ICECUBE

ICECUBE GEN2


PRECISION ICECUBE NEXT GENERATION UPGRADE

# Measuring the neutrino mass hierarchy with atmospheric neutrinos in IceCube(-Gen2)

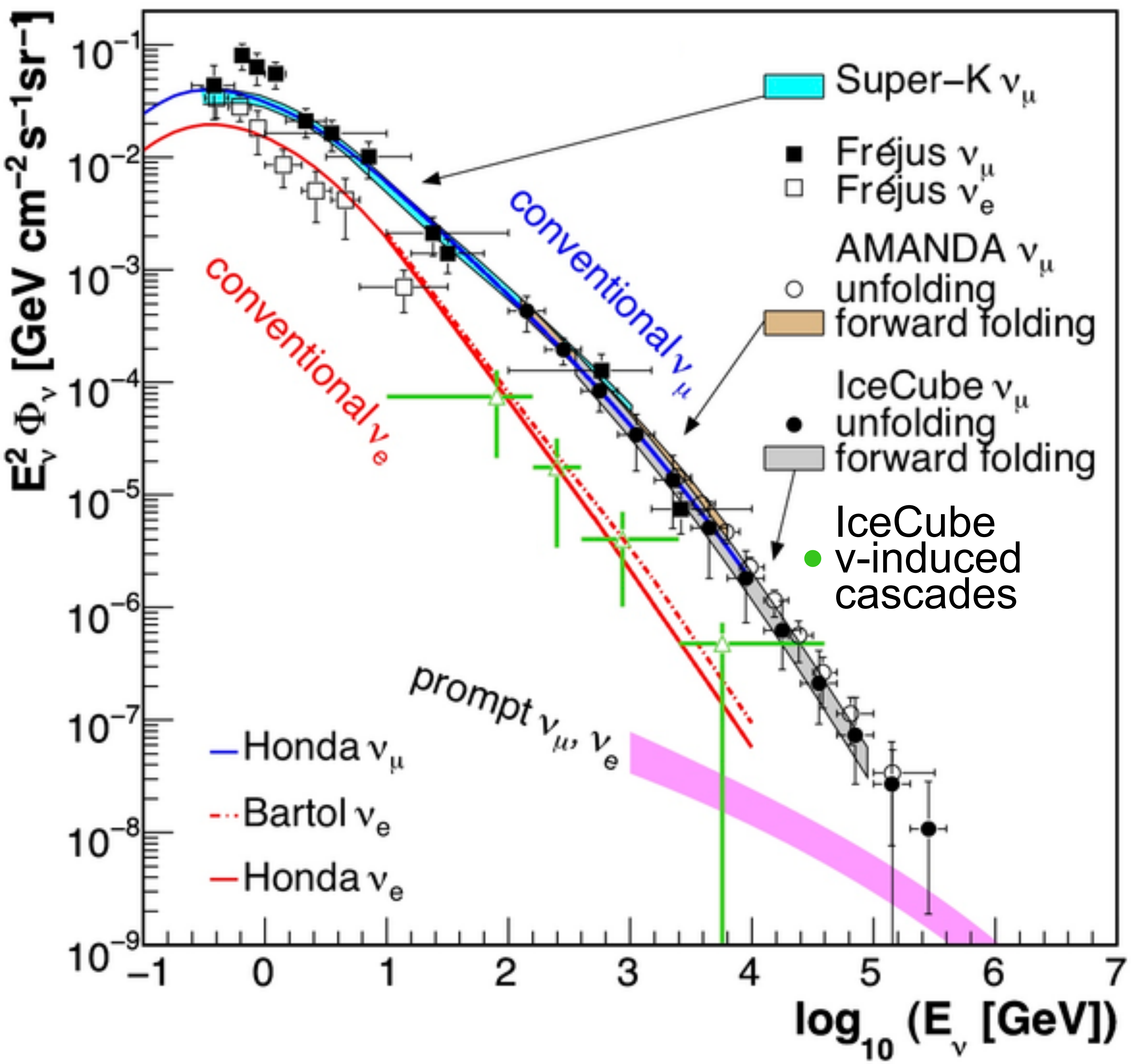
## Beyond the Standard Model with Neutrinos and Nuclear Physics

Solvay Workshop
November 30, 2017

UNIVERSITY OF ALBERTA

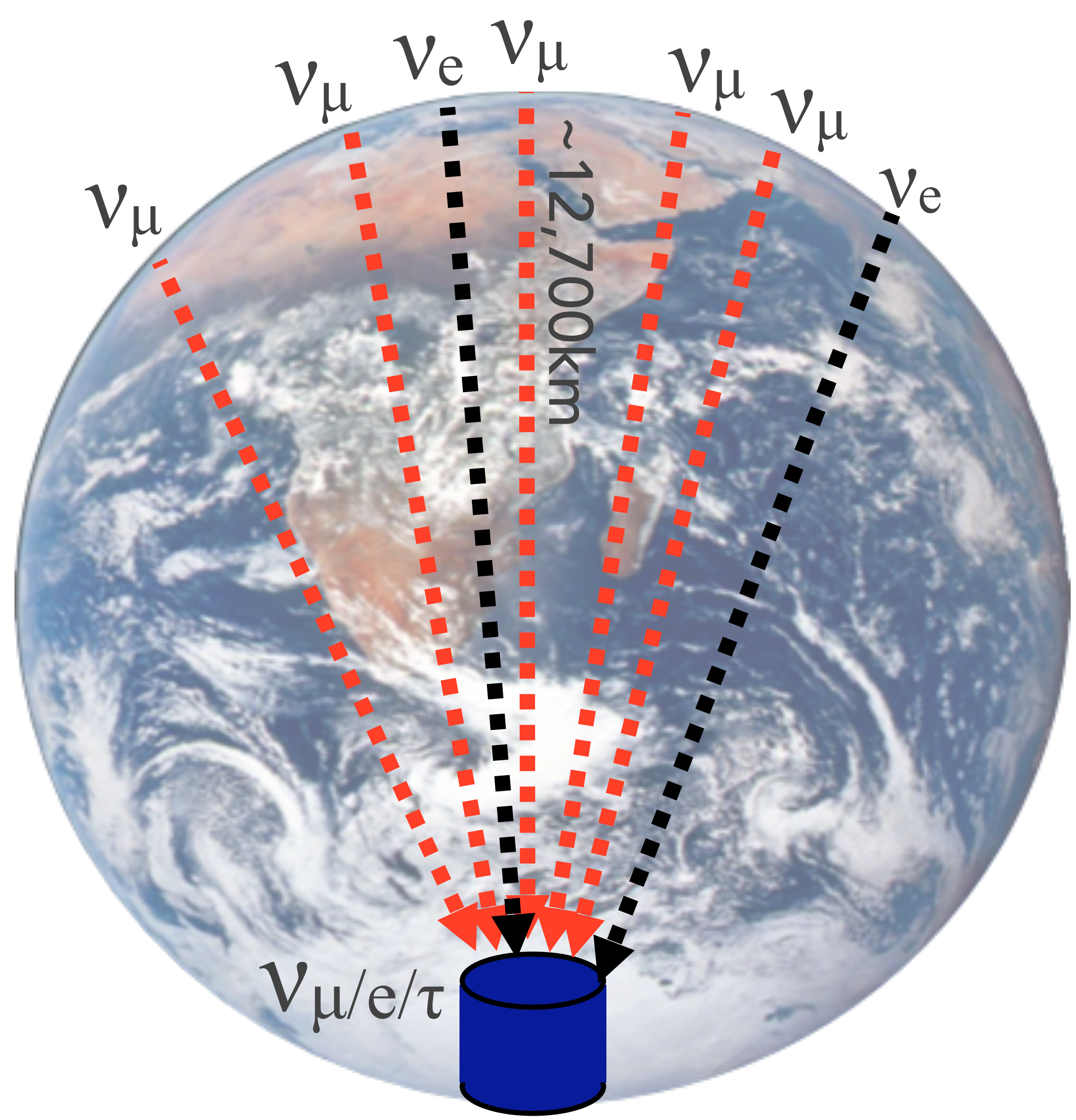
Darren R Grant

# The atmospheric neutrino signal



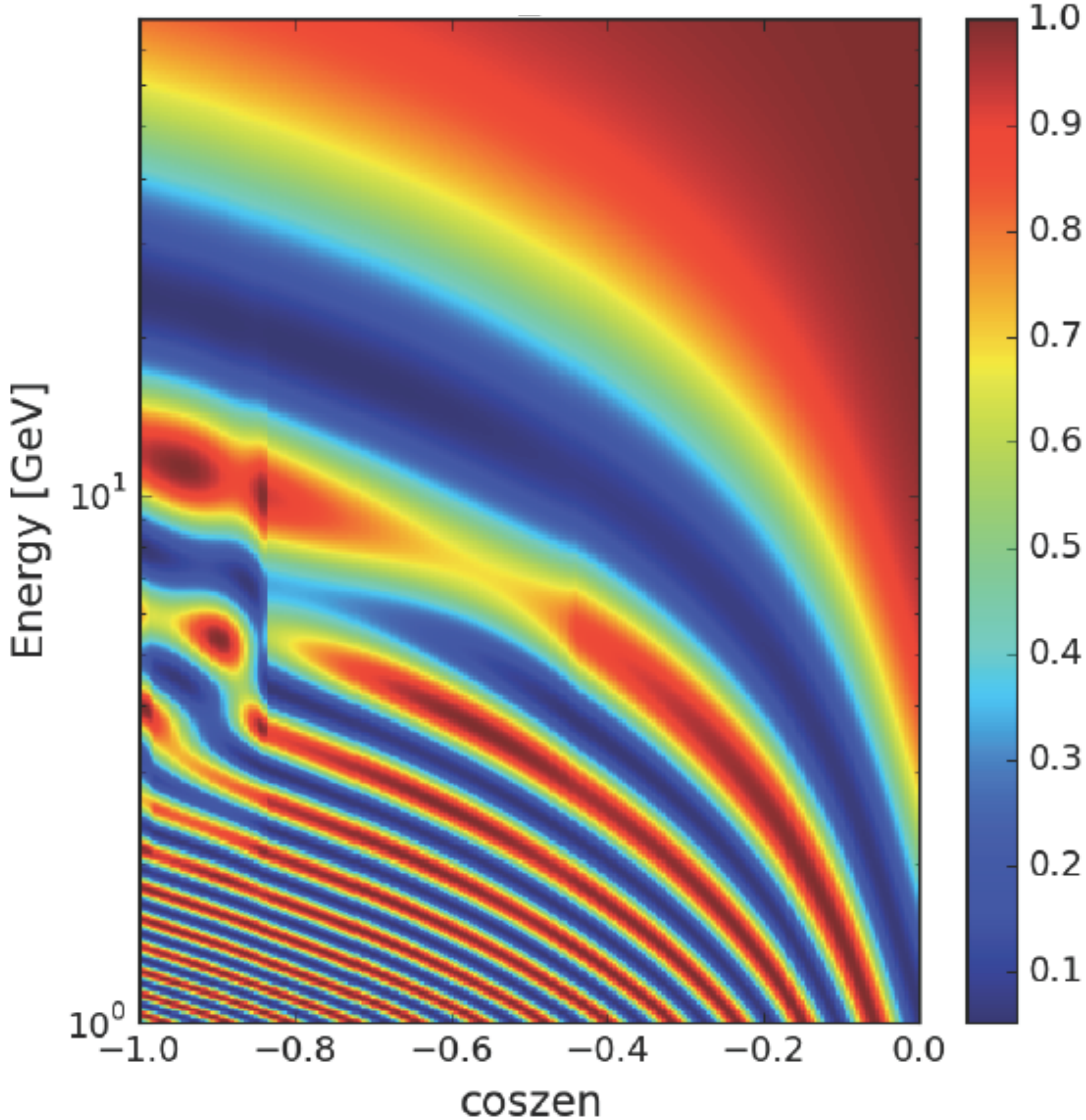
# Oscillations with Atmospheric Neutrinos

- 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

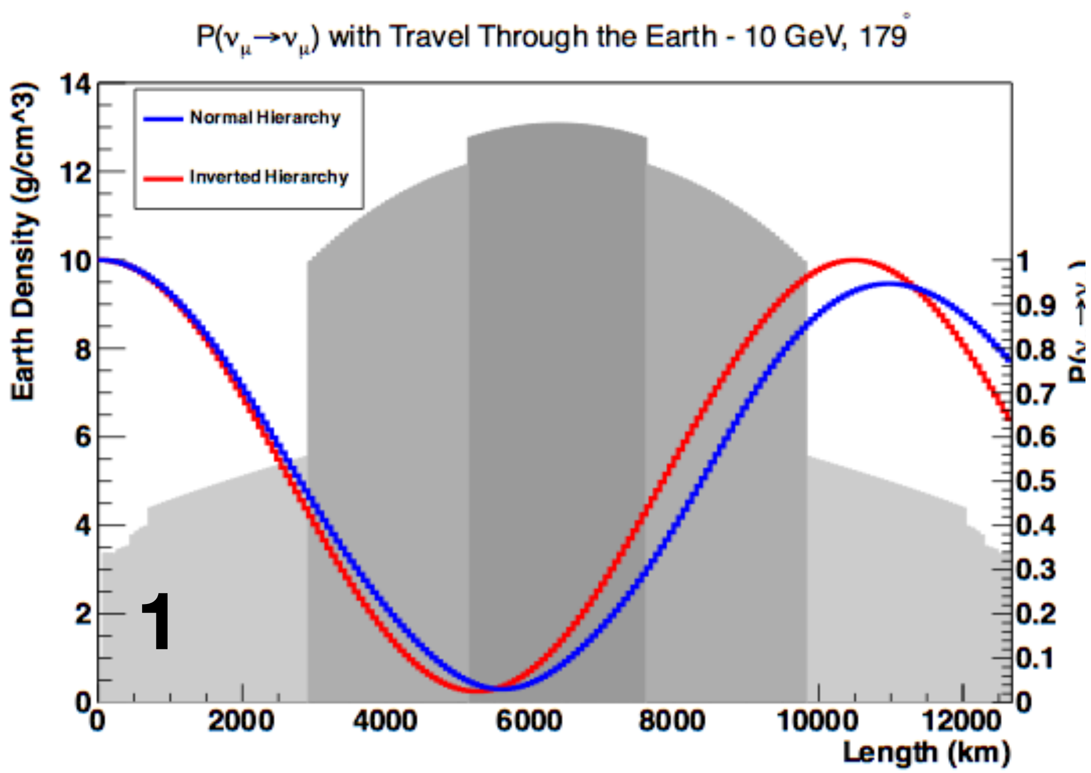
- Neutrinos are available over a wide range of energies and baselines
  - Comparison of observations from different baselines and energies is crucial for controlling systematics
  - Essentially, a generalization of the up-down ratio approach
- Atmospheric neutrinos oscillating over one Earth diameter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

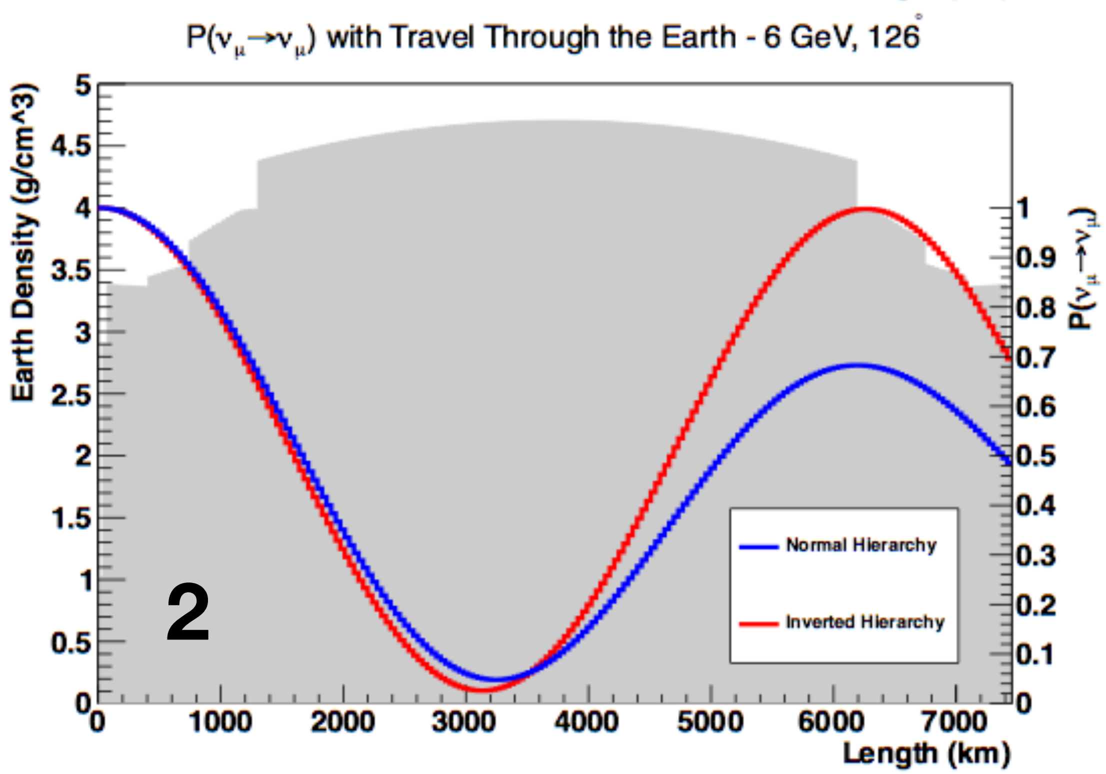


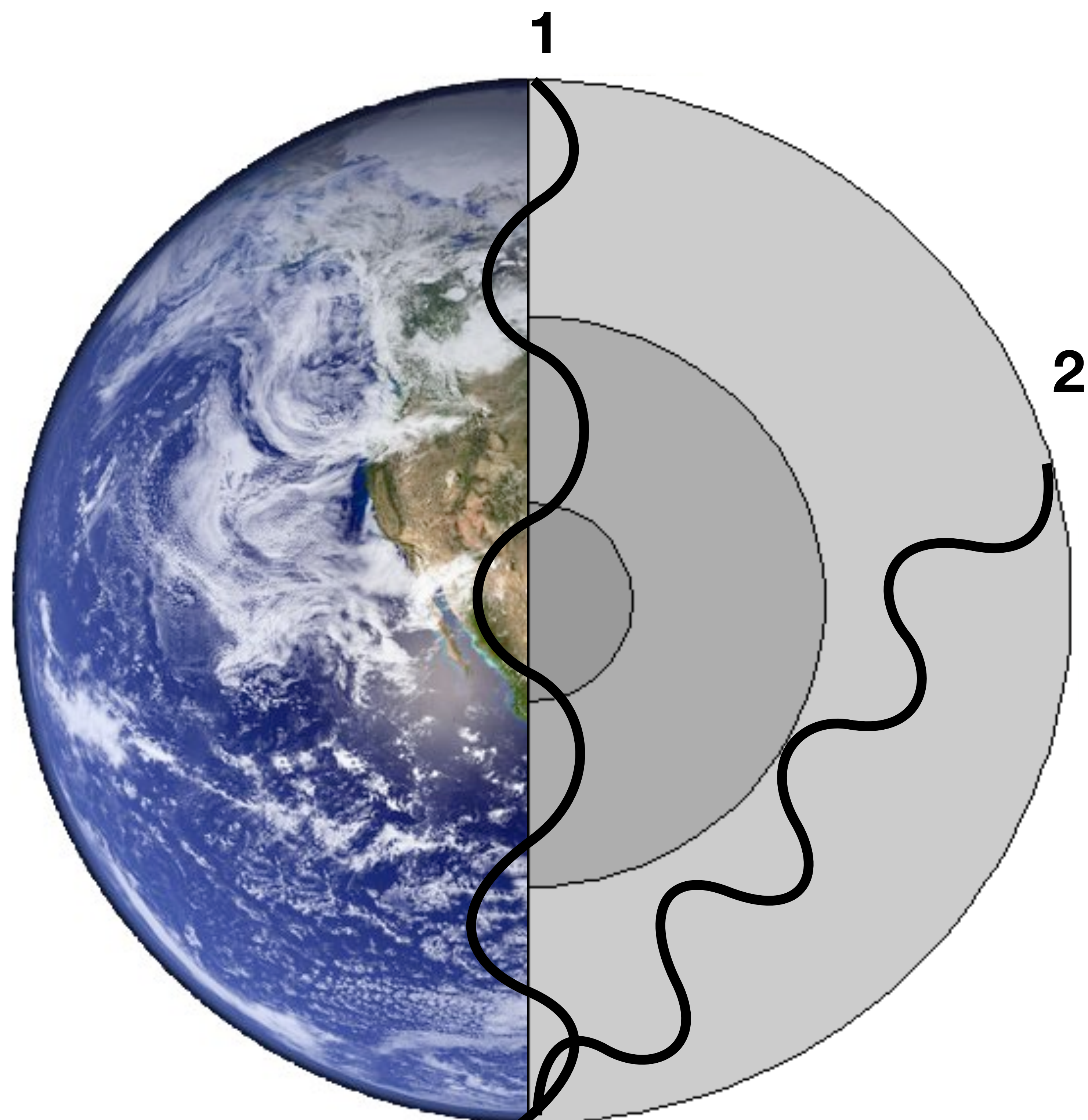

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

# Using atmospheric neutrinos to measure the mass ordering

Up to 20% differences in $\nu_\mu$ survival probabilities for various energies and baselines, depending on the neutrino mass ordering (NMO)



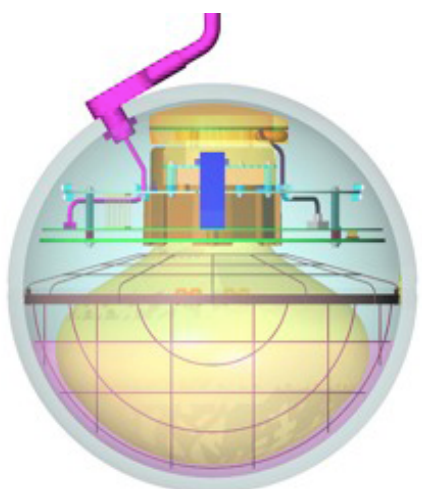



# The IceCube Neutrino Observatory

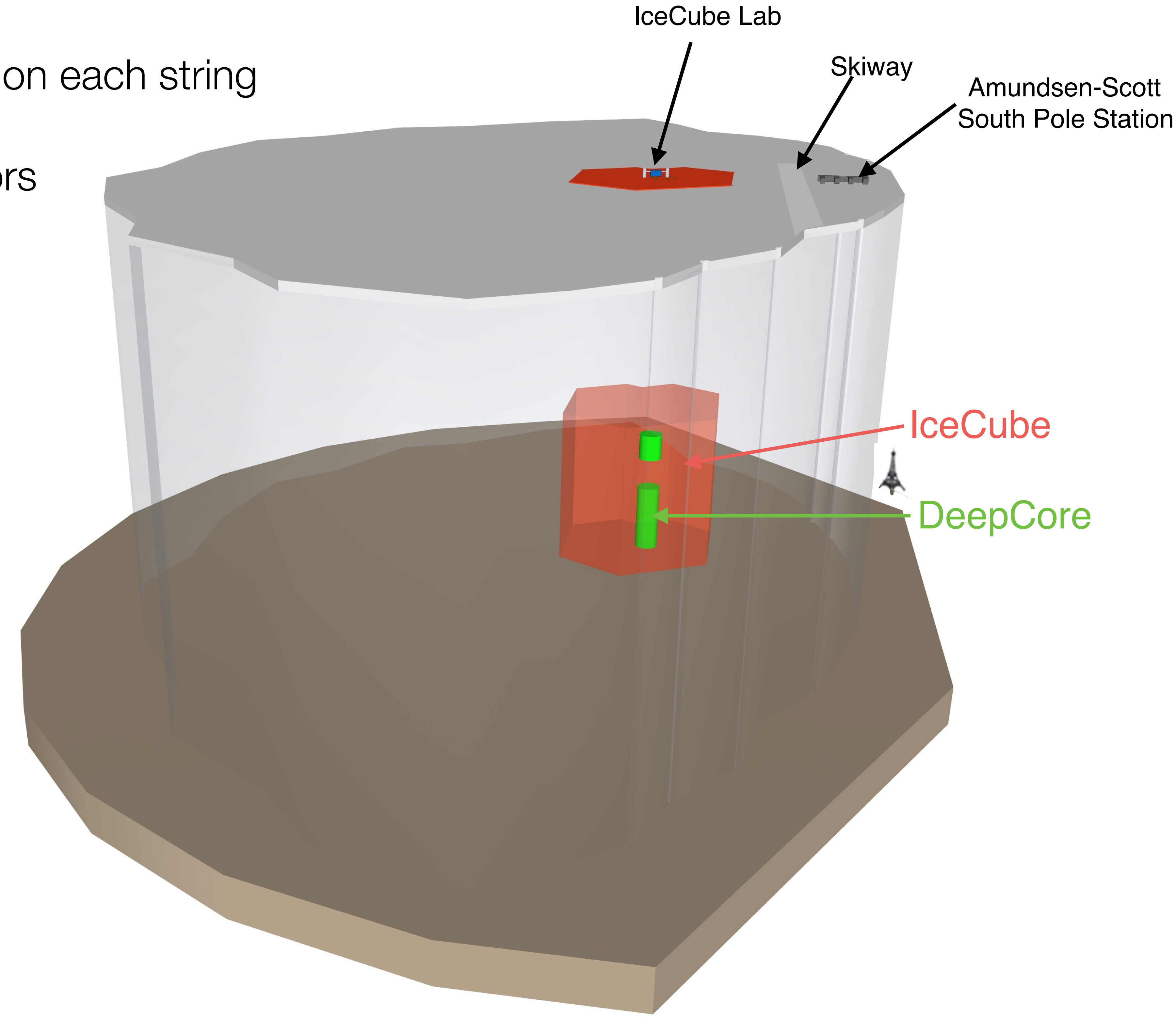
IceCube Array
86 total strings, including 8
DeepCore strings

60 optical sensors on each string

5160 optical sensors



Digital Optical Module

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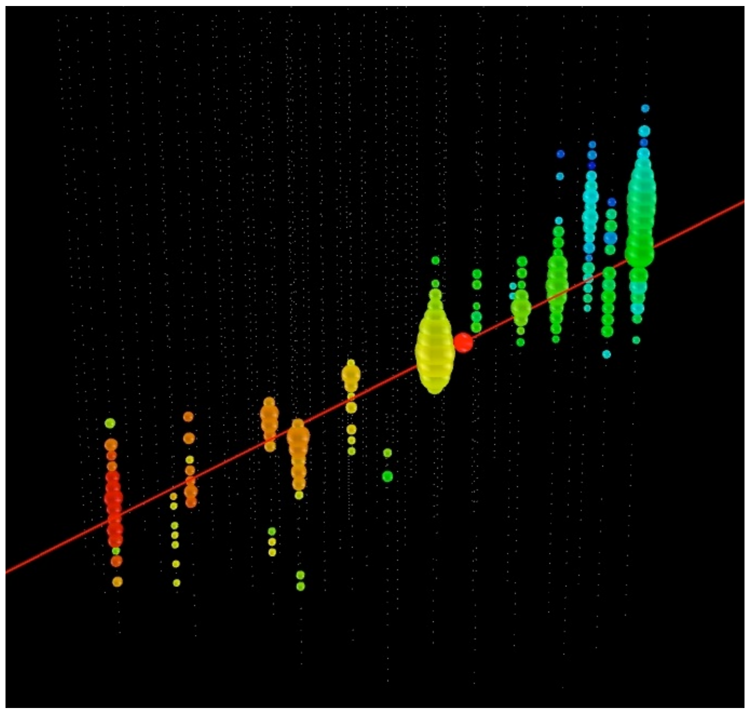
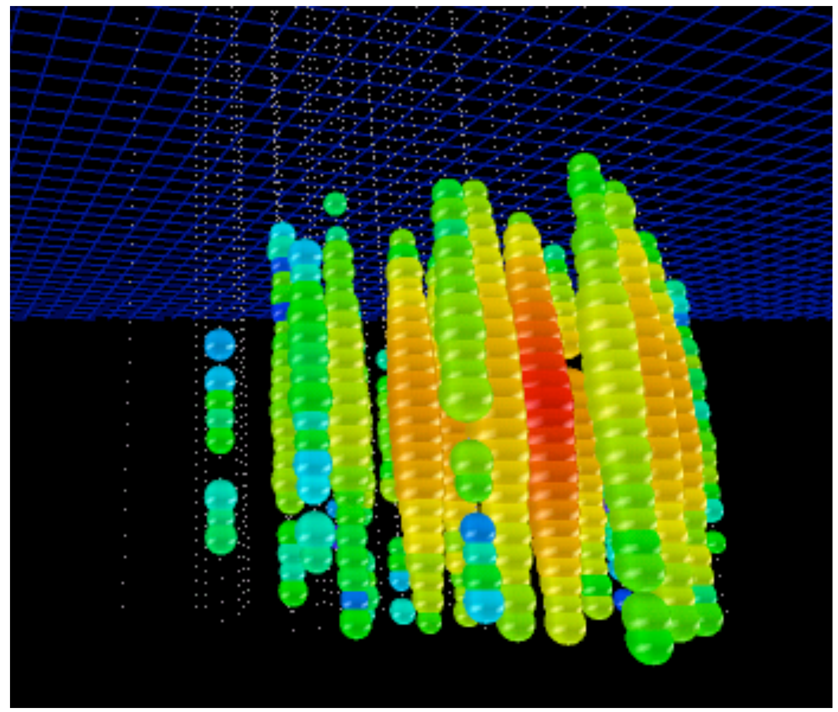
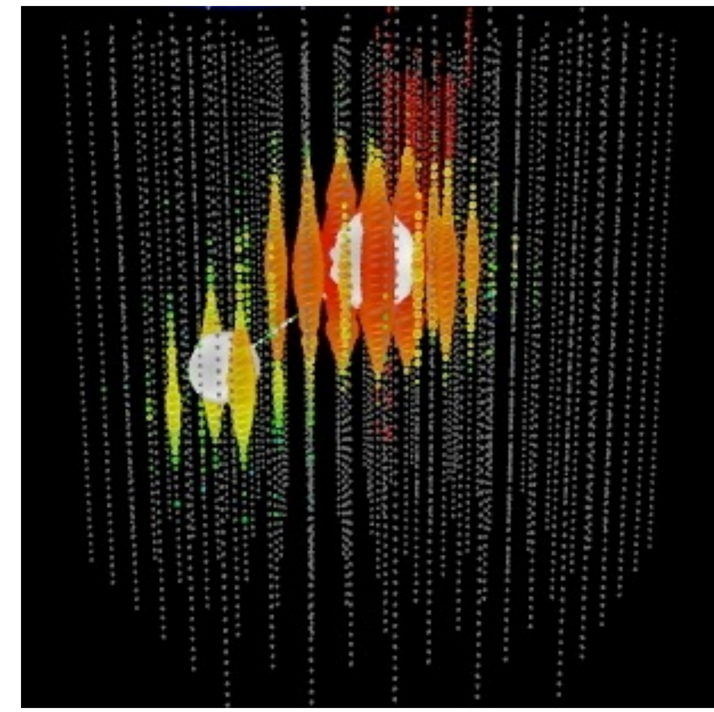
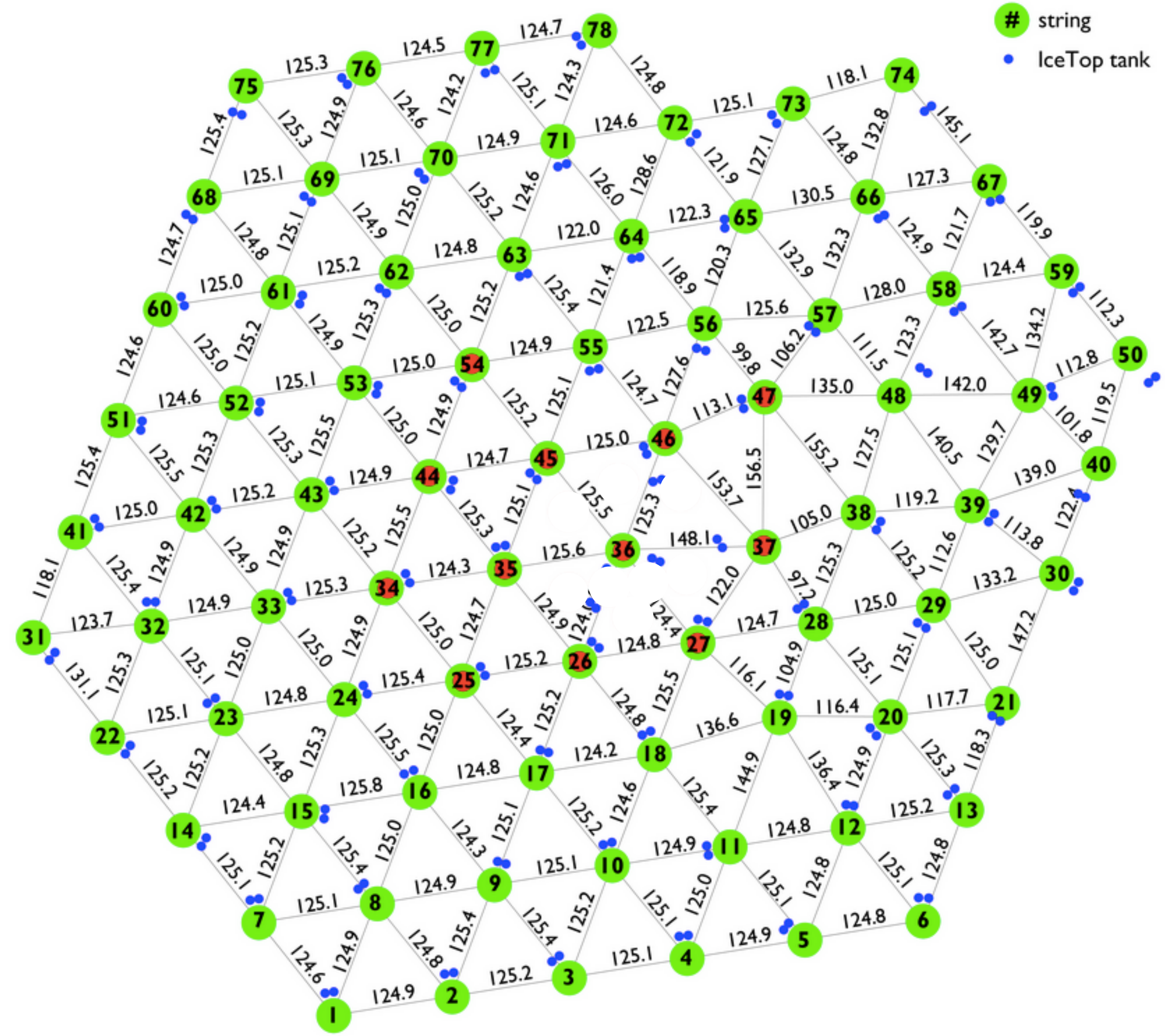
# IceCube detection principle

| CC Muon Neutrino | Neutral Current / Electron Neutrino | CC Tau Neutrino |
|---|---|---|
|  |  |  |
| track (data) | cascade (data) | “double-bang” (≳10PeV) and other signatures (simulation) |
| factor of ≈ 2 energy resolution<br>< 1° angular resolution at high energies | ≈ ±15% deposited energy resolution<br>≈ 10° angular resolution (at energies ≳ 100 TeV) | (not observed yet: τ decay length is 50 m/PeV) |

# IceCube

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

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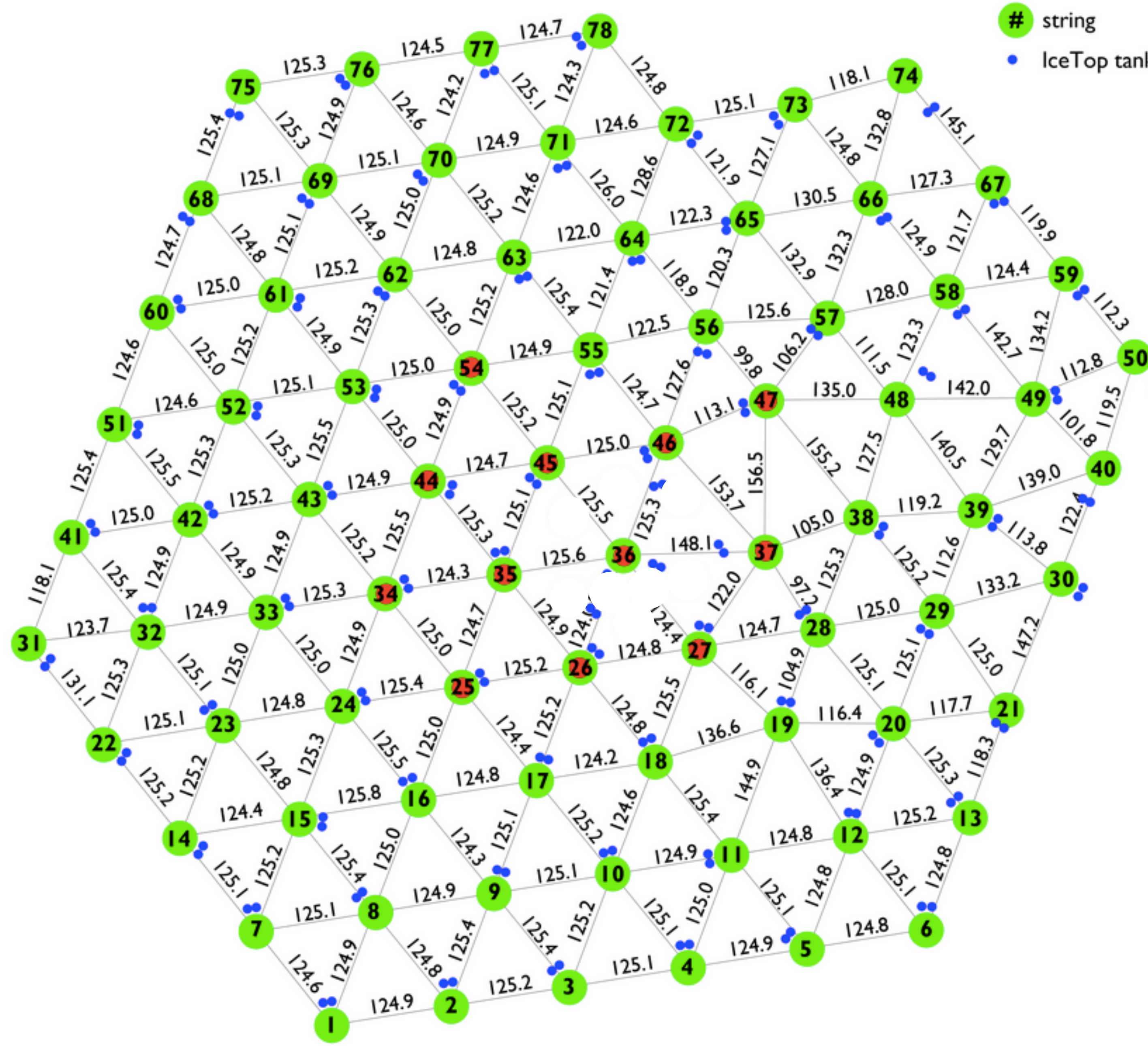


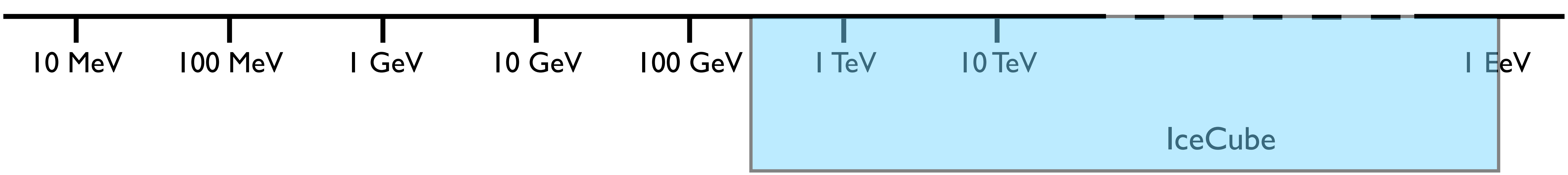


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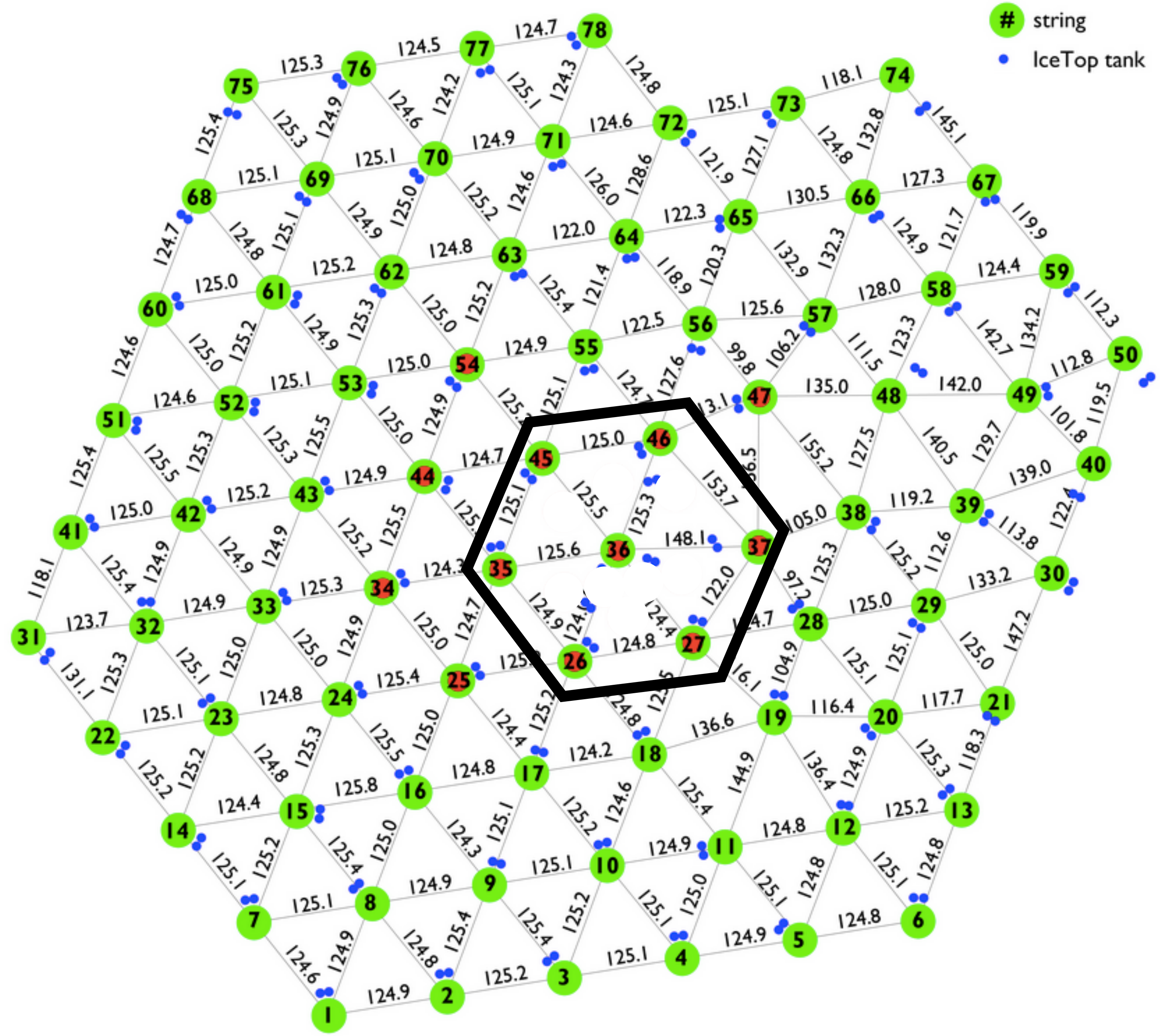


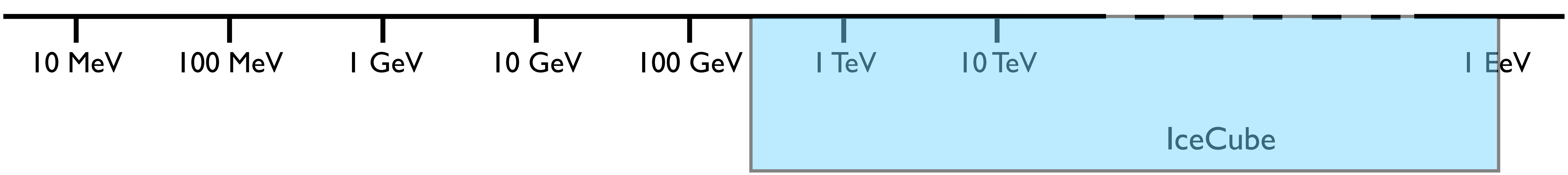


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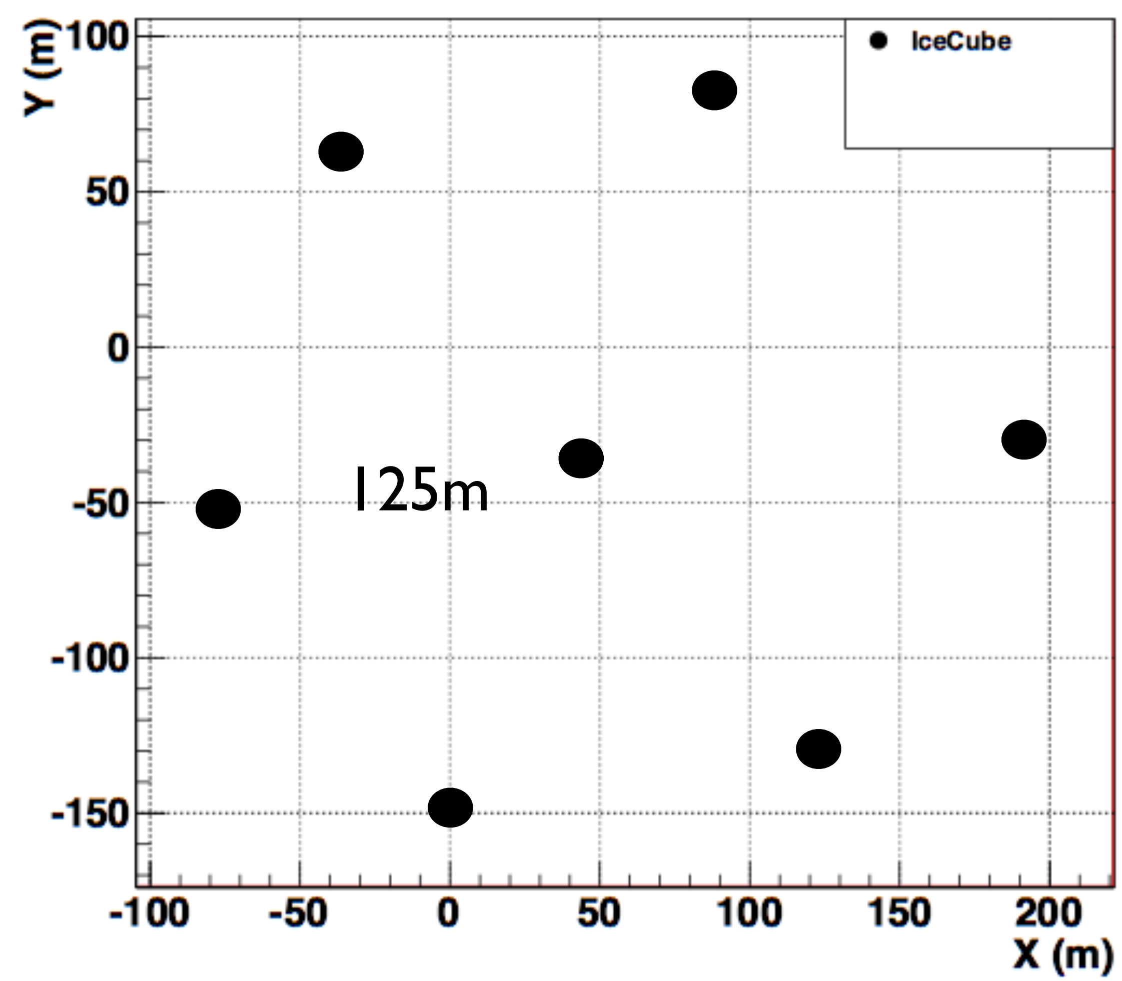
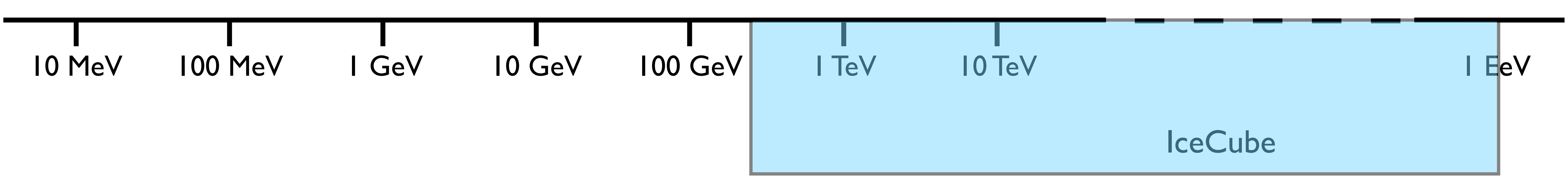
IceCube top view

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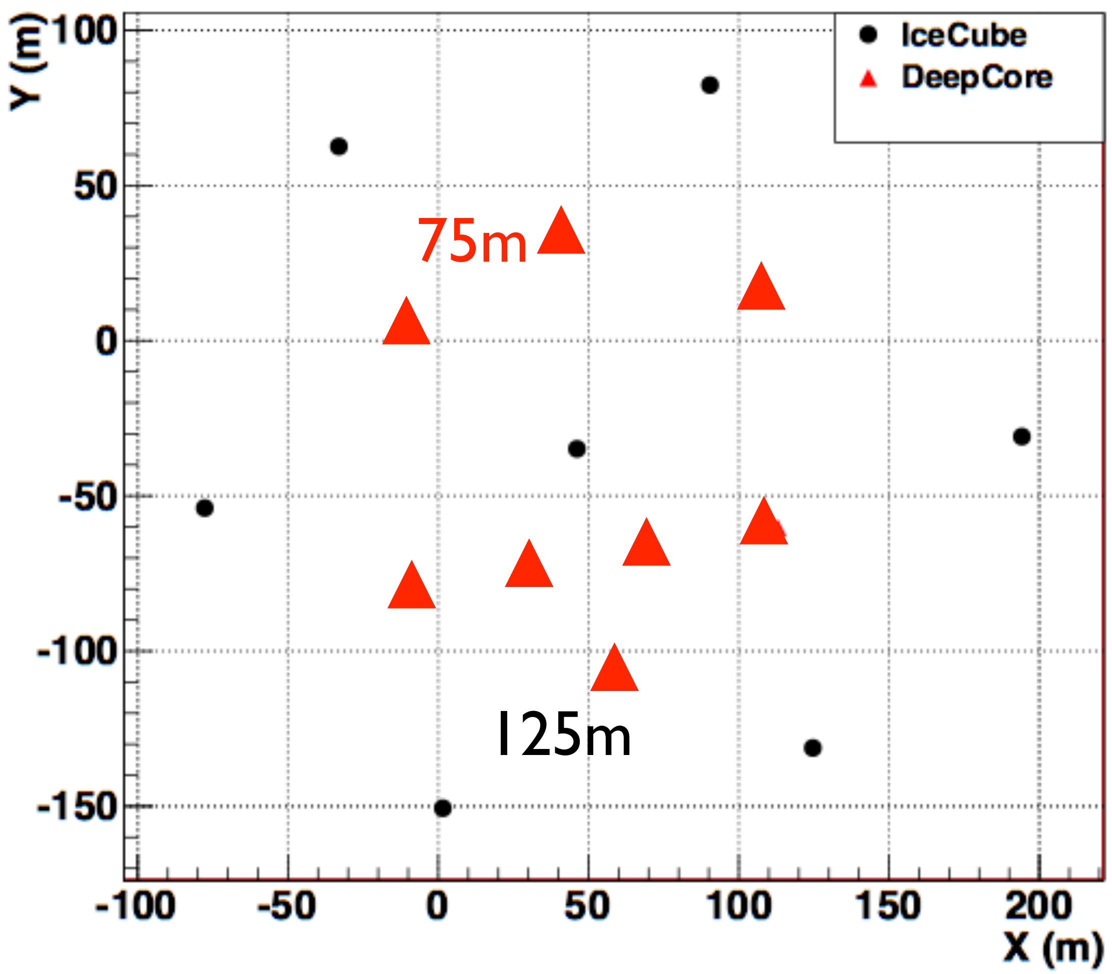
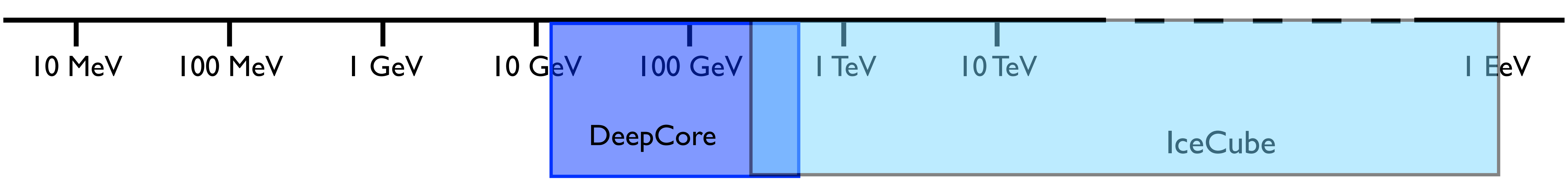
# IceCube-DeepCore

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

IceCube-DeepCore top view

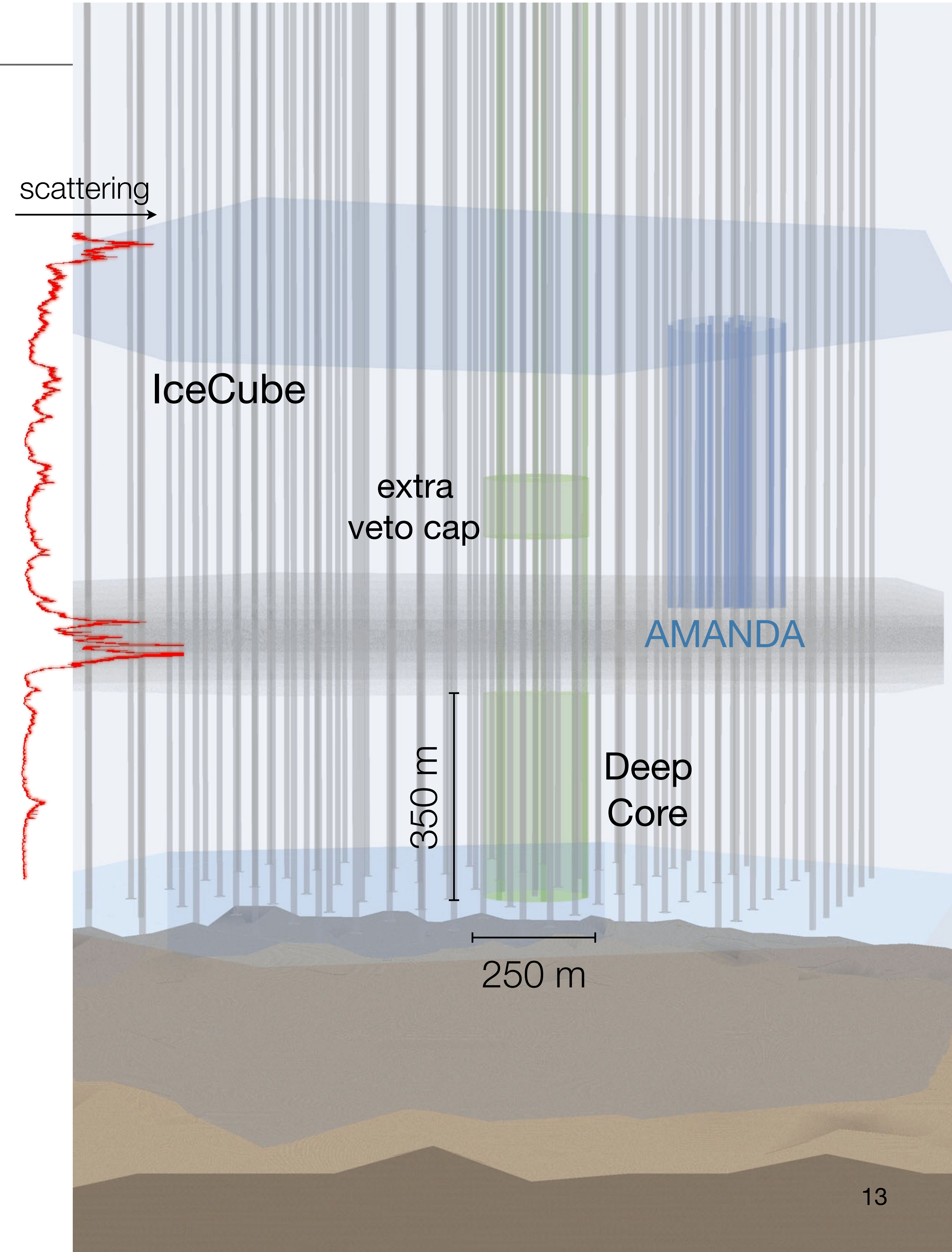


# IceCube-DeepCore

Astropart. Phys. Vol.35 Issue 10 (615-624)

- More densely instrumented region at the bottom centre of IceCube
  - Eight special strings plus 12 nearest standard strings (72 m inter-string horizontal spacing (six with 42 m spacing)
  - ~35% higher Q.E. PMTs
  - ~5x higher effective photocathode density
- Deployed mainly in the clearest ice, below 2100 m

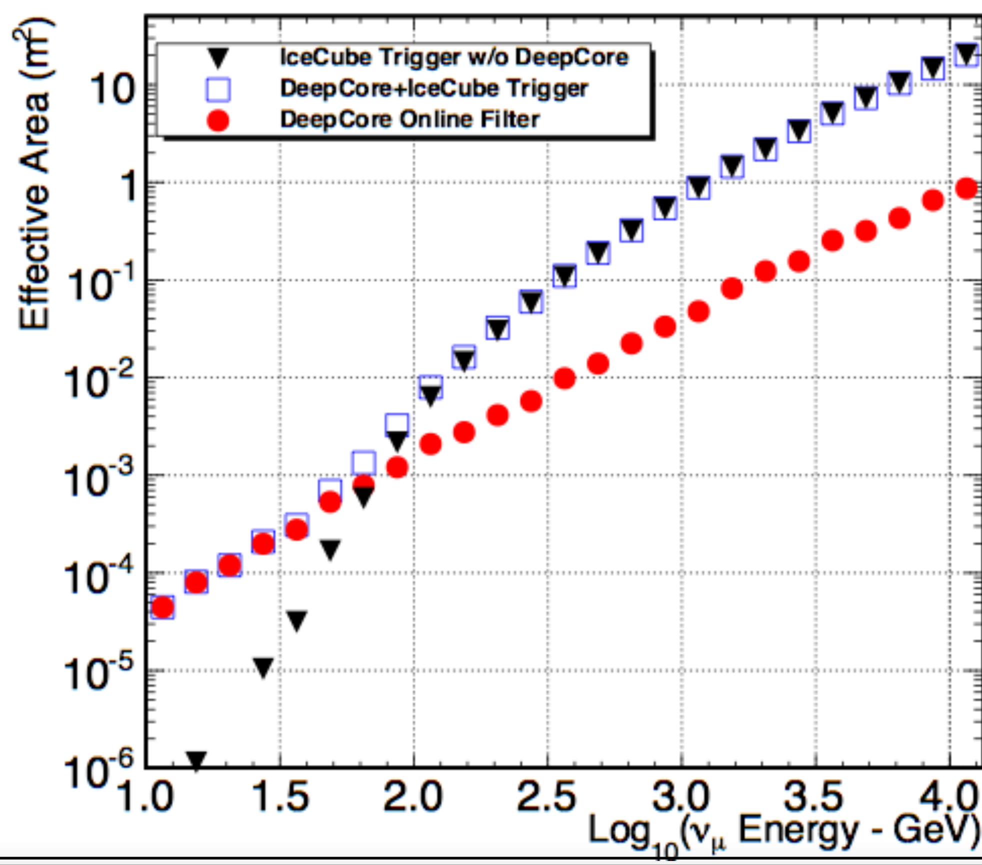


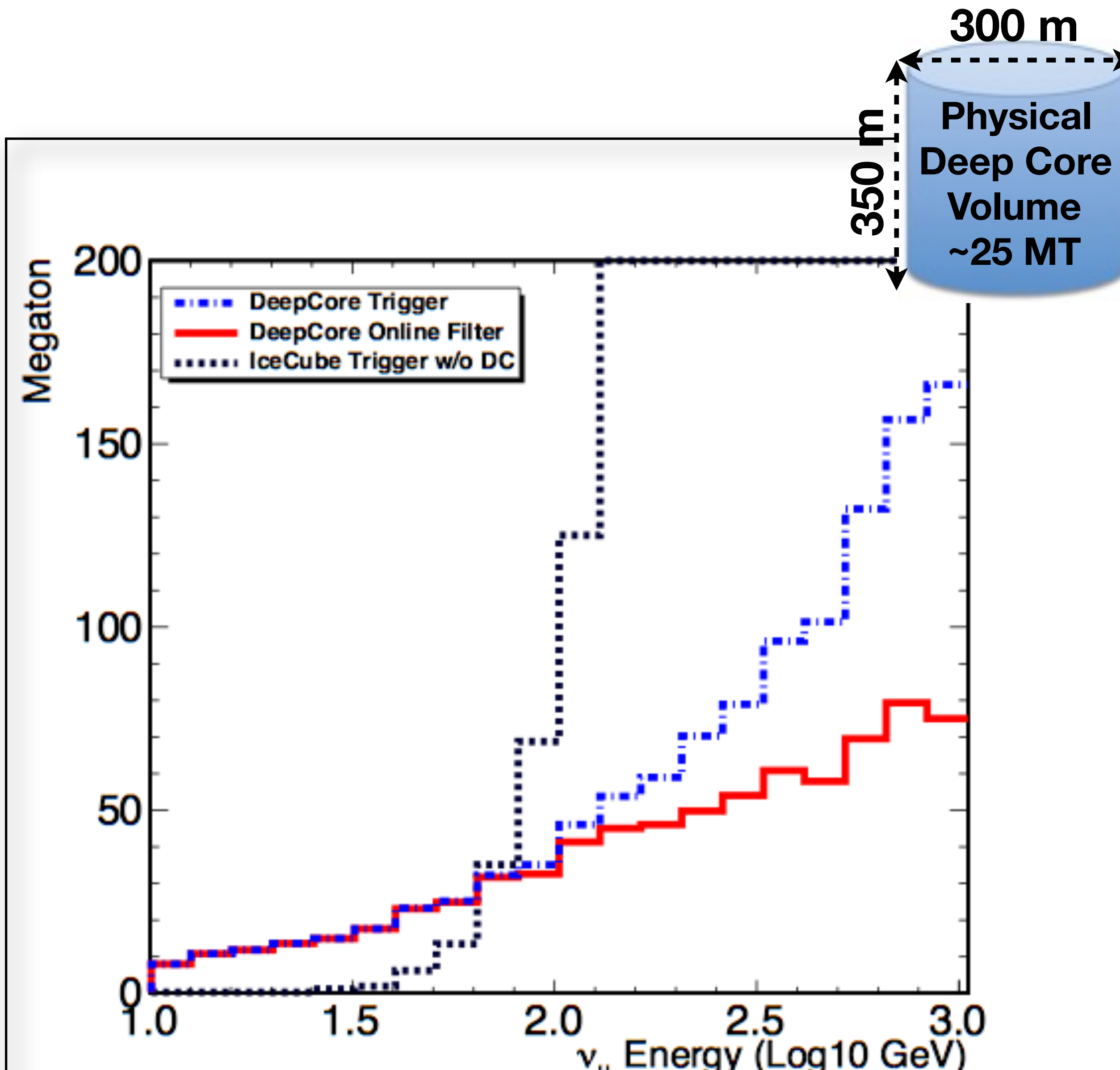
# DeepCore Effective Area and Volume

DeepCore provides an ~25MTon volume with a lower energy threshold that results in O($10^5$) neutrino triggers per year

## Effective area for $\nu_\mu$ at trigger level

Reconstruction efficiencies not included yet – relative effect likely to increase



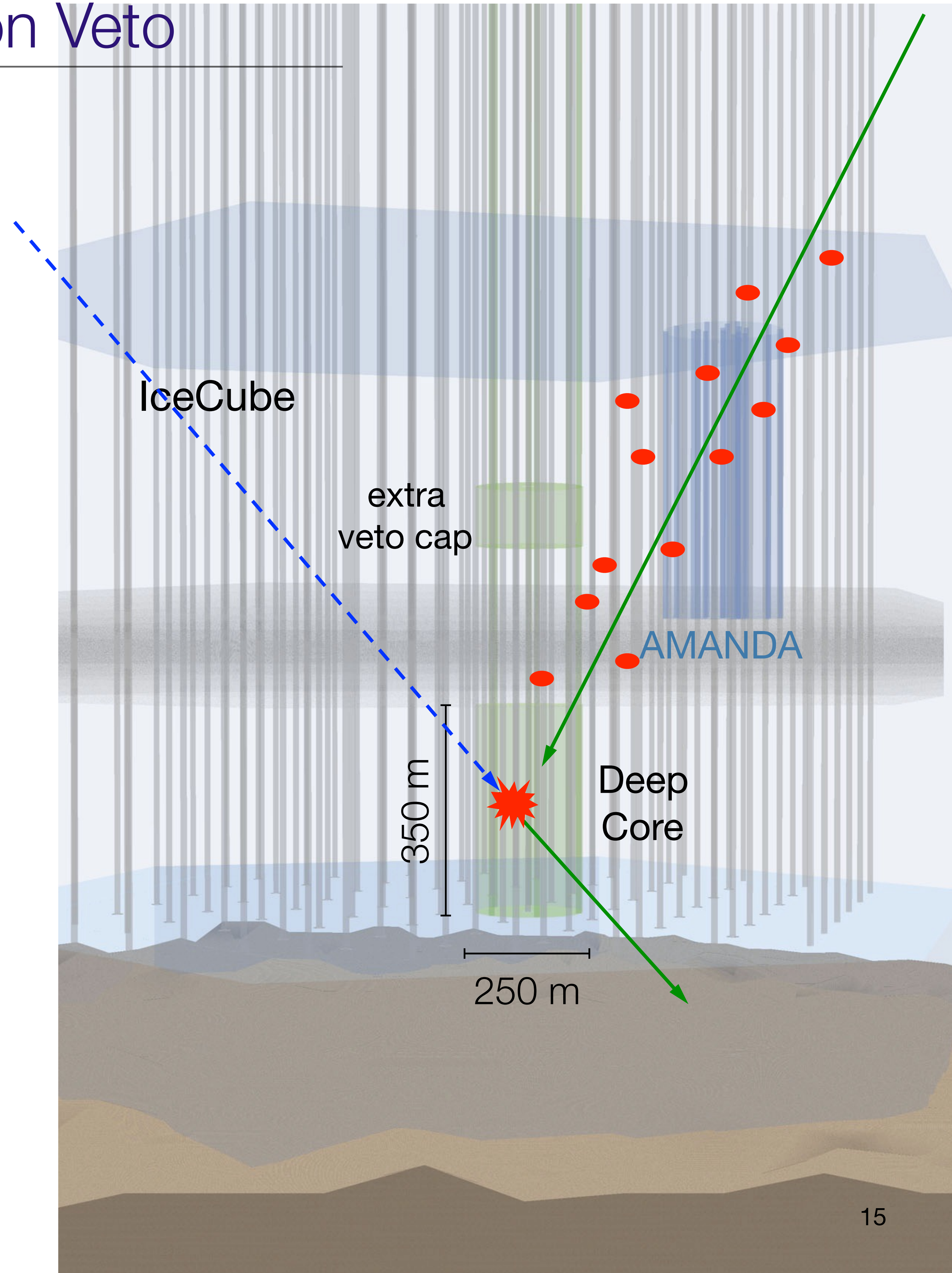

Effective volume for muons from $\nu_\mu$ interacting in Deep Core

NB: full analysis efficiency *not* included yet

Trigger: $\geq$3 DOMs hit in 2.5$\mu$s;
Online Veto: No hits consistent with muons outside DeepCore volume

# DeepCore Atmospheric Muon Veto

- The cosmic ray muon background (around $10^6$ times the atmospheric neutrino rate)
- Overburden of 2.1 km water-equivalent is substantial, but not as large as at deep underground labs
- However, top and outer layers of IceCube provide an active veto shield for DeepCore
  - ~40 horizontal layers of modules above; 3 rings of strings on all sides
  - Effective μ-free depth much greater



# IceCube-DeepCore

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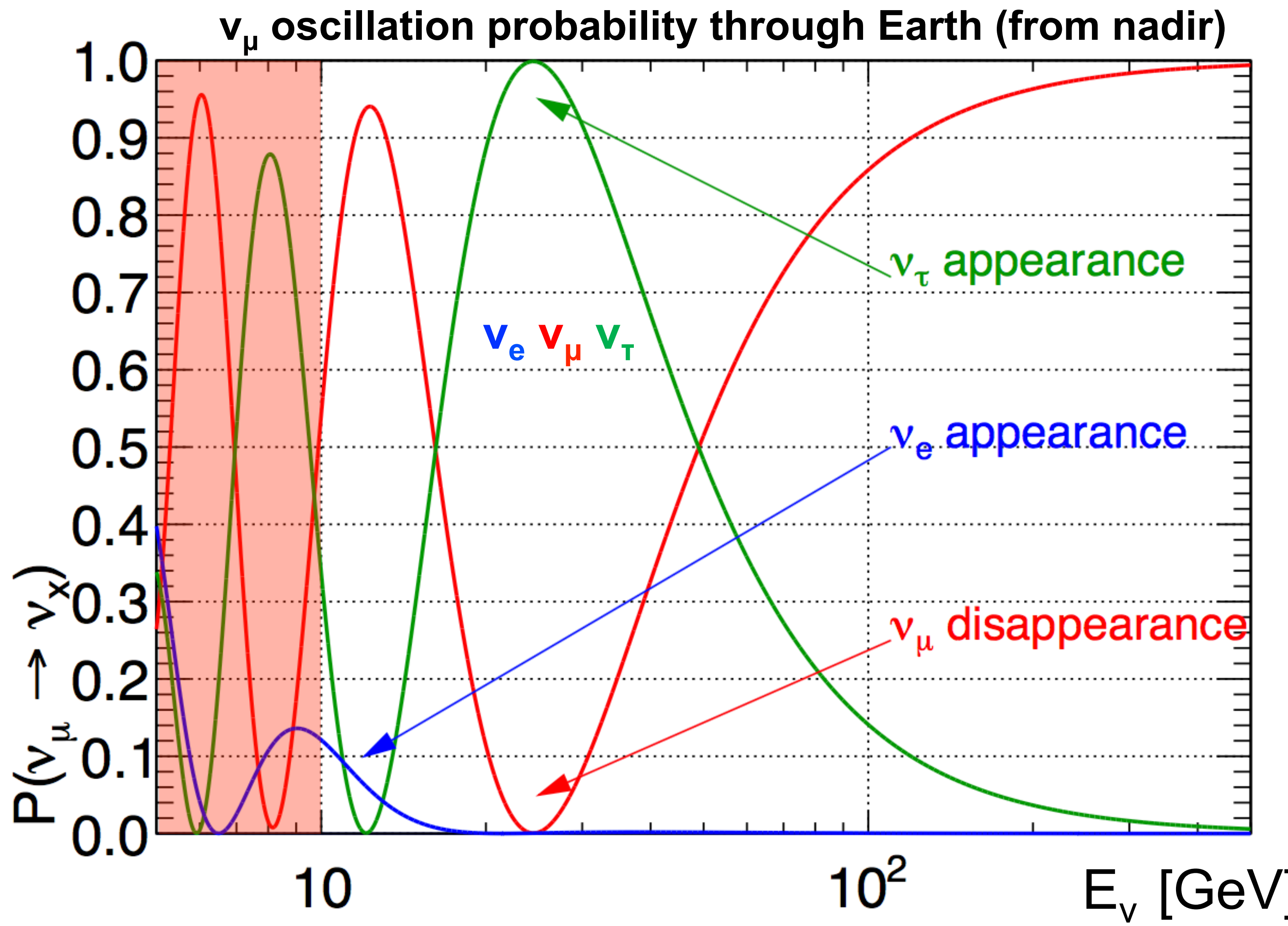
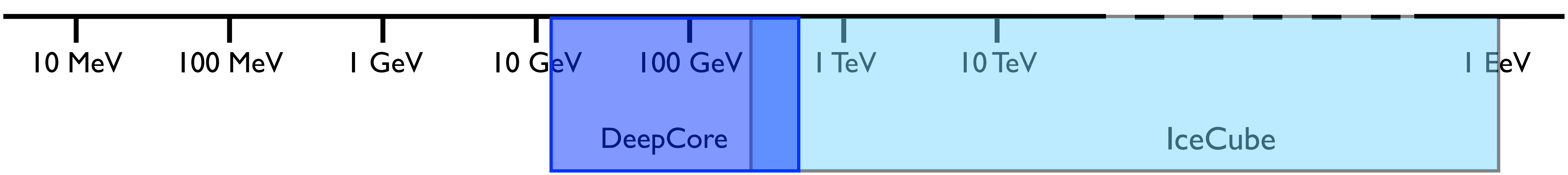
- Add 8 strings
  - 75m string spacing
  - 7m DOM spacing




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




Atmospheric neutrinos

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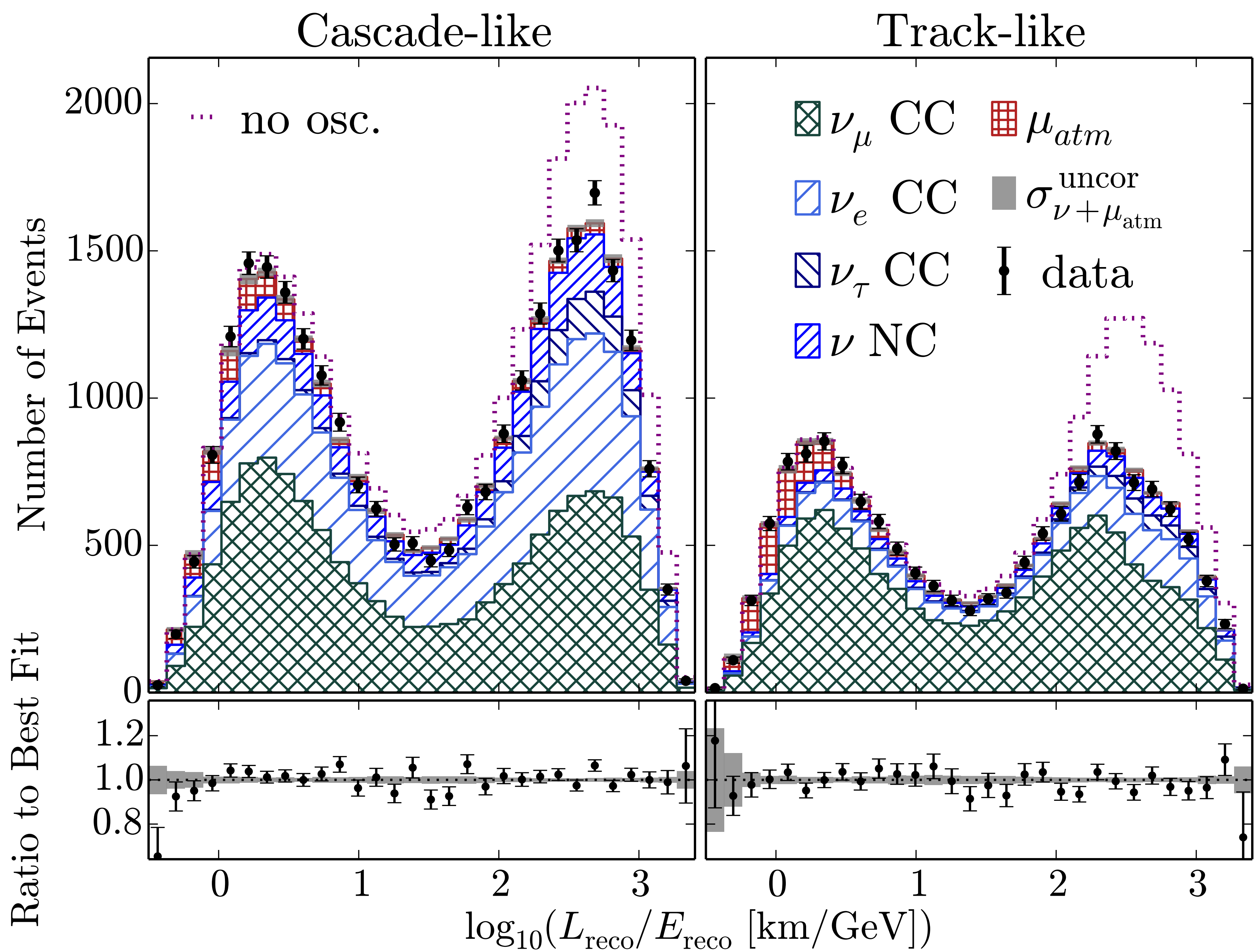
# DeepCore muon neutrino disappearance




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

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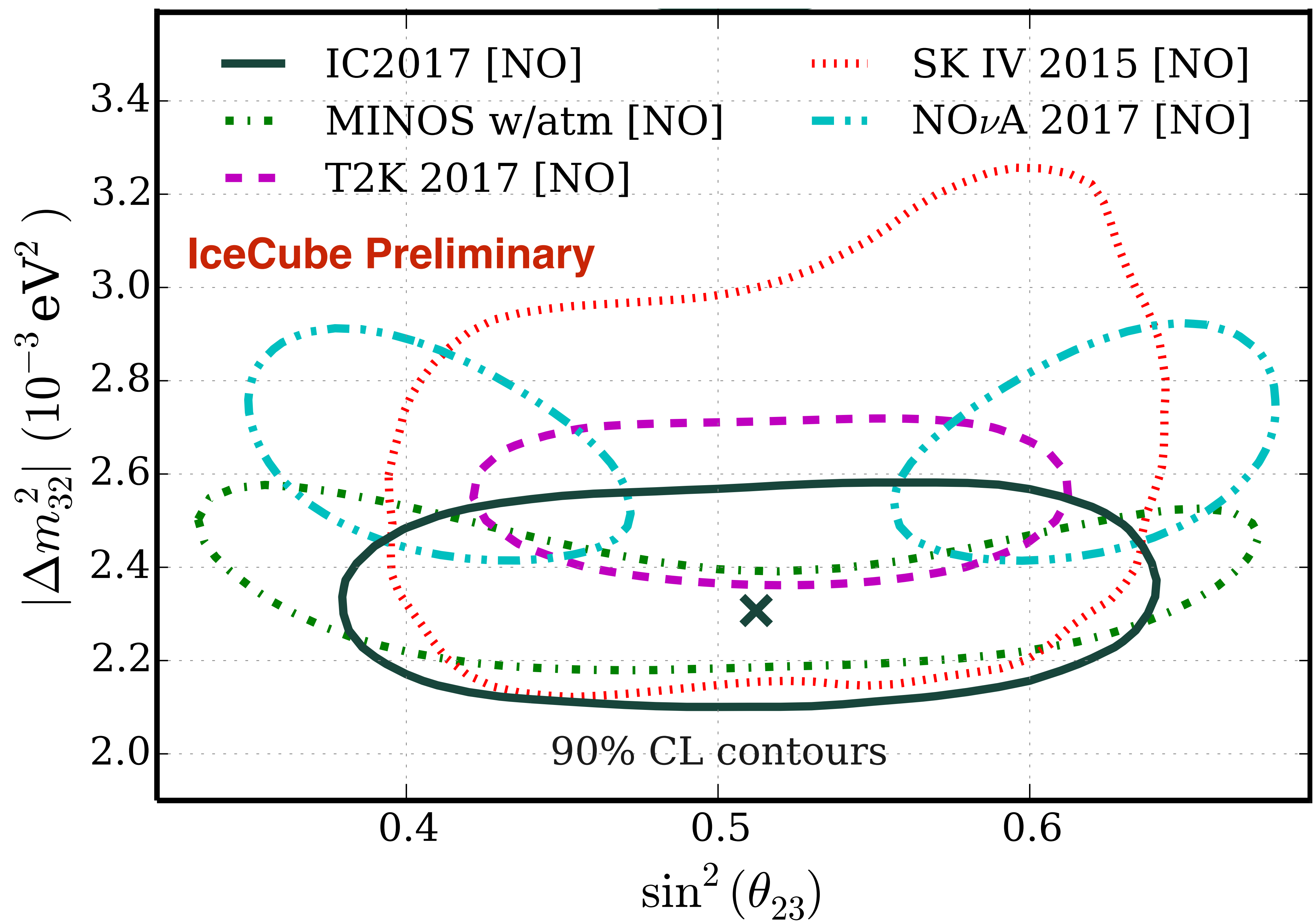
# DeepCore muon neutrino disappearance

*arXiv:1707.07081




Best Fit: $\Delta m^2_{32} = 2.31^{+0.11}_{-0.13} \cdot 10^{-3}\mathrm{eV}^2$ & $\sin^2\theta_{23} = 0.51^{+0.07}_{-0.09}$

41,599 total events from 2012-2014

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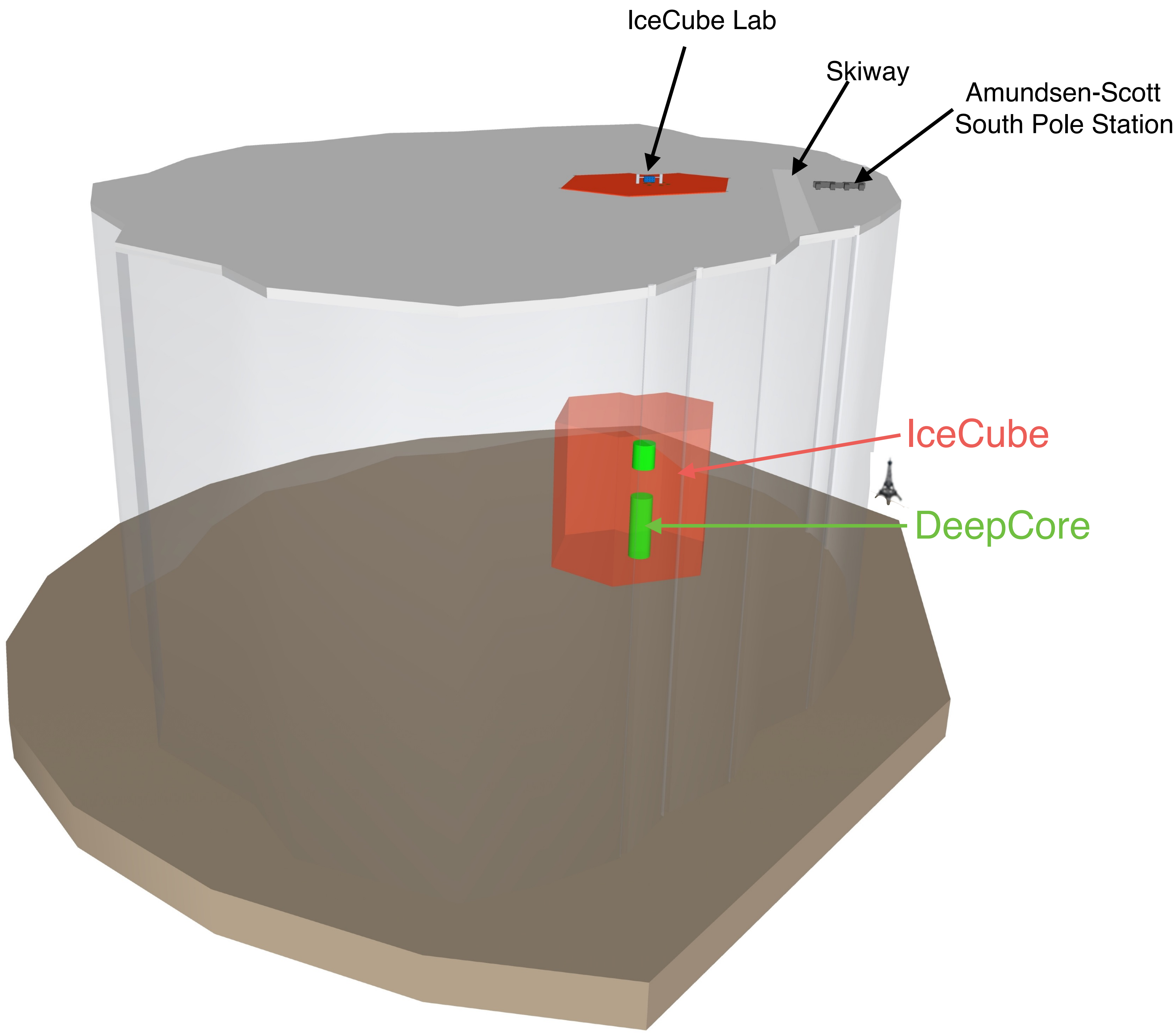
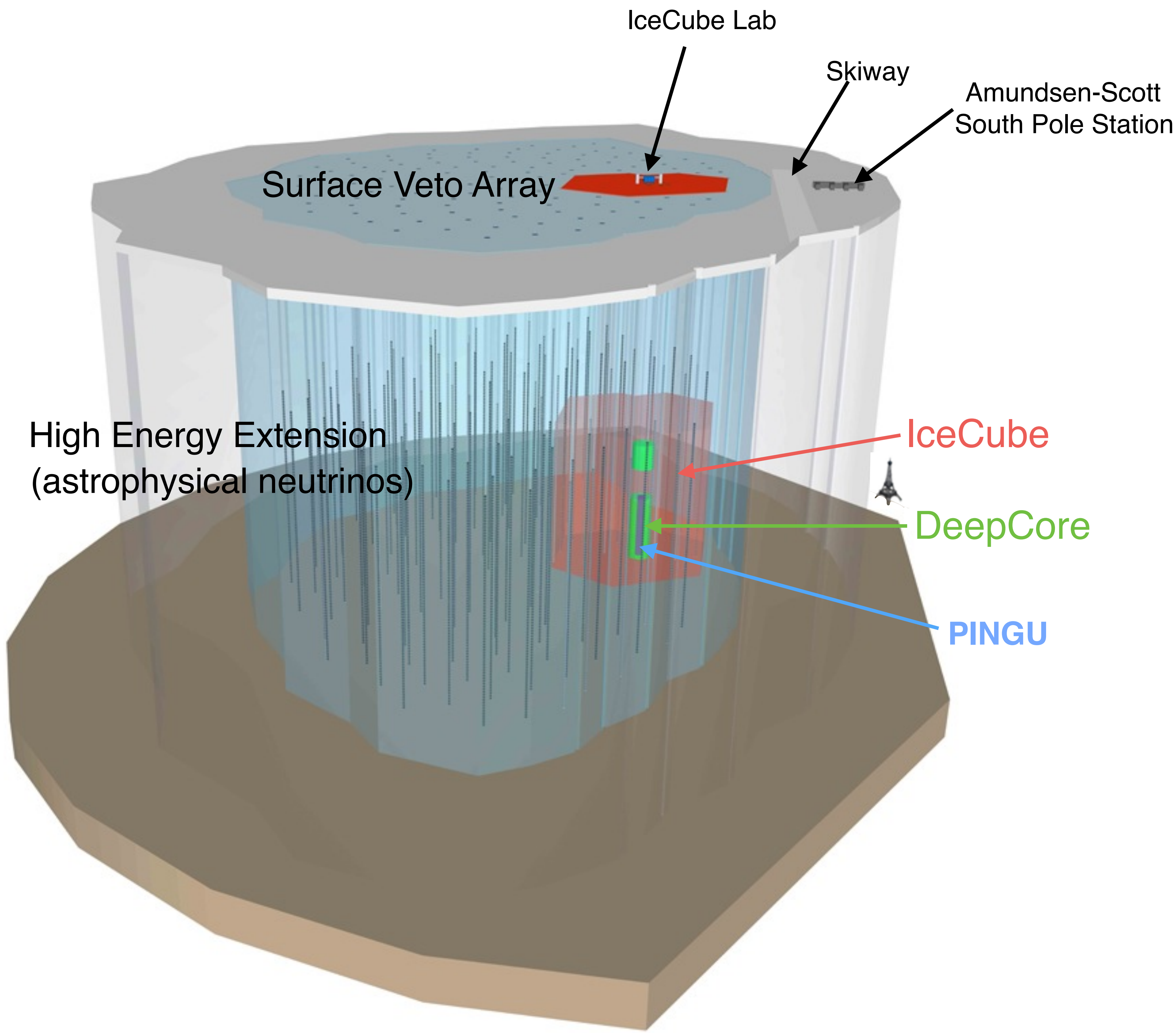
# The IceCube Neutrino Observatory



# The IceCube Neutrino Observatory - Generation 2

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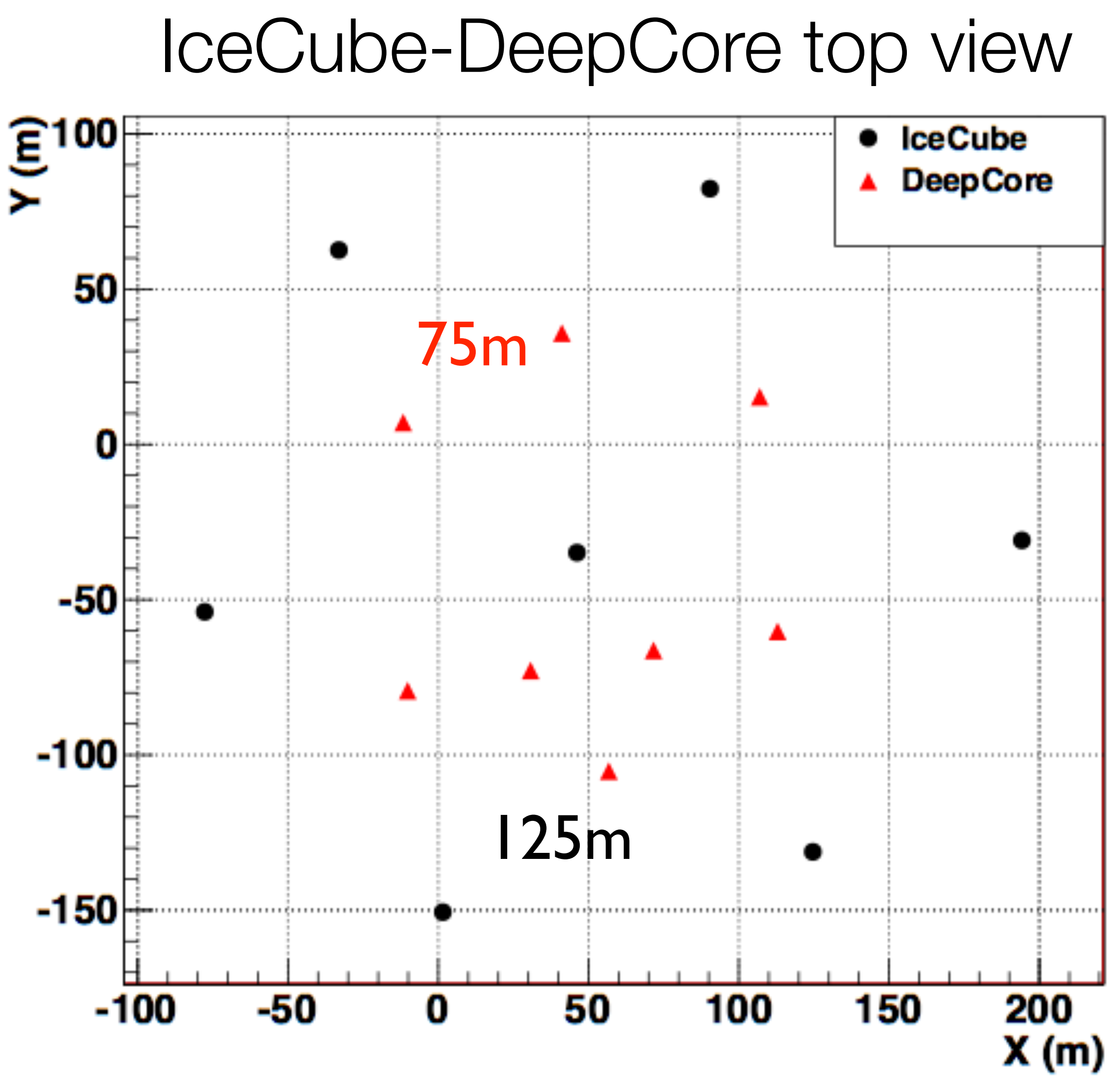
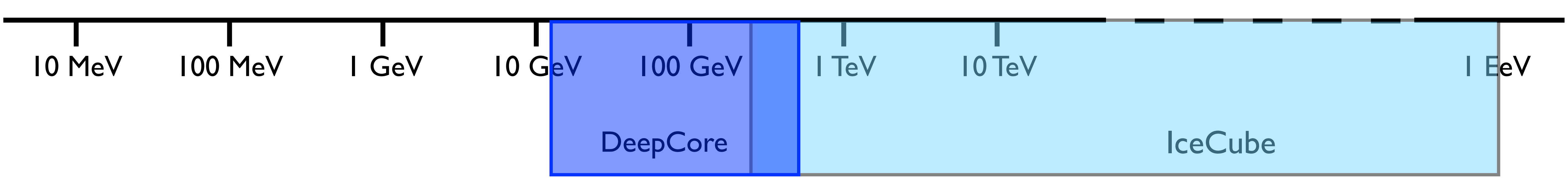
# Beyond IceCube-DeepCore

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

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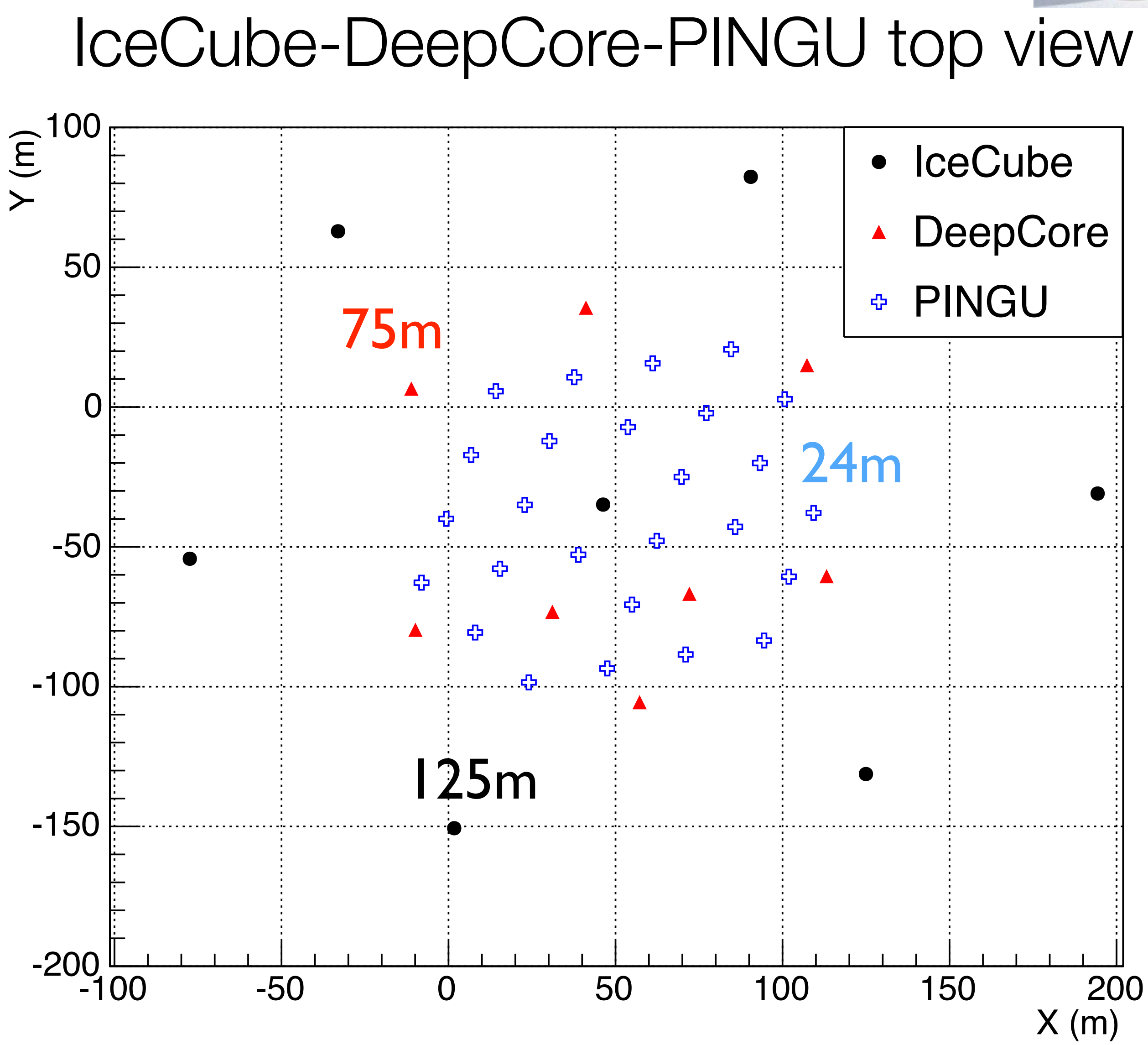
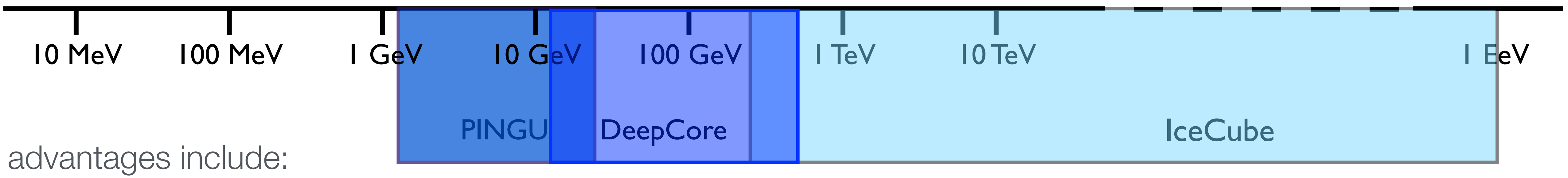
# IceCube-DeepCore-PINGU

- 78 Strings
  - 125m string spacing
  - 17m DOM spacing
- Add 8 strings
  - 75m string spacing
  - 7m DOM spacing
- Add 26 strings (baseline target)
  - ~24m string spacing
  - 1.5m DOM spacing




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

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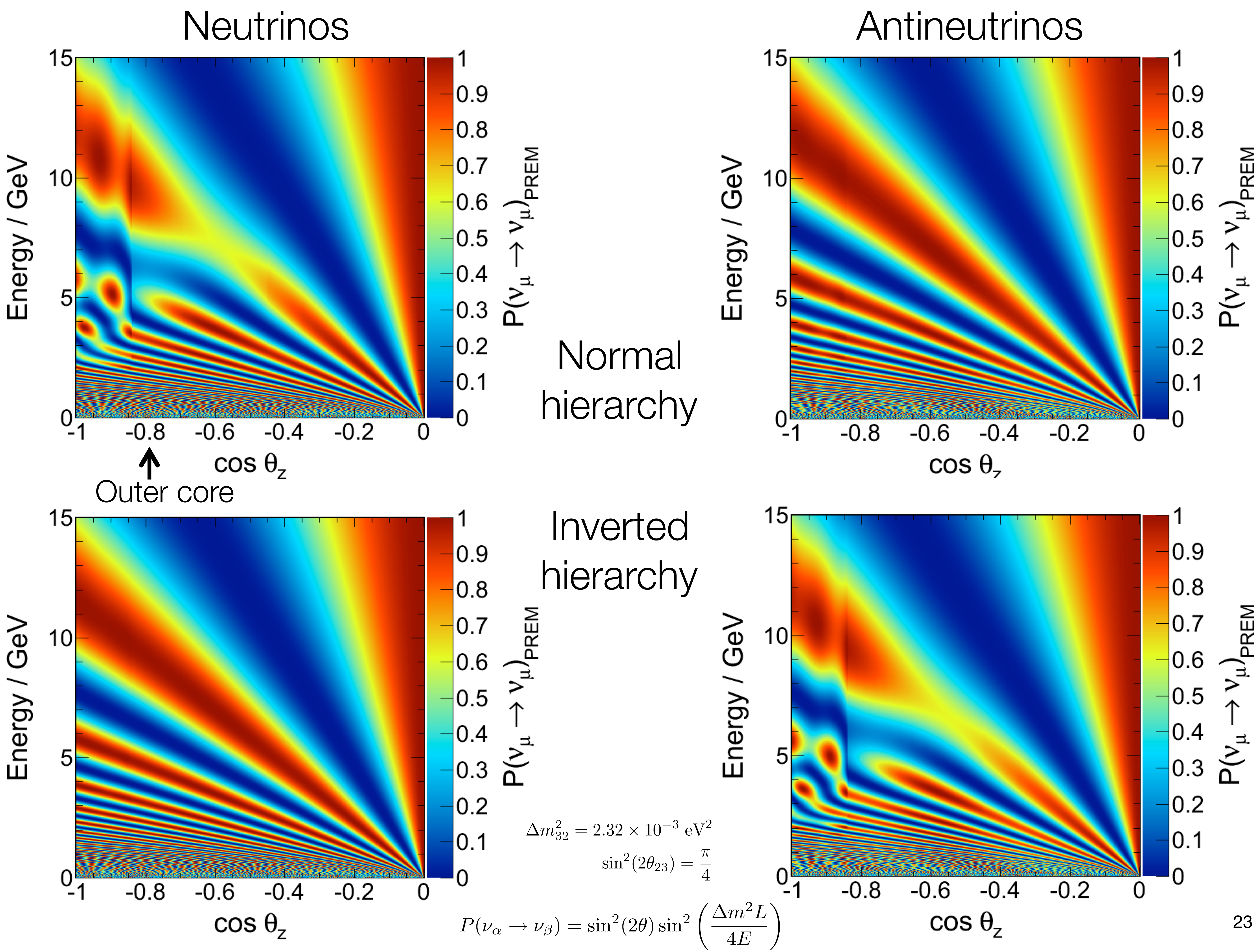


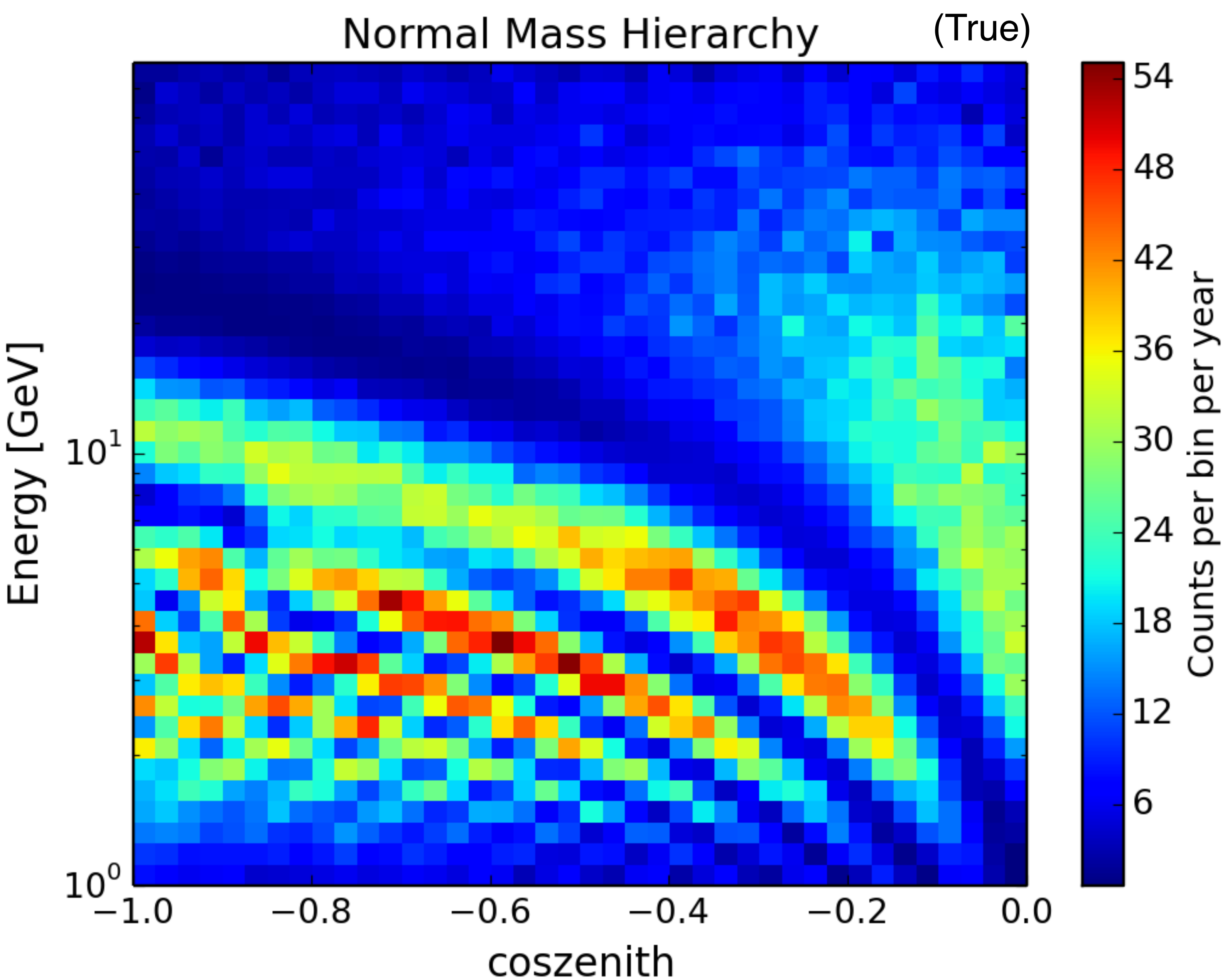

$$\Delta m^2_{32} = 2.32 \times 10^{-3}\ \mathrm{eV}^2$$

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

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

# PINGU and the NMO

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



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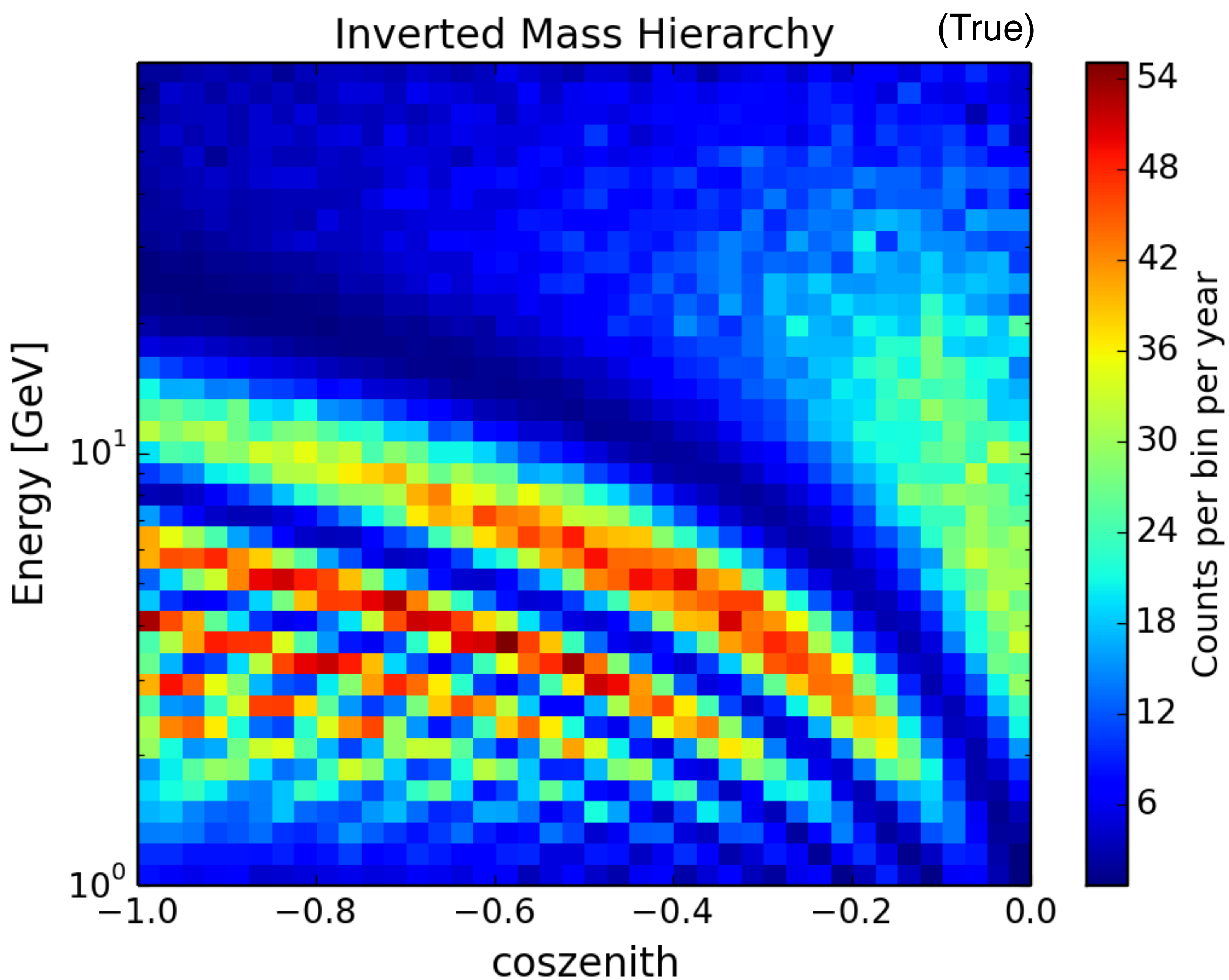
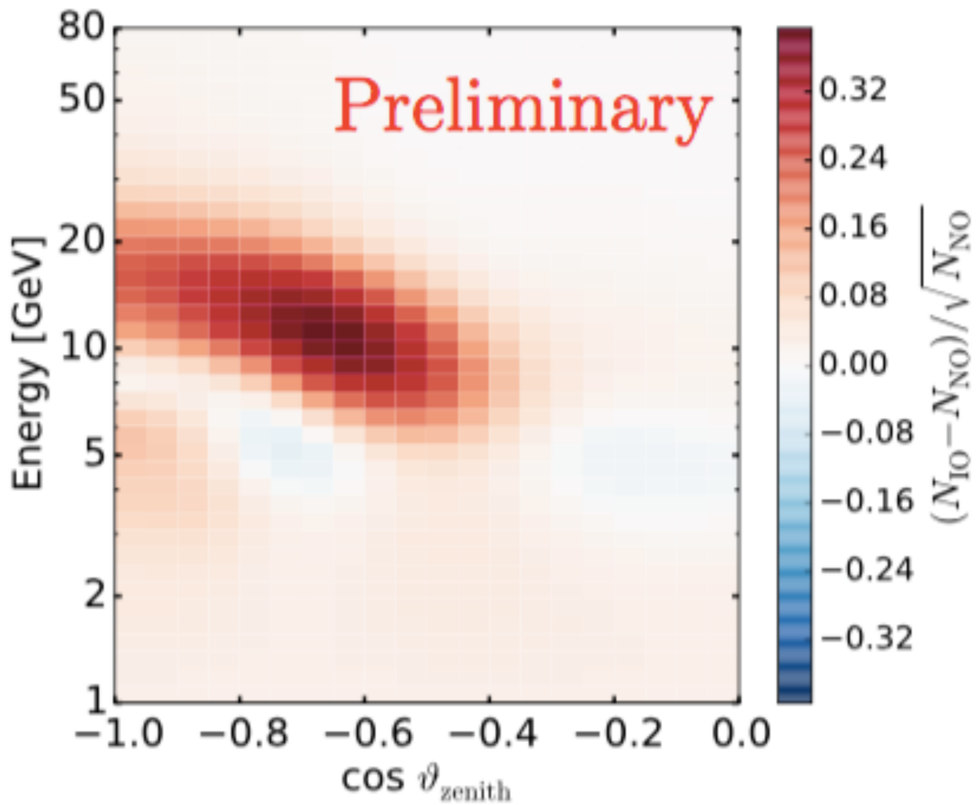


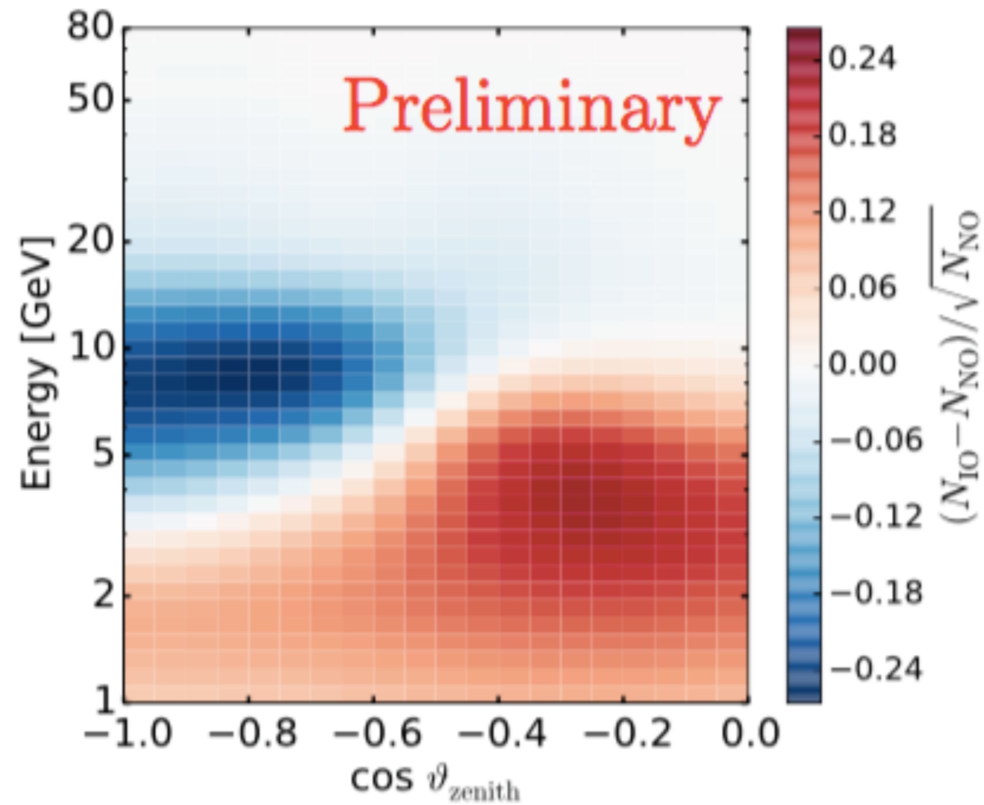
# PINGU and the NMO

arXiv:1401.2046-2

Events ID'd as tracks ($\nu_\mu$ CC)

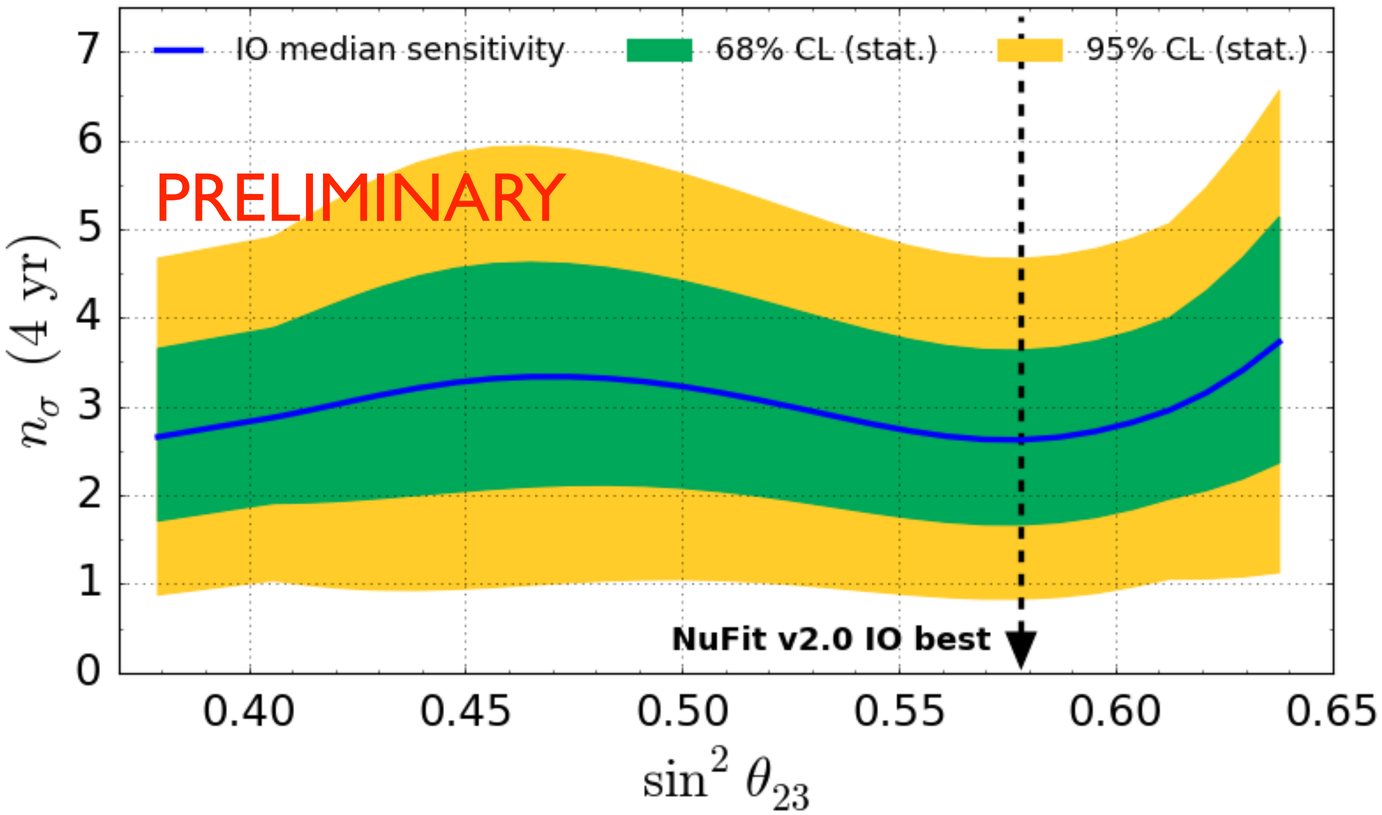


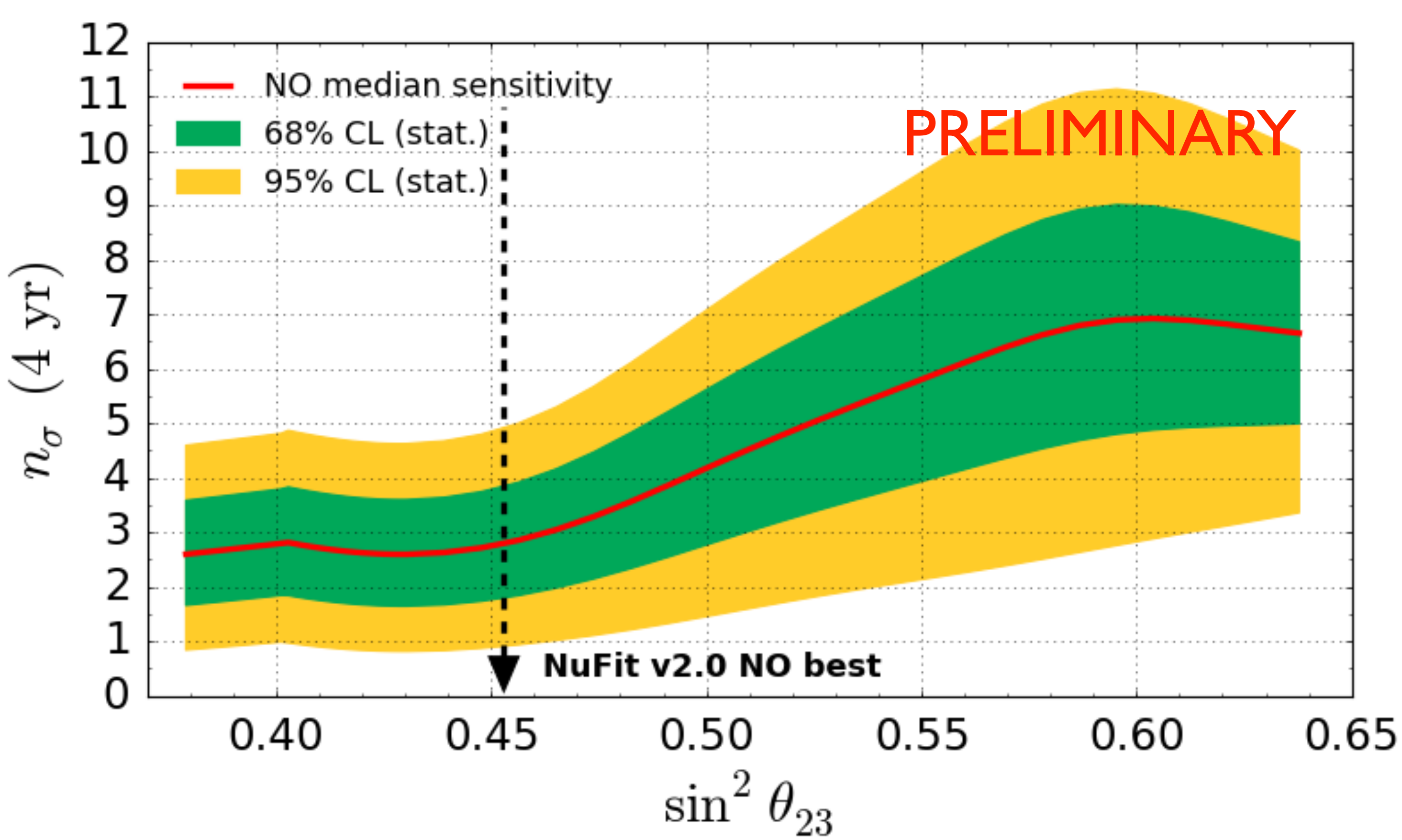

Events ID'd as cascades ($\nu_e$, NC)




- Distinctive (and quite different) mass ordering-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
  - These spaces become the input templates for a full likelihood analysis

# PINGU and the NMO - the bottom line




- The confidence determination depends on the true value of $\theta_{23}$ and the ordering
- In most scenarios PINGU achieves a sensitivity of 3 sigma to the neutrino mass ordering in approximately 4 years of data taking (DeepCore and partial deployment years helps reduce this)

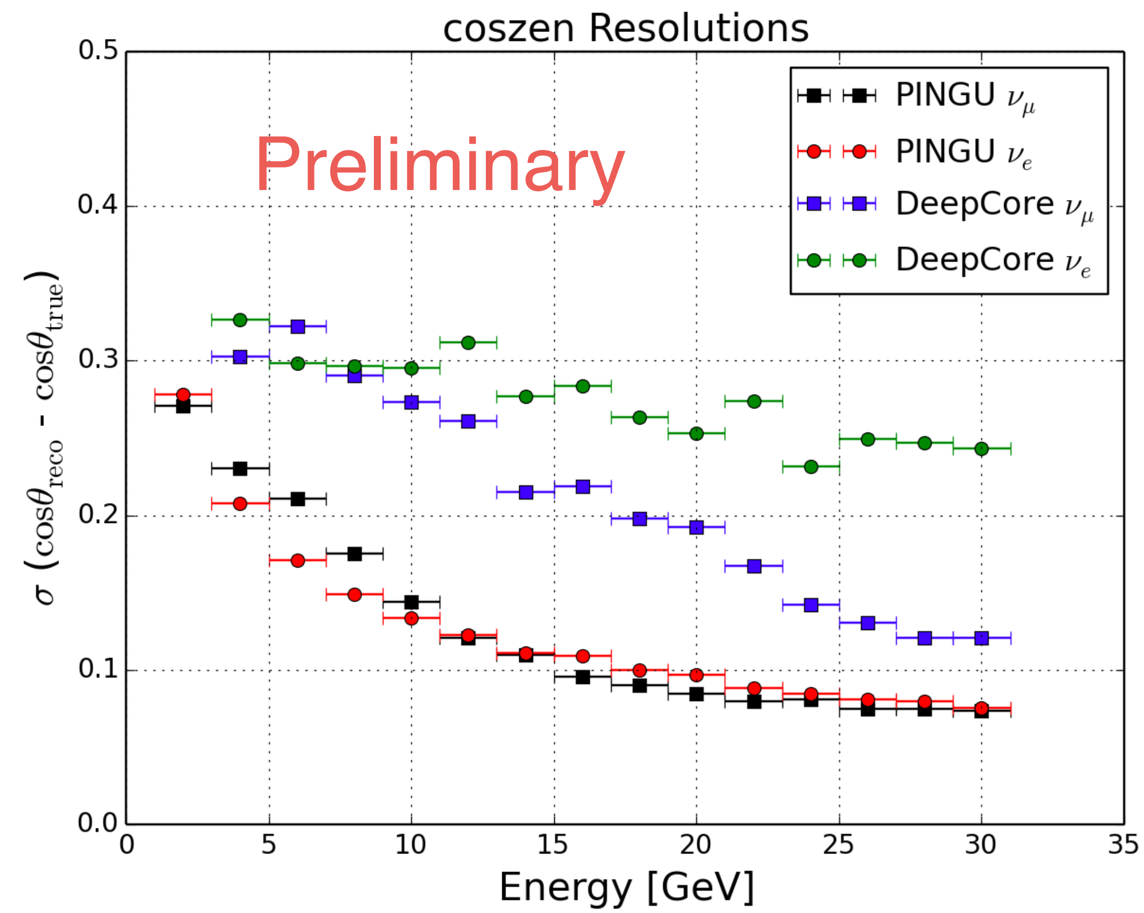
# Summary and Outlook

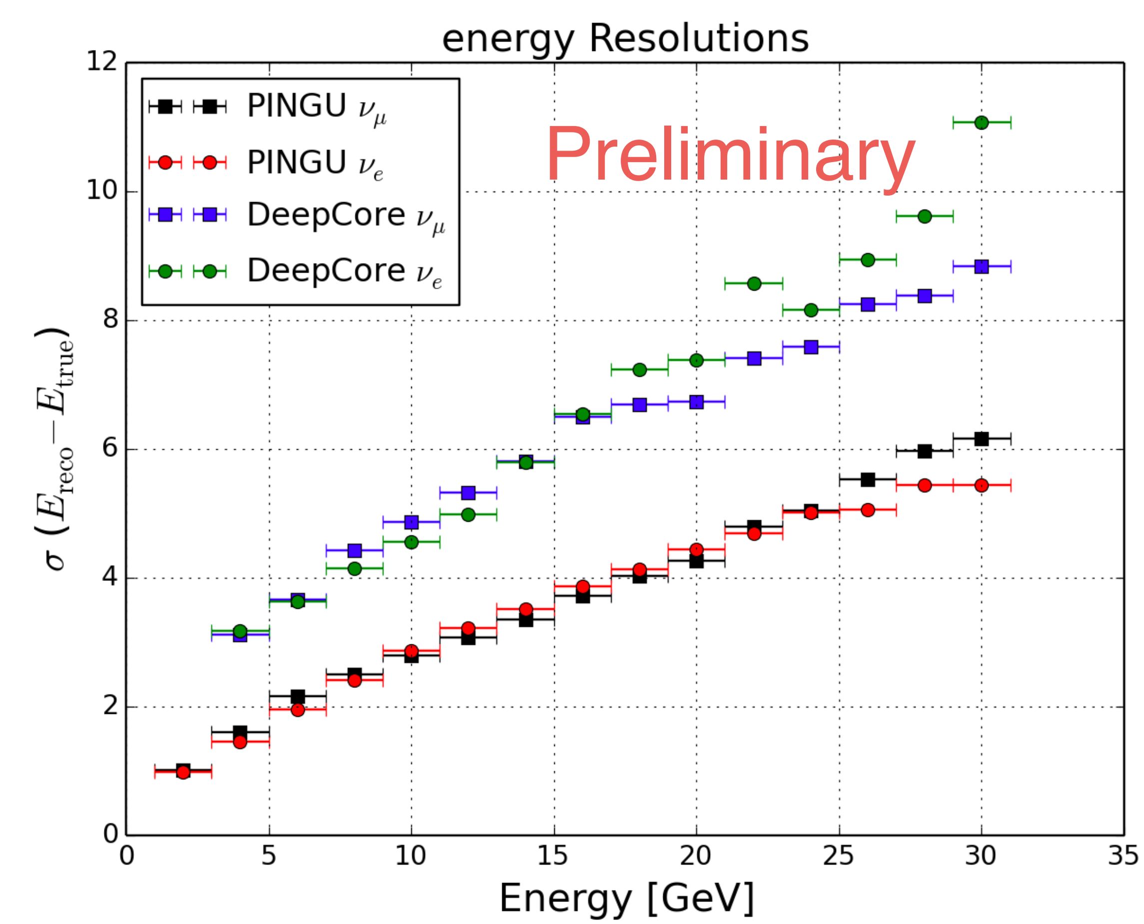
- IceCube is currently world's largest neutrino detector; has provided a breakthrough discovery of very high energy neutrinos from astrophysical sources
- DeepCore has demonstrated that the technology of neutrino telescopes can be applied to precision measurements of atmospheric neutrino properties and world-leading dark matter searches
- A robust measurement of the mass hierarchy is within reach using atmospheric neutrinos (INO/ORCA/PINGU)
- IceCube is now preparing for the next generation:
  - IceCube Upgrade (proposals under review):
    - first 7 strings deployed in PINGU volume.
    - includes deployment of prototype optical modules and advanced calibration sources, providing significant enhancements at both low and high energies
  - Gen2 (future facility) - includes full high-energy (10x IceCube), PINGU, radio, surface arrays

# Backup Slides

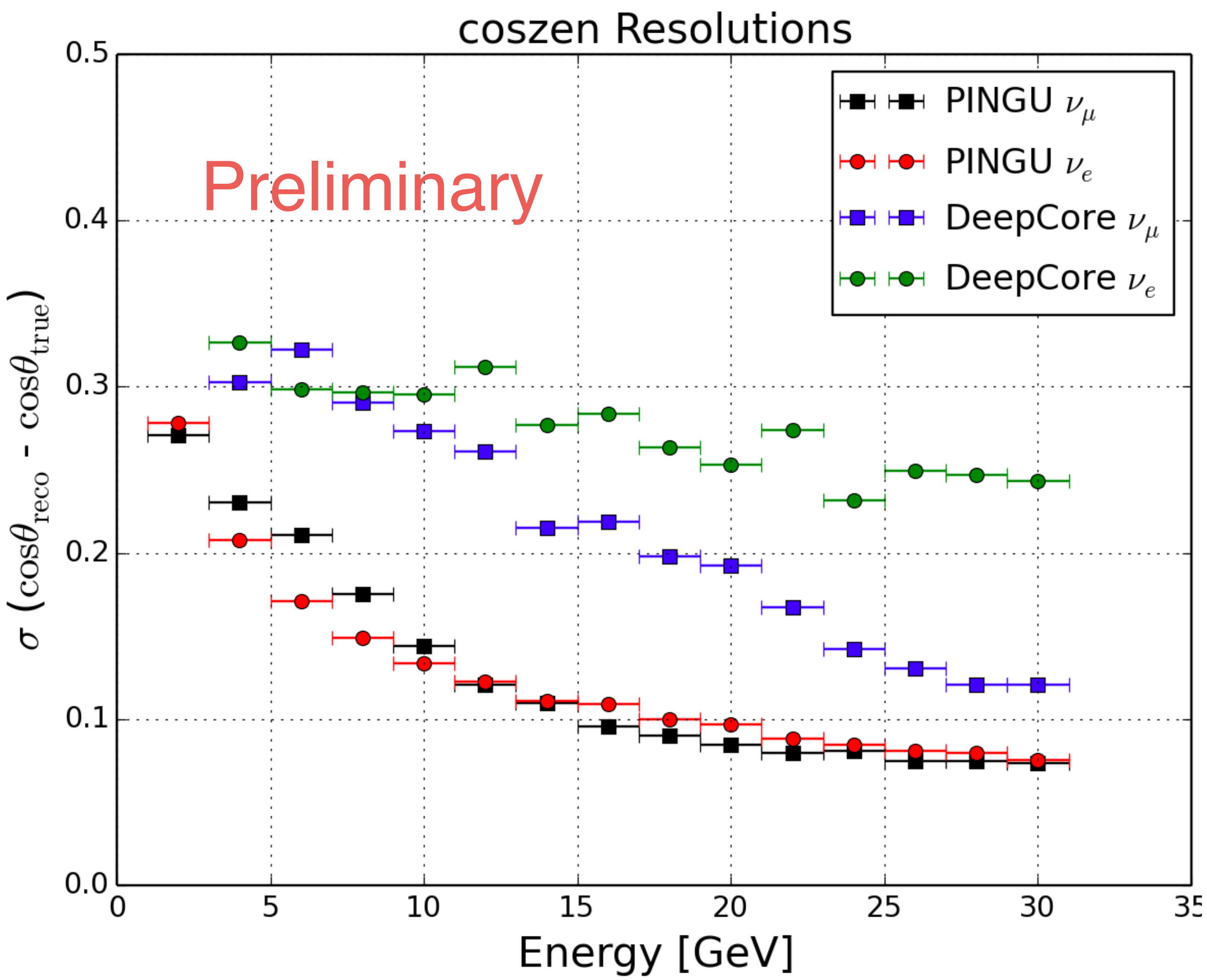
# PINGU event reconstruction

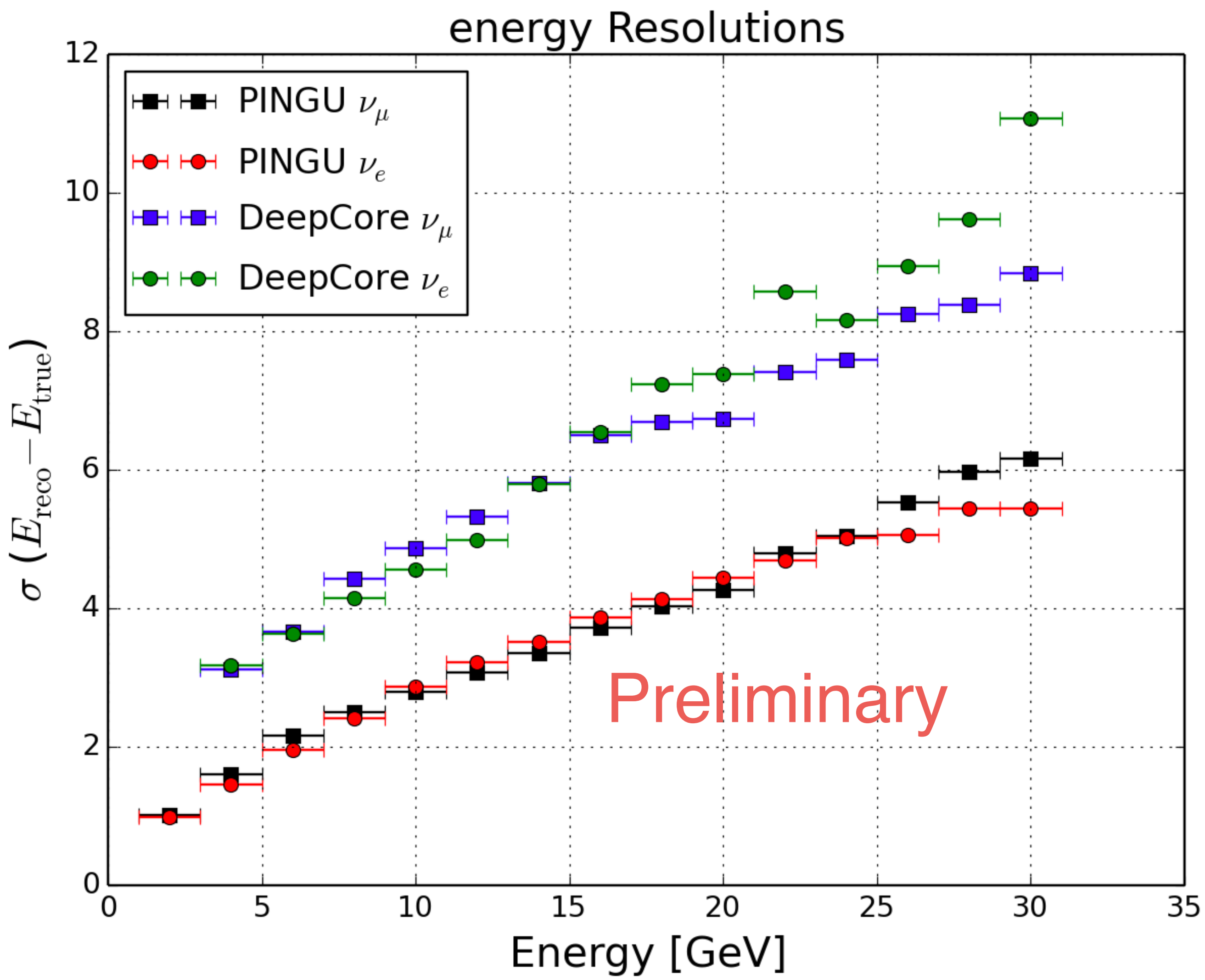
- Matter effects alter oscillation probabilities for neutrinos or antineutrinos traversing the Earth
    - Maximum effects seen for specific energies and baselines (= zenith angles) due to the Earth's density profile
    - Neutrino oscillation probabilities affected if hierarchy is normal, antineutrinos if inverted
    - Rates of all flavors are affected



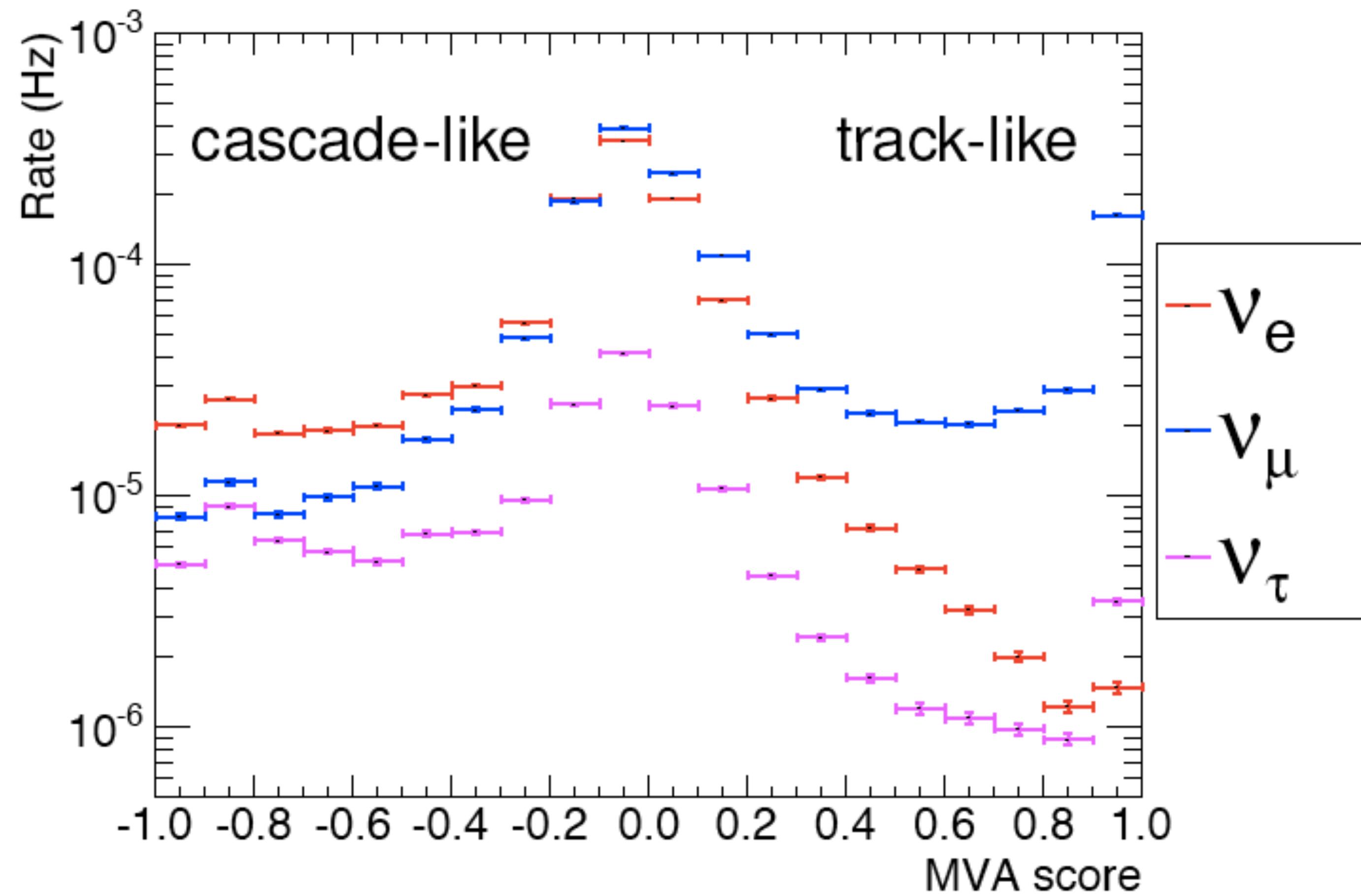
# PINGU event reconstruction

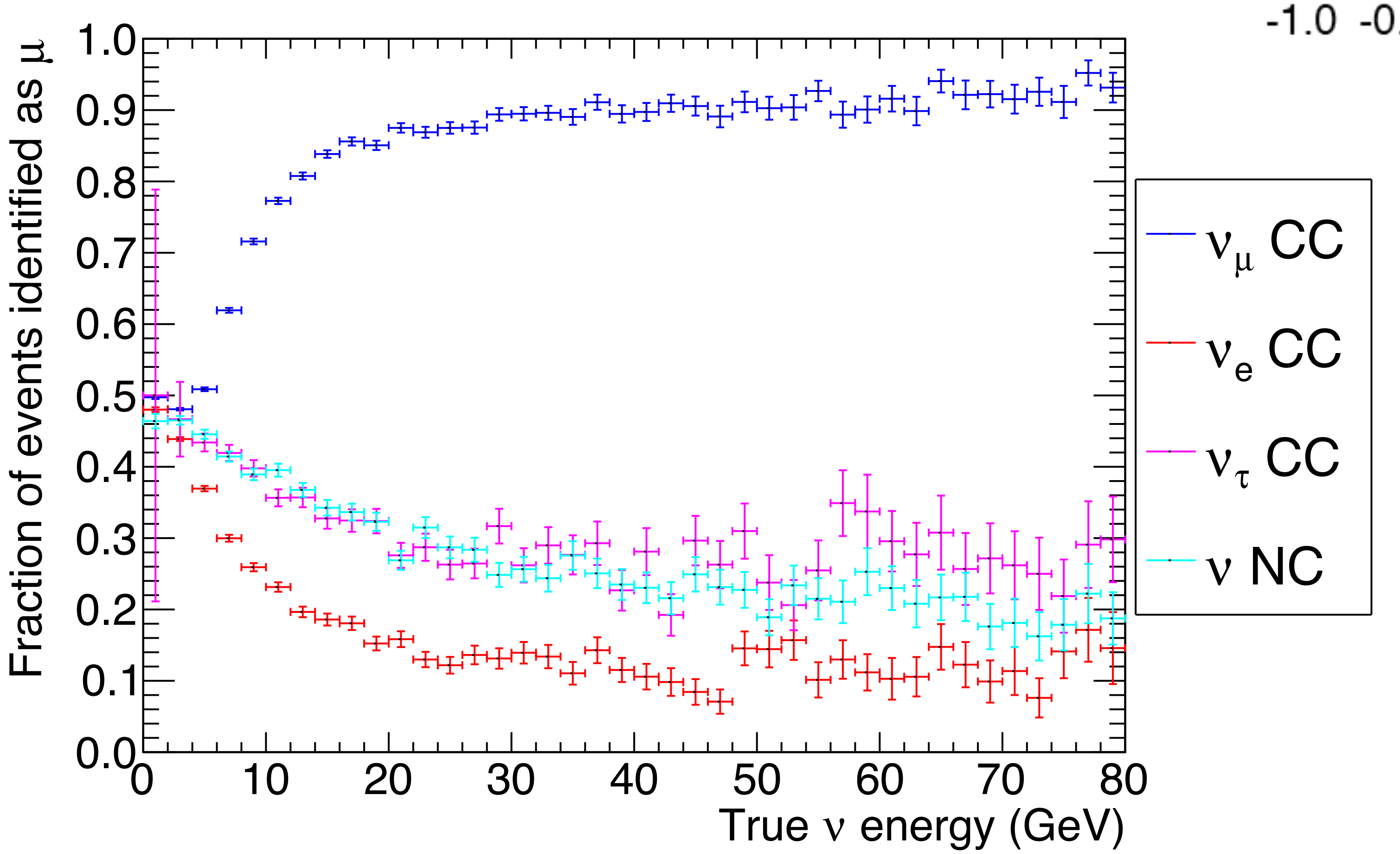


# PINGU Particle ID

- $\nu_\mu$ CC events distinguishable by the presence of a muon track
  - Distinct signatures observable in both track ($\nu_\mu$ CC) and cascade ($\nu_e$ and $\nu_\tau$ CC, $\nu_x$ NC) channels

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