PINGU
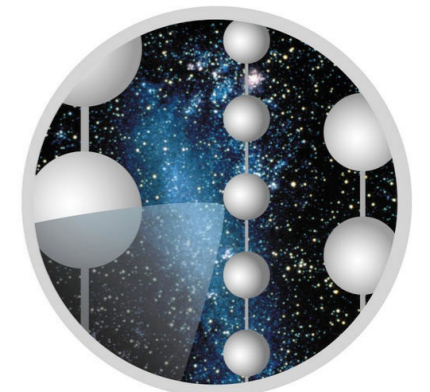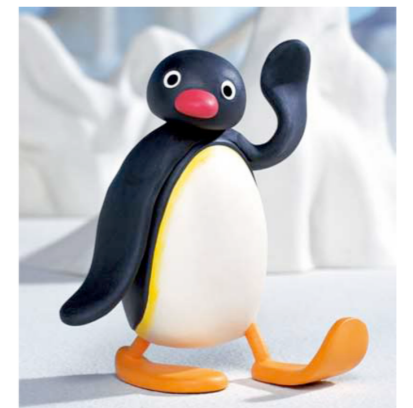## Status and Plans

Tyce DeYoung
Department of Physics and Astronomy
Michigan State University

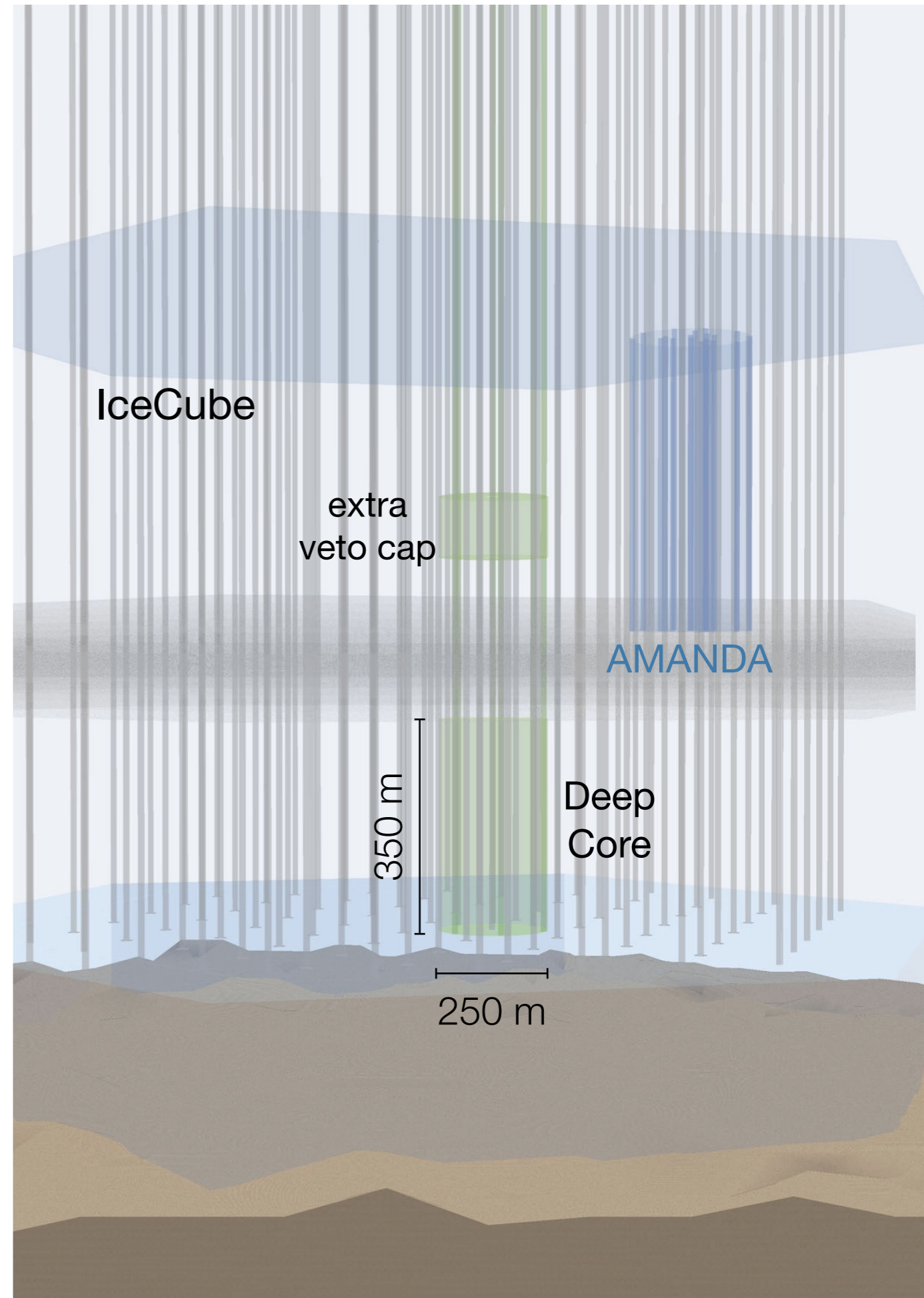IceCube Science Advisory Committee
Madison, Wisconsin
October 19, 2015

IceCube

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

IceCube

extra veto cap
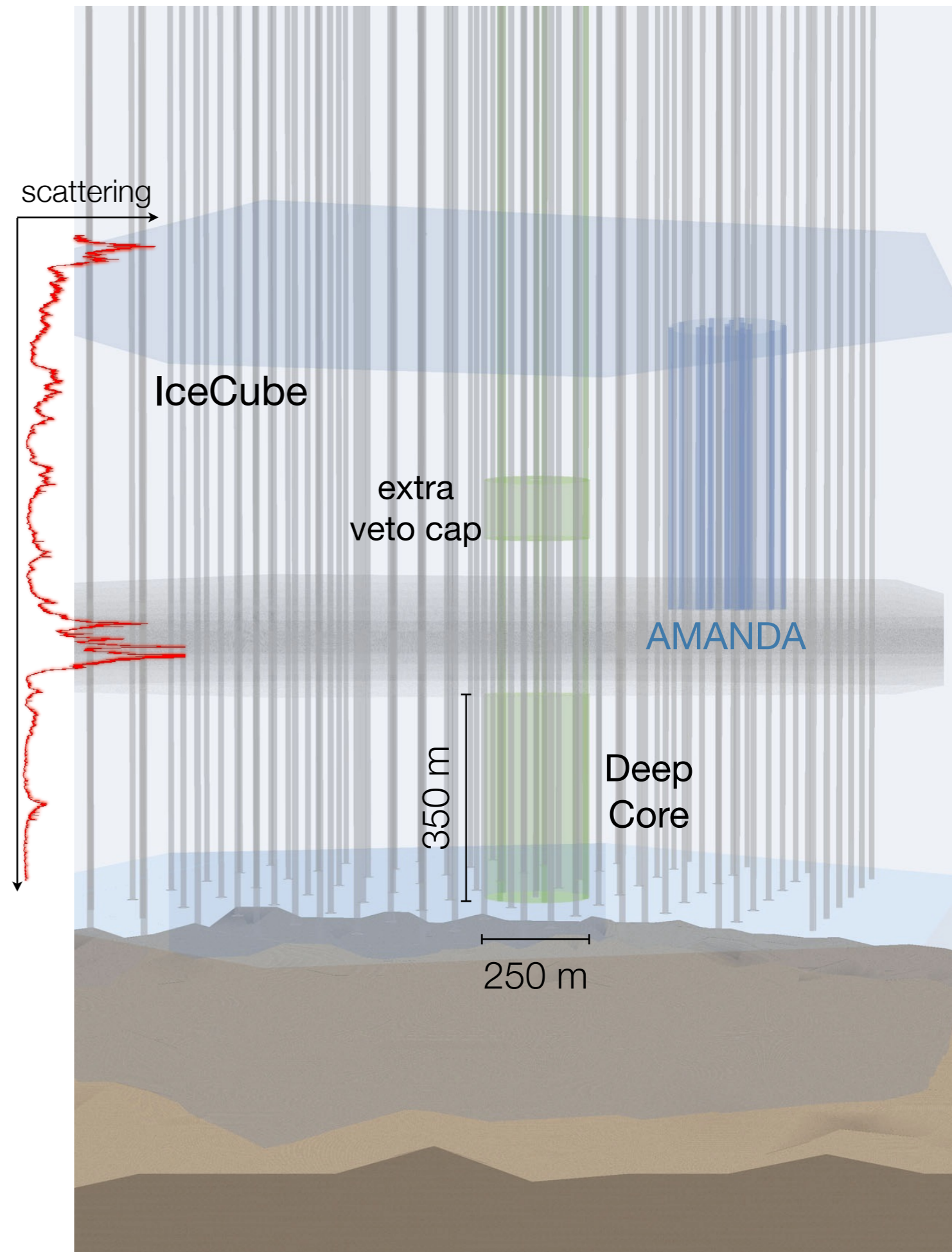
AMANDA

350 m

Deep Core

250 m

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

- In the clearest ice, below 2100 m

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

scattering

IceCube

extra
veto cap

AMANDA

350 m

Deep
Core

250 m

IceCube DeepCore

- A more densely instrumented region at the bottom center of IceCube

  - Eight additional strings, super-bialkali PMTs

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- In the clearest ice, below 2100 m

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

- IceCube provides an active veto against cosmic ray muons
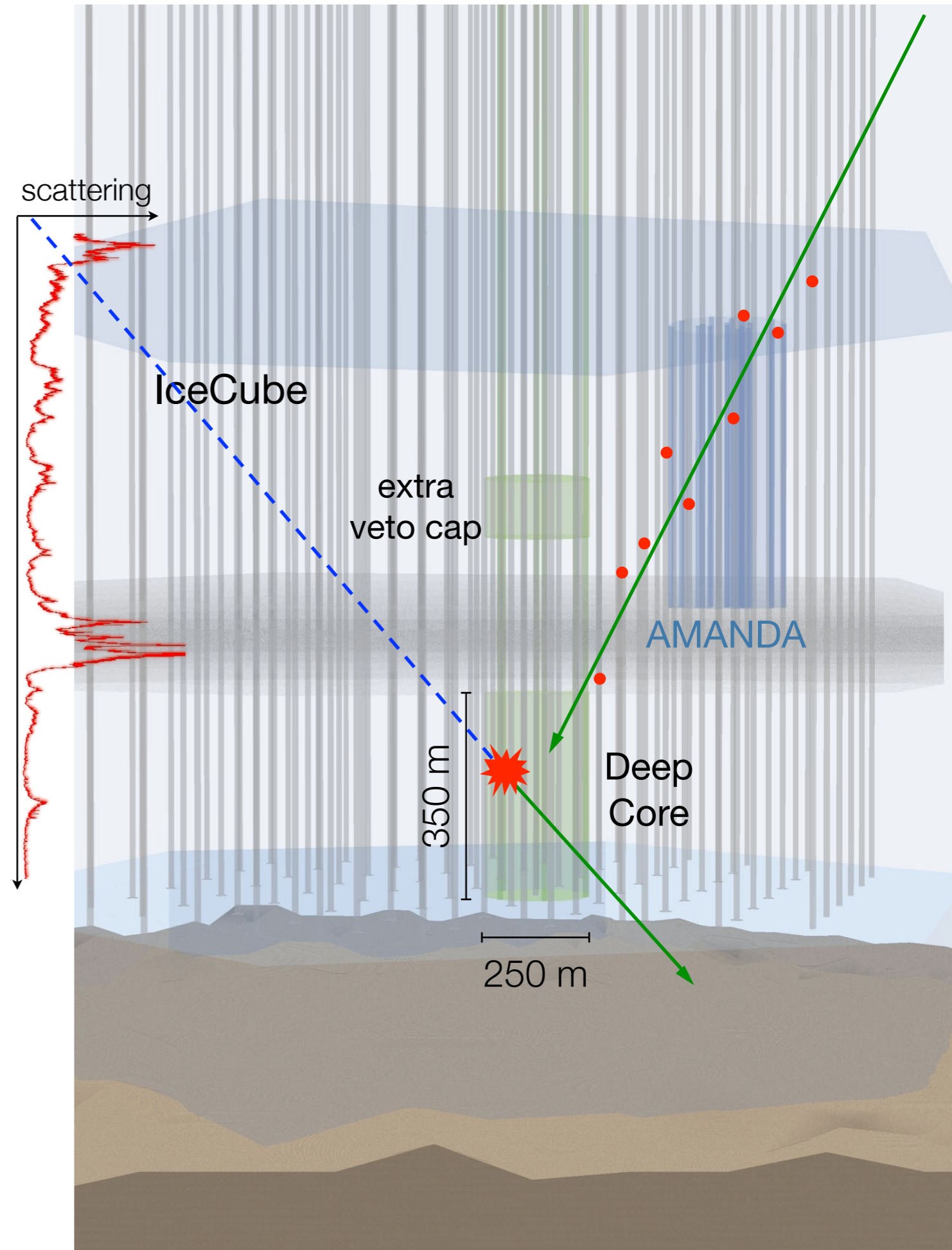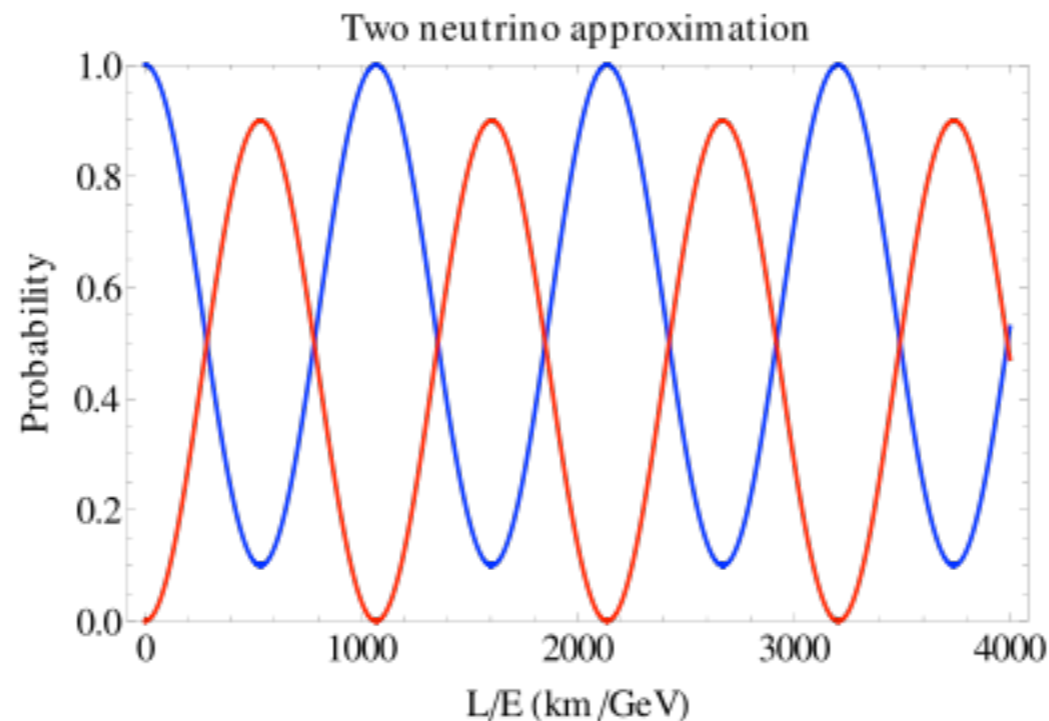
DeepCore Physics Results

- 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:

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

Two neutrino approximation

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

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

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

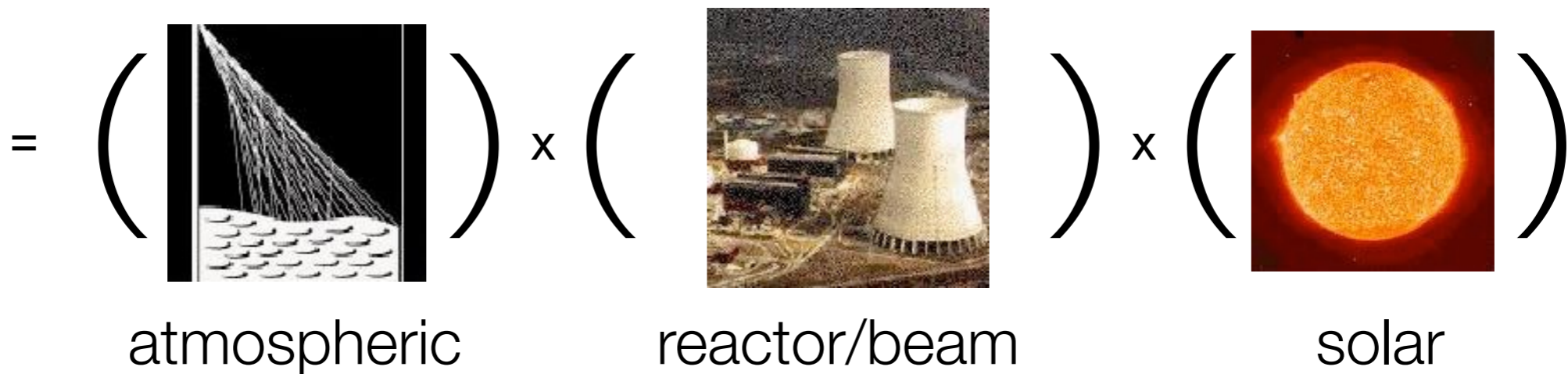= (atmospheric) x (reactor/beam) x (solar)

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

Potential CP violation ~ θ_{13}

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

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

$= \begin{pmatrix} \end{pmatrix}$ x $\begin{pmatrix} \end{pmatrix}$ x $\begin{pmatrix} \end{pmatrix}$

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

~12,700km

ν_μ ν_μ ν_μ ν_μ ν_μ ν_μ ν_μ ν_μ ν_μ

IceCube
DeepCore
PINGU
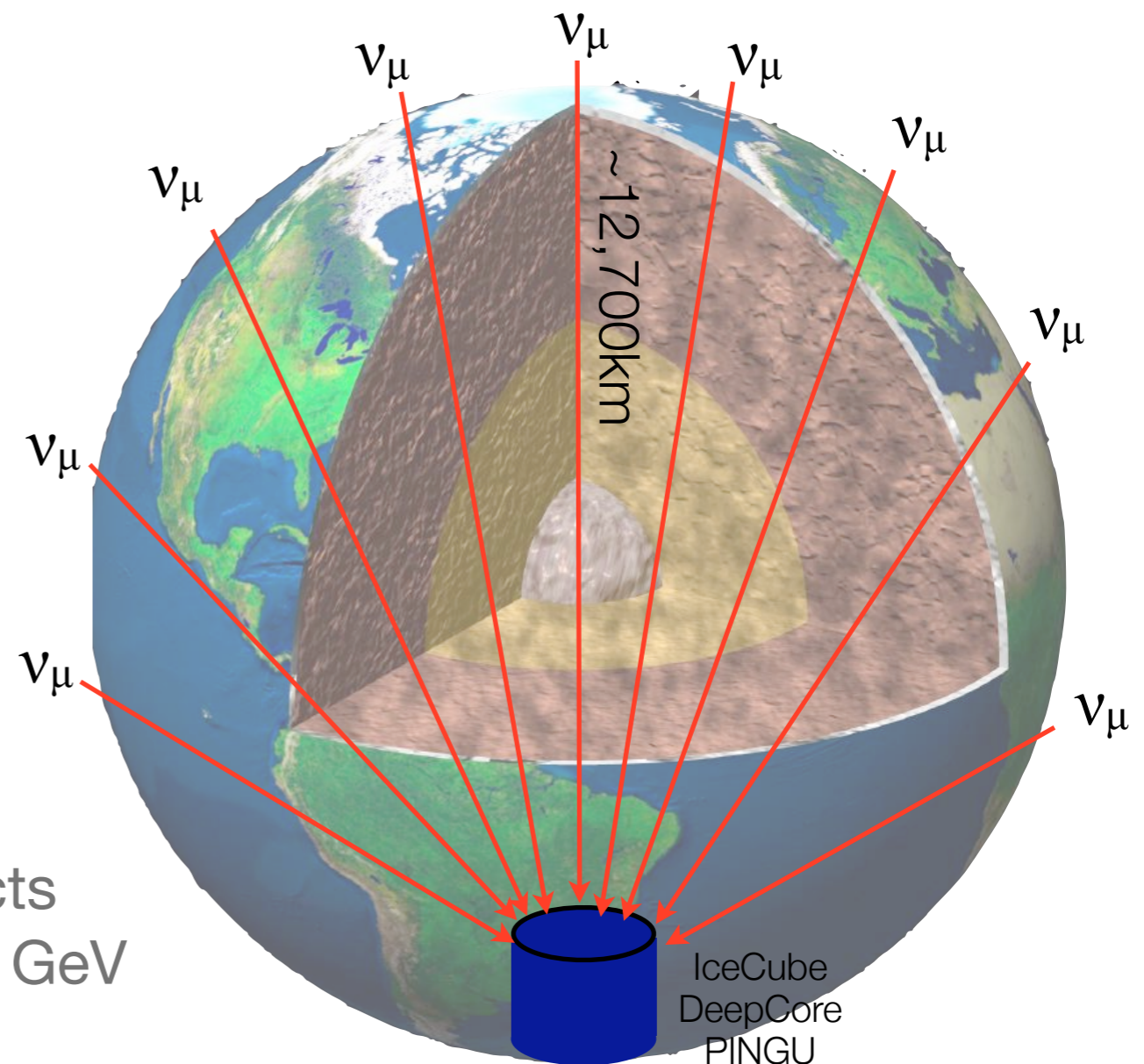
# Current IceCube Oscillation Results

- Data projected onto reconstructed (L/E$_\nu$) 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
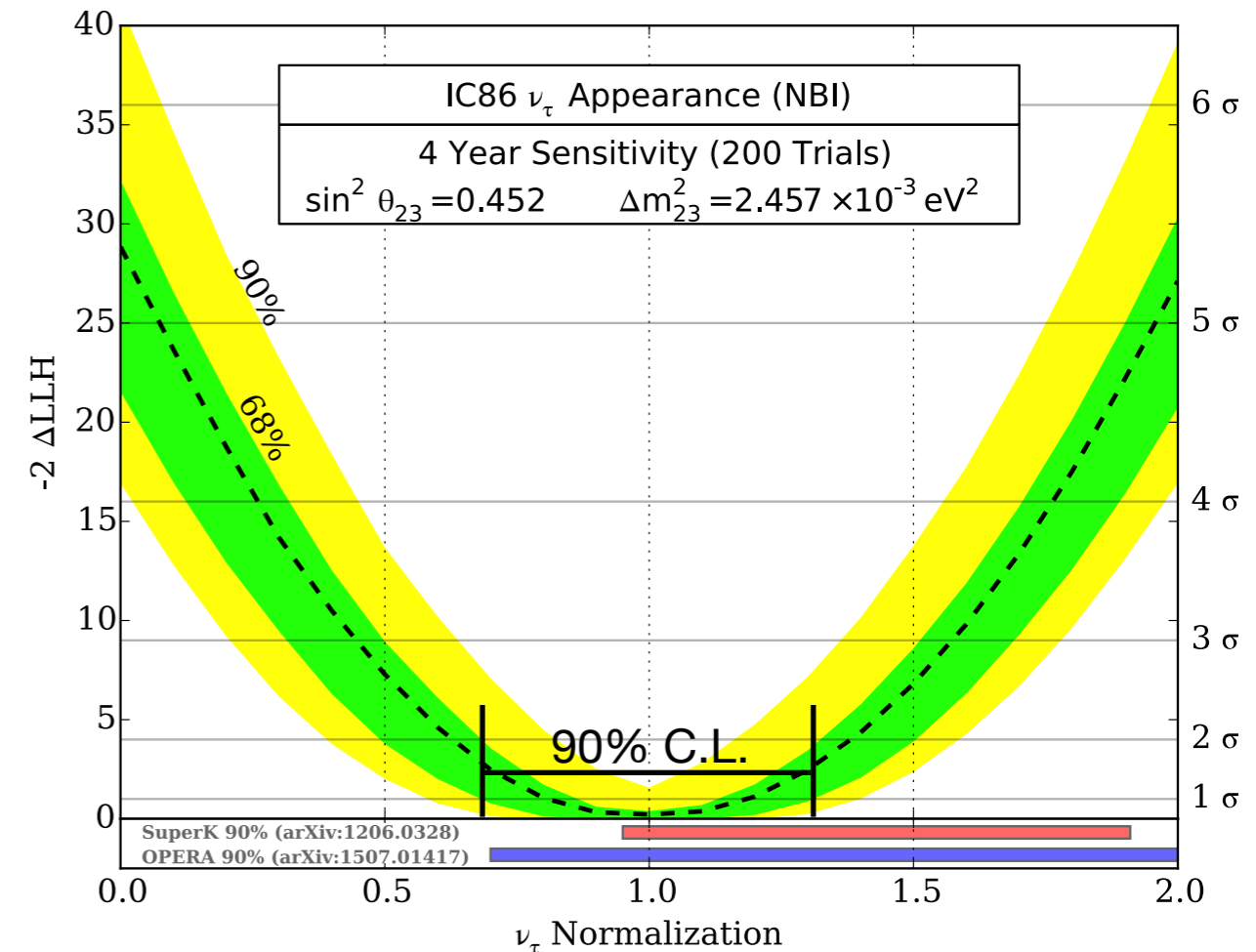

Phys. Rev. D91, 072004 (2015)
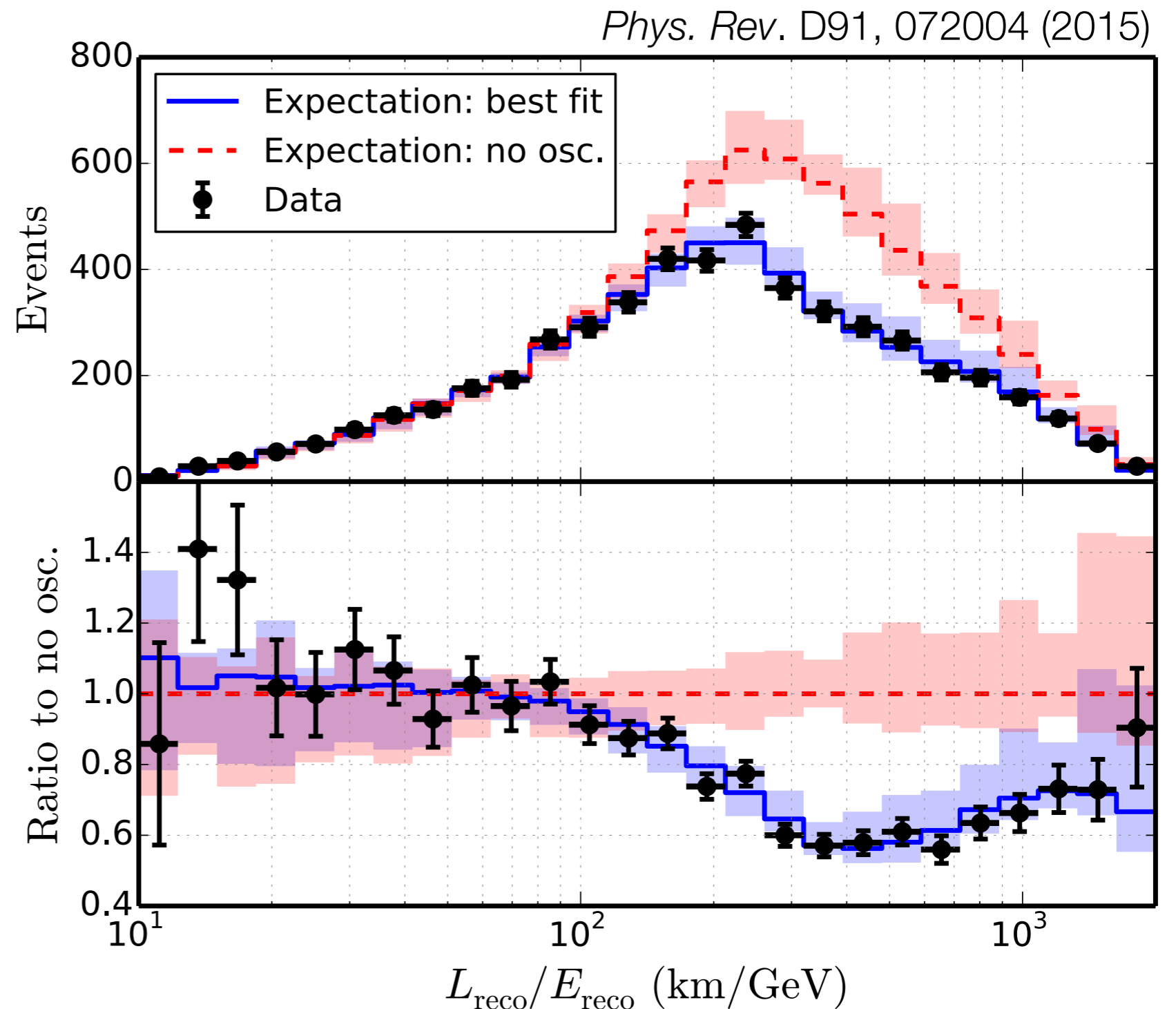
Coming Attractions

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

- Higher event rates, allowing better constraints on systematics
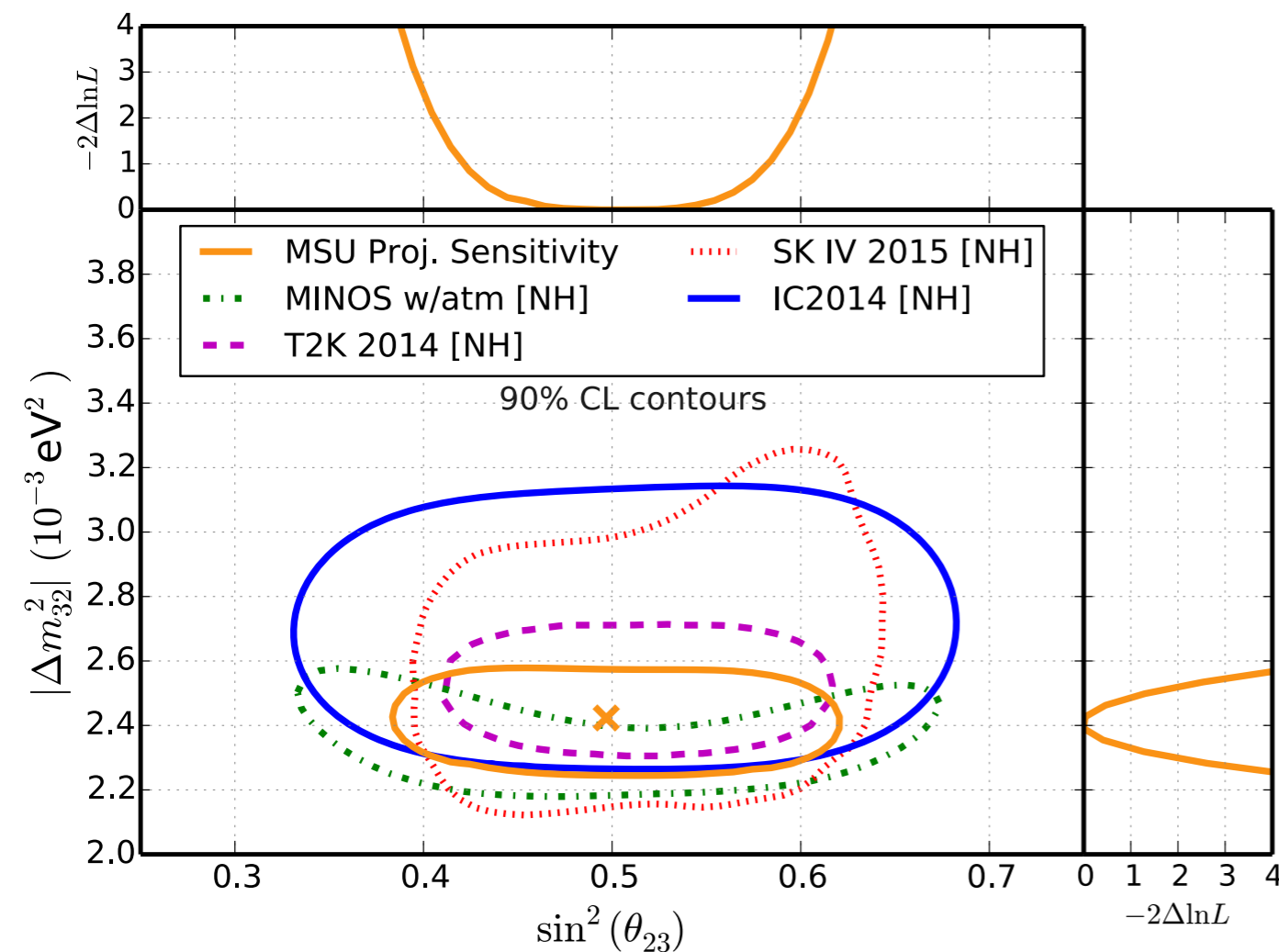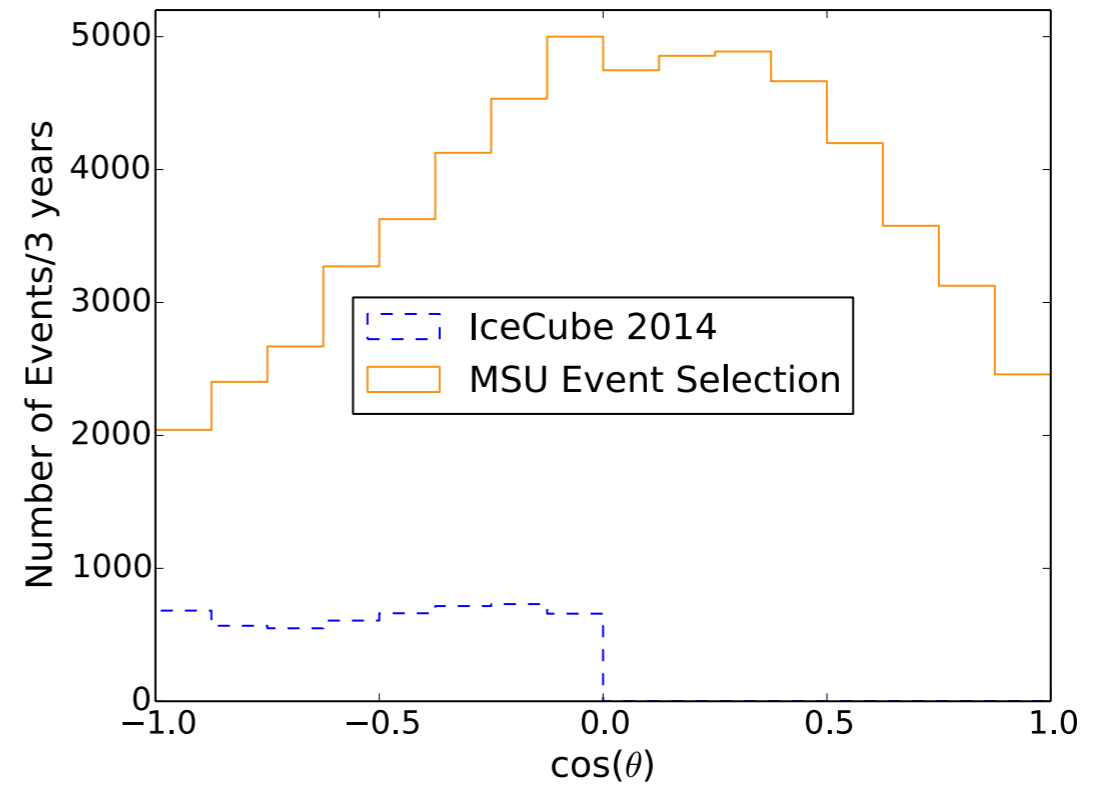

ν_τ appearance: NBI, MSU, PSU

PINGU

- 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

Precision IceCube Next Generation Upgrade

Top view of the PINGU new candidate detector
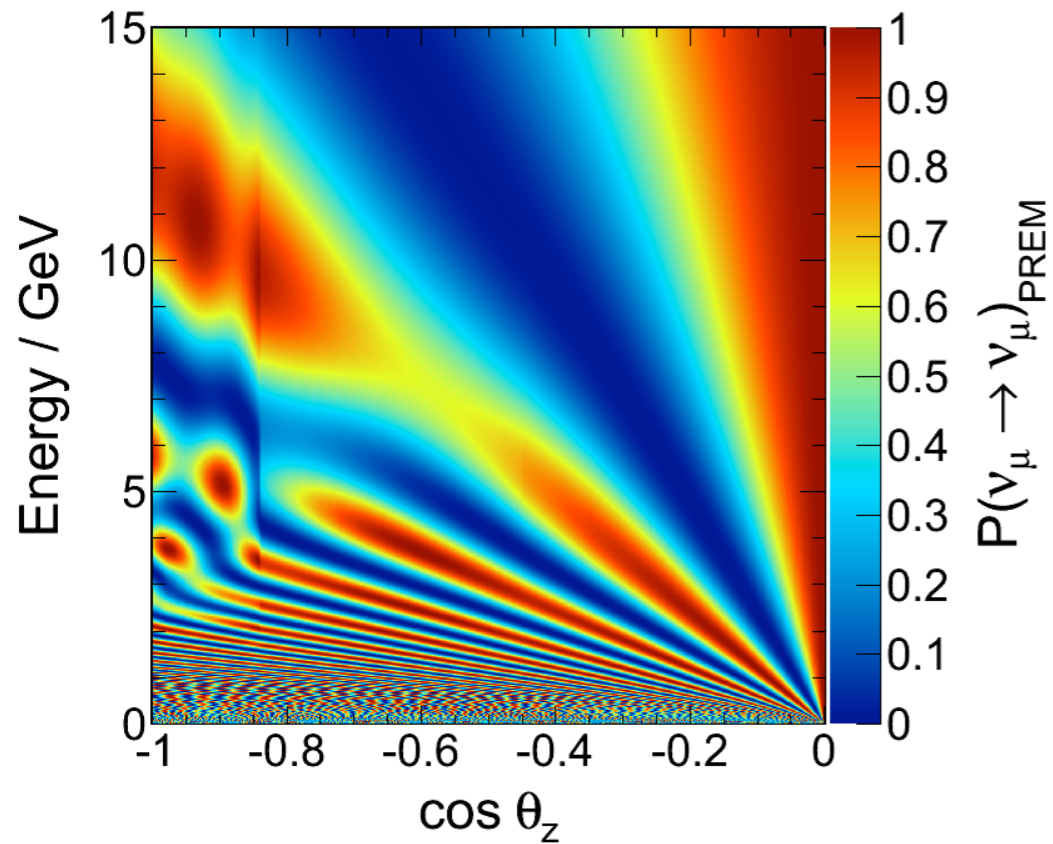
IceCube
DeepCore
PINGU

Y (m) / X (m)
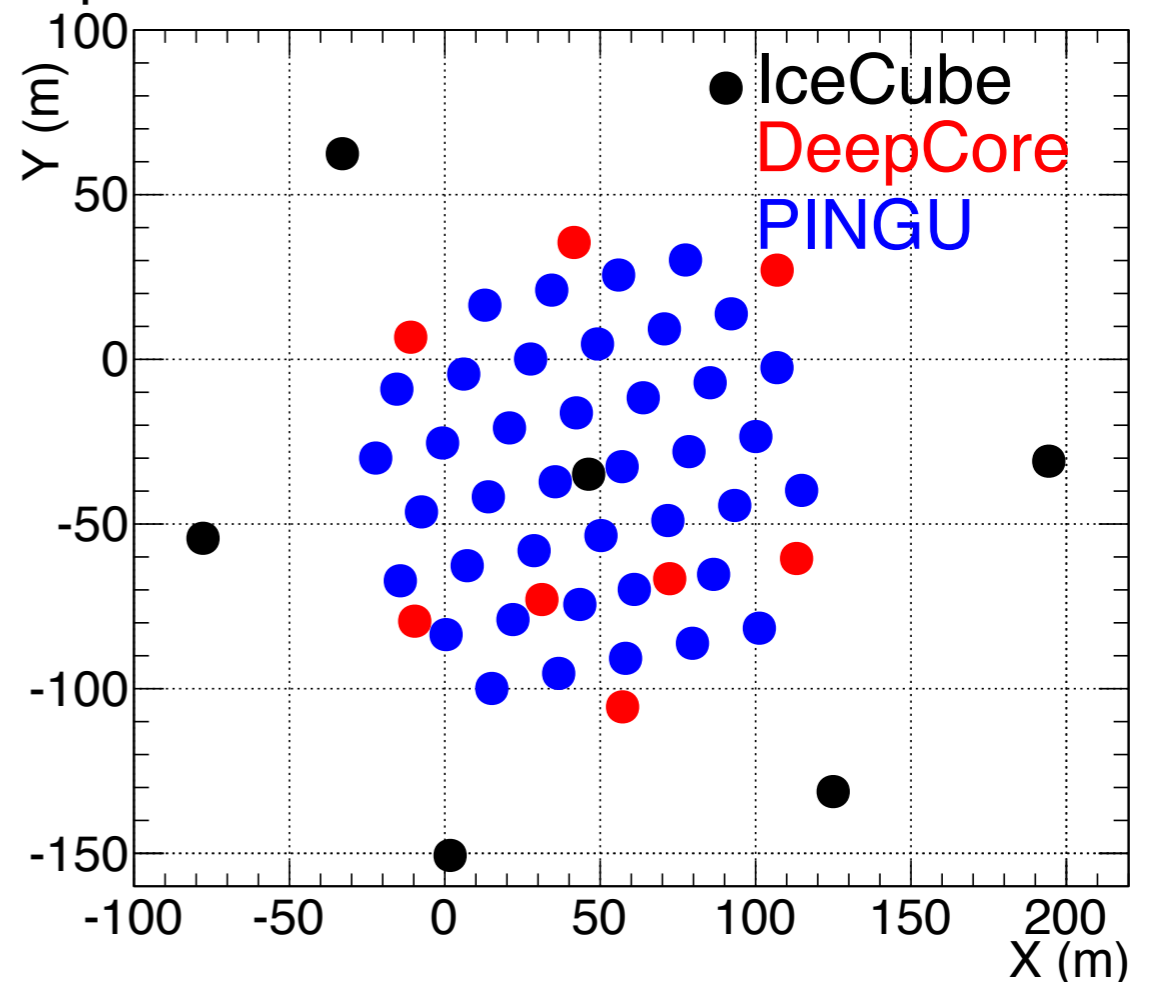
Neutrino Mass Ordering

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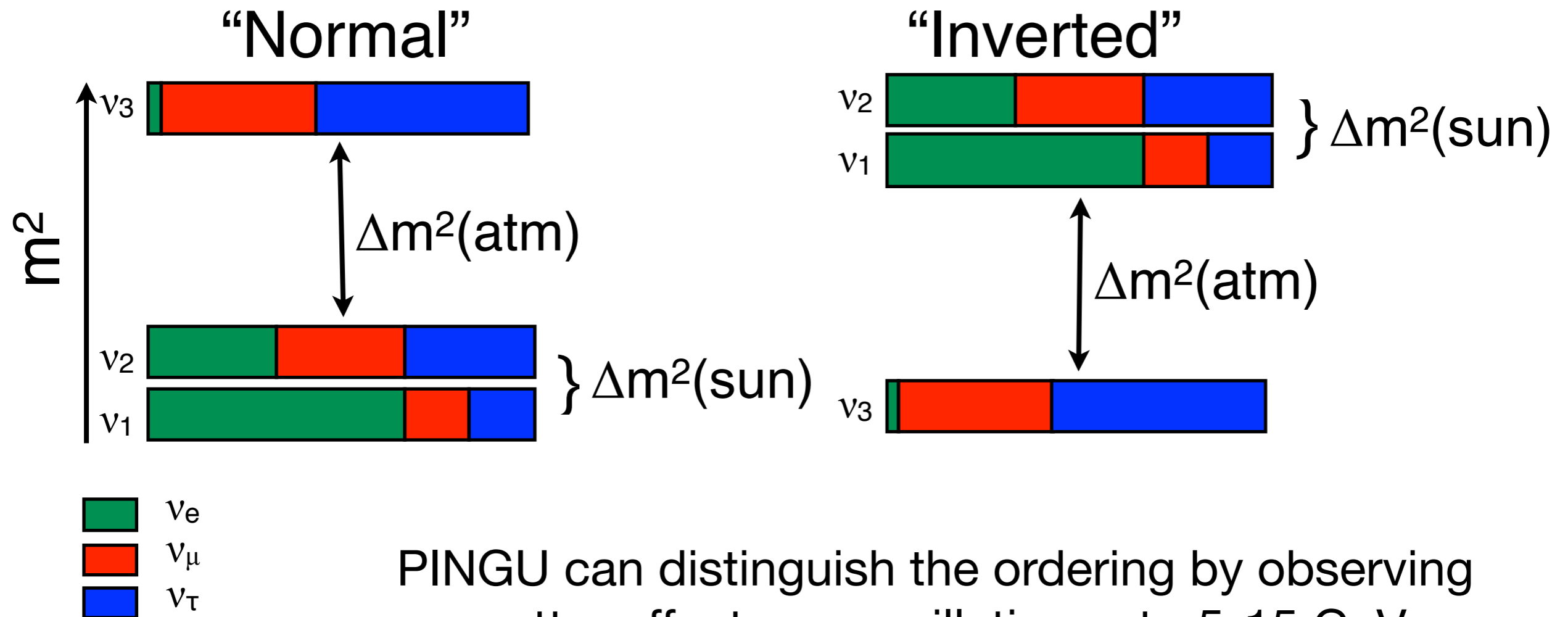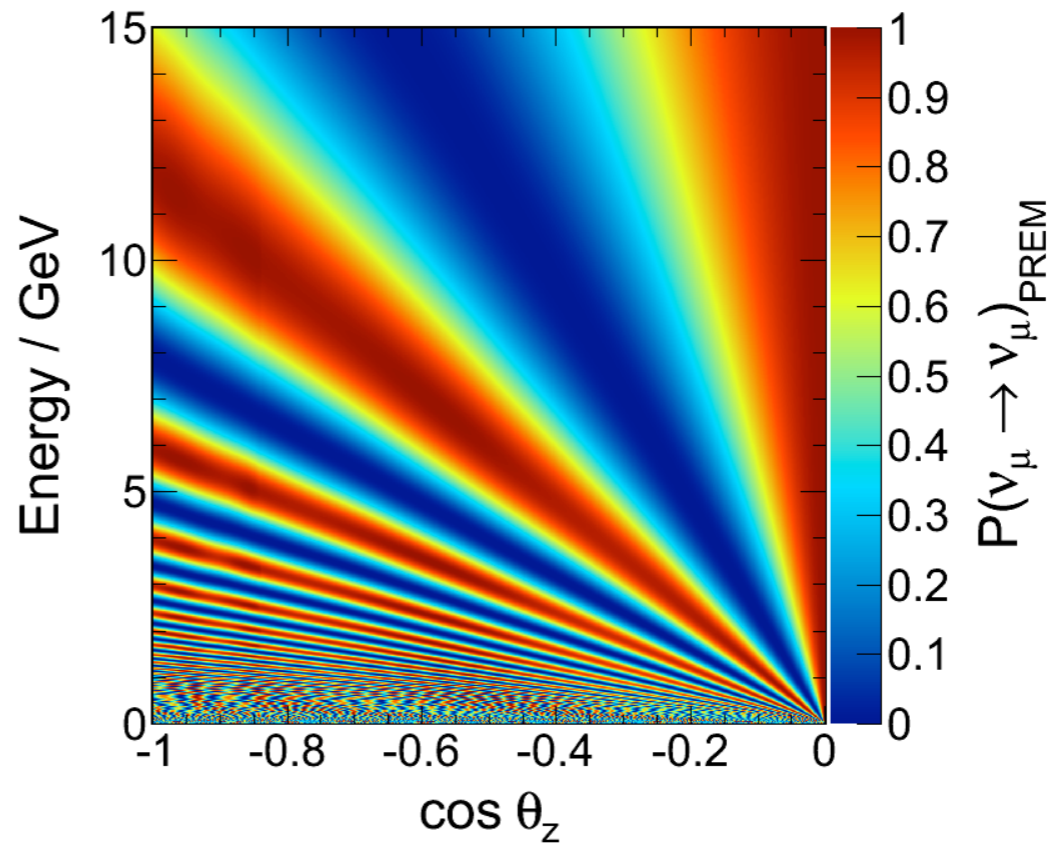

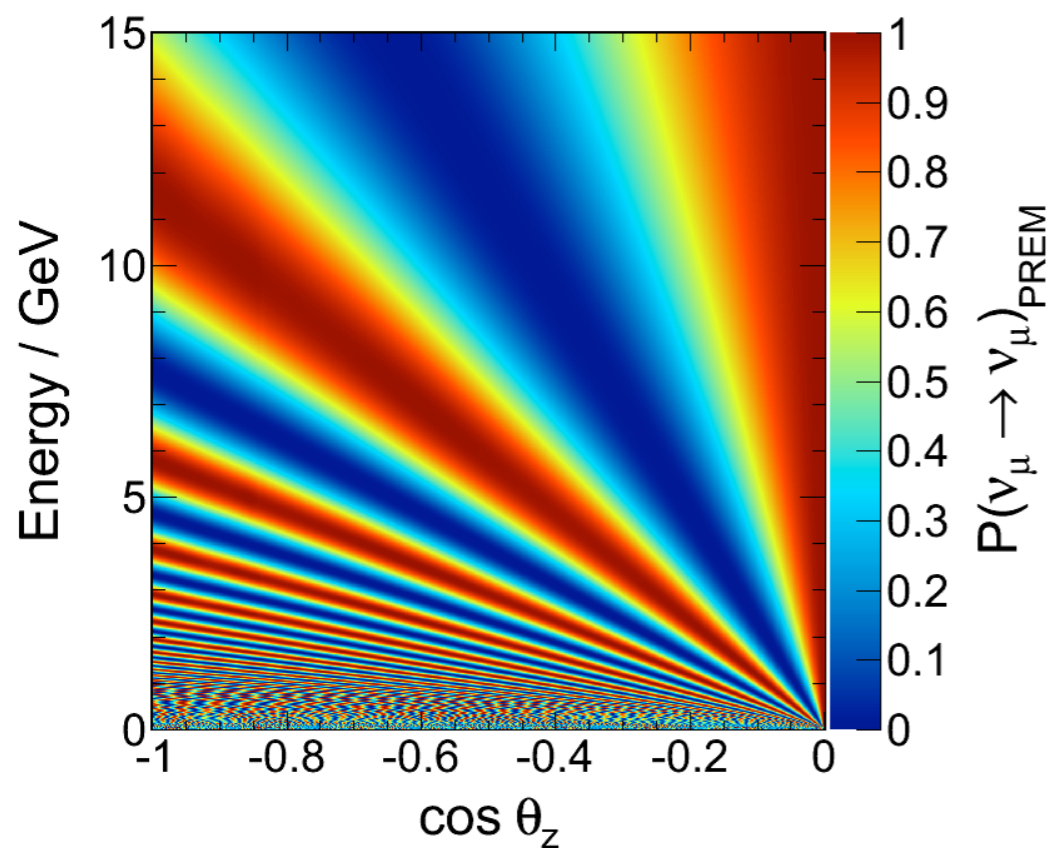PINGU can distinguish the ordering by observing matter effects on oscillations at ~5-15 GeV

Neutrinos + Antineutrinos = NO
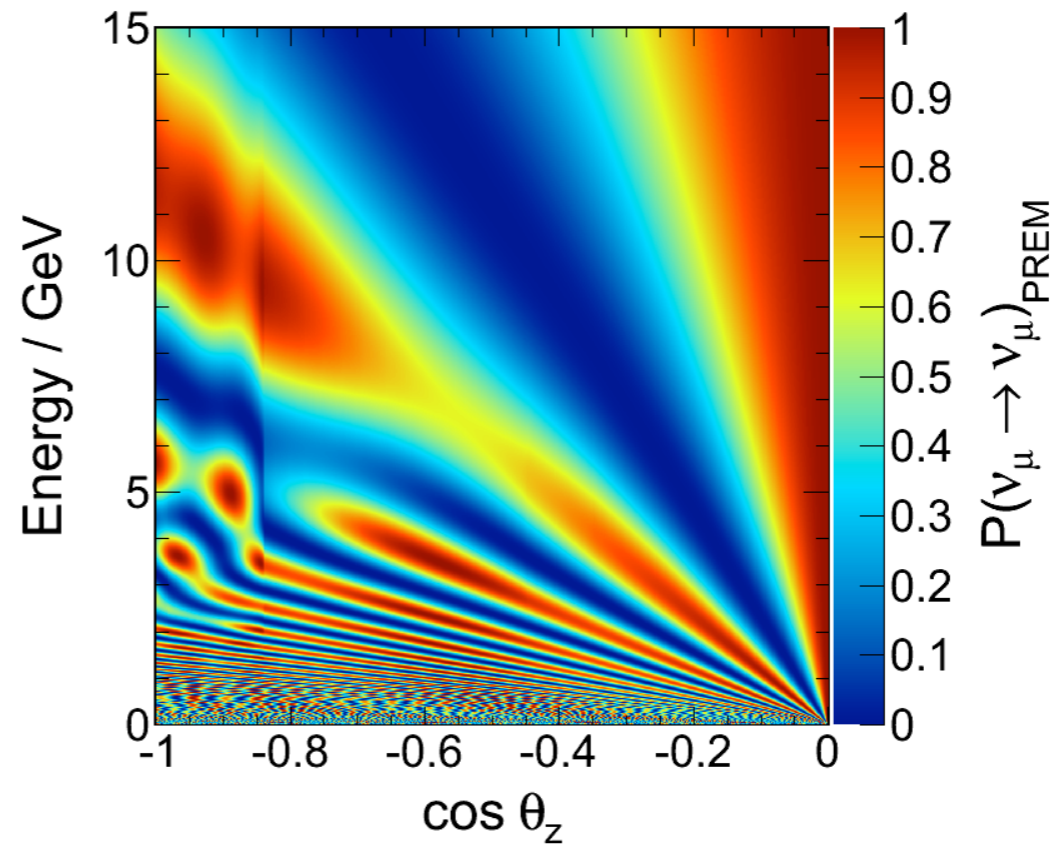
Neutrinos + Antineutrinos = IO
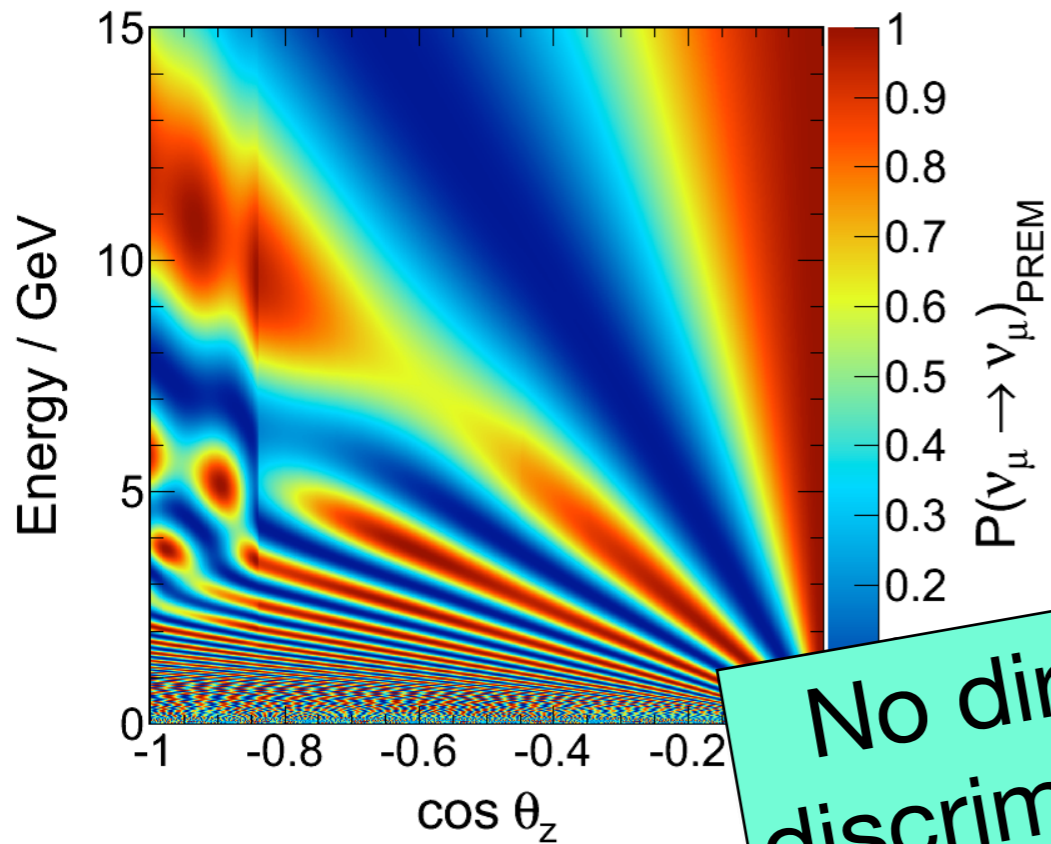
Neutrinos   Antineutrinos

$P(\nu_\mu \to \nu_\mu)_{PREM}$

Energy / GeV

$\cos \theta_z$

$+$ $=$ NO

$+$ $=$ IO

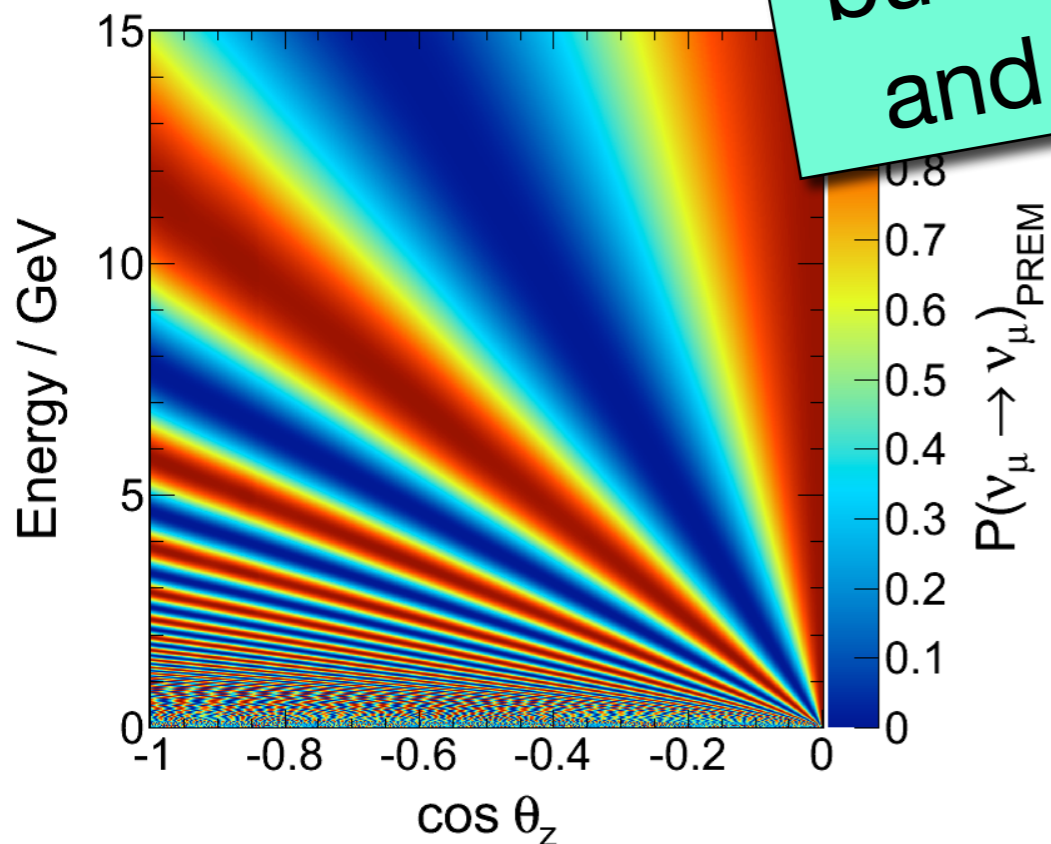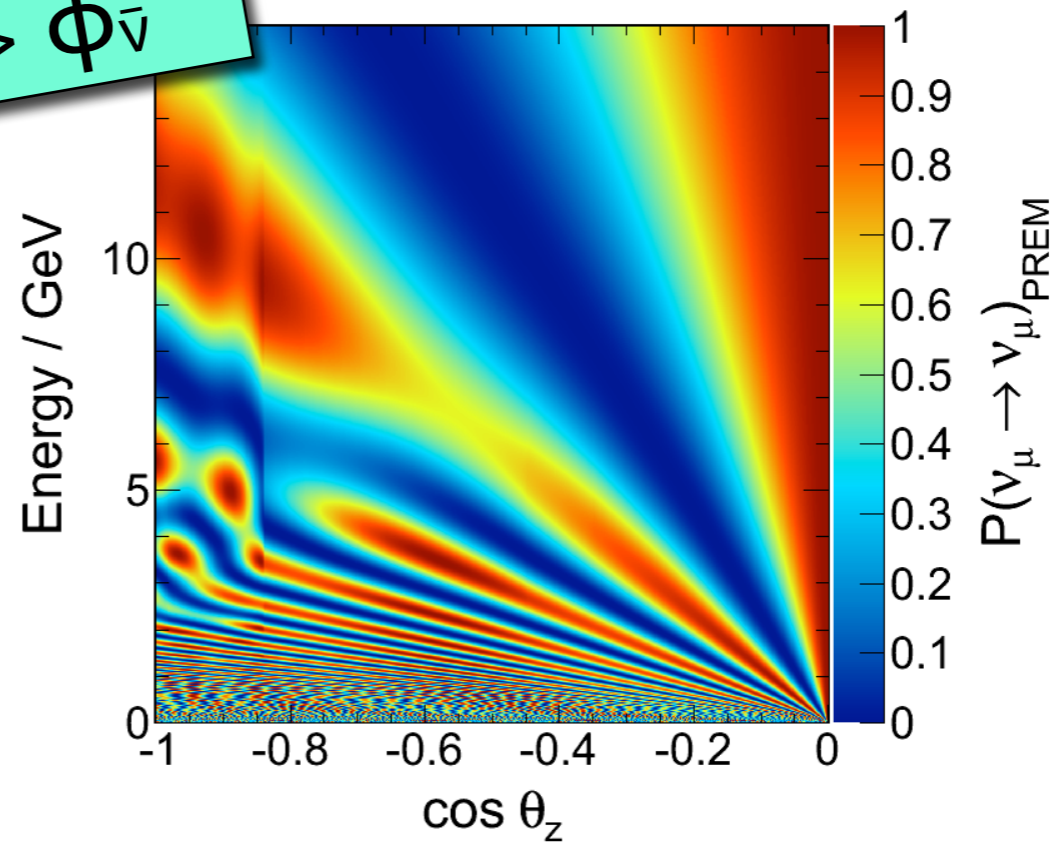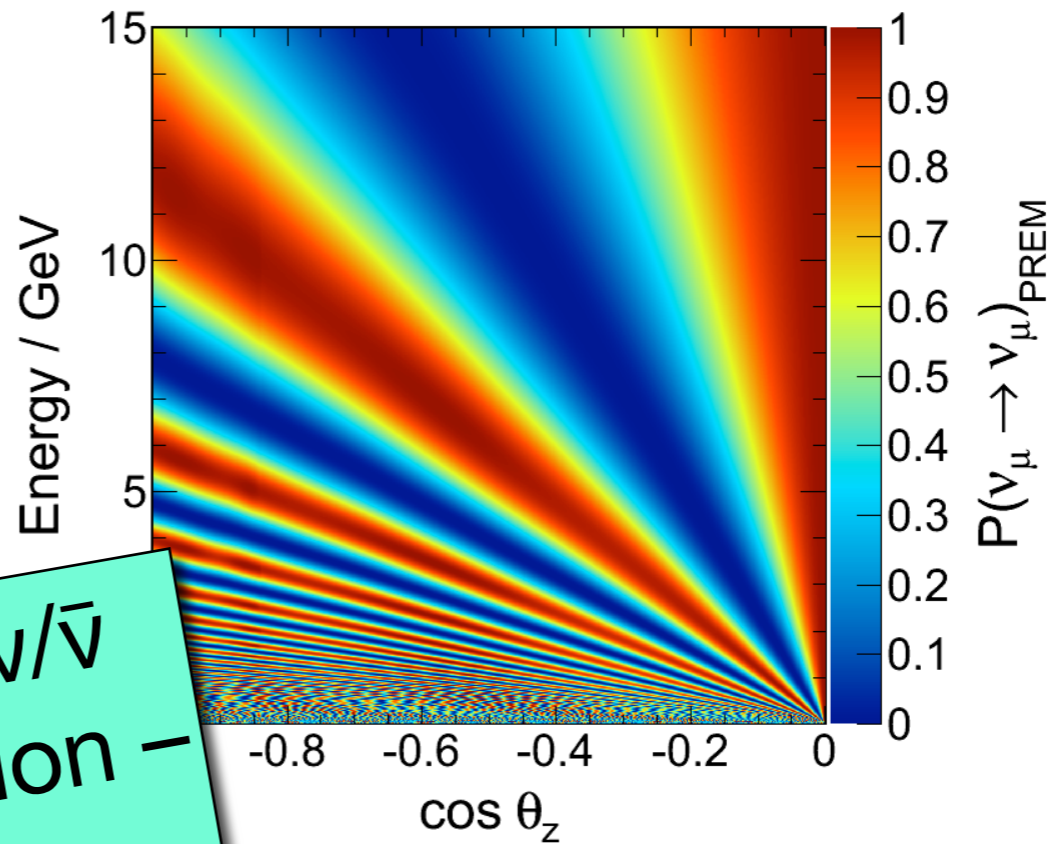No direct $\nu/\bar{\nu}$ discrimination – but $\sigma_{\nu N} \sim 2\sigma_{\bar{\nu}N}$ and $\phi_\nu > \phi_{\bar{\nu}}$

Neutrinos

Antineutrinos

= NO

= IO

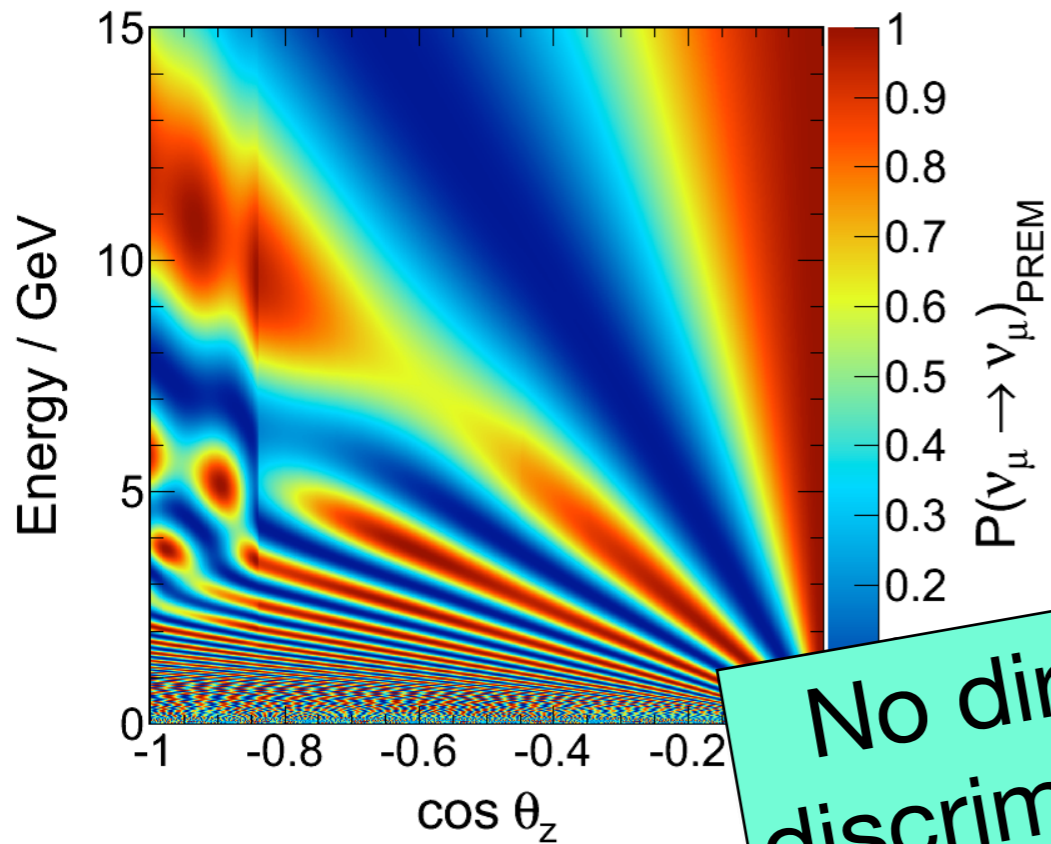No direct ν/ν̄ discrimination – but $\sigma_{\nu N} \sim 2\sigma_{\bar{\nu}N}$ and $\phi_\nu > \phi_{\bar{\nu}}$
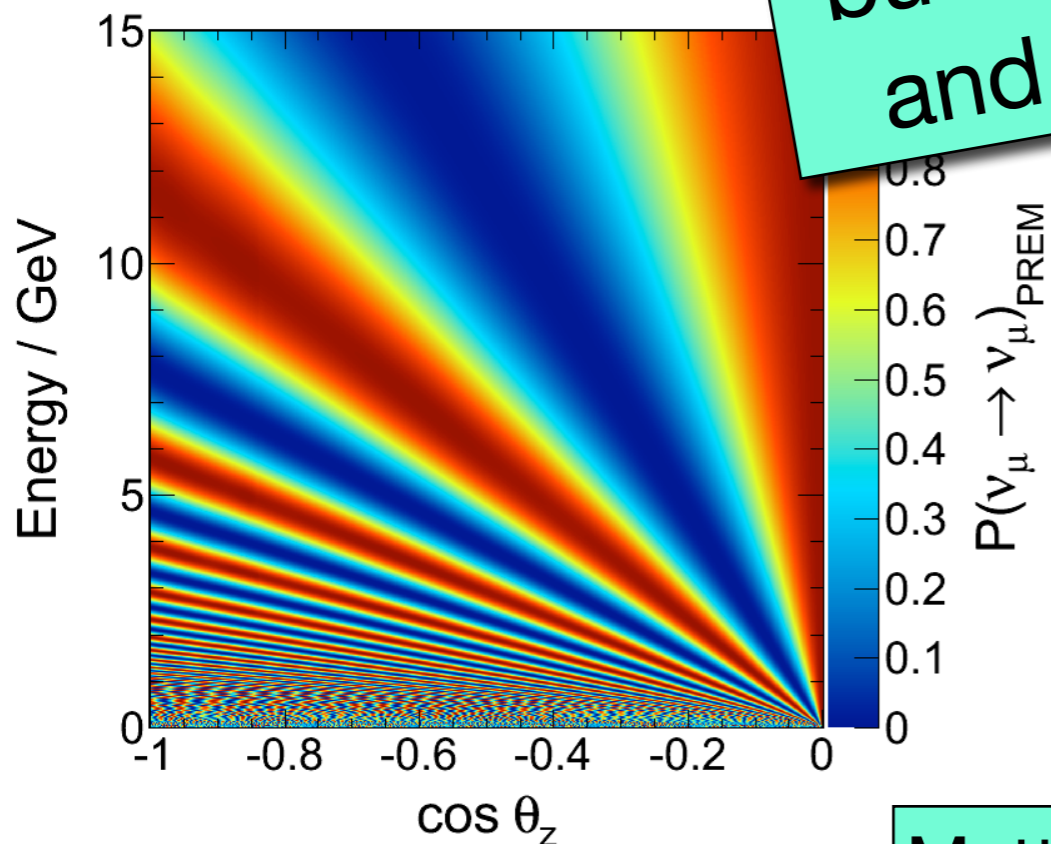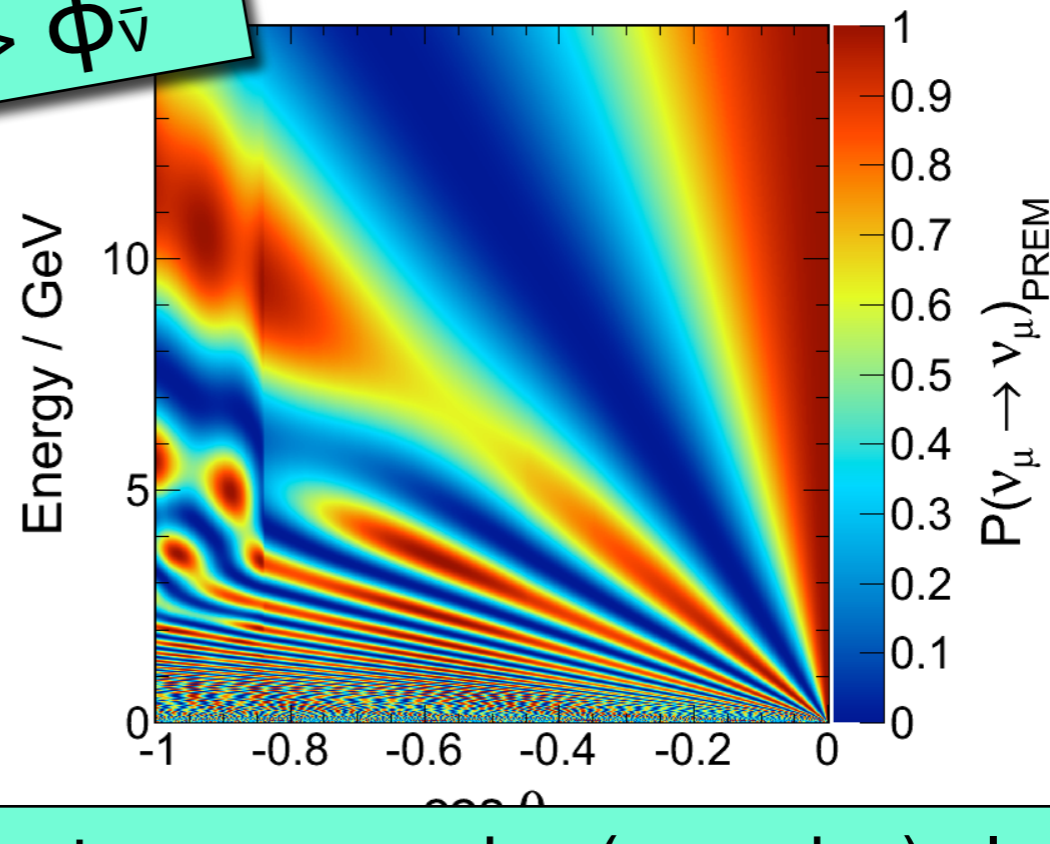
Matter effects on cascades (ν_e and ν_τ) also important

Hierarchy Signature: Observables

Events ID'd as tracks (ν_μ CC)

Events ID'd as cascades (ν_e, NC)
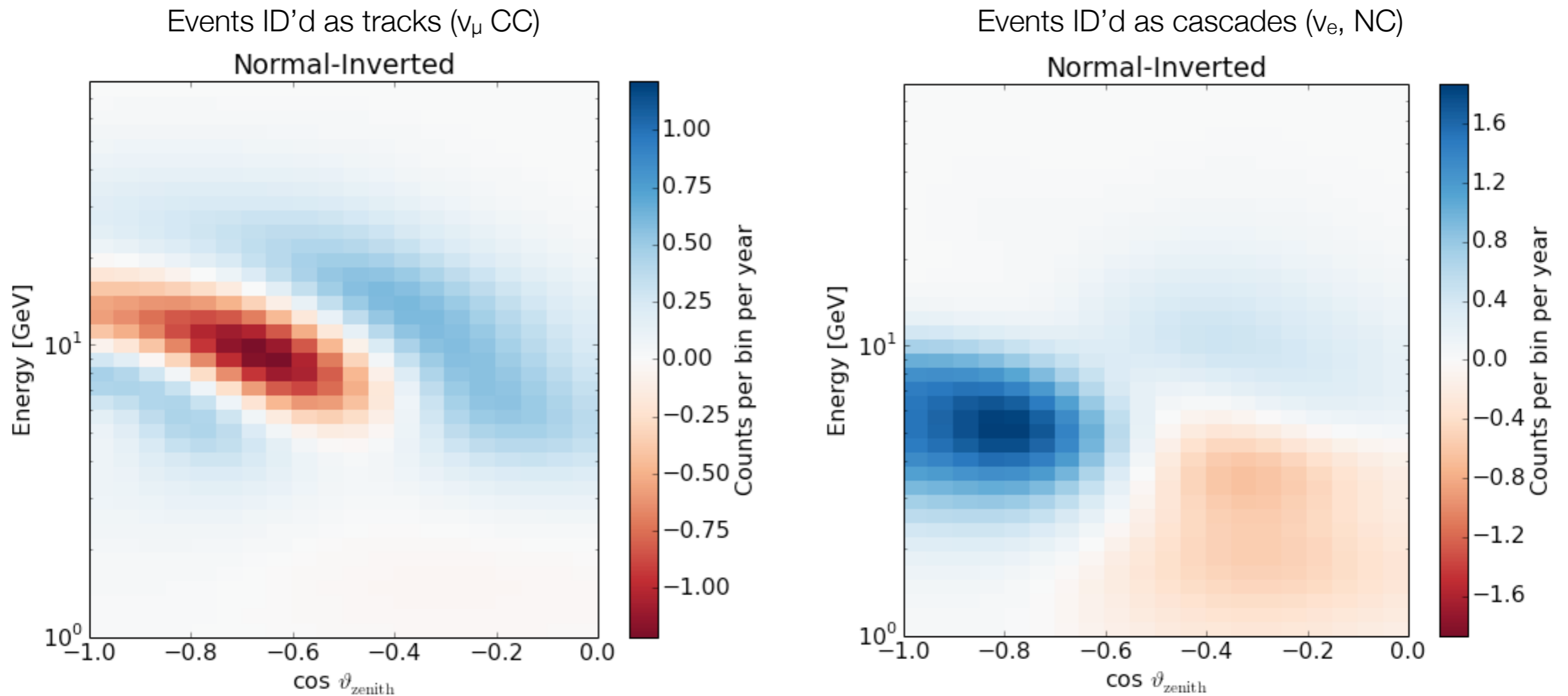
- Event rates, detector resolutions and efficiencies parametrized from full detector Monte Carlo to eliminate statistical fluctuations

- Expect ~50k ($\nu_\mu + \bar{\nu}_\mu$) and ~40k ($\nu_e + \bar{\nu}_e$) 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
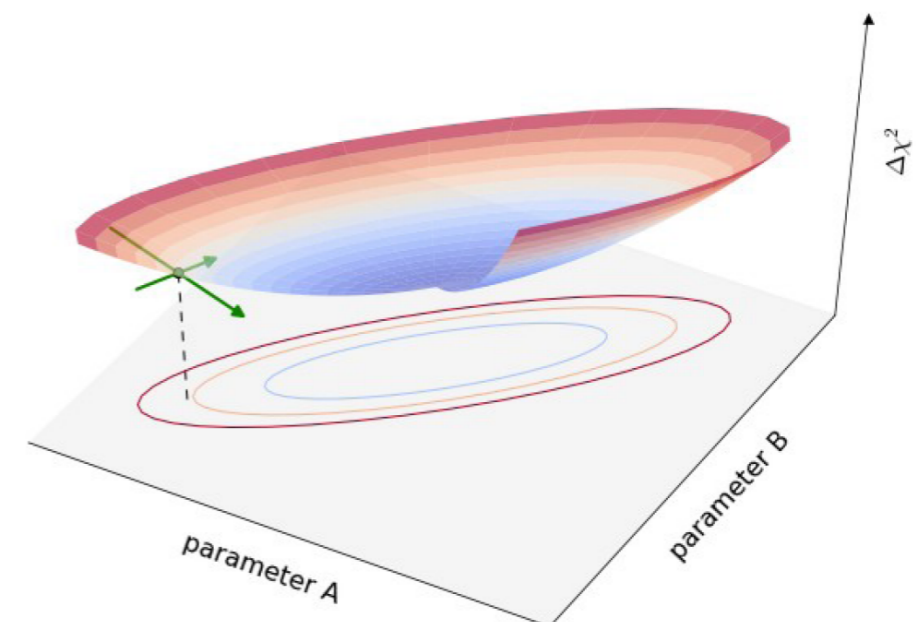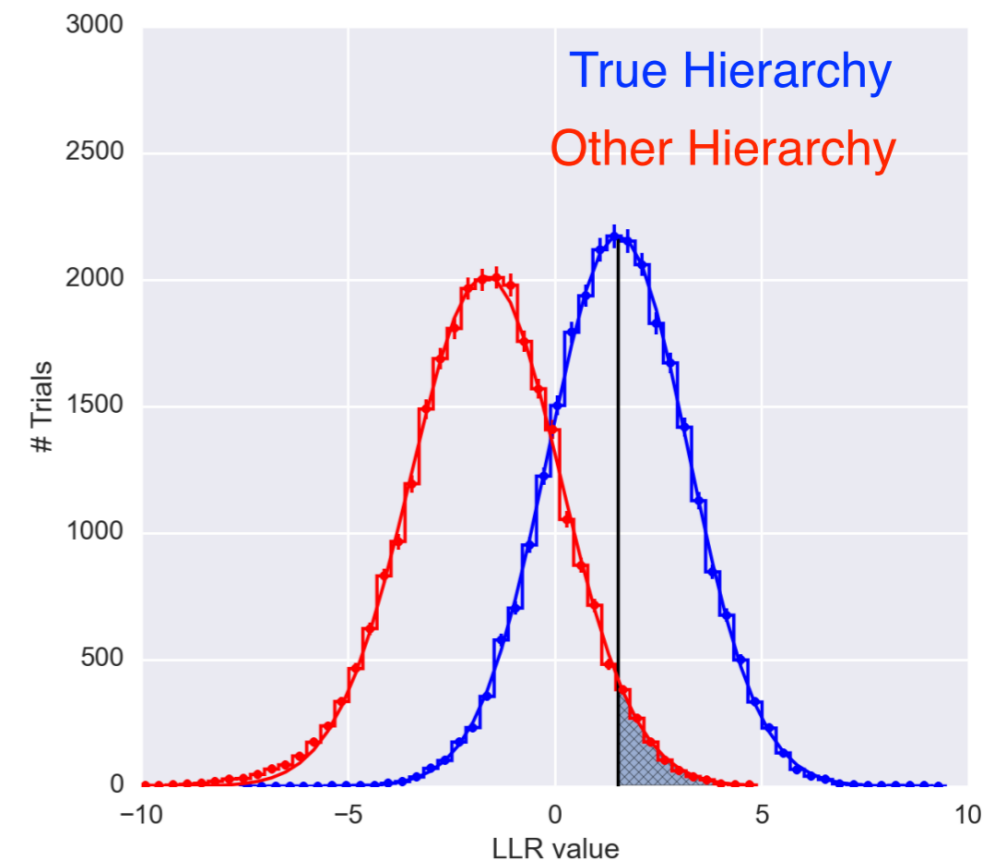
Significance vs. Time

- 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
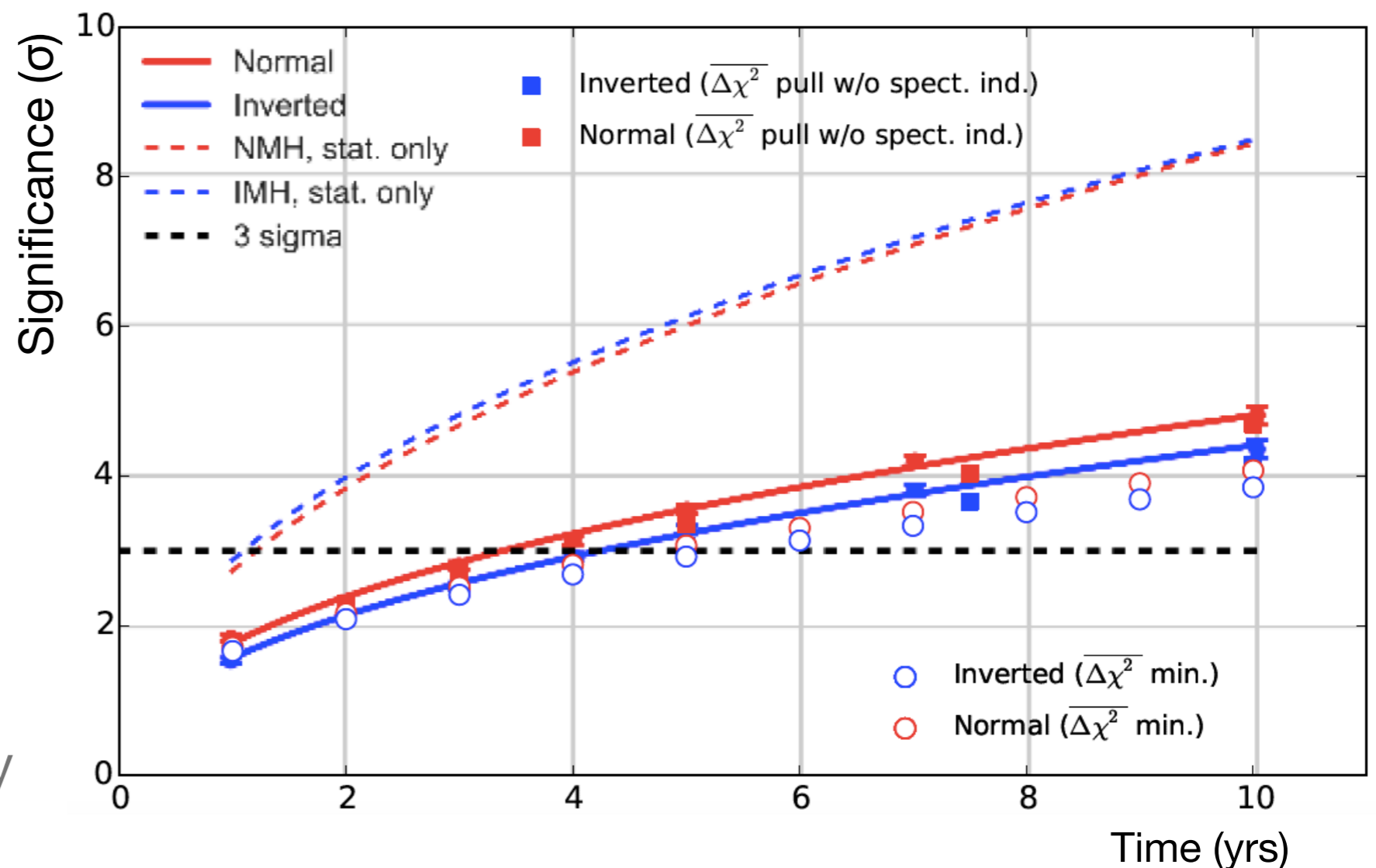
Effects of Systematics

- 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*

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

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

*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 $\geq 3\sigma$ within ~4 years over full $\pm 2\sigma$ range of global fit

  - Statistical methods agree acceptably well over most of range – discrepancy at high significance under study

4 year significance vs. θ_{23}

- Normal
- Inverted
- Normal ($\overline{\Delta\chi^2}$)
- Inverted ($\overline{\Delta\chi^2}$)

σ(4 yr)

$\sin^2 \theta_{23}$
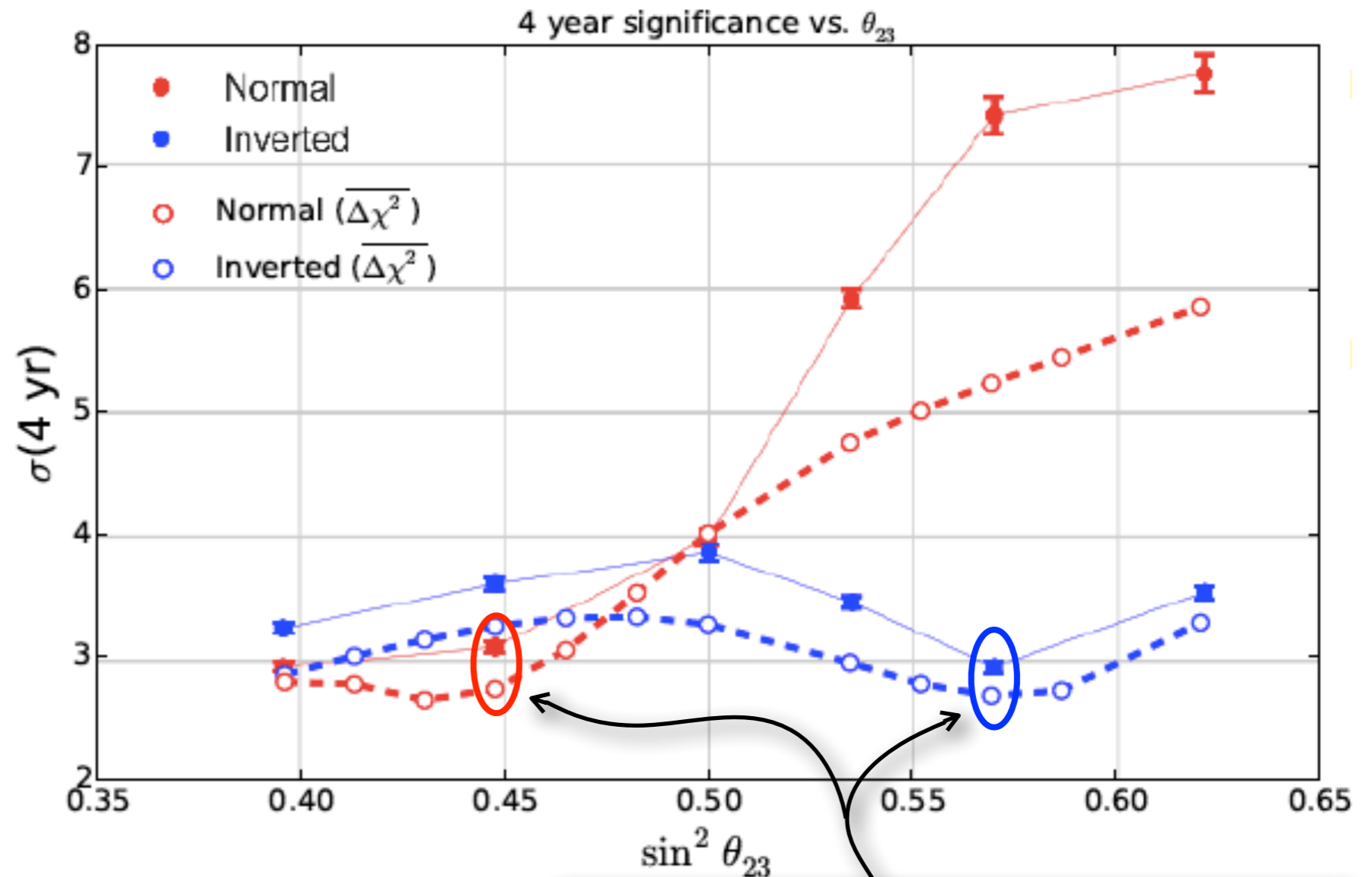
nu-fit 2014 (does not include IceCube or NOvA)

Impact of CP Violation

- **Previously have fixed $\delta_{CP} = 0$**

  - As θ_{23} has drifted closer to maximal, potential impact increases

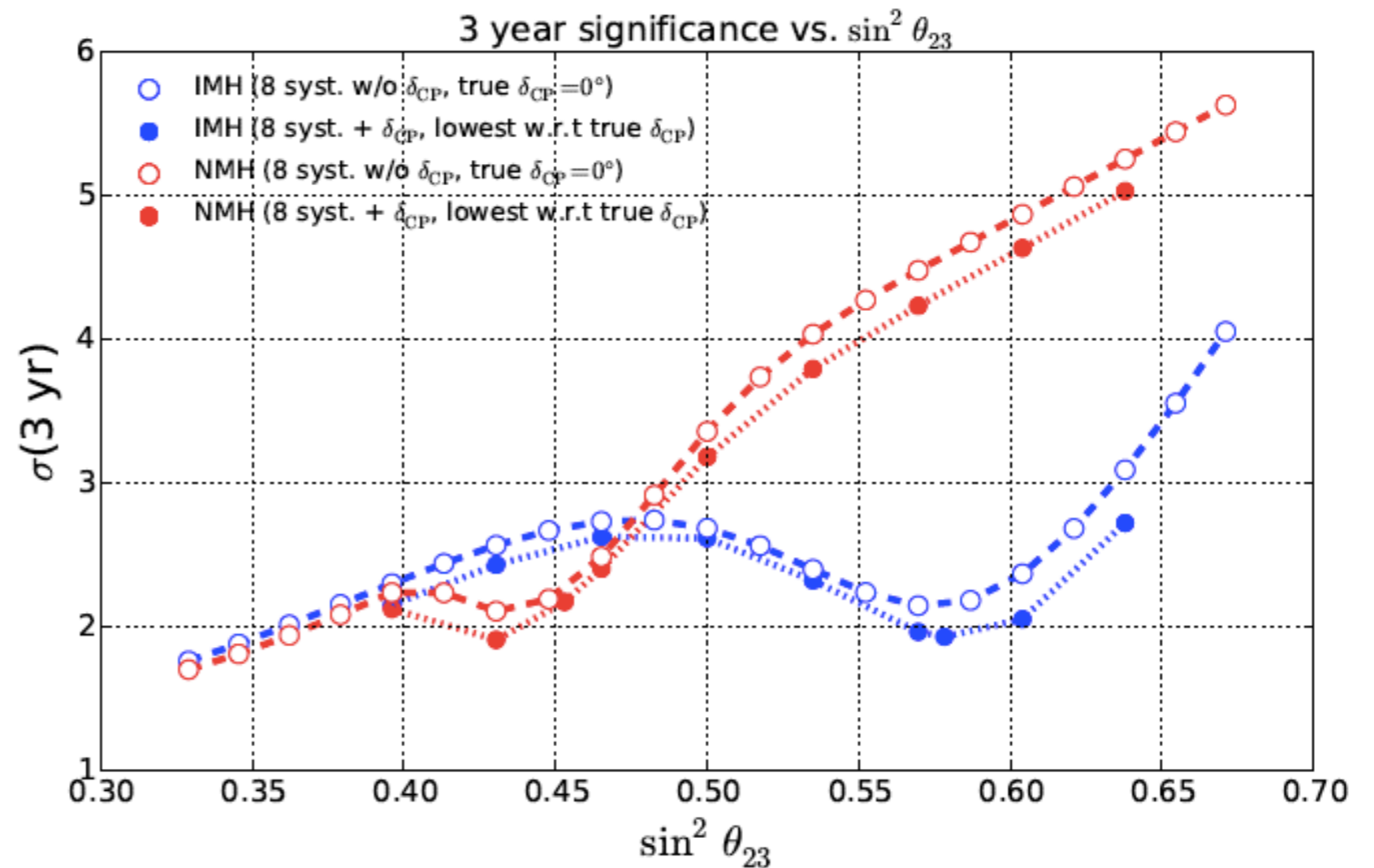- **Worst-case appears to reduce NMO 4-yr significance by ~0.2σ**

  - Preliminary study including δ_{CP} as a nuisance parameter ($\Delta\chi^2$ method only)

3 year significance vs. $\sin^2 \theta_{23}$

IMH (8 syst. w/o δ_{CP}, true $\delta_{CP} = 0°$)
IMH (8 syst. + δ_{CP}, lowest w.r.t true δ_{CP})
NMH (8 syst. w/o δ_{CP}, true $\delta_{CP} = 0°$)
NMH (8 syst. + δ_{CP}, lowest w.r.t true δ_{CP})

Other Oscillation Measurements with PINGU

- Complementary to other measurements – interesting tests of standard oscillations

  - Higher energies, different systematics
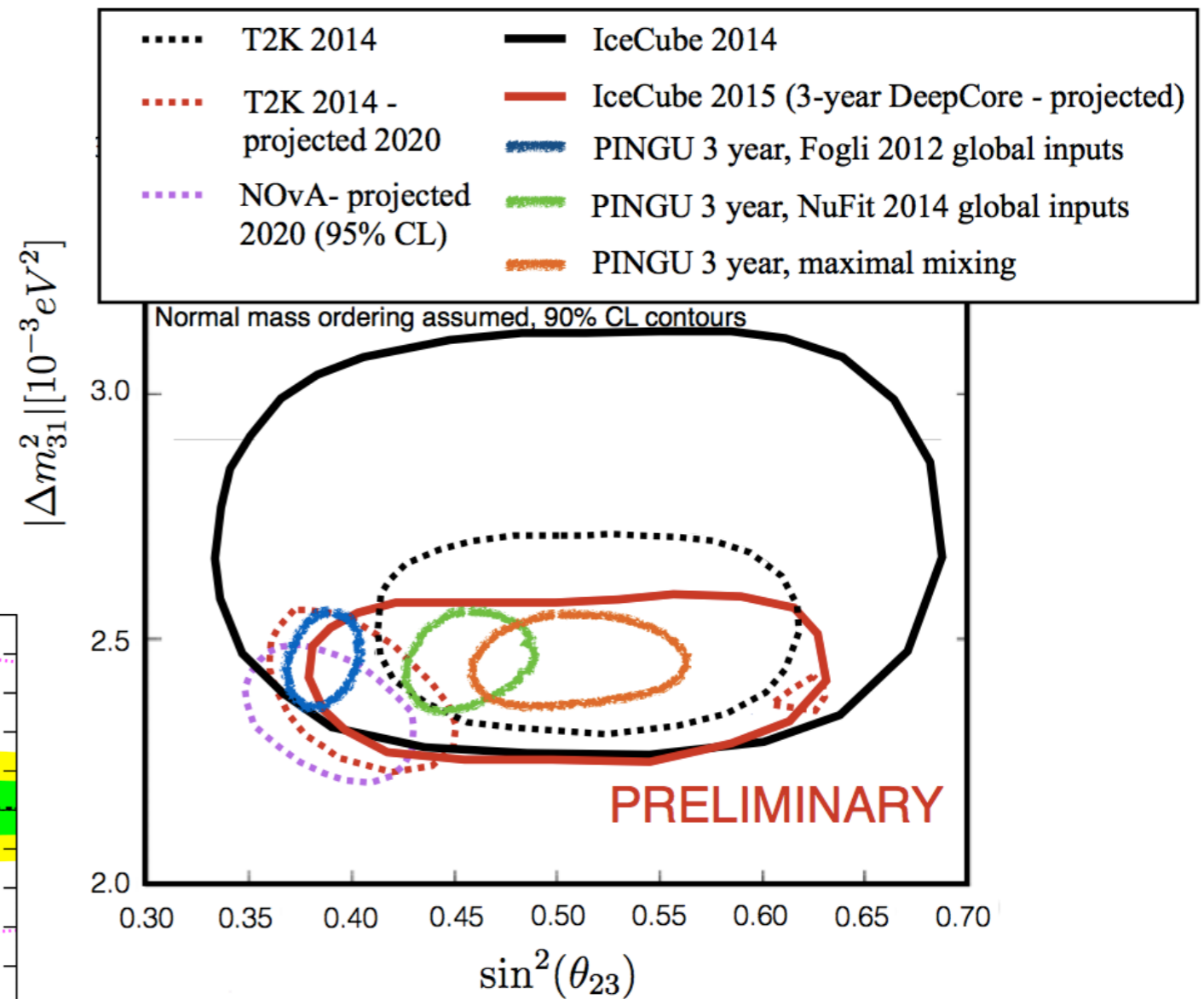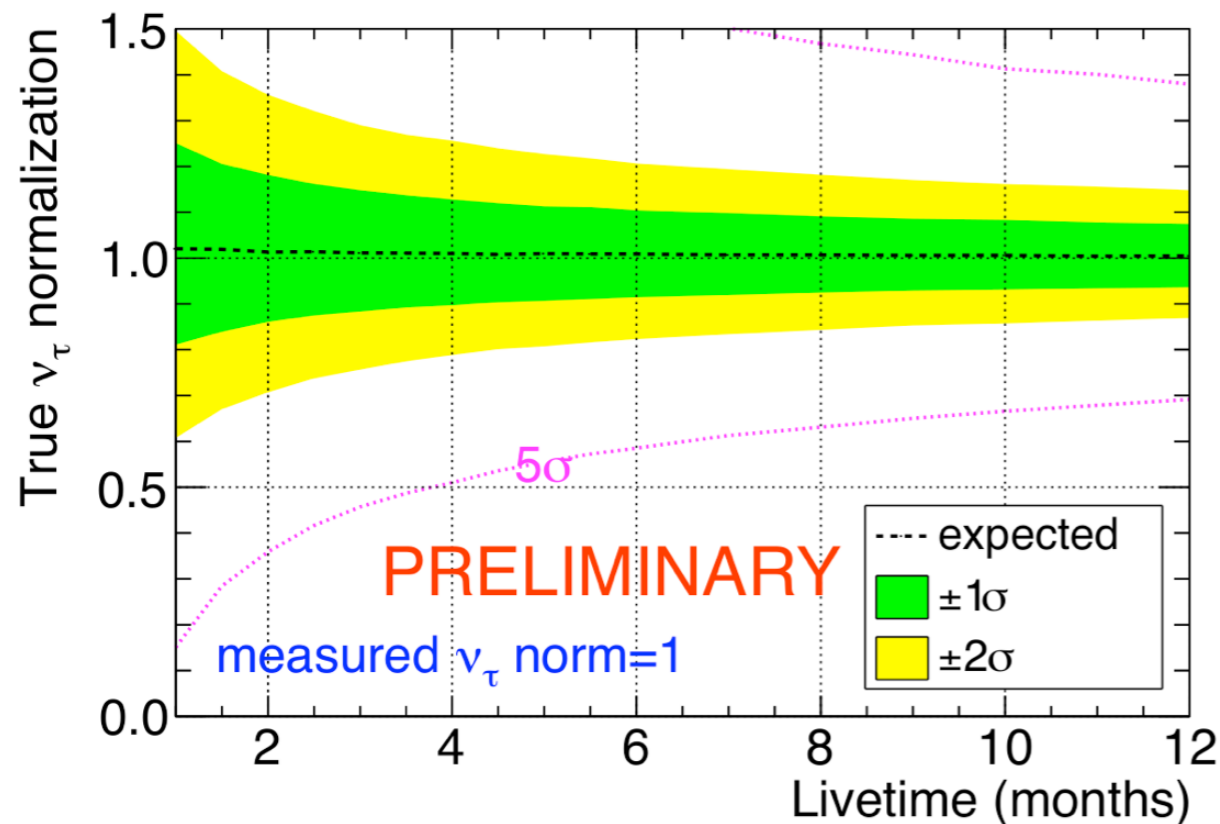
Dark Matter Sensitivity with PINGU

WIMP Limit on SD Cross-Section
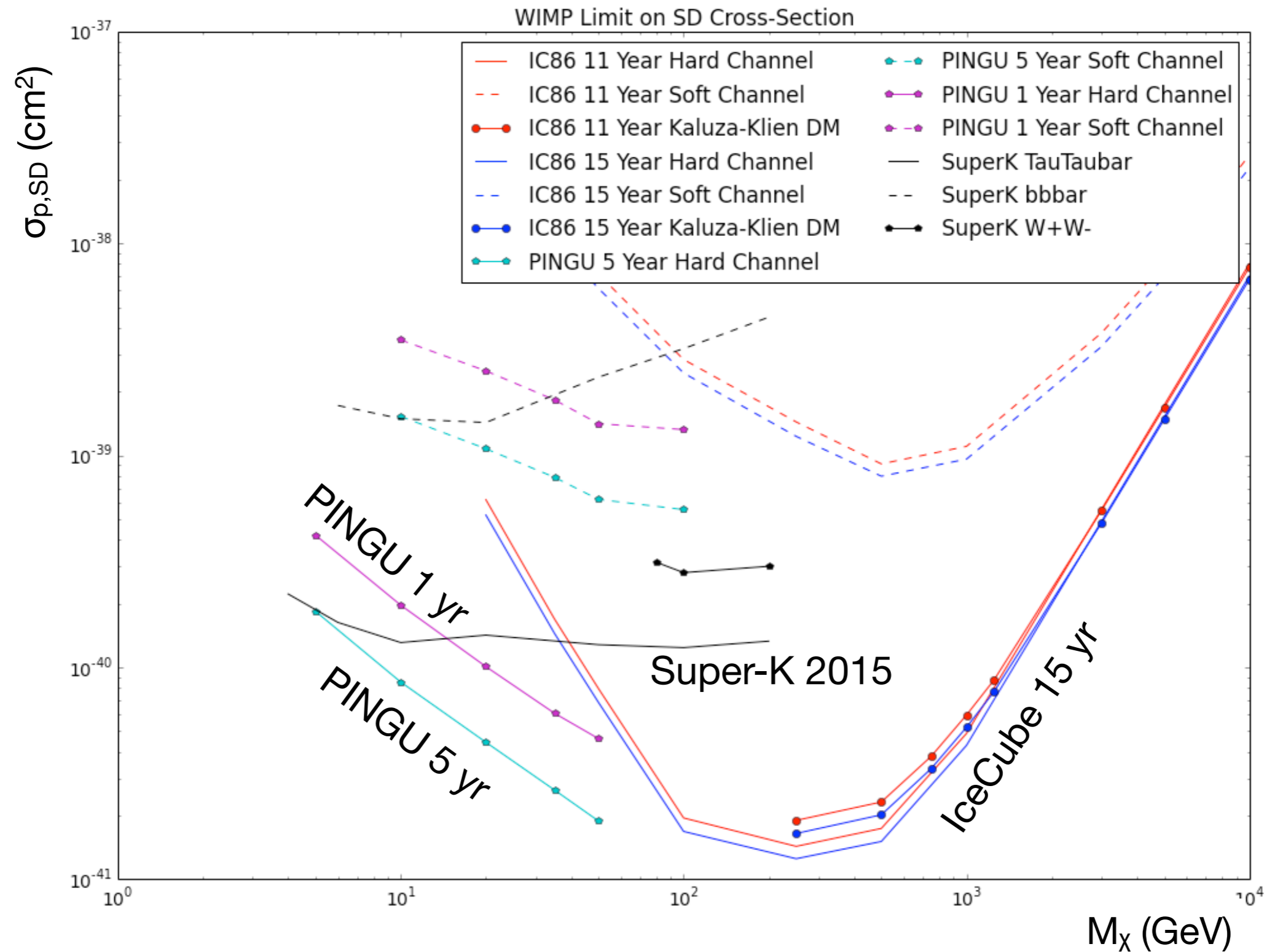
PINGU (& Gen2) Calibration

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 viewed PINGU 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

  - Japan: U. of Tokyo

  - US: MIT, Columbia, Notre Dame

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 – multi-year funding cycles

  - 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?
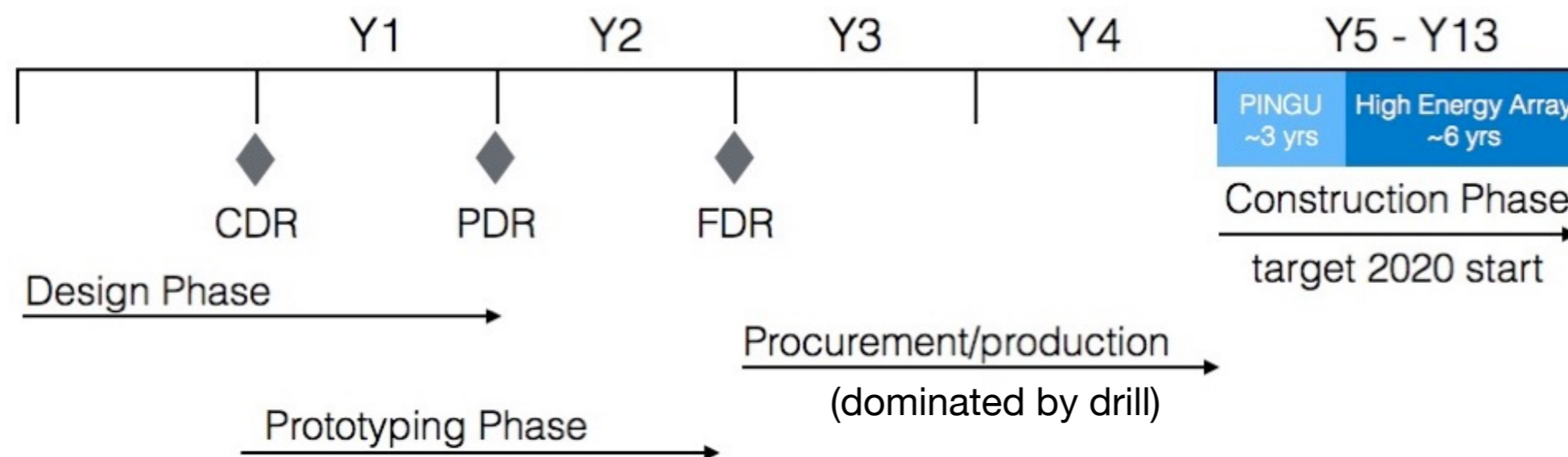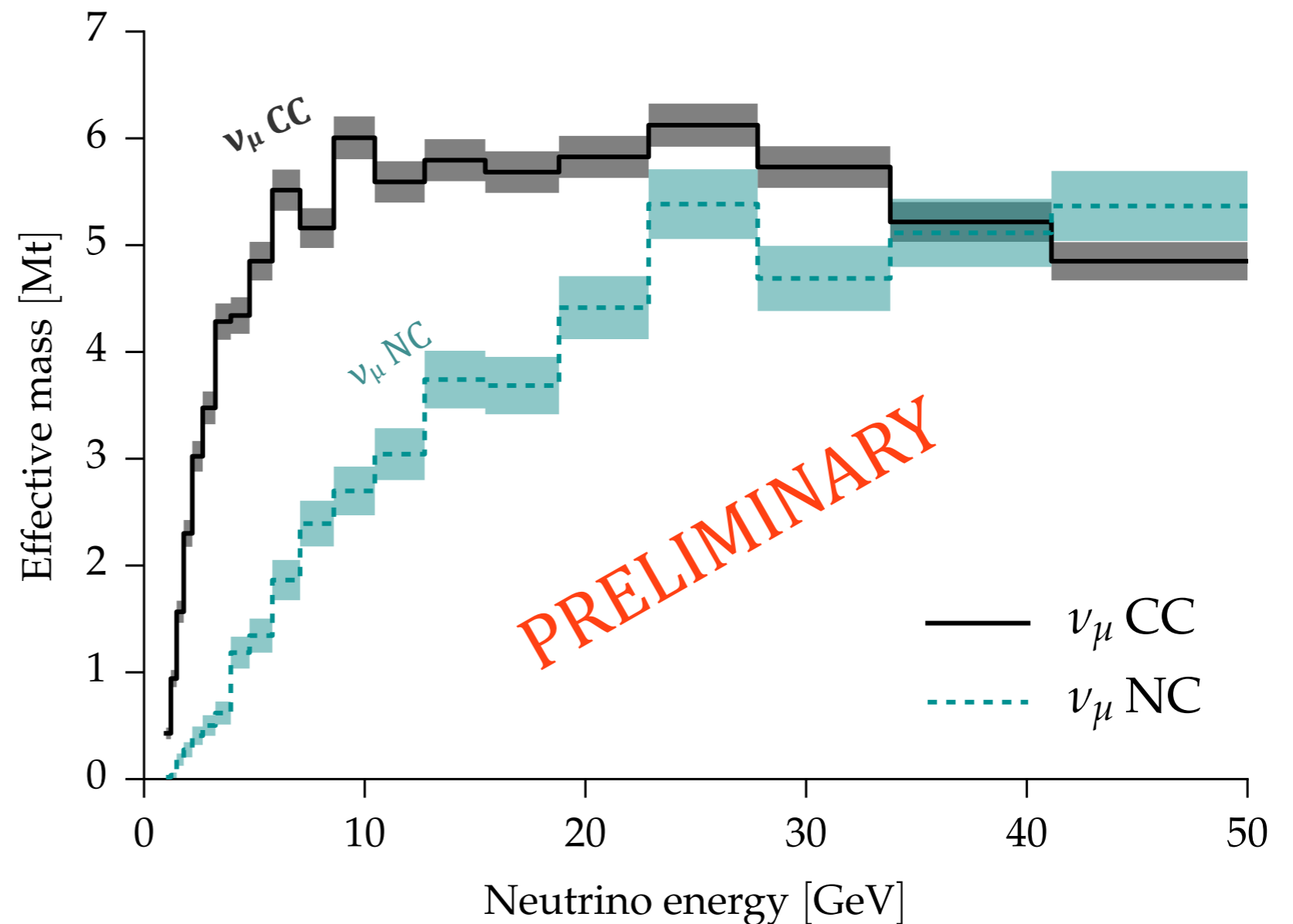
Conclusions

- ## 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.
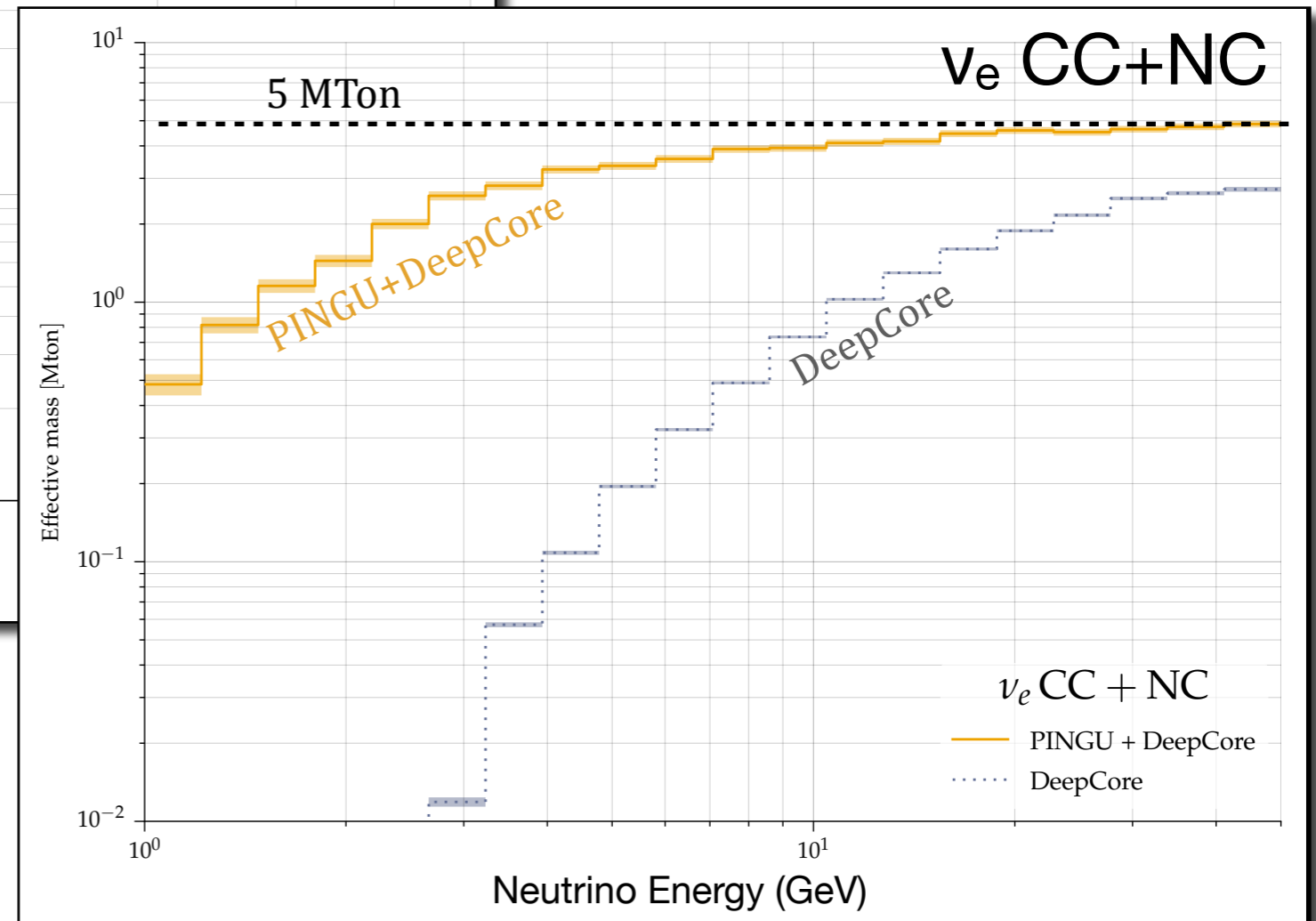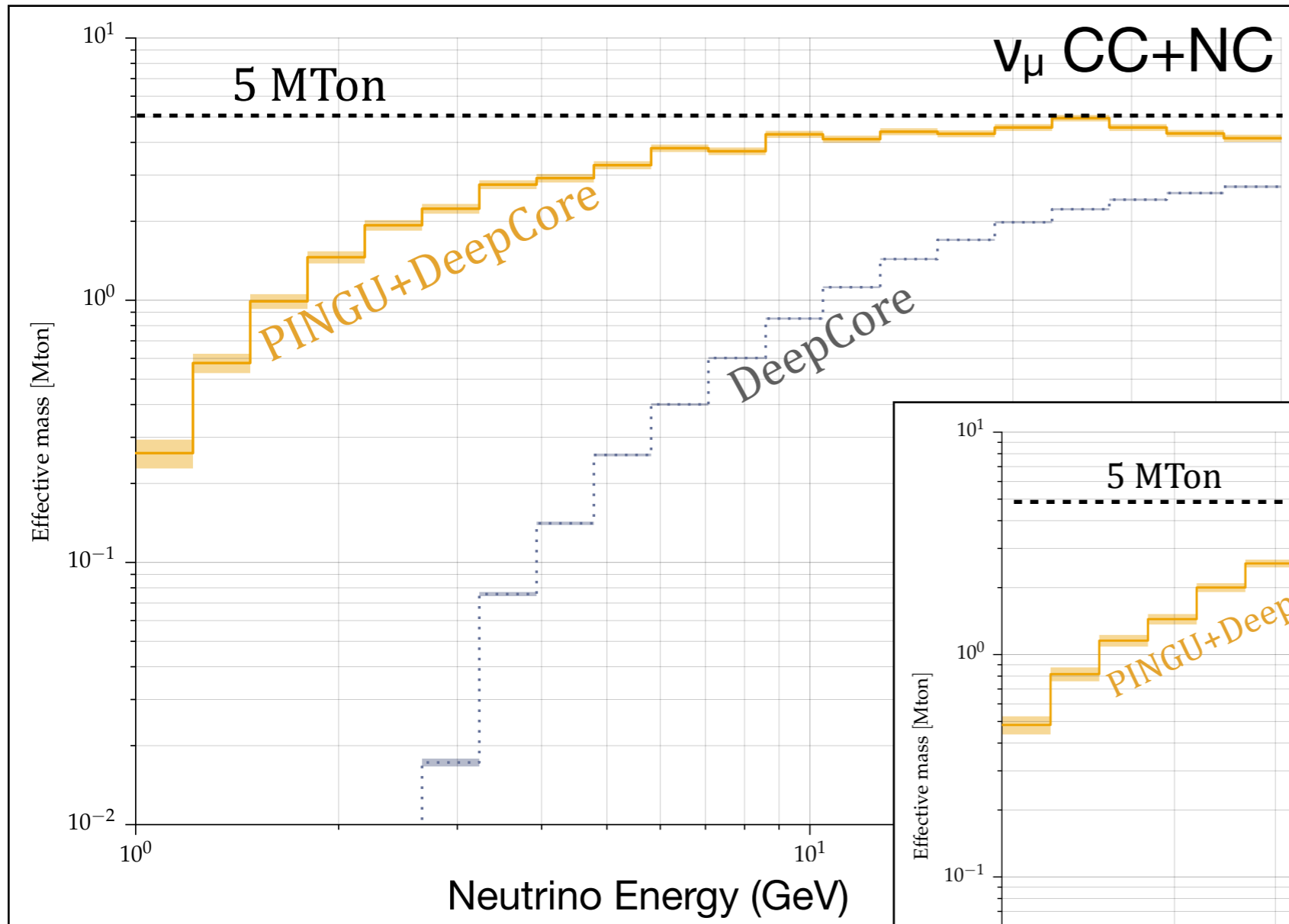
Backup Slides

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
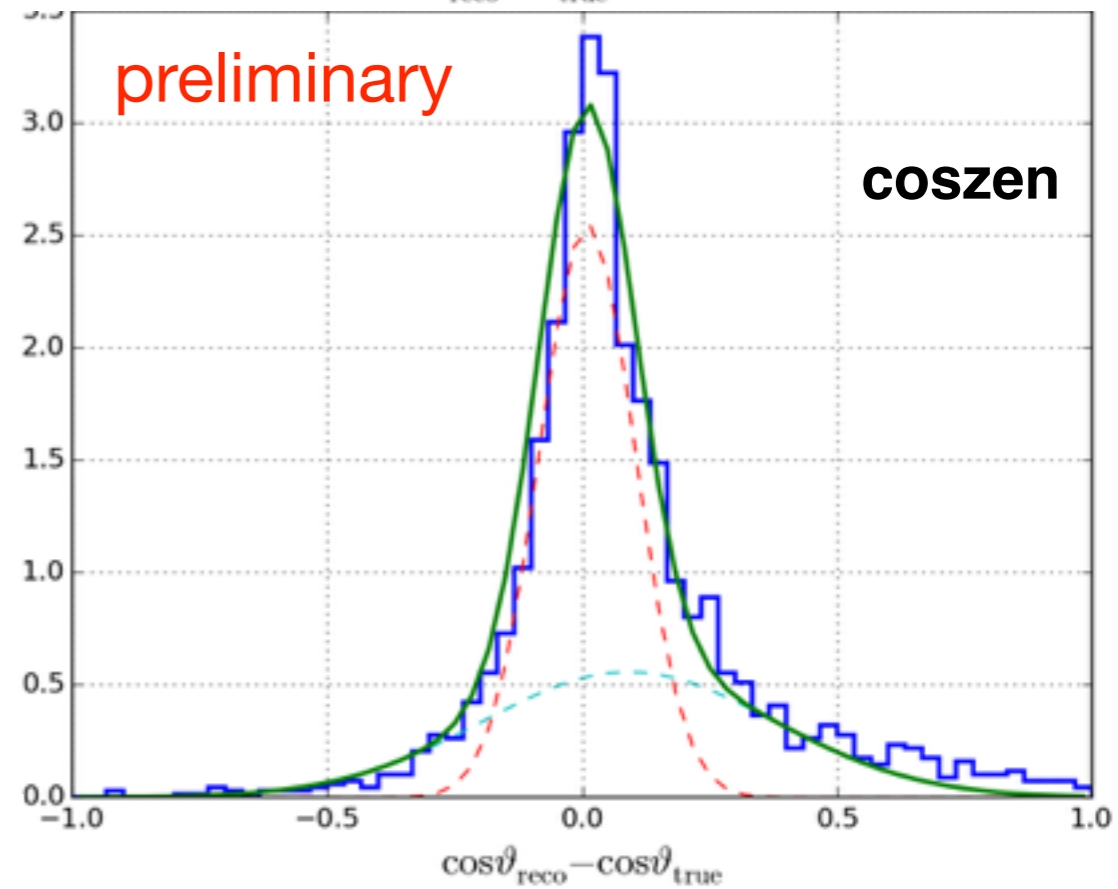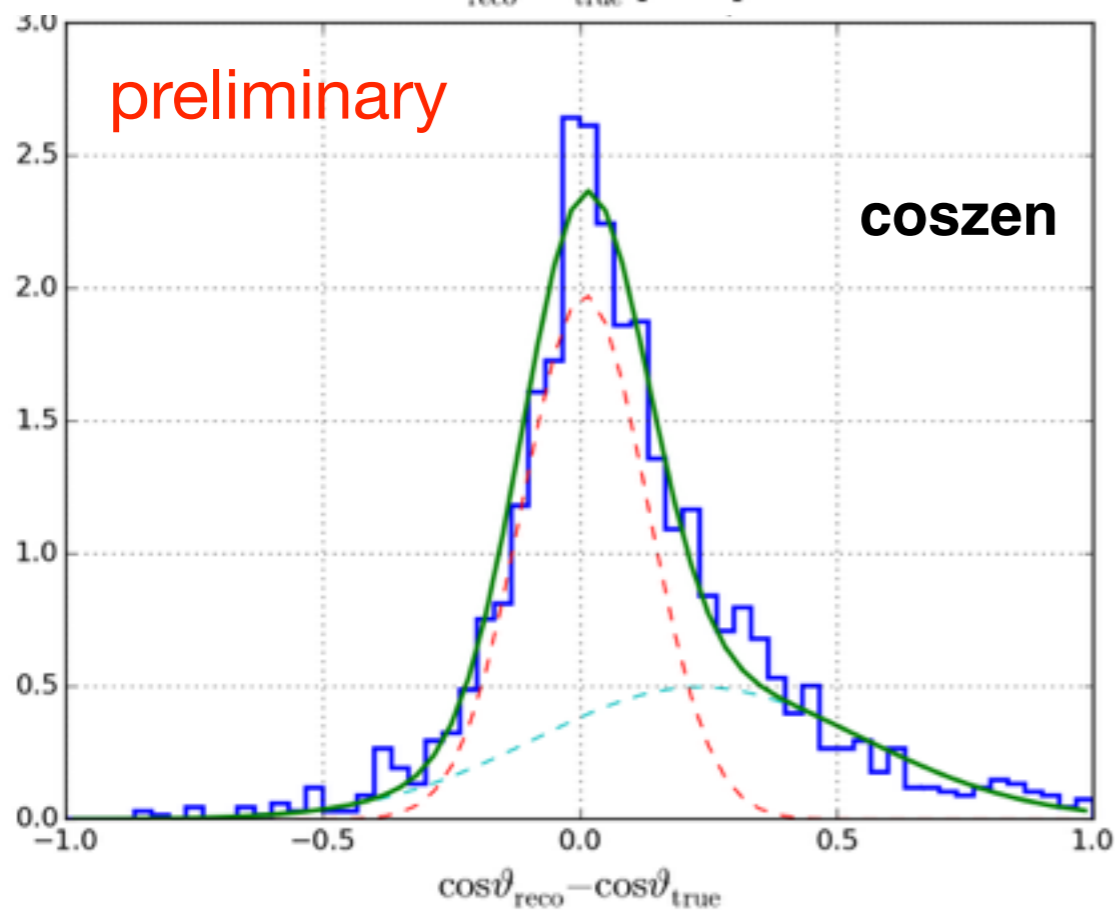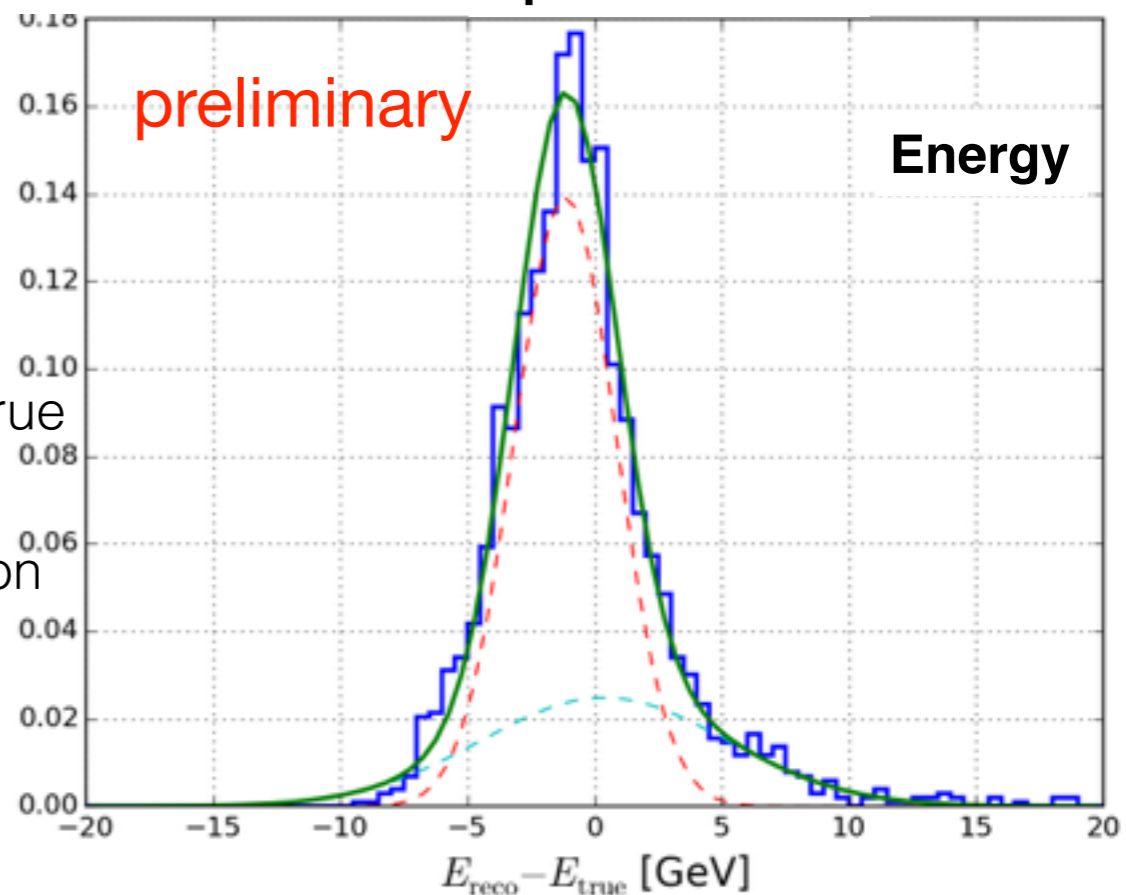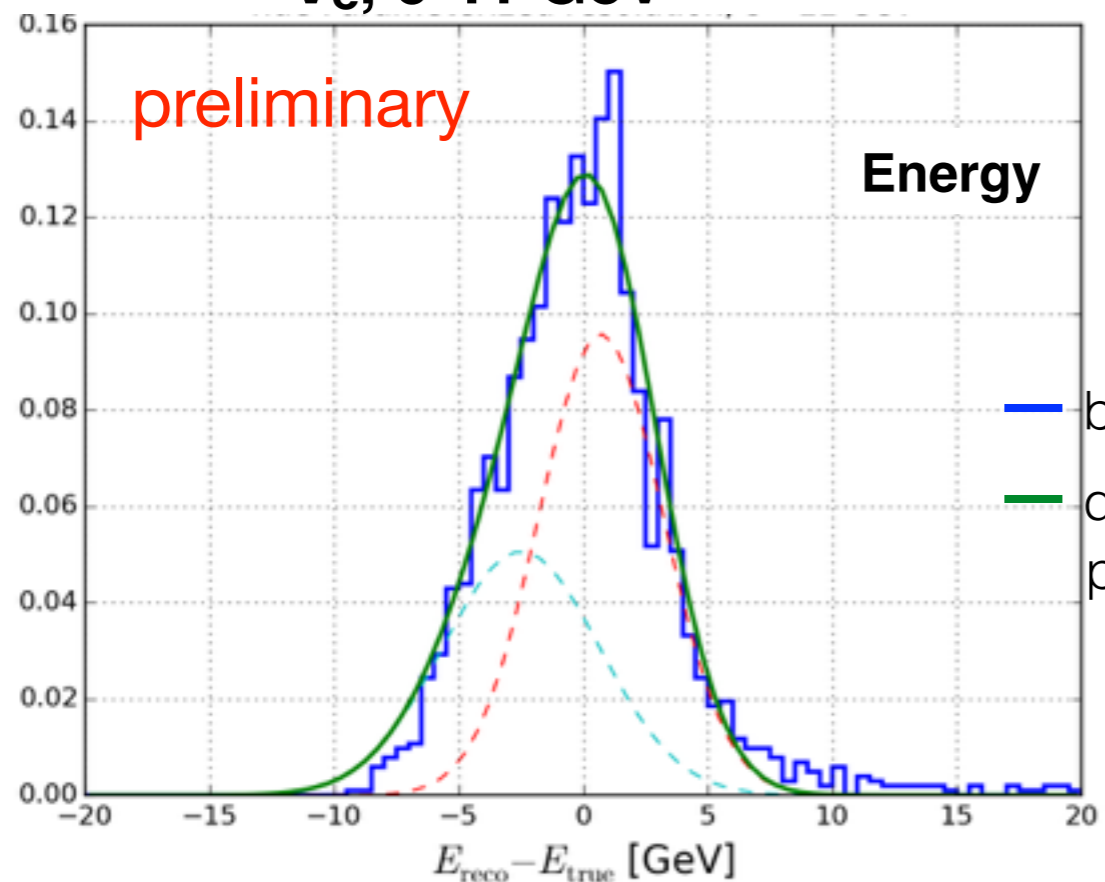

- **Similar effective mass for other neutrino flavors**

PINGU & DeepCore Meffs

Resolutions

νe, 9-11 GeV

νμ, 9-11 GeV

preliminary

Energy

preliminary

Energy

binned reco - true

double gauss
parameterization

$E_{reco} - E_{true}$ [GeV]

$E_{reco} - E_{true}$ [GeV]

preliminary

coszen

preliminary

coszen

$\cos\vartheta_{reco} - \cos\vartheta_{true}$
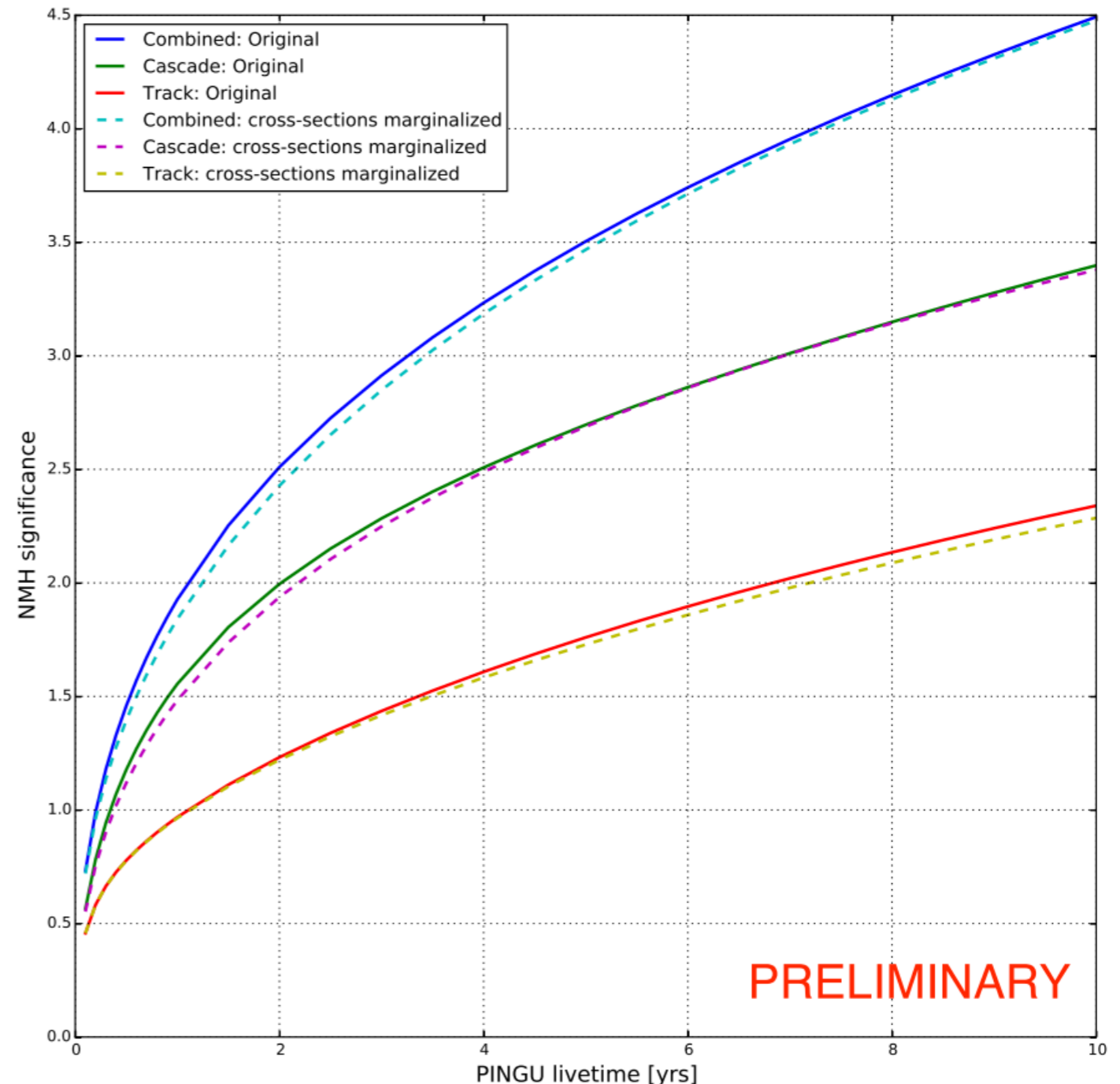
$\cos\vartheta_{reco} - \cos\vartheta_{true}$

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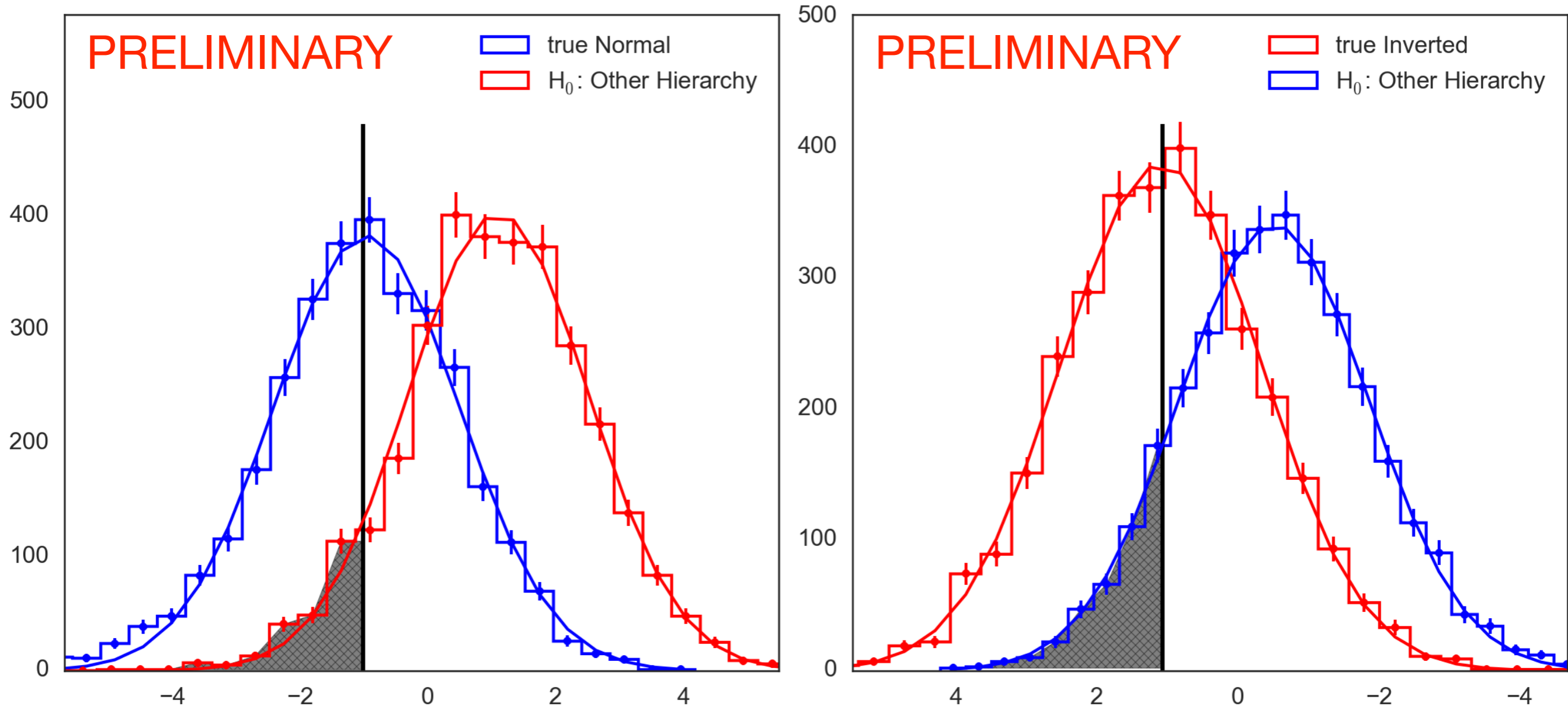
[1] M.C. Gonzalez-Garcia, et al. *JHEP* **11** 052, 2014

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

Legend:
- Combined: Original
- Cascade: Original
- Track: Original
- Combined: cross-sections marginalized
- Cascade: cross-sections marginalized
- Track: cross-sections marginalized

Y-axis: NMH significance
X-axis: PINGU livetime [yrs]

PRELIMINARY

Oscillation Parameters with PINGU

after 3 years of livetime, with normal hierarchy correctly identified
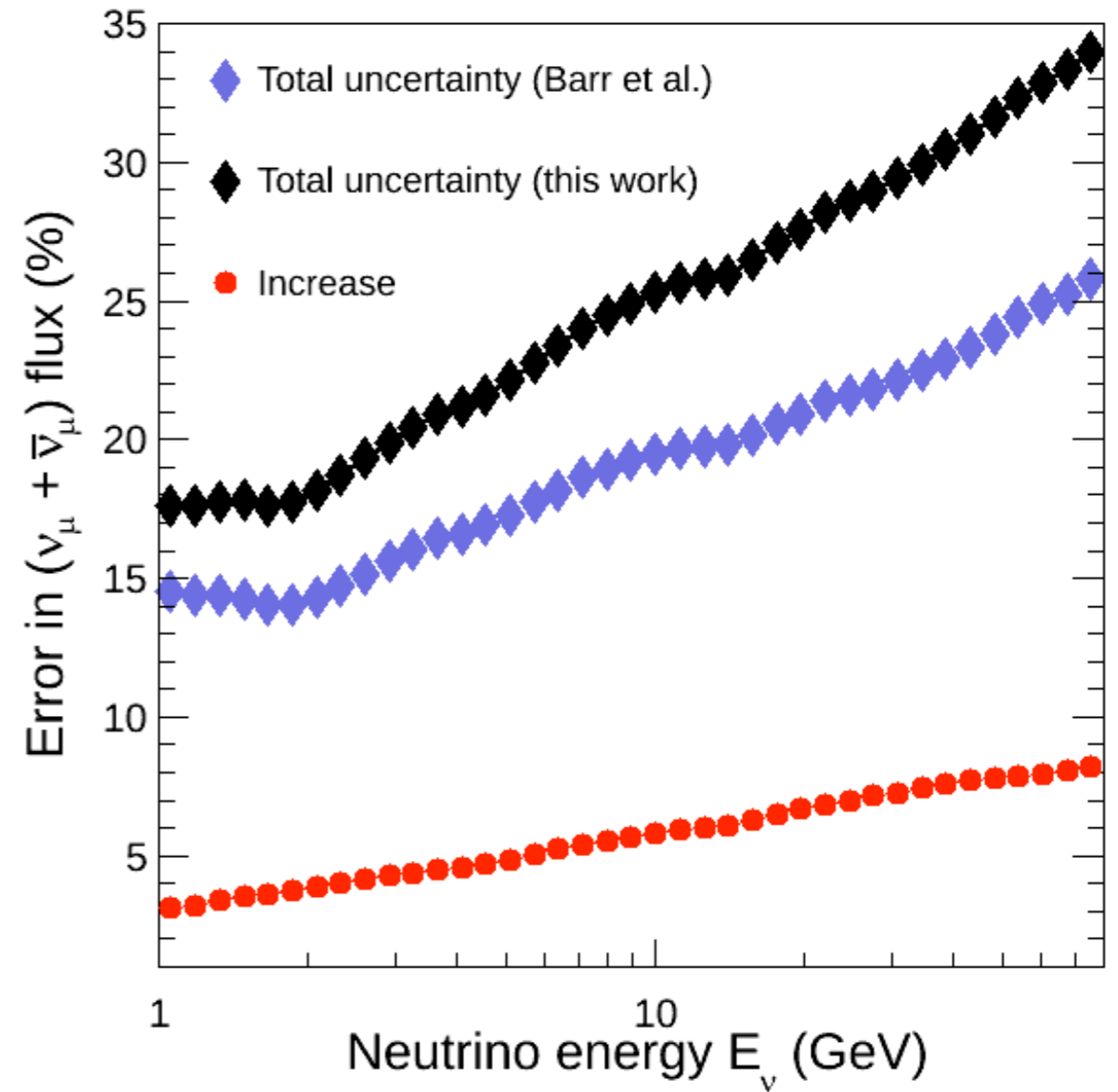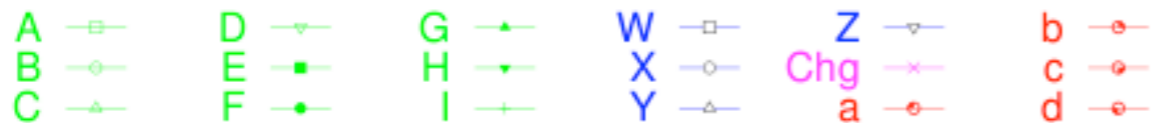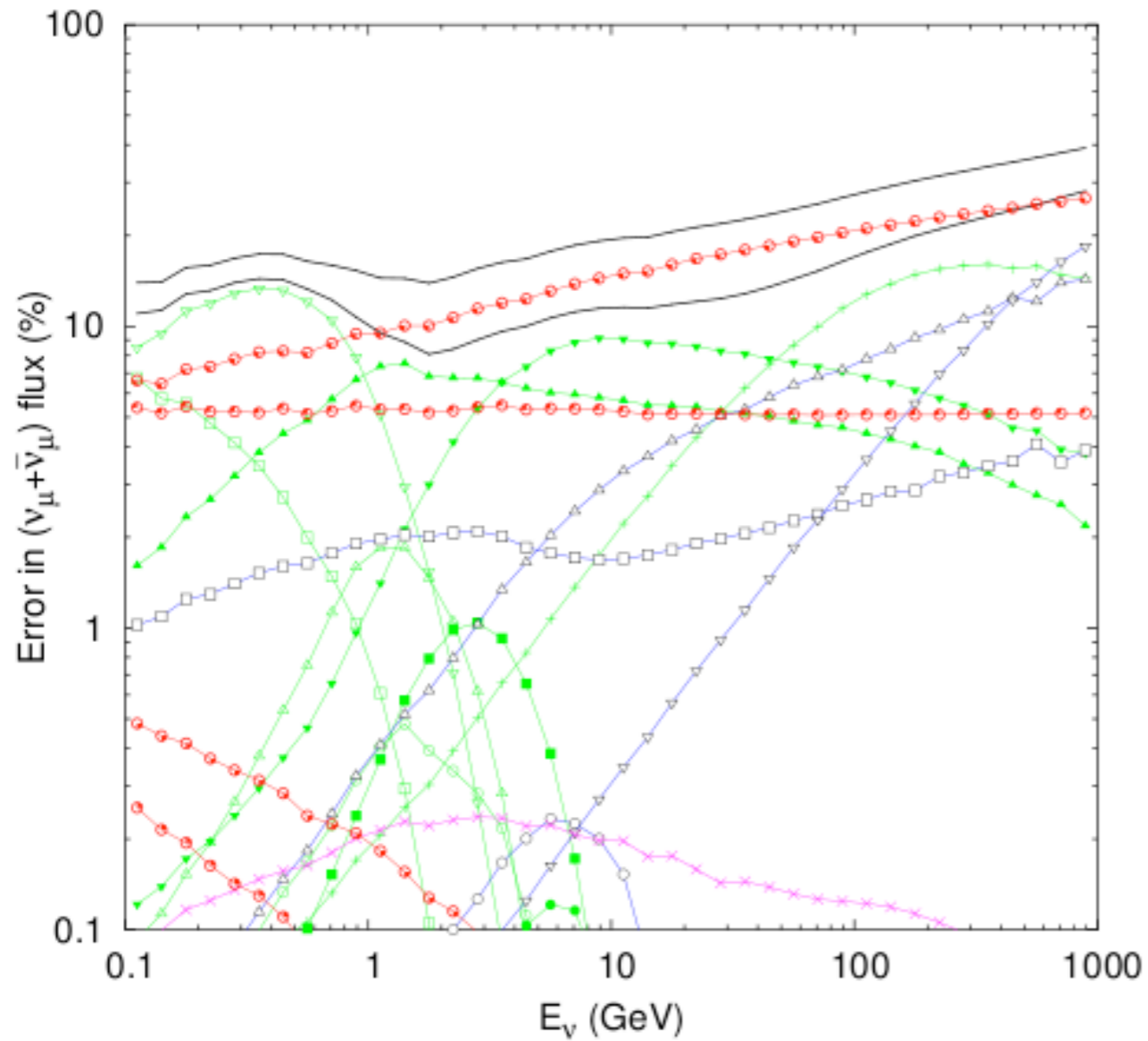

true normal, fit normal (3yrs, 7 syst.)

PRELIMINARY
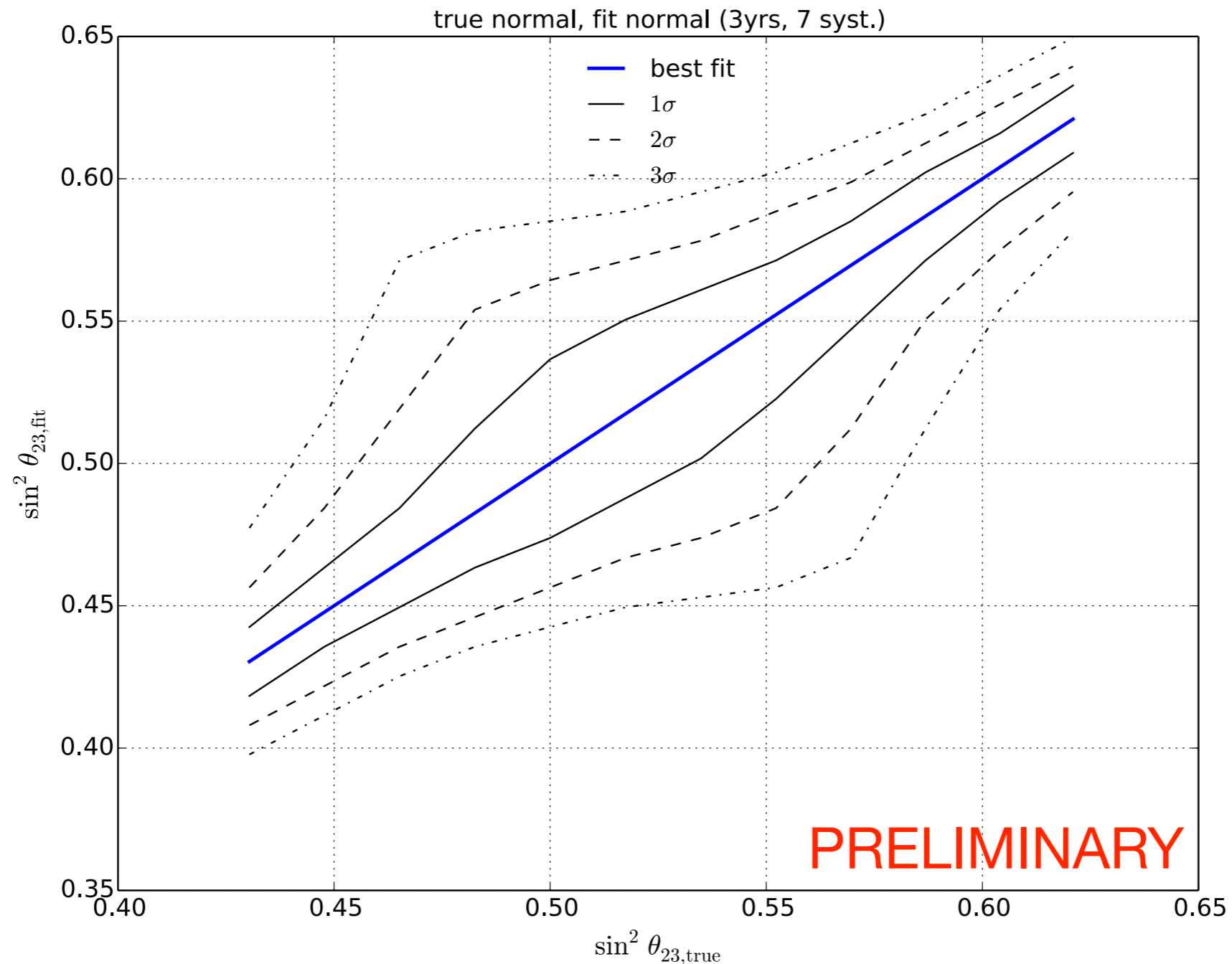
Oscillation Parameters with PINGU

after 3 years of livetime, with inverted hierarchy correctly identified
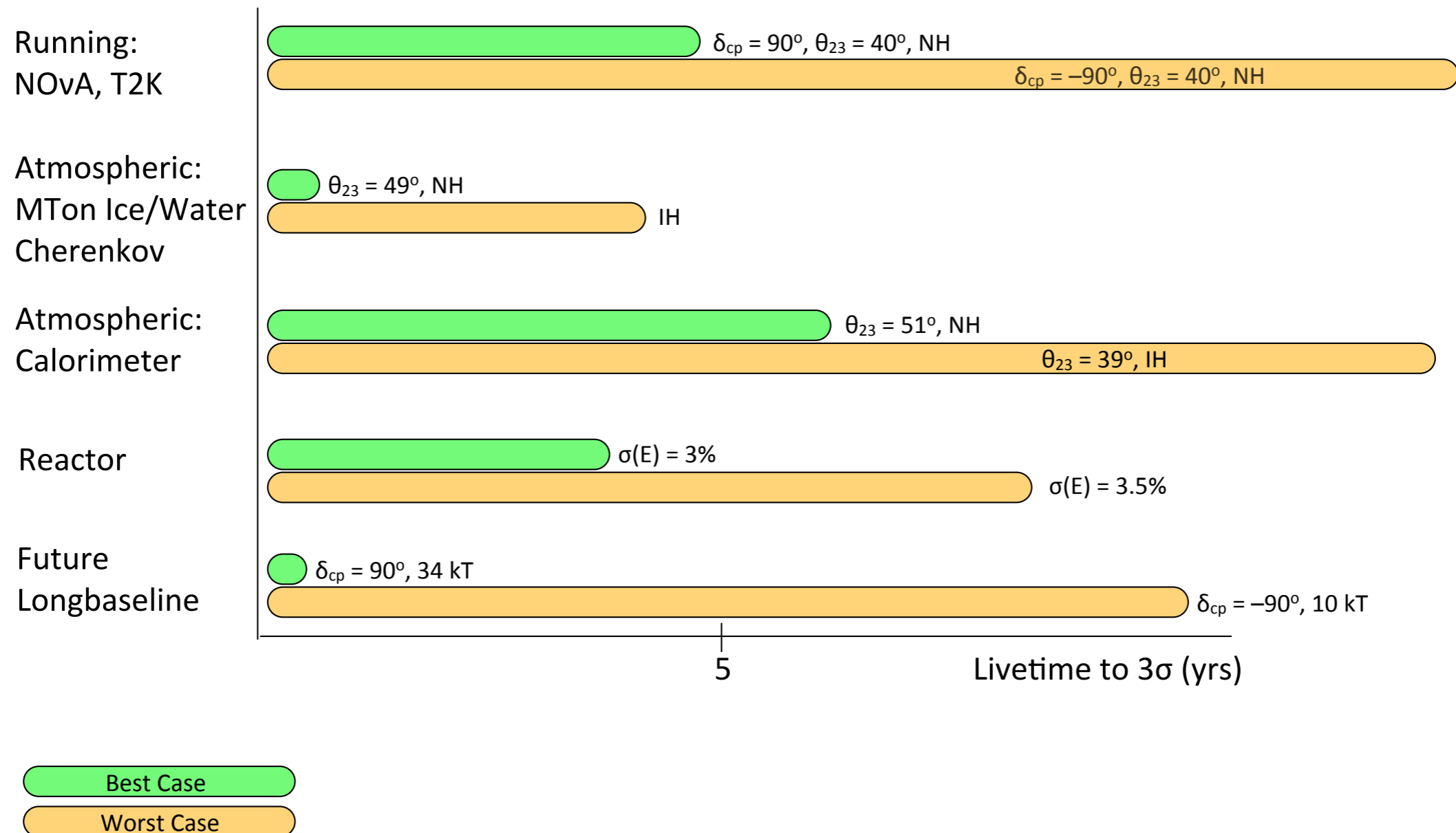

true inverted, fit inverted (3yrs, 7 syst.)

PRELIMINARY
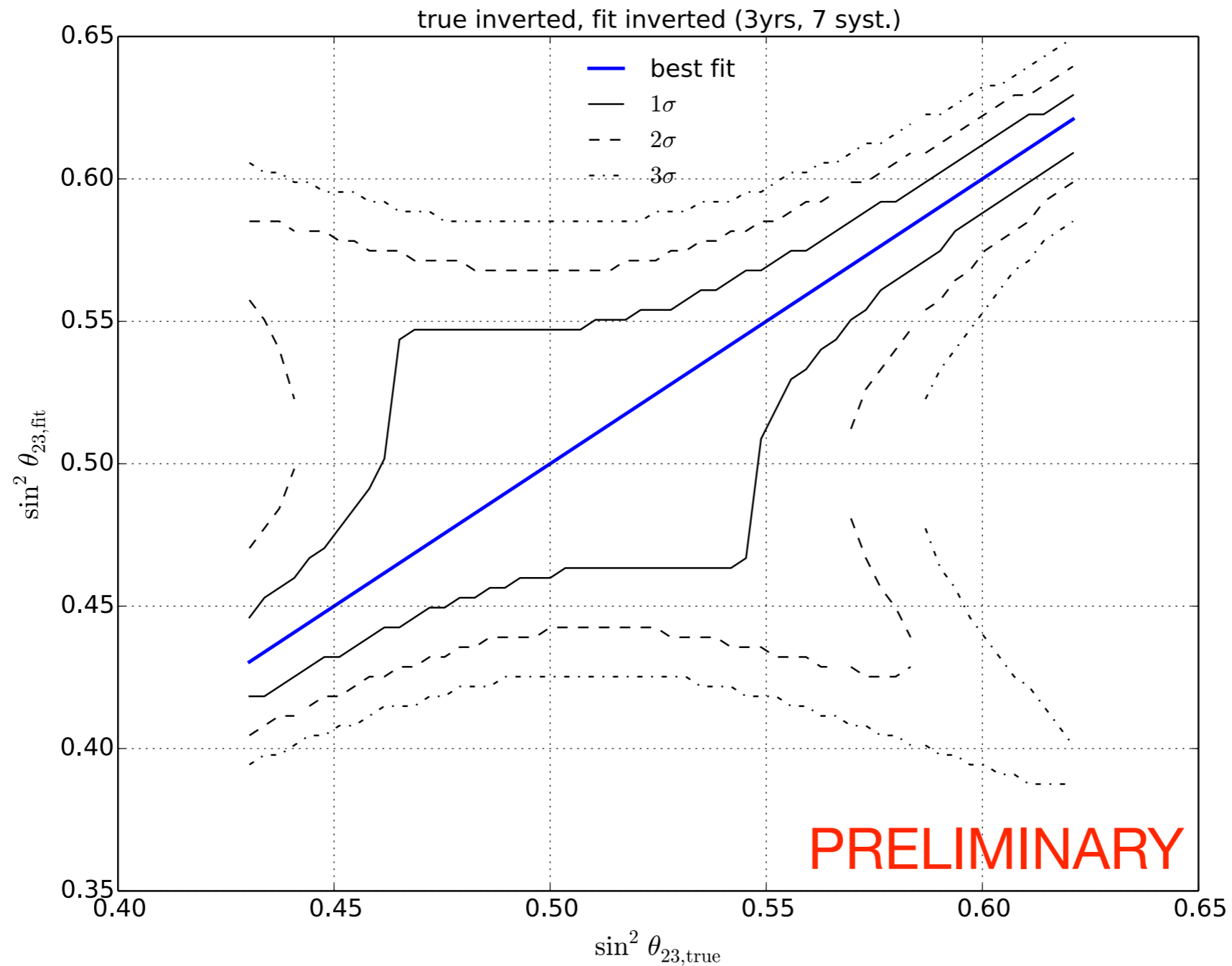
Atmospheric Flux Systematics

Using Down-Going Neutrinos
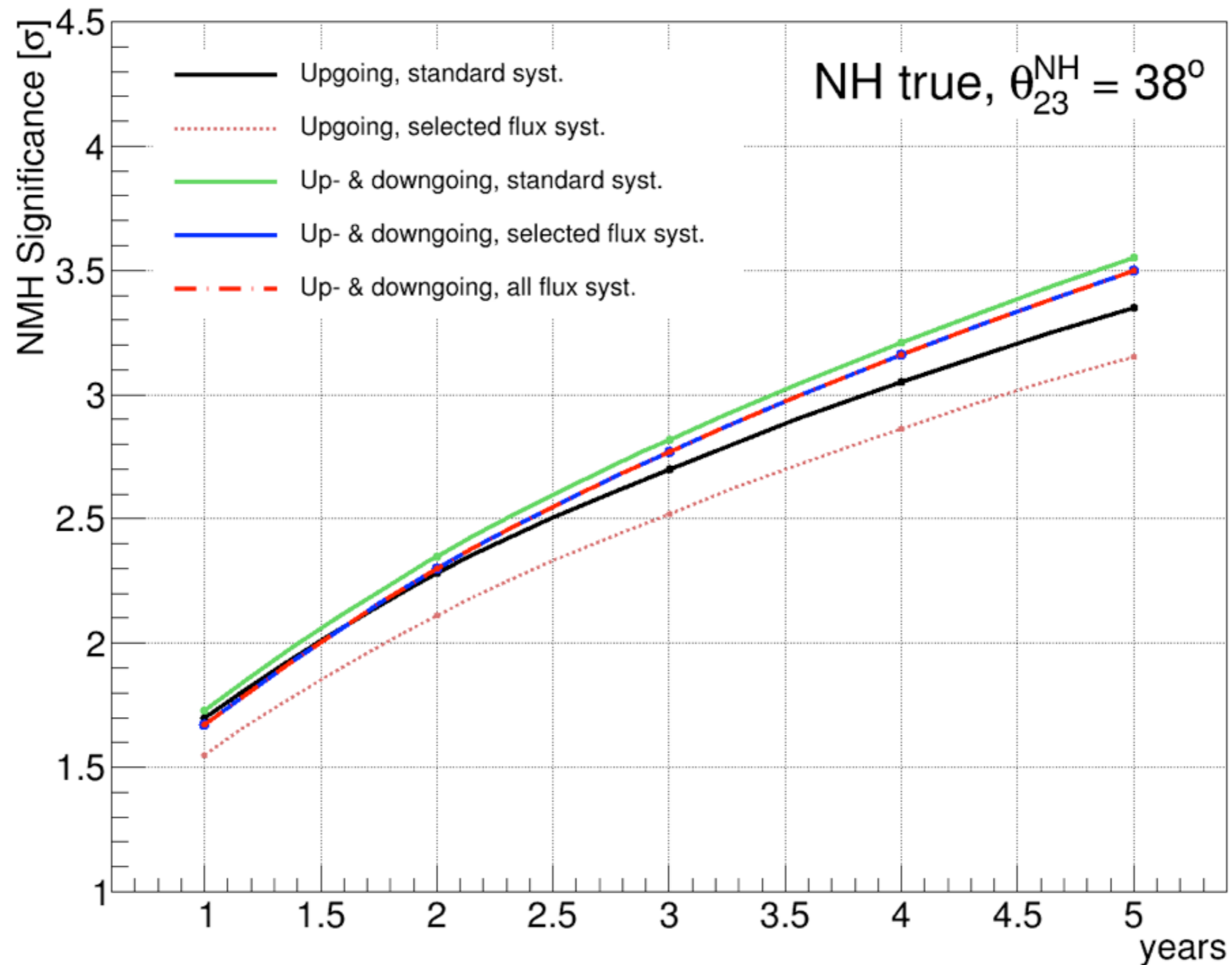
Global Context

Sensitivity to the Neutrino Mass Hierarchy

Running: NOvA, T2K — $\delta_{cp} = 90°$, $\theta_{23} = 40°$, NH (Best Case); $\delta_{cp} = -90°$, $\theta_{23} = 40°$, NH (Worst Case)

Atmospheric: MTon Ice/Water Cherenkov — $\theta_{23} = 49°$, NH (Best Case); IH (Worst Case)

Atmospheric: Calorimeter — $\theta_{23} = 51°$, NH (Best Case); $\theta_{23} = 39°$, IH (Worst Case)

Reactor — $\sigma(E) = 3\%$ (Best Case); $\sigma(E) = 3.5\%$ (Worst Case)

Future Longbaseline — $\delta_{cp} = 90°$, 34 kT (Best Case); $\delta_{cp} = -90°$, 10 kT (Worst Case)

5 — Livetime to 3σ (yrs)

Best Case
Worst Case

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