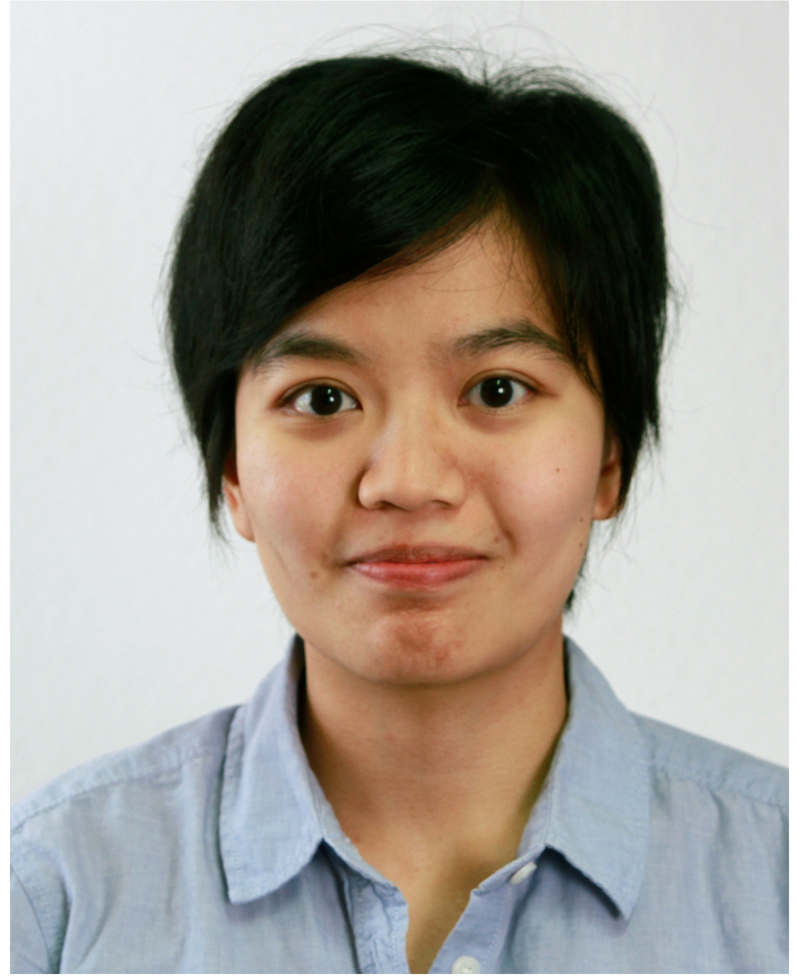
Atmospheric Neutrino Oscillation Experiments



Wing Yan Ma (DESY)
for the IceCube Collaboration

FPCP 2021 (Shanghai, China)
9th June 2021

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

ICECUBE

DESY.

Outline

> Neutrino oscillations and atmospheric neutrinos
> Status of 3-flavour neutrino oscillation studies using atmospheric neutrinos
> BSM measurements with atmospheric neutrinos
> Future prospects

Neutrino Oscillations

> Mixing matrix in standard 3-neutrino mixing framework:

$s_{ij} = sin\theta_{ij}$

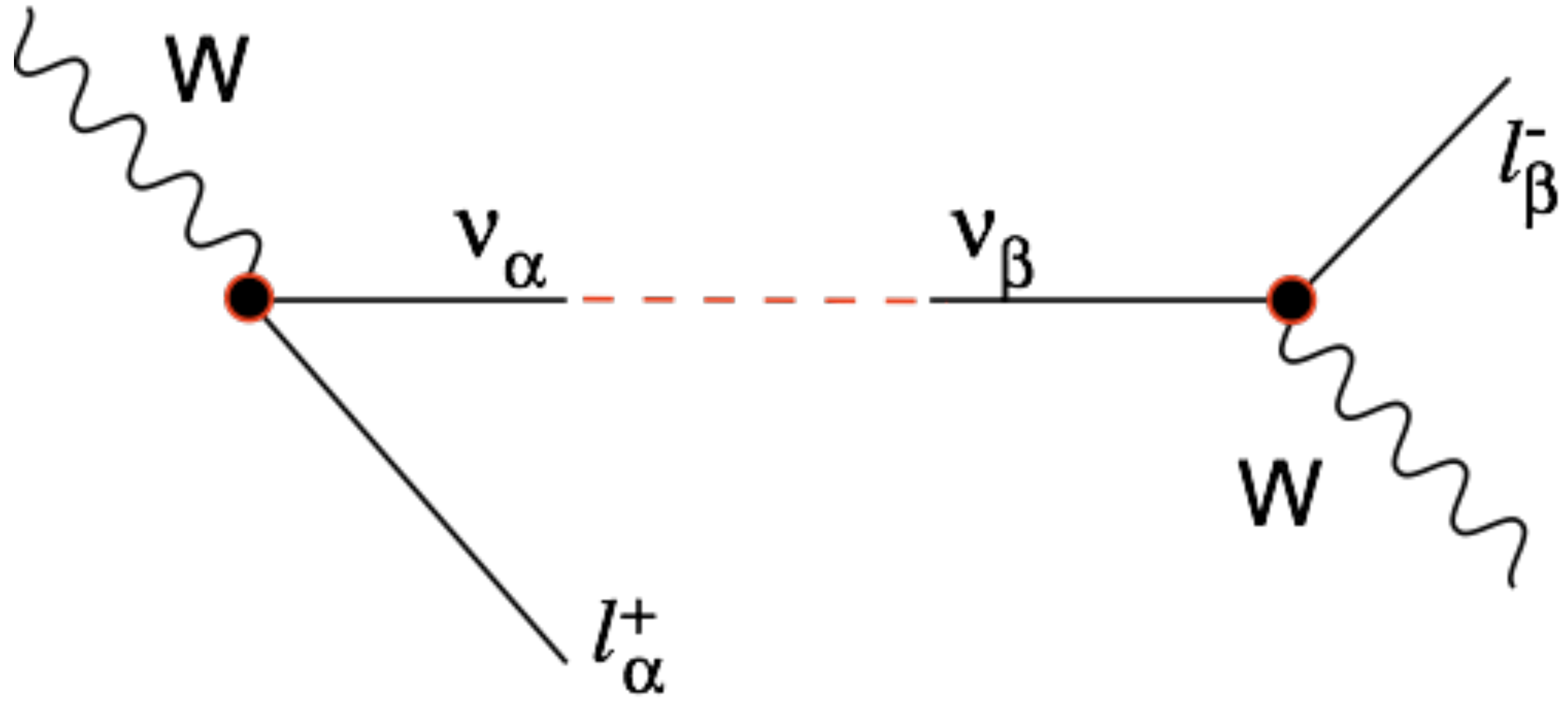
$c_{ij} = cos\theta_{ij}$

$$U = \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{Cross-mixing}} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmospheric}} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{pmatrix}}_{\text{Majorana}}$$

- > 3 mixing angles θ_{12}, θ_{13}, θ_{23} and complex phase δ_{CP} (+α_1, α_2 if neutrinos are Majorana)
- > Non-zero δ_{CP} would give $P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$

> Mixing amplitude: $A_{\nu_\alpha \to \nu_\beta} = \sum_{i=1}^{N_\nu} U^*_{\alpha i} e^{-i(E_i t - p_i L)} U_{\beta i}$

> Oscillation probability: $P_{\nu_\alpha \to \nu_\beta} \approx \boxed{sin^2(2\theta)}.\ sin^2\left(\boxed{\frac{1.267\Delta m^2(eV^2)L(km)}{E(GeV)}}\right)$



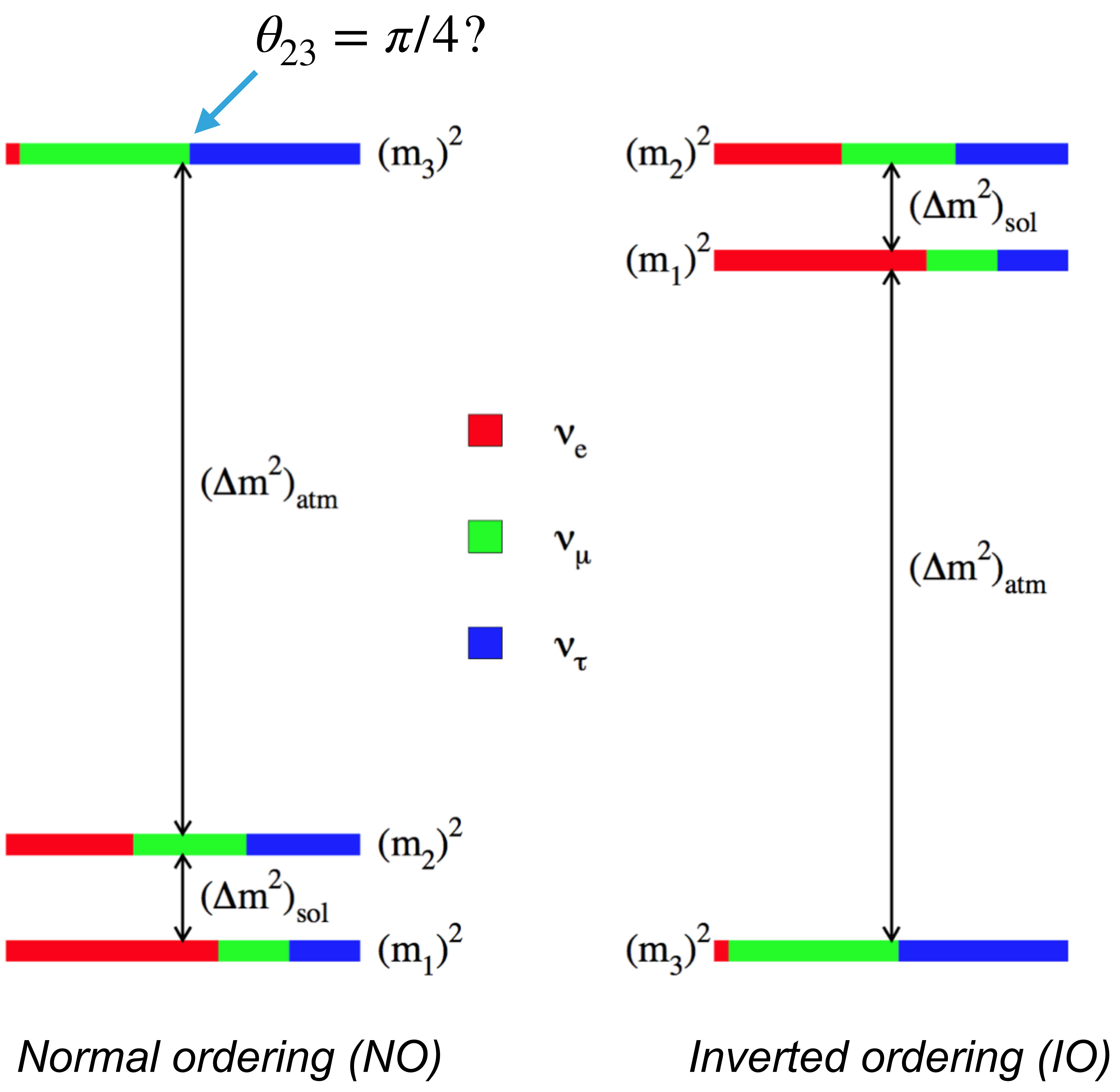
> Amplitude of oscillations depends on θ

> Frequency of oscillations depends on Δm^2, L, E

Neutrino Oscillations

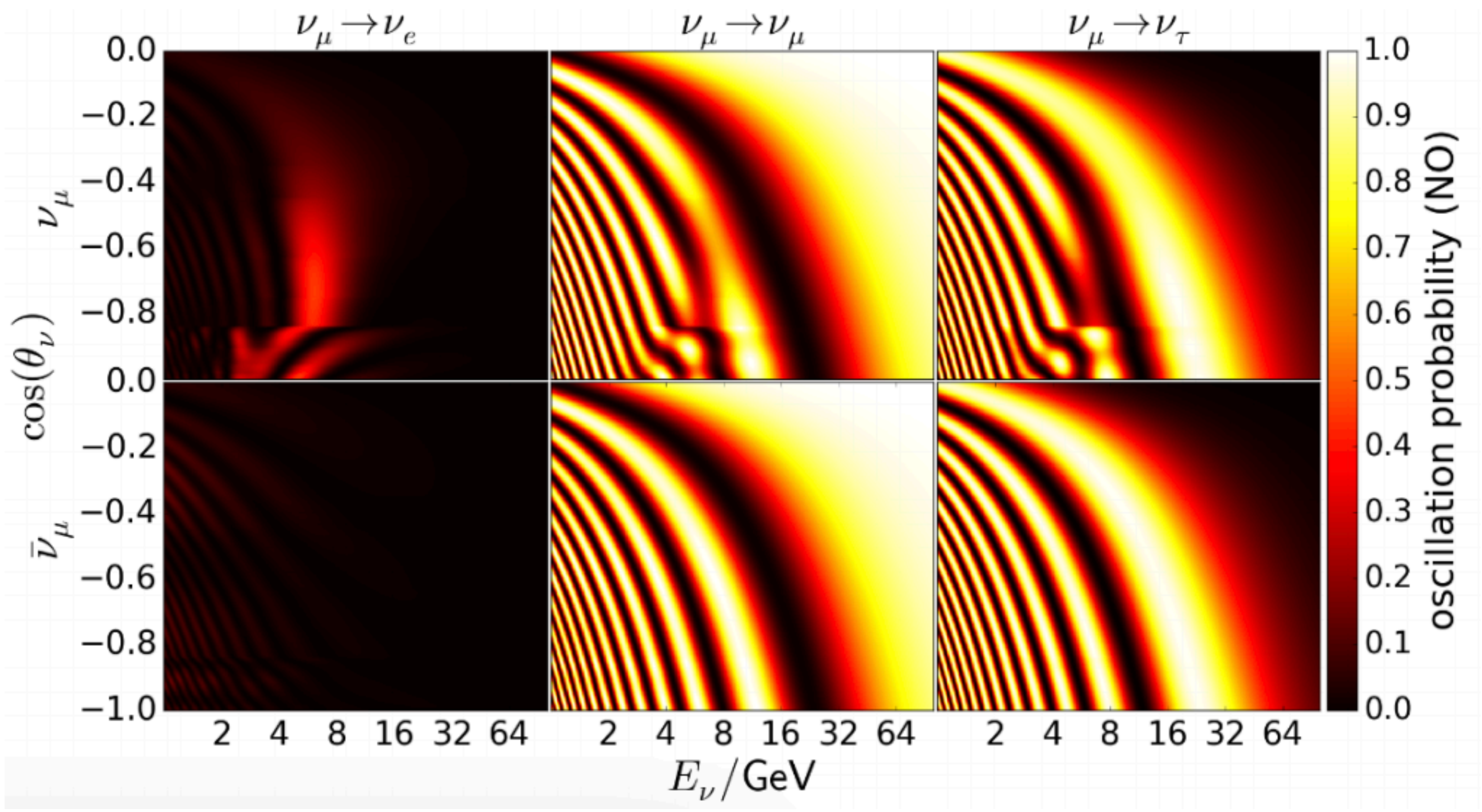
Open Questions

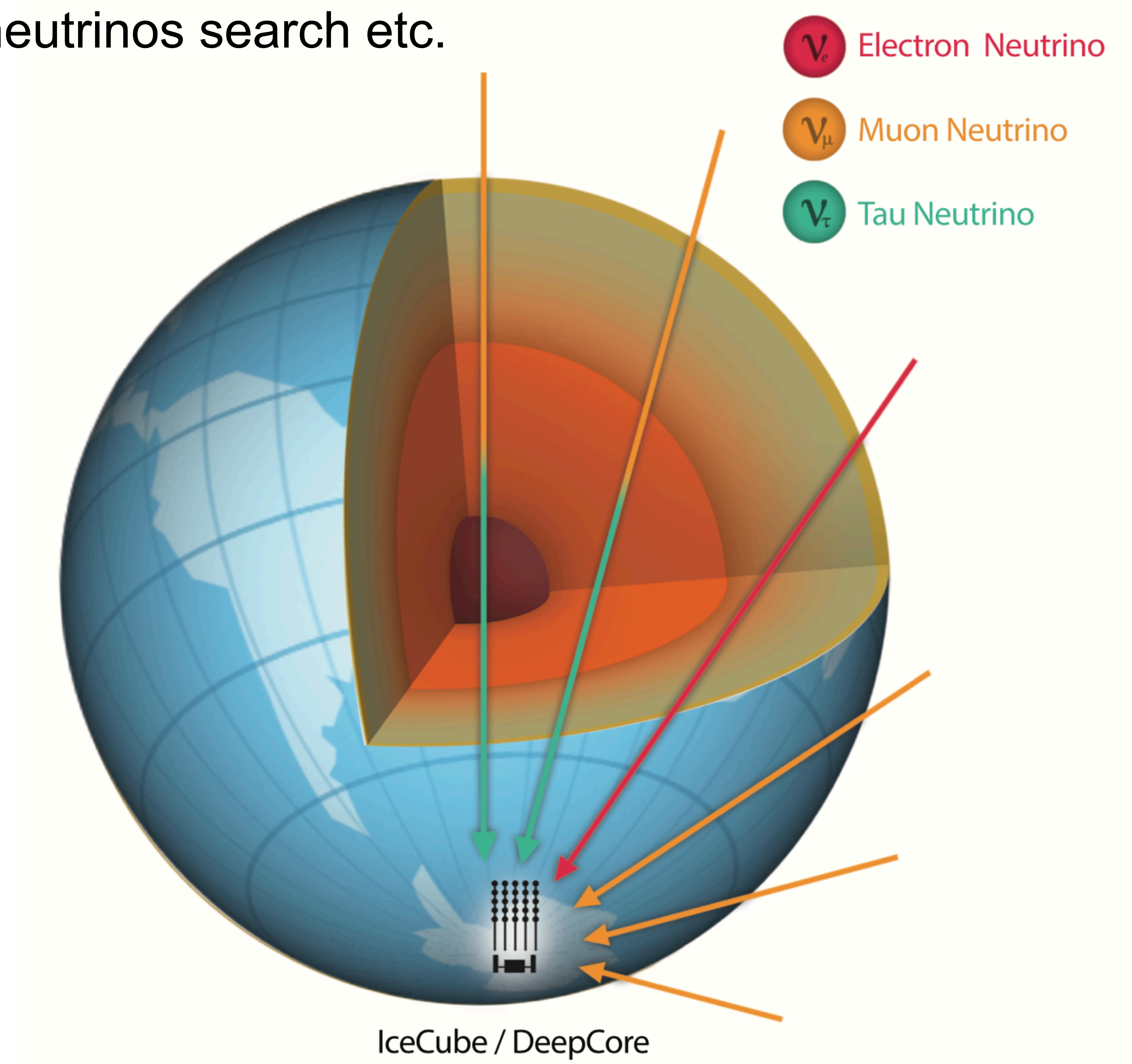
- m_3 state is heaviest (normal ordering) or lightest (inverted ordering) still undetermined
- Octant of θ_{23} (symmetry in μ/τ?)
  - Current data consistent with $\theta_{23} = \pi/4$ (maximal mixing)
- Value of δ_{CP}
  - Could explain matter/antimatter asymmetry in the universe
  - Weak global preference for $\delta_{CP} \sim 3\pi/2$ mainly driven by LBL+Reactor results



Oscillation Physics

- Atmospheric neutrinos have large energy range (GeV-TeV), with baseline: ~$O(10)$ - $O(10^4)$ km
- Most sensitive to flavour oscillations with $\Delta m^2 \sim 10^{-1} - 10^{-4} eV^2$
- Matter effects for core-crossing neutrinos
- TeV range neutrinos can be used to study Earth absorption, eV-scale sterile neutrinos search etc.
- GeV range neutrinos can be used to study standard oscillation
  - $\nu_\mu \rightarrow \nu_\tau$ transition and Neutrino Mass Ordering (NMO)





Atmospheric neutrino production

- Decay of pions/kaons from cosmic ray interactions atmospheric nuclei produces $\mu + \bar{\nu}_\mu$ ($e + \bar{\nu}_e$)
- μ decay produces $e + \bar{\nu}_e + \nu_\mu$
- If all muons decay, expect $\dfrac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} = 2$
- Kamiokande experiment first reported an indication of a deficit of ν_μ flux
- **Clear evidence of neutrino oscillation**:
  - μ-like events showed a clear deficit of up-going events
  - No deficit for e-like events

2015

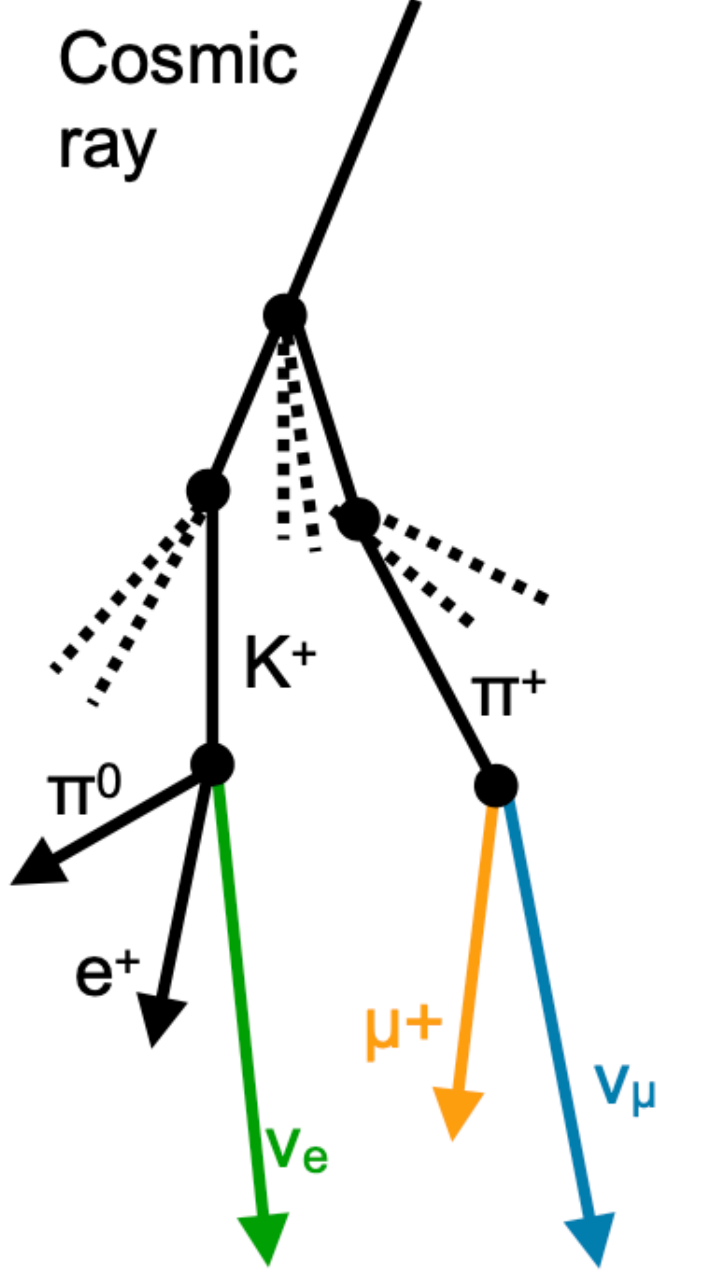
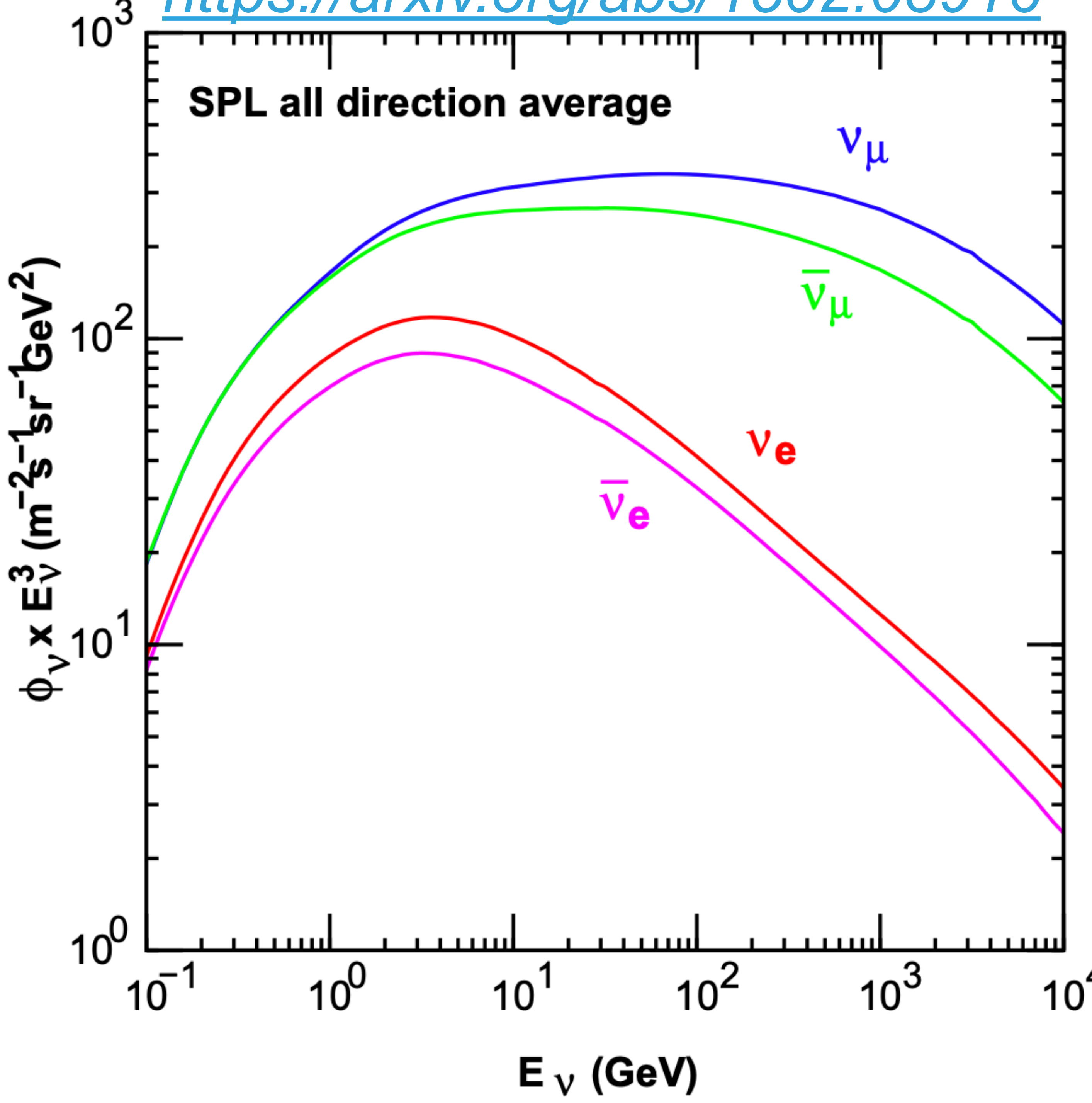


Figure from S. Blot

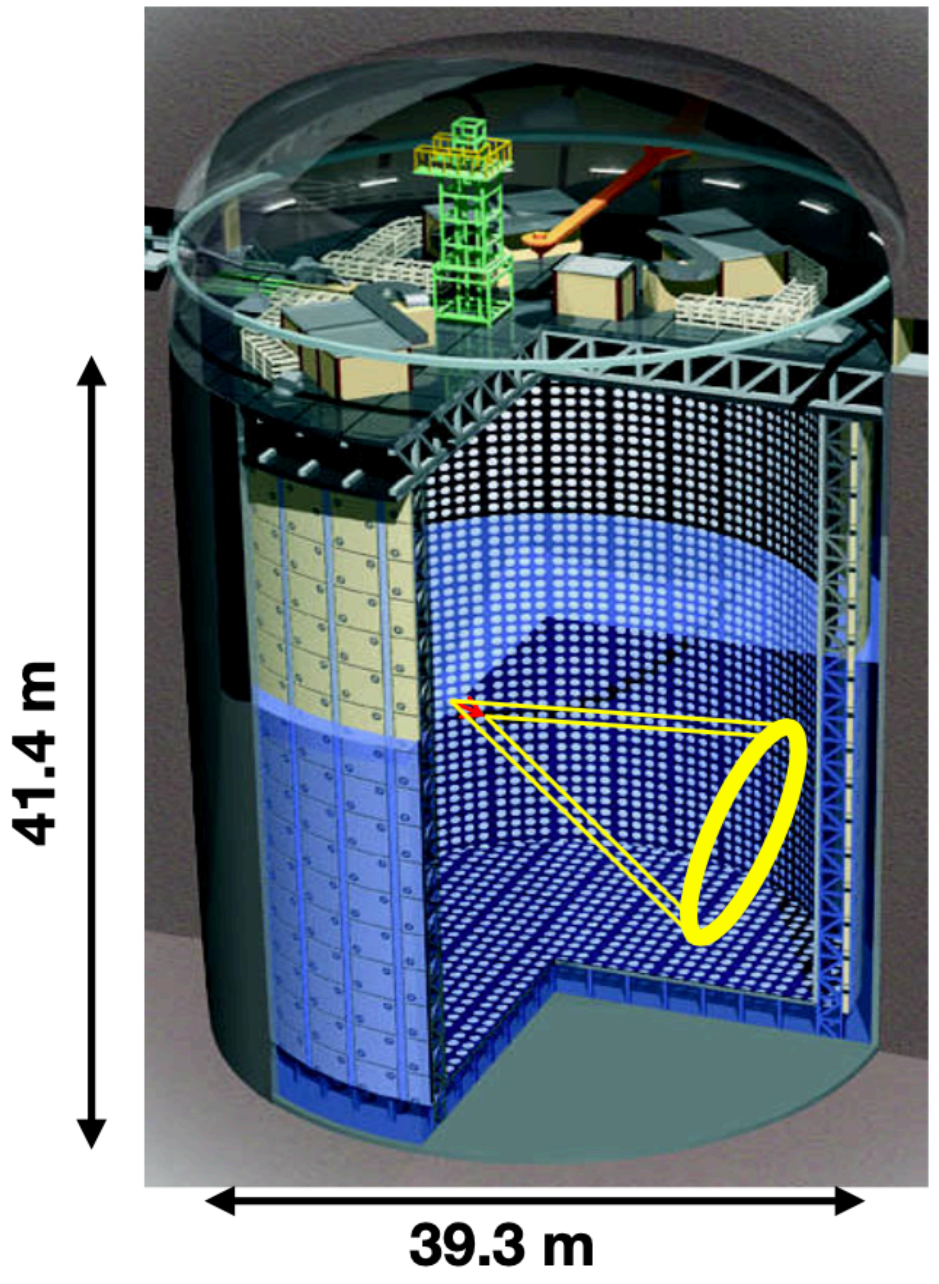
Honda, et. al: https://arxiv.org/abs/1502.03916



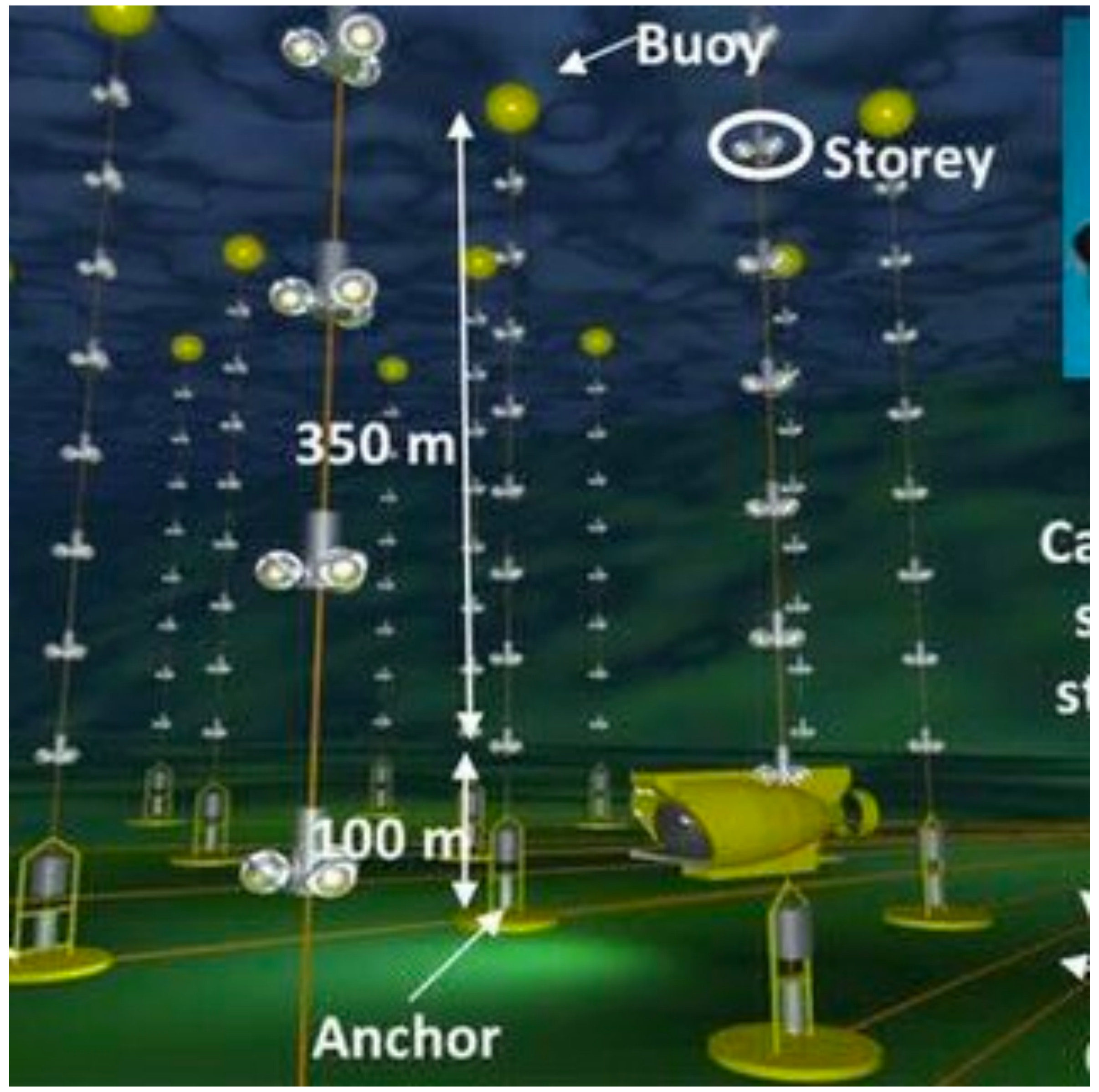
Atmospheric neutrino detectors

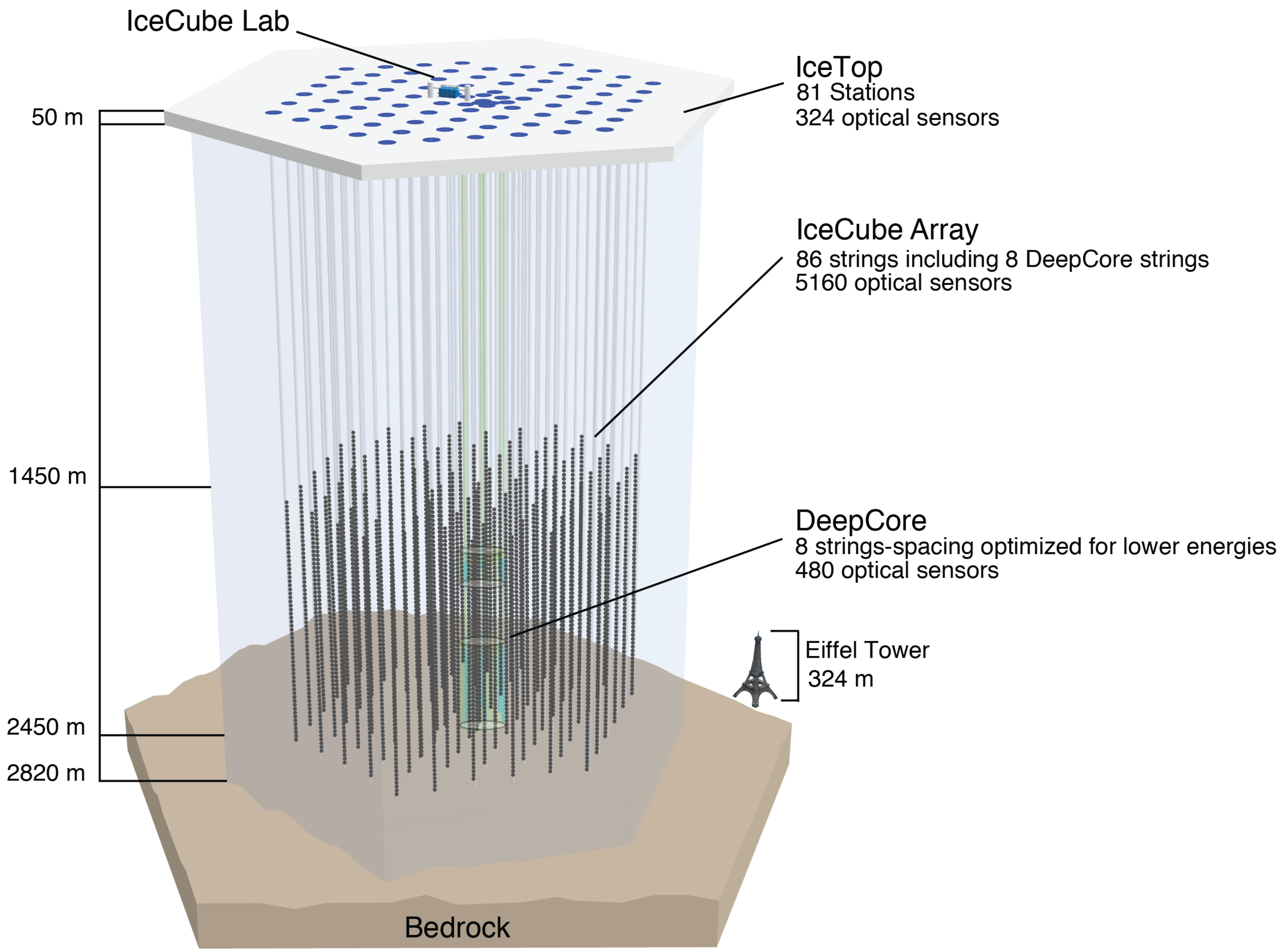
- Charged particles travelling through water/ice faster than light will emit **Cherenkov radiation**
- These photons can be collected by PMTs that instrument the detection medium

Super-K

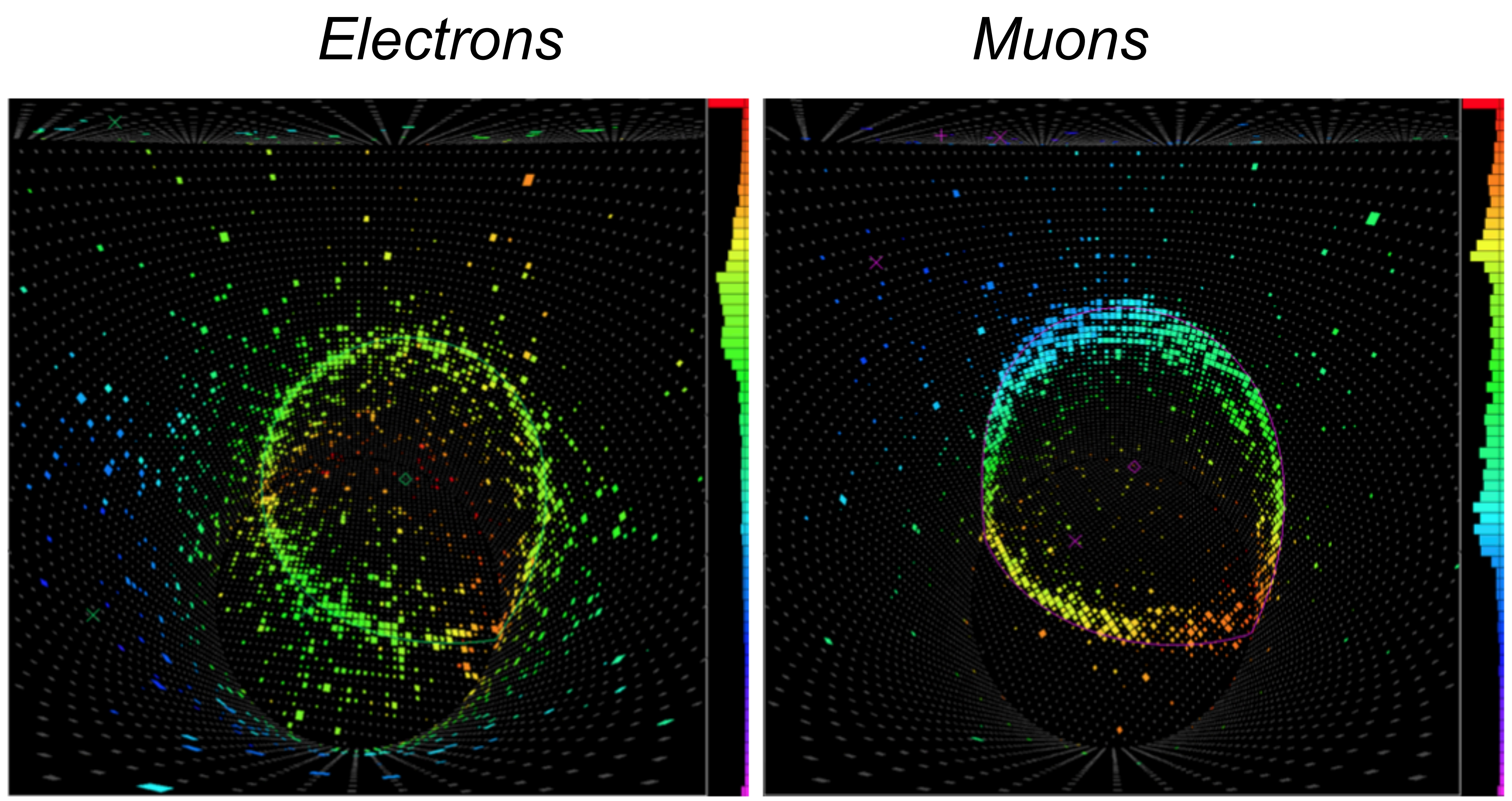


ANTARES

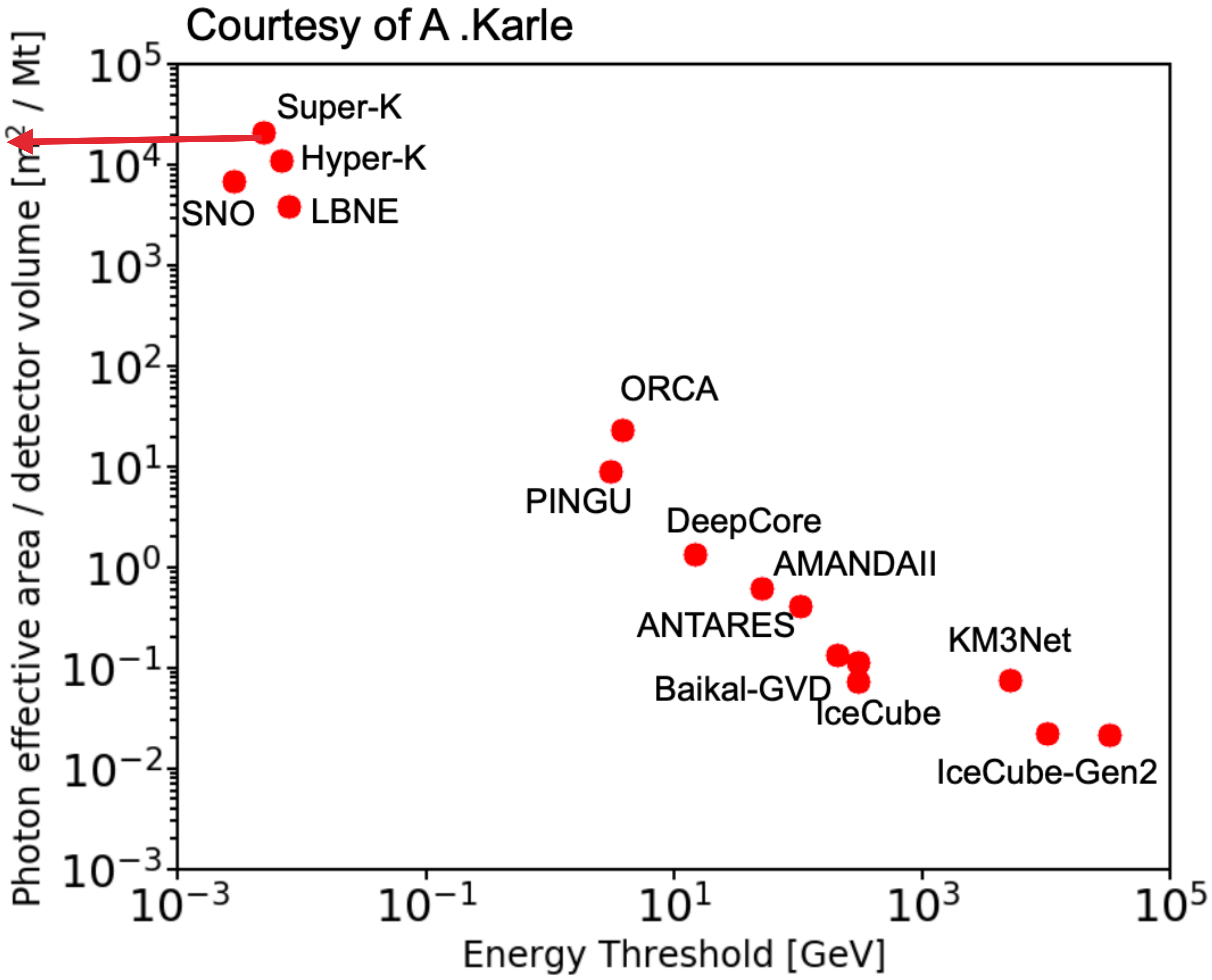




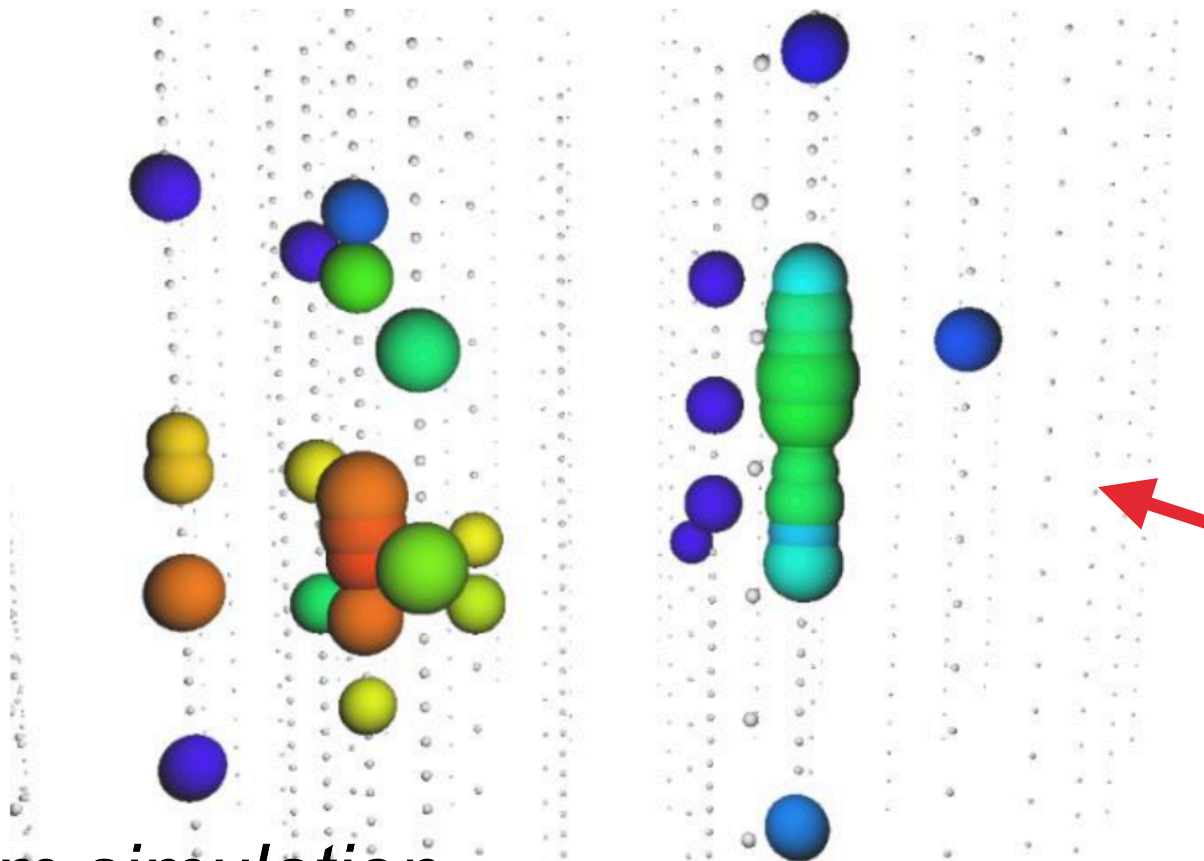
Event Signatures



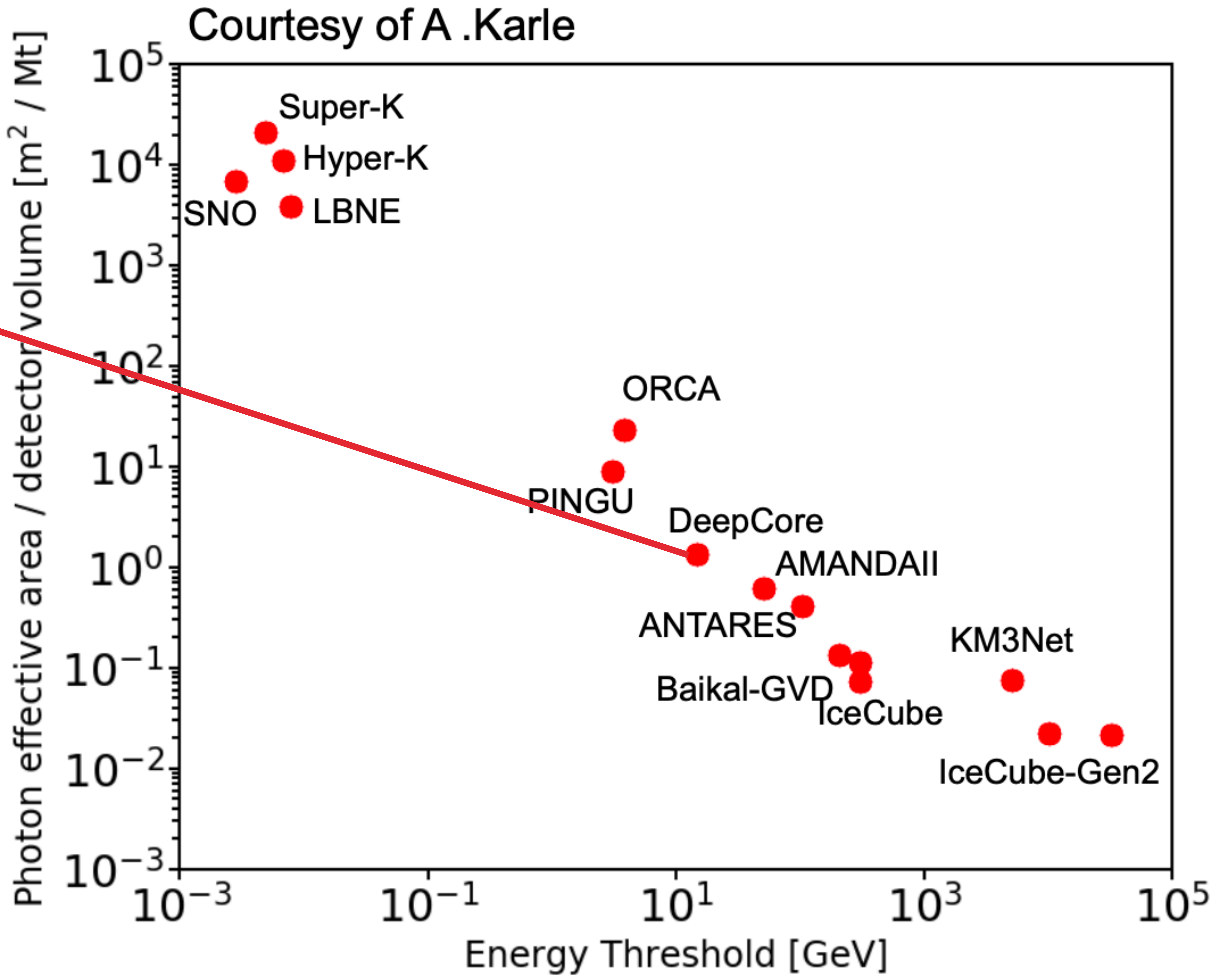
- Electrons: multiple scattering inside the detector gives “fuzzy” ring
- Muons: little scattering, produces a well-defined Cherenkov cone



Event Signatures

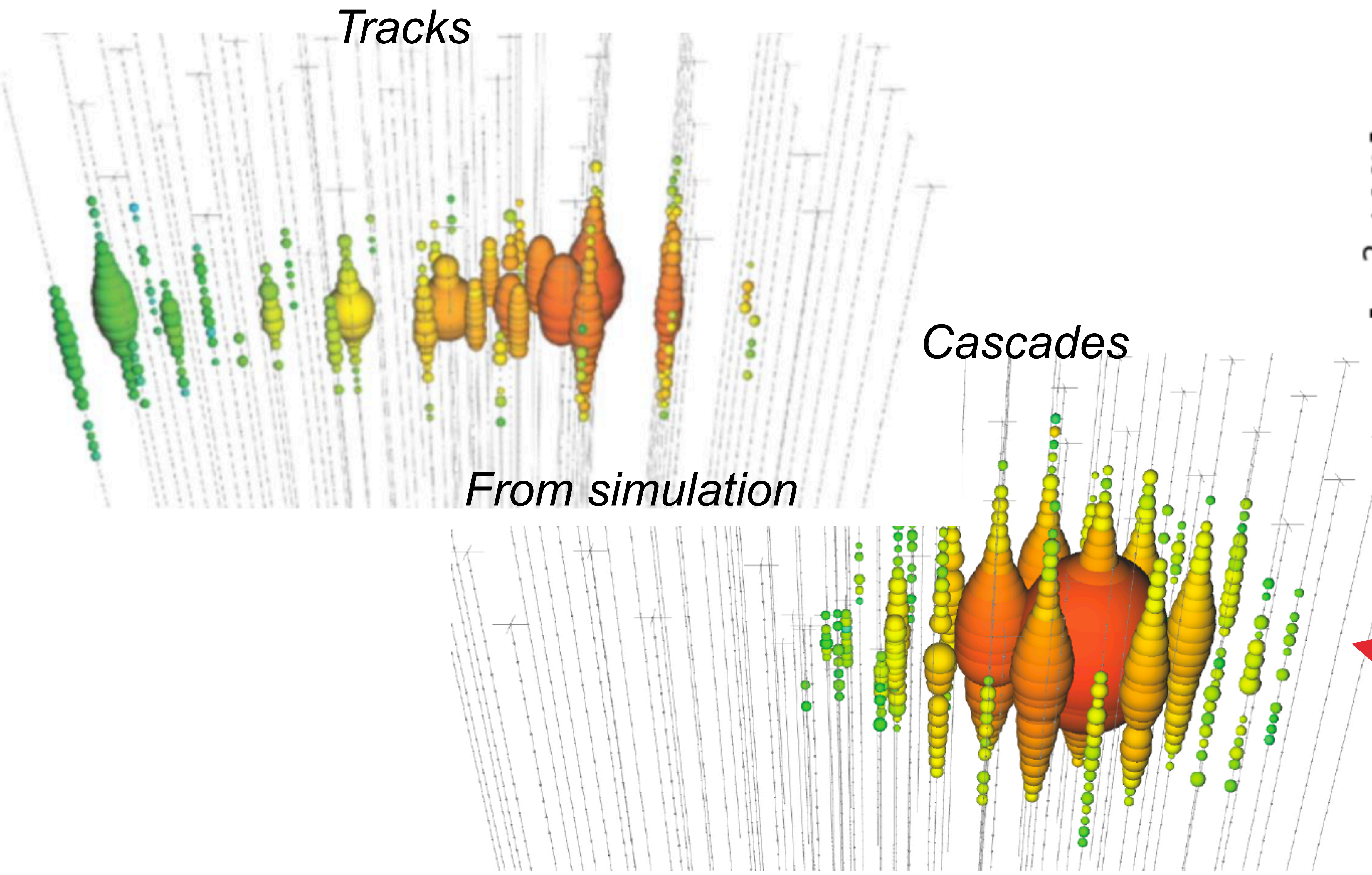


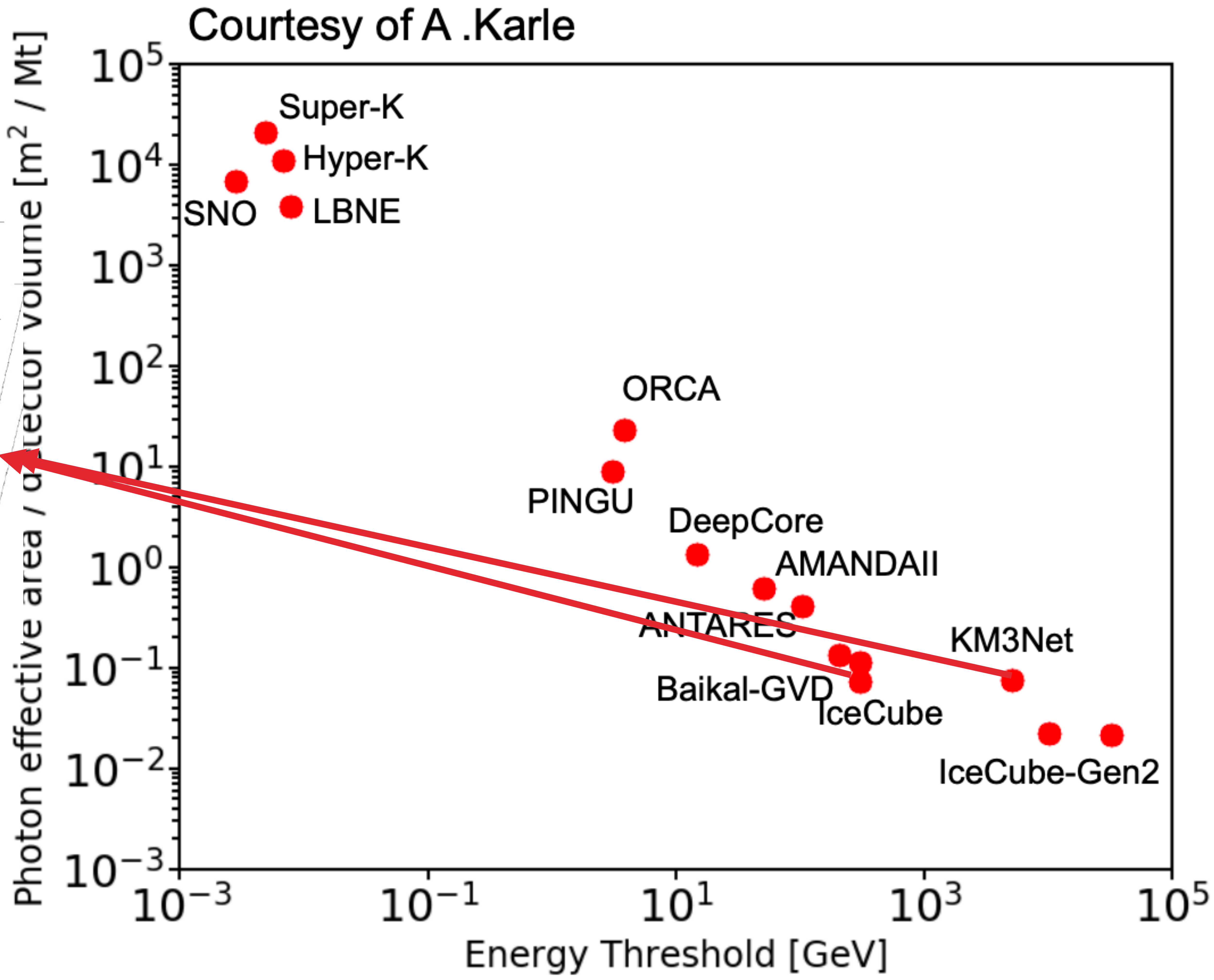
From simulation



- Photons arrive at a few strings/PMTs
- Cannot tell topology by eye
- Rely on advance reconstruction algorithm for PID

Event Signatures





- Photons arrive at many strings/PMTs
- Very clear track/cascade topology

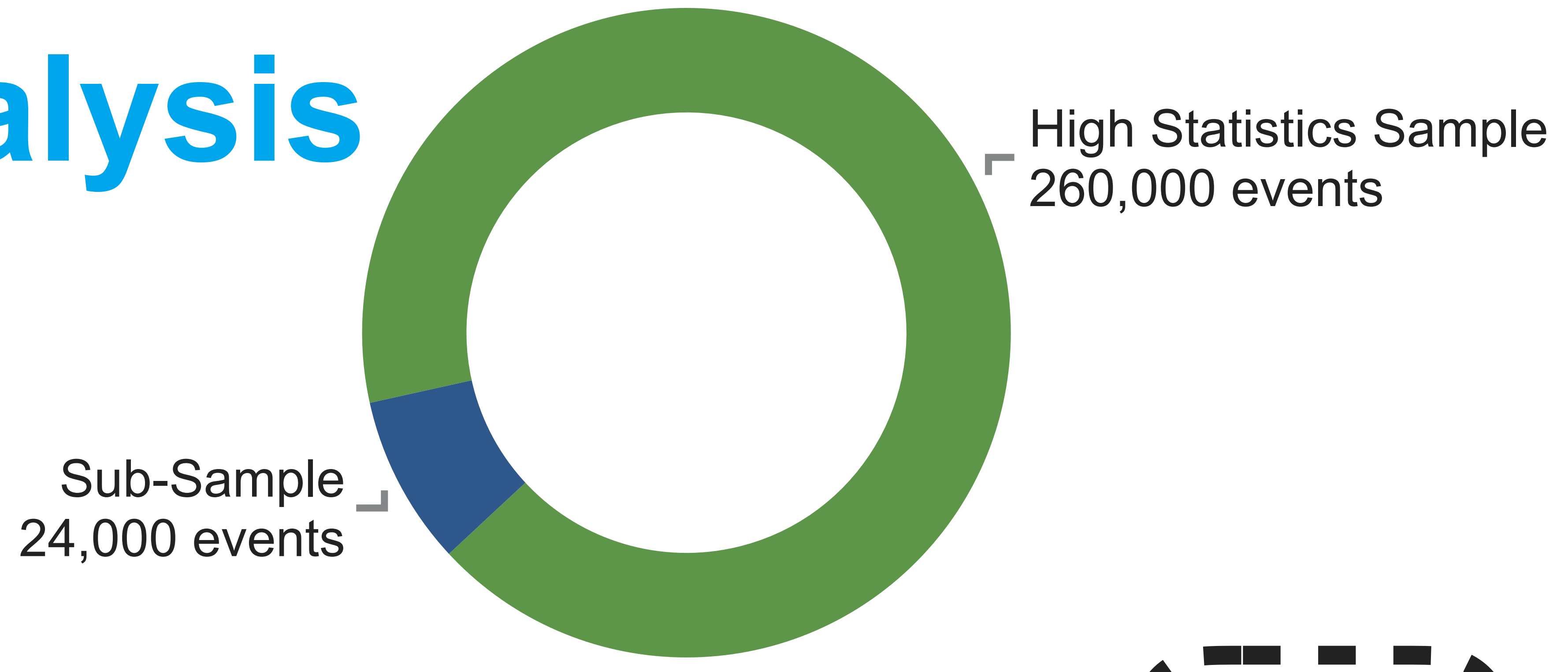
Comparison between detectors

Detector	Energy range	Energy resolution	Zenith resolution	PID
SuperK	~ few MeV - GeV	3% @ 1GeV	2-3°	e, μ, π^0
ANTARES*	~ 20 GeV - PeV	50 ± 22%	3° @ 20 GeV	μ, “cascade”
IceCube/ DeepCore*	~ 5 GeV - PeV	25% @ 20 GeV	8° @ 20 GeV	μ, “cascade”

- *ANTARES and DeepCore resolutions quoted for tracks
- SK: lower energy range, can distinguish e, μ, π^0
- ANTARES: good directional resolution
- IceCube: good energy resolution

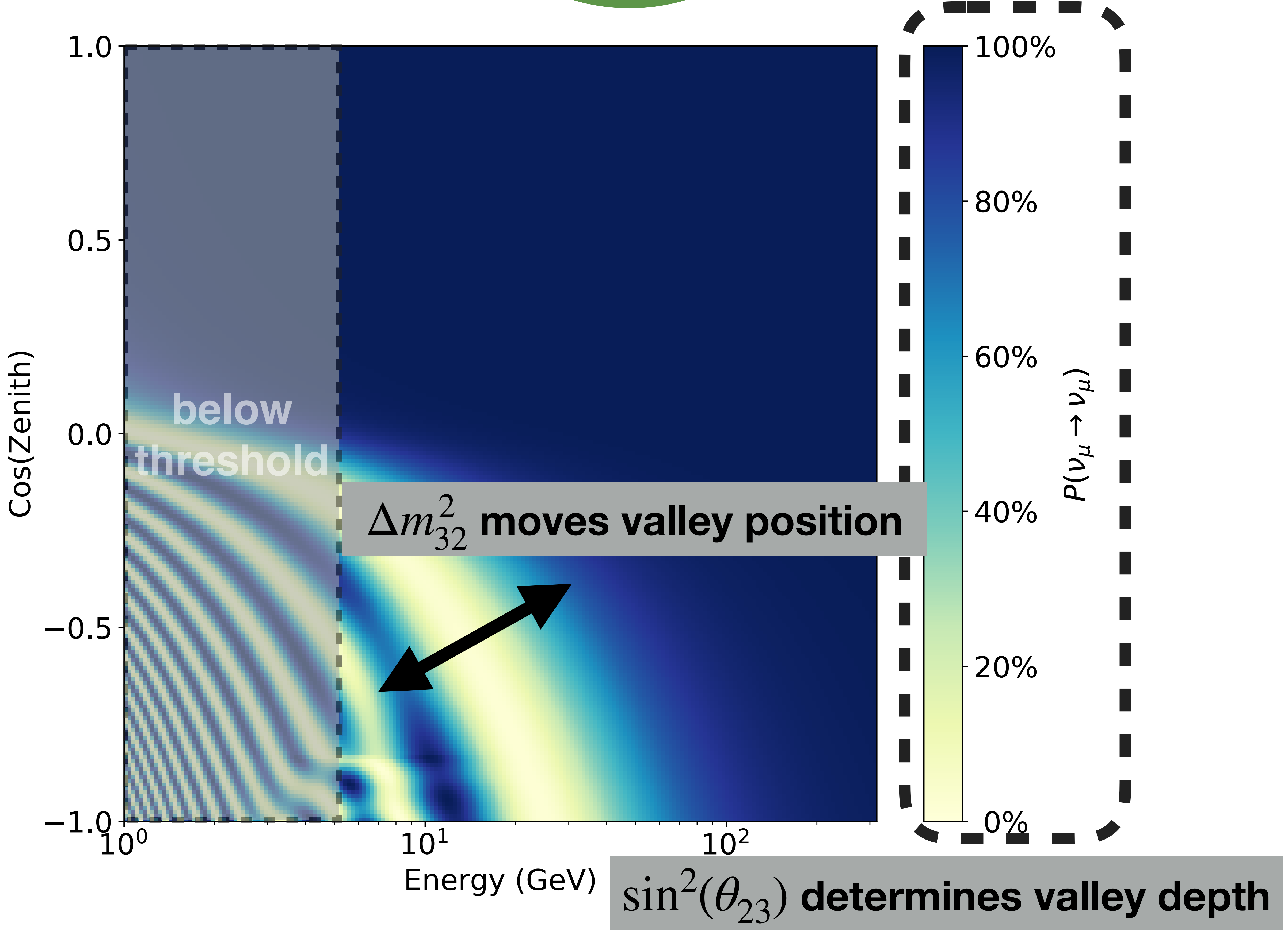
Atmospheric Neutrino Analysis

DeepCore Atmospheric Neutrino Analysis



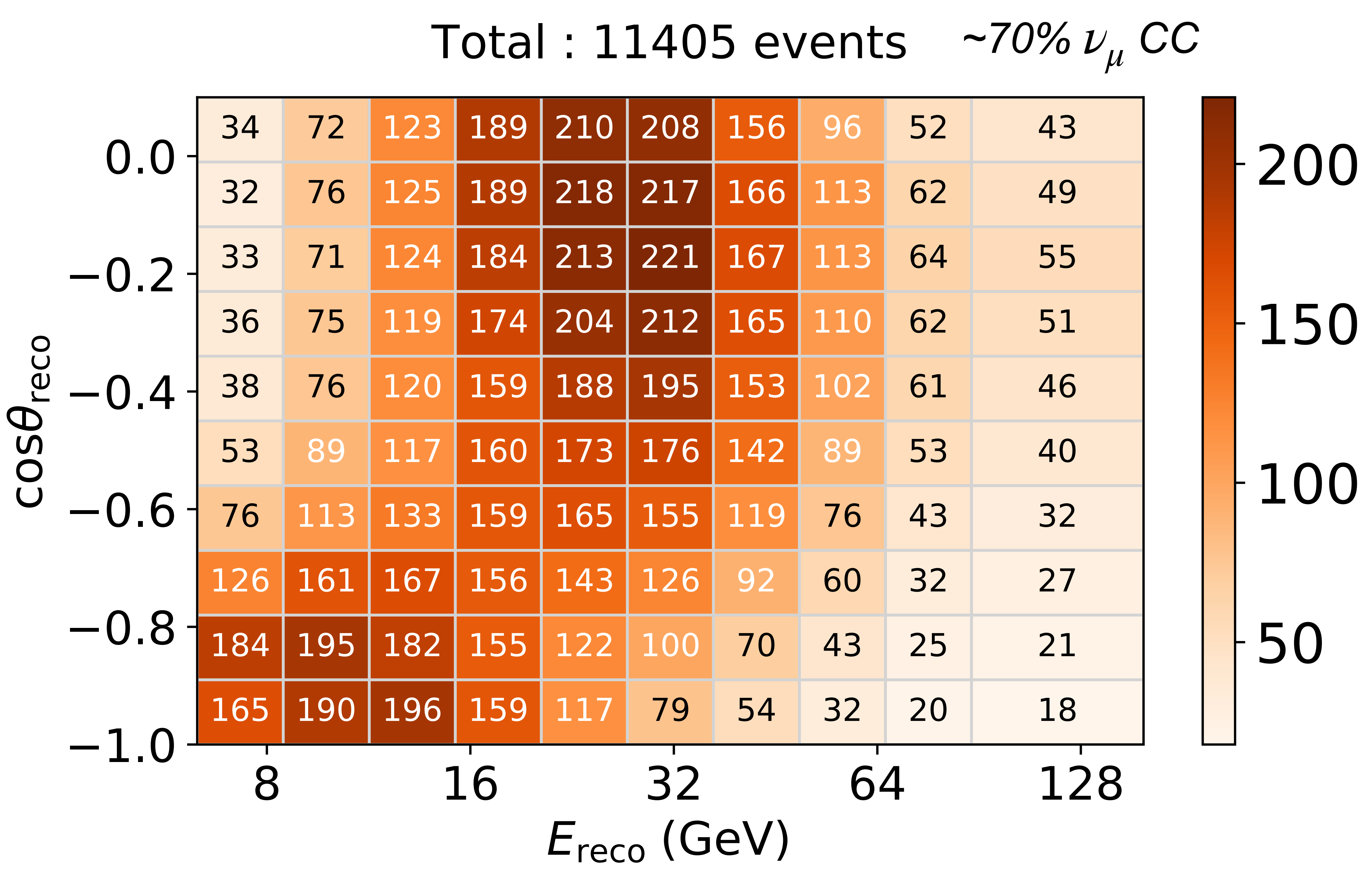
- Maximal disappearance of up-going ν_μ at ~25 GeV
- Mostly oscillated to ν_τ at this energy

- 8 years of DeepCore data with new analysis framework
- Major advances in calibration, BDT, reconstruction, treatment of systematic uncertainties, etc.
  - Robust reconstruction to select **sub-sample of ~24k high-quality, track-like "Golden events"**
  - Final sample: ~80% signal events ($\nu_\mu/\bar{\nu}_\mu$ CC), ~2% background atmospheric muons
  - Focus on **measurement of $sin^2\theta_{23}$ and Δm^2_{32} in NO**

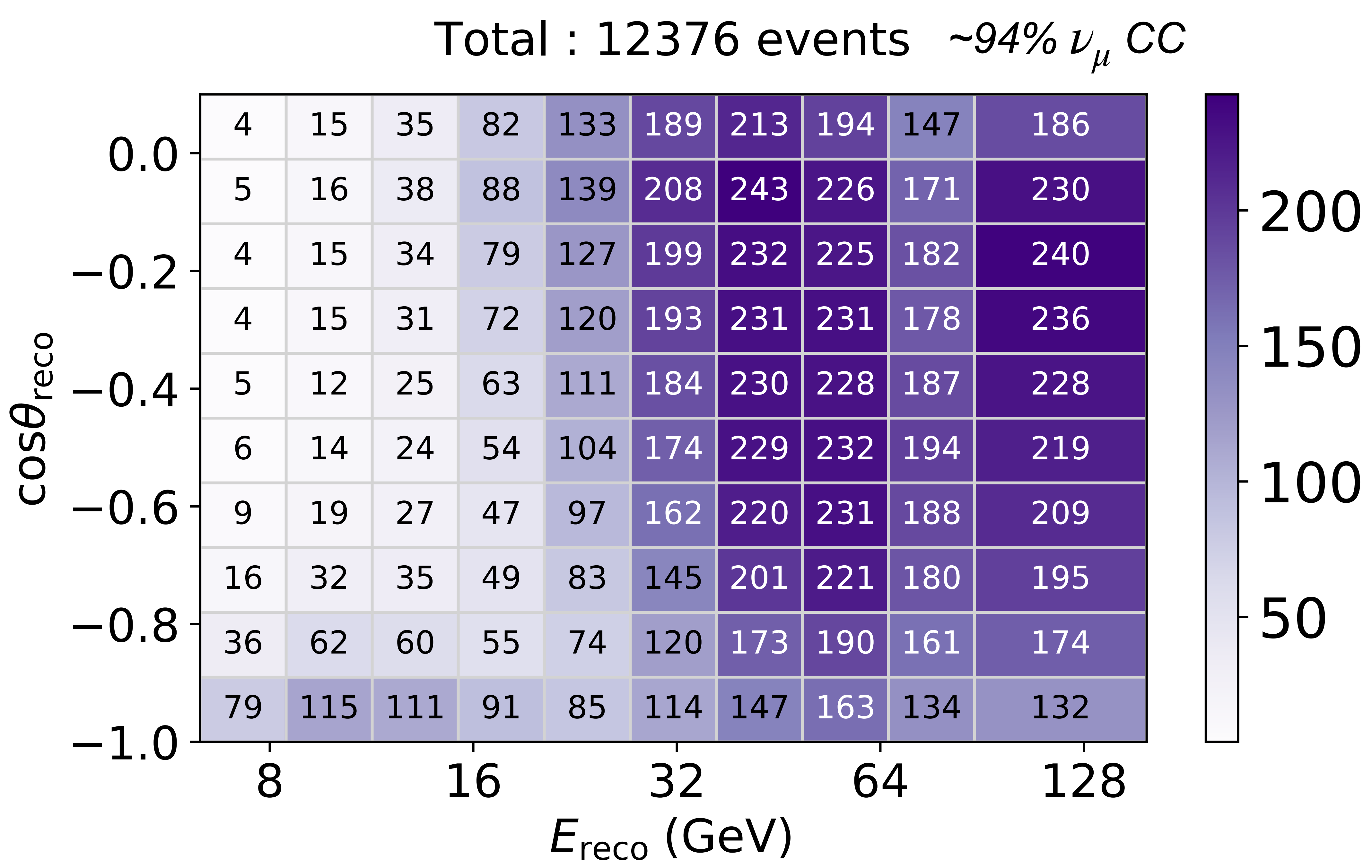


Analysis space

Mixed PID channel



Track PID channel



10 (E) x 10 (cosZ) x 2 (PID) bins

> Extract oscillation parameters by comparing data with expectation of standard 3-flavour neutrino oscillation

Systematic Uncertainties

- Include uncertainties from atmospheric flux, cross-sections and detector
- Extensive studies to include systematics that have non-negligible effect

- Detector uncertainty dominates the systematic uncertainty

	name	nominal	prior
flux	neutrino Δɣ	0	±0.1
	barr_af_Pi	0.0	±0.63
	barr_g_Pi	0.0	±0.3
	barr_h_Pi	0.0	±0.15
	barr_w_K	0.0	±0.4
	barr_y_K	0.0	±0.3
	barr_w_antiK	0.0	±0.4
cross sec.	GENIE M_A QE	0.0	±1.0
	GENIE M_A RES	0.0	±1.0
	DIS CSMS	0.0	±1.0
nu weight	A_{eff} scale	1.0	uniform
	nu NC norm	1.0	±0.2
detector systematics	DOM efficiency	1.0	±0.1
	hole ice p0	0.101569	uniform
	hole ice p1	-0.049344	uniform
	ice absorption coeff	1.0	±0.05
	ice scattering coeff	1.05	±0.05
muons	muon weight scale	1.0	uniform

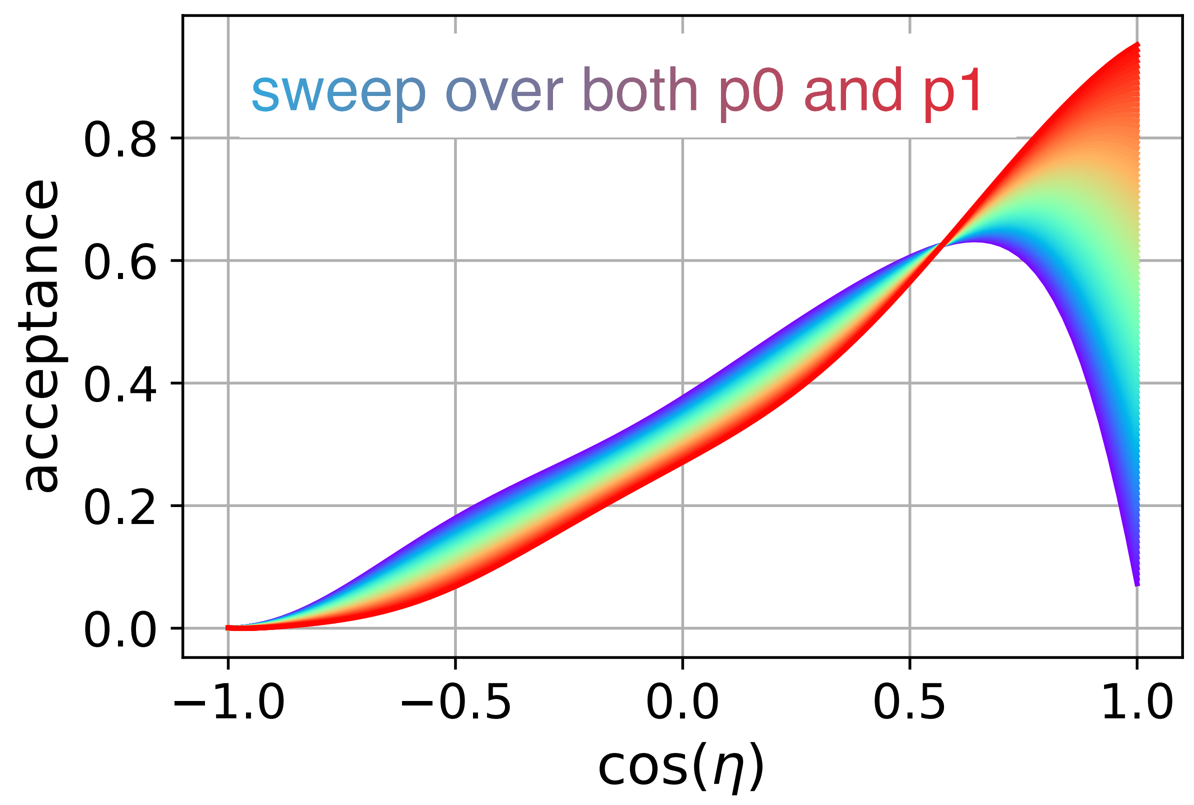
Systematic Uncertainties

Detector systematics

DOM efficiency

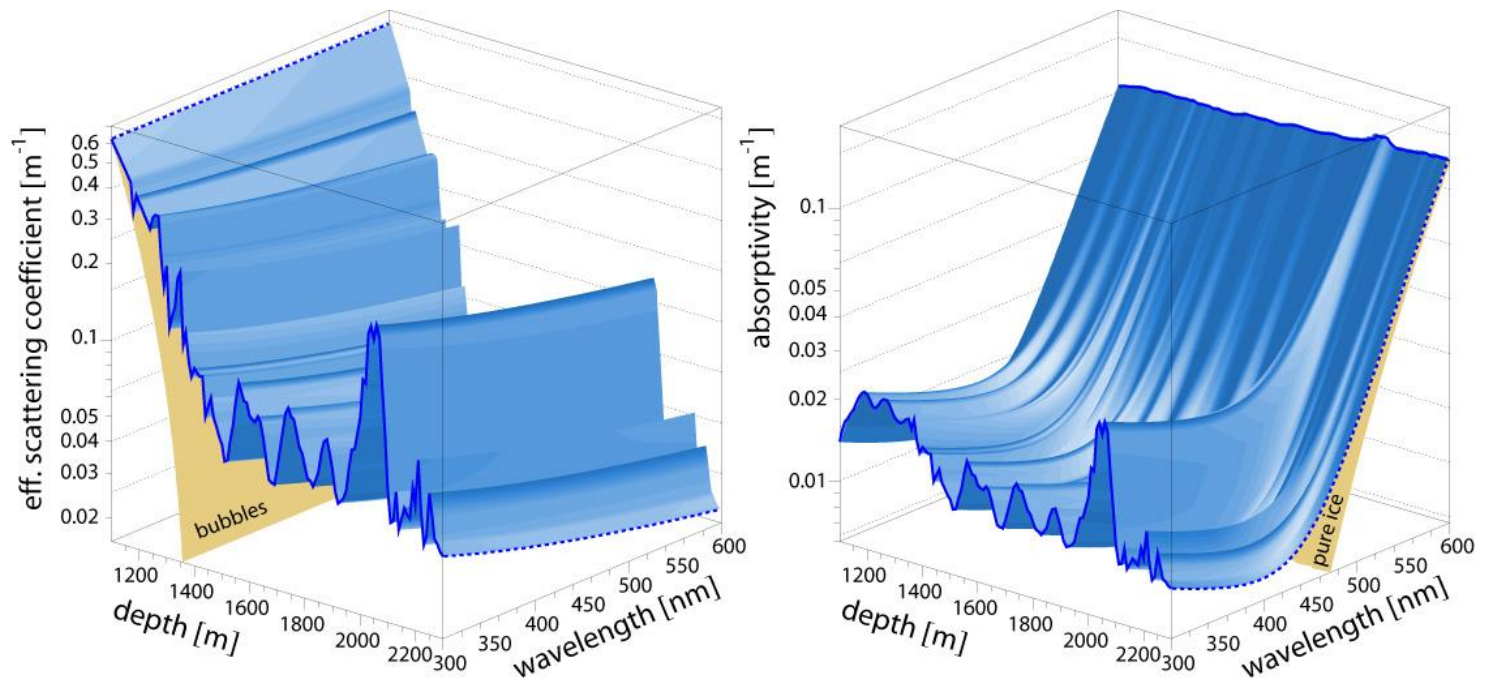
- MC sets generated at different values: [0.8, 1.2]
- prior: 1±0.1

Hole ice



- modelled as change in angular acceptance
- parametrisation:
  2 components (p0, p1) from PCA over different existing models
- flat prior

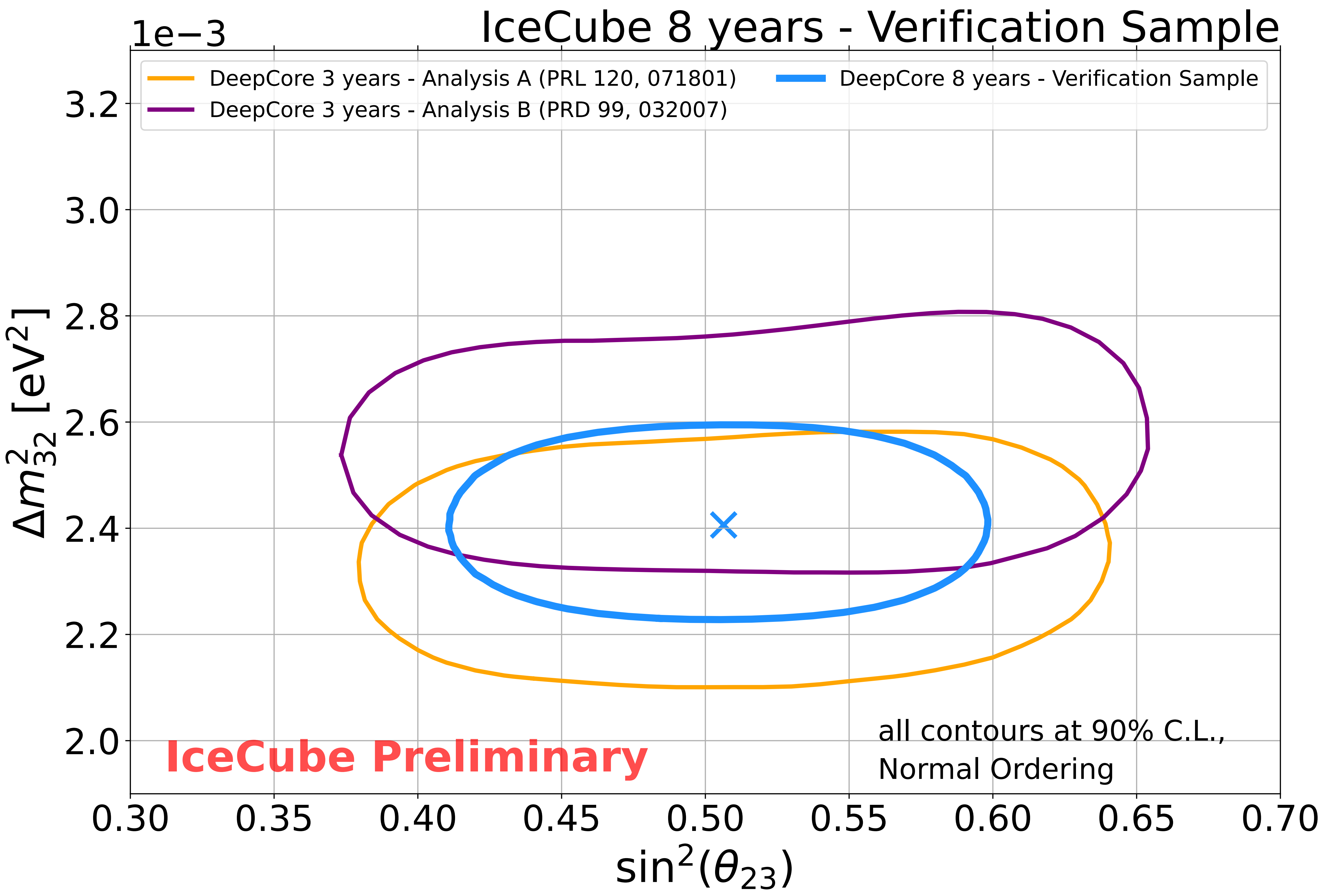
Ice scattering and absorption



- scale scattering and absorption coefficients of all ice layers
- 4 systematic simulation sets: ±5% scattering, ±5% absorption
- bounds: ±10% around nominal
- prior 1σ = 5%

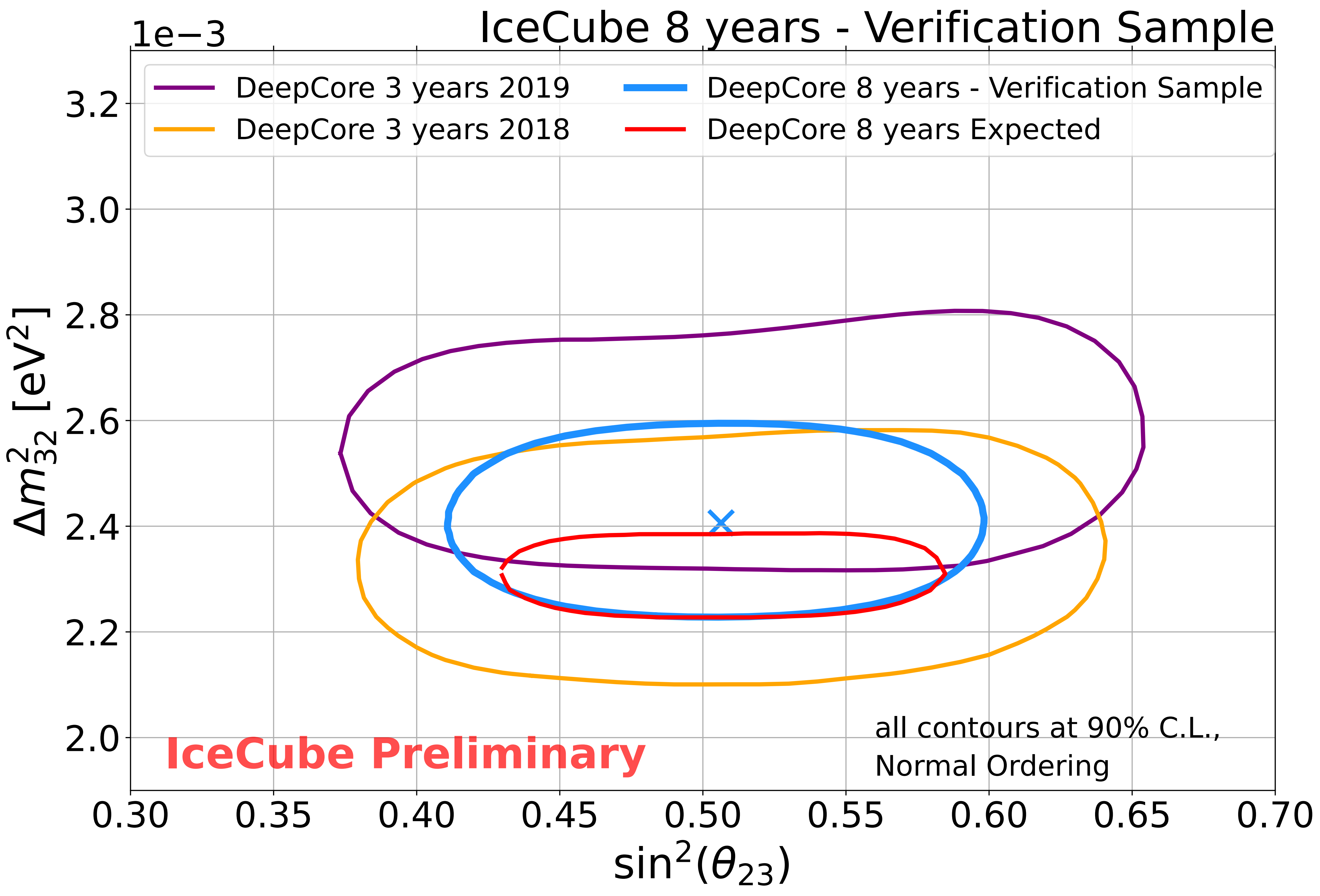
Analysis results using Sub-Sample

- Using this sub-sample ("Golden events") shows improvement compare to previous results
- Results consistent with both analyses, continues to be compatible with maximal mixing
- Best-fit:
  - $\sin^2\theta_{23} = 0.505^{+0.051}_{-0.050}$
  - $\Delta m^2_{32} = 2.41^{+0.084}_{-0.084} \times 10^{-3} eV^2$



Expected Sensitivity with full statistics

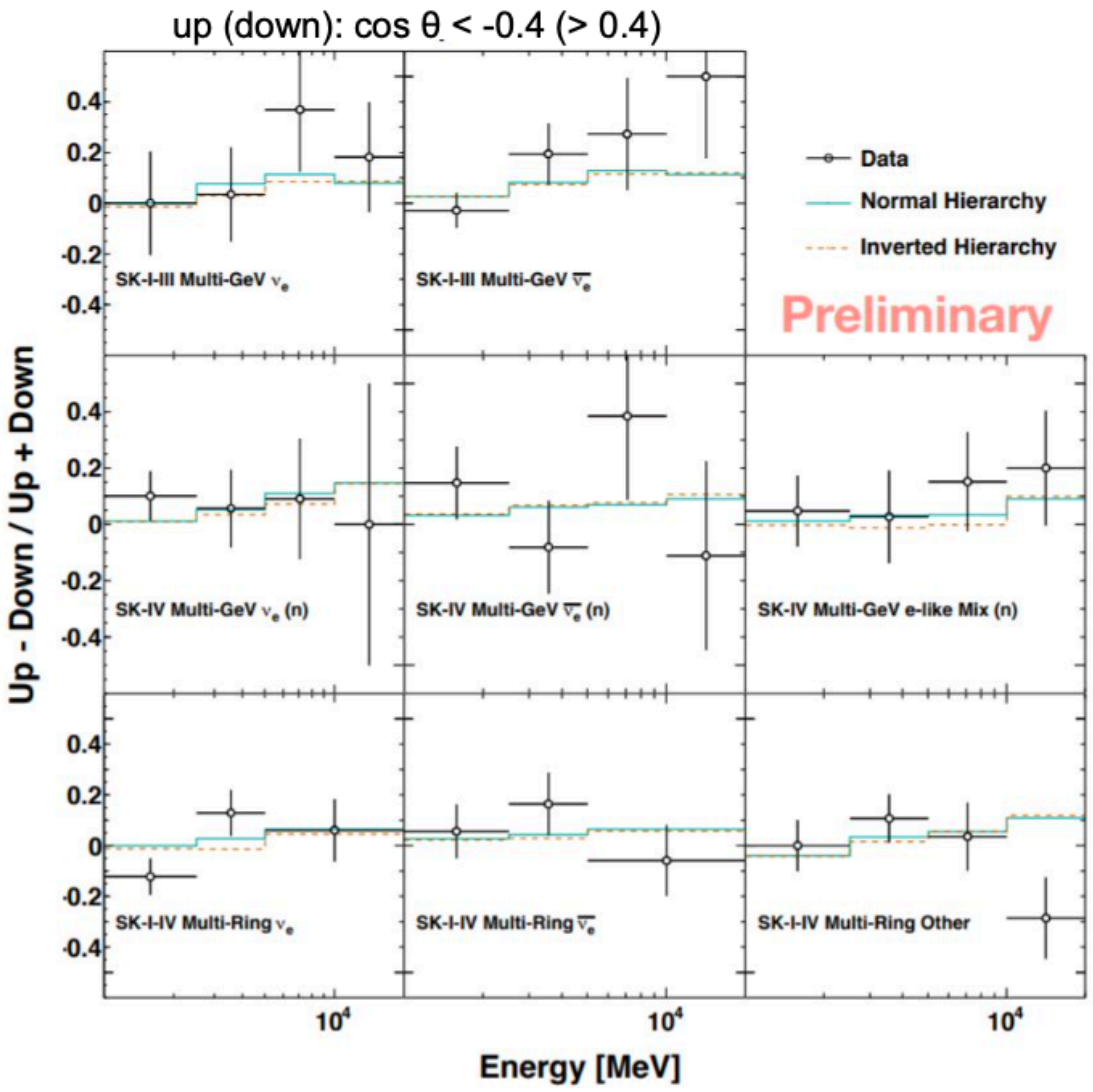
- Expect even better constrains with full statistics
  - Consistent with all other DeepCore results



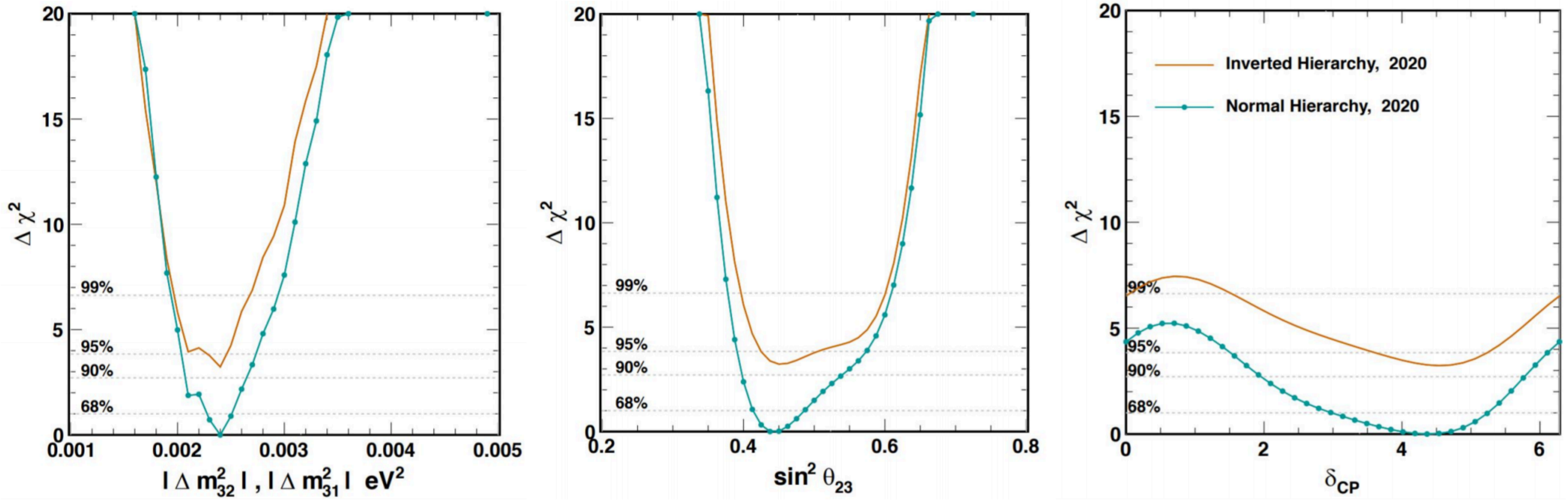
SK Atmospheric Neutrino Analysis

ICHEP2020 Talk + Proceedings

- Lower energy threshold, sensitive to δ_{CP}
- Simultaneous fit to 3 parameters, fixed θ_{13}
- Full SK I-IV livetime, exposure: 364.8 kton-yrs
- 78 data samples, > 150 systematics are taken into account
- Main improvements:
  - Neutron tagging efficiency ~ 25% (for $\nu/\bar{\nu}$ separation)
  - New BDT-based selection for multi-ring events
    - Increased signal efficiency, sample purity



SK Atmospheric Neutrino Analysis



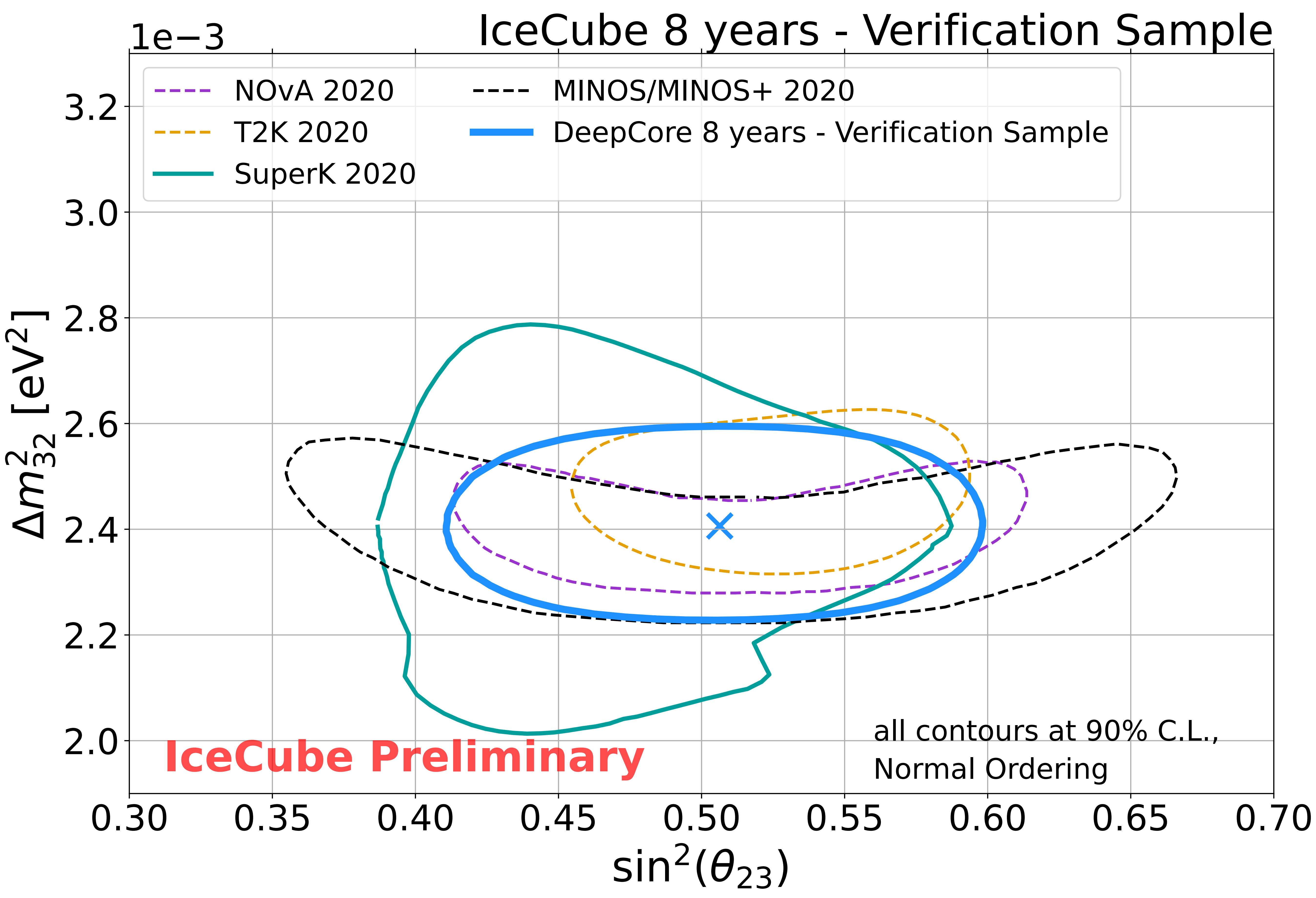
Fit (930 bins)	χ^2_{min}	θ_{13}	δ_{cp}	θ_{23}	$\Delta m_{23}\,(\times 10^{-3})$
Normal Hierarchy	1037.5	0.0218	$4.36^{+0.88}_{-1.39}$	$0.44^{+0.05}_{-0.02}$	$2.40^{+0.11}_{-0.12}$
Inverted Hierarchy	1040.7	0.0218	$4.54^{+0.88}_{-1.32}$	$0.45^{+0.09}_{-0.03}$	$2.40^{+0.09}_{-0.32}$

> Data disfavours IH (IO) at 71.4 - 90.3% C.L.

> Data prefers 1st θ_{23} octant and $\delta_{CP} \sim 3\pi/2$

Atmospheric oscillation parameters sensitivity

- Comparison with other experiment results
  - shows comparable precision with LBL experiments

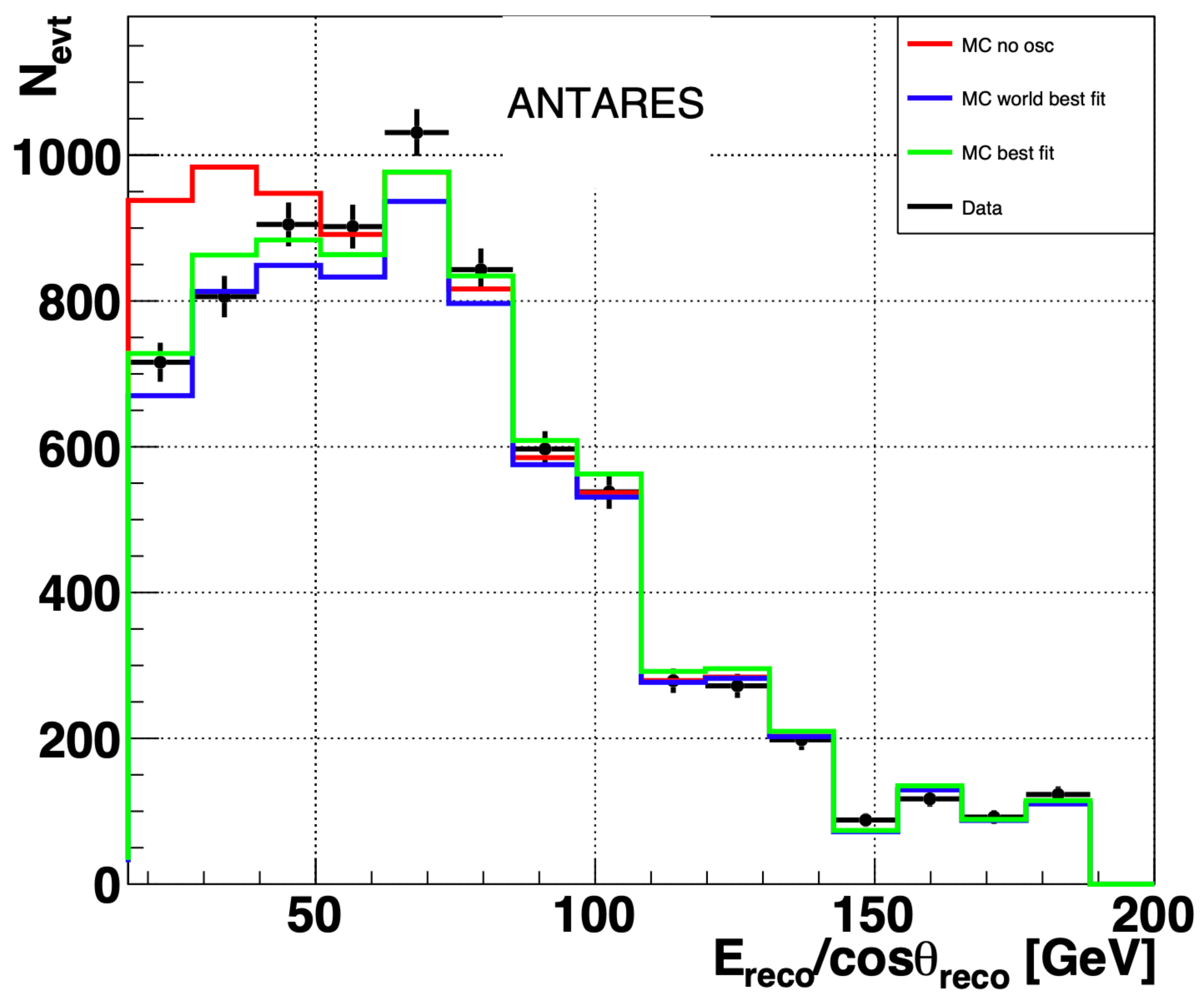


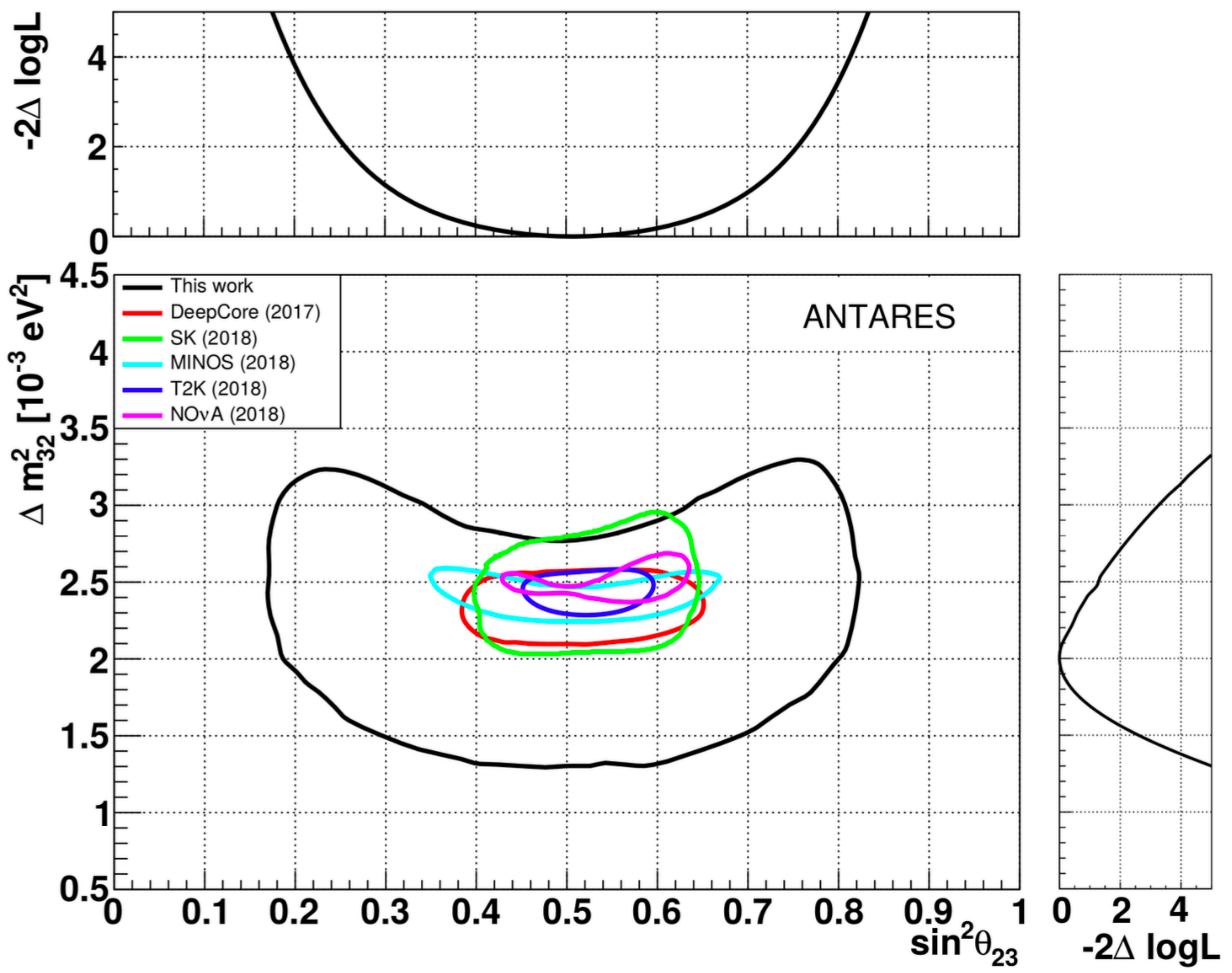
ANTARES Atmospheric Neutrino Analysis

J. High Energ. Phys. 2019, 113 (2019)

- Data taken from 2007-2016, 2830 days of lifetime
- Track channel only, 7710 events selected
- Atmospheric muon background extrapolated from data
- Binned likelihood fit in 2D ($log_{10}E_{reco}$, $cos(\theta_{reco})$)
- Consistent with other results

Parameter	Prior	Fit result
Δm^2_{32} [10^{-3} eV^2]	none	$2.0^{+0.4}_{-0.3}$
θ_{23} [°]	none	45^{+12}_{-11}
n_ν	none	$0.81^{+0.10}_{-0.09}$
$\nu/\overline{\nu}$ [σ]	0.0 ± 1.0	$1.10^{+0.64}_{-0.56}$
$\Delta\gamma$	0.00 ± 0.05	-0.003 ± 0.036
N_μ	740 ± 120	414^{+48}_{-24}
θ_{13} [°]	8.41 ± 0.28	8.41 ± 0.28
M_A [σ]	0.0 ± 1.0	0.0 ± 1.0





Other Measurements

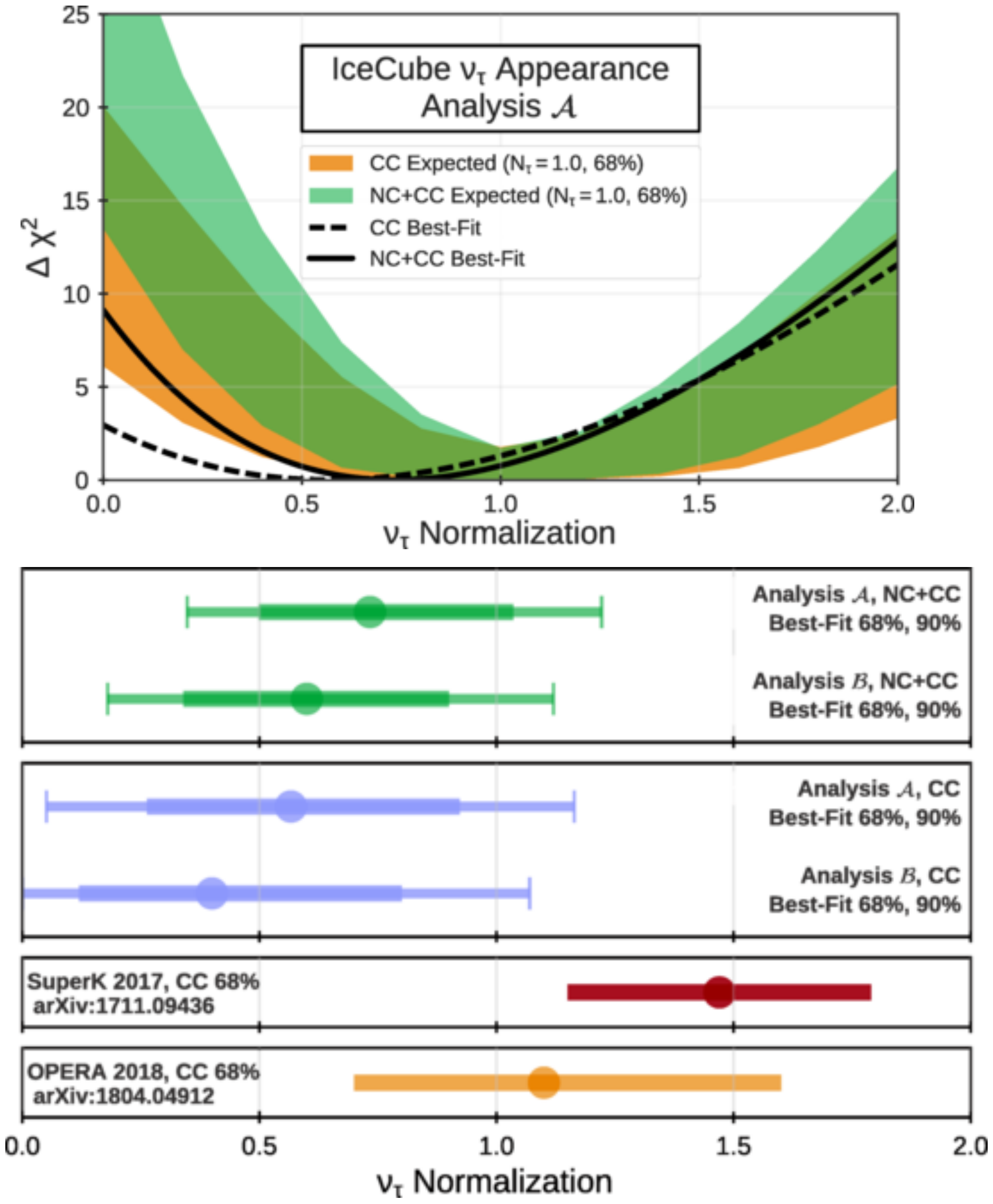
Selection of results

ν_τ appearance

Phys. Rev. D **99**, 032007 (2019)

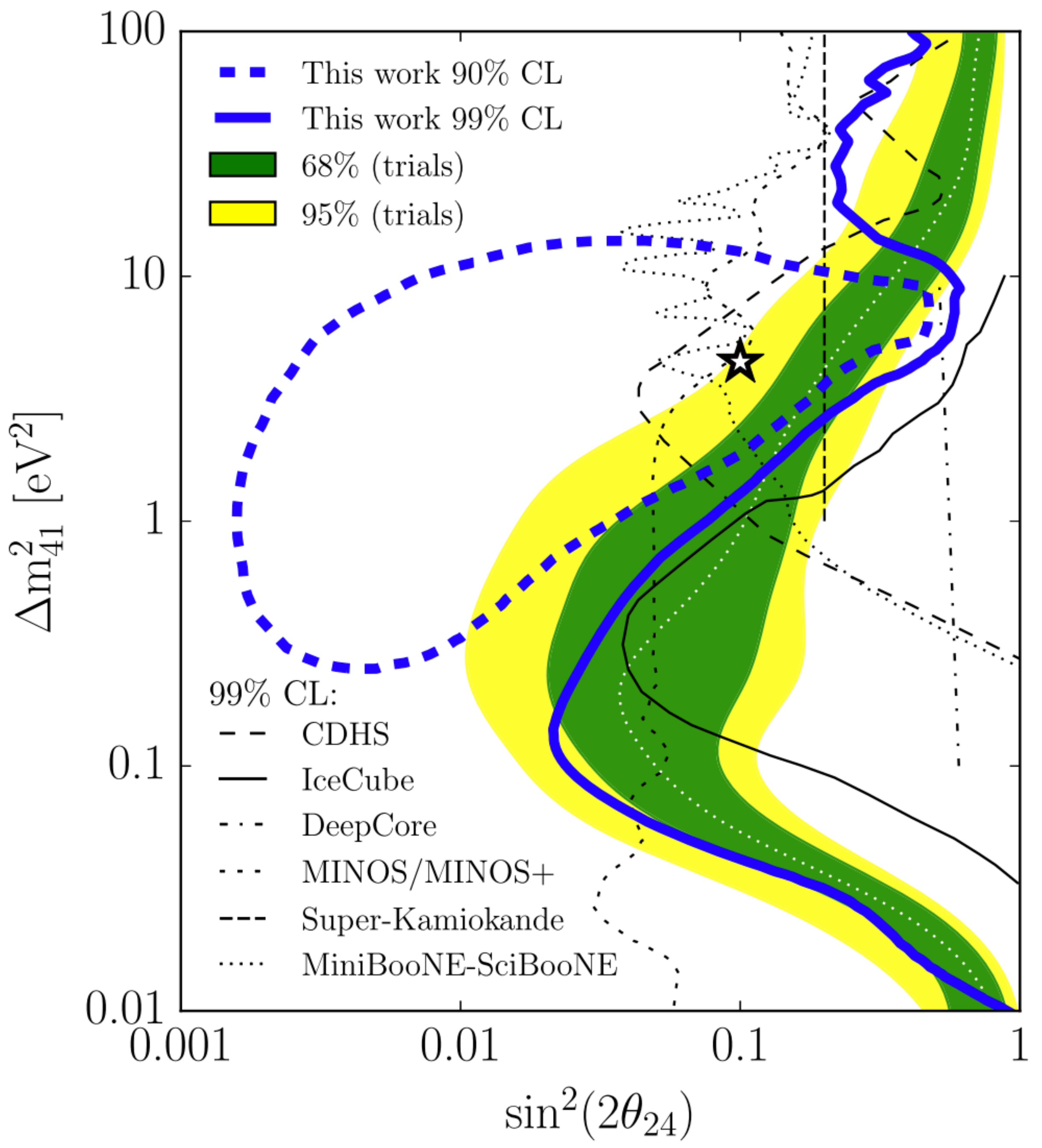
- Measure ν_τ normalisation (N_{ν_τ}) w.r.t. unitary PMNS expectation
  - Constraining ν_τ normalisation (N_{ν_τ}) can test PMNS mixing matrix unitarity
  - Deviation from 1 would imply non-unitarity
  - Not accessible by LBL experiments

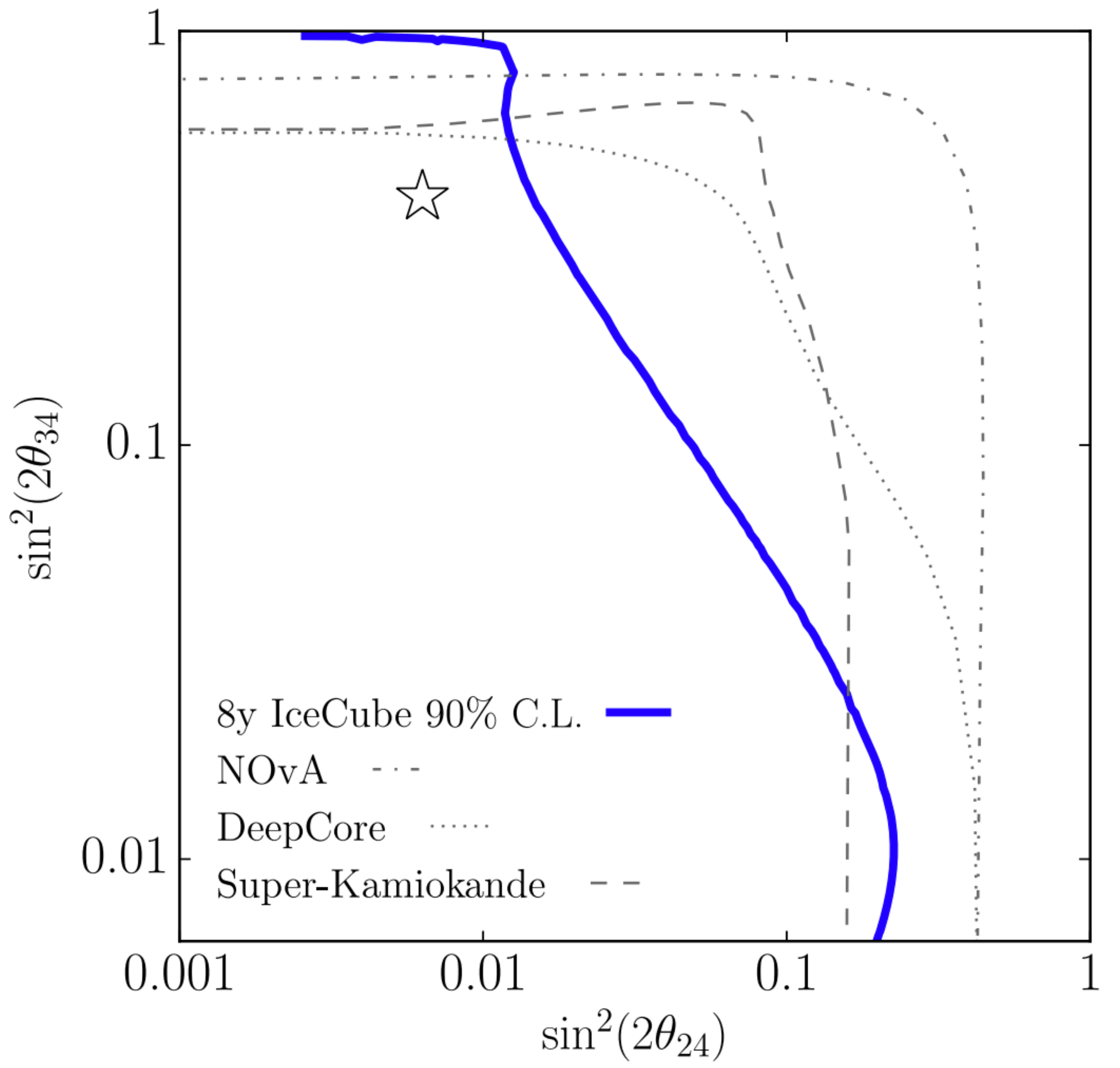
- 8 year results with DeepCore (low energy) data on the way
  - **Expect ~2 times world-best measurement on N_{ν_τ}**



eV-scale sterile neutrino search

PhysRevLett.125.141801 PhysRevD.102.052009

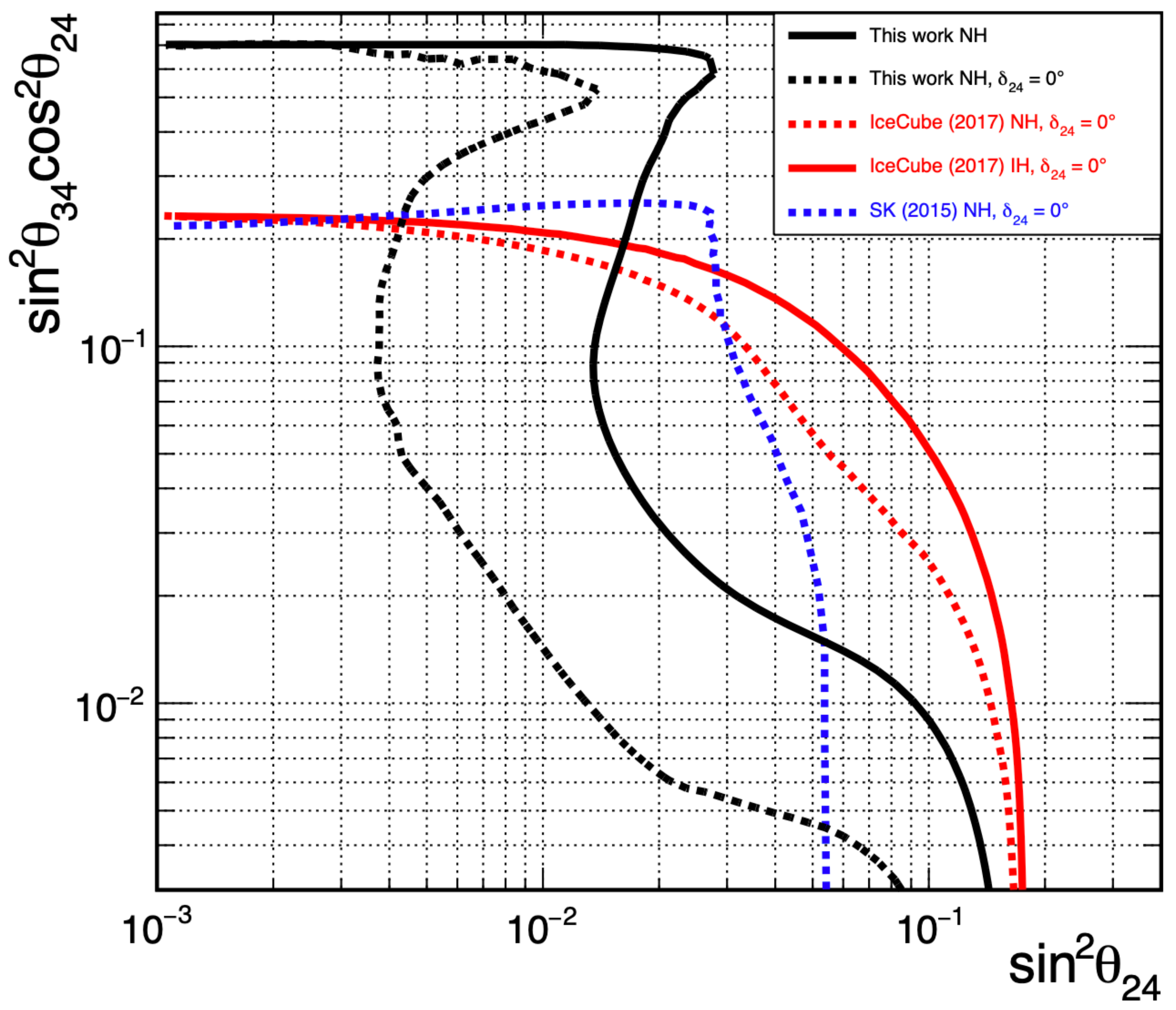




- IceCube 8 years of data, ~300k up-going atmospheric and astrophysical ν_μ
- **Results consistent with the no sterile neutrino hypothesis**, increased tension with short baseline anomalies

- ANTARES uses same dataset for atmospheric neutrino analysis to set constrains on $|U_{\mu 4}|^2 = sin^2\theta_{24}$ and $|U_{\tau 4}|^2 = sin^2\theta_{34}cos^2\theta_{24}$
- $|U_{\mu 4}|^2 < 0.13$ and $|U_{\tau 4}|^2 < 0.68$ at 99% C.L.

J. High Energ. Phys. 2019, 113 (2019)



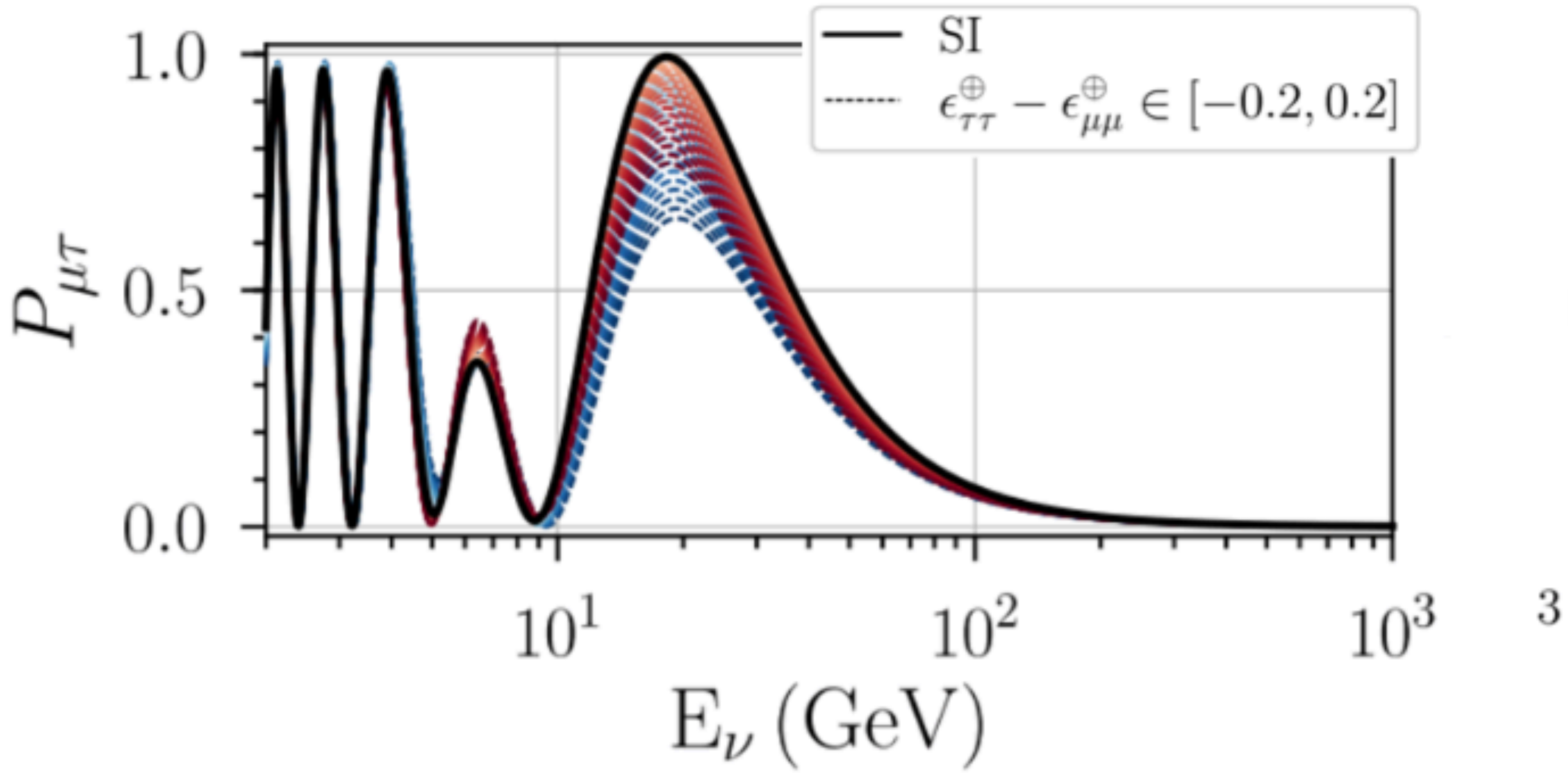
Non-Standard Interaction (NSI)

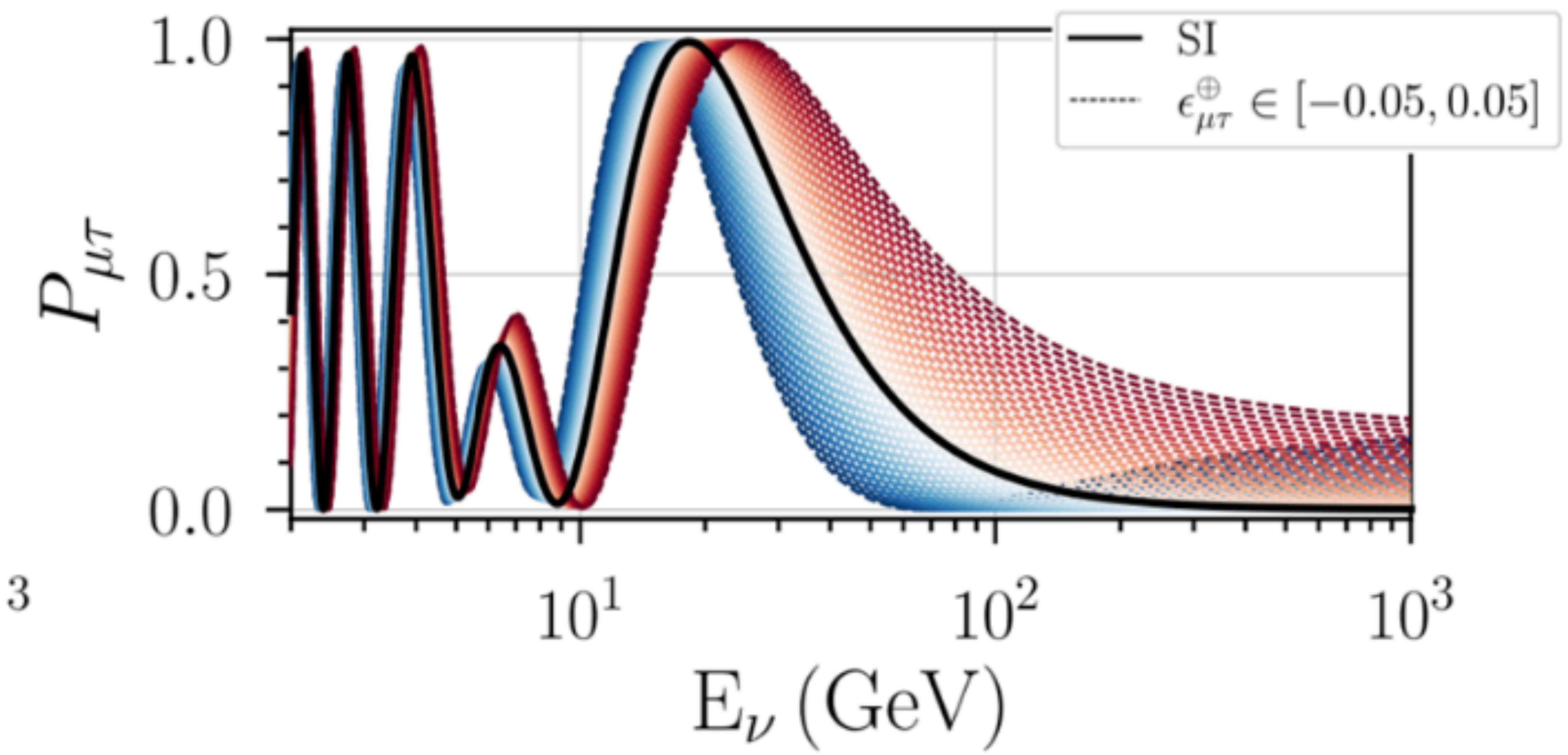
- Search for modified matter potential due to new vector forces as neutrinos cross the Earth
- Modify effective matter Hamiltonian via a 3×3 NSI matrix

$$H_{\mathrm{mat}}(x) = V_{\mathrm{CC}}(x) \begin{pmatrix} 1 + \epsilon^{\oplus}_{ee} - \epsilon^{\oplus}_{\mu\mu} & \epsilon^{\oplus}_{e\mu} & \epsilon^{\oplus}_{e\tau} \\ \epsilon^{\oplus *}_{e\mu} & 0 & \epsilon^{\oplus}_{\mu\tau} \\ \epsilon^{\oplus *}_{e\tau} & \epsilon^{\oplus *}_{\mu\tau} & \epsilon^{\oplus}_{\tau\tau} - \epsilon^{\oplus}_{\mu\mu} \end{pmatrix}$$

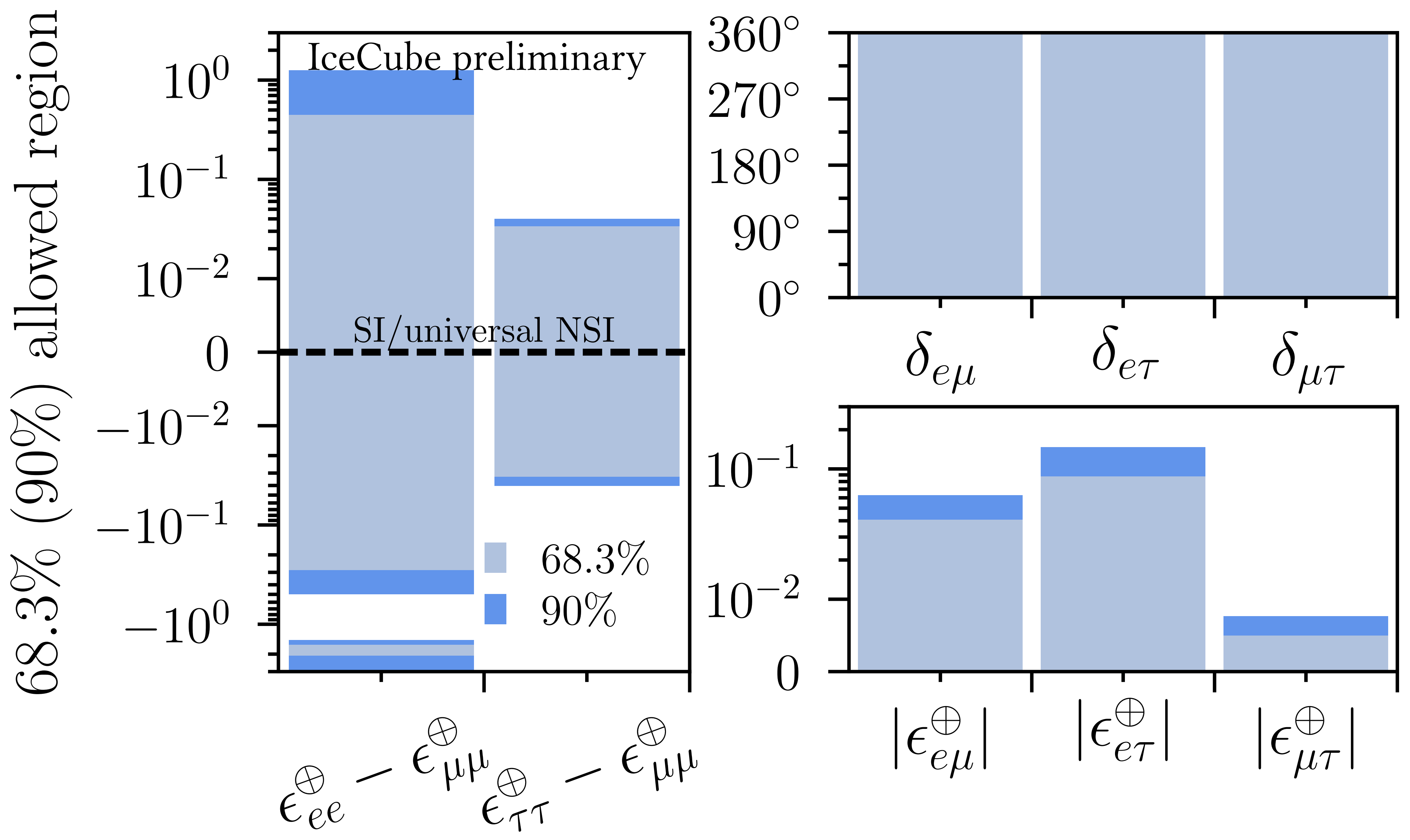
Lepton flavor violating

Lepton universality violating



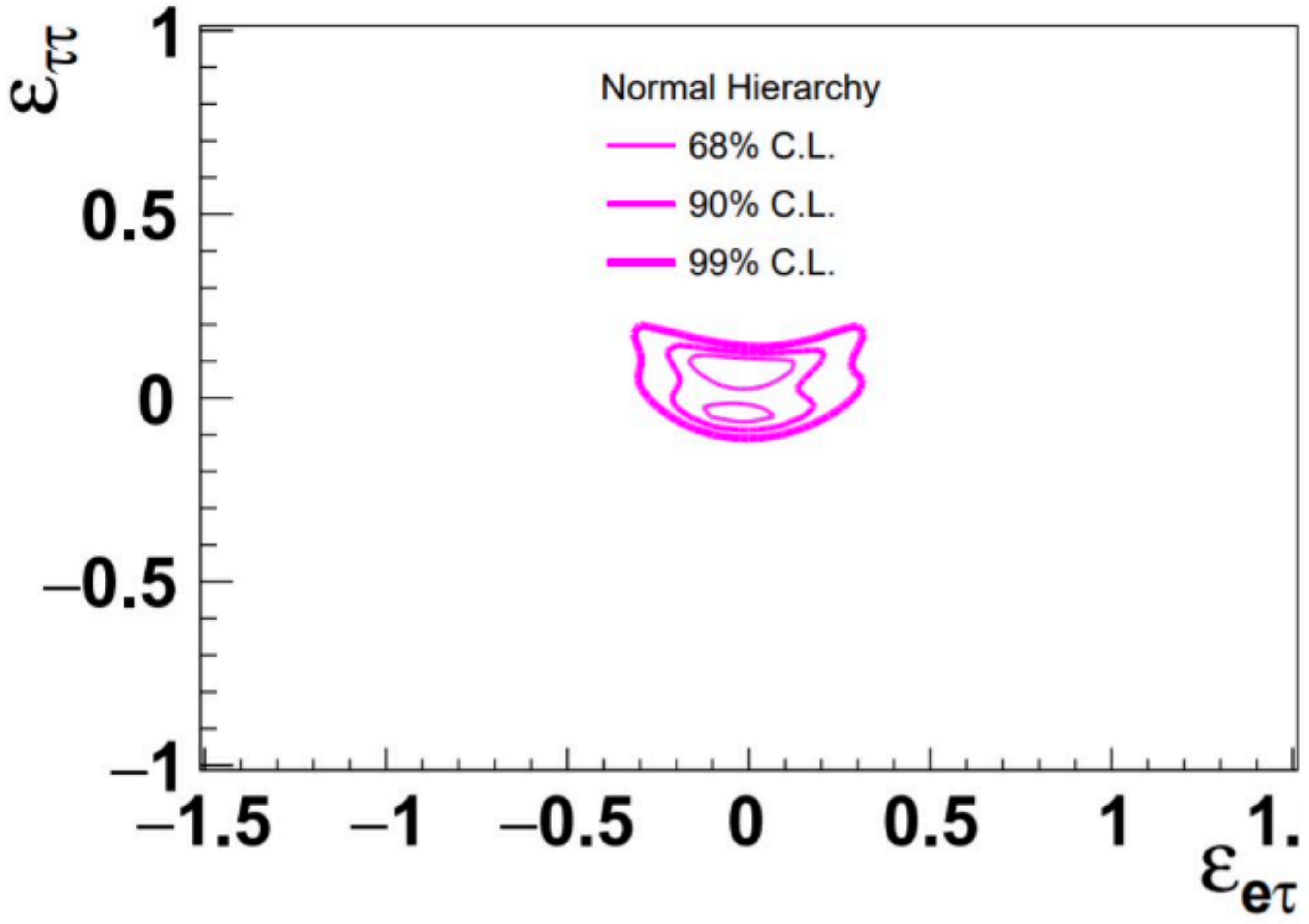


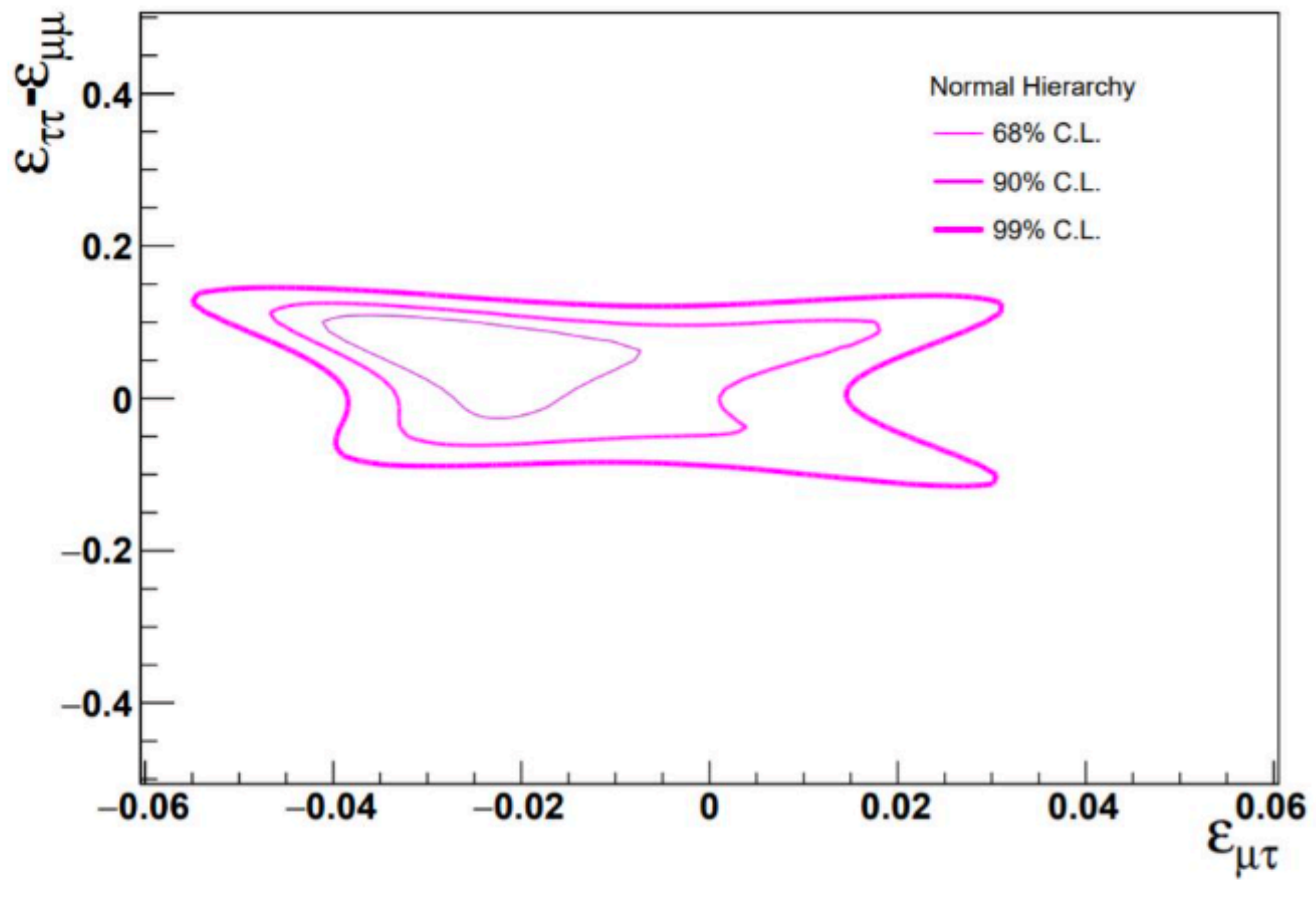
Non-Standard Interaction (NSI)



- DeepCore data can be used to put constraints on all matrix elements
- Results consistent with no NSI hypothesis
- Can achieve world-best limits in multiple channels

- SK reported best fit ϵ in $e - \tau$ sector and $\mu - \tau$ sector





ICHEP2020 Talk + Proceedings

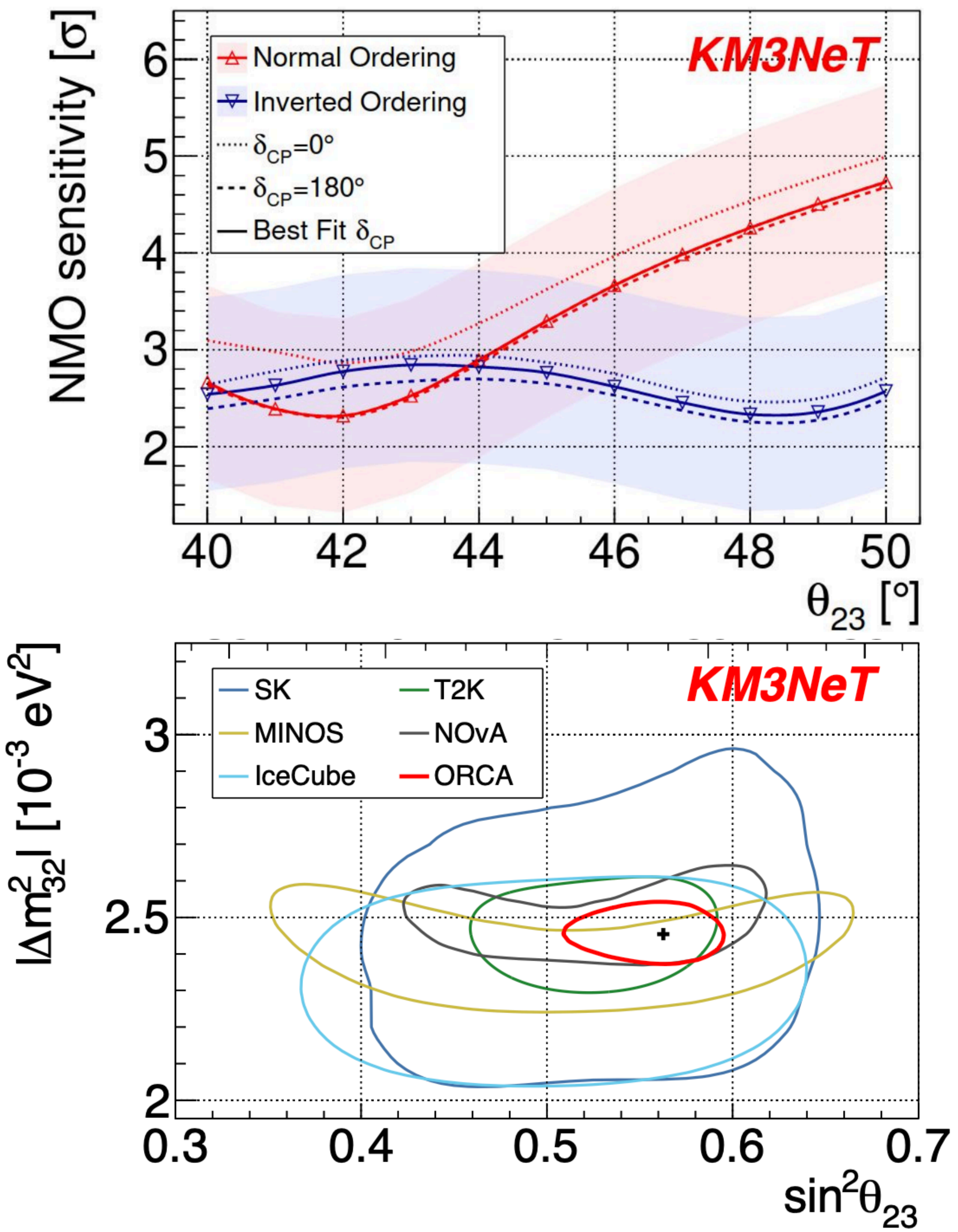
Future Prospects

KM3NeT/ORCA

https://arxiv.org/abs/2103.09885

Next generation Water Cherenkov telescope

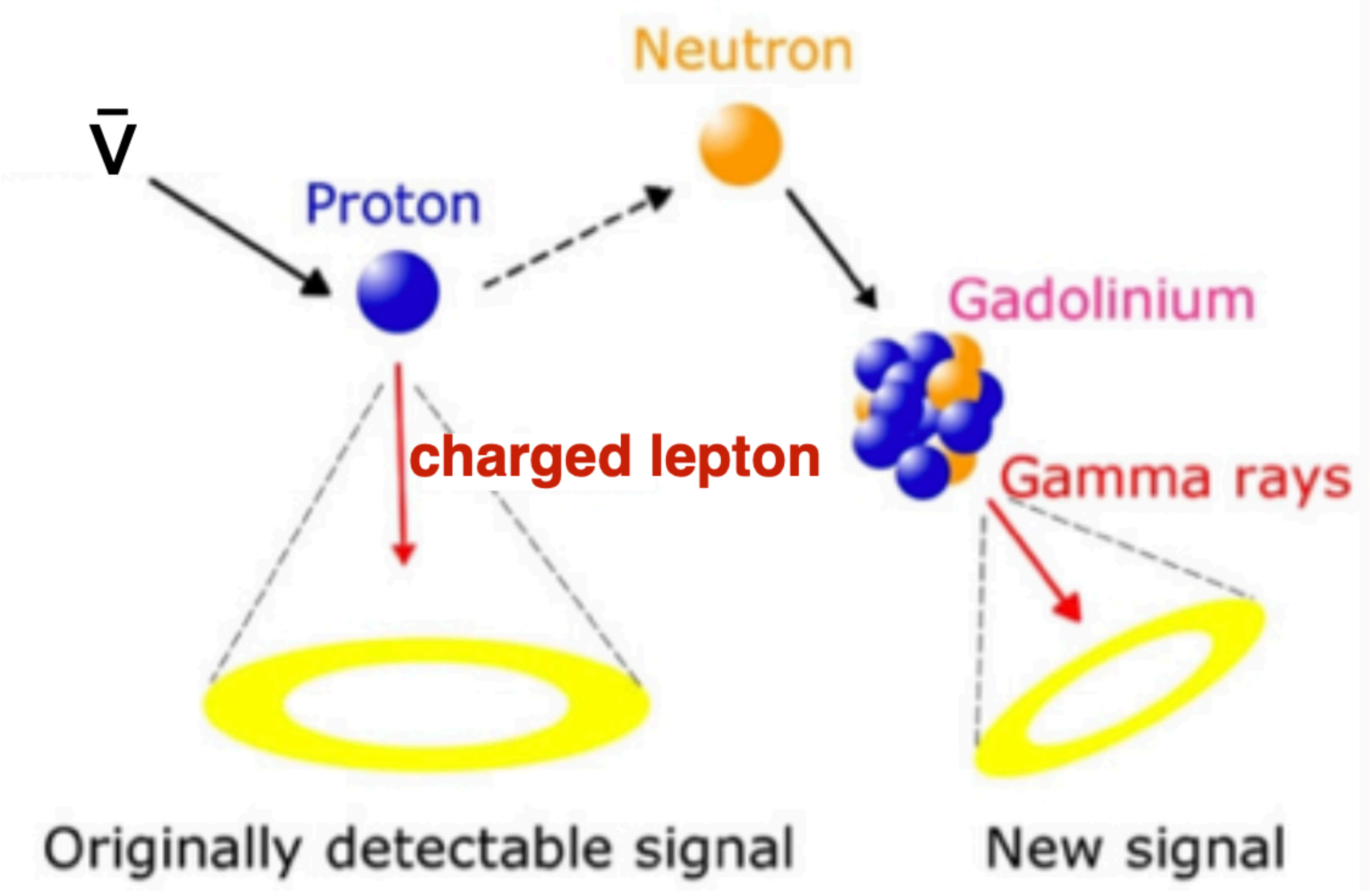
> Large volume of sea water as detection volume
> ORCA : low energy neutrino telescope optimised for GeV neutrino detection
> Can achieve competitive sensitivity with atmospheric mixing parameters and NMO with 3 years of data
> First 6 Detection Unit (Strings) operating since Feb 2020 shows good data/MC agreement



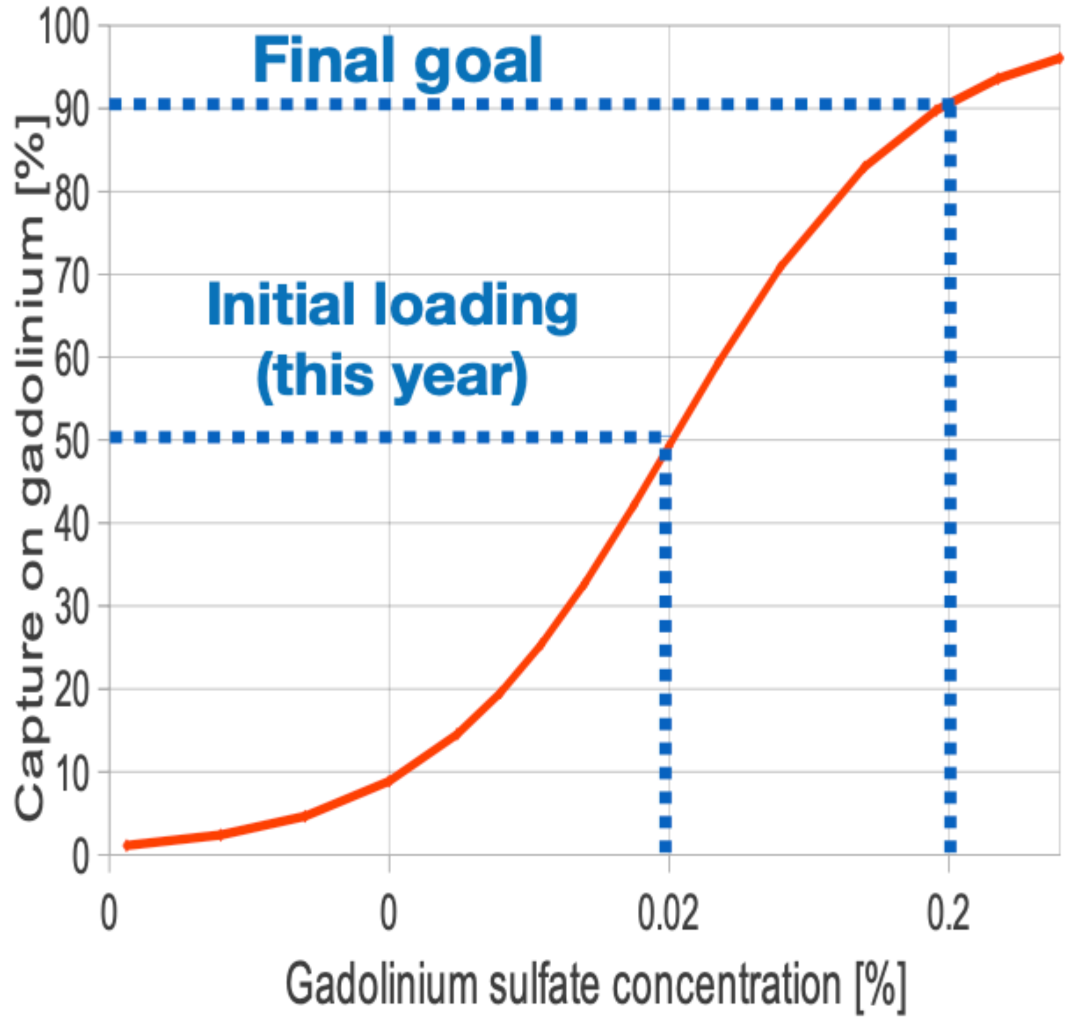
SK with Gadolinium

Improving neutron tagging efficiency

- Delayed gamma cascades from Gd can help distinguish between $\nu/\bar{\nu}$
- CC/NC separation, neutrino energy reconstruction
- Currently loading 0.02% Gd achieved ~50% n-capture on Gd
  - Aim to achieve 90% with 0.2% loading
- Also benefits other analyses such as supernova neutrinos and proton decay



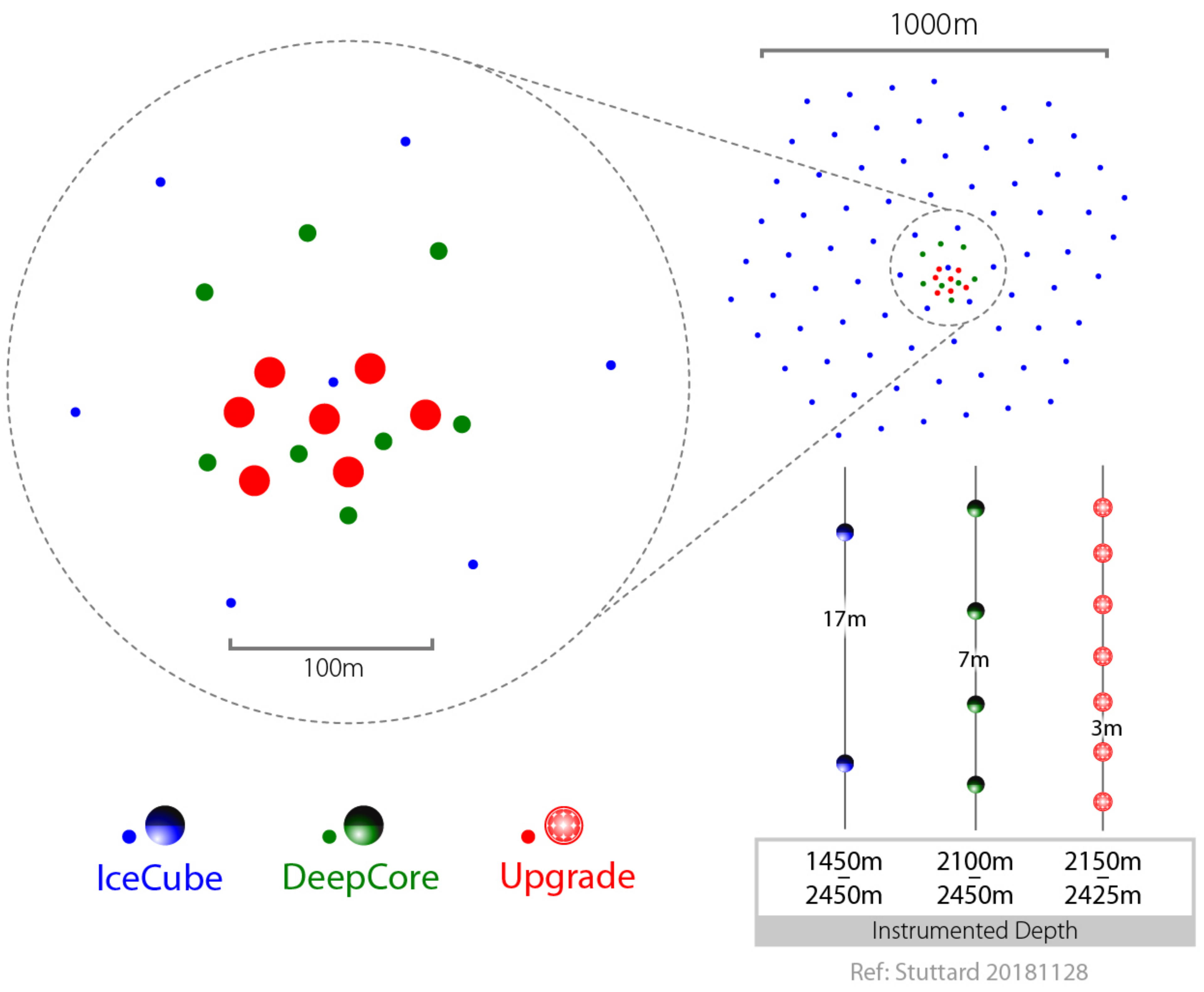
Talk at Neutrino2020



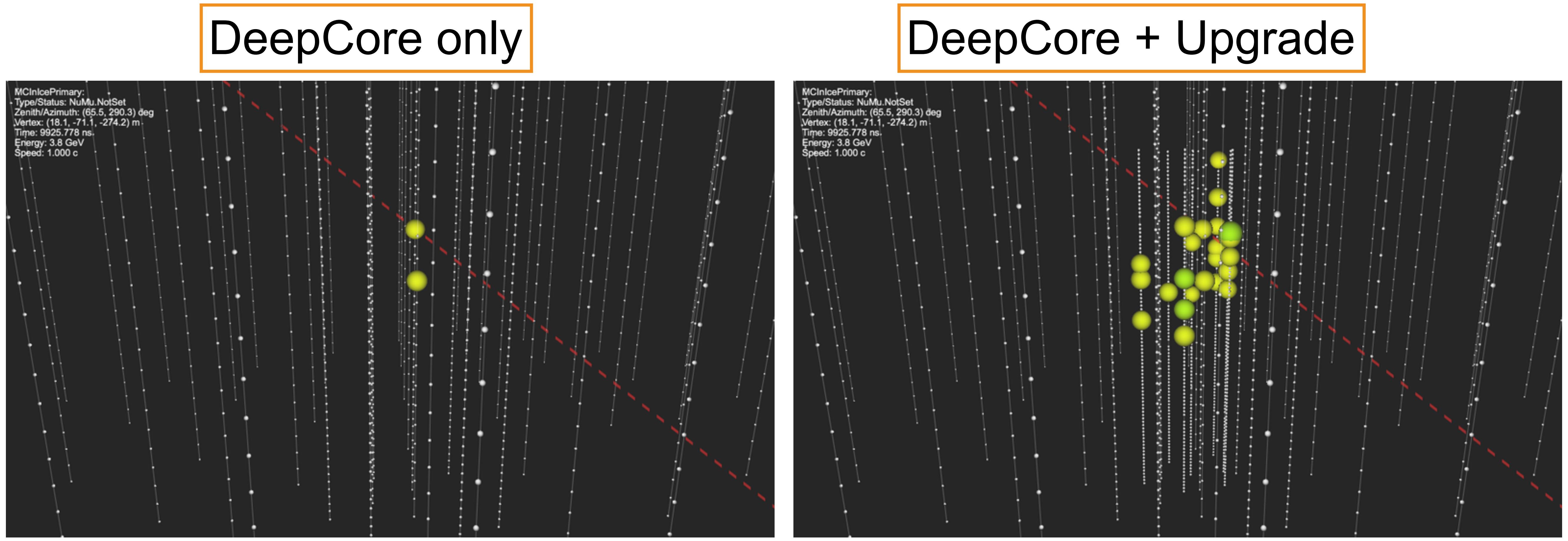
IceCube Upgrade

Improvements to low-energy sensitivity

- > 7 new strings deploy within DeepCore
- > Densely packaged in 2 Mton core
- > Improved detector/ice calibration
- > Funded, planned deployment in 2022/3
- > Schedule under review due to COVID-19



- > Large increase in detected photons with the Upgrade
- > Events as low as **~1 GeV** can be triggered and reconstructable by the Upgrade
- > All DeepCore science but better!



3.8 GeV ν_μ

Summary

> Atmospheric neutrinos provides good opportunities for exploring oscillations
    > Many new measurements with full 8 year statistics of DeepCore on the way
> Upcoming experimental developments shows high potential in further probing BSM Physics
> Some effects could complicate extraction of CP phase because of degenerate effects (e.g. NSI, sterile neutrinos)

> Together with next generation LBL experiments, promise to be an exciting decade with many new measurements
> Important to get high precision oscillation parameters to determine the amount of CPV in leptonic sector

Thank you for listening!

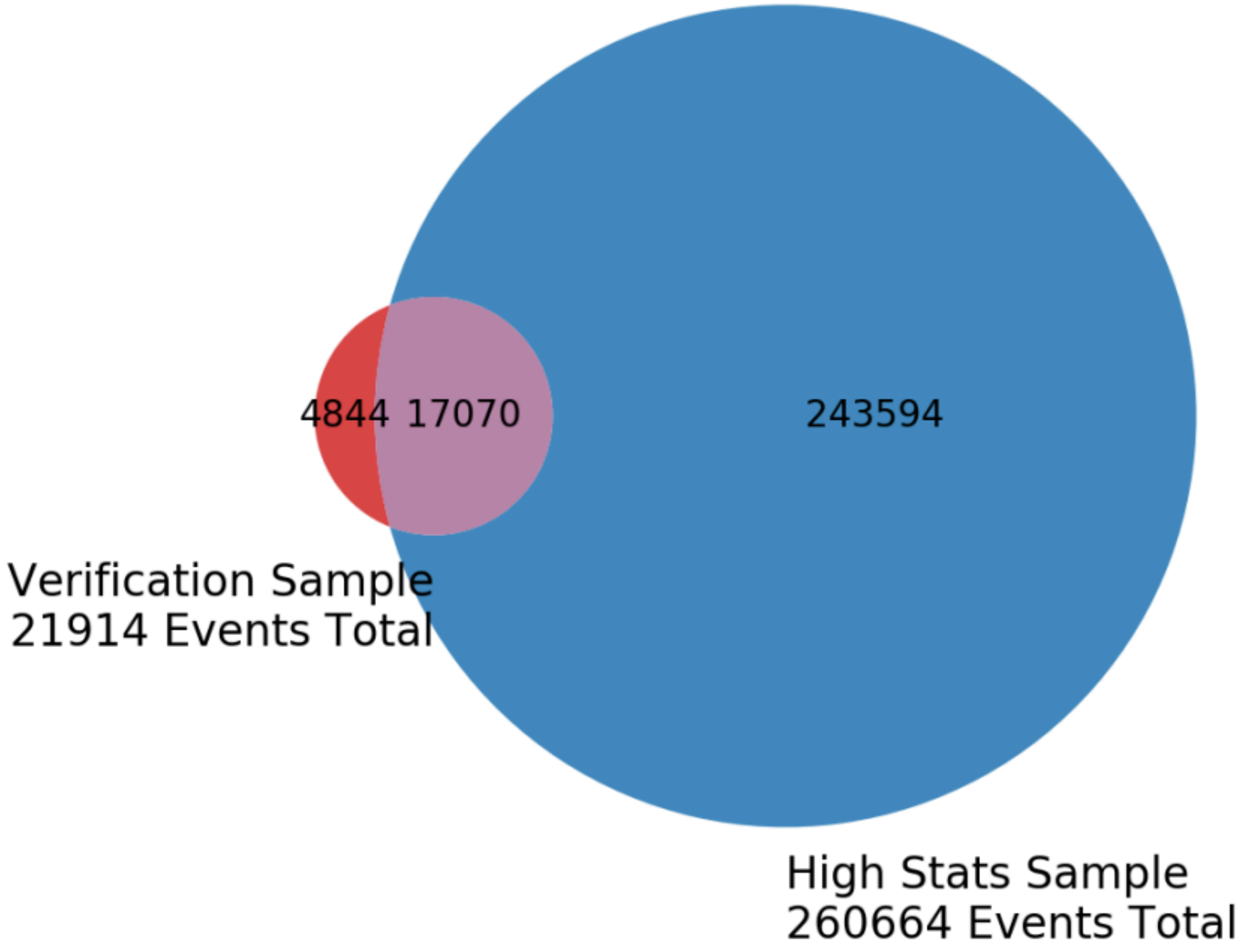
Backup

Overlap between Samples

DeepCore 8 year High Statistics Sample and Sub-sample

Entire Verification Sample	21,914 events
Entire High Stats Sample	260,664 events

Verification Sample Only	4,844 events
Present in Both Samples	17,070 events
High Stats Sample Only	243,594 events



From K. DeHolton