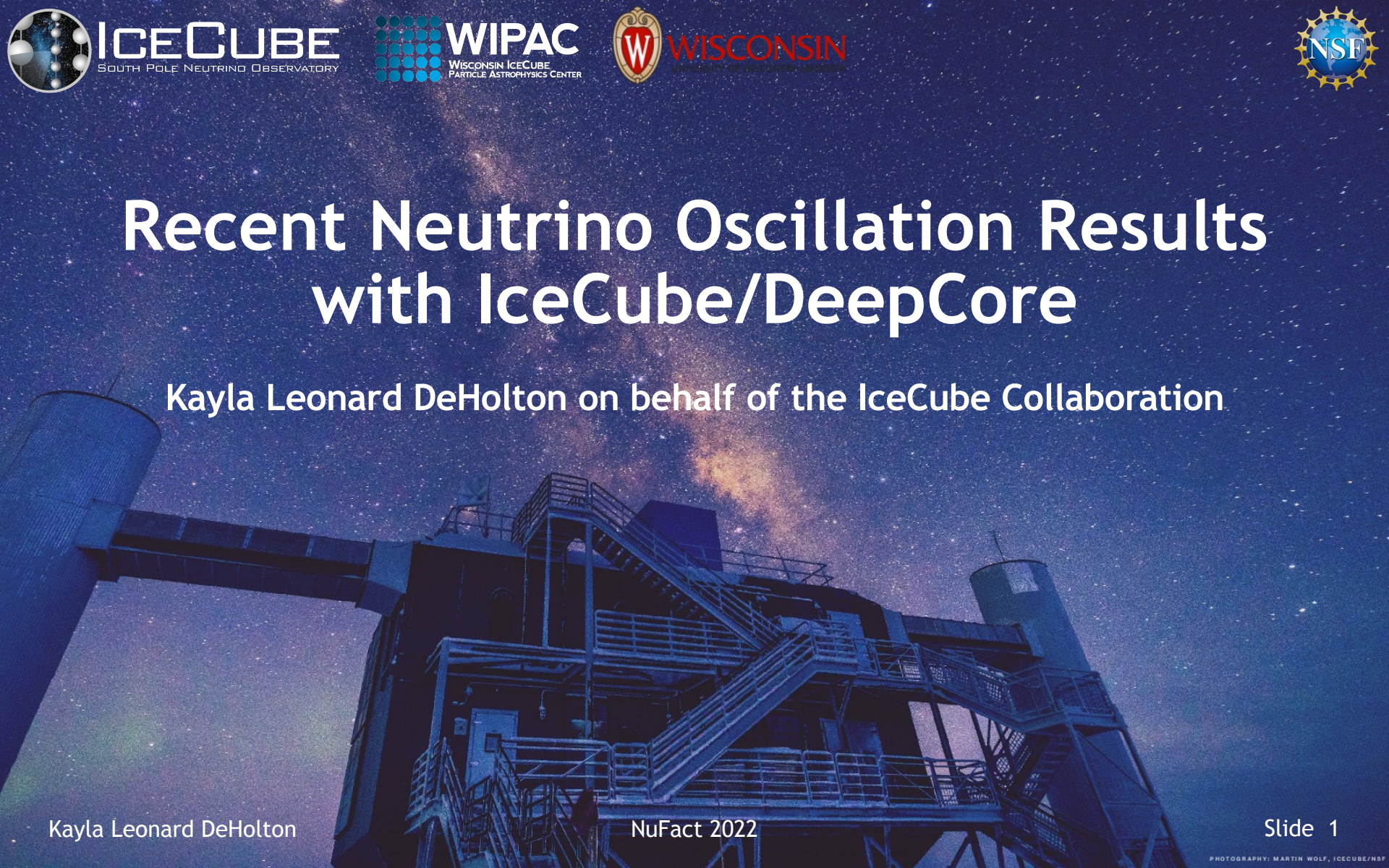
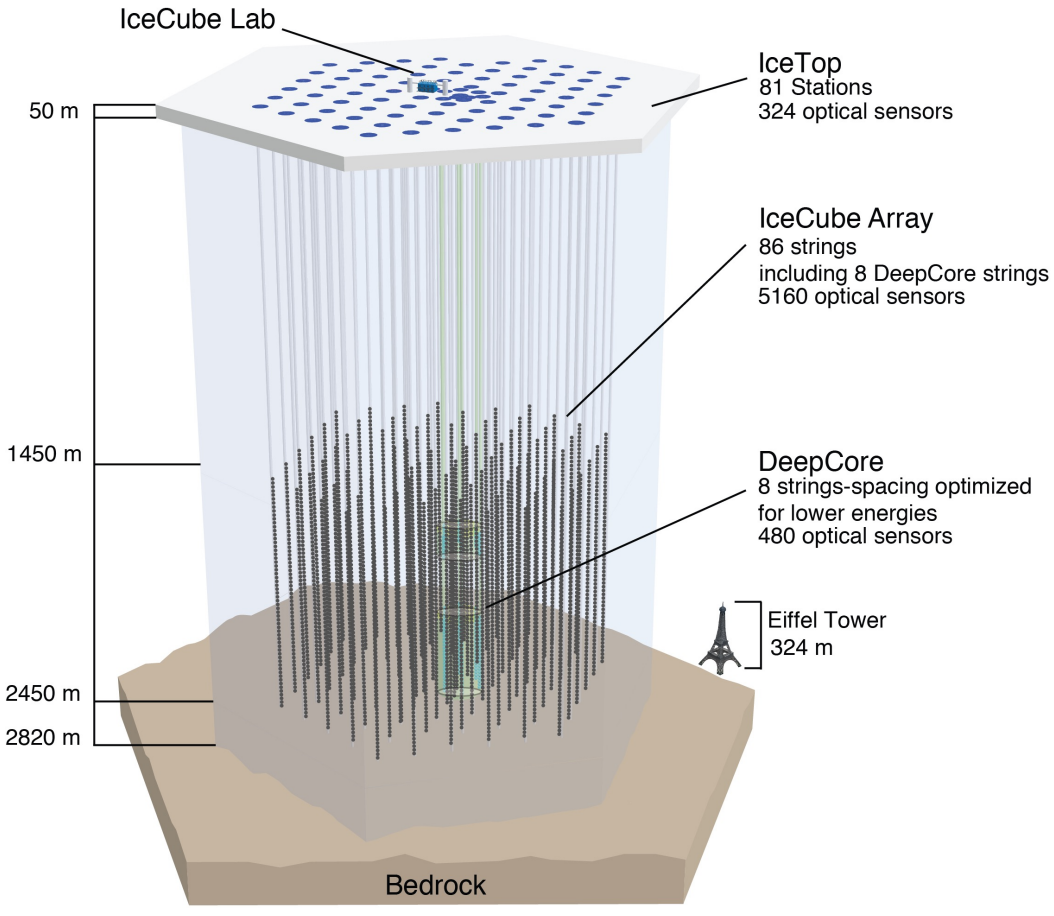
Recent Neutrino Oscillation Results with IceCube/DeepCore

Kayla Leonard DeHolton on behalf of the IceCube Collaboration



IceCube



IceCube

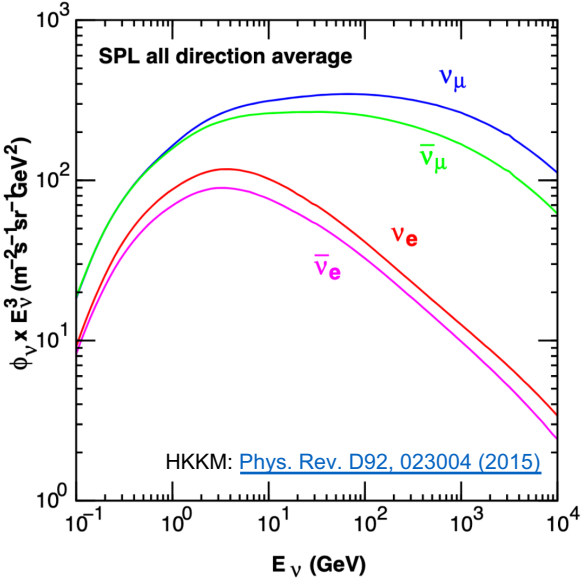
- 1 km^3 detector located at the South Pole
- 5,160 modules across 86 strings
- Detects Cherenkov light from neutrino interactions
- Optimized for TeV-PeV

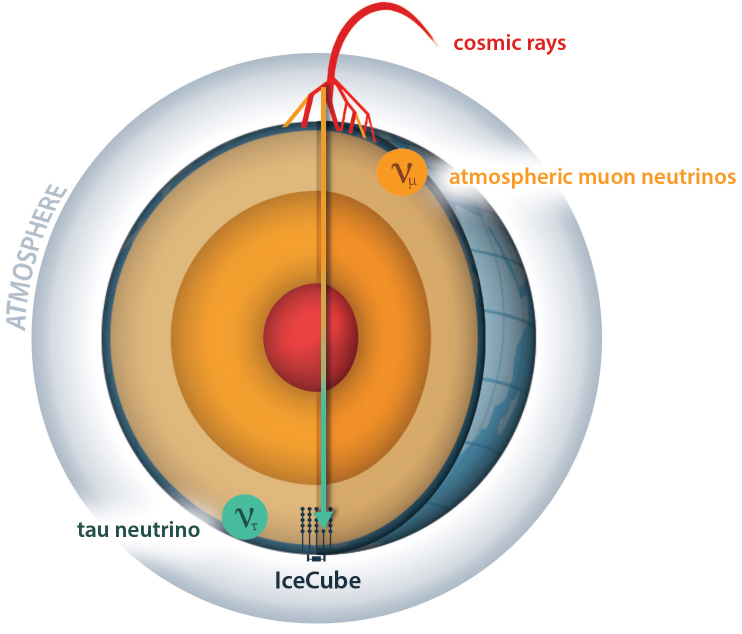
DeepCore

- 8 dedicated strings with denser spacing
- High quantum efficiency modules
- Optimized for GeV

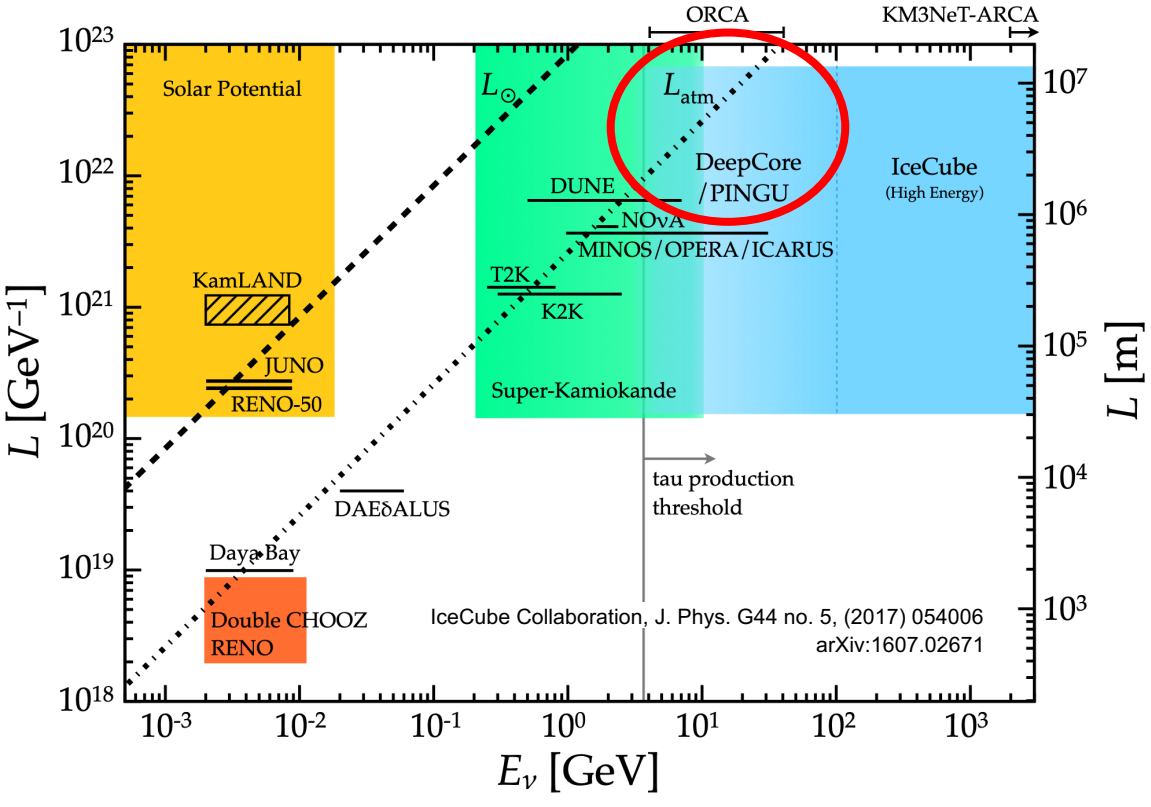
Atmospheric Neutrinos

- Neutrinos produced in cosmic ray air showers via pions and kaons
- Dominated by ν_μ , then $\overline{\nu}_\mu$, then ν_e then $\overline{\nu}_e$
- Detector can't distinguish ν versus $\overline{\nu}$, but ratio is important because of differing interactions





IceCube/DeepCore in the experimental ν landscape



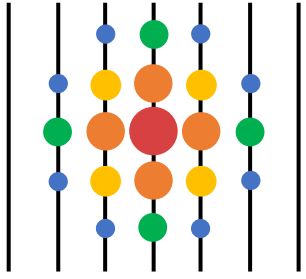
Complementarity of DeepCore and accelerator experiments

Probes the same physics but w/ different sources of systematic uncertainties:

- Energy
- Cross sections (DIS regime)
- ν production mechanisms
- Detector uncertainties
- Oscillation peak above tau production threshold

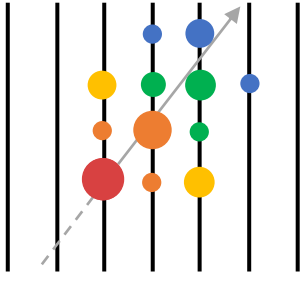
Event Signatures

Cascades



- Spherical
- NC, ν_e CC, ν_τ CC

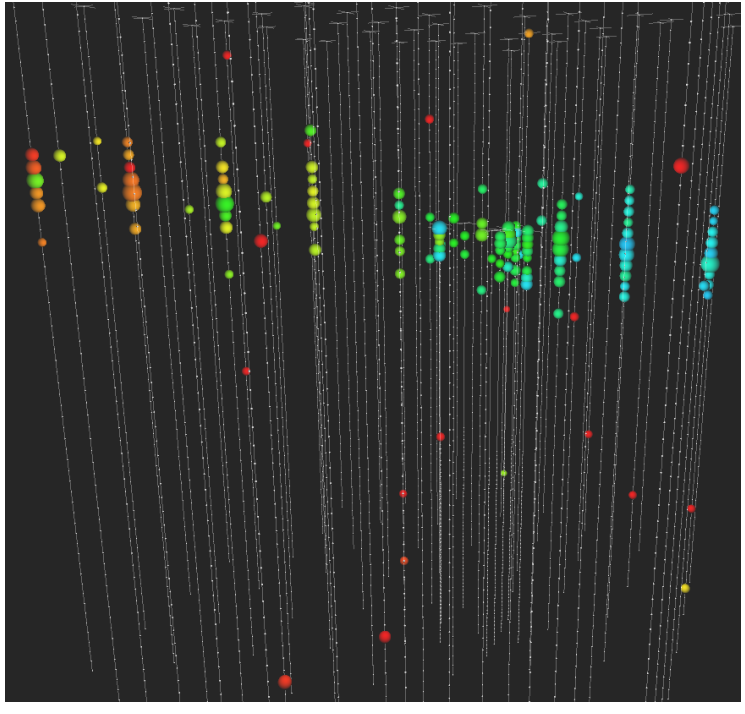
Tracks



- Elongated
- ν_μ CC

color = time
early hits
late hits

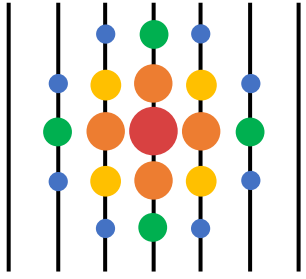
simulated 9 TeV track event



Event display courtesy of Ben Smithers

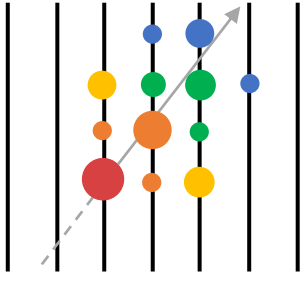
Event Signatures

Cascades



- Spherical
- NC, ν_e CC, ν_τ CC

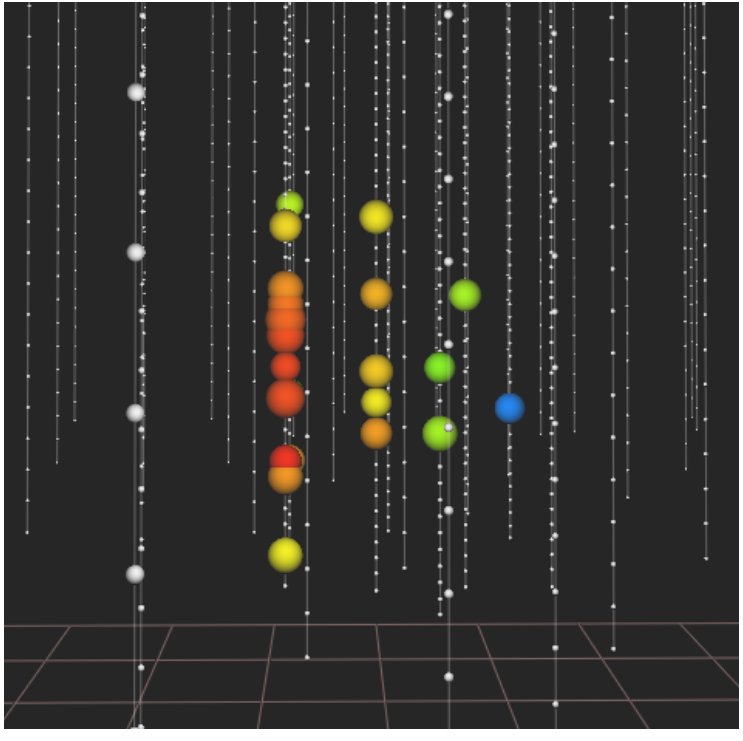
Tracks



- Elongated
- ν_μ CC

color = time
early hits
late hits

simulated 25 GeV track event

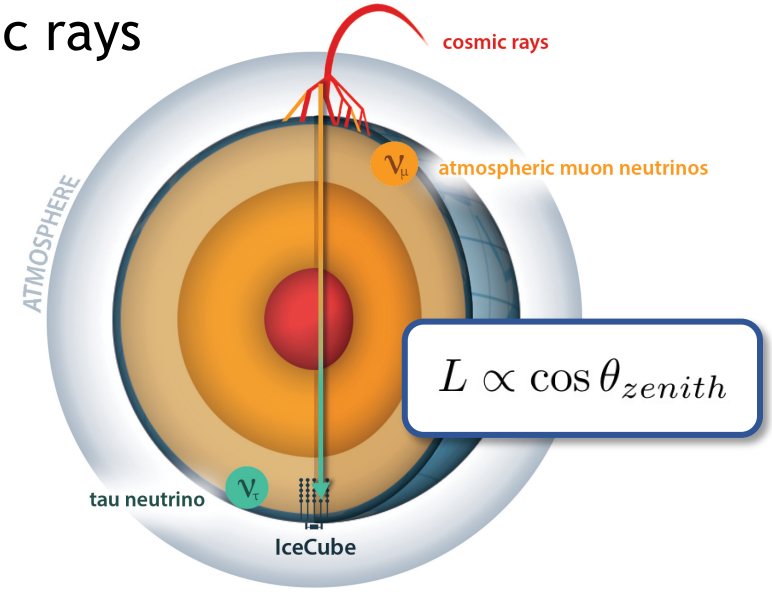


Probing oscillations with GeV neutrinos

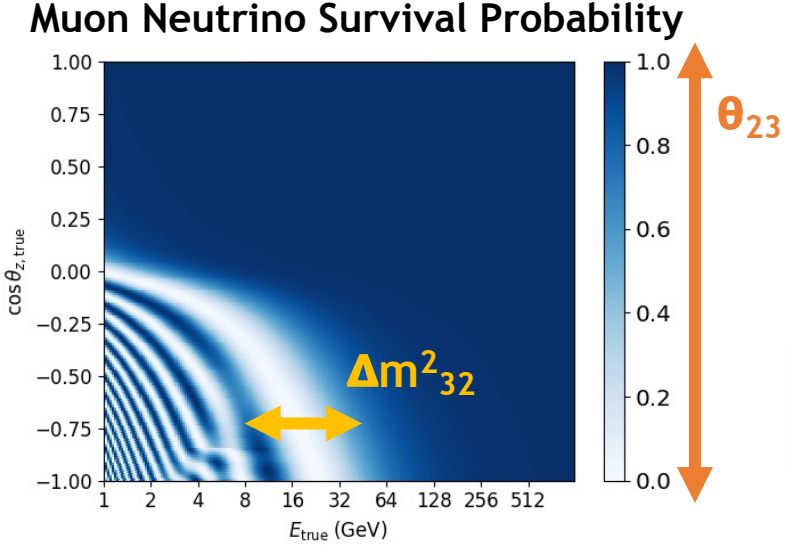
(DeepCore)

Atmospheric Neutrino Oscillations

- Atmospheric neutrinos produced by cosmic rays
- Predominantly ν_μ oscillating to ν_τ
- Oscillation maximum near 25 GeV



$$L \propto \cos\theta_{zenith}$$



$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2\left(1.27 \frac{\Delta m^2_{32} L}{E}\right)$$

Current Generation Analyses

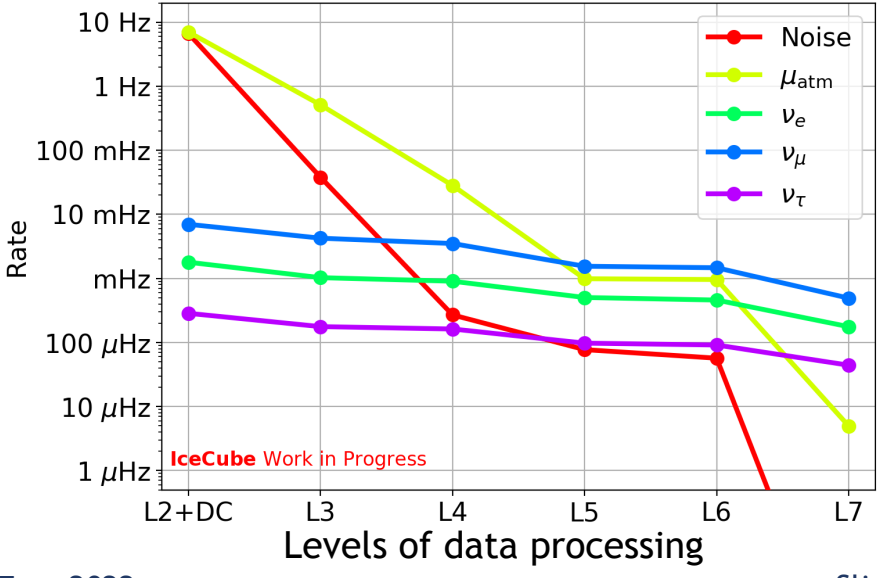
- New **event selection / background rejection** to suppress backgrounds by 6+ orders of magnitude

  → PoS(NuFact2021)062

- Improved treatment of many **systematic uncertainties**
- New **reconstruction** and **particle id**

  → arXiv:2203.02303

- More years of **data**

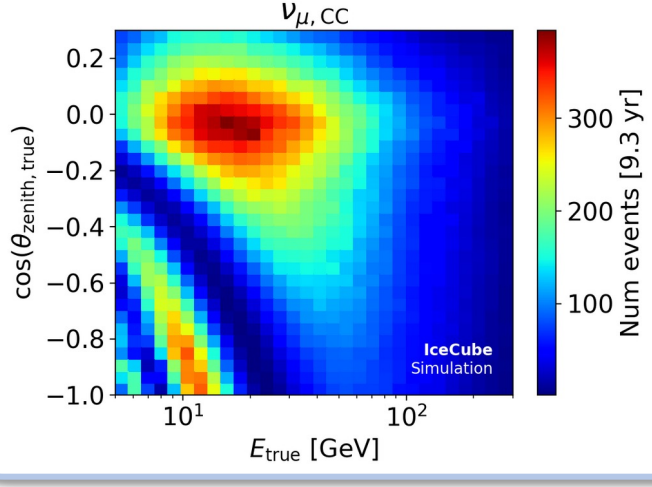


Typical Analysis Procedure

- Simulate flux + oscillations + cross sections + detector response
- Perform a binned analysis varying physics & nuisance parameters in templates

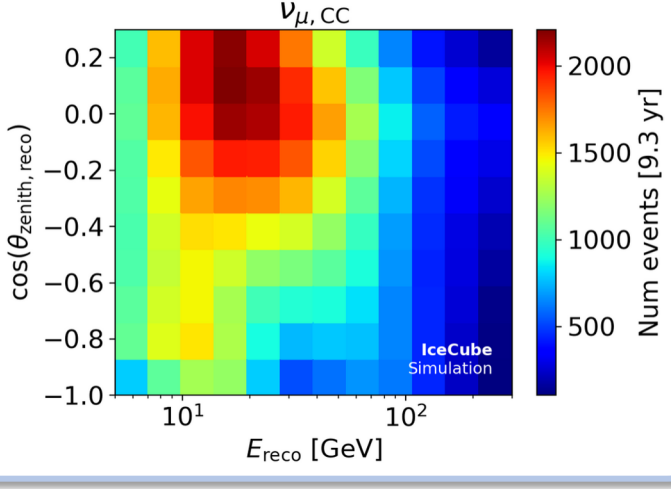
True

Oscillation peaks and valleys are visible in truth level information



Reconstructed

Smeared out by detector resolution and finite analysis binning



Systematic uncertainties considered

- **Flux uncertainties**
  - Cosmic ray spectrum
  - Pion & Kaon production uncertainties

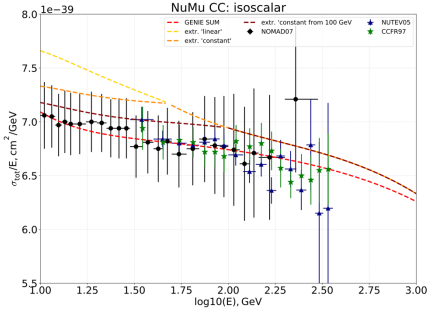
E_i (GeV)	Pions			Kaons		
<8	10%		30%	40%		
8–15	30%	10%	30%	40%		
15–30	30	10 5%	10%	30	20 10%	
30–500	30	15%		40	30%	
>500	30	15%+Energy dep.		40	30%+Energy dep.	

0 0.5 x_{LAB} 1 0 0.5 x_{LAB} 1

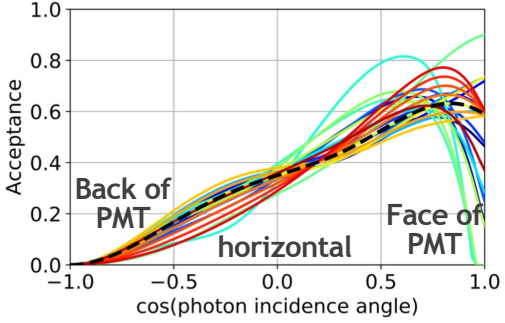
Barr et al, Phys. Rev. D 74, 094009

- **Cross sections**
  - Axial mass uncertainties for QE and resonance events
  - DIS **σ** transformation between GENIE and CSMS

JHEP **08**, 042 (2011).
arXiv:1106.3723



- **Detector and Ice Properties**
  - Improved treatment for modeling the optical properties of ice layers and refrozen drill column
  - PMT charge calibration



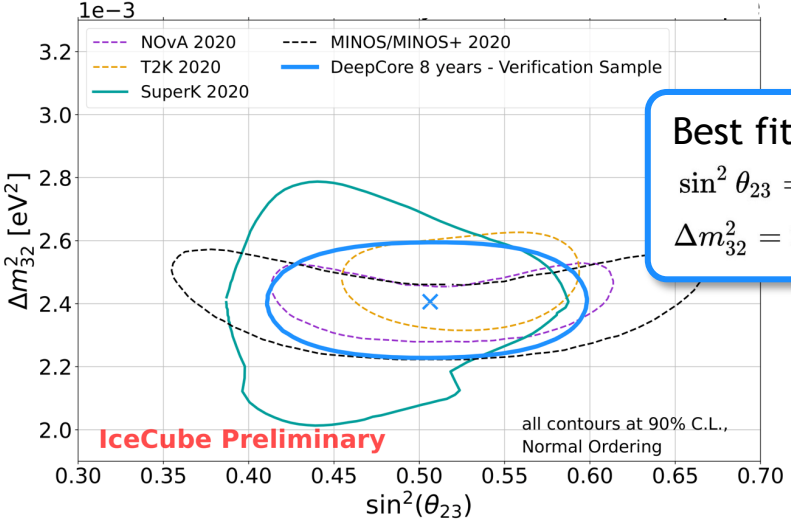
→ In total, about **40** systematic parameters are studied; approx. half are included as nuisance parameters in fit

Current Generation Samples / Analyses

Sub-sample	Full Sample
High quality events	High statistical power
~20k events	~200k events
Fast reconstructions • separate recos for energy and direction/vertex • can only be applied to certain high-quality events	Full 8d reconstruction • energy, direction, vertex fit simultaneously • can be applied to almost any event
Results available	**In progress**

Latest measurement of oscillation parameters

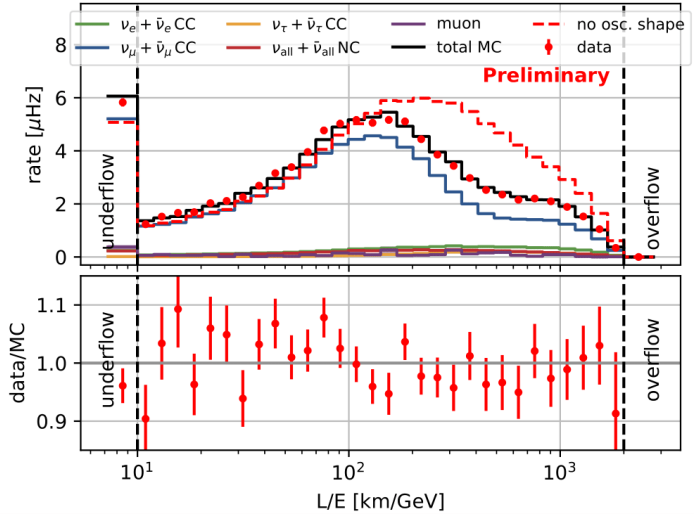
- Sub-sample of ~10% of full data set; events with lots of direct, unscattered light
  - Less susceptible to detector-related ice systematic uncertainty
- In agreement with other global neutrino experiments



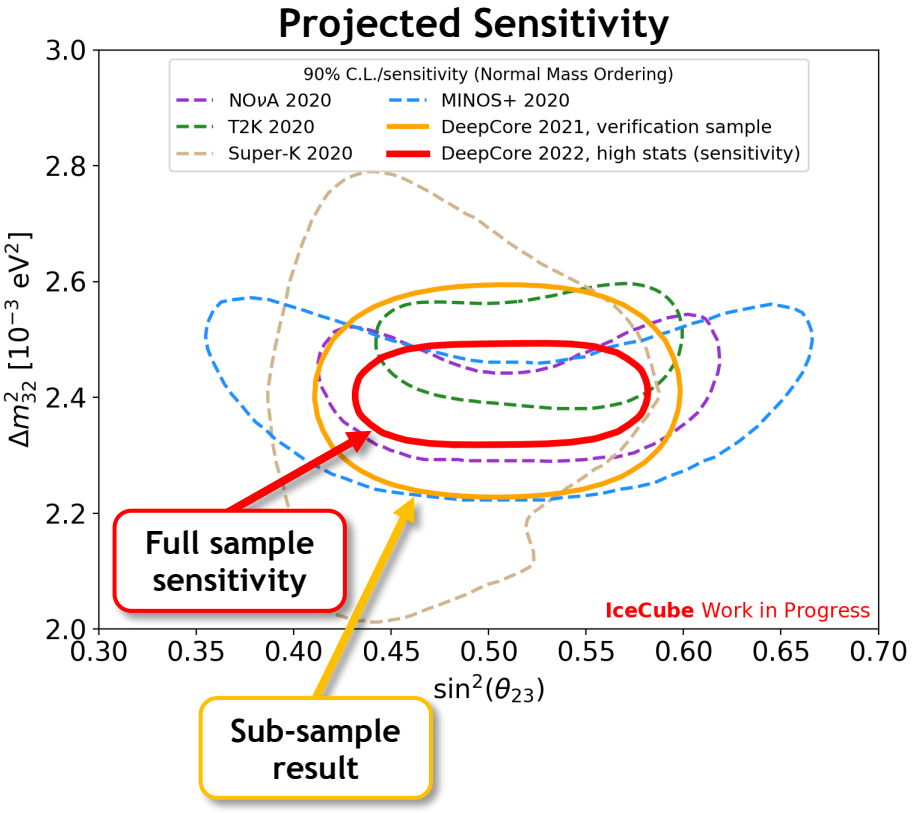
Best fit point result:

$\sin^2\theta_{23} = 0.505^{+0.051}_{-0.050}$

$\Delta m^2_{32} = 2.41^{+0.084}_{-0.084} \times 10^{-3} eV^2$



Upcoming measurement w/ full statistical power



- ~200,000 events in sample
- 99% neutrino purity
- Expected sensitivity is competitive with long baseline accelerators
- Complementary to accelerator measurements
  - probes higher energies
  - deep inelastic scattering regime
  - above tau lepton production threshold for ν_τ CC
  - different systematics at production and detection

Additional 3ν analyses in progress

- Atm. oscillation measurement using a CNN reconstruction
  → *See talk later in the week by Shiqi Yu*

WG1
Th. 2:42 PM
S. Yu

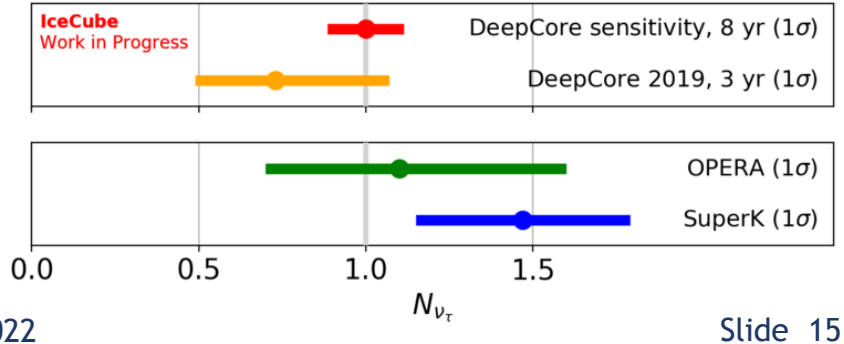
- Neutrino mass ordering
  → *See talk later in the week by Maria Prado*

WG1
Fri. 11:42AM
M. Prado

- Tau Neutrino Appearance
  - DeepCore is above the tau lepton production threshold for ν_τ CC
  - ν_τ appearance analysis fits a separate normalization N_{ν_τ}
  - Expect a world leading measurement of the tau neutrino normalization

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$|U_{e3}|^2 + |U_{\mu 3}|^2 + |U_{\tau 3}|^2 = 1$$



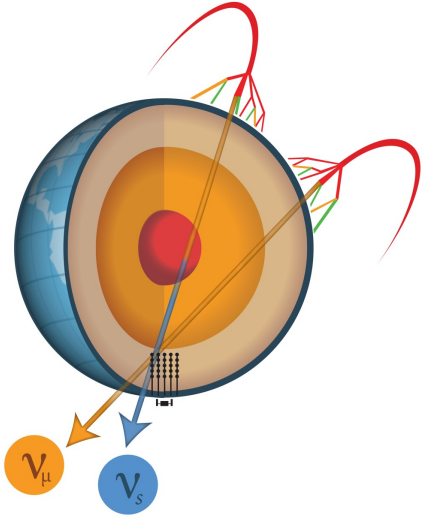
Probing oscillations with TeV neutrinos

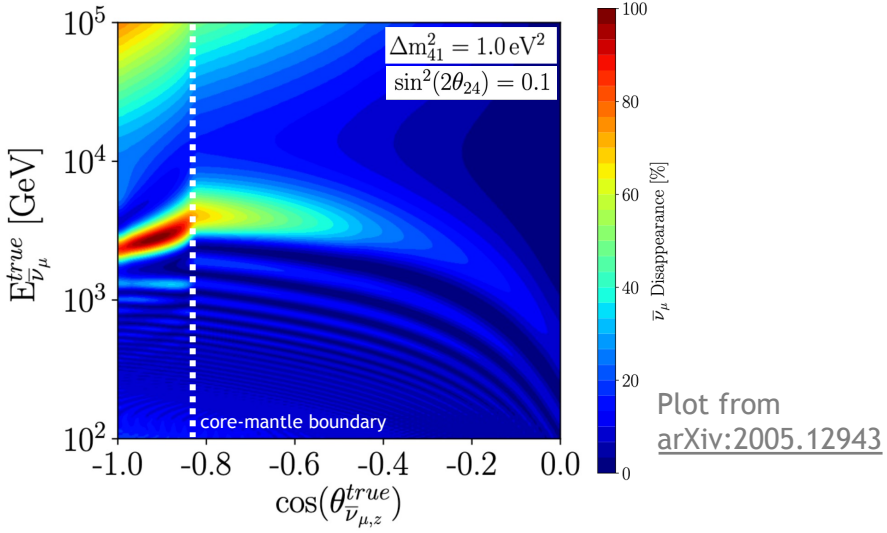
(IceCube)

High Energy searches for matter-enhanced oscillations

- TeV sample of $\boldsymbol{\nu_{\mu,cc}}$ and $\boldsymbol{\overline{\nu_{\mu,cc}}}$
- Matter effects are enhanced for neutrinos passing through the core
- Originally developed for a 3+1 eV-scale sterile neutrino search
- Additional analyses to study neutrino decay, NSI, and more

WG5
Tue. 4:54 PM
A. Garcia Soto

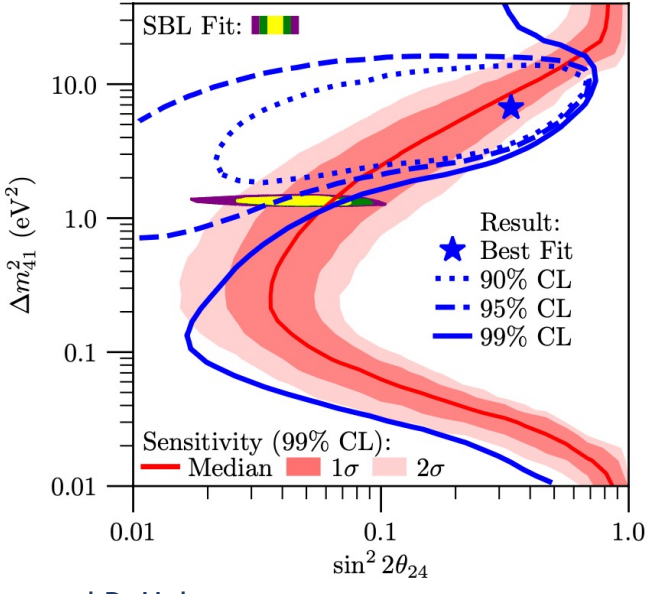


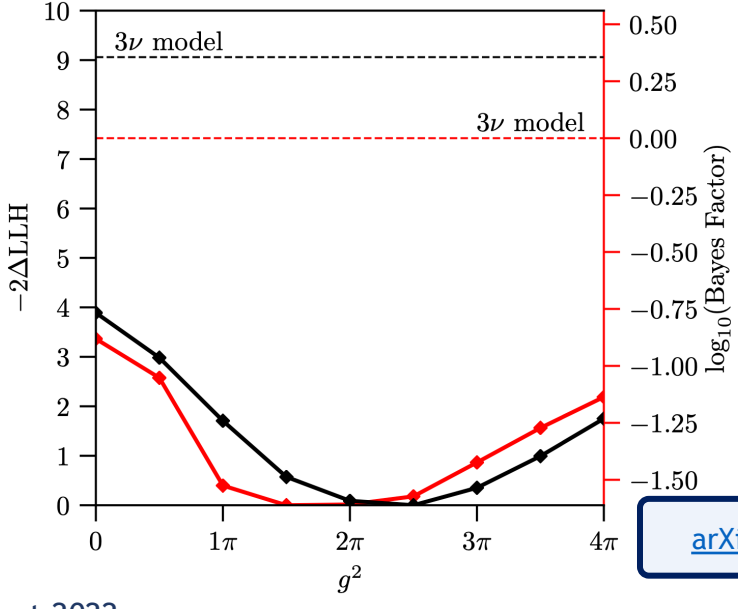


Plot from
arXiv:2005.12943

Unstable Sterile Neutrinos (3+1+decay)

- Allowing ν_4 to decay introduces a dampening of oscillations
- Coupling constant g^2 related to the lifetime of ν_4 through $\tau = \frac{16\pi}{g^2 m_4}$
- Best fit at $g^2 = 2.5\pi$ ($\tau \sim 10^{-15}$ s)
- No evidence it is preferred over 3ν model; p-value ~3%





arXiv:2204.00612

Non-standard Interactions (NSI)

- Standard matter potential for neutrinos traversing Earth arises from interactions with electrons (MSW effect)
- Matter potential is modified by introducing non-standard interactions

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

DeepCore analysis

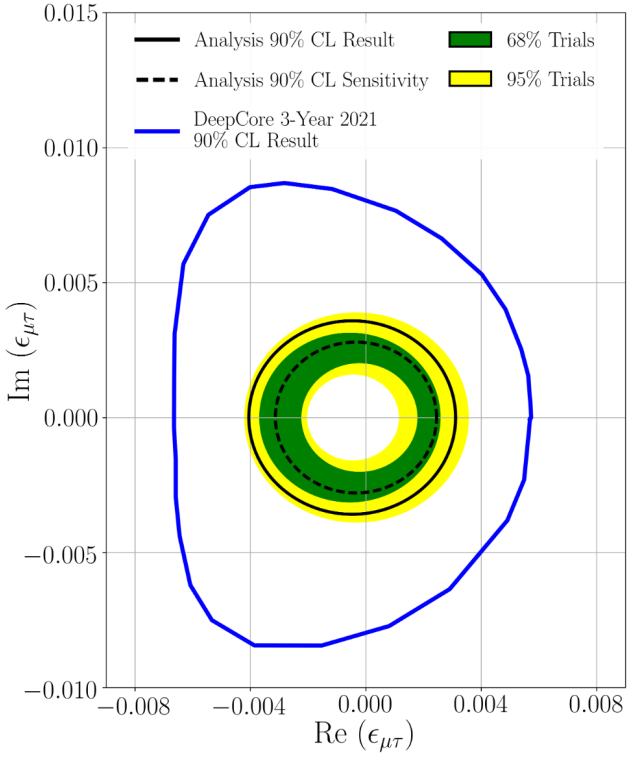
- Lower energy sample (5-100 GeV)
- All flavors
- PRD 104, 072006; arXiv:2106.07755

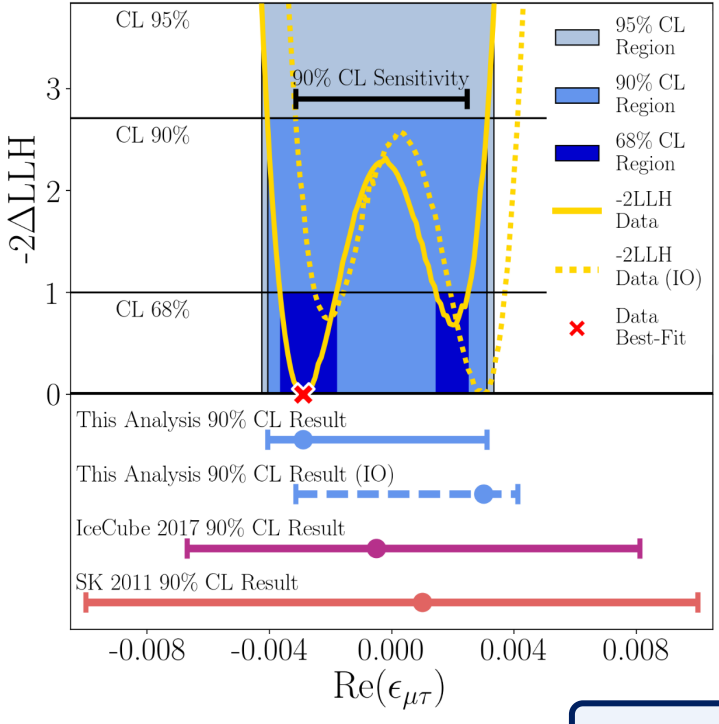
IceCube analysis

- Higher energy sample (500 GeV - 10 TeV)
- Tracks only (ν_μ CC)
- PRL 129, 011804; arXiv:2201.03566

Non-standard Interactions (NSI)

- Recent constraints on $\epsilon_{\mu\tau}$:





arXiv:2201.03566

Beyond Oscillations

Inelasticity for ν_μ CC DIS interactions

- The inelasticity *y* can be determined from the fraction of energy that goes into the cascade/shower portion (rather than the secondary muon track)

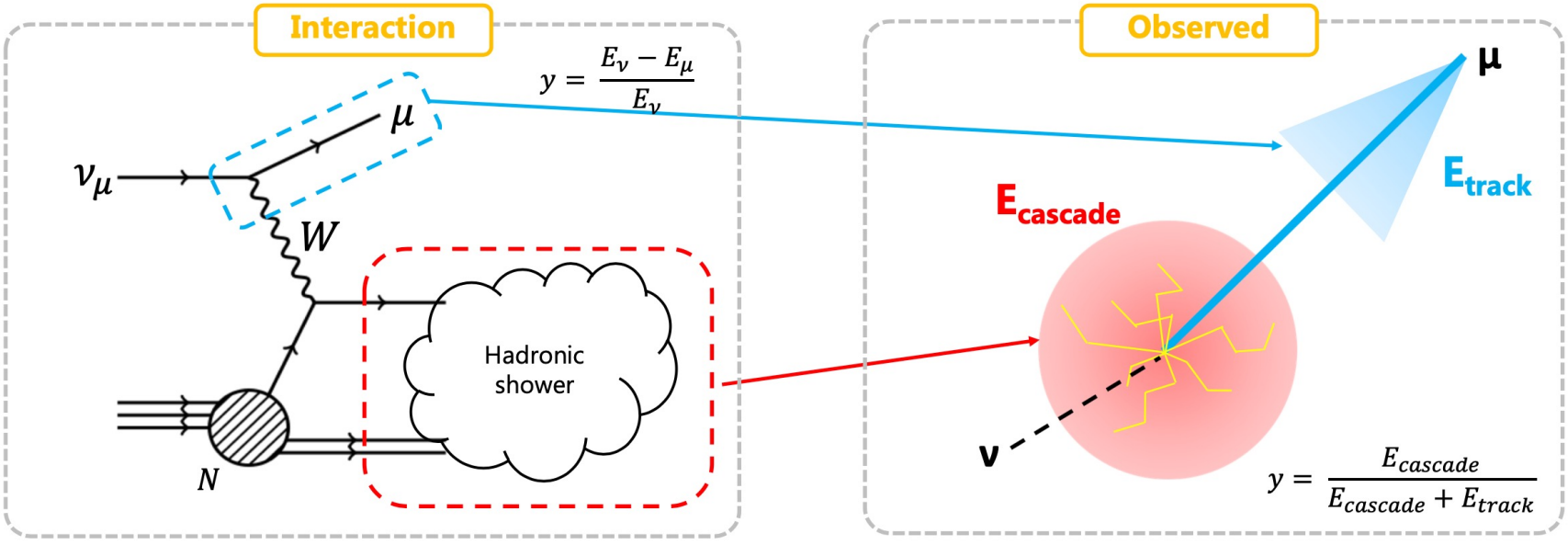
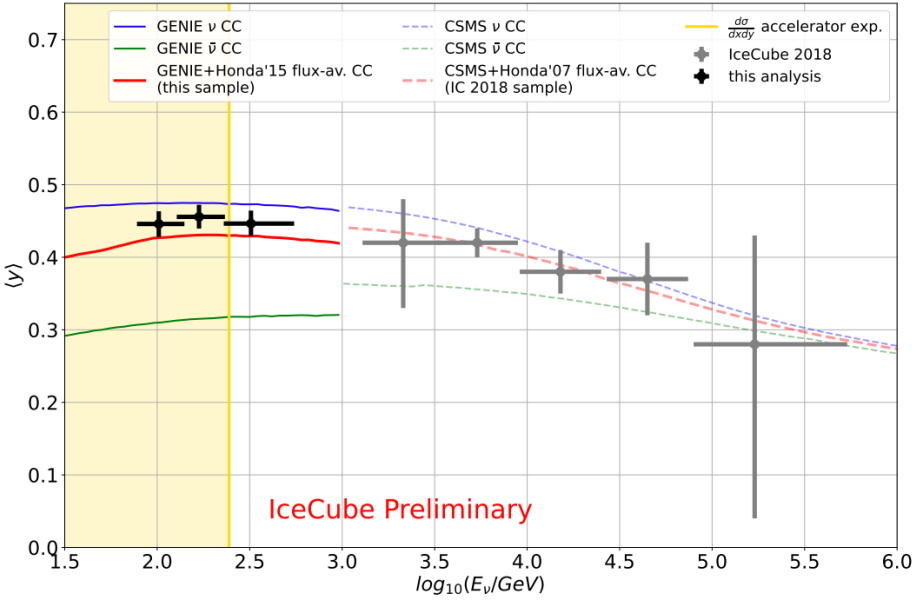
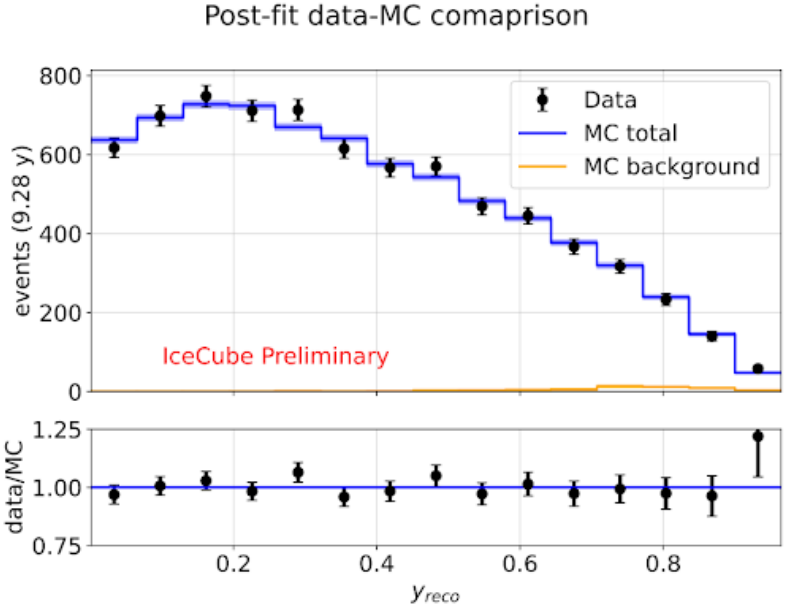


Diagram courtesy of Tom Stuttard

Flux Averaged Inelasticity for $(\overline{\nu}_\mu)$ CC

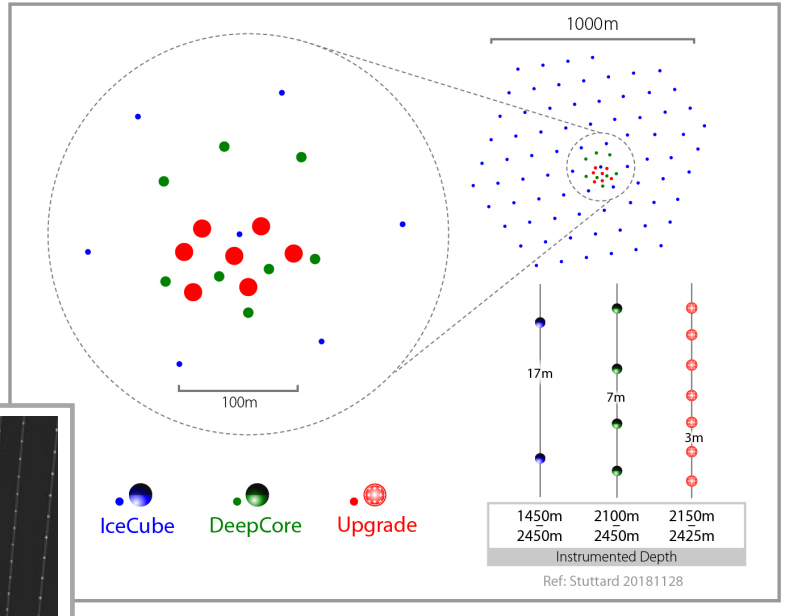
- Preference towards higher values of <y>
  - Multiple interpretations: $\nu/\overline{\nu}$ flux ratio, preference for CSMS-like, etc.

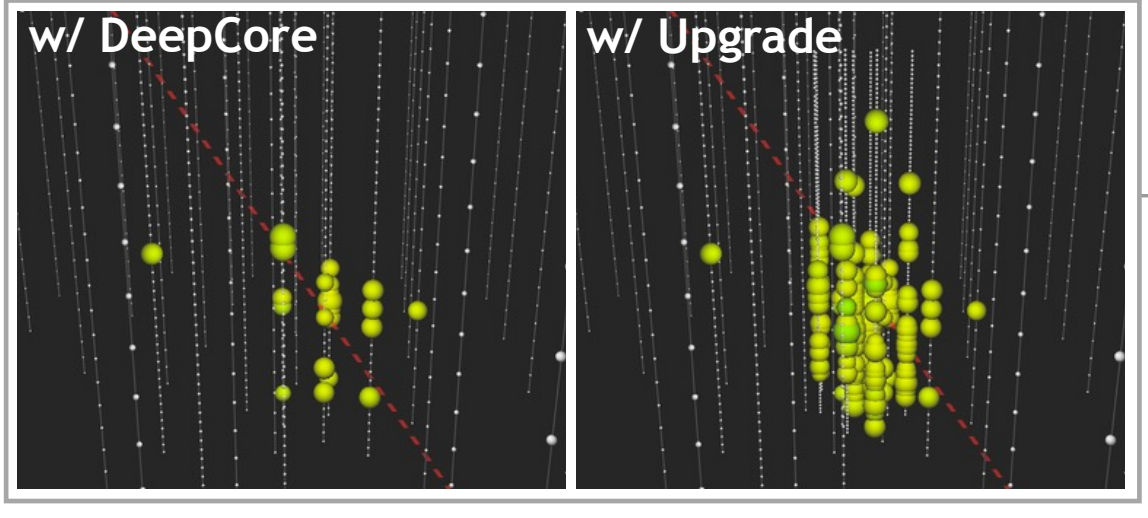




IceCube Upgrade

- Denser infill
- Multiple PMTs per module
- Lower energy threshold & improved resolution
- Already funded. Deployment scheduled for 2025-26.





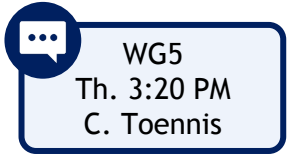
WG6
Tue. 3:00 PM
M. DuVernois

WG6
Fri. 2:38 PM
W. Kang

More IceCube work to check out this week:

WG5 – BSM

- Dark Matter searches



WG7 – Inclusion, Diversity, Equity, Education, & Outreach

- DEI in Masterclasses

Conclusions & Outlook

- IceCube and DeepCore provide a unique view of oscillations to complement long baseline experiments
  - Higher energies, DIS regime, different production/detection mechanisms
- Broad neutrino physics scope spanning GeV and TeV energies
  - Standard oscillations, NSI, sterile neutrinos, dark matter, scattering
  - Current datasets are being used for more analyses in progress than could be mentioned here
- Next generation detector rapidly approaching (Deployment in 2025-26)
  - IceCube Upgrade will expand GeV capabilities and improve calibration

Thank you!