IceCube

PRECISION ICECUBE NEXT GENERATION UPGRADE

Future atmospheric neutrino measurements with multi-megatonne Water Cherenkov detectors

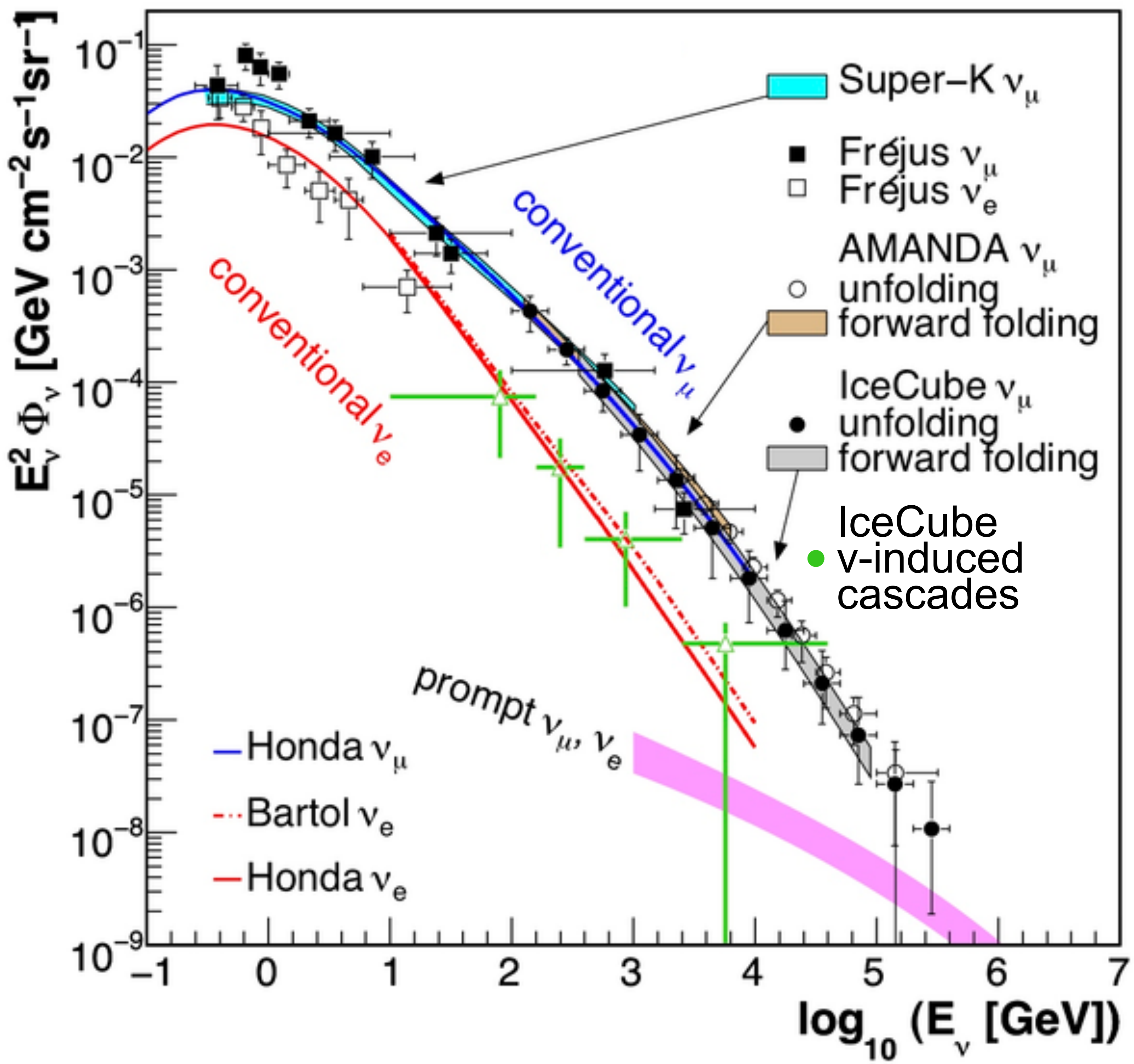
Workshop for Neutrino Programs with facilities in Japan

Tokai Japan
August 5, 2015

Darren R Grant

UNIVERSITY OF ALBERTA

The atmospheric neutrino signal

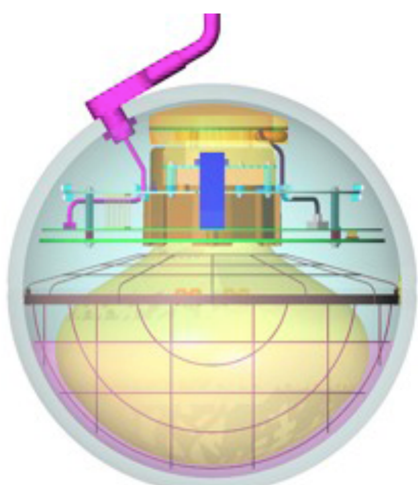


The IceCube Neutrino Observatory

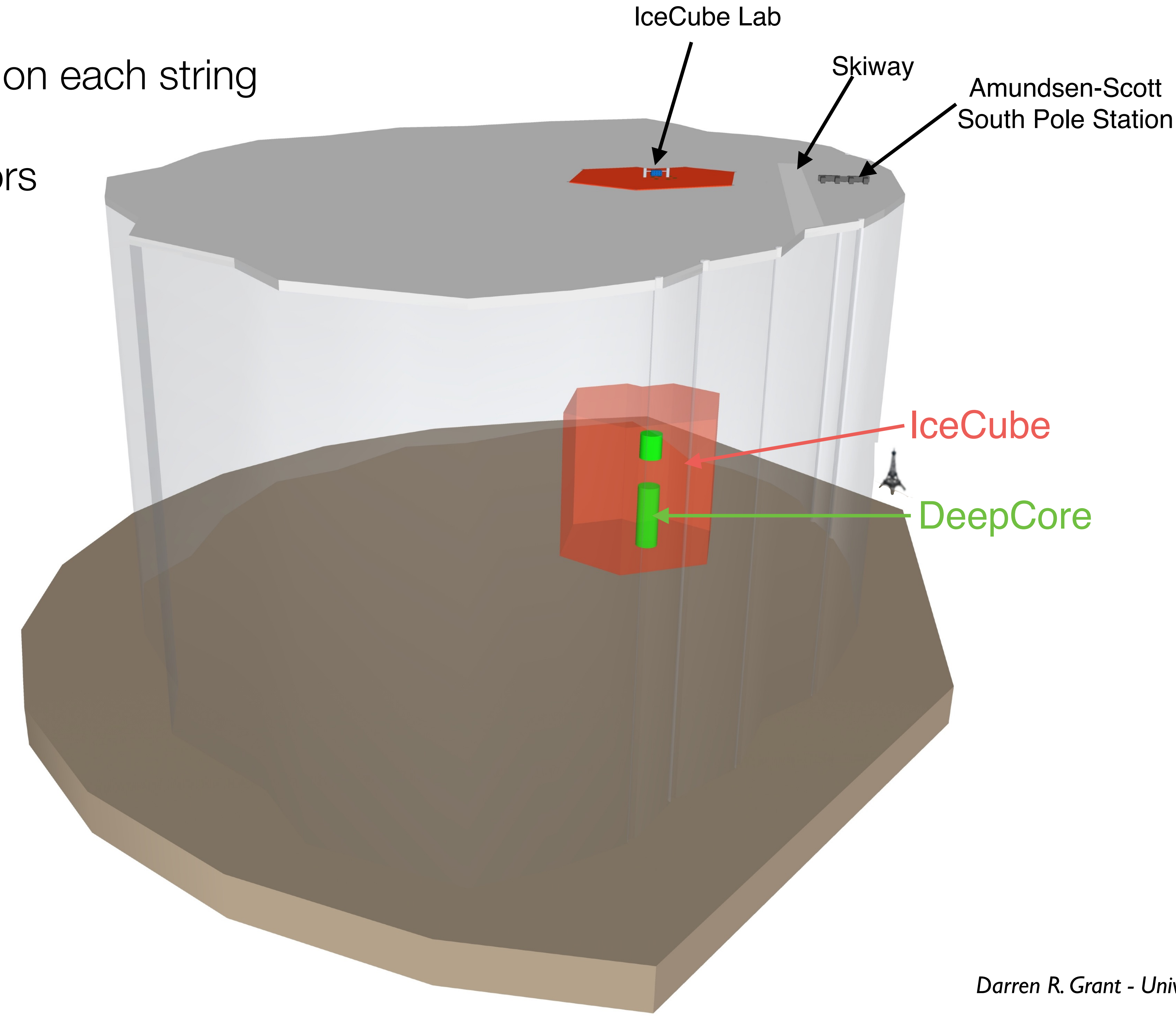
IceCube Array
86 total strings, including 8
DeepCore strings

60 optical sensors on each string

5160 optical sensors



Digital Optical Module



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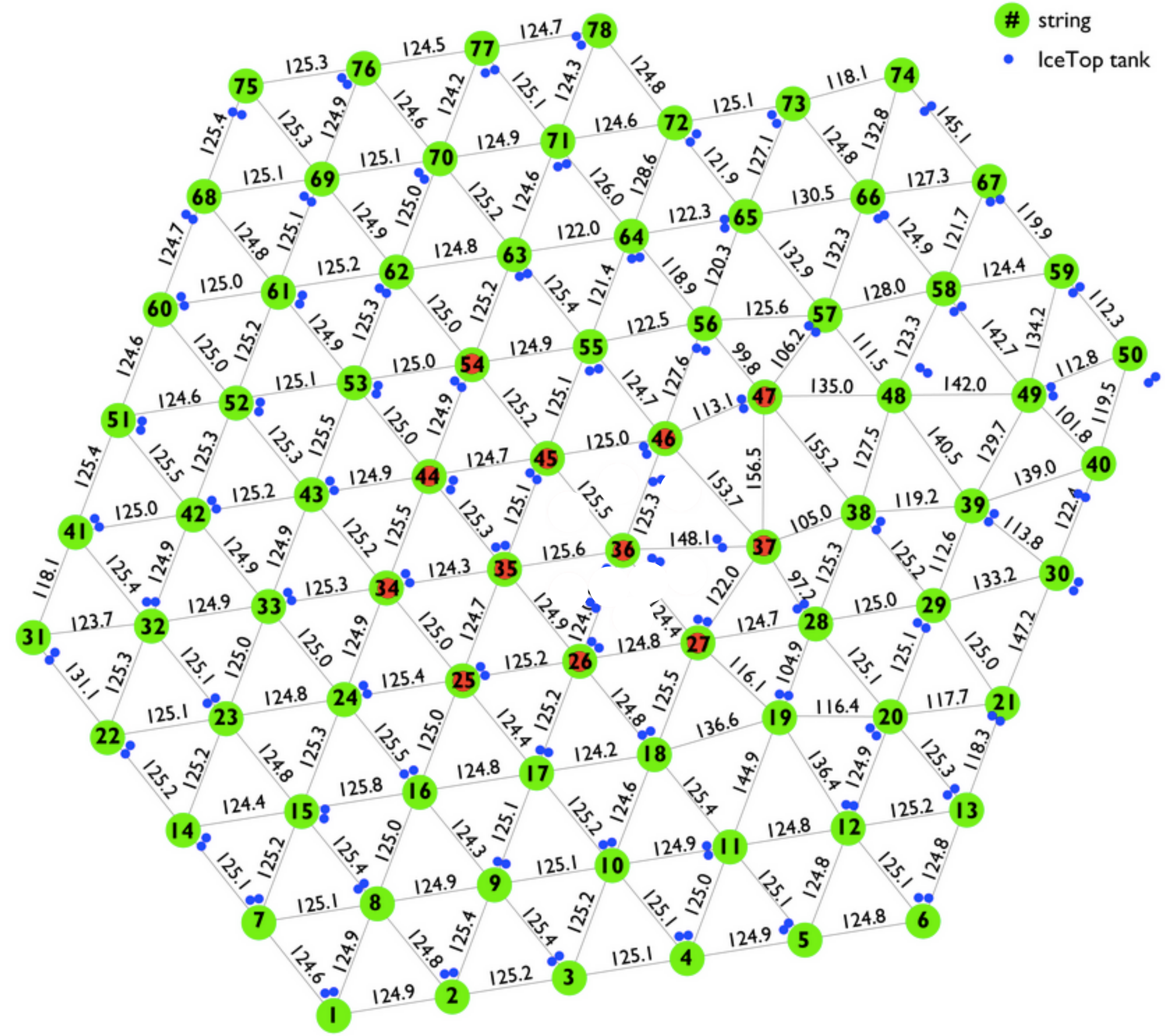
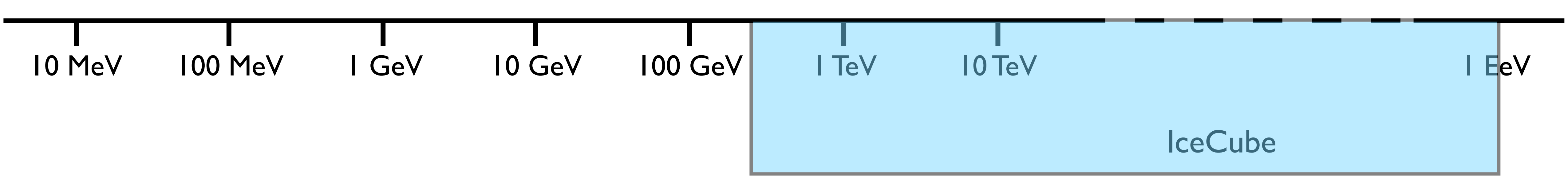
IceCube

- 78 Strings
  - 125m string spacing
  - 17m DOM spacing





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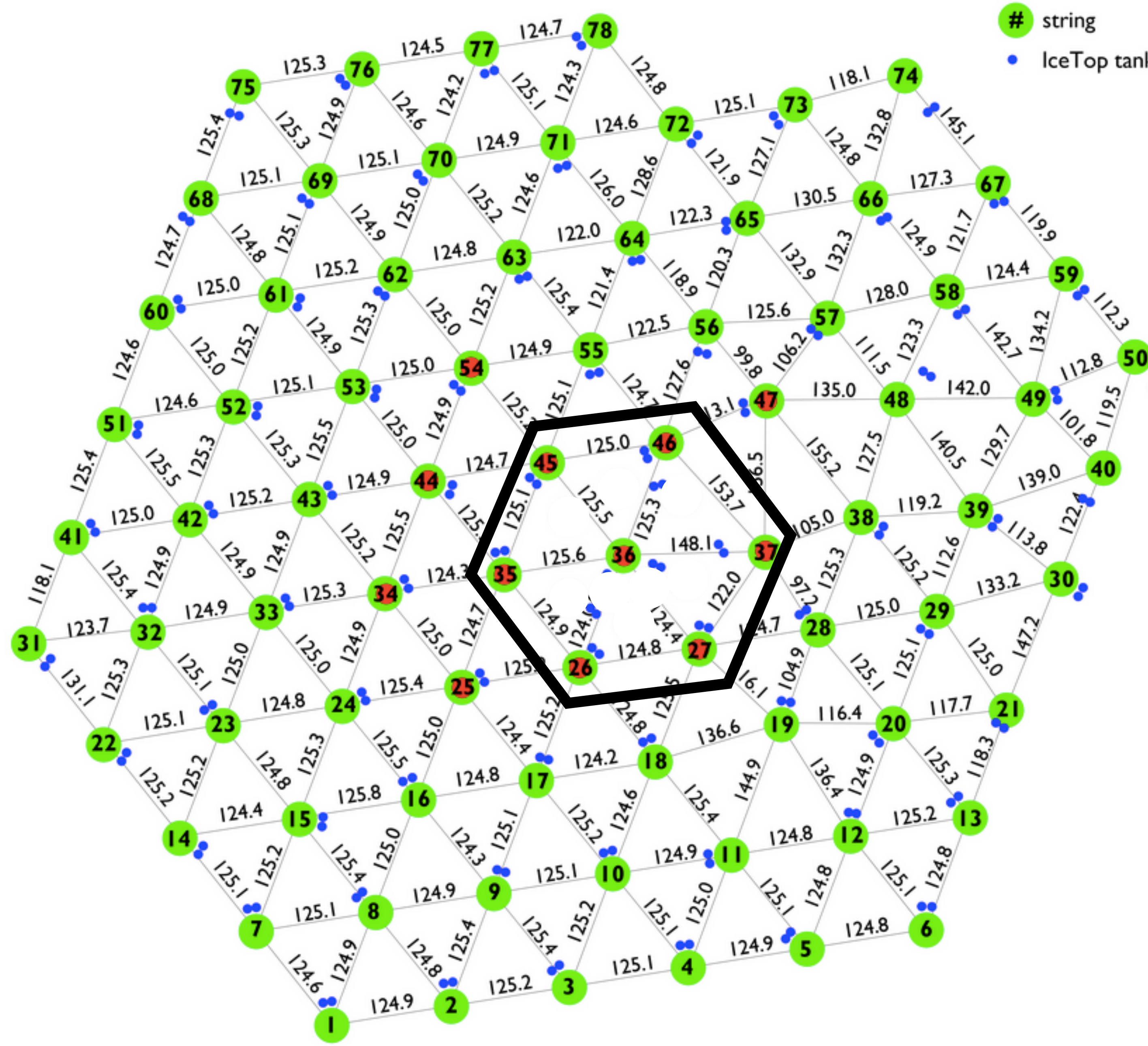

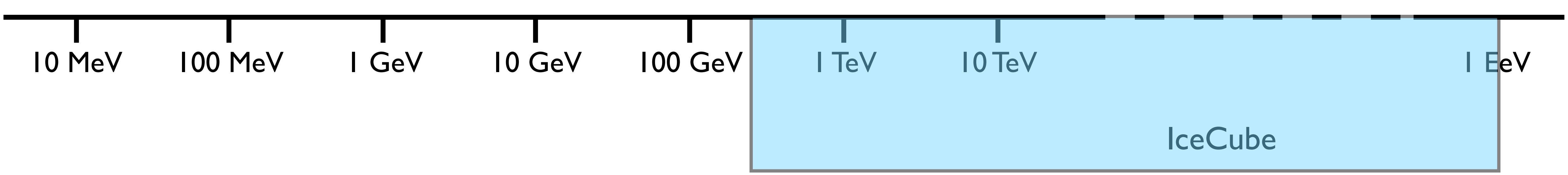

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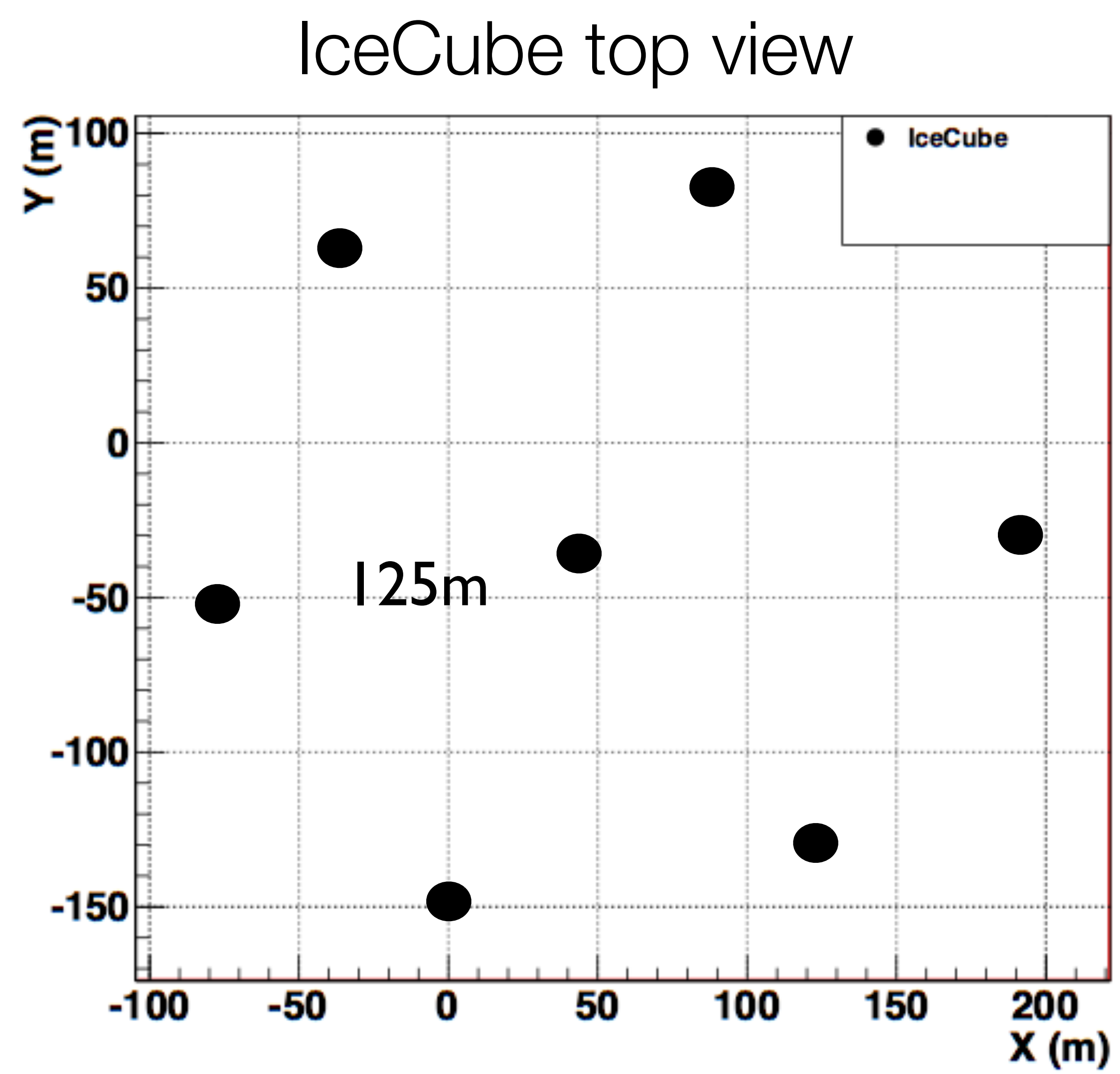
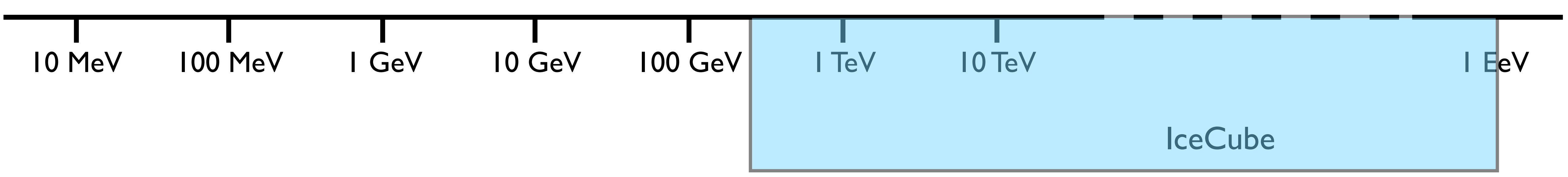
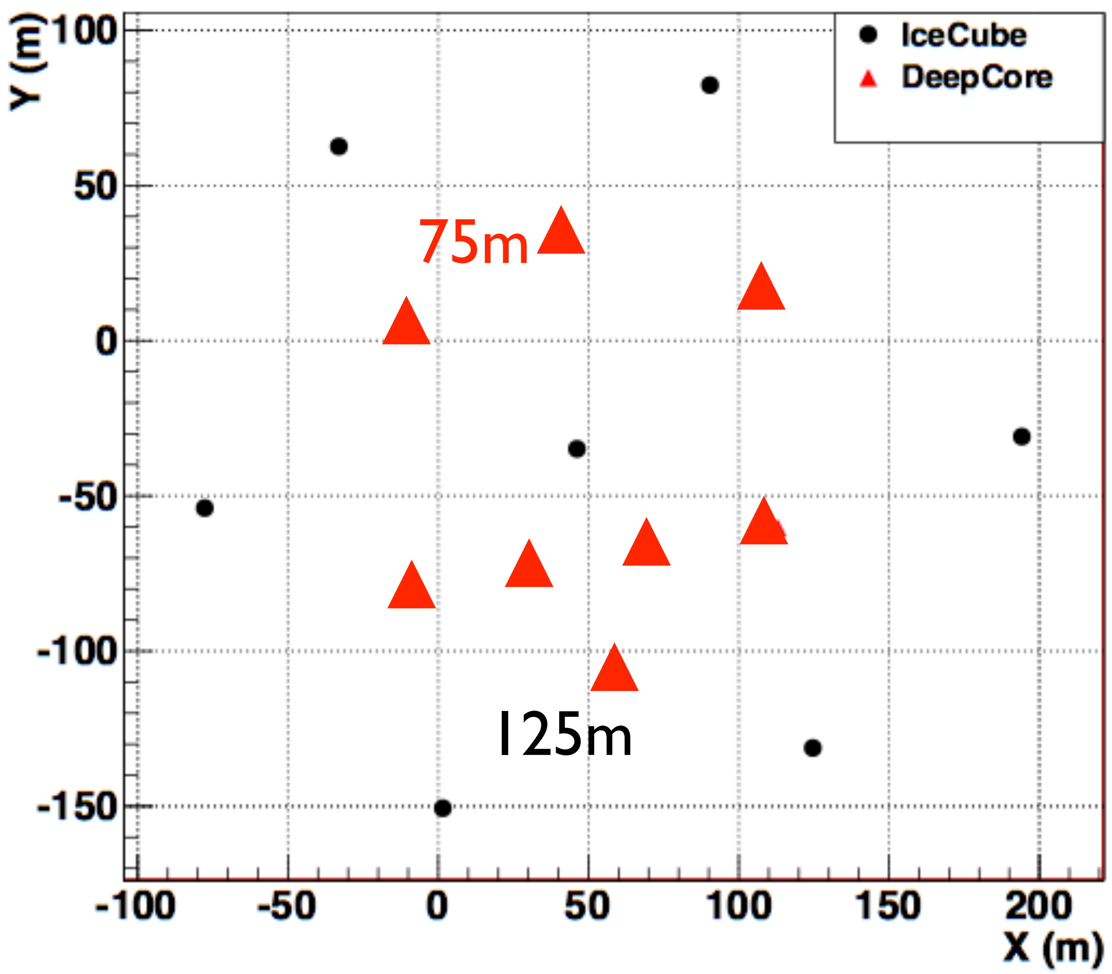


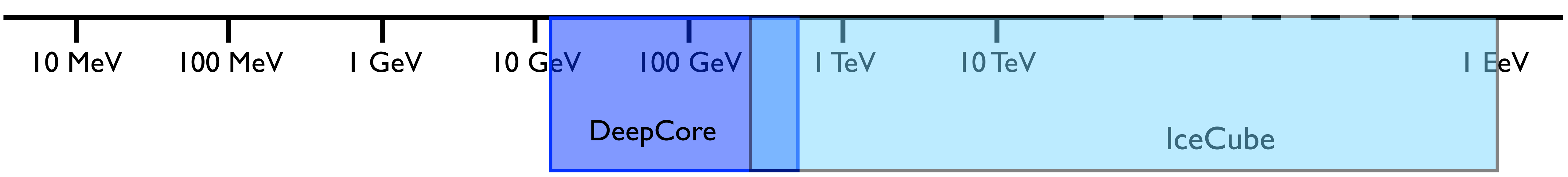


IceCube-DeepCore

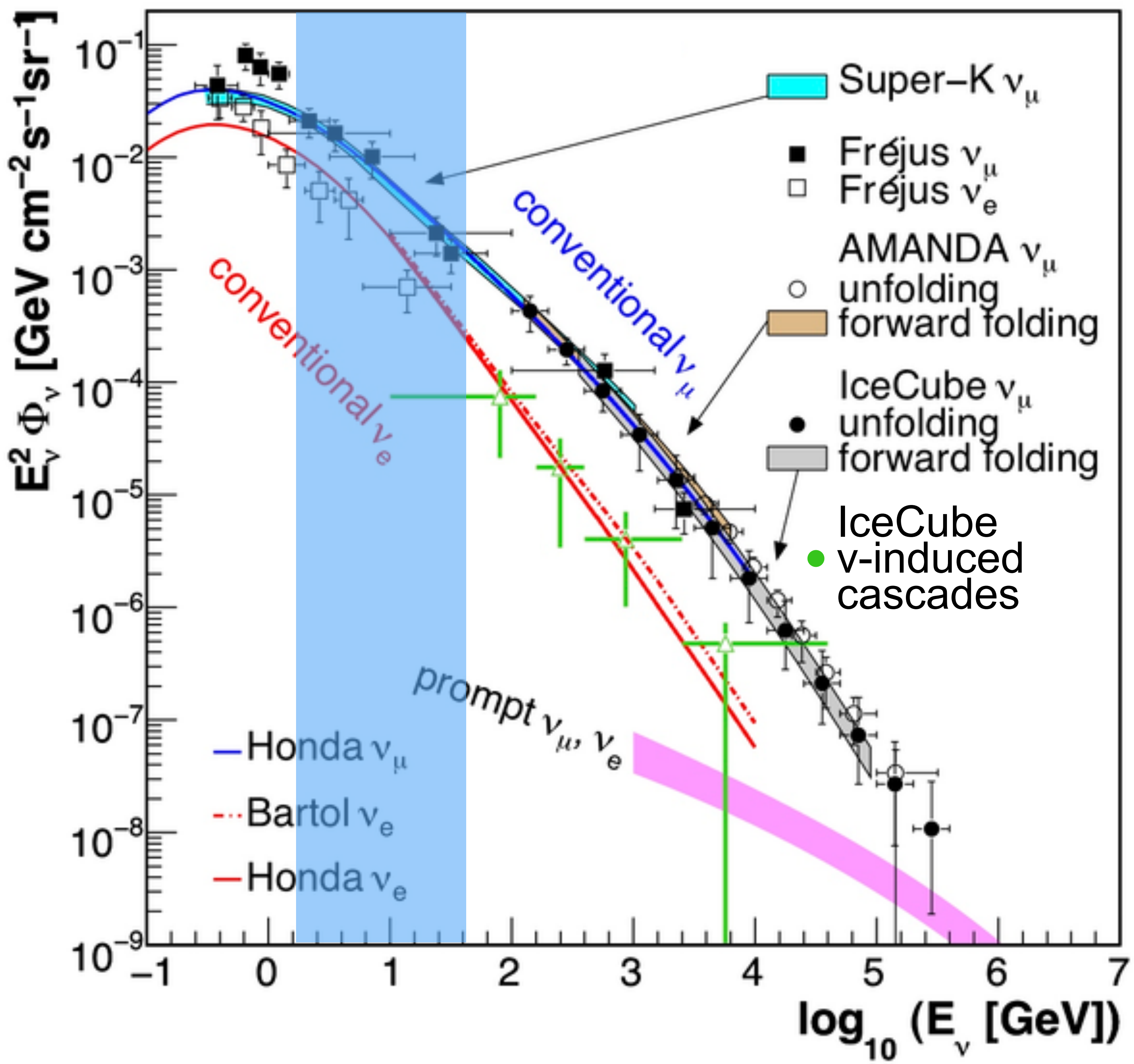
- 78 Strings
  - 125m string spacing
  - 17m DOM spacing
- Add 8 strings
  - 75m string spacing
  - 7m DOM spacing

IceCube-DeepCore top view



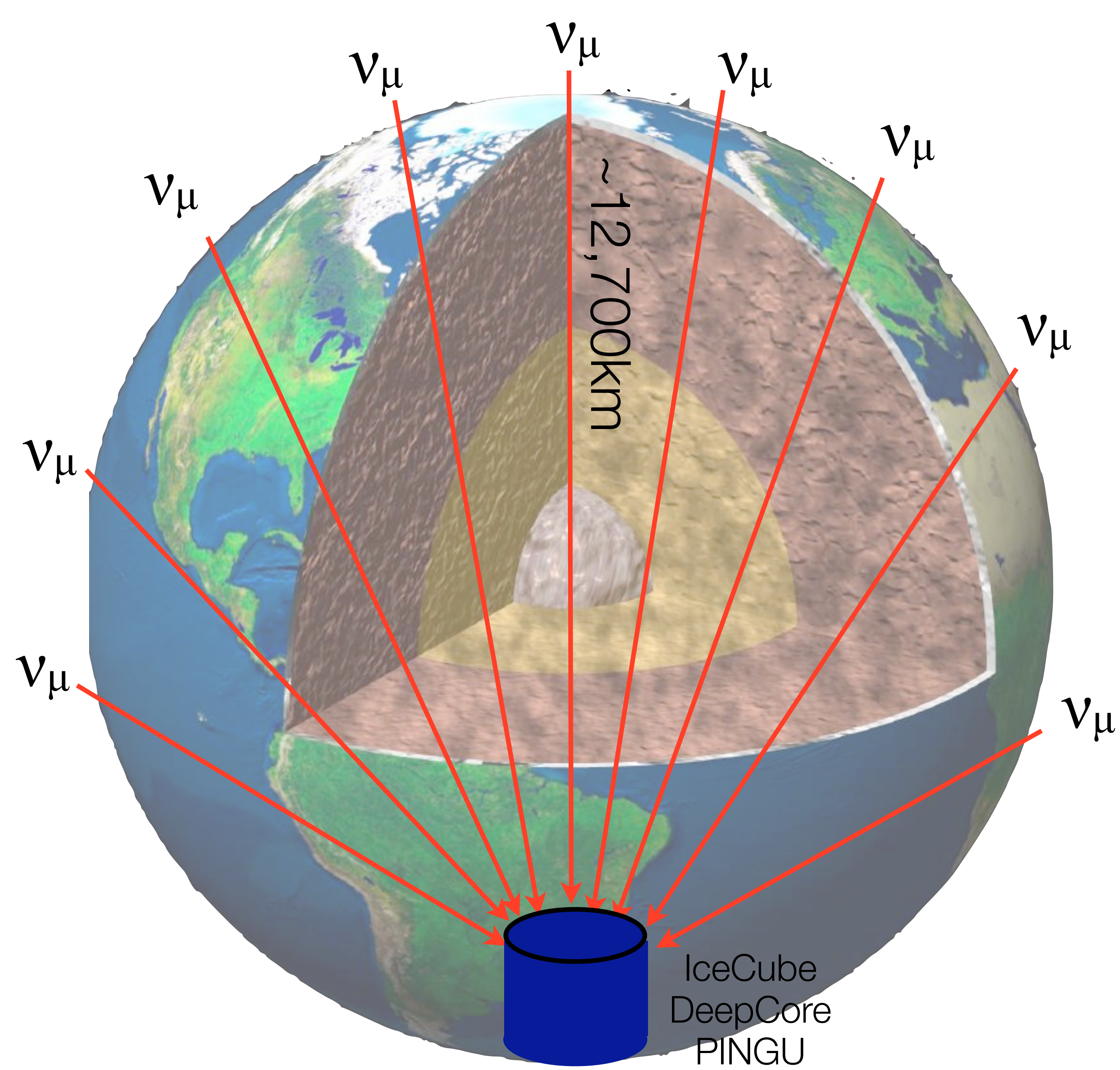


The atmospheric neutrino signal



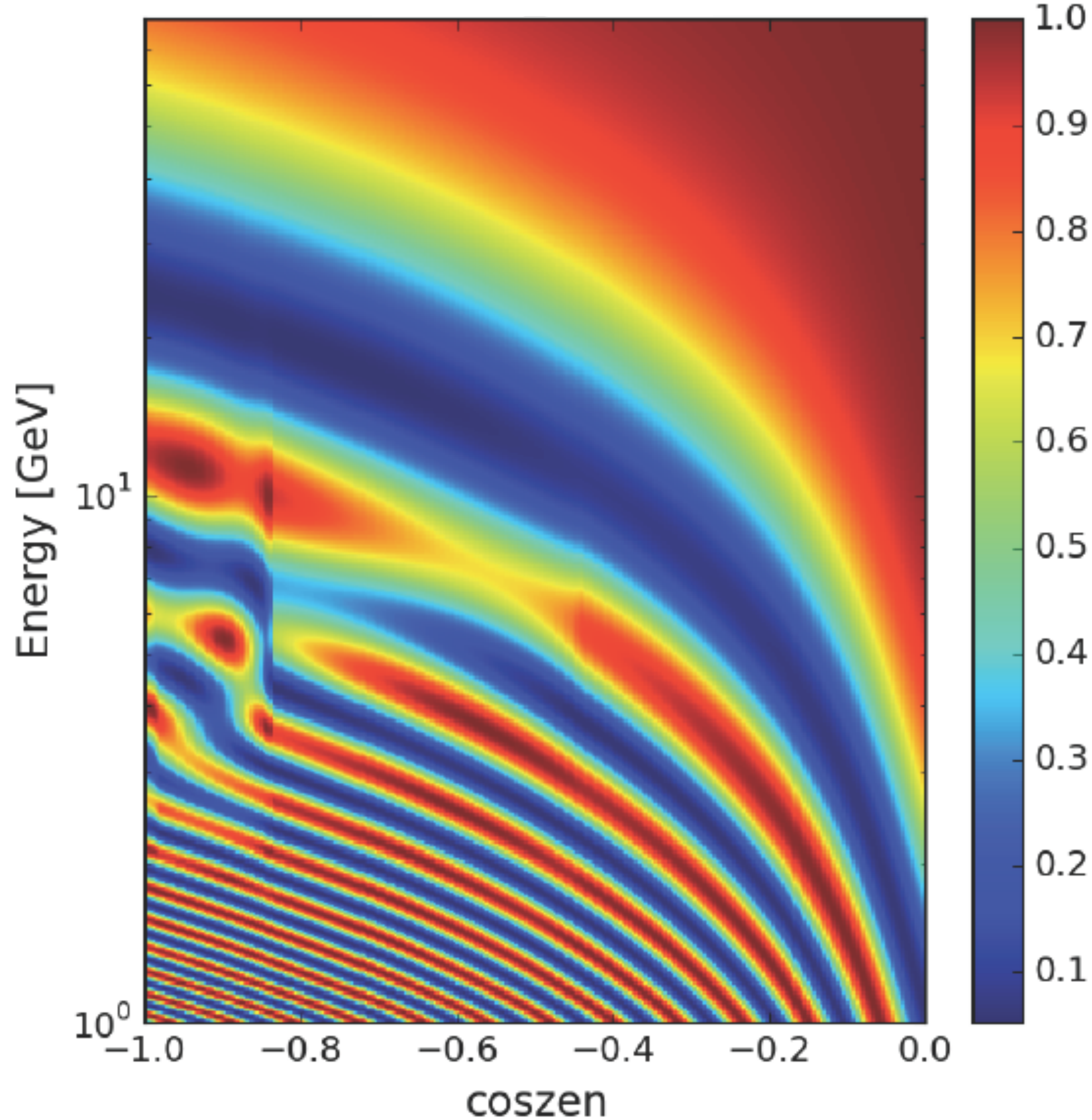
Oscillations with Atmospheric Neutrinos

- Neutrinos are available over a wide range of energies and baselines
  - Comparison of observations from different baselines and energies is crucial for controlling systematics
  - Essentially, a generalization of the up-down ratio approach



Oscillations with Atmospheric Neutrinos

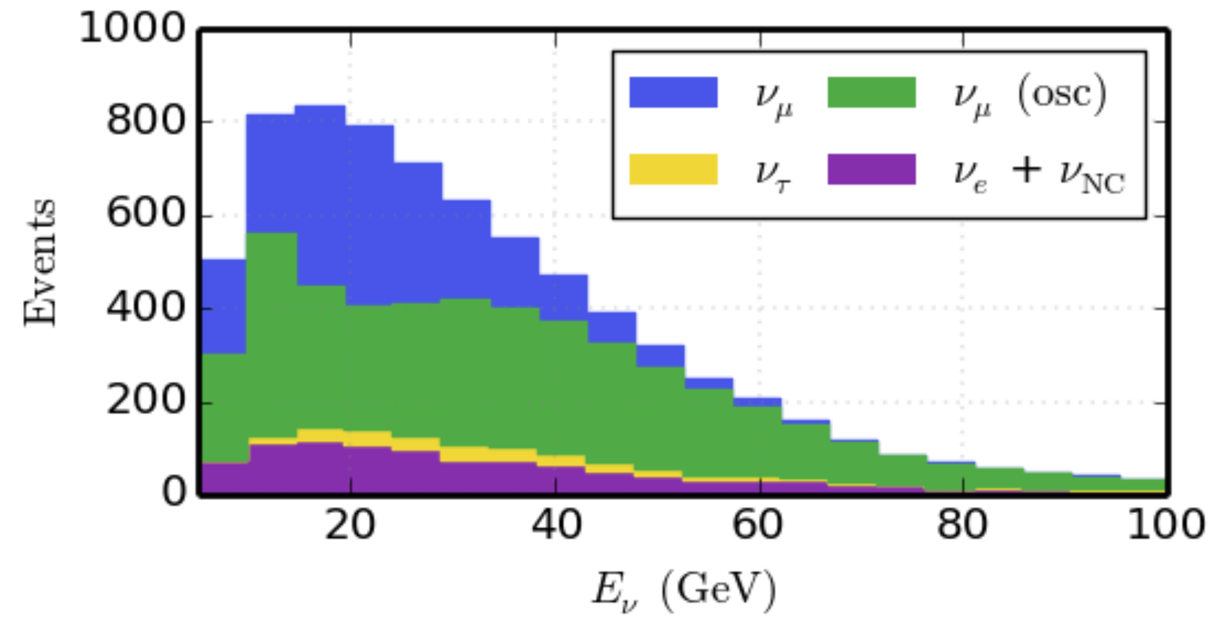
- Neutrinos are available over a wide range of energies and baselines
  - Comparison of observations from different baselines and energies is crucial for controlling systematics
  - Essentially, a generalization of the up-down ratio approach
- Atmospheric neutrinos oscillating over one Earth diameter have a ν_μ survival minimum at ~25 GeV, below ~10 GeV sensitivity to the mass ordering (near ~500 MeV potentially to CP-violation)

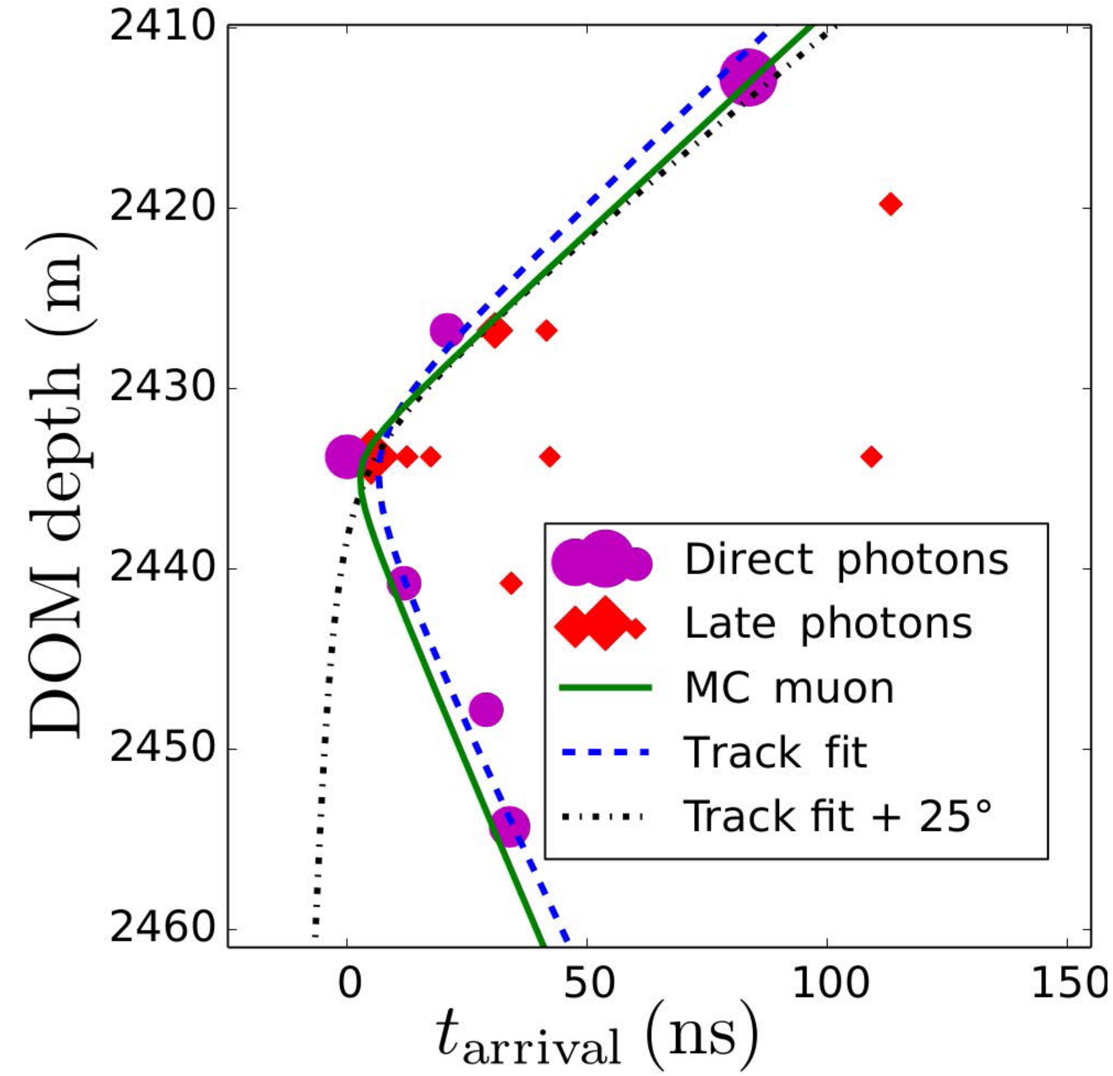


$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Atmospheric neutrino oscillations with DeepCore

- Analysis focused on utilizing clear μ tracks (reducing contamination from cascades, including ν NC and ν_e CC)
- Require several non-scattered photons in selected events; making it relatively easy to reconstruct:
  - 10° resolution in neutrino zenith (equivalent to path length)
  - 25% resolution in neutrino energy





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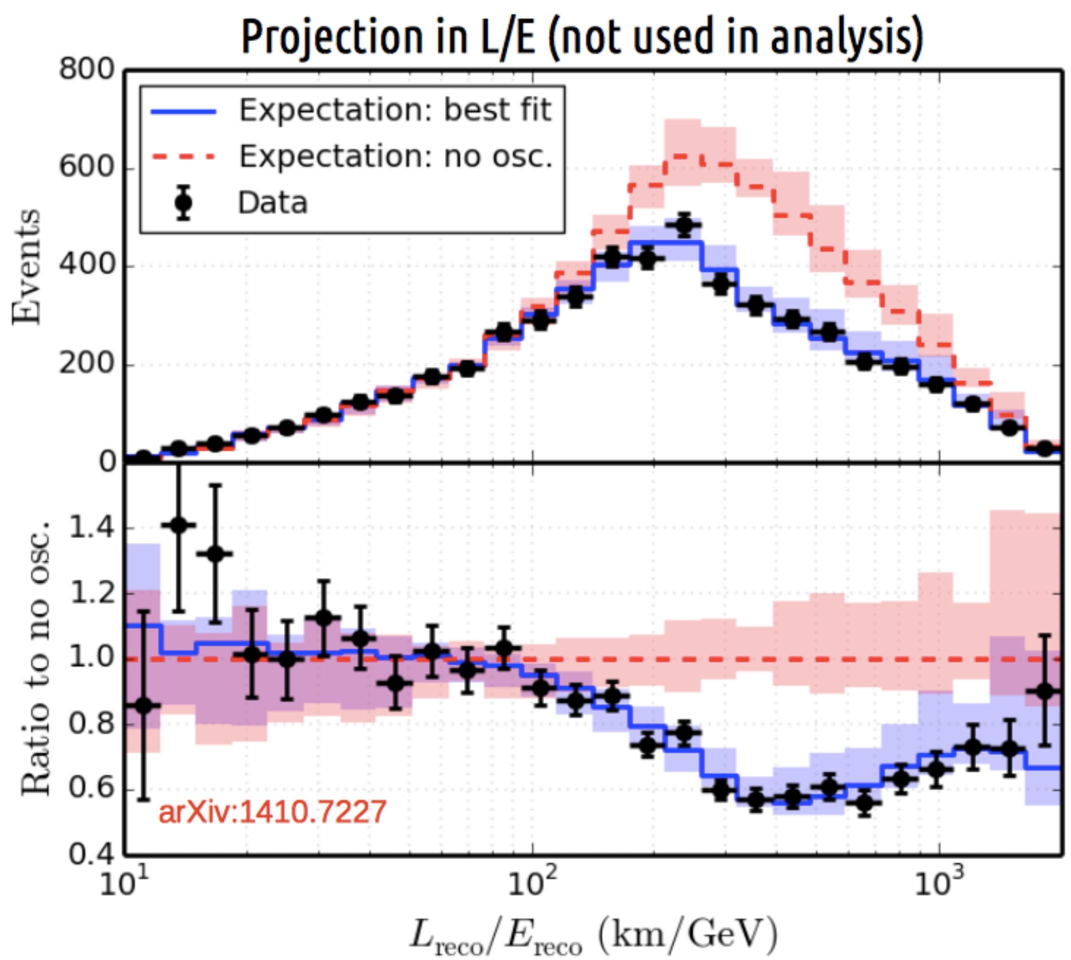

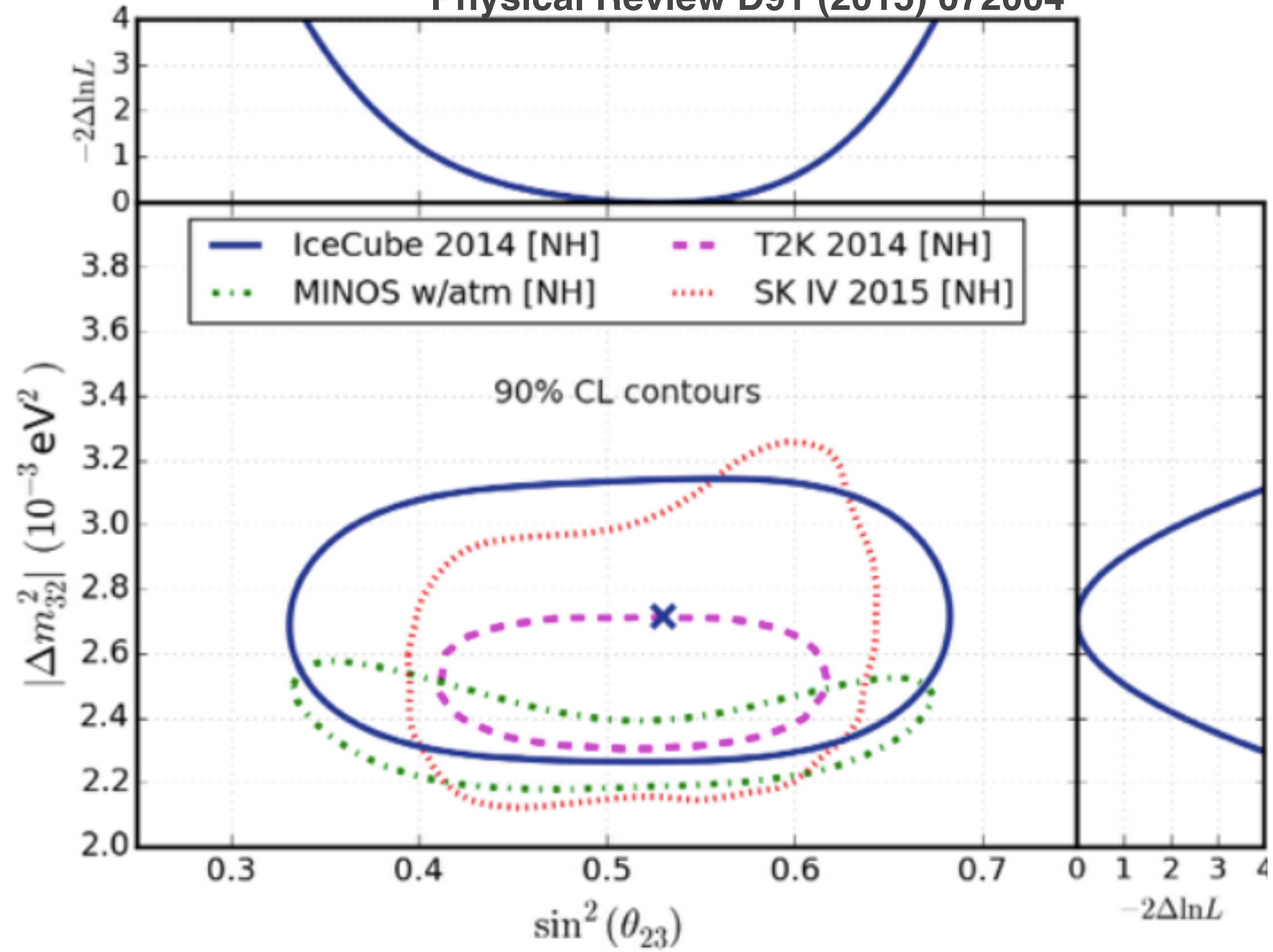

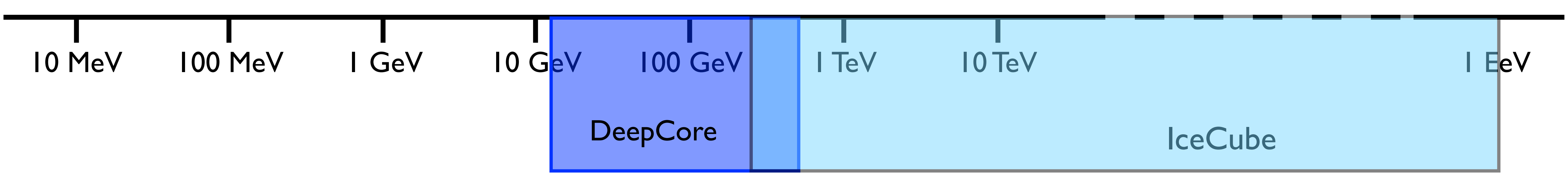

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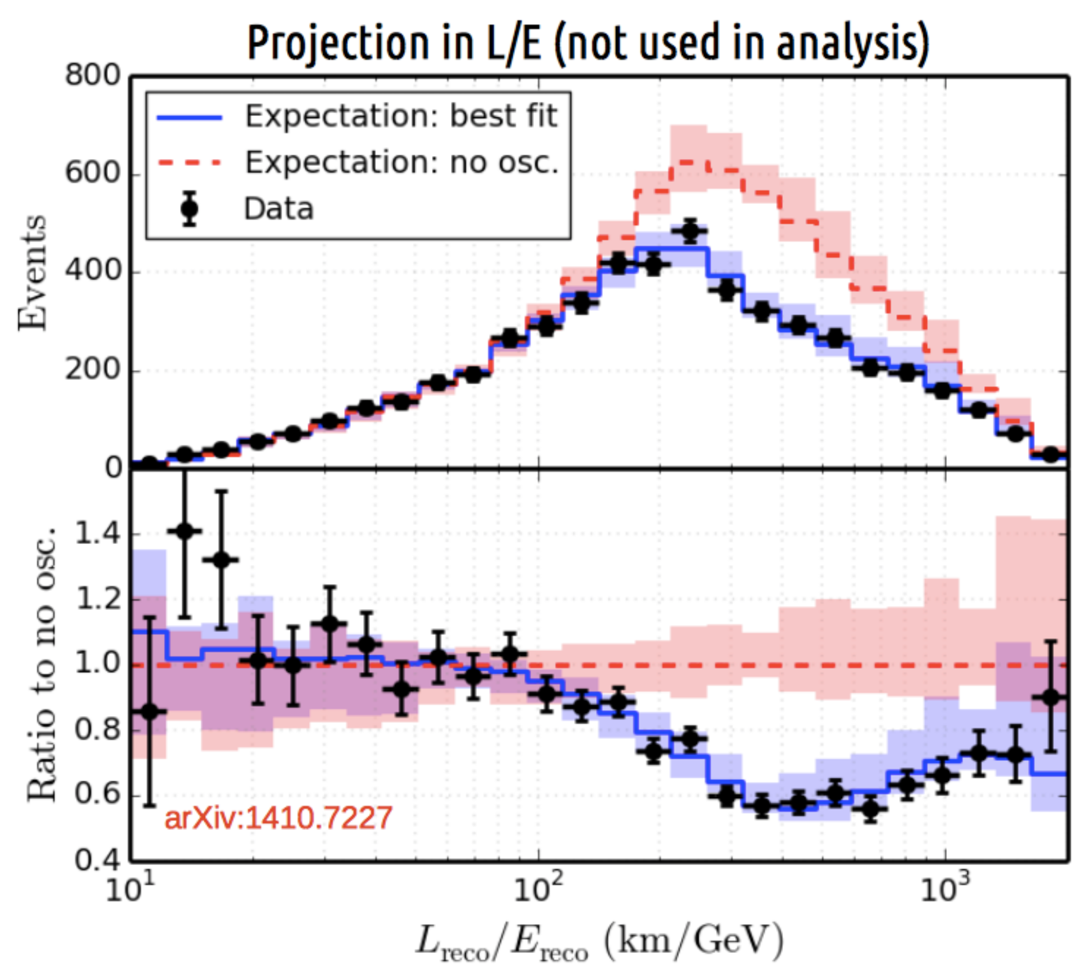
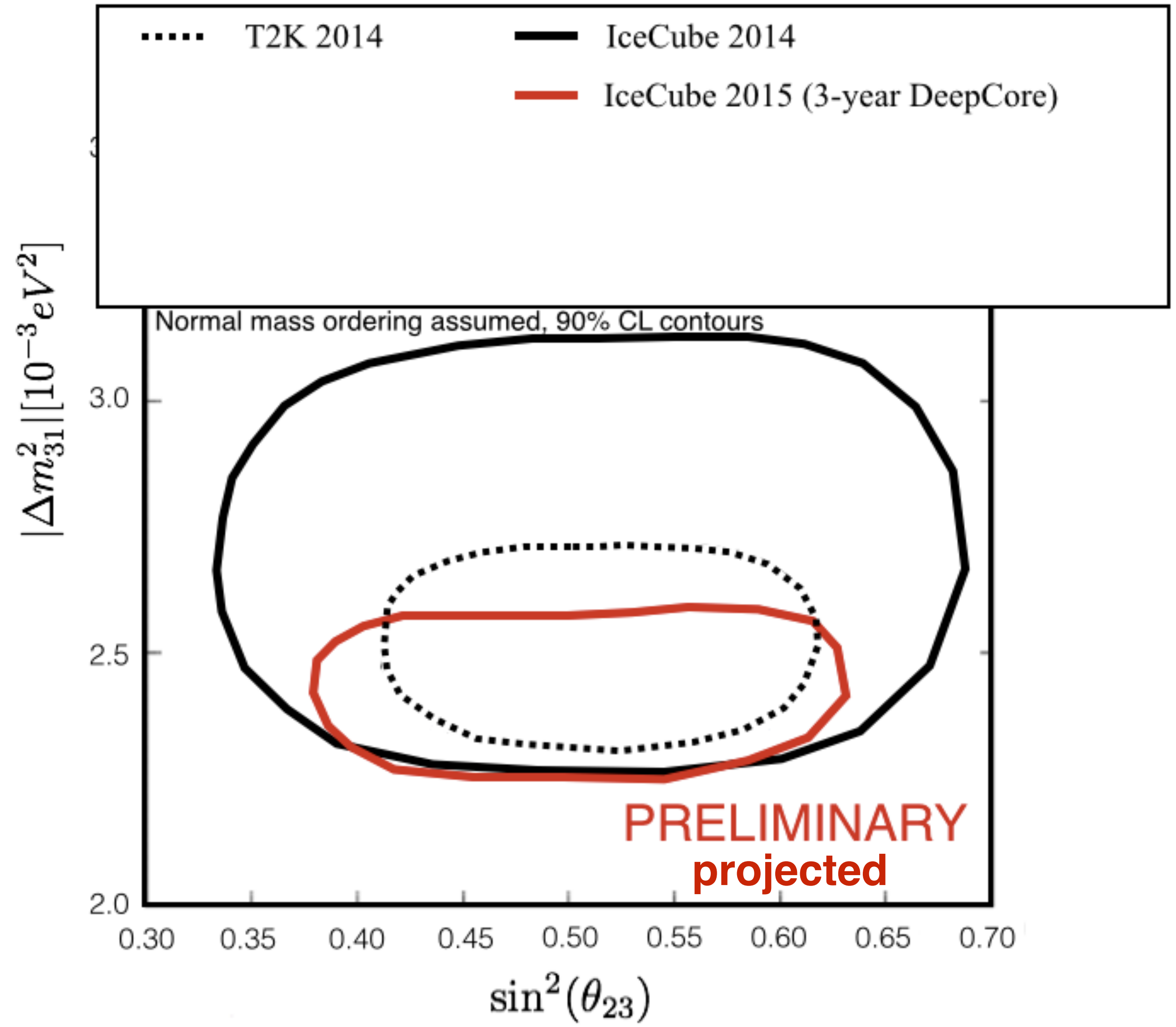
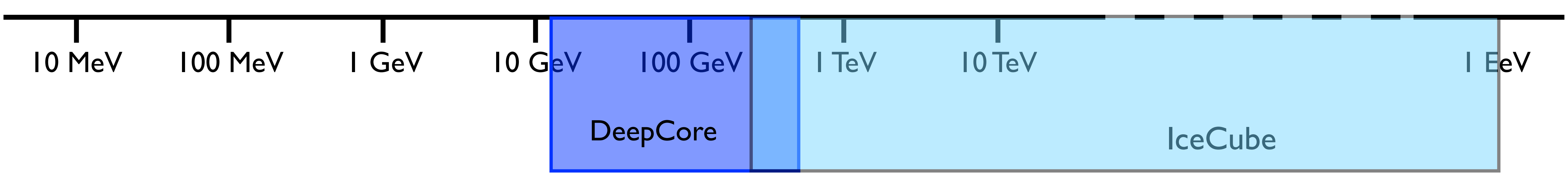
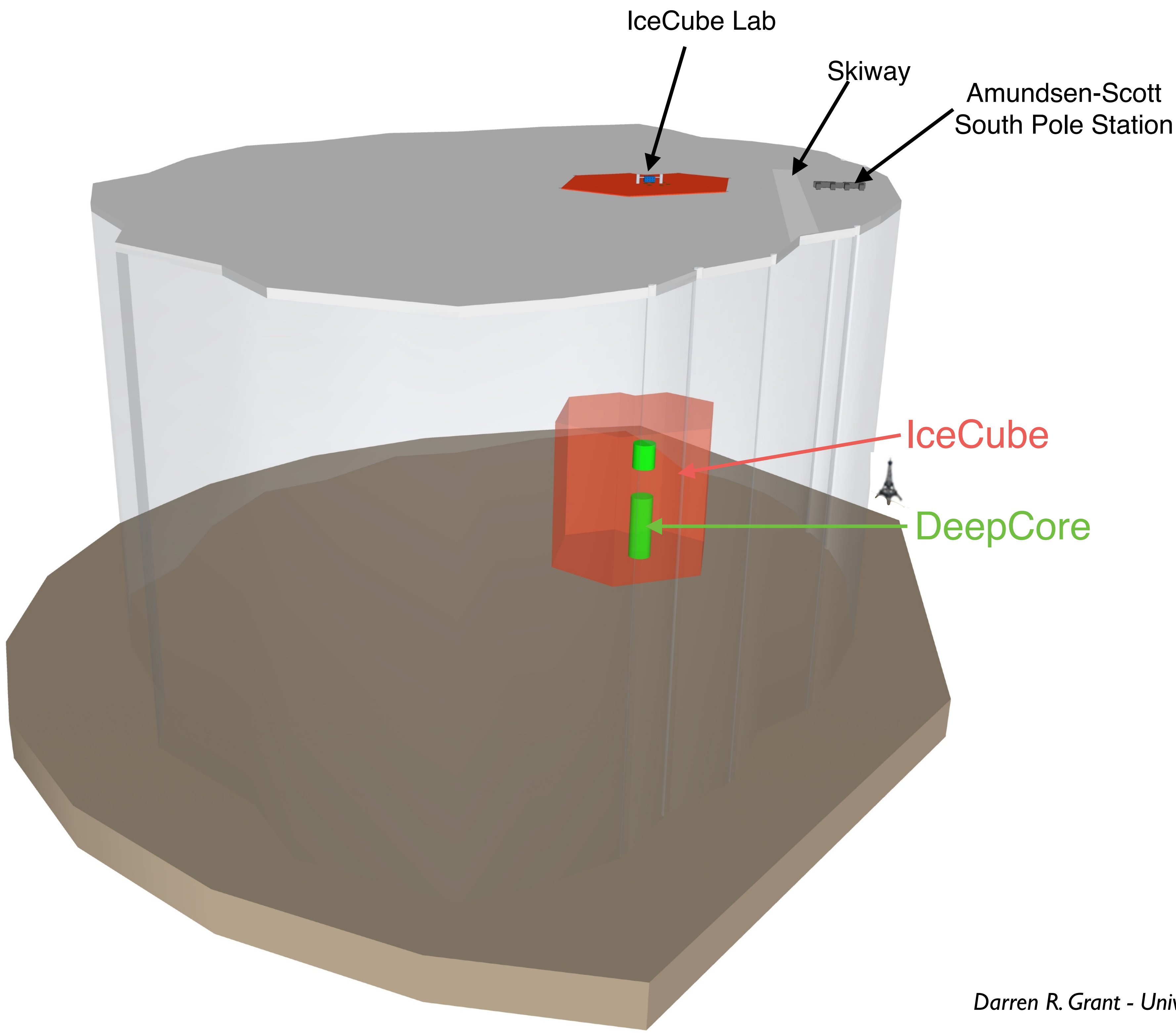


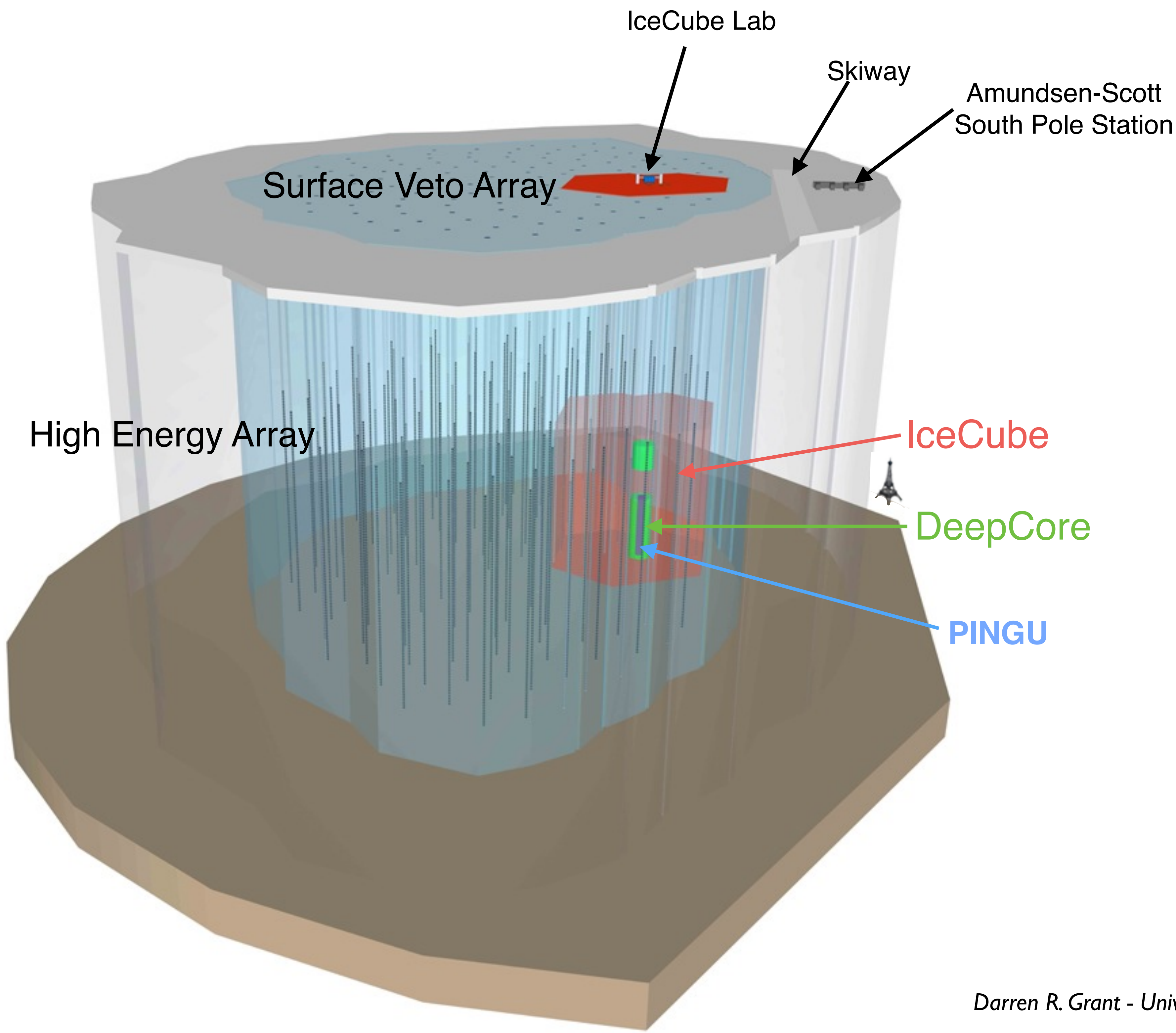




The IceCube Neutrino Observatory



The IceCube Neutrino Observatory - Generation 2 (GEN2)



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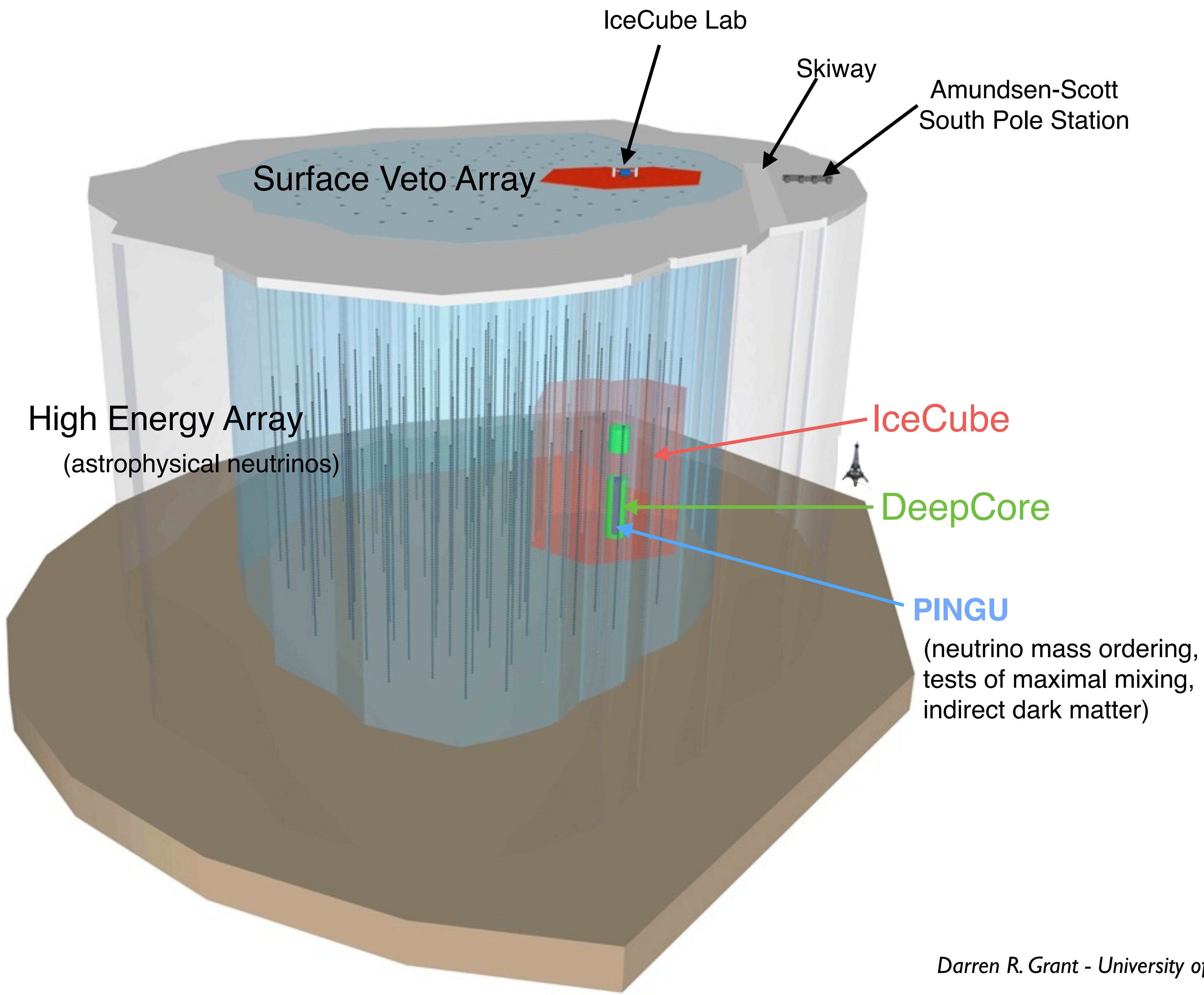
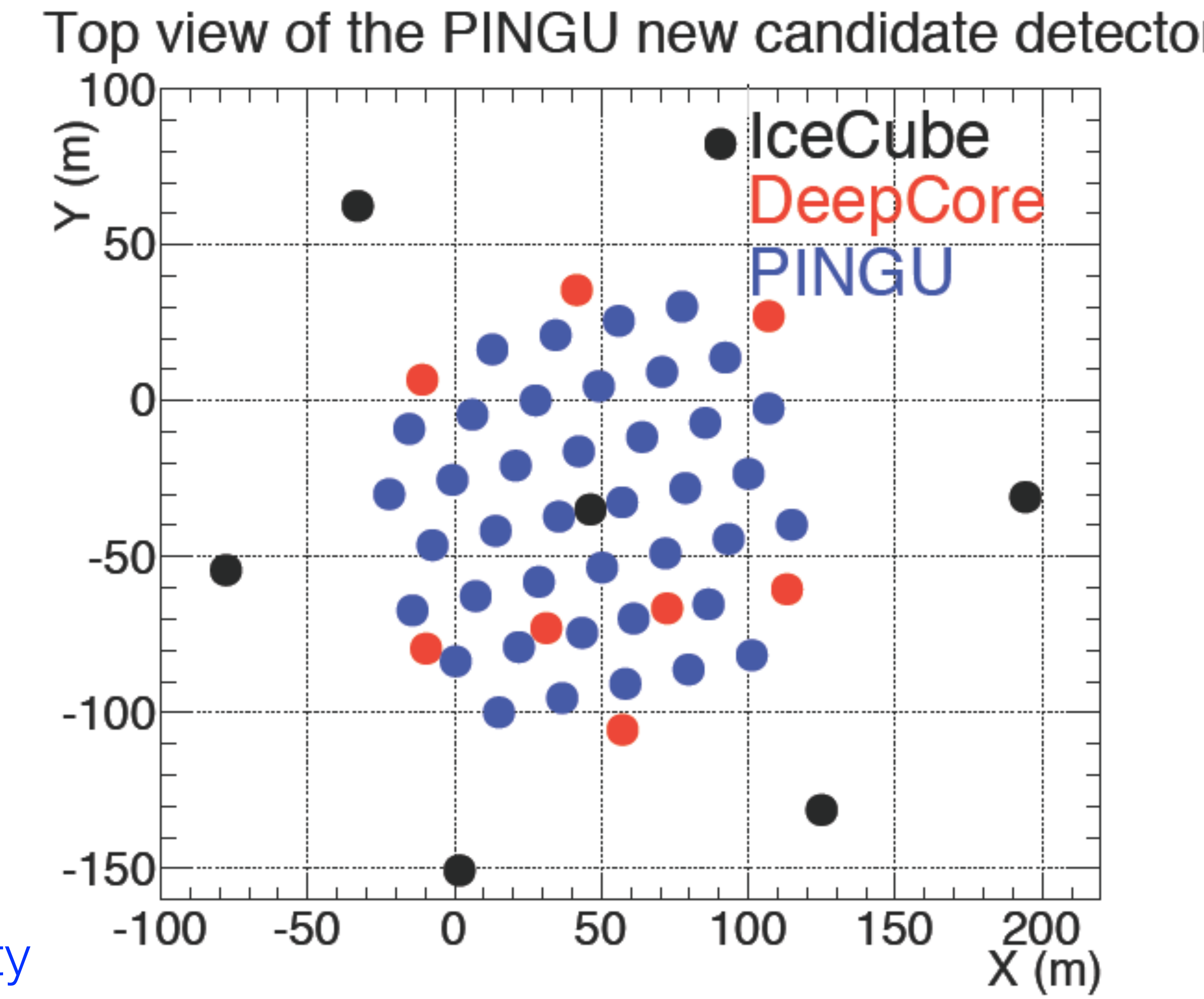


IceCube-DeepCore-PINGU

- 78 Strings
  - 125m string spacing
  - 17m DOM spacing
- Add 8 strings
  - 75m string spacing
  - 7m DOM spacing
- Add 40 strings (baseline target)
  - ~20m string spacing
  - 3-5m DOM spacing
  - ~15x higher photocathode density

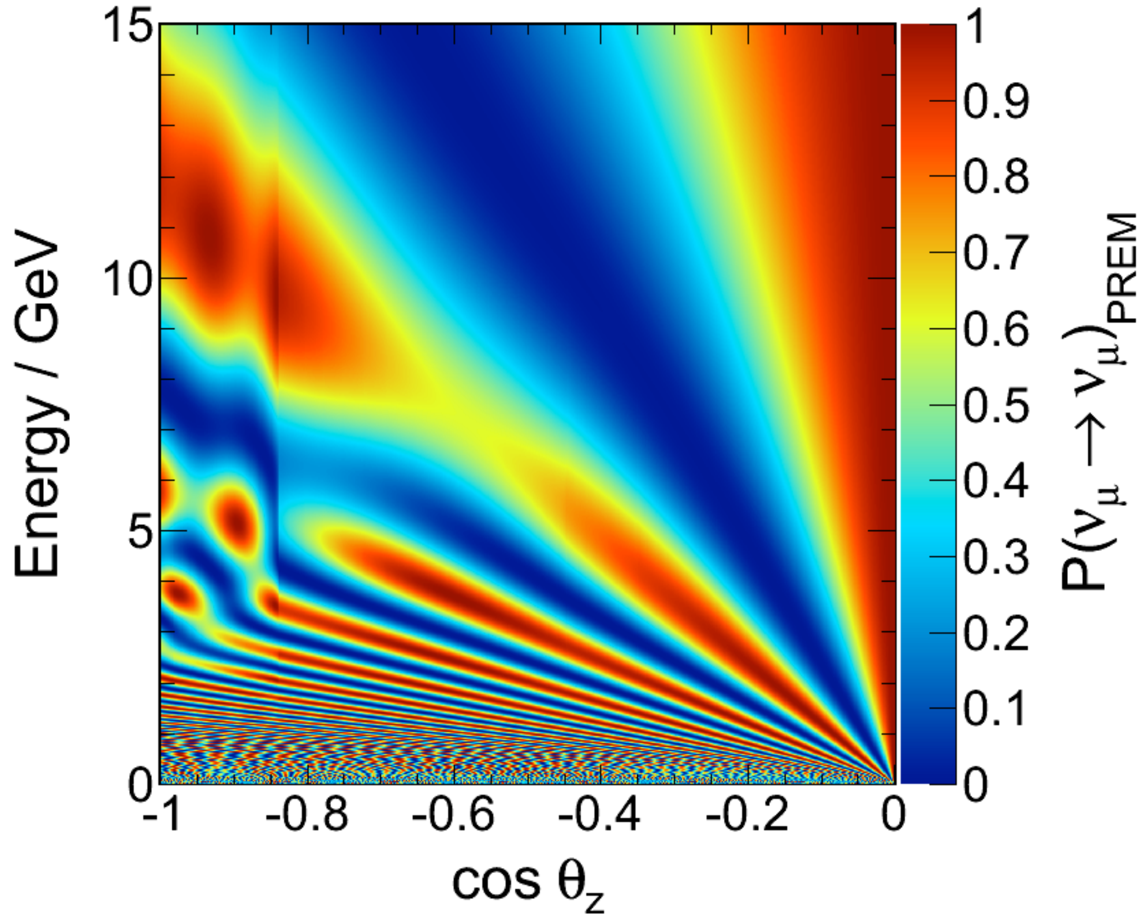


- advantages include:
  - Use of the similar hardware and deployment techniques as IceCube would significantly reduce project risk
  - Could be quick, dependent on funding (2 years of procurement and fabrication; 2-3 years of deployment)

IceCube-DeepCore-PINGU physics program

- Precision atmospheric neutrino oscillation measurements at a few GeV with very high statistics (focus today's talk)
  - measurements of the neutrino mass ordering
  - precise measurements of Δm_{23}^2, θ_{23}
  - high statistics measurement of ν_τ appearance
- Probe lower mass WIMPs
- Increased sensitivity to supernovae ν bursts
- Earth tomography
- For full details refer to the PINGU Letter of Intent (arXiv:1401.2046); updates coming this Fall

Neutrinos



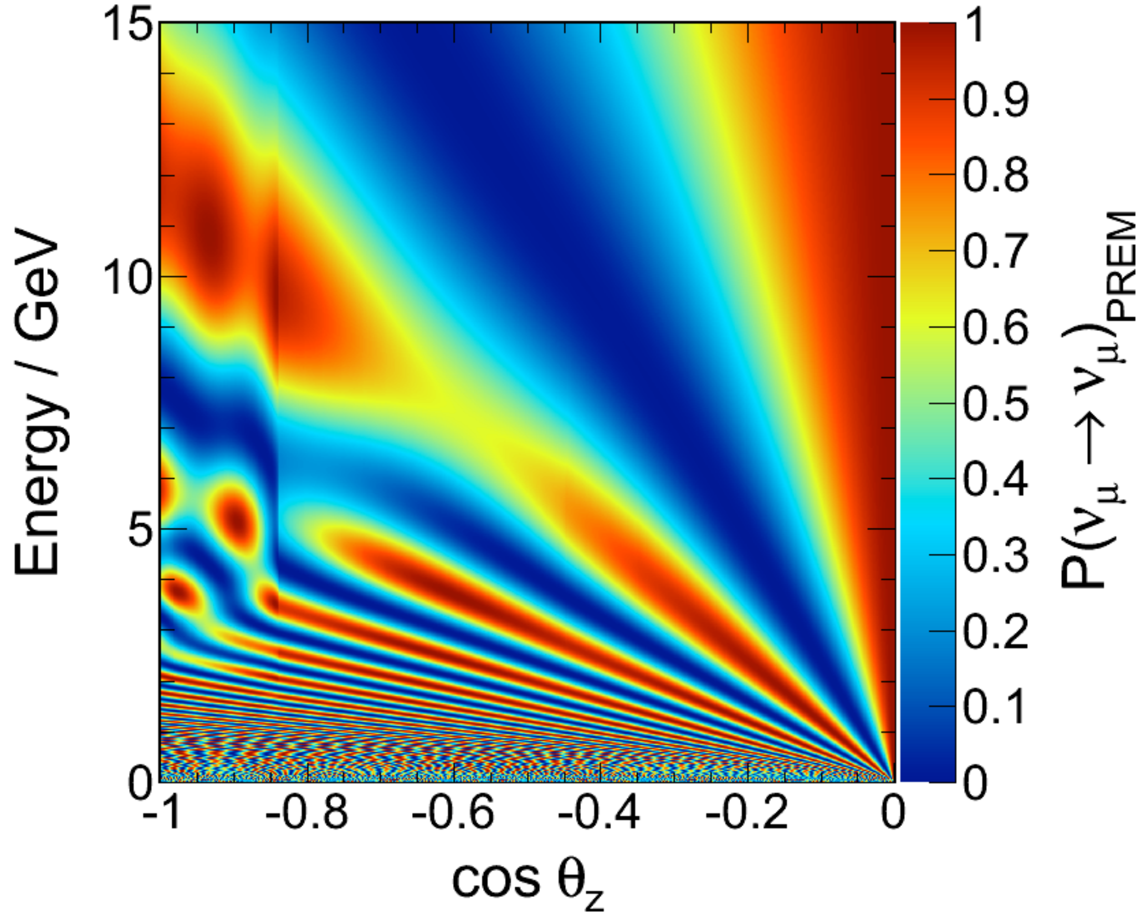
Normal hierarchy

$$\Delta m^2_{32} = 2.32 \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2(2\theta_{23}) = \frac{\pi}{4}$$

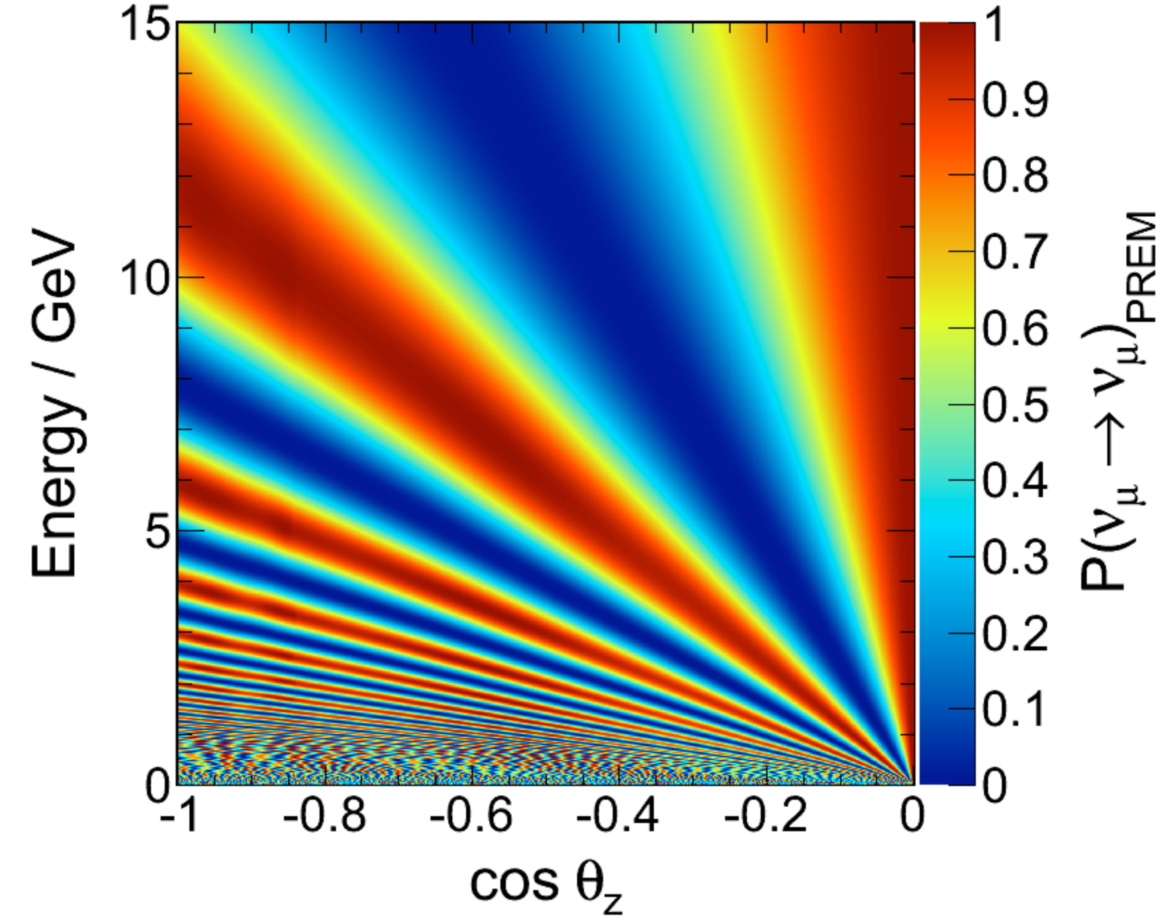
$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Neutrinos



Normal hierarchy

Antineutrinos



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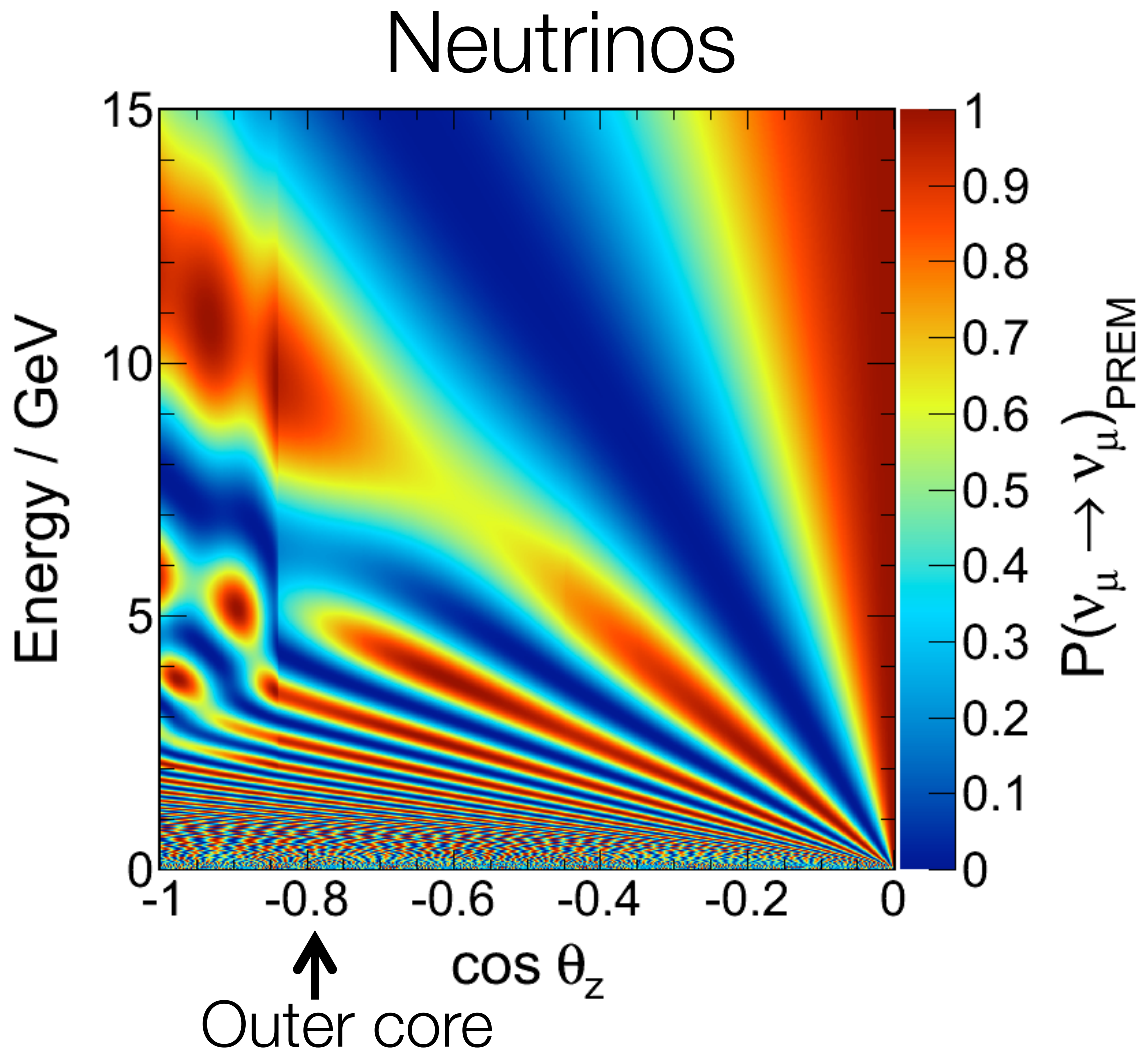

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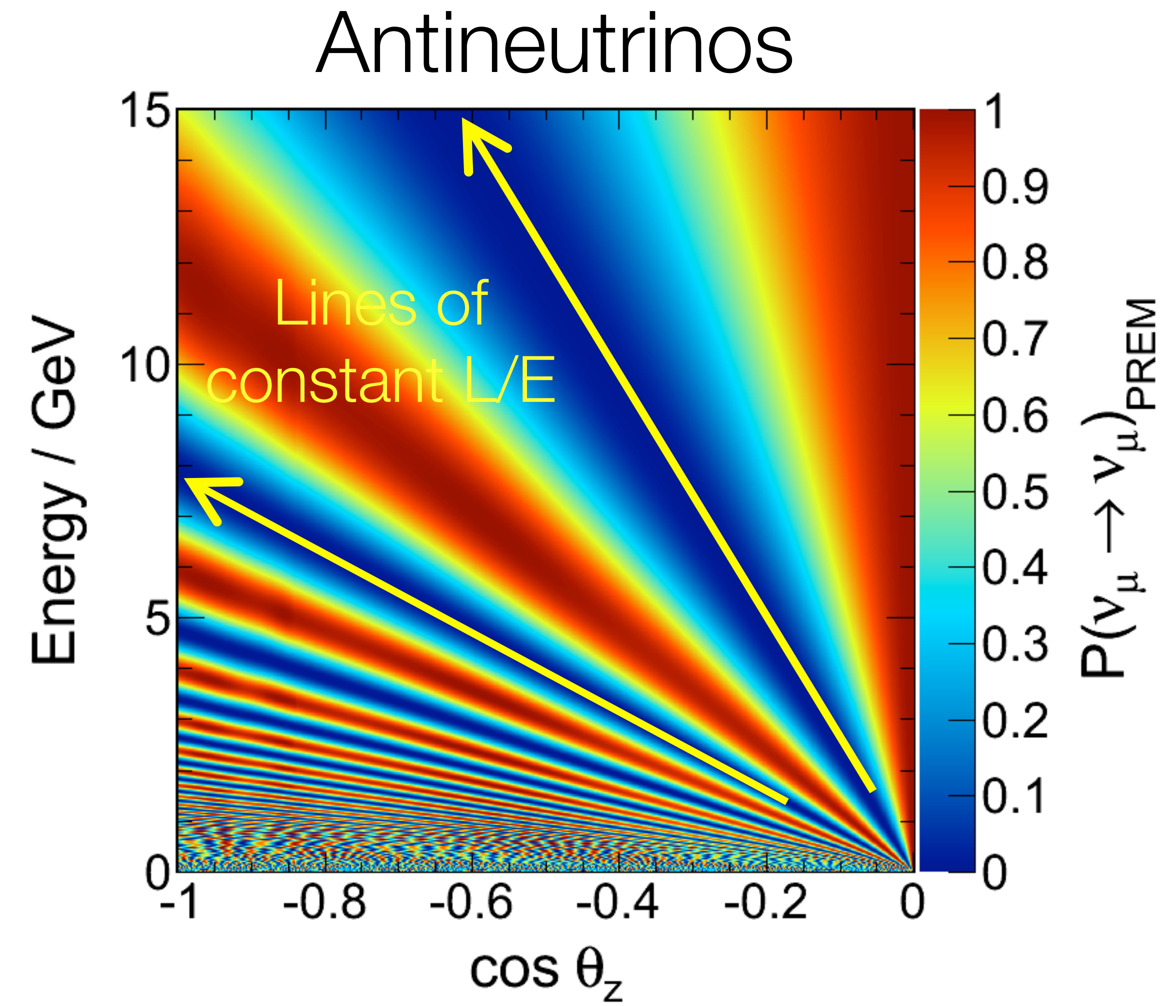

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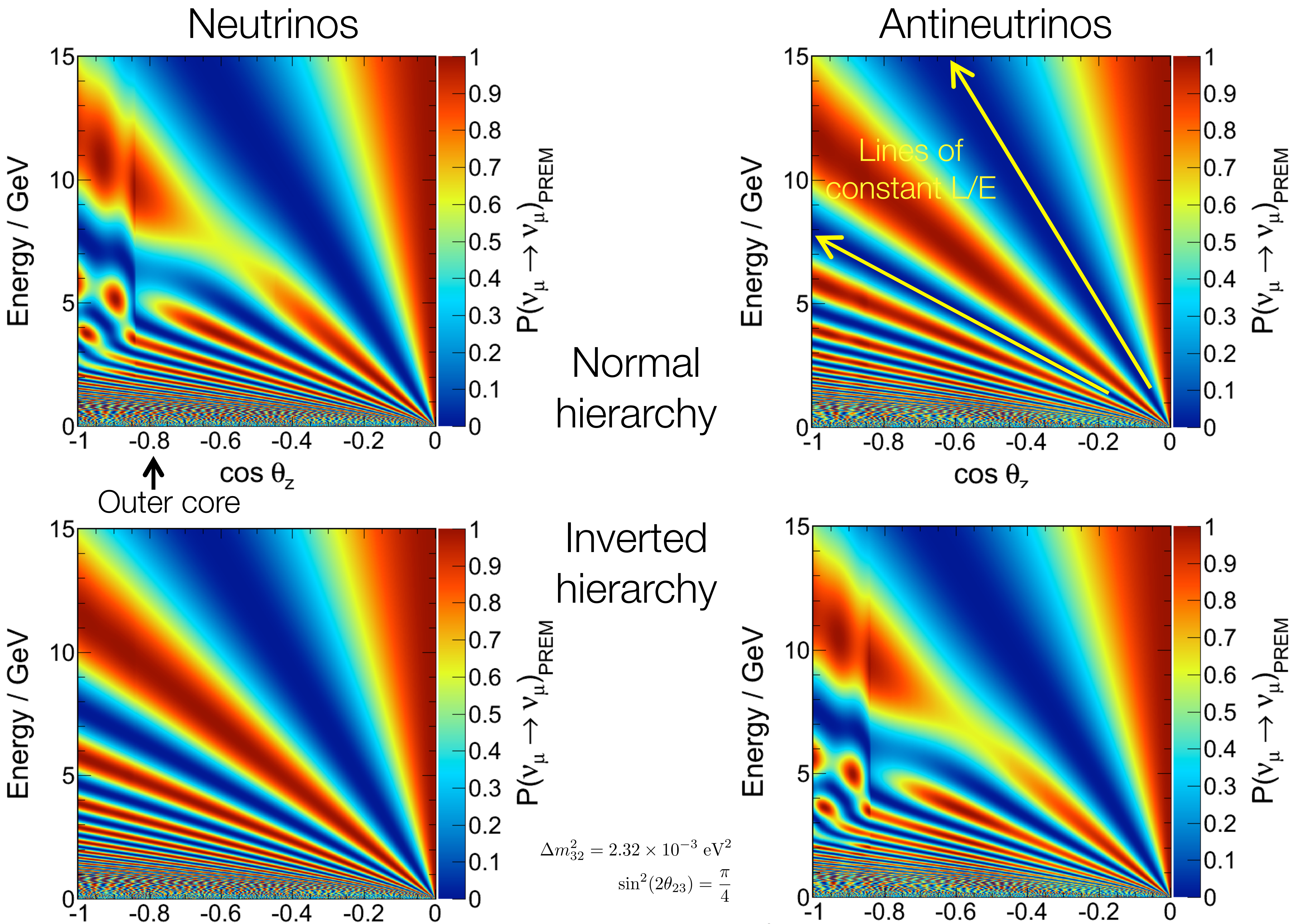

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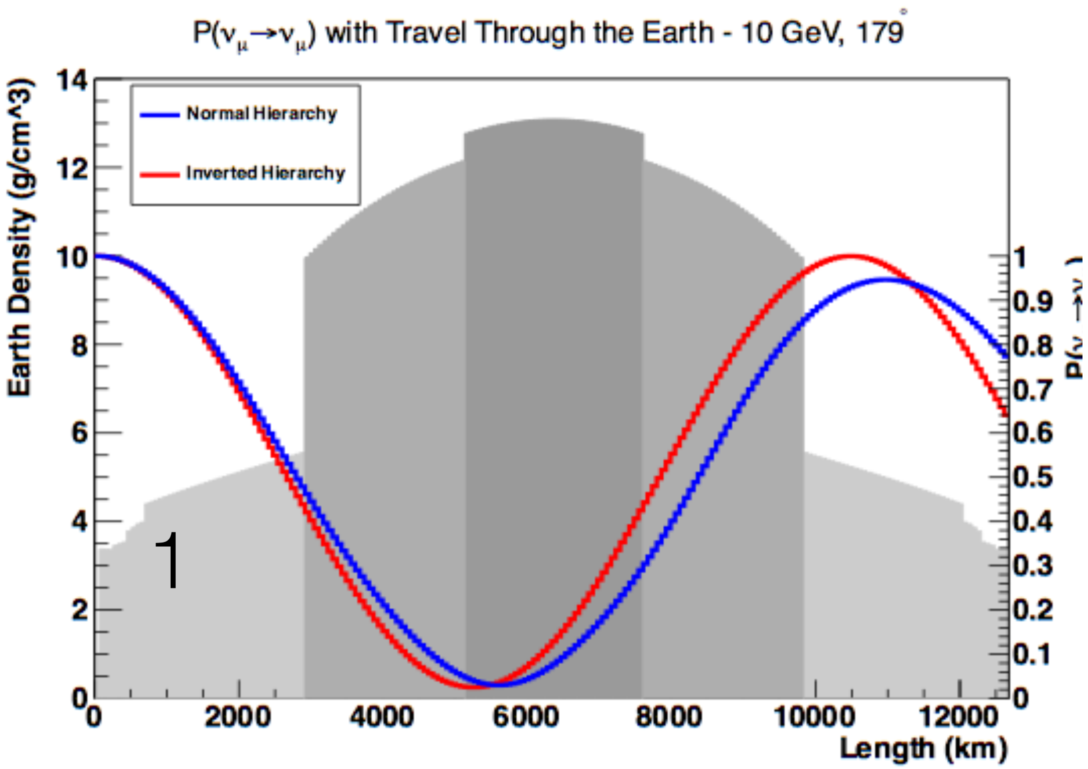
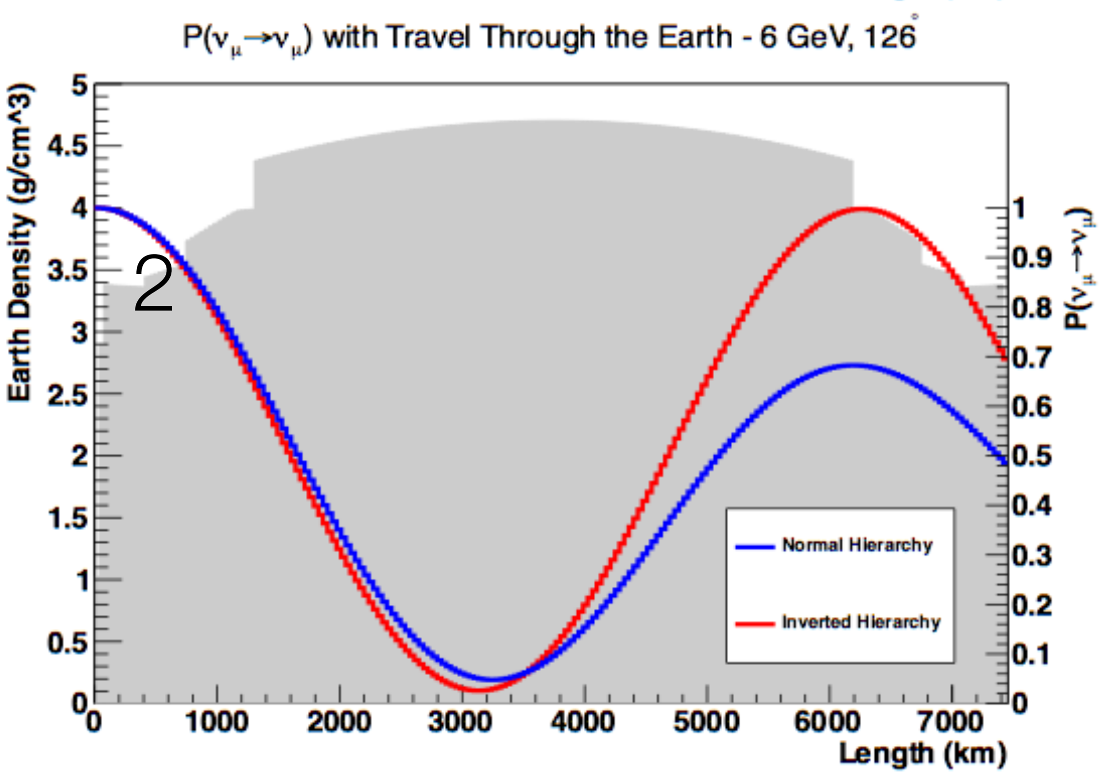
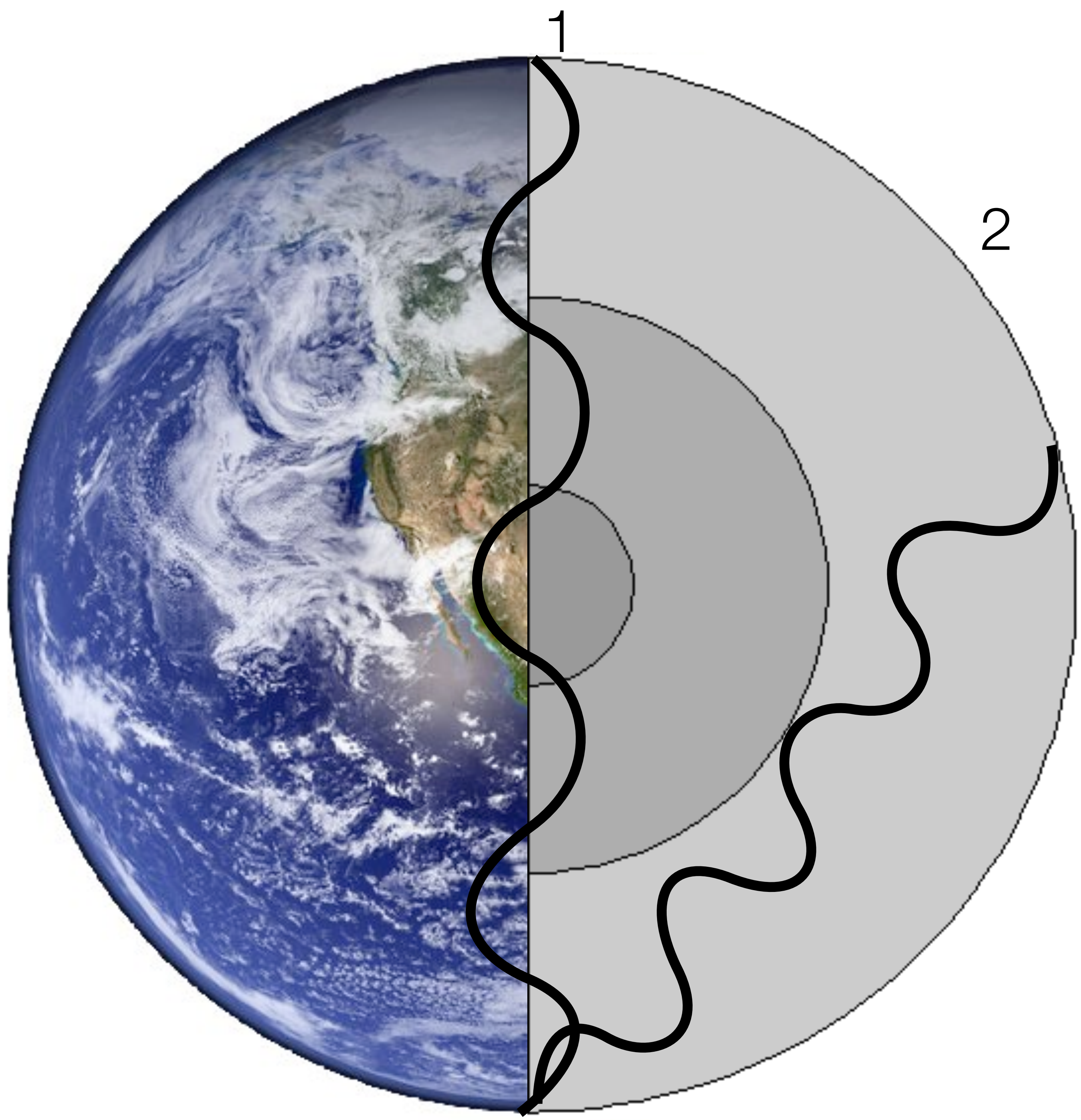
Using atmospheric neutrinos to measure the NMO

Up to 20% differences in ν_μ survival probabilities for various energies and baselines, depending on the neutrino mass hierarchy



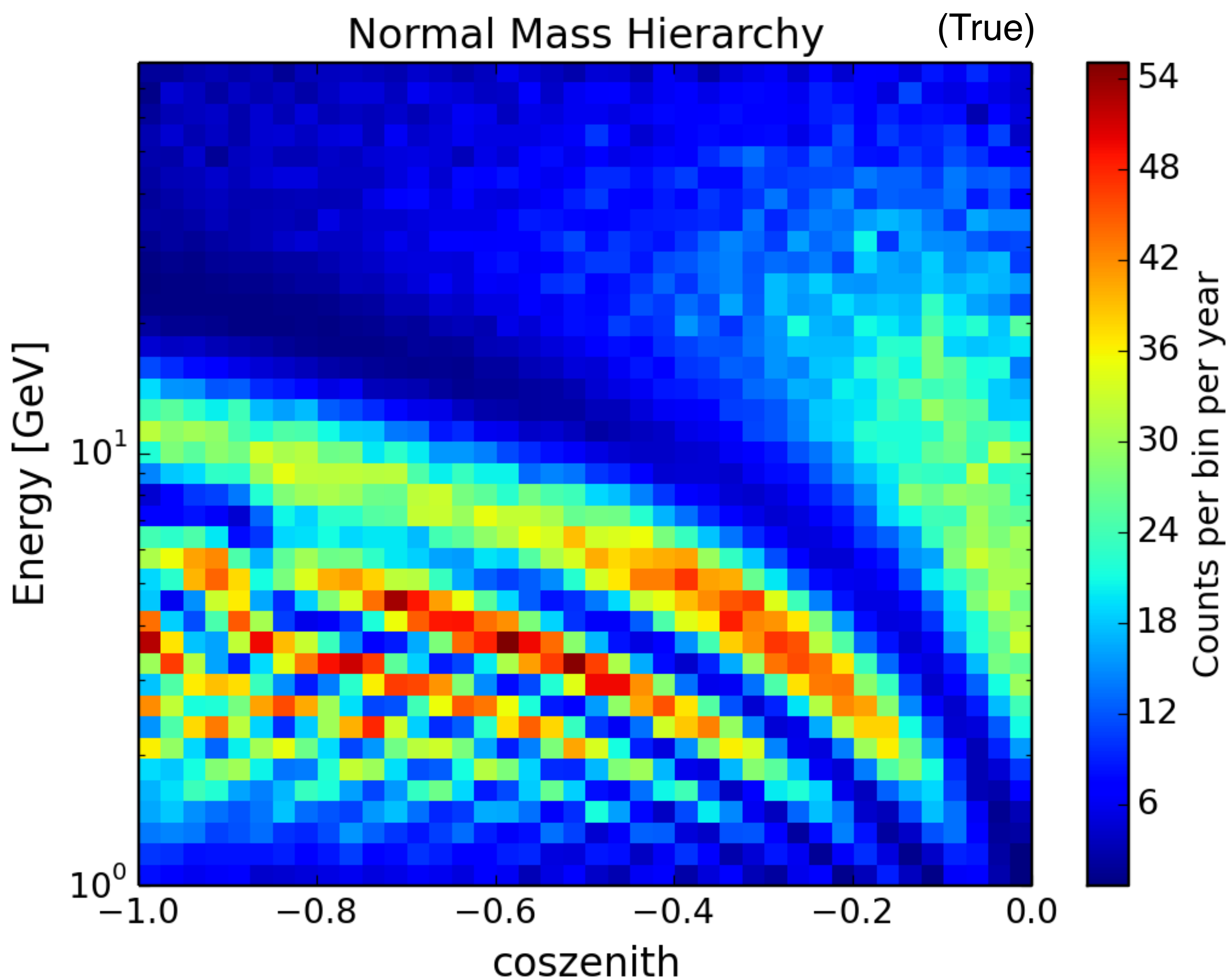




Darren R. Grant - University of Alberta

PINGU and the NMO

- Cannot distinguish ν from $\bar{\nu}$ directly – rely instead on differences in fluxes, cross sections (and kinematics)
- Differences clearly visible in expected atm. muon (ν + $\bar{\nu}$) rate even with 1 year's data
  - Note: detector resolutions not yet included here



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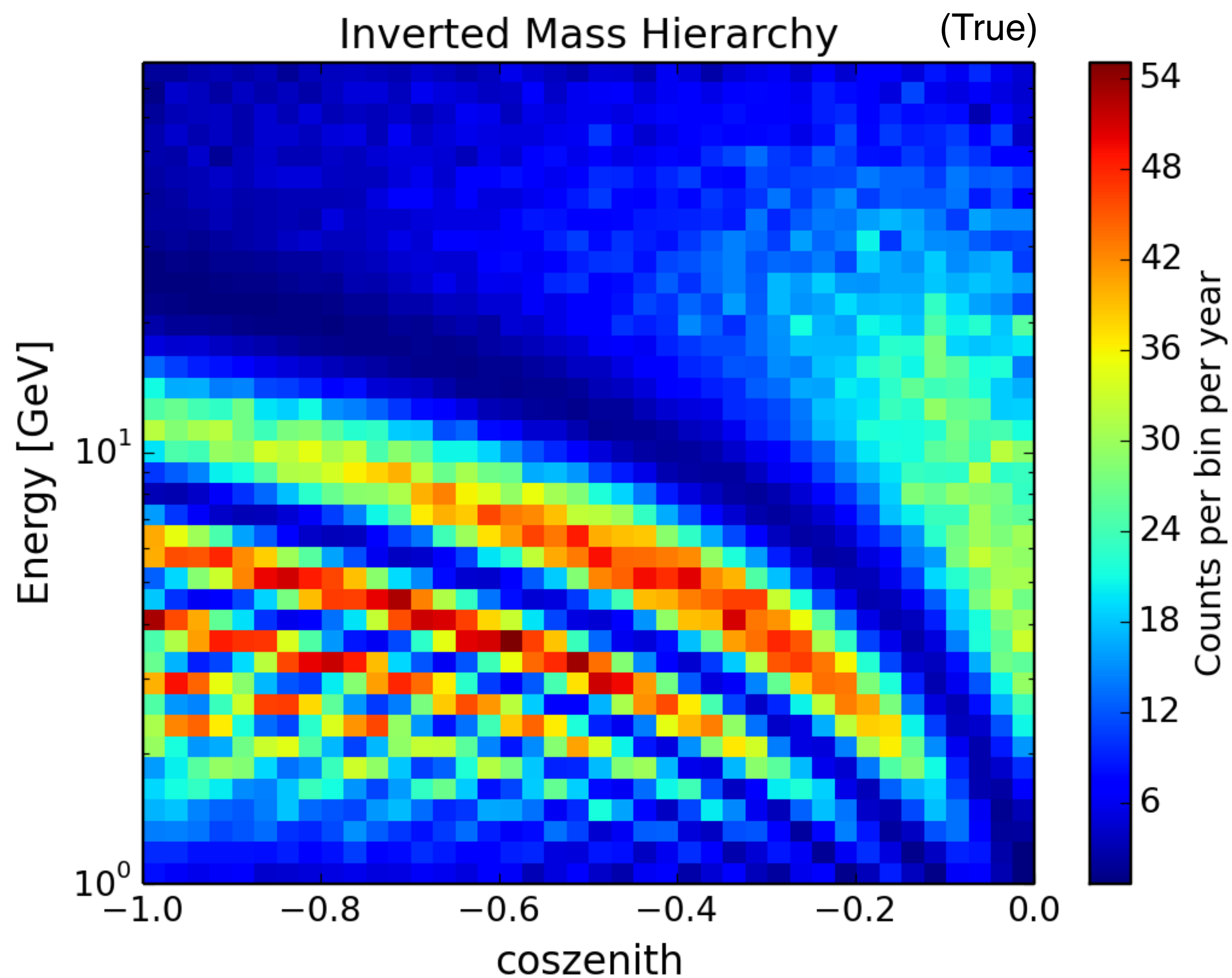
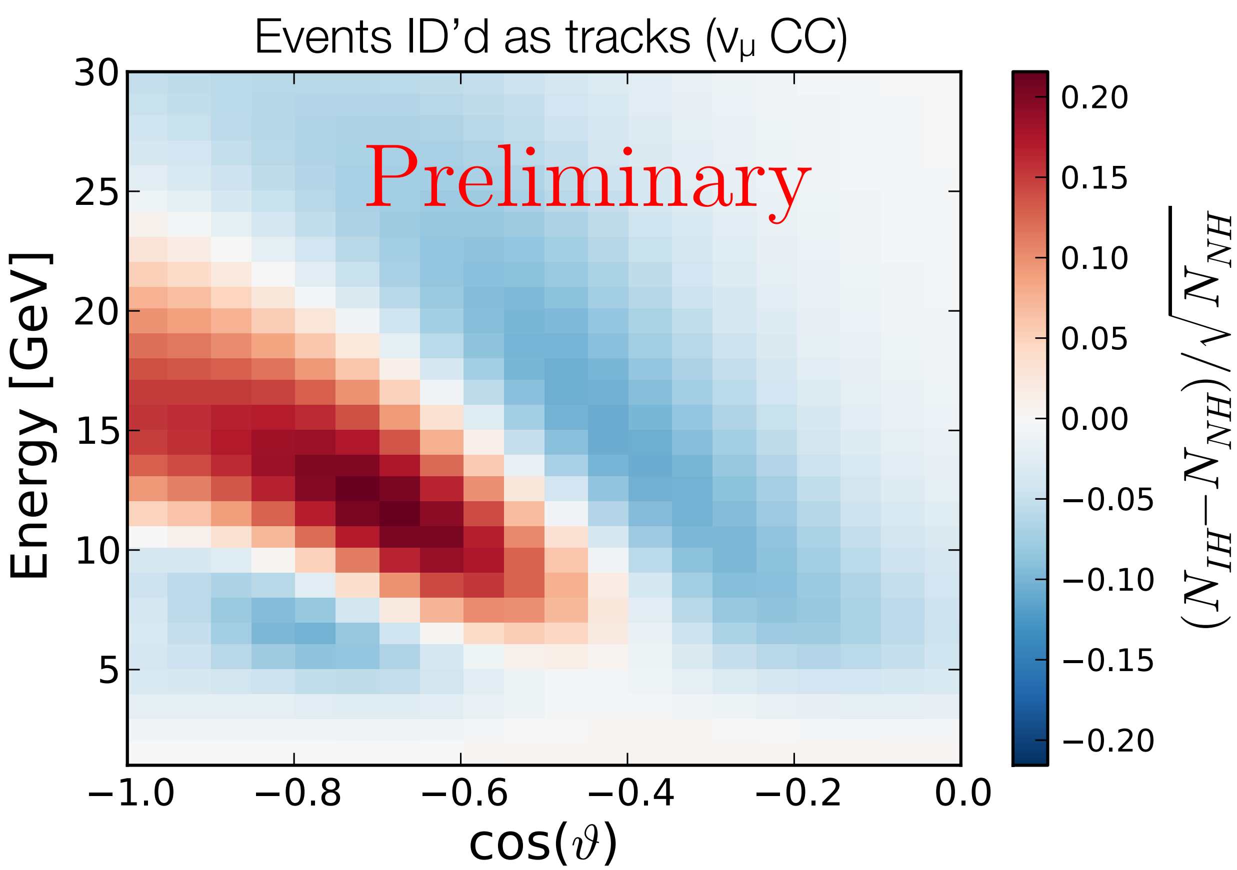
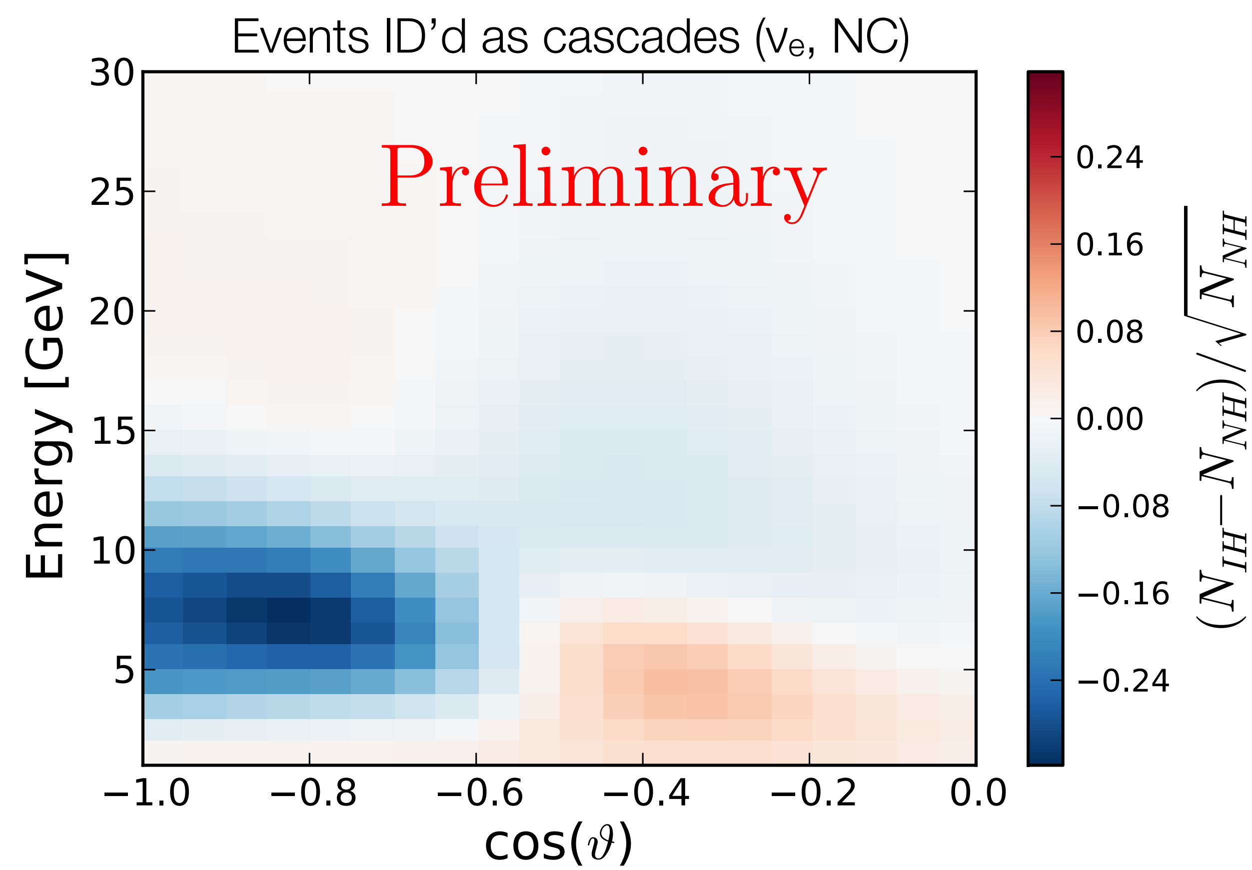


PINGU and the NMO

arXiv:1401.2046



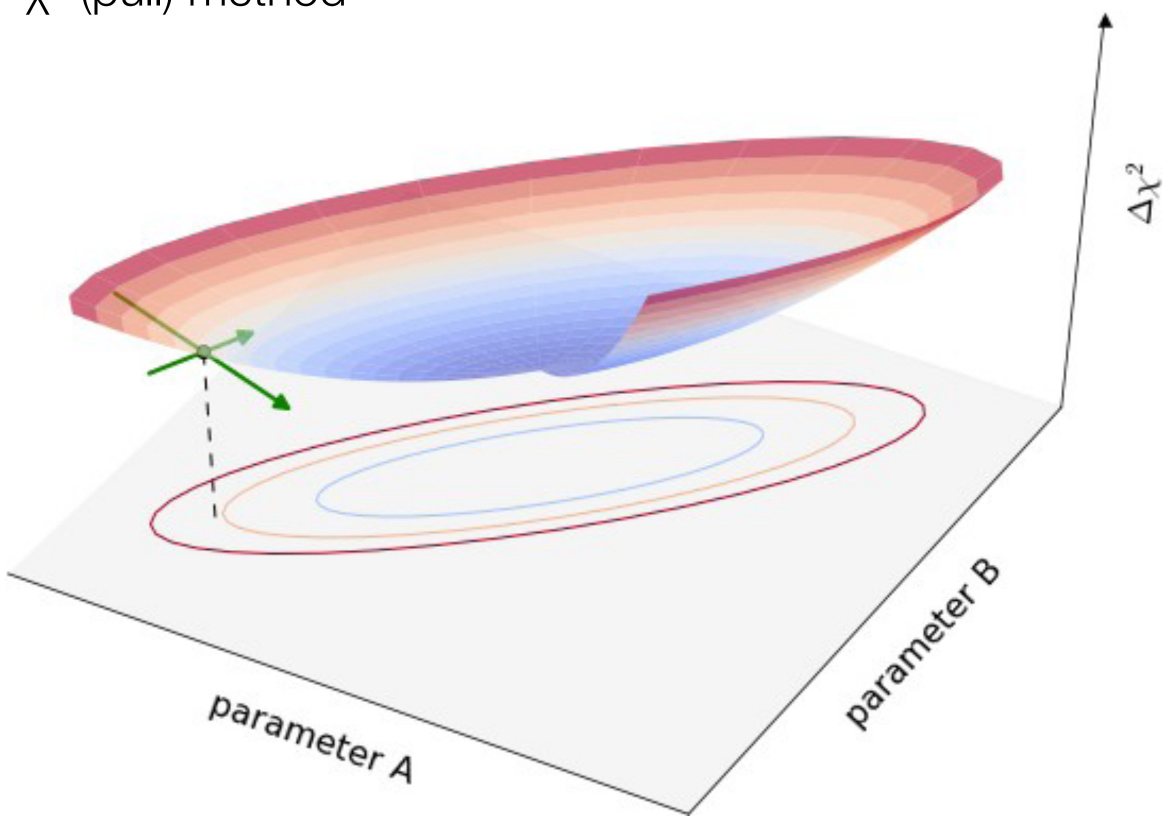


- Distinctive (and quite different) hierarchy-dependent signatures are visible in both the track and cascade channels
  - Quantity shown is an illustration of statistical significance per bin (as per Akhmedov et al. arXiv:1205.7071)
  - Full MC for detector efficiency, reconstruction, and particle ID included

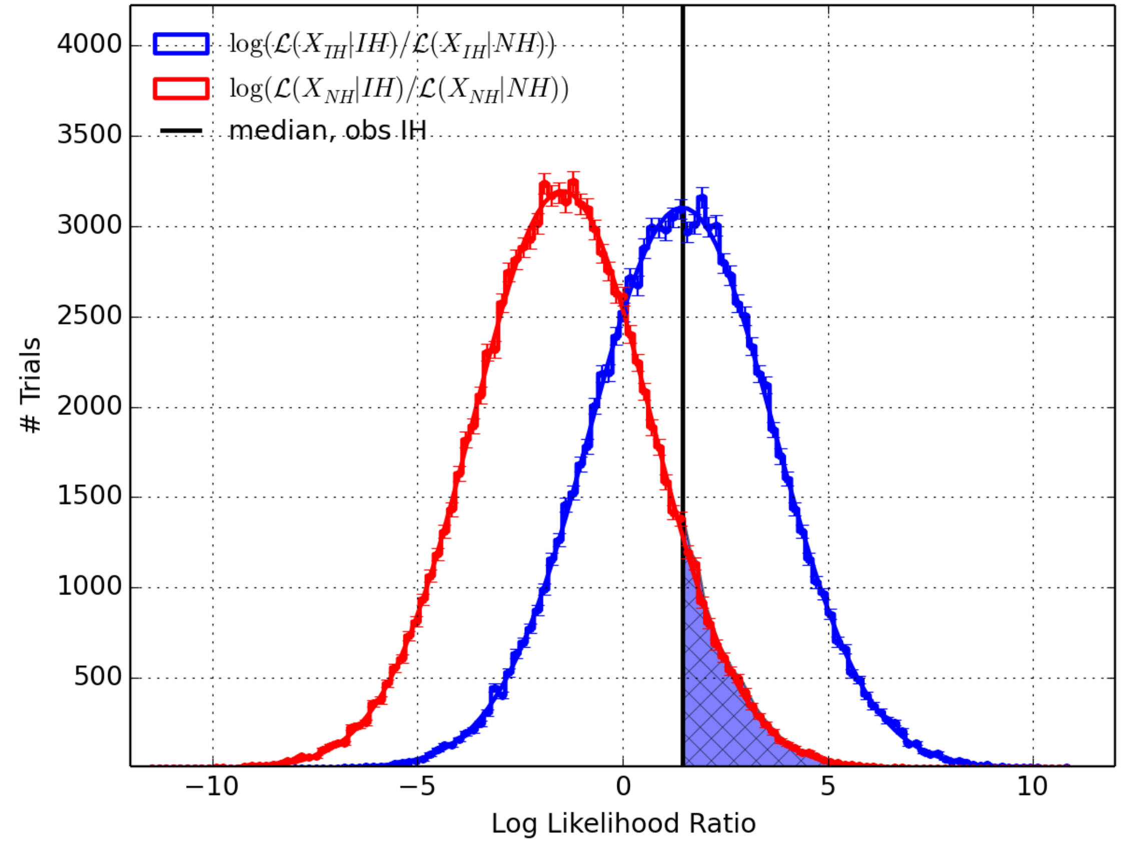
PINGU and the NMO

arXiv:1401.2046

χ^2 (pull) method



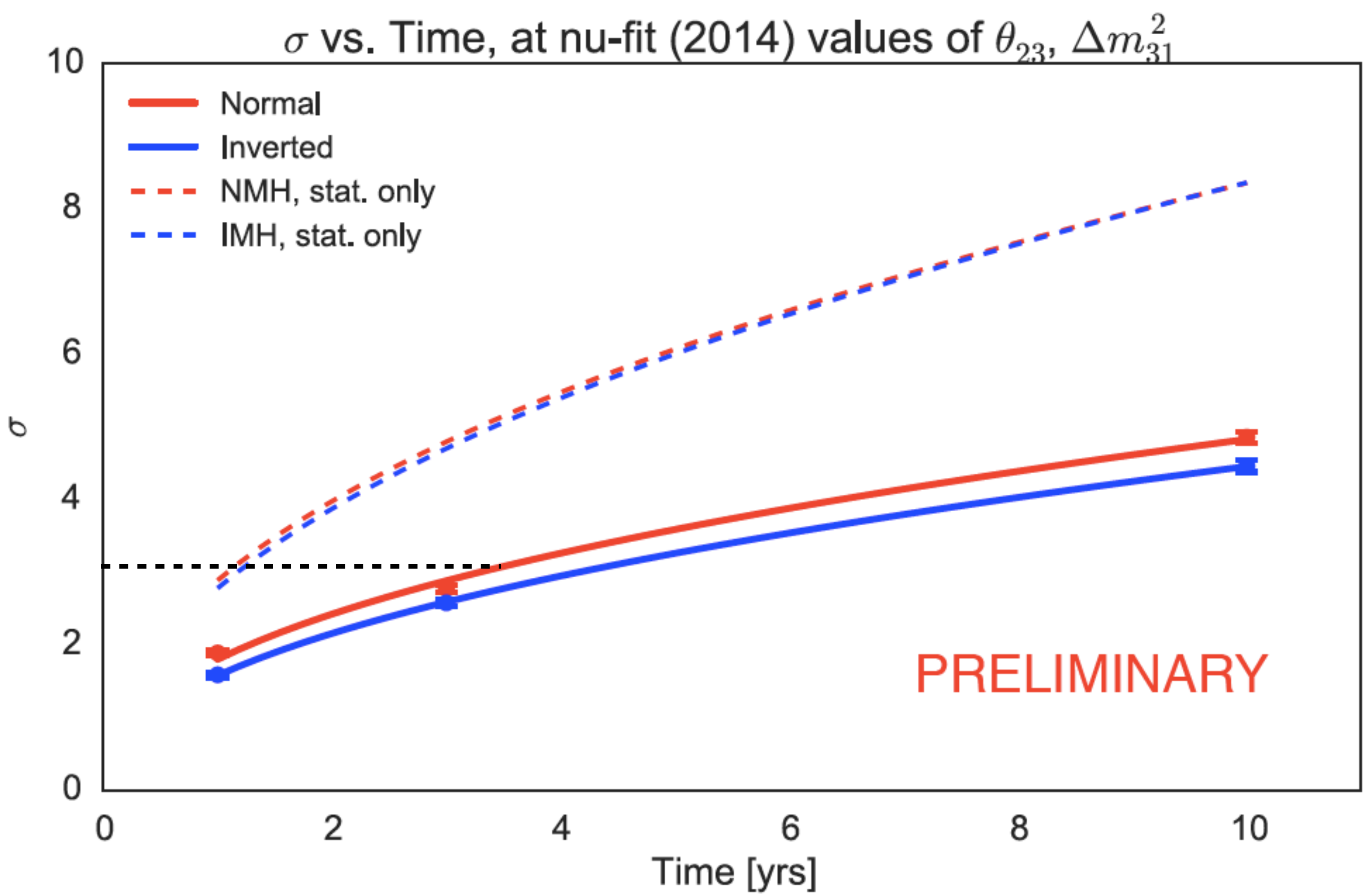
Likelihood Ratio



- Currently two methods used to extract the NMO significance: χ^2 (pull) and Likelihood ratio
  - output of full simulation and reconstruction parameterization (pull method) are used
  - analysis completed in energy x cos(zenith) space in 2 particle ID bins
  - the “other” hierarchy parameter is chosen to minimize distinguishability

PINGU and the NMO - predicted sensitivity

- With baseline geometry, a determination of the mass hierarchy with 3σ significance appears possible with ~3.5 years of data
    - Vetted against full Monte Carlo studies with complete range of systematics



Type	3yr σ (NMH)	3yr σ (IMH)
stat. only	4.84	4.82
flux only	4.55	4.56
det. only	4.06	3.99
θ_{23} only	3.52	3.26
osc. only	2.96	2.53
All	2.90	2.51

Preliminary

- systematics dominated by uncertainties in the oscillation parameters; no prior on θ_{23} or Δm^2. Detector includes rate/normalizrion (free), energy scale (10%). δcp held fixed. Flux includes ratio e/μ, ν/anti-ν, flux uncertainties.

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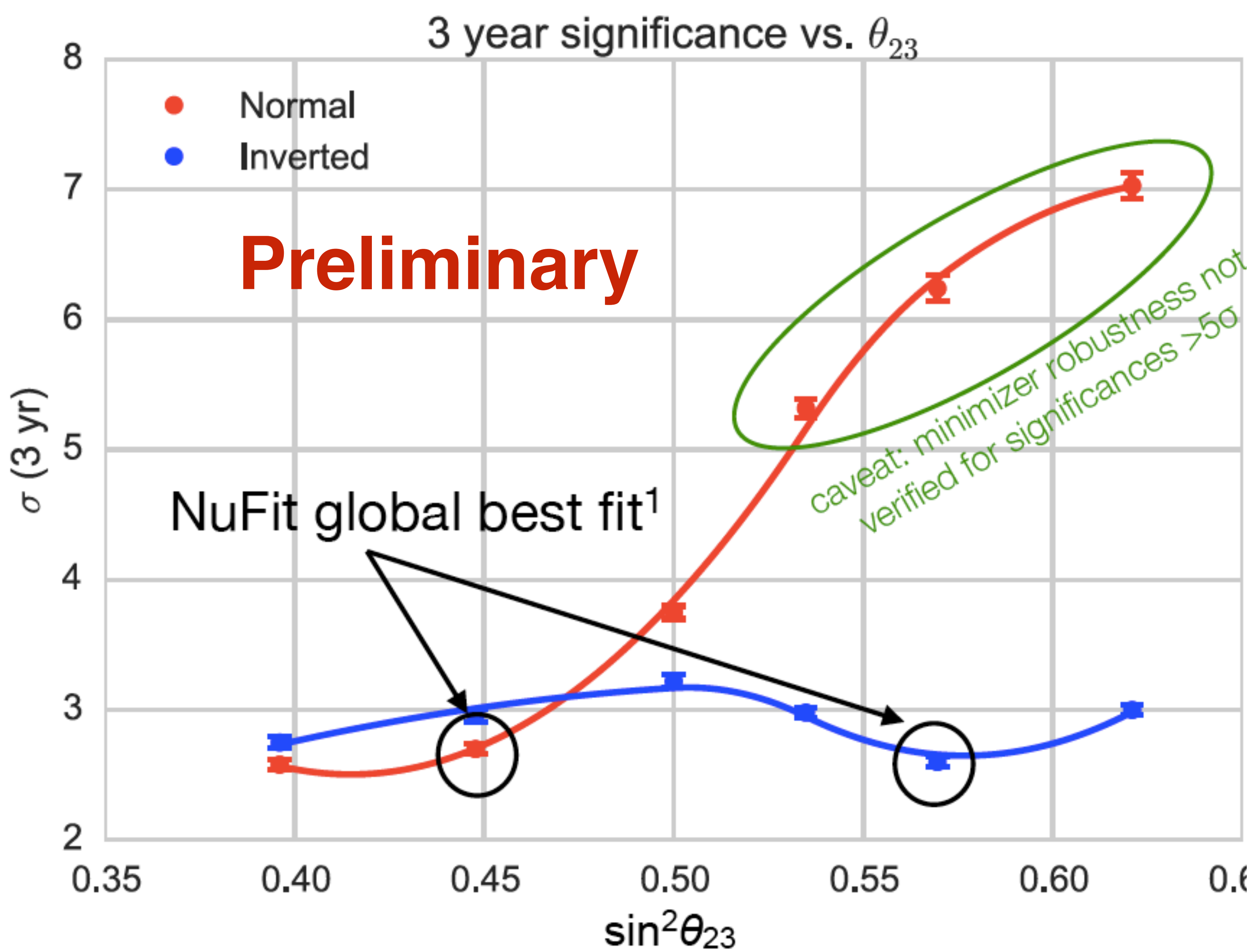
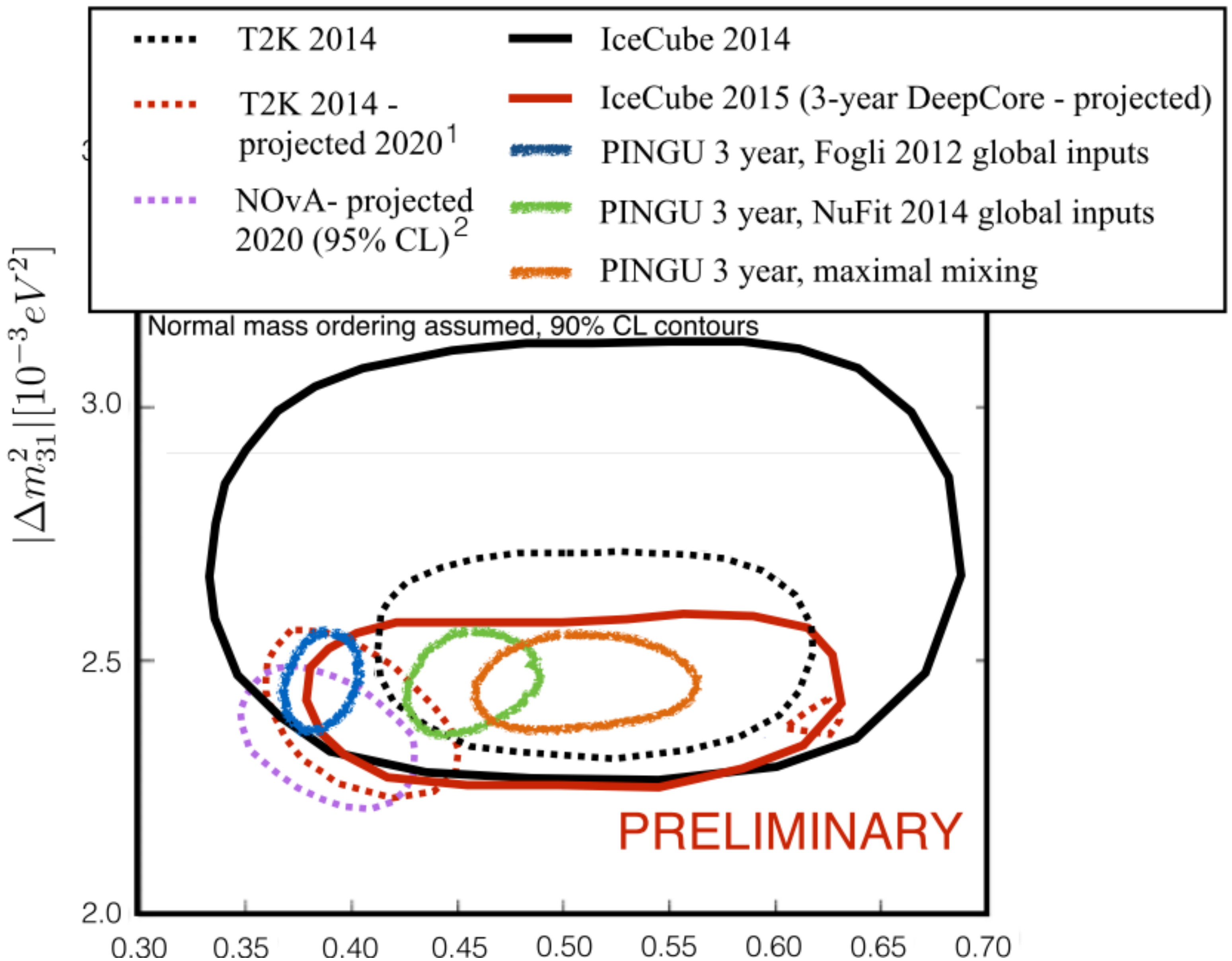


[1] M.C. Gonzalez-Garcia et al. *JHEP* 11, 052 (2014)

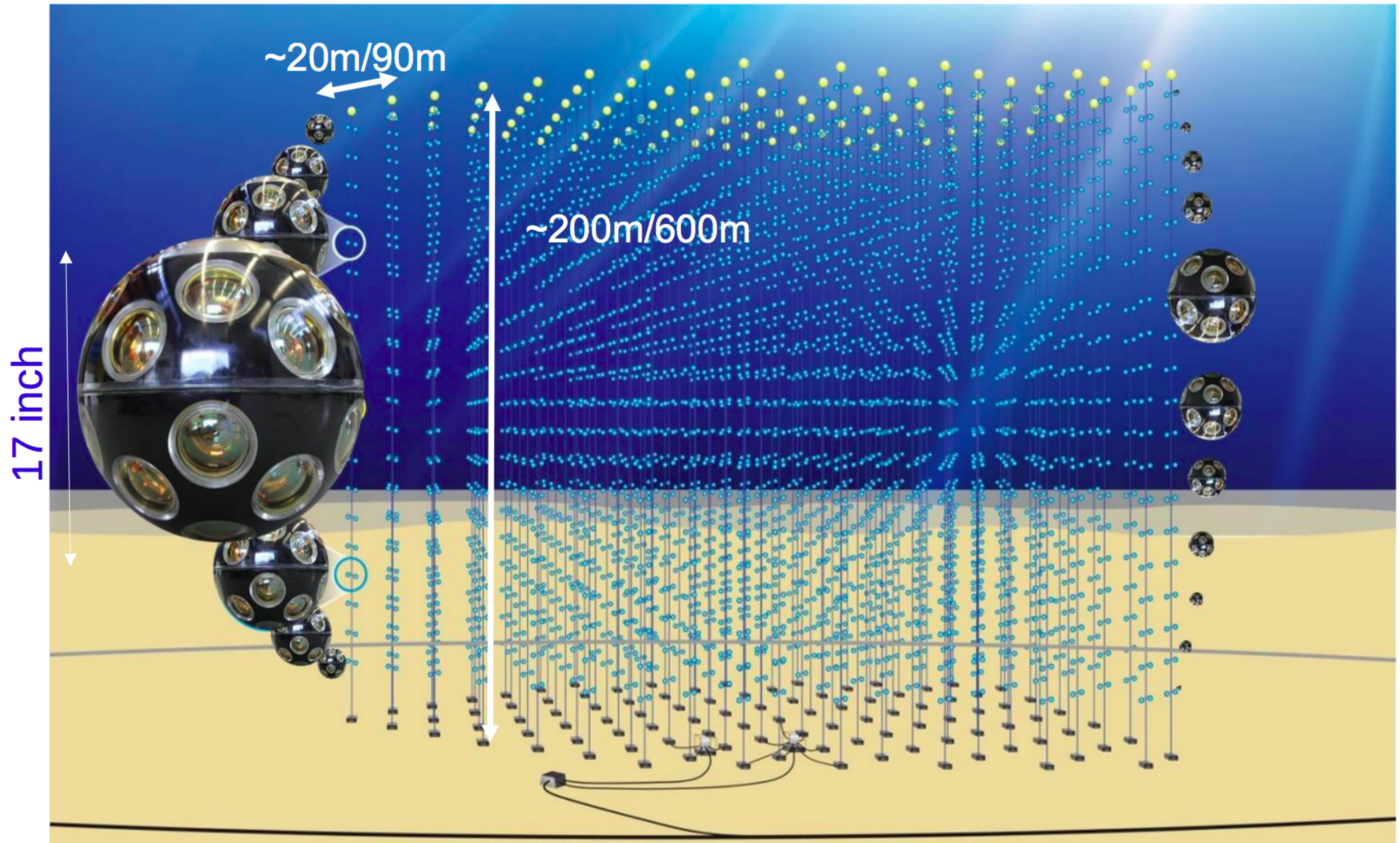
PINGU and the atmospheric mixing parameters

- Expected constraints of atm. oscillation parameter precision comparable to NOvA and T2K (projected)



The ORCA detector

- Proposed upgrade of the ANTARES detector as a part of KM3NeT. Planned 115 strings at 20 m spacing with 18 (multi-PMT) optical modules per string



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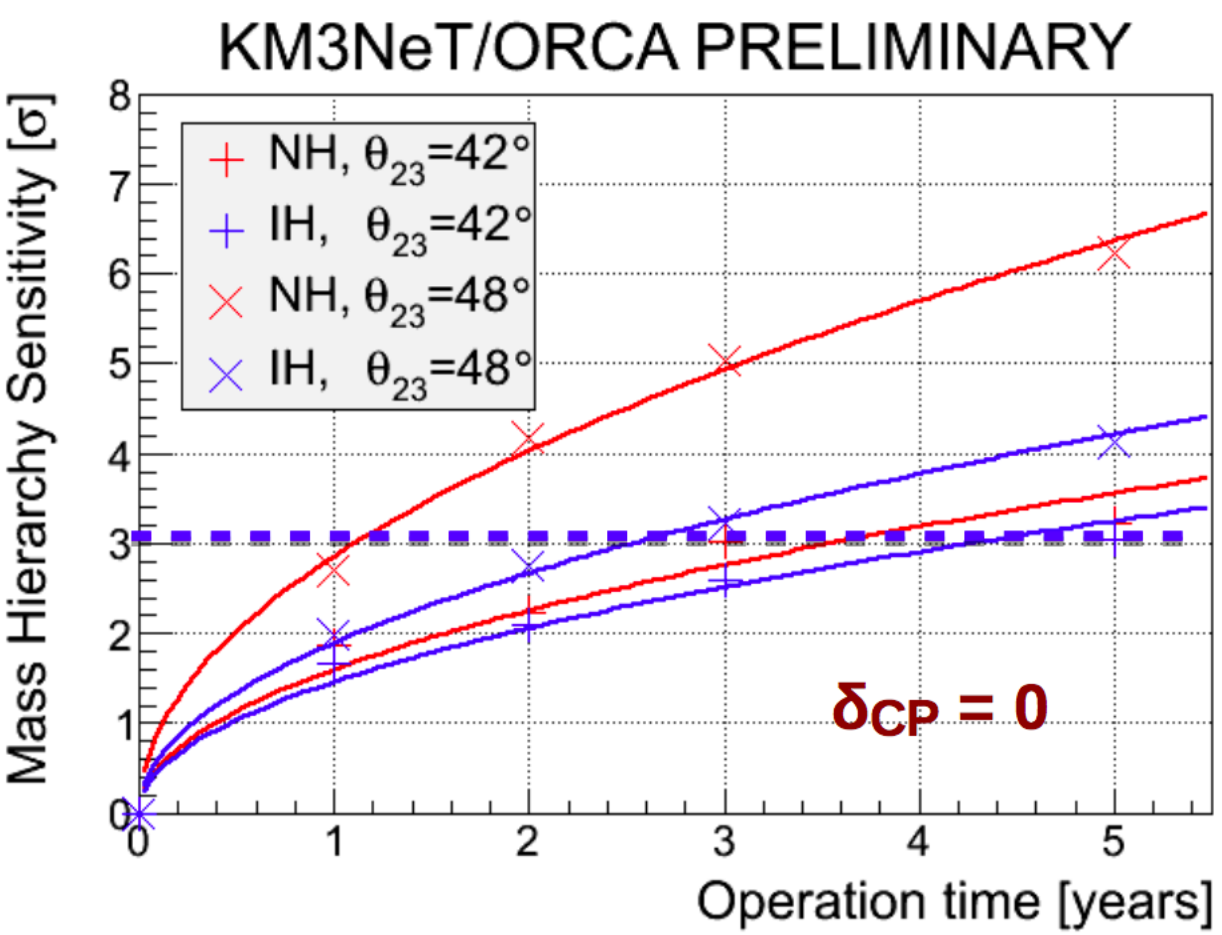
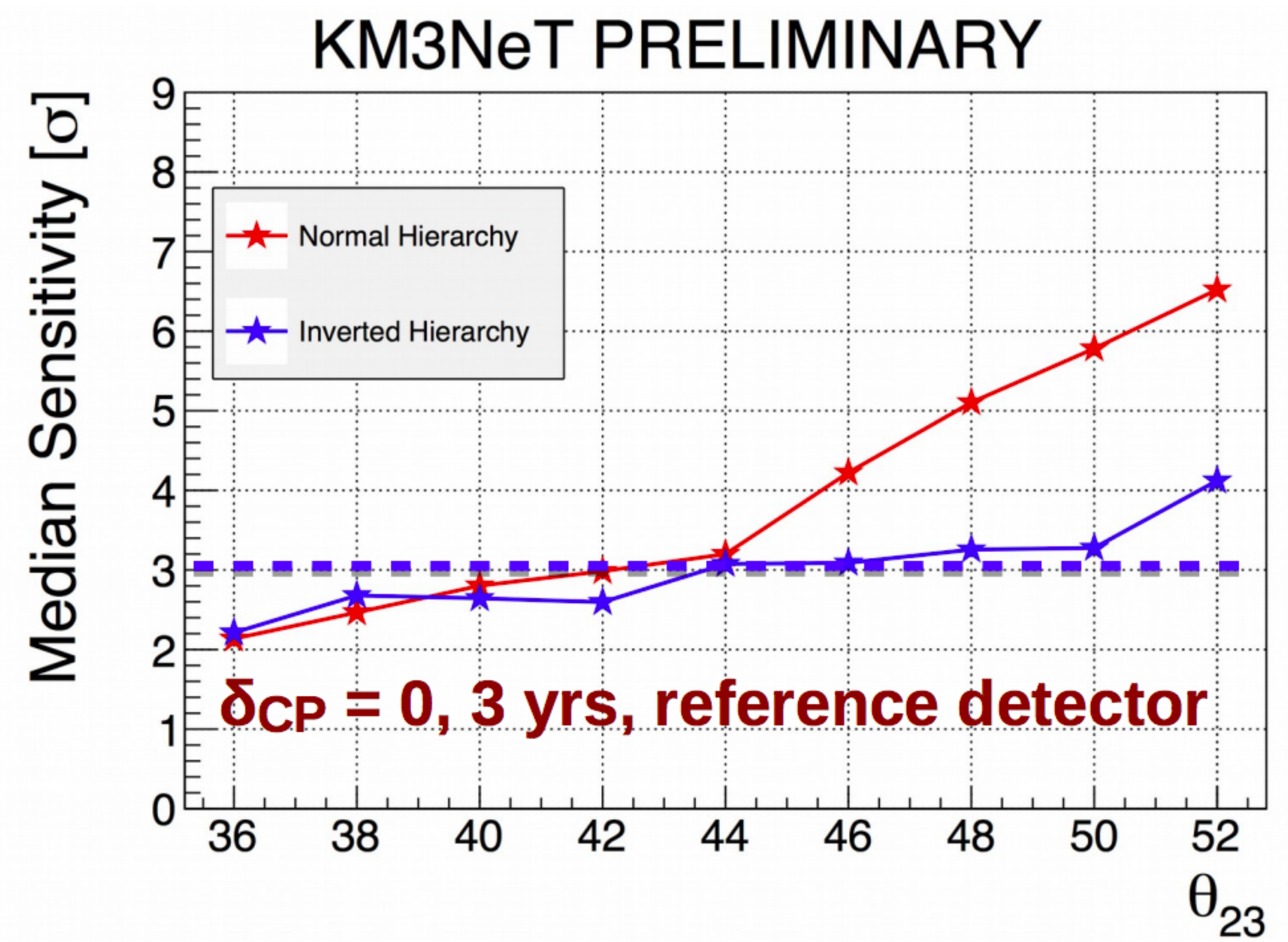


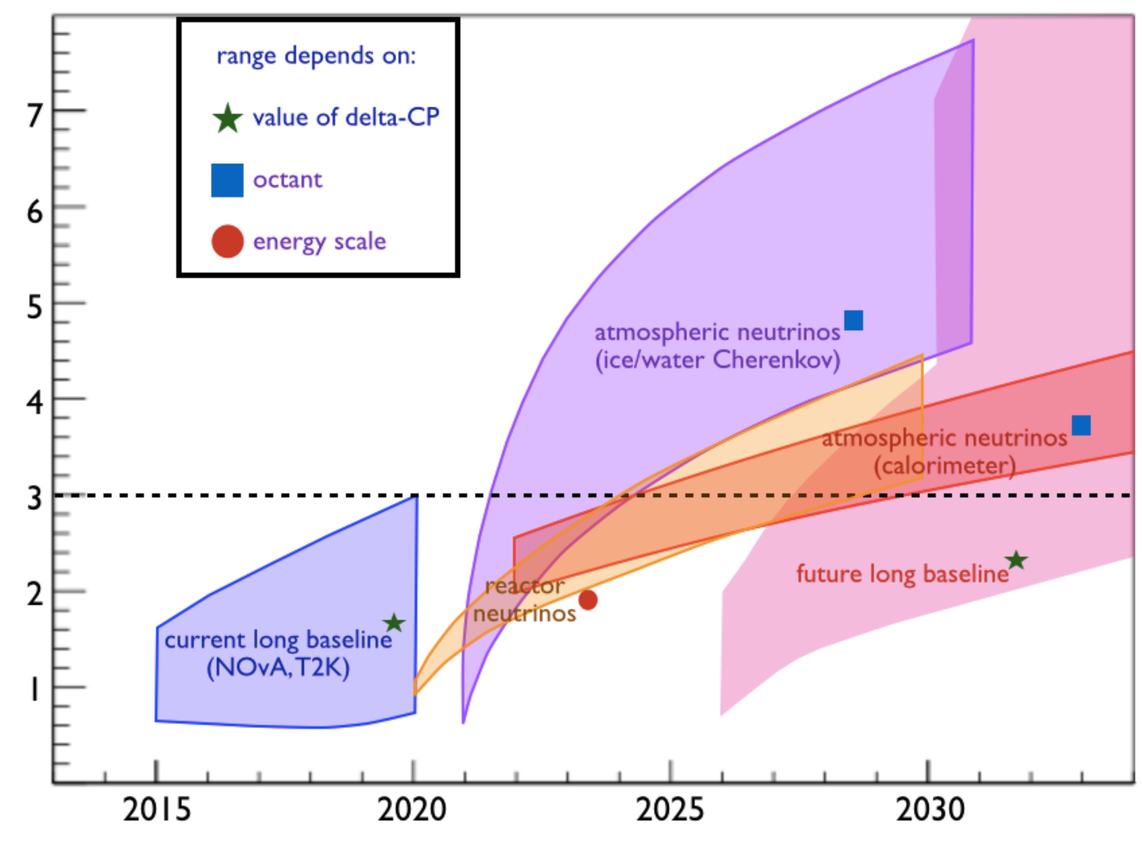


- Currently constructing a 6-string demonstrator

- multi-PMT optical modules also under development by IceCube for Gen2

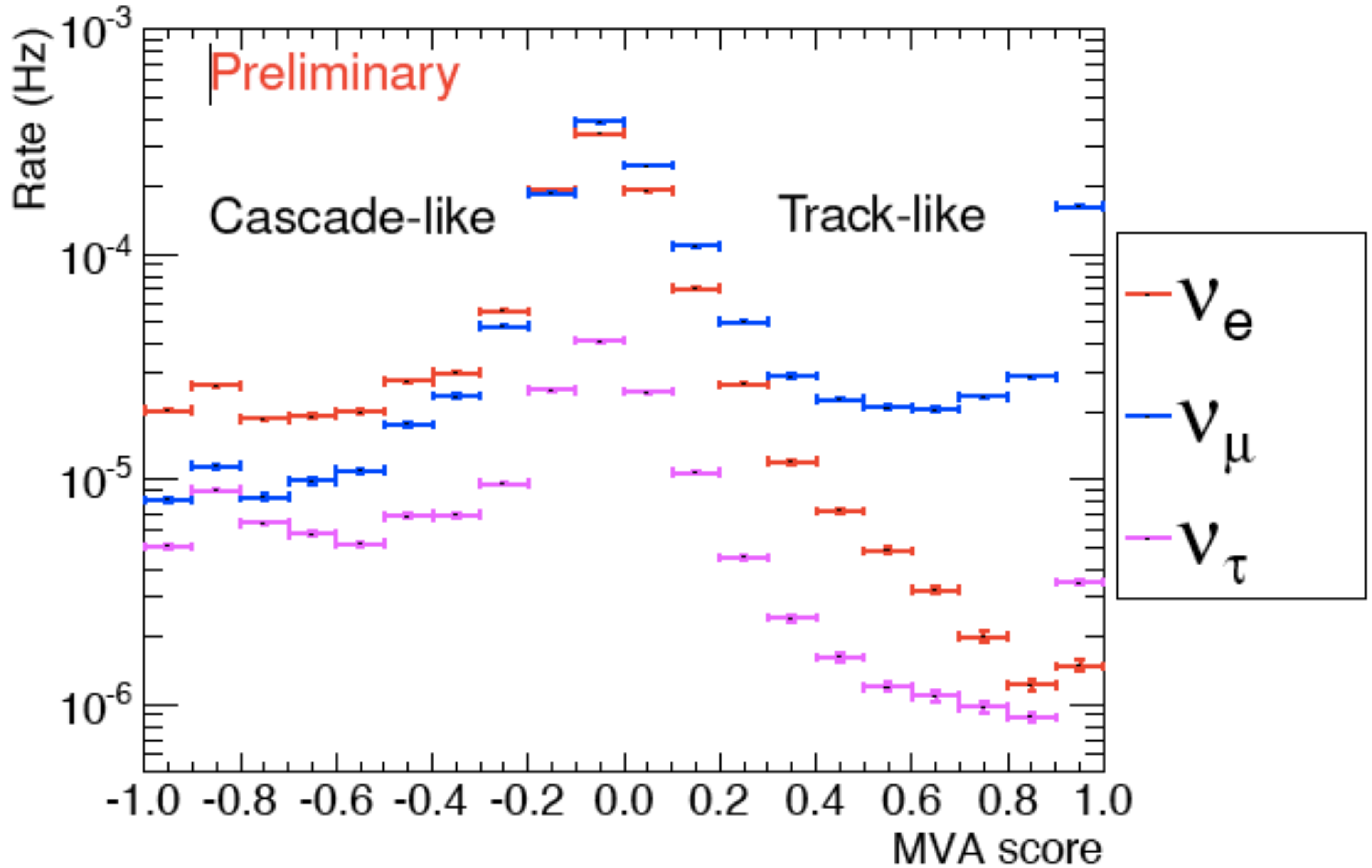
Summary and outlook

- IceCube-DeepCore has demonstrated the ability to measure atmospheric neutrino oscillations with sensitivity starting to approach dedicated oscillation experiment.
- Neutrino telescope technology applied to more densely instrumented arrays holds the potential to produce enormous detectors for precision atmospheric neutrino measurements.
  - neutrino mass ordering to 3σ in 3-4 years with a full detector
  - improved precision measurements of atm. oscillation parameters
  - enhanced sensitivity to ν_τ appearance, low-mass indirect WIMP searches, etc.
- This detector approach builds on existing expertise, reducing project risk and presenting the opportunity for relatively fast construction. The project timeline is currently only limited by agency funding, not technological challenges.
- PINGU final optimized detector Letter of Intent is now under collaboration review; public this Fall. ORCA currently preparing deployment of 6 demonstrator strings of KM3NeT multi-PMT modules.

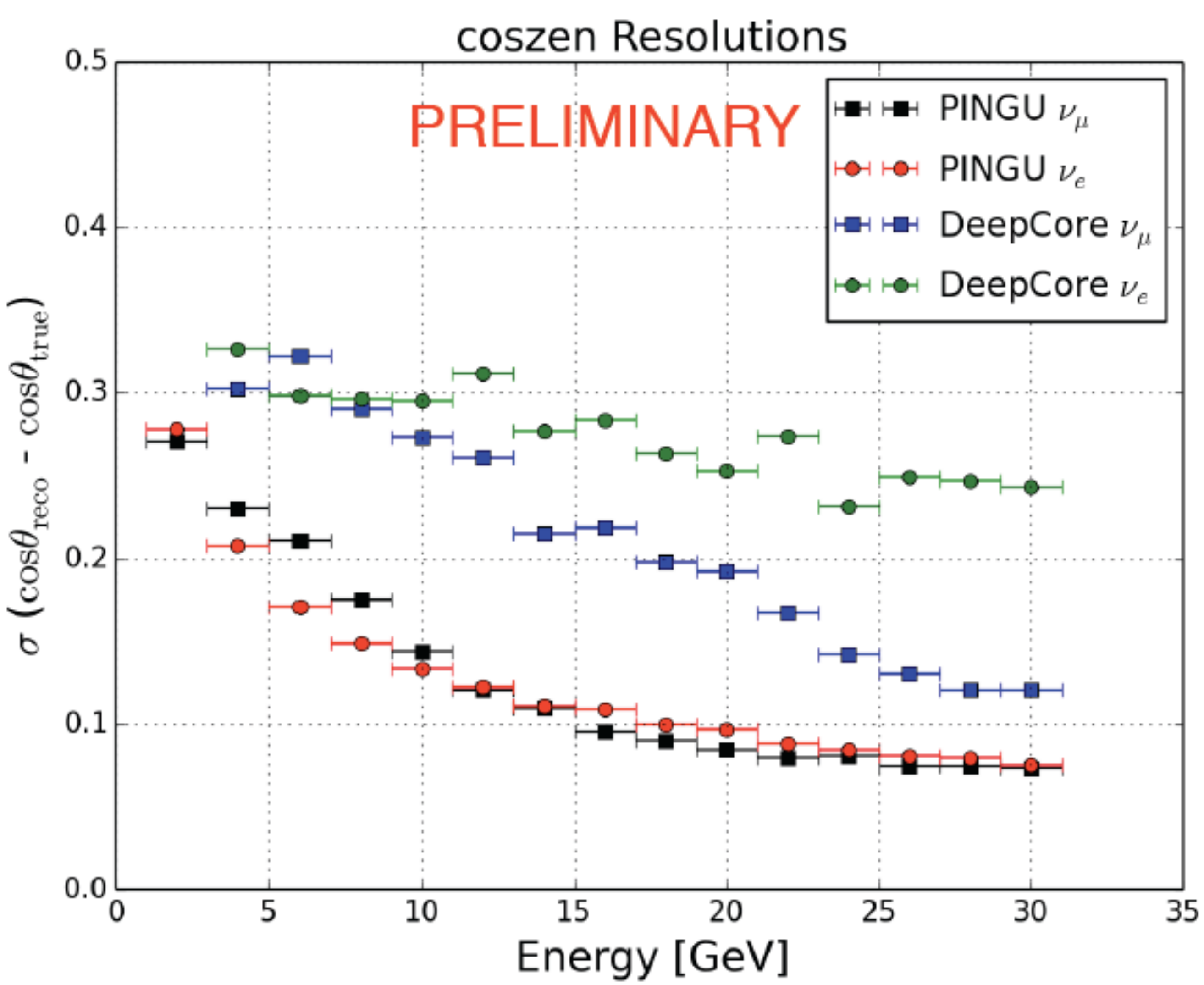


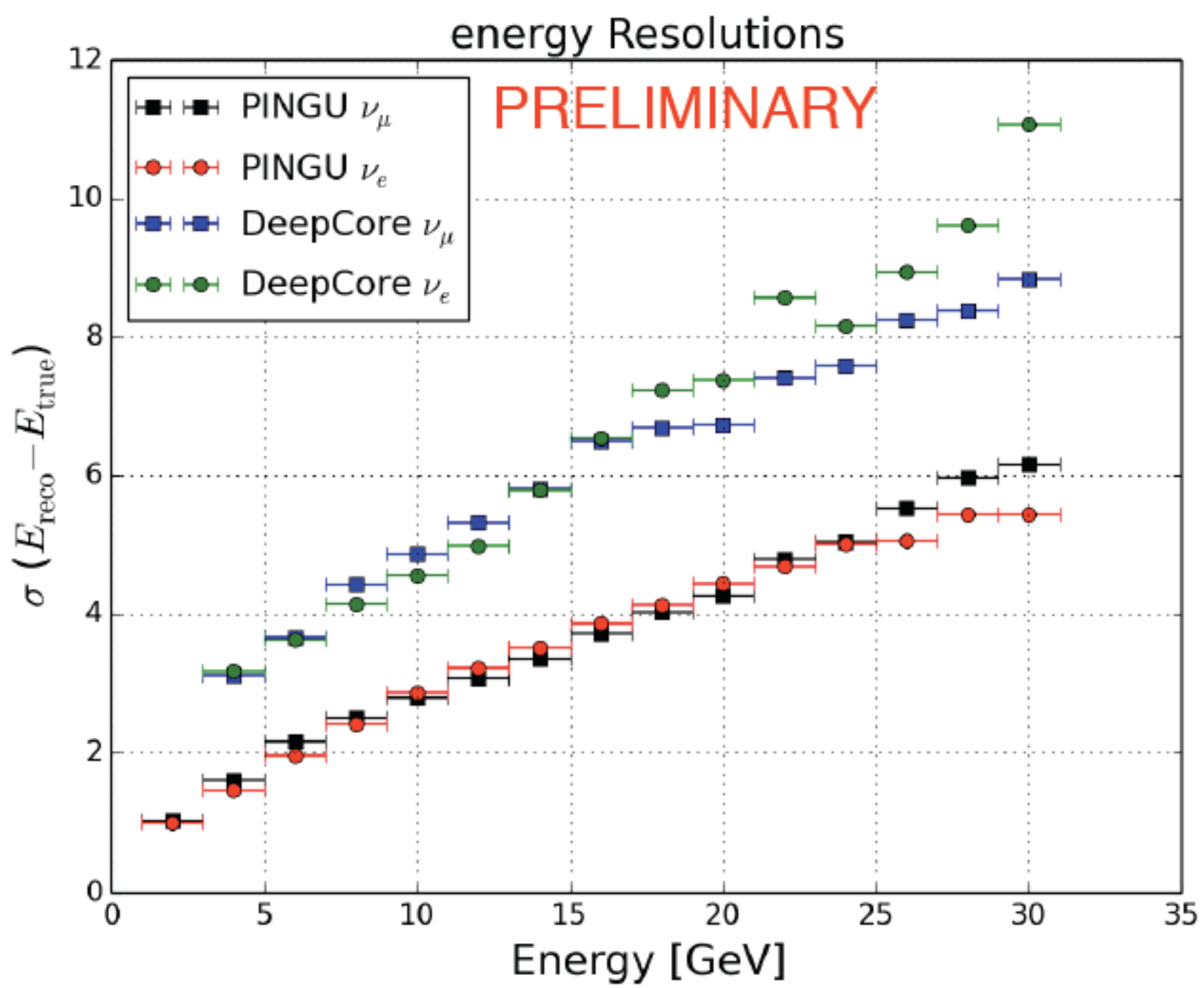
Backup Slides

PINGU particle identification



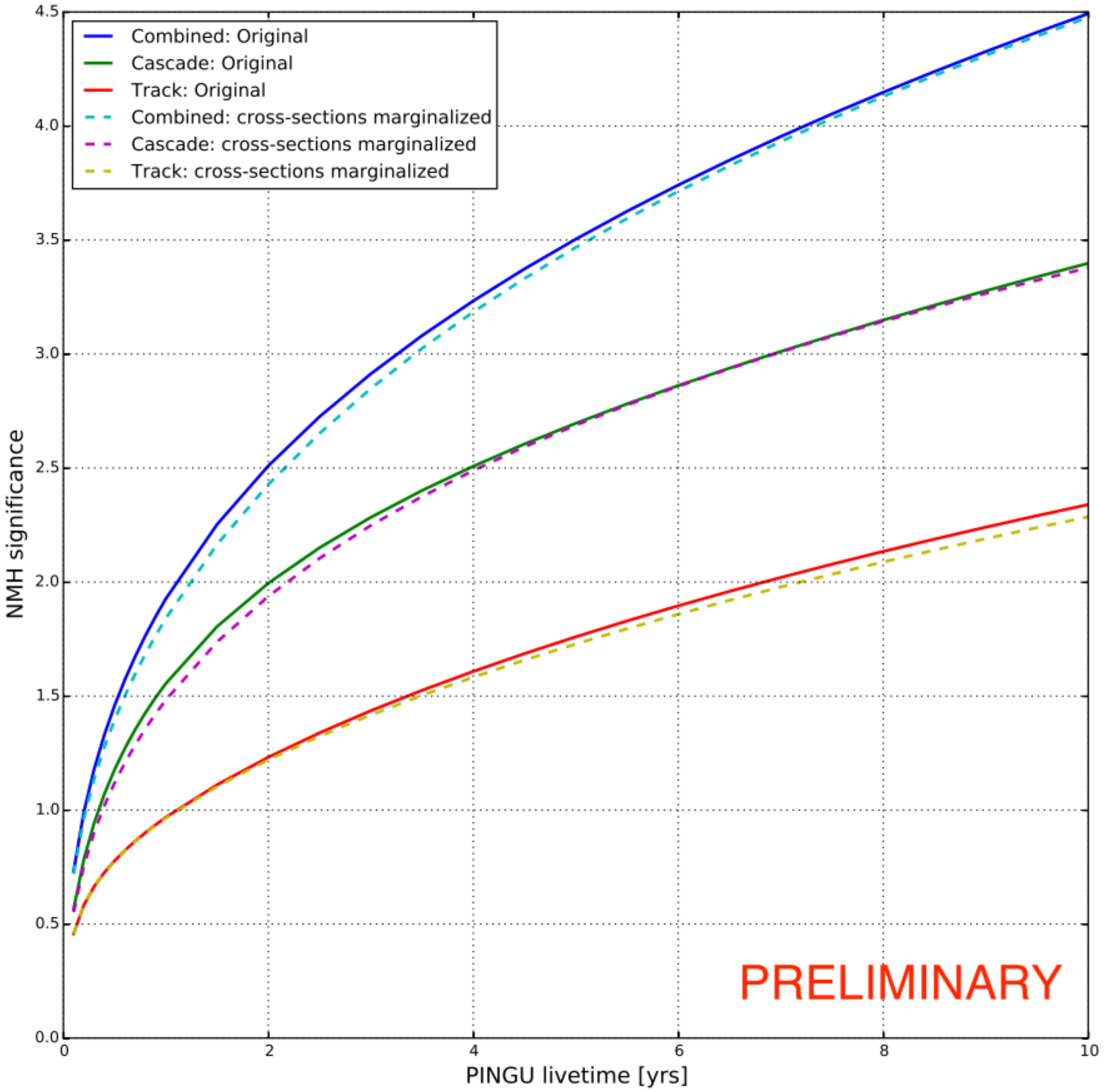
PINGU event reconstruction resolutions





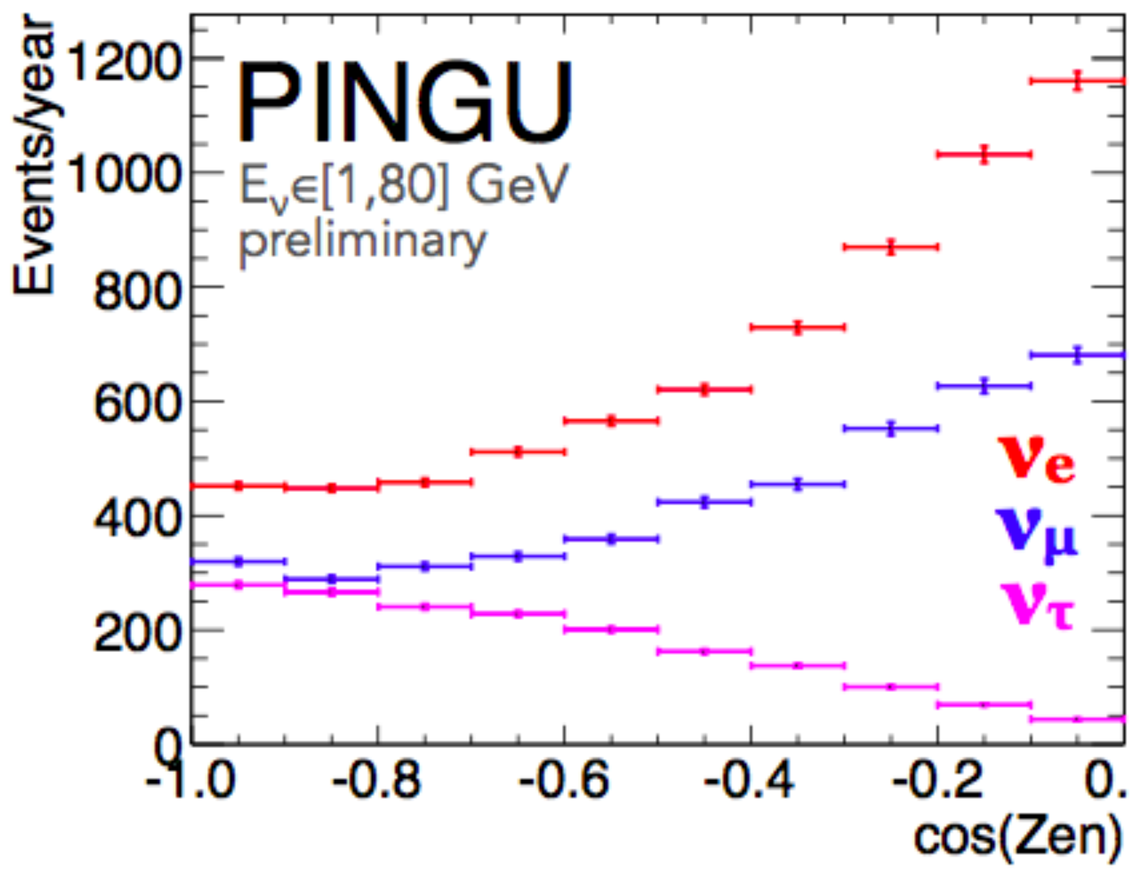
Neutrino interaction cross-section uncertainties

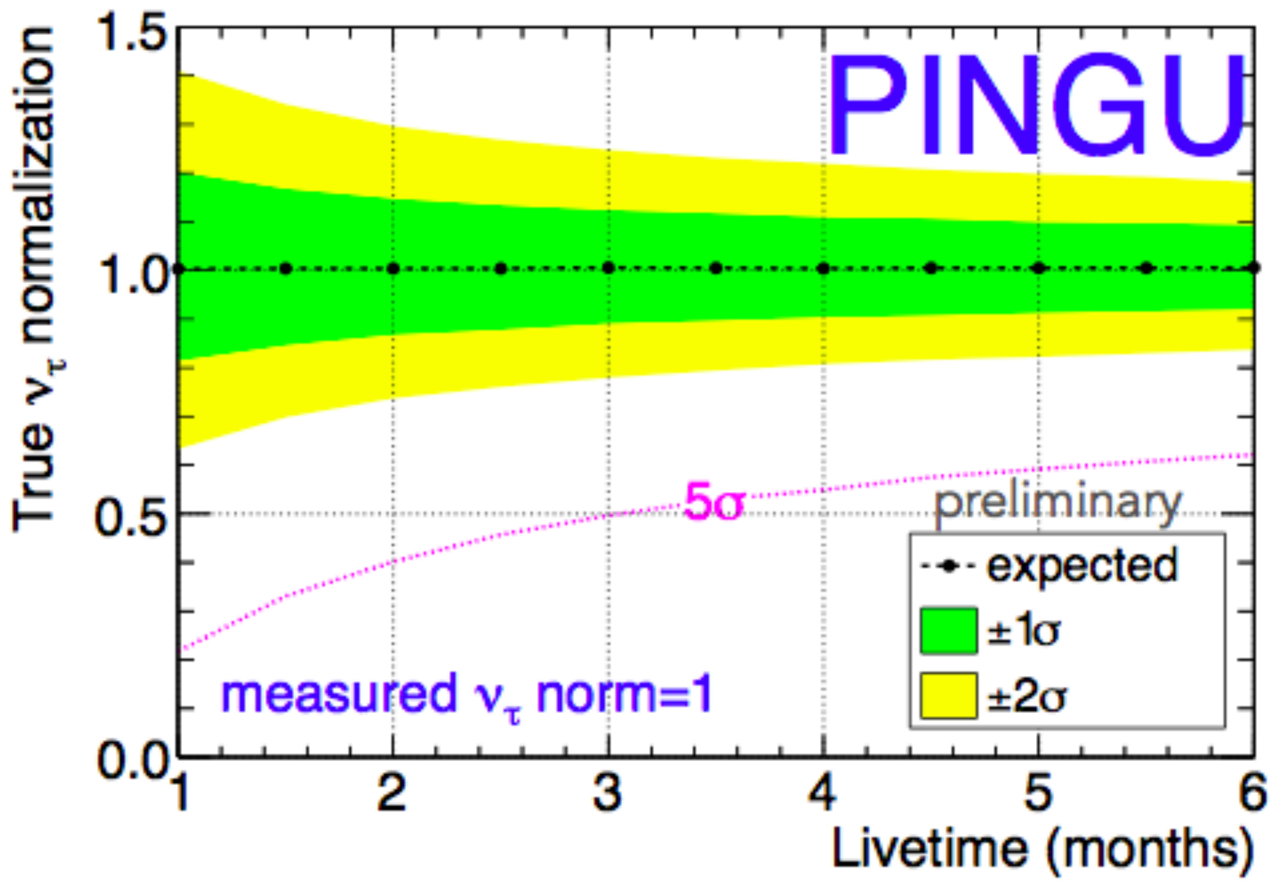
- x-section uncertainties from GENIE
- Strongest impact from:
  - axial mass parameters for CCQE and hadron resonance production
  - Bodek-Yang higher twist parameters for DIS
- small additional effect compared to existing systematics studied



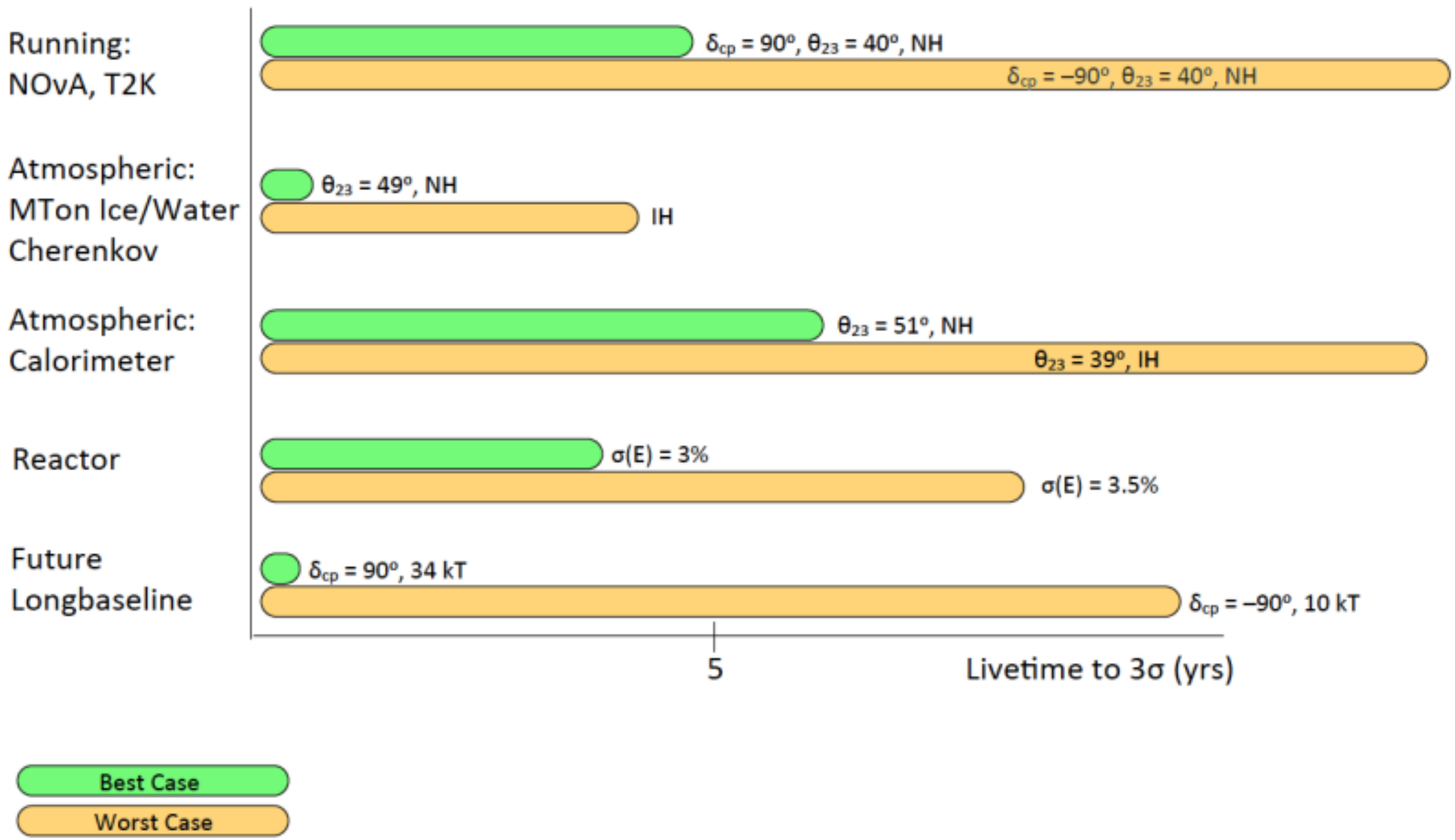
ν_τ appearance

- utilizes a similar analysis to that for the mass ordering
- reaches a 5 sigma observation in a matter of months…





NMO sensitivity for various detection techniques



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