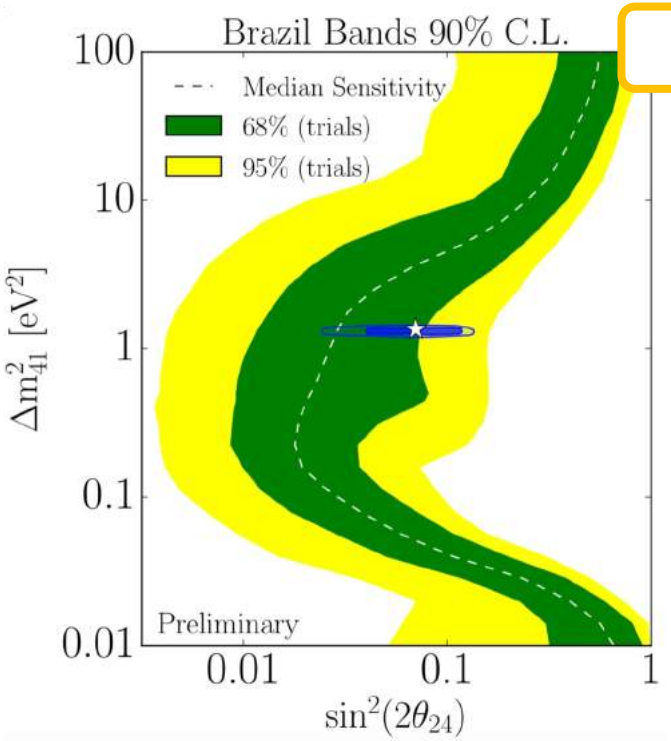
See other talks @ NuFact

WG1 - Latest Results on Neutrino Oscillation from the IceCube Neutrino Observatory

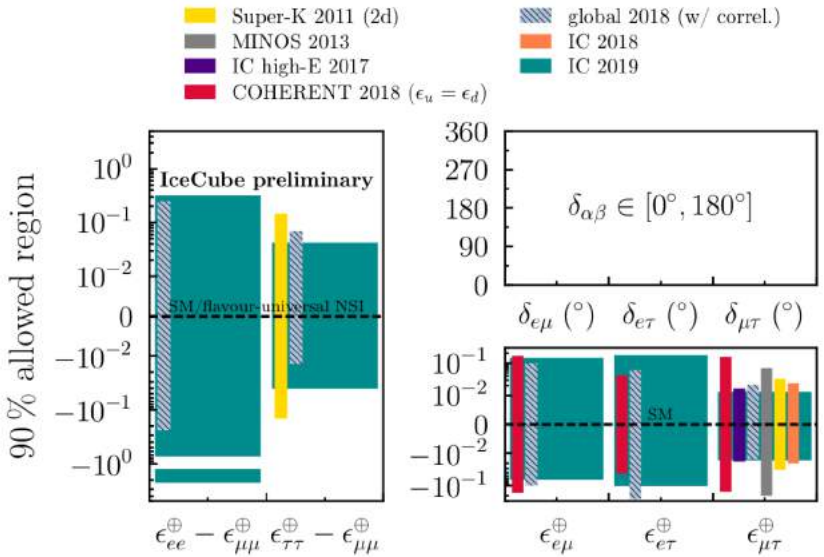
WG5 - Search for Dark Matter and BSM Physics with the IceCube Neutrino Observatory

WG1+5 Sterile Neutrino Searches with IceCube

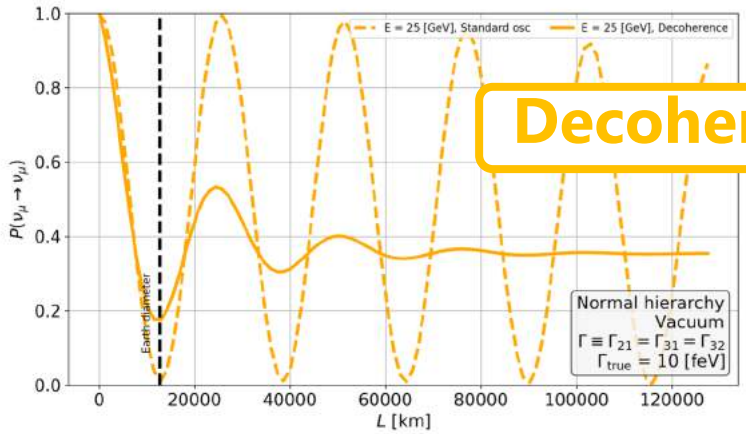
Sterile ν



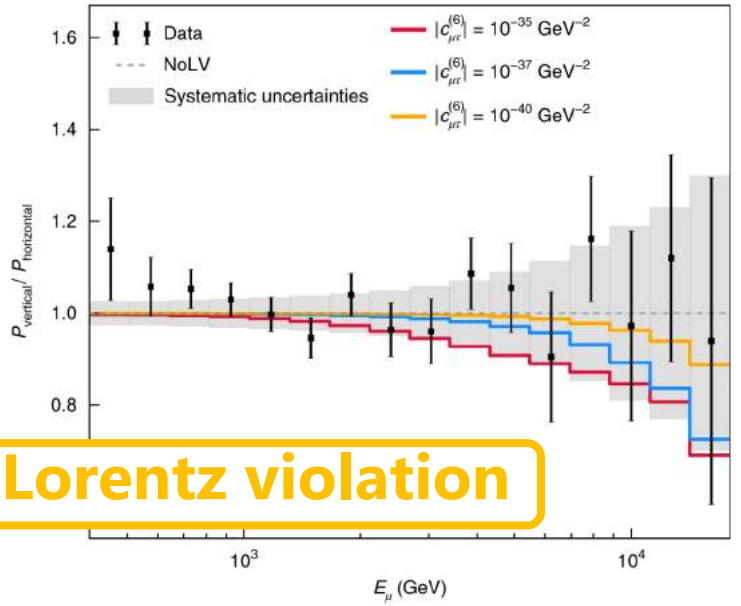
NSI



Decoherence



Lorentz violation



Summary

- Testing **PMNS unitarity** offers a powerful, model-independent search for new neutrino states and other BSM physics

- Currently **limited by precision in ν_τ sector**, but improving with **world-leading ν_τ appearance** measurements by IceCube/DeepCore

- Recently funded **IceCube Upgrade can achieve 10% precision** in ν_τ sector after 1 year of operation

- Exciting IceCube/DeepCore/Upgrade oscillation physics program over the coming decade

Backup slides

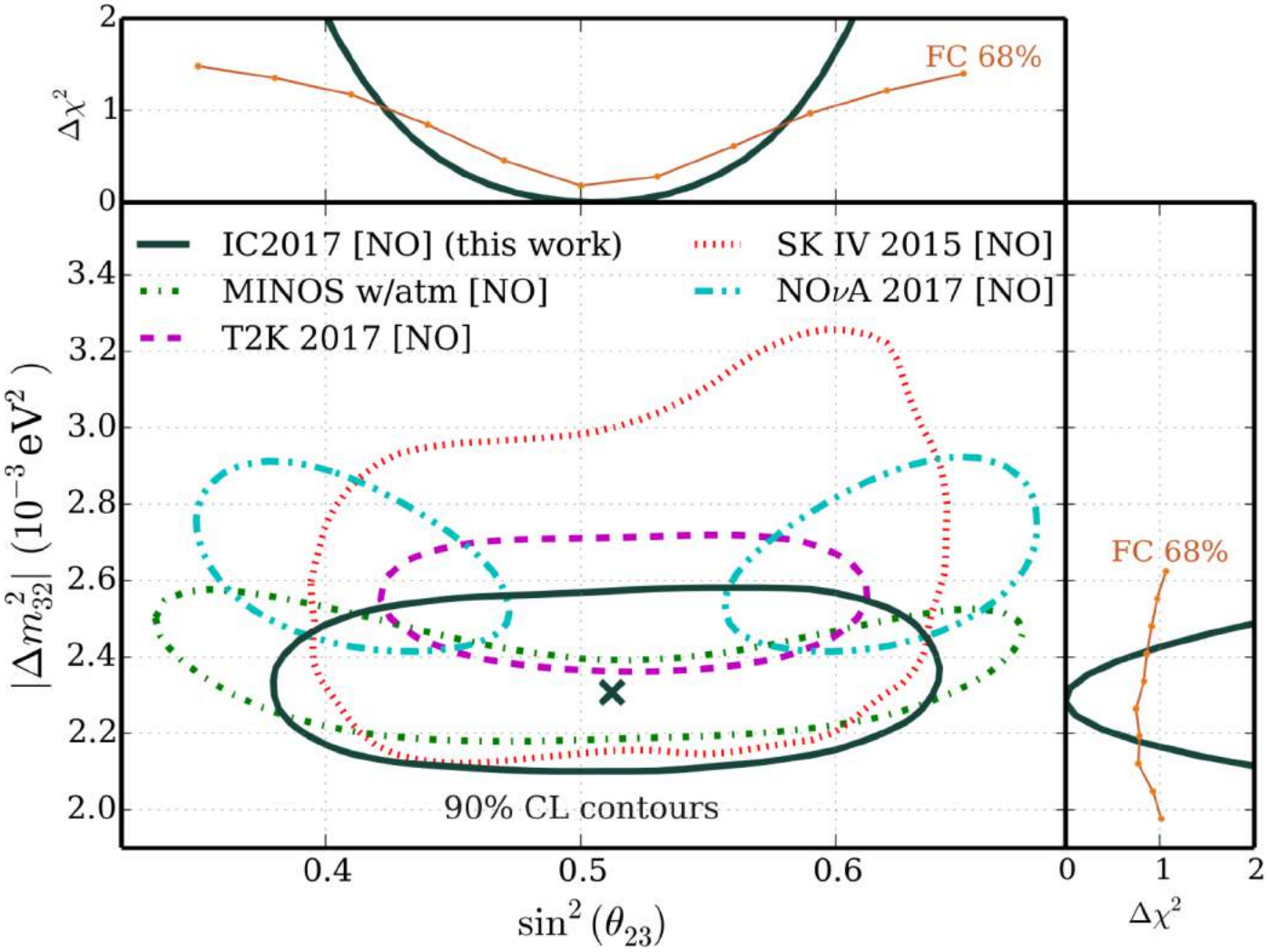
PMNS elements measured

Parke, Ross-Lonergan, arXiv:1508.05095

Experiment	Measured quantity with unitarity	Without unitarity	Normalisation
Reactor SBL ($\overline{\nu}_e \to \overline{\nu}_e$)	$4\lvert U_{e3}\rvert^2 \left(1-\lvert U_{e3}\rvert^2\right) = \sin^2 2\theta_{13}$	$4\lvert U_{e3}\rvert^2 \left(U_{e1}\rvert^2+\lvert U_{e2}\rvert^2\right)$	$\left(\lvert U_{e1}\rvert^2+\lvert U_{e2}\rvert^2+\lvert U_{e3}\rvert^2\right)^2$
Reactor LBL ($\overline{\nu}_e \to \overline{\nu}_e$)	$4\lvert U_{e1}\rvert^2\lvert U_{e2}\rvert^2 = \sin^2 2\theta_{12}\cos^4\theta_{13}$	$4\lvert U_{e1}\rvert^2\lvert U_{e2}\rvert^2$	$\left(\lvert U_{e1}\rvert^2+\lvert U_{e2}\rvert^2+\lvert U_{e3}\rvert^2\right)^2$
SNO (ϕ_{CC}/ϕ_{NC} Ratio)	$\lvert U_{e2}\rvert^2 = \cos^2\theta_{13}\sin^2\theta_{12}$	$\lvert U_{e2}\rvert^2$	$\lvert U_{e2}\rvert^2+\lvert U_{\mu 2}\rvert^2+\lvert U_{\tau 2}\rvert^2$
SK/T2K/MINOS ($\nu_\mu \to \nu_\mu$)	$4\lvert U_{\mu 3}\rvert^2\left(1-\lvert U_{\mu 3}\rvert^2\right) =$ $4\cos^2\theta_{13}\sin^2\theta_{23}\left(1-\cos^2\theta_{13}\sin^2\theta_{23}\right)$	$4\lvert U_{\mu 3}\rvert^2\left(U_{\mu 1}\rvert^2+\lvert U_{\mu 2}\rvert^2\right)$	$\left(\lvert U_{\mu 1}\rvert^2+\lvert U_{\mu 2}\rvert^2+\lvert U_{\mu 3}\rvert^2\right)^2$
T2K/MINOS ($\nu_\mu \to \nu_e$)	$4\lvert U_{e3}\rvert^2\lvert U_{\mu 3}\rvert^2 = \sin^2 2\theta_{13}\sin^2\theta_{23}$	$-4\,\mathrm{Re}\{U^*_{e3}U_{\mu 3}\left(U^*_{e1}U_{\mu 1}+U^*_{e2}U_{\mu 2}\right)\}$	$\lvert U_{e1}U^*_{\mu 1}+U_{e2}U^*_{\mu 2}+U_{e3}U^*_{\mu 3}\rvert^2$
SK/OPERA ($\nu_\mu \to \nu_\tau$)	$4\lvert U_{\mu 3}\rvert^2\lvert U_{\tau 3}\rvert^2 = \sin^2 2\theta_{23}\cos^4\theta_{13}$	$-4\,\mathrm{Re}\{U^*_{\tau 3}U_{\mu 3}\left(U^*_{\tau 1}U_{\mu 1}+U^*_{\tau 2}U_{\mu 2}\right)\}$	$\lvert U_{\mu 1}U^*_{\tau 1}+U_{\mu 2}U^*_{\tau 2}+U_{\mu 3}U^*_{\tau 3}\rvert^2$

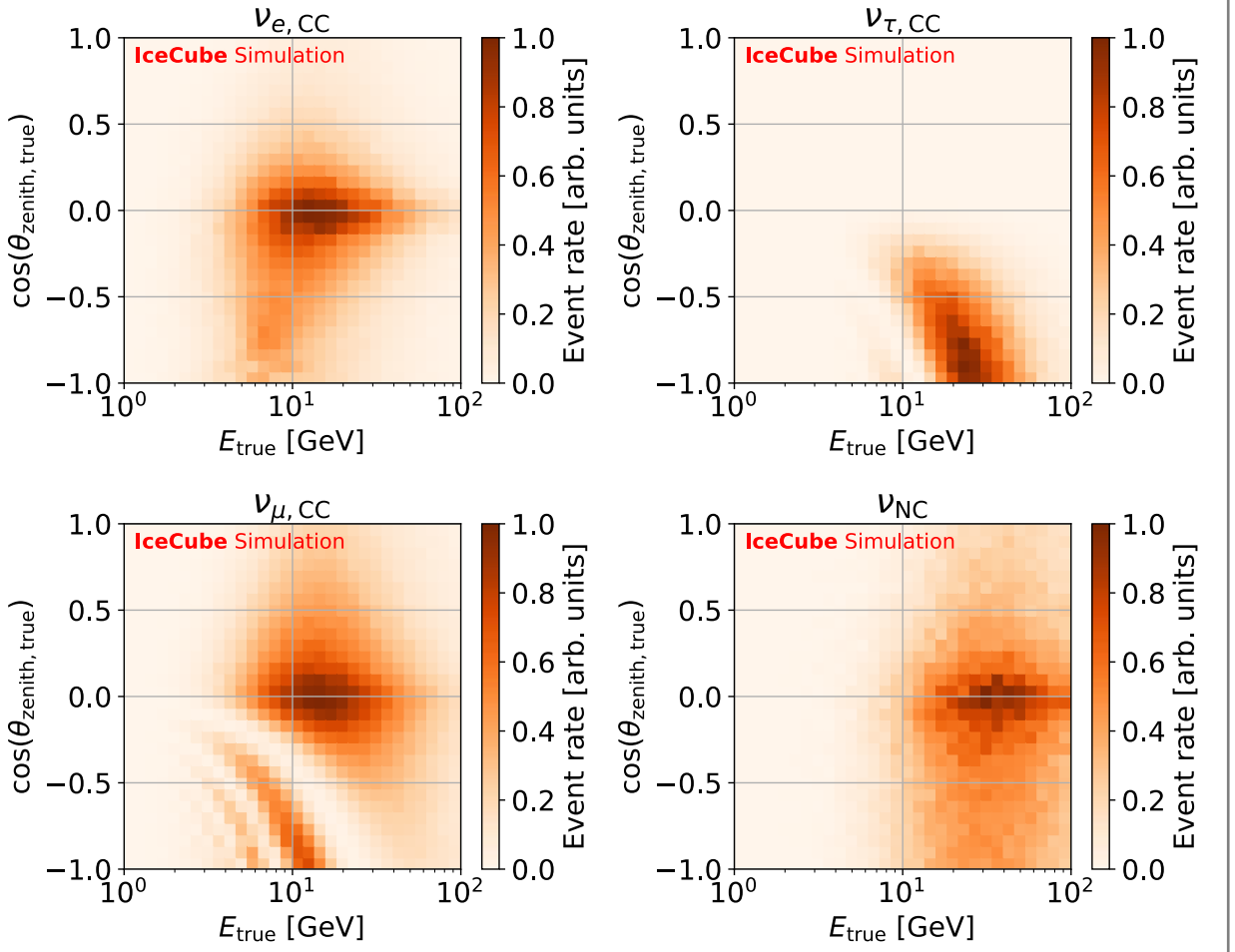
DeepCore ν_μ disappearance

- 3 year result, 2018 PRL [1707.07081]

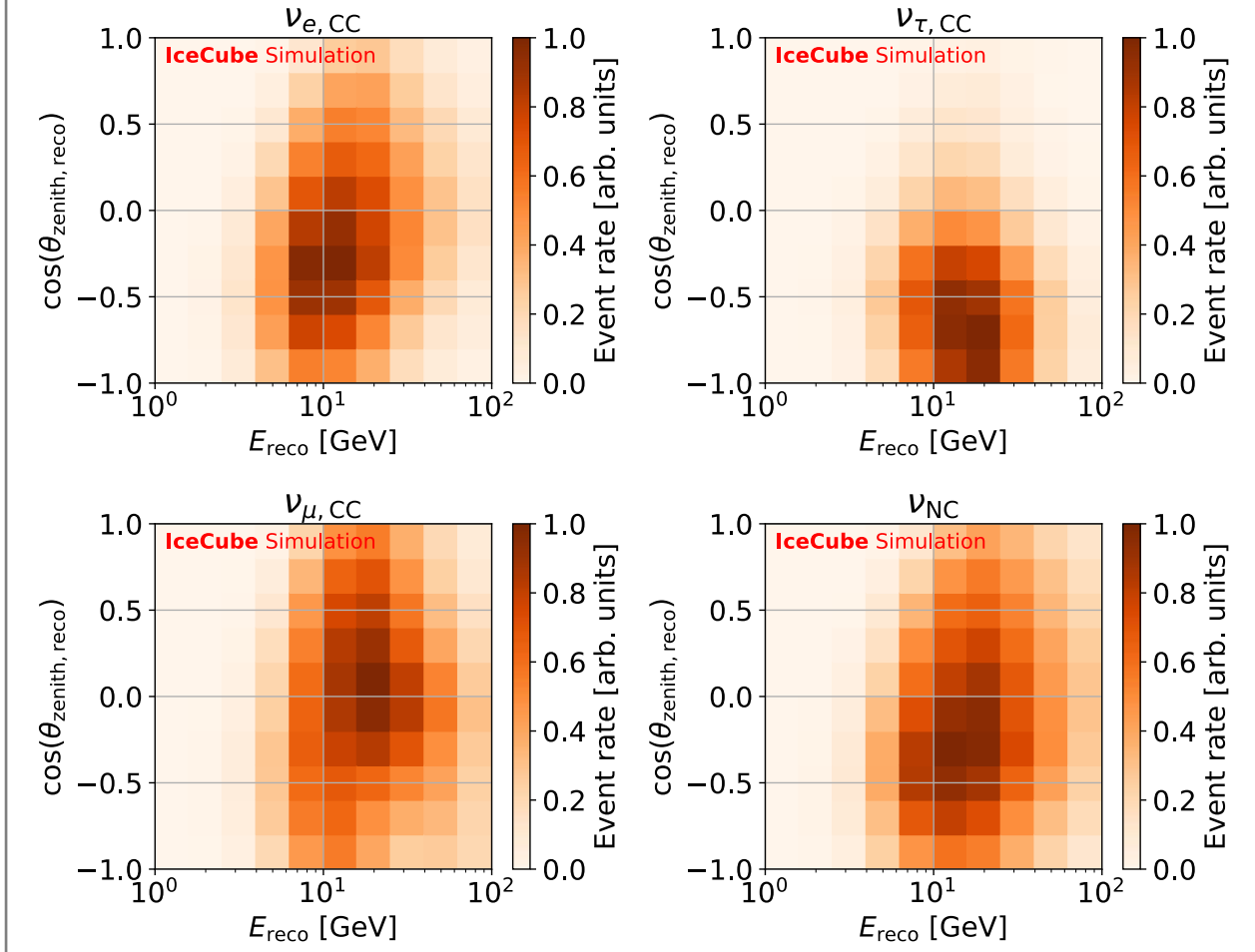


ν_τ appearance analysis templates

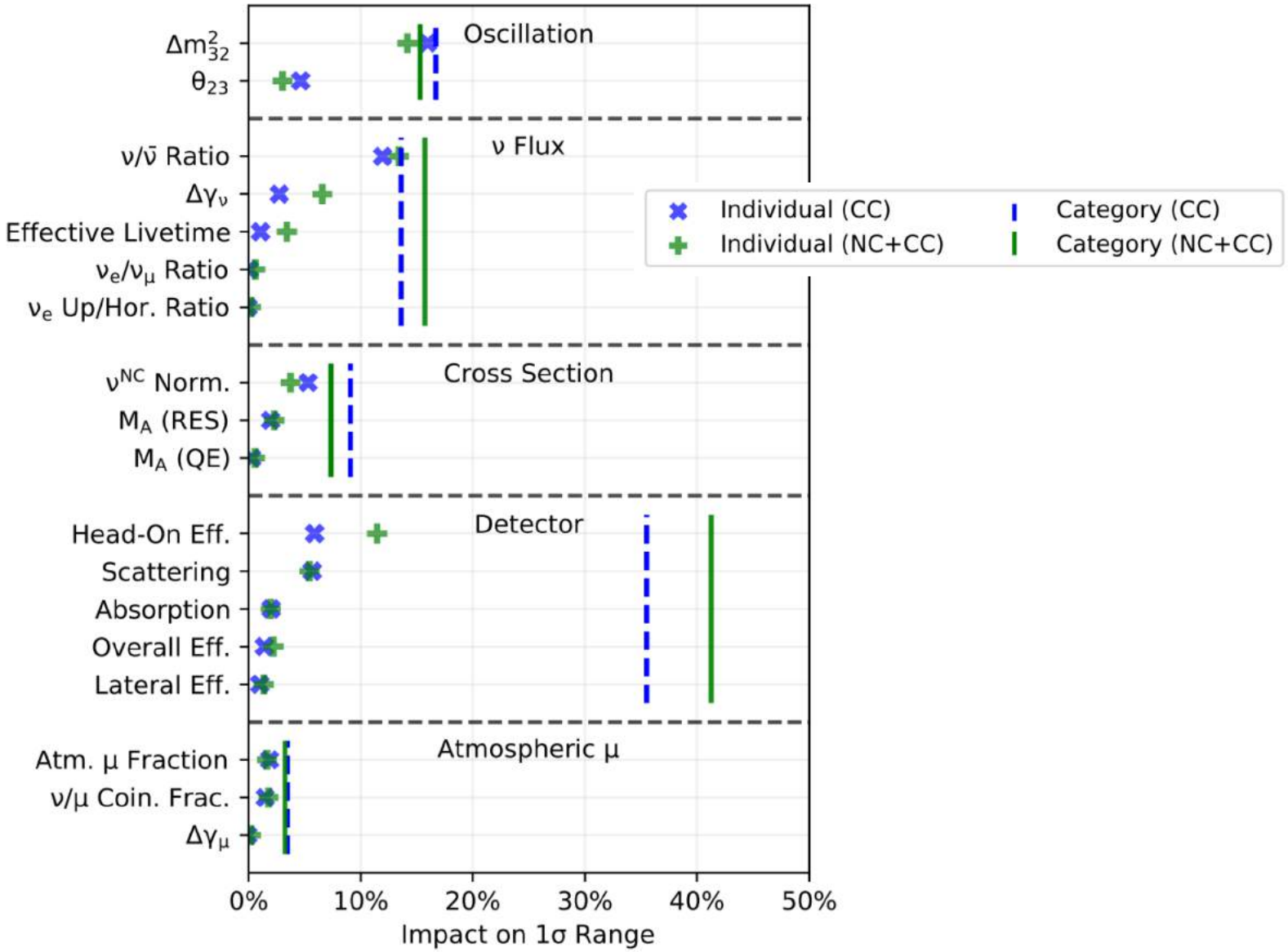
Truth parameters



Reconstructed parameters



ν_τ appearance analysis systematics



Ice/detector uncertainties