Neutrino Mass Hierarchy Determination with PINGU

Ken Clark
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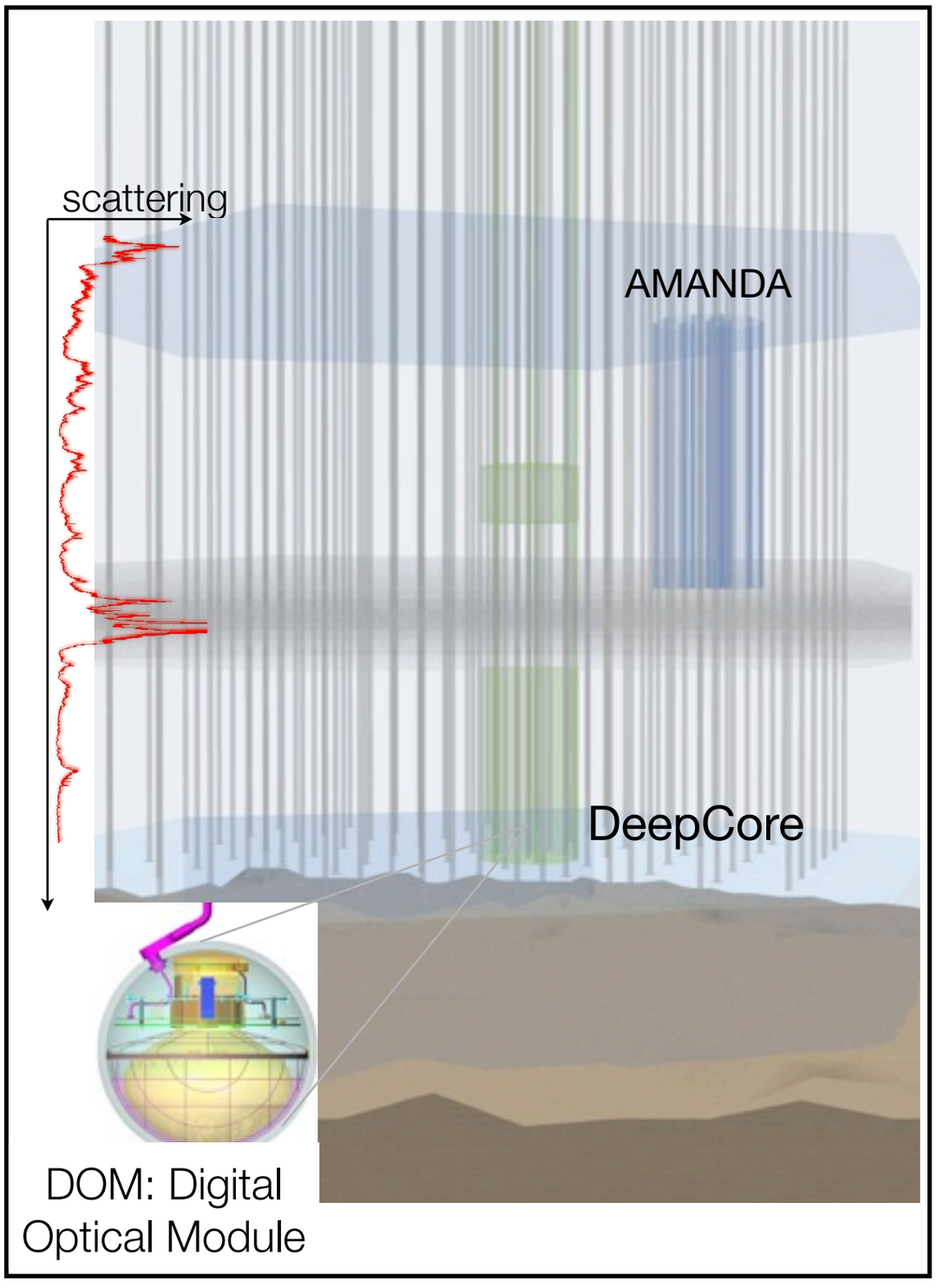
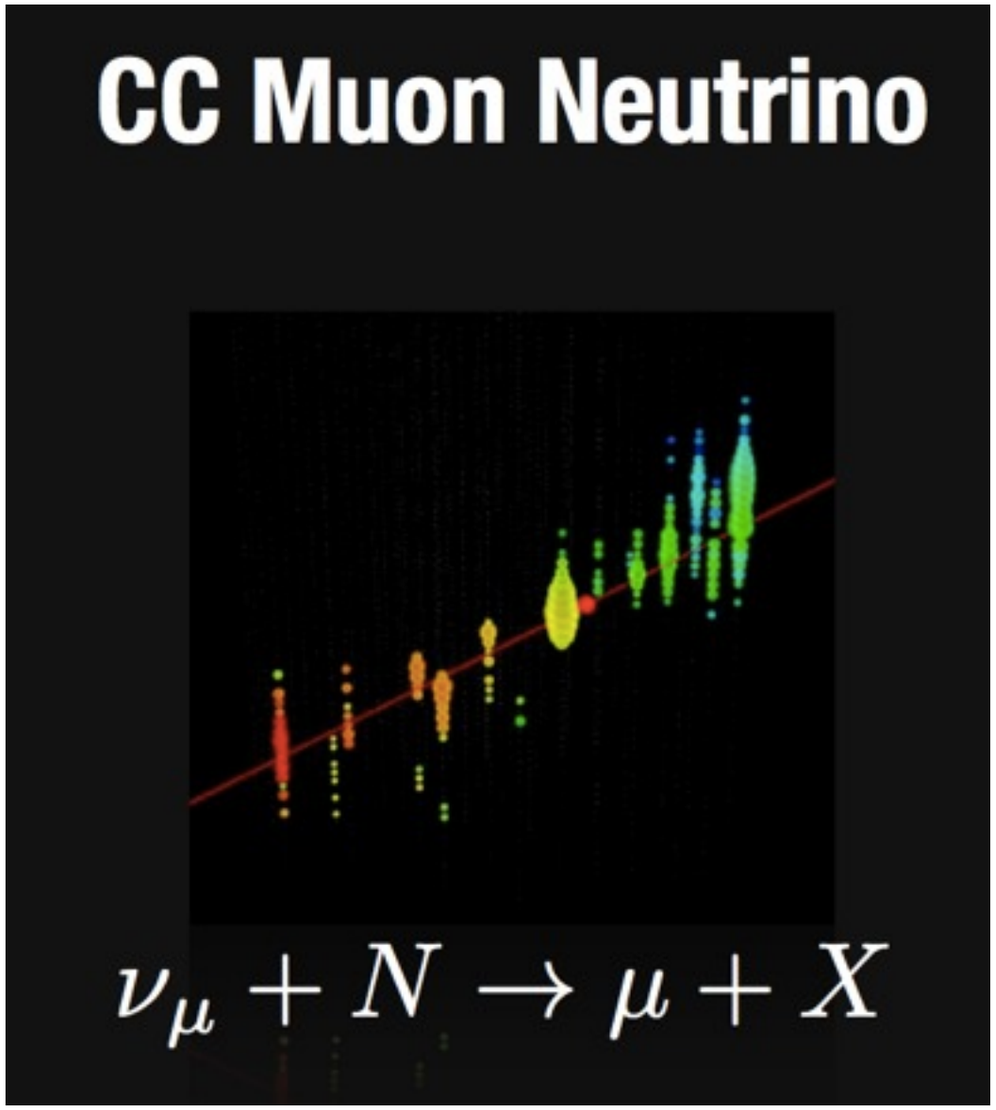
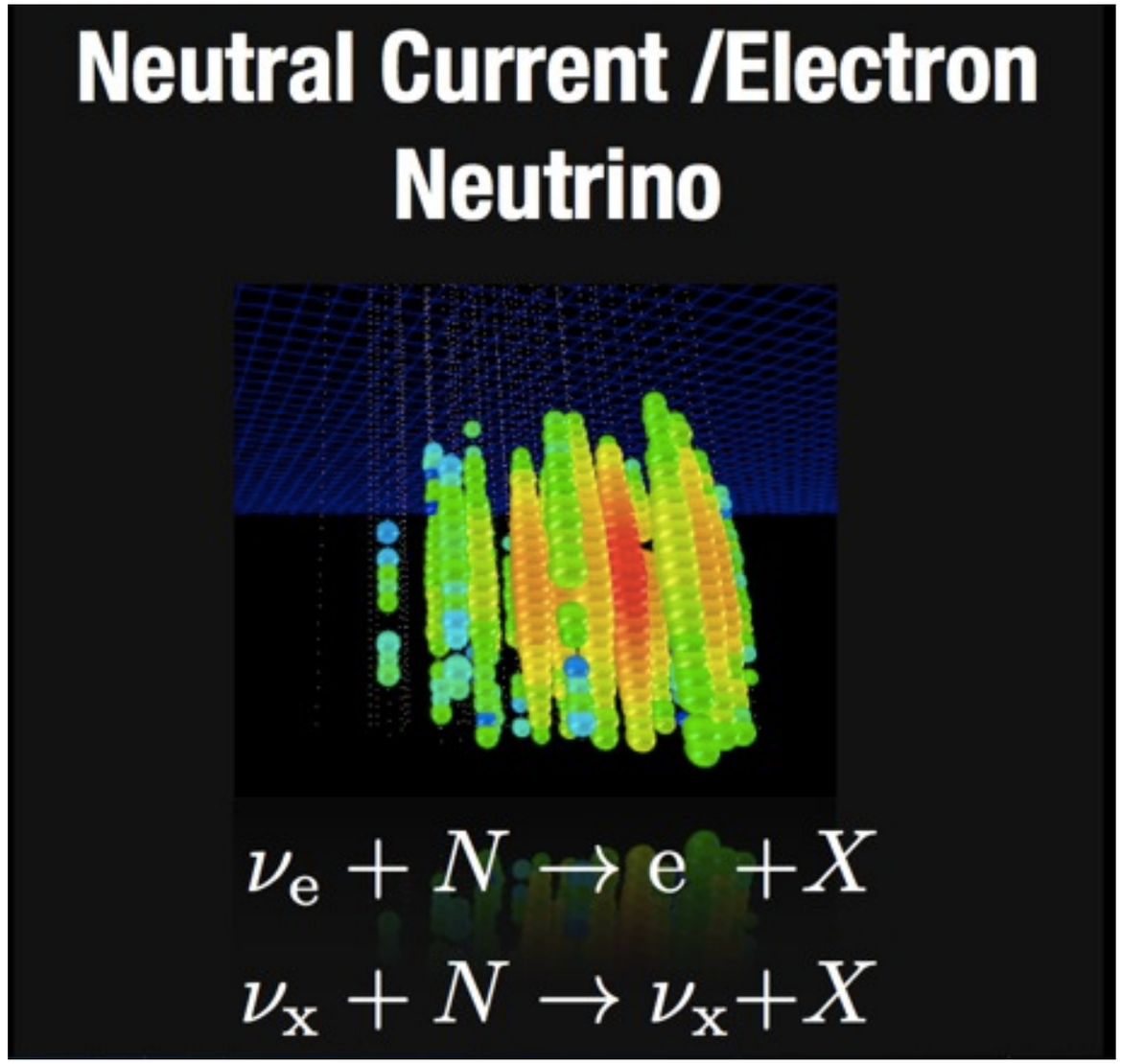
IceCube

- First need to introduce IceCube
- Instrumented ~1km^3 of ice with ~5000 DOMs
- 78 vertical strings, 60 DOMs per string



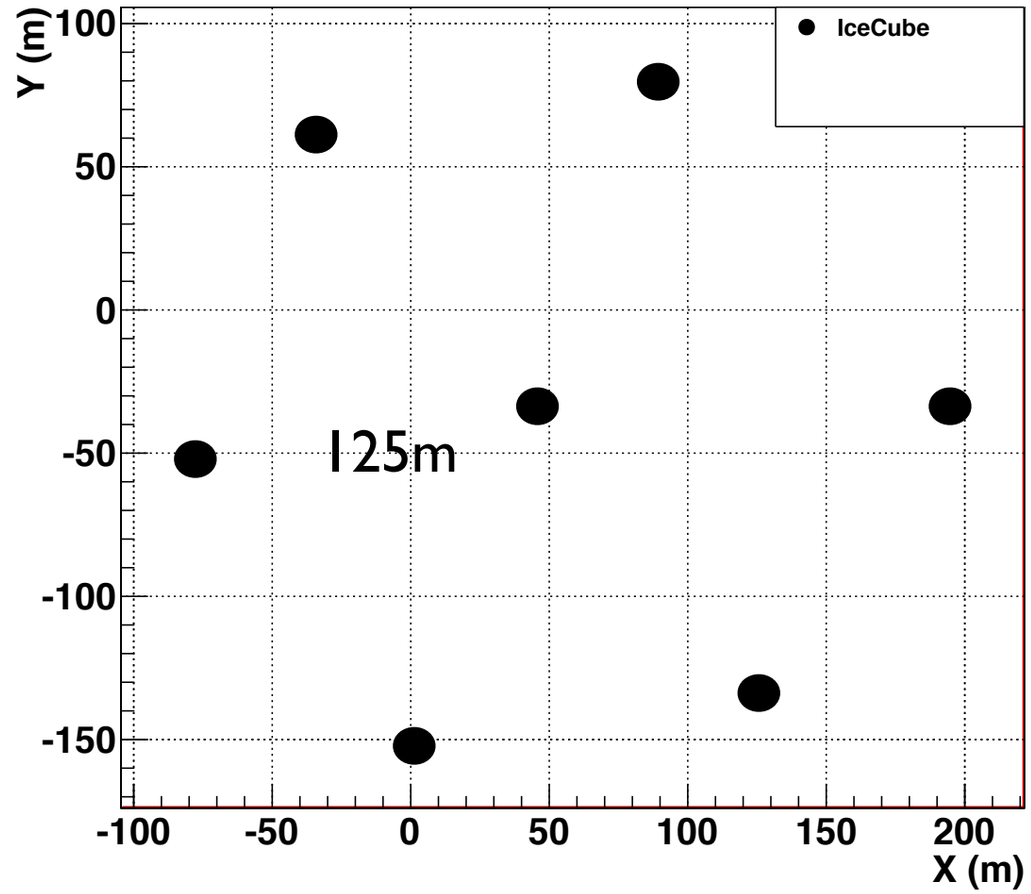
IceCube Events

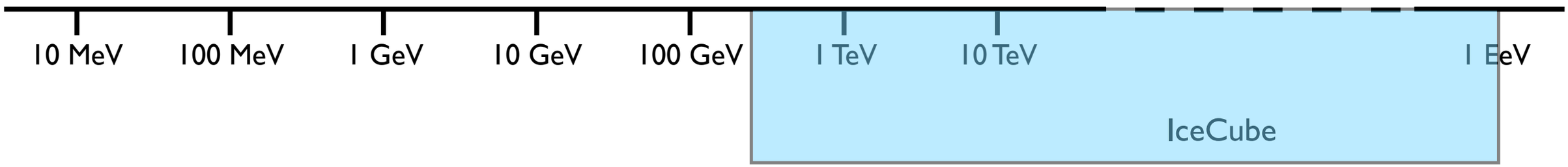




IceCube

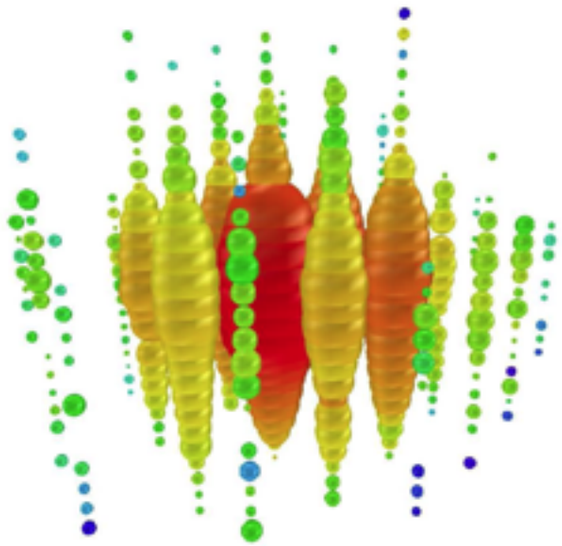
- 78 Strings
  - 125m string spacing
  - 17m DOM spacing



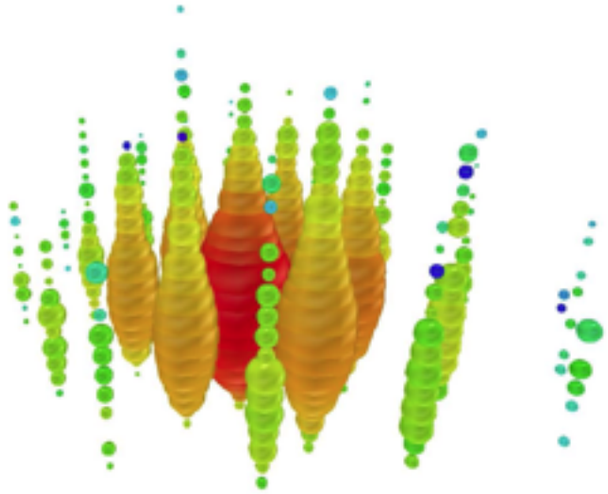


IceCube Results

- Designed to look for high energy (TeV - PeV) events
- Much success in recent studies at these energies



1.04 ± 0.16 PeV



1.14 ± 0.17 PeV

IceCube

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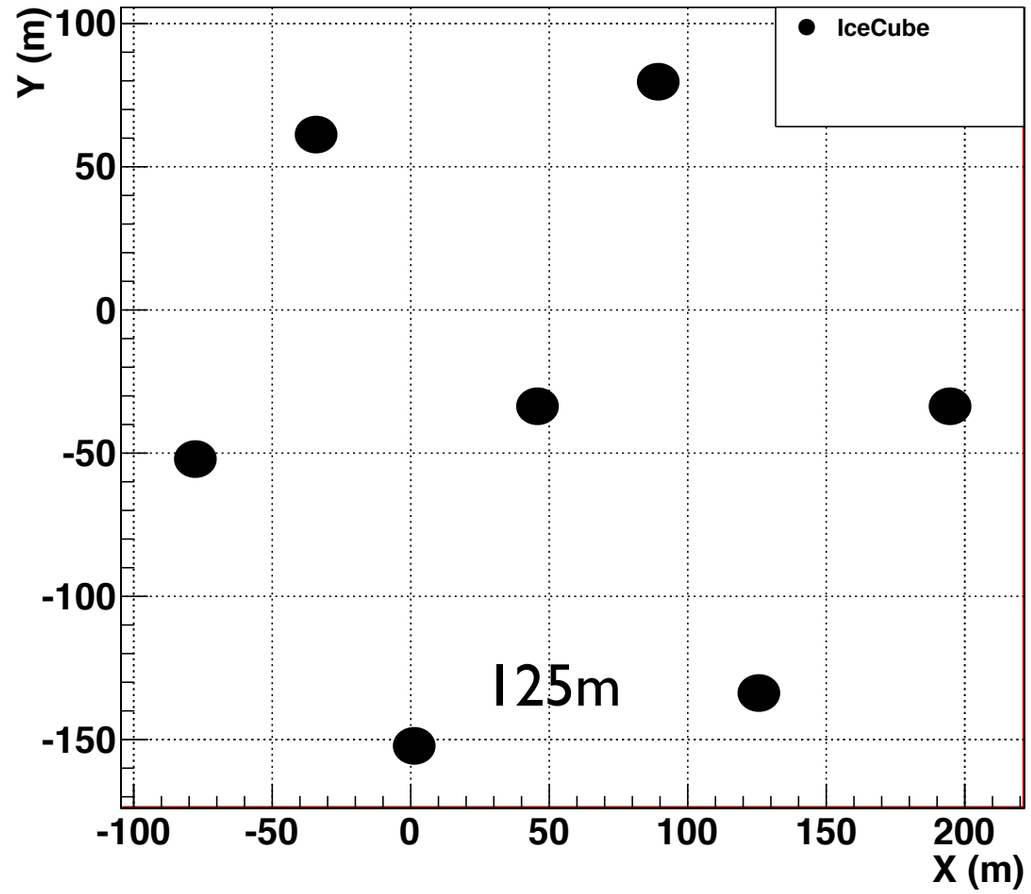
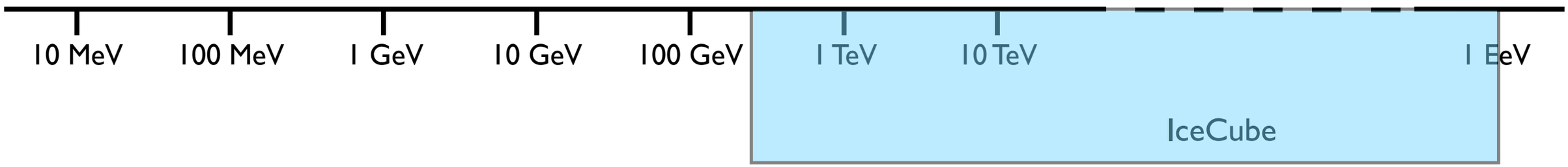
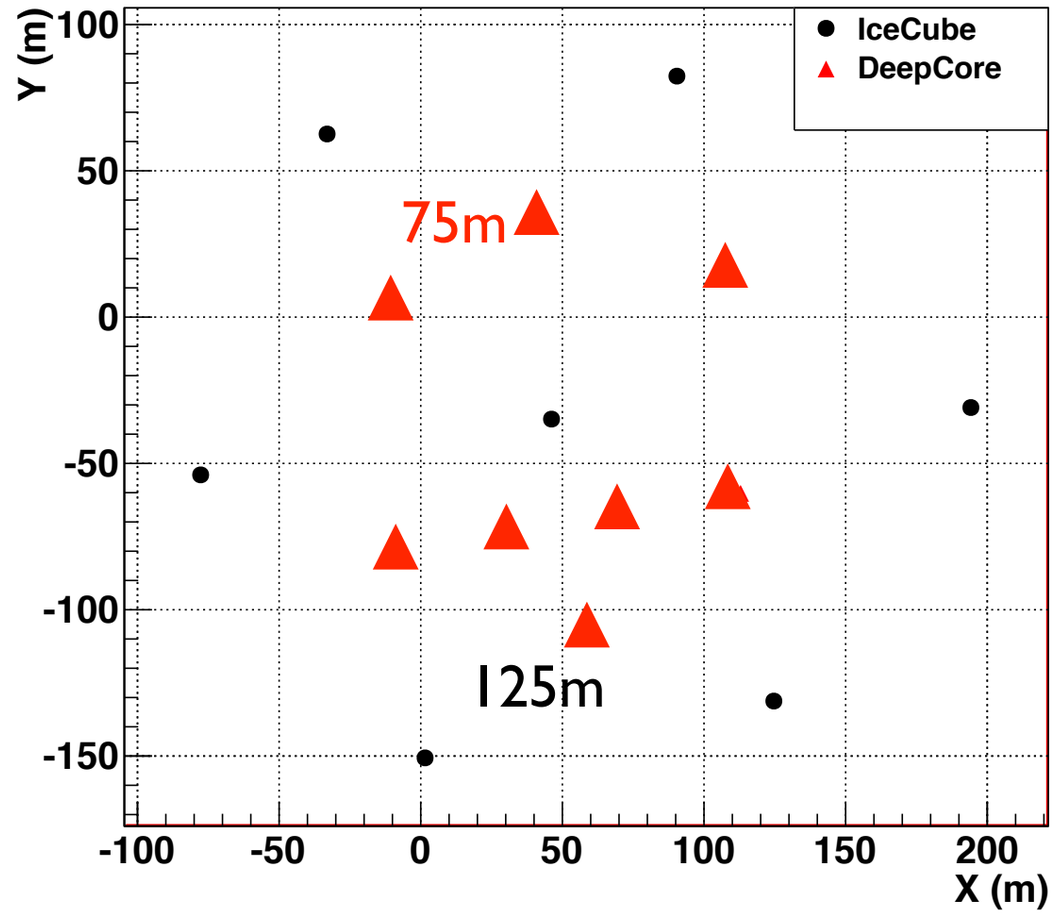
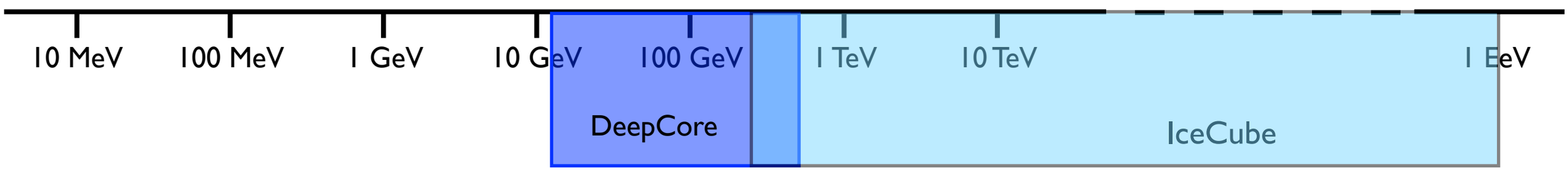




IceCube + DeepCore

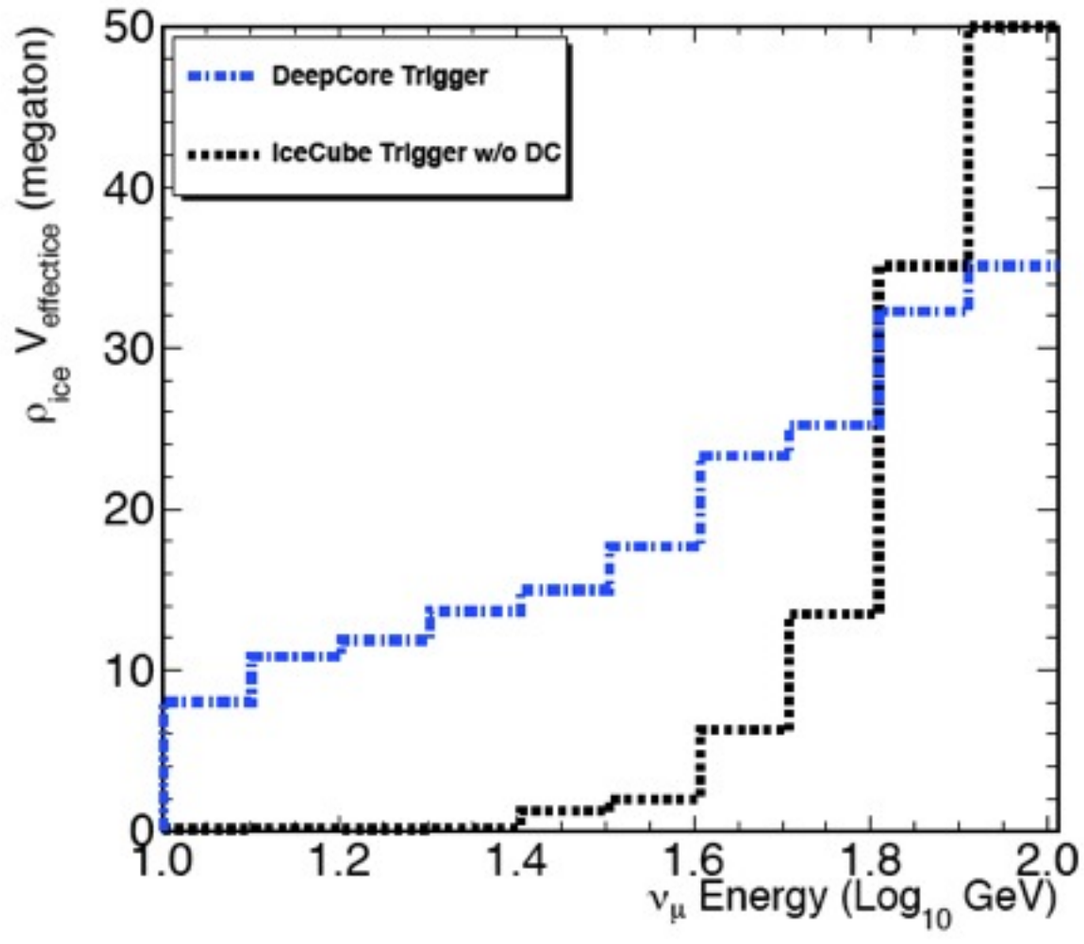
- 78 Strings
  - 125m string spacing
  - 17m DOM spacing
- Add 8 strings
  - 75m string spacing
  - 7m DOM spacing





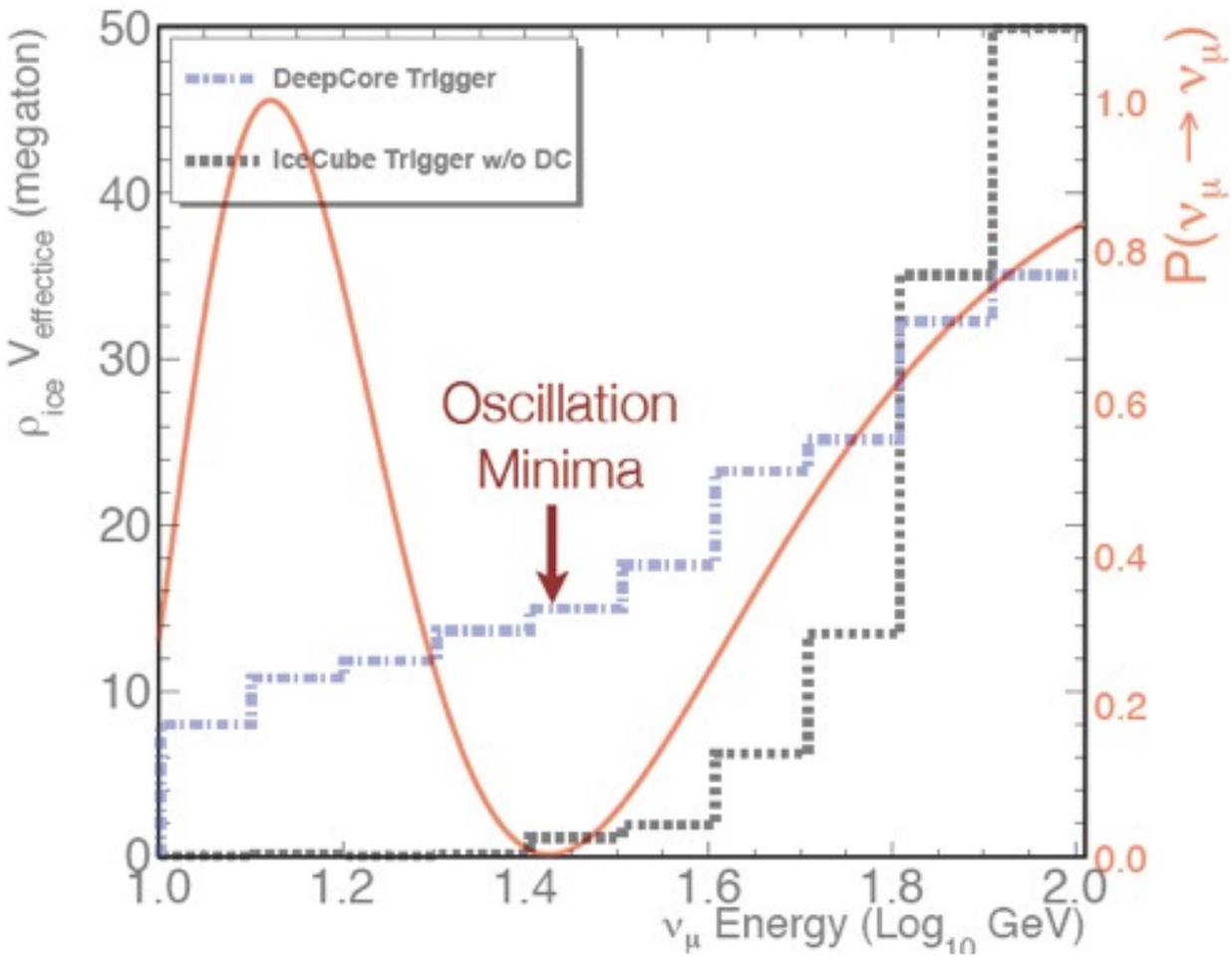
IceCube + DeepCore

- Addition of extra strings in closer proximity lowers the detection threshold energy
- Volumes shown are calculated at trigger level



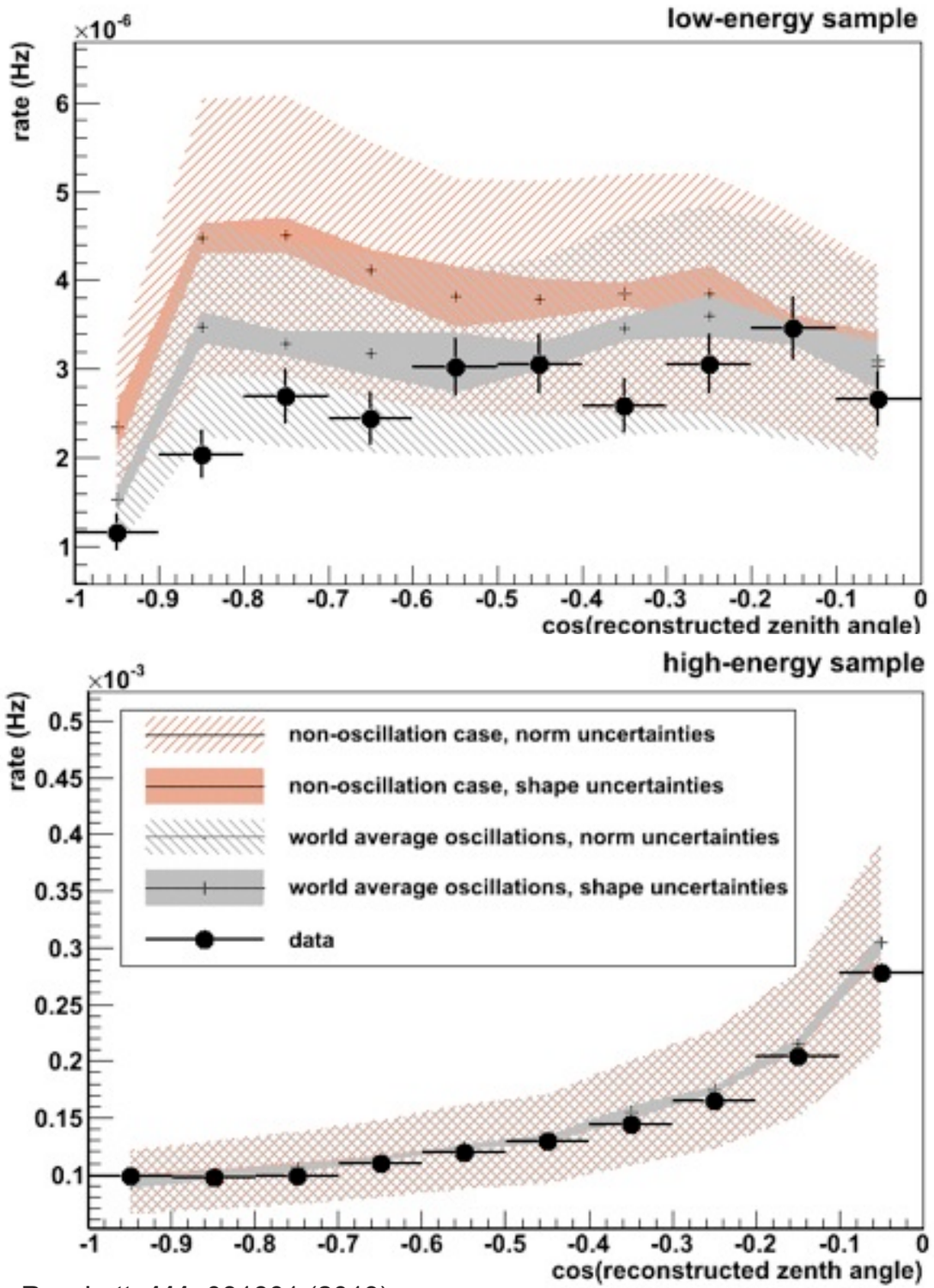
IceCube + DeepCore

- Addition of extra strings in closer proximity lowers the detection threshold energy
- This allows for sensitivity at the energy of an oscillation minimum



DeepCore Results

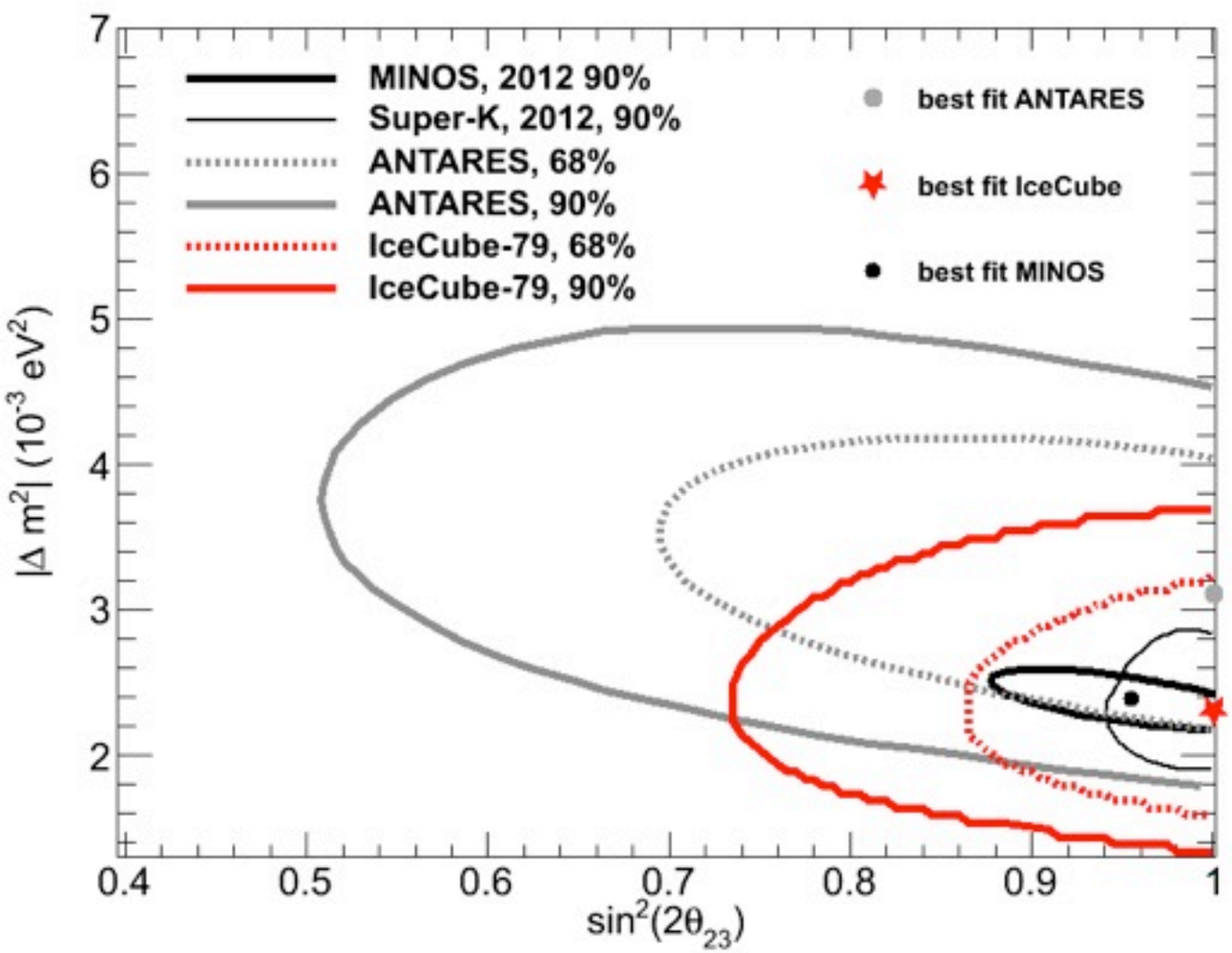
- Approximately 1 year of data analyzed
- High rate in detector provides large event sample
- High energy sample constrains uncertainties in fit



Phys. Rev. Lett. **111**, 081801 (2013)

DeepCore Results

- Oscillation parameters extracted
- Very good agreement with world averages
- Possible improvement with more advanced reconstructions and event selection



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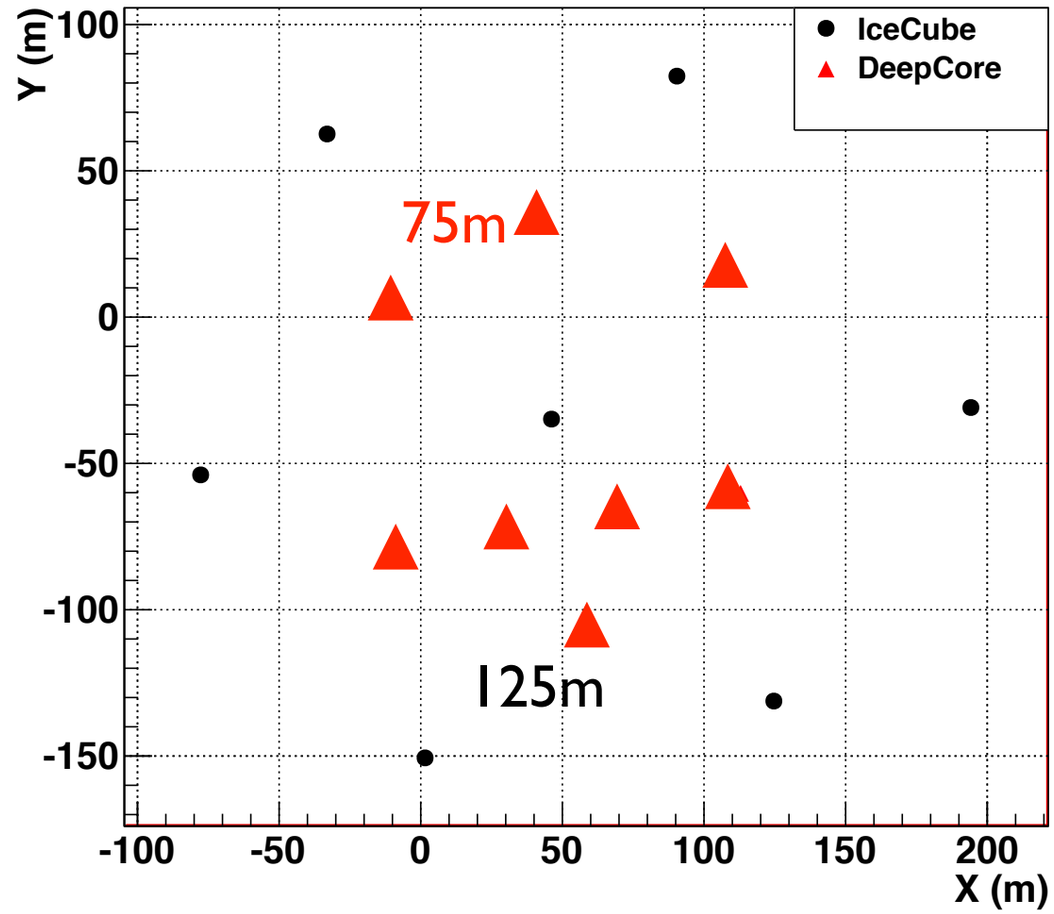
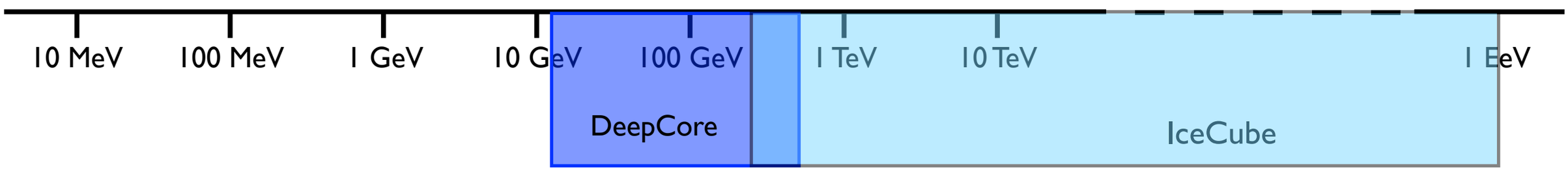
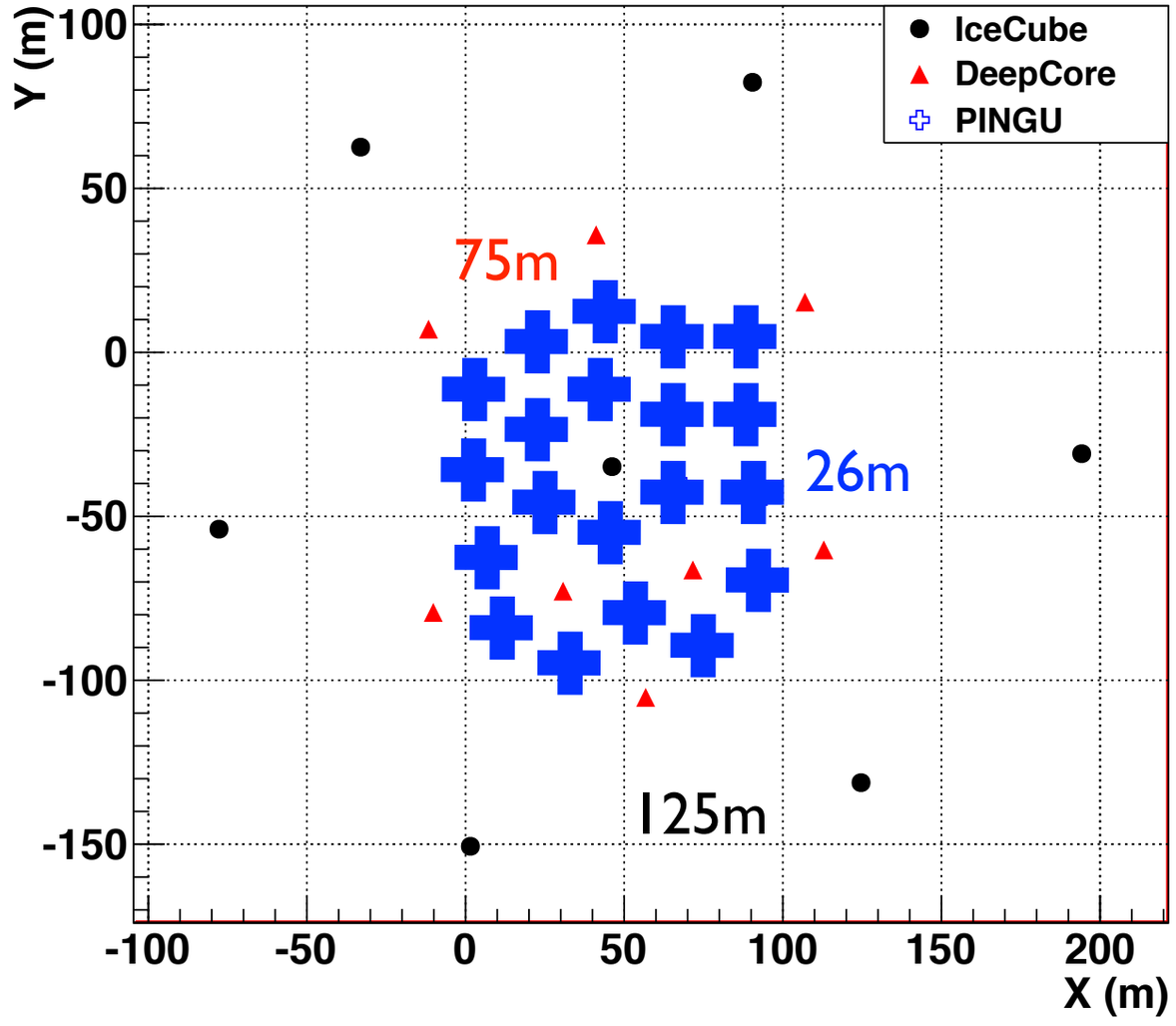
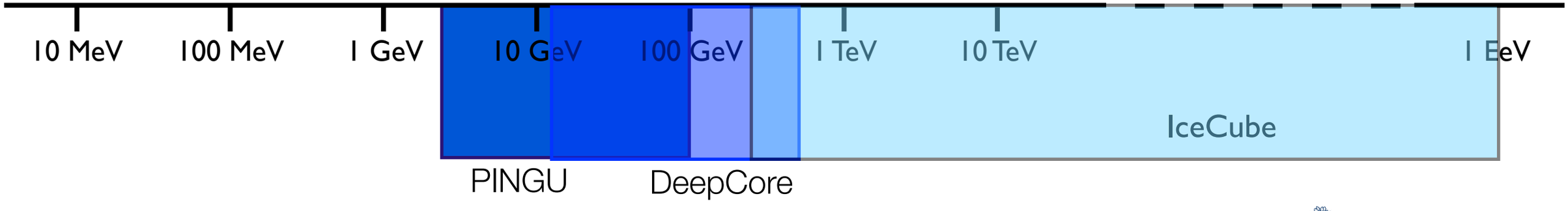




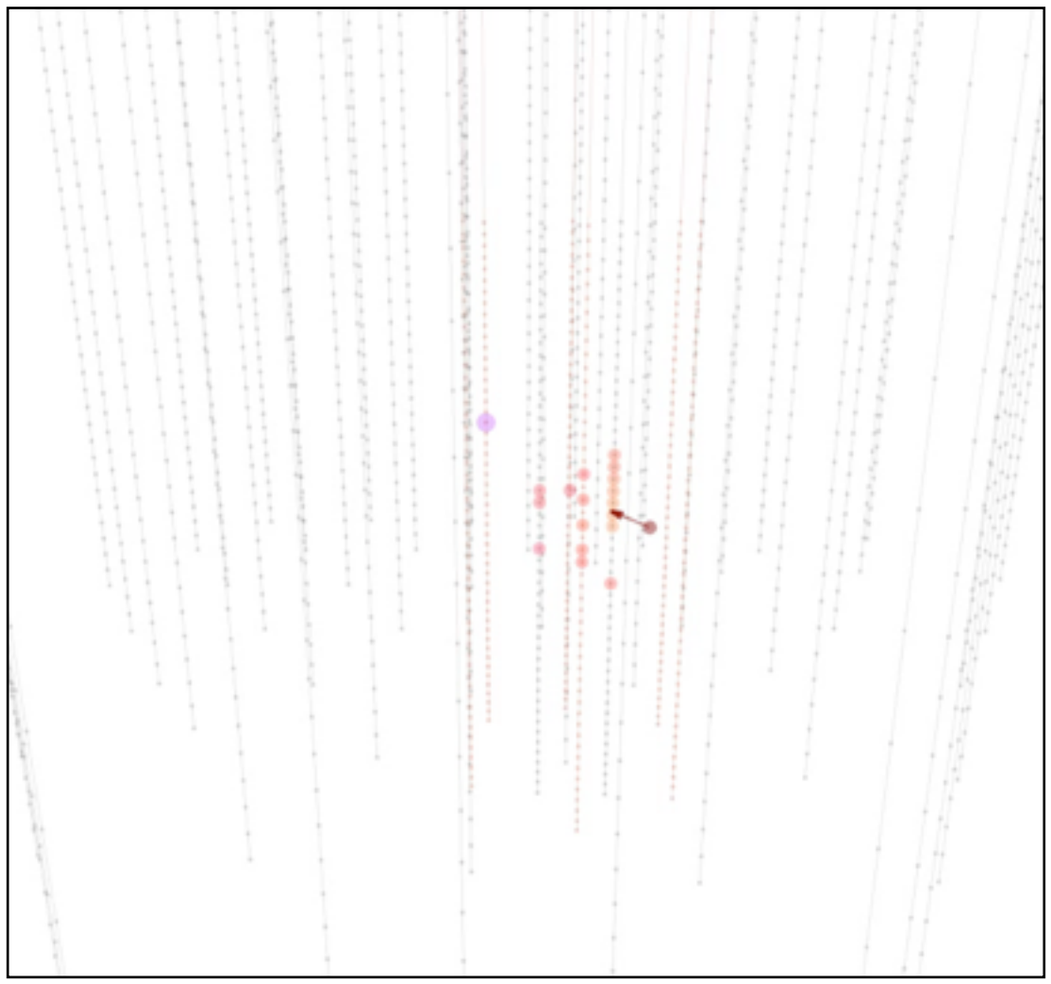
IceCube + DeepCore + PINGU

- 78 Strings
  - 125m string spacing
  - 17m DOM spacing
- Add 8 strings
  - 75m string spacing
  - 7m DOM spacing
- Add >=20 strings
  - 26m string spacing
  - 5m DOM spacing





Improvement with PINGU



IceCube + DeepCore

- 9.28 GeV Neutrino, 4.9 GeV muon, 4.5 GeV cascade

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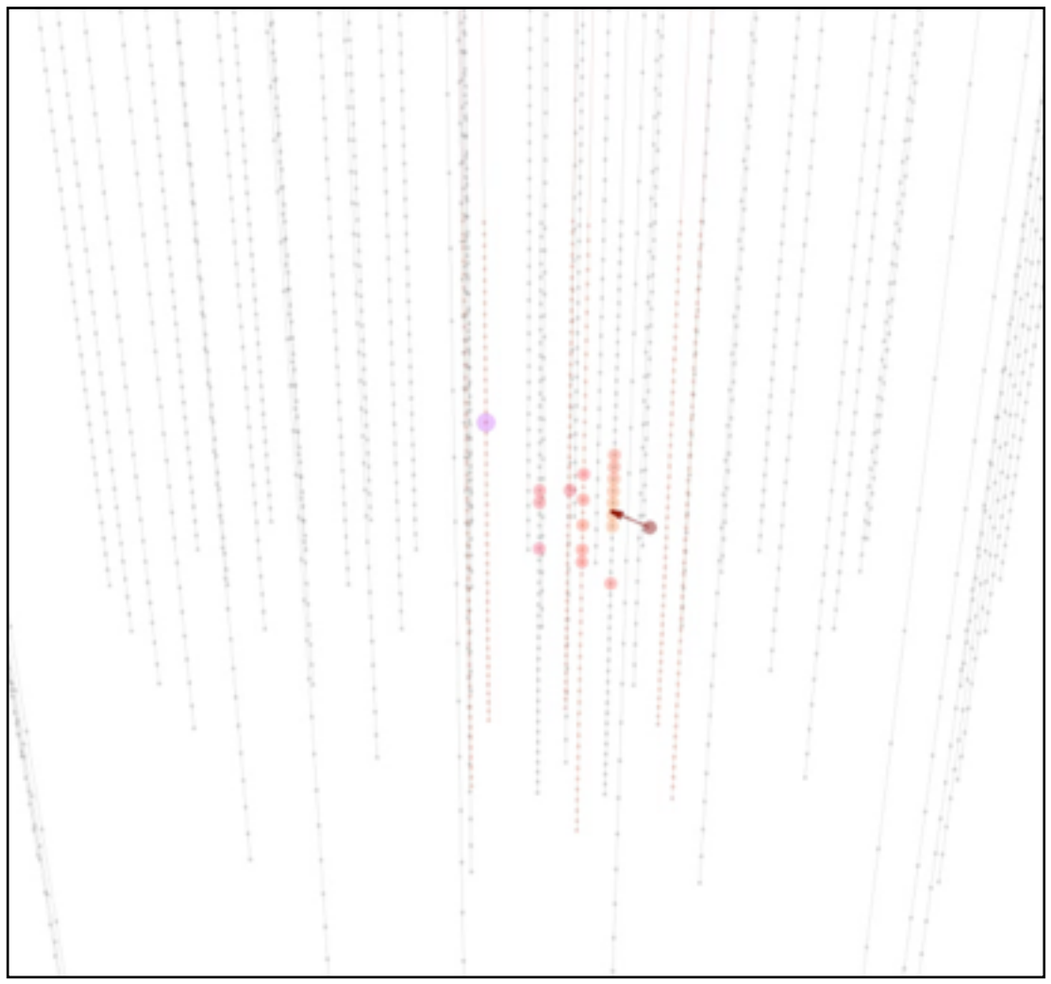

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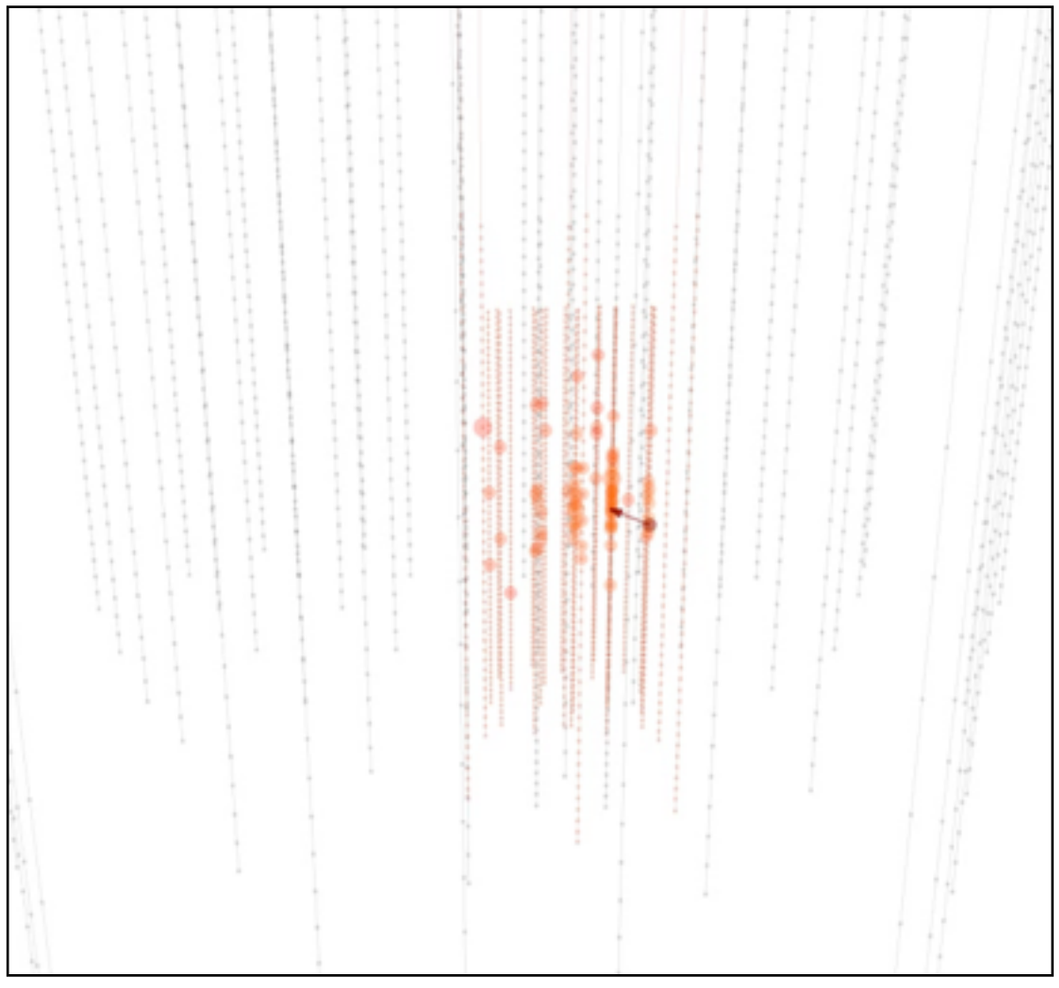

IceCube + DeepCore + PINGU

PINGU Physics

- Many topics opened up by the lowering of the energy threshold
  - muon neutrino disappearance
  - tau neutrino appearance
  - maximal θ_{23}
  - dark matter
  - neutrino mass hierarchy

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  - muon neutrino disappearance
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  - dark matter
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Neutrino Mass Hierarchy

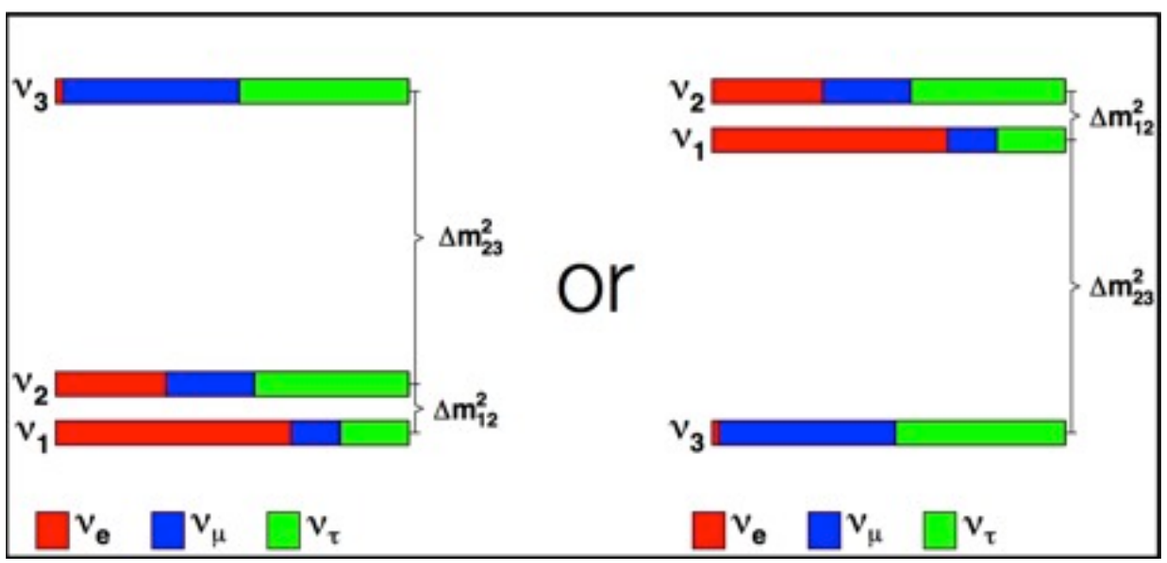
- Three flavour oscillations mean disappearance/ appearance of ν_μ are both important

$$P_{\nu_\mu \to \nu_\mu} = 1 -$$

$$cos^2\theta_{13}^m sin^2 2\theta_{23} \times sin^2\left[1.27\left(\frac{\Delta m^2_{31} + A + (\Delta m^2_{31})^m}{2}\right)\frac{L}{E}\right]$$

$$-sin^2\theta_{13}^m sin^2 2\theta_{23} \times sin^2\left[1.27\left(\frac{\Delta m^2_{31} + A - (\Delta m^2_{31})^m}{2}\right)\frac{L}{E}\right]$$

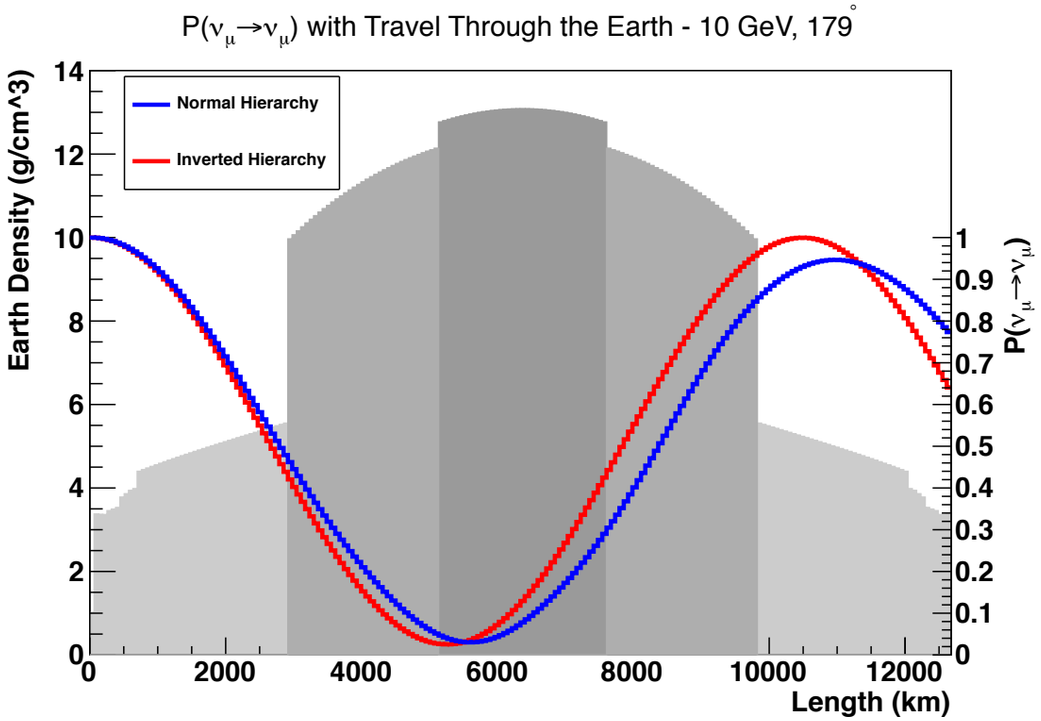
$$-sin^4\theta_{23} sin^2 2\theta_{13}^m sin^2\left[1.27(\Delta m^2_{31})^m \frac{L}{E}\right]$$

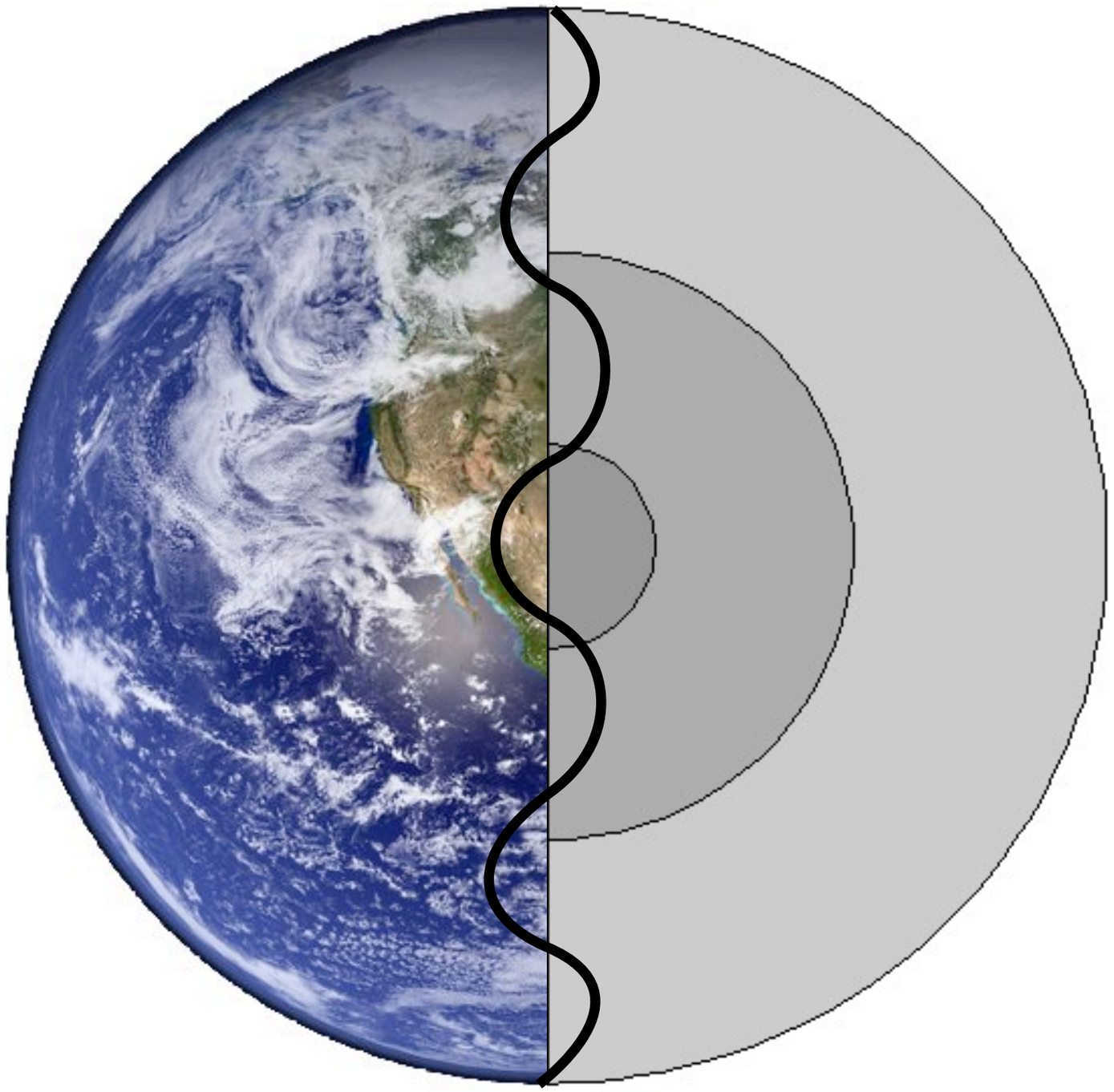


- Can be used to distinguish mass hiearchy

UNIVERSITY OF TORONTO

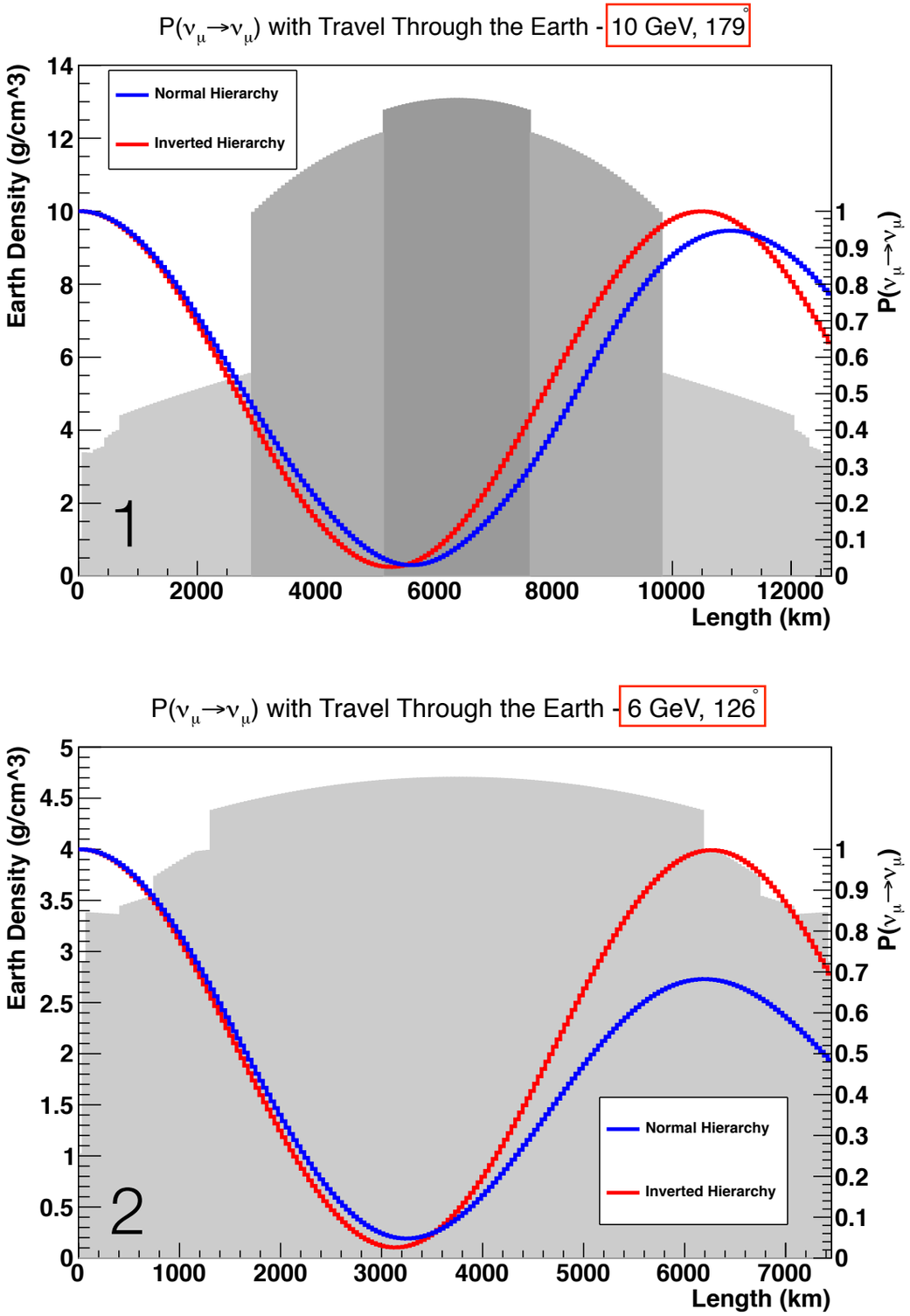
Why Atmospheric Neutrinos?

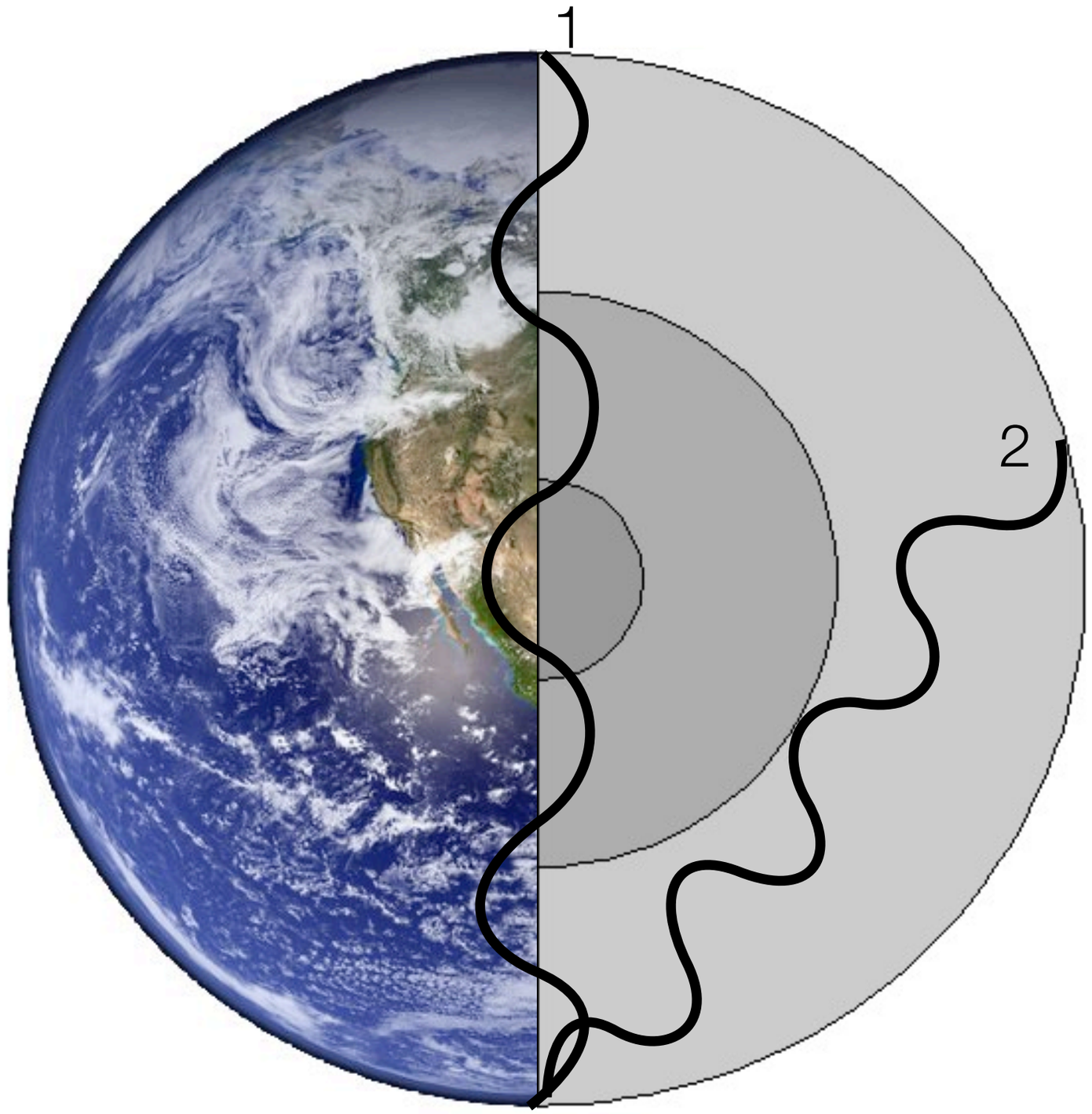




- Oscillation probability $P(\nu_\mu \rightarrow \nu_\mu)$ directly related to L/E
- L measured using angle through the Earth

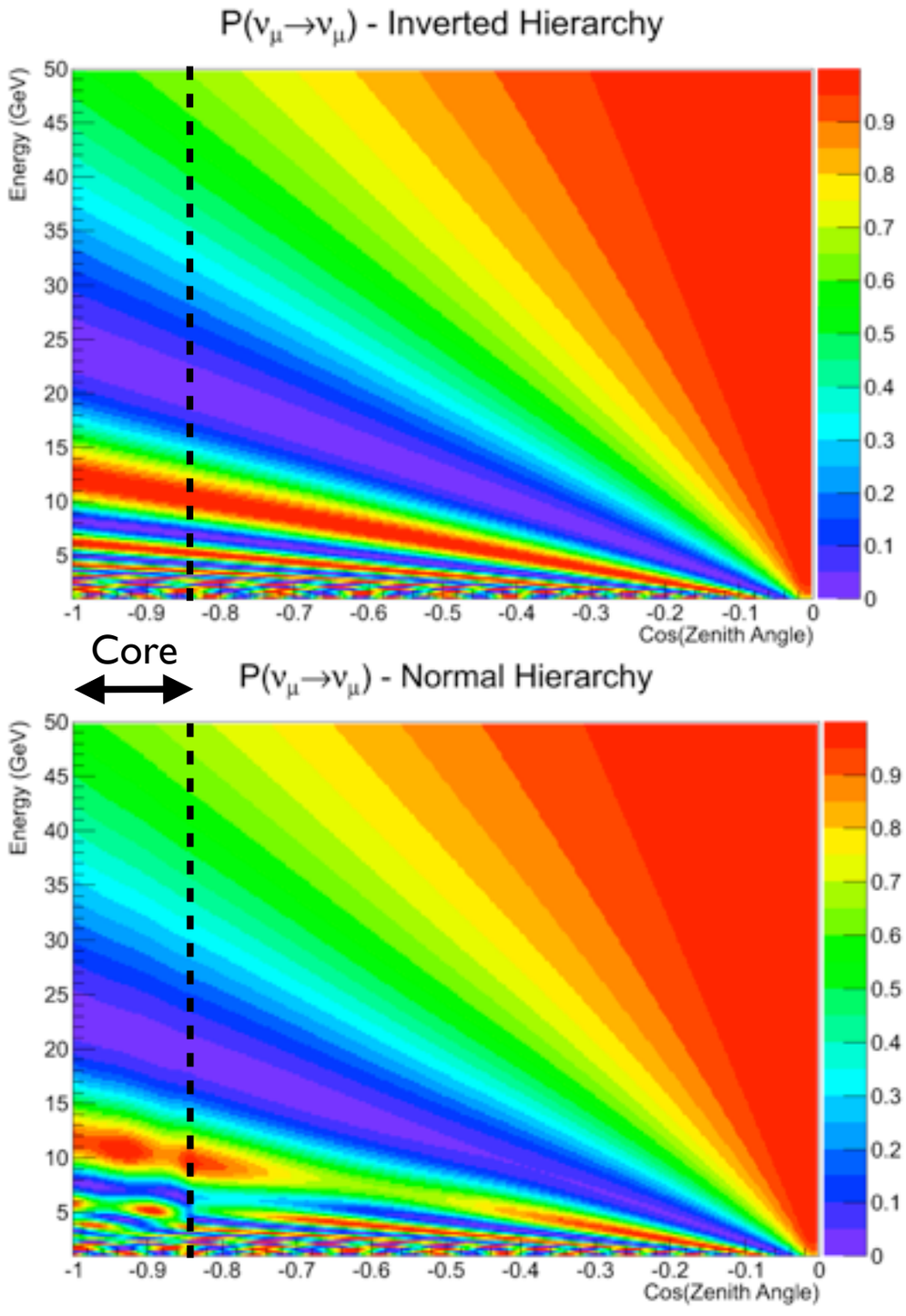
Why Atmospheric Neutrinos?





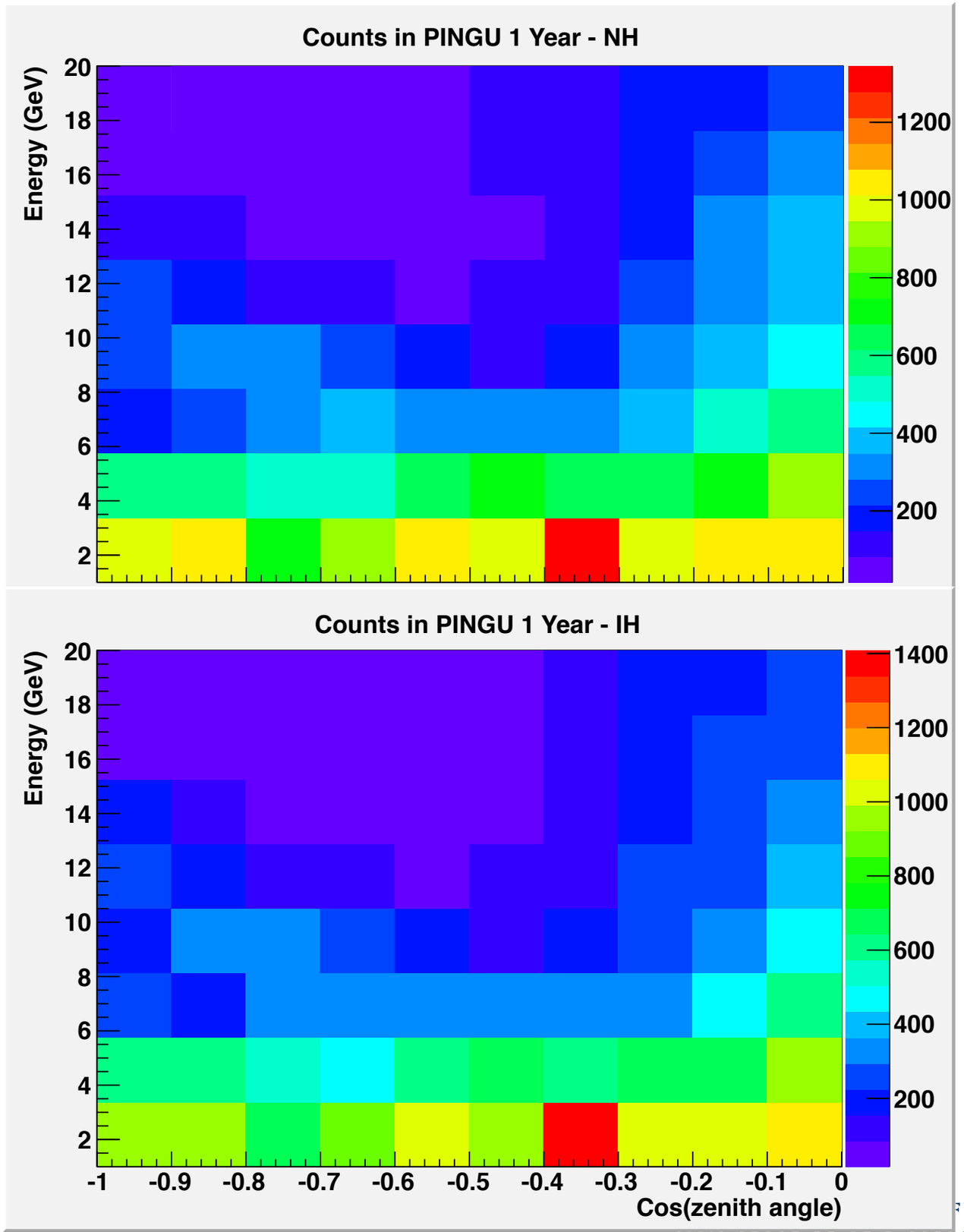
PINGU Significance

- Atmospheric neutrinos provide a large flux of incoming neutrinos at a range of incoming angles and energies
- Non-resonance MSW effects make up roughly 2/3 of PINGU's sensitivity as (anti-)neutrinos travel through the mantle
- Parametric resonance occurs for neutrinos traveling through the core to make up the remaining 1/3
  - Resonances are due to matter-induced oscillation phase changes



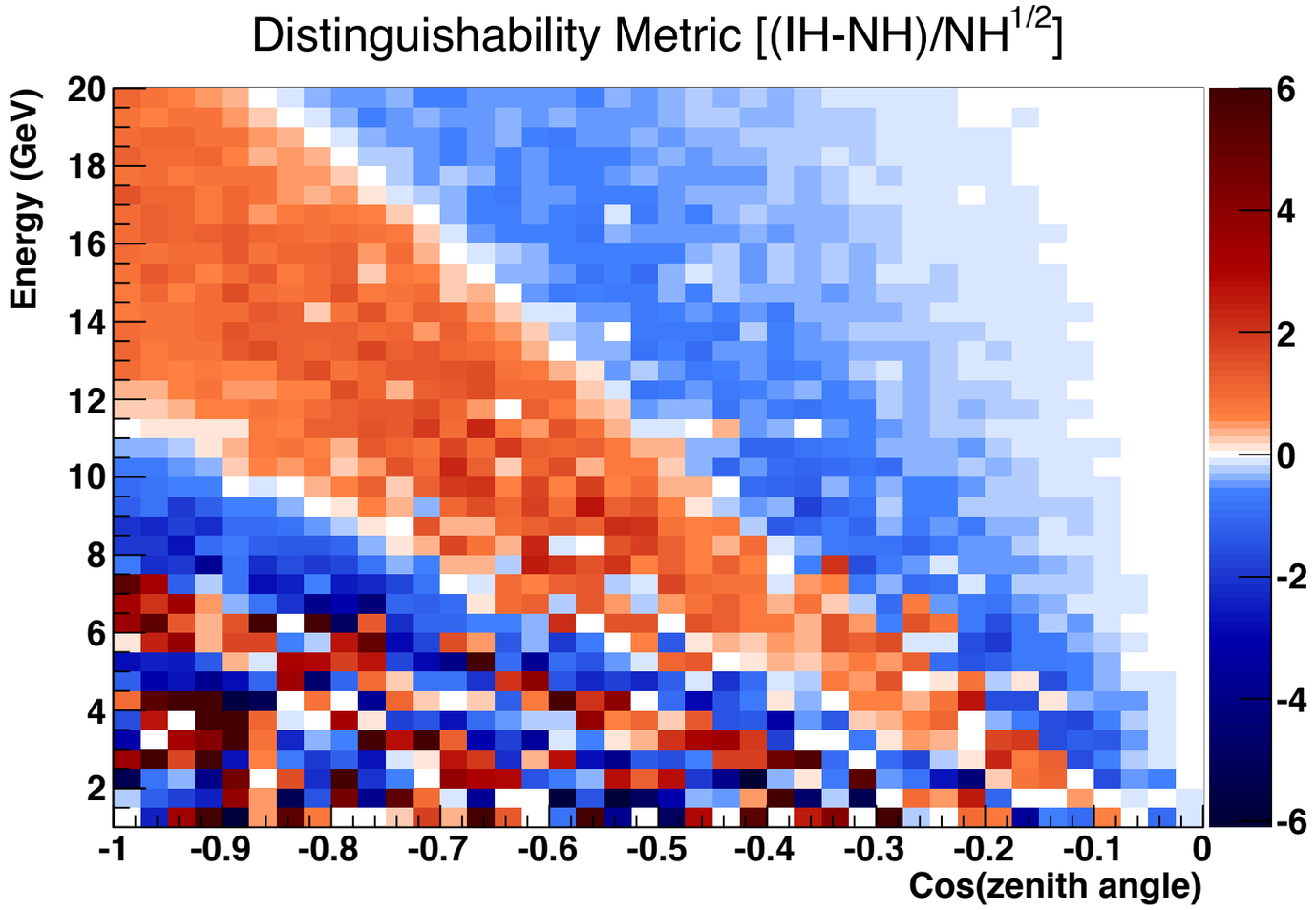
Calculating Significance

- Counts in one year are binned depending on energy and zenith angle
- This includes both ν_μ and $\overline{\nu}_\mu$
- There are differences in the number of counts per bin
- These differences create the patterns which give the distinguishability



Calculating Significance

- As an illustration, a scaled subtraction between hierarchies can be done
- Not the way significance is calculated, but illustrative
- As an example of systematics, look at resolutions



Perfect detector resolution

Calculating Significance

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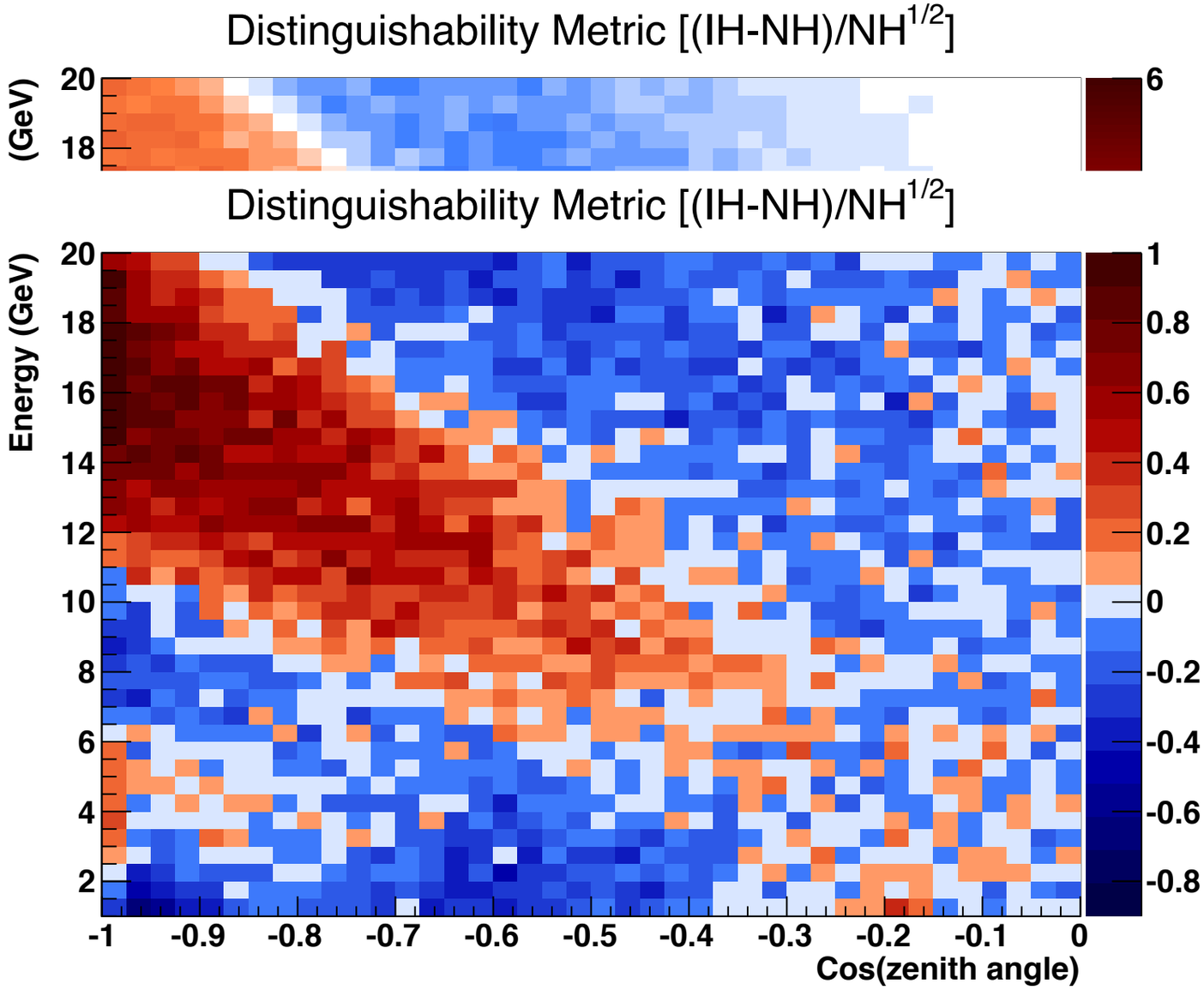

Zenith resolution: 10° Energy resolution 1 GeV

Calculating Significance

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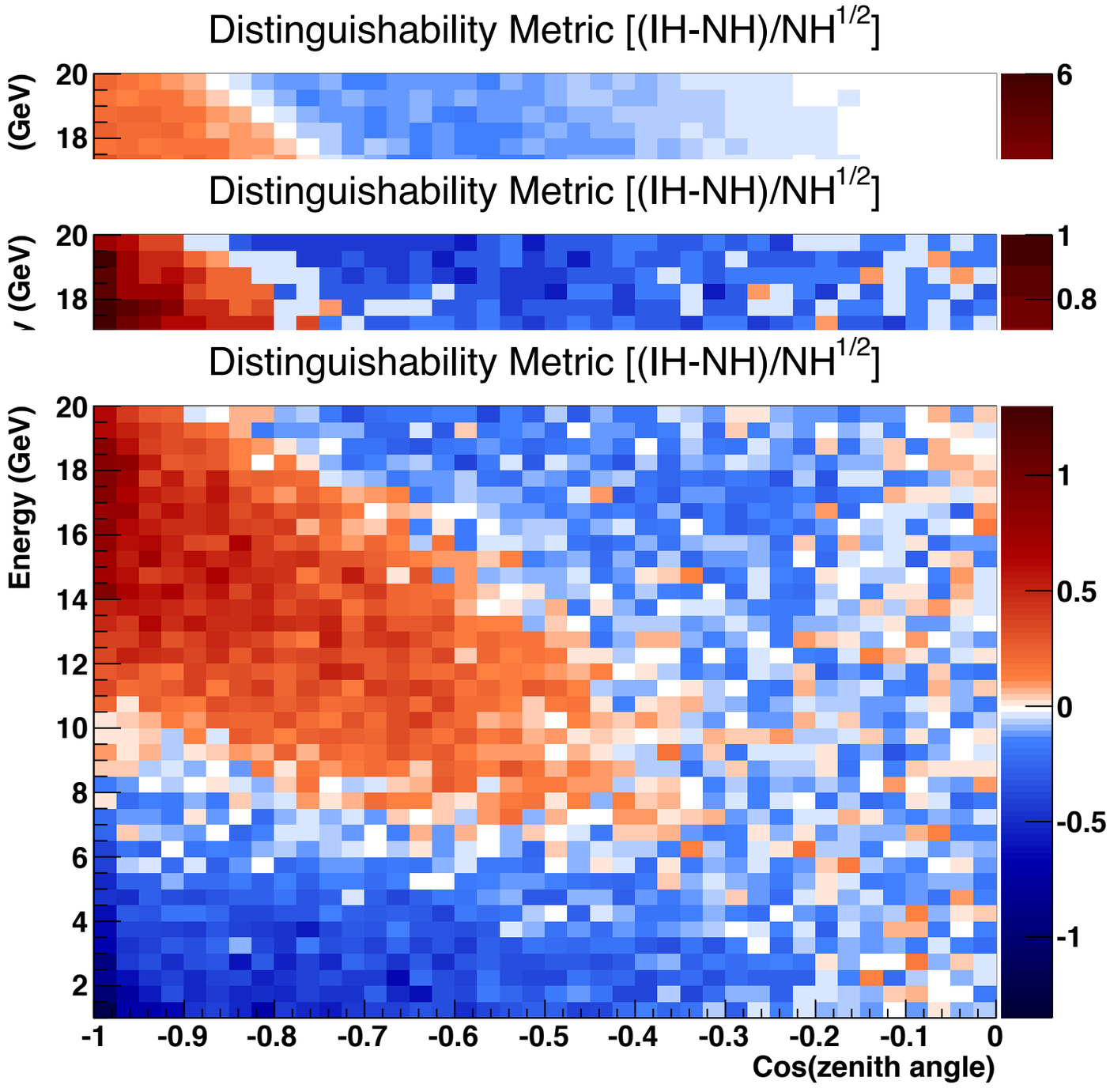
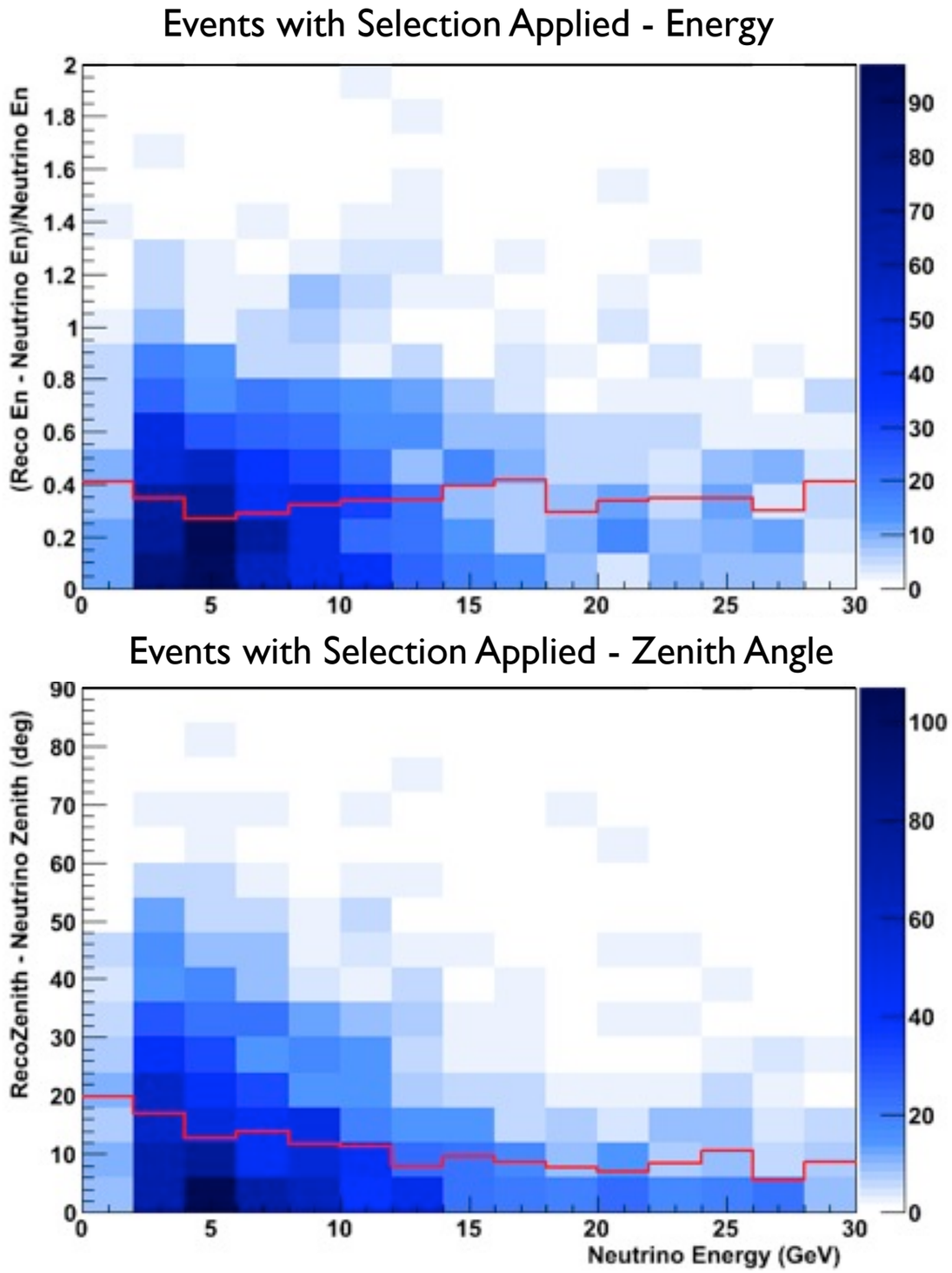


Zenith resolution: 12.5° Energy resolution 3 GeV

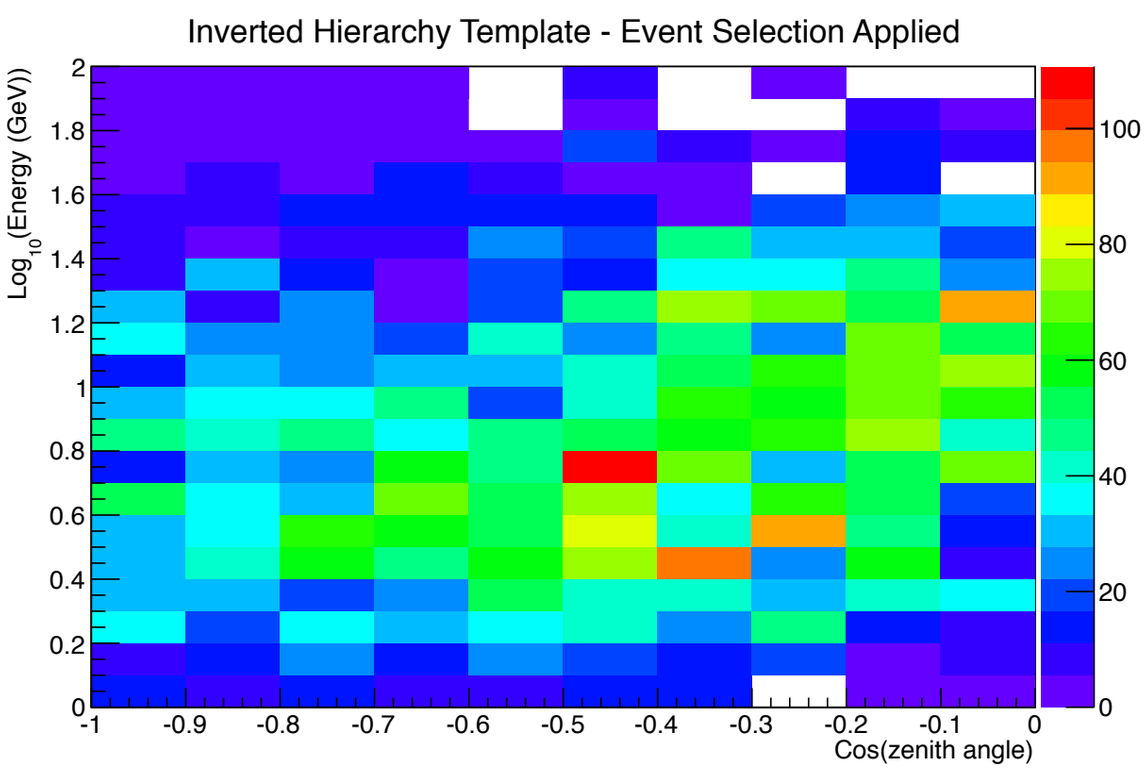
PINGU Systematics

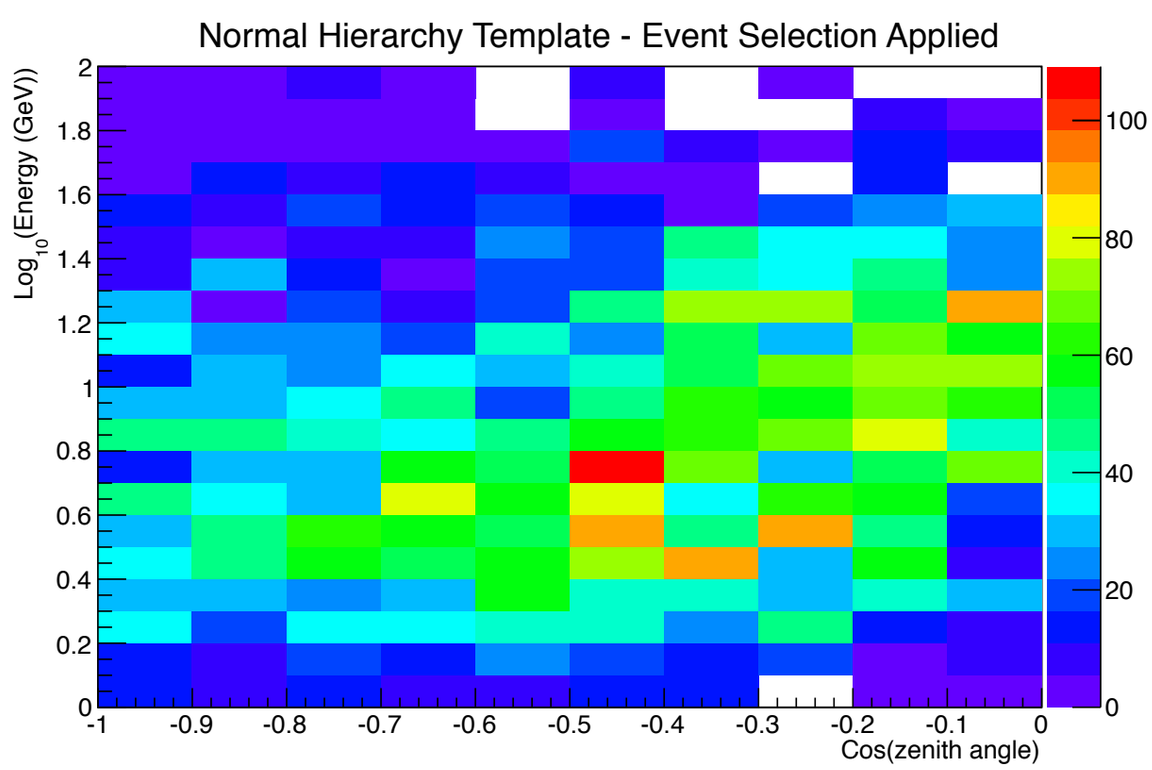
- Reconstructions are obviously a significant factor in the hierarchy determination
  - Currently using DeepCore algorithms
  - New more computationally intensive algorithms may improve resolutions
- Also studying many other sytematics
  - θ_{23}, θ_{13} Δm^2_{atm}, δ_{CP}
  - Atmospheric ν spectrum, efficiency errors, etc.



PINGU Hierarchy Analysis

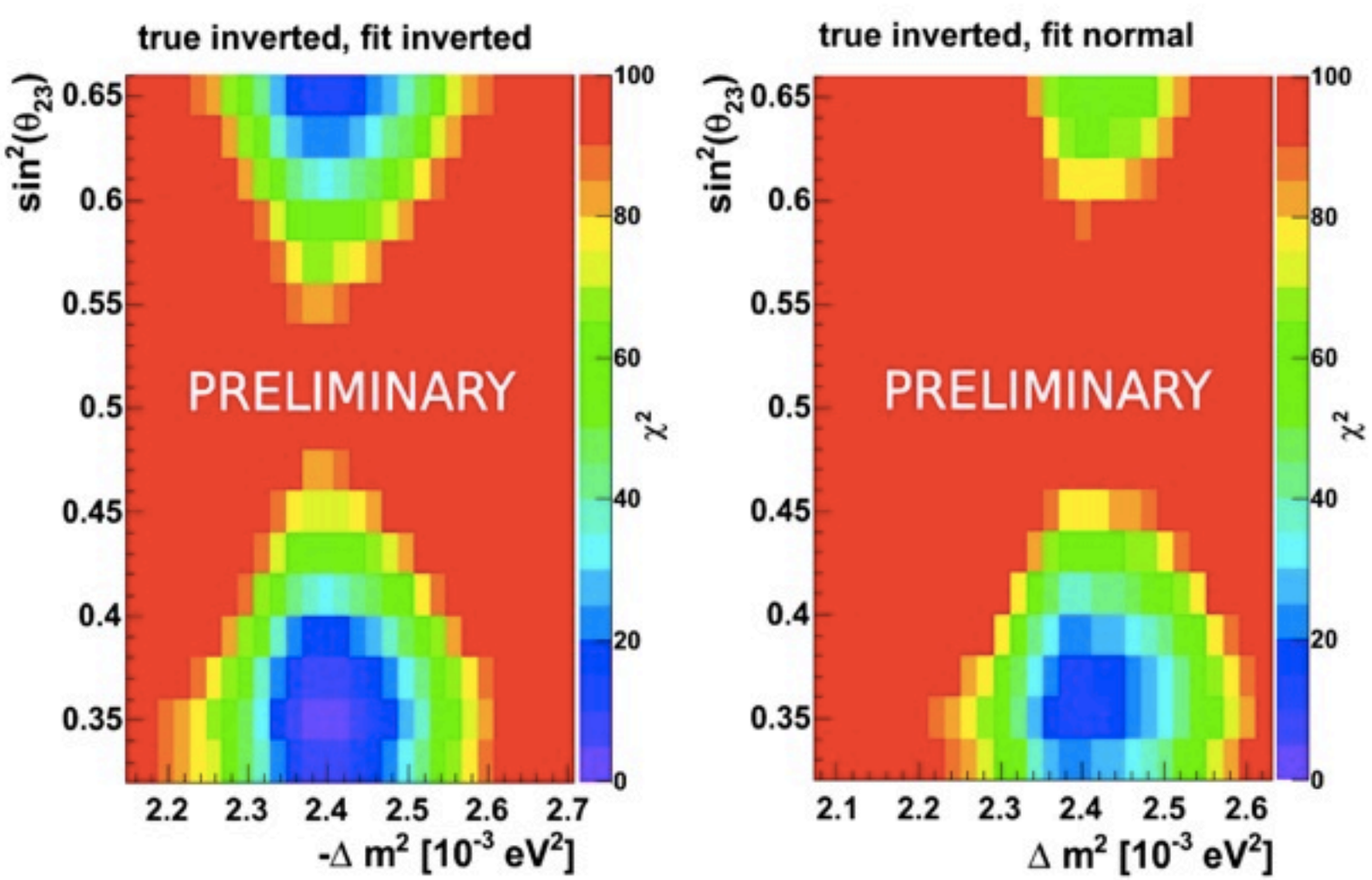
- For the final result, two different analysis methods are being pursued
- Both rely on the creation of “templates” from simulated data





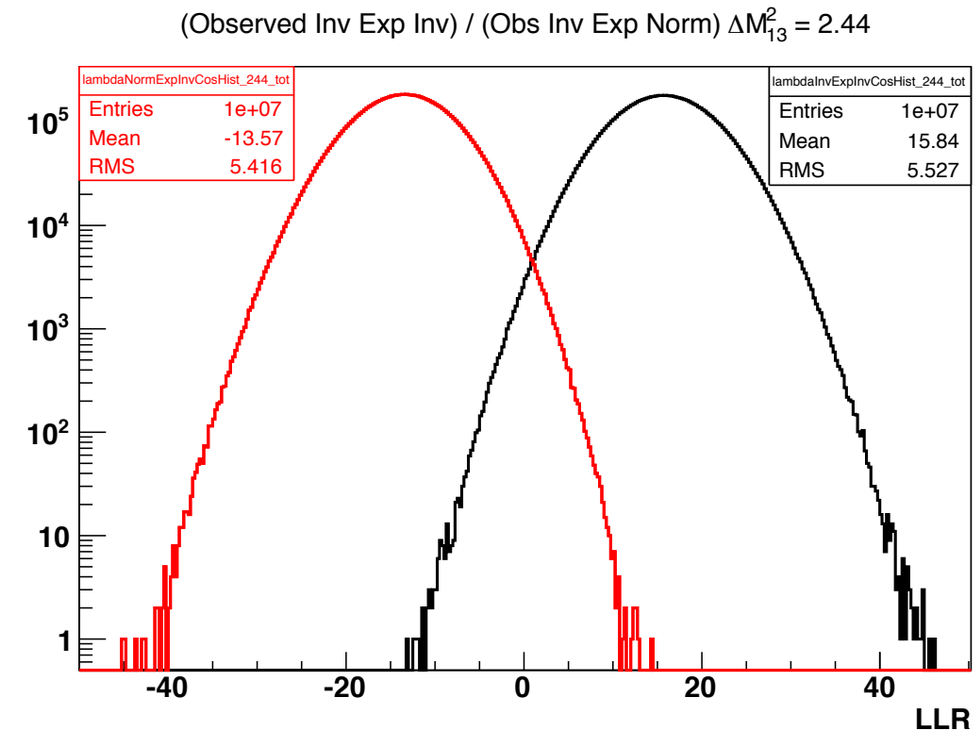
Analysis Method 1

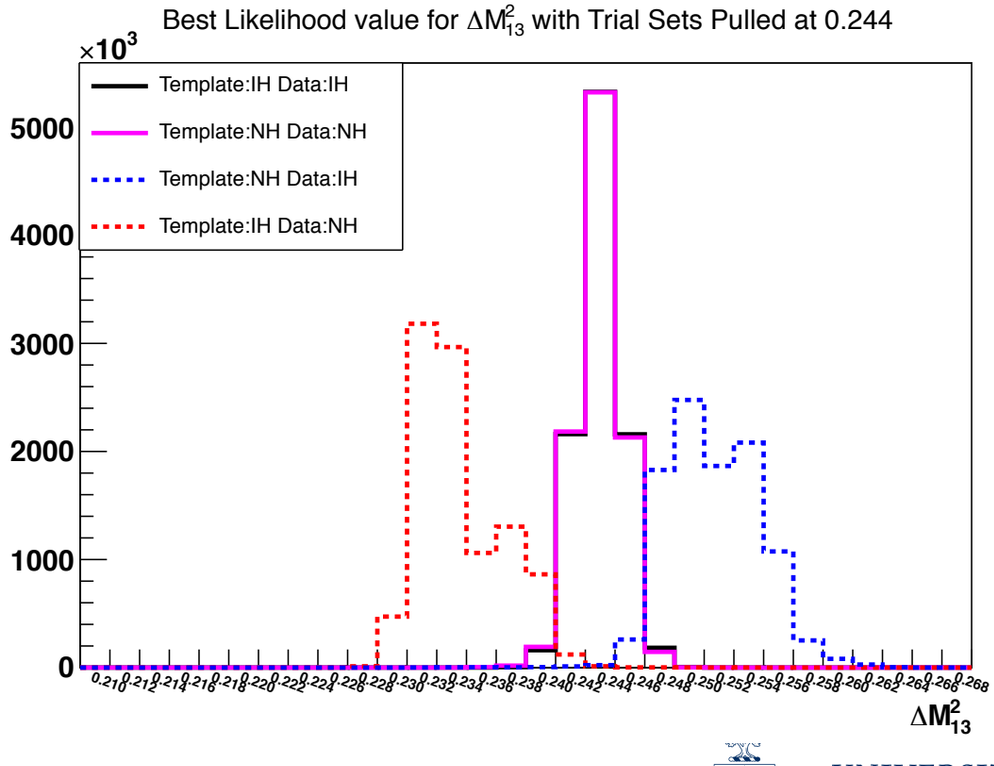
- Uses the “Asimov” method using the most likely dataset at each value of the oscillation parameters
- Calculate the χ^2 as a function of these parameters and minimize for $\Delta m^2>0$ and $\Delta m^2<0$



Analysis Method 2

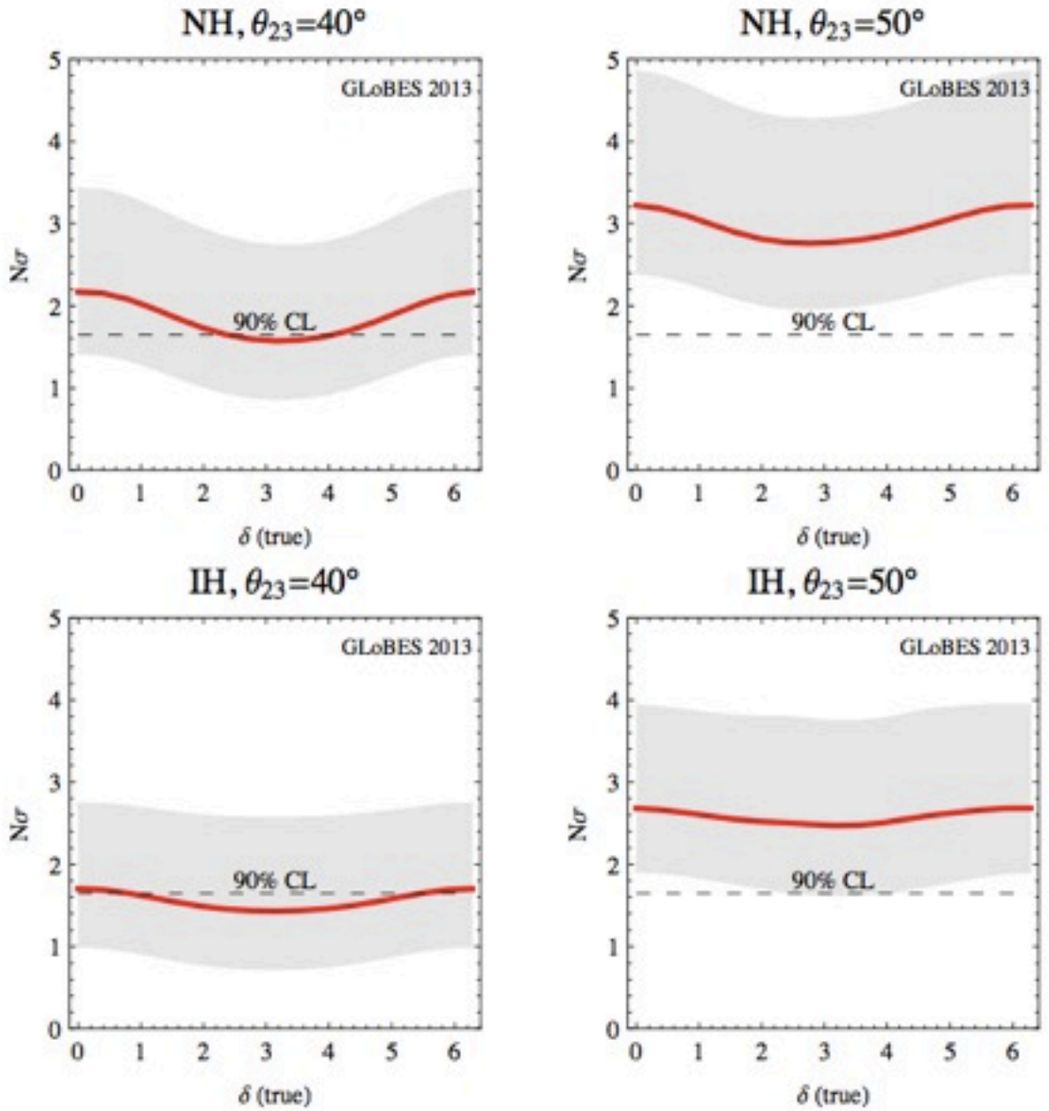
- Throw many pseudo-experiments varying the bin contents with statistical errors, allow oscillation parameters to be fit
- Generate likelihood ratios, determine significance from these

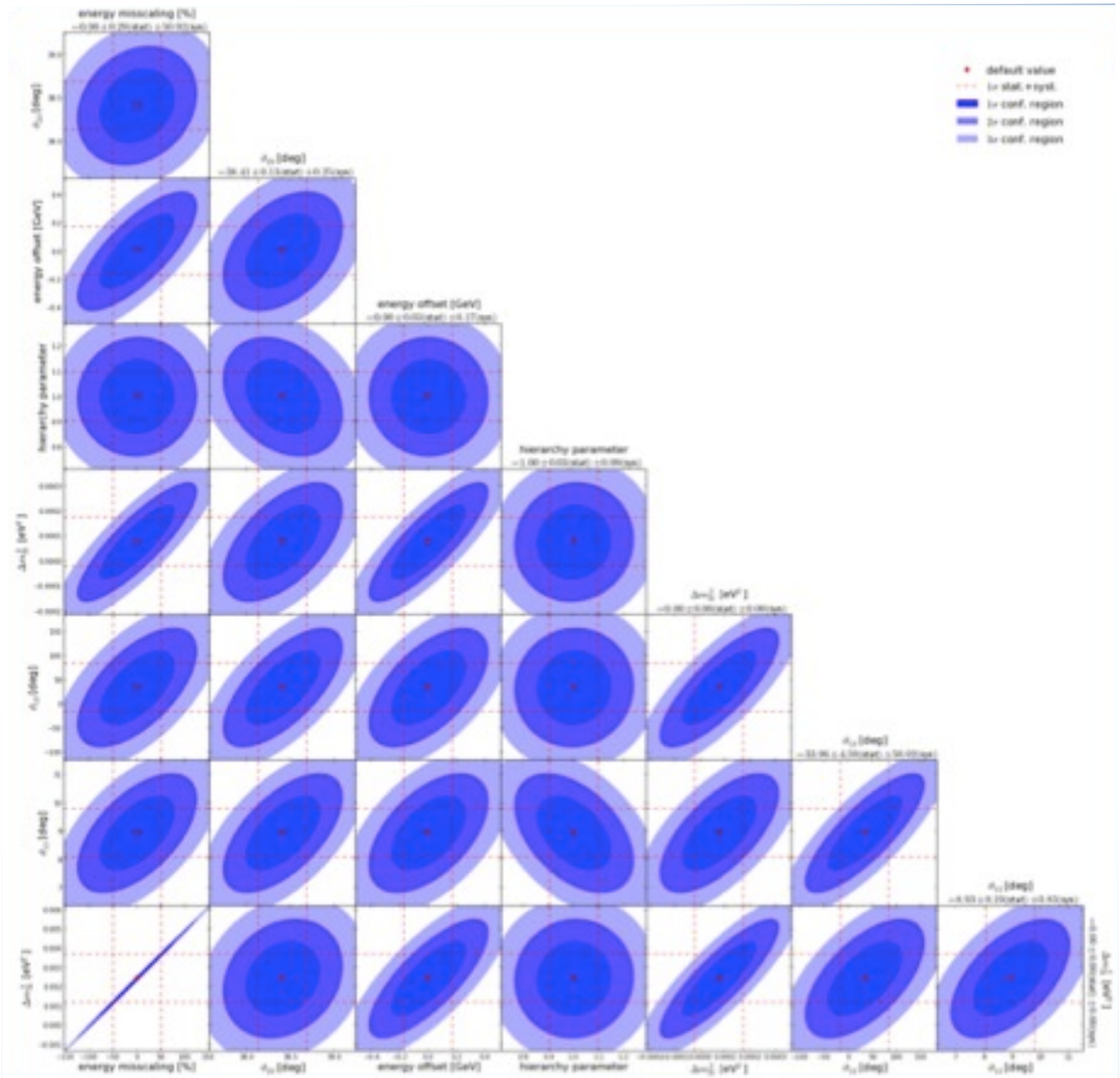




Supplemental Methods

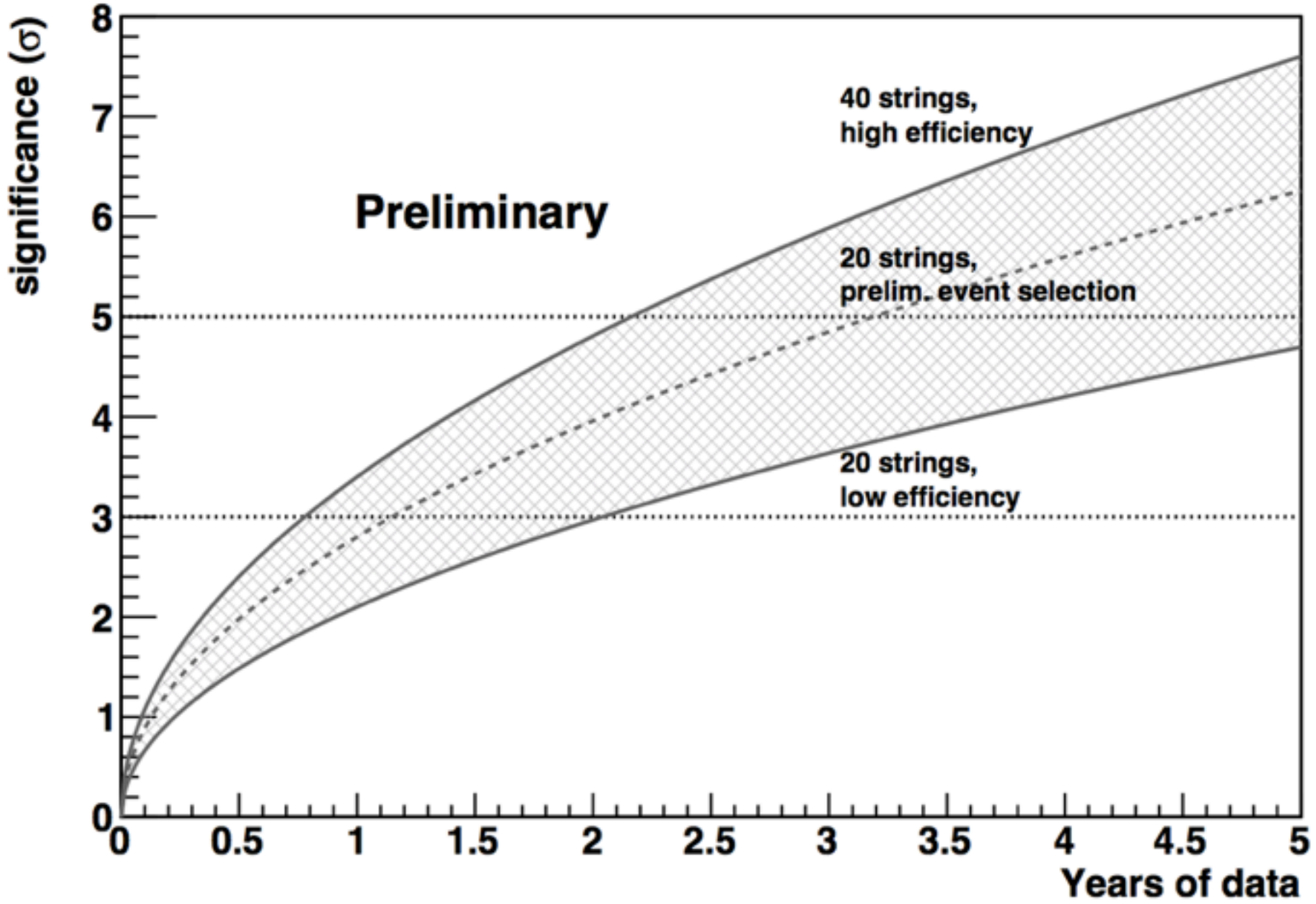
- Two relatively fast analysis methods used to study effects of systematics & parameters





Hierarchy Sensitivity

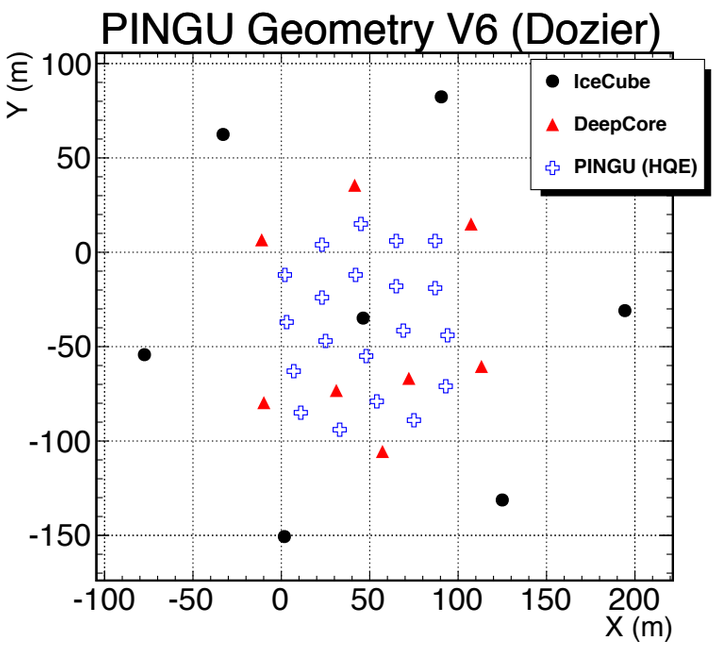
arXiv: 1306.5846

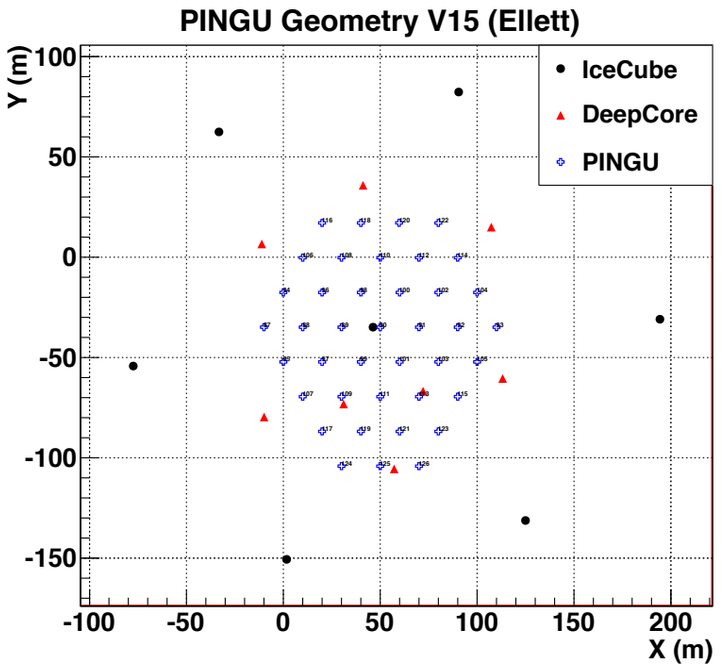


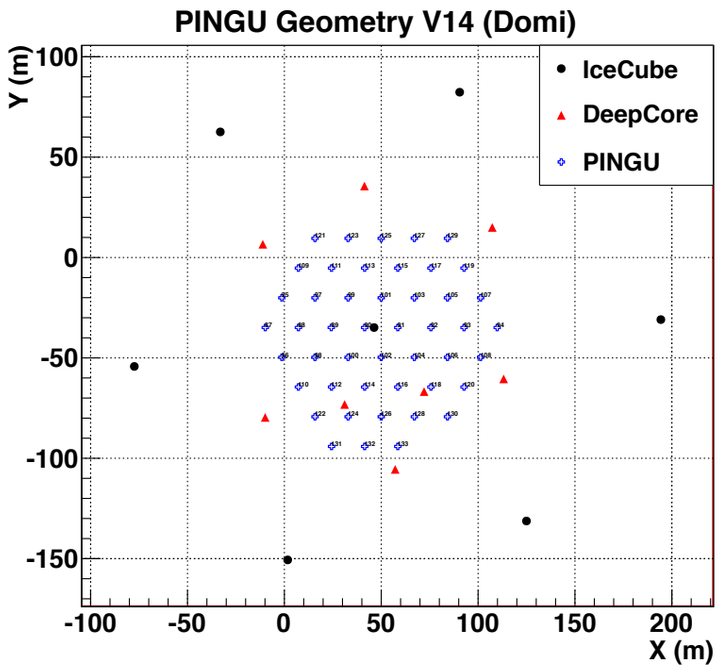
- Calculated sensitivity shown under several assumptions
  - Event selection, efficiency and detector geometry varied
- Note that all systematics have not been included here

PINGU Current Activities

- Clearly no data to show yet
- Studies underway for detailed LoI
- Example: choosing a detector geometry





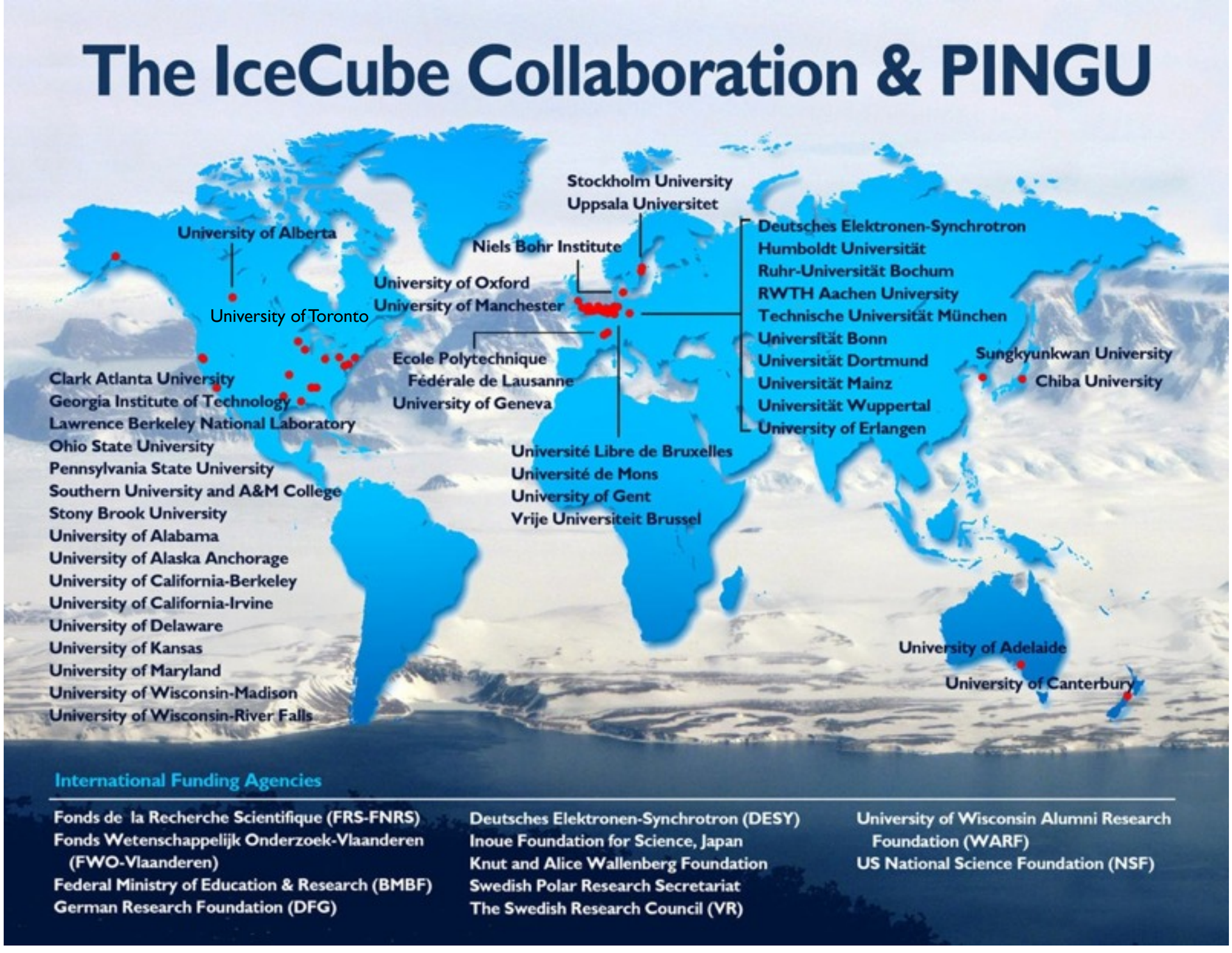


PINGU Advantages

- Relatively fast
  - Deployment could begin in the 2016-2017 season, takes 2-3 years
- Relatively inexpensive
  - Start up costs on the order of $10M plus ~$1.25M per string
- IceCube provides well understood veto
- Well understood technology
  - IceCube techniques have proven to be robust

Conclusions

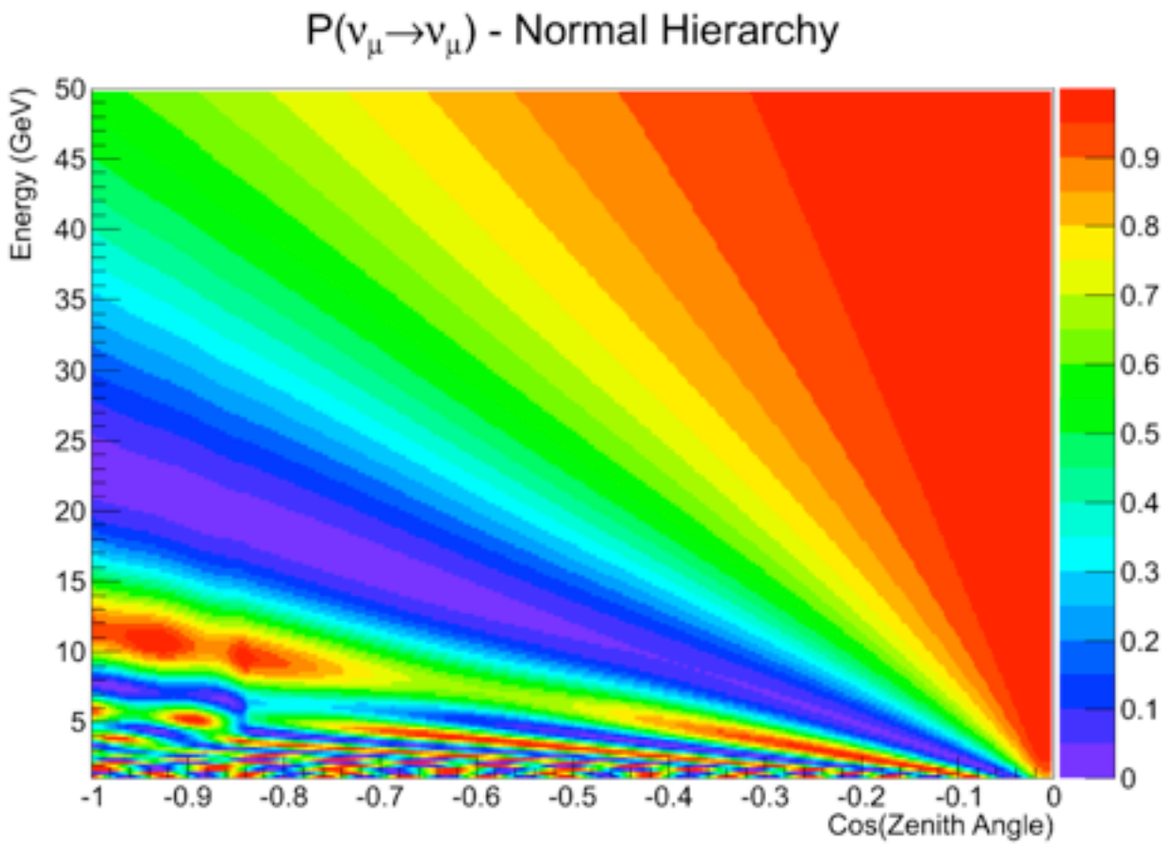
- IceCube and DeepCore have shown the viability of neutrino oscillation physics in the ice
- PINGU will extend the reach of these analyses to lower energies
- Detailed LoI and full proposal will be available soon

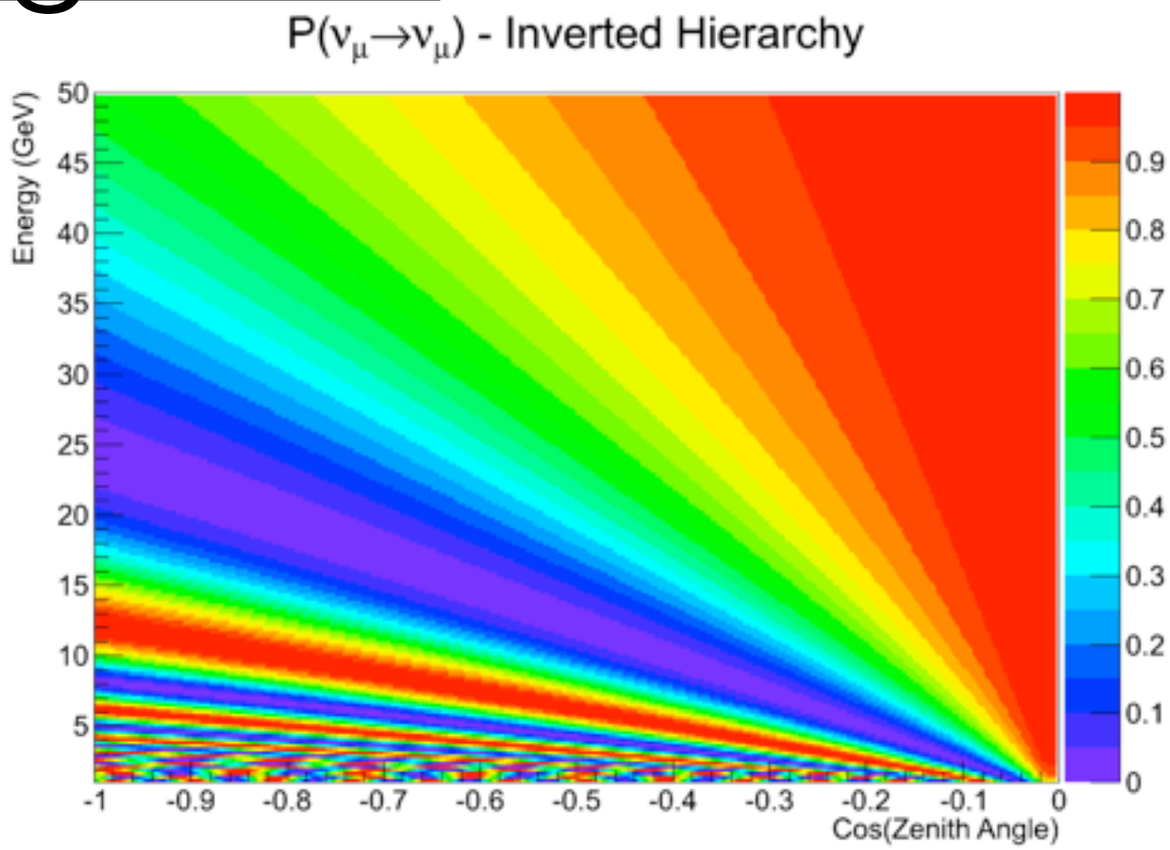


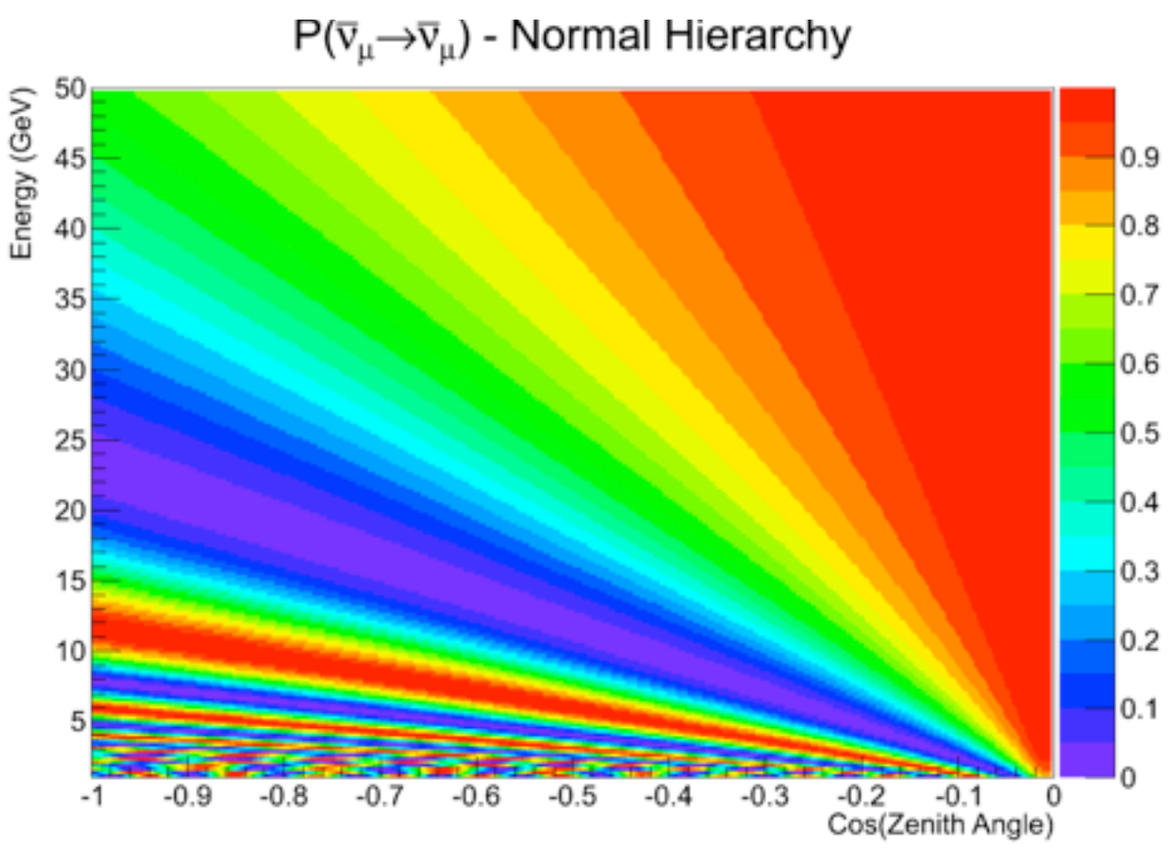
The IceCube/PINGU Collaboration

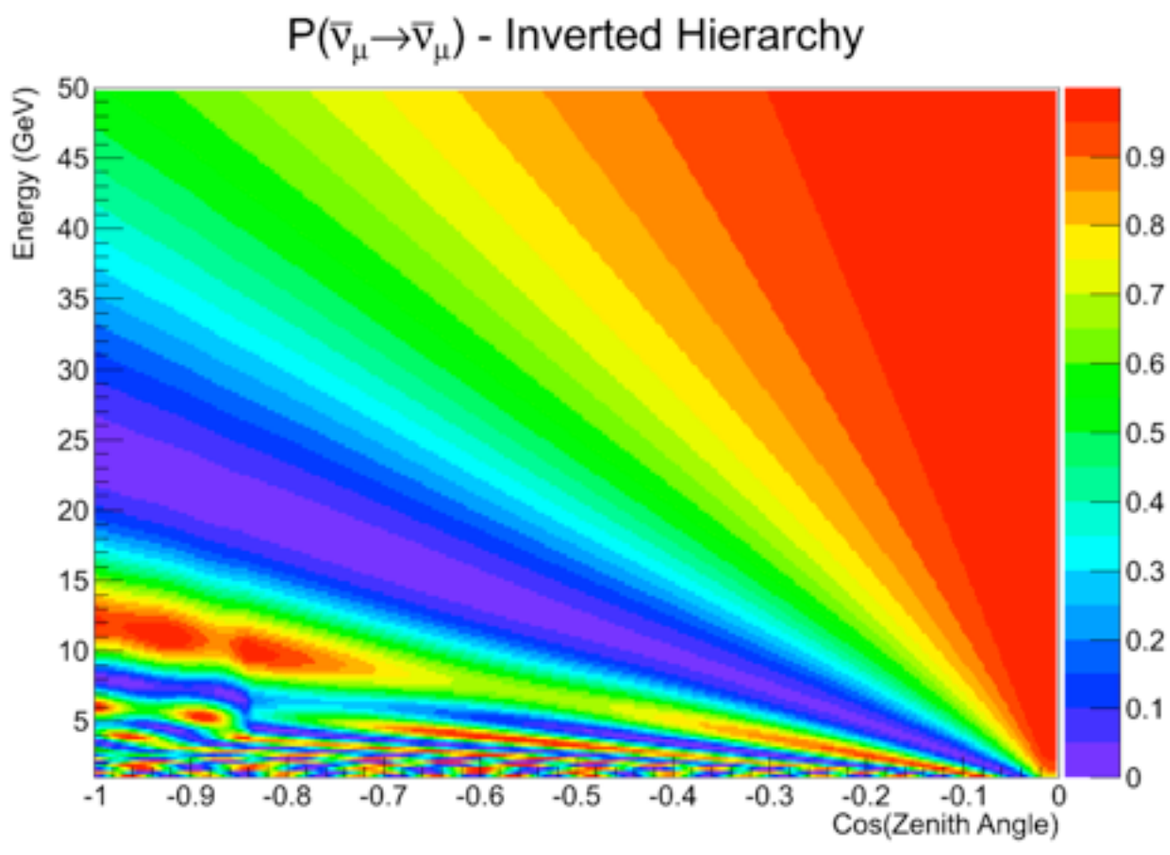
44 institutions - 4 continents - ~250 Physicists

Oscillograms



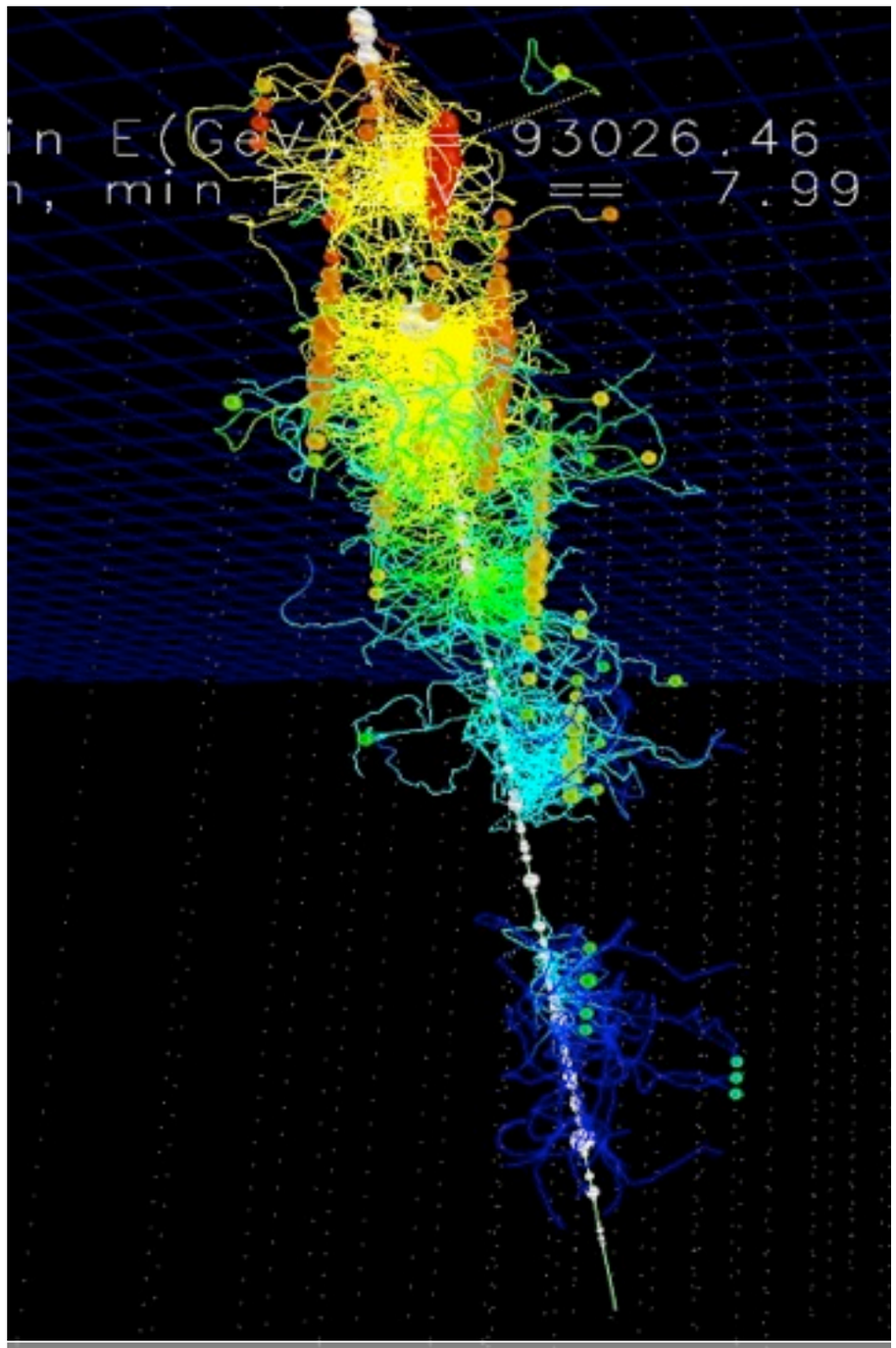






Monte Carlo Procedure

- Neutrino interactions modeled with GENIE
- Results passed to Geant4 to create light-generating particles
- Custom GPU software propagates light through detector



PINGU Advantages

- This is all known technology
- Drilling, installation can be done “quickly”
- Low cost (relative to other experiments)
- “We know how to do this”