PINGU
Status and Plans

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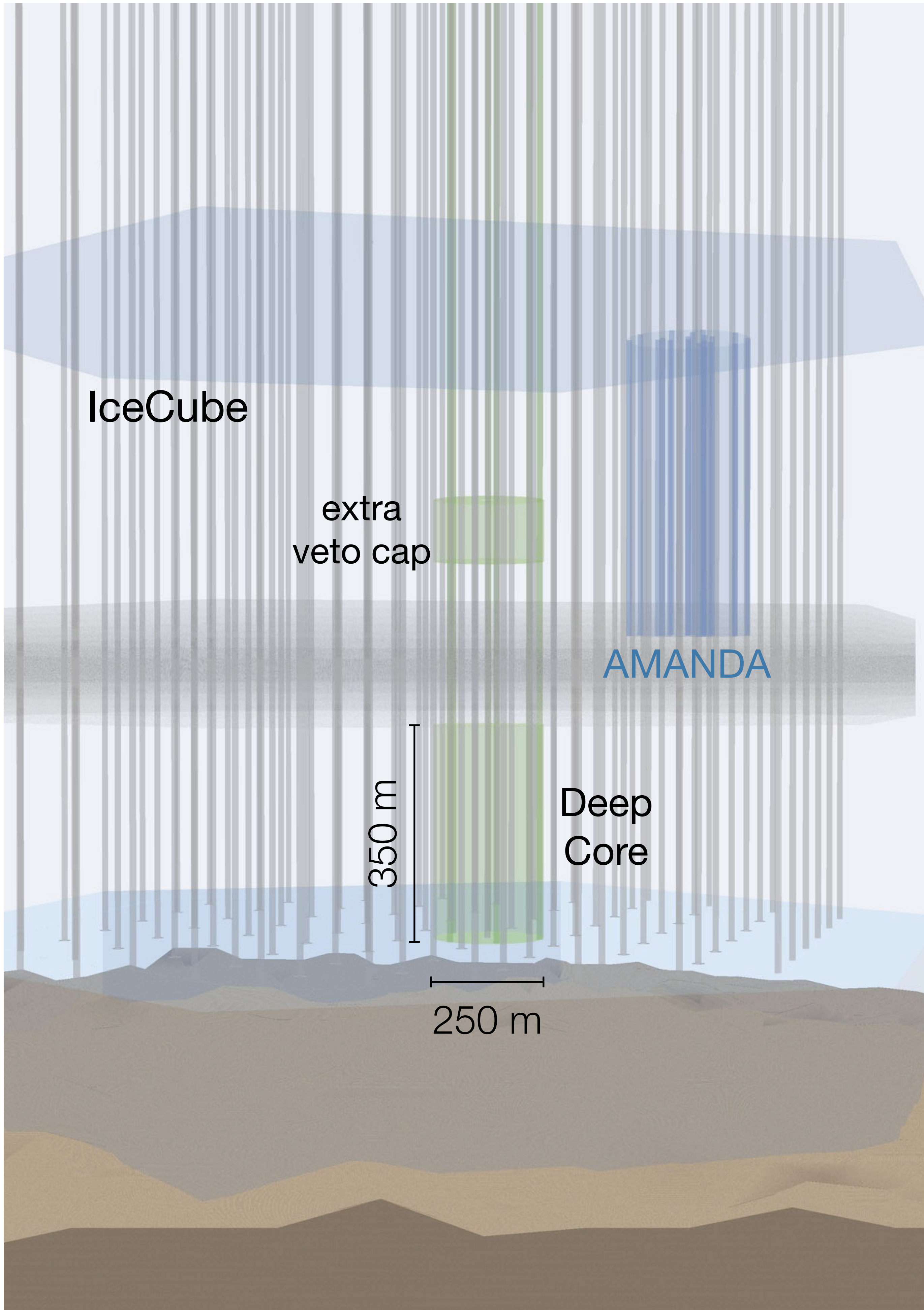
ICECUBE

IceCube Science Advisory Committee
Madison, Wisconsin
October 19, 2015

PRECISION ICECUBE NEXT GENERATION UPGRADE

IceCube DeepCore

- A more densely instrumented region at the bottom center of IceCube
  - Eight additional strings, super-bialkali PMTs
  - String spacing ~70 m, DOM spacing 7 m: ~5x higher photon collection efficiency than IceCube



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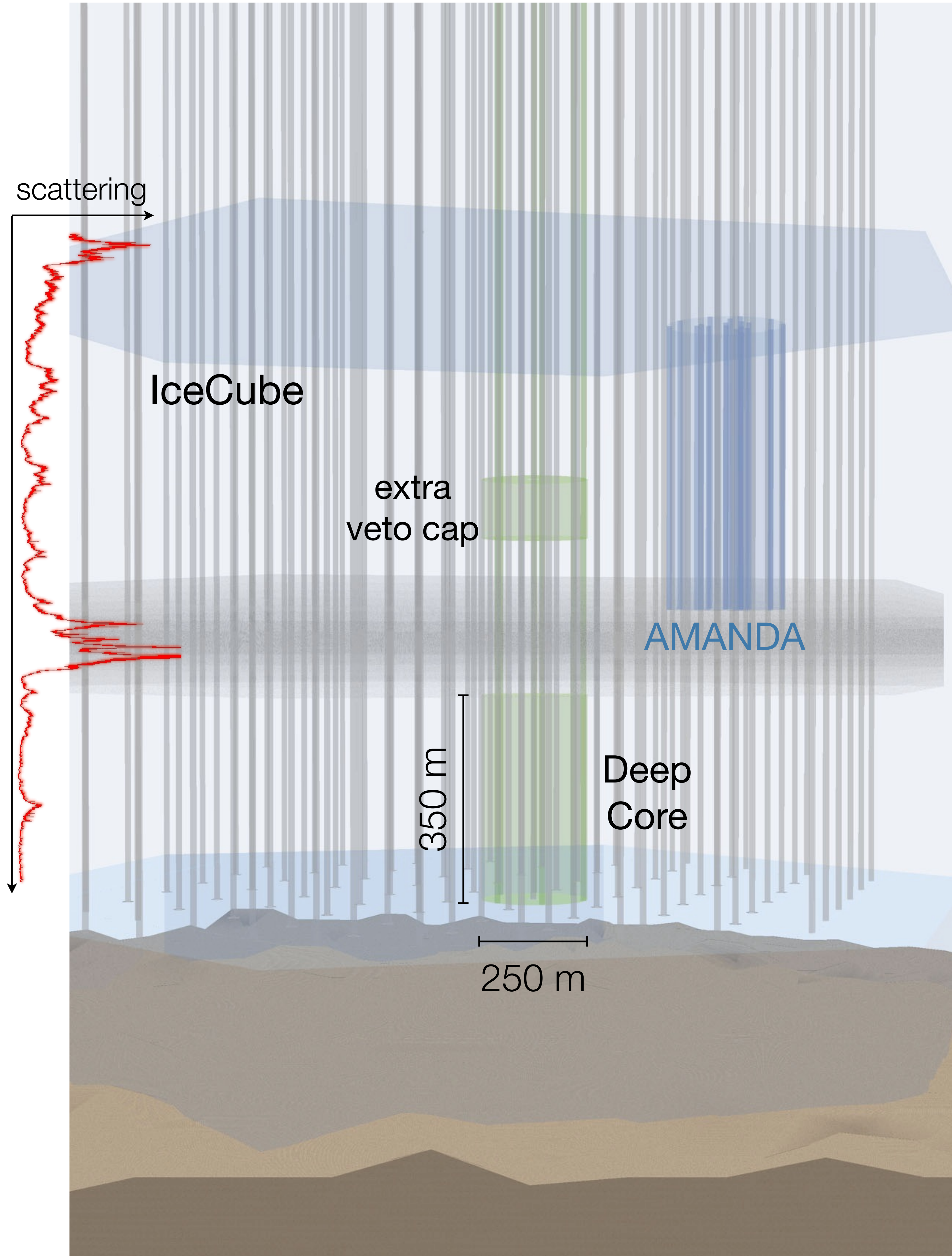
  - $\lambda_{atten} \approx$ 45-50 m, very low levels of radioactive impurities



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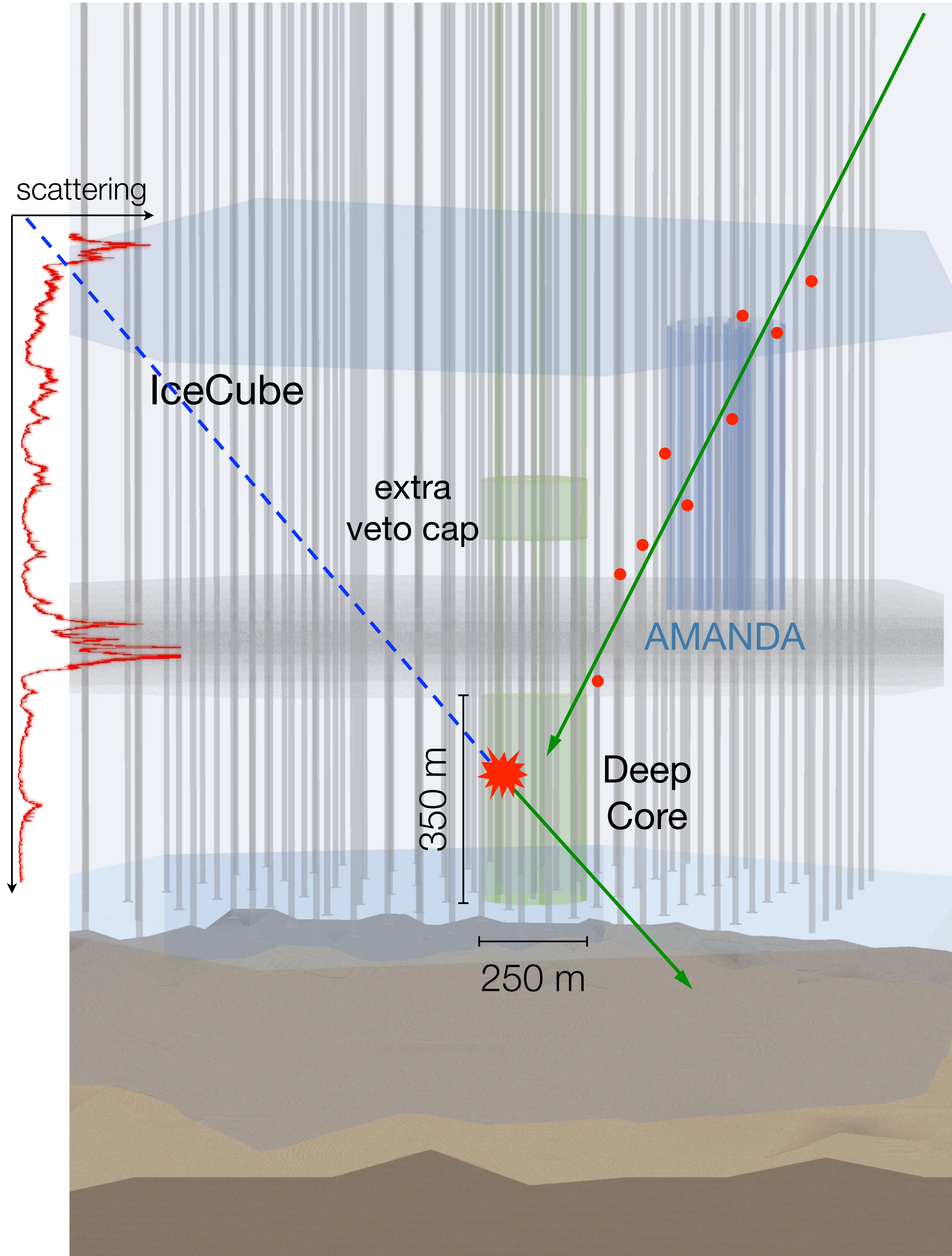
  - $\lambda_{atten} \approx$ 45-50 m, very low levels of radioactive impurities
- IceCube provides an active veto against cosmic ray muons



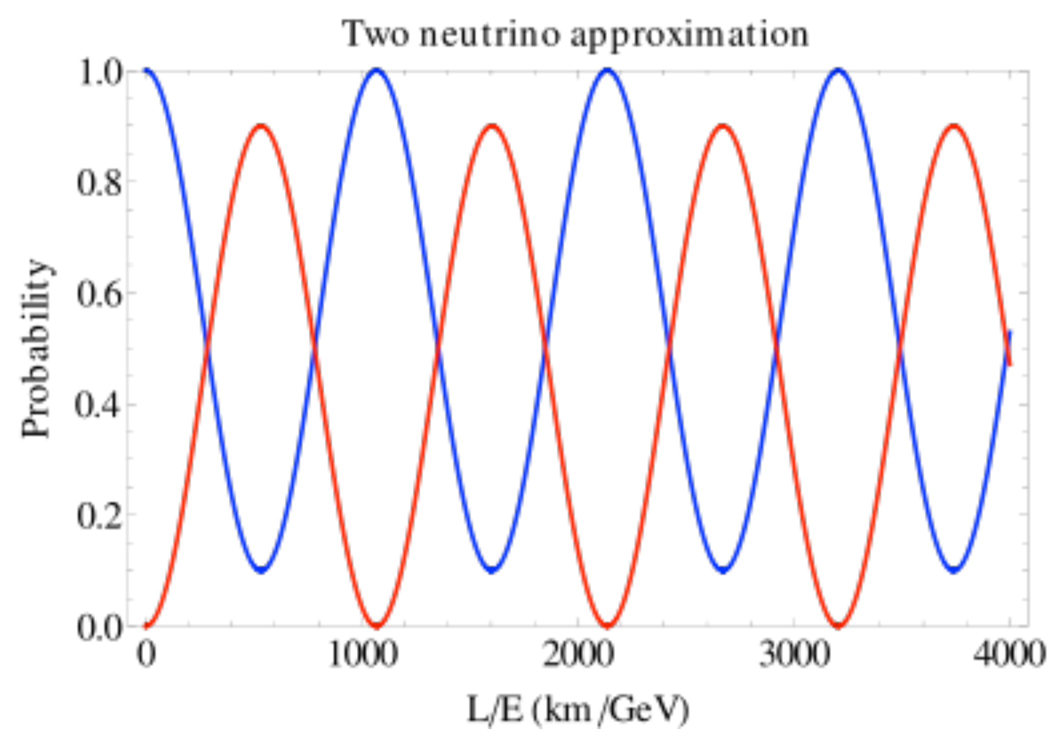
DeepCore Physics Results

- Measurement of atmospheric neutrino oscillations
  - First IceCube observation: *Phys Rev. Lett*. 111, 081801 (2013)
  - Improved analysis with reduced energy threshold and two-dimensional data fit greatly improves precision: *Phys. Rev.* D91, 072004 (2015)
- Dark matter searches
  - Solar WIMP annihilation: *Phys. Rev. Lett*. 110, 131302 (2013) – preliminary update at ICRC
  - Dwarf galaxies: *Phys. Rev.* D88, 122001 (2013)
  - Galactic Halo: *Eur. Phys. J.* C75, 20 (2015)
- Measurement of atmospheric electron neutrino spectrum
  - First measurement above 50 GeV: *Phys. Rev. Lett*. 110, 151105 (2013)
- Direct searches for exotic particles
  - E.g. monopoles: *Eur. Phys. J.* C74, 2938 (2014)

Neutrino Flavor Oscillations

- Neutrinos are produced in flavor eigenstates, but propagation through space depends on the Hamiltonian and thus the mass
  - The three mass components of each flavor eigenstate propagate at different speeds, leading to interference between the flavor components of each mass eigenstate
  - Can calculate the survival probability of each flavor:

$$P_{\alpha\to\alpha} = |\langle\nu_\alpha|\nu_\alpha(t)\rangle|^2 \rightarrow \boxed{\text{Algebra!}} \rightarrow P_{\mu\mu} \approx 1 - \sin^2 2\theta \, \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

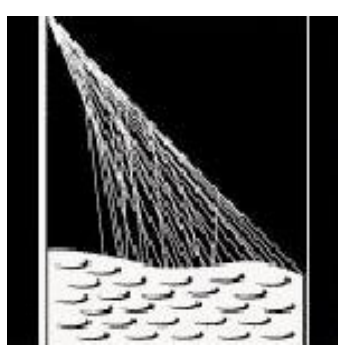
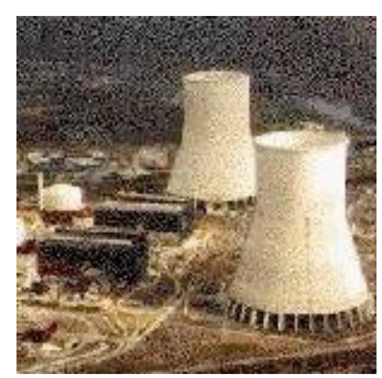


Three-Flavor Mixing

- Pontecorvo-Maki-Nakagawa-Sakata matrix describes mixing between neutrino flavor eigenstates and mass eigenstates
  - Analogous to CKM matrix for quarks, but off-diagonal element are large

($s_{ij} = \sin\theta_{ij}$ $c_{ij} = \cos\theta_{ij}$)

$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\,e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}\,e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

= () x () x ()

atmospheric reactor/beam solar

Three-Flavor Mixing

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Potential CP violation ~ θ_{13}

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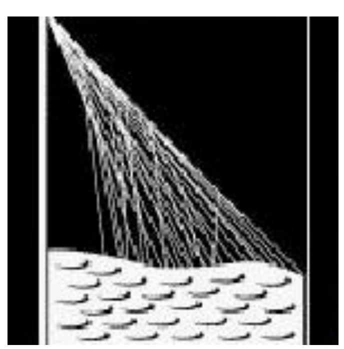
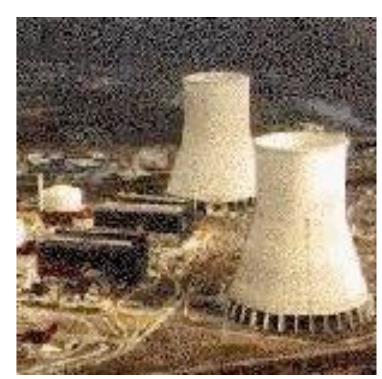
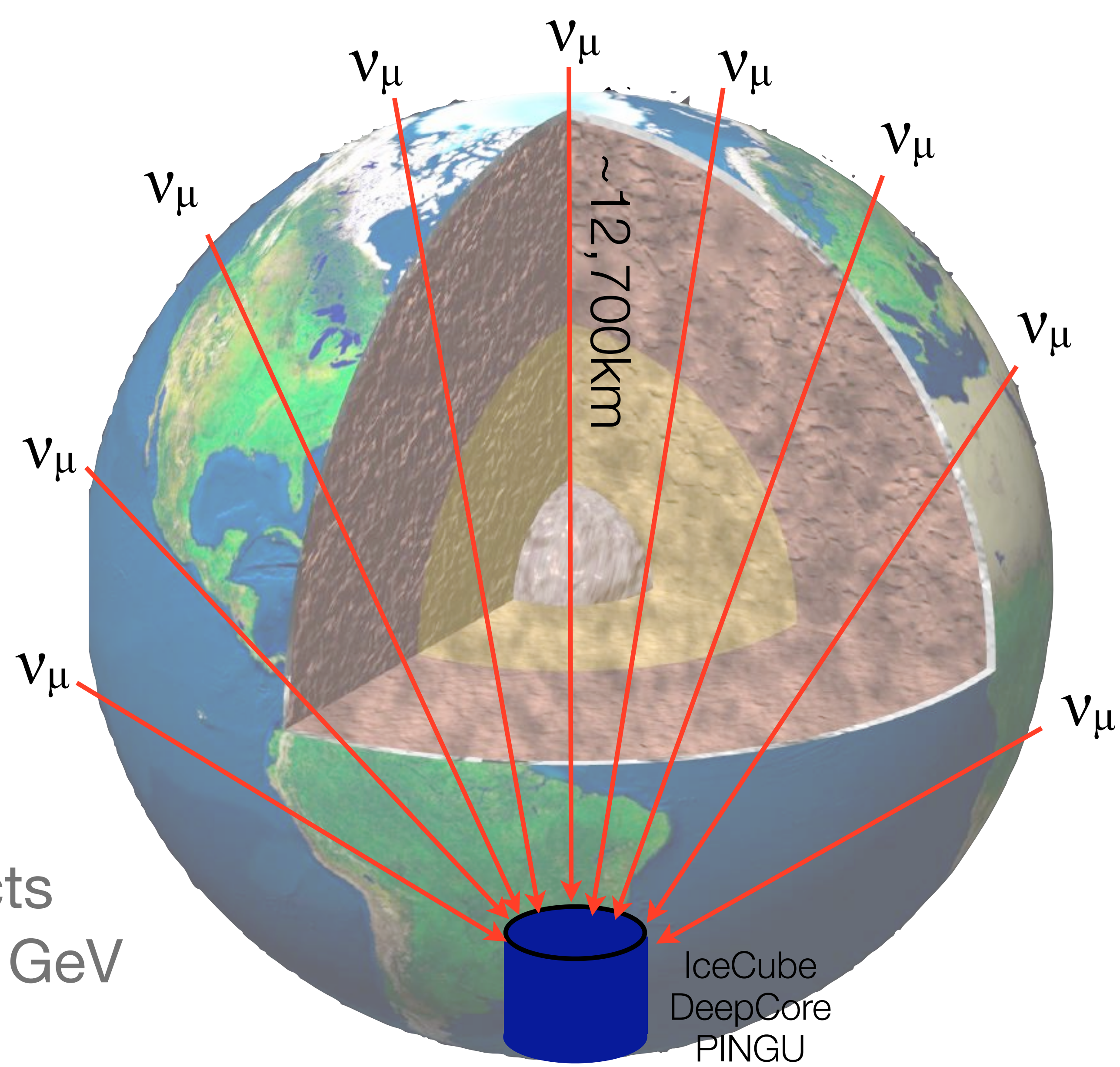
$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\,e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}\,e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

= () x () x ()

atmospheric reactor/beam solar

Oscillation Physics with Atmospheric Neutrinos

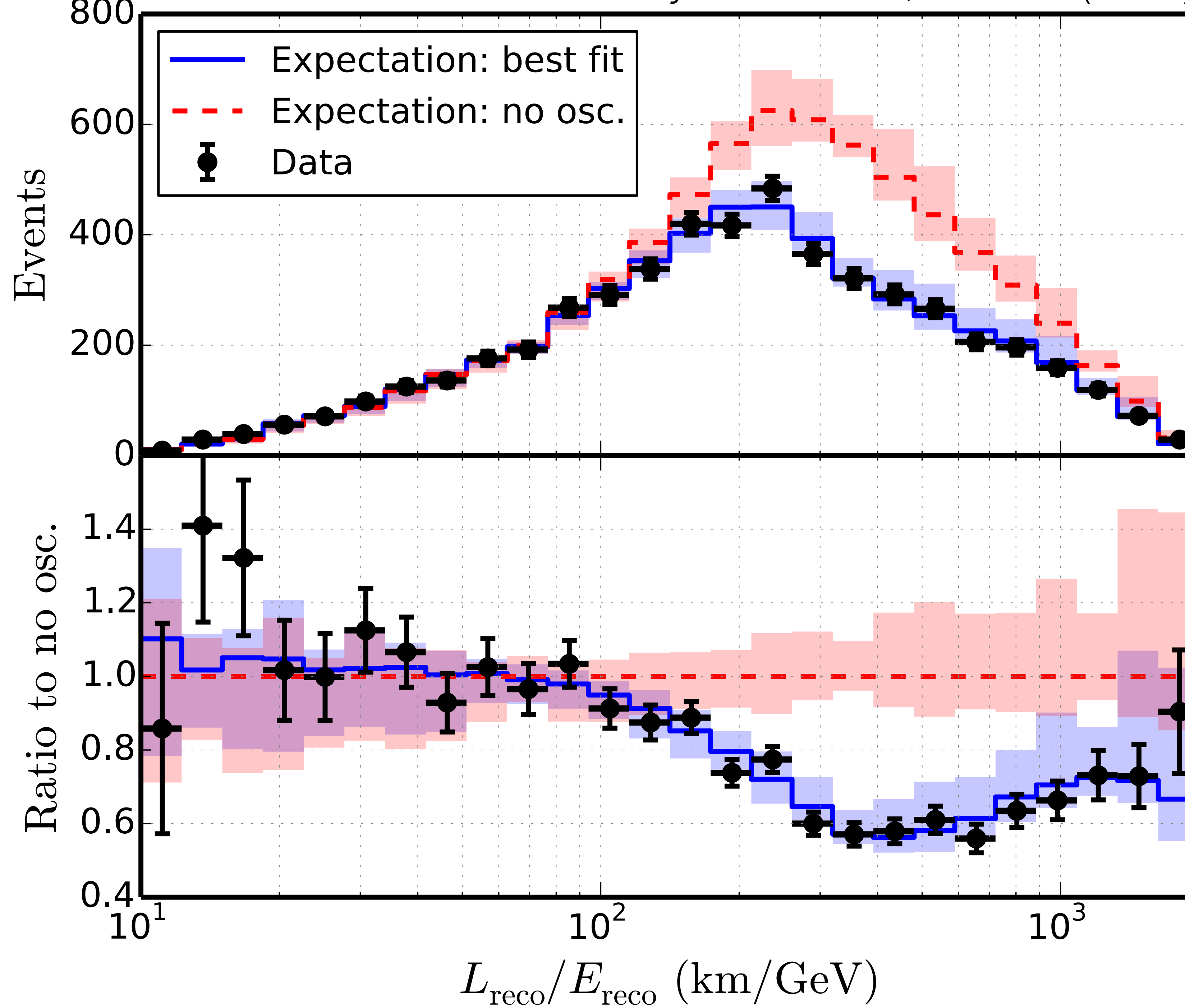
- Neutrinos observed over a wide range of energies and baselines
  - Oscillations produce distinctive pattern in energy-angle space
  - Approach: control systematics using events in “side band” regions – trade statistics for constraints on systematics
- Neutrinos oscillating over one Earth diameter have a ν_μ survival minimum at ~25 GeV
  - Hierarchy-dependent matter effects on ν or $\bar{\nu}$ (MSW etc.) below 10-20 GeV



Current IceCube Oscillation Results

- Data projected onto reconstructed (L/Eν) here for illustration
  - Real analysis is done in 2D to maximize separation between systematics and oscillations
  - Shaded range shows systematic uncertainties allowed by IceCube data

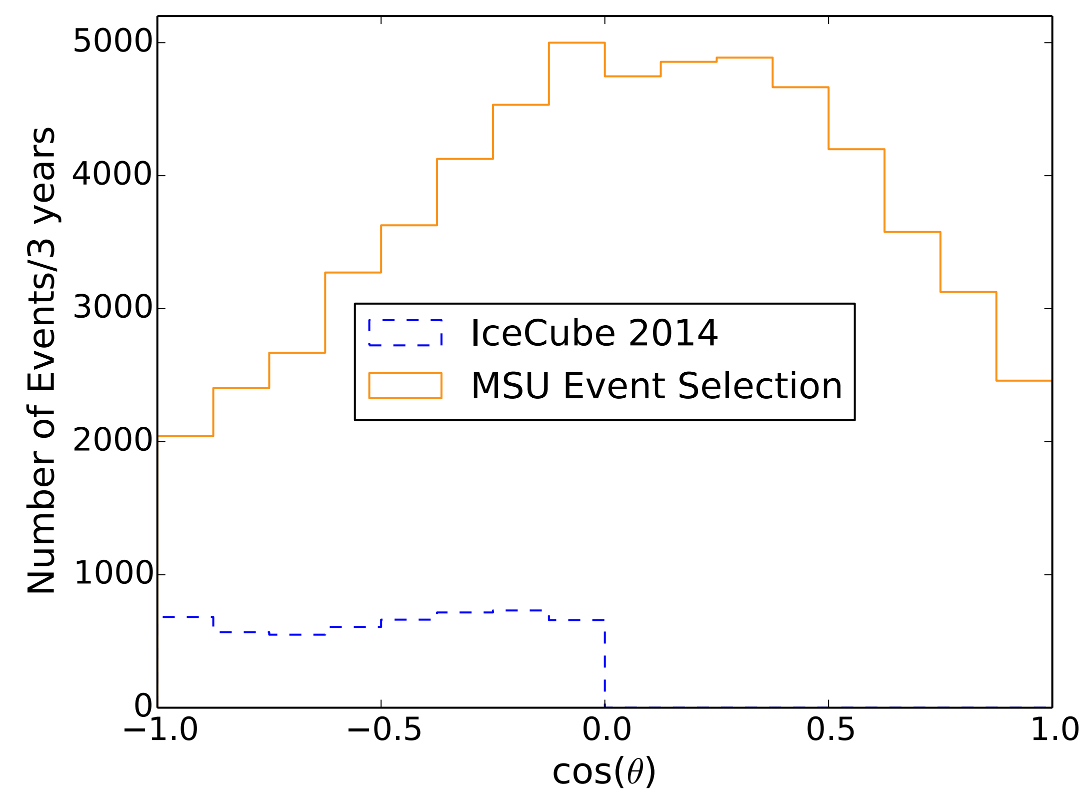
Phys. Rev. D91, 072004 (2015)

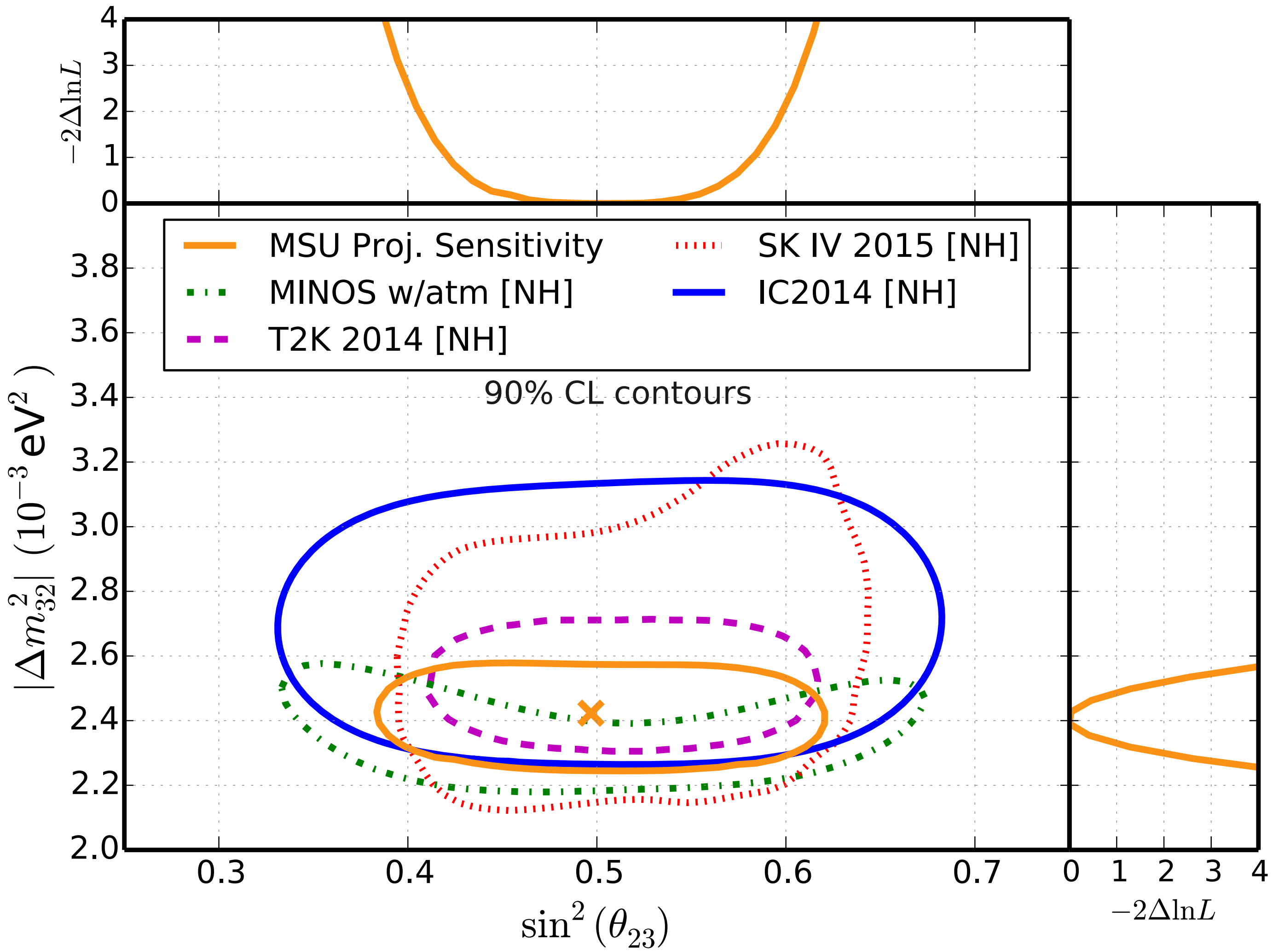


Coming Attractions

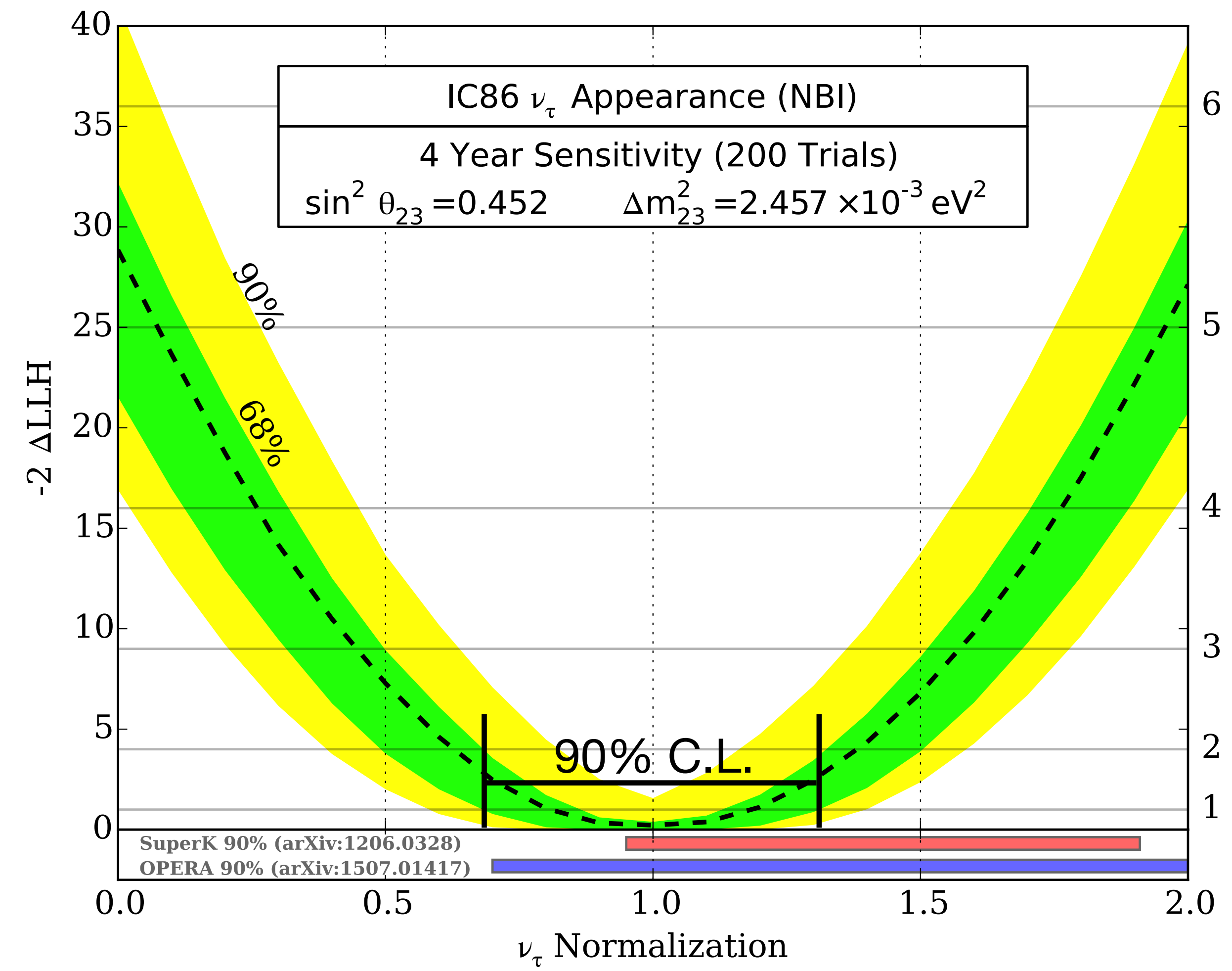
Two semi-independent ν_μ disappearance analyses: MSU and DESY follow-up

- Higher event rates, allowing better constraints on systematics





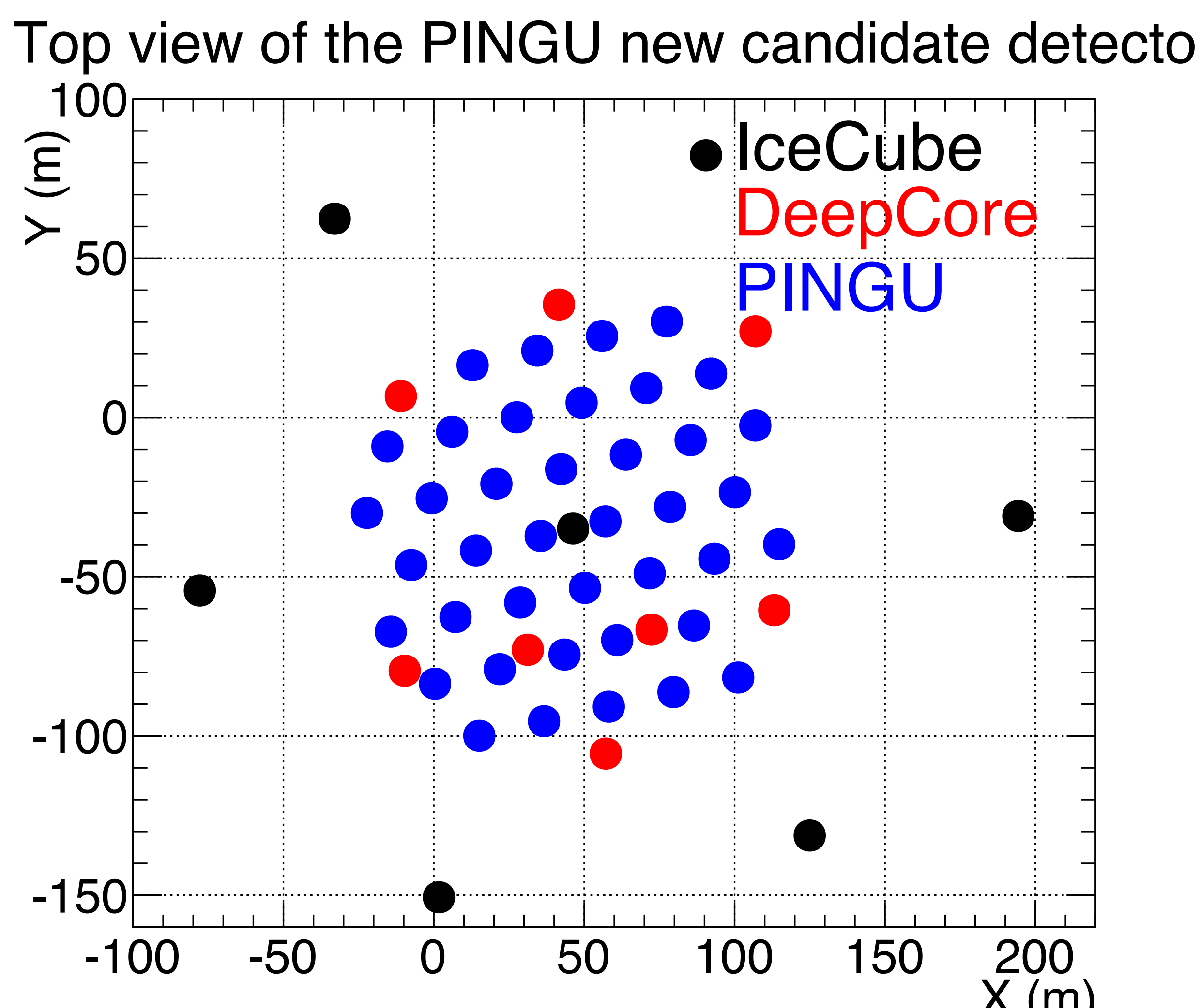
ν_τ appearance: NBI, MSU, PSU



PINGU

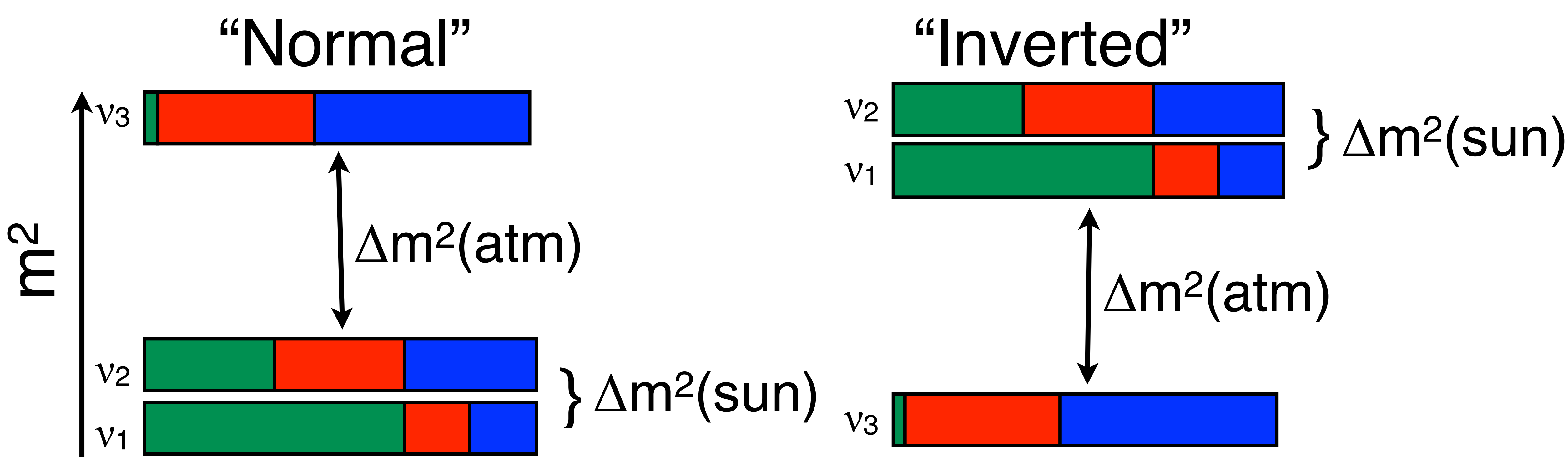
Precision IceCube Next Generation Upgrade

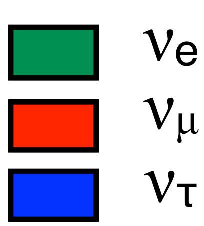
- 40 additional strings embedded in DeepCore with 22 m spacing, 96 DOMs spaced vertically at 3 m
  - ~25x higher photocathode density than DeepCore
  - Additional calibration devices to better control detector systematics (not included in projections)
- Achieve few GeV energy threshold with 6 MTon fiducial volume
- Closely follow IceCube design to minimize costs, risks, timeline



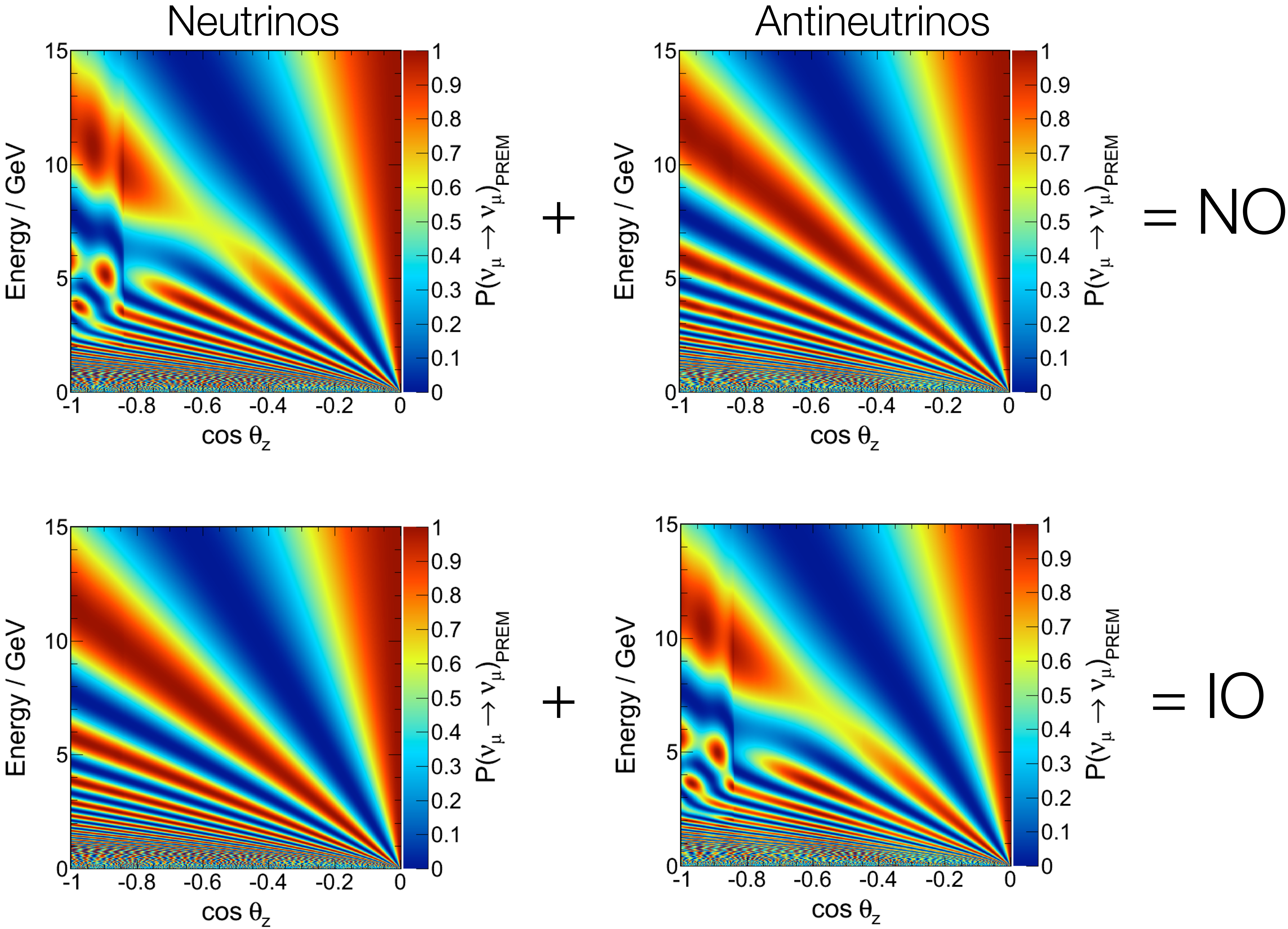
Neutrino Mass Ordering

- One of the few remaining unmeasured fundamental parameters in particle physics – significant impact on theories of neutrino mass

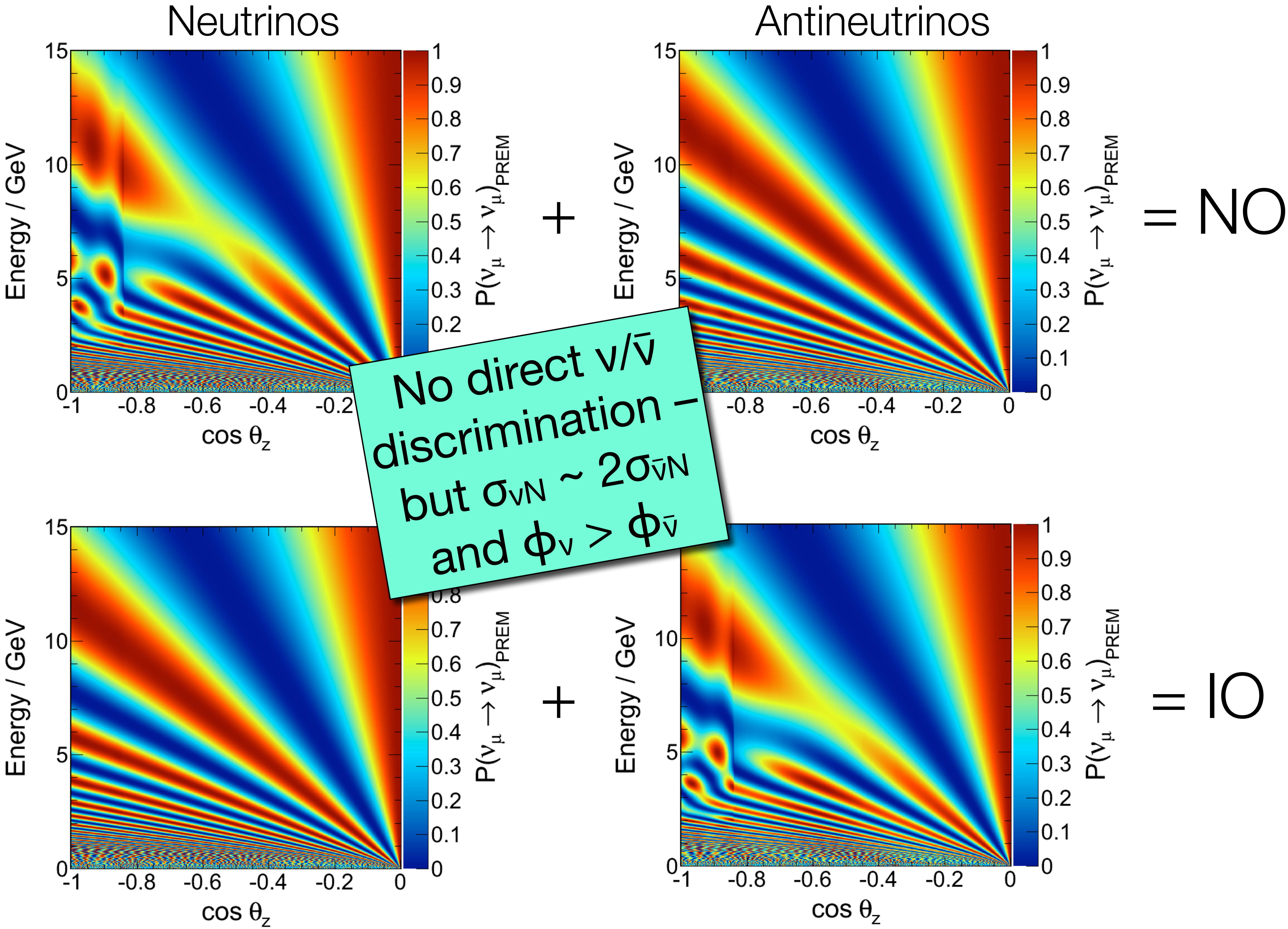




PINGU can distinguish the ordering by observing matter effects on oscillations at ~5-15 GeV



Neutrinos
Antineutrinos
+
= NO
+
= IO
Energy / GeV
cos θ_z
P(ν_μ → ν_μ)_PREM
0
5
10
15
-1
-0.8
-0.6
-0.4
-0.2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1


Neutrinos
Antineutrinos
Energy / GeV
cos θz
P(νμ → νμ)PREM
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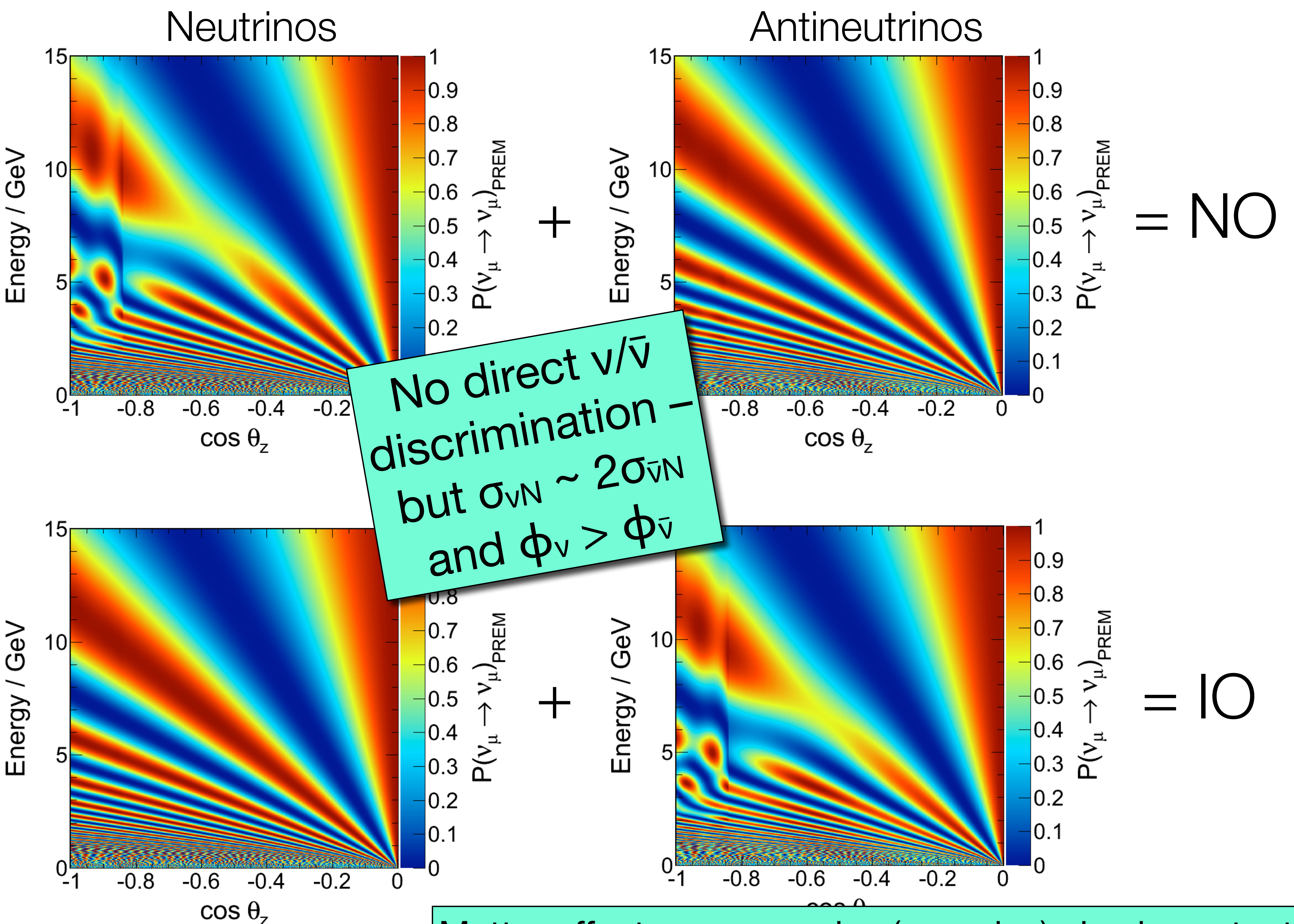
= NO
= IO
No direct ν/ν̄ discrimination – but σνN ~ 2σν̄N and φν > φν̄

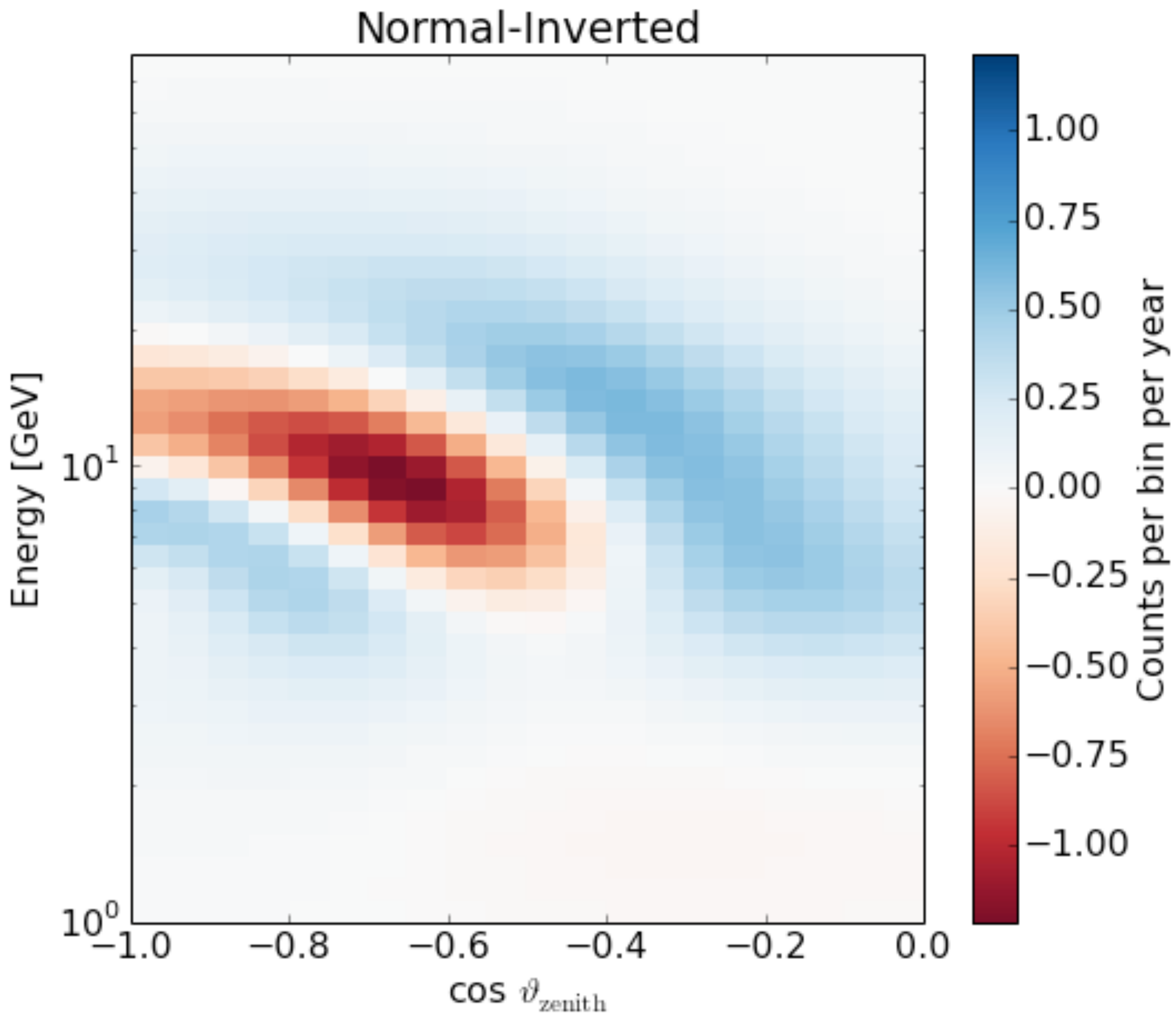


No direct ν/ν̄ discrimination – but $\sigma_{\nu N} \sim 2\sigma_{\bar{\nu}N}$ and $\phi_{\nu} > \phi_{\bar{\nu}}$

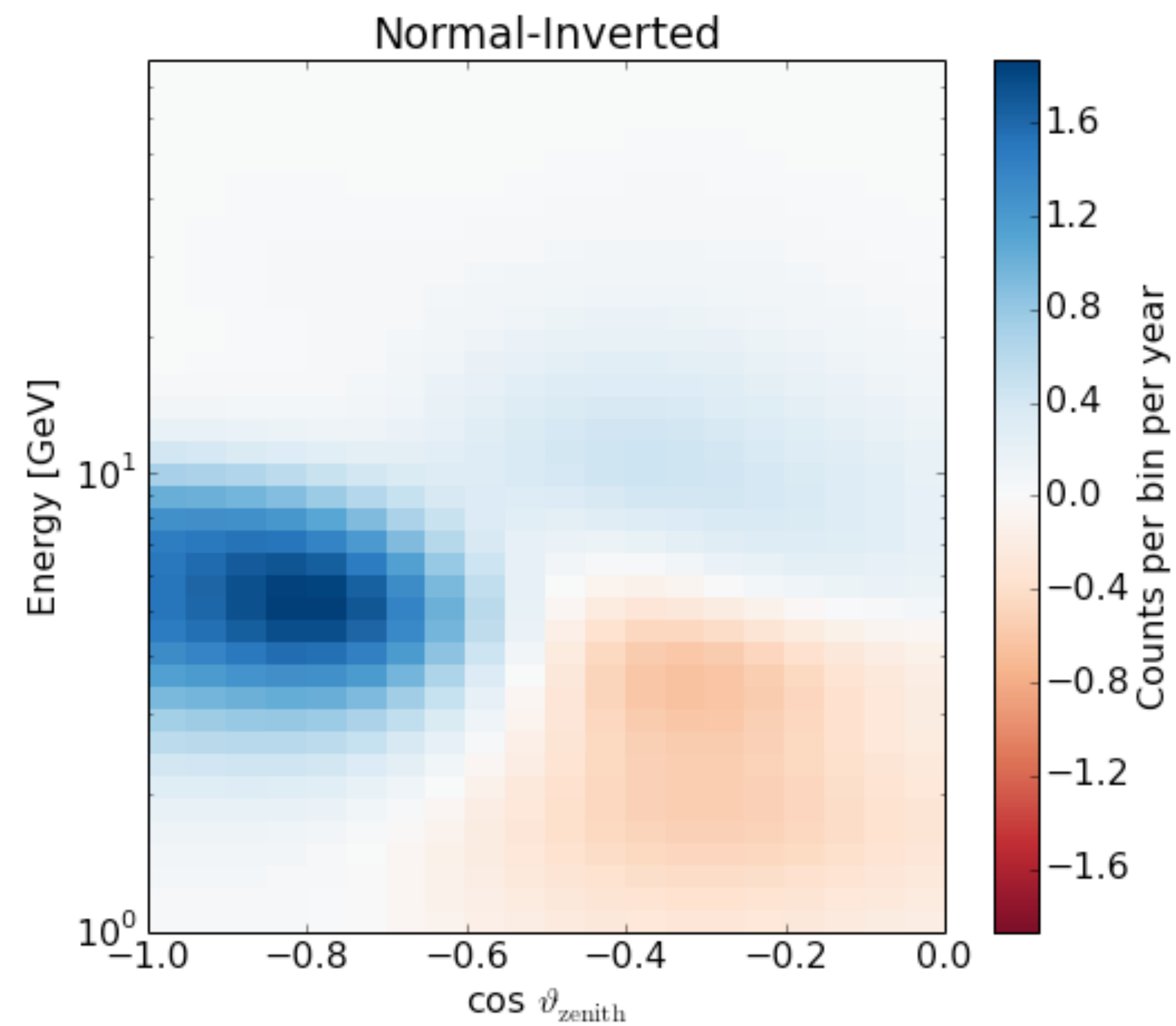
Matter effects on cascades (ν_e and ν_τ) also important

Hierarchy Signature: Observables

Events ID'd as tracks (ν_μ CC)



Events ID'd as cascades (ν_e, NC)



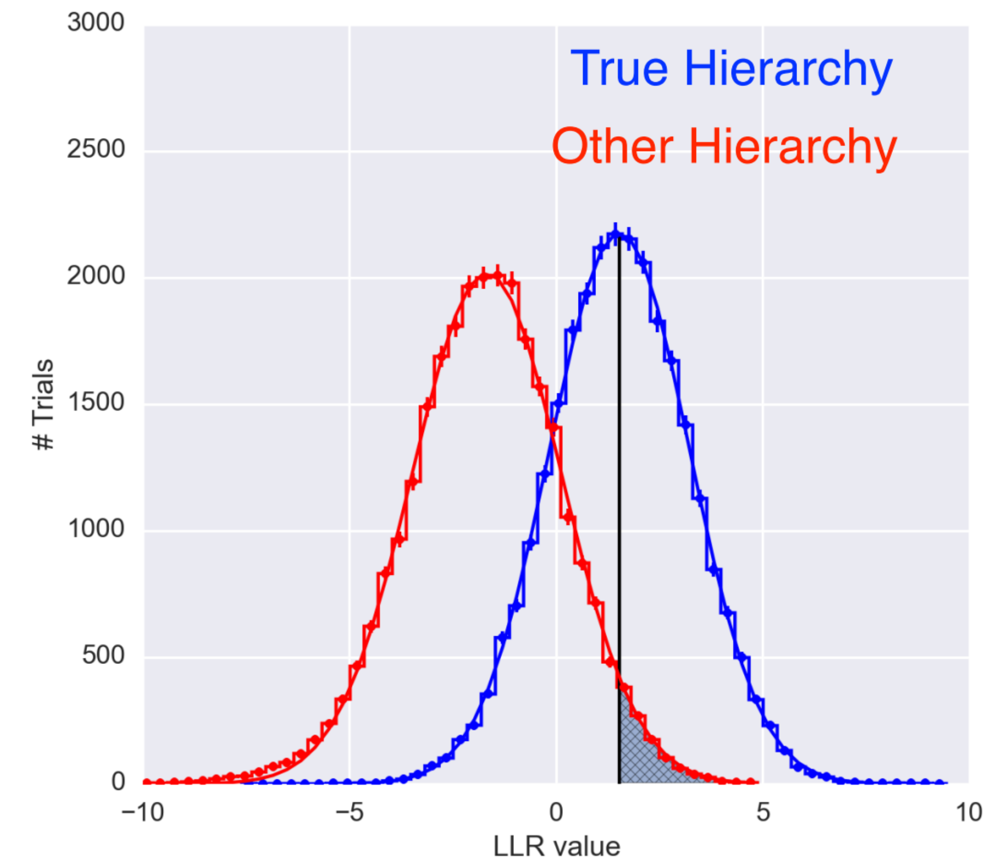
- Event rates, detector resolutions and efficiencies parametrized from full detector Monte Carlo to eliminate statistical fluctuations
- Expect ~50k (ν_μ+$\bar{\nu}_\mu$) and ~40k (ν_e+$\bar{\nu}_e$) per year – largest sample ever in this energy range

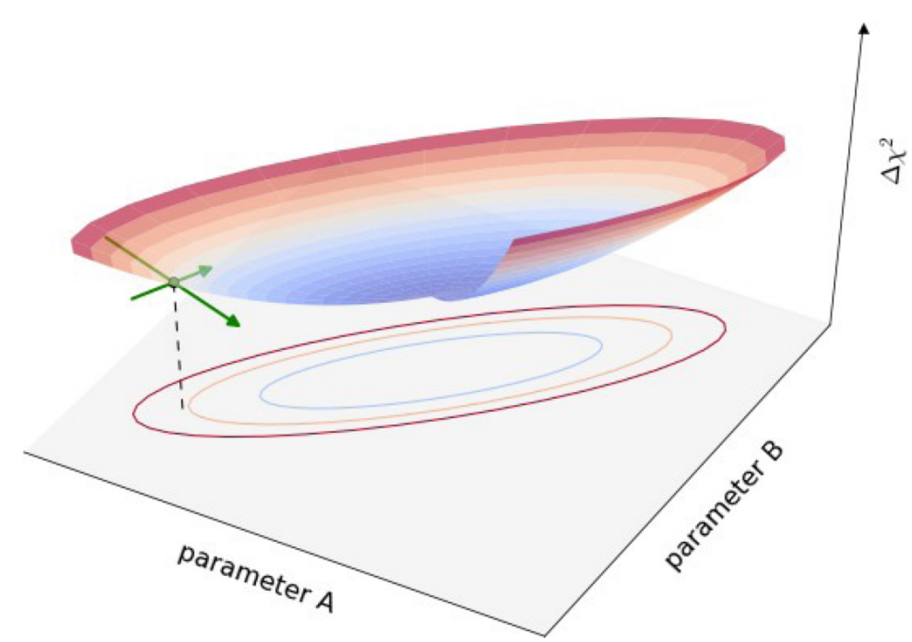
Statistical Methods

- Two independent methods of calculating expected significance

- Log-likelihood ratio method
  - Large ensemble of pseudo-data sets, best-fit physics and nuisance parameters determined numerically
  - Build up distribution of test statistic and integrate tail for expected significance

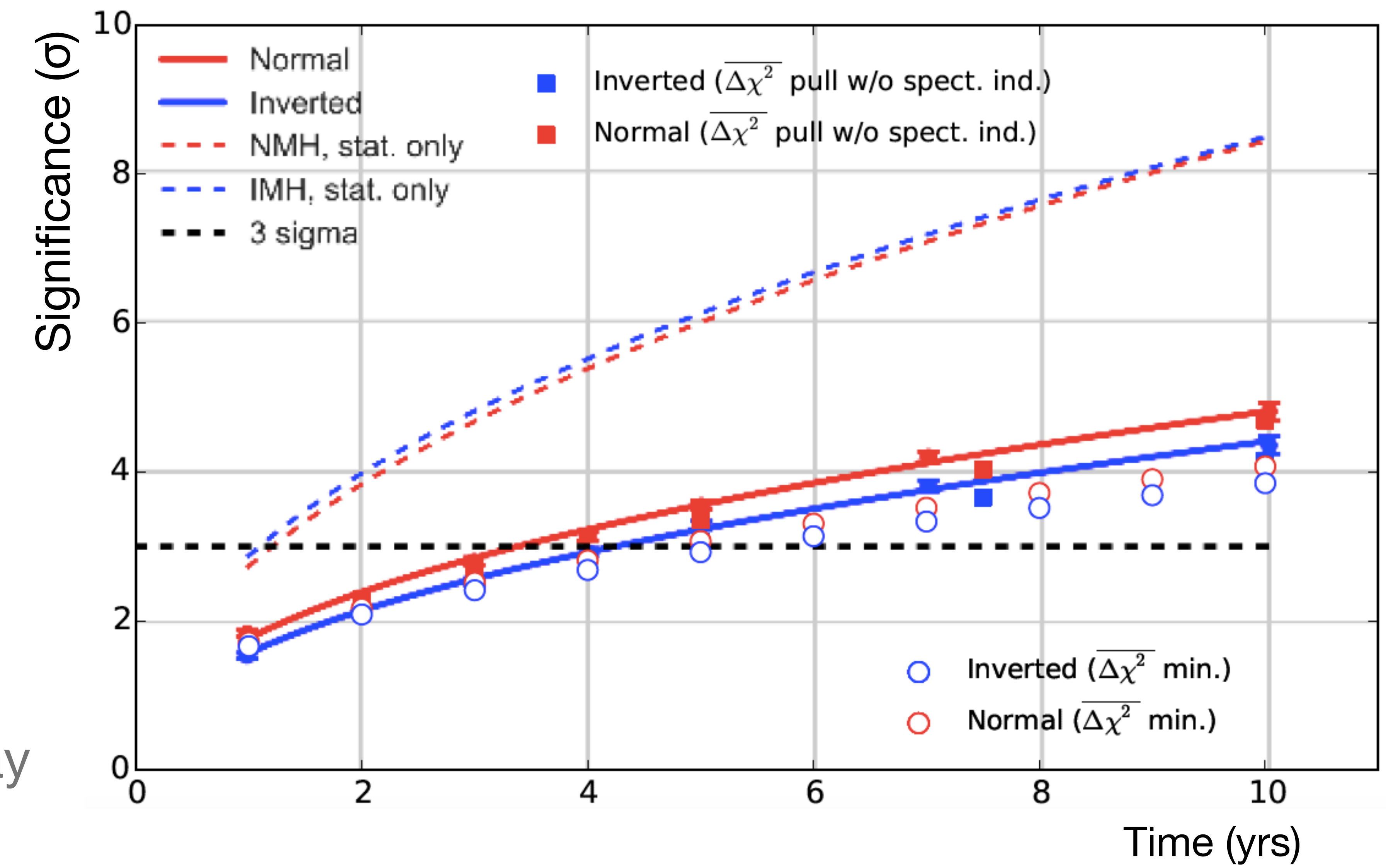
- Penalized $\Delta\chi^2$ method
  - Asimov data sets rather than ensembles
  - Linear error propagation for linear parameters, minimize over nonlinear ones
  - Fast: semi-analytic minimization of $\Delta\chi^2$, no need to generate ensembles of pseudo-data





Significance vs. Time

- Expect 3σ measurement of the mass ordering in 3.5-4 years
  - Using nu-fit* 2014 global fit values for parameters – nearly worst case
- Systematics are constrained by same data set in global fit
  - Small differences between $\Delta\chi^2$ and LLR methods, may be breakdown of Asimov assumption



*M.C. Gonzalez-Garcia et al. *JHEP* 11, 052 (2014)

Effects of Systematics

- Oscillation physics produces distinctive patterns – decouple from systematics
- Uncertainties in oscillation parameters (mainly θ_{23}) dominate systematics
  - No prior placed on θ_{23} or Δm^2_{atm} – fit jointly with NMH
  - θ_{13} fit with prior, solar parameters and δ_{CP} (=0) held fixed
- Flux: ν_e/ν_μ ratio (3%), $\nu/\bar{\nu}$ ratio (10%), spectral index (.05), detailed flux uncertainties from Barr et al. 2006*

Type	4y σ (NO)	4y σ (IO)
none	5.4	5.5
flux only	4.3	4.6
det only	4.4	4.6
osc only	3.4	2.9
All	3.1	2.9

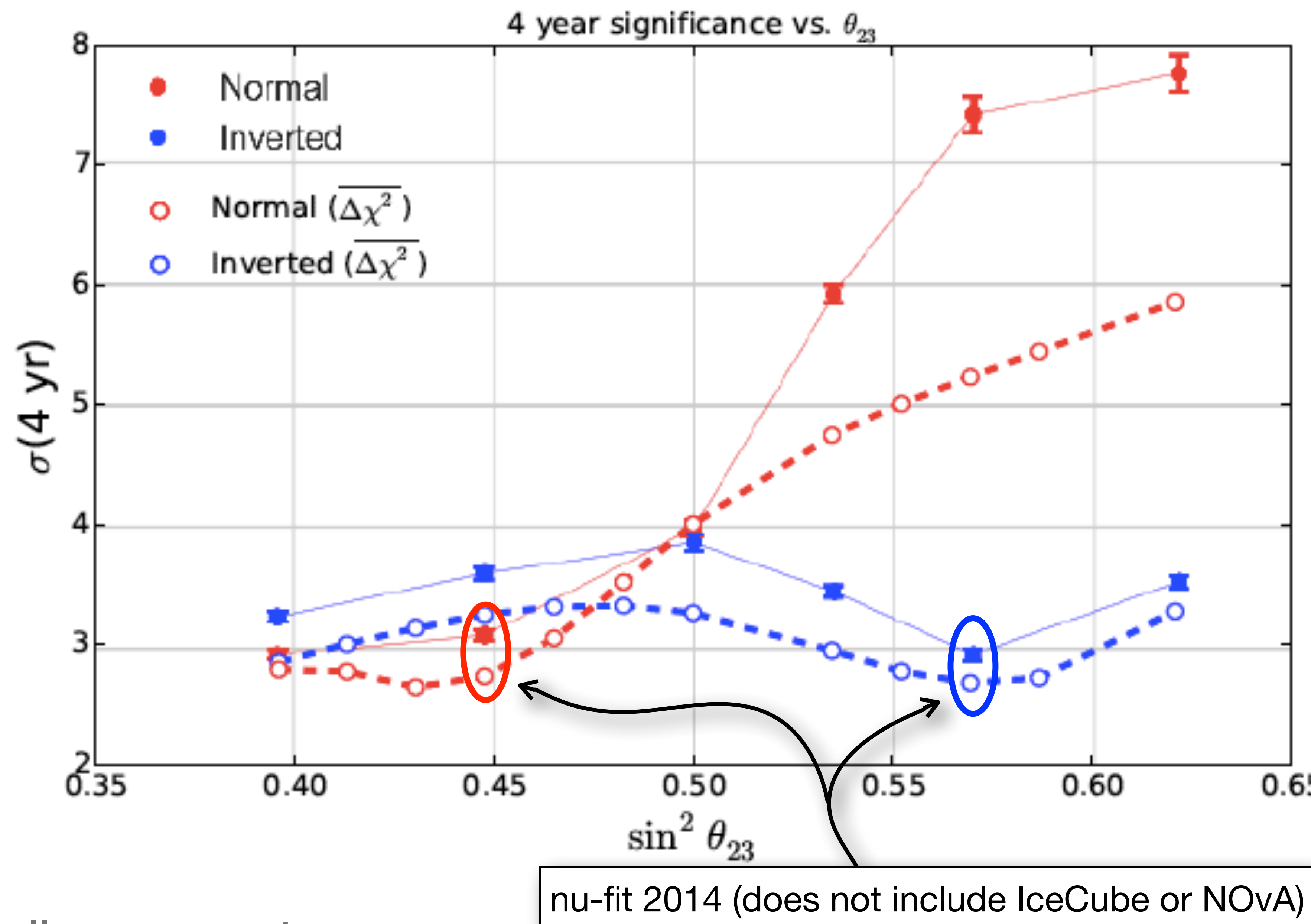
PRELIMINARY

- Detector: rate = eff. mass × flux norm. (free), energy scale (10%), detailed cross-section systematics from GENIE*

*only with $\Delta\chi^2$ method

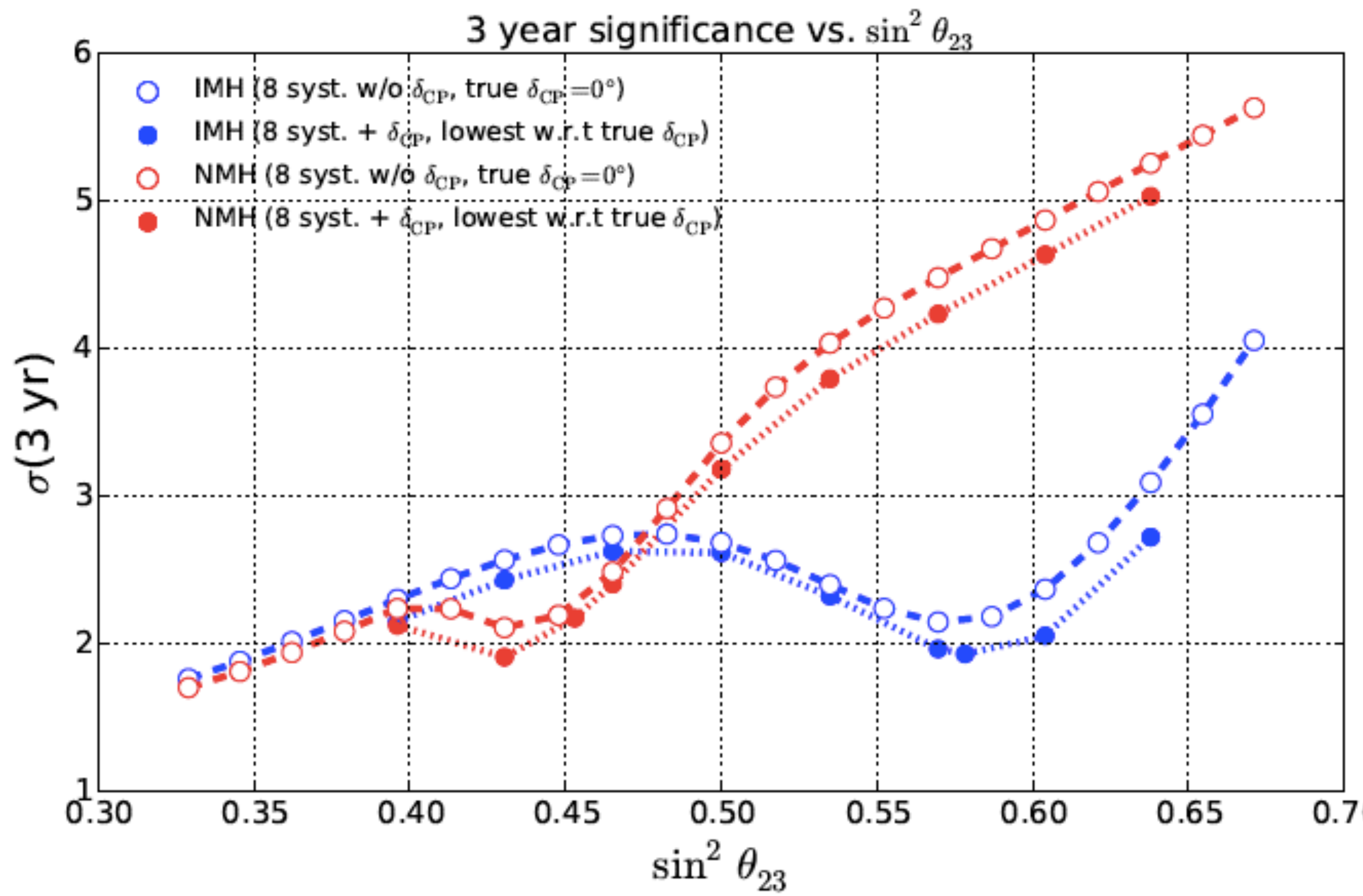
Impact of Atmospheric Mixing Angle

- Drift of global fit θ_{23} toward maximal since PINGU LoI has increased both matter effects and degeneracies
  - Mass ordering measured at ≥3σ within ~4 years over full ±2σ range of global fit
  - Statistical methods agree acceptably well over most of range – discrepancy at high significance under study



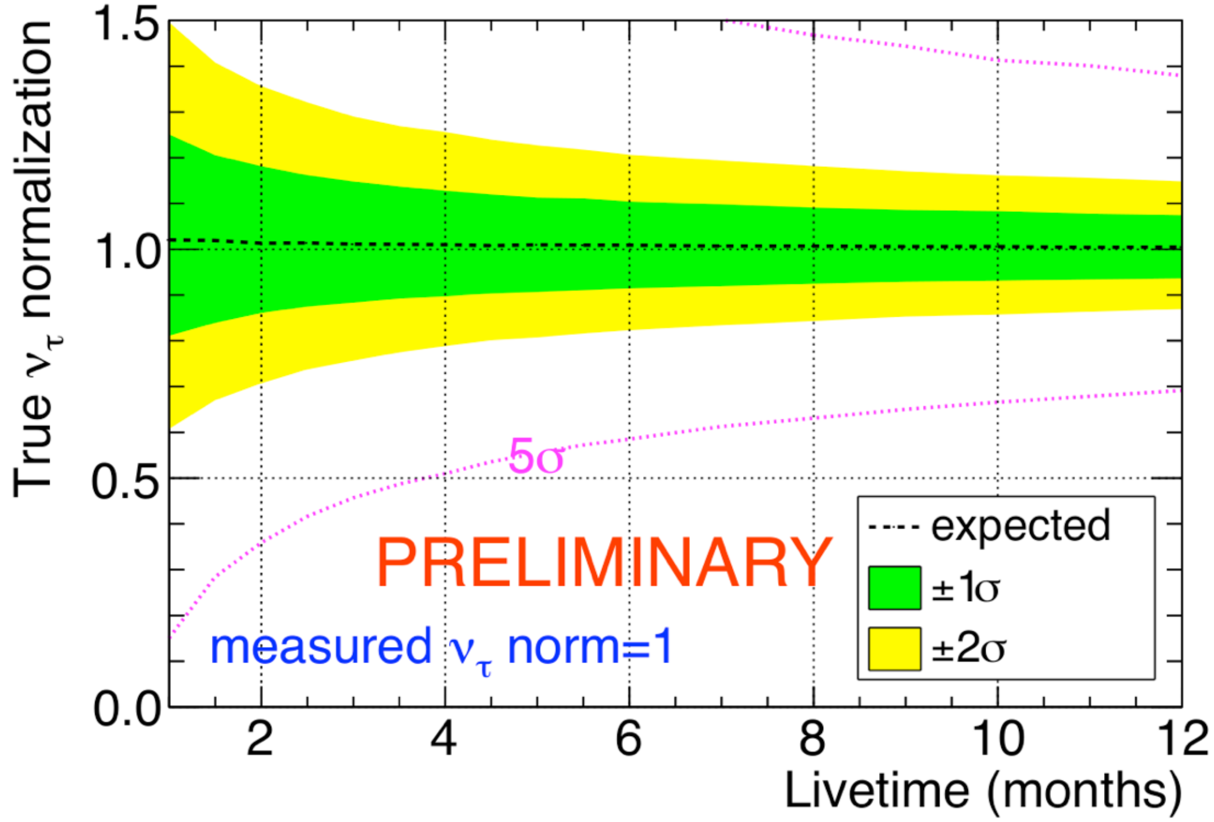
Impact of CP Violation

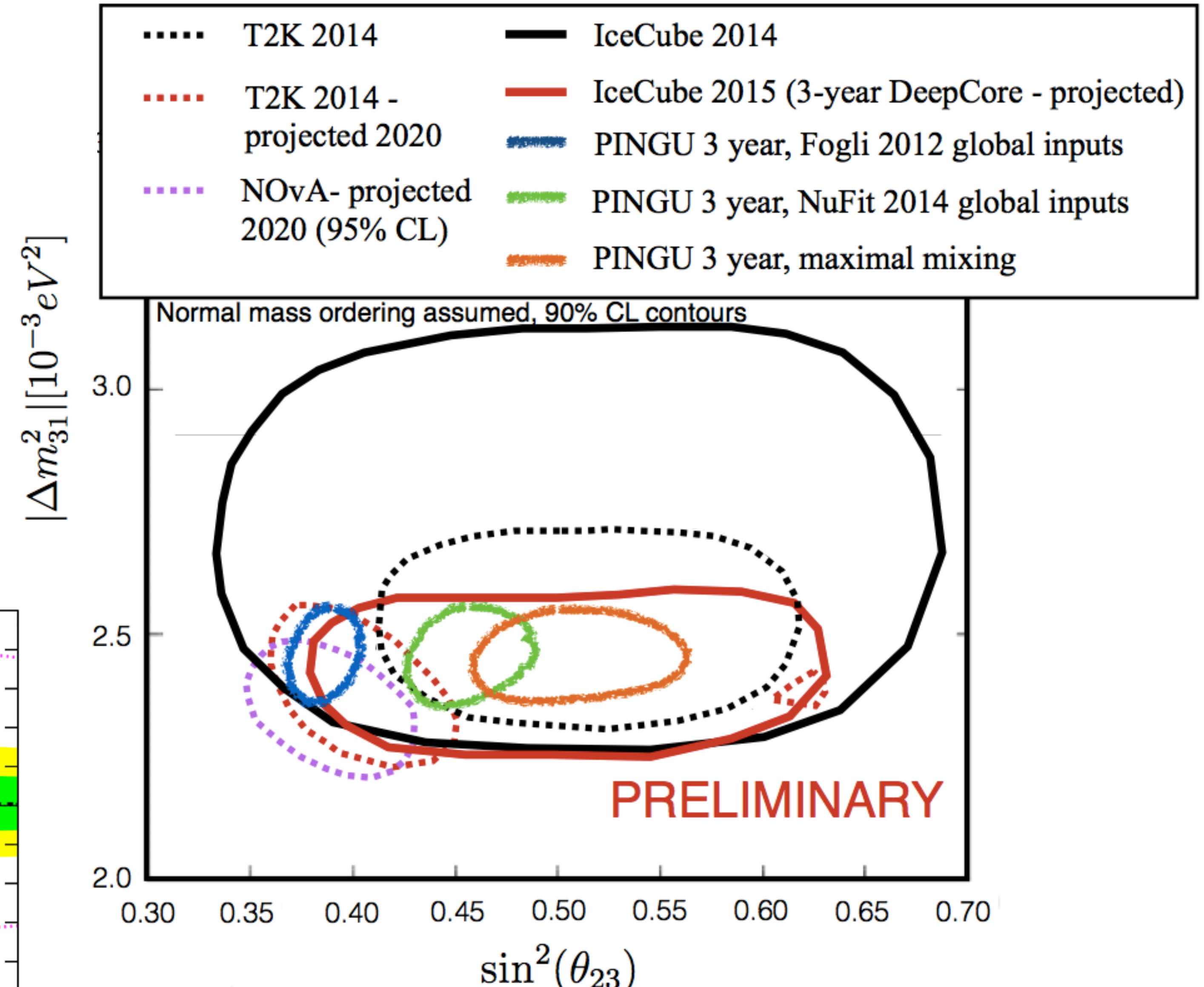
- Previously have fixed $\delta_{CP} = 0$
  - As θ_{23} has drifted closer to maximal, potential impact increases
- Worst-case appears to reduce NMO 4-yr significance by ~0.2σ
  - Preliminary study including δ_{CP} as a nuisance parameter ($\Delta\chi^2$ method only)



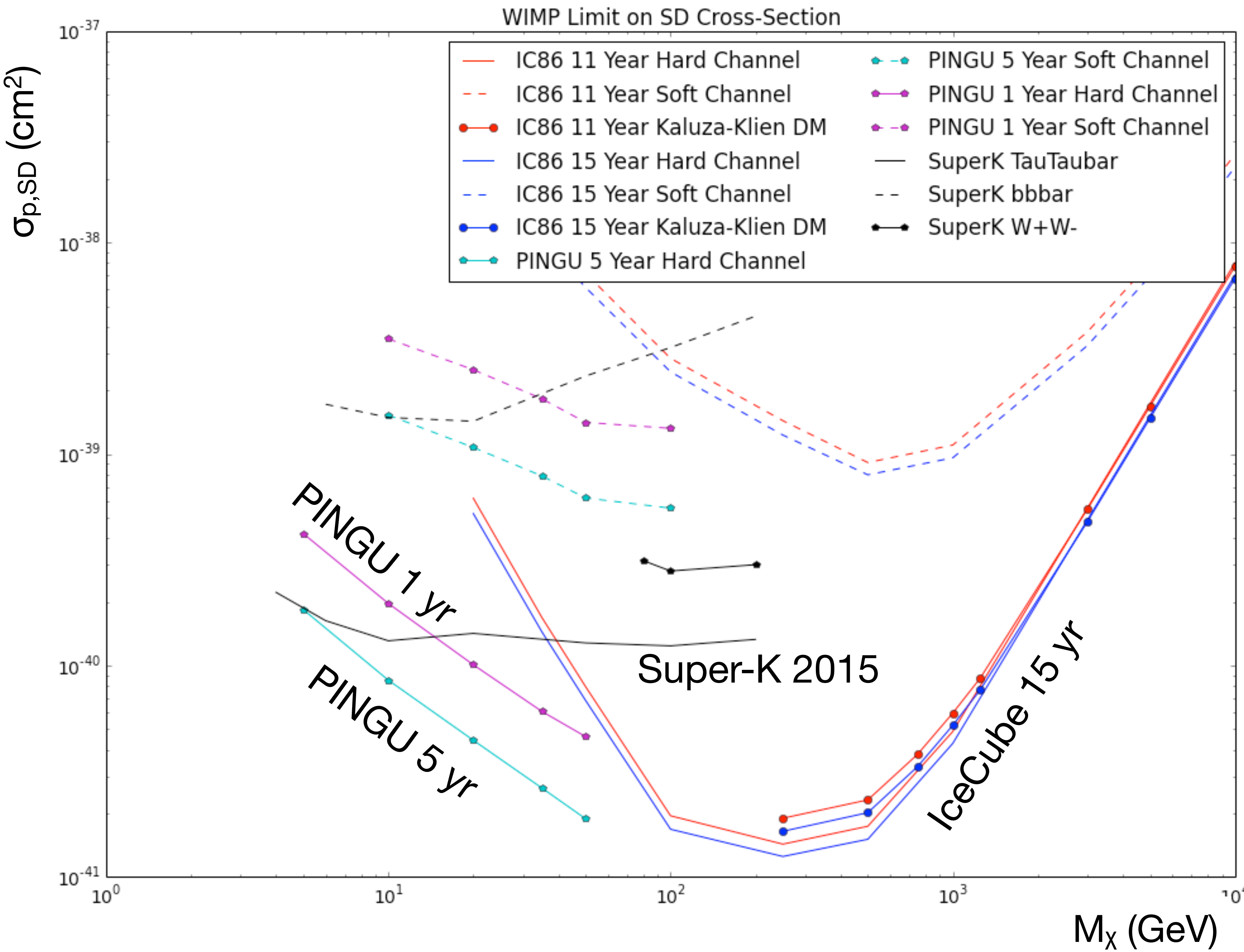
Other Oscillation Measurements with PINGU

- Complementary to other measurements – interesting tests of standard oscillations
  - Higher energies, different systematics





Dark Matter Sensitivity with PINGU



PINGU (& Gen2) Calibration

Table 14: Summary of proposed PINGU calibration devices and their purposes.

	LED flashers	POCAM	Cameras	MTOMs	Compass	Inclinometer
Energy scale	✓	✓				
Bulk ice	✓	✓				
Hole ice	✓	✓	✓			
DOM sensitivity	✓	✓		✓		
Geometry	✓		✓		✓	✓
Timing	✓					
Direction	✓		✓		✓	✓
Ice motion	✓					✓
Cable shadow			✓			

- PINGU's close spacing will enable us to better constrain ice properties
- Also impacts high energy event reconstruction – better ang. resolution

Community Interest

- Considerable excitement regarding PINGU
  - P5 felt it was too early to make a recommendation either way, but viewed it as promising and recommended further investigation
  - Questions identified in the P5 process now answered, no major changes in performance expectations – revised version of LOI available soon
- Invited talks on PINGU at ~10 conferences this year
- People voting with their feet – joining Gen2 for PINGU/particle physics
  - Canada: Alberta, Toronto,
  - UK: Manchester, Queen Mary, interest from Birmingham
  - Denmark: Copenhagen
  - South Korea: SKKU
  - US: MIT, Columbia

Cost Estimate

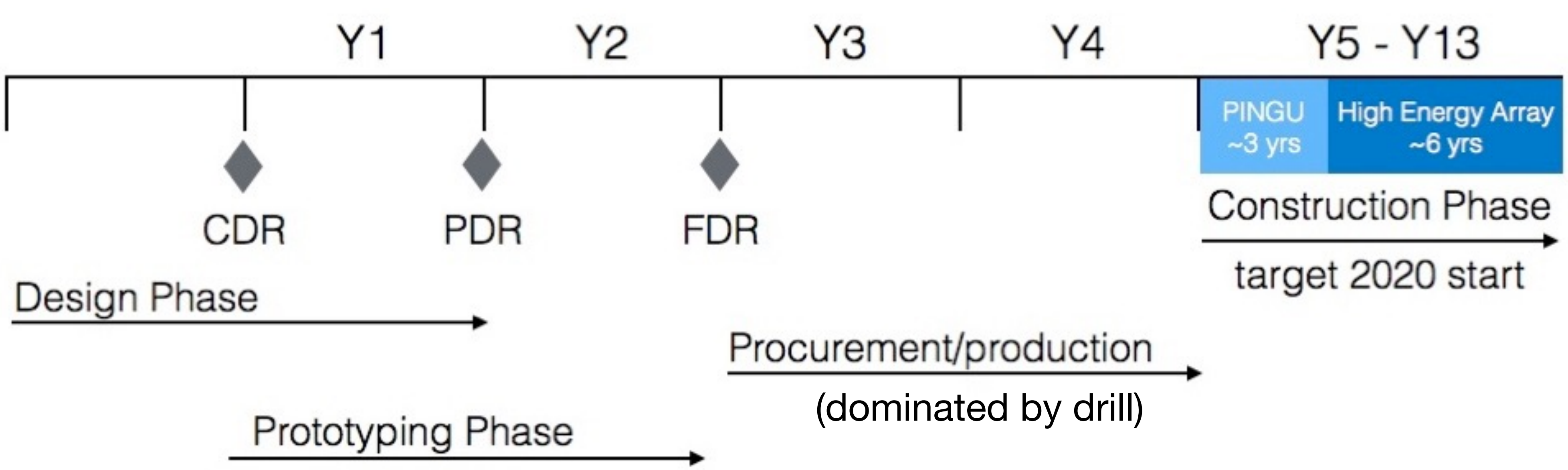
- Many items common to PINGU and other Gen2 elements
  - Drill, DOM and cable engineering, calibration devices, software, project management, etc.
- Anticipate non-US contributions will offset a large portion of costs
  - Considerable interest in current partner countries, e.g. Germany
  - Canadian proposal for $12M highly ranked at final level, declined due to concerns re: NSF commitment

Cost for PINGU Component	
Hardware	$48M
Logistics	$23M
Contingency	$16M
Increase in TPC	$88M
Expected non-US contributions	-$25M
Total US Cost	$63M

(elements do not sum to total due to rounding)

Schedule and Risks

- Several neutrino oscillation projects proposed or underway
  - JUNO, ORCA (part of KM3NeT – at proposal stage), DUNE
- Substantial complementarity with JUNO, but science case for PINGU will be less compelling in a few years
  - International partners looking for forward motion from NSF – even R&D would send the right signal, probably open up non-US funding
  - Baseline schedule has two “lost” years before drill is ready at Pole – can we accelerate this?



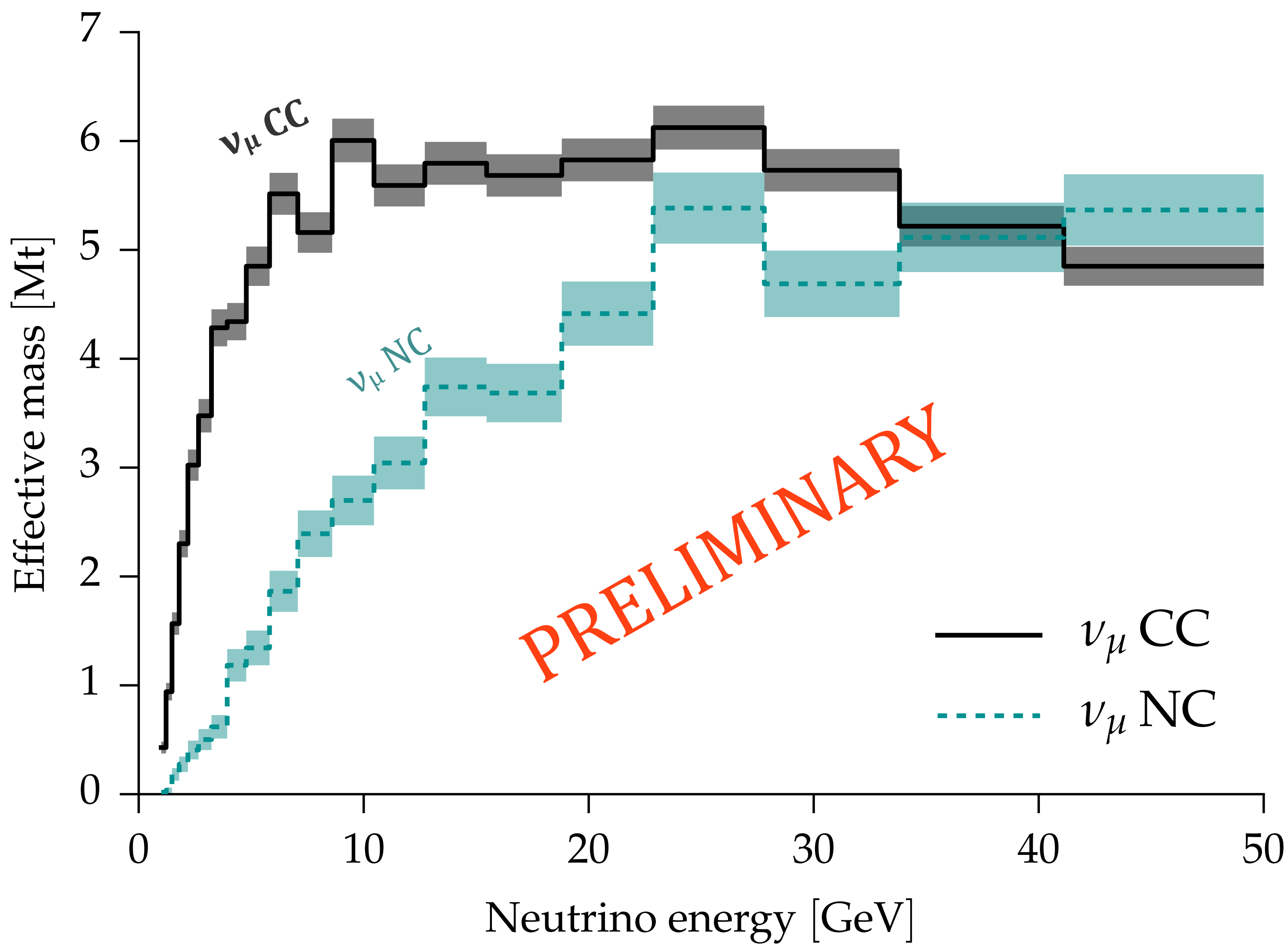
Conclusions

- The PINGU science case is compelling
    - Measurements at a range of higher energies/longer baselines, with high statistics
    - Opportunity to discover new physics is greatly enhanced by PINGU's complementarity with other experiments
- The neutrino mass ordering is a fundamental parameter, sensitivity estimates have been robust as refinements were made
    - Drift of θ_{23} toward maximal has increased degeneracies but effect on the NMO measurement has been small – current values are ~worst
- Also provides other interesting measurements – oscillation parameters, dark matter searches, etc.

Backup Slides

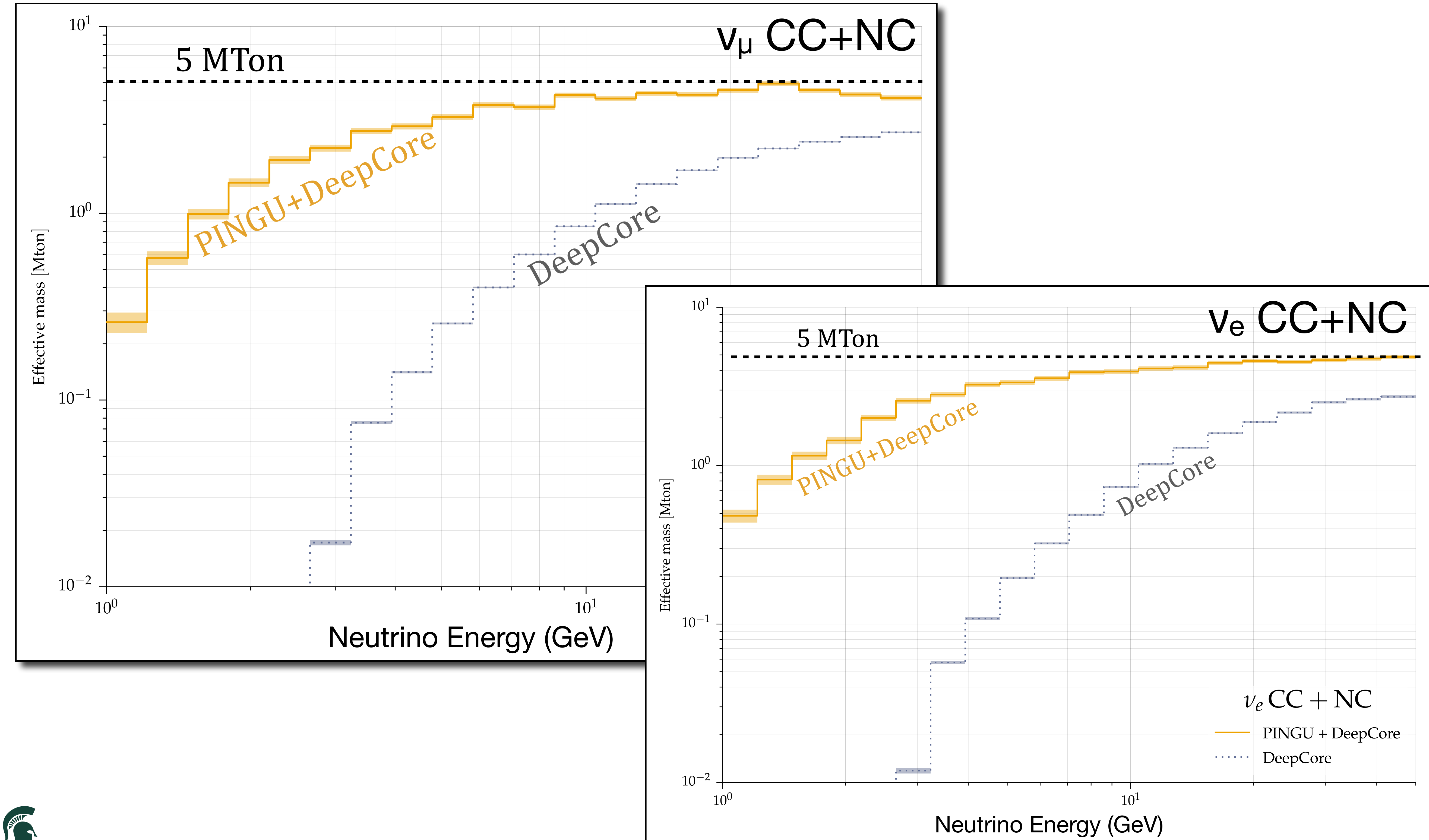
PINGU Effective Mass

- Fiducial mass of approx. 6 MTon
  - Event selection fully above ~7 GeV
  - Baseline event selection allows slightly higher atm. μ rate than in DeepCore analyses – real selection may be ~10-20% less efficient



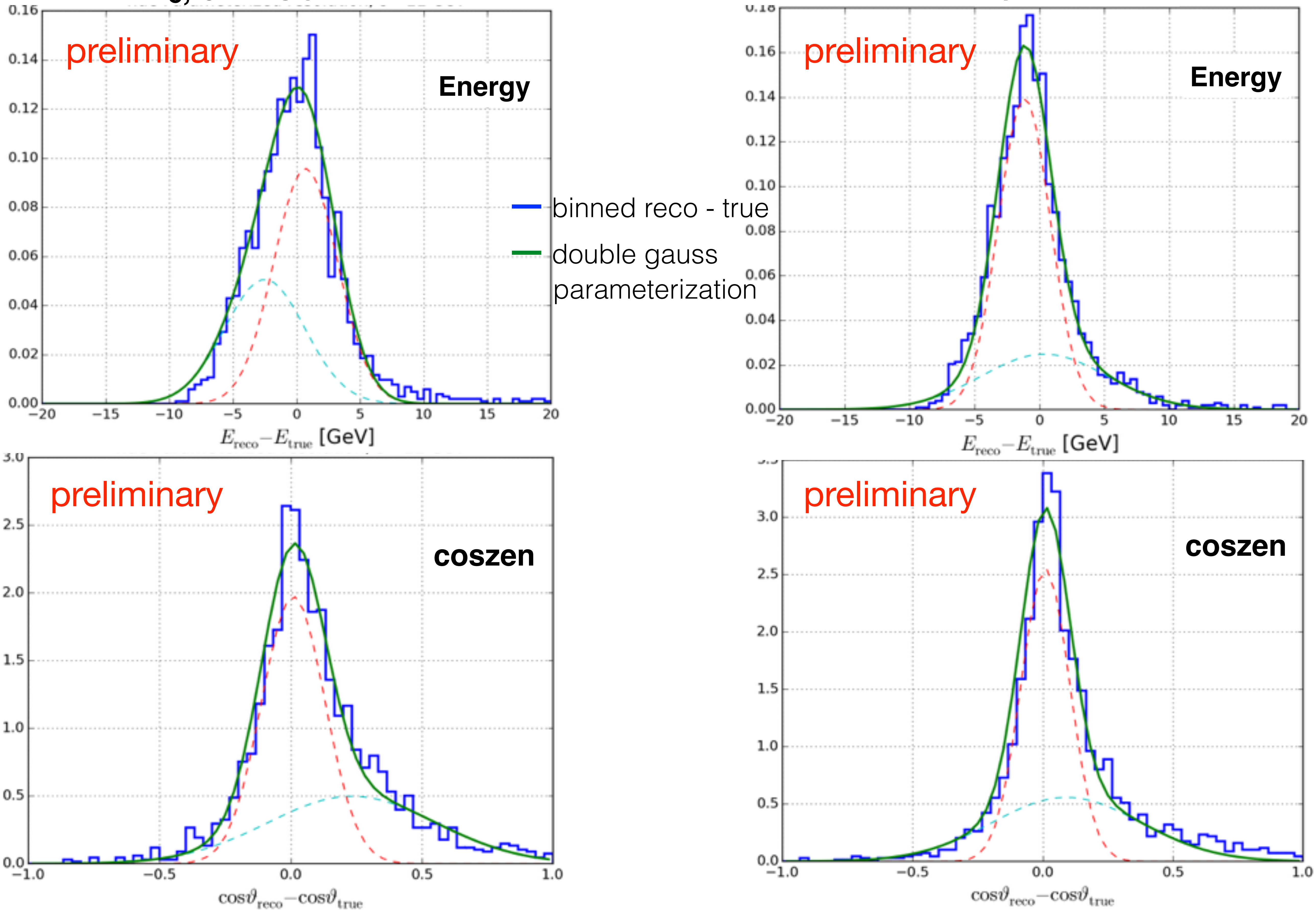
- Similar effective mass for other neutrino flavors

PINGU & DeepCore Meffs

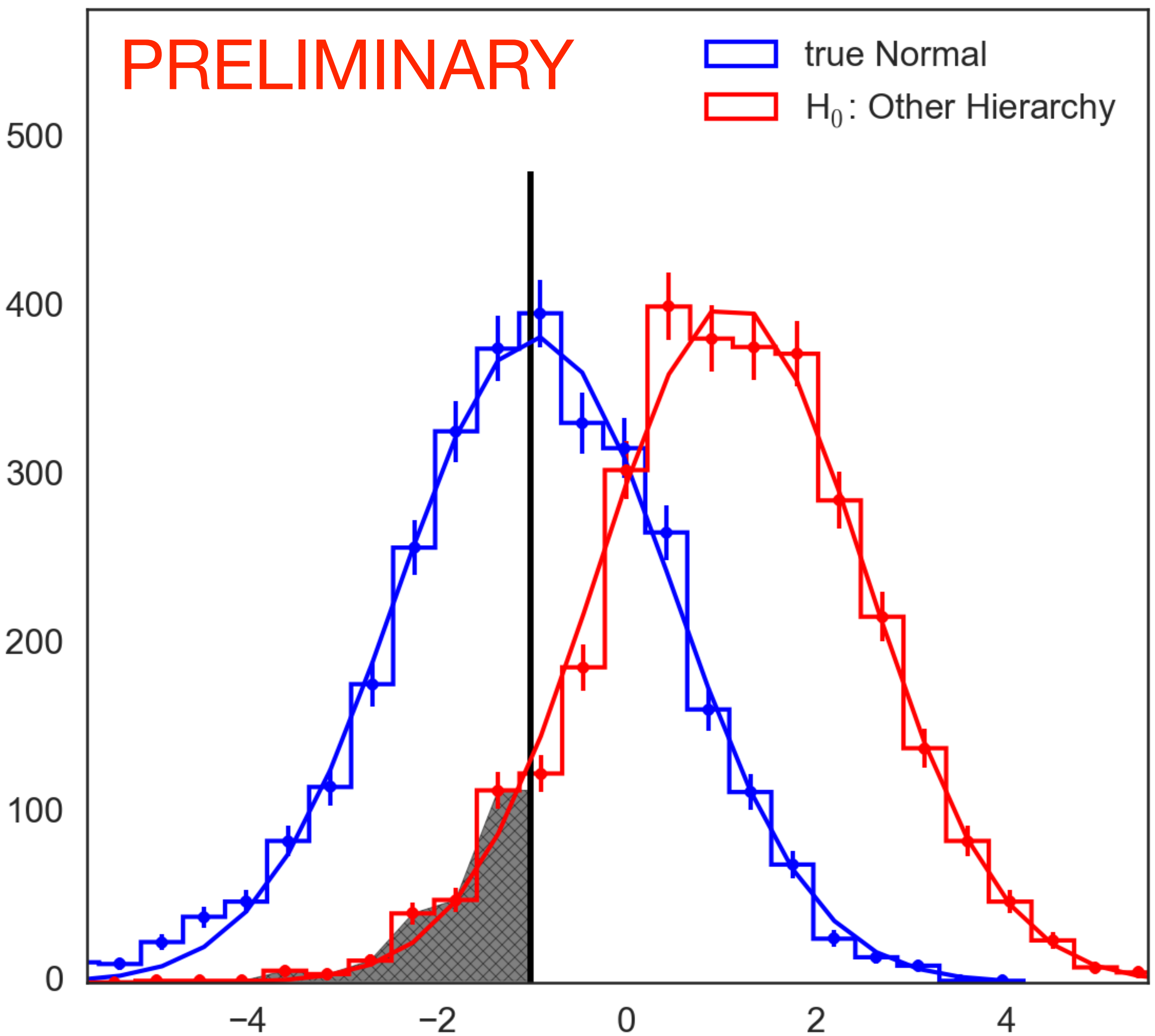


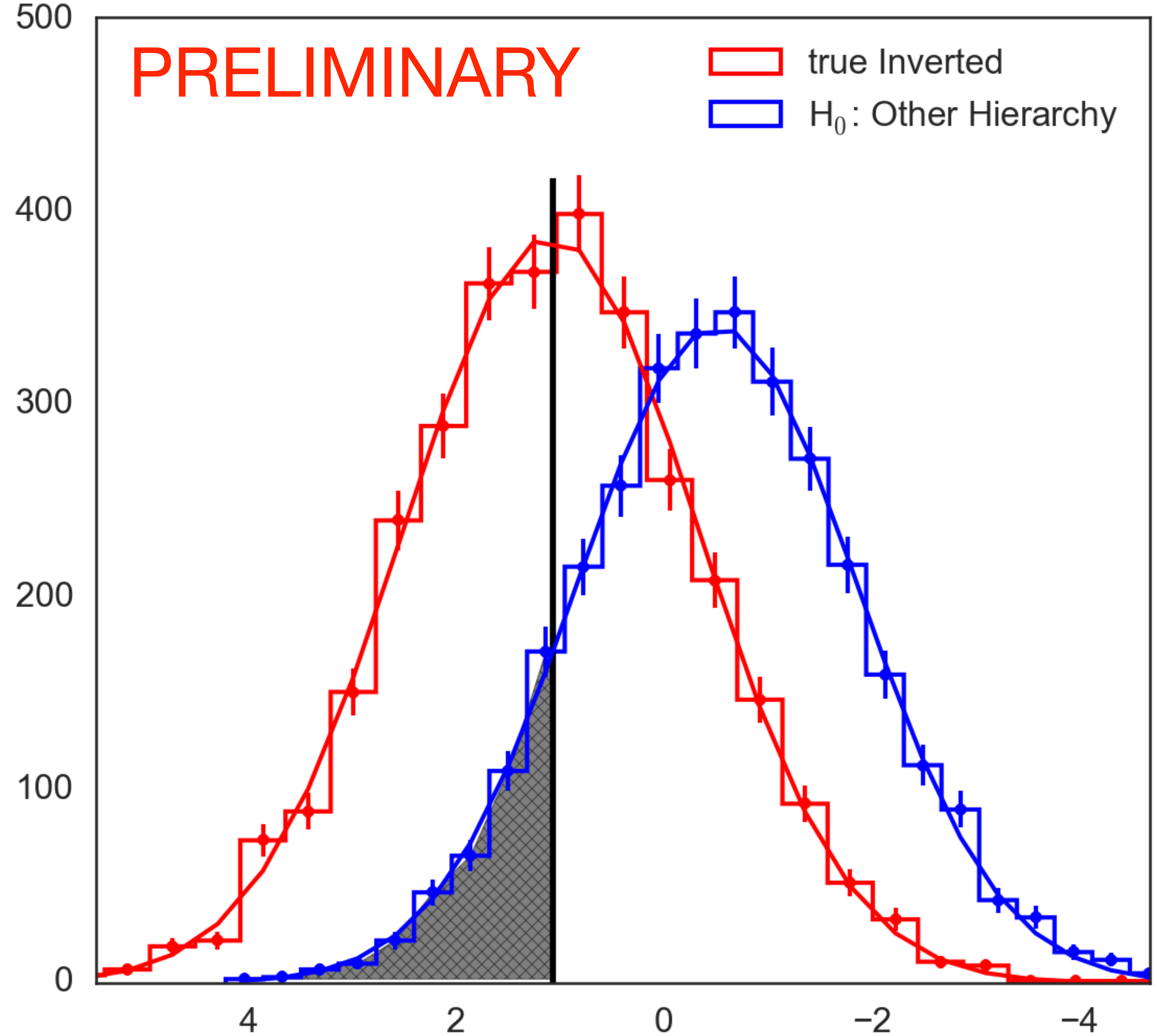
Resolutions

ν_e, 9-11 GeV **ν_μ, 9-11 GeV**



- example: LLR distributions for PINGU for True NH and True IH
  - 1 year significance: 1.83 (NH) and 1.55 (IH) for the NuFit[1] values of oscillation parameters

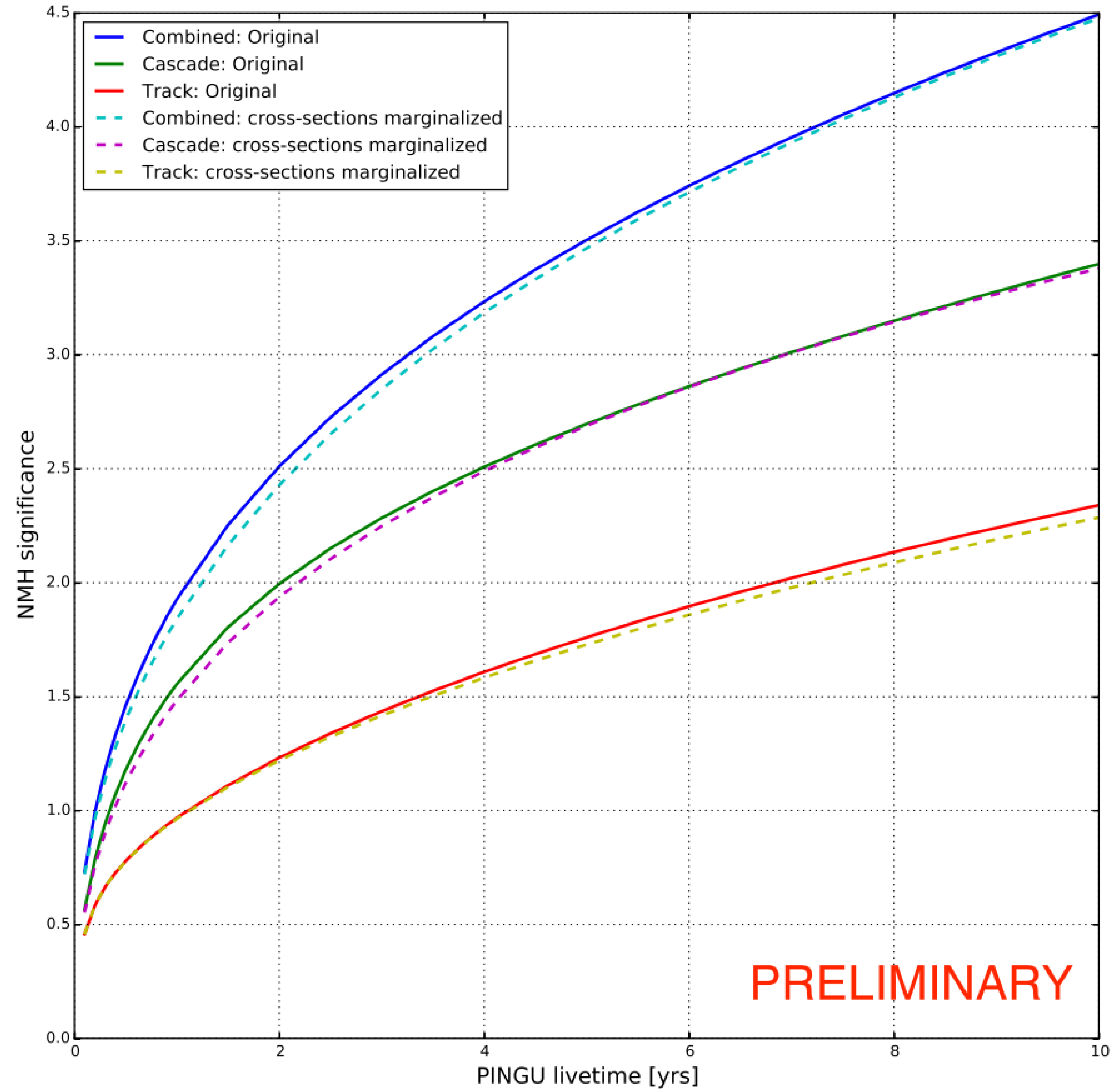




[1] M.C. Gonzalez-Garcia, et al. *JHEP* **11** 052, 2014

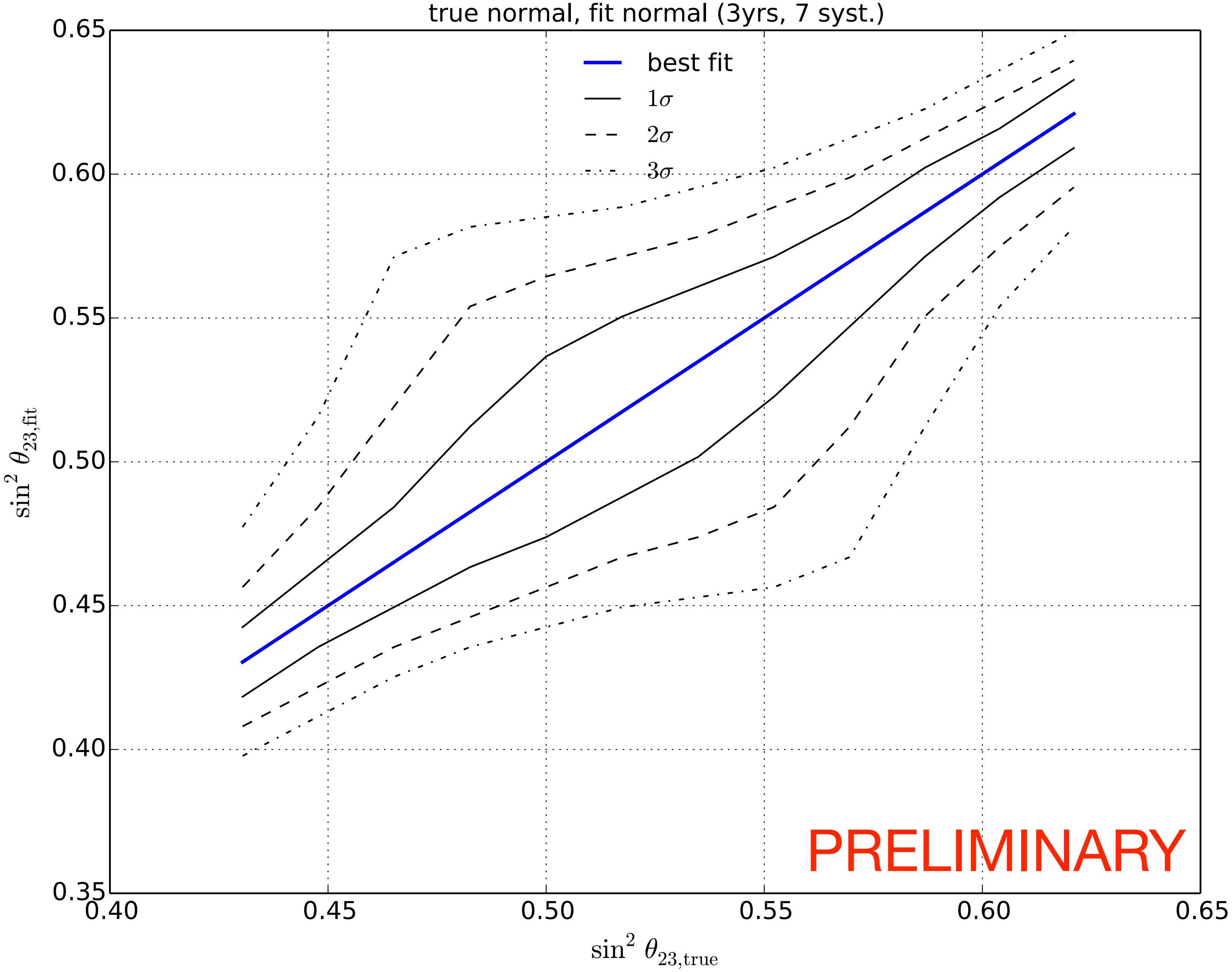
Neutrino-Nucleon Interaction Uncertainties

- Comparison of impact of GENIE uncertainties to original ad hoc treatment
- Net impact of full treatment is negligible – oscillation uncertainties dominate
  - Largest impacts from m_A in CCQE and resonance interactions, higher twist parameters in Bodek-Yang DIS model



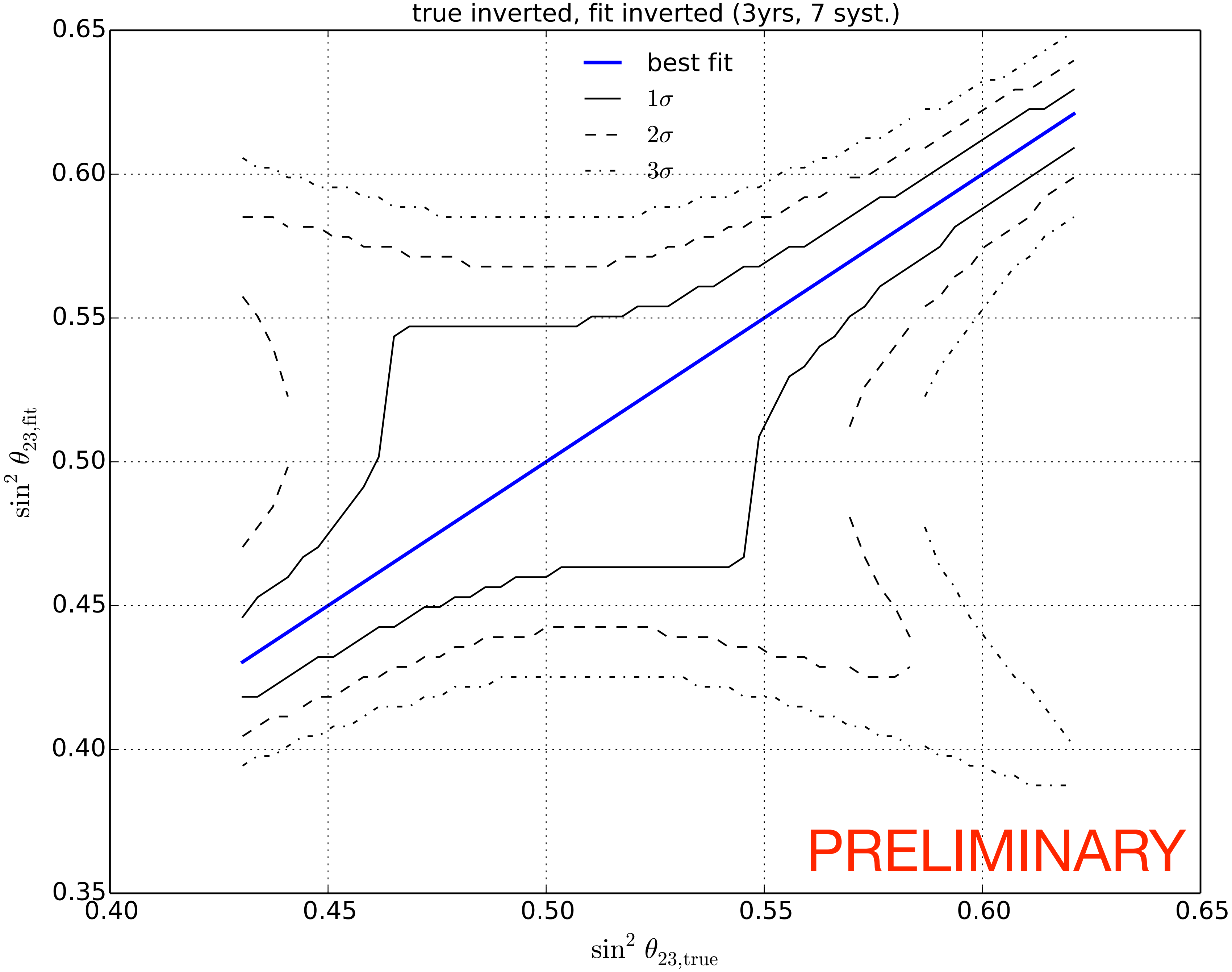
Oscillation Parameters with PINGU

after 3 years of livetime, with normal hierarchy correctly identified

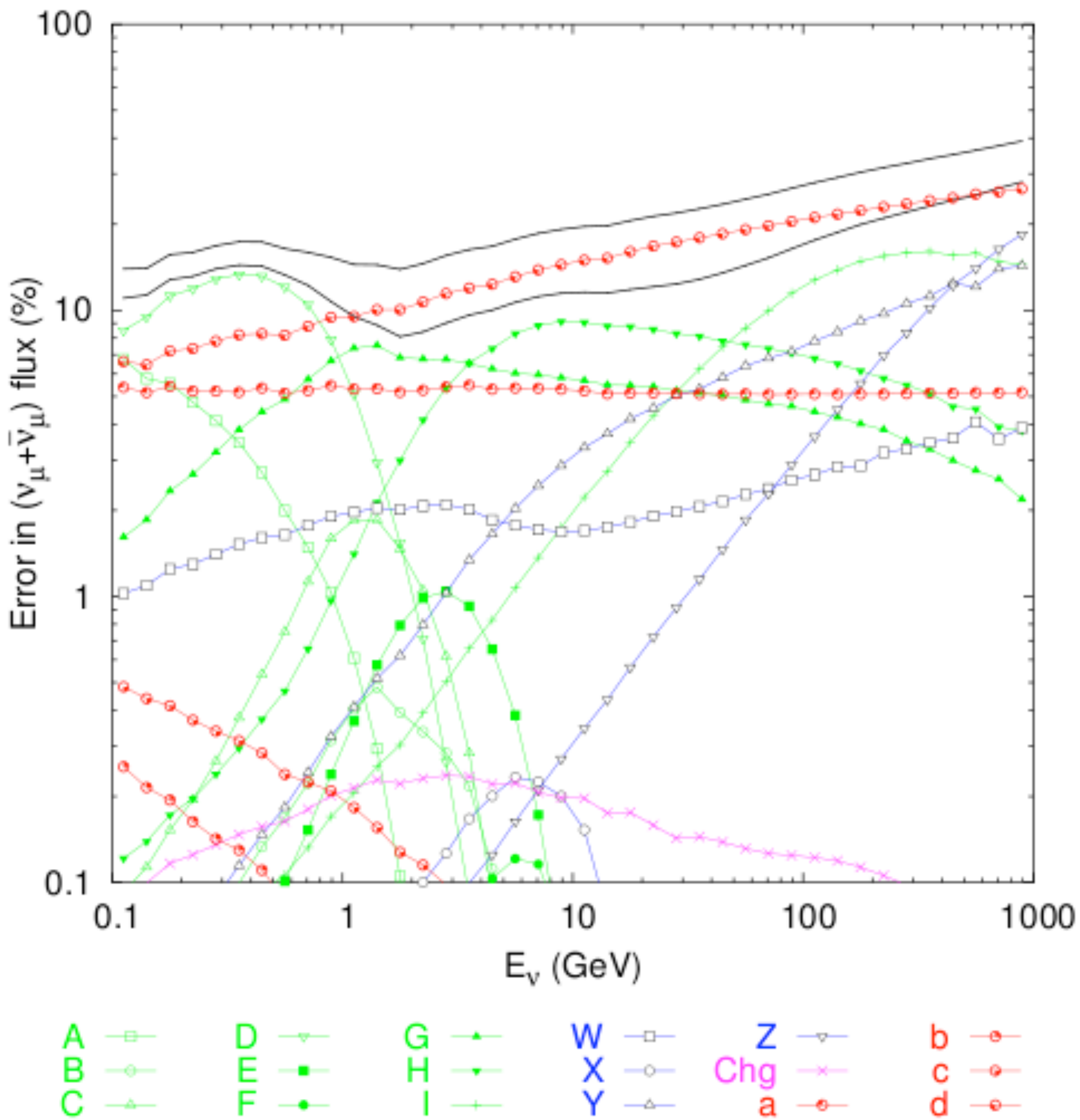


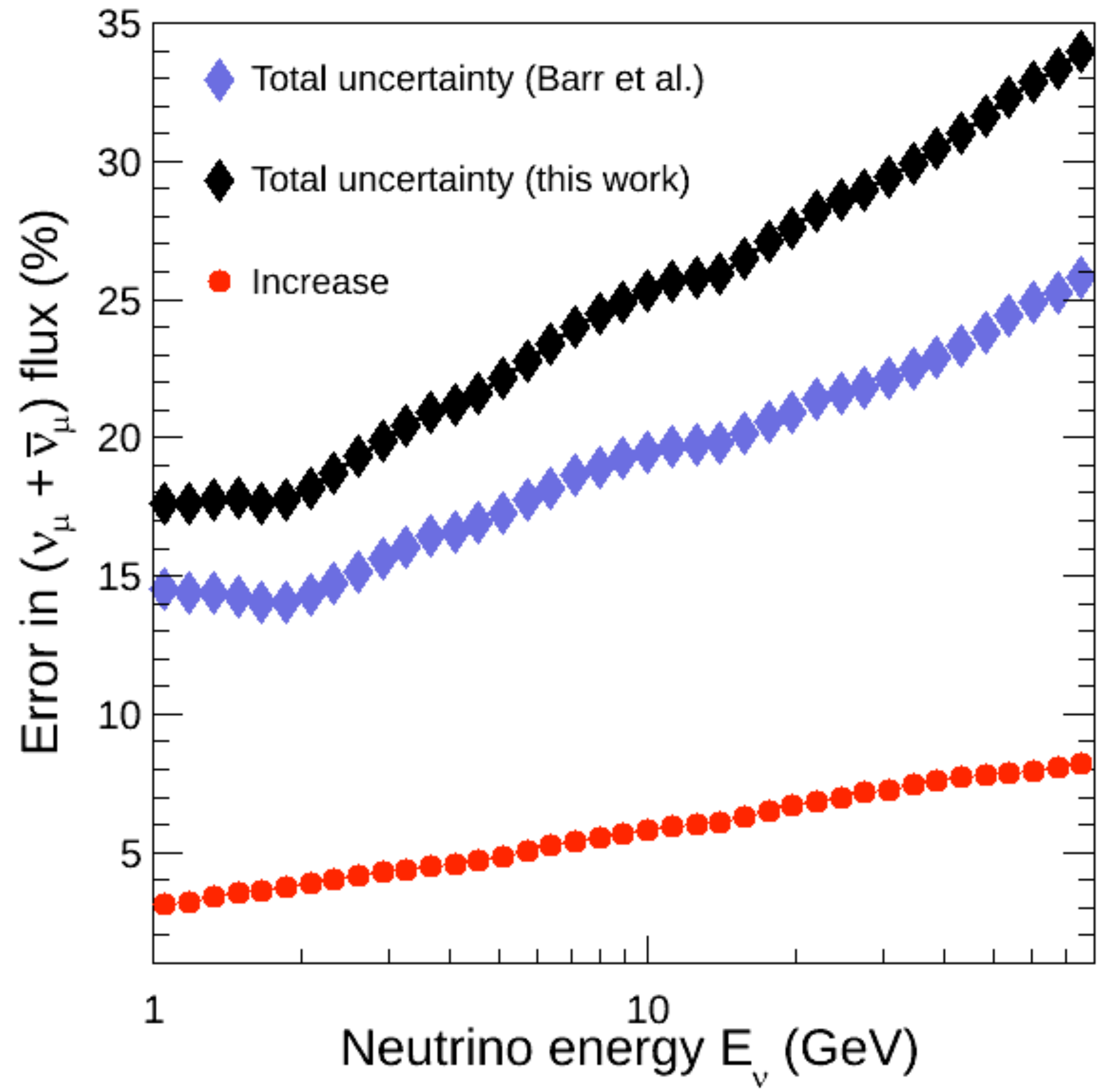
Oscillation Parameters with PINGU

after 3 years of livetime, with inverted hierarchy correctly identified

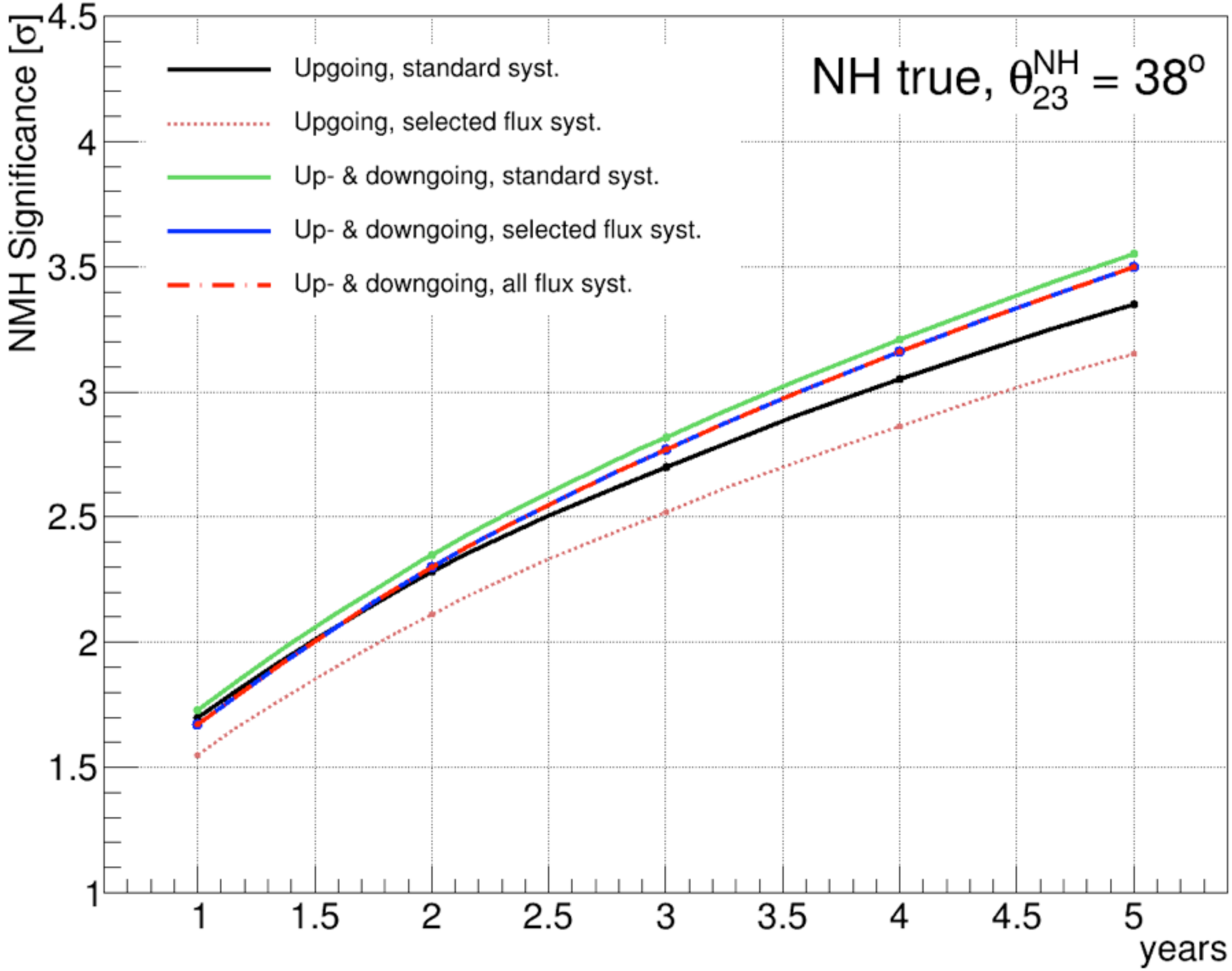


Atmospheric Flux Systematics

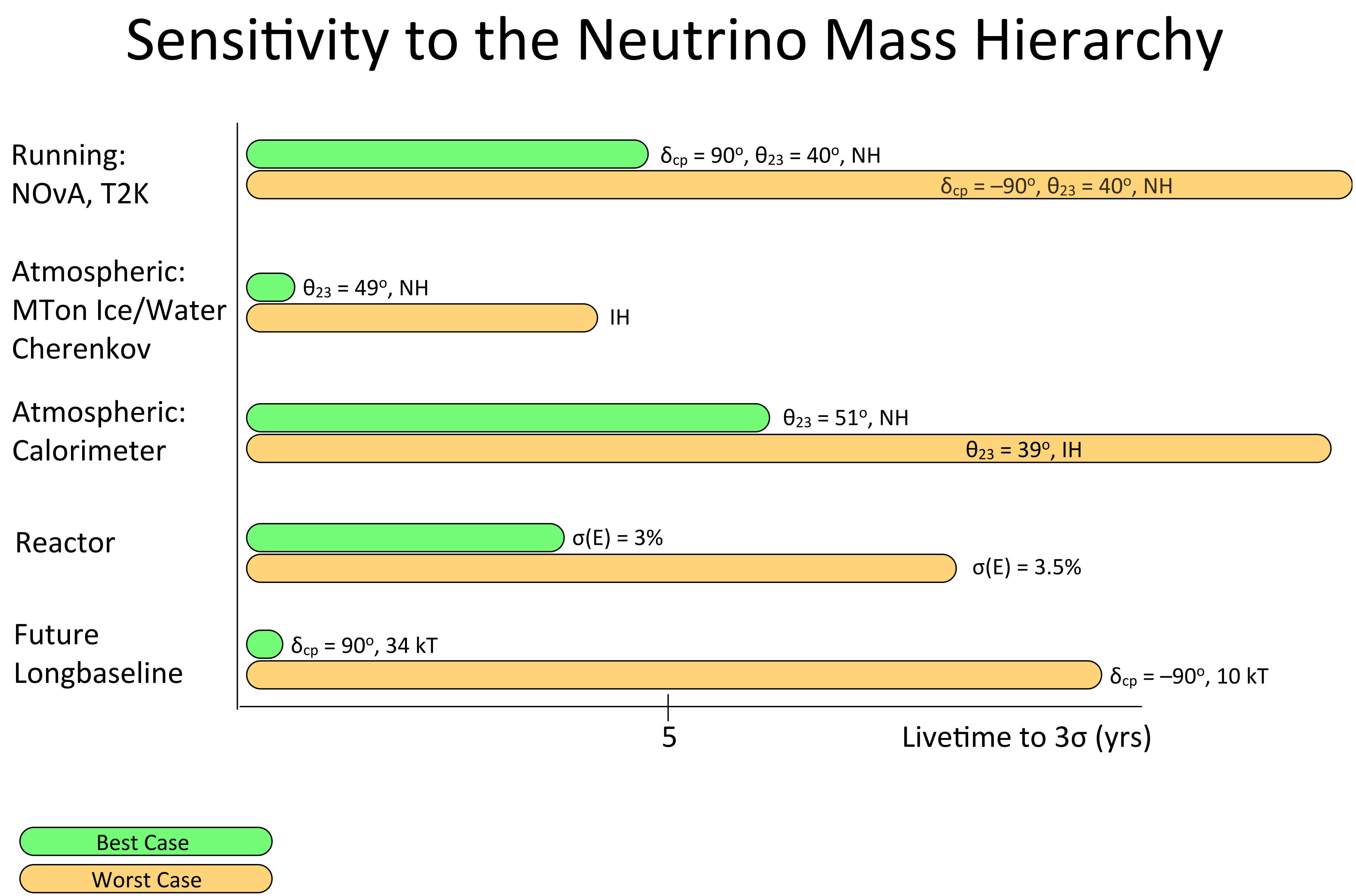




Using Down-Going Neutrinos



Global Context



Sources: arXiv:1311.1822, arXiv:1401.2046v1, arXiv:1406.3689v1, Neutrino 2014, LBNE-doc-8087-v10