Status of Large Under-ice/ Underwater Detectors

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Next Generation Nucleon Decay and Neutrino Detectors
Stony Brook University
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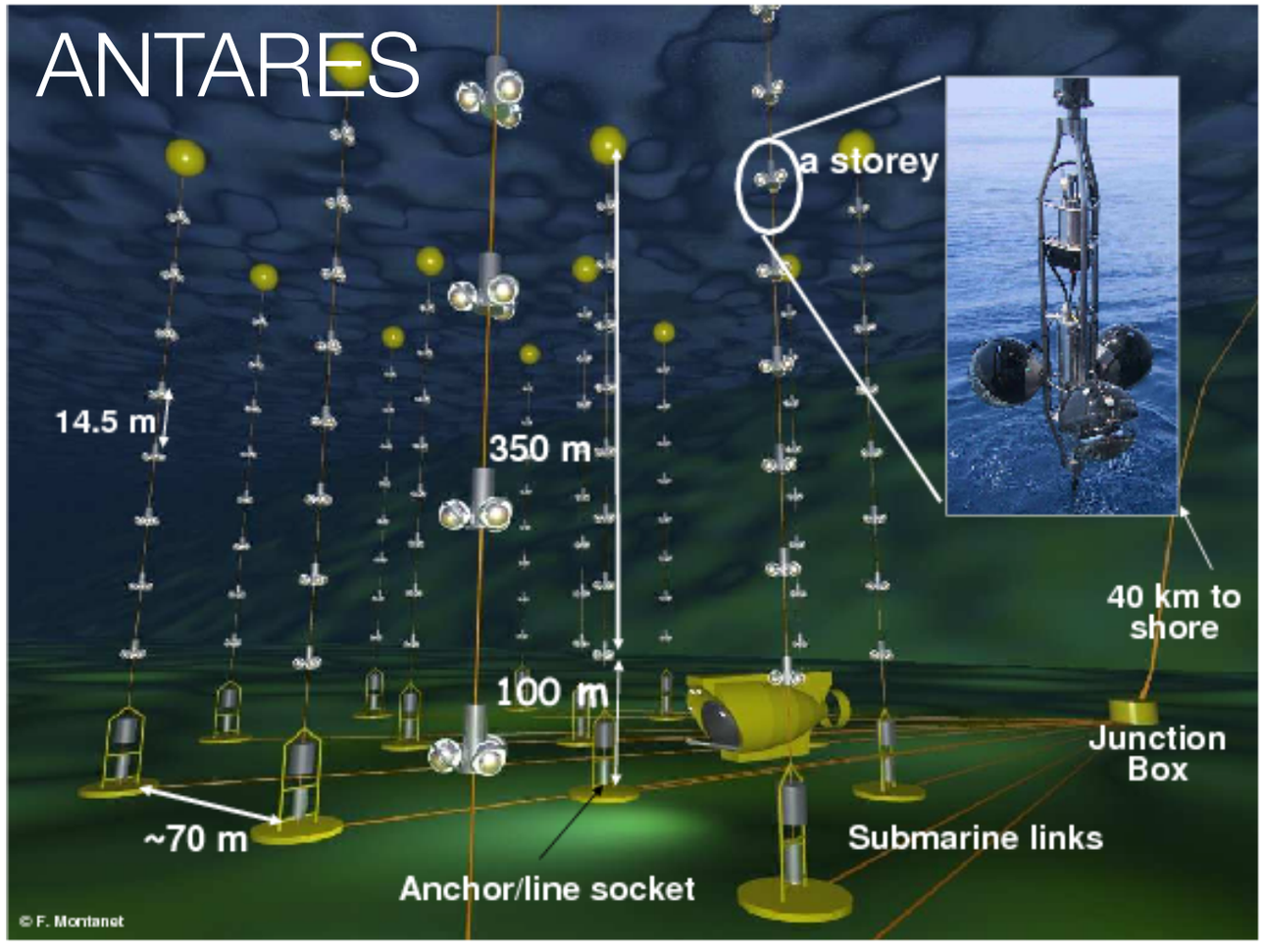
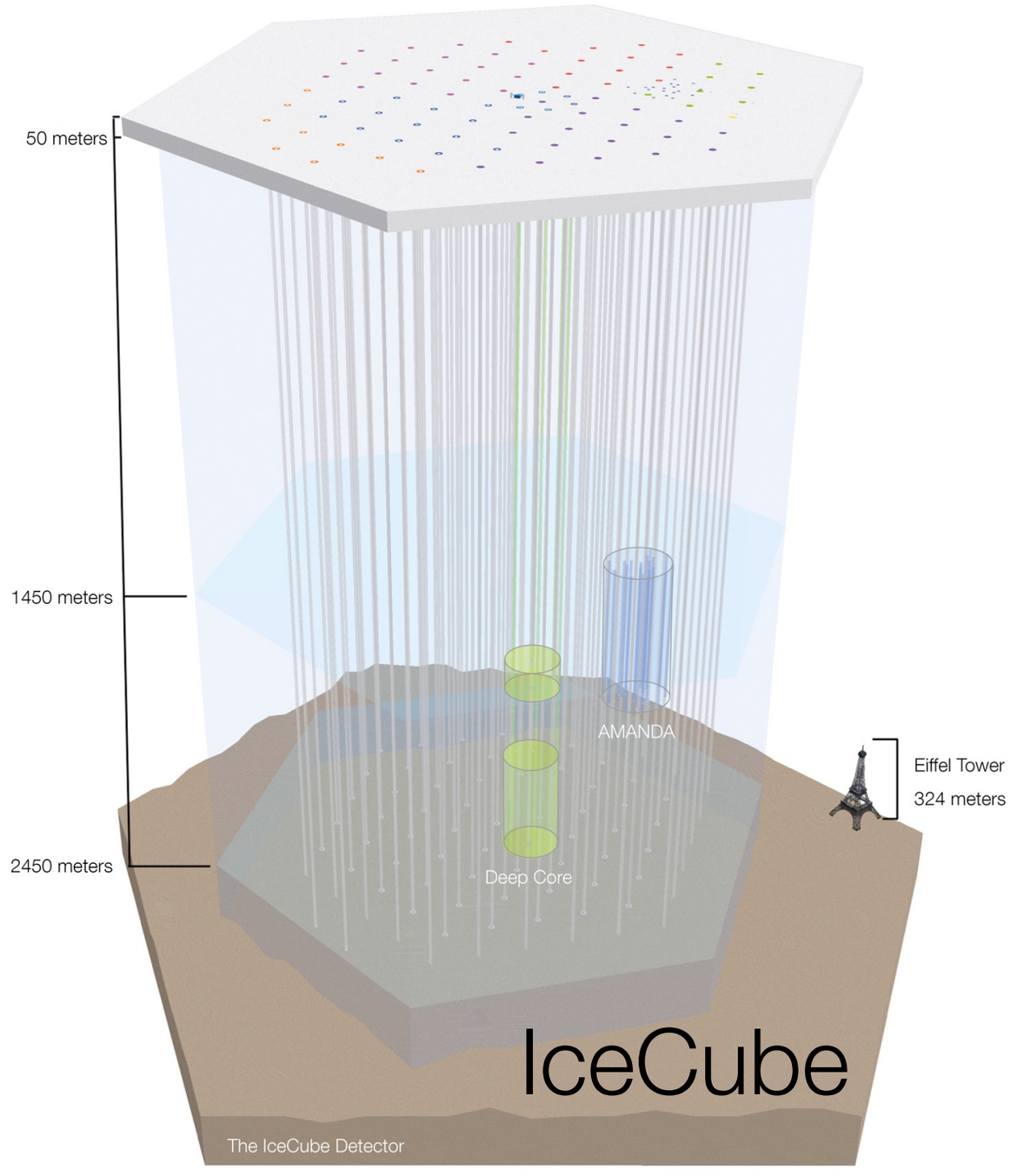
Very Large Volume Neutrino Telescopes

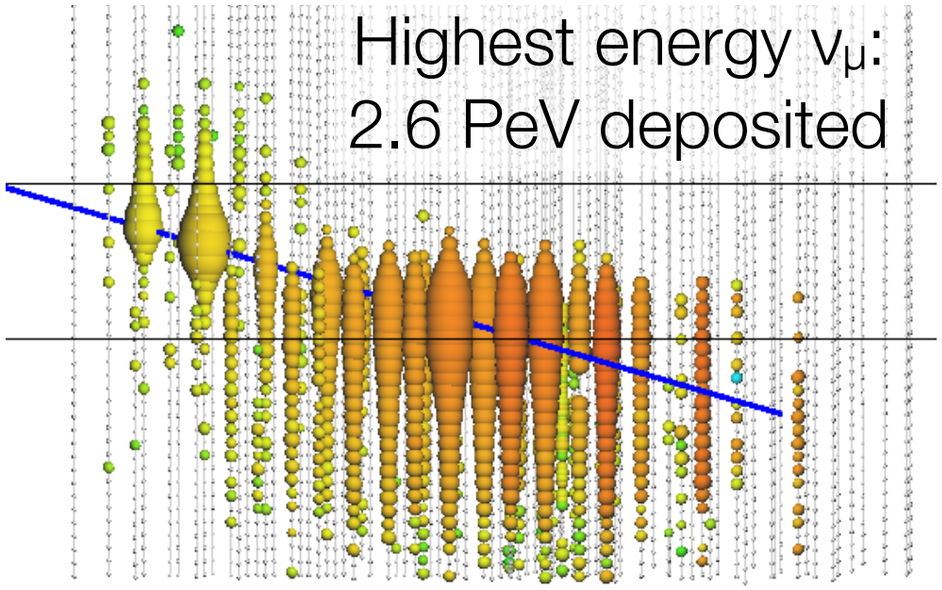
- Primary goal: neutrino astronomy
  - Understanding the sources of cosmic rays

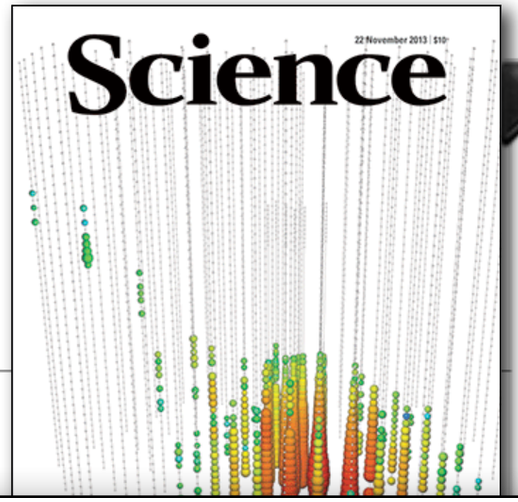


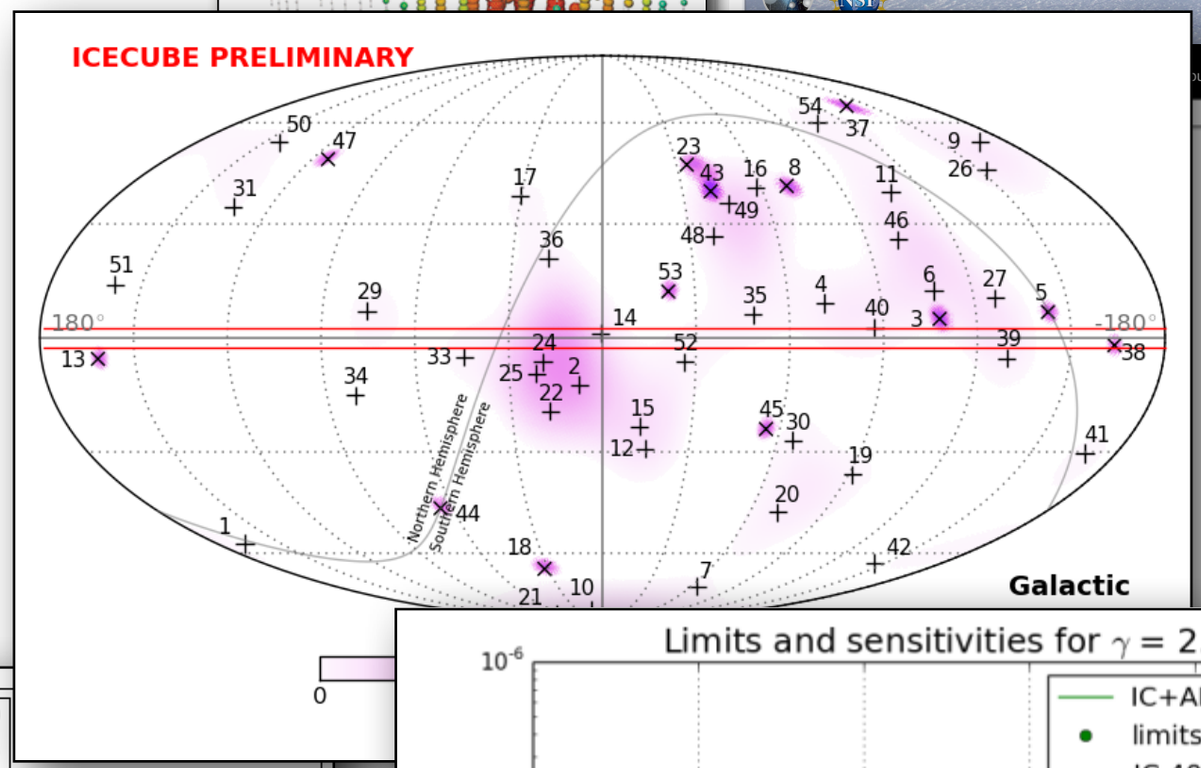


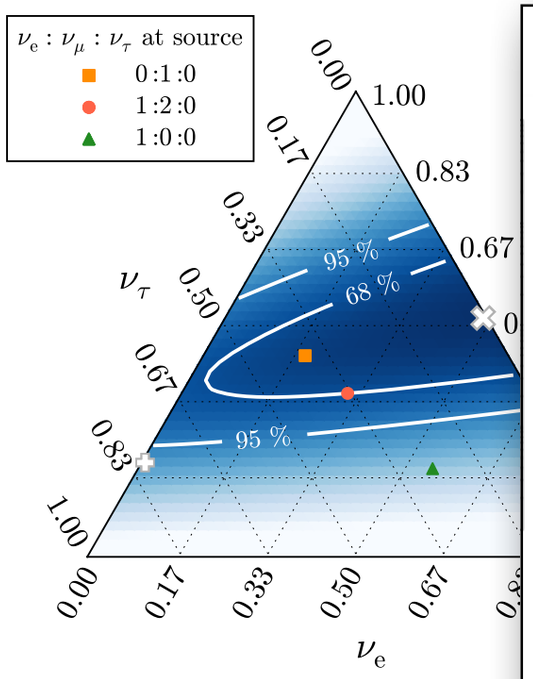
- Secondary science topics
  - Dark Matter searches
  - Neutrino oscillations

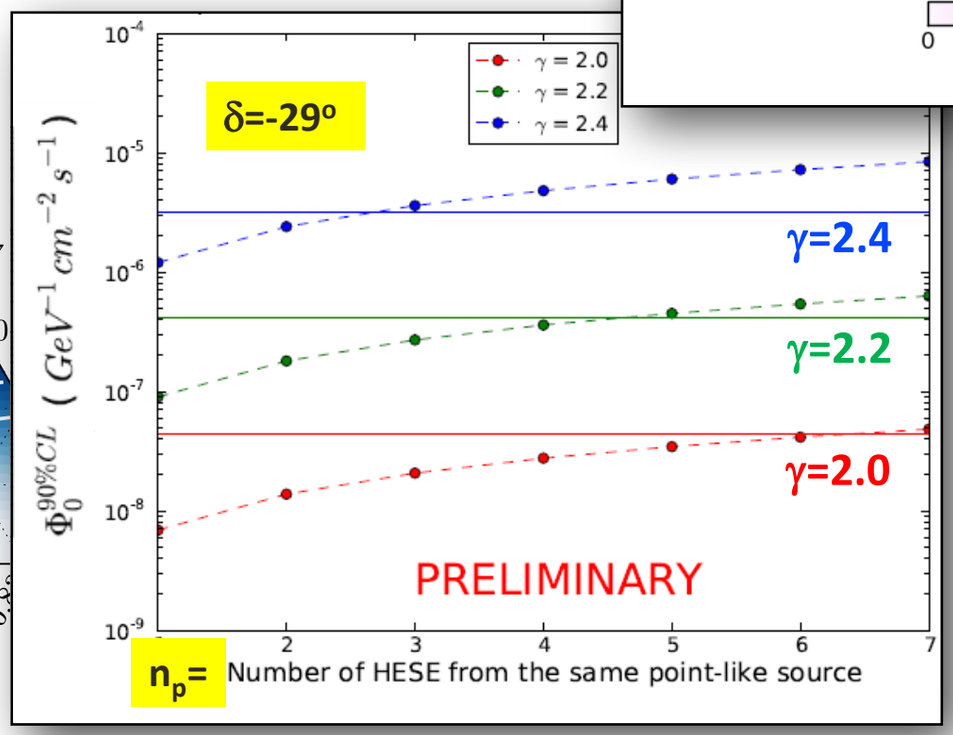
Neutrino Astronomy

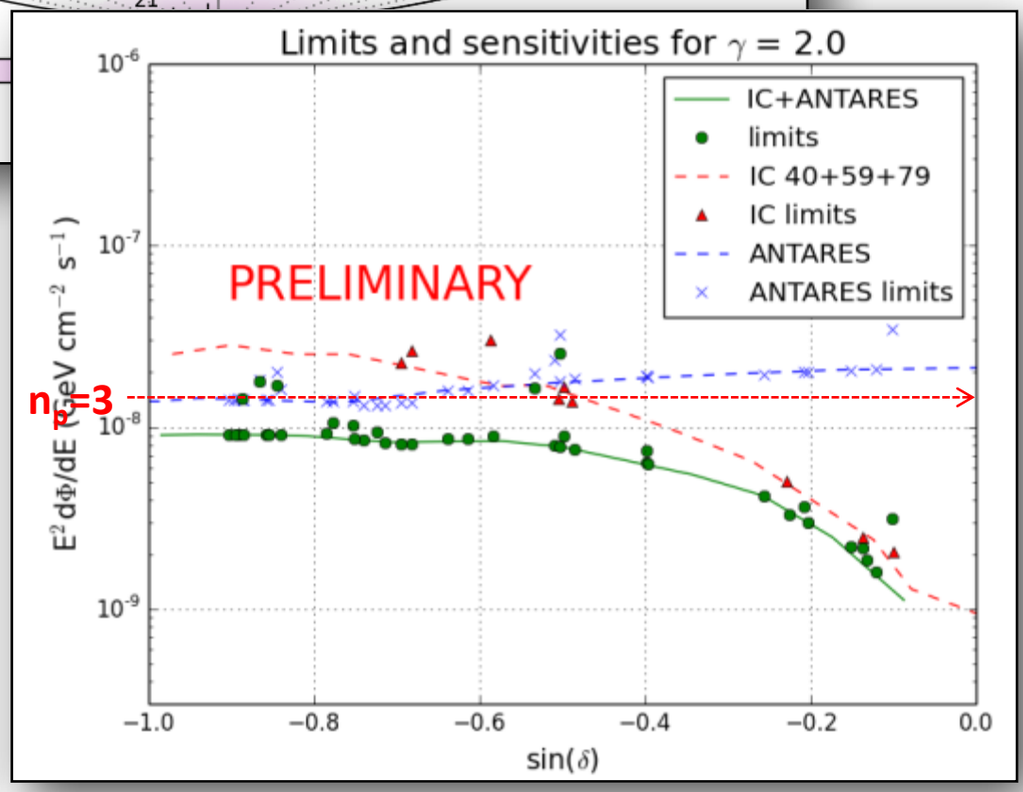








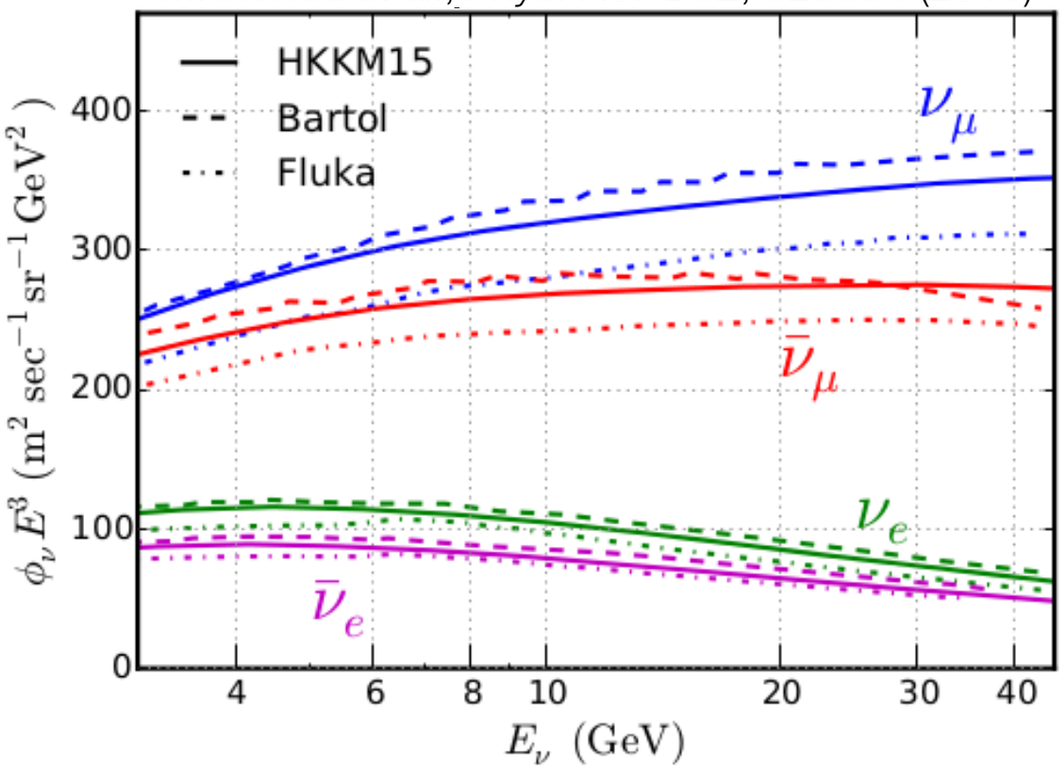


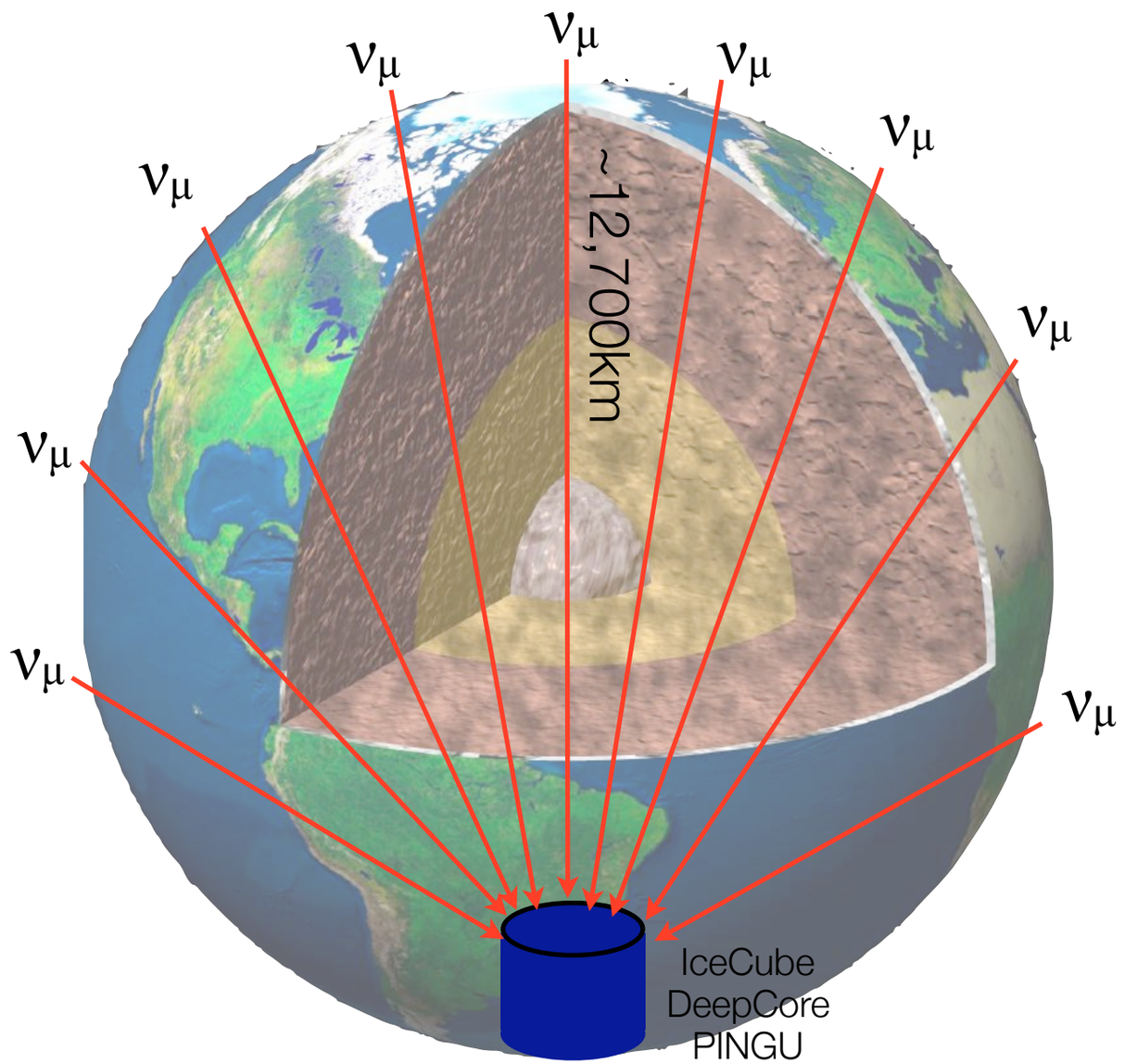


Oscillations with Very Large Volume Detectors

- Neutrinos available over a wide range of energies and baselines
  - Oscillations produce distinctive patterns in energy-angle space
  - Control systematics by comparing energies and path lengths – trade statistics for systematics

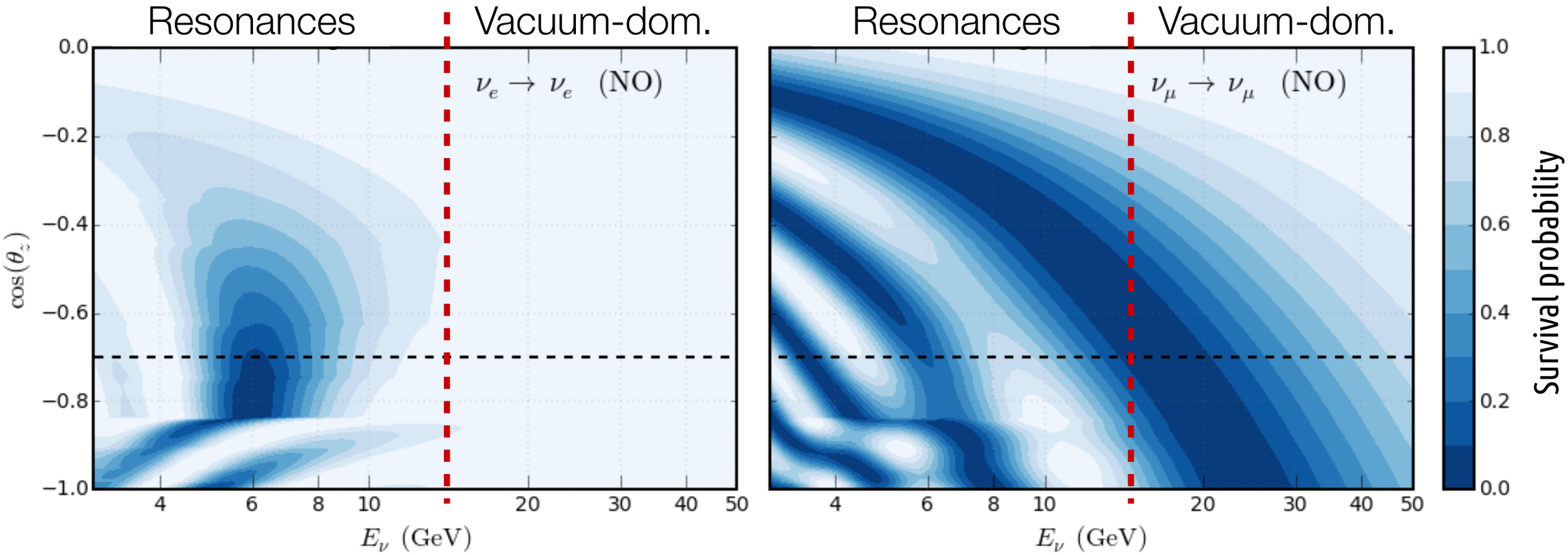
M. Honda et al., *Phys. Rev* D92, 023004 (2015)





Oscillograms

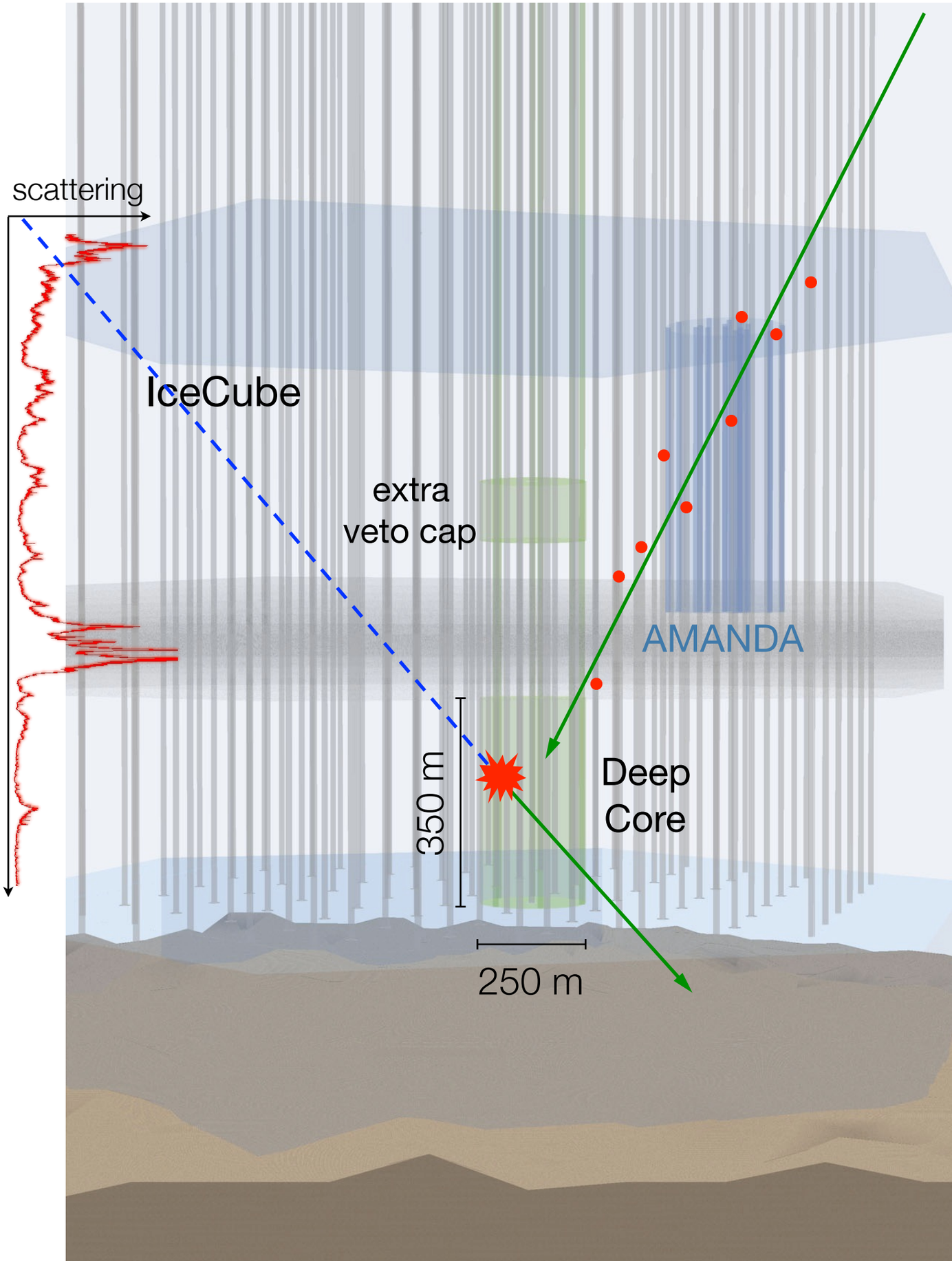
Yáñez and Kouchner, arXiv:1509.08404



- Measure atmospheric parameters (Δm^2_{atm}, θ_{23}) at high energies
  - Tau neutrino appearance also accessible – test of 3x3 mixing paradigm
- Below ~15 GeV, matter resonances (MSW) depend on mass ordering

IceCube DeepCore

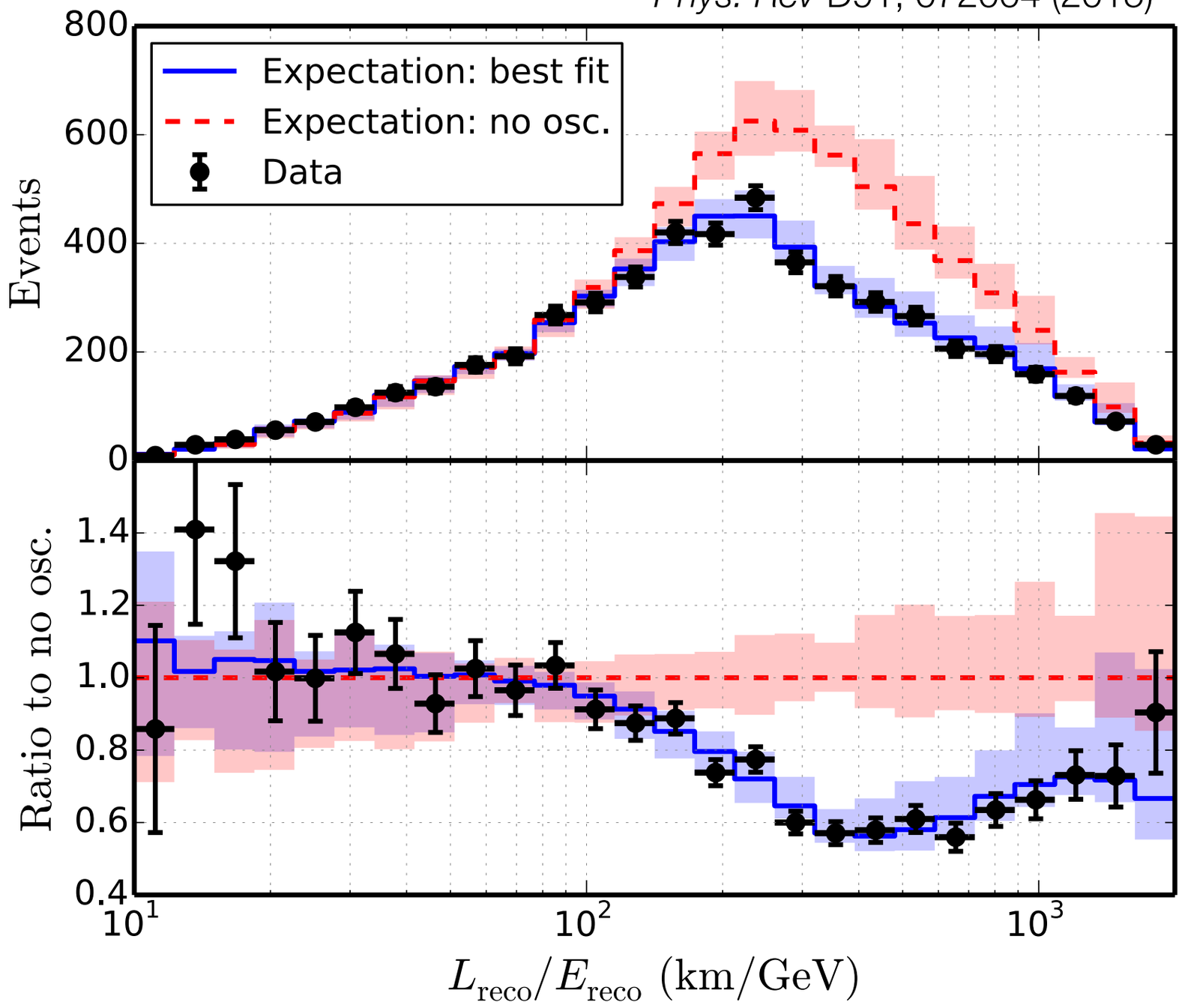
- A more densely instrumented region at the bottom center of IceCube
  - Eight additional strings, super-bialkali PMTs
  - String spacing ~70 m, DOM spacing 7 m: ~5x higher photon collection efficiency than IceCube
- In the clearest ice, below 2100 m
  - $\lambda_{atten} \approx$ 45-50 m, very low levels of radioactive impurities
- IceCube provides an active veto against cosmic ray muons



Atmospheric Oscillations

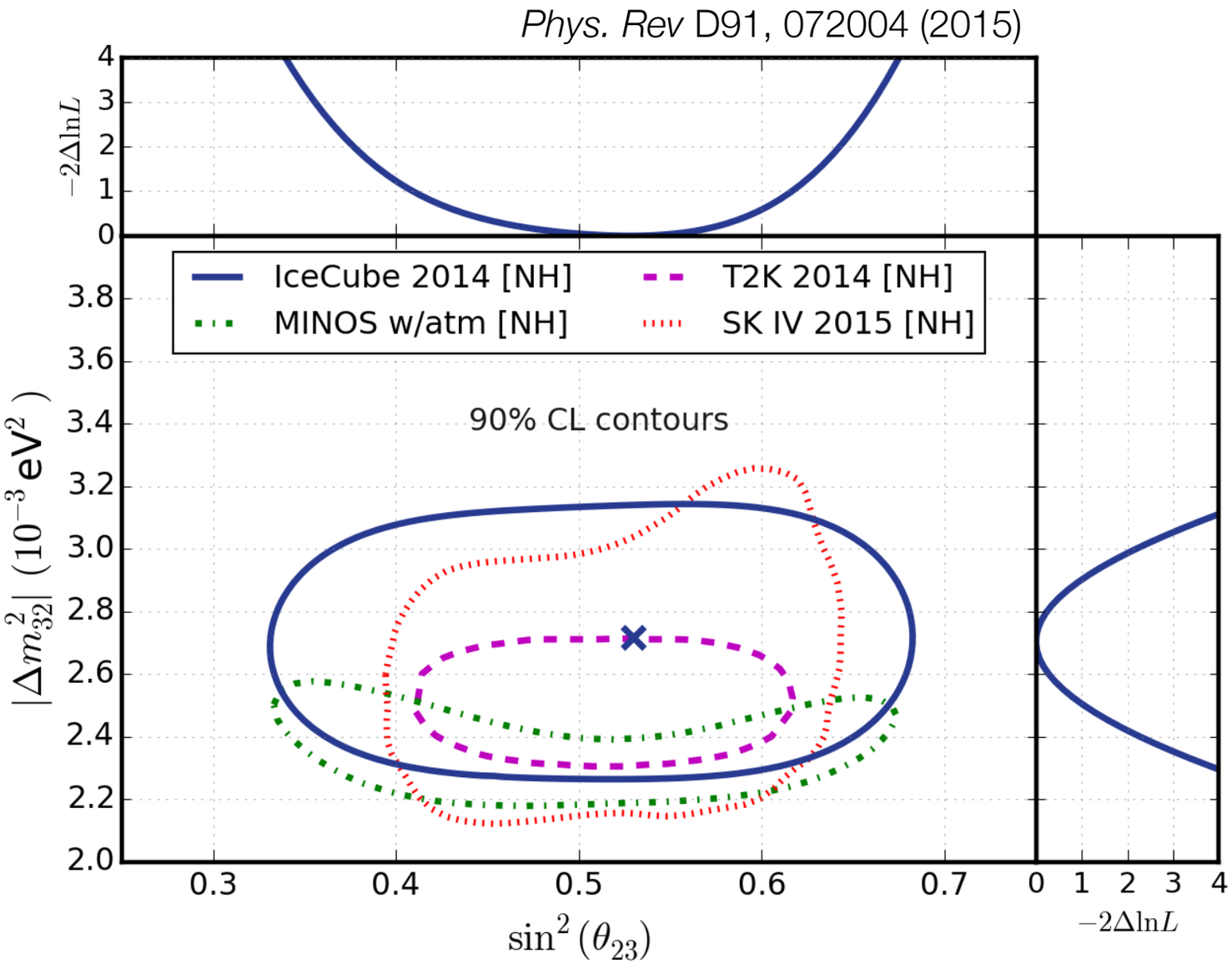
- Project data onto reconstructed (L/E_ν) for illustration
  - Actual analysis is performed in 2D to control systematics
- Shaded range shows allowed systematics with constraints from current data
- Second survival maximum just below DeepCore's energy threshold

Phys. Rev D91, 072004 (2015)



Current Measurements

- Two follow-up analyses with greatly improved statistics now in collaboration review process
  - Monte Carlo data challenges predict precision comparable to leading oscillation measurements

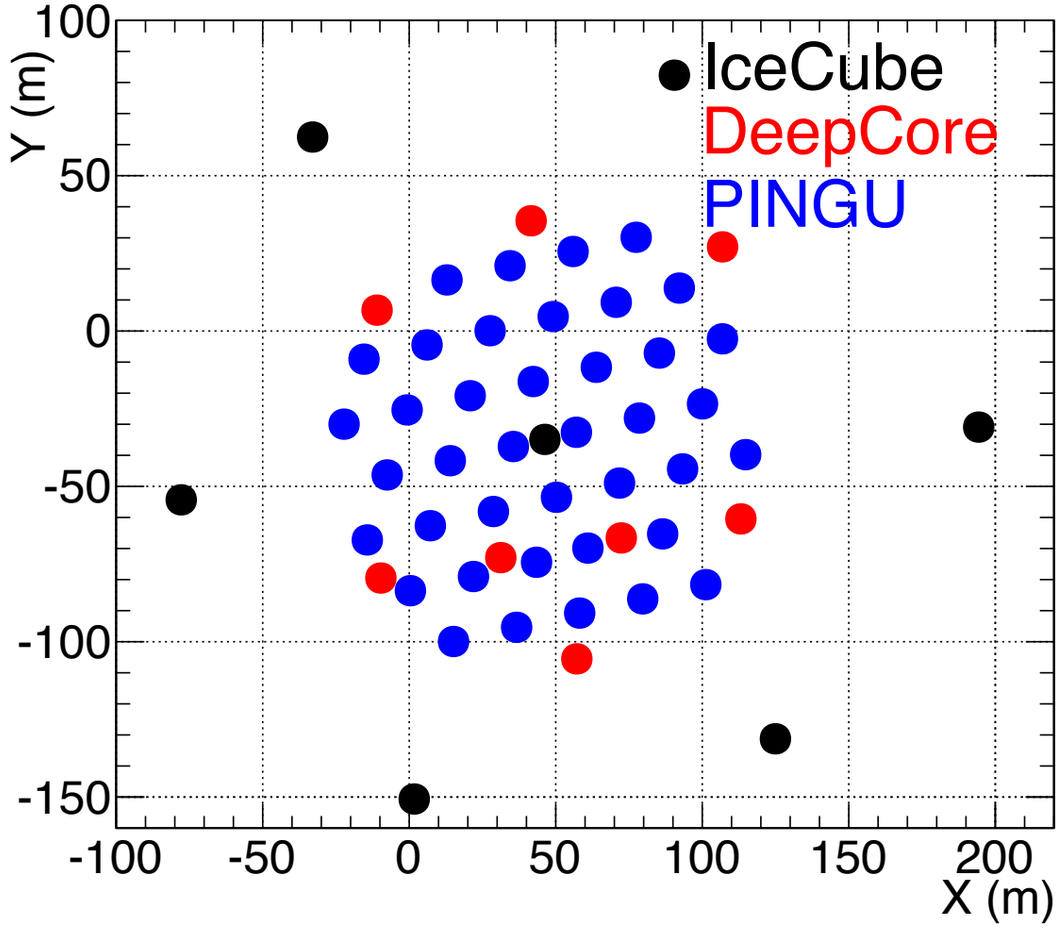


PINGU

PRECISION ICECUBE NEXT GENERATION UPGRADE

- 40 additional strings embedded in DeepCore with 22 m spacing, 96 DOMs spaced vertically at 3 m
  - Increase photon collection efficiency by more than an order of magnitude over DeepCore
  - Additional calibration devices to better control detector systematics (not included in projections)
- Achieve few GeV energy threshold with ~5 MTon fiducial volume
- Closely follow IceCube design to minimize costs, risks, timeline
  - Engineering issues and cost of deploying instrumentation are well understood from IceCube experience

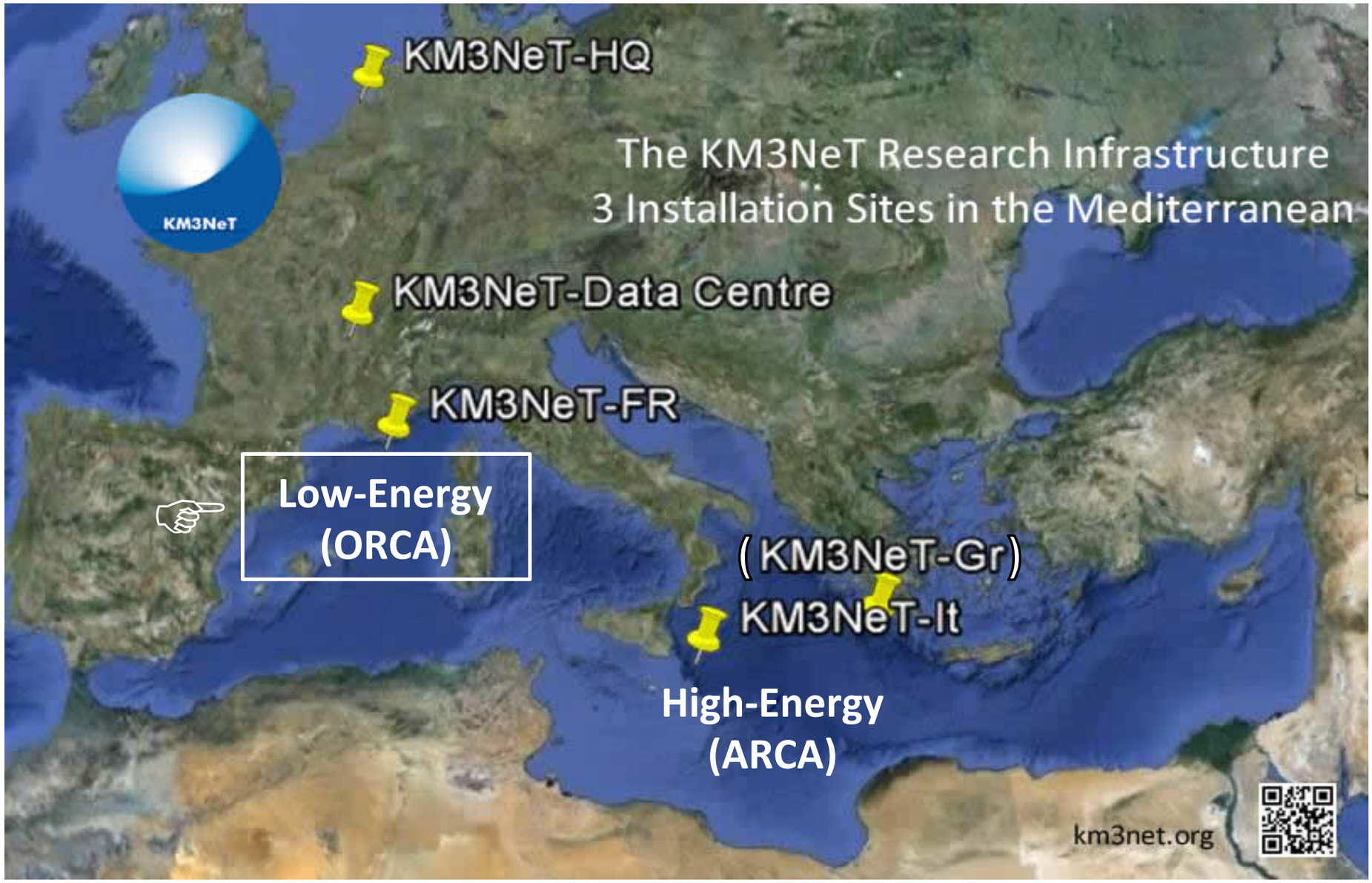
Top view of the PINGU new candidate detector



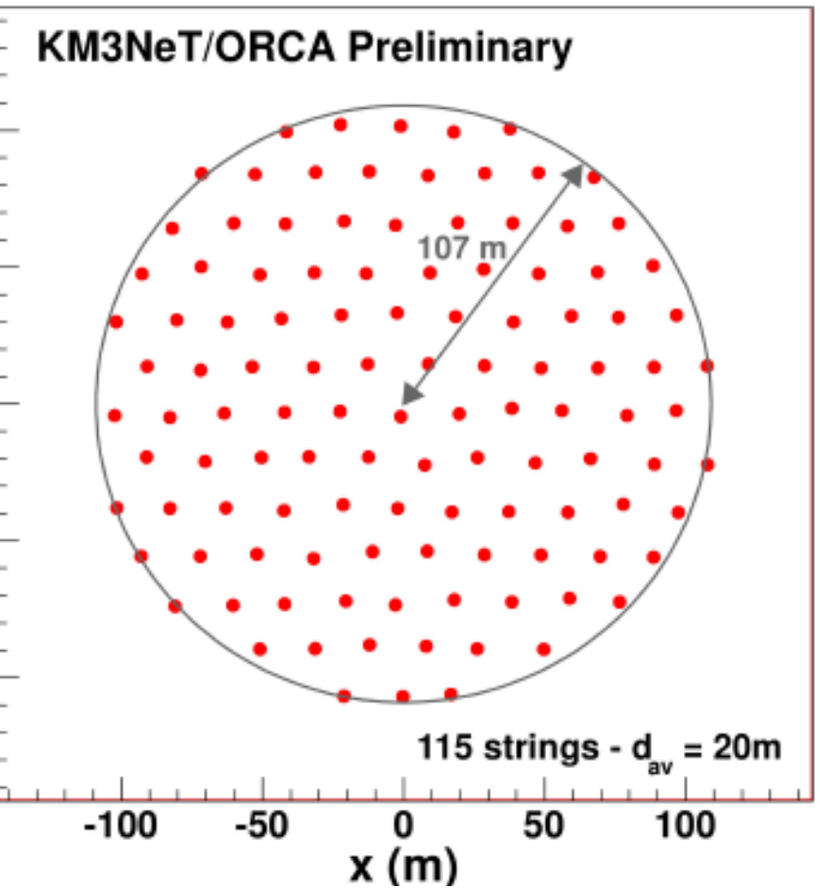
KM3NeT

Distributed research infrastructure with 2 main physics topics:

Low-Energy studies of atmospheric neutrinos – High-Energy search for cosmic neutrinos



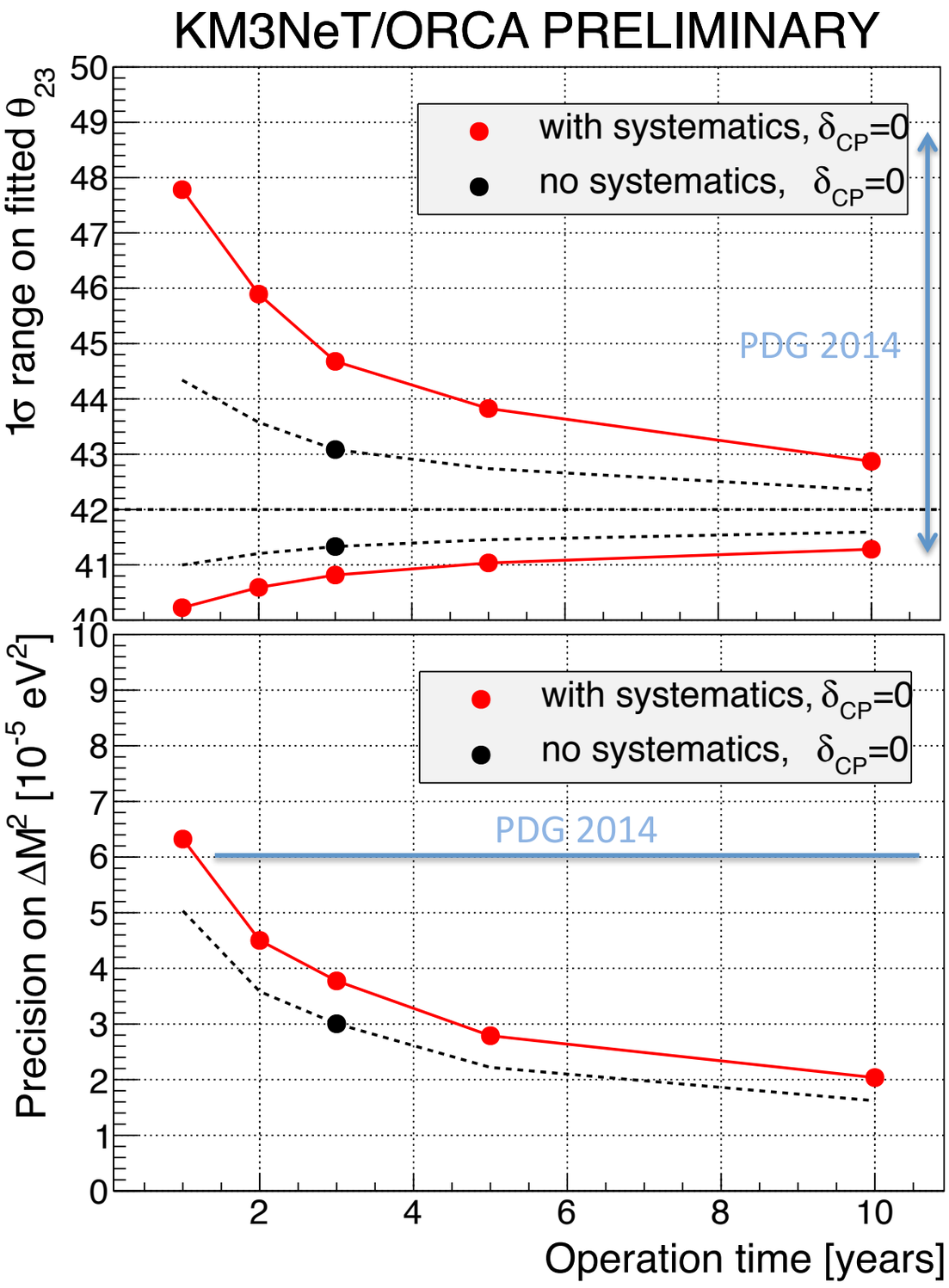
ORCA

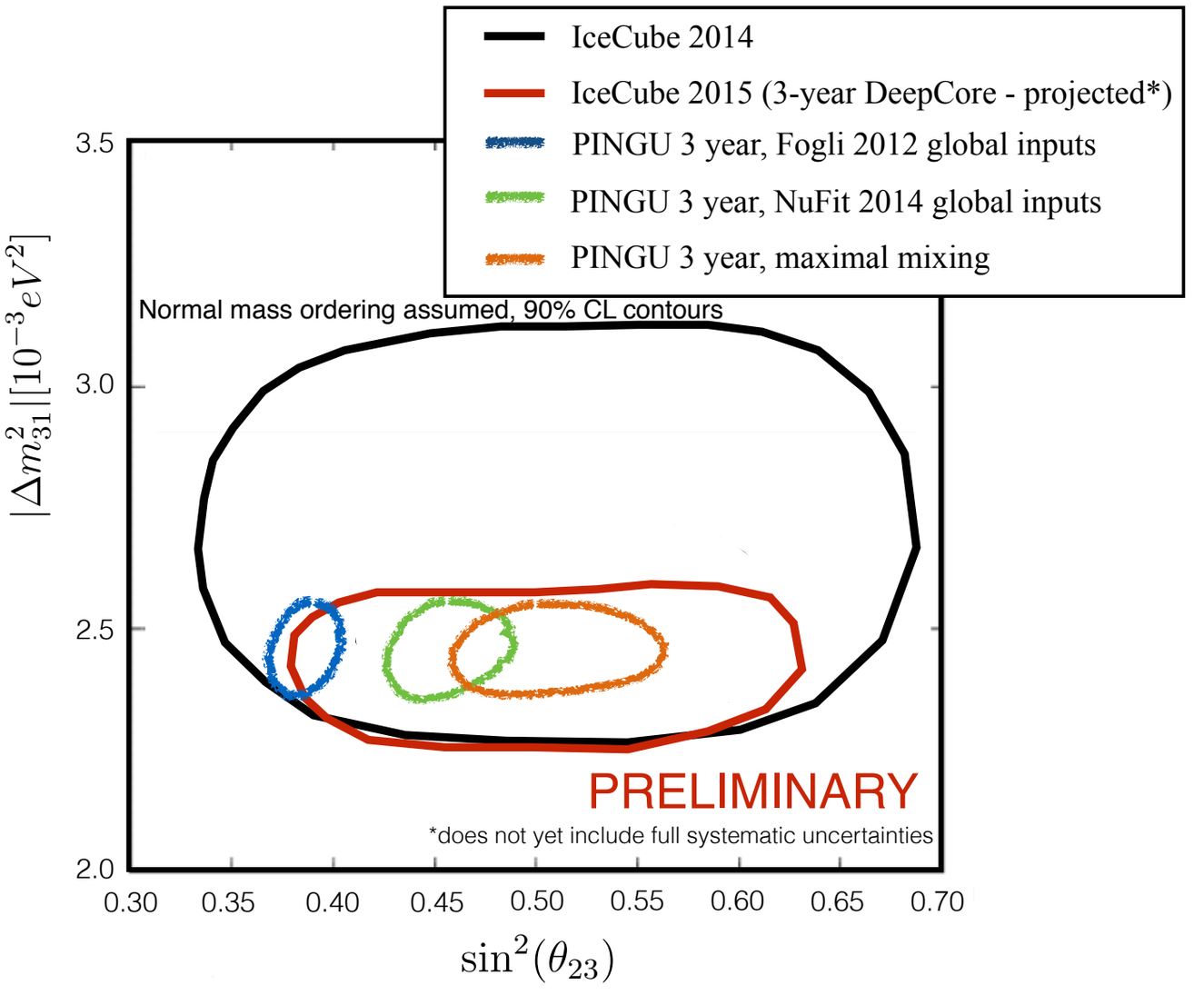


18 DOMs/line at 6 m spacing
2070 DOMs
~4 MTon Effective mass

DOMs with 31 x 3” PMTs:
~3x IceCube photocathode
Directional information on photon arrival
Use PMT coincidence to reduce ^{40}K background

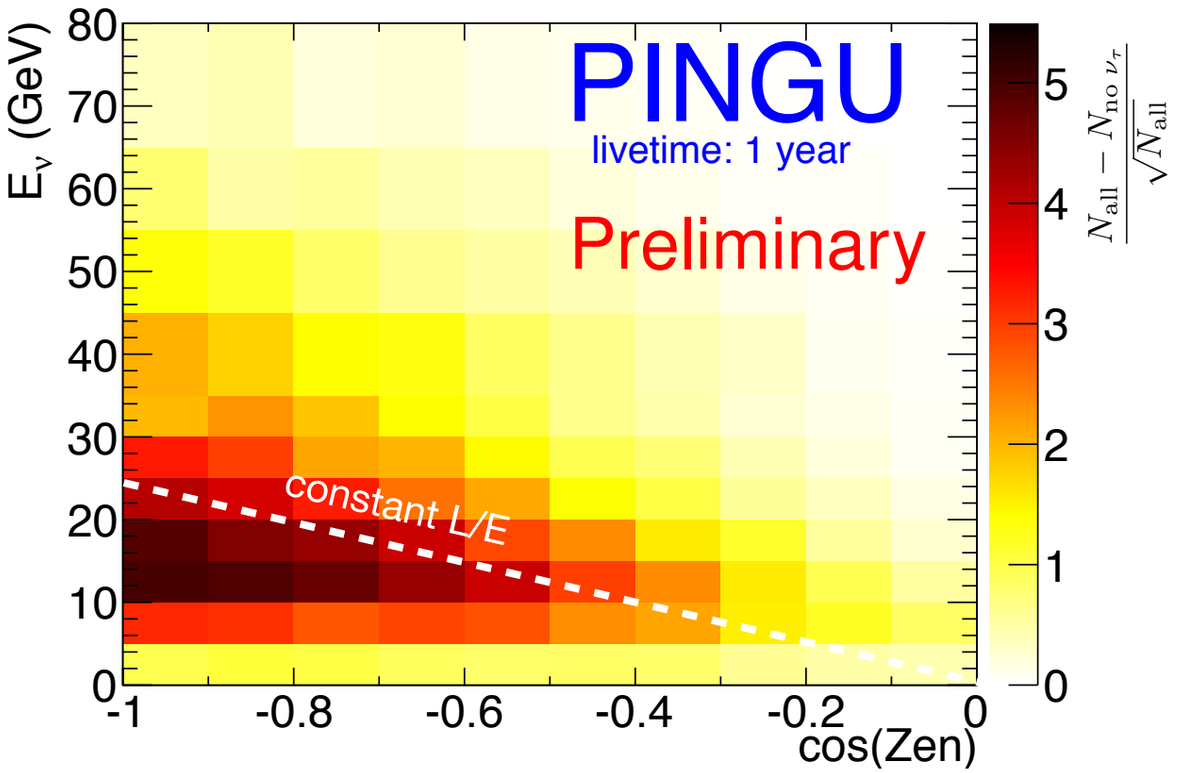
Precision Oscillation Measurements

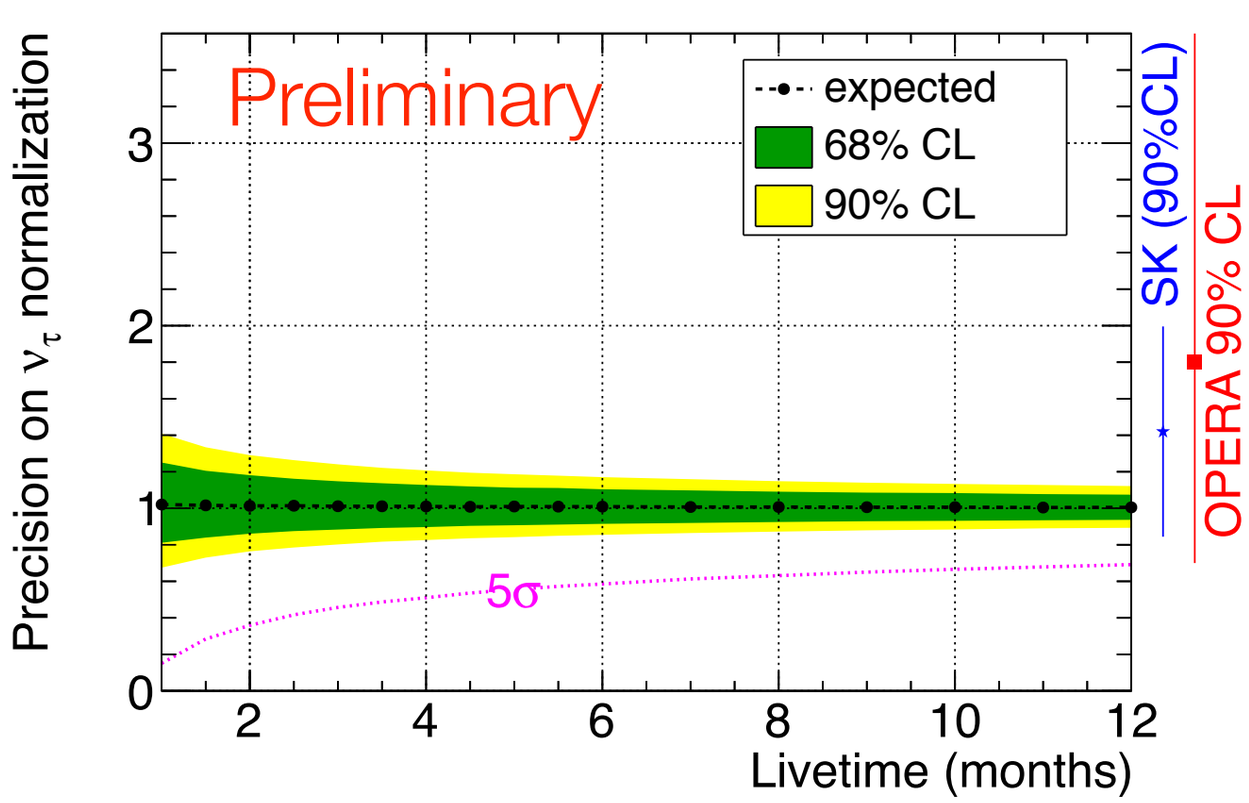




Tau Neutrino Appearance

- Unique opportunity for precision measurement of ν_τ appearance
  - Cross section increases rapidly with energy due to τ lepton mass
  - Signature is a vertically-peaked spectral feature, nearly 1000 events/year
- Interesting test of standard oscillations/neutrino interactions





Primary Systematic Uncertainties

- Oscillation parameters (from nu-fit.org [1]):
  - Δm^2_{31} (NH/IH) = 0.00246 / -0.00237 eV [2] (no prior)
  - θ_{23} (NH/IH) = 42.3° / 49.5° (no prior)
  - θ_{13} = 8.5° ± 0.2°
- Detector/flux/cross sections:
  - **event rate** (effective area, flux normalization) = nominal (no prior)
  - **energy scale** = nominal ± 0.10 (from current calibration data)
  - ν_e/ν_μ **ratio** = nominal ± 0.03 (ref [2])
  - **ν/anti-ν ratio** = nominal ± 0.10 (ref [2] and [3])
  - **atmospheric spectral index**: nominal ± 0.05 (ref [2])
  - Also studied separately:
    - detailed cross section systematics based on GENIE [3] parameters
    - detailed atmospheric flux uncertainties from [2]

similar list for ORCA

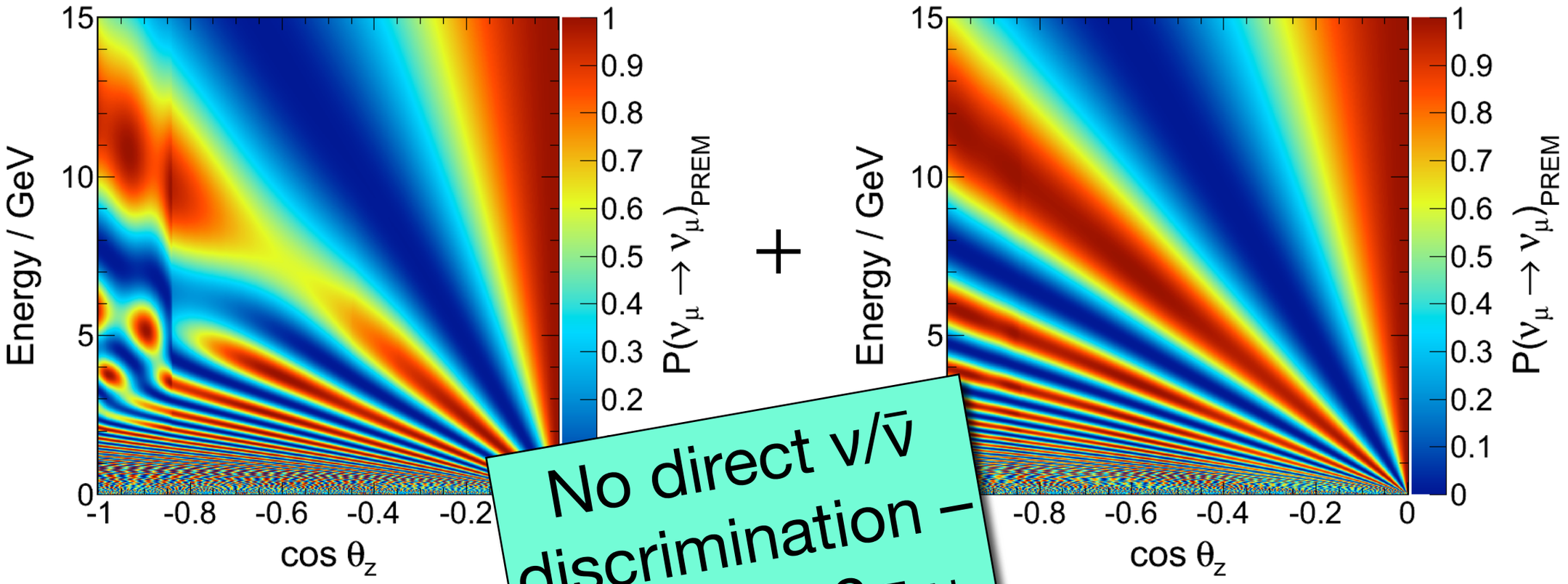
[1] M.C. Gonzalez-Garcia, et al. *JHEP* **11** 052, 2014

[2] G.D. Barr, T.K. Gaisser, et. al. *Phys. Rev. D* **74** 094009, (2006)

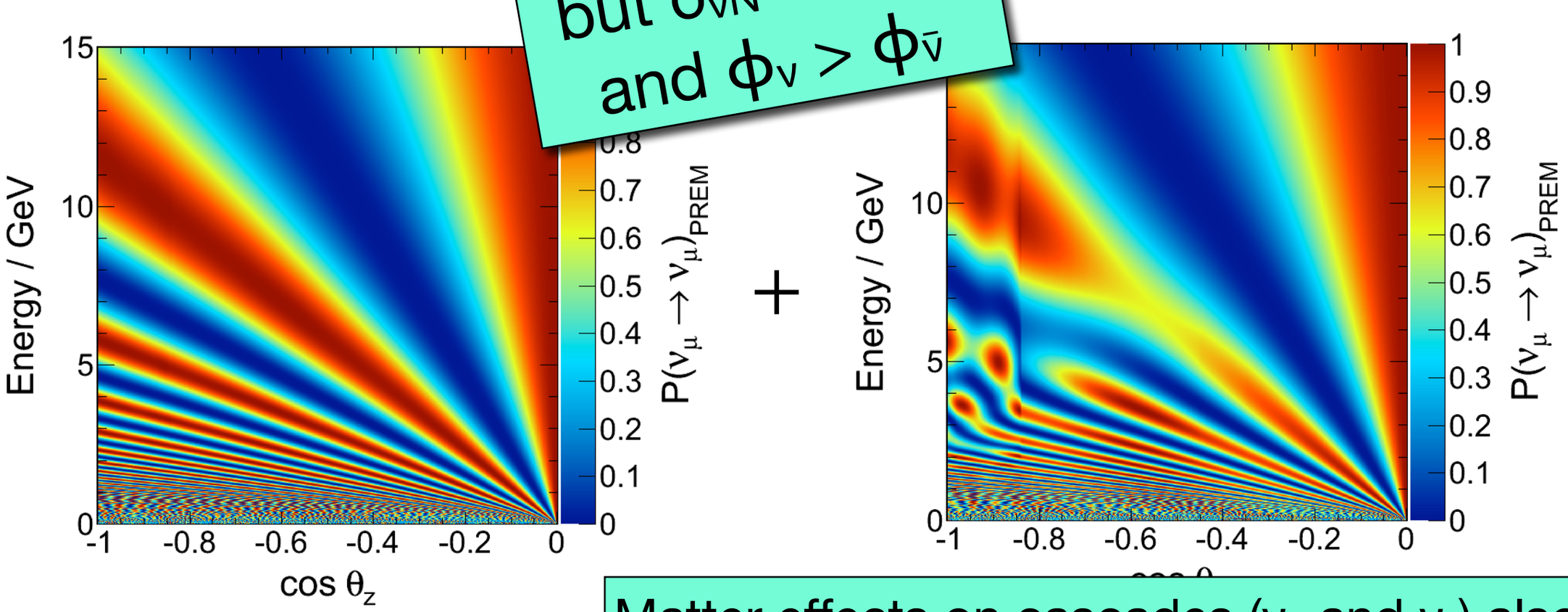
[3] C.Andreopoulos et al., *Nucl.Instrum.Meth. A* **614**:87-104 (2010)

Neutrinos

Antineutrinos

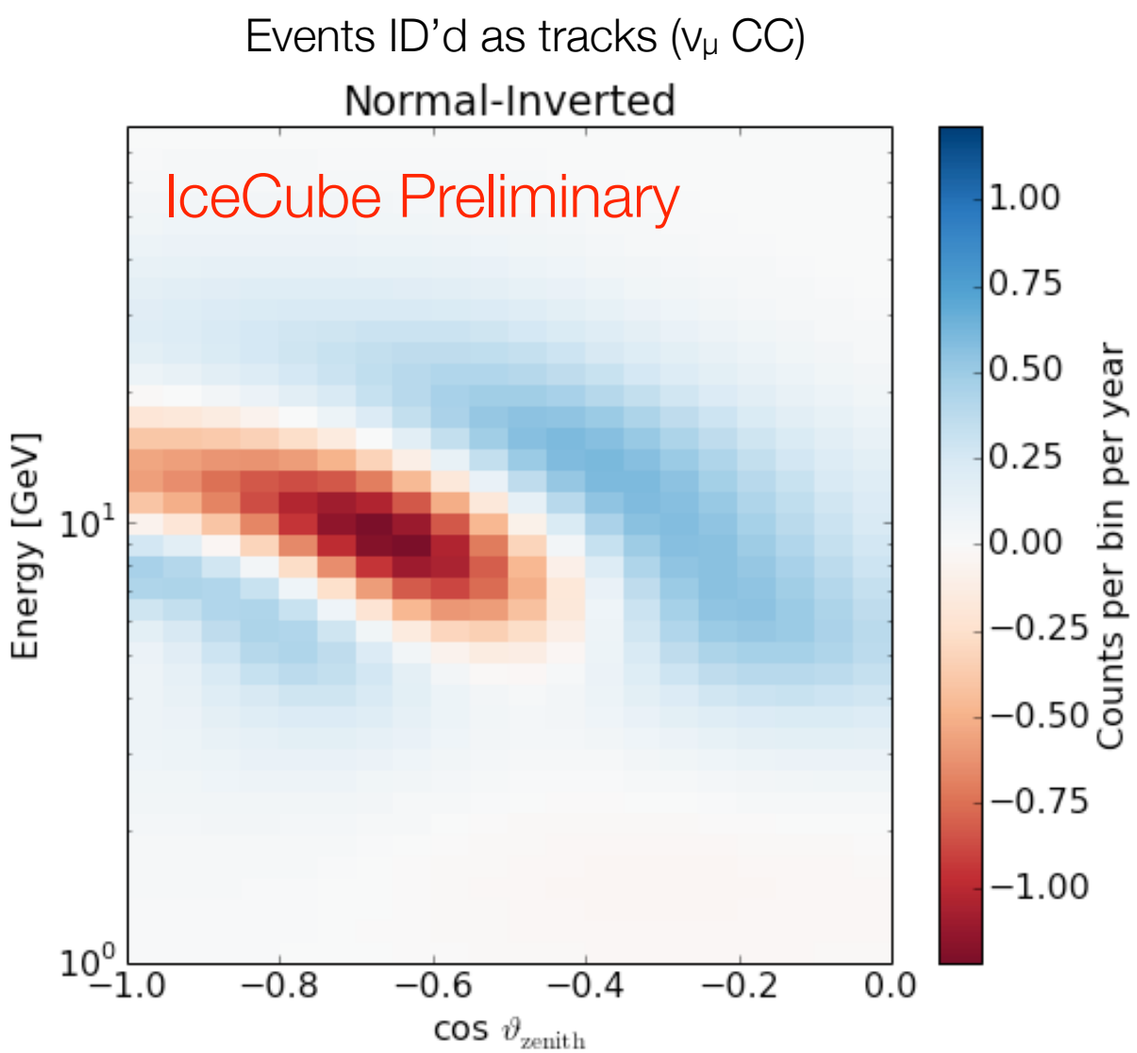


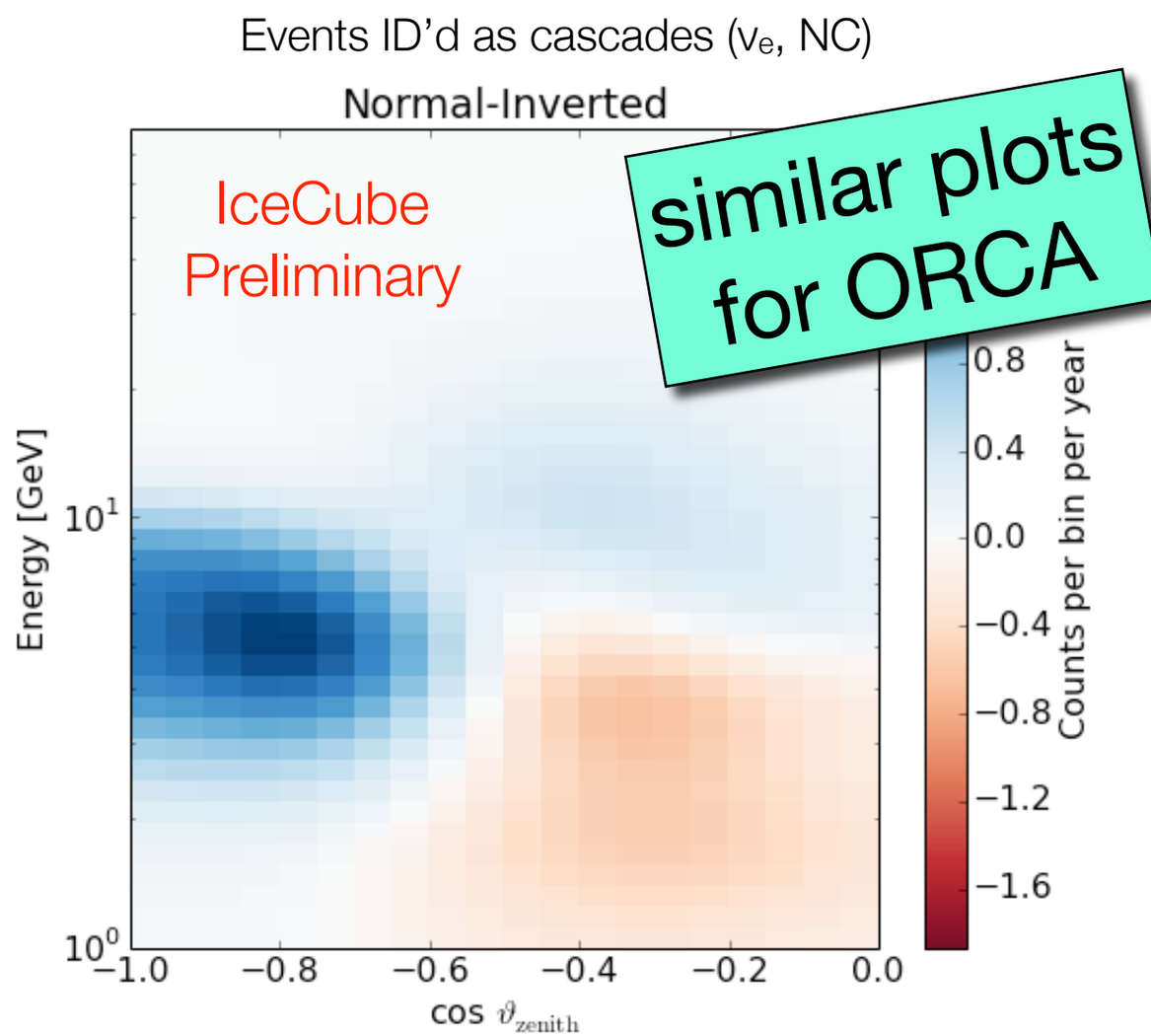
No direct ν/ν̄ discrimination – but $\sigma_{\nu N} \sim 2\sigma_{\bar{\nu}N}$ and $\phi_\nu > \phi_{\bar{\nu}}$



Matter effects on cascades (ν_e and ν_τ) also important

Signature of Mass Ordering (PINGU)





- Event rates, detector resolutions and efficiencies parametrized from full detector Monte Carlo to eliminate statistical fluctuations

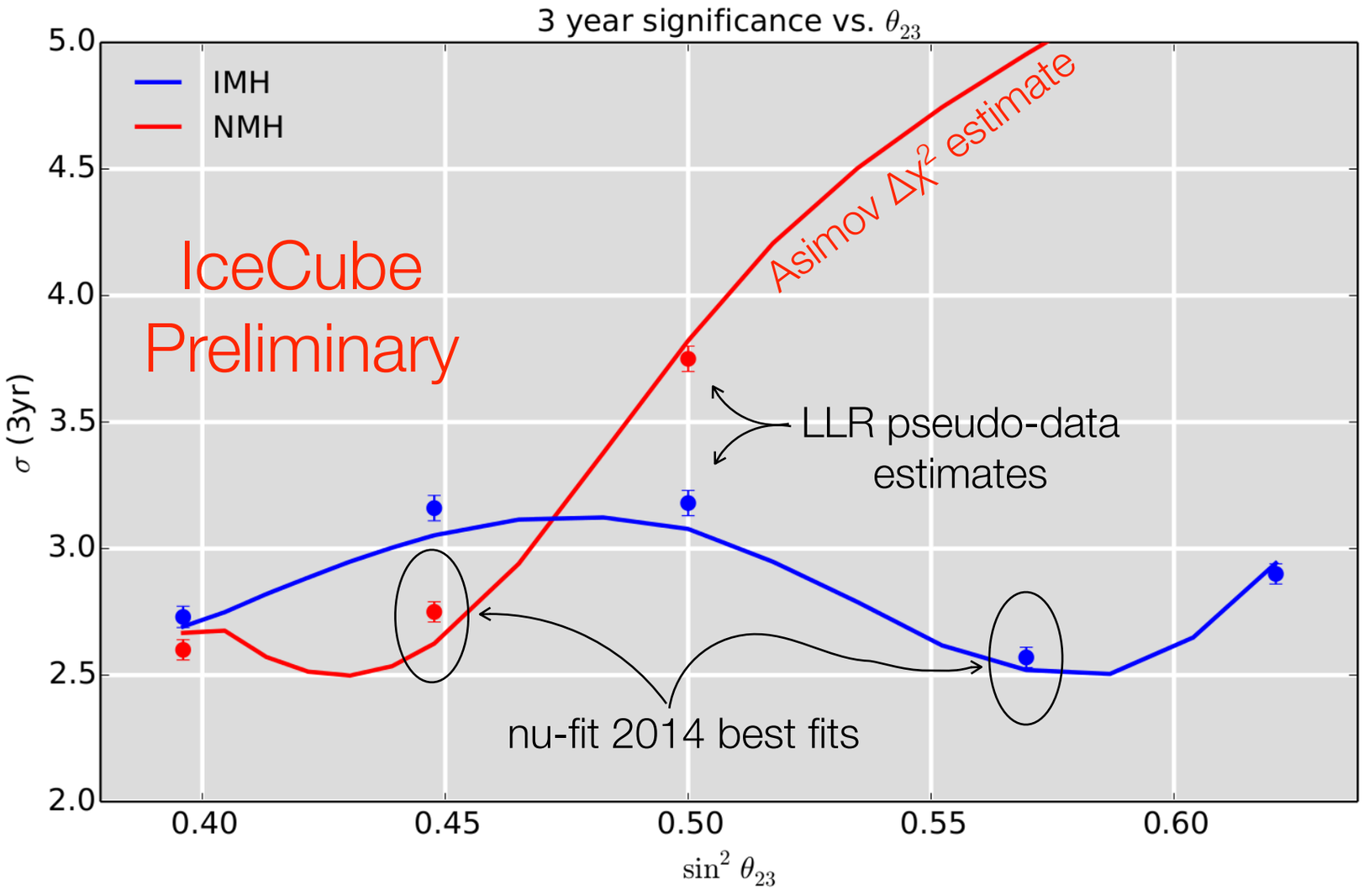
- Expect ~50k ($\nu_\mu+\bar{\nu}_\mu$) and ~40k ($\nu_e+\bar{\nu}_e$) per year – largest sample ever in this energy range

Sensitivity to Mass Ordering

- Determine mass ordering at 3σ significance in ~3.5-4 years at current global fit parameters

- True oscillation parameters (esp. θ_{23}) have a strong impact
  - Current values roughly worst case

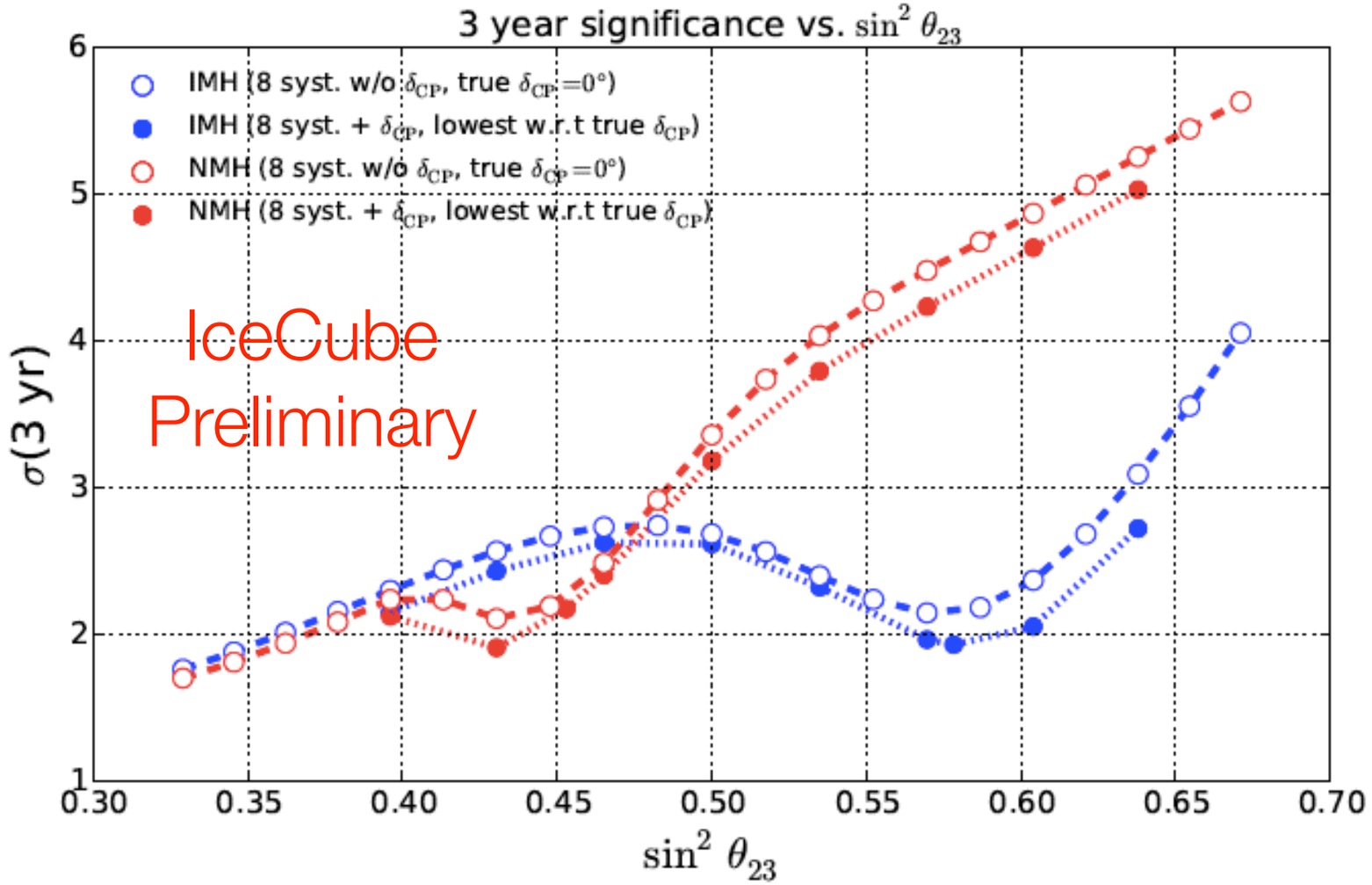
very similar significance for ORCA



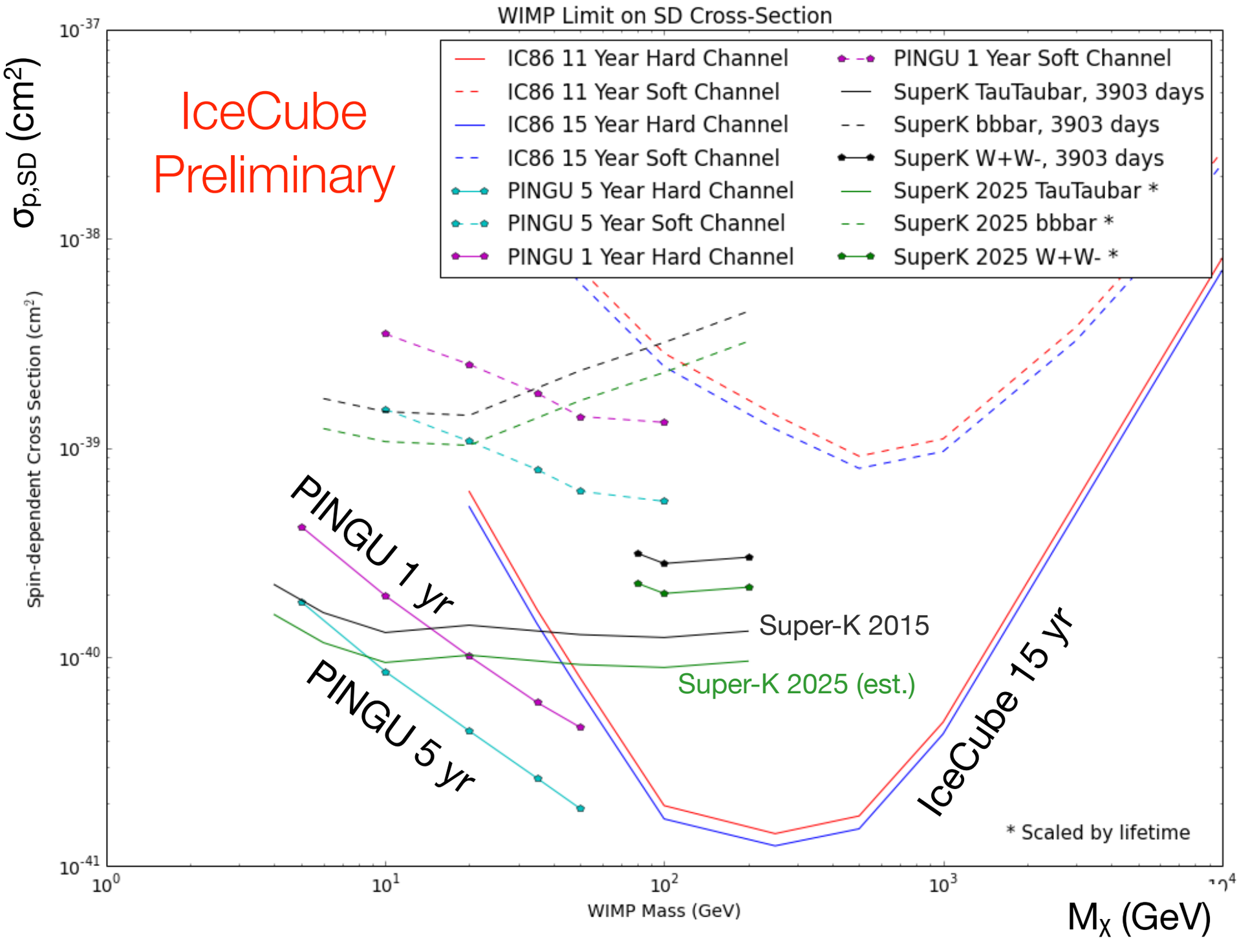
NB: δ_{CP} fixed at 0

Impact of CP Violation

- Previous studies fixed $\delta_{CP} = 0$
  - As θ_{23} has drifted closer to maximal, potential impact increases
- Worst-case appears to reduce NMO 3-yr significance by ~0.2σ
  - Preliminary study including δ_{CP} as a nuisance parameter ($\Delta\chi^2$ method only)

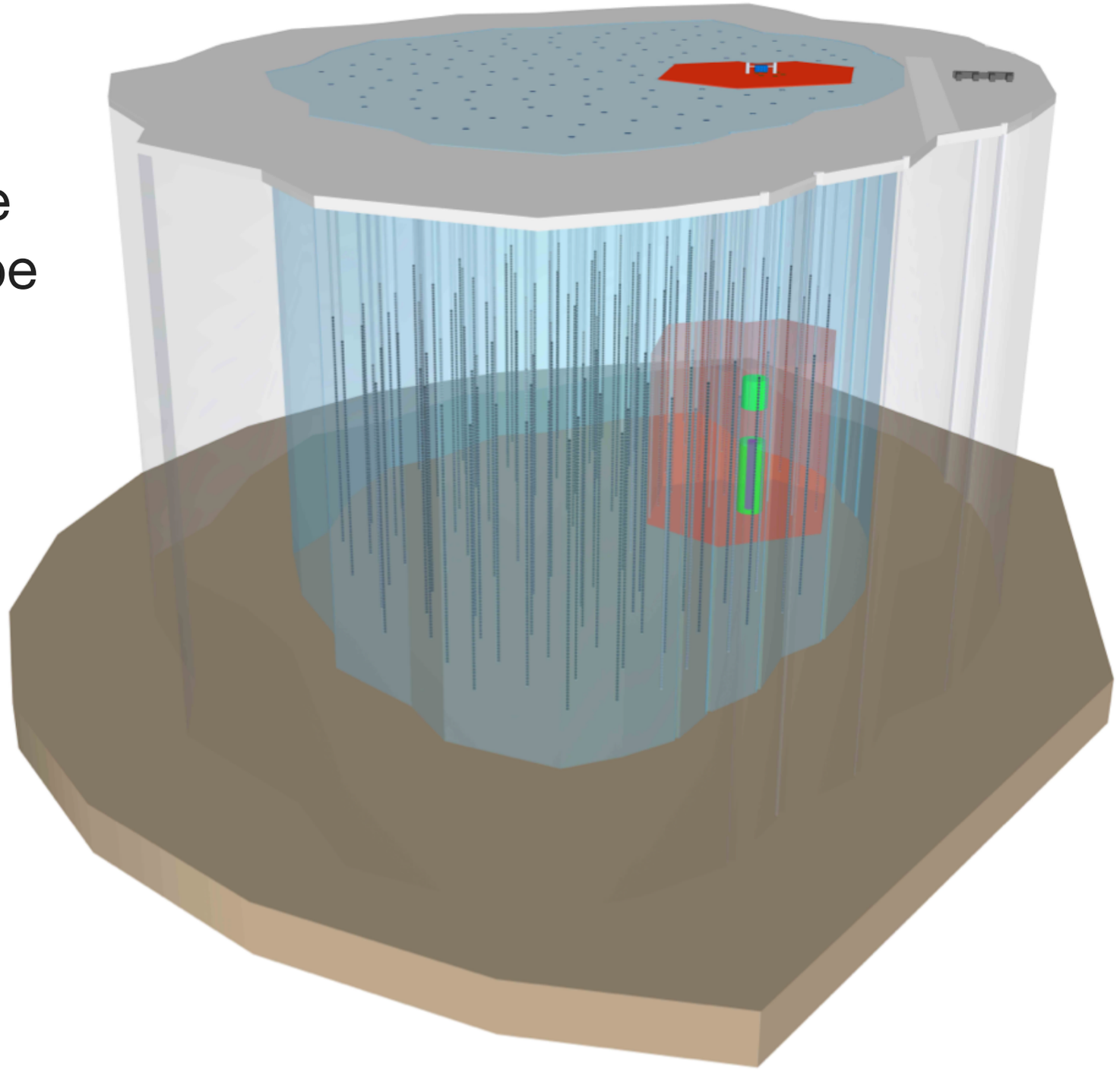


Indirect Search for Dark Matter



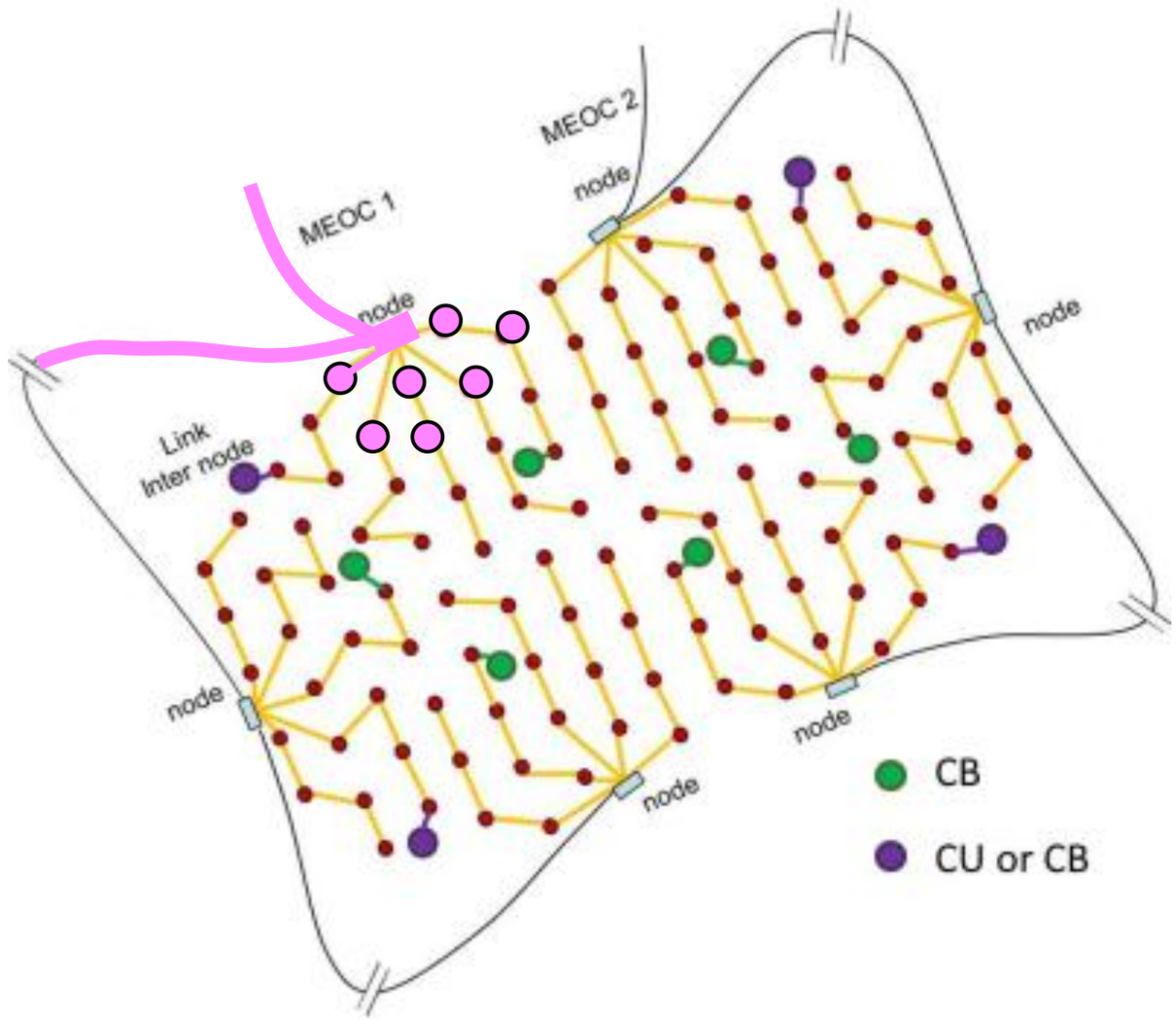
IceCube-Gen2 and PINGU

- Planning underway for a multipurpose facility leveraging the experience and investment in IceCube
  - White paper describing our vision of this detector at arXiv:1412.5106
- PINGU will be one component of IceCube-Gen2
  - Marginal TPC ~$65M US + ~$25M non-US



ORCA Status

- 6 strings to be deployed in 2016 as part of KM3NeT phase 1
  - Demonstrate performance in the few-GeV range
- Proposals submitted to build 115-string array as part of Phase 2 (~40M€ hardware)
  - French KM3NeT site
  - Target 2017 construction start, 2020 completion



Conclusions

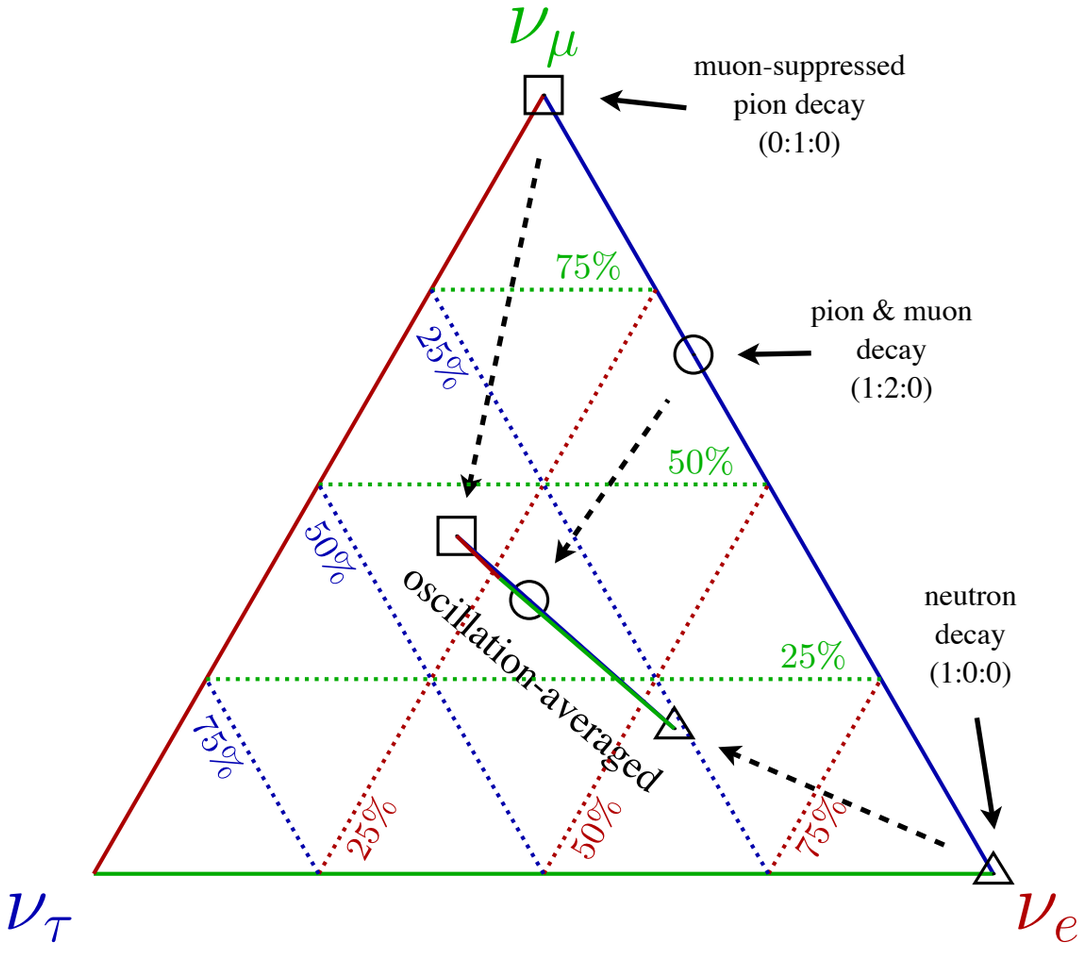
- Very large underwater/under-ice detectors have a unique place in the world-wide neutrino program
  - Measurements at a range of higher energies/longer baselines
  - Unique capabilities (precision tau neutrino appearance, dark matter)
- Opportunity to discover new physics is greatly enhanced by complementarity of these detectors with other experiments
- Both PINGU and ORCA are technically mature and can be deployed relatively quickly and at moderate cost

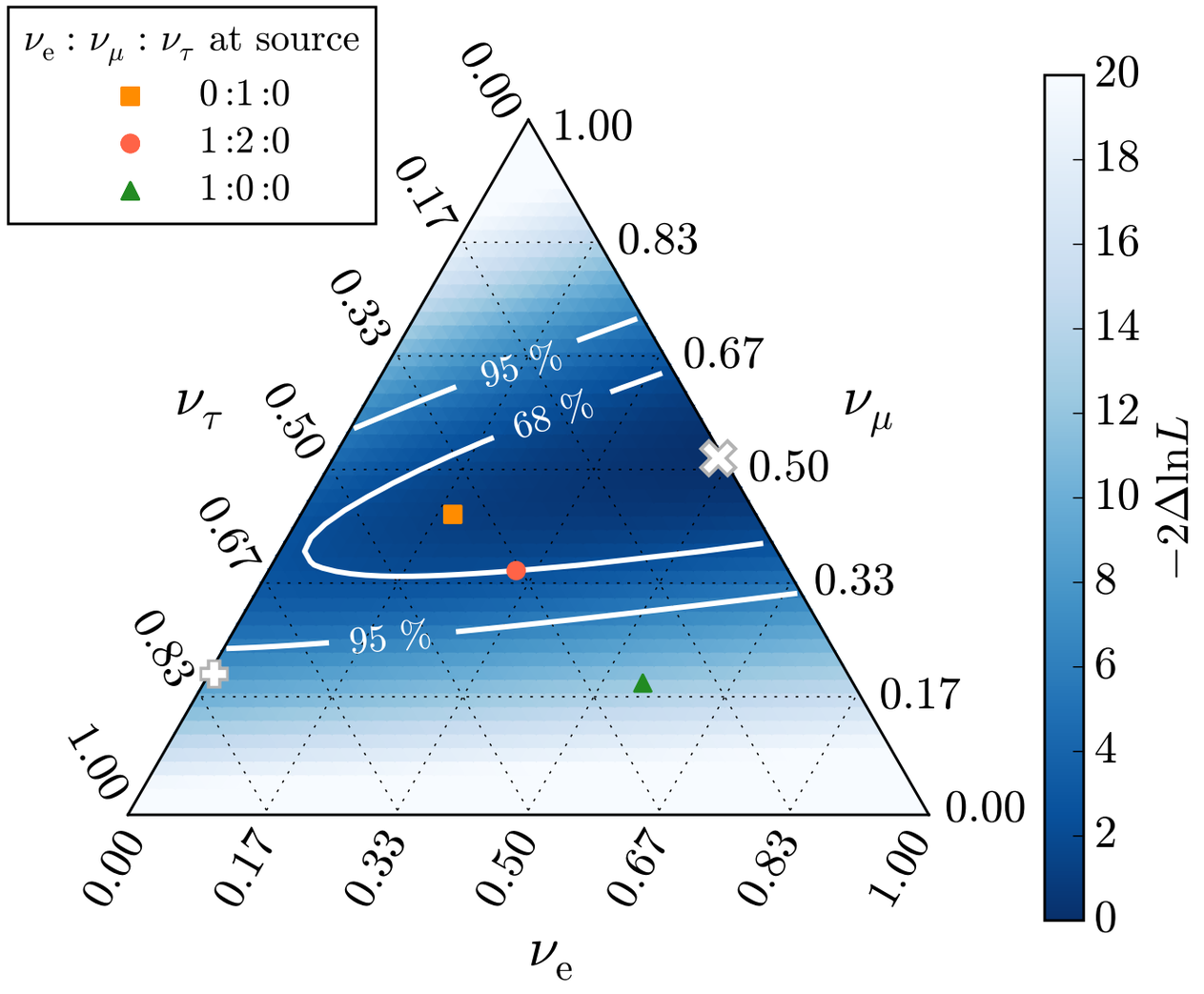
Backup Slides

Flavor Ratios

Astrophys. J. 809, 98 (2015)

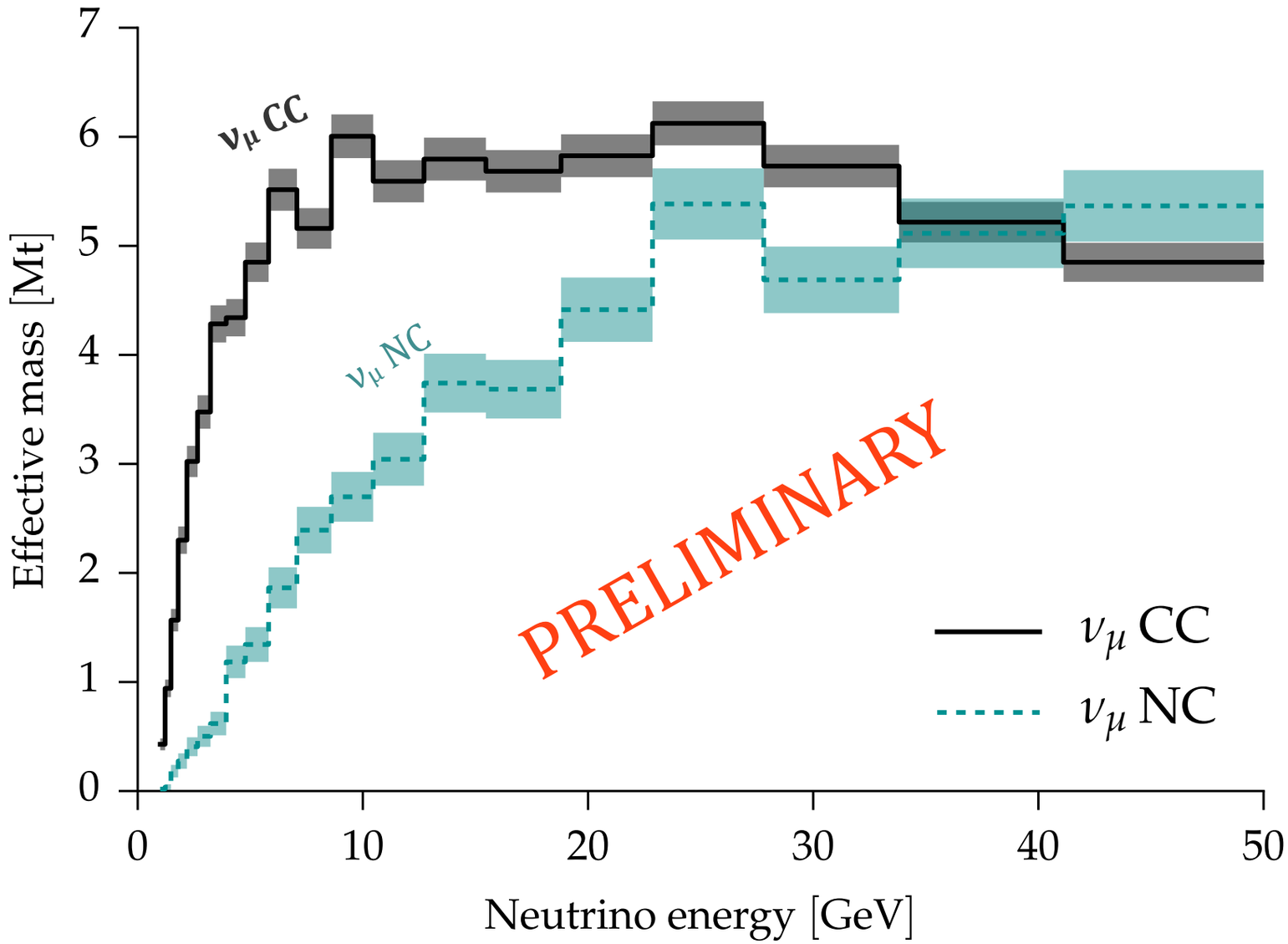
- After oscillations, all sources should wind up inside the triangle
- Pure neutron-escape scenario disfavored





PINGU Effective Mass

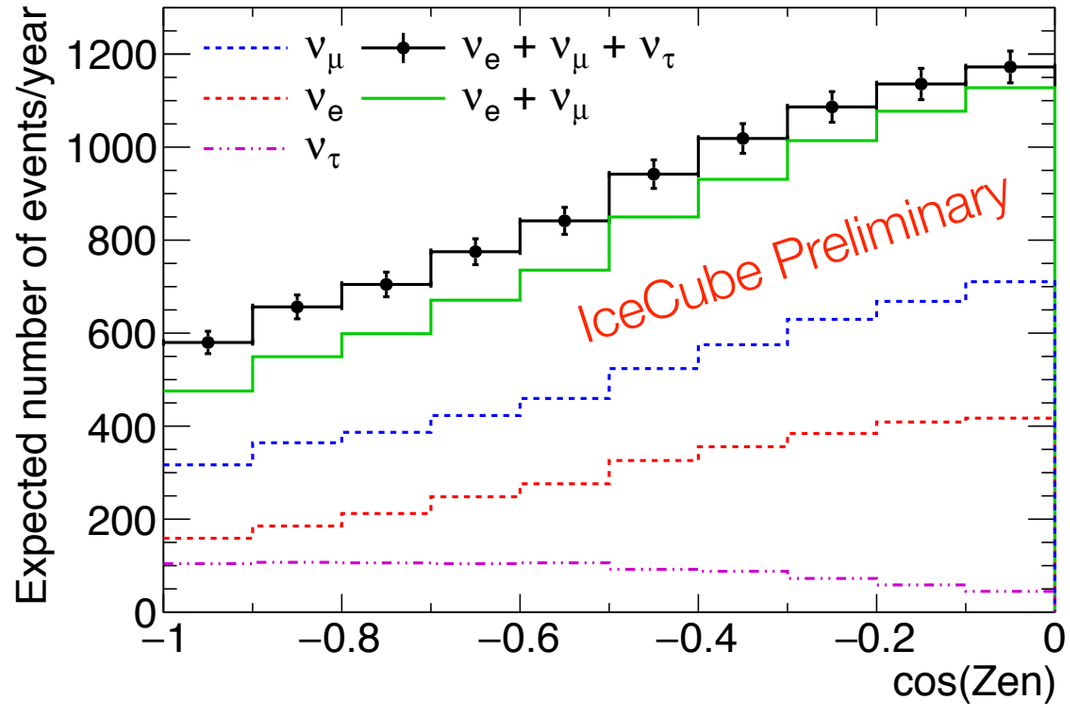
- Fiducial mass of approx. 6 MTon
  - Event selection fully above ~7 GeV
  - Baseline event selection allows slightly higher atm. μ rate than in DeepCore analyses – real selection may be ~10-20% less efficient

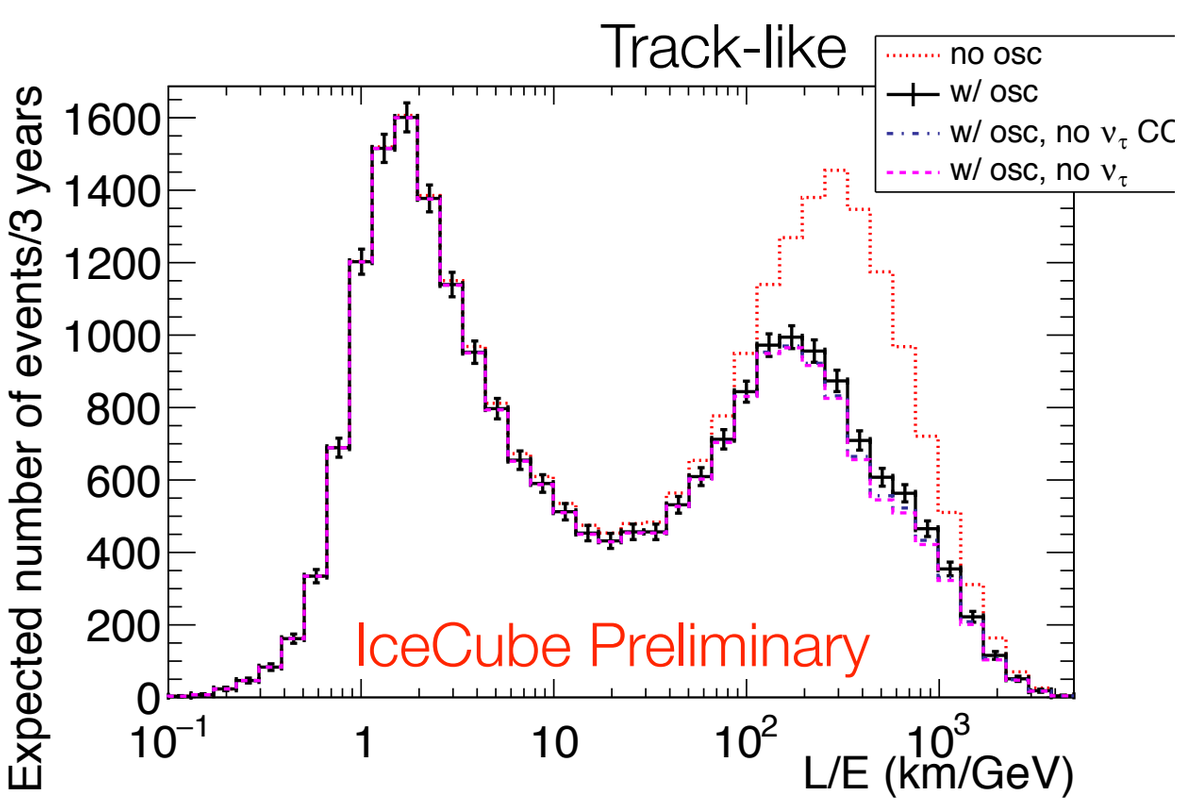


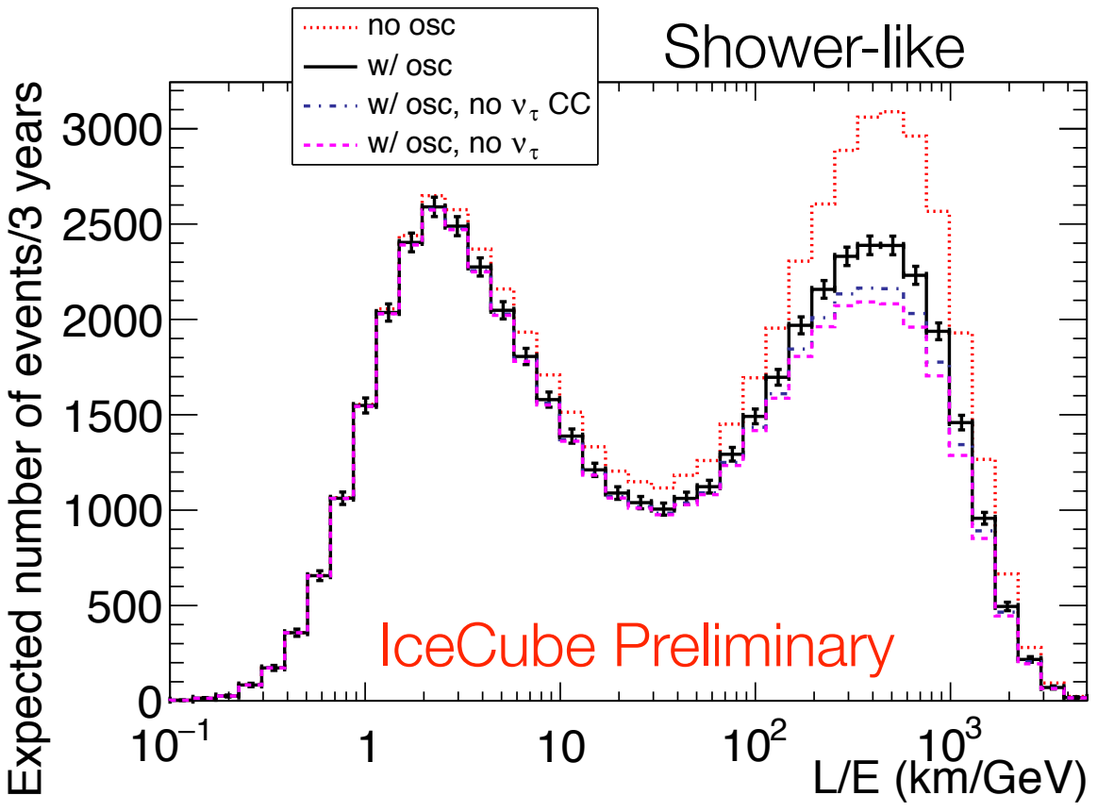
- Similar effective mass for other neutrino flavors

Tau Neutrino Appearance in DeepCore

- Tau neutrinos peak vertically, with a specific spectrum
  - Backgrounds are highest near the horizon, broad spectrum

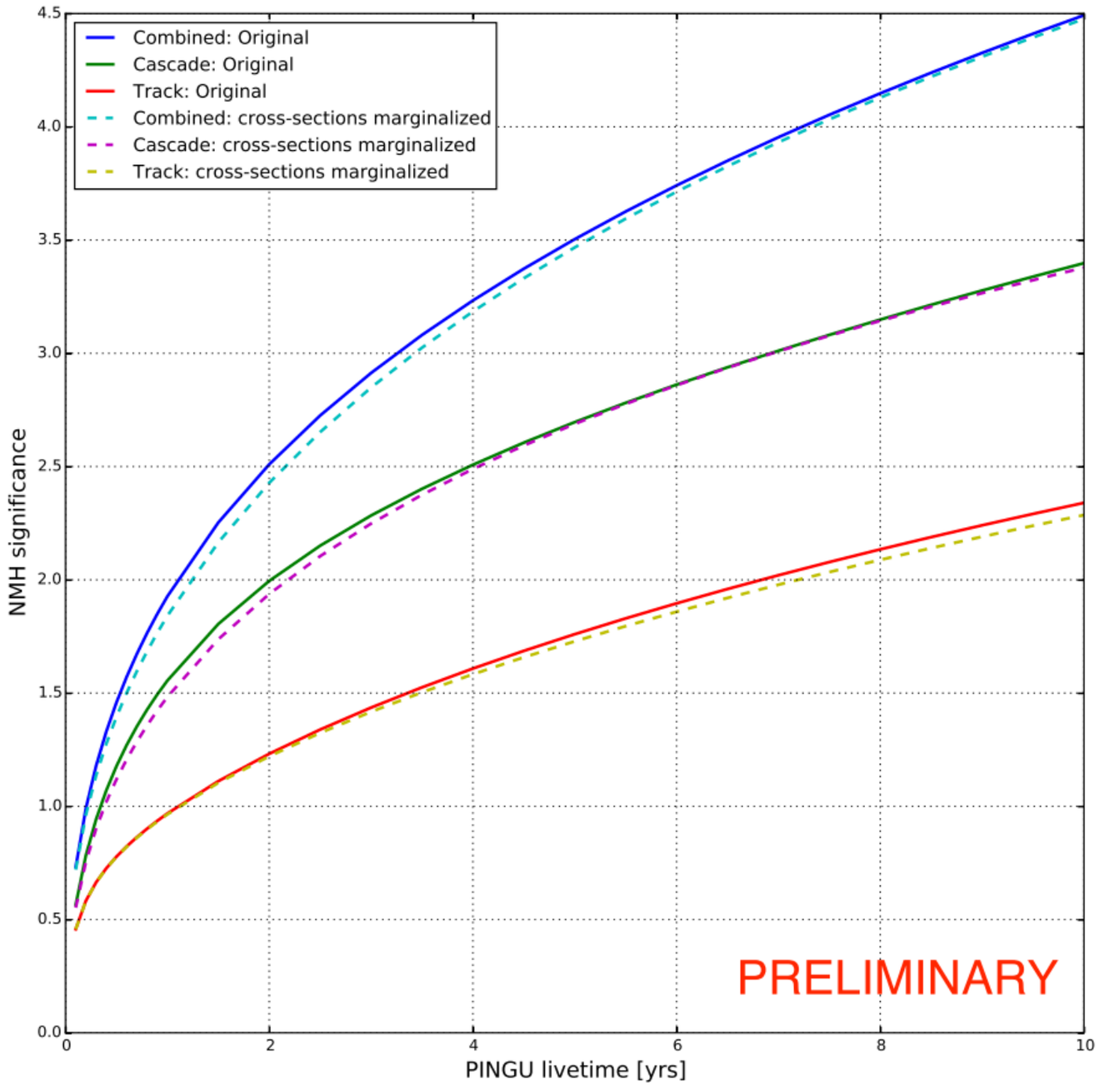






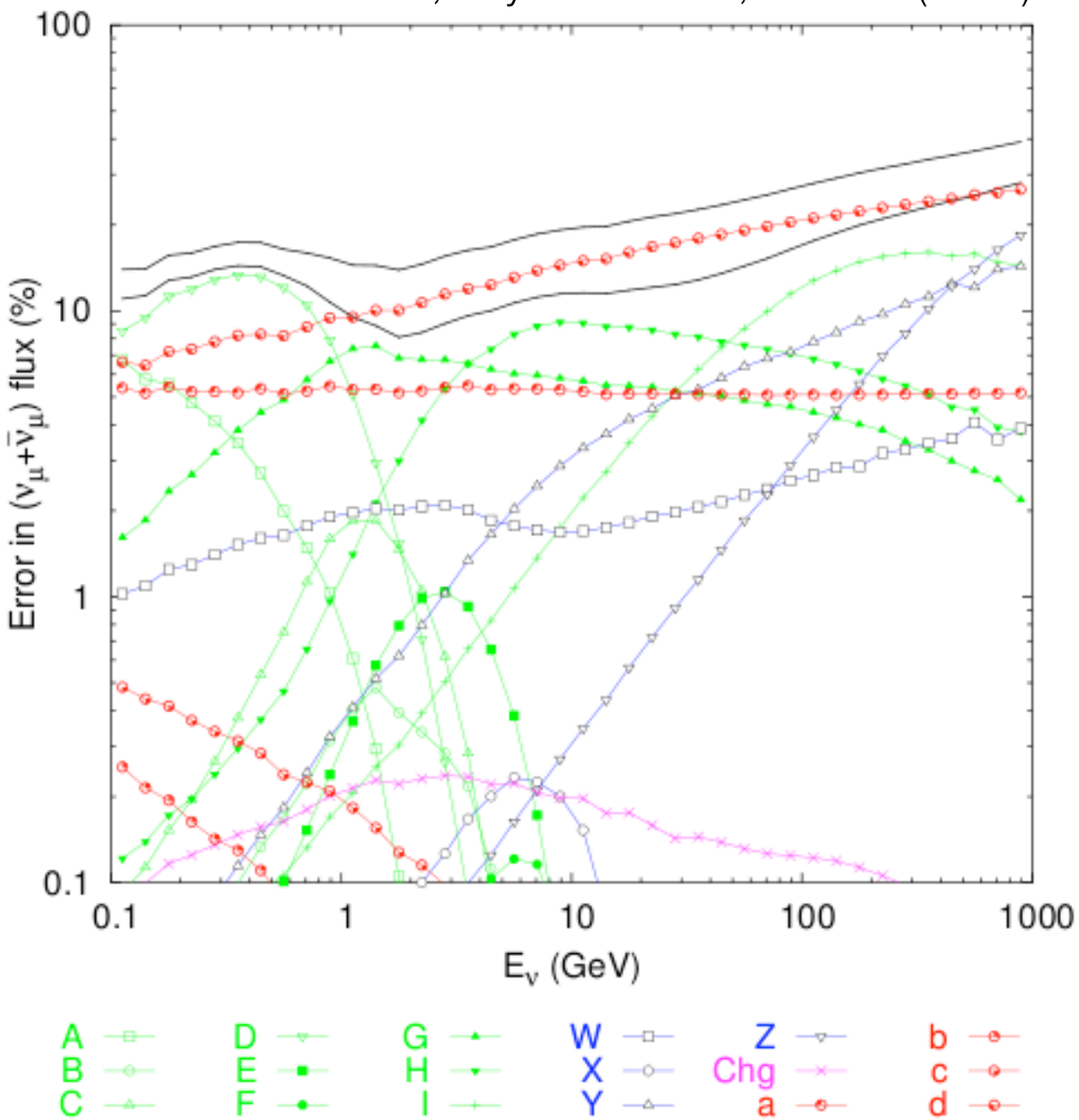
Neutrino-Nucleon Interaction Uncertainties

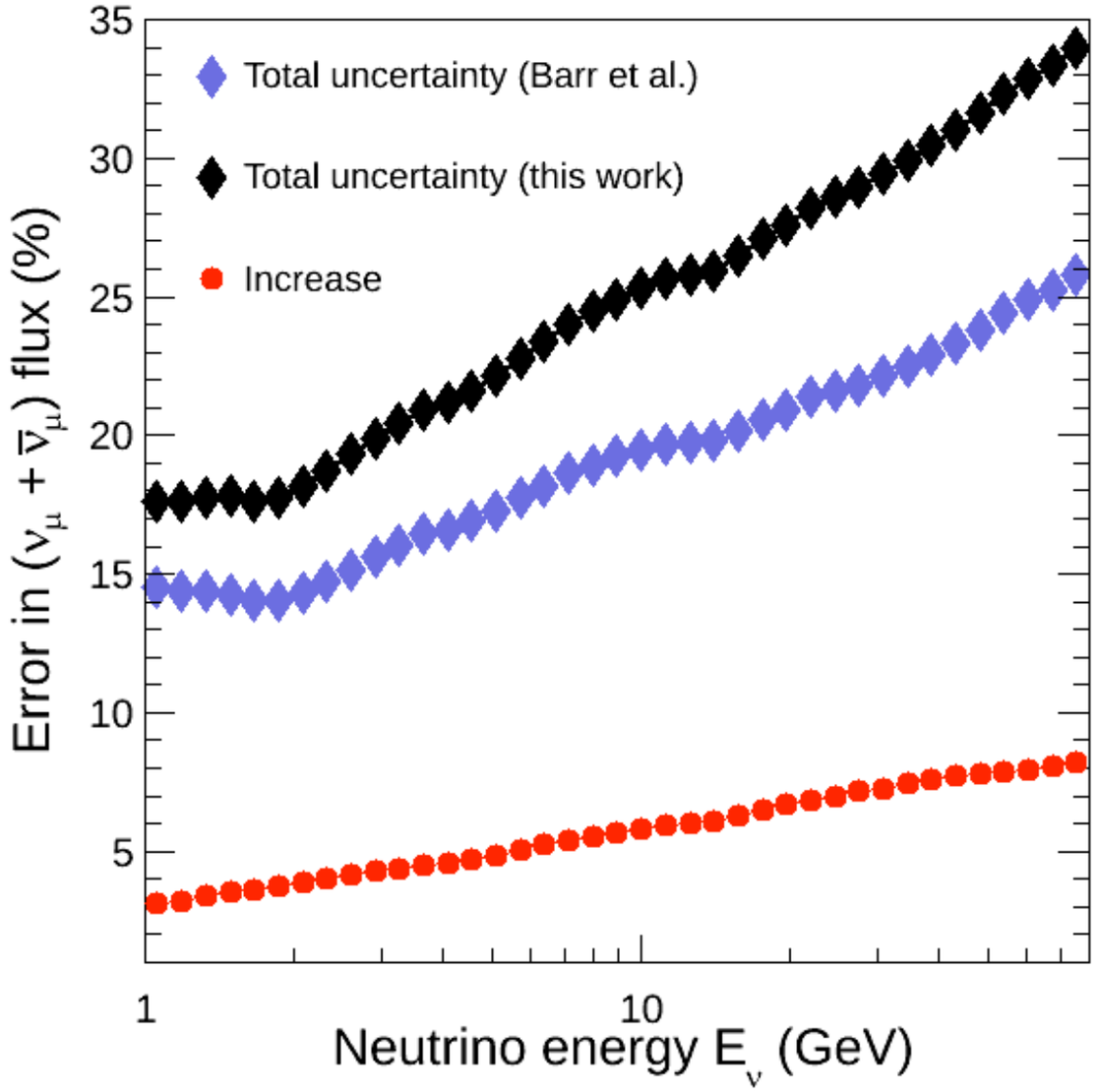
- Comparison of impact of GENIE uncertainties to original ad hoc treatment
- Net impact of full treatment is negligible – oscillation uncertainties dominate
  - Largest impacts from m_A in CCQE and resonance interactions, higher twist parameters in Bodek-Yang DIS model



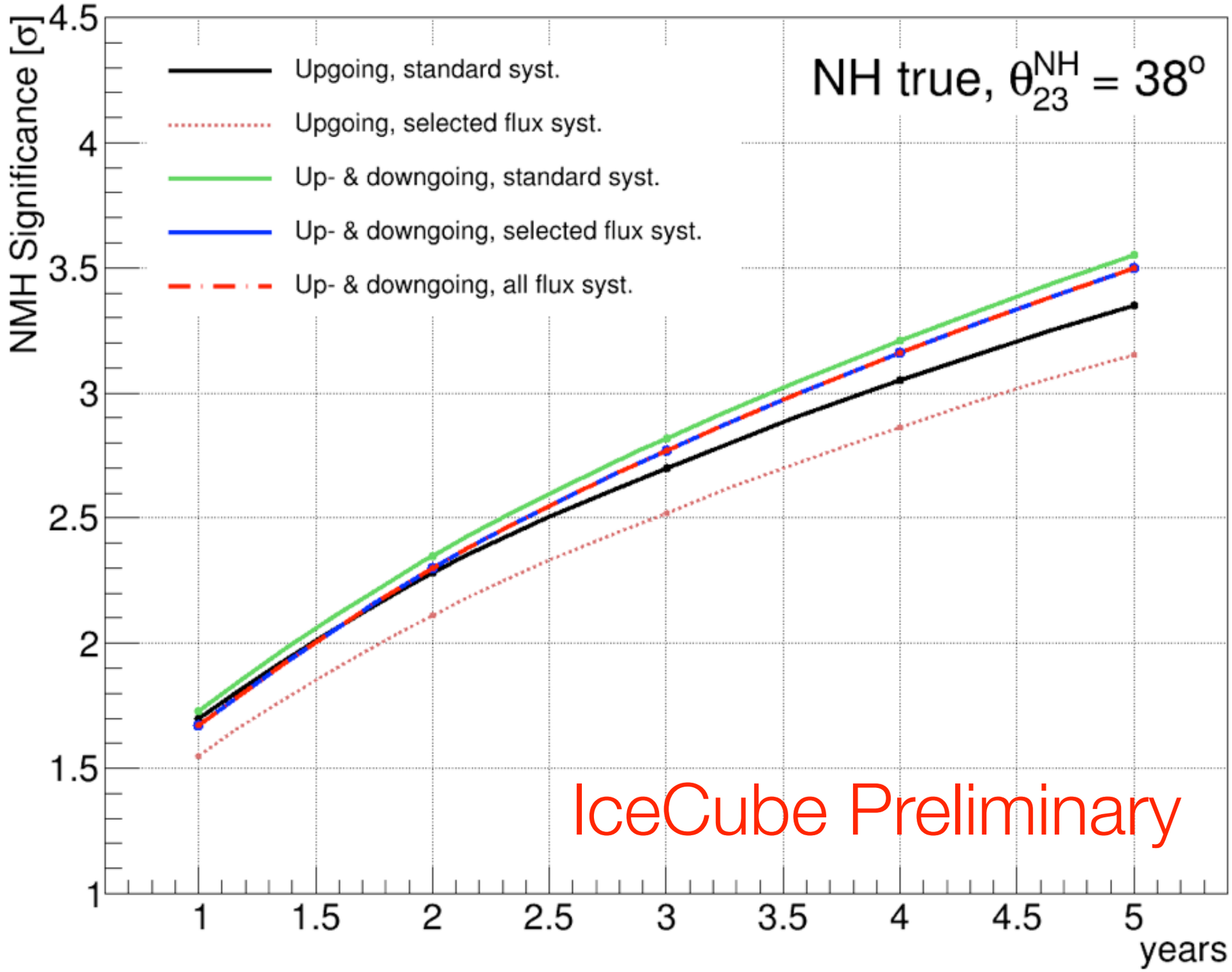
Atmospheric Flux Systematics

G. D. Barr et al., Phys. Rev. D74, 094009 (2006)



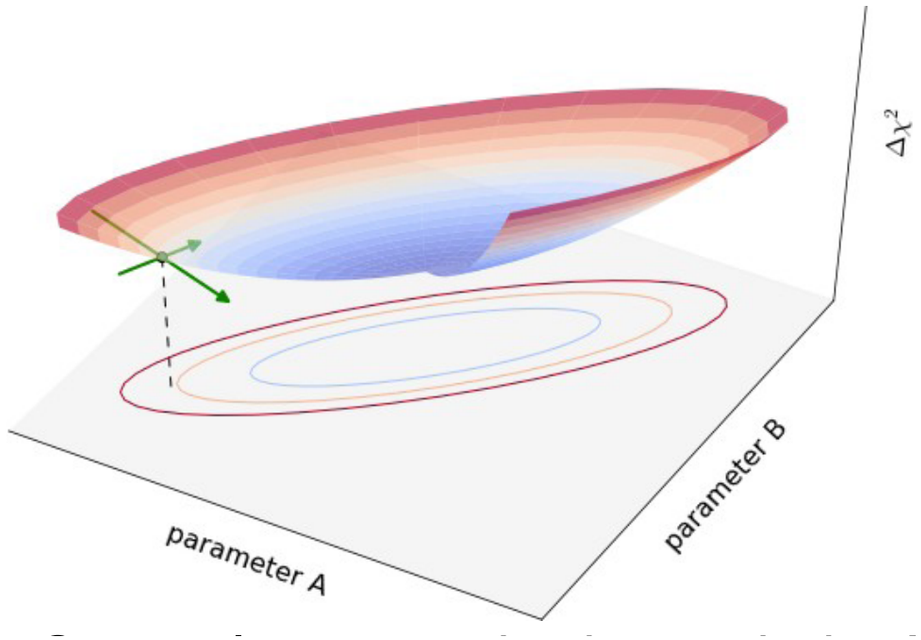


Constraints from Down-Going Neutrinos



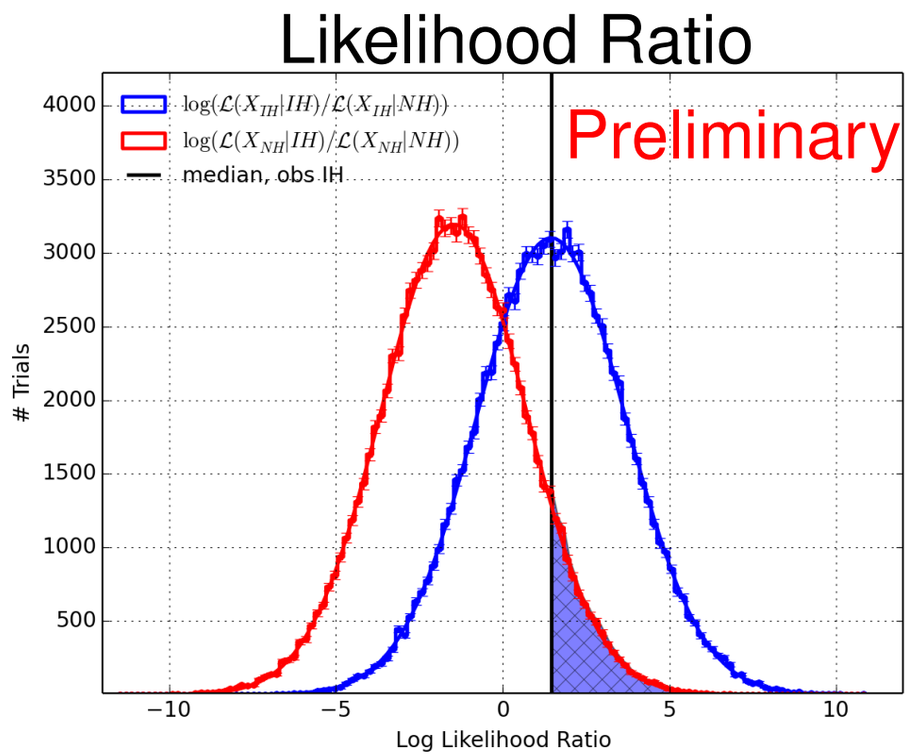
Estimating Sensitivity to the Mass Hierarchy

- Delta χ^2 method uses Asimov data sets, uses gradients in likelihood space to determine width of parabolic minimum for linear parameters, fits non-linear ones

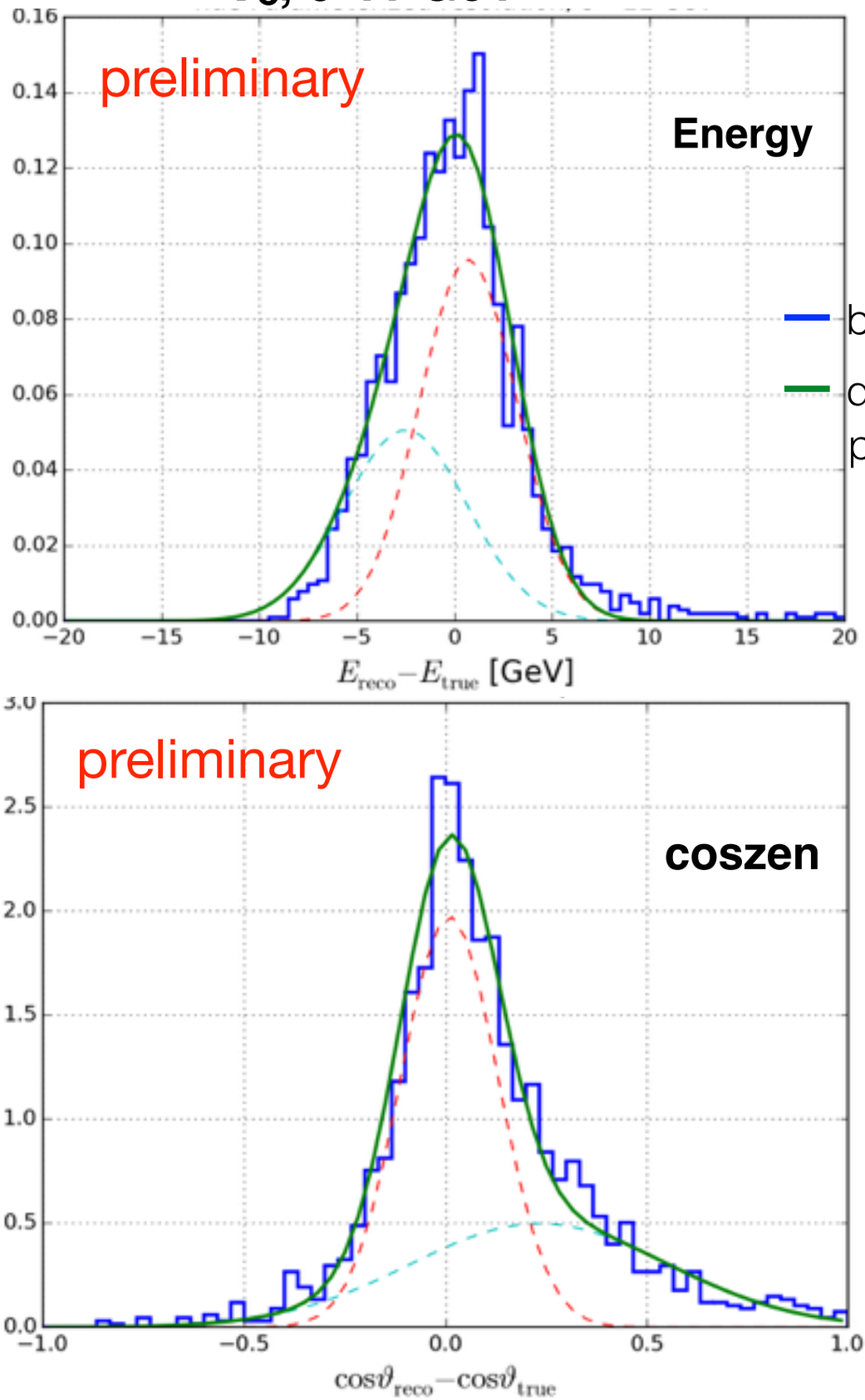


- Likelihood ratio method uses ensembles of pseudo-data sets and fits all parameters: slower, but does not require Asimov assumption

- Both methods use parametrizations of reconstructed Monte Carlo events for detector response model, to avoid statistical fluctuations in expectations

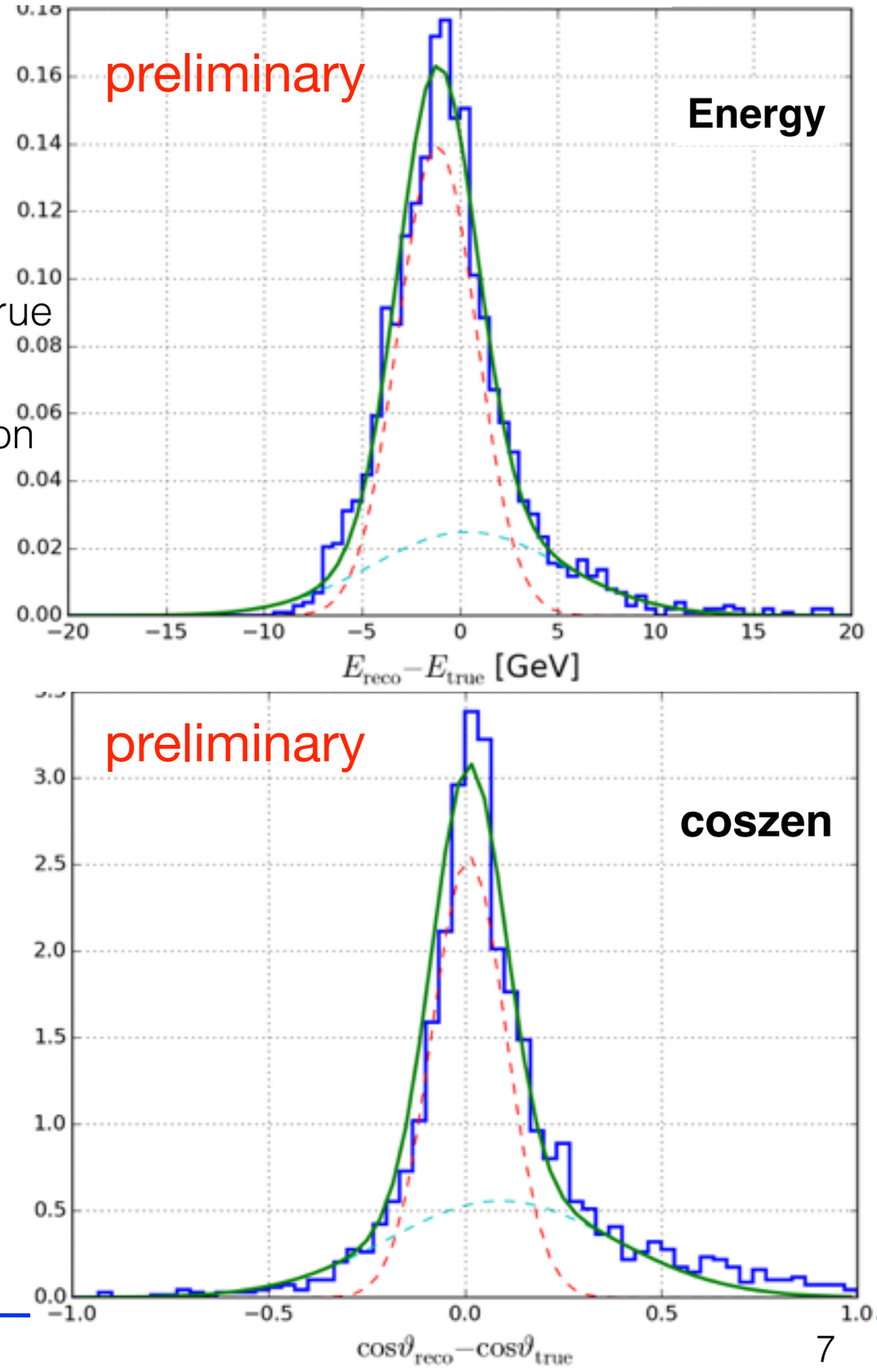


Resolutions



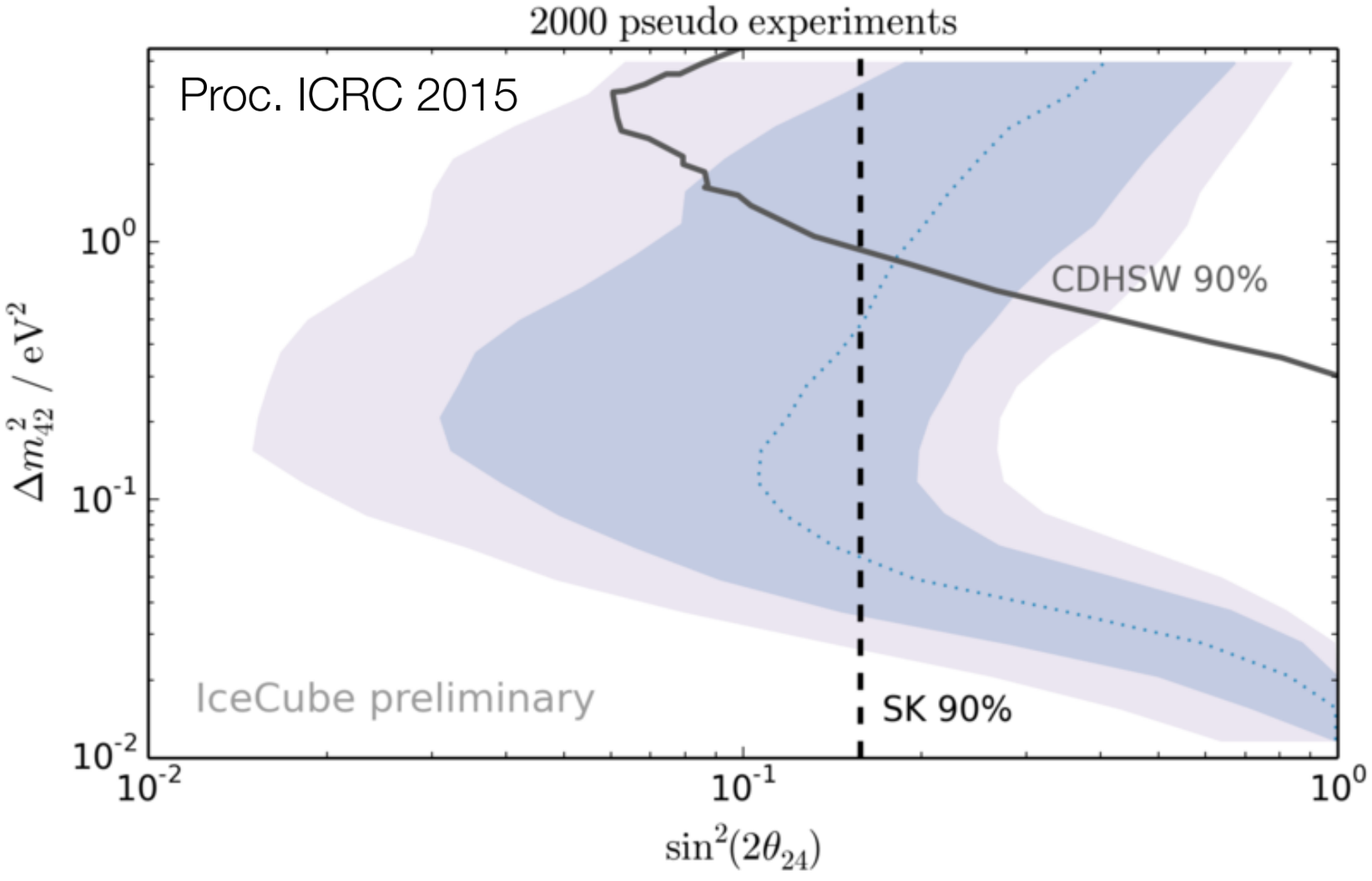
binned reco - true

double gauss parameterization



Sterile Neutrino Sensitivity

- Two analyses: IC59 and IC86
  - Based on general high energy (>TeV) ν_μ selections
  - Sensitivities similar, slightly different energy ranges
- Sensitivity taken from 2,000 MC data challenges
- Results available soon!



PINGU Cost and Schedule

- Primary US funding source for IceCube-Gen2 would be NSF
  - MREFC-scale facility, total cost comparable to original IceCube
  - Many items common to PINGU and other elements (drill, engineering, etc.)
    - Marginal cost of PINGU within larger IceCube-Gen2 is $88M, with expected non-US contributions of $25M
- Gen2 conceptual design document and PINGU performance update this year
- In a technically limited timeline, PINGU completion possible by January 2021 or 2022

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

(elements do not sum to total due to rounding)